



INTERNATIONAL DOCTORAL
SCHOOL OF THE USC

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PhD Thesis

New approaches to the direct
search of BSM physics with
Codex-b and LHCb
experiments.

Santiago de Compostela, 2024

Doctoral Programme in Nuclear and Particles Physics

DOCTORAL THESIS

NEW APPROACHES TO THE DIRECT SEARCH OF BSM PHYSICS WITH CODEX-B AND LHCb EXPERIMENTS

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"I didn't choose this town, I dream of getting out."

Taylor Swift

"And I cry, it's not fair."

Chappell Roan

"These are what they call hard feelings."

Lorde

Abstract

This work presents studies in Beyond Standard Model Physics, using two different experiments, LHCb and future CODEX-b.

A search for Dark Matter from Λ_b decays is performed within the LHCb experiment during the LHC Run II at a center of mass energy of $\sqrt{s} = 13$ TeV. Two dark matter operators are studied, $\mathcal{O}_{cd}(\bar{b} \rightarrow \psi_{\text{DM}}cd)$ and $\mathcal{O}_{cs}(\bar{b} \rightarrow \psi_{\text{DM}}cs)$ with $0.940 \text{ GeV}/c^2 < m(\psi_{\text{DM}}) < 4.430 \text{ GeV}/c^2$, respectively. The Λ_b baryons originate in $\Sigma_b^{(*)}$ decays. $\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K)$ and $\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K)$ are the final observed states. No signal is observed in any of the studied decay modes and the following upper limits are set for the first time: $\mathcal{B}(\mathcal{O}_{cs}(\bar{b} \rightarrow \psi_{\text{DM}}cs)) < 8.96 \times 10^{-5} - 6.23 \times 10^{-4}$ for $0.940 \text{ GeV}/c^2 < m(\psi_{\text{DM}}) < 3.0 \text{ GeV}/c^2$ and $\mathcal{B}(\mathcal{O}_{cd}(\bar{b} \rightarrow \psi_{\text{DM}}cd)) < 2.45 \times 10^{-4} - 8.25 \times 10^{-5}$ for $0.940 \text{ GeV}/c^2 < m(\psi_{\text{DM}}) < 3.5 \text{ GeV}/c^2$ at 95% CL.

Within the CODEX-b, some studies for potential long lived particles searches are performed. A generator level efficiency for three different production modes (inclusive, Higgs-strahlung and weak-boson fusion) is computed in the framework of the CODEX-b experiment assuming a minimal Higgs portal model. These Higgs production modes are the dominant ones, while the Higgs portal decay models show a minimal decay model that would allow for future searches within the CODEX framework.

This two experiments could also work together for collaborative searches, as showcased in this work.

Limiar

Este traballo presenta estudos de física alén do modelo estándar, usando dous experimentos diferentes, LHCb e o futuro CODEX-b.

Realizouse unha busca de materia escura a partir de desintegracións de Λ_b recollidas polo experimento LHCb durante a Run II do LHC a unha enerxía no centro de masas de $\sqrt{s} = 13$ TeV. Estudáronse dous operadores de materia escura, $\mathcal{O}_{cd}(\bar{b} \rightarrow \psi_{\text{DM}}cd)$ e $\mathcal{O}_{cs}(\bar{b} \rightarrow \psi_{\text{DM}}cs)$, con masas $0.940 \text{ GeV}/c^2 < m(\psi_{\text{DM}}) < 4.430 \text{ GeV}/c^2$, respectivamente. Os barións Λ_b orixínanse en desintegracións de $\Sigma_b^{(*)}$. $\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K)$ e $\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K)$ son os estados finais observados. Non se observou sinal en ningún dos modos de desintegración estudados e establécense por primeira vez os seguintes límites superiores: $\mathcal{B}(\mathcal{O}_{cs}(\bar{b} \rightarrow \psi_{\text{DM}}cs)) < 8.96 \times 10^{-5} - 6.23 \times 10^{-4}$ para $0.940 \text{ GeV}/c^2 < m(\psi_{\text{DM}}) < 3.0 \text{ GeV}/c^2$ e $\mathcal{B}(\mathcal{O}_{cd}(\bar{b} \rightarrow \psi_{\text{DM}}cd)) < 2.45 \times 10^{-4} - 8.25 \times 10^{-5}$ para $0.940 \text{ GeV}/c^2 < m(\psi_{\text{DM}}) < 3.5 \text{ GeV}/c^2$ ao 95% CL.

No marco de CODEX-b, realízanse estudos para potenciais búsquedas de partículas de vida media longa. Calculouse unha eficiencia a nivel de xerador para tres modos de produción diferentes (inclusivo, Higgs-strahlung e fusión de bosóns débiles) no marco do experimento CODEX-b supoñendo un modelo mínimo de portal de Higgs. Estes mecanismos de produción do Higgs representan os dominantes, mentres que os modelos portais de Higgs amosan un modelo mínimo que permitiría búsquedas destas partículas no detector CODEX-b.

Estes dous experimentos tamén poderían utilizarse conxuntamente para realizar diferentes búsquedas, como se amosa neste traballo.

Resumen

Este trabajo presenta estudios de física más allá del modelo estándar, usando dos experimentos diferentes, LHCb y el futuro CODEX-b.

Se realiza una búsqueda de materia oscura a partir de desintegraciones de Λ_b recogidas por el experimento LHCb durante el Run II del LHC a una energía en el centro de masa de $\sqrt{s} = 13$ TeV. Se estudian dos operadores de materia oscura, $O_{cd}(\bar{b} \rightarrow \psi_{\text{DM}} c d)$ y $O_{cs}(\bar{b} \rightarrow \psi_{\text{DM}} c s)$ con $0.940 \text{ GeV}/c^2 < m(\psi_{\text{DM}}) < 4.430 \text{ GeV}/c^2$, respectivamente. Los bariones Λ_b se originan en desintegraciones de $\Sigma_b^{(*)}$. $\Lambda_b \rightarrow \psi_{\text{DM}} K (D \rightarrow \pi \pi K)$ y $\Lambda_b \rightarrow \psi_{\text{DM}} K (D \rightarrow \pi \pi K)$ son los estados finales observados. No se observa señal en ninguno de los modos de desintegración estudiados y se establecen los siguientes límites superiores por primera vez: $\mathcal{B}(O_{cs}(\bar{b} \rightarrow \psi_{\text{DM}} c s)) < 8.96 \times 10^{-5} - 6.23 \times 10^{-4}$ para $0.940 \text{ GeV}/c^2 < m(\psi_{\text{DM}}) < 3.0 \text{ GeV}/c^2$ y $\mathcal{B}(O_{cd}(\bar{b} \rightarrow \psi_{\text{DM}} c d)) < 2.45 \times 10^{-4} - 8.25 \times 10^{-5}$ $0.940 \text{ GeV}/c^2 < m(\psi_{\text{DM}}) < 3.5 \text{ GeV}/c^2$ al 95% CL.

Se calcula la eficiencia a nivel de generador para tres modos de producción diferentes (inclusivo, Higgs-strahlung y fusión de bosón débil) en el marco del experimento CODEX-b asumiendo un modelo de portal de Higgs mínimo. Estos mecanismos de producción de Higgs representan los dominantes, mientras que los modelos portales de Higgs suponen un modelo mínimo que permitiría búsquedas de estas partículas en el detector CODEX-b.

Estos dos experimentos también podrían utilizarse conjuntamente para realizar diferentes búsquedas, como se muestra en este trabajo.

Acknowledgements

A cantidade de xente que me levo destes anos roza o innumerable, pero creo que comezar cos meus pais, Muchi e Camilo, é o mellor punto, xa que sen o seu apoio e educación, e contra vento e marea, sería imposible que eu puidese escribir isto.

Agradecer tamén aos meus directores, Xabi e Carlos, pola guía neste traballo, así tamén aos meus titores na sombra Adrián e Alexandre, sen os cales non podería nunca ter feito esta tese; e Emilio e Miguel, polo código compartido. Por suposto incluír tamén a inestimable axuda académica e persoal de todos os compañeiros do despacho 26: Moncho, Pablo e Asier (o compi de piso máis chill que ninguén podería desexar) que acompañaron todos estes anos e aos achegados, que tiveron a sorte de rematar antes: Dulla, Gabis, Gonzalo e Marcos. E ás persoas que aguantaron o verán en Suíza, facendo del algo máis ameno: Eloi e Erl.

Tampouco isto sería posible sen os descansos para os cafés, que comezaron cun grupo modesto e rematou por ser un grupo de amizades do que sigo e seguirei a desfrutar: Clara, Juan, Martina, Miguel e especialmente Arnau; e ás novas fichaxes que toman o relevo: Bea, David, Fran e Carmen. Julián, Alicia, Martín e Xoán, tamén abonados aos cafés pero tamén a moitas mais cousas fóra, moitas grazas por todos estes anos ao voso carón, así como para os que non estaban nos cafés pero si en todo o demáis: Carol, Cris, Antía, Sergio, Mar, Diego, Tomás, Juanma, Rocío, Kiara, Iago, Aitor, Eugenia, María, Pedrito, Saruki, Sampi... e persoas que inevitablemente estou a olvidar e pido desculpas por iso.

No ámbito persoal e non académico, Xabi, mereces unha mención máis especial xa que penso que confiaches máis en min durante estes anos máis do que eu o fixen; grazas por iso.

E ás dúas persoas que mais me apoiaron e nas que máis me apoiei durante todos estes anos, Verónica e Carlos, os meus pronomes favoritos, non teño palabras para plasmar aquí todo que sinto por vos, a moita felicidade que me produce cada intre que pasamos xuntos e o moi querido que me sinto. Sodes unhas persoas totalmente excepcionais e o agradecemento que sinto é infinito.

Por último, á persoa que me quixo nas últimas etapas máis duras e insufribles, onde cada día era peor que o anterior excepto por ti, que pinta todo dunha cor máis bonita e que sempre pensou que podía conseguir todo, aínda que non fose así ás veces, grazas, por todo, Fermín.

List of Figures

1.1	SM transition of a s quark to a u quark via W^- emission. The full decay would be $\Lambda \rightarrow p\mu^-\bar{\nu}_\mu$	2
1.2	Diagram of the proposed model and how it ensures the Sakharov conditions. The figure has been adapted from [18].	6
1.3	The two decays that will be studied in this work. Any of them could be enough to a successful explanation of the model provided that its BR is large enough. The first one is the one associated with the O_{cd} operator whereas the second is related to O_{cs}	8
1.4	Current limits on inclusive $\text{Br}(B \rightarrow \mathcal{B}\psi_{\text{DM}}\mathcal{M})$ as a function of the DM particle ψ_{DM} constrained by the recast of a search conducted by ALEPH as well as indirect searches from ATLAS and CMS for particles similar to the propagator of the model (TeV-scales color-triplet scalars). The excluded area would be the lightest coloured one. Figure obtained from [18] under Creative Commons license.	10
1.5	$\mathcal{L} \supset A_S SH^\dagger H$ associated diagram where the parameter A_S has already been substituted by a mixing angle and the S field identified with the A^0 particle has inherited the fermionic decay of the SM Higgs.	12
1.6	Main production modes of the SM Higgs: Higgs-strahlung (left), weak-boson fusion (right) and gluon-gluon fusion (bottom).	13
1.7	Diagram of potential physics cases covered by current, proposed and future experiments depending on the LLP mass, lifetime or allowed Center-of-Mass energy. Reproduced from [33] under Creative Commons license.	14
3.1	Diagram of a potential location for the CODEX-b detector in relation to the LHCb detector. Reproduced from [33] under Creative Commons license.	18
3.2	Cern accelerator complex diagram taken from [61] under Creative Commons licensing. Many of the experiments of the institution are also shown in this diagram.	20
3.3	Diagram of the LHCb detector with the described components. Taken from [80] under Creative Commons License.	22

3.4	Schedule of the LHC data taking periods. LHC Run 1 took place from 2011 to 2013 and Run 2 from 2015 to 2018. Taken from [81] under Creative Commons License.	23
5.1	Efficiencies plot for all detection modes described. Both axes are in logarithmic scale, and no event with both A^0 in CODEX is found. .	31
5.2	Efficiencies plot for the detection modes described for the Higgsstrahlung production. Both axes are in logarithmic scale.	32
5.3	Efficiencies plot for the described detection modes for the jets associated production mode. Both axes are in logarithmic scale. Note that almost no events with two jets in CODEX are produced since the requirements of detection are very tough.	33
5.4	Efficiencies plot (right) and expected events (left) to be detected at the CODEX-b experiment for a $\mathcal{L} = 300 \text{ fb}^{-1}$	34
6.1	Diagram of the Run 2 trigger configuration. Taken from [106] under Creative Commons License.	45
6.2	Histogram with the importance of each of the features used in the first iteration of the BDT in the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay. No $\Sigma_b^{\pm(*)}$ tagging particles are used in the BDT. $p_{\text{minus}1,2}$ and K_{plus} variables are related to the D daughters, and the K_{soft} variables refer to the Λ_b daughter. A $m(\psi_{\text{DM}}) = 940 \text{ MeV}$ MC sample is used.	48
6.3	Distributions of signal and background variables of every feature used in the classifier. The label on top of each subplot indicates the variable plotted in each one. Every plot has arbitrary units on the y-axis.	49
6.4	Correlation matrix for the most relevant variables used to train the BDT for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940 \text{ MeV}$	50
6.5	Histogram with the importance of each of the features used in the second iteration of the BDT for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940 \text{ MeV}$	51
6.6	Performance of the classifier for the train/test samples for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940 \text{ MeV}$. . .	52
6.7	ROC curve obtained for the BDT using a train/test method for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940 \text{ MeV}$	52
6.8	Effect of different BDT cuts over the background of this analysis. No fake peaking structures appear for a wide range of this classifier cut.	53

6.9	BDT response for different mass bins for a potential signal region (left) and for a guaranteed background region (right) for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV. . .	53
6.10	Histogram with the importance of each of the features used in the first iteration of the BDT in the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay. No $\Sigma_b^{\pm(*)}$ tagging particles are used in the BDT. <i>p</i> minus1,2 and <i>K</i> plus variables are related to the D daughters, and the <i>pi</i> plus variables refer to the Λ_b daughter. A $m(\psi_{\text{DM}}) = 940$ MeV MC sample is used.	54
6.11	Distributions of signal and background variables of every feature used in the classifier for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV. The label on top of each subplot indicates the variable plotted in each one. Every plot has arbitrary units on the y-axis.	55
6.12	Correlation matrix for the most relevant variables used to train the BDT for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.	56
6.13	Histogram with the importance of each of the features used in the second iteration of the BDT for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.	57
6.14	Performance of the classifier for the train/test samples for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV. . .	58
6.15	ROC curve obtained for the BDT using a train/test method for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.	58
6.16	Effect of different BDT cuts over the background of this analysis. No fake peaking structures appear for a wide range of this classifier cut for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.	59
6.17	BDT response for different mass bins for a potential signal region (left) and for a guaranteed background region (right) for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV. . .	59
6.18	Normalised FOM computation for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ (left) and for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ (right) decay using three different masses: the lightest available by theory, the heaviest allowed by phase space, and an intermediate one of 2 GeV proposed as the benchmark by [18].	60

- 6.19 $m_{\min}$ computation for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using the same three benchmark masses as in Figure 6.18: the lightest available (top left), the 2 GeV benchmark (top right) and the heaviest possible (bottom). Only the stripping selection is applied for these plots since the whole selection has already trimmed down lots of the events and the distributions are not easily seen. 63
- 6.20 $m_{\min}$ computation for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay using the same three benchmark masses as in Figure 6.18: the lightest available (top left), the 2 GeV benchmark (top right) and the heaviest possible (bottom). Only the stripping selection is applied for these plots since the whole selection has already trimmed down lots of the events and the distributions are not easily seen. 64
- 6.21 $\Sigma_b^{\pm}$, $\Sigma_b^{\pm*}$ and background events where the $\Sigma_b^{\pm}$ mass hypothesis is chosen. The distributions in this case are normalised since only their functional form is relevant. Both decays are shown (left: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$, right: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$) and a $m(\psi_{\text{DM}}) = 2$ GeV has been used. 67
- 6.22 $\Sigma_b^{\pm}$ and $\Sigma_b^{\pm*}$ mixed under the $\Sigma_b^{\pm}$ mass hypothesis, and background events. The distributions in this case are normalised since only their functional form is relevant. Both decays are shown (left: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$, right: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$) and a $m(\psi_{\text{DM}}) = 2$ GeV has been used. The proportion of $\Sigma_b^{\pm}$ and $\Sigma_b^{\pm*}$ obtained in the normalisation channel throughout Section 6.5 has been used. 67
- 6.23 Signal fits performed for both decay modes (left: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$, right: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$) for a $m(\psi_{\text{DM}}) = 2$ GeV. The tail parameters obtained in these fits are fixed for the remaining of the analysis. In this case the blue and green lines are coincidental since only one PDF contributes to the full model PDF. Only signal MC is used in this fit. 69
- 6.24 Full model fits performed for both decay modes (left: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$, right: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$) for a $m(\psi_{\text{DM}}) = 2$ GeV. The signal and background histograms are shown in this case to demonstrate the good agreement between what the fitter identifies as signal and background and what is the actual signal Monte Carlo and background events. The signal is MC and for the background a small set of data is used. 71

6.25	Full model fits performed for both decay modes (left: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$, right: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$) for a $m(\psi_{\text{DM}}) = 2$ GeV. The distance in σ between the fit and the data is shown in the plot below the fits. Same as Figure 6.24 but signal and background histograms are not shown explicitly.	72
6.26	Pull plots obtained for both decay modes (left: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$, right: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$). The $m(\psi_{\text{DM}})$ used here is 2 GeV as it is the benchmark proposed in the model.	73
6.27	Histogram with the importance of each of the features used in the first iteration of the BDT for the normalisation channel. As in Figures 6.2 and 6.10, no $\Sigma_b^{\pm(*)}$ particles are used in the BDT.	76
6.28	Distribution of signal and background variables of every feature used in the first iteration of the classifier. The label on top of each subplot indicates the variable plotted. The units in the y-axis are arbitrary since every distribution is normalised.	77
6.29	Histogram with the importance of each of the features used in the final iteration of the BDT for the normalisation channel.	78
6.30	Correlation matrix for the most important variables used to train the BDT for the normalisation channel.	79
6.31	ROC curve obtained for the BDT using a train/test method for the normalisation channel.	79
6.32	Performance of the classifier for the train/test samples normalisation decay.	80
6.33	BDT response for different mass bins for the signal region (left) and for background region (right) for the normalisation channel. Note that both responses are very similar due to being background-dominated, if the full BDT response was plotted, both would peak overwhelmingly as seen in Figure 6.32.	80
6.34	Effect of different BDT cuts over the mass spectrum of this decay. No peaking structures arise for a wide range of classifier cuts and the functional form is preserved.	80
6.35	Figure of merit computation for the normalisation channel. The BDT cut of FOM=0.9 is chosen since it is the one that maximises the quantity.	81
6.36	Mass spectrum after computing the quantity in Equation (6.17).	82
6.37	Full model fits performed for the normalisation channel. Each component is plotted separately.	83
6.38	Missing mass plot obtained for $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \Lambda^0\pi(D \rightarrow K\pi\pi))$ for different BDT cuts. No significant excess is seen at any BDT cut.	87

7.1	Efficiencies plot (right) and expected events (left) to be detected at the CODEX-b experiment for a $\mathcal{L} = 300 \text{ fb}^{-1}$	91
A.1	Mass distribution for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ for mass hypothesis of $m(\psi_{\text{DM}}) = 0.94, 1.5, 2.4$ and 3.0 GeV	97
A.2	Mass distribution for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ for mass hypothesis of $m(\psi_{\text{DM}}) = 0.94, 1.5, 2.0, 2.4, 3.0$ and 3.5 GeV	98
A.3	Signal fit for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ for mass hypothesis of $m(\psi_{\text{DM}}) = 0.94, 1.5, 2.4$ and 3.0 GeV	98
A.4	Mass distribution for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ for mass hypothesis of $m(\psi_{\text{DM}}) = 0.94, 1.5, 2.0, 2.4, 3.0$ and 3.5 GeV	99
A.5	Full model fit for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ for mass hypothesis of $m(\psi_{\text{DM}}) = 0.94, 1.5, 2.4$ and 3.0 GeV	99
A.6	Full model fit for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ for mass hypothesis of $m(\psi_{\text{DM}}) = 0.94, 1.5, 2.0, 2.4, 3.0$ and 3.5 GeV	100
A.7	Pull plots for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ for mass hypothesis of $m(\psi_{\text{DM}}) = 0.94, 1.5, 2.0, 2.4$ and 3.0 GeV	101
A.8	Pull plots for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ for mass hypothesis of $m(\psi_{\text{DM}}) = 0.94, 1.5, 2.0, 2.4, 3.0$ and 3.5 GeV	101
B.1	Diagrama do modelo a estudar e como satisfai as condicións de Sakharov. A figura adaptouse de [18].	106
B.2	Límites actuais en buscas inclusivas de $\text{Br}(B \rightarrow \mathcal{B}\psi_{\text{DM}}\mathcal{M})$ en función da masa da materia escura restrinxido polas busquedas de ALPEH, CMS e as re-análises de ALPEH. Figura obtida de [18] baixo licencia creative commons.	108
B.3	Diagrama dunha potencial desintegración permitida polo modelo de portal de Higgs a estudar.	109
B.4	Diagrama de estado actual e previsto deste campo de estudo. Reproducido de [33] baixo licenza creative commons.	110
B.5	Eficiencias (dereita) e eventos esperados (esquerda) en CODEX-b para unha luminosidade integrada de $\mathcal{L} = 300 \text{ fb}^{-1}$	112
B.6	Curvas ROC para o modo de desintegración $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ (esquerda) e $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ (dereita) para unha masa de materia escura de 940 MeV	114
B.7	Figura de mérito normalizada para $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ (left) e para $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ (right) para tres masas: a máis lixeira, a máis pesada dispoñible, e unha intermedia de 2 GeV proposta como referencia por [18].	114

B.8	Axustes obtidos para ambos modos de desintegración (left: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$, right: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$) for a $m(\psi_{\text{DM}}) = 2$ GeV. A distancia en σ entre o axuste e os datos aparece no histograma inferior.	115
B.9	Axuste obtido para a canle de normalización con todas as súas compoñentes.	117

List of Tables

1.1	Lightest decay processes and their mass differences that would allow baryogenesis and dark matter production. It must be noted that, given a particular operator, the decay rate for each of the allowed modes is expected to be similar since no big differences in phase space suppression are present. More light mesons would be allowed in final states and different quark groups may be studied, this would only translate into a proportional phase space suppression depending on the ΔM of the new final states proposed. Adapted from [18] under Creative Commons license.	9
5.1	Production cross sections and amounts of events generated for each of the Higgs production modes studied. The cross section is given in fb^{-1}	29
5.2	Potential constraints imposed over the μ for the counting experiment performed for the Higgs inclusive production. Distances are in mm and p_T are in GeV.	30
5.3	Efficiencies computed for all detection modes described. Lifetimes are given in terms of $c\tau$ and in meters.	31
5.4	Efficiencies computed for all detection modes described. Lifetimes are given in terms of $c\tau$ and in meters.	32
5.5	Efficiencies computed for all detection modes described for weak boson fusion production mode. Lifetimes are given in terms of $c\tau$ and in meters.	33
5.6	Number of events expected for all detection modes described for every studied production mode. Lifetimes are given in terms of $c\tau$ and in meters.	34

6.1	Generator level cuts imposed over the particles of the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$. The subindex in each particle indicates the mother of the semi-stable particles. η is the pseudorapidity of the particle, this requirement is imposed due to LHCb being a forward region detector [100]. An additional condition of truth matching via TRUEID [101] is applied. This is, the MC flag for the ID of the particle is required to be the same in the reconstructed and in the generated decays. This is something not achievable in the real reconstruction.	37
6.2	Generator level cuts imposed over the particles of the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \Lambda^0\pi(D \rightarrow K\pi\pi))$. The subindex in each particle indicates the mother of the semi-stable particles. All particles are truth matched.	38
6.3	Generator level cuts imposed over the particles of the $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \pi(\Lambda_c \rightarrow pK\pi))$. The subindex in each particle indicates the mother of the semi-stable particles. Every particle is truth matched.	38
6.4	Generator level efficiencies of every signal mode. The normalisation channel generator level efficiency is independent of the DM particle mass. The masses are given in GeV. Only one mass has been generated so far for the $\Sigma_b^{\pm}$ decays, and that is the one used in the whole analysis.	39
6.5	Reconstruction efficiency table for the $\Sigma_b^{\pm} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay modes. It is clear that a mass dependency exists in this case.	40
6.6	Stripping line for $\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K)$, LambdaDecaysDMLambdaToDKLine. The subindex of the K and π particles indicates its direct ascendant. As mentioned, the cuts for Stripping34r0p3 are also those for Stripping29r2p3 and Stripping28r2p3. The misalignment in the cuts is expected to not affect much, the difference in value is not big and does not affect many variables, in fact it only affects three of them (four in reality, since there are two π_D^-): $\pi_D^- (p_T)$, $\Lambda_b^0 (\text{IP}\chi^2 \text{ OWNPV})$ and $K_D^+ (p_T)$.	41
6.7	Stripping line for $\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K)$, LambdaDecaysDMLambdaToDPiLine. The subindex of the K and π particles indicates its direct ascendant. As mentioned, the cuts for Stripping34r0p3 are also those for Stripping29r2p3 and Stripping28r2p3. As shown in this table, no misalignment had to be fixed for this line in particular.	42
6.8	Stripping efficiency table for the $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay modes. It is clear that a mass dependency exists in this case.	43

6.9	Efficiencies table for the $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay mode. The three trigger stages requirements are TOS. The efficiencies are calculated in a sequential way, this being, the HLT1 efficiencies are calculated over the events that passed the L0 selection, this also applies to the HLT2 efficiency with respect to the HLT1 efficiency. .	47
6.10	Efficiencies table for the $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay mode. The three trigger stages requirements are TOS. The efficiencies are calculated in a sequential way, this being, the HLT1 efficiencies are calculated over the events that passed the L0 selection, this also applies to the HLT2 efficiency with respect to the HLT1 efficiency. .	47
6.11	Scores obtained using a k-fold cross-validation method for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV. . .	50
6.12	Scores obtained using a k-fold cross-validation method for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV. . .	51
6.13	Efficiencies table for the $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay modes. The BDT cuts are applied in a sequential way, this being, the BDT efficiencies are calculated over the events that passed the stripping and trigger selection.	60
6.14	Efficiencies table for the $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay modes.	60
6.15	Efficiencies table for the $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay modes. The $d > 0$ cuts are applied in a sequential way, this being, the $d > 0$ efficiencies are calculated over the events that passed the stripping, the trigger selection and the BDT cut.	62
6.16	Efficiencies table for the $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay modes. The m_{min} cuts are applied in a sequential way, this being, the m_{min} efficiencies are calculated over the events that passed the stripping, the trigger selection, the BDT cut and the tagging cut.	63
6.17	Table with the fit results of the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay mode. The model used for the signal is the one shown in Equation (6.11) extended to the events of the simulation, so the integral over the full model does not add to one but to the N_{sig} parameter instead.	68

6.18	Table with the fit results of the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay mode. The model used for the signal is the one shown in Equation (6.11) extended to the events of the simulation, so the integral over the full model does not add to one but to the N_{sig} parameter instead.	69
6.19	Table with the fit results of the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay mode. The full model is taken into account as shown in Equation (6.16). The tail parameters are those in Table 6.17. Different amounts of the signal to background ratio are studied, and it is shown that the fitter shows a better convergence consistency when $\frac{N_{\text{sig}}}{N_{\text{bkg}}} \approx 1$	70
6.20	Table with the fit results of the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay mode. The full model is taken into account as shown in Equation (6.16). The tail parameters are those in Table 6.18. Different amounts of the signal to background ratio are studied, and it is shown that the fitter shows a better convergence consistency when $\frac{N_{\text{sig}}}{N_{\text{bkg}}} \approx 1$	71
6.21	Results of the fits performed to a gaussian of all the pseudo-experiments computed for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay.	72
6.22	Results of the fits performed to a gaussian of all the pseudo-experiments computed for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay. In this case some higher and lower limits of N_{fit} were studied to check if some dependency around this input arose, but it did not.	73
6.23	Generator level cuts imposed over the particles of the $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \pi(\Lambda_c \rightarrow pK\pi))$. The subindex in each particle indicates the mother of the semi-stable particles. An additional condition of truth matching via TRUEID [101] is applied.	74
6.24	Scores obtained using a k-fold cross-validation method for the normalisation decay classifier.	76
6.25	Results of the full model fit performed to an exponential background modulated by a power law to describe the background and two relativistic Breit-Wigner describing the two components of the signal.	84
6.26	Computed expected limit for both decay modes and every mass.	85
6.27	Calculated values of $\mathcal{B}_{\text{signal}}$ for each mass and decay mode.	86
6.28	Calculated values of $\mathcal{B}_{\text{signal}}$ for each mass and decay mode adjusted to luminosity.	88
7.1	Table with all of the efficiencies computed for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ Dark matter and B-mesogenesis LHCb search.	89

7.2	Table with all of the efficiencies computed for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ Dark matter and B-mesogenesis LHCb search. .	90
7.3	Calculated values of $\mathcal{B}_{\text{signal}}$ for each mass and decay mode extrapolated to total luminosity.	90
7.4	Number of events expected for all detection modes described for every studied production mode. Lifetimes are given in terms of $c\tau$ and in meters.	90
B.1	Desintegracións máis lixeiras e diferencias de masas obtidas no modelo. Para cada operador particular as fraccións de desintegración que esperamos atopar son similares, xa que o espazo fásico é similar. Máis mesóns lixeiros poderían aparecer nos estados finais, unicamente cambiando a diferenza de masa e cunha supresión na fracción de desintegración. Adaptado de [18].	107
B.2	Eventos esperados para todos os modos de produción e detección descritos. As vidas medias $c\tau$ están en metros.	112
B.3	Resultados obtidos para todas as masas para o modo de desintegración de $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$	115
B.4	Resultados obtidos para todas as masas para o modo de desintegración de $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$	116
B.5	Resultados obtidos da canle de normalización.	116
B.6	Valores de $\mathcal{B}_{\text{signal}}$ para todas as masas e modos de desintegración. .	116
B.7	Táboa con todas as eficiencias da desintegración $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$	118
B.8	Táboa con todas as eficiencias da desintegración $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$	118

Contents

Abstract	iv
Limiar	v
Resumen	vi
Acknowledgements	vii
1 Introduction	1
1.1 The Standard Model of Particle Physics	1
1.2 CKM matrix	2
1.3 Dark Matter and B-mesogenesis	4
1.3.1 Foundations of the B -mesogenesis	6
1.3.2 Formal description and kinematic constraints	7
1.3.3 Dark matter operators and allowed decays	8
1.3.4 Current experimental status	9
1.4 BSM long lived particles	11
1.4.1 Simplified models studied	11
1.4.2 State-of-the-art on BSM LLP searches	13
2 Objectives	15
3 Experimental setup	17
3.1 CODEX-b experiment	17
3.1.1 CODEX-b detector	17
3.2 LHCb experiment	19
3.2.1 The Large Hadron Collider	19
3.2.2 The LHCb experiment	20
The LHCb subdetectors	21
Stripping	23
Simulation	23
4 Methodology	25

4.1	LHCb search	25
4.2	CODEX efficiency	27
5	CODEX-b studies	29
5.1	Monte Carlo samples	29
5.2	Generator level efficiency	30
5.2.1	Inclusive production	30
5.2.2	Higgs-strahlung	31
5.2.3	Weak-boson fusion	32
5.3	Results	33
6	Dark matter and B-mesogenesis	35
6.1	Data and Monte Carlo Samples	35
6.1.1	Recorded data samples	35
6.1.2	MC samples	36
6.2	Selection	38
6.2.1	Generator level selection	38
6.2.2	Reconstruction	39
6.2.3	Stripping Selection	40
	Stripping Variables	43
6.2.4	Trigger Selection	44
	Trigger independent of signal / Trigger on Signal	44
	L0 Trigger	45
	HLT1 Trigger	46
	HLT2 Trigger	46
6.2.5	Multivariate Classifier	46
6.2.6	Total efficiencies	55
6.3	Tagging	61
6.3.1	Mathematical description	61
6.3.2	Tagging efficiency	62
6.3.3	$m_{\min}$ computation	62
6.4	Mass fit	64
6.4.1	Mathematical description	64
6.4.2	Fitting basis	65
6.4.3	Mass model	66
6.4.4	Signal fit	68
6.4.5	Full model fit	69
6.4.6	Toys	71
6.5	Normalisation channel	73
6.5.1	Generator level selection	74
6.5.2	Reconstruction and stripping	74
6.5.3	Trigger	75

6.5.4	Multivariate classifier	75
6.5.5	Fit for normalisation channel	82
6.5.6	$N(\Sigma_b^{\pm(*)})$ computation	83
6.6	Limits	84
6.6.1	Branching ratio limit	86
6.7	Backgrounds	86
6.8	Results	88
7	Results and discussion	89
7.1	Dark matter and B-mesogenesis results	89
7.2	Long lived particles results	90
7.3	Discussion	91
8	Conclusions	93
	Appendices	95
A	Appendix Analysis	97
A.1	Mass distributions for every dark matter mass	97
A.2	Signal fits for every dark matter mass	97
A.3	Pull plots for every dark matter mass	101
B	Resumo	103
B.1	Introdución	103
B.1.1	Matriz CKM	104
B.1.2	Materia escura e B-mesoxénese	105
	Bases da B-mesoxénese	105
	Descrición formal e restricións cinemáticas	105
	Operadores de materia escura e desintegracións permitidas	106
	Estado experimental actual	107
B.1.3	Partículas de vida media longa	108
	Modelos de vida media longa	109
	Estado experimental actual	109
B.2	Obxectivos	109
B.3	Montaxe experimental	110
B.3.1	Experimento CODEX-b	110
B.3.2	Experimento LHCb	110
B.4	Metodoloxía	111
B.5	Partículas de vida media longa	111
B.6	Materia escura e B-mesoxénese	112
B.6.1	Datos e Monte Carlo	112
B.6.2	Selección	113

	Selección de Stripping	113
	Selección do disparador	113
	Clasificador multivariante	113
B.6.3	Etiquetado	114
B.6.4	Axuste á masa	115
B.6.5	Canle de normalización	115
B.6.6	Límites	116
B.6.7	Fondos	117
B.7	Resultados e discusión	117
B.7.1	Resultados da materia escura e B-mesoxénese	117
B.7.2	Resultados das partículas de vida media longa	118
B.7.3	Discusión	118
B.8	Conclusións	119

Chapter 1

Introduction

1.1 The Standard Model of Particle Physics

The Standard Model of particle physics (SM) [1–4] has proven itself to be an exceptionally effective theory to describe and predict the observed subatomic particles and how they interact with each other. Numerous testing has been performed at different particles colliders and no physics beyond it has been found yet. On the other hand, evidence from astrophysics and cosmology supports the standard cosmological model: this theory suggests that the intensely hot early Universe [5] was preceded by a period of rapid inflationary growth [6,7], offering an explanation for the early stages of the Universe and its subsequent development. These two very successful models are inconsistent with each other and common ground does not seem to be found at first glance, indicating the necessity for new physics phenomena beyond the Standard Model (BSM).

Up-to-date precise measurements of the cosmos indicate that approximately 16% of the universe's matter is composed of ordinary (baryonic) matter [8,9], with the remaining 84% being attributed to an as-yet unidentified component known as dark matter (DM) [8,9]. The SM of particle physics has not been able to provide any potential dark matter candidate, nor a mechanism for its production [10–12]. Additionally, the Standard Model fails to account for the observed asymmetry between matter and antimatter in the universe. According to SM predictions, a universe originating from a hot Big Bang and governed solely by SM physics should contain less different amounts of matter and antimatter. This discrepancy necessitates the proposal of an alternative mechanism, commonly referred to as baryogenesis (or mesogenesis when specifically discussing mesons), to explain the imbalance. Both terms, baryogenesis and mesogenesis, revolve around the same fundamental concept aimed at addressing this critical issue.

This observation arises due to the C and P operators. The C operator, or charge operator, changes every particle by its anti-particle, while the P operator, or parity operator, changes the sign of the position quantity: $\vec{x} \rightarrow -\vec{x}$. The CP is the product of these two operators and due to some particles not being eigenstates of it, a matter-antimatter asymmetry arises.

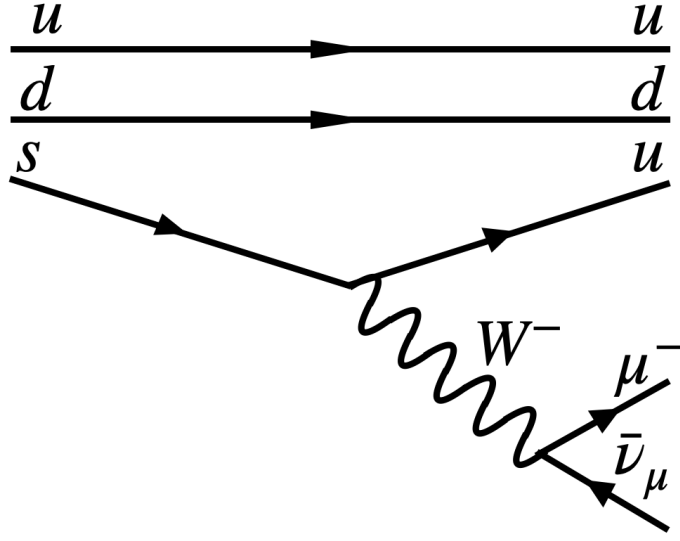


Figure 1.1: SM transition of a s quark to a u quark via W^- emission. The full decay would be $\Lambda \rightarrow p \mu^- \bar{\nu}_\mu$.

1.2 CKM matrix

Many common SM quark transitions are characterised by the interaction of quarks with $W^\pm$ bosons that decay into the leptonic sector. In this process the quark changes its flavour. For example, within the $\Lambda \rightarrow p \mu^- \bar{\nu}_\mu$ decay the $s \rightarrow u \mu^- \bar{\nu}_\mu$ transition takes place, as seen in Figure 1.1. These kinds of decay are usually called semileptonic decays since a hadron and a charged lepton with its correspondent neutrino are produced in the final state.

These kind of decays are described by the Standard Model via the Cabibbo-Kobayashi-Maskawa (CKM) matrix [13–15]. To start building the matrix, the SM gauge lagrangian may be written down as:

$$\mathcal{L}_G = - \sum_a \frac{1}{4g_a^2} + i \sum_\Psi \sum_{i=1}^3 \bar{\Psi}_i \not{D} \Psi_i, \quad (1.1)$$

where a is each of the interactions of the SM and $\Psi = Q_L, u_R, d_R, L_L, e_R$. Note that every other right-handed is neglected since it will not add significant differences to any calculation performed. This lagrangian density is invariant under 5 different $U(3)$ global symmetries for each of the fermions considered for Ψ under the following transformation:

$$\Psi_i \rightarrow U_i^j \Psi_j, \quad (1.2)$$

where the subindexes being covariant or contravariant is not relevant in this case since no spatial or temporal transformation is being performed, only internal variables change under this gauge transformation.

This flavour degeneracy may be broken by a Yukawa interaction in the quark sector given by the following lagrangian density:

$$\mathcal{L}_Y = -Y_{i,j}^d \bar{\Psi}_{L,i} \phi d_{R,j} - Y_{i,j}^u \bar{\Psi}_{L,i} \varepsilon \phi^* u_{R,j} + h.c. \quad (1.3)$$

with Y^q being complex matrices, ϕ the Higgs field and i, j indexes indicating the doublet/singlet of each particle. ε is the two-dimensional Levi-civita symbol [16] and $h.c.$ is the hermitian conjugate of the previous terms, which changes every particle for its anti-particle and vice versa.

By exploiting the gauge symmetry a single flavour basis may be defined where only one of the Yukawa terms is diagonal, for example

$$Y^u = \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix}, \quad Y^d = V \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix}. \quad (1.4)$$

In order for this construction to make sense, V must be an unitary matrix, where $VV^\dagger = \mathbb{I}$ and $\mathbb{I}$ is the 3×3 identity matrix, so the following may also be written:

$$Y^d = \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix} \text{ and } Y^u = V^\dagger \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}.$$

Since both bases are incompatible (no third basis exists that diagonalises both at once) flavours may be mixed via the V matrix, which is the matrix modulating the W bosons interactions with quarks. This interaction may be written by the following conserved current:

$$J_W^\mu = \frac{-g}{\sqrt{2}} \bar{u}_L \gamma^\mu W_\mu^+ V_{CKM} d_L + h.c. \quad (1.5)$$

which couples different generations of quarks from one flavour basis to another, making one basis a linear combination of the other according to the so-called Cabibbo-Kobayashi-Maskawa (CKM) matrix [13–15]:

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}. \quad (1.6)$$

This V_{CKM} matrix describes the flavour physics intensity in the Higgs sector and the relative strength of interactions between different flavour generations of quarks is given by the V_{ij} matrix elements. In fact, the transition probability via $W^\pm$ emission is

proportional to $\|V_{ij}\|^2$ since these elements may be given by complex numbers, since the only requirement imposed over the CKM matrix is the unitary condition.

An allowed parametrisation of the CKM matrix is given by three flavour rotations and a CP-violating complex unitary number [17]. This parametrisation is given explicitly by:

$$V_{CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1.7)$$

Other parametrisations, more convenient, exist: even though the previous ones show the importance of the different flavours, others show the two generations gap suppression and that flavour jumps are favoured towards the following or previous generation (this means $b \rightarrow u \dots$ is heavily suppressed in favour of $b \rightarrow c \dots$). This is known as the Wolfenstein parametrisation [15] and may be written as follows:

$$V_{CKM} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \quad (1.8)$$

This construction of the Higgs flavour sector may have some similarities to a potential construction of the dark sector physics. In fact, the decays and operators studied in this work are very similar to those shown here, but while the quark transitions shown so far produce additional leptons, one may suppose that the dark sector may arise instead of these leptons, in decays such as $b \rightarrow cs\psi_{DM}$, where ψ_{DM} would be a dark matter candidate that would solve one of the problems of the SM up to date.

1.3 Dark Matter and B-mesogenesis

A phenomenological model presented in [18, 19] that could be probed at LHCb [20] is shown here as part of BSM physics has been proposed in order to explain the mentioned mechanisms of B-mesogenesis and Dark Matter, which resemblances the flavour physics mechanisms of the Standard Model, and that is studied experimentally in this thesis. This framework requires CP-violating oscillations and a later decay of B mesons (or b -baryons) into dark sector particles in the early Universe. This is what will be referred to as B -mesogenesis, from which baryogenesis also arises. Some of the innovations proposed by this model are:

- No high temperatures are required in the early Universe, in fact, B-mesogenesis would operate at low temperatures: $5 \text{ MeV} \lesssim T \lesssim 30 \text{ MeV}$.

- Universal baryon number has to be conserved, this is done by relating baryogenesis to dark sector particles that would be charged under baryon number, as baryons are in the SM, being this charged carried by quarks. No violation of baryon number conservation in the SM has been found [21–24] so a potential apparent violation in the dark sector is proposed.
- The baryon asymmetry (different behaviour under CP symmetry and different amount of matter-antimatter) of the universe would be related to B -meson observables with unique signatures at existing hadron colliders and B -factories.

The direct potential measurements that arise from this model and that can be experimentally tested at existing accelerators and B -factories are:

- Relatively large branching ratios (BR) of B mesons to a SM baryon ($\mathcal{B}$), any number of SM mesons ($\mathcal{M}$), and a DM particle (ψ_{DM}) are to be expected:

$$\text{BR}(B \rightarrow \psi_{\text{DM}} \mathcal{B} \mathcal{M}) > 10^{-4} \quad (1.9)$$

- Relatively large branching ratios of b -baryons to any number of SM mesons ($\mathcal{M}$) and a DM anti-particle ($\bar{\psi}_{\text{DM}}$) are once again expected:

$$\text{BR}(\mathcal{B}_b \rightarrow \bar{\psi}_{\text{DM}} \mathcal{M}) > 10^{-4} \quad (1.10)$$

- The predicted CP violation in the neutral B meson systems is expected to be

$$A_{\text{SL}}^q > 10^{-4},$$

with A_{SL}^q being the semileptonic charge asymmetry in the mentioned B meson system.

This B -Mesogenesis mechanism is also controlled by some indirect measurements, for example those that arise from B meson oscillations or the mediator particle for decays such as those described in Equations (1.9) and (1.10):

- The parameters that control the $B_q^0 - \bar{B}_q^0$ meson oscillations: $\phi_{12}^{d,s}$, $\Delta\Gamma_{d,s}$ and $\Delta M_{d,s}$, where ϕ is the CP violating phase of the B meson system, and ΔM and $\Delta\Gamma$ are the mass and width differences for each of the B mesons respectively. These three quantities determine the value of A_{SL} .
- A color triplet scalar, Y , is required for the B mesons or b -baryons to decay into DM and SM particles. This is a particle that could also be searched for in heavy resonances (at the order of TeV in mass) at the LHC.

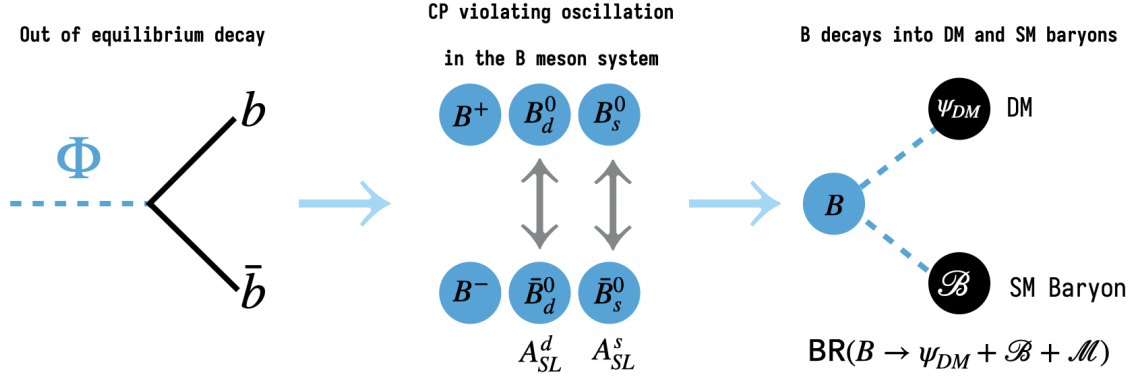


Figure 1.2: Diagram of the proposed model and how it ensures the Sakharov conditions. The figure has been adapted from [18].

1.3.1 Foundations of the B -mesogenesis

Some conditions must be met in the early Universe so its evolution to a matter-dominated Universe is possible. These being the so-called Sakharov conditions [25]:

- *C and CP violation:* matter and antimatter are required to be somehow different at a fundamental level (not only charge-wise) for domination of one over the other to be possible. This is allowed in this model by the CP violating oscillations of the B meson system.
- *Departure from thermal equilibrium:* if the Universe is in thermal equilibrium, even if the first condition is met, the amount of particles and antiparticles produced and annihilated is the same. The B -mesogenesis model solves this by proposing that the early Universe is dominated by radiation and a weakly coupled scalar particle (Φ) with $m(\Phi) \gtrsim 11 \text{ GeV}/c^2$ and a lifetime of $\tau(\Phi) \sim 10^{-3} \text{ s}$. These Φ particles decay mostly into b quarks that eventually hadronise yielding a significant amount of B mesons in the early Universe that are out of thermal equilibrium.
- *Baryon number violation:* interactions that violate baryon number are required in a matter-dominated Universe. This model proposes an apparent baryon number violation since DM would be charged under baryon number. Then we end up with an apparent violation in the SM model sector and another apparent one in the dark sector that cancel each other out, resulting in a total baryon number conservation.

With all these considerations, summarised in Figure 1.2, one can proceed to analyse the implications of them, study which constraints are to be imposed and which ones arise from them, and how can this model and interactions be formalised.

1.3.2 Formal description and kinematic constraints

The ψ_{DM} can not describe the whole DM of the Universe [18]. This is due to the fact that for $B \rightarrow \mathcal{B}\psi_{\text{DM}}$ to take place the DM must interact with three quarks and therefore the inverse process could also take place, erasing the generated asymmetry and apparent baryon number violation.

To solve this, one condition that must be then imposed over this ψ_{DM} particle is that it can quickly decay into at least two other states in the dark sector. This can be achieved via a Yukawa interaction of the ψ_{DM} particle with a singlet scalar antibaryon (ϕ) and a singlet Majorana fermion (ξ) coupled with the effective lagrangian in Equation (1.11).

$$\mathcal{L} \supset -y_d \bar{\psi}_{\text{DM}} \phi \xi + \text{h.c.} \quad (1.11)$$

This lagrangian assumes the existence of a $\mathbb{Z}_2$ symmetry stabilising the ϕ and ξ singlets. Given this lagrangian density and with $m_{\psi_{\text{DM}}} > m_\phi + m_\xi$ the ϕ and ξ DM particles could represent the observed DM density observed by the Planck satellite, $\Omega_{\text{DM}} h^2 = 0.1200 \pm 0.0012$ [8].

Once the minimal dark sector has been characterised (note that a more rich and complex dark sector is allowed in this model, but the minimal one is being shown by completeness), mass limits on the dark sector ψ_{DM} can be studied. First, the $B \rightarrow \mathcal{B}\psi_{\text{DM}}$ is allowed if:

$$m_B > m_{\psi_{\text{DM}}} + m_p \Rightarrow m_{\psi_{\text{DM}}} < m_B - m_p \simeq 4.34 \text{ GeV}/c^2, \quad (1.12)$$

and proton stability requires:

$$m_p < m_{\psi_{\text{DM}}} + m_e \Rightarrow m_{\psi_{\text{DM}}} > m_p - m_e \simeq 937.8 \text{ MeV}/c^2. \quad (1.13)$$

Finally, ϕ and ξ singlets are required to be stable in this minimal model. If they were not stable they could decay into one another by antiproton and electron emission compensating for the apparent baryon asymmetry from the B meson decays. This stabilisation under the $\mathbb{Z}_2$ symmetry implies that:

$$|m_\xi - m_\phi| < m_p + m_e \simeq 938.8 \text{ MeV}/c^2. \quad (1.14)$$

These conditions establish the widest mass range for the searched ψ_{DM} particle:

$$0.94 \text{ GeV}/c^2 < m_{\psi_{\text{DM}}} < 4.34 \text{ GeV}/c^2, \quad (1.15)$$

note that the real mass range could be narrower provided that, for example, the dark sector was richer and populated with more particles.

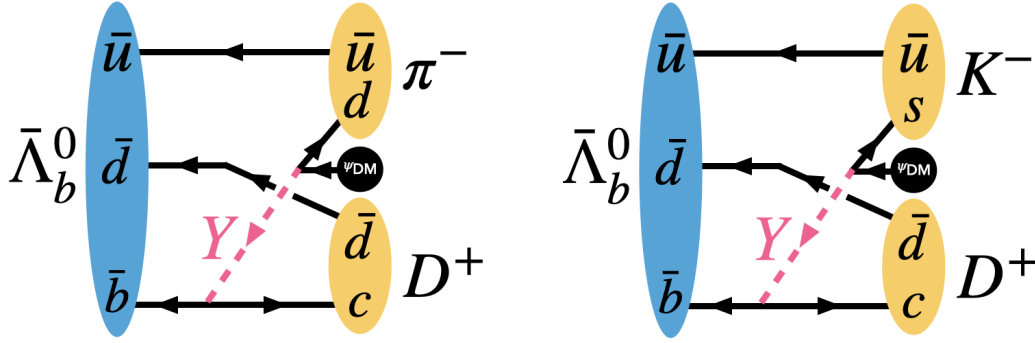


Figure 1.3: The two decays that will be studied in this work. Any of them could be enough to a successful explanation of the model provided that its BR is large enough. The first one is the one associated with the O_{cd} operator whereas the second is related to O_{cs} .

1.3.3 Dark matter operators and allowed decays

As mentioned, for $B \rightarrow \mathcal{B}\psi_{\text{DM}}\mathcal{M}$ to exist a BSM TeV-scale bosonic mediator is required [18]. This Y mediator would be a colour-triplet scalar that couples the dark sector to the SM sector. An effective Lagrangian for this kind of coupling can be written as follows:

$$\mathcal{L}_{\text{eff}} = O_{u_id_j} \frac{y_i y_j}{M_Y^2}, \quad (1.16)$$

where Einstein summation convention has been used, and $y_i y_j$ is the product of the coupling referred to the i -quark and j -quark. This kind of Lagrangian allows for four different possible operators O_{ij} that can act over any b -quark:

$$O_{ud} = \psi_{\text{DM}} b u d, \quad (1.17a)$$

$$O_{us} = \psi_{\text{DM}} b u s, \quad (1.17b)$$

$$O_{cd} = \psi_{\text{DM}} b c d, \quad (1.17c)$$

$$O_{cs} = \psi_{\text{DM}} b c s. \quad (1.17d)$$

These operator would allow the decay of anti- b quarks contained by the B mesons and baryons to decay into two lighter quarks and a dark antibaryon $\bar{\psi}_{\text{DM}}$. The lightest possible hadronic decays allowed by the introduction of this operator are listed in Table 1.1. It is important to note that in this work only O_{cd} and O_{cs} are being studied, and due to some considerations that will be discussed later, a heavier case will be the chosen one for O_{cd} .

In particular, the search in this work will be performed over the decays in Figure 1.3. Note that one of them is not the lightest search one can perform.

Operator and Decay	Initial state	Final state	ΔM (MeV)
$O_{ud} = \psi_{\text{DM}} b u d$ $\bar{b} \rightarrow \psi_{\text{DM}} u d$	B_d	$\psi_{\text{DM}} + n(udd)$	4340.1
	B_s	$\psi_{\text{DM}} + \Lambda(uds)$	4251.2
	B^+	$\psi_{\text{DM}} + p(duu)$	4341.0
	Λ_b	$\bar{\psi}_{\text{DM}} + \pi^0$	5484.5
$O_{us} = \psi_{\text{DM}} b u s$ $\bar{b} \rightarrow \psi_{\text{DM}} u s$	B_d	$\psi_{\text{DM}} + \Lambda(USD)$	4164.0
	B_s	$\psi_{\text{DM}} + \Sigma^0(uss)$	4025.0
	B^+	$\psi_{\text{DM}} + \Sigma^+(uus)$	4090.0
	Λ_b	$\bar{\psi}_{\text{DM}} + K^0$	5121.9
$O_{cd} = \psi_{\text{DM}} b c d$ $\bar{b} \rightarrow \psi_{\text{DM}} c d$	B_d	$\psi_{\text{DM}} + \Lambda_c + \pi^-(cdd)$	2853.6
	B_s	$\psi_{\text{DM}} + \Sigma_c^0(cds)$	2895.0
	B^+	$\psi_{\text{DM}} + \Lambda_c^+(dcu)$	2992.9
	Λ_b	$\bar{\psi}_{\text{DM}} + D^0$	3754.7
$O_{cs} = \psi_{\text{DM}} b c s$ $\bar{b} \rightarrow \psi_{\text{DM}} c s$	B_d	$\psi_{\text{DM}} + \Sigma_c^0(csd)$	2807.8
	B_s	$\psi_{\text{DM}} + \Omega_c(css)$	2671.7
	B^+	$\psi_{\text{DM}} + \Sigma_c^+(csu)$	2810.4
	Λ_b	$\bar{\psi}_{\text{DM}} + D^- + K^+$	3256.2

Table 1.1: Lightest decay processes and their mass differences that would allow baryogenesis and dark matter production. It must be noted that, given a particular operator, the decay rate for each of the allowed modes is expected to be similar since no big differences in phase space suppression are present. More light mesons would be allowed in final states and different quark groups may be studied, this would only translate into a proportional phase space suppression depending on the ΔM of the new final states proposed. Adapted from [18] under Creative Commons license.

To wrap up this introduction, the two searches that will be conducted are $\Lambda_b^0 \rightarrow \psi_{\text{DM}} \pi^+ (D^- \rightarrow \pi^- \pi^- K^+)$ (second lightest decay for O_{cd} , not a big suppression to be expected, if any), and $\Lambda_b^0 \rightarrow \psi_{\text{DM}} K^+ (D^- \rightarrow \pi^- \pi^- K^+)$ (lightest decay for O_{cd}).

1.3.4 Current experimental status

Not many direct searches of the particular signatures mentioned have been performed at colliders or B-factories. As a matter of fact, at the present moment, this is the second work that searches for these signatures in general, being the first one conducted by the BaBar Collaboration.

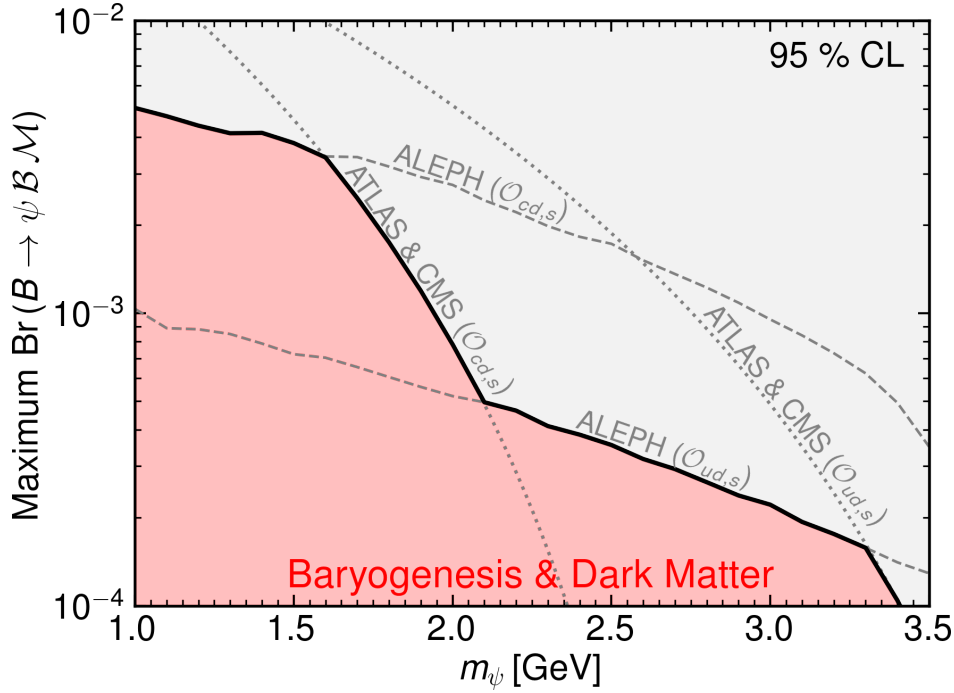


Figure 1.4: Current limits on inclusive $\text{Br}(B \rightarrow \mathcal{B}\psi_{\text{DM}}\mathcal{M})$ as a function of the DM particle ψ_{DM} constrained by the recast of a search conducted by ALEPH as well as indirect searches from ATLAS and CMS for particles similar to the propagator of the model (TeV-scales color-triplet scalars). The excluded area would be the lightest coloured one. Figure obtained from [18] under Creative Commons license.

One direct search of $B \rightarrow \Lambda\psi_{\text{DM}}$ has been performed by BaBar collaboration finding a nonsignificant signal sensitivity and setting a limit to the branching fraction from 0.13 to 5.2×10^{-5} for $1.0 < m_{\psi_{\text{DM}}} < 4.2 \text{ GeV}/c^2$ at a 90% CL [26]. The BaBar collaboration also performed another direct search of $B^+ \rightarrow \psi_{\text{DM}} + p$ where no significant signal is found and limits to the branching fraction in the range from 10^{-7} to 10^{-5} for $1.0 < m_{\psi_{\text{DM}}} < 4.3 \text{ GeV}/c^2$ at a 90% CL [27] are set. These two searches set a constraint to one of the four operators allowed by this model.

Indirect searches from CMS [28] and ATLAS [29], as well as recasts from ALEPH [30] allow to set some upper limits of around 10^{-3} to the other three operators mentioned in this work. The summary from these works are the limits shown in Figure 1.4

1.4 BSM long lived particles

Other extensions proposed to the Standard Model are those involving long lived particles (LLPs), which are defined as particles with lifetimes (usually measured in terms of $c\tau$) larger than most of those within the SM. It is important to note that not every LLP is a Beyond Standard Model particle, since some of the most studied mesons in colliders are LLPs, such as $\mu^\pm$, $\pi^\pm$ or π^0 , or even the neutron, n , with a $c\tau \sim 10^{11}$ m, among others.

It is possible to extend the Standard Model in many directions, and some of these extensions require of new LLPs to work. Notably, some supersymmetric models may hint towards the existence of these particles, such as those with decouples supersymmetric scalars or decays to gravitino (the proposed supersymmetric partner of the graviton) suppressed by SUSY-breaking scale [31,32].

Other models, such as the ones studied in this work, are the so-called hidden sector models, accessible via Higgs-portal, that allows Higgs bosons to decay into a whole new zoo of particles.

1.4.1 Simplified models studied

As mentioned, LLPs may arise from different theoretical models, since the landscape for this field is vast and rich, with a significant amount of theories proposing BSM LLPs from different mechanisms. In this work, one possibility is studied, this being a certain minimal model, a Higgs-portal model. In this case the SM Higgs, H^0 is allowed to decay to a new BSM Higgs sector particles, in this work, a new scalar long-lived particle, A^0 [33].

An Allowed minimal operator describing this could be: $SHH^\dagger$, $S^2HH^\dagger$ where H is the SM Higgs field doublet and S is the new scalar particle field, that can be identified with the A^0 field. Requiring the lagrangian density to be gauge invariant imposes the following form of the lagrangian:

$$\mathcal{L} \supset A_S SH^\dagger H + \frac{\lambda}{2} S^2 H^\dagger H + \dots \quad (1.18)$$

where arbitrary higher dimension operators would be allowed but would not dominate the branching ratios. The LHCb experiment has constrained this model [34,35] and CODEX-b could potentially probe regions with smaller coupling constant and longer lifetimes.

By replacing A_S with a mixing angle $\sin \theta$ of Higgs field with the new scalar field, it inherits every SM Higgs coupling [36], allowing it to decay to, for example, two muons, as it will be studied in this work. Every SM coupling would be suppressed by small enough values of $\sin \theta$. The SM couplings contribute to potential decays

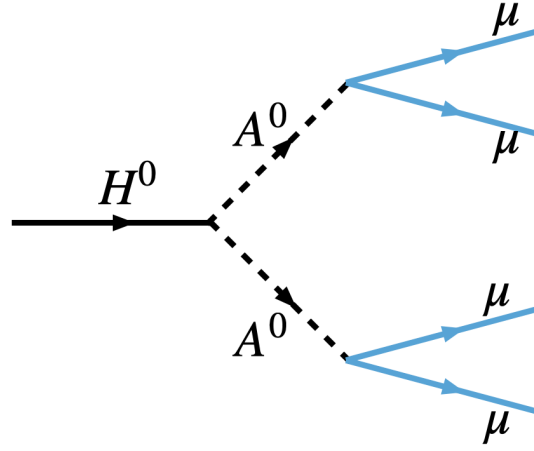


Figure 1.5: $\mathcal{L} \supset A_5 SH^+ H$ associated diagram where the parameter A_5 has already been substituted by a mixing angle and the S field identified with the A^0 particle has inherited the fermionic decay of the SM Higgs.

of the S field and to its production cross-section. [37, 38] The decays allowed by this mechanism and presented in this work can be seen in the diagram in Figure 1.5.

In order to study this mechanism, three different Higgs production mechanism will be studied [39–41]:

- inclusive production: widely dominated by **gluon-gluon fusion**, but every possible production cross-section predicted by the SM is considered. In this mechanism two different cases will be studied: a single detection of one A^0 in the CODEX volume, and a second case where one A^0 is detected in the CODEX volume while the other is detected in the LHCb. The gluon-gluon fusion diagram can be found in Figure 1.6 (bottom).
- Higgs-strahlung: associated production mechanism of the Higgs boson with a gauge boson. The signature of this events is the detection of one A^0 in the CODEX volume while a μ generated in the decay of the Z^0 or $W^\pm$ and it is detected in LHCb. The associated Feynman diagram is shown in Figure 1.6 (left).
- weak-boson fusion: in this production mechanism, two vector bosons ($W^\pm W^\mp$ or $Z^0 Z^0$) merge into a Higgs boson, which is produced together with hadronic jets. The signature of this mechanism is the detection of one A^0 in CODEX and one jet in LHCb. The associated Feynman diagram is shown in Figure 1.6 (right).

Data samples for these decay modes, as well as a generator level efficiency study is performed in this work.

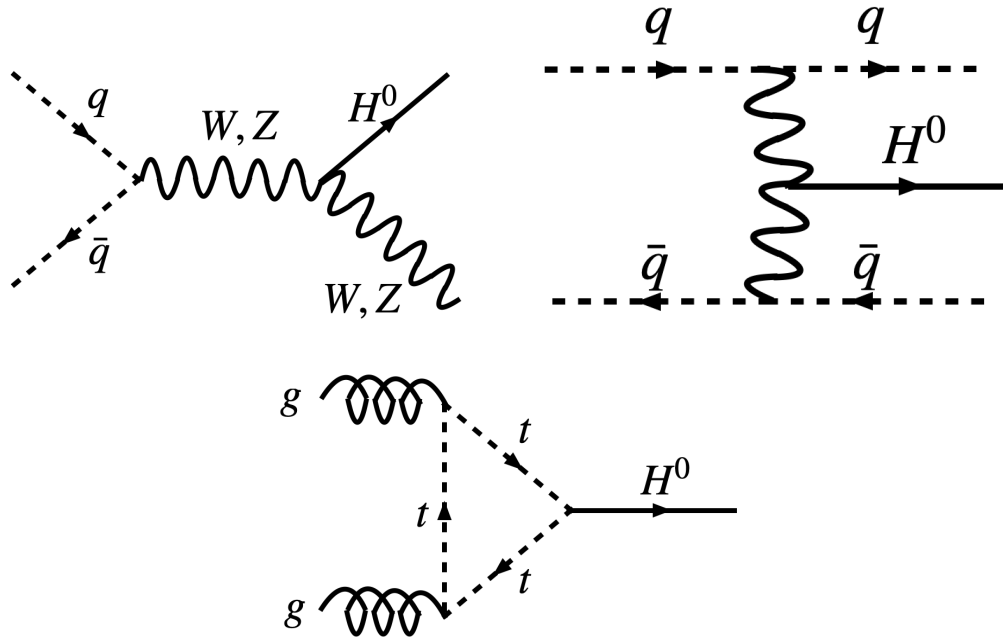


Figure 1.6: Main production modes of the SM Higgs: Higgs-strahlung (left), weak-boson fusion (right) and gluon-gluon fusion (bottom).

1.4.2 State-of-the-art on BSM LLP searches

The main CERN experiments, even though the search of LLPs is not their main topic, have shown some results in studying some physics cases for LLPs [42, 43]. Accessing some regions of the parameter space at low LLP masses becomes very challenging for the main CERN detectors, due to the presence of an overwhelming background component populating the forward region.

Some other beam dump experiments such as SHiP [44] or NA62 [45], or forward experiments like FASER [46] have access to said regions by using shielding that removes most of the SM background while having access to more boosted LLPs in a narrower cone. This allows great searches in the low mass region of the space parameter but the higher masses are extremely suppressed due to lower $\sqrt{s}$, this also has the additional drawback of not allowing any physics case of LLPs through heavy portals (LLPs that arise from heavy particles such as Higgs or W/Z bosons).

The last case are transverse shielded detectors such as CODEX or ANUBIS, which both are expected to have great shielding that would allow to remove most of the SM background allowing for low mass LLPs searches by having a smaller solid angle, which drastically reduces the luminosity available. On the other hand, very high $\sqrt{s}$ of proton-proton collisions at CERN would allow this experiments to probe many

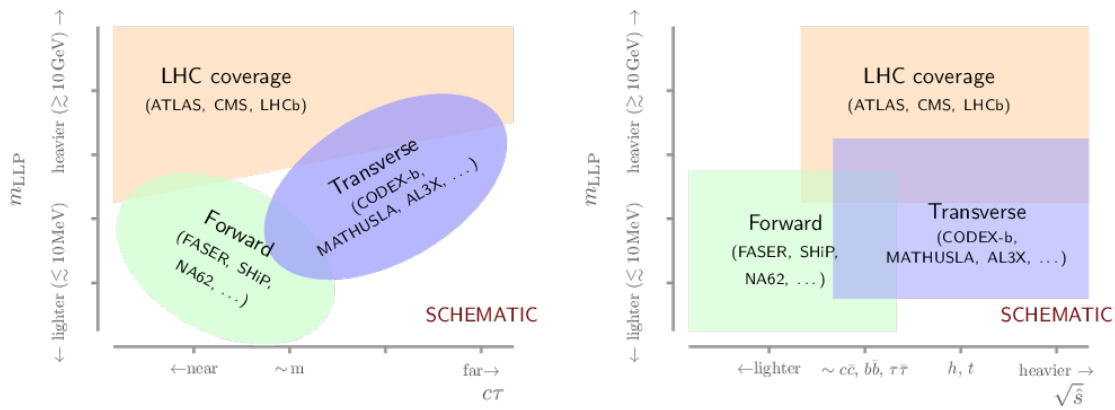


Figure 1.7: Diagram of potential physics cases covered by current, proposed and future experiments depending on the LLP mass, lifetime or allowed Center-of-Mass energy. Reproduced from [33] under Creative Commons license.

portal physics through Higgs or Z decays. To sum up, the expected regions are those shown in Figure 1.7.

Chapter 2

Objectives

This thesis has two main objectives:

1. Provide a brand new measurement for some dark matter decay modes described in Section 1.3.3 and aiming for a world-first measurement of these modes. For this the branching fraction of two decays will be measured:

$$\mathcal{B}(\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))) \quad (2.1)$$

$$\mathcal{B}(\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))), \quad (2.2)$$

which are related to the $\mathcal{O}_{cs}$ and $\mathcal{O}_{cd}$ respectively. The introduction of the Σ_b decay head is a new approach to these kind of measurements where a loss of signal efficiency is to be expected in a tradeoff for a significantly better background discrimination.

In case of finding no significative signal over the background, an upper limit to the branching ratios will be set, which is expected to be a world best measurement at the moment of writing. This is framed within the LHCb experiment at CERN, since its detectors and data will be used throughout most of the work.

2. The other main objective is to provide a generator level efficiency to some Higgs portal model, as stated in Sections 1.4 and 1.4.1. This is made within the CODEX-b collaboration, which is a project of a detector to be installed aiming to be a candidate to potentially study SM and BSM long lived particles, as it will be described in the experimental section.

Chapter 3

Experimental setup

3.1 CODEX-b experiment

Current LHC experiments have shown immense ability and future potential in discovering new particles such as the Higgs boson [47,48] and its characterisation [40], or the discoveries of new and exotic resonances such as bound states of five quarks [49] and in general many other short range physics cases [50,51].

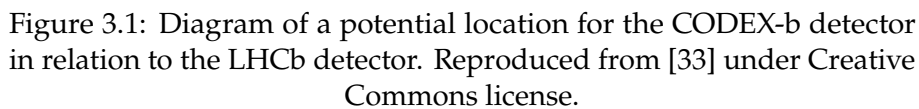
Not only SM searches have been done at the LHC but also some BSM physics have been studied, setting new limits to other physics cases [52]. All of these experiments excel at searches of SM and BSM signatures of particles with very short lifetimes [53–55]. Even though steps are being made, no change in the state of the art in the beyond standard model physics has been found in any of these experiments.

A more novel approach some physicists are currently following is the search for long lived particles. These are, in general, BSM particles characterised by the wide variance that is present in their masses and lifetimes, providing current experiments of an almost impossible challenge of discovery. For this purpose new detectors have been proposed, such as the one that will be studied in this work, CODEX-b [33,56] but not exclusively since others exist such as Mathusla [57] or Anubis [58].

In the case of CODEX-b, it is expected to be a very general purpose detector for LLPs, being able to probe different physics cases such as: Abelian hidden sector, Scalar-Higgs portal (the one studied in this work), Axion-like particles... The physics cases studied by this experiment are expected to be out of reach for most of current detectors. Classical examples of SM LLP searches can also be probed at CODEX, such as K_L^0 , π , neutron and muon decays.

3.1.1 CODEX-b detector

The proposed CODEX location is the room next to the LHCb experiment. About 25 meters from the interaction point of the LHCb. It would be formed by a volume of 10 m × 10 m × 10 m. Resistive Plate Chambers (RPCs) are the main tracking technology of the experiment [56]. Modules of RPCs (in the demonstrator two modules of 2 m ×



The approximate location of the detector can be parametrised by the following volume:

- $25,75 \text{ m} < x < 35,75 \text{ m}$
- $-5 \text{ m} < y < 5 \text{ m}$
- $5 \text{ m} < z < 15 \text{ m}$,

Its location, very transverse to the proton beams, allows for a realistic background simulation and characterisation, taking the well known SM interaction of particles and radiation with matter and its propagation through it. Its location behind the shielding wall allows for a higher uptime of maintenance of the electronics and hardware, since this area is accessible more time of the year due to lower levels of ionisation after the beam.

In order to allow for a better characterisation of backgrounds, and as well as some concept physics studies, a demonstrator is being assembled at the moment of the writing, namely CODEX- β in opposition to the name of the experiment and final detector, CODEX-*b*. Finally, it is important to note that the CODEX experiment will have an interplay with the LHCb detector [56], which is a characteristic that will be exploited in this work.

3.2 LHCb experiment

The LHCb detector is one of the four main detectors at the Large Hadron Collider (LHC) at Conseil Européen pour la Recherche Nucléaire (CERN) and it is at the moment of this writing the biggest collider and that with the highest center of mass energy in the world.

3.2.1 The Large Hadron Collider

This circular accelerator is located on the border between Switzerland and France, close to the city of Geneva. It is a 27 km long circumference where some of the latest technologies known to humankind play an important role, such as superconductors or aerogel. Previous beam facilities such as the proton synchrotron (PS) or the super proton synchrotron (SPS) are used to pre-accelerate the protons that are then injected into the LHC, gaining energy in each of the steps [59].

In the final step, two beams of extremely high energy protons circulate through the ring, one in each direction, and they collide frontally at the points where the experiments are located. These beams are stabilised under an extreme vacuum condition in order to guarantee precisely known measuring conditions in the impact points.

The four points where the beams are crossed and collided are where the four biggest experiments are located, these being: ATLAS, CMS, ALICE and LHCb, as seen in Figure 3.2. At the moment of their installation, each of these detectors was supposed to fulfill different roles within the LHC:

- ATLAS (A Toroidal LHC AparatuS): was designed to be a general purpose detector, where many physics cases could be studied, such as Higgs decays at the moment of its construction.
- CMS (Compact Muon Solenoid): also a general purpose detector, where a very efficient tracking of muons was made due to its design.
- ALICE (A Large Ion Collider Experiment): it is the main experiment to study proton to ion collisions, and vice versa.

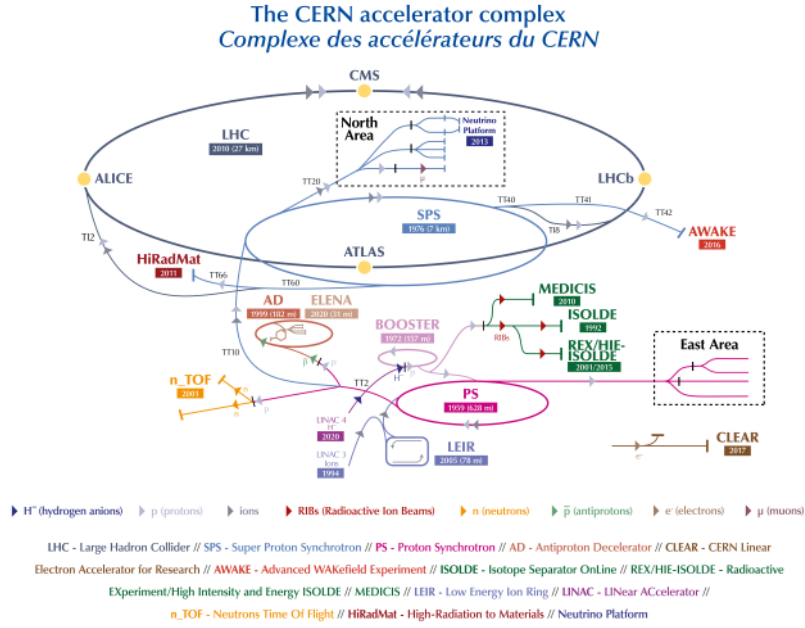


Figure 3.2: Cern accelerator complex diagram taken from [61] under Creative Commons licensing. Many of the experiments of the institution are also shown in this diagram.

- LHCb: at first was designed as a forward detector to study the beauty quark and a lot of the physics related to it, such as CP violation. But it is more of a general purpose detector now since it is able to study many different physics cases [60]. This is the experiment where much of this work takes place.

3.2.2 The LHCb experiment

The LHCb detector design [62] aims to reconstruct particles containing a b quark. These particles decay very rapidly and do not fly a lot, since they are very short lived. This is the main reason for the forward design of this detector instead of covering the full solid angle like ATLAS [53,63] or CMS [64,65].

While these two detectors may reconstruct particles decaying in any direction (provided that they decay within the detector volume), or, equivalently, particles with any given pseudorapidity η while only forward particles may be detected at LHCb provided that their direction of flight falls within the acceptance window of $1.6 \leq \eta \leq 4.9$ where the pseudorapidity is given by:

$$\eta = \frac{1}{2} \ln \frac{p + p_z}{p - p_z} = -\ln \tan \frac{\theta}{2}, \quad (3.1)$$

where the z -axis has been chosen as the direction of the protons within the beam without any loss of generality. In this equation θ is given by the angle formed by the studied particle's direction of flight and the beam's trajectory. By substituting the values from the previous inequality in the equation the angular acceptance of this experiment is obtained, being: $10 \text{ mrad} \leq \theta \leq 300 \text{ mrad}$.

The LHCb subdetectors

An array of several subdetectors is assembled in order to track the particles flying through the detector and to reconstruct its ascendants. From the impact point and moving forward one may find the following subdetectors:

- **Vertex Locator:** the Vertex Locator (VELO) [66–68] is designed to be extremely precise when localising the primary and secondary vertex of very heavy hadrons, those containing b and c quarks, since this was the initial focus of this experiment. The VELO is able to obtain great time resolution and measuring of B -mesons lifetime which makes it a key part of the experiment when studying meson oscillations for some of its main measurements, such as ϕ_s [69].

The precision is around $42 \mu\text{m}$ in the z -axis and $10 \mu\text{m}$ in the detector direction, perpendicular to the protons.

- **RICH:** detector devoted to identifying the nature of the particle based on Cherenkov radiation. Charged particles moving through a medium at a speed greater than the speed of light in said medium radiate a cone of light, which is characterised by its radius, tightly related to the speed of the particle. Analysing this cone and the momentum of the particle, a prediction on the nature of the particle may be cast (note that this detector may give a wrong lecture since Cherenkov radiation does not solve the nature of a particle).

Two RICH [70,71] detectors are assembled within the LHCb: the RICH1 that is devoted to characterise charged particles in the low momentum spectrum ($1 - 60 \text{ GeV}/c$) while the RICH2 studies higher momentum ranged (from 15 to beyond $100 \text{ GeV}/c$). This detector makes an accurate prediction on the nature of a particle around 90% of time while failing about 5%.

- **Tracking system:** several tracking systems [72,73] are present in the LHCb experiment. A station is present right after RICH1 and previous to the magnet while three others may be found right after this and before RICH2. These four subdetectors assemble the so-called Silicon Tracker, one key subsystem of the experiment with a hit efficiency higher than 99% [74].
- **Magnet:** a magnetic dipole [75] with a field of 4 T·m curves charged particles, this curvature is intimately related to the momentum of any given particle.

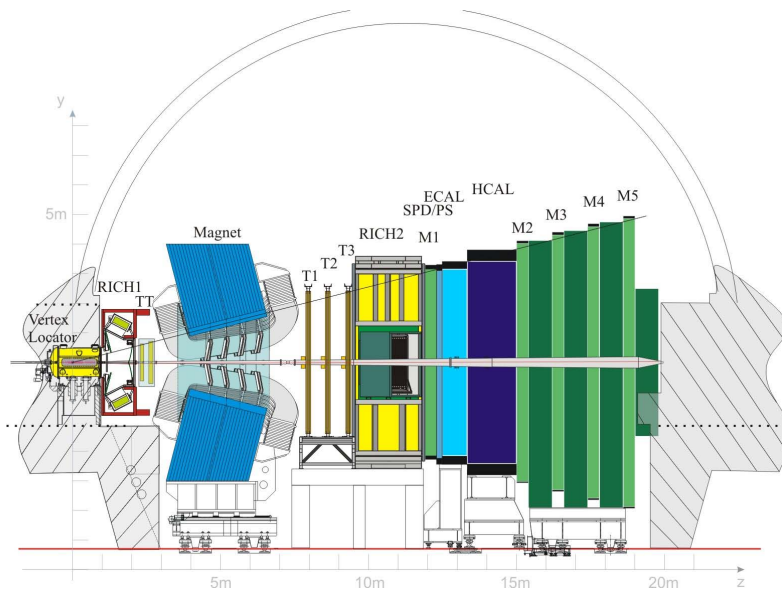


Figure 3.3: Diagram of the LHCb detector with the described components.
Taken from [80] under Creative Commons License.

- **Calorimeter system:** the LHCb calorimeter system [76,77] measures the energy of e , γ and hadrons in general, allowing a selection in terms of their transverse energy. The electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL) are two of the subsystems forming the LHCb calorimeter system, which allows to distinguish the nature of a particle in terms of how much energy is deposited in each of the subsystems. The preshower detector is another subsystem from the calorimeter system which is used to distinguish between electrically neutral or charged particles. Finally the scintillator pad detector is used to characterise and study the electromagnetic showers.
- **Muon stations:** the last subdetector of the LHCb is the muon system [78,79], composed of five muon tracking stations, being the first one located right before the PS calorimeter and the other four being the last subsystems of the experiments. Muons are known particles, so when a given one hits the muon subsystems a full reconstruction of its track may be achieved. A specific analysis variable is related to this system and is the main resource to correctly proceed in the identification of these particles.

A full schematic of the detector may be found in Figure 3.3.

As stated, part of this work is framed within the Run 2, that took place between 2015 and 2018. A full schedule of the LHC may be found in Figure 3.4.

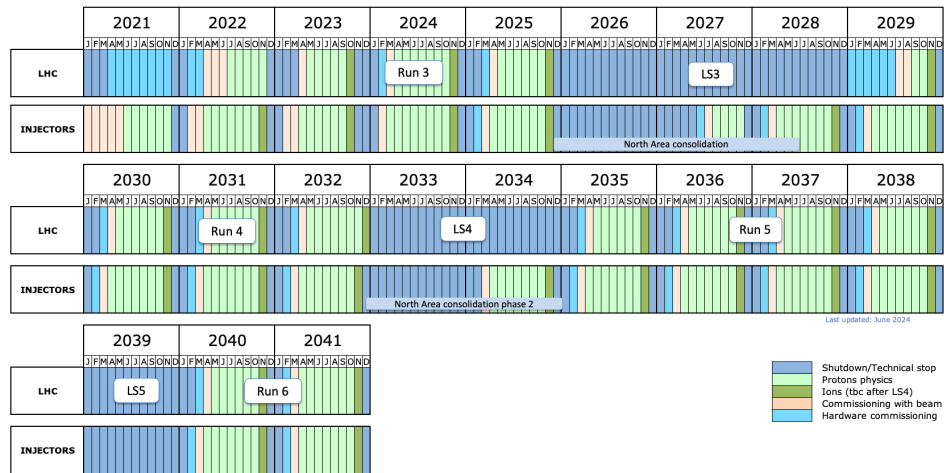


Figure 3.4: Schedule of the LHC data taking periods. LHC Run 1 took place from 2011 to 2013 and Run 2 from 2015 to 2018. Taken from [81] under Creative Commons License.

Stripping

The trimming of the data is done centralised at a LHCb collaboration level, referred to as Stripping campaigns. This is done offline, after the data taking, where a trigger selection took place, and a more in depth description of it may be found in Section 6.2.4. These are systematic efforts undertaken periodically to apply a series of selection criteria to the data that has passed through the initial trigger. The aim is to further refine the dataset by eliminating less interesting or less relevant data, leaving only the most promising events for deeper analysis. These campaigns produce a reduced dataset that is easier to handle and more focused on the physics cases of greatest interest to the collaboration.

Stripping campaigns are crucial for efficient data management and effective scientific analysis, as they ensure that researchers can focus their efforts on the most informative data, thereby optimising resources and enhancing the potential for discovery.

Simulation

Simulation samples are vital in High Energy Physics, essential for calibrating selections for potential new signals and refining various reconstruction algorithms. The LHCb utilises a framework integrating different software to create these simulated data samples. During the generation phase, Pythia 8 is used to simulate proton-proton collisions, accurately producing Standard Model hadrons with the appropriate kinematics and context.

EvtGen is utilised to specifically induce the decay of certain particles into desired final states, which is crucial for studying rare decays. The interaction of particles with the detector's described layers is modeled using Geant4, and the detector's response is digitised. This information is then processed by software that simulates the Level 0 (L0) trigger response and applies the trigger decisions similar to those used on actual data, ensuring that both real and simulated data maintain a structurally comparable format. During Run 2, the simulation framework version known as Sim09 was in use, but it was updated to Sim10 in 2022, with the primary change being an upgrade from Geant4 version 9 to version 10.

Chapter 4

Methodology

4.1 LHCb search

On the one hand, missing energy analyses are not the most popular ones at LHCb [82] due to not being a hermetic detector. As an immediate consequence of this, the total energy of an event is not a variable we can access.

On the other hand, LHCb is an extremely suitable experiment to produce and study Λ_b^0 decays. This is due to the fact that b -particles are produced at the impact point of the LHCb and decay within the VELO [83].

The $\Lambda_b \rightarrow \psi_{\text{DM}} K(D \rightarrow \pi\pi K)$ and $\Lambda_b \rightarrow \psi_{\text{DM}} \pi(D \rightarrow \pi\pi K)$ upper limits to the branching ratios will be obtained using as input the Run 2 data of 5.4fb^{-1} . Two stripping lines have been written in order to process the data from the collisions taken during 2016, 2017, and 2018. Each line corresponds to each one of the two decay modes that will be studied.

One additional decay mode is considered: $\Lambda_b \rightarrow \pi(\Lambda_c \rightarrow pK\pi)$. This decay is used as a normalisation channel to measure the amount of Λ_b produced, so the branching ratios can be computed as:

$$\mathcal{B}(\Lambda_b \rightarrow \psi_{\text{DM}} \pi(D \rightarrow \pi\pi K)) \sim \frac{N(\Lambda_b \rightarrow \psi_{\text{DM}} \pi(D \rightarrow \pi\pi K))}{N(\Lambda_b)}, \quad (4.1a)$$

$$\mathcal{B}(\Lambda_b \rightarrow \psi_{\text{DM}} K(D \rightarrow \pi\pi K)) \sim \frac{N(\Lambda_b \rightarrow \psi_{\text{DM}} K(D \rightarrow \pi\pi K))}{N(\Lambda_b)}. \quad (4.1b)$$

Moreover, the searches that will be performed are $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}} \pi(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}} K(D \rightarrow \pi\pi K))$. This allows for a mass fit to a double crystal ball (DCB) [84] probability distribution function (PDF) and a better background discrimination. The downside to this methodology [85–88] is that many statistic is lost due to two main features: not all Λ_b are produced in a Σ_b decay, and one additional particle must be reconstructed (the π from the Σ_b). This will be expanded in a latter section of this work.

Bearing all of the above in mind, the analysis strategy can be described by the following steps:

1. Generate Monte Carlo (MC) samples of the signal decay modes, as well as from the normalisation channel that will be used in order to compute the DM branching ratios as previously stated.
2. Apply the selection described in the Section 6.2.3 to all the generated Monte Carlo (MC). The objective is suppressing all peaking backgrounds and an important amount of the combinatorial.
3. Apply a different selection to the normalisation channel since it has been obtained from an older stripping campaign.
4. Apply a full trigger-on-signal (or TOSTOSTOS) trigger selection in both signal channels as well as in the normalisation channel.
5. Perform a multivariate analysis (MVA) in both signal and normalisation decays in order to be able to obtain a clean mass peak.
6. Obtain the kinematic variables associated with the methodology described in [85–88] and in Section 6.3 for the $\Sigma_b^{(*)}$ in the signal decays.
7. Reconstruct potential $\Sigma_b^{(*)}$ candidates in the signal and normalisation decay modes using the selected data after stripping and trigger selection from steps 3 and 4 and having performed the MVA described in step 5.
8. Compute all the efficiencies associated to the signal and normalisation decays (ϵ_{NORM}) to be able to compute the $N(\Sigma_b)$.
9. Fit normalisation channel to obtain $N(\Sigma_b^{(*)})$ to a multicomponent signal and background extended fit.
10. Compute $N(\Sigma_b)$ by using the result of the extended fit and the value of all the computed efficiencies mentioned.
11. Fit the signal MC and background to obtain a signal PDF to perform a hypothesis test over the data.
12. Compute the expected limit using the computed numbers mentioned above and the PDF of the signal.
13. Use the b-inclusive MC to study potential peaking backgrounds that could appear using the Σ_b tagging methodology and be confused with signal.

It is important to note that $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ have been used indistinctly without indicating the charge of the particles since both charged modes will be used since one is just the C -conjugation of the other and no differences in its BR is to be expected according to the model.

4.2 CODEX efficiency

In this case, the proceeding is as follows:

1. Generate MC samples of the described decay modes for the Higgs portal for several Higgs production modes.
2. Parametrise every counting experiment done to compute the generator level efficiency.
3. Apply the conditions obtained in the previous step to the samples produced in step 1.
4. Compute the generator level efficiency. In this case, no background is taken into account for this.

Chapter 5

CODEX-b studies

5.1 Monte Carlo samples

LHC events were generated in PYTHIA8 [89] at a center of mass energy of $\sqrt{s} = 14$ TeV, since this is the energy at which both the CODEX-b detector and the CODEX- β demonstrator will acquire the data [33].

In this case, as mentioned in Section 1.4.1, three different Higgs production modes are studied, the inclusive Higgs production, where all bosons are produced according to the known production cross-sections [90].

It must be noted that no detector effects such as pile-up, material interactions or any other non-ideality are considered in this work. The efficiencies presented in this text should be interpreted in an analogous way to those presented in Sections 6.2.1 and 6.5.1. This being, as an efficiency that could be implemented in a CODEX dedicated simulation software, analogous to the LHCb Gauss [91, 92].

The characterisation of the data samples generated can be found in Table 5.1. In this case, no previous selection is applied, and Monte Carlo is generated according to the known SM distributions [93–95].

Production mode	Cross section	Events generated
Inclusive	58151	4000000
Higgs-strahlung	2479	6000000
Weak-boson fusion	4260	16112103

Table 5.1: Production cross sections and amounts of events generated for each of the Higgs production modes studied. The cross section is given in fb^{-1}

Particle	prod-x	prod-y	prod-z	p_T	η
μ_1^-	$\in (25750, 35750)$	$\in (-5000, 5000)$	$\in (5000, 15000)$	> 0.25	$\in (2, 5)$
μ_1^+	$\in (25750, 35750)$	$\in (-5000, 5000)$	$\in (5000, 15000)$	> 0.25	$\in (2, 5)$
μ_2^-	$\in (25750, 35750)$	$\in (-5000, 5000)$	$\in (5000, 15000)$	> 0.25	$\in (2, 5)$
μ_2^+	$\in (25750, 35750)$	$\in (-5000, 5000)$	$\in (5000, 15000)$	> 0.25	$\in (2, 5)$

Table 5.2: Potential constraints imposed over the μ for the counting experiment performed for the Higgs inclusive production. Distances are in mm and p_T are in GeV.

5.2 Generator level efficiency

The proceedings followed to obtain the efficiencies for each production mode, as well as the different detection cases and the constraints imposed for each case are described. For every production mode the generated decay is $pp \rightarrow H^0 \rightarrow (A^0 \rightarrow \mu^+ \mu^-)(A^0 \rightarrow \mu^+ \mu^-)$, and only the production mode of the H^0 changes.

5.2.1 Inclusive production

In this case, no production mode is imposed and the H^0 is allowed to be generated freely according to SM production cross-sections. With all the Monte Carlo events a counting experiment is performed. The condition for counting +1 event that fulfills the requirements of a CODEX detection is the A^0 decaying within its volume. This is equivalent to requiring that at least one of the μ of the described decay is generated in the detector volume, this means that at least one row of the Table 5.2 must be met, excluding the p_T and pseudorapidity η conditions.

We studied two additional cases: one of them being that two of the A^0 decay in CODEX, this would be met if one of the μ_1 and one of the μ_2 were produced within the CODEX volume. In terms of conditions this would be true if at least one row from each subtable in Table 5.2 happened. Once again no p_T nor η criteria are required.

The other case is that at least one A^0 decays within the CODEX volume while the other decays in the LHCb volume. In this case, the counting experiment would be successful if at least one of μ_1 or one of the μ_2 were produced in the CODEX volume, while the others must meet the p_T and η requirements. This happens when the spatial production requirements of at least one of the rows from one subtable of Table 5.2 happens while both p_T and η requirements of the other subtable are true, this one must also be produced in $\text{prod-z} \in (0, 15000)$.

The obtained efficiencies are shown in Table 5.3 and Figure 5.1.

Detector	0.1 m	1 m	10 m	100 m	1000 m
One CODEX	2.13×10^{-5}	74.2×10^{-5}	22.8×10^{-5}	2.13×10^{-5}	0.2×10^{-5}
Two CODEX	0	0	0	0	0
CODEX & LHCb	5.25×10^{-6}	0.5×10^{-6}	0	0	0

Table 5.3: Efficiencies computed for all detection modes described. Lifetimes are given in terms of $c\tau$ and in meters.

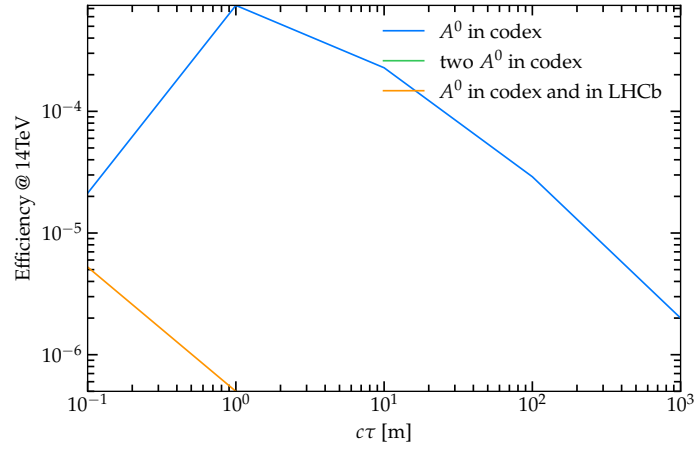


Figure 5.1: Efficiencies plot for all detection modes described. Both axes are in logarithmic scale, and no event with both A^0 in CODEX is found.

5.2.2 Higgs-strahlung

In this case only the Higgs-strahlung (also known as associated boson production) will be the allowed production mode of the SM Higgs. In this case, the counting experiment consists of one of the A^0 decaying within the CODEX volume while the W/Z^0 are assumed to decay into their leptonic modes, these being: $W \rightarrow \mu\nu$ and $Z^0 \rightarrow \mu^+\mu^-$, and one charged lepton with very high p_T is required to be found in the LHCb experiment. So this counting experience rests over the future capability of CODEX and LHCb interplay, otherwise no difference from the previous case is to be expected.

In this case the explicit conditions would be, that the μ_1 or μ_2 have their production coordinates within the CODEX volume (see Table 5.2) while one μ from a vector boson must meet the three following constraints: $\eta \in (2, 5)$, $p_T > 20$ GeV and $\text{prod-z} < 15000$, with the last one being trivially met since the W and Z bosons have short lifetimes.

The obtained efficiencies are shown in Table 5.4 and Figure 5.2.

Detector	0.1 m	1 m	10 m	100 m	1000 m
CODEX	3.13×10^{-5}	60.5×10^{-5}	20.8×10^{-5}	2.37×10^{-5}	0.18×10^{-5}
CODEX & LHCb	6.67×10^{-7}	453×10^{-7}	237×10^{-7}	2.67×10^{-7}	1.67×10^{-7}

Table 5.4: Efficiencies computed for all detection modes described. Lifetimes are given in terms of $c\tau$ and in meters.

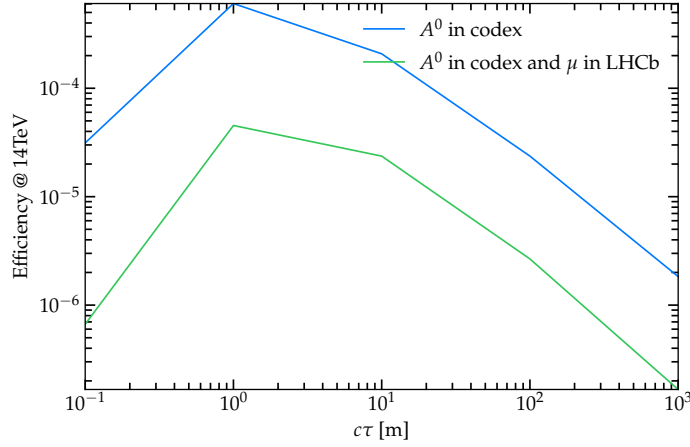


Figure 5.2: Efficiencies plot for the detection modes described for the Higgs-strahlung production. Both axes are in logarithmic scale.

5.2.3 Weak-boson fusion

The last study case is weak-boson fusion (also known as jet associated production), and this is the only allowed production mode for the SM Higgs. The counting experiment in this case is positive when one A^0 decays within the CODEX volume while a hadronisation of a quark into a jet is detected in the LHCb experiment.

This counting experiment differs a bit from the previous ones, since now there is one additional layer that is reconstructing and clusterising the hadrons of the jet into an object that LHCb understands as a jet. In order to perform the clusterisation, every stable and semi-stable particle (p, μ, K, π, e) detected by the VELO [96, 97] is clusterised into a jet according to the anti- k_t jet clustering algorithm [98] with a radius of 0.5 as the input parameter.

In this case the explicit conditions for this counting experiments are that, either the μ_1 or μ_2 must decay within CODEX volume as in the Higgs-strahlung production. On the other hand, the VELO particles must meet the following conditions: $\eta \in (2, 5)$, $p_T > 0.25$ GeV, $\rho < 38$ mm and $\text{prod-}z \in (0, 800)$ mm; where $\rho = \sqrt{x^2 + y^2}$, and the final clusterised jet must have $p_T > 20$ GeV.

The results of this methodology can be found in Table 5.5 and in Figure 5.3.

Detector	0.1 m	1 m	10 m	100 m	1000 m
CODEX	3.98×10^{-5}	77.1×10^{-5}	24.5×10^{-5}	3.02×10^{-5}	0.27×10^{-5}
CODEX & LHCb	1.74×10^{-6}	24.1×10^{-6}	6.64×10^{-6}	0.87×10^{-6}	0.12×10^{-6}
CODEX & 1 LHCb	1.74×10^{-6}	24.1×10^{-6}	6.58×10^{-6}	0.81×10^{-6}	0.12×10^{-6}
CODEX & 2 LHCb	0	6.21×10^{-8}	6.21×10^{-8}	6.21×10^{-8}	0

Table 5.5: Efficiencies computed for all detection modes described for weak boson fusion production mode. Lifetimes are given in terms of $c\tau$ and in meters.

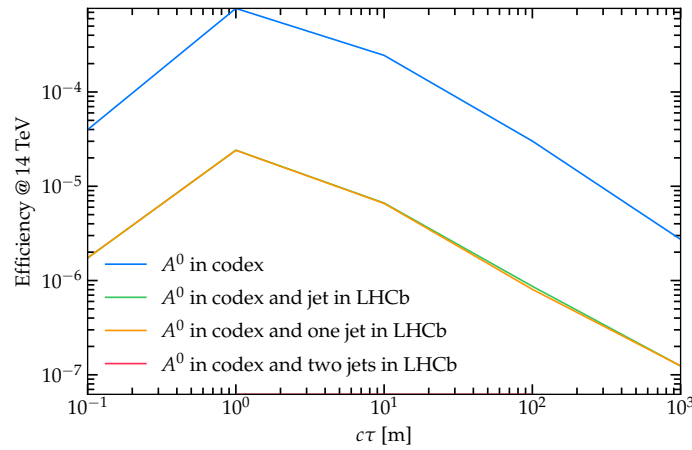


Figure 5.3: Efficiencies plot for the described detection modes for the jets associated production mode. Both axes are in logarithmic scale. Note that almost no events with two jets in CODEX are produced since the requirements of detection are very tough.

5.3 Results

By collecting all the results for the three studied production modes and their respective cross-sections [41]:

- inclusive production: 58151 fb^{-1} .
- Higgs-strahlung: 2479 fb^{-1} .
- weak-boson fusion: 4260 fb^{-1} .

we can compute the expected events for 300 fb^{-1} of integrated luminosity. The results are shown in Table 5.6 and Figure 5.4.

Production	0.1 m	1 m	10 m	100 m	1000 m
Inclusive	371	12953	3978	506	35
Inclusive & LHCb	92	9	0	0	0
Weak-boson	2	31	8	1	0
Higgs-strahlung	0	34	18	2	0

Table 5.6: Number of events expected for all detection modes described for every studied production mode. Lifetimes are given in terms of $c\tau$ and in meters.

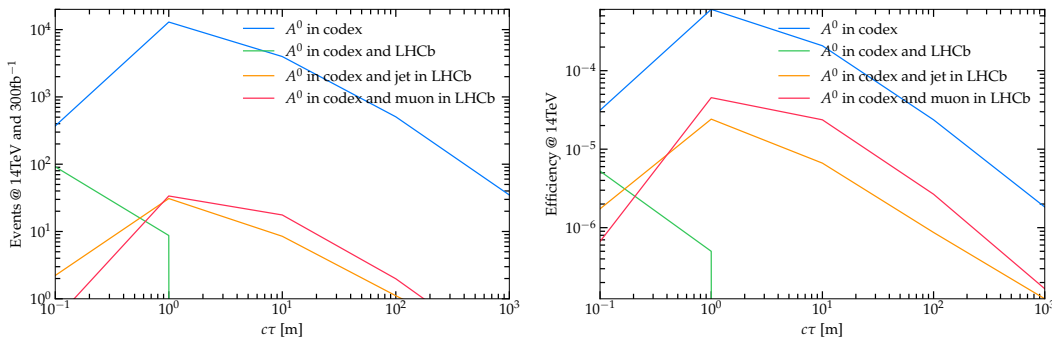


Figure 5.4: Efficiencies plot (right) and expected events (left) to be detected at the CODEX-b experiment for a $\mathcal{L} = 300 \text{ fb}^{-1}$.

Chapter 6

Dark matter and B-mesogenesis

6.1 Data and Monte Carlo Samples

In this section the data and MC used for this analysis is presented. All the data used is that collected by the LHCb experiment at the LHC during the years 2016, 2017 and 2018. The energy at the center of mass of the pp collisions is $\sqrt{s} = 13$ TeV. The whole available datasets correspond to the full Run II, 5.1fb^{-1} of integrated luminosity, being the breakdown by year: 1.6fb^{-1} in 2016, 1.5fb^{-1} in 2017 and 2.0fb^{-1} in 2018. In order to be blind under potential discoveries, only a small fraction of the available integrated luminosity has been used: 0.44fb^{-1} for the O_{cs} operator and 0.22fb^{-1} for O_{cd} .

6.1.1 Recorded data samples

As mentioned, this analysis uses the full Run II data. The signal and normalisation channels are taken from different stripping campaigns due to their availability and time constraints of the analysis.

The studied decays will be $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{DM}K(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{DM}\pi(D \rightarrow \pi\pi K))$ as mentioned in Section 4.1, but the stripping lines and the reconstructed decays are $\Lambda_b \rightarrow \psi_{DM}K(D \rightarrow \pi\pi K)$ and $\Lambda_b \rightarrow \psi_{DM}\pi(D \rightarrow \pi\pi K)$. FullDST¹ stripping lines habilitate the tagging of the Λ_b with a $\pi^{\pm}$ allowing the reconstruction of the $\Sigma_b^{\pm}$ candidates [86].

- 2018 signal lines: $\Lambda_b \rightarrow \psi_{DM}K(D \rightarrow \pi\pi K)$ and $\Lambda_b \rightarrow \psi_{DM}\pi(D \rightarrow \pi\pi K)$ lines can be found within two different stripping campaigns²: **Stripping34r0p3** and **Stripping34r0p2** with slightly different variable selection. This work has been performed with the **Stripping34r0p2** but the unblinding and the full Run 2 results should be obtained with the **Stripping34r0p3**.

¹Full DST means that the full event is stored for later processing, which allows the reconstruction of additional objects, compared to those initially analysed at the “stripping” stage.

²Stripping campaigns are LHCb tasks where analysts may write new selections that will be run over already taken data. These take place around every two years.

- 2017 signal lines: $\Lambda_b \rightarrow \psi_{\text{DM}} K(D \rightarrow \pi\pi K)$ and $\Lambda_b \rightarrow \psi_{\text{DM}} \pi(D \rightarrow \pi\pi K)$ lines are located within the Stripping29r2p3 campaign. No more 2017 lines were written for this work.
- 2016 signal lines: $\Lambda_b \rightarrow \psi_{\text{DM}} K(D \rightarrow \pi\pi K)$ and $\Lambda_b \rightarrow \psi_{\text{DM}} \pi(D \rightarrow \pi\pi K)$ lines are accessible within two different campaigns again: Stripping28r2p2 and Stripping28r2p1. The former line has the same cuts than Stripping34r0p3 and Stripping29r2p3 while the latter line should not be used due to a problem during the stripping campaign that resulted in a misalignment of the cuts for different years of data taking.
- 2018 normalisation line: $\Lambda_b \rightarrow \pi(\Lambda_c \rightarrow pK\pi)$ line is available within the Stripping34 campaign. It must be checked with MC that it can be used for 2017 and 2016 normalisation.

6.1.2 MC samples

Unless indicated otherwise, every simulation batch has been produced with both magnet polarities: magnet up (MU) and magnet down (MD).

- b-inclusive stripping filtered samples (event type³ 10000000) simulated with Sim09l and filtered with the stripping lines of the Stripping34r0p2 campaigns. With TCK⁴ 0x617d18a4 and no additional trigger was applied. After the stripping the events associated to the $\Lambda_b \rightarrow \psi_{\text{DM}} \pi(D \rightarrow \pi\pi K)$ line remaining are about 25k, while for the $\Lambda_b \rightarrow \psi_{\text{DM}} K(D \rightarrow \pi\pi K)$ line are 4.4k.
- $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}} K(D \rightarrow \pi\pi K))$ samples with the following masses: [0.94, 1.5, 2.0, 2.4, 3.0] GeV. The decay models used are PHSP and D_DALITZ to decay the D from EvtGen [99]. A collection of very soft cuts is applied at generation level, as seen in Table 6.1, to improve the reconstruction efficiency, that will later be overridden by the selection being tighter. The event types used are: [16565000, 16565001, 16565002, 16565003, 16565004] in an exact correspondence with the masses.
- $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}} \pi(D \rightarrow \pi\pi K))$ samples with the following masses: [0.94, 1.5, 2.0, 2.4, 3.0, 3.4] GeV. Note that there is an additional mass for this decay, this is because the π is lighter than the K and allows for a bigger phase space. The decay models used are PHSP and D_DALITZ to decay the D . A collection of very soft cuts is applied at generation level, as seen in Table 6.2, to improve

³an event type is an 8 digit label that identifies the decay in terms of whether they contain b quarks, c quarks, e , μ ...

⁴Trigger Configuration Key: a label identifying which trigger lines and configuration settings were running for a given process.

Particle	Cut
$K_{D,\Lambda}$	$p_T > 0.25 \text{ GeV} \ \& \ 1.9 < \eta < 5.0$
π_D	$p_T > 0.25 \text{ GeV} \ \& \ 1.9 < \eta < 5.0$
π_Σ	$p_T > 0.10 \text{ GeV} \ \& \ 1.9 < \eta < 5.0$

Table 6.1: Generator level cuts imposed over the particles of the $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$. The subindex in each particle indicates the mother of the semi-stable particles. η is the pseudorapidity of the particle, this requirement is imposed due to LHCb being a forward region detector [100]. An additional condition of truth matching via TRUEID [101] is applied. This is, the MC flag for the ID of the particle is required to be the same in the reconstructed and in the generated decays.

This is something not achievable in the real reconstruction.

the reconstruction efficiency, that will later be overridden by a tighter selection. The event types used are: [16565900, 16565901, 16565902, 16565903, 16565904, 16565905] in an exact correspondence with the masses.

- $\Sigma_b^\pm \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ samples with the same masses as in the $\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ were used. The decay models used are PHSP and D_DALITZ to decay the D . The same collection of soft cuts is applied (Table 6.1). The event types used were: [16565700, 16565701, 16565702, 16565703, 16565704].
- $\Sigma_b^\pm \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ samples with the same masses as in the $\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay were used. The same models The decay models used are PHSP and D_DALITZ to decay the D . The same collection of soft cuts is applied (Table 6.2). The event types used were: [16565800, 16565801, 16565802, 16565803, 16565804, 16565805].
- $\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \pi(\Lambda_c \rightarrow pK\pi))$ samples produced in a private production. The decay model used is PHSP to decay every unstable particle. A collection of very soft cuts is applied at generation level as seen in Table 6.3. Since this is a private the event type is not relevant.
- $\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \Lambda^0\pi(D \rightarrow K\pi\pi))$ samples with event type 16165100. The decay models used are PHSP and D_DALITZ to decay the D . The soft cuts applied to $\Sigma_b^\pm \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ (Table 6.2) are also applied to this decay, only changing the truth matching to the correspondent decay.

Particle	Cut
K_D	$p_T > 0.15 \text{ GeV} \ \& \ 1.9 < \eta < 5.0$
$\pi_{D,\Lambda}$	$p_T > 0.15 \text{ GeV} \ \& \ 1.9 < \eta < 5.0$
π_Σ	$p_T > 0.10 \text{ GeV} \ \& \ 1.9 < \eta < 5.0$

Table 6.2: Generator level cuts imposed over the particles of the $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \Lambda^0\pi(D \rightarrow K\pi\pi))$. The subindex in each particle indicates the mother of the semi-stable particles. All particles are truth matched.

Particle	Cut
K_Λ	$p_T > 0.10 \text{ GeV} \ \& \ 1.9 < \eta < 5.0$
$\pi_{\Lambda,\Sigma}$	$p_T > 0.10 \text{ GeV} \ \& \ 1.9 < \eta < 5.0$
p_Λ	$p_T > 0.10 \text{ GeV} \ \& \ 1.9 < \eta < 5.0$

Table 6.3: Generator level cuts imposed over the particles of the $\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \pi(\Lambda_c \rightarrow pK\pi))$. The subindex in each particle indicates the mother of the semi-stable particles. Every particle is truth matched.

Every sample has been produced with Sim09 of Gauss [102] using Pythia 8 [103,104] to generate pp collisions and Geant 4 [105] to simulate the material interactions and every detector related event.

6.2 Selection

6.2.1 Generator level selection

As mentioned in Section 6.1.2 some generator level selection is applied to every simulated event in this analysis to reduce the computation time and make more out of the disk space used to store the simulated data.

The pseudorapidity cut ($1.9 < \eta < 5.0$) is imposed over every semi-stable particle in the reconstruction, so one may as well add it in the generation in order to lose less events during the reconstruction making the process of simulation way more efficient, since most of the CPU time and resources are taken during the detector simulation, not the generation, so optimising this step is quite important.

The transverse momentum (p_T) requirement plays a similar role. The nature of the L0 trigger [62] of the LHCb experiment imposes a p_T cut over the hadrons in order to be available to process all the events that reach the experiment [106]. In any

	0.94	1.5	2.0	2.4	3.0	3.5
$\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$	9.637	9.619	9.527	9.405	9.051	6.873
$\Sigma_b^\pm \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$	x.xxx	9.262	x.xxx	x.xxx	x.xxx	x.xxx
$\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$	8.108	8.004	7.855	7.679	7.277	NOPHSP
$\Sigma_b^\pm \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$	x.xxx	7.808	x.xxx	x.xxx	x.xxx	NOPHSP
$\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \pi(\Lambda_c \rightarrow pK\pi))$	10.221					

Table 6.4: Generator level efficiencies of every signal mode. The normalisation channel generator level efficiency is independent of the DM particle mass. The masses are given in GeV. Only one mass has been generated so far for the $\Sigma_b^\pm$ decays, and that is the one used in the whole analysis.

case, tougher p_T cuts are imposed in the stripping lines that will be described in this section.

The signal decay modes and the normalisation mode have the generator level efficiencies shown in Table 6.4. The background decay mode $\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \Lambda^0\pi(D \rightarrow K\pi\pi))$ and the b-inclusive samples would also have a generator level efficiency associated, but its usage it is not required at any point during this analysis.

6.2.2 Reconstruction

Despite applying some generator cuts, the reconstruction efficiency is not 100%. There are several factors impacting this reconstruction efficiency, such as the finite resolution of any detector means that some particles may not be detected or may be misidentified. Factors such as electronic noise, energy resolution, and timing resolution also contribute to inefficiencies in particle identification and reconstruction [62].

Another reason is that as particles traverse the detector, interactions with the material (such as scattering or absorption) can result in energy loss or deflection from their original paths, thereby affecting the reconstruction efficiency. Some particles may also decay or completely stop within the detector materials before they can be detected [107].

The fact that the algorithms used for data reconstruction are designed to optimise speed and accuracy, but they also have intrinsic limitations. Computational constraints and algorithmic choices can lead to non-optimal reconstruction paths, affecting the overall efficiency. This also impacts the reconstruction efficiency [108].

When all of these factors are taken the efficiencies in Table 6.5 can be computed by checking how many events are lost in the MC reconstruction.

	0.94 GeV	1.5 GeV	2.0 GeV	2.4 GeV	3.0 GeV	3.5 GeV
O_{cs}	0.23342	0.22065	0.21871	0.20379	0.19550	NOPHSP
O_{cd}	0.25776	0.24652	0.22866	0.21989	0.19740	0.18820

Table 6.5: Reconstruction efficiency table for the $\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{DM}K(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{DM}\pi(D \rightarrow \pi\pi K))$ decay modes. It is clear that a mass dependency exists in this case.

6.2.3 Stripping Selection

This analysis uses several stripping lines and stripping campaigns as already described in Section 6.1.1. The definition of the variables used, the reason to use these variables as well as the collection of values will be presented in this section for every line and campaign used during the analysis. This means that the stripping for `Stripping28r2p1` will not be discussed in here.

This analysis uses three stripping lines, all from the stream `BhadronCompleteEvent`⁵:

- **LambdaDecaysDMLambdaToDPiLine**: signal line used to select $\Lambda_b \rightarrow \psi_{DM}\pi(D \rightarrow \pi\pi K)$ candidates. An additional $\pi^\pm$ tagged with the candidates coming from the stripping. The combination is required to have a somehow good enough vertex reconstruction, $(VFASPF(VCHI2/VDOF) < 10)$ is imposed over every $\Sigma_b^{\pm(*)}$ candidate in this analysis. The variables used in these stripping line as well as the cuts imposed over said variables can be found in Table 6.7.
- **LambdaDecaysDMLambdaToDKLine**: signal line used to select $\Lambda_b \rightarrow \psi_{DM}K(D \rightarrow \pi\pi K)$ candidates. The same proceeding over $\pi^\pm$ in order to reconstruct $\Sigma_b^{\pm(*)}$ candidates is followed in this case. The condition over the vertex of the $\Sigma_b^{\pm(*)}$ is also imposed. The variables used in this stripping line as well as the cuts imposed over said variables can be found in Table 6.6.
- **Lb2LcPiNoIPLc2PKPiBeauty2CharmLine**: normalisation line used to select $\Lambda_b \rightarrow \pi(\Lambda_c \rightarrow pK\pi)$ candidates. In this case, $\Sigma_b^{\pm(*)}$ candidates are also reconstructed following the same procedure as in the other two lines. The same condition over the vertex reconstruction is imposed. This stripping lines were

⁵A fullDST stream is required, such as `BhadronCompleteEvent` is required since the stripping lines, as it will be shown, only have requirements over the Λ_b and its descents. This implies that the analysis will require fullDST lines in order to be able to reconstruct $\Sigma_b^{\pm(*)}$ candidates, tagging the Λ_b candidates coming from the stripping with $\pi^\pm$ living in the `StdAllNoPIDsPions`, only accessible within complete events.

not written for this analysis, and a deeper description and usage can be found in [109,110].

Particle (Variable)	Cut(Stripping34r0p2)	Cut(Stripping34r0p3)
$\Lambda_b^0 (p_T)$	$> 2000 \text{ MeV}$	$> 2000 \text{ MeV}$
$\Lambda_b^0 (\text{DOCA})$	$< 0.5 \text{ mm}$	$< 0.5 \text{ mm}$
$\Lambda_b^0 (\text{DOCA}\chi^2)$	< 8	< 8
$\Lambda_b^0 (\text{FD}\chi^2 \text{ OWNPV})$	> 30	> 30
$\Lambda_b^0 (\text{Isolation})$	> 0.6	> 0.6
$\Lambda_b^0 (M)$	$1100 < M < 5700 \text{ MeV}$	$1100 < M < 5700 \text{ MeV}$
$\Lambda_b^0 (V\chi^2/\text{DOF})$	< 8	< 8
$\Lambda_b^0 (\text{IP}\chi^2 \text{ OWNPV})$	> 20	> 25
$K_D^+ (p_T)$	$> 800 \text{ MeV}$	$> 250 \text{ MeV}$
$K_D^+ (\text{ProbNNghost})$	< 0.1	< 0.1
$K_D^+ (\text{ProbNNk})$	> 0.8	> 0.8
$\pi_D^- (p_T)$	$> 800 \text{ MeV}$	$> 250 \text{ MeV}$
$\pi_D^- (\text{ProbNNghost})$	< 0.1	< 0.1
$\pi_D^- (\text{ProbNN}\pi)$	> 0.8	> 0.8
$K_\Lambda^+ (p_T)$	$> 250 \text{ MeV}$	$> 250 \text{ MeV}$
$K_\Lambda^+ (\text{ProbNNghost})$	< 0.2	< 0.2
$K_\Lambda^+ (\text{ProbNNk})$	> 0.7	> 0.7
$K_\Lambda^+ (\text{IP}\chi^2 \text{ OWNPV})$	> 20	> 20
$D^- (\text{DOCA})$	$< 0.4 \text{ mm}$	$< 0.4 \text{ mm}$
$D^- (\text{FD}\chi^2 \text{ OWNPV})$	> 50	> 50
$D^- (M)$	$1840 < M < 1900 \text{ MeV}$	$1840 < M < 1900 \text{ MeV}$
$D^- (p_T)$	$> 2000 \text{ MeV}$	$> 2000 \text{ MeV}$
$D^- (V\chi^2/\text{DOF})$	< 6	< 6

Table 6.6: Stripping line for $\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K)$, LambdaDecaysDMLambdaToDKLine. The subindex of the K and π particles indicates its direct ascendant. As mentioned, the cuts for Stripping34r0p3 are also those for Stripping29r2p3 and Stripping28r2p3. The misalignment in the cuts is expected to not affect much, the difference in value is not big and does not affect many variables, in fact it only affects three of them (four in reality, since there are two π_D^-): $\pi_D^- (p_T)$, $\Lambda_b^0 (\text{IP}\chi^2 \text{ OWNPV})$ and $K_D^+ (p_T)$.

Particle (Variable)	Cut(Stripping34r0p2)	Cut(Stripping34r0p3)
$\Lambda_b^0 (p_T)$	$> 3000 \text{ MeV}$	$> 3000 \text{ MeV}$
$\Lambda_b^0 (\text{DOCA})$	$< 0.3 \text{ mm}$	$< 0.3 \text{ mm}$
$\Lambda_b^0 (\text{DOCA}\chi^2)$	< 7	< 7
$\Lambda_b^0 (\text{FD}\chi^2 \text{ OWNPV})$	> 30	> 30
$\Lambda_b^0 (\text{Isolation})$	> 0.6	> 0.6
$\Lambda_b^0 (M)$	$1100 < M < 5700 \text{ MeV}$	$1100 < M < 5700 \text{ MeV}$
$\Lambda_b^0 (V\chi^2/\text{DOF})$	< 8	< 8
$\Lambda_b^0 (\text{IP}\chi^2 \text{ OWNPV})$	> 20	> 20
$K_D^+ (p_T)$	$> 800 \text{ MeV}$	$> 800 \text{ MeV}$
$K_D^+ (\text{ProbNNghost})$	< 0.1	< 0.1
$K_D^+ (\text{ProbNNk})$	> 0.9	> 0.9
$\pi_D^- (p_T)$	$> 800 \text{ MeV}$	$> 800 \text{ MeV}$
$\pi_D^- (\text{ProbNNghost})$	< 0.1	< 0.1
$\pi_D^- (\text{ProbNN}\pi)$	> 0.8	> 0.8
$\pi_\Lambda^+ (p_T)$	$> 400 \text{ MeV}$	$> 400 \text{ MeV}$
$\pi_\Lambda^+ (\text{ProbNNghost})$	< 0.2	< 0.2
$\pi_\Lambda^+ (\text{ProbNN}\pi)$	> 0.8	> 0.8
$\pi_\Lambda^+ (\text{IP}\chi^2 \text{ OWNPV})$	> 20	> 20
$D^- (\text{DOCA})$	$< 0.4 \text{ mm}$	$< 0.4 \text{ mm}$
$D^- (\text{FD}\chi^2 \text{ OWNPV})$	> 50	> 50
$D^- (M)$	$1840 < M < 1900 \text{ MeV}$	$1840 < M < 1900 \text{ MeV}$
$D^- (p_T)$	$> 2000 \text{ MeV}$	$> 2000 \text{ MeV}$
$D^- (V\chi^2/\text{DOF})$	< 6	< 6

Table 6.7: Stripping line for $\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K)$, LambdaDecaysDMLambdaToDPiLine. The subindex of the K and π particles indicates its direct ascendant. As mentioned, the cuts for Stripping34r0p3 are also those for Stripping29r2p3 and Stripping28r2p3. As shown in this table, no misalignment had to be fixed for this line in particular.

The selections shown in Tables 6.6 and 6.7 aim to minimise the combinatorial background as much as possible, but they also look forward to completely suppress any potential peaking background. This is achieved with the isolation and primary vertex (PV) variables, these being topological variables, which are the most important ones for this analysis. All the other kinematic variables affect background and signal

	0.94 GeV	1.5 GeV	2.0 GeV	2.4 GeV	3.0 GeV	3.5 GeV
O_{cs}	0.05578	0.05283	0.04888	0.04528	0.02763	NOPHSP
O_{cd}	0.03944	0.03853	0.03659	0.03258	0.02478	0.00868

Table 6.8: Stripping efficiency table for the $\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{DM}K(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{DM}\pi(D \rightarrow \pi\pi K))$ decay modes. It is clear that a mass dependency exists in this case.

in a very similar way, but these are required to have a low enough rate and being able to achieve the disk usage quota.

The variables used, as mentioned, have different natures, topological if they are related to how the tracks are positioned in the space, where they point at, how close they are to one another... Or kinematic, if they are related to momentum, mass... There is also a third kind, which are the so-called probNN, that are the probabilities assigned by a neural network to a particle to be of a certain kind, as explained in Section 6.2.3.

Applying the selections described in Tables 6.6 and 6.7 to the MC samples described in Section 6.1.2 the efficiencies in Table 6.8 are computed.

Stripping Variables

- probNN: the variables named probNN, i.e.: probNNk, probNN π , are predictions of neural networks using information coming from different LHCb subdetectors. This information is used to assign a probability to each track of being associated to a specific specie of particle. There is a different probNN variable, the so-called probNNghost, that assigns to each “track” the probability of it not being a real track by a particle, but instead being hits in the tracking misidentified as a track [111, 112].
- p_T : the transverse momentum is one of the most relevant kinematic variables at LHCb since it is a forward spectrometer. It is useful to get a better trigger efficiency, since the L0 Trigger is unable to process low transverse momentum tracks. It is defined as:

$$p_T = \sqrt{p_x^2 + p_y^2} \quad (6.1)$$

- DOCA: acronym for Distance Of Closest Approach (DOCA) of two or more tracks associated to the descendants of a given particle. It is the minimum separation between every track, calculated in pairs.
- DOCA χ^2 : the value of the DOCA significance in units of χ^2 .

- $\text{FD}\chi^2$ OWNPV: flight distance (FD) of a given particle in units of χ^2 from its own primary vertex (OWNPV), this being the point where it is originated, to the point where it decays.
- Isolation: variable that measures how isolated is a certain track from any other given track. It takes into account for the computation every track that falls within a cone defined from the track that is calculated, the radius of the cone is an input set as $R^2 = 0.6^2$. The variable is defined as

$$\text{ISO} = \frac{p_T}{p_T + p_T^{\text{CONE}}} \quad (6.2)$$

this means that the isolation variable will always be a number between 0 and 1, if the particle is entirely isolated we will have $p_T^{\text{CONE}} = 0$ and therefore $\text{ISO} = 1$. On the other hand, the less isolated the particle is, the bigger p_T^{CONE} will be, and consequently $\text{ISO} \rightarrow 0$.

- $V\chi^2/\text{DOF}$: the vertex χ^2 is a way of measuring the quality of the fit for the position of the decay vertex of a certain particle. In this case, it is normalised taking into account the degrees of freedom of the fit.
- $\text{IP}\chi^2$ OWNPV: the value of impact parameter (IP) in units of χ^2 . The impact parameter is the shortest distance between the track of a particle and a given vertex.

6.2.4 Trigger Selection

This section describes the trigger aspects of the analysis, performing an efficiency study over the 2018 $\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ samples described in Section 6.1.2 that allow for a better selection of $\Sigma_b^{\pm*}$.

Trigger independent of signal / Trigger on Signal

In the LHCb experiment candidates are categorised as TIS (Trigger independent of signal) or TOS (Trigger on signal) depending on the trigger decision. A candidate is said to be TOS if it has been selected by the trigger due to itself, while it is defined as TIS if the trigger selection is not conditioned by the candidate. This means, that removing a TOS candidate from the event, changes the trigger state, while doing the same with a TIS does not. This analysis is, as already stated, based on TOS candidates.

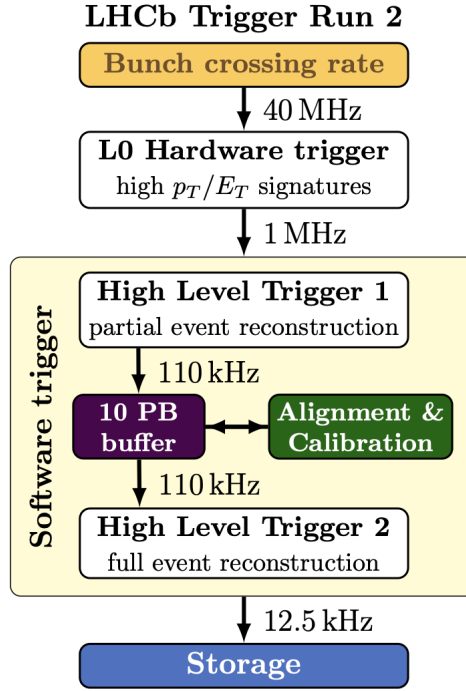


Figure 6.1: Diagram of the Run 2 trigger configuration. Taken from [106] under Creative Commons License.

L0 Trigger

The Level Zero (L0) trigger of the LHCb experiment is a critical component designed to manage the vast amount of data generated by proton collisions. It reduces the data rate from the full bunch crossing rate of 40 MHz to about 1 MHz, as seen in Figure 6.1, making it possible to record the data for offline analysis. This reduction is achieved through a system of field-programmable gate arrays (FPGAs) with a fixed latency, utilising information from the electromagnetic calorimeter, hadronic calorimeter, and muon stations in separate L0 trigger lines [113]. The LHCb trigger system, including the L0 trigger, plays a pivotal role in enabling the experiment to capture data on particles containing b and c quarks, essential for its physics program.

This trigger is the most determinant for this analysis, since the topological lines written for the High Level Trigger 2 (HLT2) and the TrackMVA lines for the High Level Trigger 1 (HLT1) have higher efficiencies overall.

Due to the nature of the studied decays in this analysis, the most efficient L0 line is `L0HadronDecision` applied over the Σ_b particle, since this is the head of the decay.

HLT1 Trigger

The HLT1 stage of the LHCb trigger system is responsible for an inclusive selection of events. This selection is based on criteria such as the presence of one or two-track signatures, muon tracks displaced from primary vertices, or dimuon combinations within an event. Selected events by HLT1 are temporarily stored in disk storage within the online system for further processing during inter-fill periods or for detector calibration and alignment before proceeding to HLT2, where a full event reconstruction occurs [113].

The HLT1 lines found to be the most efficient ones are `Hlt1TrackMVADecision` and `Hlt1TwoTrackMVADecision`, applied again over the Σ_b . These lines are selected as an OR operation between them (this is, only one is required simultaneously) and with an AND operator with the L0 line (a L0 positive trigger decision is always required, this is the reason for the efficiencies to be calculated in a sequential way).

HLT2 Trigger

The HLT2 stage in the LHCb trigger system is where full event reconstruction occurs. After HLT1 has made an initial selection, HLT2 processes these events comprehensively, allowing for a wide range of inclusive and exclusive final states to trigger events. This stage enables the fine-tuning of data selection, preparing it for detailed physics analysis without the need for further offline processing. This sophisticated triggering allows for efficient data handling and significantly contributes to the experiment's ability to perform real-time analyses [113].

The HLT2 lines found to be the most efficient ones in this analysis are `Hlt2Topo2BodyDecision`, `Hlt2Topo3BodyDecision` and `Hlt2Topo4BodyDecision`, which are different examples of “topological” trigger lines [114]. Once again an OR operator is applied between the different HLT2 lines and an AND one is required between previous trigger levels.

Taking into account the results in Tables 6.9 and 6.10 it is clear that the L0 trigger is, in general, the most determinant one, with the HLT2 requirements being also important at high DM masses, this is due to the fact that the tracks and hits recorded in the different subdetectors are associated with a smaller transverse momentum, lowering the efficiency of the L0 and HLT2 trigger requirements [113]. The mass dependency is more relevant in the HLT2 stage than in the L0 Trigger.

6.2.5 Multivariate Classifier

Using a Boosted Decision Tree (BDT) algorithm, namely a Gradient Boosting Classifier [115, 116], from the `scikit-learn` [117] python library is a usual method [118] in high energy physics (HEP) to obtain a better signal to background discrimination. The classifier optimises a loss function for binary classification. A metric that will be

	0.94 GeV	1.5 GeV	2.0 GeV	2.4 GeV	3.0 GeV	3.5 GeV
L0	0.213837	0.197694	0.178280	0.165681	0.134211	0.145561
HLT1	0.998306	1.0	0.999212	0.998071	1.0	1.0
HLT2	0.684389	0.580994	0.471609	0.389372	0.287582	0.174888
$\epsilon_{\text{Trigger}}$	0.146100	0.114859	0.084012	0.064387	0.038597	0.025457

Table 6.9: Efficiencies table for the $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay mode. The three trigger stages requirements are TOS. The efficiencies are calculated in a sequential way, this being, the HLT1 efficiencies are calculated over the events that passed the L0 selection, this also applies to the HLT2 efficiency with respect to the HLT1 efficiency.

	0.94 GeV	1.5 GeV	2.0 GeV	2.4 GeV	3.0 GeV
L0	0.227932	0.209320	0.180461	0.169569	0.124025
HLT1	0.996573	0.994700	0.998859	0.997297	0.993711
HLT2	0.669087	0.612789	0.470588	0.371274	0.161392
$\epsilon_{\text{Trigger}}$	0.151982	0.1275892	0.084826	0.062786	0.019891

Table 6.10: Efficiencies table for the $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay mode. The three trigger stages requirements are TOS. The efficiencies are calculated in a sequential way, this being, the HLT1 efficiencies are calculated over the events that passed the L0 selection, this also applies to the HLT2 efficiency with respect to the HLT1 efficiency.

used to evaluate the quality of this tool is the receiver operating characteristic (ROC) curve [119–122]. Different classifiers were tried out and no significant differences were found.

The classifier is trained using the MC samples in Section 6.1.2 as a signal proxy and a small data sample as background, the 4.55% (2.275% for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay mode) of the total available luminosity.

A first iteration of the BDT is trained with all the relevant topological and kinematic variables, and a *features importance* algorithm is executed in order to select a smaller sample of features to create the BDT. In light of the results of this proceeding, and according to Figure 6.2 the selected variables for the second iteration of the BDT will be: `pminus1IPCHI2OWNPV`, `pminus2PT`, `pminus2IPCHI2OWNPV`, `KplusIPCHI2OWNPV`, `KsoftPT`, `KsoftIPCHI2OWNPV`, `DminusPT`, `DminusIPCHI2OWNPV`, `DminusFDOWNPV`, `DminusFDCHI2OWNPV`, `Lambdab0IPCHI2OWNPV`, `Lambdab0DIRAOWNPV`, `Lambdab0DOCA` and `Lambdab0ISOLATIONSTRIPPING`.

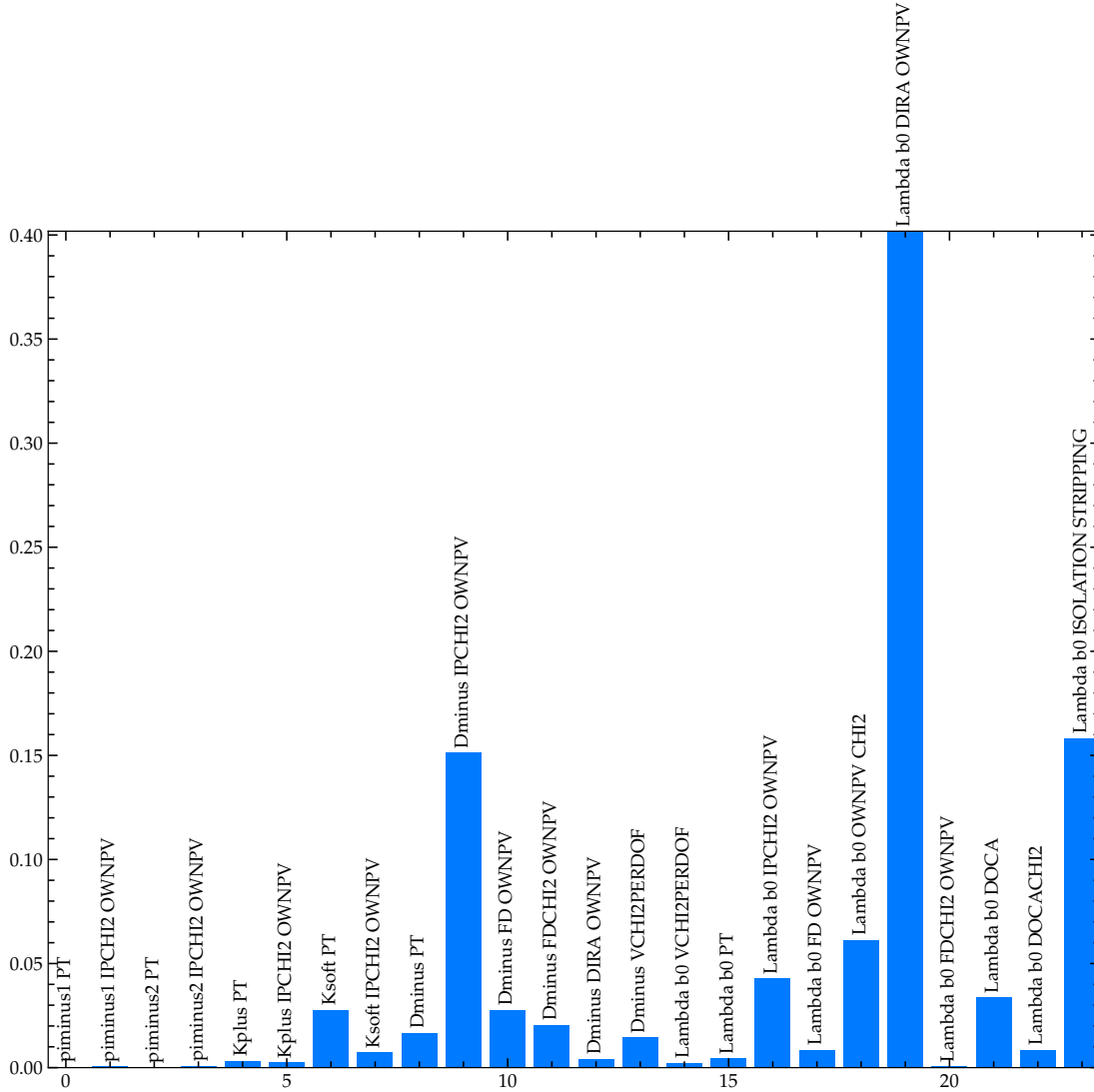


Figure 6.2: Histogram with the importance of each of the features used in the first iteration of the BDT in the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay. No $\Sigma_b^{\pm(*)}$ tagging particles are used in the BDT. pminus1,2 and Kplus variables are related to the D daughters, and the Ksoft variables refer to the Λ_b daughter. A $m(\psi_{\text{DM}}) = 940$ MeV MC sample is used.

Note that FD stands for flight distance, and OWNPV means that the variable is referred to the primary vertex of the given particle. Finally, when a variable has CHI2 in the name, it means that is measured in units of χ^2 .

The isolation and vertex variables of the Λ_b are the most relevant for the classifier,

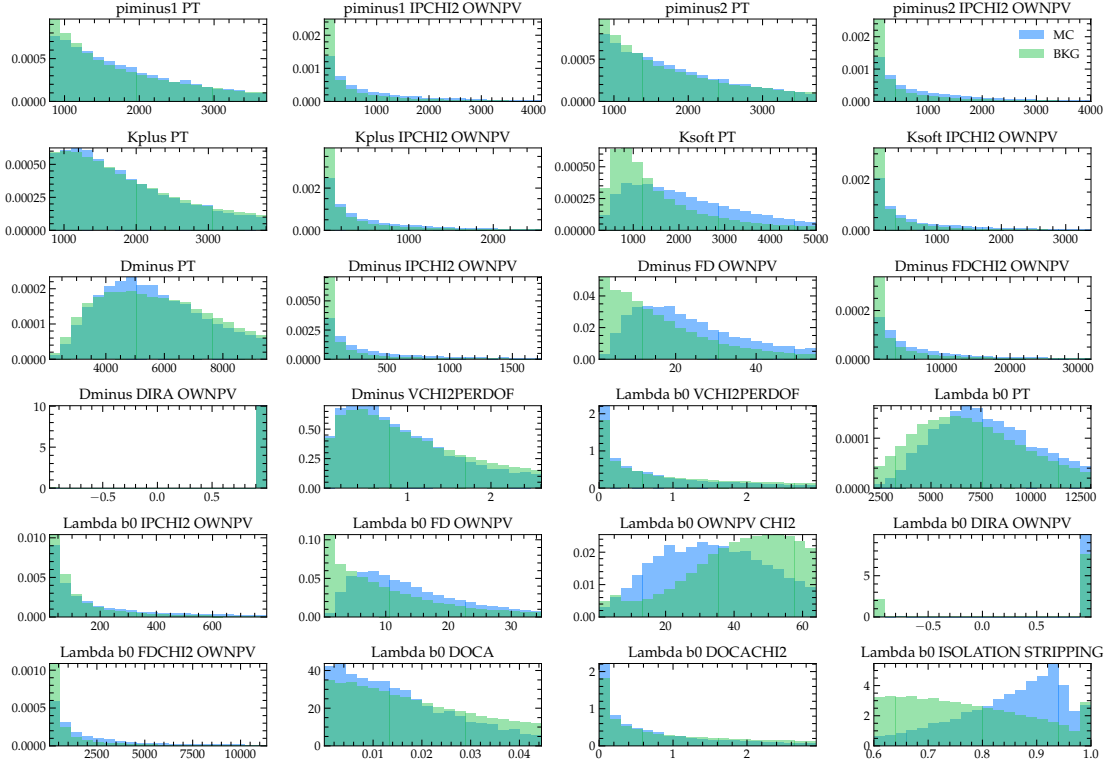


Figure 6.3: Distributions of signal and background variables of every feature used in the classifier. The label on top of each subplot indicates the variable plotted in each one. Every plot has arbitrary units on the y-axis.

as it was expected due to the nature of the decay. The different distributions of all the relevant features are shown in Figure 6.3 and their correlations may be found in Figure 6.4. The distributions are consistent with the result of the second iteration of the features importance histogram as seen in Figure 6.5.

The overtraining of the BDT is checked by using a k-fold cross-validation technique [123] with 5 folds. Each of them is validated separately by obtaining the area under the ROC curve and using a train/test sample. The scores are shown in Table 6.11, the ROC curve and the performance of BDT can be found in Figure 6.6 and Figure 6.7. The BDT does not produce artificial peaking structures on the background as it Figure 6.8 shows.

The last check is to see that the BDT response is similar in any given mass bin, both for background and for potential signal regions. This check is shown in Figure 6.9.

This proceeding is repeated for every mass and both decay modes. The results can be found in Figures 6.10 to 6.17 and table 6.12.

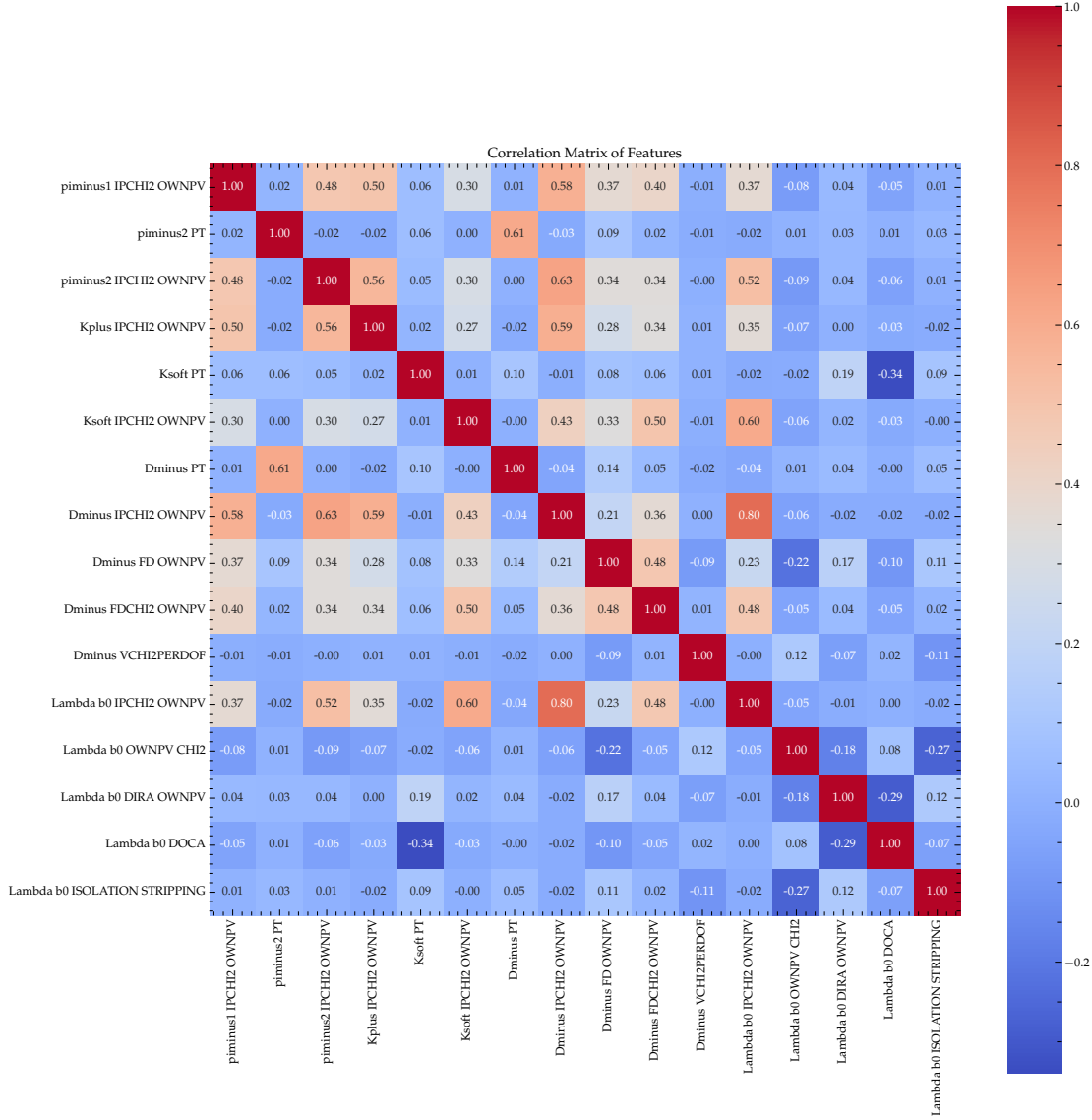


Figure 6.4: Correlation matrix for the most relevant variables used to train the BDT for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.

	Fold 1	Fold 2	Fold 3	Fold 4	Fold 5
BDT accuracy	0.8644	0.8544	0.8616	0.8580	0.8591

Table 6.11: Scores obtained using a k-fold cross-validation method for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.

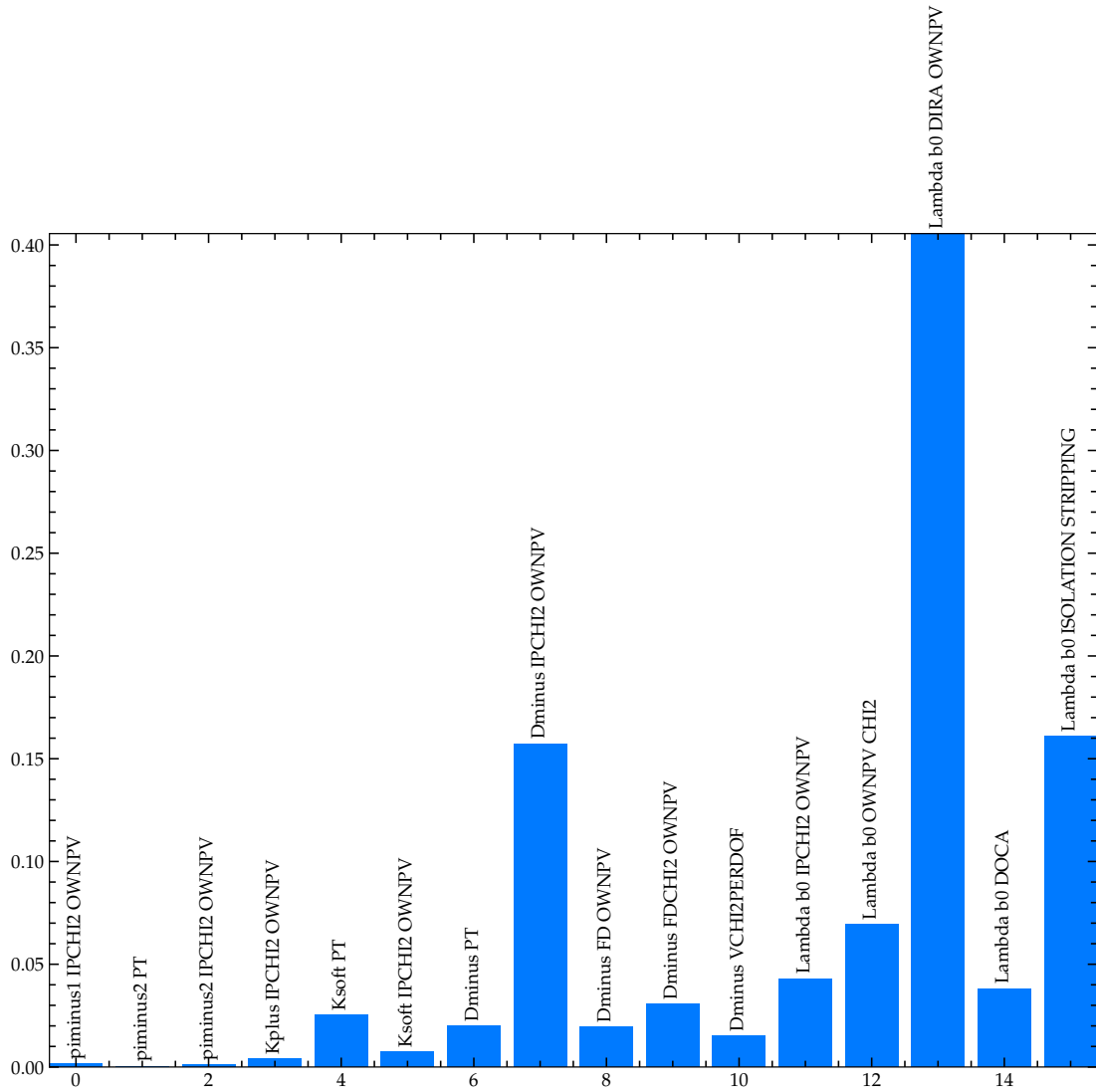


Figure 6.5: Histogram with the importance of each of the features used in the second iteration of the BDT for the $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.

	Fold 1	Fold 2	Fold 3	Fold 4	Fold 5
BDT accuracy	0.8295	0.8214	0.8260	0.8331	0.8401

Table 6.12: Scores obtained using a k-fold cross-validation method for the $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.

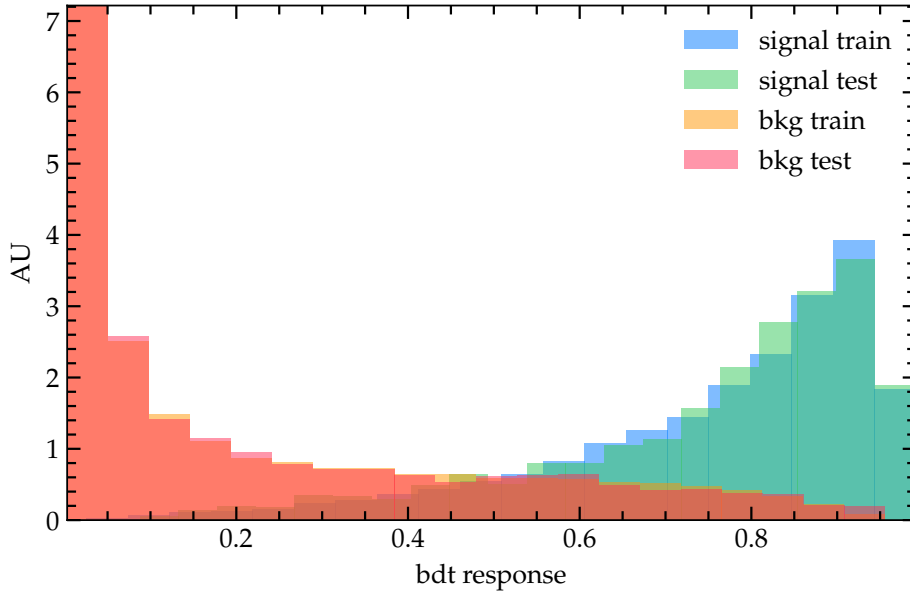


Figure 6.6: Performance of the classifier for the train/test samples for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.

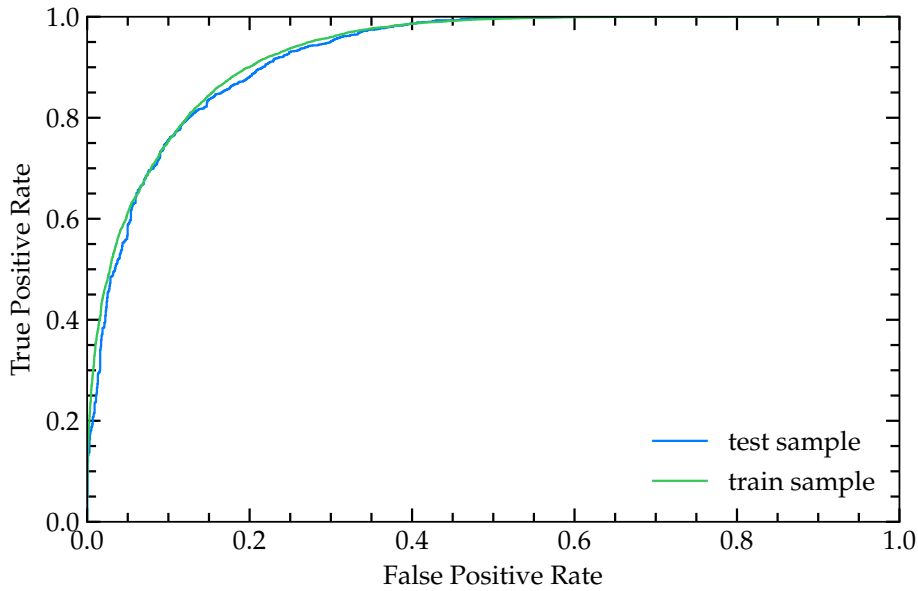


Figure 6.7: ROC curve obtained for the BDT using a train/test method for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.

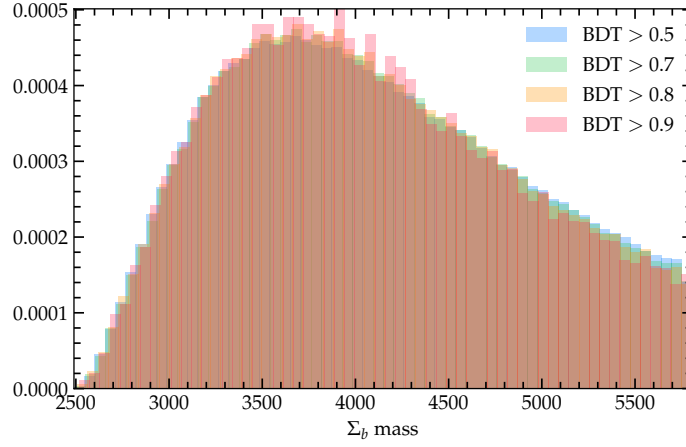


Figure 6.8: Effect of different BDT cuts over the background of this analysis. No fake peaking structures appear for a wide range of this classifier cut.

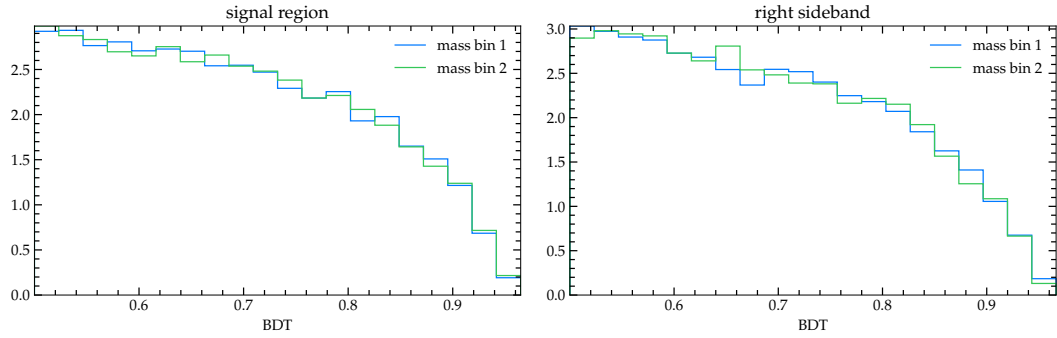


Figure 6.9: BDT response for different mass bins for a potential signal region (left) and for a guaranteed background region (right) for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}} K(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.

The BDT cut in the predictive variable is chosen by maximising the following figure of merit (FOM) [124]:

$$\text{FOM} = \frac{\varepsilon}{\frac{3}{2} + \sqrt{N_{\text{bkg}}}}, \quad (6.3)$$

where ε is the efficiency of the BDT cut over the MC test sample and $\sqrt{N_{\text{bkg}}}$ is the amount of events from the background after applying the BDT cut. By computing this quantity an optimum BDT cut can be chosen as seen in Figure 6.18.

By choosing the BDT cut that maximises the FOM in Figure 6.18 and Equation (B.10)

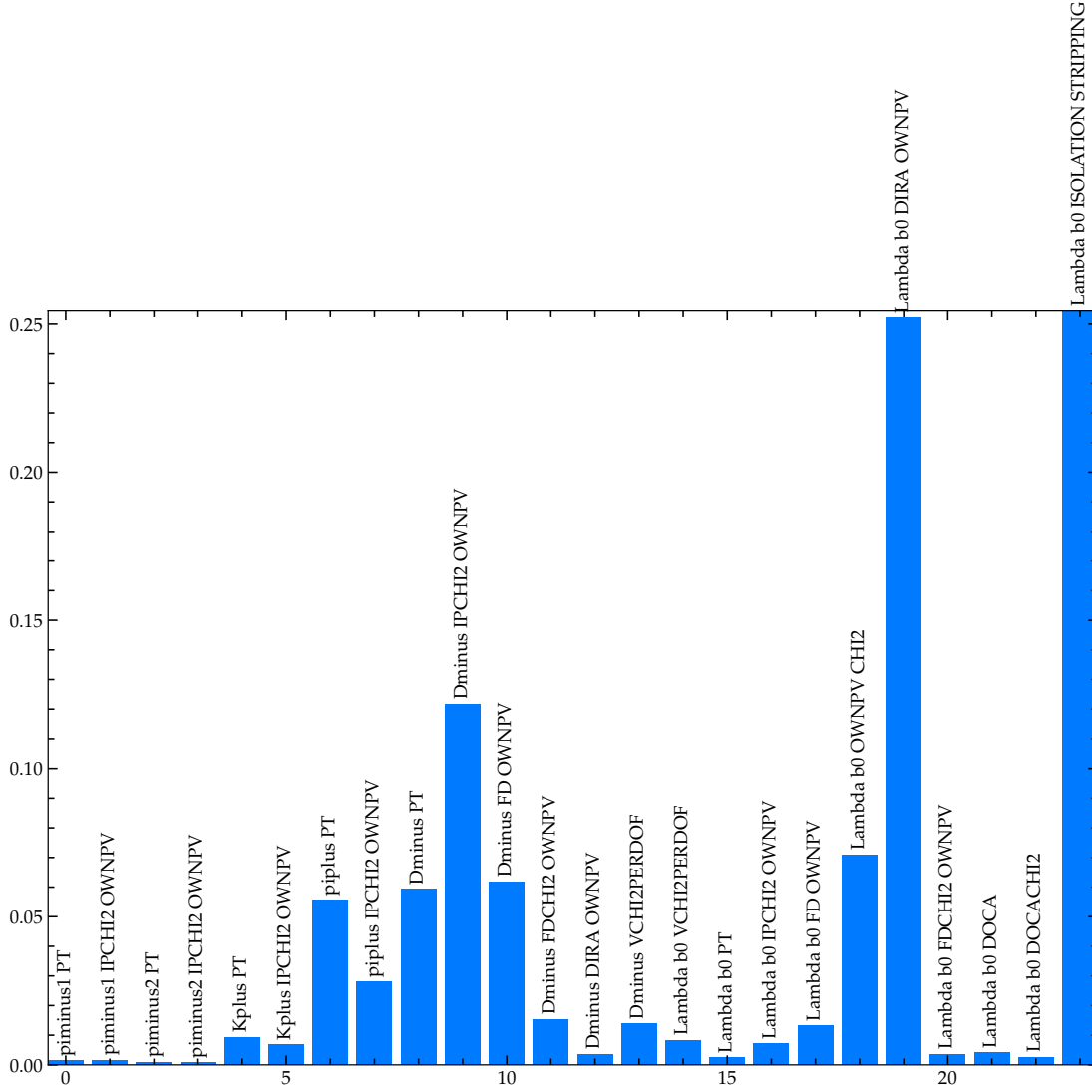


Figure 6.10: Histogram with the importance of each of the features used in the first iteration of the BDT in the $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay. No $\Sigma_b^{\pm(*)}$ tagging particles are used in the BDT. **pminus1,2** and **Kplus** variables are related to the D daughters, and the **piplus** variables refer to the Λ_b daughter. A $m(\psi_{\text{DM}}) = 940$ MeV MC sample is used.

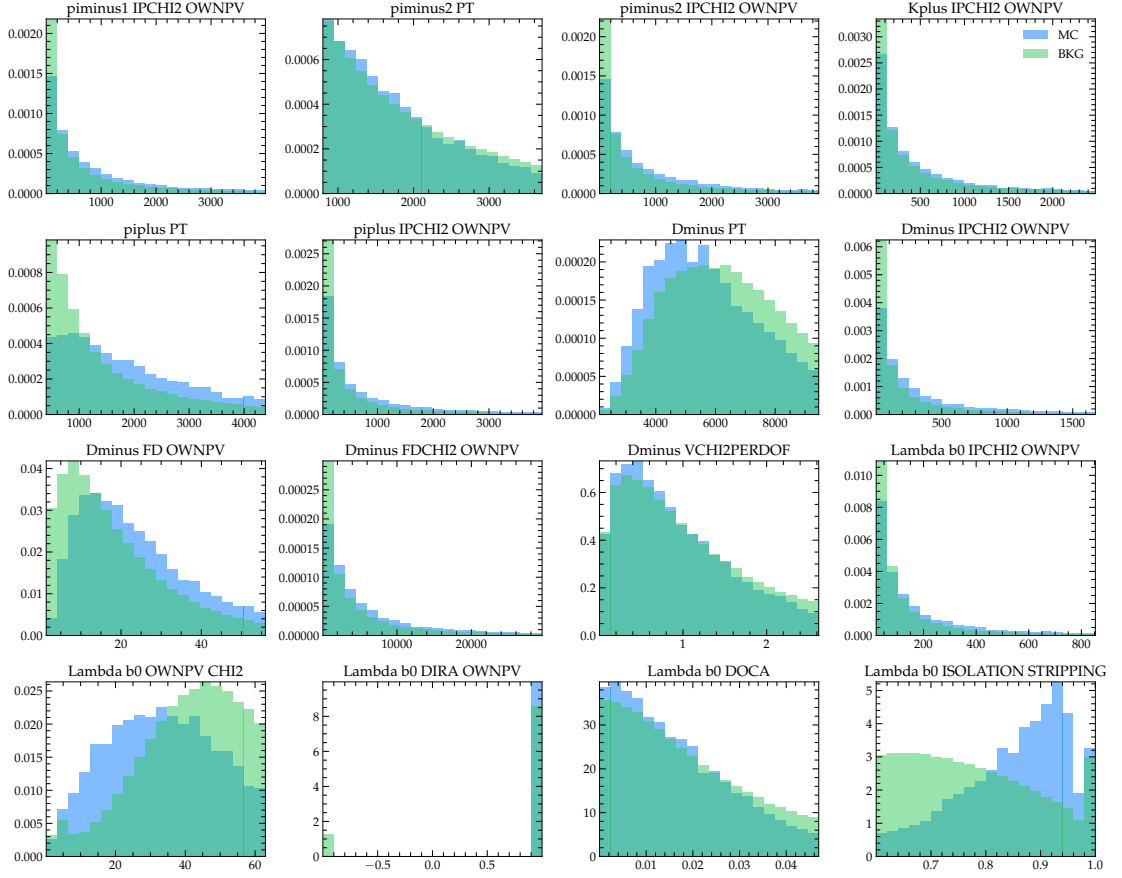


Figure 6.11: Distributions of signal and background variables of every feature used in the classifier for the $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{DM}\pi(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{DM}) = 940$ MeV. The label on top of each subplot indicates the variable plotted in each one. Every plot has arbitrary units on the y-axis.

the efficiencies in the BDT cut for the MC can be computed for every mass and decay mode.

6.2.6 Total efficiencies

By multiplying all the efficiencies for each decay mode and mass the total efficiency can be computed. In this cases, the total efficiency is given by:

$$\epsilon_{\text{tot}} = \epsilon_{\text{gen}} \epsilon_{\text{reco}} \epsilon_{\text{sel}} \epsilon_{\text{trig}} \epsilon_{\text{BDT}} \epsilon_{\text{tag}} \epsilon_{m_{\text{min}}} \quad (6.4)$$

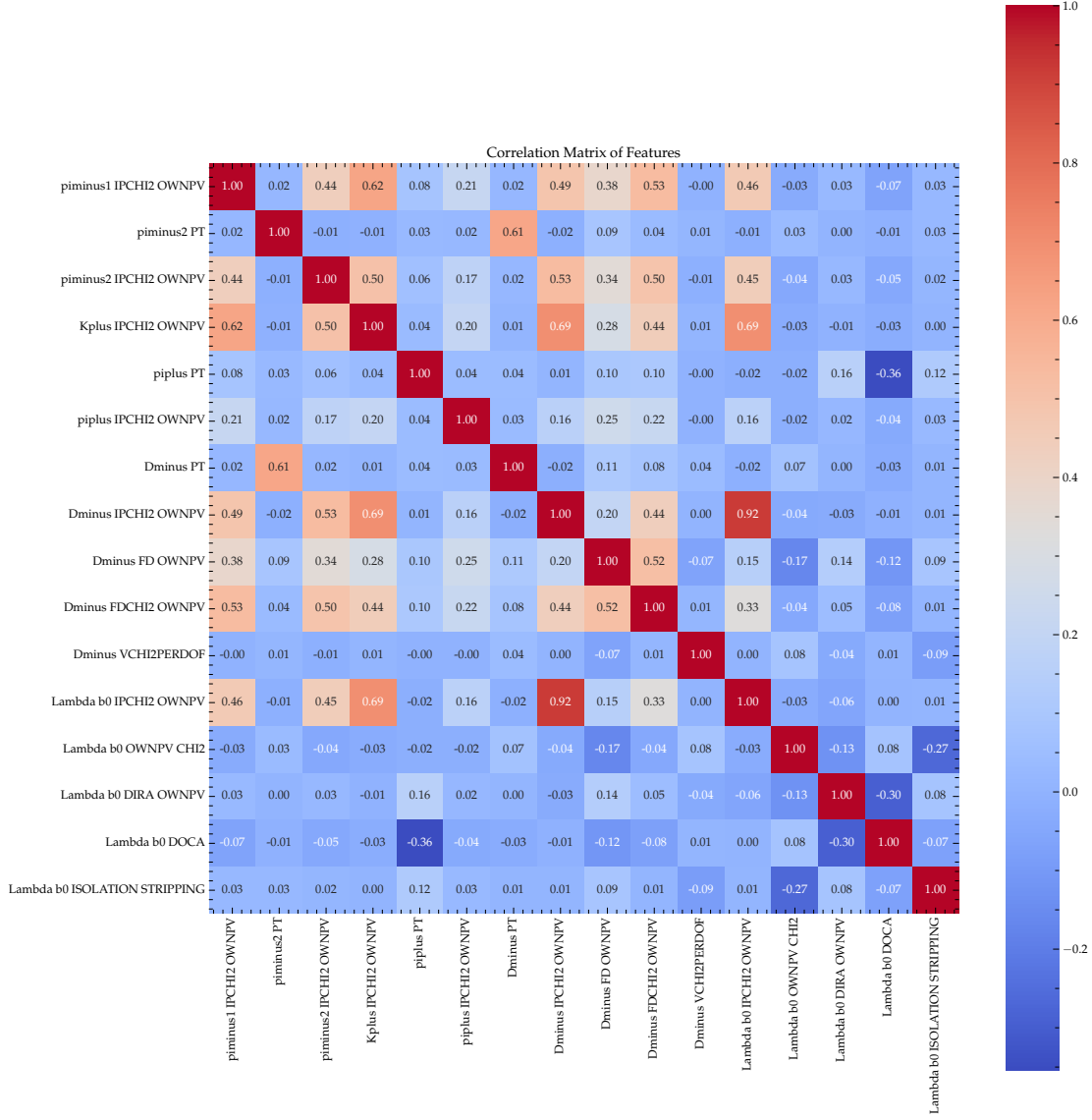


Figure 6.12: Correlation matrix for the most relevant variables used to train the BDT for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.

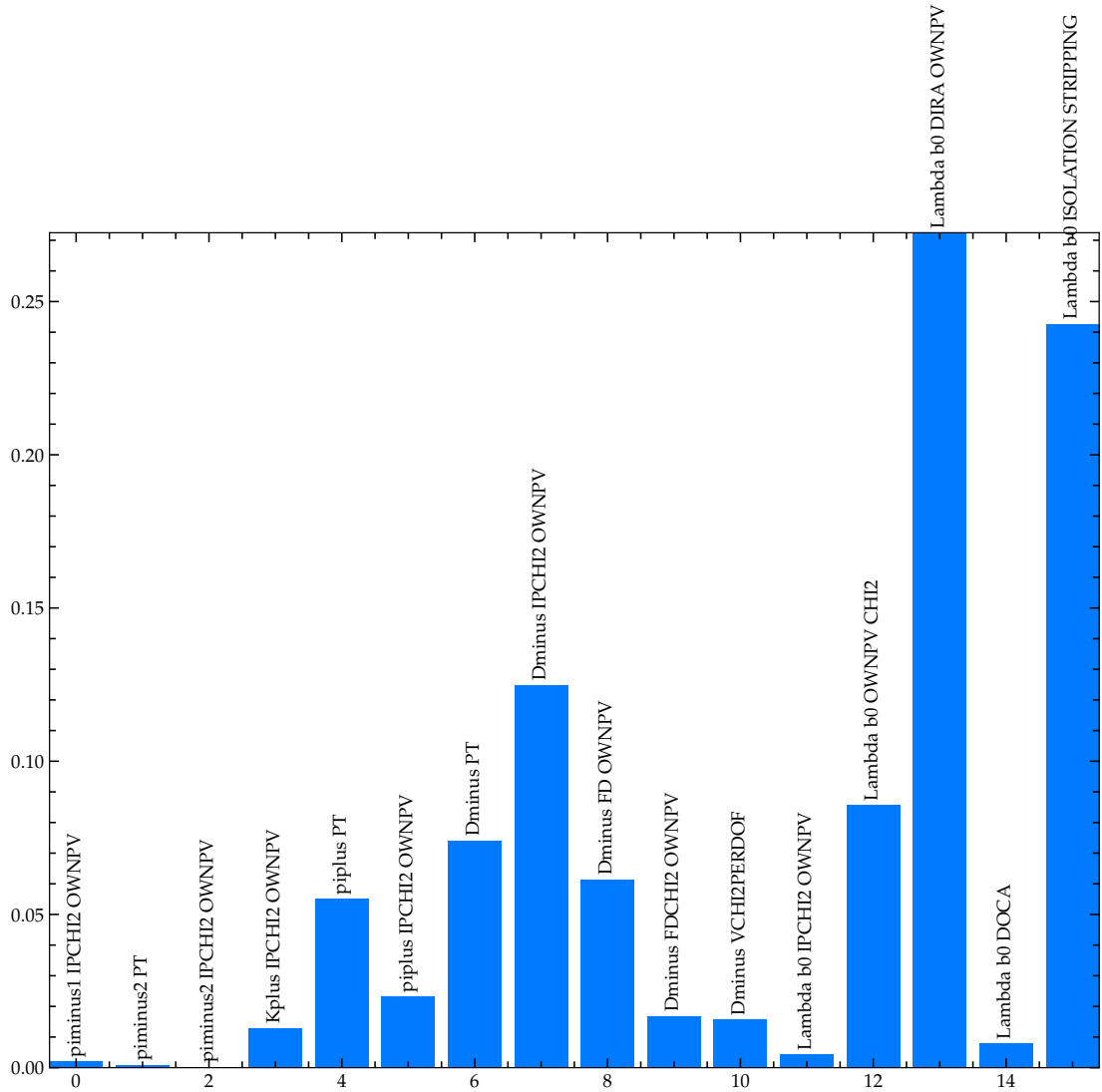


Figure 6.13: Histogram with the importance of each of the features used in the second iteration of the BDT for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.

which applied to every decay mode and mass in this analysis the values in Table 6.14 are computed.

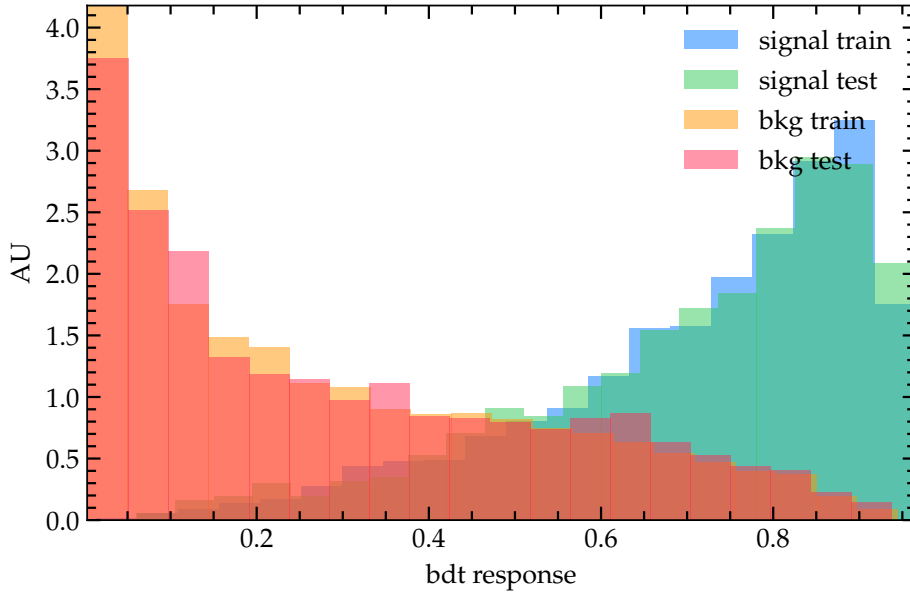


Figure 6.14: Performance of the classifier for the train/test samples for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.

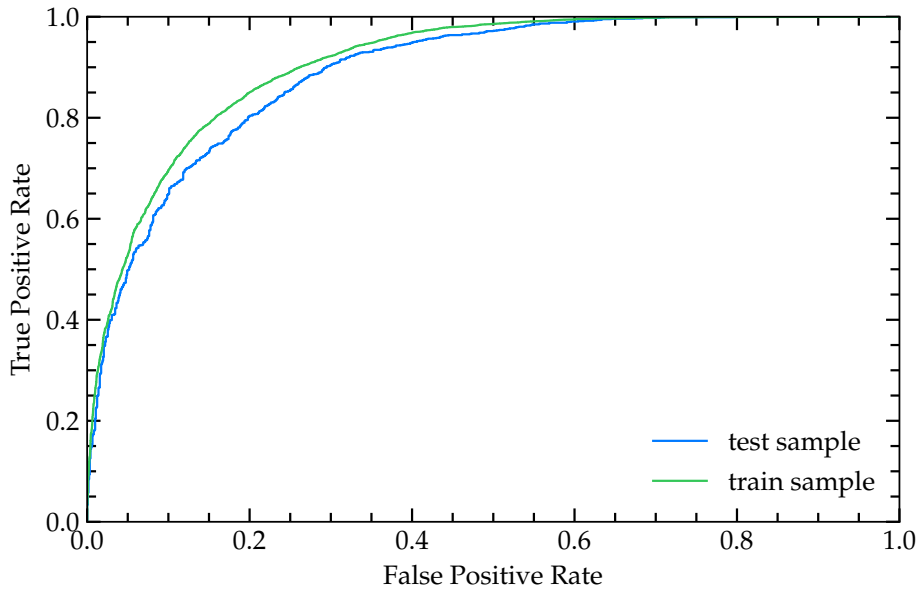


Figure 6.15: ROC curve obtained for the BDT using a train/test method for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.

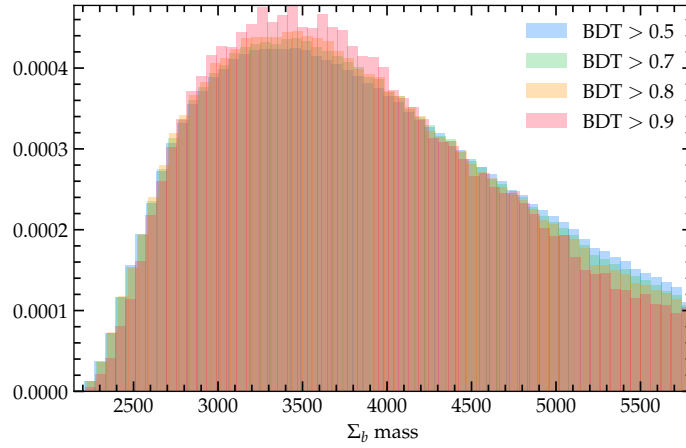


Figure 6.16: Effect of different BDT cuts over the background of this analysis. No fake peaking structures appear for a wide range of this classifier cut for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.

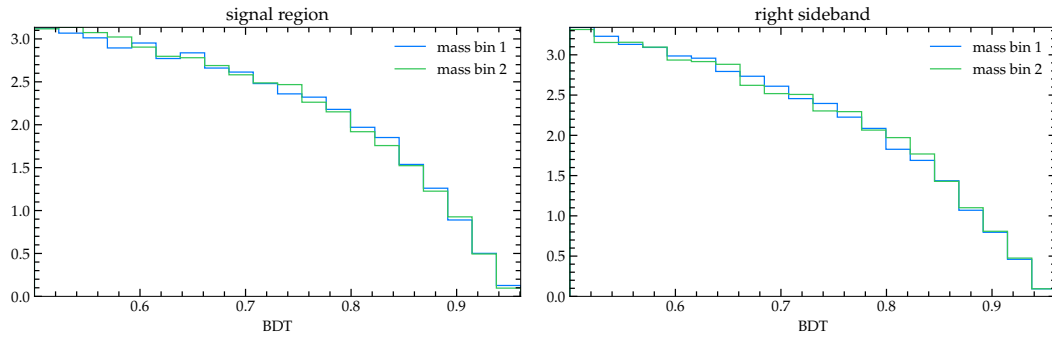


Figure 6.17: BDT response for different mass bins for a potential signal region (left) and for a guaranteed background region (right) for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using a $m(\psi_{\text{DM}}) = 940$ MeV.

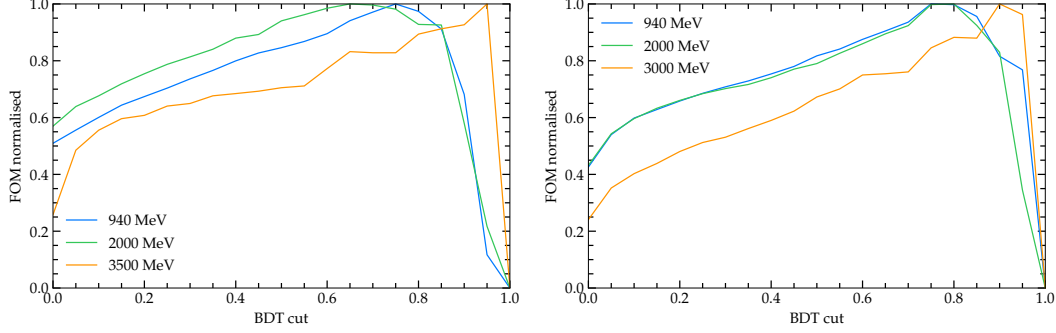


Figure 6.18: Normalised FOM computation for the $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ (left) and for the $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ (right) decay using three different masses: the lightest available by theory, the heaviest allowed by phase space, and an intermediate one of 2 GeV proposed as the benchmark by [18].

	0.94 GeV	1.5 GeV	2.0 GeV	2.4 GeV	3.0 GeV	3.5 GeV
$\mathcal{O}_{\text{cs}}$	0.55111	0.63768	0.29369	0.70072	0.54901	NOPHSP
$\mathcal{O}_{\text{cd}}$	0.45041	0.31227	0.22241	0.52109	0.38636	0.87179

Table 6.13: Efficiencies table for the $\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay modes. The BDT cuts are applied in a sequential way, this being, the BDT efficiencies are calculated over the events that passed the stripping and trigger selection.

	0.94 GeV	1.5 GeV	2.0 GeV	2.4 GeV	3.0 GeV	3.5 GeV
$\mathcal{O}_{\text{cs}}$	6.39×10^{-5}	5.45×10^{-5}	1.53×10^{-5}	2.54×10^{-5}	0.327×10^{-5}	NOPHSP
$\mathcal{O}_{\text{cd}}$	4.95×10^{-5}	2.77×10^{-5}	1.17×10^{-5}	1.68×10^{-5}	0.424×10^{-5}	0.210×10^{-5}

Table 6.14: Efficiencies table for the $\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay modes.

6.3 Tagging

As described in Section 4.1 a tagging strategy is performed over the Λ_b baryons where its mother, a $\Sigma_b^{\pm(*)}$, is reconstructed by tagging the original baryon to a $\pi^\pm$ pointing towards the primary vertex, as done in other works [85–88]. In this section the mathematical proceeding of the tagging will be shown, as well as some additional strategies and selections that improve the signal to background discrimination.

6.3.1 Mathematical description

By imposing the tagging requirement, the following kinematic calculation can be done:

$$\begin{aligned}
 m_{\Lambda\pi}^2 &= \left[\begin{pmatrix} E_\Lambda \\ 0 \\ 0 \\ \sqrt{E_\Lambda^2 - m_\Lambda^2} \end{pmatrix} + \begin{pmatrix} \sqrt{p_\pi^2 + m_\pi^2} \\ p_\pi \sin \theta \\ 0 \\ p_\pi \cos \theta \end{pmatrix} \right]^2 = \\
 &= \left(E_\Lambda + \sqrt{p_\pi^2 + m_\pi^2} \right)^2 - p_\pi^2 \sin^2 \theta - \left(\sqrt{E_\Lambda^2 - m_\Lambda^2} + p_\pi \cos \theta \right)^2 = \\
 &= 2E_\Lambda E_\pi + m_\pi^2 + p_\pi^2 (1 - \sin^2 \theta) + m_\Lambda^2 - 2p_\pi \cos \theta \sqrt{E_\Lambda^2 - m_\Lambda^2} - p_\pi^2 \cos^2 \theta,
 \end{aligned} \tag{6.5}$$

where θ is the angle between the Λ track and the π track.

By rearranging the terms in the previous expression one can write:

$$0 = E_\Lambda^2 (4(E_\pi^2 - p_\pi^2 \cos^2 \theta)) + E_\Lambda (-4E_\pi \Delta^2) + 4m_\Lambda^2 p_\pi^2 \cos^2 \theta + \Delta^4, \tag{6.6}$$

where $\Delta^2 = m_{\Lambda\pi}^2 - m_\Lambda^2 - m_\pi^2$ has been defined for shorter expressions, since it is a known constant. It is important to note that every variable in the previous equation is measured in the described experimental setup, except for E_Λ .

The Λ_b direction of flight can be determined based on the primary and secondary vertex positions, allowing for a reconstruction of its direction even though it is not a fully reconstructed particle.

For this derivation the Λ_b direction of flight is chosen as the z-axis without any loss of generality.

By solving the quadratic equation in E_Λ two possible solutions appear:

$$E_\Lambda = \frac{\Delta^2}{2E_\pi} \frac{1}{1 - (p_\pi/E_\pi)^2 \cos^2 \theta} [1 \pm \sqrt{d}], \tag{6.7}$$

$$d = \left(\frac{p_\pi}{E_\pi} \cos \theta \right)^2 - \frac{4m_\Lambda^2 p_\pi^2 \cos^2 \theta}{\Delta^4} \left(1 - \left(\frac{p_\pi}{E_\pi} \cos \theta \right)^2 \right). \quad (6.8)$$

6.3.2 Tagging efficiency

It is clear then that $d > 0$ is a required constraint for solutions to exist and imaginary solutions are not taken into account and must be discarded. When taking into account the existence of two solutions, about 90% of the time the lowest one is the correct one and choosing the incorrect one adds close to no noise into the proceeding [85,87].

This imposes a new requirement in the analysis and in the selection, this being $d > 0$. Let us call this the tagging requirement. The efficiency of this reconstruction is shown in Table 6.15.

	0.94 GeV	1.5 GeV	2.0 GeV	2.4 GeV	3.0 GeV	3.5 GeV
O_{cs}	0.72301	0.71818	0.74790	0.81521	0.76364	NOPHSP
O_{cd}	0.76867	0.84782	0.78698	0.74519	0.64286	0.84375

Table 6.15: Efficiencies table for the $\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{DM}K(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{DM}\pi(D \rightarrow \pi\pi K))$ decay modes. The $d > 0$ cuts are applied in a sequential way, this being, the $d > 0$ efficiencies are calculated over the events that passed the stripping, the trigger selection and the BDT cut.

6.3.3 $m_{\min}$ computation

A related quantity is the minimum mass of the $\Lambda\pi$ pair. This would be equivalent to taking the quadratic discriminant, setting it to zero and solving for the mass. The expression of this new quantity is:

$$m_{\min} = \sqrt{m_\Lambda^2 + m_\pi^2 + 2m_\Lambda \sqrt{p_\pi^2 \sin^2 \theta + m_\pi^2}}. \quad (6.9)$$

This observable allows for a rectangular cut to be imposed over it, allowing for further background to signal discrimination. This quantity results in a very similar distribution for every decay mode, as it is expected, since it has no relation with the dark matter particle or the decay mode at all. This can be seen in Figures 6.19 and 6.20.

The imposition of this cut ($m_{\min} > 88$ MeV) arises the need for a new efficiency computation, which can be found in Table 6.16. As seen in this table, the efficiency

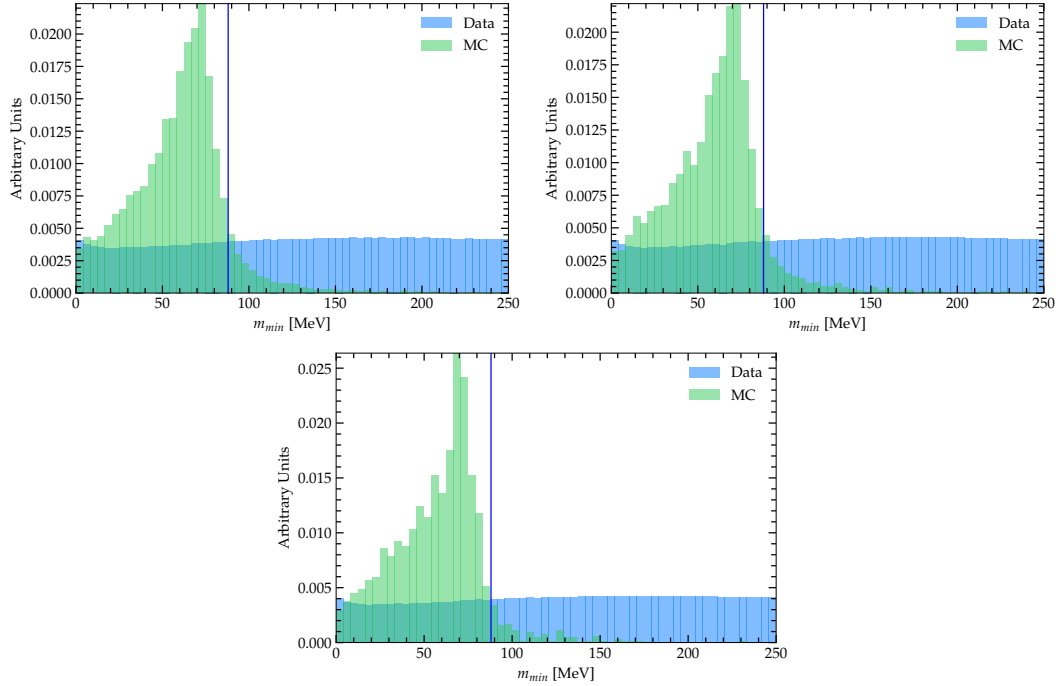


Figure 6.19: $m_{\min}$ computation for the $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay using the same three benchmark masses as in Figure 6.18: the lightest available (top left), the 2 GeV benchmark (top right) and the heaviest possible (bottom). Only the stripping selection is applied for these plots since the whole selection has already trimmed down lots of the events and the distributions are not easily seen.

	0.94 GeV	1.5 GeV	2.0 GeV	2.4 GeV	3.0 GeV	3.5 GeV
O_{cs}	1.0	1.0	1.0	1.0	1.0	NOPHSP
O_{cd}	1.0	1.0	1.0	1.0	1.0	1.0

Table 6.16: Efficiencies table for the $\Sigma_b^{\pm*} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay modes. The $m_{\min}$ cuts are applied in a sequential way, this being, the $m_{\min}$ efficiencies are calculated over the events that passed the stripping, the trigger selection, the BDT cut and the tagging cut.

after the whole selection in this variable is very close to one, since the events that do not pass it are already outliers of the selection. This also applies to background, but some outliers are eliminated in the latter case.

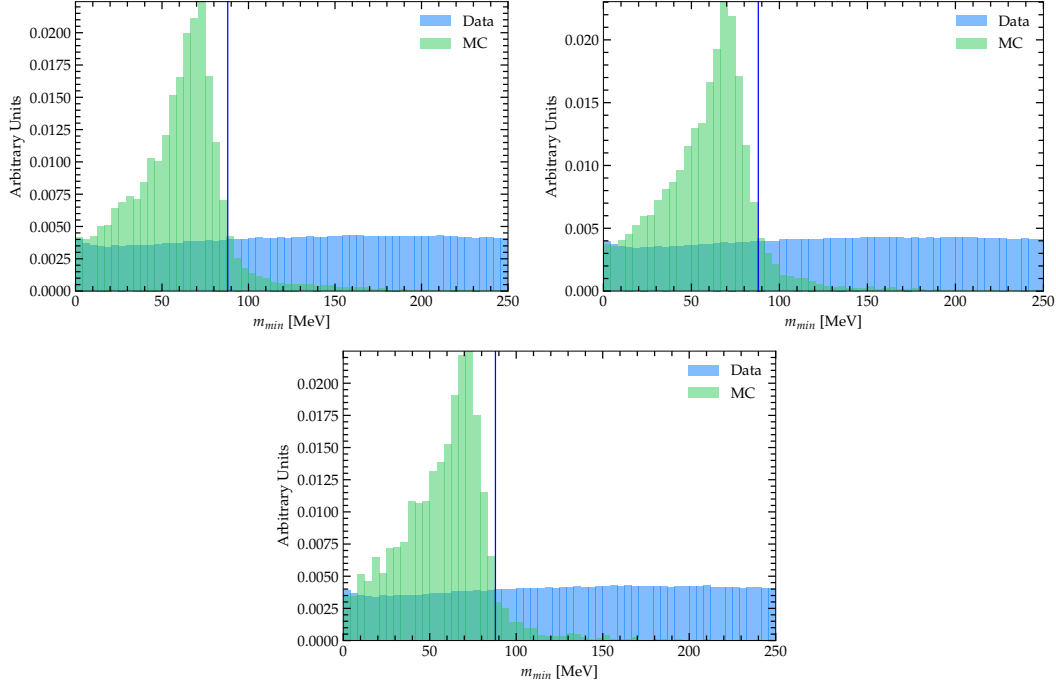


Figure 6.20: $m_{\min}$ computation for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay using the same three benchmark masses as in Figure 6.18: the lightest available (top left), the 2 GeV benchmark (top right) and the heaviest possible (bottom). Only the stripping selection is applied for these plots since the whole selection has already trimmed down lots of the events and the distributions are not easily seen.

6.4 Mass fit

In this section the fits performed to describe the background and the signal used are described.

6.4.1 Mathematical description

The calculation in Section 6.3 allows the computation of the squared missing mass (m_{miss}^2):

$$m_{\text{miss}}^2 = m_{\Lambda}^2 + (m_D^2 + m_K^2 + 2(E_D E_K - (\vec{p}_D \vec{p}_K))) - 2 \left(E_{\Lambda}(E_D + E_K) - \sqrt{E_{\Lambda}^2 - m_{\Lambda}^2} \right) \quad (6.10)$$

and this quantity can be fitted to a double sided crystal ball probability distribution function [84]. This is made by the core of a gaussian function and the tails are

moduled by power-laws. This PDF is described is given by the following expression:

$$f(m; \alpha_{L,R}, n_{L,R}, \bar{x}, \sigma) = \begin{cases} A_L \left(B_L - \frac{m-\bar{x}}{\sigma}\right)^{-n_L}, & \text{for } m - \bar{x} < -\alpha_L \sigma \\ \exp\left(-\frac{(m-\bar{x})^2}{2\sigma^2}\right), & \text{for } -\alpha_L \sigma \leq m - \bar{x} \leq \alpha_R \sigma \\ A_R \left(B_R - \frac{m-\bar{x}}{\sigma}\right)^{-n_R}, & \text{for } m - \bar{x} > \alpha_R \sigma \end{cases} \quad (6.11)$$

where the coefficients are:

$$A_i = \left(\frac{n_i}{|\alpha_i|}\right)^{n_i} \cdot \exp\left(\frac{-|\alpha_i|^2}{2}\right)$$

$$B_i = \frac{n_i}{|\alpha_i|} - |\alpha_i|.$$

The parameters that describe this PDF are:

- $\alpha_{L,R}$: parameter that defines the left and right points of transition from the Gaussian core to the power-law tails.
- $n_{L,R}$: parameter that defines the left and right tails of the PDF.
- $\bar{x}$: the mean of the Gaussian core.
- σ : the standard deviation of the Gaussian core.

6.4.2 Fitting basis

For every fit in this analysis a minimisation of a negative log-likelihood will be used. The negative log-likelihood (NLL) function is a fundamental concept in statistical modeling and inferential statistics, particularly in the context of maximum likelihood estimation (MLE). It serves as a criterion for evaluating the fit of a statistical model to observed data by quantifying the discrepancy between the observed data and the model's predictions [125].

The log-likelihood function is derived from the likelihood function, which expresses the probability of observing the given data under a specific statistical model. For a set of independent and identically distributed observations $\{x_1, x_2, \dots, x_n\}$ with a PDF $f(x, \theta)$ dependent on parameters θ , the likelihood function $L(\theta)$ is defined as:

$$L(\theta) = \prod_{i=1}^n f(x_i, \theta). \quad (6.12)$$

The log-likelihood function $\mathcal{L}(\theta)$ is the natural logarithm of the likelihood function:

$$\mathcal{L}(\theta) = \log L(\theta) = \sum_{i_1}^n \log f(x_i, \theta). \quad (6.13)$$

The negative log-likelihood function is the negative of the log-likelihood function, represented as:

$$-\mathcal{L}(\theta) = -\log L(\theta) = -\sum_{i_1}^n \log f(x_i, \theta). \quad (6.14)$$

The NLL is pivotal in MLE, where the objective is to estimate the parameters θ that maximise the likelihood of observing the given data. Minimising the NLL is equivalent to maximising the log-likelihood, making the NLL a crucial component in parameter estimation and model fitting [126].

6.4.3 Mass model

As indicated throughout the text, two signal contributions are relevant in this analysis: $\Sigma_b^{\pm*}$ and $\Sigma_b^{\pm}$. These two particles have slightly different masses, and the mass is a parameter required to compute the dark matter particle mass according to Equation (6.10), since $m(\Sigma_b^{\pm(*)})$ must be introduced in the Δ quantity present at the moment of determining E_Λ .

Several approaches were considered:

- Two dimensional mass fit: perform a simultaneous fit over two different signal PDFs where the yields are correlated. This method was discarded in a first approach due to its difficulty.
- One dimensional mass fit choosing the $\Sigma_b^{\pm*}$ mass hypothesis: perform a one dimensional mass fit over the two mixed signal contributions. Resulted in a $\Sigma_b^{\pm}$ wide signal distribution that was not centred around the theoretical $m(\psi_{\text{DM}})$. This reason led to the discard of this methodology since no simple signal PDF was reasonable to obtain.
- One dimensional mass fit choosing the $\Sigma_b^{\pm}$ mass hypothesis: perform a one dimensional mass fit over the two mixed signal contributions. Resulted in a $\Sigma_b^{\pm*}$ wide signal distribution that was centred around the theoretical $m(\psi_{\text{DM}})$, as seen in Figure 6.21. This led to perform this fit as our mass fit PDF where the mixed signal components are fitted to a double-sided crystal ball PDF according to Equation (6.11) and the background is fitted to an exponential PDF [127, 128], given by

$$f(m; \lambda) = \begin{cases} \lambda e^{-\lambda m}, & \text{for } m > 0 \\ 0 & \text{for } m < 0. \end{cases} \quad (6.15)$$

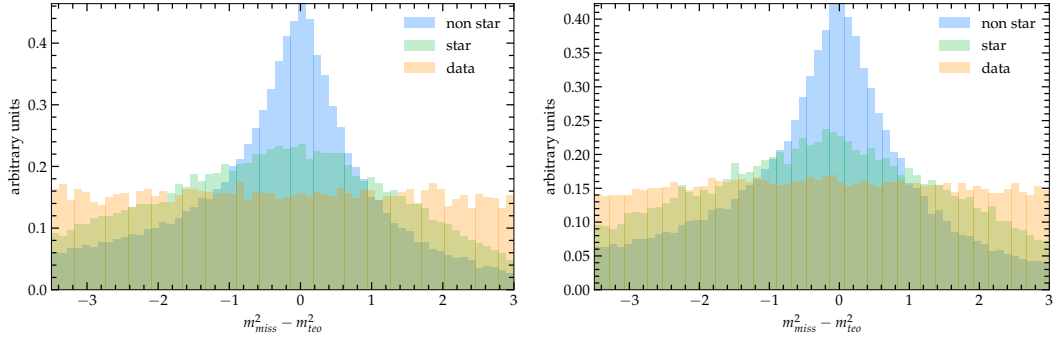


Figure 6.21: $\Sigma_b^\pm, \Sigma_b^{\pm*}$ and background events where the $\Sigma_b^\pm$ mass hypothesis is chosen. The distributions in this case are normalised since only their functional form is relevant. Both decays are shown (left: $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm (\Lambda_b \rightarrow \psi_{\text{DM}} K (D \rightarrow \pi\pi K))$, right: $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm (\Lambda_b \rightarrow \psi_{\text{DM}} \pi (D \rightarrow \pi\pi K))$) and a $m(\psi_{\text{DM}}) = 2 \text{ GeV}$ has been used.

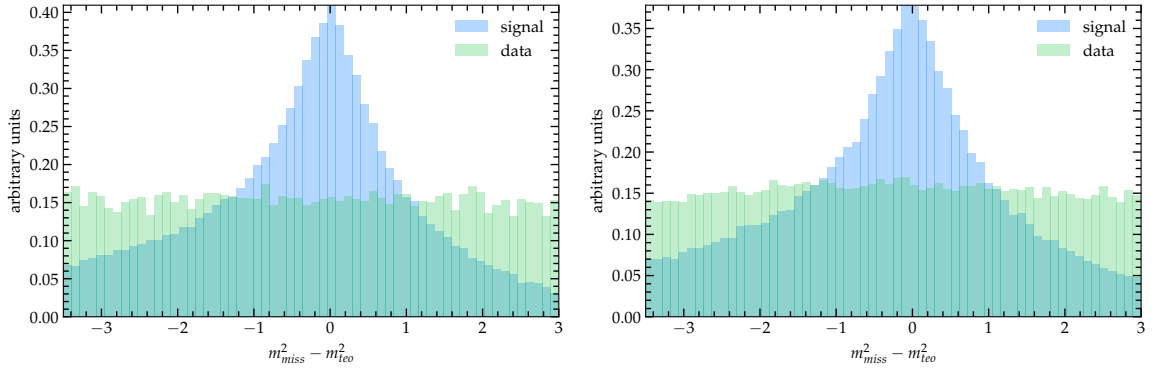


Figure 6.22: $\Sigma_b^\pm$ and $\Sigma_b^{\pm*}$ mixed under the $\Sigma_b^\pm$ mass hypothesis, and background events. The distributions in this case are normalised since only their functional form is relevant. Both decays are shown (left: $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm (\Lambda_b \rightarrow \psi_{\text{DM}} K (D \rightarrow \pi\pi K))$, right: $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm (\Lambda_b \rightarrow \psi_{\text{DM}} \pi (D \rightarrow \pi\pi K))$) and a $m(\psi_{\text{DM}}) = 2 \text{ GeV}$ has been used. The proportion of $\Sigma_b^\pm$ and $\Sigma_b^{\pm*}$ obtained in the normalisation channel throughout Section 6.5 has been used.

By doing this mixing procedure, the resulting mass distribution for the two contributions combined under the $\Sigma_b^\pm$ mass hypothesis can be obtained, as seen in Figure 6.22. The resulting distribution is very similar to the one with the correct mass hypothesis seen in Figure 6.21. All other mass distributions are presented in Section A.1.

	N_{sig}	μ	σ	α_L	n_L	α_R	n_R
0.94 GeV	48602.8	-0.0146	0.2569	0.1579	1.1406	0.1945	2.9103
1.5 GeV	13946.0	-0.0008	0.2923	0.2190	1.0588	0.2262	3.8530
2.0 GeV	25498.8	-0.0217	0.1554	0.0935	1.6417	0.0980	101.024
2.4 GeV	14558.0	0.0701	0.0291	0.0155	4.3889	0.0241	18.2598
3.0 GeV	26368.1	-0.0301	0.6217	0.4045	6.8542	1.3453	3.6784
3.5 GeV	NOPHSP	NOPHSP	NOPHSP	NOPHSP	NOPHSP	NOPHSP	NOPHSP

Table 6.17: Table with the fit results of the $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay mode. The model used for the signal is the one shown in Equation (6.11) extended to the events of the simulation, so the integral over the full model does not add to one but to the N_{sig} parameter instead.

6.4.4 Signal fit

Performing a fit to the full model is challenging due to the difficulty of distinguishing between background and tail events, which are often mismatched by the fitter software when every parameter is allowed to float at the same time. Therefore, a preliminary approach is to perform a fit solely to the signal events. In this case, one can utilise a Monte Carlo simulation to obtain the tail parameters, shown in Equation (6.11), which can then be fixed in the subsequent analysis.

The fits to the double-sided Crystal Ball function, along with all other fits in this analysis, were executed using the Python library `zfit` [129]. The probability distribution functions were extended to account for the number of events in the Monte Carlo simulations. This extension ensures that the expected limit of N_{sig} , which will be derived in Section 6.6, can be subsequently used to compute the expected branching ratio of the decays under study.

The results of all the performed fits are presented in Tables 6.17 and 6.18, where the parameters of the signal probability density functions are detailed for each available mass, alongside the number of events obtained. It is important to note that only generator and reconstruction selections are imposed over the MC events, and no additional selection has been applied. Applying further selection criteria could alter the functional form of the distributions, which should be preserved given a sufficiently large number of events.

The graphics associated with two of the fits can be found in Section 6.4.4. These were chosen because they represent the benchmark mass proposed in the theoretical model. The fit shows good agreement with the Monte Carlo data. All other fits are presented in Section A.2.

	N_{sig}	μ	σ	α_L	n_L	α_R	n_R
0.94 GeV	43675.9	0.0120	0.5615	0.2647	1.6327	0.3527	3.1162
1.5 GeV	13783.1	-0.0185	0.6031	0.3046	1.4519	0.3775	3.9430
2.0 GeV	45099.5	0.0028	0.0709	0.0343	2.6906	0.0405	9.5763
2.4 GeV	46322.4	0.0809	0.1528	0.0658	6.6325	0.0948	19.5093
3.0 GeV	13308.0	0.0331	0.8364	0.3996	41.7024	0.8183	134.465
3.5 GeV	46467.3	-0.1371	0.4815	0.4520	3.7013	1.6317	0.8621

Table 6.18: Table with the fit results of the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay mode. The model used for the signal is the one shown in Equation (6.11) extended to the events of the simulation, so the integral over the full model does not add to one but to the N_{sig} parameter instead.

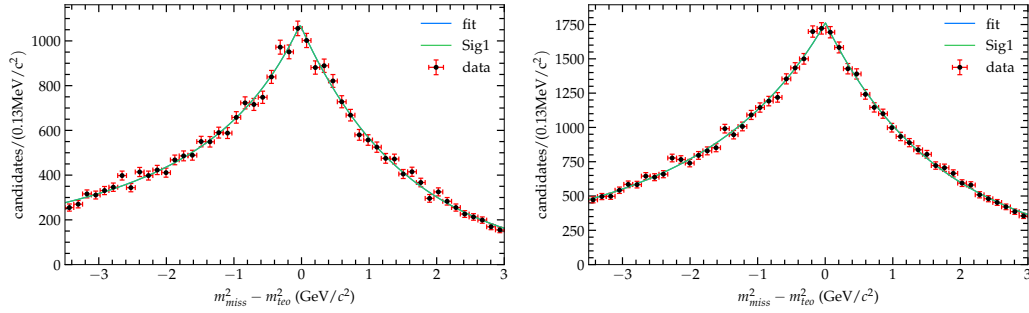


Figure 6.23: Signal fits performed for both decay modes (left: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$, right: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$) for a $m(\psi_{\text{DM}}) = 2$ GeV. The tail parameters obtained in these fits are fixed for the remaining of the analysis. In this case the blue and green lines are coincidental since only one PDF contributes to the full model PDF. Only signal MC is used in this fit.

6.4.5 Full model fit

After obtaining the tail parameters in Section 6.4.4, these parameters are fixed, allowing a full model fit to be performed. In this case, two probability density functions will be considered: an exponential PDF to describe the background, as outlined in Equation (6.15), and a double-sided Crystal Ball PDF for the signal component.

As already stated, the tail parameters will not be allowed to float, and the values used will be those obtained in Section 6.4.4 and shown in Tables 6.17 and 6.18. On the other hand, the remaining parameters (N_{sig} , μ , σ) are allowed to float. Additionally,

	N_{sig}	N_{bkg}	μ	σ	b
0.94 GeV	51014.2	16313.6	0.0073	0.0650	-0.0077
1.5 GeV	16033.7	16638.5	0.0074	0.3422	-0.0103
2.0 GeV	26755.9	17500.1	-0.0095	0.2172	-0.0135
2.4 GeV	16292.0	17000.1	0.0777	0.0325	-0.0073
3.0 GeV	26688.7	18400.7	-0.1138	0.7198	-0.0041
3.5 GeV	NOPHSP	NOPHSP	NOPHSP	NOPHSP	NOPHSP

Table 6.19: Table with the fit results of the $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ decay mode. The full model is taken into account as shown in Equation (6.16). The tail parameters are those in Table 6.17. Different amounts of the signal to background ratio are studied, and it is shown that the fitter shows a better convergence consistency when $\frac{N_{\text{sig}}}{N_{\text{bkg}}} \approx 1$.

two new parameters will be required for the full model description: N_{bkg} and b , which characterise the background present in the fit and the value of the background PDF, as shown in Equation (6.15).

With all of this taken into account, the full model fit will be represented by the sum of the two described PDFs: a double-sided Crystal Ball function to describe the signal and an exponential function to describe the background. Each PDF is multiplied by its corresponding N_{evt} :

$$f(m; \mu, \sigma, b, N_{\text{sig}}, N_{\text{bkg}}) = N_{\text{sig}} \cdot f(m; \alpha_{L,R}, n_{L,R}, \mu, \sigma) + N_{\text{bkg}} \cdot f(m; b), \quad (6.16)$$

where $f(m; \alpha_{L,R}, n_{L,R}, \mu, \sigma)$ and $f(m; b)$ are those PDFs given by Equations (6.11) and (6.15).

The results of applying this methodology can be found in Tables 6.19 and 6.20, where the free parameters of the fit are shown. In this case, for the signal events Monte Carlos is used, while a small sample of data is taken as background. As in Section 6.4.4, only generator and reconstruction efficiencies are taken into account since further selection is not expected to significantly alter the functional form, provided there is a sufficiently large number of events. An example of the resulting plot can be seen in Figure 6.24, where the good agreement between each of the components of the fit for the benchmark mass is shown.

A more realistic version of the full model plot (no explicit MC and background histograms) can be found in Figure 6.25 and every decay mode and dark matter mass is shown in Section A.3.

	N_{sig}	N_{bkg}	μ	σ	b
0.94 GeV	45000.0	33131.1	-0.0080	0.5409	0.0068
1.5 GeV	14123.3	11383.1	-0.0400	0.5940	-0.0025
2.0 GeV	47506.6	39000.1	-0.0218	0.0694	0.0051
2.4 GeV	48745.7	39000.1	0.0556	0.1515	0.0043
3.0 GeV	13704.0	11327.5	0.0054	0.8372	0.0005
3.5 GeV	48895.3	39000.0	-0.1465	0.4980	0.0091

Table 6.20: Table with the fit results of the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay mode. The full model is taken into account as shown in Equation (6.16). The tail parameters are those in Table 6.18. Different amounts of the signal to background ratio are studied, and it is shown that the fitter shows a better convergence consistency when $\frac{N_{\text{sig}}}{N_{\text{bkg}}} \approx 1$.

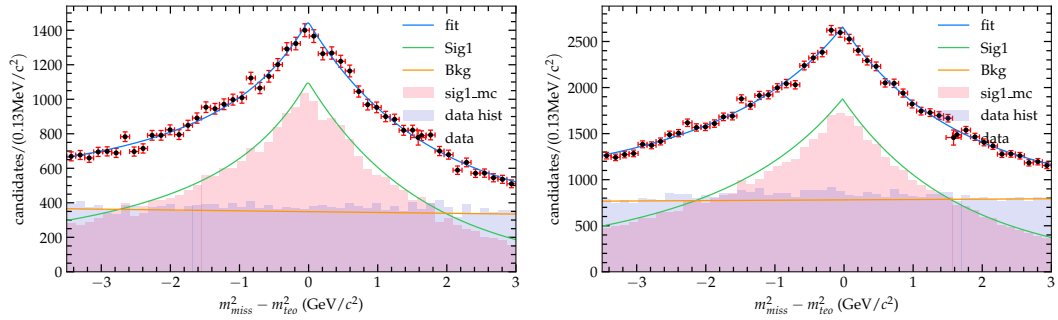


Figure 6.24: Full model fits performed for both decay modes (left: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$, right: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$) for a $m(\psi_{\text{DM}}) = 2$ GeV. The signal and background histograms are shown in this case to demonstrate the good agreement between what the fitter identifies as signal and background and what is the actual signal Monte Carlo and background events. The signal is MC and for the background a small set of data is used.

6.4.6 Toys

To check the goodness of the fit and to determine if the model is generally valid, rather than specific to this particular set of Monte Carlo and data, a study using toys of the fit is required. We define a toy as a pseudo-experiment based on the results of the fit, where new Monte Carlo simulations for signal and background are generated according to the obtained PDFs. The number of events and the same parameters

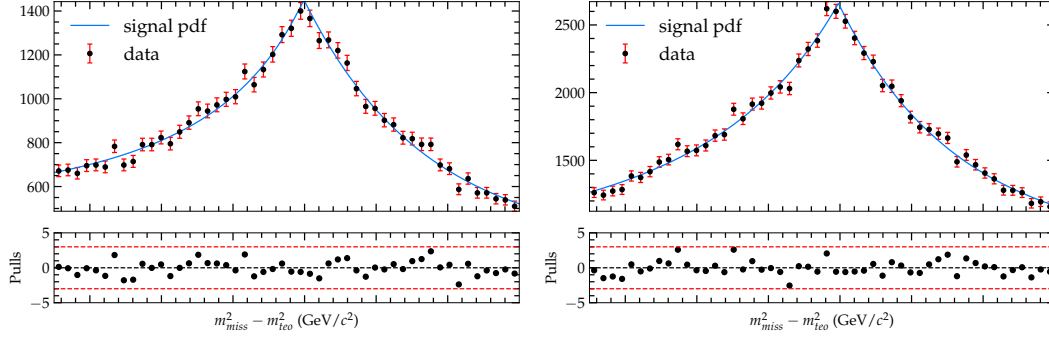


Figure 6.25: Full model fits performed for both decay modes (left: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}} K(D \rightarrow \pi\pi K))$, right: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}} \pi(D \rightarrow \pi\pi K))$) for a $m(\psi_{\text{DM}}) = 2$ GeV. The distance in σ between the fit and the data is shown in the plot below the fits. Same as Figure 6.24 but signal and background histograms are not shown explicitly.

	N_{fit}	μ	σ
0.94 GeV	2399.66	-0.0616	1.0310
1.5 GeV	2399.79	-0.0884	1.0550
2.0 GeV	2599.63	-0.0858	1.0547
2.4 GeV	2000.00	-0.0573	1.0225
3.0 GeV	1800.01	-0.0332	1.0114
3.5 GeV	2000.00	-0.0298	0.9323

Table 6.21: Results of the fits performed to a gaussian of all the pseudo-experiments computed for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}} \pi(D \rightarrow \pi\pi K))$ decay.

as in the full fit are allowed to float. A Gaussian distribution with a mean of 0 and a standard deviation of 1 is expected when $\frac{n_{\text{fit}} - n_{\text{poisson}}}{\sigma}$ is computed for a sufficiently large number of pseudo-experiments.

In this case, n_{fit} is the obtained value of the number of signal events, and n_{poisson} is the input parameter representing the number of events to be generated in the pseudo-experiment. Approximately 2000 pseudo-experiments were generated for each mass and decay mode. This ensures that the distribution of these Poisson-distributed quantities approaches a Gaussian distribution [130, 131].

The results of applying this methodology can be found in Tables 6.21 and 6.22 and Figure 6.26. These tables and figures demonstrate that the obtained mass model in Section 6.4.5 is valid.

	N_{fit}	μ	σ
0.94 GeV	2000.00	-0.0317	1.0381
1.5 GeV	1000.04	-0.1165	1.0206
2.0 GeV	2000.00	-0.0908	1.0090
2.4 GeV	3799.86	-0.0922	1.0971
3.0 GeV	2200.60	0.0063	0.9598
3.5 GeV	NOPHSP	NOPHSP	NOPHSP

Table 6.22: Results of the fits performed to a gaussian of all the pseudo-experiments computed for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ decay. In this case some higher and lower limits of N_{fit} were studied to check if some dependency around this input arose, but it did not.

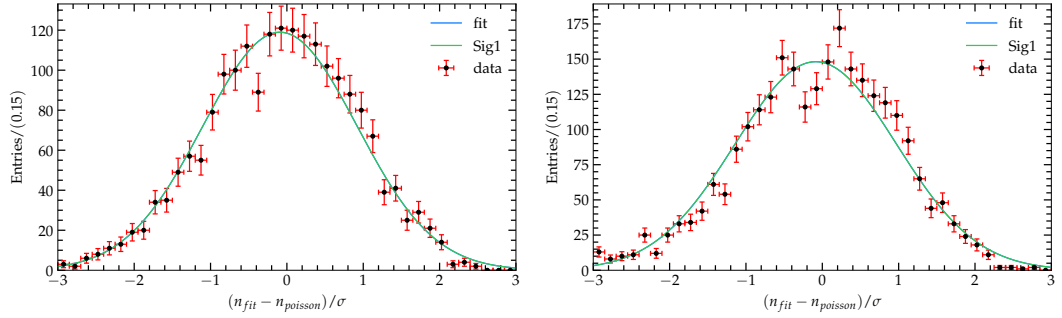


Figure 6.26: Pull plots obtained for both decay modes (left: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$, right: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$). The $m(\psi_{\text{DM}})$ used here is 2 GeV as it is the benchmark proposed in the model.

6.5 Normalisation channel

A very similar proceeding to that in Section 6.2 is followed to study the decay that will act as the normalisation channel of this analysis: $\Lambda_b \rightarrow \pi(\Lambda_c \rightarrow pK\pi)$. The proceeding is very similar.

1. MC was generated privately, as stated in Section 6.1.
2. The selection shown in Section 6.1.1 is applied to both MC and 2018 data.
3. The same trigger selection shown in Section 6.2.4 is applied.
4. A multivariate analysis is performed over this channel.

Particle	Cut
K_{Λ_c}	$p_T > 0.1 \text{ GeV} \ \& \ 1.9 < \eta < 5.0$
p_{Λ_c}	$p_T > 0.1 \text{ GeV} \ \& \ 1.9 < \eta < 5.0$
$\pi_{\Lambda_c, \pi, \Sigma}$	$p_T > 0.1 \text{ GeV} \ \& \ 1.9 < \eta < 5.0$

Table 6.23: Generator level cuts imposed over the particles of the $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \pi(\Lambda_c \rightarrow pK\pi))$. The subindex in each particle indicates the mother of the semi-stable particles. An additional condition of truth matching via TRUEID [101] is applied.

5. A similar tagging proceeding as the one in Section 6.3 is done.
6. The efficiency of each step is computed.
7. Finally, a fit is performed to obtain the number of $\Sigma_b^{\pm}$ and $\Sigma_b^{\pm*}$.

6.5.1 Generator level selection

As in Section 6.2.1 a very soft selection is applied at generator level to speed up the simulation, and waste a smaller amount of disk space. The pseudorapidity cut ($1.9 < \eta < 5.0$) is applied over every semi-stable particle at generator level. The cuts can be found in Table 6.3 in Section 6.5.1. The efficiency of these cuts is:

$$\varepsilon_{\text{gen}} = 0.10221$$

as shown in Table 6.4.

6.5.2 Reconstruction and stripping

In this case, since the stripping lines to this normalisation channel were not expressly written for this analysis, the reconstructed MC already has the stripping applied so the reconstruction and stripping efficiencies are not factorised separately, but just one factor has been computed. The obtained reconstruction and stripping efficiency is: e

$$\varepsilon_{\text{rec+sel}} = \varepsilon_{\text{rec}} \varepsilon_{\text{sel}} = 0.03611.$$

Even though the efficiencies have been computed at once, they still factorise.

6.5.3 Trigger

The same trigger selection has been applied to the normalisation channel and the signal ones, already described in Section 6.2.4. By applying the same lines an efficiency of:

$$\varepsilon_{\text{trig}} = 0.71416$$

has been computed.

6.5.4 Multivariate classifier

The proceeding shown in Section 6.2.5 has been applied again over the normalisation channel signal MC and background in order to obtain better discrimination of signal over background.

A first iteration of the BDT was trained over the topological and kinematic variables. A feature importance algorithm is used to select a smaller sample of features to train the final version of the BDT. The results obtained are shown in Figure 6.27, from where the variables chosen are: `pminusIPCHI2OWNPV`, `piplusIPCHI2OWNPV`, `pplusPT`, `KminusPT`, `LambdacplusPT`, `LambdacplusFDOWNPV`, `LambdacplusDIRAOWNPV`, `LambdacplusIPOOWNPV`, `Lambdab0PT`, `Lambdab0IPCHI2OWNPV`, `Lambdab0DIRAOWNPV`, `Lambdab0FDCHI2OWNPV`, `Lambdab0ISOLATIONSTRIPPING`, `Lambdab0VCHI2PERDOF`. Even though not all variables are as relevant as `Lambdab0IPCHI2OWNPV`, for example, at least the most relevant one from each particle has been chosen.

The distribution of all features can be found in Figure 6.28, and the correlation of the most relevant ones is presented in Figure 6.30. The distributions are consistent with the result of the second iteration of features importance histogram shown in Figure 6.29.

The overtraining of the BDT is checked by using a k-fold cross-validation technique as in Section 6.2.5. As before, 5 folds are used, each of them validated separately by computing the area under the ROC curve using different train/test samples. The scores are those presented in Table 6.24, while the ROC curve and the performance of the classifier can be found in Figures 6.31 and 6.32. As in Section 6.2.5, the search of peaking structures for different BDT cuts is performed, obtaining no results as seen in Figure 6.34.

One can finally check the BDT response in similar mass bins, as in Section 6.2.5 we checked over background and signal regions, obtaining the results shown in Figure 6.33.

The FOM from Equation (B.10) is once again used to choose the definitive BDT cut, as that maximising the FOM. This cut is $\text{BDT} > 0.9$ as seen in Figure 6.35. By imposing

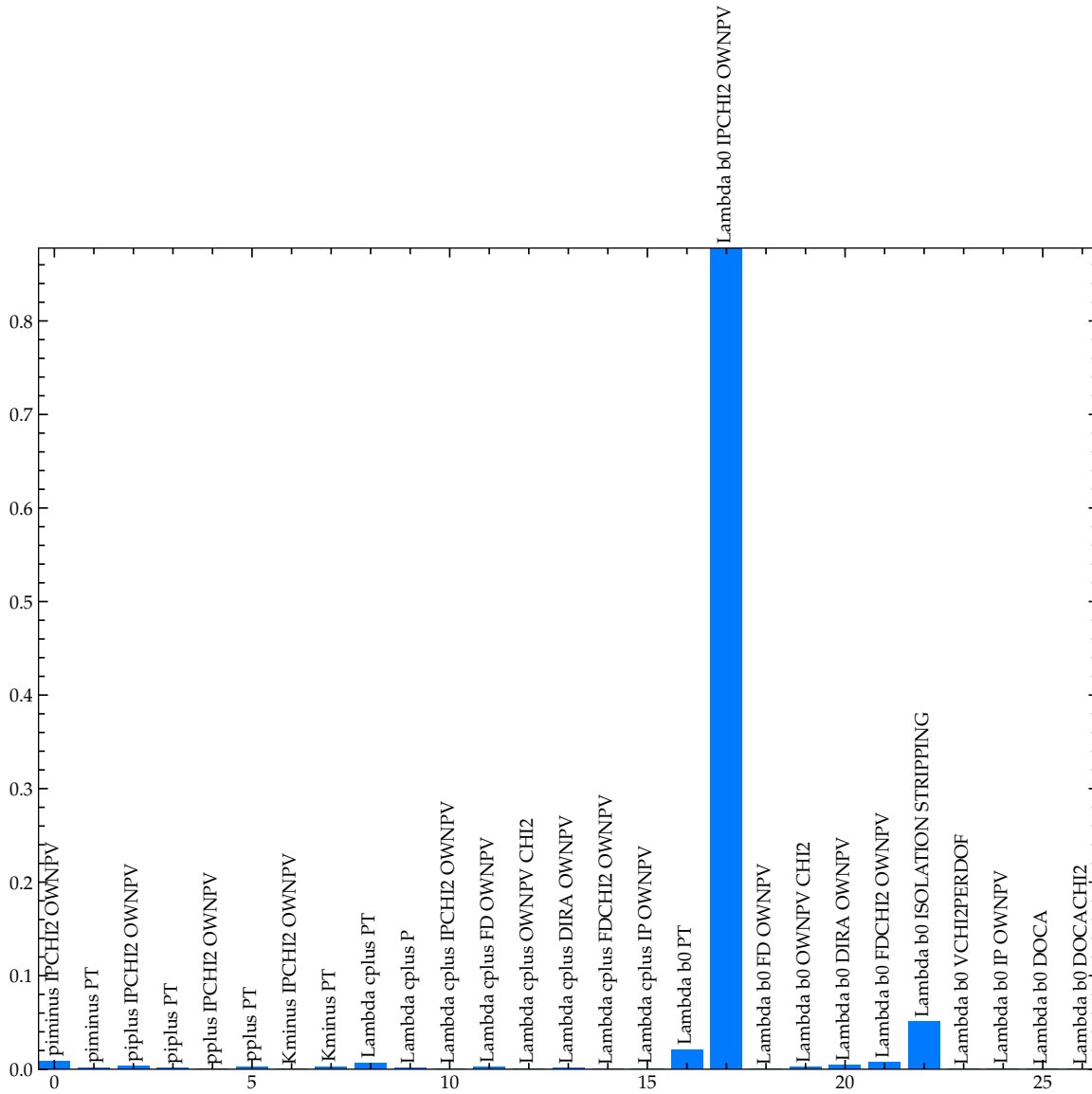


Figure 6.27: Histogram with the importance of each of the features used in the first iteration of the BDT for the normalisation channel. As in Figures 6.2 and 6.10, no $\Sigma_b^{\pm(*)}$ particles are used in the BDT.

	Fold 1	Fold 2	Fold 3	Fold 4	Fold 5
BDT accuracy	0.93042	0.92566	0.93033	0.92500	0.92262

Table 6.24: Scores obtained using a k-fold cross-validation method for the normalisation decay classifier.

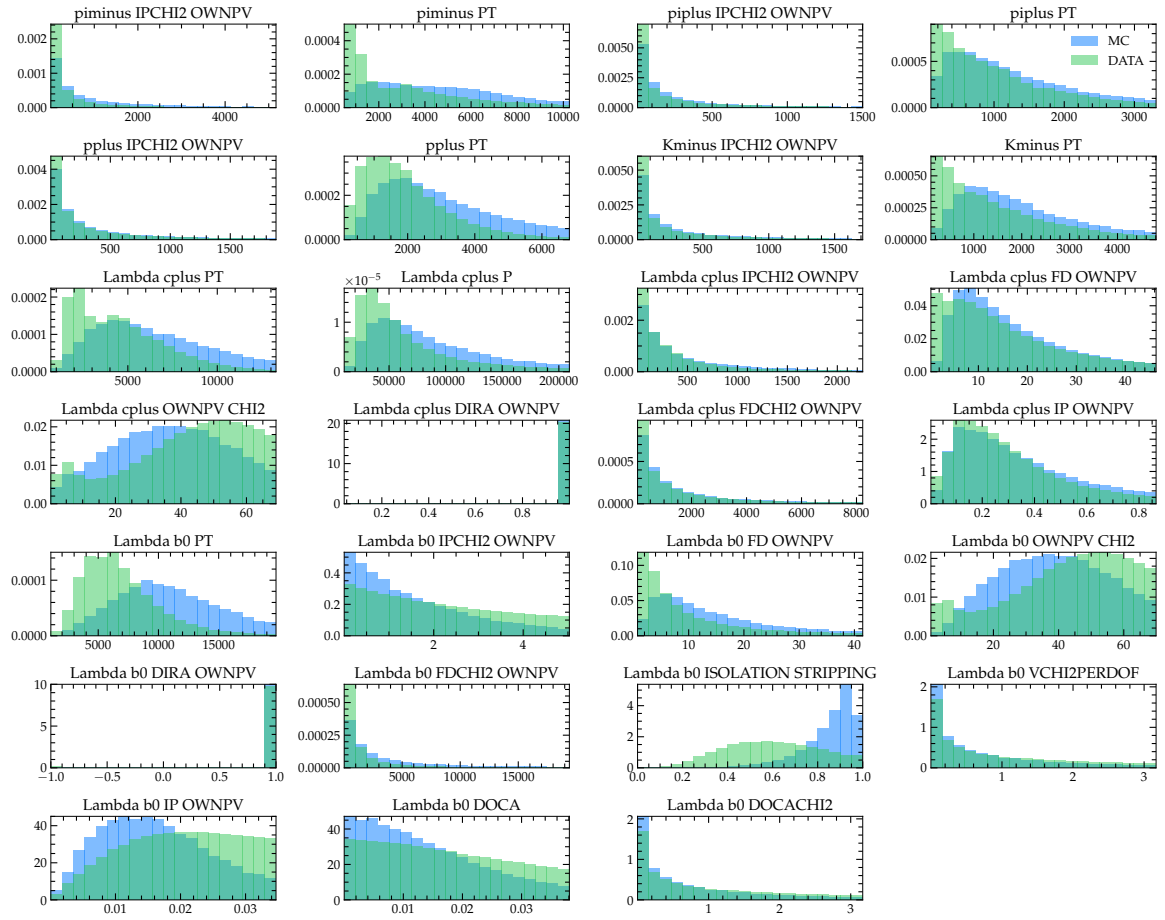


Figure 6.28: Distribution of signal and background variables of every feature used in the first iteration of the classifier. The label on top of each subplot indicates the variable plotted. The units in the y-axis are arbitrary since every distribution is normalised.

this additional selection a new efficiency can be computed for the normalisation channel:

$$\epsilon_{\text{BDT}} = 0.73647.$$

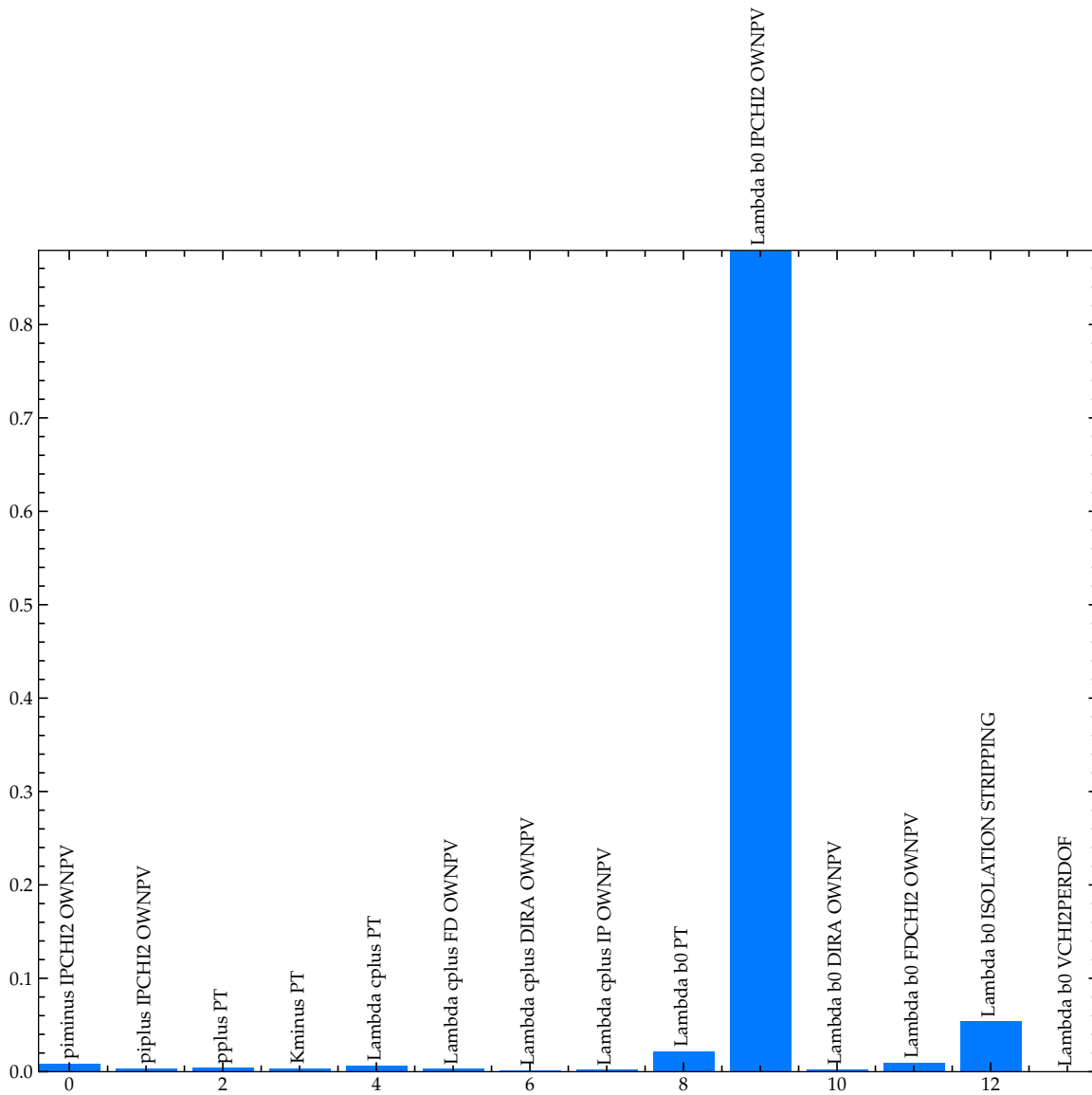


Figure 6.29: Histogram with the importance of each of the features used in the final iteration of the BDT for the normalisation channel.

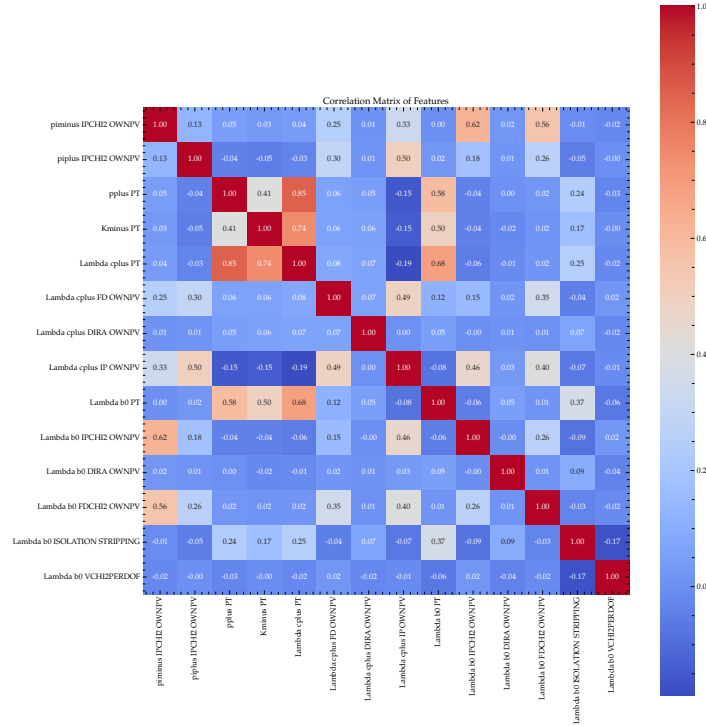


Figure 6.30: Correlation matrix for the most important variables used to train the BDT for the normalisation channel.

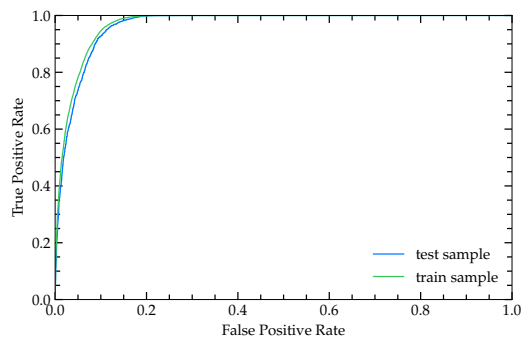


Figure 6.31: ROC curve obtained for the BDT using a train/test method for the normalisation channel.

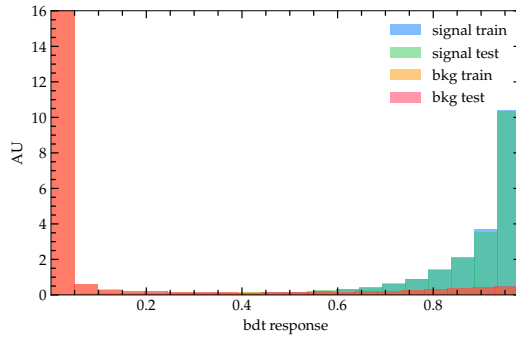


Figure 6.32: Performance of the classifier for the train/test samples normalisation decay.

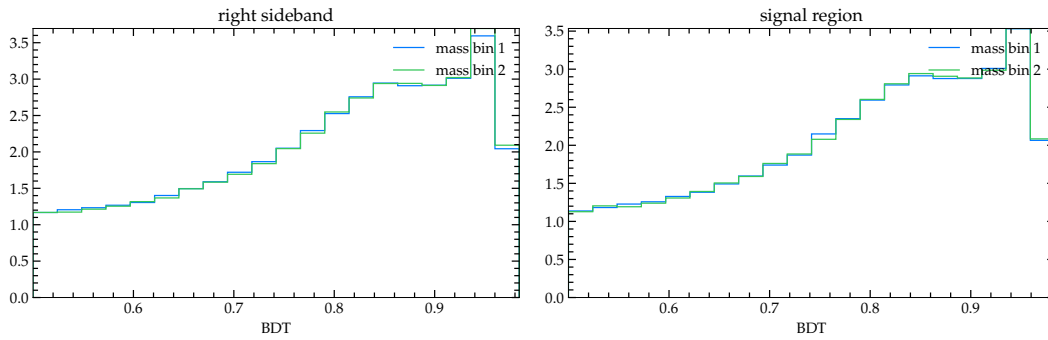


Figure 6.33: BDT response for different mass bins for the signal region (left) and for background region (right) for the normalisation channel. Note that both responses are very similar due to being background-dominated, if the full BDT response was plotted, both would peak overwhelmingly as seen in Figure 6.32.

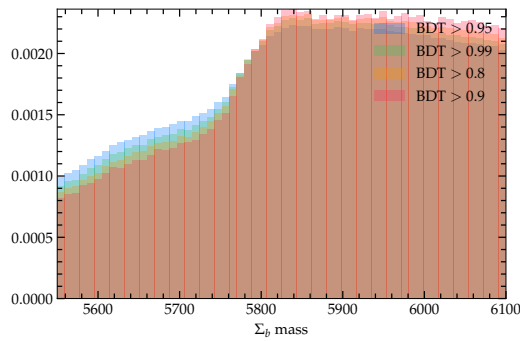


Figure 6.34: Effect of different BDT cuts over the mass spectrum of this decay. No peaking structures arise for a wide range of classifier cuts and the functional form is preserved.

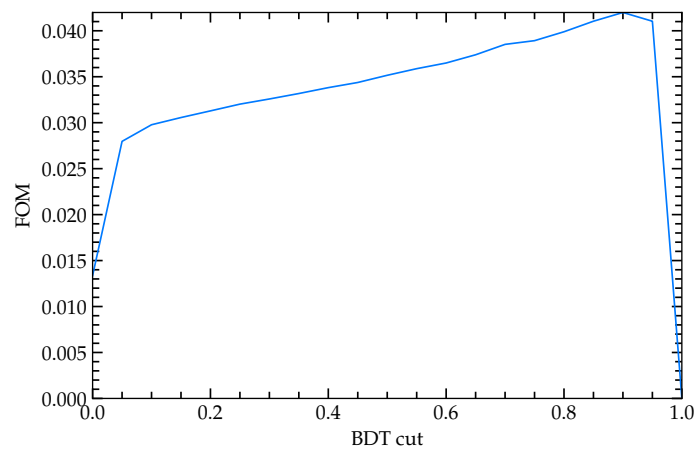


Figure 6.35: Figure of merit computation for the normalisation channel. The BDT cut of FOM=0.9 is chosen since it is the one that maximises the quantity.

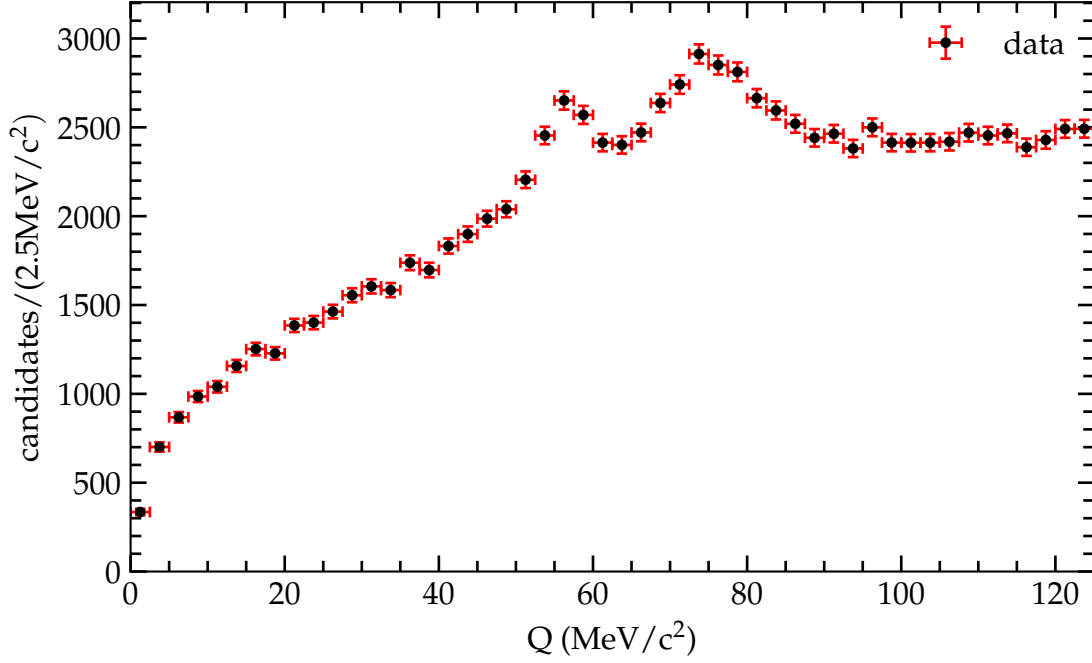


Figure 6.36: Mass spectrum after computing the quantity in Equation (6.17).

6.5.5 Fit for normalisation channel

The final step to compute the number of $\Sigma_b^{\pm(*)}$ is to fit the signal and obtain a reasonable fit to background and signal. According to [86] the best way to proceed is computing an auxiliary quantity, namely Q , because as seen in Figure 6.34 no easy background and signal PDFs can be extracted from the functional form.

By computing the following quantity:

$$Q = m(\Lambda_b^0 \pi^\pm) - m(\Lambda_b^0) - m(\pi^\pm), \quad (6.17)$$

where $m(\Lambda_b^0 \pi^\pm)$ is the mass of the pair, $m(\Lambda_b^0)$ is the reconstructed mass of the Λ_b^0 and $m(\pi^\pm)$ is the PDG mass of the pion [101].

By computing this quantity over the normalisation channel the mass spectrum of Figure 6.36 can be obtained.

It is shown in [86] that a valid description of this functional form is:

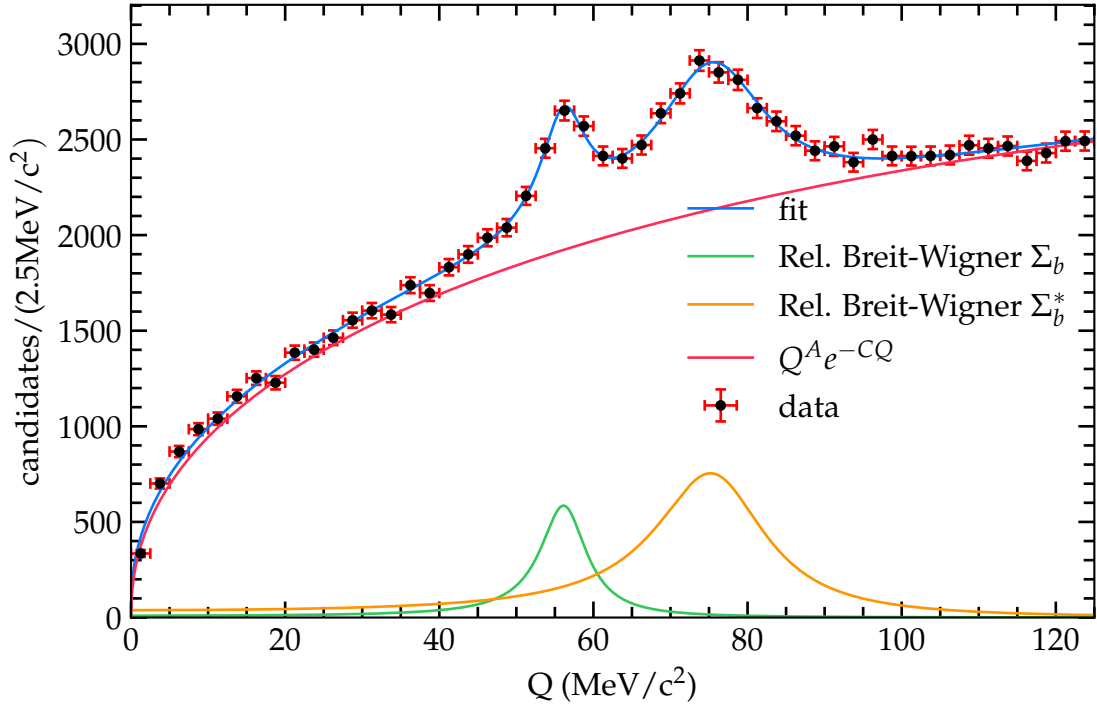


Figure 6.37: Full model fits performed for the normalisation channel. Each component is plotted separately.

$$f(Q; \mu_1, \Gamma_1, \mu_2, \Gamma_2, A, C) = Q^A \exp(-CQ) + \sum_i \frac{2\sqrt{2}\mu_i\Gamma_i\gamma_i}{\pi\sqrt{\mu_i^2 + \gamma_i}((Q^2 - \mu_i^2)^2 + \mu_i^2\Gamma_i^2)} \quad (6.18)$$

where $\gamma_i = \sqrt{\mu_i^2(\mu_i^2 + \Gamma_i^2)}$.

The first term in Equation (6.18) is an exponential modulated by a power law, that models the background, and the second term are two relativistic Breit-Wigner [2, 132, 133], each models one of the two $\Sigma_b^{\pm(*)}$ components.

By applying the described methodology the obtained results are shown in Figure 6.37 and table 6.25.

6.5.6 $N(\Sigma_b^{\pm(*)})$ computation

The initial number of $\Sigma_b^{\pm(*)}$ can be computed since every efficiency involved has been computed, and every branching ratio in $\Sigma_b \rightarrow \pi(\Lambda_b \rightarrow \pi(\Lambda_c \rightarrow pK\pi))$ is known. The

$N_{\text{sig},1}$	$N_{\text{sig},2}$	N_{bkg}	μ_1	μ_2	Γ_1	Γ_2	A	C
2660.11	7949.6	92675.8	56.11	75.19	7.30	17.42	0.453	0.00151

Table 6.25: Results of the full model fit performed to an exponential background modulated by a power law to describe the background and two relativistic Breit-Wigner describing the two components of the signal.

explicit formula for this proceeding is:

$$N(\Sigma_b^{\pm(*)}) = \frac{N_{\text{sig } 1,2}}{\varepsilon_{\text{total}} BR_s} = \frac{N_{\text{sig } 1,2}}{\varepsilon_{\text{gen}} \varepsilon_{\text{reco}} \varepsilon_{\text{sel}} \varepsilon_{\text{trig}} \varepsilon_{\text{BDT}} BR(\Sigma_b^{\pm(*)} \rightarrow \Lambda_b \pi) BR(\Lambda_b \rightarrow \pi^- \Lambda_c^+) BR(\Lambda_c \rightarrow p K \pi)} \quad (6.19)$$

By taking into account the BRs [101]:

- $BR(\Sigma_b^{\pm(*)} \rightarrow \Lambda_b \pi) = 1$
- $BR(\Lambda_b \rightarrow \pi^- \Lambda_c^+) = 4.9 \times 10^{-3}$
- $BR(\Lambda_c \rightarrow p K \pi) = 0.0628$

then:

$$N(\Sigma_b^{\pm}) = 4\,453\,202\,179 \text{ and } N(\Sigma_b^{\pm*}) = 15\,308\,162\,461.$$

Since in the analysis there is no difference in practise between $\Sigma_b^{\pm}$ and $\Sigma_b^{\pm*}$ these numbers can be added to one another, resulting⁶ in:

$$N(\Sigma_b^{\pm(*)}) = 19\,761\,364\,640.$$

6.6 Limits

A scan around the studied masses in this analysis is performed to obtain the limit on the number of signal events that we could expect for the data used. The chosen mass window is around 0.25 GeV, about 5σ for most decay modes according to Tables 6.19 and 6.20.

⁶Efficiencies for both Σ_b are assumed to be the same so these signal numbers may be added freely.

	0.94 GeV	1.5 GeV	2.0 GeV	2.4 GeV	3.0 GeV	3.5 GeV
O_{cs}	346	474	225	163	123	NOPHSP
O_{cd}	1035	922	802	417	895	148

Table 6.26: Computed expected limit for both decay modes and every mass.

Every decay mode and mass is fitted with an unbinned maximum likelihood and the expected limit is set. A confidence interval (CI) method is followed to set a value of the parameter of interest with a $1-\alpha$ probability, the confidence level (CL) [134,135]. In this analysis, the relevant value of the CI is the upper one, since it sets the limit on the observed expected ratio.

For any PDF describing a random variable with a known set of parameters the probability of finding it in the range $[a, b]$ is given by [136]:

$$CL = \int_a^b f(x|\vec{\theta})dx. \quad (6.20)$$

Usually CLs are not computed according to this expression since the functional form of the set of parameters is unknown, but an estimation is obtained from fits and different statistical proceedings [137]. To compute this CLs a hypothesis testing procedure has been used [138,139].

Two hypotheses, H_0 or null hypothesis, and H_1 or alternative hypothesis, are tested. The null hypothesis is a statement that there is no effect or no difference, and it serves as the default or baseline assumption, in this case meaning no signal in the data. The alternative hypothesis in this case is a statement that contradicts the null hypothesis, indicating that there is an effect or a difference, in this case that some signal is present in the data.

Then, a significance level is chosen, in this case $\alpha = 0.05$, and it is the probability of rejecting the null hypothesis when it is actually true. Then, the p-value is computed, this being the probability of obtaining a test statistic at least as extreme as the one calculated, assuming the null hypothesis is true. It indicates how likely the observed data would occur by random chance.

If $p > \alpha$ the null hypothesis is not rejected, this meaning that no significant signal is observed, otherwise it is [140]. The proceeding followed computes this p-value. This parameter is computed using the `hepstats` library from `scikit-hep` [141,142]. By applying this methodology the Table 6.26 is obtained.

	0.94 GeV	1.5 GeV	2.0 GeV	2.4 GeV	3.0 GeV	3.5 GeV
O_{cs}	3.05×10^{-4}	4.90×10^{-4}	8.28×10^{-4}	3.61×10^{-4}	2.12×10^{-3}	NOPHSP
O_{cd}	1.18×10^{-3}	1.87×10^{-3}	3.86×10^{-3}	1.40×10^{-3}	1.19×10^{-2}	3.97×10^{-4}

Table 6.27: Calculated values of $\mathcal{B}_{\text{signal}}$ for each mass and decay mode.

6.6.1 Branching ratio limit

By using the results in Sections 6.2.6, 6.5.6 and 6.6 the expected branching ratio can be computed. The following formula is applied:

$$\mathcal{B}_{\text{signal}} = \mathcal{B}_{\text{norm}} \times \frac{N_{\text{signal}}}{N_{\text{norm}}} \times \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{signal}}} \quad (6.21)$$

where:

- N_{signal} is the number of expected events for the signal channel.
- ϵ_{signal} is the efficiency for detecting the signal channel.
- N_{norm} is the number of observed events for the normalisation channel.
- ϵ_{norm} is the efficiency for detecting the normalisation channel.
- $\mathcal{B}_{\text{norm}}$ is the known branching ratio for the normalisation channel.

In this case, $\mathcal{B}_{\text{norm}} = (3.08 \pm 0.30) \times 10^{-4}$ according to the latest Particle Data Group review [101]. The results obtained are shown in Table 6.27.

6.7 Backgrounds

Not many other decay modes in the studied mass region could generate a peak after the proceeding of the analysis. The background identified as potentially significant is the SM predicted decay: $\Sigma_b^{\pm(*)} \rightarrow \pi(\Lambda_b \rightarrow D\pi\Lambda^0)$, which is yet to be measured.

The study of this decay was done by was generating MC samples of this decay, $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \Lambda^0\pi(D \rightarrow K\pi\pi))$, as mentioned in Section 6.1.2. We checked that the selection is expected to eliminate most of this background, if it even exists, since no significant excess was found as seen in Figure 6.38.

To study other potential backgrounds, it has been checked over the b-inclusive stripping filtered production mention in Section 6.1.2 what percentage of times an ascendant of the D is in the ascendants list of the soft π or K. The results found are:

- 22.52% the K soft mother being in the D ascendants list.

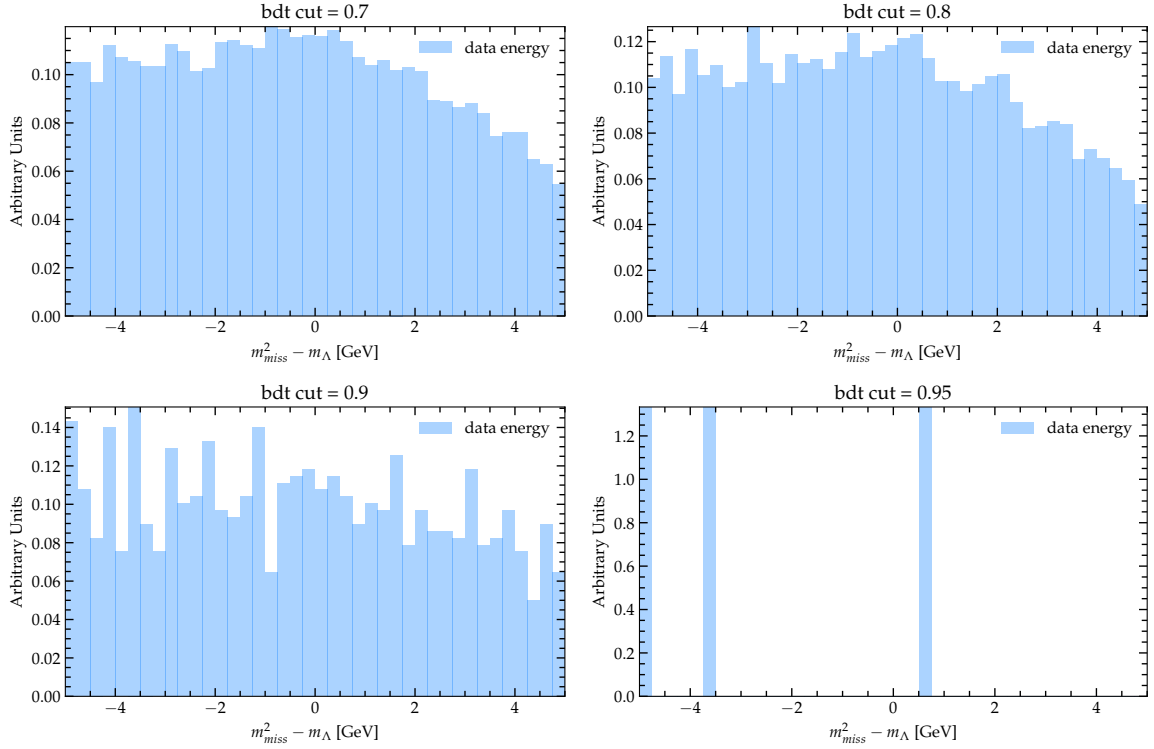


Figure 6.38: Missing mass plot obtained for $\Sigma_b^{\pm*} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \Lambda^0 \pi(D \rightarrow K\pi\pi))$ for different BDT cuts. No significant excess is seen at any BDT cut.

- 31.83% the K soft grandmother being in the D ascendants list.
- 21.95% the K soft great-grandmother being in the D ascendants list.
- 37.10% the D mother being in the K soft ascendants list.
- 29.59% the D grandmother being in the K soft ascendants list.
- 9.51% the D great-grandmother being in the K soft ascendants list.

For this decay mode, any ascendant of the K soft is in the ascendants of the D the 48.33% of the times.

For the O_{ud} decay mode, the following results are found:

- 25.25% the π soft mother being in the D ascendants list.
- 44.62% the π soft grandmother being in the D ascendants list.
- 32.89% the π soft great-grandmother being in the D ascendants list.

- 48.48% the D mother being in the π soft ascendants list.
- 40.34% the D grandmother being in the π soft ascendants list.
- 14.05% the D great-grandmother being in the π soft ascendants list.

In this case, any ascendant of the π soft is in the ascendants of the D the 63.80% of the times.

It must be noted that the trend within each category is not monotonically increasing because ascendants tagged as a hadronising quark or the pp collision are not taken into account since it could never act as a peaking background.

Within the shown cases, an additional study is performed, and potential peaking backgrounds are checked. This is done by checking if when the any ascendant requirement is met there is a dominant decay mode, and no dominating decay mode is found, being around 50 different decay modes are present with none of it being present more than 5% of the total decays.

6.8 Results

By adjusting each value of Table 6.27 by the luminosity factor, the expected limits for the branching ratio for each decay mode and mass can be computed.

In order to adjust to the full Run 2 luminosity, the following factors must be taken into account, depending on the decay mode:

- $\mathcal{L}_{cs} = \frac{\sqrt{0.44}}{\sqrt{5.1}}$
- $\mathcal{L}_{cd} = \frac{\sqrt{0.22}}{\sqrt{5.1}}$

The numerators are the used luminosities for the analysis as stated in Section 6.1, and the denominator is the full Run II luminosity as indicated in the same section. By multiplying each row of Table 6.27 by its corresponding factor, Table 6.28 is obtained, being these the expected limits of both decay modes and every mass at a 95% CL, setting a world first and best measurement of these operators.

	0.94 GeV	1.5 GeV	2.0 GeV	2.4 GeV	3.0 GeV	3.5 GeV
$\mathcal{O}_{cs}$	8.96×10^{-5}	1.44×10^{-5}	2.43×10^{-4}	1.06×10^{-4}	6.23×10^{-4}	NOPHSP
$\mathcal{O}_{cd}$	2.45×10^{-4}	3.88×10^{-4}	8.02×10^{-4}	2.91×10^{-4}	2.47×10^{-3}	8.25×10^{-5}

Table 6.28: Calculated values of $\mathcal{B}_{\text{signal}}$ for each mass and decay mode adjusted to luminosity.

Chapter 7

Results and discussion

This work scope was to prove that searches beyond the Standard Model could be done with current and future experiments, and it has been proven for already taken LHCb data and several potential searches for CODEX-b have been shown.

7.1 Dark matter and B-mesogenesis results

The most relevant results obtained here are the efficiencies, all of them collected in Tables 7.1 and 7.2, a mass model for the signal and background data, shown in Section 6.4.5 and a first draft of the expected limits shown in Section 6.6.1.

It is important to note that the analysis systematic errors have not been computed in this work, so the expected branching ratio limits computed may only be interpreted as a first approach to a result since the systematics may play a crucial role at a later stage. While this is true, the systematics of the analysis should not alter significantly the values computed for the expected limits, shown once again in Table 7.3.

	ϵ_{gen}	ϵ_{reco}	ϵ_{sel}	ϵ_{trig}	ϵ_{BDT}	ϵ_{tag}	$\epsilon_{m_{\text{min}}}$
0.94 GeV	8.108	0.23342	0.05578	0.151982	0.55111	0.72301	6.39×10^{-5}
1.5 GeV	8.004	0.22065	0.05283	0.1275892	0.63768	0.71818	5.45×10^{-5}
2.0 GeV	7.855	0.21871	0.04888	0.084826	0.29369	0.74790	1.53×10^{-5}
2.4 GeV	7.679	0.20379	0.04528	0.062786	0.70072	0.81521	2.54×10^{-5}
3.0 GeV	7.277	0.19550	0.02763	0.019891	0.54901	0.76364	0.327×10^{-5}

Table 7.1: Table with all of the efficiencies computed for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}} K(D \rightarrow \pi\pi K))$ Dark matter and B-mesogenesis LHCb search.

	ϵ_{gen}	ϵ_{reco}	ϵ_{sel}	ϵ_{trig}	ϵ_{BDT}	ϵ_{tag}	ϵ_{tot}
0.94 GeV	0.09637	0.25776	0.03944	0.146100	0.45041	0.76867	4.95×10^{-5}
1.5 GeV	0.09619	0.24652	0.03853	0.114859	0.31227	0.84782	2.77×10^{-5}
2.0 GeV	0.09527	0.22866	0.03659	0.084012	0.22241	0.78698	1.17×10^{-5}
2.4 GeV	0.09405	0.21989	0.03258	0.064387	0.52109	0.74519	1.68×10^{-5}
3.0 GeV	0.09051	0.19740	0.02478	0.038597	0.38636	0.64286	0.424×10^{-5}
3.5 GeV	0.06873	0.18820	0.00868	0.025457	0.87179	0.84375	0.210×10^{-5}

Table 7.2: Table with all of the efficiencies computed for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ Dark matter and B-mesogenesis LHCb search.

	0.94 GeV	1.5 GeV	2.0 GeV	2.4 GeV	3.0 GeV	3.5 GeV
O_{cs}	8.96×10^{-5}	1.44×10^{-5}	2.43×10^{-4}	1.06×10^{-4}	6.23×10^{-4}	NOPHSP
O_{cd}	2.45×10^{-4}	3.88×10^{-4}	8.02×10^{-4}	2.91×10^{-4}	2.47×10^{-3}	8.25×10^{-5}

Table 7.3: Calculated values of $\mathcal{B}_{\text{signal}}$ for each mass and decay mode extrapolated to total luminosity.

7.2 Long lived particles results

In this line of work it has been proven that for some Higgs portal model a lot of different signatures may be probed with the CODEX-b experiment, wheather it be in conjunction with the LHCb experiment or as a completely standalone experiment.

Production	0.1 m	1 m	10 m	100 m	1000 m
Inclusive	371	12953	3978	506	35
Inclusive & LHCb	92	9	0	0	0
Weak-boson	2	31	8	1	0
Higgs-strahlung	0	34	18	2	0

Table 7.4: Number of events expected for all detection modes described for every studied production mode. Lifetimes are given in terms of $c\tau$ and in meters.

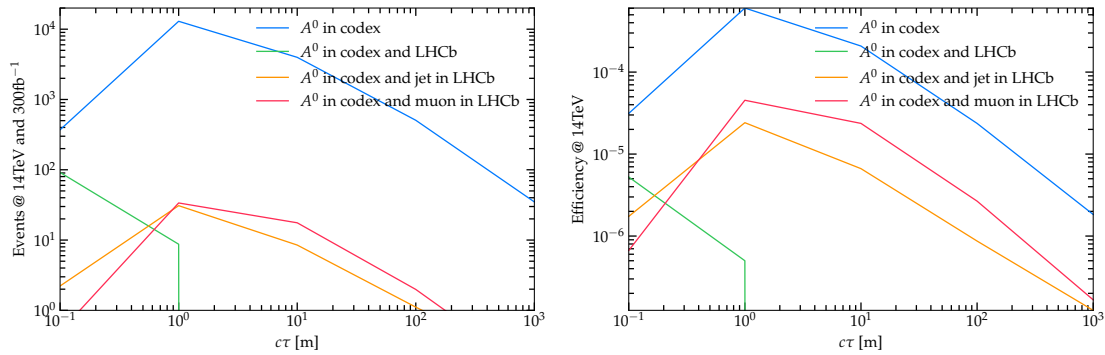


Figure 7.1: Efficiencies plot (right) and expected events (left) to be detected at the CODEx-b experiment for a $\mathcal{L} = 300 \text{ fb}^{-1}$.

7.3 Discussion

The obtained results suppose two novel approaches to the discovery of beyond Standard Model physics have been shown, on the one hand obtaining a new world best and first measurement of two operators of a B-mesogenesis and Dark Matter model with two decay modes hardly accessible by any other experiment while using a seldomly used tagging methodology that shows a very good performance in the signal to background discrimination.

On the other hand, new studies that will have a longer run as soon as the CODEx-b demonstrator, CODEx- β experiment starts taking data have been performed. These studies show that potential modes pointing to new physics could be studied at this experiment, obtaining a good performance that could compete with some of the other already consolidated experiments.

Chapter 8

Conclusions

In this thesis the first analysis studying the O_{cs} and O_{cd} proposed in [18] was performed, obtaining the first measurement of potential expected branching ratios for two decay modes, $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ and $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$. Also, a generator level efficiency to three Higgs production modes assuming Higgs portal decays has been computed.

A detailed analysis of the 2018 Run II data has been performed in order to accomplish the first of the two mentioned tasks. In this work it has been showcased a rarely used tagging mechanism that could very much be used for many other missing energy analyses at LHCb, since due to the forward geometry of the detector, different approaches may be followed and traditional missing energy analyses are out of reach. Other traditional methodologies used in high energy physics such as the training of BDTs to obtain a better signal to background discrimination or the computation of expected limits through a hypothesis testing methodology.

The CODEX-b experiment, soon to be installed near the LHCb is expected to start taking data soon at the moment of this writing, so computing and person power will be required. The job done in this thesis is expected to be a helpful tool to other scientists involved in this project. The code developed for this is very modular and easy to edit and works right out of the box, with very few python libraries, and it will be circulated to the whole collaboration.

These two tightly related topics show that many beyond Standard Model physics are yet to be probed and studied, and that novel approaches may be followed in order to obtain new results while improving some of the already obtained ones.

Appendices

Appendix A

Appendix Analysis

A.1 Mass distributions for every dark matter mass

This appendix shows every mass distribution as discussed in Section 6.4.3.

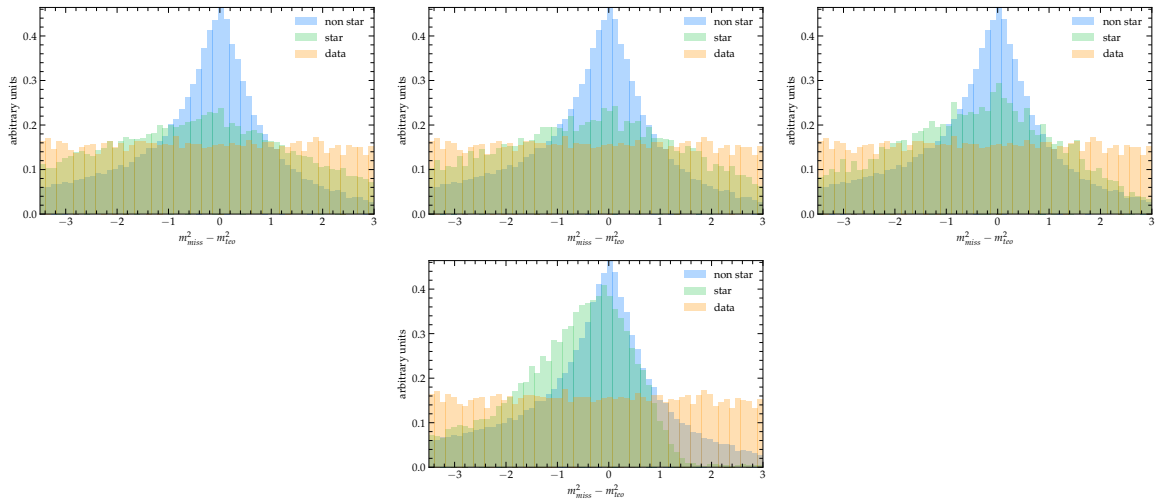


Figure A.1: Mass distribution for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ for mass hypothesis of $m(\psi_{\text{DM}}) = 0.94, 1.5, 2.4$ and 3.0 GeV.

A.2 Signal fits for every dark matter mass

This appendix shows every fit performed as discussed in Sections 6.4.4 and 6.4.5.

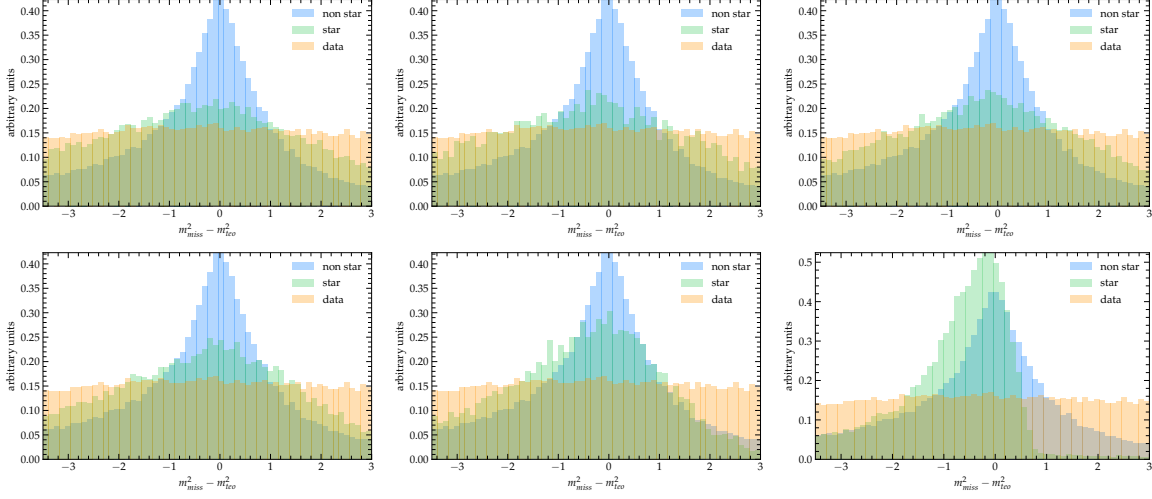


Figure A.2: Mass distribution for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ for mass hypothesis of $m(\psi_{\text{DM}}) = 0.94, 1.5, 2.0, 2.4, 3.0$ and 3.5 GeV.

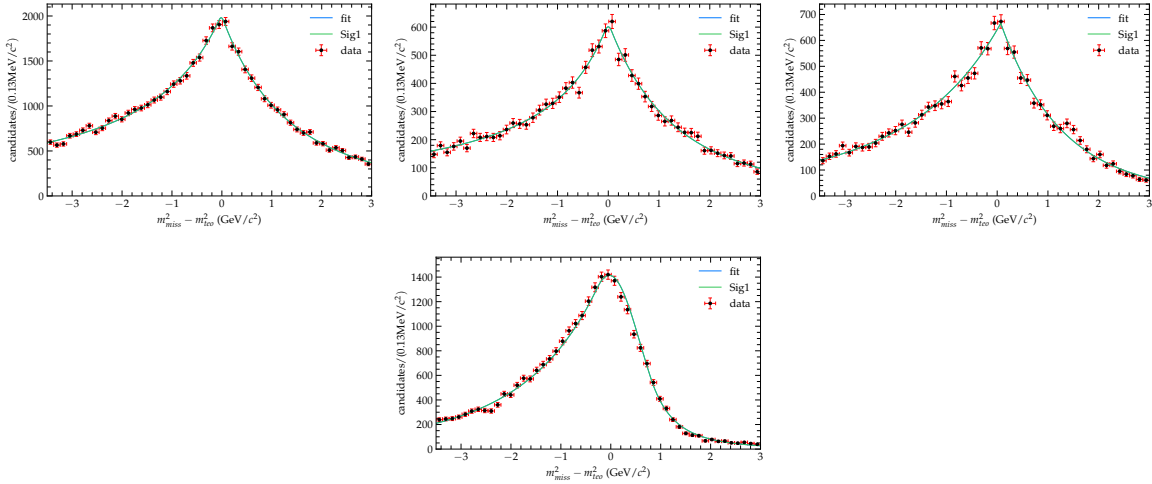


Figure A.3: Signal fit for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ for mass hypothesis of $m(\psi_{\text{DM}}) = 0.94, 1.5, 2.4$ and 3.0 GeV.

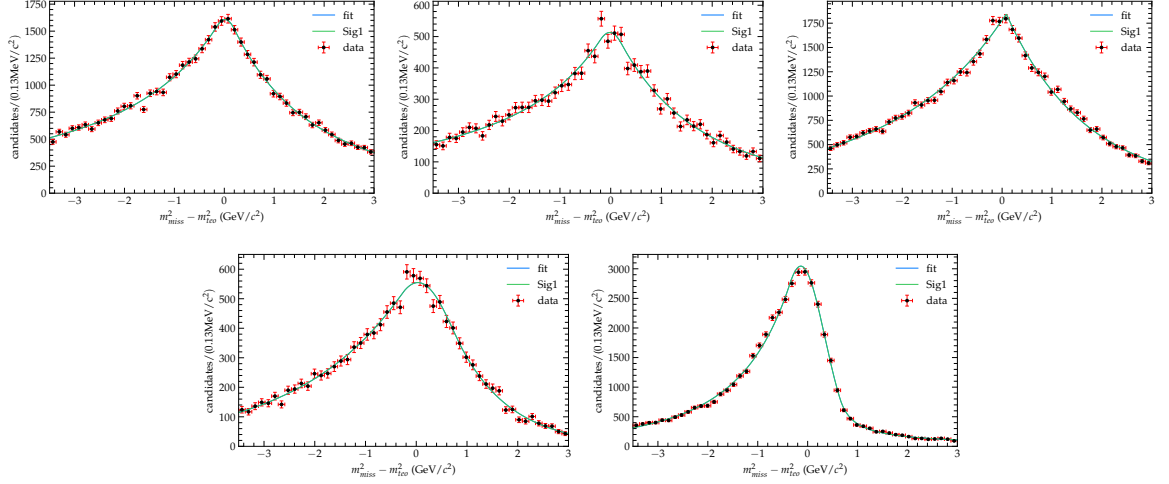


Figure A.4: Mass distribution for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ for mass hypothesis of $m(\psi_{\text{DM}}) = 0.94, 1.5, 2.0, 2.4, 3.0$ and 3.5 GeV.

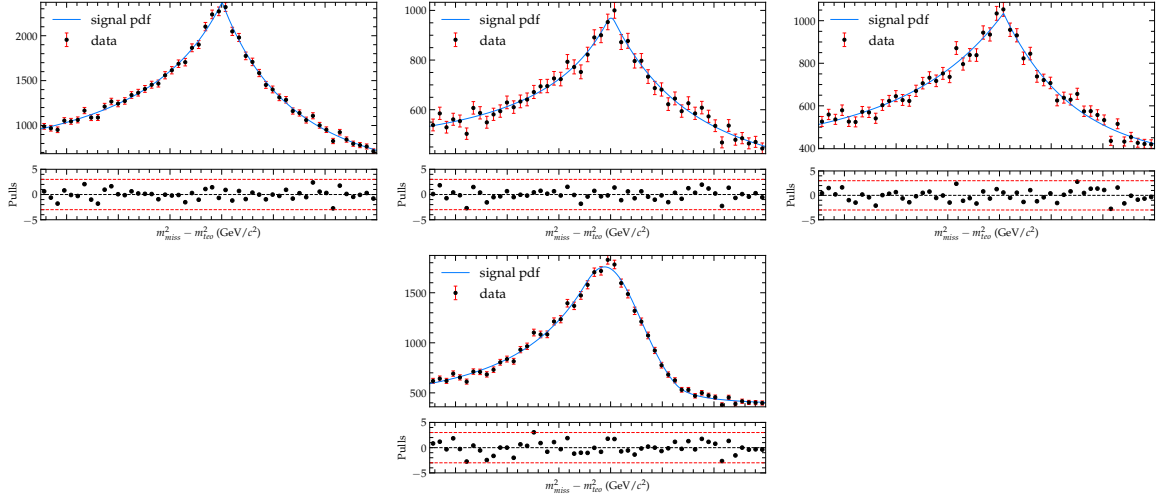


Figure A.5: Full model fit for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ for mass hypothesis of $m(\psi_{\text{DM}}) = 0.94, 1.5, 2.4$ and 3.0 GeV.

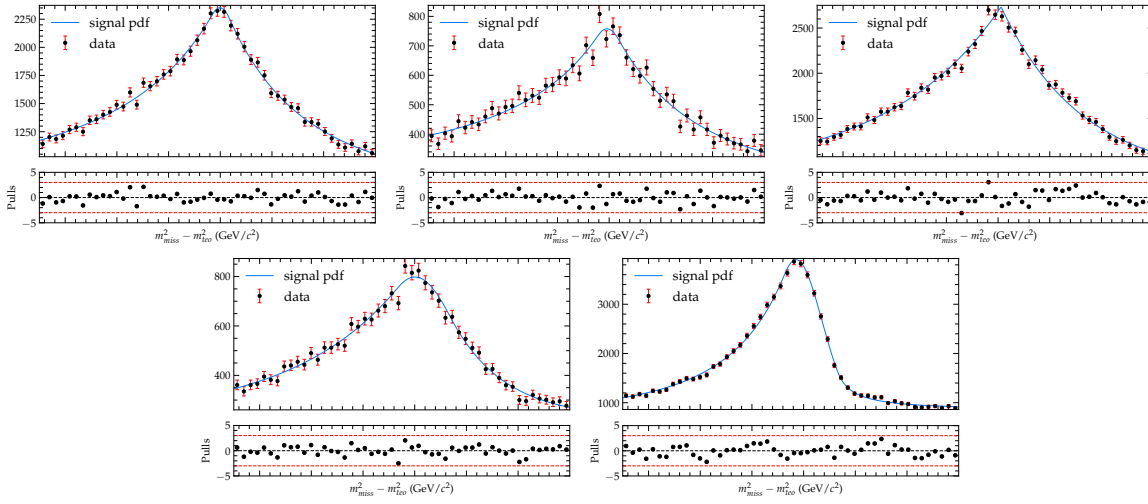


Figure A.6: Full model fit for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ for mass hypothesis of $m(\psi_{\text{DM}}) = 0.94, 1.5, 2.0, 2.4, 3.0$ and 3.5 GeV.

A.3 Pull plots for every dark matter mass

This appendix shows the pull plots for both decay modes and every dark matter mass, obtained as discussed in Section 6.4.6.

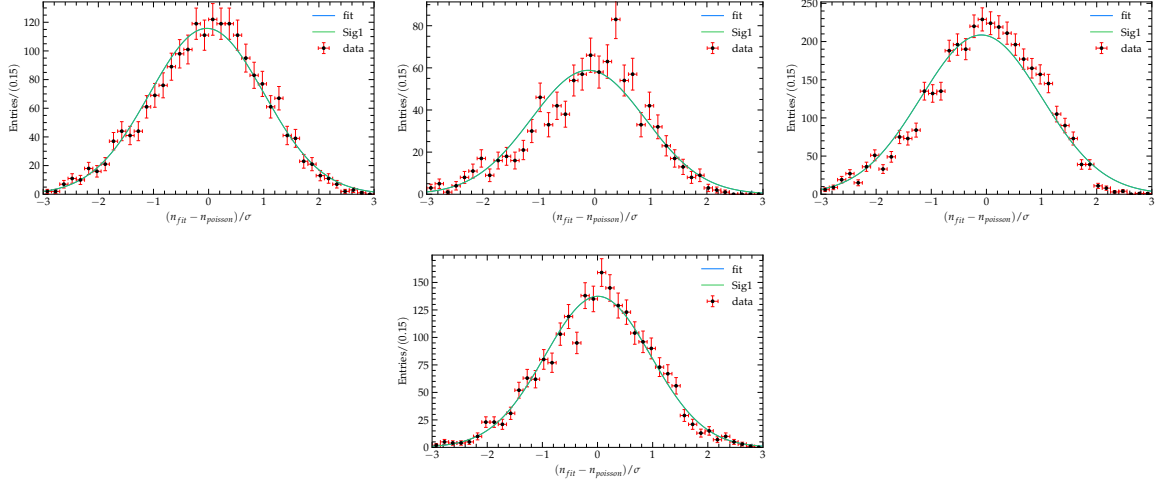


Figure A.7: Pull plots for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$ for mass hypothesis of $m(\psi_{\text{DM}}) = 0.94, 1.5, 2.0, 2.4$ and 3.0 GeV.

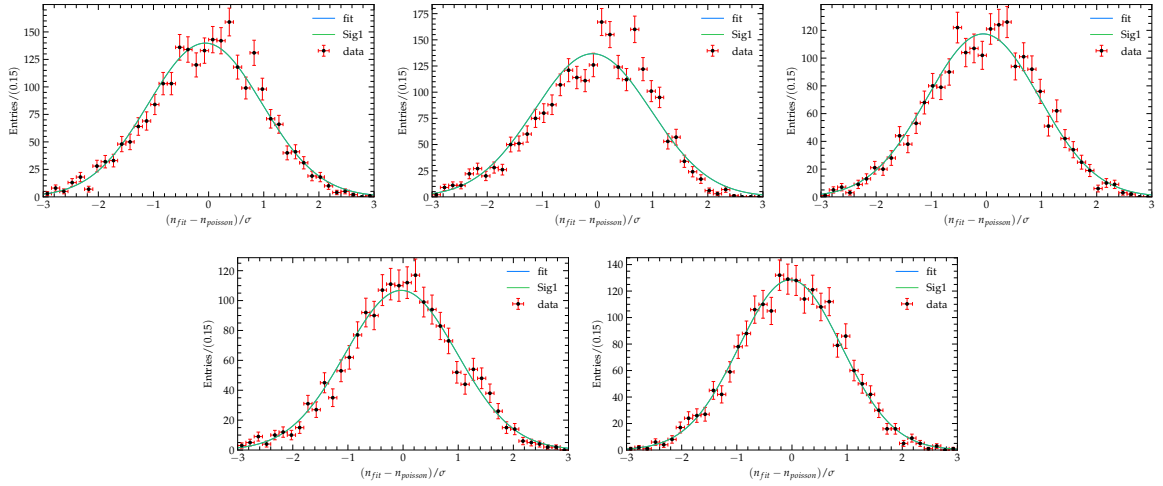


Figure A.8: Pull plots for the $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$ for mass hypothesis of $m(\psi_{\text{DM}}) = 0.94, 1.5, 2.0, 2.4, 3.0$ and 3.5 GeV.

Appendix B

Resumo

B.1 Introdución

O Modelo Estándar (SM) da física de partículas [1–4] probou ser un dos modelos máis precisos e eficaces para describir a natureza das partículas subatómicas e as súas interaccións. Por outra banda, coñecemos modelos [5–7] de física a escalas cosmolóxicas que poñen de manifesto diferentes fenómenos que non son recollidos no SM, apuntando así cara a necesidade de física alén do Modelo Estándar (BSM).

Neste modelo os constituintes fundamentais da natureza son os quarks e os leptóns, e as súas interaccións están mediadas a través dos bosóns de cada unha das interaccións fundamentais contidas dentro do Modelo Estándar. Estas interaccións representan 3 das 4 forzas fundamentais coñecidas ata agora, sendo estas a electromagnética, nuclear feble e nuclear forte as que están contempladas no modelo e a gravitatoria a que non está representada.

Os quarks máis os leptóns agrúpanse en dobletes e singletes de helicidade, a esquerdas ou a dereitas respectivamente. $\mathbf{Q}_L = \begin{bmatrix} u_L \\ d_L \end{bmatrix}$, $\begin{bmatrix} c_L \\ s_L \end{bmatrix}$, $\begin{bmatrix} t_L \\ b_L \end{bmatrix}$ para os quarks e $\mathbf{L}_L = \begin{bmatrix} e_L \\ \nu_{eL} \end{bmatrix}$, $\begin{bmatrix} \mu_L \\ \nu_{\mu L} \end{bmatrix}$, $\begin{bmatrix} \tau_L \\ \nu_{\tau L} \end{bmatrix}$ para os leptóns, sendo os singletes: $\mathbf{Q}_R = u_R, d_R, c_R, s_R, t_R, b_R$ e $\mathbf{L}_R = e_R, \mu_R, \tau_R$.

O feito de que os quarks sintan a interacción forte e non así os leptóns implica que estes últimos poden existir libremente, mentras que os primeiros están obrigados a formar estados ligados coñecidos como hadróns debido ao confinamento provocado pola liberdade asintótica.

Os bosóns son inicialmente indistinguibles excepto polas súas interaccións, xa que os gluóns interactúan con partículas con carga de cor e os bosóns W e Z interactúan con partículas que teñen hipercarga (todas excepto o hipotético neutrino a dereitas). No proceso da ruptura espontánea de simetría os bosóns W e Z adquiren masa debido á súa interacción co campo do Higgs.

Aproximadamente o 16% do Universo é a materia formada polas partículas descritas ata agora [8,9], mentras que o 84% restante sería unha materia que todavía

non se coñece, chamada materia escura (DM) [8, 9]. Este feito non está contemplado dentro do Modelo Estándar, supoñendo outra das súas limitacións [10–12]. O SM tampouco é capaz de explicar toda a asimetría observada entre materia e antimateria, necesitando de mecanismos alternativos para dar conta desta discrepancia, como por exemplo a barióxénese.

B.1.1 Matriz CKM

As interaccións do sector de sabor no Modelo Estándar están mediadas maioritariamente por bosóns $W^\pm$ en desintegracións tipo $\Lambda \rightarrow p\mu^-\bar{\nu}_\mu$ onde a nivel quarks o que está a suceder é $s \rightarrow u\mu^-\bar{\nu}_\mu$.

Estas desintegracións estan caracterizadas pola matriz de Cabibbo-Kobayashi-Maskawa (matriz CKM) [13–15]. A súa construción consiste en, a partir da densidade lagranxiana do Modelo Estándar:

$$\mathcal{L}_G = - \sum_a \frac{1}{4g_a^2} + i \sum_\Psi \sum_{i=1}^3 \bar{\Psi}_i \not{D} \Psi_i, \quad (\text{B.1})$$

onde a é cada unha das interaccións do Modelo Estándar e $\Psi = Q_L, u_R, d_R, L_L, e_R$. Observando as simetrías gauge globales desta lagranxiana obsérvase que está dexenerada en sabor, e estas simetrías poden romperse cunha interacción Yukawa do tipo:

$$\mathcal{L}_Y = -Y_{i,j}^d \bar{\Psi}_{L,i} \phi d_{R,j} - Y_{i,j}^u \bar{\Psi}_{L,i} \varepsilon \phi^* u_{R,j} + h.c. \quad (\text{B.2})$$

con Y^q matrices complexas, ϕ o campo do Higgs e i, j índices que indican a que dobrete/singlete pertencen as partículas. ε é o tensor antisimétrico en 2D [16] e $h.c.$ indica o hermítico conxugado de toda a lagranxiana.

A matriz que diagonaliza Y^d ou Y^u (non son matrices compatibles) é a coñecida como matriz CKM a cal pode escribirse como:

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}. \quad (\text{B.3})$$

Esta matriz describe a física de sabor dentro do Modelo estándar, a cal pode expresarse de dous xeitos, como xiros no espazo de sabor [17] ou coma unha matriz que indica a xerarquía desta interacción [15], onde os saltos de dúas xeracións están fortemente suprimidos fronte aos dunha soa xeración. Un comportamento similar no sector da materia escura estudárase nesta tese.

B.1.2 Materia escura e B-mesoxénese

Un modelo fenomenolóxico [18, 19] que explicaría a barioxénese e a materia escura será estudado neste traballo. As tres características que definen este modelo son as seguintes:

- Non son necesarias altas temperaturas no Universo temperán, e funcionaría con temperaturas máis baixas $5 \text{ MeV} \lesssim T \lesssim 30 \text{ MeV}$.
- O número bariónico universal sería unha cantidade conservada, asumindo que a materia escura contén número bariónico.
- A asimetría materia/antimateria estaría estreitamente ligada a diferentes observables dos mesóns B .

Este modelo permite fraccións de desintegración relativamente altas de barións a materia escura e un número arbitrario de mesóns do SM así como de mesóns a materia escura e barións.

Bases da B-mesoxénese

Este tipo de modelos requiren de cumprir as chamadas condicións de Sakharov [25]:

- *Violación de C e CP*: a materia e a antimateria son diferentes de base, o cal estaría garantido pola oscilación de mesóns B .
- *Alonxamento do equilibrio térmico*: o equilibrio térmico non pode ser constante xa que entón a mesma materia e antimateria que se produce desaparece. Isto estaría garantido por un suposto campo presente no Universo temperán que decae a quarks b .
- *Violación do número bariónico*: neste modelo a violación sería unicamente aparente no sector do Modelo Estándar, pero no global sería unha cantidade conservada.

Un diagrama destas condicións é o da Figure B.1.

Descrición formal e restricións cinemáticas

Debido a que unha soa partícula non pode describir toda a materia escura do Universo, a partícula descrita ata o de agora, ψ_{DM} , podería decaer a outras dúas diferentes do sector escuro as cales xa serían estables baixo unha simetría $\mathbb{Z}_2$ que estabilizaría os novos singletes de materia escura ϕ e ξ . A lagrangiana da interacción sería da forma:

$$\mathcal{L} \supset -y_d \bar{\psi}_{\text{DM}} \phi \xi + \text{h.c.} \quad (\text{B.4})$$

As condicións cinemáticas para a existencia deste modelo son as seguintes:

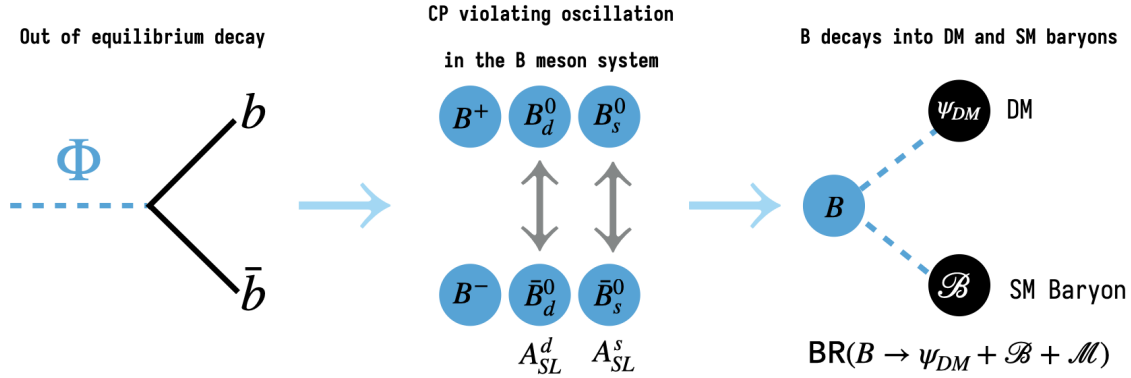


Figure B.1: Diagrama do modelo a estudar e como satisfai as condicións de Sakharov. A figura adaptouse de [18].

$$m_B > m_{\psi_{DM}} + m_p \Rightarrow m_{\psi_{DM}} < m_B - m_p \simeq 4.34 \text{ GeV}/c^2, \quad (\text{B.5})$$

o cal garante que polo menos unha desintegración é posible. Por outra banda, para non comprometer a estabilidade do protón:

$$m_p < m_{\psi_{DM}} + m_e \Rightarrow m_{\psi_{DM}} > m_p - m_e \simeq 937.8 \text{ MeV}/c^2. \quad (\text{B.6})$$

Con todo isto, o posible rango de masa da materia escura sería:

$$0.94 \text{ GeV}/c^2 < m_{\psi_{DM}} < 4.34 \text{ GeV}/c^2. \quad (\text{B.7})$$

Operadores de materia escura e desintegracións permitidas

Unha lagranxiana efectiva que permitiría as desintegracións a materia escura viría dada pola seguinte densidade:

$$\mathcal{L}_{\text{eff}} = O_{u_i d_j} \frac{y_i y_j}{M_Y^2}, \quad (\text{B.8})$$

onde $y_i y_j$ é o produto do acoplamento referido aos quarks i e j . De acordo a esta lagranxiana, os operadores permitidos serían:

$$O_{ud} = \psi_{DM} b u d, \quad (\text{B.9a})$$

$$O_{us} = \psi_{DM} b u s, \quad (\text{B.9b})$$

$$O_{cd} = \psi_{DM} b c d, \quad (\text{B.9c})$$

$$O_{cs} = \psi_{DM} b c s. \quad (\text{B.9d})$$

Operator and Decay	Initial State	Final State	ΔM (MeV)
$O_{ud} = \psi_{\text{DM}} b u d$ $\bar{b} \rightarrow \psi_{\text{DM}} u d$	B_d	$\psi_{\text{DM}} + n(udd)$	4340.1
	B_s	$\psi_{\text{DM}} + \Lambda(uds)$	4251.2
	B^+	$\psi_{\text{DM}} + p(duu)$	4341.0
	Λ_b	$\bar{\psi}_{\text{DM}} + \pi^0$	5484.5
$O_{us} = \psi_{\text{DM}} b u s$ $\bar{b} \rightarrow \psi_{\text{DM}} u s$	B_d	$\psi_{\text{DM}} + \Lambda(USD)$	4164.0
	B_s	$\psi_{\text{DM}} + \Sigma^0(uss)$	4025.0
	B^+	$\psi_{\text{DM}} + \Sigma^+(uus)$	4090.0
	Λ_b	$\bar{\psi}_{\text{DM}} + K^0$	5121.9
$O_{cd} = \psi_{\text{DM}} b c d$ $\bar{b} \rightarrow \psi_{\text{DM}} c d$	B_d	$\psi_{\text{DM}} + \Lambda_c + \pi^-(cdd)$	2853.6
	B_s	$\psi_{\text{DM}} + \Sigma_c^0(cds)$	2895.0
	B^+	$\psi_{\text{DM}} + \Lambda_c^+(dcu)$	2992.9
	Λ_b	$\bar{\psi}_{\text{DM}} + D^0$	3754.7
$O_{cs} = \psi_{\text{DM}} b c s$ $\bar{b} \rightarrow \psi_{\text{DM}} c s$	B_d	$\psi_{\text{DM}} + \Sigma_c^0(csd)$	2807.8
	B_s	$\psi_{\text{DM}} + \Omega_c(css)$	2671.7
	B^+	$\psi_{\text{DM}} + \Sigma_c^+(csu)$	2810.4
	Λ_b	$\bar{\psi}_{\text{DM}} + D^- + K^+$	3256.2

Table B.1: Desintegracións máis lixeiras e diferencias de masas obtidas no modelo. Para cada operador particular as fraccións de desintegración que esperamos atopar son similares, xa que o espazo fásico é similar. Máis mesóns lixeiros poderían aparecer nos estados finais, unicamente cambiando a diferenza de masa e cunha supresión na fracción de desintegración. Adaptado de [18].

Este formalismo arroxa diferentes desintegracións posibles, entre elas as da Table B.1.

As desintegracións a estudar nesta tese corresponden aos operadores O_{cs} e O_{cd} . En particular ás seguintes desintegracións: $\Lambda_b \rightarrow \psi_{\text{DM}} K (D \rightarrow \pi\pi K)$ e $\Lambda_b \rightarrow \psi_{\text{DM}} \pi (D \rightarrow \pi\pi K)$, respectivamente.

Estado experimental actual

Este modelo está pouco explorado na actualidade en colisores e en fábricas de mesóns B . Unha búsqueda directa de $B \rightarrow \Lambda \psi_{\text{DM}}$ foi realizada en BaBar sen obter sinal significativa e obtendo un límite á fracción de desintegración de $0.13 - 5.2 \times 10^{-5}$ para $1.0 < m_{\psi_{\text{DM}}} < 4.2 \text{ GeV}/c^2$ [26]. BaBar tamén realizou a busca de $B^+ \rightarrow \psi_{\text{DM}} + p$

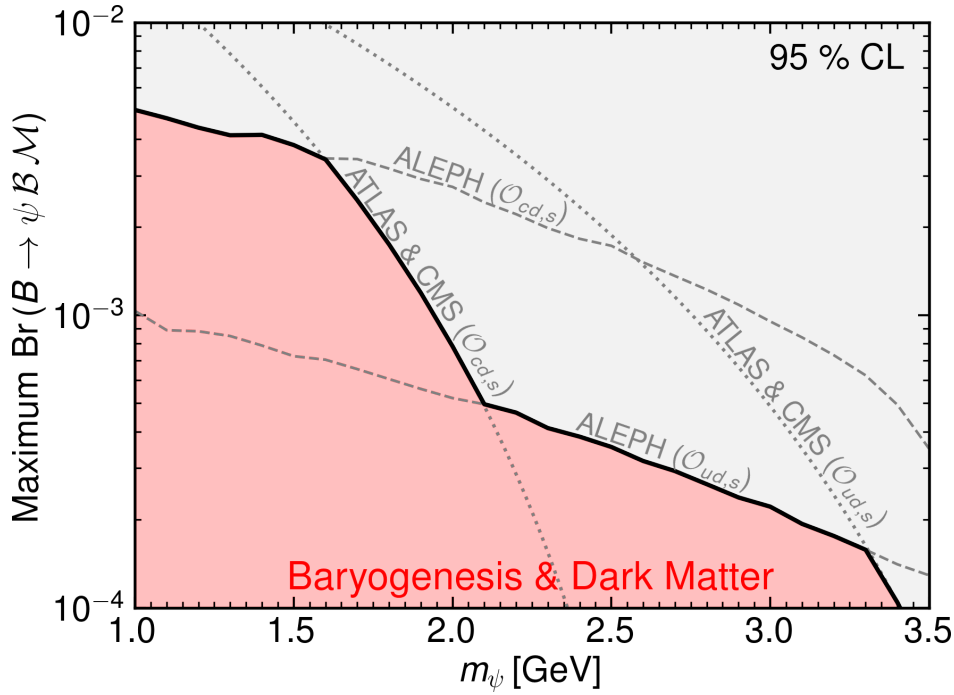


Figure B.2: Límites actuais en buscas inclusivas de $\text{Br}(B \rightarrow \mathcal{B}\psi_{\text{DM}}\mathcal{M})$ en función da masa da materia escura restrinxido polas buscas de ALPEH, CMS e as re-análises de ALPEH. Figura obtida de [18] baixo licencia creative commons.

sen atopar sinal significativa e establecendo un límite superior de $10^{-7} - 10^{-5}$ para $1.0 < m_{\psi_{\text{DM}}} < 4.3 \text{ GeV}/c^2$ [27].

Buscas indirectas en CMS [28] e ATLAS [29], así como re-análises de ALPEH [30] permiten establecer límites ás fraccións de desintegración dos outros operadores de 10^{-3} . Un resumo destes traballos pode ser atopado en Figure B.2

B.1.3 Partículas de vida media longa

Outros xeitos de expandir o Modelo Estándar implican a existencia de partículas de vida media longa [31,32], para as cales os detectores actuais non son óptimos.

Os modelos estudados nesta tese son aqueles coñecidos como portais do Higgs, os cales propoñen que hai un sector rico de desintegracións que comezan co bosón de Higgs, entre as cales hai partículas de vida media longa.

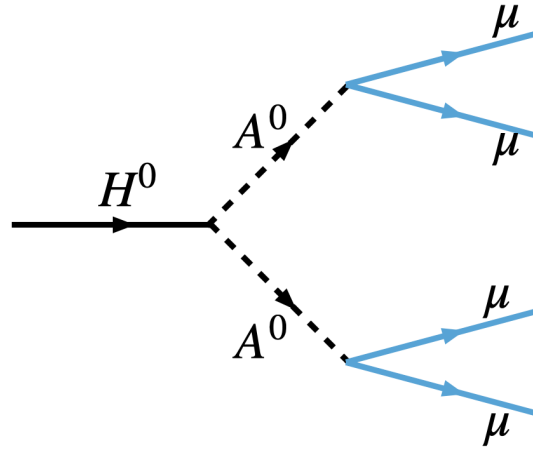


Figure B.3: Diagrama dunha potencial desintegración permitida polo modelo de portal de Higgs a estudar.

Modelos de vida media longa

Un operador que permita estas desintegracións sería, por exemplo, da forma SHH^+ , S^2HH^+ onde H é o SM Higgs e S unha nova partícula escalar. Estes operadores permitirían desintegracións como as da Figure B.3.

Para caracterizar estas desintegracións tres modos de produción diferentes do Higgs serán estudados [39–41]: produción inclusiva de Higgs, onde ningunha restrición sobre o modo produción é imposta; Higgs-strahlung, onde o Higgs e producido xunto a un bosón feble e fusión de bosón feble, onde o Higgs e producido xunto a un jet.

Estado experimental actual

Algún experimentos do CERN estudaron ás partículas de vida media longa [42,43]. Ao non seren estes experimentos dedicados ao estudo de partículas de vida media longa outros dedicados á búsqueda desta física van aparecendo [44–46], como por exemplo CODEX, o cal é o marco desta sección da tese. Un diagrama resumo pode atoparse en Figure B.4.

B.2 Obxectivos

Búscase establecer por primeira vez límites a desintegracións relacionadas cos operadores O_{cs} e O_{cd} , así como obter unha eficiencia a nivel xerador para ás desintegracións do Higgs a partículas de vida media longa descritas.

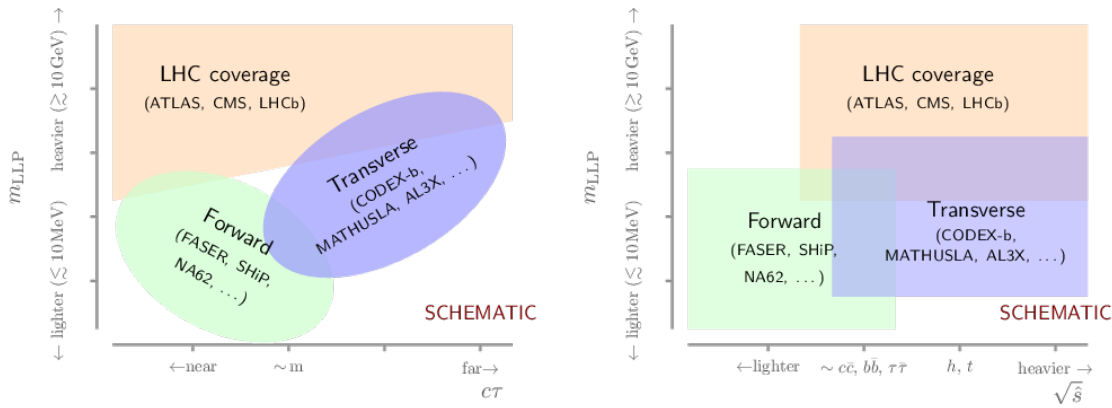


Figure B.4: Diagrama de estado actual e previsto deste campo de estudo.
Reproducido de [33] baixo licenza creative commons.

B.3 Montaxe experimental

B.3.1 Experimento CODEX-b

CODEX-b trátase dun futuro detector que será instalado preto do punto de impacto do LHCb. Este detector consistirá nun volume de $10\text{ m} \times 10\text{ m} \times 10\text{ m}$ formado por cámaras de placas resistivas (RPCs) [56]. Estes paneis de $2\text{ m} \times 1\text{ m}$ conformarán todo o volume do detector. A parametrización deste tomando o punto de impacto coma o $(0, 0, 0)$ ven dado por

- $25,75\text{ m} < x < 35,75\text{ m}$
- $-5\text{ m} < y < 5\text{ m}$
- $5\text{ m} < z < 15\text{ m}$.

Debido á súa localización detrás de diferentes blindaxes e moi transversal aos feixes de protóns permite unha representación moi fiel de todos os posibles fondos derivados do Modelo Estándar e un mantemento máis constante que outros experimentos.

B.3.2 Experimento LHCb

O LHCb é un dos catro grandes (ALICE, ATLAS, CMS e LHCb) experimentos no gran colisor de hadróns (LHC) do CERN. Este experimento caracterízase por ser un espectrómetro deseñado [62] para reconstruír e estudar a física relacionada cos quarks b . Trátase dun detector cara adiante que pode reconstruír partículas cunha pseudorapidez $1.6 \leq \eta \leq 4.9$.

Este experimento esta conformado por unha serie de subdetectores:

- VELO [66–68]: o VELO (polo seu nome en inglés Vertex Locator) encárgase de medir con gran precisión o punto no que se producen e decaen hadróns pesados, os cales tipicamente conteñen un quark b .
- RICH [70, 71]: detectores Cerenkov encargados de facer unha asignación probabilística á natureza das partículas en función da súa velocidade e con diferentes hipóteses de masa.
- Sistema de trazas [72, 73]: sistema encargado de reconstruír a traxectoria das partículas que atravesan o detector.
- Imán [75]: dipolo magnético que se utiliza para curvar a traxectoria das partículas e así medir o seu momento.
- Calorímetros [76, 77]: miden a enerxía depositada por diferentes partículas o cal permite establecer unha selección en termos da enerxía transversa e axudan na caracterización da natureza das mesmas.
- Estacións de muóns [78, 79]: sistema deseñado para reconstruír a traxectoria seguida polos muóns no detector.

B.4 Metodoloxía

Para a búsqueda en LHCb xérase Monte Carlo para todos os modos de sinal de interese, e logo procedemos a realizar unha análise multivariante utilizando unha pequena porcentaxe dos datos coma fondo. Tras a análise multivariante realizamos un proceso de etiquetado enter Λ_b e π para reconstruír candidatos a Σ_b xa que isto mellora significativamente a eficiencia no proceso de discriminar sinal de fondo.

Tras realizar o mesmo proceso sobre unha desintegración coñecida contra a cal comparar e normalizar os resultados obtidos neste traballo, procederase ao cálculo do límite da fracción de desintegración.

Por outra banda, xérase tamén Monte Carlo para os diferentes modos de produción do Higgs e aplícanse unha serie de cortes para obter as eficiencias desexadas.

B.5 Partículas de vida media longa

Xeráronse eventos de LHC en PYTHIA8 [89] cunha enerxía no centro de masas de 14 TeV para os tres modos de produción mencionados do Higgs. Aplicáronse os cortes para que as partículas de interese estean contidas nos detectores, así coma uns cortes en pseudorapidez e en momento transverso para os casos nos cales consideramos a detección simultánea en LHCb e en CODEX.

Os resultados obtidos poden atoparse en Table B.2 e en Figure B.5.

Production	0.1 m	1 m	10 m	100 m	1000 m
Inclusive	371	12953	3978	506	35
Inclusive & LHCb	92	9	0	0	0
Weak-boson	2	31	8	1	0
Higgs-strahlung	0	34	18	2	0

Table B.2: Eventos esperados para todos os modos de produción e detección descritos. As vidas medias $c\tau$ están en metros.

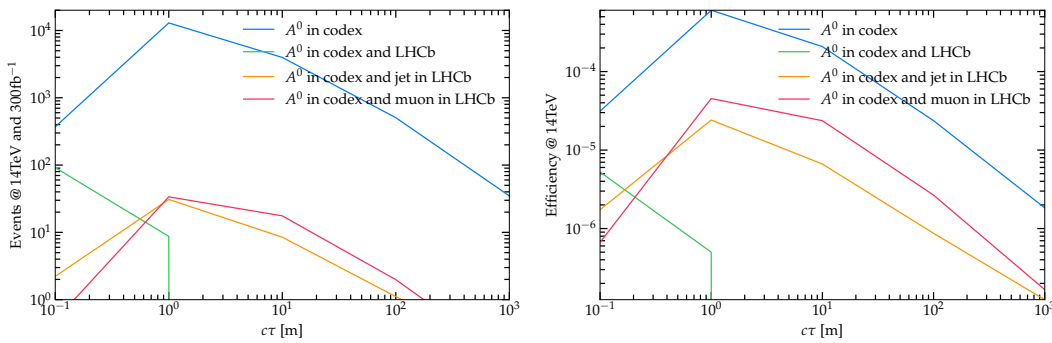


Figure B.5: Eficiencias (dereita) e eventos esperados (esquerda) en CODEX-b para unha luminosidade integrada de $\mathcal{L} = 300 \text{ fb}^{-1}$.

B.6 Materia escura e B-mesoxénese

B.6.1 Datos e Monte Carlo

Xerouse Monte Carlo para todos os modos de sinal así como para fondo e modo de normalización. Por outra banda, utilizouse unicamente unha pequena parte dos datos dispoñibles de todo o Run II, concretamente 0.44 fb^{-1} para o operador $\mathcal{O}_{cs}$ e 0.22 fb^{-1} para o operador $\mathcal{O}_{cd}$. No caso do Monte Carlo, uns pequenos cortes sobre diferentes variables cinemáticas foron impostos para axilizar a xeración de eventos que superen a posterior selección. Unha eficiencia debida a estes cortes así como outra debido á eficiencia intrínseca de reconstrución do detector é calculada. Todas as eficiencias serán presentados nunha soa táboa.

B.6.2 Selección

Selección de Stripping

Úsanse tres liñas, dúas das cales foron deseñadas para esta análise: LambdaDecaysDMLambdaToDPiLine e LambdaDecaysDMLambdaToDKLine sendo a terceira Lb2LcPiNoIPLc2PKPiBeauty2CharmLine [109,110] a de normalización. As liñas de sinal teñen uns cortes cinemáticos e topolóxicos que buscan maximizar a discriminación de sinal contra fondo baseados en buscar vértices moi alonxados do punto de impacto. Deste selección obtemos unha nova eficiencia.

Selección do disparador

O experimento LHCb ten unha serie de disparadores (L0, HLT1 e HLT2) encargados de seleccionar eventos para a súa escritura en disco de acordo cunha serie de variables (número de trazas, momento transverso das partículas, topoloxía do evento...) para poder traballar cunhas taxas de datos manexables para as diferentes compoñentes de hardware e software.

Nesta análise, as liñas do disparador para cada un dos seus niveles seleccionadas son as seguintes: L0HadronDecision para o L0; Hlt1TrackMVADecision e Hlt1TwoTrackMVADecision para o HLT1; Hlt2Topo2BodyDecision, Hlt2Topo3BodyDecision e Hlt2Topo4BodyDecision para o HLT. En base a esta selección obtesne unha nova eficiencia.

Clasificador multivariante

Resultan útiles para mellorar a discriminación de sinal contra fondo os algoritmos de aprendizaxe automático. Neste caso utilizamos unha árbore de decisión impulsada, concretamente un clasificador de aumento de gradiente [115,116]. Deste algoritmo participan moitas das variables cinemáticas e topolóxicas das partículas involucradas na análise, das cales seleccionamos mediante un algoritmo as máis importantes. Realízase finalmente unha serie de estudos sobre o clasificador para comprobar que este está a comportarse do xeito esperado e non sofre ningún tipo de sobre-entreno ou infra-entreno, sendo o principal indicador as curvas ROC de Figure B.6.

O mellor corte na variable predictiva escóllese para cada masa e modo de desintegración de acordo con aquel que maximiza a seguinte figura de mérito [124]:

$$\text{FOM} = \frac{\varepsilon}{\frac{3}{2} + \sqrt{N_{\text{bkg}}}}, \quad (\text{B.10})$$

sendo, para as masas máis representativas, as obtidas en Figure B.7.

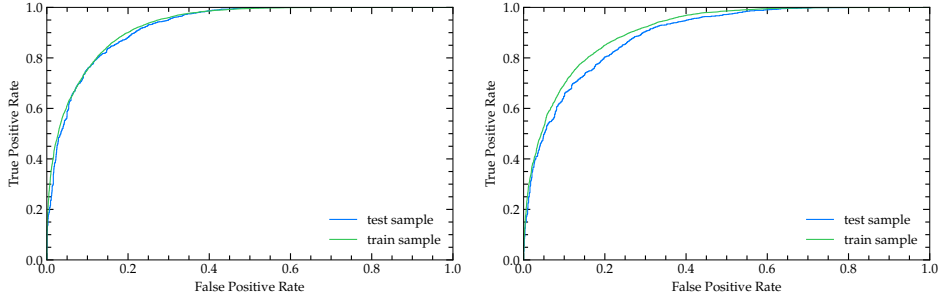


Figure B.6: Curvas ROC para o modo de desintegración $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}} K(D \rightarrow \pi\pi K))$ (esquerda) e $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}} \pi(D \rightarrow \pi\pi K))$ (dereita) para unha masa de materia escura de 940 MeV.

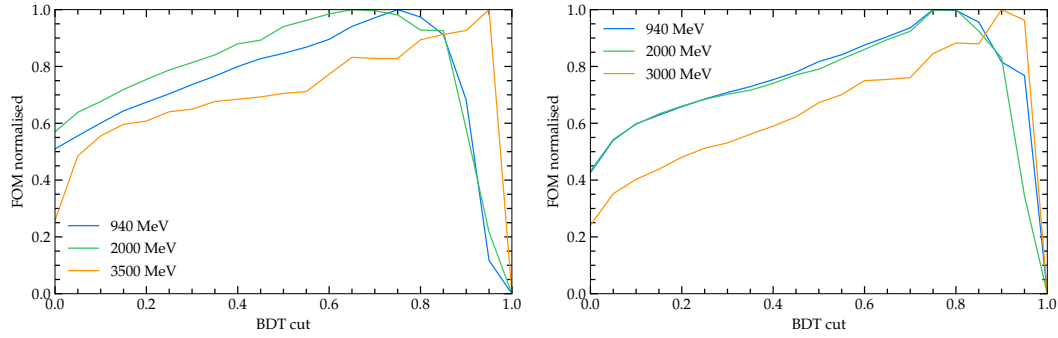


Figure B.7: Figura de mérito normalizada para $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}} K(D \rightarrow \pi\pi K))$ (left) e para $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{\text{DM}} \pi(D \rightarrow \pi\pi K))$ (right) para tres masas: a máis lixeira, a máis pesada dispoñible, e unha intermedia de 2 GeV proposta como referencia por [18].

B.6.3 Etiquetado

Séguese unha estratexia de etiquetado onde a nai dos barións Λ_b , un $\Sigma_b^{\pm(*)}$ é reconstruído asociando o Λ_b cun $\pi^\pm$ que proveña do vértice primario, como foi feito en [85–88]. Isto permite obter a masa invariante da partícula de materia escura.

Este proceso elimina Λ_b candidatos debido á existencia do discriminante:

$$d = \left(\frac{p_\pi}{E_\pi} \cos \theta \right)^2 - \frac{4m_\Lambda^2 p_\pi^2 \cos^2 \theta}{\Delta^4} \left(1 - \left(\frac{p_\pi}{E_\pi} \cos \theta \right)^2 \right), \quad (\text{B.11})$$

de tal xeito que unha nova eficiencia aparece deste proceso.

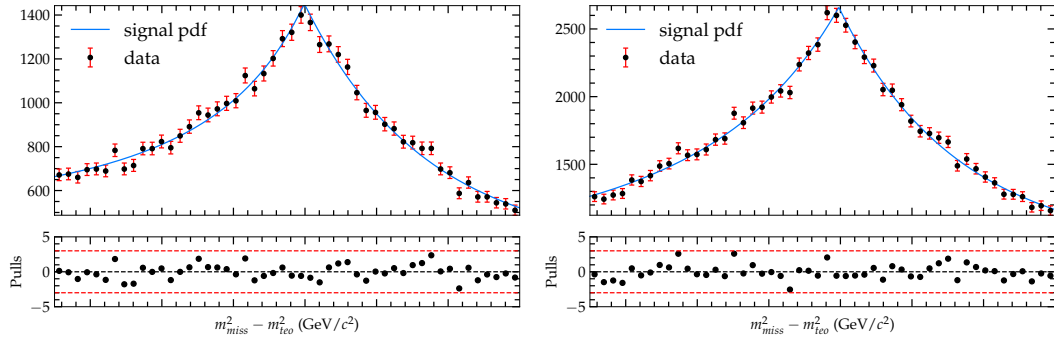


Figure B.8: Axustes obtidos para ambos modos de desintegración (left: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$, right: $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$) for a $m(\psi_{\text{DM}}) = 2$ GeV. A distancia en σ entre o axuste e os datos aparece no histograma inferior.

	N_{sig}	N_{bkg}	μ	σ	b
0.94 GeV	45000.0	33131.1	-0.0080	0.5409	0.0068
1.5 GeV	14123.3	11383.1	-0.0400	0.5940	-0.0025
2.0 GeV	47506.6	39000.1	-0.0218	0.0694	0.0051
2.4 GeV	48745.7	39000.1	0.0556	0.1515	0.0043
3.0 GeV	13704.0	11327.5	0.0054	0.8372	0.0005
3.5 GeV	48895.3	39000.0	-0.1465	0.4980	0.0091

Table B.3: Resultados obtidos para todas as masas para o modo de desintegración de $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$.

B.6.4 Axuste á masa

O sinal sumado de Σ_b^{*+} e Σ_b^+ é axustado a unha función de distribución de probabilidade (PDF) bola de cristal de dous lados [84], moi usado en física de partículas para axustar resonancias. Por outra banda o fondo, por ser unicamente combinatorio, é axustado a unha PDF exponencial. Os resultados obtidos poden observarse en Figure B.8 e en Table B.4 e Table B.3.

B.6.5 Canle de normalización

Realizamos o mesmo proceso descrito ata o de agora, pero sobre $\Lambda_b \rightarrow \pi(\Lambda_c \rightarrow pK\pi)$. Neste caso buscamos obter o número final de $\Sigma_b^{(*)}$, o cal é:

	N_{sig}	N_{bkg}	μ	σ	b
0.94 GeV	51014.2	16313.6	0.0073	0.0650	-0.0077
1.5 GeV	16033.7	16638.5	0.0074	0.3422	-0.0103
2.0 GeV	26755.9	17500.1	-0.0095	0.2172	-0.0135
2.4 GeV	16292.0	17000.1	0.0777	0.0325	-0.0073
3.0 GeV	26688.7	18400.7	-0.1138	0.7198	-0.0041
3.5 GeV	NOPHSP	NOPHSP	NOPHSP	NOPHSP	NOPHSP

Table B.4: Resultados obtidos para todas as masas para o modo de desintegración de $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$.

$N_{\text{sig},1}$	$N_{\text{sig},2}$	N_{bkg}	μ_1	μ_2	Γ_1	Γ_2	A	C
2660.11	7949.6	92675.8	56.11	75.19	7.30	17.42	0.453	0.00151

Table B.5: Resultados obtidos da canle de normalización.

$$N(\Sigma_b^{\pm(*)}) = 19\,761\,364\,640.$$

Para isto realizamos o axuste a unha función exponencial modulada por unha lei de potencias para modelas o fondo, mentras que as compoñentes de sinal axustan por función de Breit-Wigner relativistas [2, 132, 133] baseado en [86]. Os resultados poden verse en Table B.5 e Figure B.9.

B.6.6 Límites

Realízase un test de hipótese para obter o límite esperado da fracción de desintegración para ambos modos de desintegracións. Para isto, utilízanse as formas funcionais obtidas nas seccións anteriores e faise un escaneo sobre os datos utilizados, tras aplicar todas as seleccións descritas.

	0.94 GeV	1.5 GeV	2.0 GeV	2.4 GeV	3.0 GeV	3.5 GeV
O_{cs}	3.05×10^{-4}	4.90×10^{-4}	8.28×10^{-4}	3.61×10^{-4}	2.12×10^{-3}	NOPHSP
O_{cd}	1.18×10^{-3}	1.87×10^{-3}	3.86×10^{-3}	1.40×10^{-3}	1.19×10^{-2}	3.97×10^{-4}

Table B.6: Valores de $\mathcal{B}_{\text{signal}}$ para todas as masas e modos de desintegración.

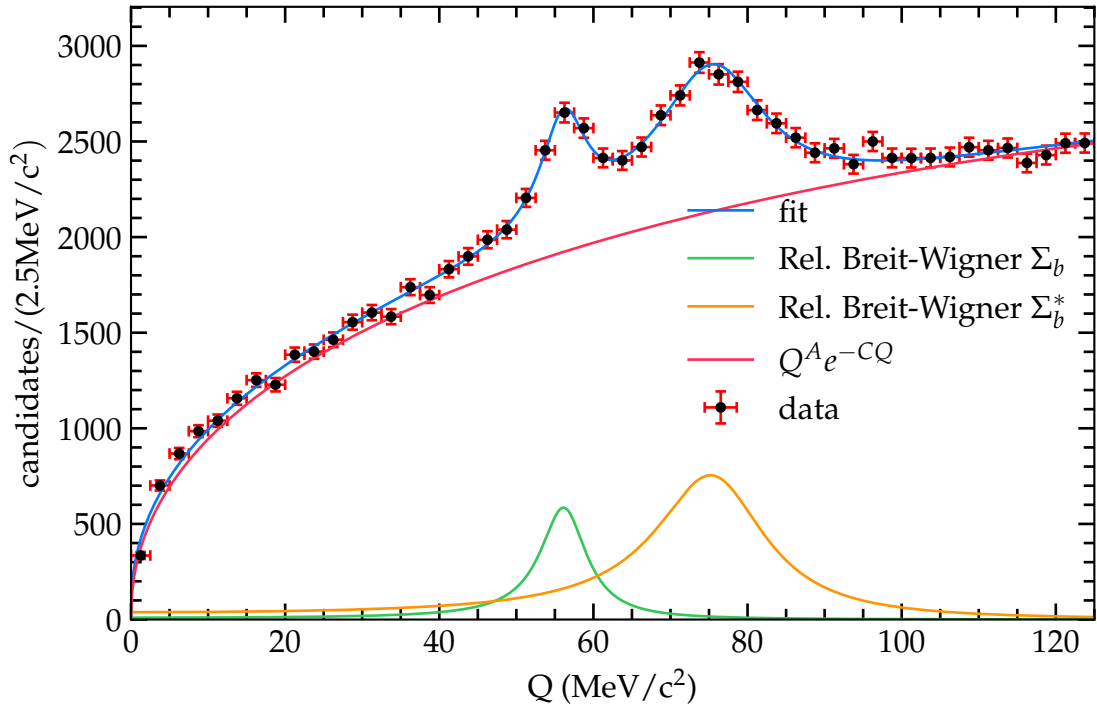


Figure B.9: Axuste obtido para a canle de normalización con todas as súas compoñentes.

B.6.7 Fondos

Realízase o mesmo procedemento de análise sobre unha mostra de Monte Carlo de fondo tipo $\Sigma_b^{\pm(*)} \rightarrow \pi(\Lambda_b \rightarrow D\pi\Lambda^0)$ por ser este o principal candidato a ser confundido con materia escura, e non se atopa ningunha interferencia posible.

Por outra banda, cracterízase o fondo obtendo que é maioritariamente combinatorio e non esperamos ningún pico doutras resonancias. Obtense que algún ascendente do D está na lista de ascendentes do K suave un 48.33% das veces para o operador O_{cs} , mentras que para o operador O_{cd} obtense que isto sucede un 63.80% das veces, mais en lugar do K sendo un π .

B.7 Resultados e discusión

B.7.1 Resultados da materia escura e B-mesoxénese

As eficiencias mencionadas atópanse en Table B.7 e Table B.8.

	ϵ_{gen}	ϵ_{reco}	ϵ_{sel}	ϵ_{trig}	ϵ_{BDT}	ϵ_{tag}	$\epsilon_{m_{\text{min}}}$
0.94 GeV	8.108	0.23342	0.05578	0.151982	0.55111	0.72301	6.39×10^{-5}
1.5 GeV	8.004	0.22065	0.05283	0.1275892	0.63768	0.71818	5.45×10^{-5}
2.0 GeV	7.855	0.21871	0.04888	0.084826	0.29369	0.74790	1.53×10^{-5}
2.4 GeV	7.679	0.20379	0.04528	0.062786	0.70072	0.81521	2.54×10^{-5}
3.0 GeV	7.277	0.19550	0.02763	0.019891	0.54901	0.76364	0.327×10^{-5}

Table B.7: Táboa con todas as eficiencias da desintegración $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}K(D \rightarrow \pi\pi K))$.

	ϵ_{gen}	ϵ_{reco}	ϵ_{sel}	ϵ_{trig}	ϵ_{BDT}	ϵ_{tag}	ϵ_{tot}
0.94 GeV	0.09637	0.25776	0.03944	0.146100	0.45041	0.76867	4.95×10^{-5}
1.5 GeV	0.09619	0.24652	0.03853	0.114859	0.31227	0.84782	2.77×10^{-5}
2.0 GeV	0.09527	0.22866	0.03659	0.084012	0.22241	0.78698	1.17×10^{-5}
2.4 GeV	0.09405	0.21989	0.03258	0.064387	0.52109	0.74519	1.68×10^{-5}
3.0 GeV	0.09051	0.19740	0.02478	0.038597	0.38636	0.64286	0.424×10^{-5}
3.5 GeV	0.06873	0.18820	0.00868	0.025457	0.87179	0.84375	0.210×10^{-5}

Table B.8: Táboa con todas as eficiencias da desintegración $\Sigma_b^{\pm(*)} \rightarrow \pi^{\pm}(\Lambda_b \rightarrow \psi_{\text{DM}}\pi(D \rightarrow \pi\pi K))$.

Os resultados obtidos aquí, aínda que limitados debido a todavía obter os erros sistemáticos, supoñen unha primeira medida de dous operador de materia escura e suporían a mellor medida no momento da escritura desta tese.

B.7.2 Resultados das partículas de vida media longa

Supoñen unha primeira aproximación ao cálculo de eficiencias no marco do experimento CODEX-b que pode ser expandido a nivel colaboración para outros modos de desintegración ou produción.

B.7.3 Discusión

Estes resultados supoñen unha nova aproximación ao estudo de física alén do modelo estándar, por estar relacionados cun novo detector aínda por ser instalado así como por propoñer unha metodoloxía pouco explotada dentro do LHCb, co cal espérase que ambas teñan un maior percorrido a futuro.

B.8 Conclusións

Nesta tese realizouse a primeira análise que estuda os operadores O_{cs} e O_{cd} propostos en [18], obtendo a primeira medición das fraccións de desintegración esperadas potenciais para dous modos de desintegración, $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{DM}\pi(D \rightarrow \pi\pi K))$ e $\Sigma_b^{\pm(*)} \rightarrow \pi^\pm(\Lambda_b \rightarrow \psi_{DM}K(D \rightarrow \pi\pi K))$. Tamén se calculou a eficiencia a nivel de xerador para tres modos de produción do Higgs supoñendo desintegracións tipo portal do Higgs.

Realizouse unha análise detallada dos datos da Run II de 2018 para lograr a primeira das dúas tarefas mencionadas. Neste traballo demostrouse un mecanismo de etiquetaxe raramente usado que podería ser utilizado para moitas outras análises de enerxía desaparecida no LHCb, xa que, debido á xeometría cara adiante do detector, poden seguirse enfoques diferentes e as análises tradicionais de enerxía desaparecida están fóra do alcance. Outras metodoloxías tradicionais utilizadas na física de altas enerxías como o adestramento de BDTs para obter unha mellor discriminación entre sinal e fondo ou o cálculo de límites esperados a través dunha metodoloxía de probas de hipóteses.

O experimento CODEX-b, que se instalará preto do LHCb, comezará a recoller datos posteriormente ao momento de escribir esta tese, polo que será necesario poder de computación e persoal. O traballo feito nesta tese espera ser unha ferramenta útil para outros científicos involucrados neste proxecto. O código desenvolvido para isto é moi modular e fácil de editar e usar directamente, con moi poucas librerías de python requiridas, e será distribuído a toda a colaboración.

Estes dous temas estreitamente relacionados mostran que aínda hai moita física alén do Modelo Estándar por probar e estudar, e que se poden seguir enfoques novidosos para obter novos resultados ao tempo que se melloran algúns dos xa obtidos.

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This thesis provides a dark matter search in the LHCb experiment using 2018 data. A novel approach of DM being charged under baryon number is proposed, allowing for unseen decay modes so far. This work shows the first physics case of these models in the LHCb performing a direct search over final state SM charged particles for DM in the [0.94, 3.5] GeV. World best sensitivity is achieved. A study of some other BSM physics cases within the Codex-b experiment are also presented.