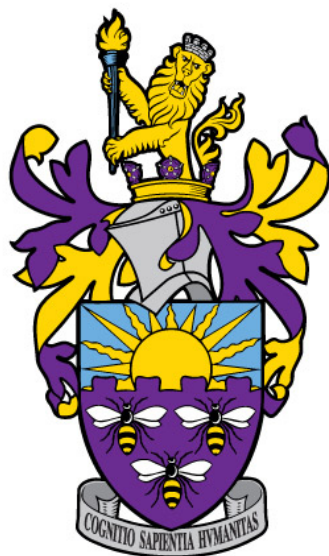




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Search for CP Violation in charm meson decays to final states with at least one neutral particle

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Abstract

CP violation is a phenomenon embedded within the Standard Model to explain the matter anti-matter asymmetry seen in the universe today. Searches for CP violation in hadrons containing charm quarks are interesting in the field of flavour physics because they contain up-type quarks which could be sensitive to new interactions/particles that would leave down-type quarks unaffected. Beyond Standard Model (BSM) physics can enhance the magnitude of CP violation in decays of hadrons containing charm quarks, hence measurements of CP asymmetry in charm decays provide an excellent laboratory to probe the precision of the standard model.

The decay of neutral charm mesons into a final state containing at least one neutral particle are sensitive to beyond standard model physics. One family of decays known as radiative charm decays of the form $D^0 \rightarrow V\gamma$ ($V = \phi, \rho, \bar{K}^*$) can have CP asymmetries reaching $\mathcal{O}(10^{-3})$ in the standard model and can be enhanced by an order of magnitude by new particles entering quantum loop transitions which are an inherent feature of radiative decays.

Measurement of CP asymmetries and branching fractions of radiative charm decays has never been performed at a hadron collider due to busy collision environment. In this thesis, a method to measure the CP asymmetries and branching fractions of the family of radiative decays is presented as well as a proof of principle on how to extract the signal yield in the $D^0 \rightarrow \phi\gamma$ channel by performing multi-dimensional fits to data recorded in the first operational run of the LHC. Including data from the second operational run would allow LHCb to make the most precise measurement of the CP asymmetries and branching fractions for radiative decays, an unprecedented feat for a hadron collider.

This thesis also analyses $D^0 \rightarrow \pi^-\pi^+\pi^0$ decays which have non-trivial phase space due to contributions from various resonances that contribute to strong phase varying across the Dalitz space. This can provide additional sensitivity to CP violation. The search for CP violation is performed using a statistical method known as the energy test which computes a T value that is converted into a p -value to quantify whether the data is consistent with the null hypothesis of CP symmetry. A p -value of 0.62 was obtained once the energy test was applied to the $D^0 \rightarrow \pi^-\pi^+\pi^0$ channel which is consistent with the null hypothesis of CP symmetry.

Declaration

This work represents the combined efforts of the LHCb collaboration. Hence, parts of the content has been published elsewhere and/or presented to several audiences. I hereby declare that, subject to the above comment, the submission is my own original work undertaken while being at the University of Manchester and that no portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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I don't think I would have pursued a PhD had it not been for my time as summer student in the particle physics department at the University of Manchester. Therefore I would like to thank Chris Parkes for the opportunity and the subsequent guidance he provided as my masters supervisor. As part of my summer project, I was working on the Energy Test analysis in four-body charm decays and I have to thank William Barter in particular for allowing me time to become accustomed with the analysis as well as the sage advice he offered in subsequent years about the Energy Test method. The clear explanations helped solidify my understanding of physics, statistics and analysis methods within LHCb.

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They say it takes a village to raise a child. Nowhere is this apparent than in my own extended family. To all my cousins, aunties and uncles, thank you for all your support and having my best interests at heart. I always felt immensely loved in your presence and a special shout out to my family in India who have seen me grow and looked after me ever since I was a child. Special mention to my brother who always found a way to motivate me during times of hardship such that I felt I could overcome any challenge after conversing with him. I acknowledge how lucky I am to have a sibling like him who is more like my closest friend.

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from their unconditional love for me. I will forever be grateful to them for instilling a strong work ethic in me without which I would not have been able to write this thesis.

I would like to dedicate this thesis to all my grandparents including my paternal grandmother, the only grandparent who is still alive today. I know she is proud of me and I hope that all my other grandparents would feel the same way if they were alive today. Finally, I would like to thank God for giving me the freedom to pursue what I found interesting and for this life in general. Any words of gratitude would be insufficient to express my sincere thanks in this regard.

Preface

The physics analyses presented in this thesis is my work which includes all the results and plots shown in this thesis. However, the work could not have been carried out without the support of the LHCb collaboration has often relied on the work of many other members of the collaboration who have laid the foundation for some aspects of the work carried out in this thesis in previous years.

There are other aspects of work I have carried out within LHCb to aid the functioning of the collaboration, some of which are listed below:

- **Stripping Liaison for Charm Working Group:** I was appointed the stripping liaison for the charm working group in January 2020 for a period of two years. The role involved reviewing various stripping lines in multiple stripping campaigns for around 40 active analyses within the charm working group.
- **RAMP challenge-** Although not documented in this thesis, I spent some time working with parametric simulation to investigate pattern recognition algorithms that would be necessary in 2030 (Upgrade-II of LHCb) for the VELO where the instantaneous luminosity will be 50 times the corresponding value in Run 2. This was necessary because the current algorithms would be insufficient to replicate the excellent vertex reconstruction in the increased luminosity environment.

Knowledge is as wings to man's life, and a ladder for his ascent. Its acquisition is incumbent upon everyone. The knowledge of such sciences, however, should be acquired as can profit the peoples of the earth, and not those which begin with words and end with words. Great indeed is the claim of scientists and craftsmen on the peoples of the world.

- Bahá'u'lláh

Chapter 1

Introduction

The discipline of science is a system of knowledge seeking to explain the physical world around us. Additions or revisions to this system of knowledge are made through the scientific method. The development of the scientific method can perhaps be attributed to Greeks, specifically Thales of Miletus who is referred to as the Father of Science. Analogous to Thales, Isaac Newton also hypothesised fundamental laws about the universe based on observations and rational principles. They both refused to ascribe physical phenomenon to the heavens, thereby setting in motion the scientific revolution which channelised the human intellect to explain observed phenomenon through theories and hypothesis that must be validated by experimental measurement.

Scientific theories have evolved to probe the fundamental processes at work in systems where patterns of behaviour have been identified. A prime example of this is quantum theory which was used to explain the theoretical underpinning of the atomic structure based on empirical observations. One such observation was the quantisation of fundamental quantities such as energy levels in the atom which was incompatible with the best theoretical models of the universe at the time based on classical physics.

As quantum theory developed at the beginning of the 20th century, questions regarding the most fundamental particles came to light. Fermi and Yang postulated that the recently discovered π meson was a nucleon-antinucleon state rather than being a fundamental particle itself [2]. A few years later, Gell-Mann and Zweig both came up with the quark model of particle physics [3] independently despite protons and neutrons being established as the building blocks of the universe at the time. The theory was initially ridiculed by theoretical physicists [4] but the overwhelming evidence for the model has stacked up such that it has given birth to the field of particle physics.

Particle physics is a field dedicated to the study of the most fundamental building blocks of our universe and the forces that govern their interaction. The research objectives of the field are diverse and are primarily aimed at answering questions related to our understanding of the universe around us such as how the universe came to be dominated by matter or how the fundamental forces will be unified. As with any scientific discipline, theoretical models and experimental evidence have to tread

the path of understanding in unison and this is evident today as well as throughout the history of particle physics.

The state of the art theory for particle physics is quantum field theory (QFT). The most successful QFT that defines the fundamental constituents of the universe is known as the Standard Model (SM). A brief overview of the SM is provided in Sec. 2.1. Despite being very successful in describing many different physical phenomenon, physicists believe that SM is an incomplete description of nature (see Sec. 2.1). This motivates the construction of large-scale facilities for performing particles physics research, such as the Large Hadron Collider (LHC) at CERN. High energy particle collisions at such facilities allow the performance of precision measurements and searches for undiscovered particles to be undertaken. The increasing amounts of data collected at experiments based at CERN is unprecedented and can potentially provide constraints or evidence for Beyond Standard Model (BSM) phenomenon.

One of the many open questions in the SM is the matter-antimatter asymmetry seen in the universe today. This stems from the fact that the big bang should have created matter and anti-matter in equal proportions but an excess of matter is observed in today's universe [5]. Within the SM, there is a mechanism known as CP violation which addresses this issue but the amount of baryon asymmetry produced by CP violation in the SM is orders of magnitude too small to explain the observed asymmetry in the universe today [6]. The theoretical underpinnings behind CP violation are expounded on in Sec. 2.3. CP violation in the neutral decays of hadrons containing a charm quark is briefly described in Sec. 2.5.

Measurements to verify the theoretical models have to be performed at experimental collaborations and Chapter 3 details the accelerator complex at CERN before delving into the experimental setup of the LHCb experiment as it is data from this experiment that has been utilised in this thesis to search for CP Violation in decays of charm mesons. The components of the apparatus to detect and identify particles originating from high energy particle collisions are described.

Chapter 4 describes the analysis method used to search for CP violation in the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ decays and provides the experimental results regarding CP asymmetry in this channel. This is followed by Chapter 5 where the procedure to select these decays is outlined through the application of cuts and a multi-variate classifier. The method to search for CP violation in these decays can be validated through data-driven studies either using the control channel or flavour randomised signal samples, as described in Chapter 6.

Chapter 8 gives an overview of the analysis method to measure CP asymmetry and the branching fraction of $D^0 \rightarrow V\gamma$ decays. The best measurements in these channels is also provided in the same chapter. This is followed by Chapter 9 where the details of the selection procedure to select $D^0 \rightarrow V\gamma$ decays is outlined. The method to extract signal yields by fitting the data to a suitable parameterisation is also outlined in the same chapter.

Chapter 2

Theory

The SM is the lens through which experimental measurements are interpreted. In this chapter, I will provide an overview of the SM and its basic constituents. The three fundamental forces that characterise interactions between the constituents of the SM are described qualitatively as well as mathematically. The concept of spontaneous symmetry breaking responsible for the generation of fermion and gauge boson masses is outlined through the description of the Higgs mechanism. The limitations of the SM is explored in the context of CP violation since this is the main shortcoming of the SM examined in this thesis. More specifically, CP violation in decays of hadrons containing the charm quark is explored to contextualise the work carried out in this thesis where CP violation is measured for two specific final states, each of which contains at least one neutral particle.

2.1 Standard Model

The SM of particle physics [7] is the theory describing the constituents of the known universe and the laws that govern the interactions between those constituents. It describes three of the four fundamental forces in nature including the weak and strong force as well as the electromagnetic force. It is possible to include the gravitational force within the SM but the predictive power of such a theory is removed at large energy scales where quantum effects of gravity become apparent. However, the absence of gravity from the SM does not alter any measurements due to its negligible impact at the characteristic mass scales for fundamental particles. The constituents of the SM are spin- $\frac{1}{2}$ fermions, spin-1 gauge bosons which mediate the fundamental forces and a spin-0 Higgs Boson.

There are two types of spin-1/2 fermions; leptons and quarks. There are six quarks (up, down, strange, charm, bottom and top) and six leptons (electrons, muons, taus and their corresponding neutrinos). Each fermion has an antiparticle equivalent which has the same properties as the original fermion with the quantum numbers reversed. An example of a quantum number is the electrical charge of a fermion.

Different quarks interact with one another via the weak force which is mediated by the $W^\pm, Z$ bosons.

Interactions between leptons is also mediated by the same mechanism. All charged fermions can also interact with one another via the electromagnetic force which is mediated by the massless photon. The quarks carry colour charge and can interact with one another via the strong force which is mediated by 8 gluons. Finally, the charged fermions interact with the Higgs field which is mediated by the spin-0 Higgs boson that provides these particles with their respective masses through the Higgs mechanism and spontaneous symmetry breaking. The building blocks of the SM are shown visually in Fig. 2.1. The interactions between the different constituents is also represented visually.

Quarks and leptons are split into three generations according to their mass. Each generation contains a u -type quark with electric charge $Q = 2/3$ and a d -type quark with electric charge $Q = -1/3$. Inter-generational mixing between the quarks is governed by the Cabbibo-Kobayashi-Maskawa (CKM) matrix [8] as the mass eigenstates of the quarks are themselves a linear combination of the flavour eigenstates. Figure. 2.2 shows the Feynman diagrams of all the allowed interactions within the SM. The only interaction that allows for quark flavour changes is mediated by the W boson. These interaction vertices can be described by the CKM matrix and CP violation in the SM is introduced via the CKM matrix. This is discussed in further detail in Sec. 2.3.

Theoretically, the SM is parameterised as a quantum field theory where the Lagrangian governs the dynamics and transformations of particles under certain symmetries. The particles themselves are described by fields which permeate all of space-time. The gauge theory which leaves the Lagrangian invariant in the SM is a product of three unitary groups:

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \quad (2.1)$$

where $SU(3)_C$ is the gauge group describing the theory of the strong force which is often referred to as Quantum Chromodynamics (QCD) [9, 10]. The C refers to the colour charge as the strong force couples to fields carrying the colour quantum number. The $SU(2)_L \otimes U(1)_Y$ describes the electroweak interactions developed by the theory of Glashow-Weinberg-Salam [7, 11, 12]. Here L refers to the left chirality of the $SU(2)$ group and Y refers to hypercharge, $Y = 2(Q - T_3)$, where Q is the electric charge and T_3 is the weak isospin. Each gauge group has n degrees of freedom and $n^2 - 1$ generators. So the $SU(3)_C$ group has $n=3$ and has 8 generators. These 8 generators correspond to the 8 gluons responsible for mediating the strong interaction between fields carrying colour charge. The $SU(2)_L \otimes U(1)_Y$ consists of 4 generators, $W_{1,2,3}$ and B where a linear combination of $W_{1,2}$ corresponds to the $W^\pm$ bosons. The W_3 and B generators mix and a linear combination of these generators results in the Z boson and the massless photon.

Historically, an interplay between experimental observations and theoretical framework has motivated the constituents of the three groups and the interactions between them. The final piece of the SM jigsaw arrived in 2012 with the discovery of the Higgs boson at the ATLAS [13] and CMS [14] experi-

ments. The Higgs Boson is a necessary constituent of the SM because its presence leads to the gauge bosons becoming massive as will be demonstrate in Sec. 2.1.2. Despite the discovery of the Higgs Boson, the SM remains incomplete with many shortcomings. Firstly, cosmological evidence from galaxy rotation curves and the angular power spectrum of the cosmic microwave background motivates the need for dark matter and the SM doesn't include a dark matter candidate. Secondly, observations of neutrino oscillations [15, 16] indicate that neutrinos have mass and a mechanism within the SM for generating these masses has not yet been determined. Additionally, as mentioned earlier, the reach of the SM doesn't extend to describing the gravitational force. Consequently, it must be a stepping stone towards a more complete grand unification theory which unites the four fundamental forces of nature. Finally, the abundance of matter over anti-matter in our universe can not be explained by the amount of CP violation included in the SM alone and hence additional sources of CP violation are necessary.

2.1.1 Electroweak Theory

The unification of the electromagnetic and weak forces is governed by electroweak theory which is described by the $SU(2)_L \otimes U(1)_Y$ gauge group. The generators of the electroweak theory couple to left chiral fermions hence these fields form $SU(2)$ doublets whereas right chiral fermion fields form singlets. The left handed fermion fields, Q_L^i L_L^i can be written as:

$$Q_L^i = \begin{pmatrix} u^i \\ d^i \end{pmatrix}_L, \quad L_L^i = \begin{pmatrix} \nu_{e^i} \\ e^i \end{pmatrix}_L, \quad (2.2)$$

where u^i d^i are the u-type and d-type quarks for $i=1,2,3$ which is the flavour index for the 3 generations of quarks. Electron, muons and taus are denoted by e^i and ν_{e^i} denotes the corresponding neutrinos. The right chiral quark fields are represented by u_R^i and d_R^i . Similarly the right chiral lepton field is e_R^i for the three generations of leptons. No field is provided for right handed neutrinos since they aren't a constituent of the SM. To summarise, the following fields are constituents of the SM and representations of the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ gauge group:

$$Q_L^i(3, 2)_{+1/6}, \quad L_L^i(1, 2)_{-1/2}, \quad u_R^i(3, 1)_{+2/3}, \quad d_R^i(3, 1)_{-1/3}, \quad e_R^i(1, 1)_{-1} \quad (2.3)$$

where the numbers in brackets make the quantum numbers apparent. For example, the left chiral quark field, $Q_L^i(3, 2)_{+1/6}$ is a triplet of $SU(3)_C$ and a doublet of $SU(2)_L$ and carries hypercharge, $Y = +1/6$. The Lagrangian for a particle under the influence of electroweak interaction can be derived by looking at a free particle's Lagrangian, $\mathcal{L}_0$,

$$\mathcal{L}_0 = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi \quad (2.4)$$

where γ^μ are the Dirac matrices and ψ is the Dirac spinor with $\bar{\psi} = \psi^\dagger\gamma^0$ being the adjoint spinor. Applying the Euler Lagrange equation to $\mathcal{L}_0$ retrieves the Dirac equation. The Lagrangian must be

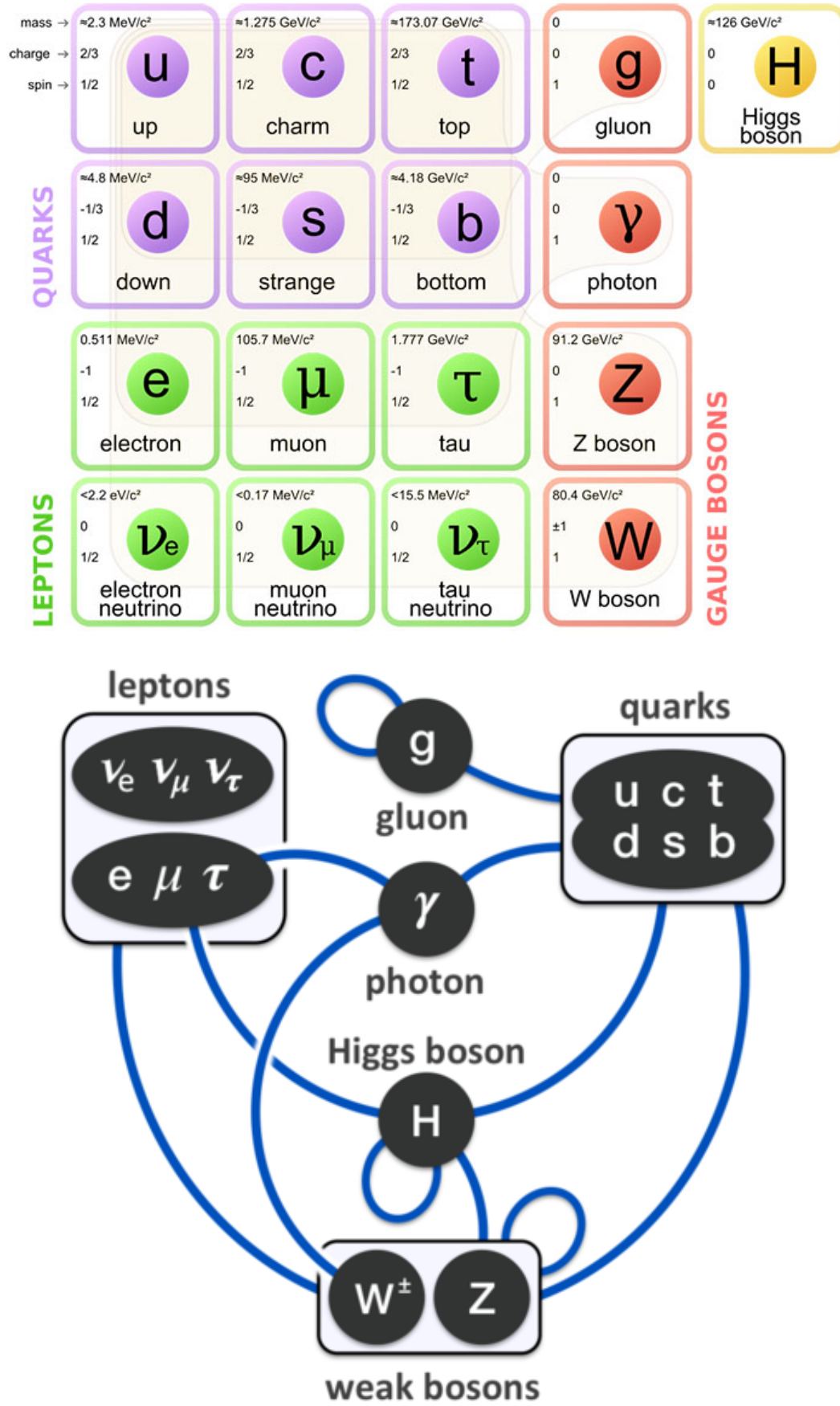


Figure 2.1: Visual representation of the fundamental particles within the SM (top). Also shown are the interactions and couplings between particles (bottom). Taken from Refs. [17] and 2.1

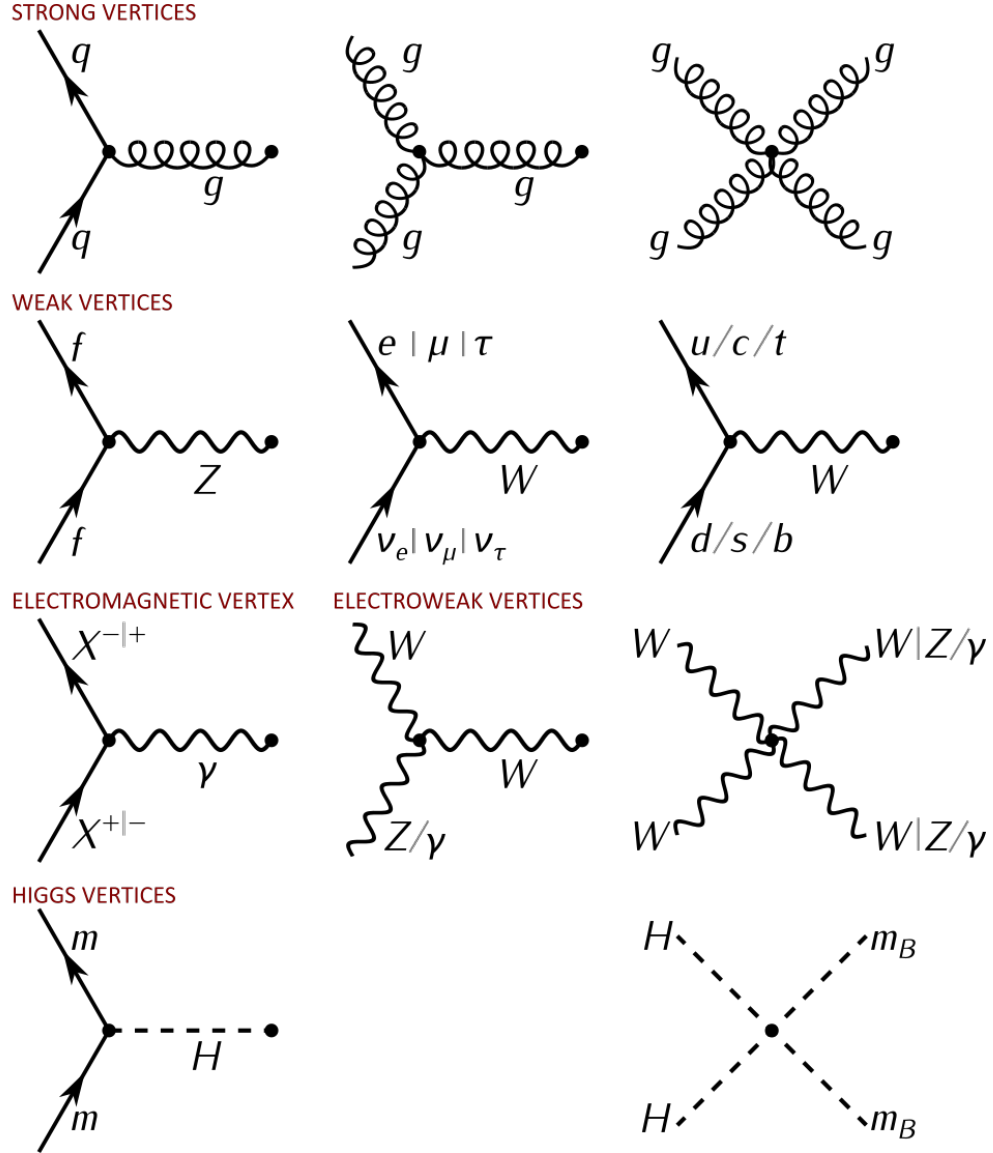


Figure 2.2: Feynman diagrams showing the allowed interactions within the SM. All diagrams are built from the following vertices; q is any quark, g is a gluon, X is any charged particle, γ is a photon, f is any fermion, m is any particle with mass (with the possible exception of the neutrinos) and m_B is any boson with mass. The only interaction that allows for a change of quark flavour is the weak interaction mediated by the W -boson. Figure taken from Ref. [18].

invariant under the following gauge transformation:

$$\psi(x) \rightarrow \psi(x)' = e^{i\theta(x)}\psi(x) \quad (2.5)$$

which is true only for a global gauge invariance i.e. if θ is a constant. However, the Lagrangian has to be invariant under a local gauge transformation so we replace the derivative with a covariant derivative:

$$D_\mu = \partial_\mu + igA_\mu \quad (2.6)$$

where g is the coupling strength of the fermion to the field, A_μ . The field A_μ must transform as:

$$A_\mu \rightarrow A'_\mu = A_\mu + \frac{1}{g}\partial_\mu\theta. \quad (2.7)$$

The Lagrangian, $\mathcal{L}_0$, therefore transforms as:

$$\mathcal{L}_0 \rightarrow \mathcal{L}'_0 = i\psi\gamma^\mu(\partial_\mu + igA_\mu)\bar{\psi} - m\psi\bar{\psi} = i\psi\gamma^\mu D_\mu\bar{\psi} - m\psi\bar{\psi} \quad (2.8)$$

which is invariant under the local gauge transformation in Eq. 2.5. The gauge invariance imposition results in the the field A_μ being introduced which can be interpreted physically as the field of a photon for a particle experiencing only the electromagnetic force. When including the contribution from the photon itself, the Quantum Electrodynamics Lagrangian can be written as:

$$\mathcal{L}_{\text{QED}} = i\psi\gamma^\mu D_\mu\bar{\psi} - m\psi\bar{\psi} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (2.9)$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electric field strength tensor. The logic can be extended to form the electroweak Lagrangian for left chiral fermions:

$$\mathcal{L}_{\text{EW}} = i\psi\gamma^\mu D_\mu\bar{\psi} - m\psi\bar{\psi} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W_{\mu\nu}^d W^{d,\mu\nu} \quad (2.10)$$

where

- $D_\mu = \partial_\mu + \frac{ig}{2}W_\mu^d\sigma_d + \frac{ig'}{2}B_\mu Y$
- $W_{\mu\nu}^d = \partial_\mu W_\nu^d - \partial_\nu W_\mu^d$
- $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$
- σ_d (d=1,2,3) are the Pauli matrices and are the generators of the $SU(2)_L$ gauge group
- Y is the weak hypercharge and is the generator of the $U(1)_Y$ gauge group
- $W_{\mu\nu}^d$ is the weak field tensor that represent three gauge fields, W_μ^d
- $B_{\mu\nu}$ is the electromagnetic field tensor that represents the gauge field, B_μ
- g and g' are the coupling strengths to the W_μ^d and B_μ fields respectively

As mentioned previously, a linear combination of the vector fields, $W_\mu^{1,2}$, leads to the following physical fields,

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2) \quad (2.11)$$

where each physical field describes the massive $W^\pm$ bosons. Similarly, the B_μ and W_μ^3 fields will mix which produces the massless photon and the Z boson. The mixing is mediated by θ_W , the Weinberg angle, according to,

$$\begin{pmatrix} \gamma \\ Z \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B \\ W_3 \end{pmatrix}. \quad (2.12)$$

2.1.2 Higgs Mechanism

The Higgs mechanism involves the interaction of the fundamental particles within the SM with the Higgs field. This interactions leads to spontaneous symmetry breaking which causes the gauge bosons and the fermions to become massive. In the SM, the Higgs mechanism is encapsulated within the $SU(2)_L \times U(1)_Y$ electroweak gauge symmetry group. The following example will show how the Higgs mechanism leads to generation of masses of the gauge bosons.

Consider a complex scalar Higgs field in the spinor representation of the $SU(2)_L$ group:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad (2.13)$$

The Lagrangian for this doublet scalar field is:

$$\mathcal{L}_{Higgs} = (D^\mu \phi)^\dagger (D_\mu \phi) - V(\phi) \quad (2.14)$$

where the covariant derivative takes on the same form as Eq. 2.8. The Higgs potential, $V(\phi)$ is given by:

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \quad (2.15)$$

where μ and λ describe the nominal and quartic self coupling amongst the scalar fields. The potential has a minimum when $\mu^2 > 0$ such as:

$$\phi^\dagger \phi = \frac{\mu^2}{2\lambda}. \quad (2.16)$$

This leads to spontaneous symmetry breaking as the minimum of the potential has a non-zero vacuum expectation value, v , for the scalar field ϕ^0 . Since there are an infinite number of states that satisfy the condition in Eq. 2.16, the arbitrary choice of the ground state is utilised:

$$\phi_G = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}. \quad (2.17)$$

Inserting the ground state spinor into the Higgs Lagrangian (Eq. 2.18) such that it is invariant under the $SU(2)_L \times U(1)_Y$ local gauge symmetry yields the masses of the gauge bosons,

$$\mathcal{L}_{Higgs} \supset \frac{1}{8}v^2 g^2 (W_\mu^1 W^{1\mu} + W_\mu^2 W^{2\mu}) + \frac{1}{8}v^2 (gW_\mu^3 + g'B_\mu)(gW^{3\mu} + g'B^\mu). \quad (2.18)$$

Identifying the relevant terms in the Lagrangian and comparing with the mass terms such as:

$$\frac{1}{2}m_W^2 W_\mu^1 W^{1\mu} \quad \text{and} \quad \frac{1}{2}m_W^2 W_\mu^2 W^{2\mu}, \quad (2.19)$$

yields the mass of the $W^\pm$ boson,

$$m_W = \frac{1}{2}gv \quad (2.20)$$

The remaining neutral bosons, Z_μ and A_μ representing the Z boson and photon respectively, are identified as:

$$\begin{aligned} Z_\mu &= \frac{gW_\mu^3 - g'B_\mu}{\sqrt{g^2 + g'^2}} \quad \text{with mass} \quad m_Z = \frac{v}{2}\sqrt{g^2 + g'^2} \\ A_\mu &= \frac{gW_\mu^3 + g'B_\mu}{\sqrt{g^2 + g'^2}} \quad \text{with mass} \quad m_A = 0 \end{aligned} \quad (2.21)$$

Therefore, it can be seen that the Higgs mechanism for the spontaneous symmetry breaking of the $SU(2)_L \times U(1)_Y$ gauge group generates the masses of the gauge bosons. The Higgs mechanism is similarly responsible for the generation of the masses of fermions through spontaneous symmetry breaking in the Yukawa component of the electroweak Lagrangian. After following a similar procedure to the one expounded on above, the mass of the up and down type quarks is found to be:

$$m_u = \frac{g_u v}{\sqrt{2}} \quad \text{and} \quad m_d = \frac{g_d v}{\sqrt{2}} \quad (2.22)$$

where g_u and g_d are the Yukawa couplings of the up and down quarks to the Higgs doublet respectively. For completeness, the vacuum expectation value of the Higgs field, v , is ~ 246 GeV.

2.1.3 Quantum Chromodynamics (QCD)

As mentioned previously, the theory of the strong interaction, Quantum Chromodynamics (QCD), is described by the non-abelian gauge group $SU(3)_C$. There are 8 generators of this gauge group, T_a , known as the Gell-Mann matrices which satisfy the commutation relations,

$$[T_a, T_b] = if_{abc}T_c \quad (2.23)$$

where f_{abc} are anti-symmetric coefficients. The QCD Lagrangian employs a similar technique to the QED Lagrangian where a covariant derivative is introduced in terms of the field generator,

$$D_\mu = \partial_\mu + igT_a G_\mu^a \quad (2.24)$$

where the field G_μ^a transforms under a local gauge transformation as:

$$G_\mu^a \rightarrow G_\mu^{a'} = G_\mu^a - \frac{1}{g}\partial_\mu\theta^a - f^{abc}\theta_b G_{c,\mu}. \quad (2.25)$$

Thus, the gauge invariant QCD Lagrangian for a colour field, q , can be written as:

$$\mathcal{L}_{QCD} = \bar{q}i\gamma^\mu D_\mu q - m\bar{q}q - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu} \quad (2.26)$$

which is invariant under the local gauge transformation of the colour field q :

$$q(x) \rightarrow e^{i\theta_a(x)T^a} q(x) \quad (2.27)$$

where $G_{\mu\nu}^a$ is the strong field tensor defined as:

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - gf_{abc}G_\mu^b G_\nu^c. \quad (2.28)$$

The generators of $SU(3)_C$, T^a , where $a=1, \dots, 8$ correspond with 8 gluons that mediate the strong force.

2.2 Symmetries in Particle Physics

One of the most important concepts in particle physics is that of symmetries which is formulated according to Noether's theorem that links every differentiable symmetry of a action of a system with a corresponding conservation law [19]. Noether's theorem concerns itself with continuous symmetries such as translational and rotational symmetries which correspond with the conservation of momentum and angular momentum respectively.

With the advent of quantum mechanics, it is possible to extend the same principle to discrete symmetries such as those that make up *CPT* symmetry. The *C* stands for charge conjugation which transforms the particle into its antiparticle by reversing the signs of quantum numbers such as colour charge and magnetic moment of a particle. The *P* stands for parity which inverts the spatial coordinates of a particle within a system. Under a parity transformation, certain physical quantities change sign (velocity and momentum) whilst others do not (angular momentum). The final term, *T*, stands for time reversal. *T*-transformation thus reverse the signs of any time dependent quantities i.e. velocities and momenta.

CPT symmetry is a consequence of the *CPT* theorem and is therefore expected to be an exact symmetry of the universe. Individual symmetries within *CPT* can be violated as long as there is a corresponding violation amongst the product of the other terms which preserves *CPT* symmetry. Individual symmetry violations have been observed beginning with Parity-Violation in the β decays of ^{60}Co [20]. Around the same time charge conjugation violation was observed in the decays of muons and anti-muons [21]. It was thought that *CP* symmetry would be conserved but a consequence of *CPT* theorem is that *CP* symmetry can be violated as long as *T*-symmetry is also violated to conserve *CPT*.

2.3 CP Violation

In 1967, Andrei Sakharov proposed three necessary conditions that must have been satisfied in the early universe to produce matter-antimatter asymmetry observed in today's universe [22]. The three conditions according to Sakharov are:

1. Baryon number violation

2. Interaction taking place out of thermal equilibrium

3. Violation of C and CP symmetry

No particle interactions have yet provided evidence for the violation of baryon number. Particle interaction taking place out of thermal equilibrium was another condition proposed by Sakharov to prevent the loss of any baryon asymmetry. In a CP symmetric universe, the laws of physics would be invariant under these transformations. The violation of the C and CP symmetry would have been necessary in the early universe so that interactions that violate baryon number produce an excess of baryons compared with anti-baryons. CP violation thus plays an important role in cosmology as well as in particle physics.

CP violation was first discovered in the decay of neutral kaons [23] in 1964 and has since been discovered in the the beauty quarks by the BELLE and BaBar collaborations [24, 25] and later again at LHCb [26]. In the charm sector CP violation was recently discovered for the first time in 2019 in the decay of neutral charm mesons into two hadrons [27].

CP violation is incorporated into the SM via a complex phase in the CKM mixing matrix. As stated previously, the CKM matrix governs the inter-generational mixing between quarks as seen in Fig. 2.3 where the W boson mediates the changing of the quark flavour. For up-type quarks, the CKM matrix can be parameterised mathematically as:

$$\begin{pmatrix} u' \\ c' \\ t' \end{pmatrix} = V_{CKM} \begin{pmatrix} u \\ c \\ t \end{pmatrix} \quad (2.29)$$

where u', c', t' are the weak eigenstates of the quarks, as seen by the W boson, which are themselves a linear combination of the strong eigenstates, u, c, t . The CKM matrix is represented by a complex 3×3 matrix.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}. \quad (2.30)$$

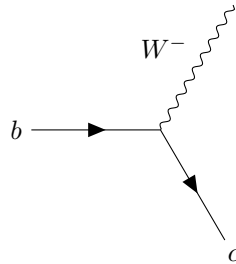


Figure 2.3: $b \rightarrow c$ transition mediated by the W boson. Any flavour changing current is always mediated by the W boson.

The matrix can be written in terms of three rotation angles and a complex phase:

$$V_{\text{CKM}} = \begin{pmatrix} s_{12}c_{13} & s_{12}s_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{-i\delta} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{-i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{-i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{-i\delta} & c_{23}c_{13} \end{pmatrix}. \quad (2.31)$$

where $s_{12} = \sin \theta_{12}$ and $c_{12} = \cos \theta_{12}$ and δ is the complex phase. Each element in the CKM matrix, V_{ij} describes the coupling strength associated with the flavour changing weak current when quark i transitions to quark j which is mediated by the W gauge boson. The corresponding antiparticle process is described by the hermitian conjugate amplitude, which converts V_{ij} into V_{ij}^* . Since V_{ij} can be complex, these two amplitudes are in general different, and so the rates of particle and antiparticles processes can differ. That is how the complex phase produces *CP* violation in the quark sector of the SM.

There is hierarchical structure to the CKM matrix where the diagonal elements are of $\mathcal{O}(1)$ and the off-diagonal elements are smaller. Quarks are therefore more likely to change flavour within the same generation. This gives rise to nomenclature where decays are described as either Cabibbo favoured (CF) or singly/ doubly Cabibbo suppressed (SCS/DCS). Decays involving quarks transitioning within the same generation are referred to as CF decays whereas decays that involve one inter-generational quark transition are referred to as SCS decays. Certain decays also contain two instances of quarks transitioning between different generations and are referred to as DCS decays.

The hierarchical structure of the CKM matrix becomes more apparent when parameterising the matrix in terms of Wolfenstein variables,

$$V_{\text{CKM}} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4), \quad (2.32)$$

where A , λ , ρ and η are the Wolfenstein parameters. The parameter of interest is λ (~ 0.23) since $V_{cs} \sim \mathcal{O}(1)$ and $V_{cd} \sim \mathcal{O}(\lambda)$ showing the distinction between $c \rightarrow s$ (CF decay) and $c \rightarrow d$ (CS decay) transitions and how CKM matrix elements are expanded in power series in λ . Despite *CP*-violation being established as a mechanism for explaining the matter-antimatter imbalance in the universe, its magnitude can not yet explain the observed matter-antimatter asymmetry observed in today's universe [28]. Consequently, additional sources of *CP*-violation are necessary that can be introduced in Beyond Standard Model (BSM) physics through undiscovered particles or an undiscovered fundamental force. Searches for additional sources of *CP* violation can be carried out by performing precise measurements in flavour physics which can provide a probe towards new physics where *CP*-violation can be enhanced by new particles/interactions in the quantum loop transitions. This is known as the flavour frontier and constitutes the primary research carried out at the LHCb experiment at CERN. This can complement the direct searches for new particles at the energy frontier, which are limited to search for particles with mass scales at or below to the collision energy of the beam. As an aside, violation of the charge-parity symmetry is possible in QCD but unlike the electroweak sector, no experimental evidence has

been found for the violation of such a symmetry. Theoretically, there is no reason to expect this and is known as the strong CP problem.

CP violation can be classified into two categories; direct and indirect CP violation. Direct CP violation can occur in decays of charged and neutral mesons, and baryons. Indirect CP violation occurs when neutral mesons oscillate to their CP conjugate state. CP violation can occur when the rate of oscillations themselves are asymmetric, or when an asymmetry arises due to interference between decays with and without oscillations. The next paragraphs describe the phenomenology of the different types of CP violation, specifically for neutral charm mesons.

2.3.1 Direct CP violation

Direct CP violation can be classified according to the ratio of decay amplitudes i.e.

$$\left| \frac{\bar{A}_{\bar{f}}}{A_f} \right| \neq 1 \quad (2.33)$$

where A_f is the decay amplitude for the $D^0 \rightarrow f$ state whilst $\bar{A}_{\bar{f}}$ is the decay amplitude for the corresponding CP conjugate process, $\bar{D}^0 \rightarrow \bar{f}$. In the SM, direct CP violation is dependent on the decay mode under study and as such has to be measured exclusively for each decay process.

The overall decay amplitude, A_f is the sum of all the amplitudes that contribute to the decay process. Direct CP -violation requires the interference of two or more amplitudes and this can be illustrated by defining the amplitude for a decay process that can occur via several amplitudes going to a final state, f :

$$A_f = \sum_k A_k e^{i(\phi_k + \delta_k)} \quad \bar{A}_{\bar{f}} = \sum_k \bar{A}_k e^{i(-\phi_k + \delta_k)} \quad (2.34)$$

where δ_k and ϕ_k are the strong and weak phases respectively. The strong phases originate from final state interactions amongst daughter hadrons. The strong phases do not change sign under a CP transformation. The weak phases originate from the CKM matrix in SM and are named as such because they are part of the electroweak sector. Unlike the strong phases, they change sign under CP transformation. Using Eq. 2.34, the difference in the the two amplitudes can be calculated,

$$|A_f|^2 - |\bar{A}_{\bar{f}}|^2 = -2 \sum_{l,k} |A_l| |A_k| \sin(\phi_l - \phi_k) \sin(\delta_l - \delta_k), \quad (2.35)$$

which demonstrates the need for two or more decay amplitudes with different weak and strong phases to interfere to produce a non-zero CP asymmetry ($\mathcal{A}_{CP} \neq 0$). An experimental observable to quantify CP violation in decay is the CP asymmetry, defined as

$$\mathcal{A}_{CP}(D^0 \rightarrow f) = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow \bar{f})}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow \bar{f})}, \quad (2.36)$$

where $\Gamma(D^0 \rightarrow f)$ is the time integrated decay rate of the $D^0 \rightarrow f$ process and is proportional to the square of the decay amplitude i.e. $\Gamma(D^0 \rightarrow f) \propto |A_f|^2$ and $\Gamma(\bar{D}^0 \rightarrow \bar{f}) \propto |\bar{A}_{\bar{f}}|^2$. Thus the

experimental observable CP asymmetry can be expressed as:

$$\mathcal{A}_{CP}(D^0 \rightarrow f) = \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2}. \quad (2.37)$$

More generically, Eq. 2.37 can be factorised and written as

$$\mathcal{A}_{CP}(D^0 \rightarrow f) = \frac{1 - R_f^2}{1 + R_f^2}, \quad R_f^2 = \left| \frac{\bar{A}_f}{A_f} \right|^2 \quad (2.38)$$

For direct CP violation to occur i.e. $\mathcal{A}_{CP}(D^0 \rightarrow f) \neq 0$ the condition in Eq. 2.33 is retrieved.

2.3.2 Indirect CP violation

Indirect CP violation can occur due to CP violation in mixing or CP violation in the interference between mixing and decay. Mixing is the process of a particle transforming into its antiparticle and vice-versa and occurs only in neutral mesons. There are four neutral mesons which all undergo mixing (K^0, D^0, B_d^0, B_s^0). The phenomenon of mixing was first established in the kaon system where the short lived kaons regenerated from a beam of long lived kaons [29]. The discovery of mixing in the B_d^0 system was a pre-cursor to the discovery of the top quark. The discovery of the top quark was widely anticipated even before the discovery of mixing in the B_d^0 system [30]. However the higher rate of mixing in this system was a consequence of the larger than expected mass of the top quark since mixing must occur through an intermediate state involving a heavier particle.

In the charm sector, mixing occurs when a D^0 meson transitions into a $\bar{D}^0$ (or vice versa). There are contributions from s and d intermediate quarks as shown in the box diagram in Fig. 2.4. The contributions from these amplitudes cancel one another because they are both almost equivalent in magnitude but have opposite signs where the sign change comes from the CKM matrix. This cancellation is down to the Glashow-Iliopoulos-Maiani (GIM) mechanism [31] where the sum of the amplitudes contributing effectively cancel one another. The contribution from transitions involving the b quark is also suppressed due to the off-diagonal elements of the CKM matrix $V_{cb}^* V_{ub}$. Therefore, mixing in charm

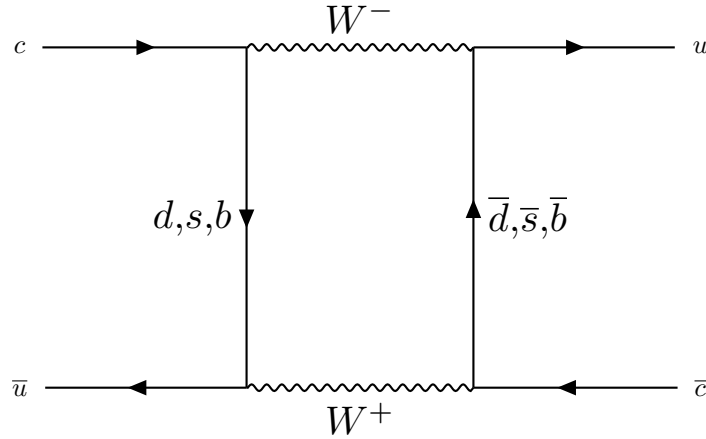


Figure 2.4: Box Feynman diagram showing the $D^0 - \bar{D}^0$ mixing through the exchange of intermediate quarks.

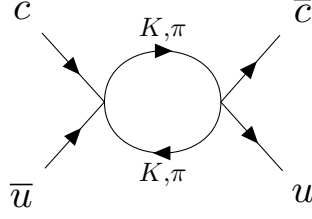


Figure 2.5: Feynman diagram showing the $D^0 - \bar{D}^0$ mixing through long range hadronic interactions.

is dominated by long distance hadronic interactions shown in Fig. 2.5. These calculations are difficult due to the non-perturbative QCD contributions and hence theoretical predictions for mixing from long distance hadronic interactions have large uncertainties. The combination of the GIM mechanism and CKM suppression meant that $D^0 - \bar{D}^0$ oscillations from a single experiment weren't observed until 2013 [32]. The phenomenon was established earlier by combining results from the BELLE, BABAR and CDF collaborations [33].

Mixing in charm can be characterised by expressing mass eigenstates as a linear combinations of flavour eigenstates such that:

$$|D_{1,2}\rangle = p |D^0\rangle \pm q |\bar{D}^0\rangle \quad (2.39)$$

where p and q are complex numbers that must satisfy $|p|^2 + |q|^2 = 1$. CP violation in mixing will occur when the rate of D^0 mixing into a $\bar{D}^0$ is different to the reverse process:

$$\Gamma(D^0 \rightarrow \bar{D}^0) \neq \Gamma(\bar{D}^0 \rightarrow D^0). \quad (2.40)$$

This only occurs when $|q| \neq |p|$. Interference between mixing and decay occurs when D^0 meson can decay to a charge conjugate final state, $f = \bar{f}$, directly or by first mixing into $\bar{D}^0$ and subsequently decaying into the final state. These two processes will exhibit interference, and that can induce CP violation defined through the relation::

$$\Gamma(D^0 \rightarrow \bar{D}^0 \rightarrow f, t) \neq \Gamma(\bar{D}^0 \rightarrow D^0 \rightarrow f, t). \quad (2.41)$$

Such interference-induced CP violation is quantified by a single phase which combines those from mixing and decay:

$$\phi = \arg \left(\frac{q \bar{A}_f}{p A_f} \right), \quad (2.42)$$

where CP symmetry corresponds to a phase of zero. Therefore, indirect CP violation is characterised by the parameters $|q/p|$ and ϕ .

2.4 CP Violation in Charm decays

Studying CP violation in hadrons containing the charm quark has garnered interest because they contain up-type quarks that could be sensitive to new interactions/particles which would leave down-type quarks unaffected [34, 35, 36]. Within the SM, CP violation in charm hadrons is predicted to

be $\sim \mathcal{O}(10^{-3} - 10^{-4})$ [34] but low energy strong interactions mean that these predictions have large uncertainties. In fact, it remains unclear whether the observation of CPV in charm is compatible with SM expectation [37] or whether BSM physics is needed to explain this phenomenon. Hence complementary measurements of CP violation in other decays of the D^0 meson are necessary to establish if CP -violation in decays of charm hadrons is a sign of new physics. The magnitude of CP -violation in the charm sector can be enhanced by new physics so measurements of CP asymmetry in charm decays provide an excellent laboratory that is sensitive to BSM physics. Charm decays of interest usually undergo transitions that are referred to as flavour changing neutral currents (FCNC). These are processes that change quark flavour without changing the overall charge and are forbidden at the tree level in the SM. Pairs of W boson(s) mediate such a process but they are also highly suppressed at higher orders due to the GIM mechanism [31].

2.5 Neutral Charm Decays

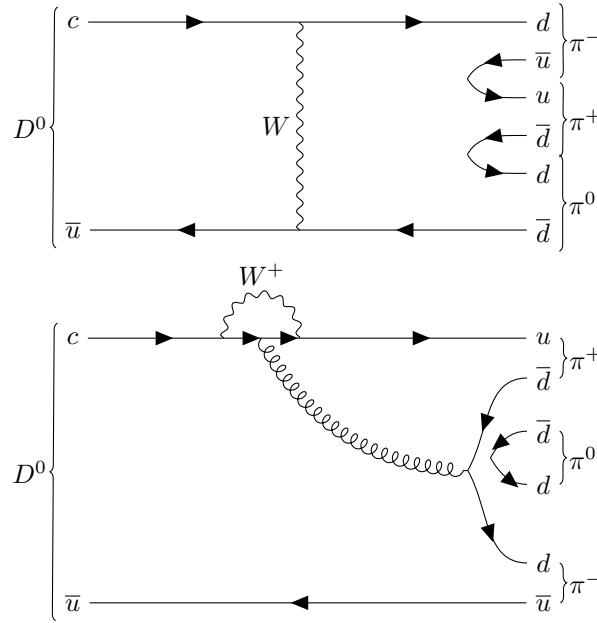


Figure 2.6: Quark level Feynman diagrams. A colour-favoured tree diagram (top) and the penguin diagram (bottom) for the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ channel .

Studying the decay of neutral charm mesons into a final state containing neutral particle(s) presents an experimental challenge at LHCb due to the difficulty involved in the detection and reconstruction of neutral particles in the background heavy environment of a hadron collider. One such decay is $D^0 \rightarrow \pi^- \pi^+ \pi^0$. This three body decay proceeds at highest order via the Singly-Cabibbo-Suppressed (SCS) $c \rightarrow d u \bar{d}$ process, which can occur through both tree-level and electroweak loop annihilation (penguin) diagrams, as illustrated in Fig. 2.6. Additionally, the decay can proceed via different intermediate resonances and the interference between these different resonances results in the strong phase varying across phase space. There can be specific (‘local’) regions in phase space where CP

violation appears due to the particular strong phase differences between interfering processes. Modelling the intermediate resonant and non-resonant contributions to the final state can be done via an amplitude analysis through the isobar formalism which models the three-body decay through a linear superposition of quasi two-body amplitudes. If the D^0 decays through intermediate resonance, r , $D^0 \rightarrow r(\rightarrow ab)c$, the dynamics of the decay can be completely described by the Dalitz variables which are invariant squared masses, m_{ab}^2 and m_{ac}^2 . The matrix element for the three-body decay is expressed as:

$$\mathcal{M}_{\pi^-\pi^+\pi^0}(m_{ab}^2, m_{ac}^2) = \sum_r a_r e^{i\phi} \mathcal{M}_r(m_{ab}^2, m_{ac}^2) \quad (2.43)$$

where $\mathcal{M}_r(m_{ab}^2, m_{ac}^2)$ is the matrix element for the quasi two-body decay through the resonance, r and $a_r e^{i\phi}$ is complex amplitude for resonance, r that encodes the relative difference in amplitudes and phases to nominal resonance. The electroweak contributions to the decay amplitude for $D^0 \rightarrow \pi^-\pi^+\pi^0$ match those in the two body decay $D^0 \rightarrow \pi^+\pi^-$ which was one of the two channels used in the initial discovery of CP violation in charm, and where single channel evidence for CP violation has recently been found [38]. This makes it a promising candidate to investigate when searching for local CP violation.

Another family of decays known as radiative charm decays of the form $D^0 \rightarrow V\gamma$, where V is vector meson, represent an exciting opportunity to test the SM. This is because when $V = \phi/\rho$, CP asymmetries can reach up to $\mathcal{O}(10^{-3})$ in the SM and can be enhanced by an order of magnitude in BSM models [39]. The enhancement in the CP asymmetries could originate from undiscovered particles participating in quantum loop transition that are an inherent feature of radiative decays. Additionally, the branching ratio measurements of this family of decays are quite diverse with large uncertainties so a precise measurement of the branching ratio will constrain SM theories as well as necessitate the need for BSM models.

Radiative charm decays can occur either via short range or long range contributions. Fig. 2.7 shows the long range contributions for the $D^0 \rightarrow \phi\gamma$ channel that dominate the branching ratio measurement and are not expected to violate CP symmetry. The short range contributions, shown in Fig. 2.8) for $D^0 \rightarrow \phi\gamma$ channel are heavily suppressed ($\mathcal{O}(10^{-8})$) [40] but undiscovered particles from beyond the standard model can enhance their contribution to the branching fraction. The short range contributions are CP violating so an enhancement in the branching fraction will likely lead to an enhancement in the amount of CP violation in decay. Therefore, these channels are an excellent laboratory to test the upper limits of the SM and constrain BSM models.

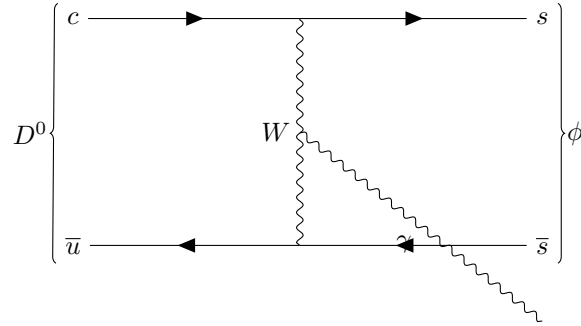


Figure 2.7: Long range contribution in the $D^0 \rightarrow \phi\gamma$ channel that are not expected to violate CP symmetry.

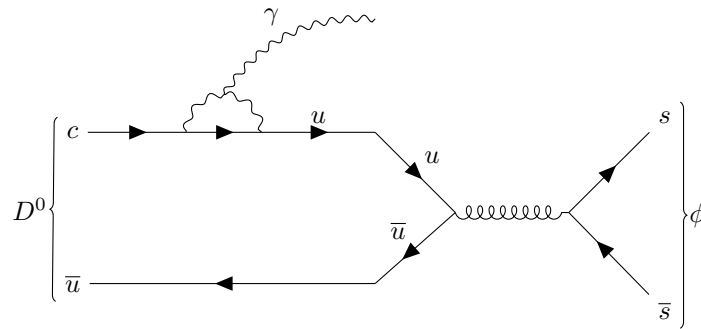


Figure 2.8: Short range contribution in the $D^0 \rightarrow \phi\gamma$ channel that is expected to violate CP symmetry but is heavily suppressed.

Chapter 3

Experimental Environment

The European Organisation for Nuclear Research (CERN) hosts several accelerators dedicated to understanding the most fundamental aspects of our universe. This includes the Large Hadron Collider (LHC) which is the largest particle accelerator in the world, straddling the French-Swiss border near Geneva. The accelerator itself is located inside a closed near-circular tunnel which can be up to 100m below the Earth's surface. The LHC was primarily designed to study proton-proton (pp) collisions unlike its predecessor (the Large Electron-Positron (LEP) collider) which studied collisions between electrons and positrons. The pp collisions take place at high energies (TeV-scale) as two beams travelling in opposite directions are brought together at four collision points around the LHC ring. The four main LHC experiments surround the various collisions points:

1. ATLAS (A Toroidal Lhc ApparatuS) [41] is a multi-purpose detector built for Higgs-Boson searches, direct searches for new physics as well as precision SM measurements at high energies.
2. CMS (Compact Muon Solenoid) [42] is also a multi-purpose detector that covers the same physics programme as ATLAS but using different experimental technologies.
3. ALICE (A Large Ion Collider Experiment) [43] is designed to study heavy nuclei collisions which results in the formation of a phase of matter called quark gluon plasma
4. LHCb (Large Hadron Collider Beauty) [44] is built to study hadrons containing b and c quarks. This is the detector which has been used for the analysis carried out in this thesis and will be discussed further in Sec. 3.3

3.1 Accelerator System

The LHC is a proton synchrotron acceleration ring, 27km in circumference, that makes up the final stage in an acceleration process of CERN's accelerator complex. In order for the pp collisions to occur at the design Centre of Mass (CoM) energies, the protons must be accelerated to close to the

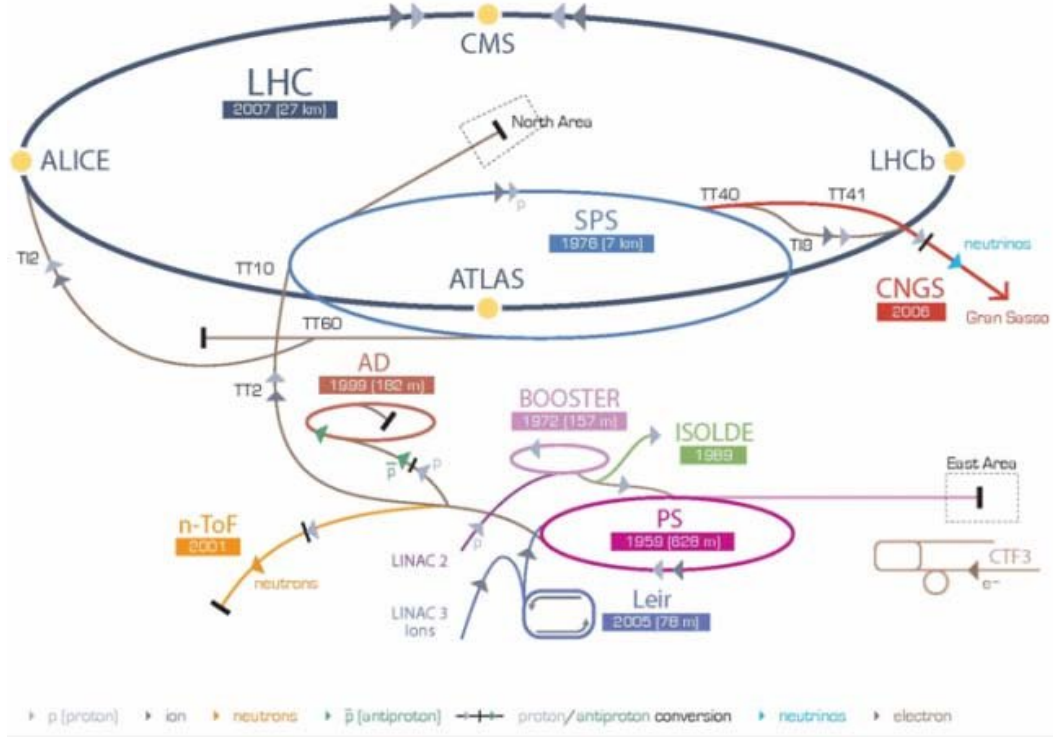


Figure 3.1: CERN's accelerator complex. The different colors show different particles being accelerated. Figure taken from Ref. [45]

speed of light. The acceleration process occurs progressively using modified versions of pre-existing machines that make up CERN's accelerator infrastructure as shown in Fig. 3.1. Firstly, protons must be extracted so they can be fed into the accelerator complex. This is done by applying an electric field to gaseous hydrogen to strip away the electrons in hydrogen atoms to leave protons. These protons are injected into the accelerator complex so they can reach higher energies. The first machine in the accelerator complex is the LINAC2 which is a linear accelerator that accelerates the protons to 50 MeV using radiofrequency (RF) cavities. These are metallic chambers containing an electromagnetic field which provides an electrical impulse to charged particles in the vicinity of the field. The chambers themselves are placed within refrigerators called cryomodules to allow the RF cavities to function in superconducting state. The beam of protons is then injected into the proton synchrotron booster (PSB) which accelerates the protons to an energy of 1.4 GeV before they are injected into the proton synchrotron (PS). The PS accelerates the protons to an energy of 25 GeV and here the protons form bunches where each bunch contains $\sim 10^{11}$ protons. The bunches are time-spaced 25 ns from one another. The bunches are then injected into the super proton synchrotron (SPS), a accelerator ring of circumference 7km that boosts the energy of the bunches to 450 GeV. Finally, the bunches are fed into the LHC where they are accelerated until they reach the required energy using 8 RF cavities located around the ring.

The bunches are bent around the LHC complex using dipole magnets which are cooled to near absolute zero so they can operate in a superconducting state. There are 1232 of these types of magnets around

the 27km circumference of the LHC ring. The particles bunches are focused using quadrupole magnets such that the beams width and height are constrained to be within the LHC vacuum chamber. There are 858 such magnets located around the LHC ring.

The LHC began data taking in 2009 and has thus far completed two operational runs with a period of detector maintenance and upgrade, known as Long shutdown (LS1), sandwiched in between. The first operational run, termed Run 1, lasted 4 years (2009-2013) but primarily collected data in 2011 and 2012. During 2011 (2012), the machine operated at a CoM of $\sqrt{s}=7$ (8) TeV. The subsequent second operational run of the LHC (Run 2) took place between 2015 and 2018 with the machine operating at $\sqrt{s} = 13$ TeV. The LHC has recently ended the second period of long shutdown (LS2) where the machine underwent further upgrades to prepare for operation at higher energies. Analysis quality data taking for the third operational run (Run 3) will begin in 2023 with commissioning of the machine currently ongoing.

3.2 Luminosity at colliding experiments

The LHC must collide a large number of protons every second in order to fully realise the potential and the physics goals of the machine. The rate at which protons collide with one another, R , is dictated by the pp cross-section (σ_{pp}) and the instantaneous luminosity (L) of the machine:

$$R = \sigma_{pp} \times L. \quad (3.1)$$

The instantaneous luminosity is the number of beam particles passing each other per centimetre squared per second ($\text{cm}^{-2}\text{s}^{-1}$). It is a key parameter in colliding beam experiments and encapsulates many factors. Among them is the transverse size of the beam at the interaction point, described by σ_x and σ_y , which are the transverse beam cross-sections in the vertical and horizontal planes respectively. The luminosity is proportional to the number of protons per bunch in each beam upon collision (N_1 , N_2) as well as the beam crossing frequency, f , measured in the number of bunch crossings per second. The instantaneous luminosity is thus expressed as:

$$L = f \frac{N_1 N_2}{4\pi\sigma_x\sigma_y}. \quad (3.2)$$

Maximising the instantaneous luminosity requires a highly collimated beam, a high beam intensity and maximal beam overlap at the interaction point. The large number of protons per bunch and the high frequency of bunch crossings per second means that it is also useful to use the integrated luminosity, $\mathcal{L}$, which is the time integral of the instantaneous luminosity:

$$\mathcal{L} = \int L dt. \quad (3.3)$$

Integrated luminosity has units of inverse area and measured in inverse barns (b^{-1}) with one barn being equivalent to 10^{-24} cm^2 . The units are chosen for convenience based on the scales under consideration. The LHC was designed to provide an instantaneous luminosity of $L=10^{34} \text{ cm}^{-2}\text{s}^{-1}$ but

has been providing twice this value since 2017 [46]. The number of protons in each bunch decreases over time. This can be due to the proton collisions with residual gas in the beam pipe or collisions amongst the protons in the beam that causes protons to scatter. Consequently, the quality of the beam degrades over time and when the beam intensity becomes too low, the beam is dumped on an absorber and a new fill is generated. The length of the fill is optimised to ensure ATLAS and CMS receive the highest integrated luminosity with some inputs from the other experiments.

General purpose detectors such as ATLAS and CMS benefit from a high peak instantaneous luminosity in order to search for new physics process with small cross-sections. Operating at high luminosities boosts the sensitivity of these experiments to find or place limits on the rate of such processes as well as on various measurements. However, the high instantaneous luminosity can be disadvantageous to some experiments because of the high number of pp collisions per bunch crossing. The presence of multiple collisions per bunch crossing, known as pile-up, makes reconstruction of events with high multiplicities more difficult. This is particularly the case for LHCb which was designed to study processes involving beauty & charm quarks which are produced in high numbers at a lower luminosity. At high luminosity, these processes have high multiplicities and are hard to analyse. Therefore LHCb must operate at a reduced instantaneous luminosity. The instantaneous luminosity at each interaction point is adjusted to account for the processes under study. This is done through a process known as luminosity levelling where the transverse beam profile overlap is changed using dipole magnets [47]. This reduces the active collision area as well as reducing the radiation damage on detector elements close to the beam pipe. The process of luminosity levelling and the performance of the trigger meant that an instantaneous luminosity of $\sim 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ was delivered to LHCb, corresponding to approximately 1.8 collision per bunch crossing [48]. Fig. 3.2 shows the integrated luminosity at LHCb for every year during which data was collected as well as the centre of mass energies at which collisions took place.

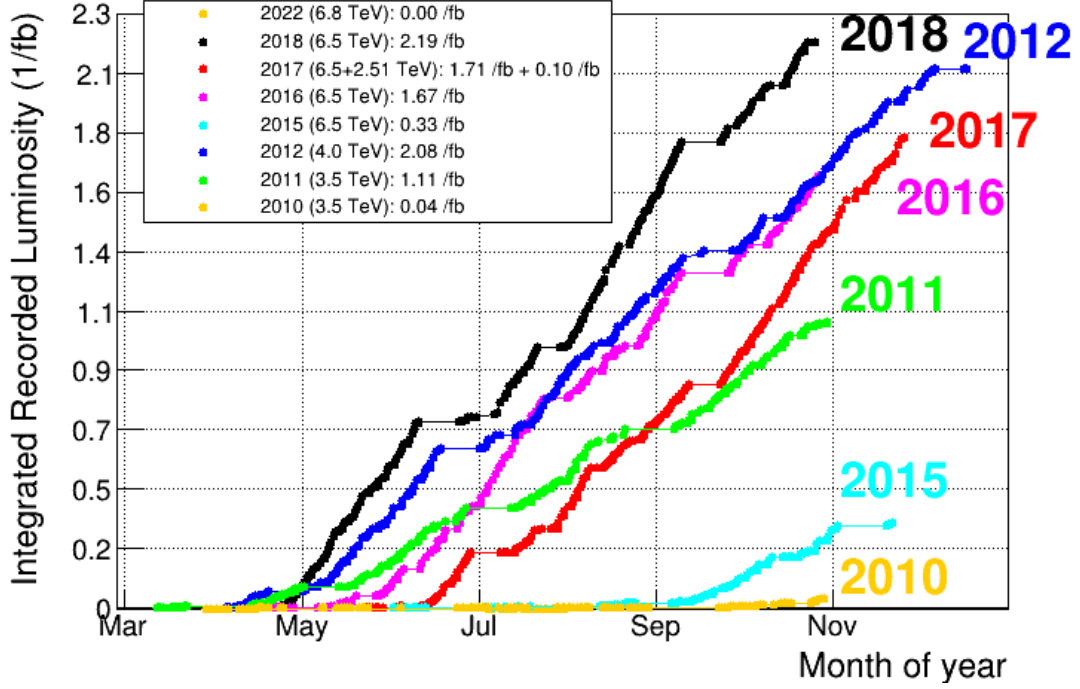


Figure 3.2: Cumulative integrated luminosity recorded by LHCb over each individual data-taking year, with collision energies shown in the legend. 2010 and 2015 were commissioning years at the start of Run 1 and Run 2 respectively which explains why the instantaneous luminosity is lower for these years.

3.3 LHCb Detector

The LHCb detector is a single arm forward spectrometer [49] which is located at one of the four interactions points around CERN’s Large Hadron Collider. It was primarily designed to perform measurements of CP violation and searches for rare decays of beauty hadrons, but the physics programme has since expanded significantly. Some highlights of the experimental results from Run 1-2 include the observation of the rare decay $B_s \rightarrow \mu\mu$ [50], many discoveries of new hadrons including conventional and exotic states [51], probes of lepton universality [52], and precise determination of mixing and CP violation parameters in beauty and charm hadrons [53, 54]. The experiment also has a successful heavy-ion programme, and is used for dedicated measurements of the electroweak sector in the forward direction. LHCb uses a right handed Cartesian coordinate system where the z -axis is along beam line and passes through the detector. The y -axis is perpendicular to the z -axis in the vertical plane with the a positive upward direction and the x -axis defined similarly but in the horizontal plane with a positive direction towards the centre of the LHC ring. Particles containing charm and beauty quarks have low masses relative to the beam energy and hence any boost to the lab frame causes them to be confined around the beam pipe. Hence, the LHCb detector operates over a pseudorapidity range of $2 < \eta < 5$ where the pseudorapidity, η is defined as,

$$\eta = -\ln \tan \frac{\theta}{2}, \quad (3.4)$$

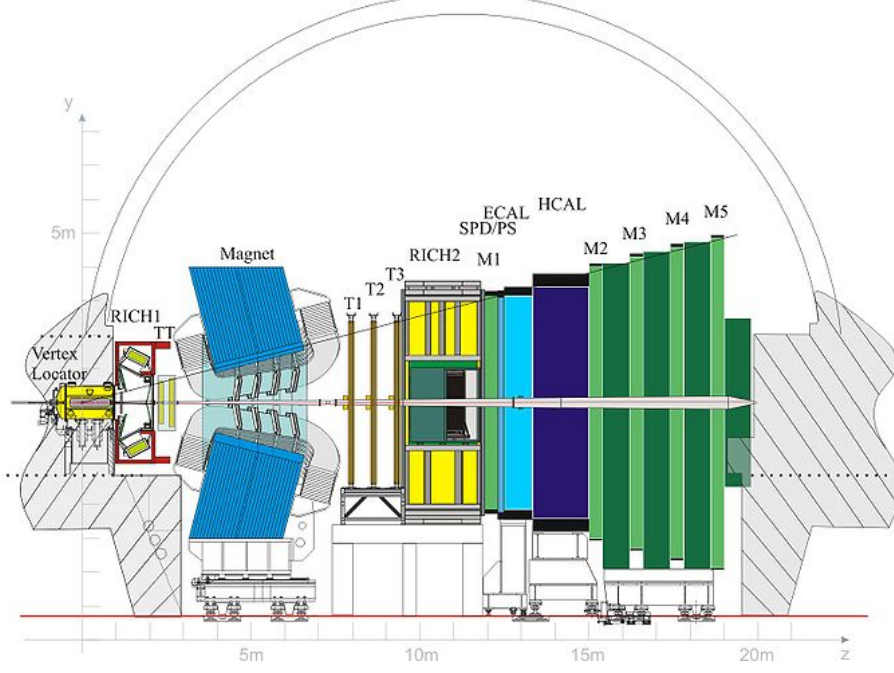


Figure 3.3: Schematic of the LHCb detector [55]. The detector is known as a forward spectrometer because the detector extends 20m along the beam line with a system of sub-detectors stacked behind one another. pp collisions take place in the middle of the Vertex Locator (on the left) and the beam travels from left to right through the centre of the detector.

where θ is the polar angle between the beam line (z -axis) and the direction of particle decays. This means that particles travelling perpendicular to the beam line will have $\eta=0$. Proton beams are brought together in a region called the ‘Interaction region’ which has a width of $\sim 50\text{mm}$ along the z -axis and $100\mu\text{m}$ in the x and y -axis. The specific location of a single pp interaction is called a primary vertex (PV). Unstable weakly-decaying particles will travel some distance from the PV before decaying at a secondary vertex (SV). In this section, an overview of the detector as well as its sub-components will be presented. The sub-components of the detector can be broadly categorised into two groups:

- **Tracking System** - consisting of the Vertex Locator, the dipole magnet as well as the four tracking stations
- **Particle Identification** - comprising two ring imaging Cherenkov (RICH) detectors, a calorimetry system composed of a Scintillator Pad Detector (SPD), Preshower Detector (PS), Electromagnetic Calorimeter (ECAL) and Hadronic Calorimeter (HCAL), and five muon stations (M1-M5).

3.3.1 Vertex Locator (VELO)

A high precision vertex locator (VELO), surrounds the interaction region where pp collisions occur. The VELO sensors are enclosed within the beam pipe separated from the collisions (and the primary LHC vacuum) only by a thin aluminium foil. The VELO makes precise measurements of the coor-

dinates of the PV and secondary vertices through track reconstruction of particles in the vicinity of the interaction region. The displaced secondary vertices [56] are a common signature of decays of interest at LHCb. The ability to identify SVs and precisely measure properties of long-lived particles is essential to many analyses performed at LHCb [56]. Consequently, the VELO must (and does) provide excellent vertex and impact parameter (IP) resolution. The impact parameter is defined as the distance of closest approach between a PV and a reconstructed track. The VELO itself is a silicon micro-strip detector containing silicon modules spaced evenly along the beam axis. There are 21 silicon modules positioned along the beam line with the closest part of the sensor displaced from the beam line by just 8mm in the radial direction during data taking. The VELO is divided into two halves where each half can be mechanically moved towards and away from the beam. This ensures that the sensors can be retracted to a safe position during beam injection, and only moved into their nominal data taking position during stable beams. The VELO modules are retractable so each module overlaps with another during data taking, thus ensuring full angular coverage. Outside of data taking, each module can retract by 35mm, which ensures minimal radiation exposure during beam injection and beam dump. The configuration of the modules is shown in Fig. 3.4 as well how the modules retract.

Each silicon module contains two sensors to determine the coordinates of the hits. These two sensors

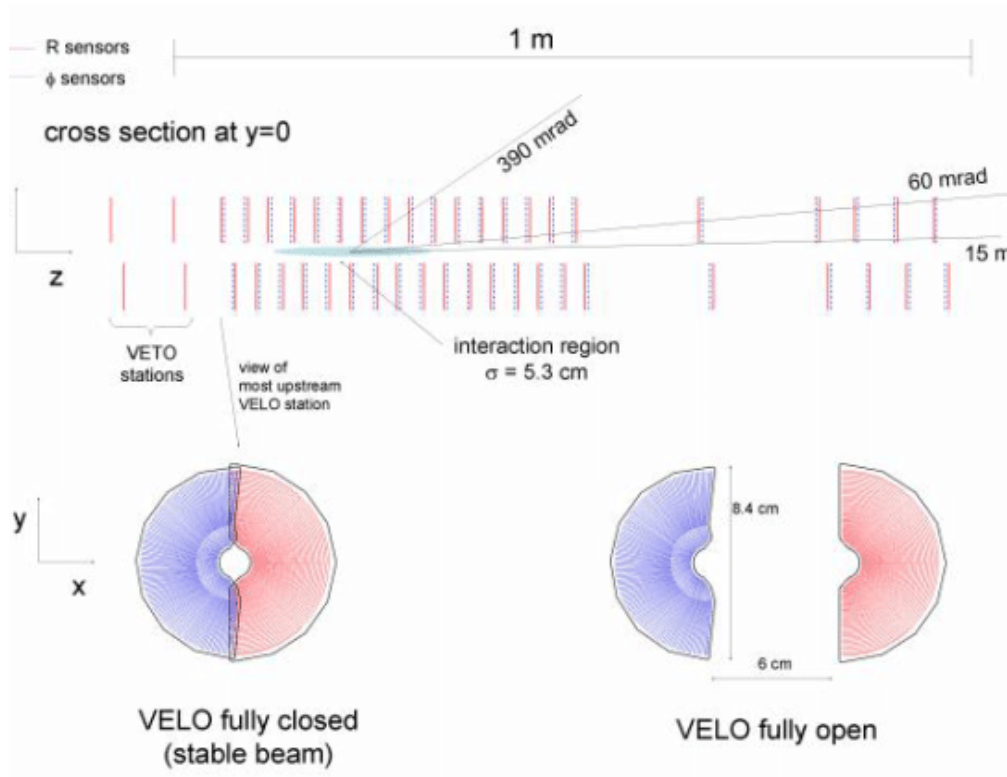


Figure 3.4: Layout of the VELO detector (top) and an $(x - z)$ cross section of a VELO module (bottom)

are placed back to back and are known as the R and Φ sensors. As can be gleaned from the names of the sensors, they measure the radial position and the azimuthal angle ϕ of the hit relative to the beam line using circular and radial strips respectively. There are 2048 strips in each sensor with a strip pitch that varies between 40-100 μm . The information from these sensors is read out around the full circumference of the sensor, hence determining the coordinates of the different hits. The cylindrical configuration of the silicon modules allows a 2D trajectory to be reconstructed using cluster reconstruction algorithms within the VELO software. A module schematic is shown in Fig. 3.5. The modules are themselves placed in a container that maintains a vacuum which is separated from the beam vacuum by a thin walled aluminium sheet. This prevents the contamination of the beam vacuum as well as ensuring that the sensors in the VELO modules are isolated from the radio frequency electromagnetic fields generated by the LHC beam. Finally, four further modules are placed behind

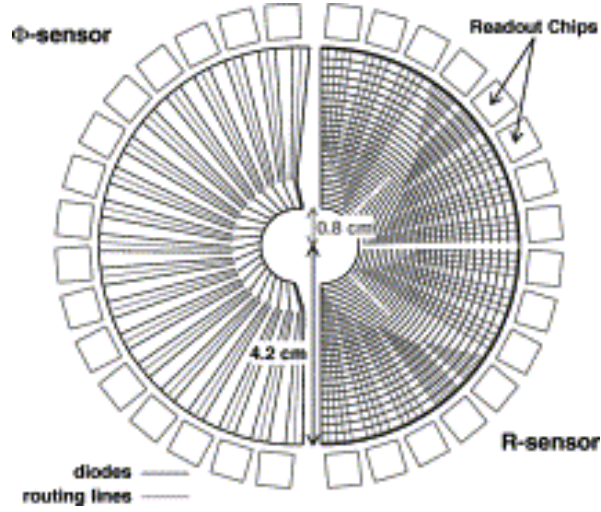


Figure 3.5: Configuration of the R and Φ sensors in a single VELO module

the interaction point i.e. at the most upstream position. These modules are placed either side of the beam just like all other modules but only contain R-sensors. They help to measure the number of pp interactions per bunch crossing which helps the trigger identify events with a high number of PV's and veto such high pileup events. The VELO measures IP with a resolution of $(15 + 29/p_T) \mu\text{m}$, where p_T is expressed in GeV/c . In 2011, a PV of 25 tracks achieved a vertex resolution of 71 μm along the z -axis and 13 μm along the transverse plane [56].

3.3.2 Tracking Stations

The VELO is the first sub-detector responsible for tracking charged particles. Additional trackers are placed either side of the magnet and measure the momentum of charged particles. The trackers that are made up of large area silicon detectors are collectively known as silicon trackers. These are located both upstream and downstream of the dipole magnet. Additionally, trackers made up of gas filled straw

tubes are placed downstream of the dipole magnet and are known as outer trackers. The dipole magnet itself deflects tracks and provides information on track momentum and charge which in combination with the VELO information is used by the RICH detectors for particle identification.

The first tracking station upstream of the dipole magnet is called the trigger Turicensis (TT). This is a $(130 \times 130) \text{ cm}^2$ station encircling the beam pipe to provide complete angular acceptance in ϕ , the azimuthal angle. It uses silicon technology with four silicon micro-strip sensor layers arranged along the beam line. The sensors are positioned precisely such that the position of the track hit can be measured to within $50 \mu\text{m}$. Each sensor is $500 \mu\text{m}$ thick and contains 512 readout strips with a strip pitch of $\sim 183 \mu\text{m}$. The TT layers are arranged in a stereo configuration whereby the first and last layers measure the track coordinates perpendicular to the magnetic field from which the momenta of the tracks can be determined by measuring the radius of curvature. The second and third layers are rotated by $+5^\circ$ and -5° with respect to the first and last layers allowing the measurement of the longitudinal coordinate as shown in Fig 3.6. The information from the four layers can be combined to determine the 3D coordinates of each hit, thus providing input for track reconstruction algorithms.

Information from the TT is combined with that from the downstream tracking stations to provide

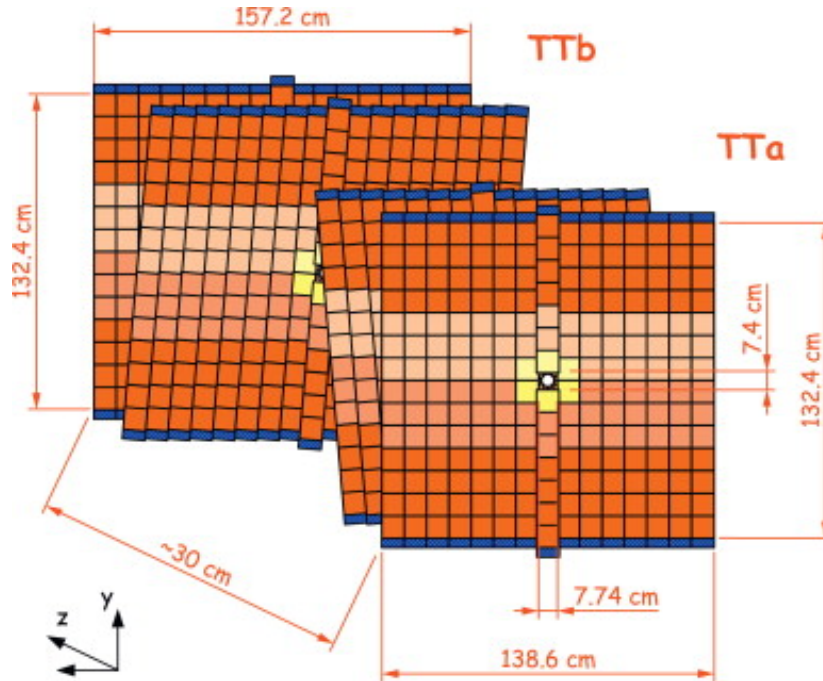


Figure 3.6: Layout of the TT stations showing the stereo configuration of the different layers [57].

excellent momentum resolution for high momentum tracks. However, the TT also has a role to play for low momenta tracks. These tracks are bent out of the acceptance region by the magnetic field and can be reconstructed from hits in the TT. They have poorer momentum resolution due to the absence of hits in the downstream trackers but can be useful inputs for pattern recognition algorithms employed within the RICH detectors.

Trackers downstream of the magnet are denoted the T1-T3 stations and are made up of two distinct

subdetectors using different detection technologies: the Inner Tracker (IT) and Outer Tracker (OT). The IT is cross shaped with an area of (120×40) cm² placed around the beam pipe with a similar configuration to the TT with each station comprising four stereo layers. Each sensor in the IT has 384 readout strips, with a strip pitch of $198 \mu\text{m}$. The IT and the TT are collectively known as the silicon trackers (ST) because they have similar spatial resolution for measuring track position and can be used in conjunction to provide excellent momentum resolution for charged tracks.

The OT surrounds the IT and is the only non-silicon detector in the tracking system. Instead it is made out of layers of straw drift tubes. The modular design of the OT mimics that of the TT and IT in terms of the four layer stereo configuration where each module contains two layers of drift tubes. This gives a total of 24 layers in total over the three OT stations. Each drift tube module contains 256 gas filled straw tubes. There is potential difference created between the cathode and anode causing the charged particles to drift. Each straw tube contains a mixture of Ar(70%), CO₂(28.5%) and O₂(1.5%) which provide a drift time of less than 50 ns as well as good spatial resolution [58]. The detection of a charged particle occurs in the straw tubes when the gas ionises due to the high local electric fields caused by the passage of the charged particles causing the free electrons to drift towards the anode. At the anode, the free electrons cause a signal current to propagate and the time difference between the inception of the signal current and the gas being ionised is used to determine the coordinates of the particles. The three OT stations are shown in Fig. 3.7 which also illustrates the relative size of the OT compared with the IT. The design of the OT covers a large area and thus ensures that all charged particles within the LHCb acceptance can be reconstructed.

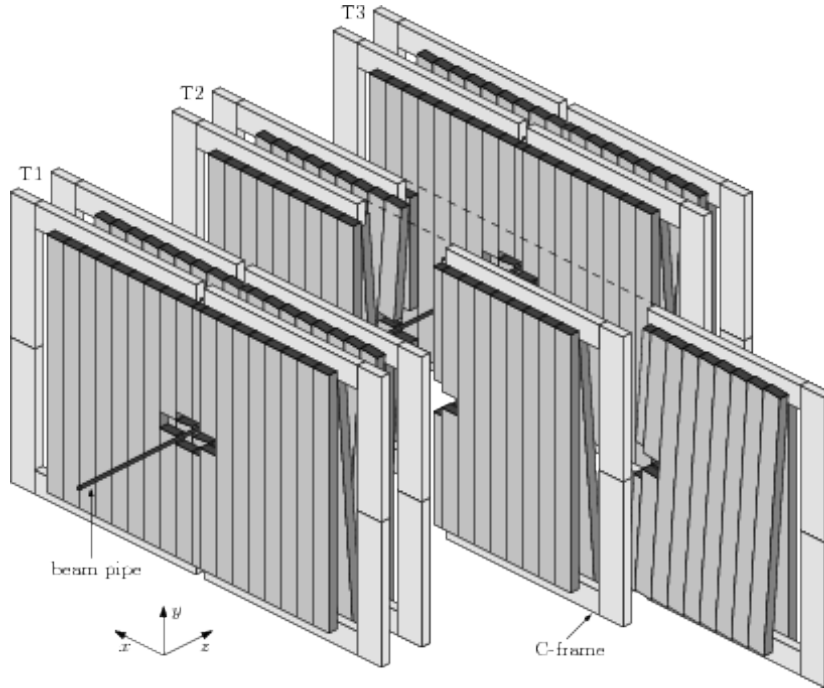


Figure 3.7: The LHCb Outer Tracker stations [58]. The IT can be seen as the cross-shaped gap around the beam pipe. The three stations where each station holding four layers in a stereo configuration is also shown.

3.3.3 Dipole Magnet

Between the TT and T1-T3 stations is a dipole magnet which has an integrated bending power of 4 Tm and measures the curvature of particle tracks from charged particles traversing the detector [59]. The momentum of the charged particles can be measured from the curvature of tracks in the magnetic field with a resolution of $\sim 0.4\%$ for $p \leq 200 \text{ GeV}/c$ [60]. The chosen field strength is a compromise to maximise the field strength between the upstream and downstream tracking stations, while ensuring a field strength of below 2 Tm in the RICH detectors. The magnet is made up of two 25 tonne trapezoidal shaped coils inside a 1450 tonne iron frame as shown in Fig. 3.8. The magnetic field is produced between the pole faces causing charged particles to be deflected horizontally.

The polarity of the magnet is reversed periodically throughout data taking to reduce the effect of charge detection asymmetries caused by variations in efficiency across the detector. This is important to understand systematic biases for any CP asymmetry measurements caused by the left-right detector asymmetries. The magnet is kept warm to allow for an easier inversion of the direction of magnetic field. Imagining a charged particle originating from the PV travelling near the edge of the horizontal acceptance can help visualise this effect. Depending on the charge of the particle, it can either be swept into or out of the detector acceptance, so there are large charge asymmetries in acceptance for these edge regions within a given polarity. If the two polarities are averaged these asymmetries cancel to first order. Higher order effects can remain and need to be studied for any analyses where charge asymmetries are relevant.

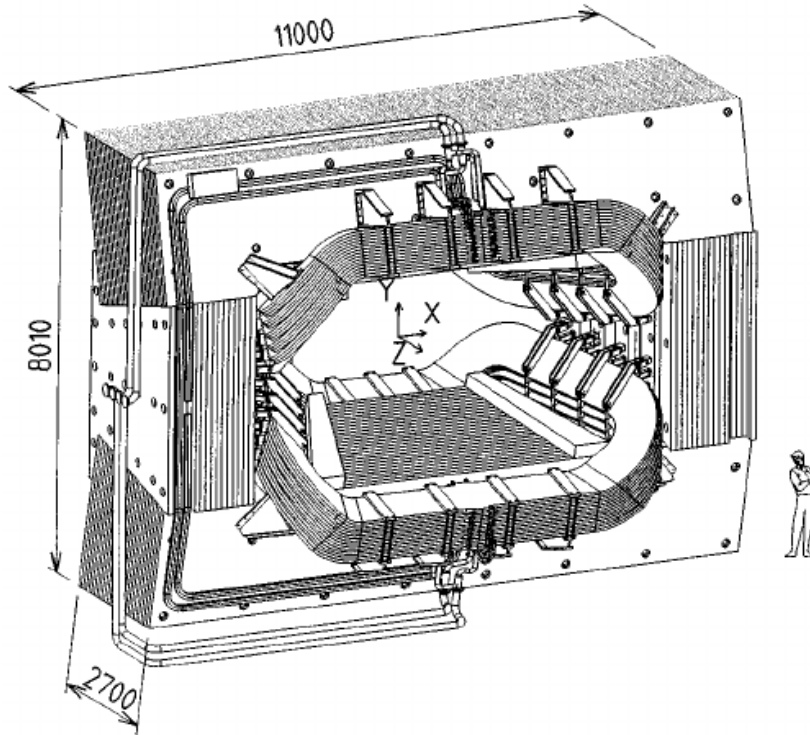


Figure 3.8: Dipole Magnet at LHCb.

3.3.4 Track Reconstruction

As mentioned previously, powerful track reconstruction algorithms are employed to convert the hits in the various sub-detector systems into particle tracks. The algorithms search for tracks with a certain number of hits in the system. Reconstructed tracks are placed in 5 broad categories based on the hits left in the tracking system:

- **VELO Tracks** are tracks with associated hits only in the VELO. These tracks are typically produced at large angles and are primarily used to locate the PV for an event
- **Upstream Tracks** are those with associated hits in the VELO and TT stations. As mentioned previously, these are usually low momentum tracks that are swept out of detector acceptance by the magnetic field before reaching the downstream tracking stations. These track trajectories are poorly constrained and have poor momentum resolution but they do leave hits in the RICH so can be used as identify backgrounds.
- **Downstream Tracks** are tracks associated with hits in the TT and T1-T3 stations. These tracks typically originate from long lived particles such as K_L^0 that decay outside of the VELO acceptance.
- **T Tracks** are tracks that are associated with hits only in the T-stations. These tracks are used for pattern recognition algorithms in the RICH detectors.
- **Long Tracks** are tracks that are associated with hits in all the tracking stations. As the tracks are precisely mapped, the momentum resolution on these tracks is better than all other types of tracks.

These track trajectories are also shown in Fig. 3.9. Tracks are reconstructed by searching for track

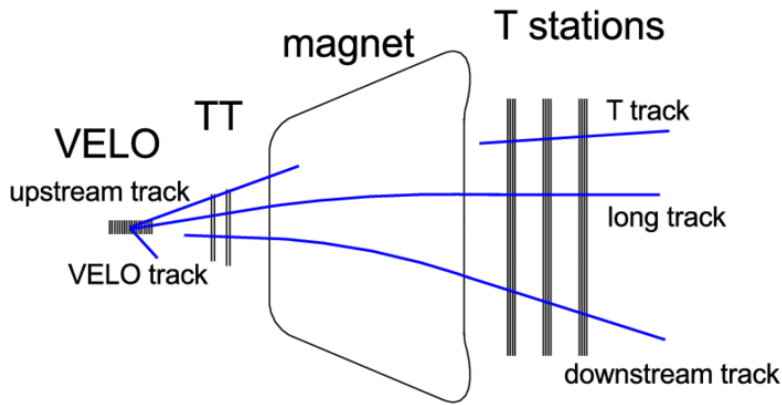


Figure 3.9: Various track trajectories based on the hits left in the tracking stations [1].

seeds which are track segments within the VELO and TT station where the magnetic field has a negligible impact on track trajectories. Extrapolation of the seeds to other regions of the detector, accounting for the magnetic field, allows for track trajectories to be constructed. The trajectories

are refitted with a Kalman Filter [61, 62] to account for multiple scattering effects and energy loss of particles through interaction with detector material. The quality of the tracks is measured using the χ^2/ndf metric to provide only the best reconstructed tracks for offline analysis.

A single charged particle can end up being reconstructed as more than one track. Such cases are called clones. They can cause problems in some analyses if both tracks are selected and used to reconstruct a signal candidate. Clones are associated with two or more almost collinear tracks, so can be identified and removed with good efficiency.

Tracks which do not correspond to a true charged particle trajectory, but simply reflects a group of unrelated hits which happen to fulfil the track reconstruction requirements are known as ghosts. Ghost tracks cause a bottle-neck for high track reconstruction efficiency as the number of ghosts scales with event multiplicity. A machine learning algorithm is used to assign a ghost rate probability to tracks which allows for a large fraction of ghosts to be vetoed. Overall, the track reconstruction efficiencies as functions of momentum and event multiplicity are determined using a data driven approach whereas the ghost rates are determined from simulation. The track reconstruction efficiency from data is found to be above 95% whilst the ghost probability variable used in Run 2 retained more than 99% of the well reconstructed tracks and reduced the proportion of ghost tracks by 60% [63].

3.3.5 Primary Vertex Reconstruction

Primary vertex reconstruction is performed using dedicated algorithms and is done in two stages; seeding and fitting. Firstly, seeding finds points close to the interaction region where a sufficient number of tracks pass close to one another. Each track pair is evaluated individually and two tracks are close to one another if they are separated by a distance less than 1mm at the point of evaluation. Each seed is considered a PV candidate if at least four close tracks are found and seeds are then ranked according to their multiplicity. The highest multiplicity candidates are the first ones to be reconstructed.

Each seed is reconstructed by performing a fit using the weighted least squares method whereby weights are assigned to each track in the seed based on the value of the χ^2 parameter. The χ^2 is calculated from the IP of tracks with respect to the seed location. Every PV reconstructed for each seed is required to be spatially separated from any previously reconstructed vertex. The position of the reconstructed PV can be determined once 5 tracks (including a backwards track) are assigned to a PV candidate. A weighted χ^2 optimisation based on the track IP χ^2 is used to calculate the position of the PV. The backward track ensures that a SV is not mistaken for a PV. In general there can be many secondary vertices in an event. The reconstruction technique for a SV is similar to that of a PV with the exception that there will be fewer tracks converging to the same point since there could be as few as two tracks originating from the SV. For analyses of beauty and charm hadrons, a powerful tool to remove background contamination is to require that the SV is significantly displaced from the corresponding PV. In particular, the flight distance of the intermediate particle is often used, including in the analyses presented in this thesis using neutral charm mesons. For the majority of

LHCb events there is just one reconstructed PV, but in some cases there are several. In those cases each SV, and the particles originating from it, needs to be identified with a PV so that the properties of the intermediate particle can be determined. There are different ways to do this, the most common being to pick the PV closest in space to the SV.

3.3.6 Cherenkov Detectors (RICH1 and RICH2)

The Ring Imaging Cherenkov (RICH) detectors are used to identify charged hadrons at high and low momenta using RICH2 and RICH1 respectively. These detectors are located either side of the magnet and measure the velocity of the particles based on the Cherenkov radiation emitted by the particles as the particle travels through the medium of the detector. Cherenkov radiation emitted by the particles is seen through the presence of a cone of light with a polar angle θ_C , known as the Cherenkov angle. The Cherenkov angle is related to the velocity of the particle through the following equation:

$$\cos(\theta_C) = \frac{1}{n\beta} \quad (3.5)$$

where n is the refractive index of the medium through which the charged particle travels and β is the ratio between the speed of the particle, v and the speed of light, c ($\beta = \frac{v}{c}$). The information on the velocity of the particle is combined with the momentum measurements made by the tracking detectors to determine particle masses and hence identify charged hadrons. Fig. 3.10 shows how different mass hypotheses result in variations of the Cherenkov angle as a function of particle momentum.

The functioning of both RICH detectors is similar in that the cone of light is reflected by flat mirrors. The projections of the reflected light cones are detected by hybrid photon detectors placed outside the acceptance region. The difference between RICH1 and RICH2 is the medium through which charged particles propagate. RICH1 contains C_4F_{10} gas and covers a momentum range of 1-60 GeV/c. On the other hand, RICH2 uses a CF_4 medium to cover a momentum range of 15-150 GeV/c [65]. The RICH detectors primarily provide distinction between kaons, pions and protons but can also be used in conjunction with muon chambers and calorimeters to identify muons and electrons. A schematic of the RICH detectors is shown in Fig. 3.11.

3.3.7 Calorimeters

The calorimeters measure the position and energy of hadrons, electron and photons. Layers of material are utilised to stop these particles when entering this portion of the detector. Before the calorimeter, these particles travel through the Scintillating Pad Detector (SPD) and Pre-Shower (PS) which are separated from one another by a lead wall of 1.5cm thickness. The lead wall is used to distinguish between hadrons and electrons as it causes showers in the Pre-Shower detector for electrons but not for hadrons. Furthermore, the energy deposits left in the SPD by electrons means that the SPD/PS system can also distinguish between photons and electrons. The two calorimeters; ECAL (Electromagnetic Calorimeter) and HCAL (Hadronic Calorimeter) follow the SPD/PS system. The SPD, PS and the two calorimeters are constructed using similar technology whereby they are composed of alternating layers

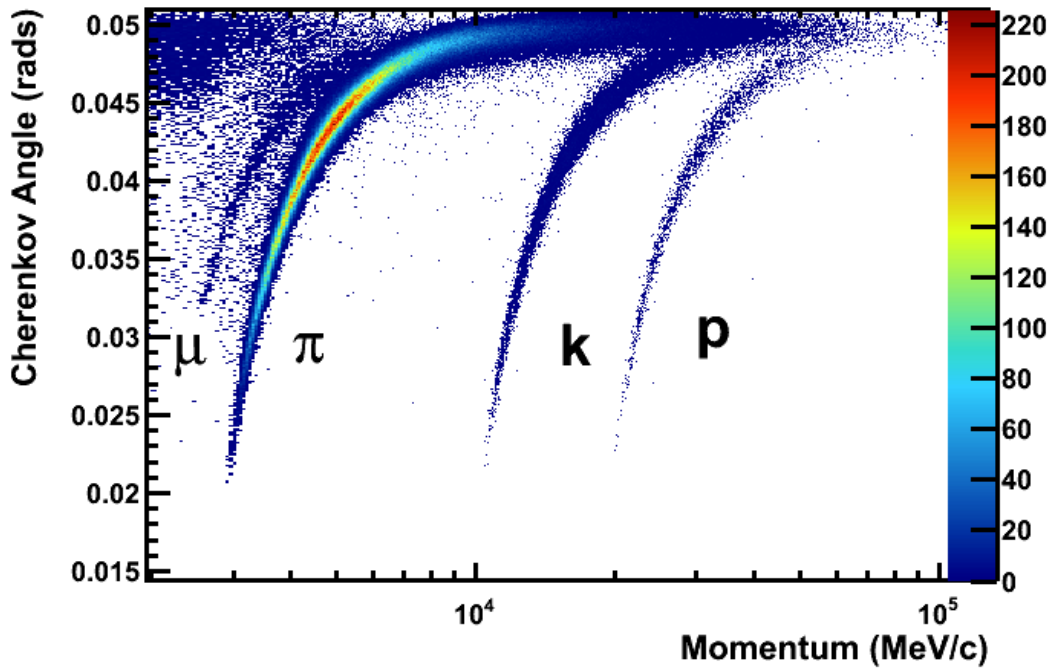


Figure 3.10: Reconstructed Cherenkov angles from 2011 data for charged particles passing through the RICH1 detector [64].

of thin lead absorbers and scintillating plates. Interaction with the absorber produces electromagnetic showers in the scintillating plates where the scintillating light produced by the incident particles is transmitted to a photo-multiplier tube by wavelength shifting fibres [67]. The intensity of the scintillating light is proportional to the energy of the incident particle. The calorimeters collect only a fraction of the total particle energy. The detectors must therefore be calibrated using well known processes to determine the absolute energies. The calorimeter system is thus able to measure the energy of electrons, positrons, photons, pions and other hadrons, thereby providing information for the Level 0 (L0) trigger for any of these particles with high transverse momenta [67].

The ECAL is composed of alternating layers of 4mm-thick scintillating tiles and 2mm-thick lead

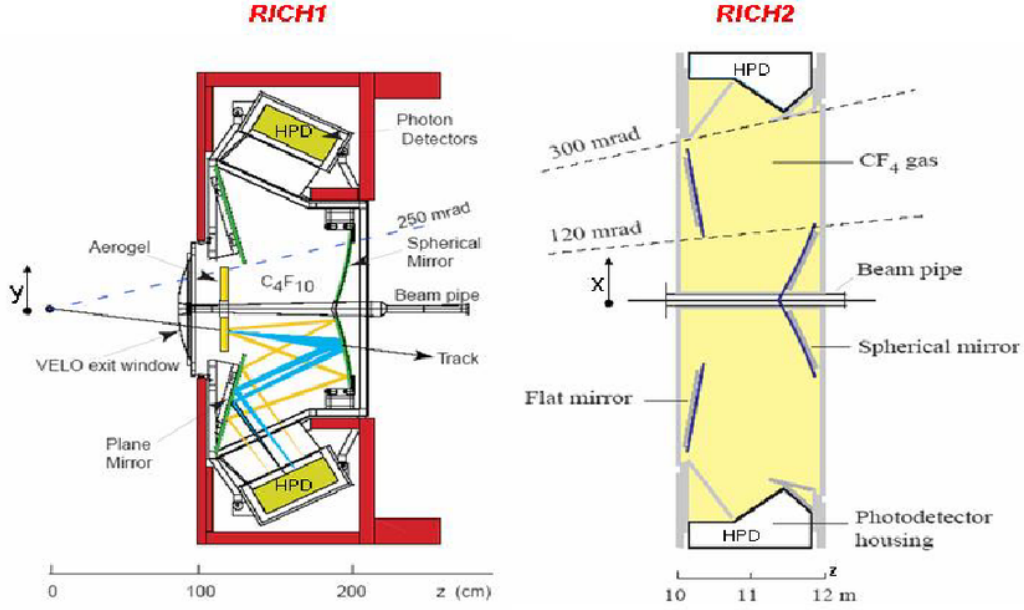


Figure 3.11: Schematic of RICH1 (left) as seen from the side and RICH2 (right) as seen from above [66].

plates with photo-multipliers to detect light emissions. There are three different cell sizes used to accommodate the variation in hit density with distance from beam; $(4 \times 4)\text{cm}^2$, $(6 \times 6)\text{cm}^2$, $(12 \times 12)\text{cm}^2$ in the inner, middle and outer parts of the detector respectively. There are 3312 modules within the ECAL which covers a transverse area of $(7.6 \times 6.3)\text{m}^2$. The thickness of the lead absorber is chosen to fully confine the highest energetic photon showers ensuring optimal energy resolution. The energy of a shower is measured through a weighted combination of hits in the PS and ECAL with a measured energy resolution of:

$$\delta_E/E = (8.5 - 9.5)\%/\sqrt{E} \oplus 0.8\%[68] \quad (3.6)$$

where E is in GeV.

The HCAL measures shower energies of hadrons that interact with the detector. The process for producing these showers is analogous to the showers produced in the ECAL. Instead of lead absorbers, the HCAL employs iron absorbers 16mm in thickness alternating with 4mm scintillating plates. Similarly to the ECAL, the HCAL cell size varies with distance from the beam pipe. The energy resolution of the HCAL for hadronic showers is:

$$\delta_E/E = (69 \pm 5)\%/\sqrt{E} \oplus (9 \pm 2)\%[68]. \quad (3.7)$$

Fig. 3.12 shows the cell segmentation of the calorimeters at LHCb.

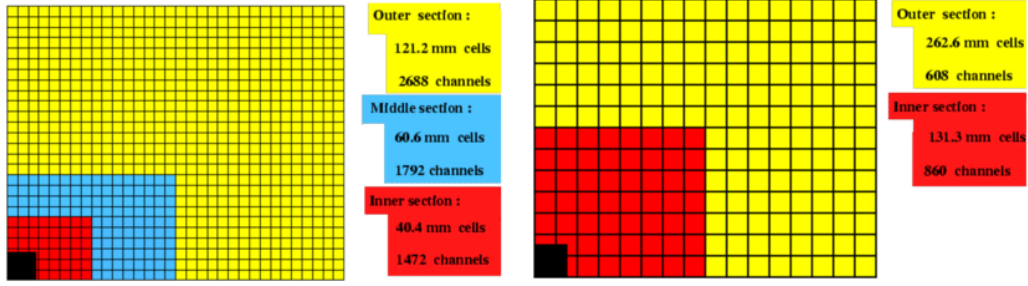


Figure 3.12: Side view of the SPD/PS and ECAL (left) and the HCAL (right) with the beam pipe shown in black. [69].

3.3.8 Muon Chambers

Muons do not produce hadronic showers and are often described as minimum ionising. They are not stopped by the calorimeters so require a set of separate detectors to enable fast muon detection and identification for fast online triggering on high momentum muon candidates. The muon chambers are thus located around the edge of the detector and are made up of five rectangular shaped muon stations, M1-M5, in layers behind one another around the beam pipe and increasing in size. The first station, M1, is located before the calorimeter and the other four are located downstream of the HCAL. The location of the upstream muon station allows for the muon momentum to be measured for the L0 trigger. To mitigate against the effect of misidentifying muons, any other particles that are not stopped by the calorimeters are absorbed by 80cm thick iron plates positioned between muon stations. Each of the muon stations is split into four regions (R1-R4) where each region is positioned at an increasing distance from the beam pipe. The granularity is finest in the region closest to the detector (R1) and the dimensions of each region are chosen to ensure a similar occupancy and particle flux over all regions. The side view of the muon chambers and the layout of the four regions is shown in Fig. 3.13.

With the exception of the M1 station, the muon stations utilise multi-wire proportional chambers (MWPC's) [70] containing 5mm gas gaps containing a mixture of Ar, CO₂ and CF₄ gases. As the muons pass through the detector, they ionize the gas mixture producing free electrons which drift due to the presence of an electric field. The electrons are gathered by a tungsten wire of diameter 30 μm , achieving a drift time resolution of 5 ns [70]. The first muon station (M1) uses triple GEM (gas electron multiplier) detectors to accommodate the higher occupancy in this station. The triple GEM detectors comprise of a cathode, and electrode, and three GEM foils separated by the same gas mixture used in MWPC's [71].

3.3.9 Particle Identification

Each particle traversing the detector will leave a unique signature track as shown in Fig. 3.14. Information from the various sub-detectors has to be combined to identify the particle in question. Charged

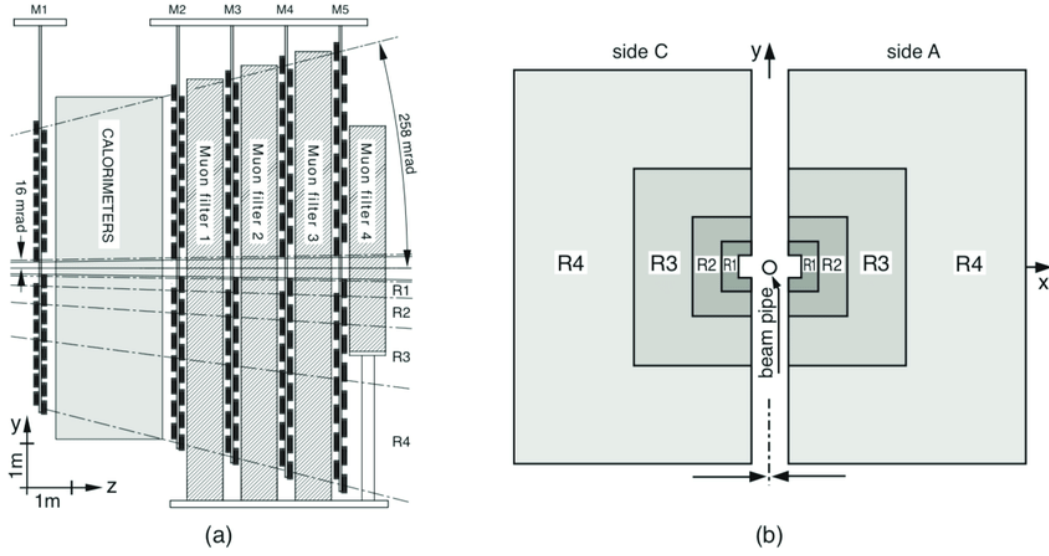


Figure 3.13: (a) Side view of the LHCb muon detector. (b) Four regions (R1-R4) in the muon stations [72].

particles are identified using inputs combined from the RICH, calorimeter and muon systems. On the other hand, neutral particles are identified based on information gathered only from the calorimeter system. The different types of particles are identified as follows:

- **Charged Particles** - A pattern recognition algorithm associates the Cherenkov rings from the RICH detector with possible reconstructed tracks for a certain mass hypothesis. Initially, a pion mass hypothesis is assigned to all tracks since it is the most probable track type at LHCb. A global likelihood is constructed that compares the observed and expected patterns under this hypothesis. For each track, successive mass hypothesis are tested to construct a new global likelihood. The set of mass hypotheses that maximise the global likelihood are assigned to tracks [64]. The identification likelihoods are combined with information from other sub-detectors as an input into a neural network to predict the probability, ProbNN_X of a given track to be of certain particle, X .
- **Muons** - Muons are identified from information gathered by the RICH, calorimeter and muon systems. An initial selection is applied to select muons that leave hits within the muon chambers from extrapolated tracks found in the tracking system. A likelihood comparing the muon and non-muon hypotheses is calculated using the distance between the hits in the muons stations and extrapolated tracks. Information from the RICH and calorimeters is combined with the likelihood to assign a muon identification probability to a particle.
- **Electrons** - Electrons are identified using information from the RICH detector, calorimeter and tracking systems. Electrons form clusters in the ECAL defined as a group of 3×3 adjacent cells around a local maximum of energy. The clusters are matched to tracks by constructing a χ^2_γ variable which is based on the distance between the clusters and the extrapolated tracks

from the tracking system. A small χ_γ^2 value is associated with clusters originating from charged particles while a high value is used to identify a neutral cluster. Electrons also deposit most of their energy inside the PS and ECAL and hence don't reach the HCAL. This information can be used to distinguish between electrons and hadrons.

- **Neutral Particles** - Neutral particles are identified using information from only the calorimeter and are therefore the most difficult type of particles to identify. Firstly, photon clusters are reconstructed as neutral clusters in the ECAL associated with a high χ_γ^2 value. The photon confidence level is used to remove calorimeter clusters associated with hadrons. The confidence level is constructed from the output of a Neural Network classifier that takes as input the energy deposits and shower shapes in the PS and ECAL, the multiplicity of hits in the SPD in front of the cluster and a variable that quantifies the compatibility of the cluster with the closest reconstructed track. The π^0 confidence level is also computed similarly with the addition of the photon confidence level as a variable to train the Neural Network classifier.

Converted photons (those that decay into an electron-positron pair before the lead absorber) are distinguished from unconverted photons using the number of hits in the SPD. Neutral pions decay into two photons and these photons are well separated when the π^0 transverse momenta is below $2.5 \text{ GeV}/c$. These are known as resolved pions and are reconstructed by finding pairs of calorimeter clusters with a total invariant mass compatible with the π^0 mass hypothesis. However the angle between photons from π^0 with transverse momenta over $2.5 \text{ GeV}/c$ is so small that their energy deposit is within a single cluster. These are known as merged pions and are reconstructed by splitting into sub-clusters that are superimposed on one another. The energy of the sub-clusters is computed iteratively using the expected energy distribution of a photon shower. The cluster is identified as being associated with merged π^0 if the distance between the two photons is kinematically allowed and if the invariant mass is compatible with that of a π^0 .

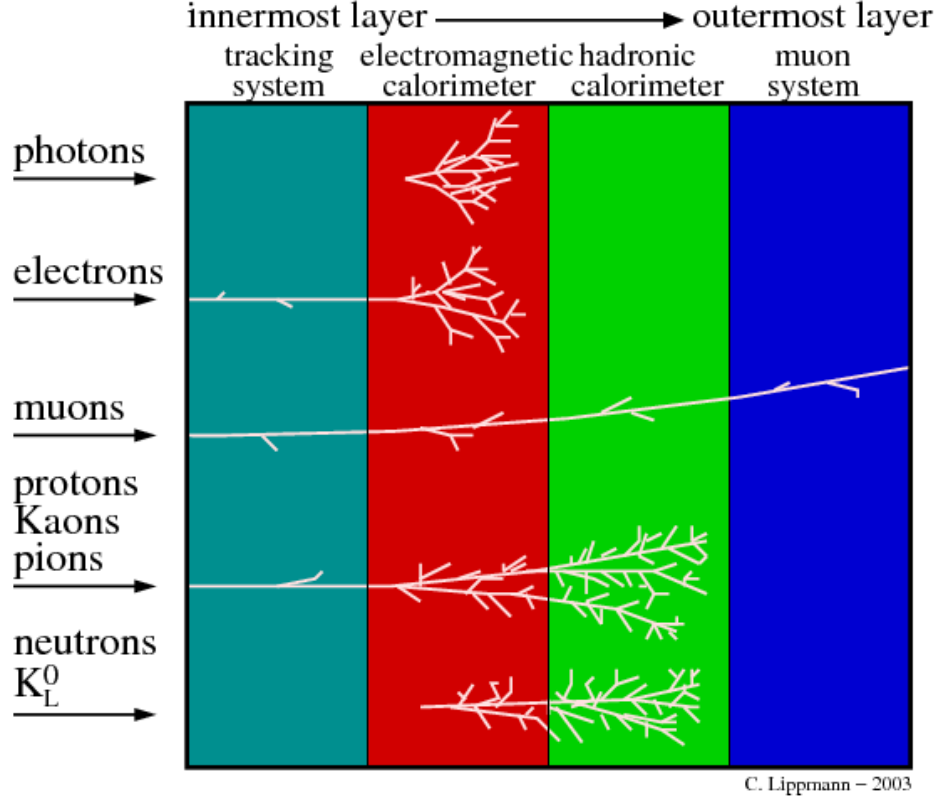


Figure 3.14: Unique signature tracks left by photons, electrons, muons and various charged particles [73].

3.4 LHCb Trigger

Proton bunches collide at LHCb at 40MHz, typically with one pp interaction per bunch crossing. This necessitates a trigger system that reconstructs detector signal such that only the most interesting events from pp collisions are stored. At LHCb, the trigger is split into two levels. The hardware trigger, commonly known as the L0 trigger, uses the calorimeter and muon systems to store events containing high transverse momenta (p_T) muons or high transverse energy particles. Events that pass the L0 trigger are assessed by the software trigger, known as the High Level Trigger (HLT). The software trigger is further split into two stages and events passing both stages are then stored on tape, ready to be analysed. The trigger can be adapted as run conditions change and utilises a variety of techniques to identify decays of interest including multivariate classifiers.

3.4.1 Level-0 (L0)

The hardware trigger is the first point at which data can be discarded. The L0 trigger is responsible for reducing the event rate from 40MHz down to 1MHz which means a decision on keeping or discarding an event has to be made within $4 \mu\text{s}$. During this time, the L0 trigger makes use of information from three L0 trigger systems; L0-Muon, L0-Calorimeter and L0-PileUp. Events passing requirements in at least one of these three triggers are passed to software trigger for further processing whilst all other events are discarded.

The L0-Muon processes hits from the five muon stations and typically selects a single muon with $p_T > 1.76 \text{ GeV}/c$ or a pair of muons for which the product of their transverse momenta is $p_T > 1.6(\text{GeV}/c)^2$. As mentioned previously, these constraints can change depending on the run conditions. The L0-Calorimeter uses information from the SPD, PS, ECAL and HCAL to select events with high transverse energy (E_T). For hadrons, a typical threshold value is $E_T > 3.68 \text{ GeV}$ based on the energy deposits within the HCAL. For electron and photons, the energy deposited in the ECAL must be greater than 3 GeV . The calorimeter trigger is thus able to build photon, electron and hadron candidates based on its energy deposits. Finally, the L0-PileUp vetoes events containing multiple collisions per bunch crossing using information from the VELO and SPD, thereby retaining only those events with a single collision per bunch crossing. Events passing the L0 trigger are passed to the software trigger.

3.4.2 High Level Trigger (HLT)

The HLT is a software trigger that runs on C++ algorithms on a farm of multi-core processors located at the Event Filter Farm. The purpose of the HLT is to reduce the event rate down to a few kHz. To do this, the HLT must perform event reconstruction within the given computing time constraints. There were significant changes implemented within the HLT framework between Run 1 and Run 2. During Run 1, a simplified procedure was used, of using only VELO and tracking station information to reconstruct events in HLT1 to provide an output a bandwidth compatible with subsequent HLT2 reconstruction. A full reconstruction was performed in HLT2 using information from all sub-detectors but the implementation of the reconstruction differed from the offline reconstruction applied during analysis. The Run 2 changes meant that the online event reconstruction was the same as the one used for offline analysis. The changes to the trigger pipeline are illustrated in Fig. 3.15. Further changes to the High Level Trigger including storing events to a buffer for detector calibration and alignment can be found in Ref. [74].

The first stage of the software trigger (HLT1) performs a partial event reconstruction on events passing the L0 trigger. The partial event reconstruction is based on the VELO reconstruction software which determines the mean position of the pp collisions from track reconstruction. The tracks within $300 \mu\text{m}$ that either have a large impact parameter (distance between PV and reconstructed track) or hits in the muon chambers are extended into the main tracker. The track segments are extended to the tracking stations by searching for hits consistent with high p_T tracks. In general, inclusive HLT1 lines are designed to select heavy flavour decays with different topologies in addition to a limited number of exclusive lines dedicated to selecting events with a certain final state particles.

The second stage of the software trigger (HLT2) processes events written by HLT1 by performing a full offline event reconstruction. Unlike HLT1, most lines in HLT2 are exclusive meaning they select specific decays with a particular decay topology. There are some inclusive lines which select either b-hadrons or charmed hadron decays with a few charged particles in the final state. These lines use multi-variate

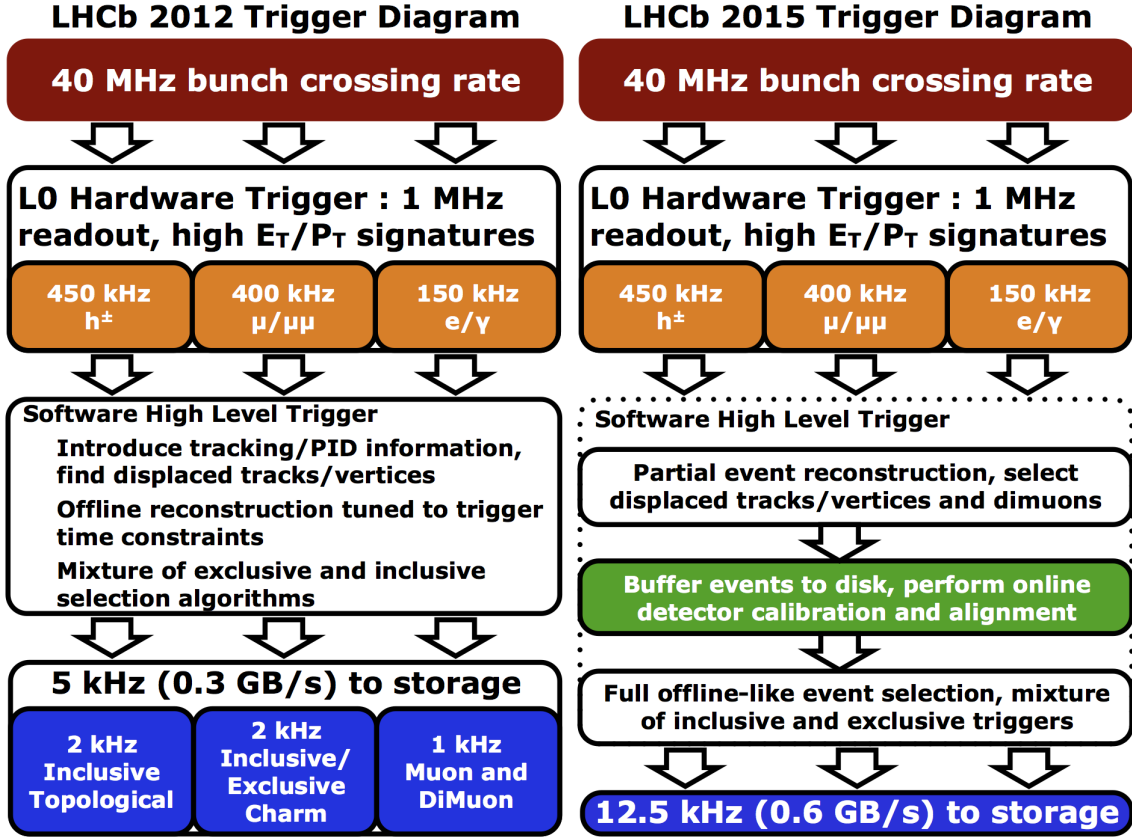


Figure 3.15: Outline of triggers used in 2012 (left) and 2015 (right) [75].

classifiers to select events that have decay topologies consistent with the hadron decay of interest. For the analyses described in this thesis, and LHCb analyses more generally, a specific set of trigger requirements are imposed at each of the three levels. This ensures a well defined sample with known selections applied at the trigger stage.

3.5 Data Flow and Simulation

Data collected at LHCb pass through a sequential data processing pipeline designed to maximise data efficiency and quality. This is done on a per event basis where several software applications are performing specific operations. The foundational data processing software is called GAUDI [76] which provides a common infrastructure and environment for all other software applications [77].

The first stage of the data processing procedure is to filter the detector output which is done by a software called MOORE [78] that runs the HLT. All data must pass the trigger selections before being processed further. Individual events are reconstructed using the BRUNEL [79] application which calculates particle properties from digitised information coming from various sub-detectors. Hits recorded in the trackers are used to compute particle trajectories and momenta allowing PV's to be reconstructed. Additionally, PID variables are also computed from information gathered in the RICH, calorimeters and muon system. Data processed by the BRUNEL application is stored as a Data-Summary-Type

(DST) file. At this stage, the data are almost ready to be used by analysts.

The final step in the the data-pipeline utilises the **DAVINCI** [80] application to run a full event reconstruction on the DST file from **BRUNEL** output. In the first part of data processing in **DAVINCI**, data is filtered through a centralised selection procedure known as stripping. Stripping is carried out to reduce the size of the triggered, fully reconstructed dataset. After the imposition of loose pre-selection requirements designed by analysts in the form of stripping lines, data is split into smaller groups containing similar selections. Analysts typically use one or two dedicated stripping lines which are written to select decays of interest and reject background. The stripping selections will differ between data taking years as selections evolve based on improved understanding of the detector and backgrounds. Stripping is run centrally by the collaboration over the whole dataset during different ‘campaigns’ where the most up to data reconstruction software is used. The output of the stripping procedure are smaller DST files that either contain full event information or contain information about candidates of interest. In the case of the latter, the output is written to μ DST files.

Finally, **DAVINCI** can be used by analysts to run algorithms on stripped DST files and compute variables relevant to their specific analysis. This is done on a per-analysis basis and is hence the only component of the data-pipeline that is not run centrally. The output of this procedure is saved as **ROOT** [81] Ntuple files.

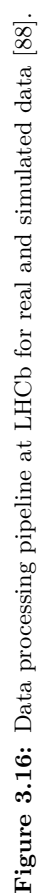
3.5.1 Simulation

Particle physics analysis relies on the availability of simulated Monte Carlo (MC) samples that try to replicate what is expected in real data. For this reason, MC produced by LHCb will undergo a similar data processing pipeline to real data. This ensures that effects associated with imperfect reconstruction will also occur in MC which eliminates bias originating from deficiencies in the data processing pipeline.

MC can be produced for any decay of interest and this is done by modelling the dynamics of pp collisions using software applications within the **GAUDI** framework. The **GAUSS** [82] application simulates the pp collisions as well as the subsequent hadronisation and particle decays. Several MC generators are called within **GAUSS** to simulate the various steps; **PYTHIA** [83] is used to model pp collisions and particle production; **EVTGEN** [84] is used to model dynamics of particle decay; and **PHOTOS** [85] is used to model final state radiation. Samples produced with only MC generators are labelled as generator level.

It is possible to include detector related effects in the simulation and these samples are known as reconstructed MC. For this case, **GAUSS** calls the **GEANT4** [86] toolkit which models the propagation of particles and its interactions with various sub-detectors. The **BOOLE** [87] application is responsible for modelling the detector response which converts the virtual hit information from **GEANT4** into a digitised detector readout designed to mimic real detector output during data taking. The response also incorporates the simulation of the L0 hardware trigger and additional hits from spillover. Once reconstructed level MC has been produced, it can follow a similar data processing pipeline as real

data, beginning with the **BRUNEL** stage. The data processing pipeline for simulation and real data is shown in Fig. 3.16. The detector performance improves over time as the collaboration gains a greater understanding of the detector itself. Thus, improvements in the data-taking conditions are implemented in different versions of the simulated software which are released periodically under the umbrella of updated versions of the **GAUDI** framework.



Part 1 - Analysis of $D^0 \rightarrow \pi^- \pi^+ \pi^0$ decays

Chapter 4

$D^0 \rightarrow \pi^- \pi^+ \pi^0$ Analysis Overview

Whilst CP violation has been recently observed in the charm sector in $D^0 \rightarrow hh$ decays [27], that remains the only significant experimental sign of CPV in any charm quark decay, despite many searches [89]. In particular, there is as yet no evidence for CPV in any multibody decays of charm hadrons. Such decays include a non-trivial phase space, in which strong phases can vary significantly due to the resonant structure. This can provide additional sensitivity to CPV when compared to phase-space integrated searches, as has been found, for example, in beauty mesons [90]. As such, further searches for so-called ‘local’ CP violation within the phase space of multibody charmed hadron decays may be key to help understand the nature of CPV in the charm sector: is it driven by SM processes alone, or are there additional contributions from physics beyond the SM?

The three body $D^0 \rightarrow \pi^- \pi^+ \pi^0$ decays contain an electroweak contribution to the decay amplitude that matches those in the two body decay $D^0 \rightarrow \pi^+ \pi^-$ in which evidence for CP violation has been found as outlined in Chapter. 2. The contribution from different resonances means that the strong phase will vary across the Dalitz space which is necessary condition for CP violation to arise. Both these factors make $D^0 \rightarrow \pi^- \pi^+ \pi^0$ decays a promising channel to probe the precision of the SM through searches for local CP violation.

Searches for CP violation in multi-body decays can be broadly divided into two types of techniques; model dependent and model independent. Model dependent techniques rely on summing individual resonant and non-resonant amplitudes to build a model that describes the decay dynamics. The resonant and non-resonant amplitudes are modelled by complex coefficients. The various amplitudes can interfere constructively or destructively over the phase space. The decay probability is given by magnitude squared of the sum of amplitudes.

The complex coefficients can differ between particle and anti-particle decays. Any such observed differences between complex coefficients would point towards CP violation once systematic effects related to production and detection asymmetries have been taken into account. These approaches are advantageous in that they allow a measurement of the CP asymmetry for specific decay paths

and therefore amplitudes responsible for CP violation can be determined. However this approach also relies on a thorough understanding of the underlying decay dynamics (i.e. resonant and non-resonant amplitudes) as well as the detector effects that can bias the measurement for a decay compared to its charge conjugate process.

On the other hand, model independent techniques don't require exact knowledge of the underlying decay dynamics but instead search for local sources of CP asymmetry in the phase space of the decay regardless of the origin of CP violation. Model independent techniques can be further divided into binned and unbinned approaches. As the name suggests, the model independent binned approaches are reliant on the binning scheme across the Dalitz phase space. This means that the choice of binning needs to be motivated by an underlying amplitude model such that the regions of large interference between amplitudes that have enhanced sensitivity to CP violation can be chosen appropriately. An example binned method is the asymmetry significance (S_{CP}) evaluation [91], as used in a recent LHCb publication [92]. The obvious drawback is that coarse binning can dilute CP violation below the sensitivity of the analysis whereas fine binning can diminish the statistical power of the analysis. Unbinned model independent technique circumvent this problem by allowing sensitivity of the analysis to be enhanced without any underlying knowledge of the resonant structure of the decay. There are several well known techniques in literature, namely the nearest neighbour approach and adaptations of the Kolmogorov-Smirnov test for more than one dimension. These methods and their respective advantages/drawbacks are discussed in Ref [93].

In this analysis, we utilise the energy test (ET) method which is described in the next paragraphs. We proceed with the null hypothesis based on the assumption of CP symmetry in the decay $D^0 \rightarrow \pi^- \pi^+ \pi^0$. Relevant selection cuts (see Sec 5.4.1) are applied to obtain a sample of flavour tagged $D^0 \rightarrow \pi^- \pi^+ \pi^0$ decays. The analysis remains blind until the method has been developed and validated using toy studies and data driven checks with a control mode and flavour randomised signal samples as described in Chapter 6. Upon unblinding, the ET is applied to the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ sample to test the CP symmetry hypothesis.

4.1 Energy Test

The energy test is an unbinned model-independent statistical test used to search for CP asymmetry in a decay [94, 95]. The test takes as input two disjoint samples of candidates (in this case from $D^0 \rightarrow \pi^- \pi^+ \pi^0$, and from $\overline{D}^0 \rightarrow \pi^+ \pi^- \pi^0$ decays). Each candidate is characterised by a set of phase-space coordinates. For this analysis we choose to use the usual Dalitz coordinates expressed in terms of invariant-mass-squared of pairs of the daughter particles. To allow for a direct comparison, we enforce consistent distributions for D^0 and $\overline{D}^0$ in the case of CP symmetry. This means that the definitions of the Dalitz coordinates m_{13} and m_{23} are flipped for the two flavour choices.

The energy test compares the two disjoint samples and evaluates a probability that the two samples

are drawn from the same underlying statistical distribution. The energy test relies on the calculation of a statistic T . The T -value calculation takes as input a phase-space separation variable d_{ij} for pairs of candidates in the sample. The distance between two events i and j , d_{ij} , is defined as the length of the displacement vector $\Delta\vec{x}_{ij}$. This is a function of the coordinates defined in Table 4.1 and is given by

$$\Delta\vec{x}_{ij} = (m_{12}^{2,j} - m_{12}^{2,i}, m_{23}^{2,j} - m_{23}^{2,i}, m_{13}^{2,j} - m_{13}^{2,i}). \quad (4.1)$$

Using this definition of the displacement vector, the test statistic should be proportional to the average distances between points belonging to the two samples. The test statistic is evaluated over a phase space that spans the Dalitz coordinates of particle and anti-particle decays. The test statistic, T , for a given dataset consisting of n selected events and $\bar{n}$ anti-particle events is defined as

$$T = \sum_{i,j>i}^n \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\bar{n}} \frac{\psi_{ij}}{\bar{n}(\bar{n}-1)} - \sum_{i,j}^{n,\bar{n}} \frac{\psi_{ij}}{n\bar{n}}, \quad (4.2)$$

for pairs of events i and j and a distance function or metric ψ_{ij} which is a function of d_{ij} . The selection of the form of ψ_{ij} is crucial for determining the sensitivity to global asymmetries as well as locally varying asymmetries. The distance function should depend on the distance between events in phase space as it should decrease with increasing distance d_{ij} between events i and j for increased sensitivity to local asymmetries. The distance function in this analysis is defined as a Gaussian of the form

$$\psi_{ij} = \exp\left(\frac{-d_{ij}^2}{2\delta^2}\right), \quad (4.3)$$

where δ is a tunable parameter describing the effective radius in phase-space within which local asymmetries can be measured and therefore must not be greater than the resolution of d_{ij} but small enough to take into account the local asymmetries without loss of their significance. The previous studies of this decay found an optimal value of $\delta = 0.2 \text{ GeV}^2/c^4$ but this value can change with additional data. The optimal value is re-computed based on sensitivity studies performed on toy data which simulates potential CP violating scenarios (Chapter 6).

Consequently, the first and second terms in Eq. 4.2 correspond to a weighted average distance for n particles and $\bar{n}$ anti-particles respectively while the third term is a measure of the weighted average distance between the two flavour samples. The denominators of the terms act as normalisation factors

Coordinate	D^0	$\bar{D}^0$
m_{12}	$m_{\pi^+\pi^-}$	$m_{\pi^+\pi^-}$
m_{13}	$m_{\pi^+\pi^0}$	$m_{\pi^-\pi^0}$
m_{23}	$m_{\pi^-\pi^0}$	$m_{\pi^+\pi^0}$

Table 4.1: Notation for the Dalitz Projections.

to remove the effect of global asymmetries between both flavour samples. If the two samples are drawn from the same underlying distribution (i.e. no CP-violation), a T -value close to zero is expected whilst asymmetries between the distributions increase the value of T .

4.2 Hypothesis testing through the energy test

The T -value computed by the energy test (Eq. 4.2) can not be interpreted in isolation. To use this number we need to know the expected distribution of T -values under the null hypothesis. From this, we can compute a p -value for the data to be consistent with this null hypothesis (i.e. CP symmetry) by integrating the area of the normalised T -value distribution above the nominal value from the data.

The procedure to compute the T -value distribution under the null hypothesis [94] is as follows. Firstly, CP symmetric pseudosamples are generated by randomly assigning a flavour to all events in the original dataset and calculating a T -value for these samples. A sample produced in this process is referred to as a permutation sample and the produced distribution, the T -value distribution. Using a null hypothesis of CP symmetry, the p -value for the original dataset is defined as the fraction of T -values in the permutation distribution which are greater than the T -value calculated for the original dataset referred to as T_{sample} . The precision to which the p -value is calculated is dependent on the total number of permutations used, effectively quantising the precision. To reach a sensitivity for p -values of 10^{-6} , at least 10^6 permutation samples need to be constructed. In practice however, more samples would be necessary to avoid the impact of statistical fluctuations in the null T -value distribution. Calculation of p -values utilising this method is referred to as the counting method.

The calculation of a large number of T -values is computationally expensive because the complexity of the energy test scales with the number of events, n , as $\mathcal{O}(n^2)$. To avoid this common problem in data science, the permutations are obtained using an alternate approach known as the scaling method [96]. The means of the CP symmetric samples used to build the null T -value distributions are uncorrelated and therefore the values in the distribution can be scaled. Thus one can construct the T -value distribution by evaluating the energy test on a large number of small subsets of the data. The T -value distribution becomes independent of the subset size if the subset size is of the order of one hundred candidates and above [96] as shown in Fig. 4.1. This approach results in a significant reduction in computing time. A T -value calculated for a small subset of the data is known as a scaled T -value and must be unscaled in order to represent a true distribution value. The unscaling operation acts such that the scaled T -value is multiplied by a factor of $\frac{k}{m}$ where k is the total number of D^0 and $\overline{D^0}$ candidates in the subset whilst m is the total number of D^0 and $\overline{D^0}$ candidates in the full dataset.

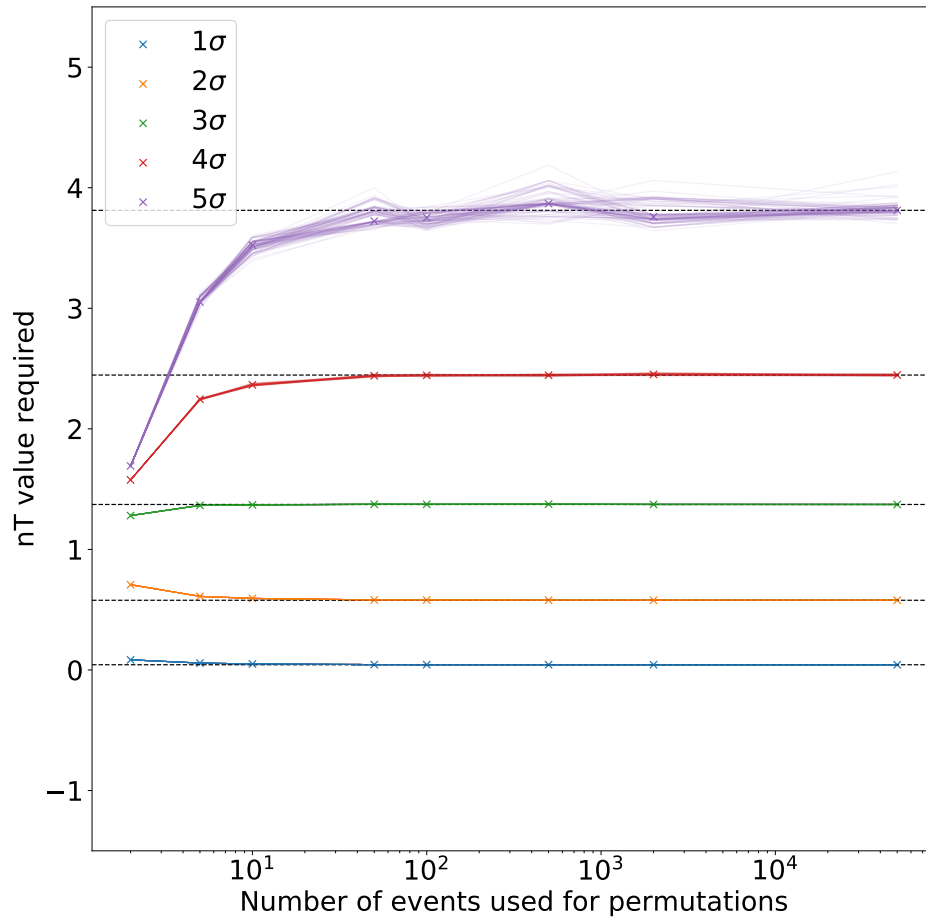


Figure 4.1: Plot showing the size of the permutation sample to reach various levels of statistical significance. Plot taken from Ref [96].

4.3 Presence of Backgrounds

For any signal sample under study, there will be sources of background from various physics processes that reduce the purity of the sample, defined as the fraction of signal decays relative to the total number of decays. Thus, the effect of background events must be taken into account before associating CP violation solely with the signal process. Furthermore, the presence of background is problematic when determining local CP violation as the purity between the two samples under study can be different. This is particularly pertinent for the energy test method where differences in purity between ‘real data’ samples are not reproduced when constructing the permutation sample i.e. when randomly assigning a flavour to the events. This is because the purities and event densities will be consistent for the two samples in every permutation sample. Consequently, background events can bias the T -values leading to a significant p -value even in the absence of CP violation in the signal process.

Techniques to remove the effect of background events from the energy test method that could result in significant T -values were considered in Ref. [94]. One approach involves weighting events such that the purity of each sample is evaluated based on regions of phase space from which the event is drawn. This allows the calculation of T -values that would be solely from signal decays.

An alternative approach is also considered which requires the availability of background samples such as those from signal side-bands. As the ET relies on the calculation of phase space distance between pairs of events, the background sample can be used to subtract the effect of signal and background event pairs, and background and background event pairs. To achieve this, the test statistic from Eq. 4.2 can be altered. Details on how the test statistic changes is further expounded upon in Ref. [94]. The main conclusion is that this approach is recommended when there are asymmetric backgrounds which can bias the ET results. If the backgrounds are symmetric, there is nothing to be gained, and it can dilute sensitivity of the method.

4.4 Previous Results

The LHCb collaboration has previously analysed the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ channel using Run 1 data collected in 2012 [97], corresponding to an integrated luminosity $\mathcal{L}_{int} = 2\text{fb}^{-1}$, yielding approximately 570k signal candidates. The energy test method was used to determine a p -value quantifying the consistency of the data with the hypothesis of CP symmetry: $p = (2.6 \pm 0.5)\%$. While not significant, the p -value is small. If this is due to the presence of genuine CP violating effects in this channel, the Run 2 data should be sensitive to it, with around a fivefold increase in signal yield.

The BaBar collaboration has previously searched for CP asymmetry in this channel using a binned χ^2 method with a signal yield of $\sim 82\text{k}$ [98]. No significant asymmetries were observed, and an overall global asymmetry was measured as $\mathcal{A}_{CP} = (-0.31 \pm 0.41)\%$.

Chapter 5

Event Selection for $D^0 \rightarrow \pi^- \pi^+ \pi^0$

This analysis uses data collected at LHCb between 2015 and 2018 at a centre-of-mass energy $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of, $\int \mathcal{L} dt \sim 5.7 \text{ fb}^{-1}$. The control channel ($D^0 \rightarrow K^- \pi^+ \pi^0$) and signal mode ($D^0 \rightarrow \pi^- \pi^+ \pi^0$) are analysed independently. To distinguish between the D^0 meson and its antiparticle, the candidates are tagged at production which means that the flavour of the D^0 meson is determined when it is produced. The charge of the ‘soft’ pion, $\pi_s^\pm$, produced in the strong decay, $D^{*+} \rightarrow D^0 \pi_s^+$, is used to assign the flavour. In this chapter, I describe the generic online selection cuts followed by the more specific offline cuts to reduce background and enhance the statistical sensitivity of the analysis. The generic online selection cuts employ the LHCb trigger which selects the most signal decays of interest (see Sec. 3.4). The offline selection procedure begins with the stripping where events are filtered through a centralised selection procedure (see Sec. 3.5). Following stripping, customised offline cuts are applied to the sample that minimises contamination from various physics backgrounds. An MVA is then trained and applied to the sample such that a cut can be applied which optimises the signal significance. This suppresses combinatorial background arising from the mis-association of D^0 with a soft pion.

The control channel, $D^0 \rightarrow K^- \pi^+ \pi^0$, primarily decays via a Cabibbo-Favoured process, $c \rightarrow s \bar{u} \bar{d}$, with small contributions from a doubly Cabibbo-Suppressed decay, $c \rightarrow d \bar{u} s$. The selection requirements placed on the control channel are also described in this chapter. Since the control channel is expected to be in agreement with a null-hypothesis of CP symmetry and the selection requirements are more or less mirrored with the signal channel, it can be used to calibrate the method against experimentally induced effects that may bias the final results.

5.1 Different π^0 candidates

A schematic of the decay topology for the signal channel is shown in Fig. 5.1. The final state of $D^0 \rightarrow \pi^- \pi^+ \pi^0$ decay is charge conjugate (i.e. the final state is indistinguishable from its charge

conjugate state) and hence the charge of the soft pion is used to assign the flavour to the D^0 meson. The neutral pion is not reconstructed but rather decays into two photons which are reconstructed in the Electromagnetic Calorimeter (ECAL). The method of reconstruction provides a natural option to split the π^0 candidate into merged or resolved samples. The π^0 decays into two photons and if the two photons are reconstructed in separate ECAL cells, then the π^0 candidate is said to be resolved whereas if the reconstruction of the photons occurs in the same ECAL cell, the π^0 candidate is said to be merged (see Chapter. 3.3.9).

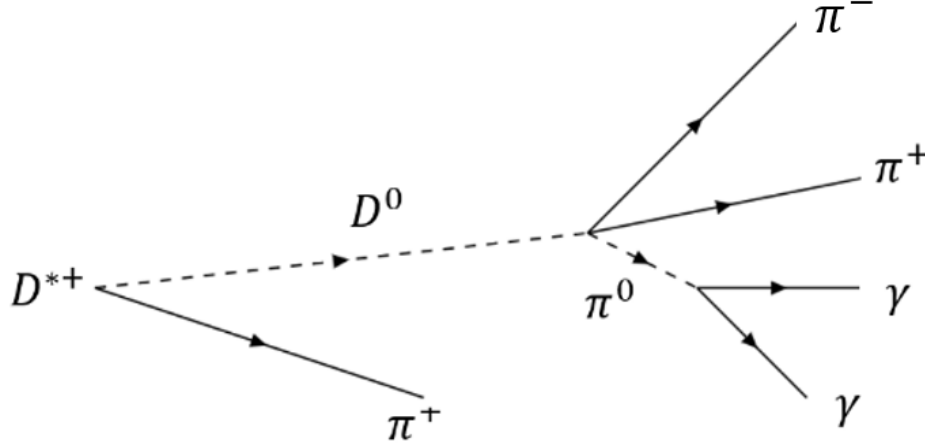


Figure 5.1: A schematic of the decay topology. Particles which are measured and used in the reconstruction procedure are shown using solid lines. Particles which decay but do not interact with the detector directly are shown using dashed lines.. Flight distances are not shown to scale particularly for the π^0 which decays immediately after production so the two photons emerge from the same vertex as the two charged pions.

Due to the different reconstruction methods, the kinematics of the resolved and merged π^0 candidates vary and hence the selection strategy will differ between the two samples as will be made evident in the next sections.

5.2 Trigger selection

Events that are available for offline processing have trigger information stored such that analysts can select events that satisfy a well defined set of trigger lines. The trigger lines are algorithms that return a decision on whether to accept or reject an event based on a specific event topology. For a given trigger line and track (or a combination of tracks), events can be classified into two categories:

- *Trigger on Signal (TOS)*. These events are triggered for a specific signal decay, independent of the other tracks in the event. The event is accepted if the information used to reconstruct the signal tracks satisfies selection criteria for a particular trigger line.
- *Trigger independent of Signal (TIS)*. These events are triggered independently of presence of signal tracks. A candidate is therefore said to be TIS if the event would pass the selection criteria even if the candidate were not present. This means that the other tracks/particles are

sufficient to satisfy the trigger condition.

The trigger requirements imposed in this analysis are presented in Table 5.1. We require candidates to pass one of four L0 lines, with the strategy to keep a high efficiency without introducing charge asymmetries. Candidates must also pass one of the two HLT1 trigger lines (see below). Finally, we make use of dedicated HLT2 lines specifically designed for the final states under consideration.

Level	Trigger Line
L0	Dstr_L0_Global_TIS OR H1_L0HadronDecision_TOS OR H2_L0HadronDecision_TOS OR pi0_L0PhotonDecision_TOS
HLT1	HLT1TwoTrackMVA OR HLT1TrackMVA
HLT2	Dstr_Hlt2CharmHadDstp2D0Pip_D02[Km,Pim]PipPi0_Pi0_[M,R]_Decision_TOS OR Dstr_Hlt2CharmHadInclDstr2PiD02HHXBDTDecision_TOS

Table 5.1: Summary of the trigger requirements used in the analysis.

5.2.1 L0 Selection

The overall L0 trigger strategy is designed to select D^0 mesons based on the presence of a large energy deposit in the hadronic calorimeter. The energy resolution of these deposits in the calorimeter is large and hence L0 requirements don't provide great discriminatory power. Nevertheless, we require either of the charged daughters of D^0 to be TOS on L0Hadron or the π^0 to be TOS on L0Photon. The TOS requirement on the daughters of D^0 selects explicitly those specific daughter particles in the final state. Finally, we also trigger any other events where the D^{*+} candidate is TIS on L0Global. This ensures that the trigger decision doesn't depend on the properties of the soft pion from the D^* decay, which can cause sizeable charge asymmetries as a result of the dependence on the properties of the $\pi_s^\pm$.

The selection for the control channel must mimic as closely as possible the selection of the signal channel. This is done to provide a calibration sample on which the energy test can be performed to cross-check the presence of any nuisance asymmetries arising from detector effects. The same L0 requirements are placed on the $D^0 \rightarrow K^- \pi^+ \pi^0$ channel. The breakdown of candidates passing each of the L0 trigger lines is shown in Table 5.2. The majority of candidates are selected through the line L0_Global_TIS, although other lines provide important increases to the signal yield, especially for the merged sample.

5.2.2 HLT1

At the HLT1 level, at least one of the children of the D^0 should fire the HLT1TrackMVA line, or the combination of the two children should fire the HLT1TwoTrackMVA line. The HLT1TrackMVA line requires

ID	L0 configuration	Retention [%]			
		$D^0 \rightarrow \pi\pi\pi^0$		$D^0 \rightarrow K\pi\pi^0$	
		Resolved	Merged	Resolved	Merged
1	L0_Global_TIS	82.8	69.9	75.3	56.1
2	1 or H1_LOHadron_TOS	88.5	78.4	84.4	67.2
3	2 or H2_LOHadron_TOS	92.5	83.2	89.0	71.6
4	3 or pi0_LOPhoton_TOS	92.5	86.2	89.2	78.6

Table 5.2: Cumulative retention of each L0 requirement applied in this analysis. The retention is calculated with respect to the number of candidates passing the first stage of offline selection (‘stripping’ - see below).

that the track parameters satisfy the following

$$[(p_T > 25.0) \wedge (\chi_{\text{IP}}^2 > 7.4)] \vee \left[(p_T \in [1.0, 25]) \wedge \left(\ln(\chi_{\text{IP}}^2) > \left(\ln(7.4) + \frac{1.0}{(p_T - 1.0)^2} + \lambda \left(1 - \frac{p_T}{25.0} \right) \right) \right) \right],$$

where momenta are expressed in GeV/c and λ is a constant which is varied in the range [1.1,2.3] for the duration of Run 2. The χ_{IP}^2 is defined as the difference between the χ^2 of the PV reconstructed with and without the track under consideration. The constraint placed on this quantity allows the selection of tracks originating from a detached secondary vertex i.e. the D^0 decay vertex.

In principle, requiring the HLT1TrackMVA to fire should be enough but in practice we can gain efficiency by exploiting the fact that our signal has two tracks originating from the D^0 . The presence of the second track enables a looser constraint to be placed on the momenta by considering the sum of the momenta of both tracks rather than the momenta of a single track. Consequently, some events lost to HLT1TrackMVA are retrieved when requiring the events to alternatively pass HLT1TwoTrackMVA. The HLT1TwoTrackMVA applies a requirement on the output of a Boosted Decision Tree (BDT) which determines the quality of the two daughter tracks by taking the following inputs:

- The χ^2 of the distance between the PV and the Decay Vertex (DV) (known as χ_{FD}^2) of the mother particle
- Sum of p_T of both daughter tracks
- Number of tracks with $\chi_{\text{IP}}^2 < 16$
- χ^2 of the vertex fit of both daughter tracks

The same HLT1 requirements are placed on the $D^0 \rightarrow K^- \pi^+ \pi^0$ channel and the breakdown of the efficiency of the HLT1 trigger lines is shown in Table 5.3 with respect to the number of candidates passing the first stage of the offline selection (‘stripping’).

ID	HLT1 Configuration	Retention [%]			
		$D^0 \rightarrow \pi\pi\pi^0$		$D^0 \rightarrow K\pi\pi^0$	
		Resolved	Merged	Resolved	Merged
1	HLT1TrackMVA	90.3	91.8	94.4	95.3
2	1 or HLT1TwoTrackMVA	92.2	94.5	96.1	97.9

Table 5.3: Cumulative retention of each HLT1 requirement applied in this analysis. The retention is calculated with respect to the number of candidates passing stripping.

5.2.3 HLT2

The HLT2 software trigger selects decays of the form $D^{*\pm} \rightarrow D^0(\rightarrow hh\pi^0)\pi^\pm$ using exclusive lines HLT2CharmHadDstp2D0Pip_D02xxPipPi0_Pi0_y with xx standing for Km or Pim and y standing for M or R corresponding to merged or resolved π^0 candidates (Sec. 5.1). Signal and control mode lines have the same requirements other than different cuts for the particle identification (PID) of daughter kaons and pions used to distinguish between the modes. The HLT2 requirements are presented in Table 5.4. Kinematic and topological quantities used in Table 5.4 and the subsequent stages of selection are defined below:

- **Primary Vertex (PV):** The location of the primary pp collision from which the decay originates.
- **DOCA:** The distance of closest approach between all pairs of particles, measured in mm.
- **DOCA χ^2 :** The χ^2 of the distance of closest approach, between all pairs of particles computed assuming that the particles come from a common origin, taking into account the uncertainty on the track parameter. This quantity is calculated separately for each pair of particles.
- **χ^2 w.r.t best PV:** χ^2 of the track fit pointing to the best PV (can be normalised to degrees of freedom). For particles not originating from the PV, this quantity assumes a higher value.
- **Vertex χ^2 :** χ^2 of the vertex combination fit (can be normalised to degrees of freedom). Vertices reconstructed with good quality produce a lower vertex χ^2 .
- **D^0 DIRA:** Cosine of the direction angle between the particle momentum vector and the displacement vector joining the production and decay vertices. For a fully reconstructed particle, the particles momentum vector is aligned with the displacement vector resulting in a direction angle of close to zero.
- **τ_{D^0} :** Decay time of the D^0 particle.
- **PID:** Particle Identification based on a particle hypothesis i.e. PIDK is particle ID for the kaon hypothesis so this quantity will assume a higher value if the particle is indeed a kaon.
- **ghost probability** - Probability that a track does not correspond to a true charged parti-

cle trajectory, but simply reflects a group of unrelated hits which happen to fulfil the track reconstruction requirements. See Sec.3.3.4.

In addition to the dedicated exclusive lines, this analysis also makes use of an inclusive trigger line to further increase the selected signal yield. This is the BDT-based line,

`Dstr_Hlt2CharmHadInclDstr2PiD02HHXBDTDecision_T0S`. As previously, the control mode and the signal mode share the same HLT2 requirements. The efficiency of the HLT2 trigger lines is shown in Table 5.5 with respect to the number of candidates passing stripping. The mass of the D^0 can be calculated through 3-body invariant mass calculation of the hadrons ($\pi^- \pi^+ \pi^0$) with and without a global kinematic re-fit. The former is defined as m_{D^0} and latter as $m_{\pi^- \pi^+ \pi^0}$ in the cuts shown in Tab. 5.4.

Particle	Quantity	Cut
$\pi^\pm$ pair	DOCA	< 0.08 mm
	$m_{\pi\pi}$	< 1900 MeV/ c^2
	vertex χ^2	< 20
	χ^2 w.r.t best PV	> 25
	χ^2_{IP}	> 36
	Total p_T	> 1900 MeV/ c
π^0	p_T	> 1700 MeV/ c
	χ^2_{IP}	> 36
D^0	vertex χ^2/DoF	< 20
	p_T	> 1400 MeV/ c
	$m_{\pi^- \pi^+ \pi^0}$	$\in [1700, 2020]$ MeV/ c^2
	m_{D^0}	$\in [1745, 1985]$ MeV/ c^2
	χ^2 w.r.t best PV	< 50
	D^0 DIRA	> 0.9995
	τ_{D^0}	> 0.2 ps
$D^{*\pm}$	$m_{D^{*\pm}} - m_{D^0} - m_{\pi_s}$	< 45.43 MeV/ c^2
	vertex χ^2/DoF	< 10
	$m_{\pi^- \pi^+ \pi^0 \pi_s} - m_{\pi^- \pi^+ \pi^0} - m_{\pi_s}$	< 55.43 MeV/ c^2

Table 5.4: HLT2 requirements for the HLT2CharmHadDstp2D0Pip_D02PimPipPi0_Pi0 line

ID	HLT2 Configuration	Retention [%]			
		$D^0 \rightarrow \pi\pi\pi^0$		$D^0 \rightarrow K\pi\pi^0$	
		Resolved	Merged	Resolved	Merged
1	[...]InclDstr2PiD02HHXBDT	47.3	23.1	70.6	36.2
2	1 or [...]Dstp2D0Pip_D02PimPipPi0_Pi0	48.9	60.3	73.1	83.5

Table 5.5: Cumulative retention of each HLT2 requirement applied in this analysis. The retention is calculated with respect to the number of candidates passing stripping.

5.3 Stripping

Events passing the trigger requirements are stored on tape but preceding the customised offline cuts is the application of another set of cuts known as ‘Stripping’. Stripping at LHCb is defined as centralised offline analysis stage as defined in Chapter. 3.5 and its purpose is to reduce the size of the data which needs to be stored and analysed.

The stripping selection consists of two lines, `StrippingDstarD2hhpi0_pipipi0_[M,R]`, one each for the merged (`_M`) and resolved (`_R`) π^0 candidates. Resolved pions have a larger opening angle between the two photons, which is associated with lower π^0 transverse momentum. Combinatorial background are larger for low momentum pions and as such, the resolved sample includes a large contamination from combinatorial background. In contrast, the merged neutral pions tend to have higher transverse momentum and thus a smaller contribution from combinatorial background. However, the resolution of the merged π^0 invariant mass is significantly worse than that for the resolved π^0 , thus there is no cut applied on this mass in the merged stripping line. The stripping selection is shown in Tables 5.6 and 5.7 gives a summary of the data samples used in this analysis, along with the total candidate yields after the stripping stage.

Particle	Quantity	Cut
GEC	number of long tracks	<180
$\pi^\pm$	p_T	> 500 MeV/c
	ghost probability	< 0.35
	PIDK	< 0
π^+ or π^-	p_T	> 1700 MeV/c
	χ^2 w.r.t best PV	> 36
$\pi^\pm$ pair	DOCA χ^2	< 15
	$m_{\pi\pi}$	< 1850 MeV/c
	vertex χ^2/dof	< 3
	χ^2 w.r.t best PV	> 100
π^0	p_T	> 500 MeV/c
π^0 (resolved only)	$ m_{\gamma\gamma} - 135 \text{ MeV}/c^2 $	< 15 MeV/c ²
D^0	vertex χ^2/dof	< 20
	p_T	> 1400 MeV/c
	$ m_{\pi^-\pi^+\pi^0} - 1864.84 \text{ MeV}/c^2 $	< 160
	$ m_{D^0} - 1864.84 \text{ MeV}/c^2 $	< 150 MeV/c ²
	p_T	> 300 MeV/c
	ghost probability	< 0.35
	PIDe	< 5
	$\min \chi_{IP}^2$	< 9
$D^{*\pm}$	$m_{D^{*\pm}} - m_{D^0}$	< 180 MeV/c ²
	vertex χ^2/dof	< 9
	DOCA χ^2	< 20
	$m_{\pi^-\pi^+\pi^0\pi_s} - m_{\pi^-\pi^+\pi^0}$	< 185 MeV/c ²

Table 5.6: Summary of selection criteria applied in the `StrippingDstarD2hhpi0_pipipi0_[R,M]` stripping lines. Here π_s refers to the soft pion from the $D^{*\pm}$ decay. GEC is a general event cut to reduce the number of tracks in every event.

Polarity	$D^0 \rightarrow \pi\pi\pi^0$		$D^0 \rightarrow K\pi\pi^0$		$\int \mathcal{L} dt [fb^{-1}]$
	Merged	Resolved	Merged	Resolved	
<i>2015 MagUp</i>	566,436	16,425,192	675,004	15,261,399	0.122
<i>2015 MagDown</i>	708,842	22,550,090	875,079	21,871,083	0.162
<i>2016 MagUp</i>	4,666,880	105,610,065	5,880,051	89,709,513	0.775
<i>2016 MagDown</i>	4,920,805	124,837,389	6,178,817	107,431,164	0.825
<i>2017 MagUp</i>	5,033,764	131,460,430	6,618,835	118,003,449	0.820
<i>2017 MagDown</i>	5,273,950	137,125,239	7,038,766	123,341,727	0.862
<i>2018 MagUp</i>	8,514,805	168,959,408	11,868,824	150,348,772	1.101
<i>2018 MagDown</i>	7,937,461	158,187,000	11,108,499	140,782,692	1.024

Table 5.7: Number of reconstructed candidates passing stripping selections for different years and magnet polarities.

5.4 Offline selection for signal mode $D^0 \rightarrow \pi^- \pi^+ \pi^0$

The final signal sample used in this analysis is selected in two offline stages. First a loose cut based preselection is applied, followed by a multivariate analysis.

When reconstructing the charm mesons from the final state particles, the Decay Tree Fitter (DTF) is used. The DTF simultaneously considers all of the tracks within the decay topology, adjusting particle kinematics to give the best vertex fit, within a set of externally-imposed constraints. The full D^{*+} decay chain is reconstructed with a constraint imposed that the D^{*+} originates from the pp collision point. The π^0 candidates also have their mass constrained to the known value from the PDG [89]. When calculating the Dalitz variables used as inputs to the energy test, an additional constraint is imposed that the reconstructed mass $m(\pi^- \pi^+ \pi^0)$ matches the known D^0 meson mass. This ensures both that the candidates lie in the physically allowed Dalitz region, and it also improves the mass resolutions of the D^* , and the intermediate two-body states (and hence the Dalitz variables).

The difference in the reconstructed invariant mass between the D^* and D^0 ($\equiv \Delta m$), is used as a handle to improve the purity and signal significance of the selection. Whenever stated in the analysis, Δm corresponds to the reconstructed mass difference given by $m(\pi^- \pi^+ \pi_s^0 \pi_s^+) - m(\pi^- \pi^+ \pi^0)$, where π_s^+ is the soft pion from the D^{*+} decay. The low Q-value of the decay results in a sharply peaked signal, giving improved purity for the analysed sample.

5.4.1 Preselection

The preselection requirements are as follows:

- A cut is imposed on the direction of DIRA of the D^0 meson, defined as the angle between the particle momentum vector and the displacement vector joining the production and decay vertices. The angle is required to be less than fifty millirads, $\arccos(\text{D_DIRA_OWNPV}) < 0.05$ rad.
- A cut is imposed on the logarithm of the χ^2 of the kinematic fit in which the D^* is required to originate from the primary vertex. A cut value of $\log(\chi_{D^*}^2) < 2.3$ is chosen based on the signal and background distributions of $\log(\chi_{D^*}^2)$ (Fig. 5.2). The signal and background distributions are disentangled using the `sPlot` technique which assigns the relevant weight to each candidate, based on fits to the ΔM distributions (see later). Note that this requirement implicitly requires that the DTF refit converges successfully.
- For merged π^0 candidates, a cut is imposed on the reconstructed invariant mass of the neutral pion. The cut value is chosen by inspecting the final state phase space as well as fitting the reconstructed merged pion mass, as shown in Fig. 5.3. Here, the reconstructed π^0 mass is parameterised by a Gaussian function and the background is parameterised using a first order polynomial. The selected region is defined by $|m(\pi^0) - 135| < 28 \text{ MeV}/c^2$, corresponding to approximately two standard deviations of the fitted Gaussian. This cut removes backgrounds from mis-identified resolved pions in the instance that only one of the final state photons is

present or contributions from converted e^+e^- pairs. A corresponding selection is not performed for resolved π^0 candidates since a requirement for the candidates to be within $\pm 15 \text{ MeV}/c^2$ is applied in the stripping line.

- The reconstructed mass of the D^0 candidates must be in the range $|m(D^0) - 1864.84| < 60 \text{ MeV}/c^2$ for both resolved and merged candidates. The reconstructed D^0 mass for both categories is shown in Fig. 5.4, along with the selected mass region. For this plot the final selections are applied except for a much looser requirement on $\text{DTF}\chi^2 < 5$. This choice allows the D^0 mass peak to be clearly compared to the signal mass window. The tighter cut $\text{DTF}\chi^2 < 2.3$ applied in the final selection significantly suppresses the background, but it also sculpts the distribution of the remaining background making it hard to separate easily by eye from the signal peak (note: we do not use the D^0 mass distribution for any aspect of this analysis, except for this mass window criterion).

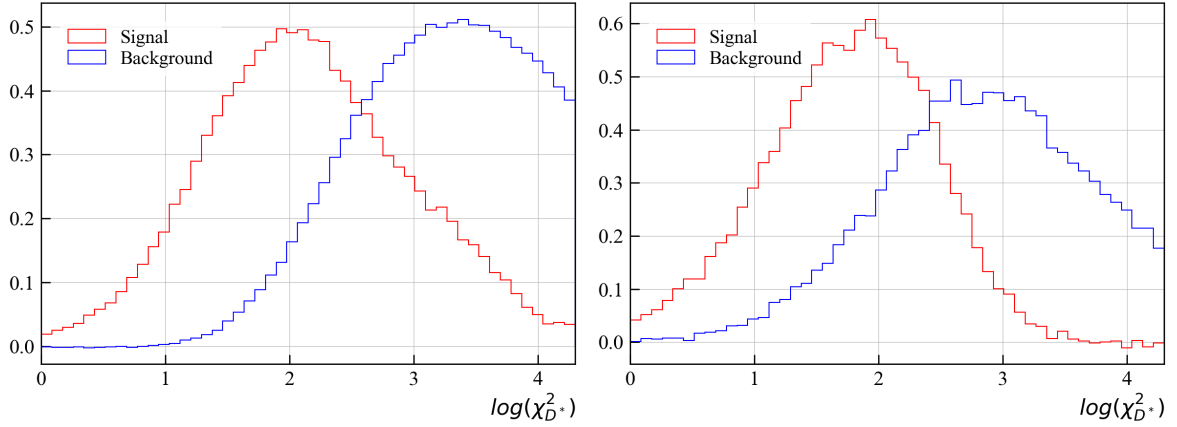


Figure 5.2: Signal and Background distributions of $\log(\chi^2_{D^0})$ for the resolved (left) and merged (right) sample before imposing the aforementioned cut to suppress background.

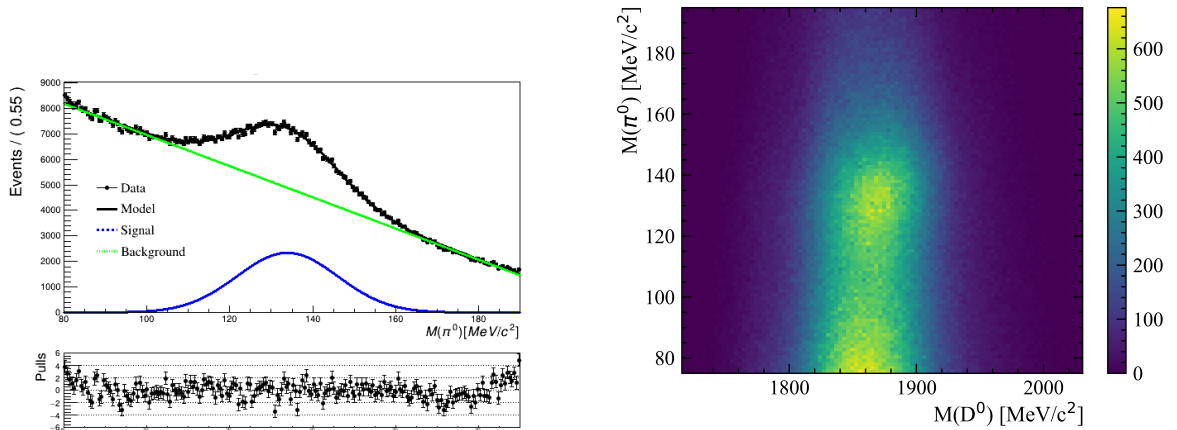


Figure 5.3: Left: Fit to the neutral pion mass for the merged sample, with blue (signal) and green (background) PDFs shown separately. Right: 2D plot of the reconstructed masses of the merged pion and the associated D^0 meson candidate.

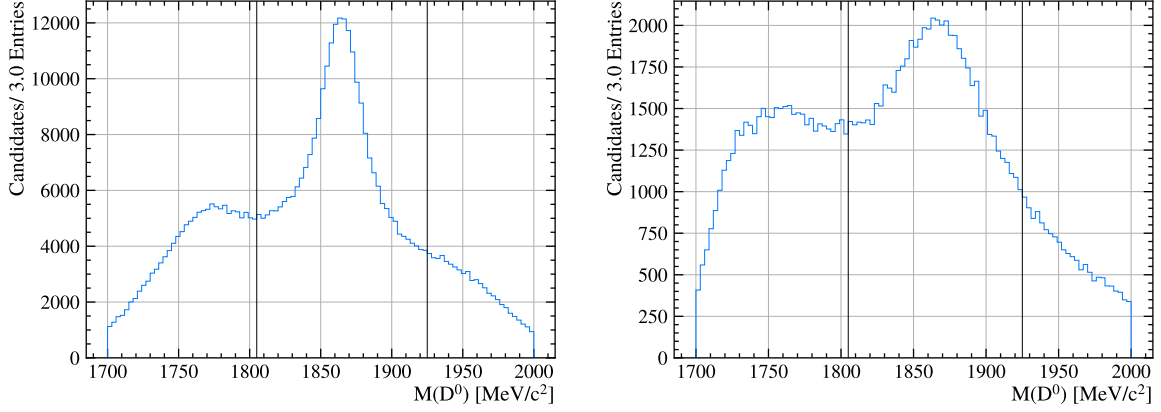


Figure 5.4: The D^0 mass distribution for resolved (left) and merged (right) samples after all selections except with a looser requirement on the DTF χ^2 . This is to illustrate the choice of signal mass window (delimited by vertical lines) compared to the width of the mass peak..

5.4.2 Multivariate analysis

In high energy physics, multivariate analysis tools are used to distinguish between signal and background. These tools comprise supervised machine learning algorithms that learn about the key characteristics of the signal and background candidates from input features provided to the algorithm. The training of the algorithm is typically performed on Monte Carlo (MC) simulation samples which are generated using a variety of different packages that simulate the pp collisions, the decay of particles and the interaction of particles and final state radiation with the detector. The algorithm can then be applied to real data to obtain a probability of an event belonging to a signal decay from the features that were used to train the algorithm. However, the training of the MVA in this analysis is carried out in a completely data-driven manner as explained in the next paragraphs.

Separate MVA based classifiers are developed for the resolved and merged samples, with the aim of suppressing the combinatorial background. The use of separate classifiers is motivated by the differing decay kinematics which can be seen in the Δm distributions in Fig. 5.5. The resolved sample includes a significant combinatorial background contribution, a consequence of the low transverse momentum of the neutral pion. In contrast, the merged sample already shows high purity after the preselection stage. We find that there is no appreciable gain in signal significance to be made by applying an MVA requirement on the merged sample, and so the MVA is only applied to the resolved sample.

In order to eliminate bias in the training, the resolved sample is further divided into two subsets defined by odd and even event numbers. A classifier is then trained and evaluated on the even sample and used to classify the odd sample, and vice versa. This method of cross validation removes bias from the training by ensuring that the classifier is not applied to candidates used in the training [99].

The classifiers are trained in a data driven manner with the signal and background training samples obtained using the `sPlot` technique. This technique is a statistical method that can unravel a

distribution into its signal and background components. The input for this technique is a fit performed on a variable that is statistically independent of any variables that will be reconstructed using the output of the technique. In this analysis, an unbinned maximum likelihood fit performed on the Δm distribution is utilised which is independent of the variables that will be used to train the classifier. Performing a fit assigns a probability to determine whether each candidate belongs to the signal or background class. The `sPlot` converts these probabilities into weights from which signal and background `sWeights` are assigned to each candidate. The signal and background `sWeights` of each candidate sum to one and correspond to the respective population likelihoods [100]. In the Δm fit, the signal is parameterised by three independent Gaussian functions, with the background parameterised using the empirical formula

$$F_{bkg} = (\Delta m - m_{th})^\alpha e^{-\beta(\Delta m - m_{th})}. \quad (5.1)$$

Here m_{th} is a fixed threshold parameter defined as the charged pion rest mass, and the factors α and β are free parameters in the fit. The `sPlot` technique is applied to 40% of the resolved sample and the full merged sample with the fit projections shown in Fig. 5.5. A fraction of the resolved sample is chosen to ensure the sample sizes are manageable, considering the large yields, and the fact that larger sample sizes give negligible gain in the performance of the classifier. While these fits show some mismodelling for the resolved sample, the impact on the final analysis would only be a small degradation in selection performance. As such, we judge the fit quality to be sufficient for our purposes. The fit parameters for both categories are presented in Table 5.8.

Parameter	Resolved Sample	Merged Sample
Signal [10^3]	832 ± 3.28	816 ± 2.52
σ_1 [MeV/ c^2]	0.387 ± 0.00220	1.96 ± 0.0716
σ_2 [MeV/ c^2]	1.17 ± 0.0152	0.908 ± 0.0306
σ_3 [MeV/ c^2]	0.225 ± 0.0226	0.533 ± 0.00762
μ_1 [MeV/ c^2]	145.47 ± 0.0094	146.079 ± 0.0640
μ_2 [MeV/ c^2]	145.493 ± 0.00943	145.525 ± 0.0102
μ_3 [MeV/ c^2]	145.785 ± 0.0256	145.424 ± 0.00279
α	0.655 ± 0.00304	0.697 ± 0.0133
β	0.119 ± 0.000619	0.0648 ± 0.00301
Background [10^3]	2771.4 ± 3.55	298.7 ± 2.42

Table 5.8: Results of the Pre-MVA fit to the ΔM distribution for 40% of resolved sample and the full merged sample as presented in Fig. 5.5

We consider several different types of classifiers, and use the area under the receiver-operator characteristic (ROC) curve as a figure of merit to select the final classifier to be used. The ROC curve shows the signal efficiency as a function of background rejection for a range of classifier cuts and hence area under this curve is greatest for the best performing classifier i.e. one that optimises signal efficiency

and background rejection. A variety of Boosted Decision Trees (BDTs) are considered. A decision tree is a simple structure which contains layers of nodes. At each node, a criterion, consisting of one or more variables such as kinematic properties, is evaluated and yields a binary output. Each node leads to a new node whereby a new criterion is evaluated. The process is iterated until each candidate is assigned to a particular species, signal or background. Boosting is a method that creates many trees iteratively and combines the weak trees (a classifier that is only slightly better than random guessing) into a strong classifier. This is done by assigning a weight to the output of a tree to quantify its performance. The greater the misclassification, the higher the weight assigned to the output of that tree. The process is repeated iteratively until a pre-defined objective function is minimised. The set of discriminating variables has been selected with the aim of maximising background suppression. The final input variables are as follows:

- **log_FITCHI2:** The log of the χ^2 probability calculated for the DTF fit obtained by imposing only the D^* PV constraint and the π^0 mass constraint.
- **Dstr_PT:** The transverse momentum of the D^{*+} candidate.
- **D_PT:** The transverse momentum of the D^0 candidate.
- **D_FDCHI2_OWNPV:** The flight distance χ^2 of the D^0 meson.
- **log_D_IPCHI2_OWNPV:** The logarithm of the χ^2_{IP} of the primary vertex of the D^0 given as the difference in χ^2 of the kinematic refit in the presence and absence of the D^0 .
- **D_CosTheta:** The cosine of the angle between the D^0 momentum in the D^{*+} rest system and the D^{*+} momentum in the lab frame.
- **Kstr_CosTheta:** The cosine of an angle between the $\pi^+ \pi^-$ resonance momentum in D^0 rest frame and D^0 momentum in lab frame.
- **acos_D_DIRA_OWNPV:** The angle between the particle momentum vector and the displacement vector joining the production and decay vertices.
- **pi0_CosTheta:** The cosine of the angle between the π^0 momentum in the D^0 rest system and the D^0 momentum in the lab frame.
- **pi0_PT:** The transverse momentum of the π^0 .
- **pi0_P:** The momentum of the π^0 .
- **H_PT_SUM:** The scalar sum of the transverse momenta of π^- and π^+ .
- **log_pi0_CL:** The log of the confidence level of the neutral pion. The confidence level of the π^0 is a PID variable comparing a species hypothesis for a π^0 candidate. The greater the confidence level, the more likely the particle in question is a π^0 .

The various ROC curves of the classifiers trained with these variables are shown in Fig. 5.6. The classifiers utilised are the ones available in TMVA [101]. The analysis proceeds with the Decorrelated

BDT (BDTD) as this method has the largest area under the ROC curve, averaged over the folds as well as the greatest stability when training with negative sWeights for both the resolved samples [102]. The ranking of variables for this classifier is given in Table 5.9. The signal and background distributions of the discriminating variables for the resolved sample are shown in Fig. 5.7.

TMVA Rank	Variable	Separation
1	Dstr_FIT_Pi0PT	0.4039
2	pi0_CosTheta	0.3567
3	Kstr_CosTheta	0.3565
4	Dstr_FIT_Pi0P	0.3318
5	log_pi0_CL	0.2405
6	Dstr_FIT_DPT	0.1198
7	Dstr_FIT_PT	0.1159
8	acos_D_DIRA_OWNPV	0.0714
9	log_FITCHI2_Prob	0.0595
10	D_FDCHI2_OWNPV	0.0558
11	log_D_IPCHI2_OWNPV	0.0525
12	D_CosTheta	0.0320
13	H_PT_SUM	0.0238

Table 5.9: Rank of BDT variables. The separation is defined according to an integral which accounts for the signal and background P.D.F's [101]. It is zero for identical signal and background shapes and one for shapes with no overlap.

Signal and background distributions of the MVA output variable for the training and testing samples are superimposed on the same plot to check for over-training as shown in Fig. 5.8. The Kolmogorov-Smirnov (KS) test is also applied to the training and testing samples which quantifies the likelihood that the two samples are drawn from the same distribution. The KS probabilities are reasonable, indicating no sign of over-training.

The figure-of-merit to be optimised when choosing a cut value for the MVA is the signal significance, defined as $S/\sqrt{S+B}$, where S is the signal yield and B is the background yield in the signal mass region ($|\Delta m - 145.4| < 1.8 \text{ MeV}/c^2$). The signal significance is maximised based on the preliminary signal and background yields from the binned fit to the Δm distributions after the pre-selection stage (Fig. 5.5).

The maximum signal significance is achieved with a requirement that the BDT output value exceed 0.05. This also happens to give a near-maximum value for the alternative metric of signal efficiency multiplied by purity. This requirement is therefore imposed for the resolved sample.

5.4.3 Final selected signal sample

After applying the trigger, stripping, preselection, and MVA requirements, two final selection criteria are imposed to handle clone tracks and multiple candidates.

Clone tracks occur due to mis-reconstruction, whereby a single charged particle ends up being reconstructed as multiple near-colinear tracks (see Chapter. 3.3.4). Signal candidates can then include the same track twice, which forms a small but potentially problematic background. Such candidates are characterised by having pairs of tracks in the final state with very small angular separations. In this analysis there are three final-state tracks, two from the D^0 decay and the soft pion from the $D^{*\pm}$ decay, giving three possible track-pairs which can suffer from clones. Figure 5.9 shows the three corresponding angular separations. In all three cases, the distribution falls steadily as the separation approaches zero, but there are peaks near zero coming from cloned tracks. These are rejected from the data sample by imposing a cut at > 0.0005 rad on all three track separation angles. This reduces the contamination from clones to negligible levels. Approximately 0.5% of the events are removed as a result of applying these cuts.

It is also possible to reconstruct multiple distinct signal candidates in a single pp bunch crossing (event). For this analysis, by far the most common source of multiple candidates is a single D^0 candidate being associated with multiple soft pions to produce several $D^{*\pm}$ candidates. In this case, the D^0 properties (such as Dalitz variables) are identical between candidates (or near identical, since the DTF can shift kinematics slightly based on the soft pion properties). This can be dangerous for the energy test, if the effect differs for D^0 and $\bar{D}^0$ candidates. As such, we limit our sample to at most one signal candidate per event, randomly selected. Multiple candidates are present in approximately 3% (6%) of events in the merged (resolved) samples before this random selection is imposed.

The Δm distributions after applying all selection criteria, including clone and multiple candidates rejection, are shown in Fig. 5.10. While this analysis does not rely on fitting these distributions, it is useful to do so to assess the purity and yields of the samples. This information can then be fed into the toy sensitivity studies (discussed in Sec. 6.1) to ensure that they are as realistic as possible.

For these Δm fits, the signal component is modelled for the resolved case as the sum of two Gaussians and a bifurcated Gaussian with different widths for left and right tails of the distribution. For the merged case three symmetric Gaussian functions are used. The background model in both cases is the threshold shape given by Eq. (5.1). The fit results are summarised in Table 5.10. The final signal sample is selected from the signal region corresponding to the mass window $|\Delta m - 145.4| < 1.8 \text{ MeV}/c^2$. This yields a purity of 81% and significance of 1181.5 for the resolved sample. Additionally, a purity of 91% and a significance of 810 is obtained for the merged sample without the application of an MVA cut. A final yield of 1713×10^3 and 757×10^3 events are selected for the resolved and merged channels respectively. This is more than four times the yield used in the Run 1 analysis [97].

Parameter	Resolved	Merged	Resolved (Fit as Pre-MVA)
N(Signal) [10^3]	1878 ± 5.27	816 ± 2.52	1878 ± 5.48
N(Background) [10^3]	1190 ± 5.20	298.7 ± 2.42	1189 ± 5.42
σ_1 [MeV/ c^2]	0.307 ± 0.00302	1.96 ± 0.0716	0.305 ± 0.00260
σ_2 [MeV/ c^2]	1.666 ± 0.0173	0.908 ± 0.0306	1.664 ± 0.0150
σ_3 [MeV/ c^2]	-	0.533 ± 0.00762	0.558 ± 0.00596
σ_L [MeV/ c^2]	0.575 ± 0.0120	-	-
σ_R [MeV/ c^2]	0.550 ± 0.00747	-	-
μ_1 [MeV/ c^2]	145.411 ± 0.00206	146.079 ± 0.0640	145.415 ± 0.00104
μ_2 [MeV/ c^2]	145.420 ± 0.00725	145.525 ± 0.0102	145.414 ± 0.00653
μ_3 [MeV/ c^2]	145.484 ± 0.0113	145.424 ± 0.00279	145.462 ± 0.00217
α	0.907 ± 0.00624	0.697 ± 0.0133	0.907 ± 0.00581
β	0.177 ± 0.00149	0.0648 ± 0.00301	0.178 ± 0.00136

Table 5.10: Fit parameters for the Δm distribution for both resolved and merged samples after the application of all selection requirements (excepting the Δm cut) corresponding to the projections in Fig. 5.10. Also shown in the final column are the fit parameters for the resolved case with an alternative fit model - i.e. the same function used for the pre-MVA fit.

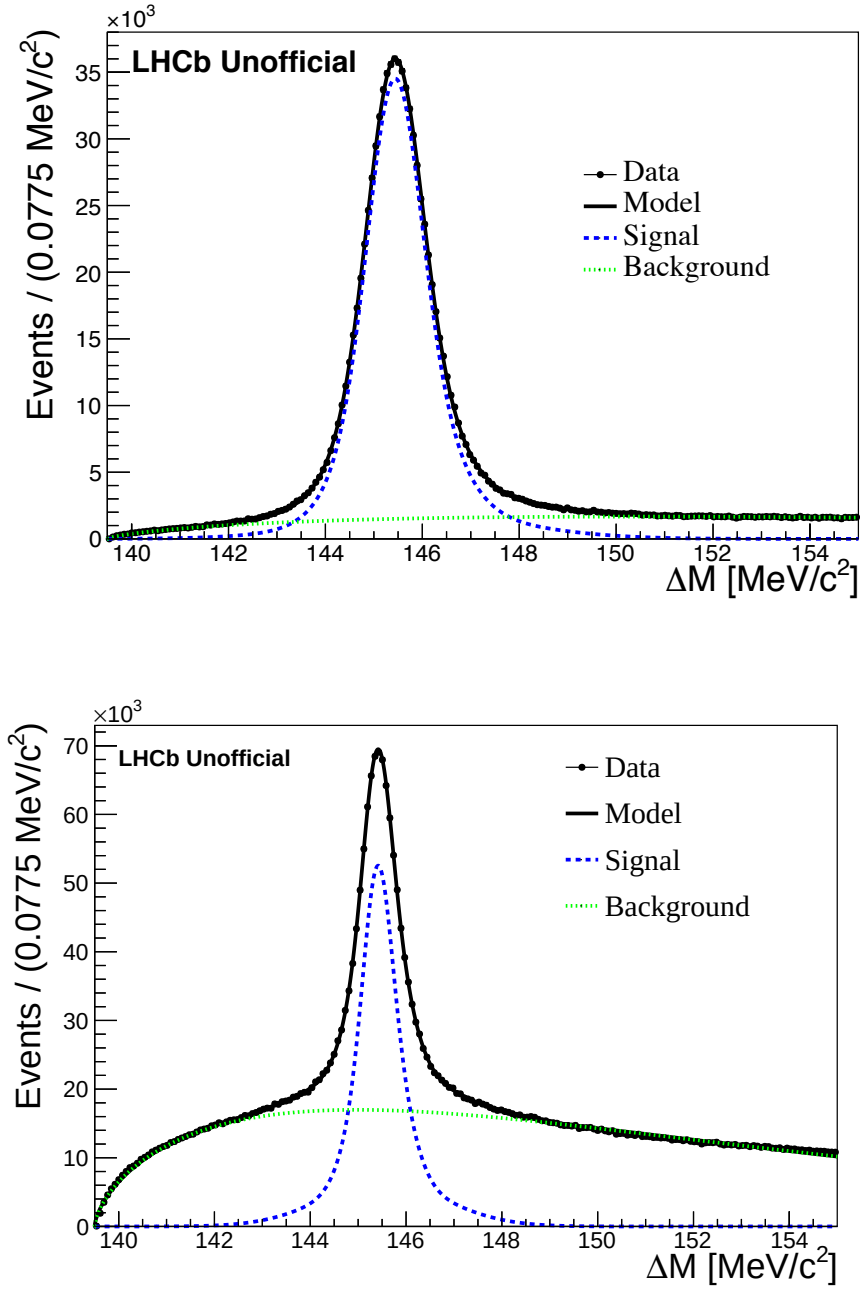


Figure 5.5: The fits for the merged (top) and sub-sample (40%) of resolved (bottom) samples before any MVA cut. The sWeights obtained from the resolved sample fit are used to train the classifier that suppresses combinatorial background.

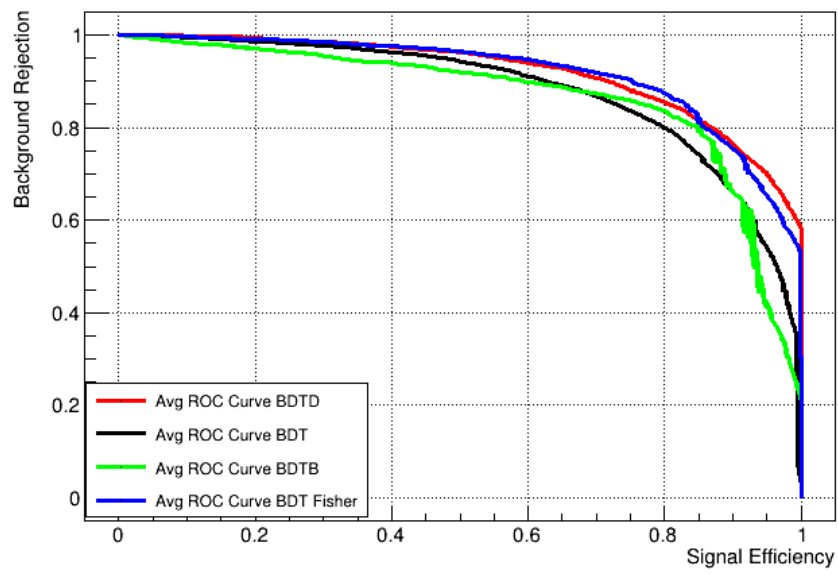


Figure 5.6: The ROC curves for the different classifiers trained on resolved sample.

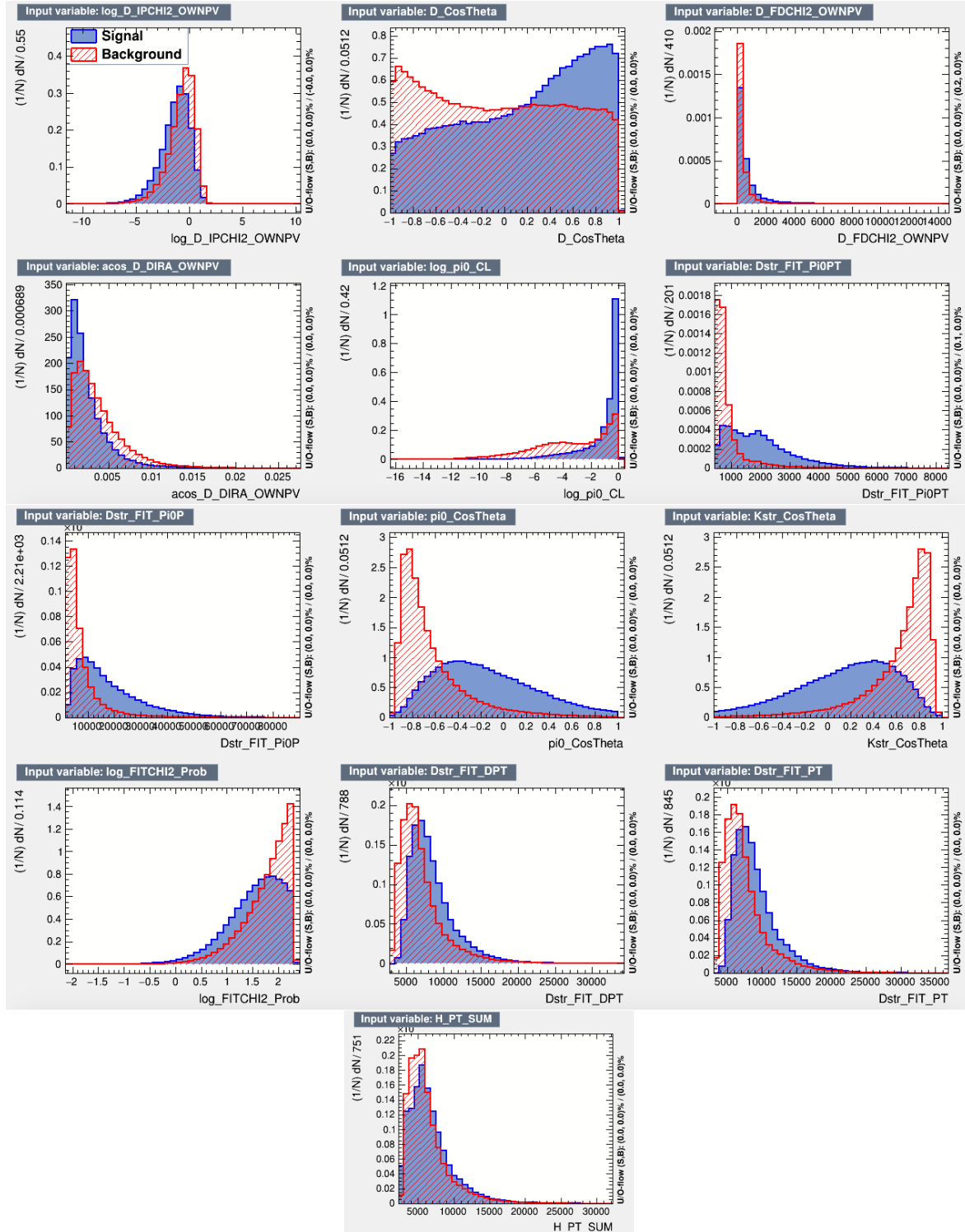


Figure 5.7: Normalised distributions of the input variables in the resolved sample.

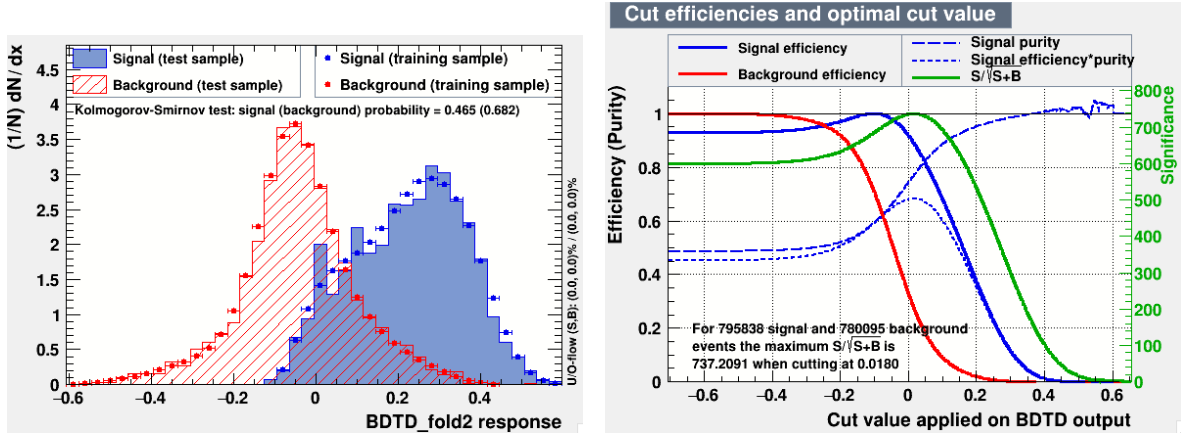


Figure 5.8: The BDT Output (left) and the significance/purity scans (right) for the resolved sample.

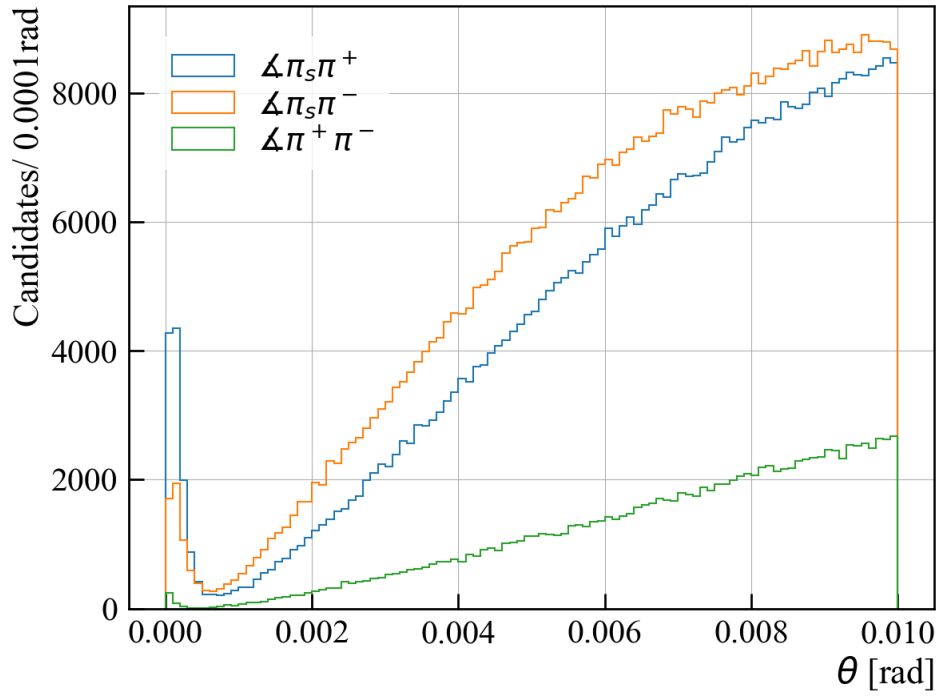


Figure 5.9: Angles between pairs of tracks of charged particles, showing the clear component from cloned tracks peaking close to zero. The cut imposed to reject these clones is > 0.0005 .

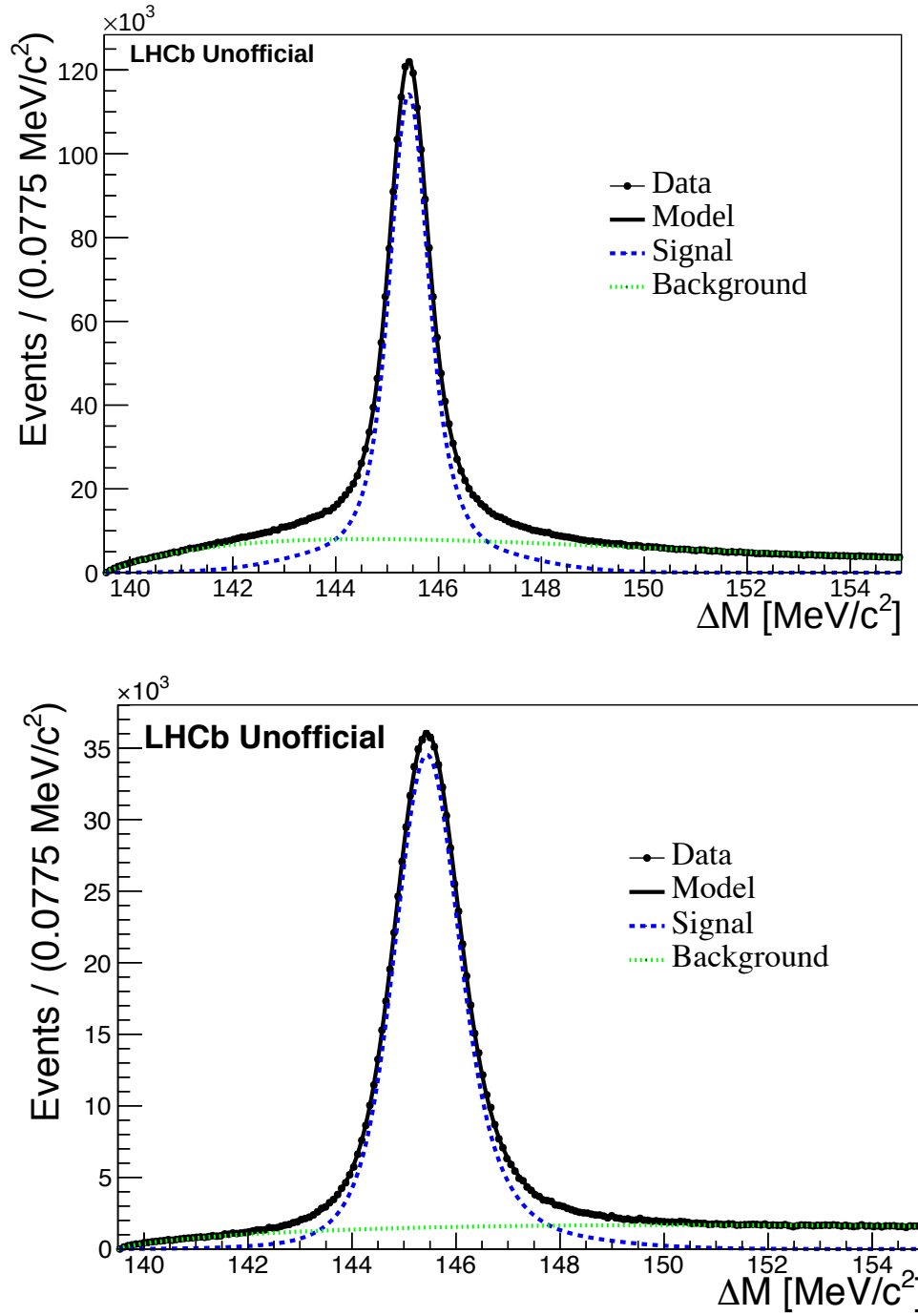


Figure 5.10: Fits of Δm distributions for the resolved (top) and merged (bottom) samples after the application of all selection requirements (excepting the Δm cut).

5.5 Dalitz plot and mass projections for $D^0 \rightarrow \pi^- \pi^+ \pi^0$

Before running the energy test on the signal sample, we perform a number of cross checks. We first inspect the Dalitz plot and the projections of the Dalitz variables for both signal and background-dominated regions in Δm . For this study, we use the same signal mass window as is used for the signal, defined by $|\Delta m - 145.4| < 1.8 \text{ MeV}/c^2$. The background region is defined by the sidebands $\Delta m > 150 \text{ MeV}/c^2$ or $\Delta m < 142 \text{ MeV}/c^2$. In addition to these samples, we also project-out pure signal and background distributions using the sPlot method. The main aim of these studies is to get an initial handle on the resonances contributing to the signal model, and the presence of potential backgrounds. We also feed the signal and background distributions into the toy studies to ensure realistic backgrounds and acceptance effects are included (see Sec. 6.1).

Figure 5.11 shows the 2D Dalitz distributions, m_{13}^2 vs m_{23}^2 for the resolved and merged samples in the signal and sideband windows. The ordering of the particles is such that the charge of the first pion matches that of the mother D^* . This means that m_{13} denotes $m_{\pi^+ \pi^0}$ for D^0 candidates and $m_{\pi^- \pi^0}$ for $\overline{D}^0$ candidates. The notation is explicitly demonstrated in Table 4.1. The corresponding one dimensional projections of the three Dalitz coordinates are shown in Fig. 5.12.

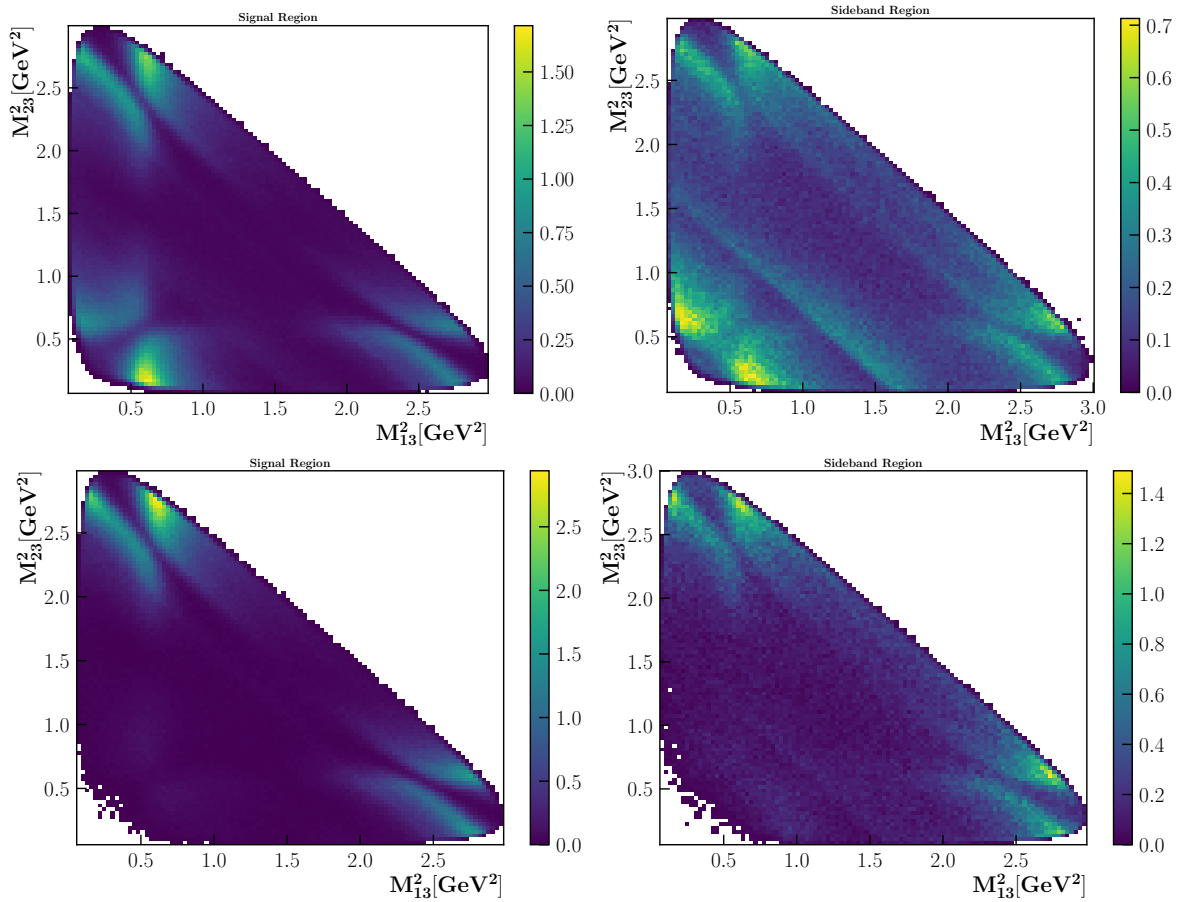


Figure 5.11: Dalitz plots m_{13}^2 vs m_{23}^2 for the resolved (top) and merged (bottom) samples in the Δm signal region (left) and Δm sidebands (right)

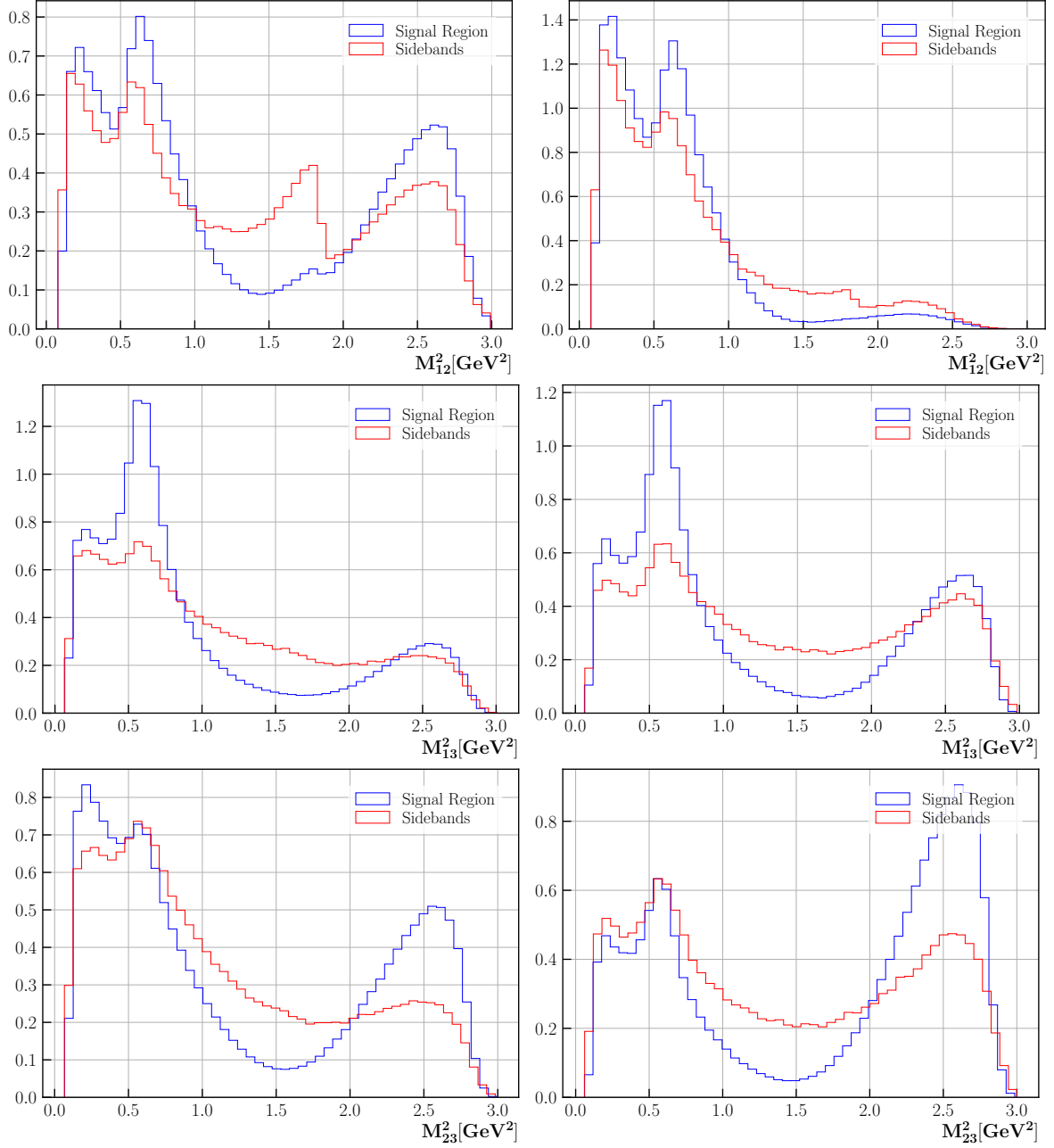


Figure 5.12: Dalitz plot projections for m_{12}^2 (top), m_{13}^2 (middle) and m_{23}^2 (bottom) for the resolved (left) and merged (right) samples in the Δm signal region (blue) and Δm sidebands (red).

From these distributions the difference in acceptance over the phase space for merged and resolved samples is clear, in particular in $m_{12}^2 \equiv m^2(\pi^+ \pi^-)$.

The corresponding sWeighted Dalitz plots and projections are shown in Fig. 5.13 and Fig. 5.14, where the sWeights used to disentangle signal from background are extracted from the Δm fit shown in Fig. 5.10. The sWeighted distributions are shown for the full Δm region. All distributions and projections have been normalised to the same area for ease of comparison.

In both the ‘signal/sideband’ and sWeighted plots, contributions from charged and neutral $\rho(770)$

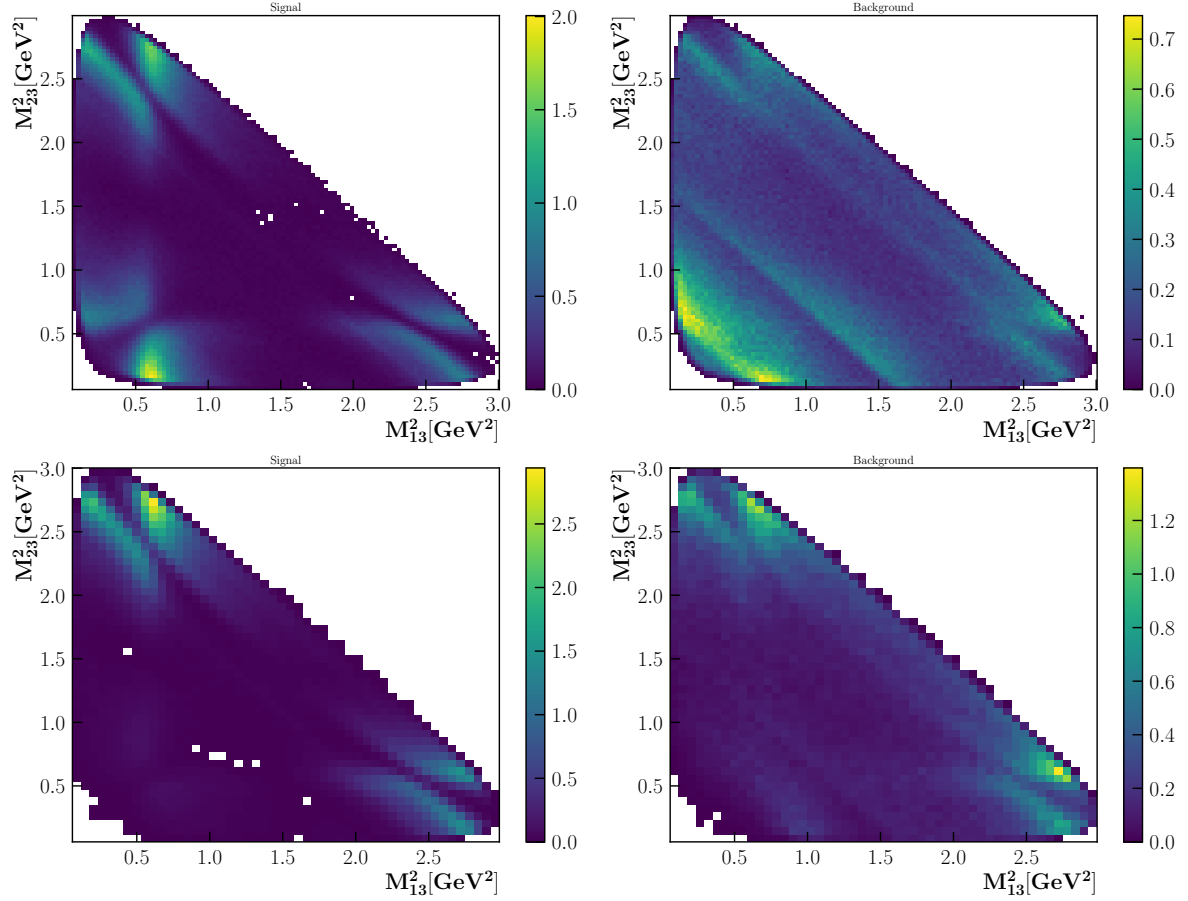


Figure 5.13: Dalitz plots m_{13}^2 vs m_{23}^2 for the sWeighted signal (left) and sWeighted background (right) for the resolved (top) and merged (bottom) samples.

resonances can be seen in the 1D Dalitz projections and as two-lobe structures in the 2D Dalitz distributions, typical of spin-1 vector particles. Other resonances contributing to the Dalitz distributions have small amplitudes and are therefore not discernible to the naked eye but are discussed in Sec. 6.1. The $\rho(770)$ resonances are also present in the background mass projections but with broader shapes suggesting that they have been mis-reconstructed. The interference between these resonances is also not as apparent in the background Dalitz distributions.

An additional structure is present in the background mass projection in m_{12}^2 , peaking at $1.8 \text{ GeV}/c^2$ and most prominent for the resolved sample (top left plot in Fig. 5.12 and Fig. 5.14). This appears in the bottom left corner in the Dalitz plot for the background. This feature was also observed in the LHCb Run 1 analysis [97] where it was postulated to originate from the cross-feed of $\rho(770)^\pm$ reconstructed with a random π^0 of higher momentum. However, in the analysis described here we find that the feature is instead associated with low p_T π^0 candidates (it is suppressed as a requirement on the minimum $p_T(\pi^0)$ is tightened). Instead, the feature could originate from $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ due to the high branching fraction of this decay and the maximum mass of the $\pi^+ \pi^-$ system in this decay peaking around the same region where this feature is seen. It is possible for the K_S^0 to fake a π^0 to build a signal D^0 candidate. Furthermore, K_S^0 decaying into two neutral pions can be mis-reconstructed as a

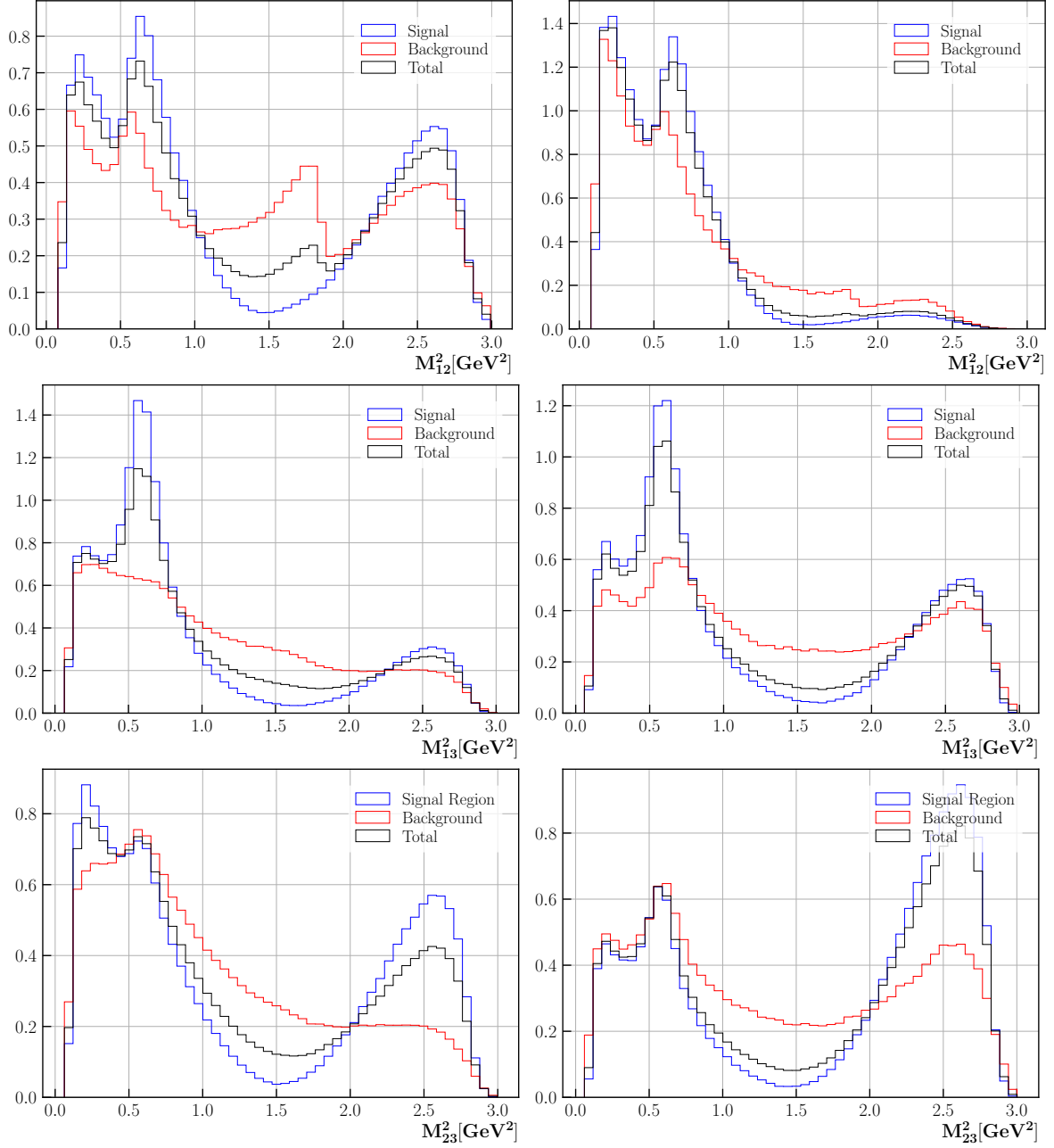


Figure 5.14: Dalitz plot projections for m^2_{12} (top), m^2_{13} (middle) and m^2_{23} (bottom) for the resolved (left) and merged (right) samples. The blue histogram shows sWeighted Signal, the red shows sWeighted background and the black shows the total distribution.

single π^0 if one of the neutral pions is missed in the reconstruction or if the opening angle between the pairs of photons is small enough that only two photons are reconstructed. To investigate this claim, an MVA was constructed to suppress this feature where the background training sample is simulated $D^0 \rightarrow K_s^0 \pi^+ \pi^-$ decays with $K_s^0 \rightarrow \pi^+ \pi^-$. The MVA showed good performance, but when applied to the data the feature was unaffected. This leads to the conclusion that this channel is not the cause. It remains a possibility that it could be coming from $D^0 \rightarrow K_s^0 \pi^+ \pi^-$ decays with $K_s^0 \rightarrow \pi^0 \pi^0$

While this feature is still under investigation, it is highly suppressed in the signal Δm region over which the energy test is performed. Furthermore, studies with the sidebands (where the feature is prominent) do not indicate any significant background asymmetry at our level of sensitivity, as discussed in Sec. 6.3. Taking these findings into account, we conclude that the background associated with this feature will not bias the ET result, and so can be neglected.

5.6 Selection for the control channel $D^0 \rightarrow K^- \pi^+ \pi^0$

The decay $D^0 \rightarrow K^- \pi^+ \pi^0$ (with flavour tag from $D^{*+} \rightarrow D^0 \pi^+$) serves as a reference channel for the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ signal mode. It has the same topology, similar kinematics, and shares three of the four final state particles with the signal mode. The purpose of the control channel is to determine the influence of detection and production (collectively termed nuisance) asymmetries on the final measurement.

The control channel proceeds via a Cabibbo-Favored (CF) decay, $c \rightarrow s\bar{u}d$, with very small contributions from Double-Cabibbo-Suppressed (DCS) diagrams, $c \rightarrow d\bar{u}s$. It is expected to be free of CP violation, and also has a reconstructed yield approximately eight times larger than the signal mode. This enables us to split the control sample into eight signal-like samples, and run the energy test on each one. In the absence of CP violation, we should observe p -values compatible with being drawn from a uniform distribution between zero and one. Any deviation from this would indicate the presence of nuisance asymmetries at a level which can influence our energy test on the signal sample.

The offline selection for the control mode is aligned completely with the signal channel, with the exception of the particle identification requirements on the kaon in the final state. The PID requirement is in the stripping `StrippingDstarD2hhpi0_Kpipi0_[R,M]_Line`, with the kaon required to satisfy `PIDK>7` making this sample completely independent from the signal mode (which has `PIDK<0` for all charged pion candidates). The MVA trained on the resolved $D^0 \rightarrow \pi^- \pi^+ \pi^0$ data is applied to the resolved control channel sample and the cut applied to the signal channel is likewise applied to the control channel. Figure 5.15 shows the Δm fits to the resolved and merged control samples after the application of all offline selection requirements (including the MVA cut on the resolved sample). The signal component for the resolved sample is parameterised by four Gaussians, two of which share the same mean. The signal component in the merged sample is parameterized by three independent Gaussians. The background component in both samples is parametrised as

$$F_{bkg} = (1 - e^{-\frac{(\Delta m - m_{th})}{a}}) + b(\frac{\Delta m}{m_{th}} - 1), \quad (5.2)$$

where a and b are free parameters and m_{th} is threshold value set to $139.5 \text{ MeV}/c^2$, the rest mass of the charged pion.

Following all selections, the signal yield in the control mode merged sample is 5,320k with a purity of 97% (to be compared to 757k signal channel candidates with 91% purity). For the resolved sample

the control mode signal yield is 13,787k with a purity of 94% (to be compared to 1,713k signal channel candidates with 81% purity).

For the control sample, the purity is sufficiently high that we limit the inspection of variables to those derived from the signal/sideband mass region approach (i.e. we don't use sWeights). Figure 5.16 shows the 2D Dalitz distributions, m_{13}^2 vs m_{23}^2 for the resolved and merged samples in the signal and sideband windows. The particle ordering for the control channel is explicitly defined in Table 5.11. Figure 5.17 shows the corresponding one dimensional projections of the three Dalitz coordinates. Figures 5.18–5.19 show the 2D Dalitz distributions and 1D Dalitz projections for the combined merged and resolved samples in the Δm signal and sideband regions. In addition to the dominant $\rho(770)^+ \rightarrow \pi^+ \pi^0$ resonance, there are contributions from the $K^*(892)^-$ and $K^*(892)^0$ resonances which can be seen as narrow peaks in the m_{12}^2 and m_{13}^2 Dalitz projections.

Coordinate	D^0	$\overline{D}^0$
m_{12}	$m_{K^-\pi^+}$	$m_{K^+\pi^-}$
m_{23}	$m_{K^-\pi^0}$	$m_{K^+\pi^0}$
m_{13}	$m_{\pi^+\pi^0}$	$m_{\pi^-\pi^0}$

Table 5.11: Definition of Coordinates for Control Mode Decay.

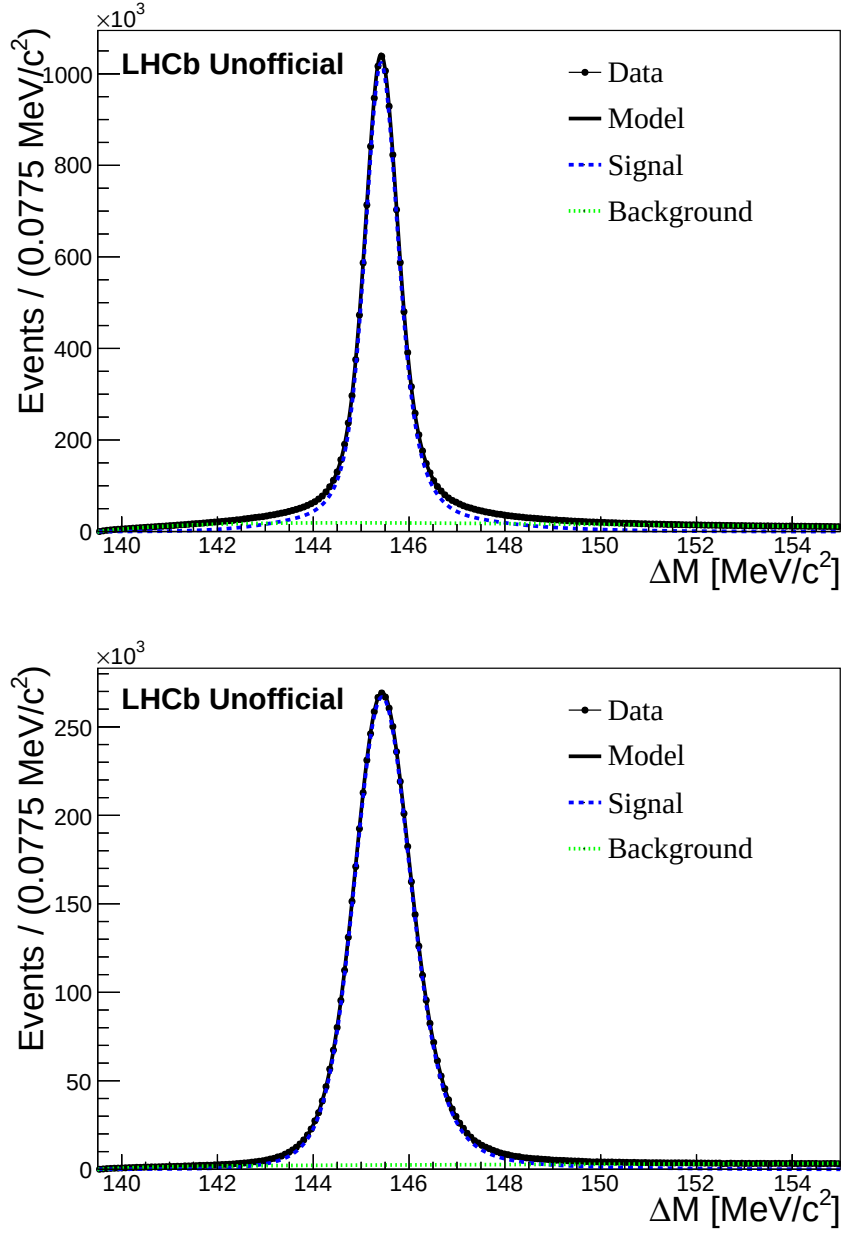


Figure 5.15: Fits of Δm distributions in the control channel for the resolved (top) and merged (bottom) samples after the application of all selection criteria.

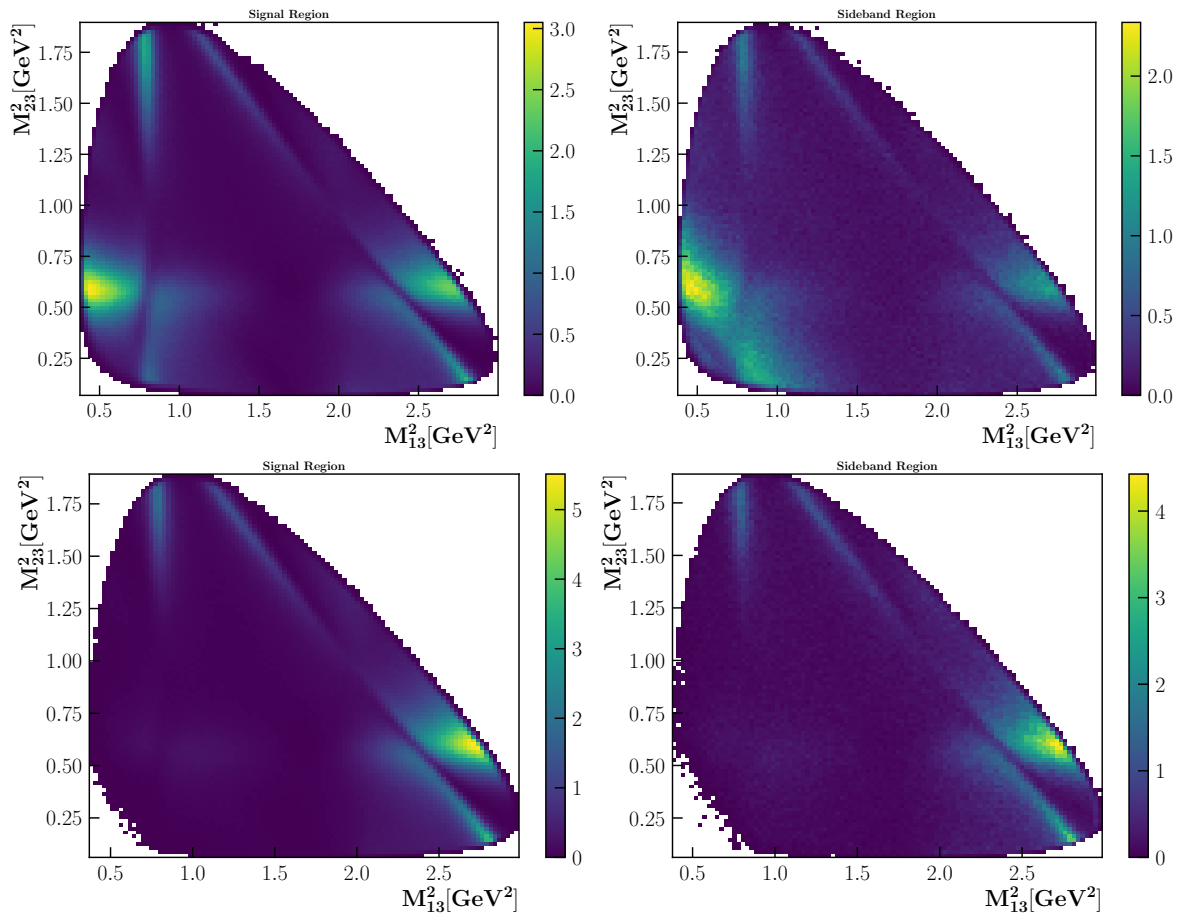


Figure 5.16: Control Channel Dalitz plots, m_{13}^2 vs m_{23}^2 for the resolved (top) and merged (bottom) samples in the Δm signal region (left) and Δm sidebands (right)

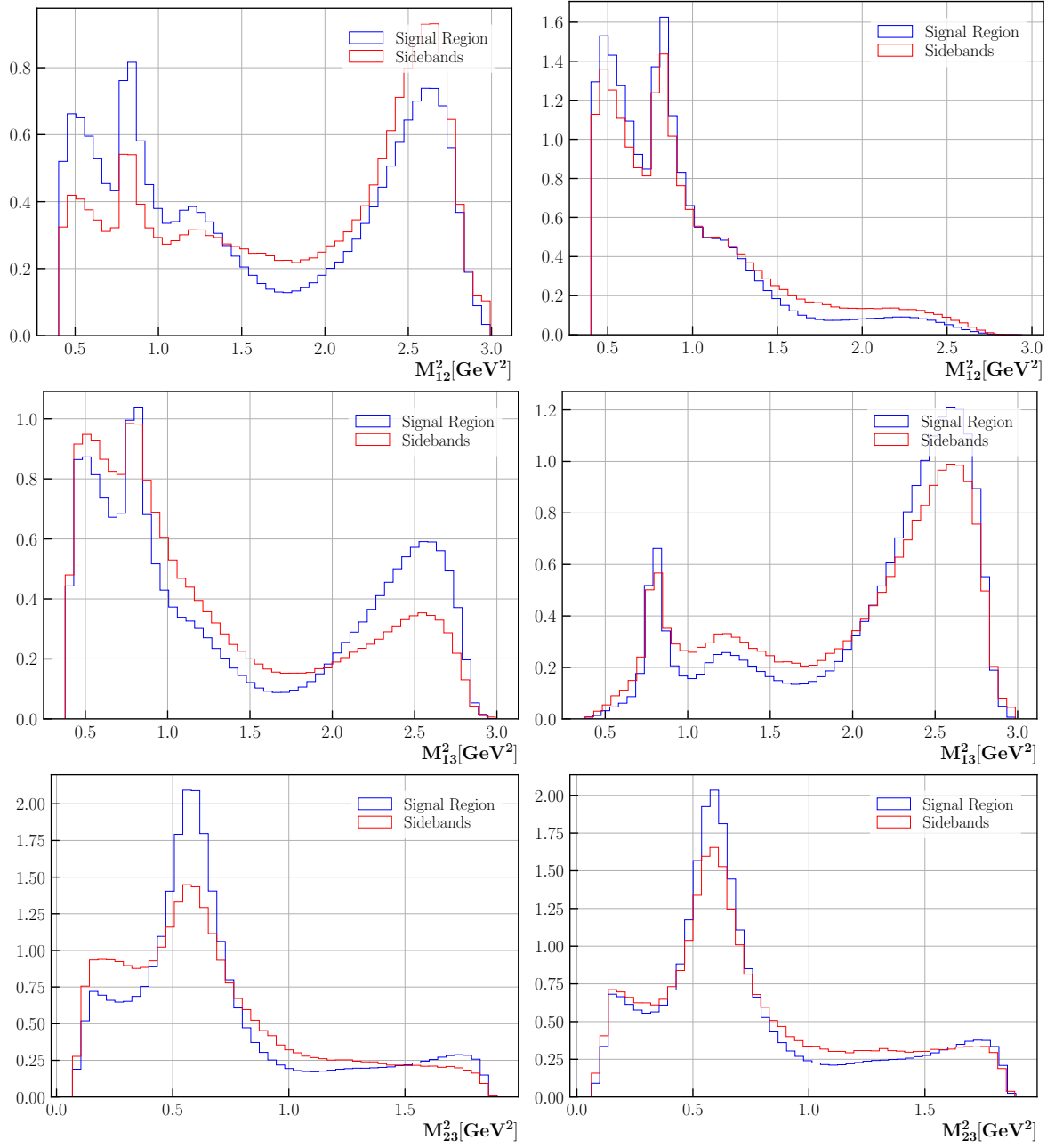


Figure 5.17: Control Channel Dalitz plot projections for m_{12}^2 (top), m_{13}^2 (middle) and m_{23}^2 (bottom) for the resolved (left) and merged (right) samples in the Δm signal region (blue) and Δm sidebands (red).

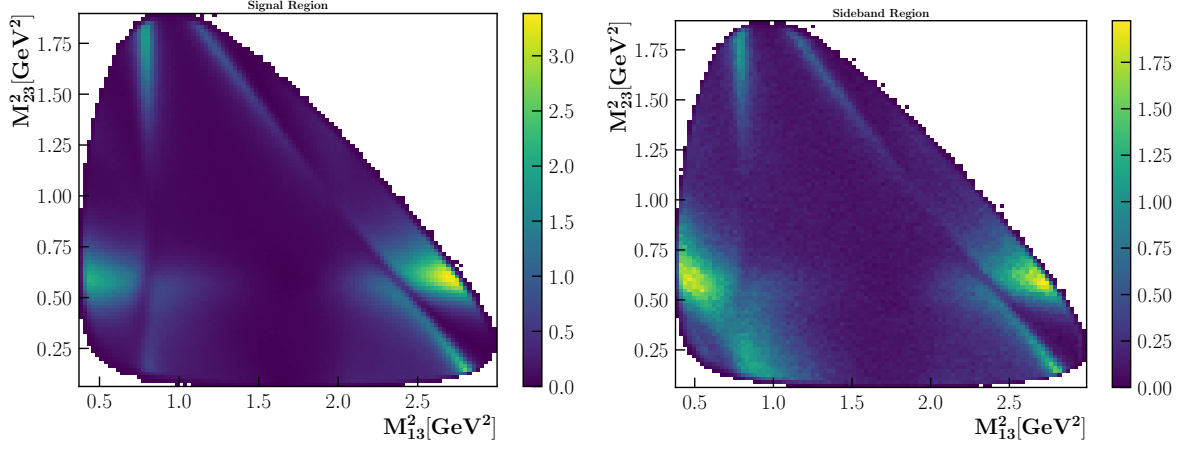


Figure 5.18: Control Channel Dalitz plots, m_{13}^2 vs m_{23}^2 for merged and resolved samples combined in the Δm signal region (left) and Δm sidebands (right)

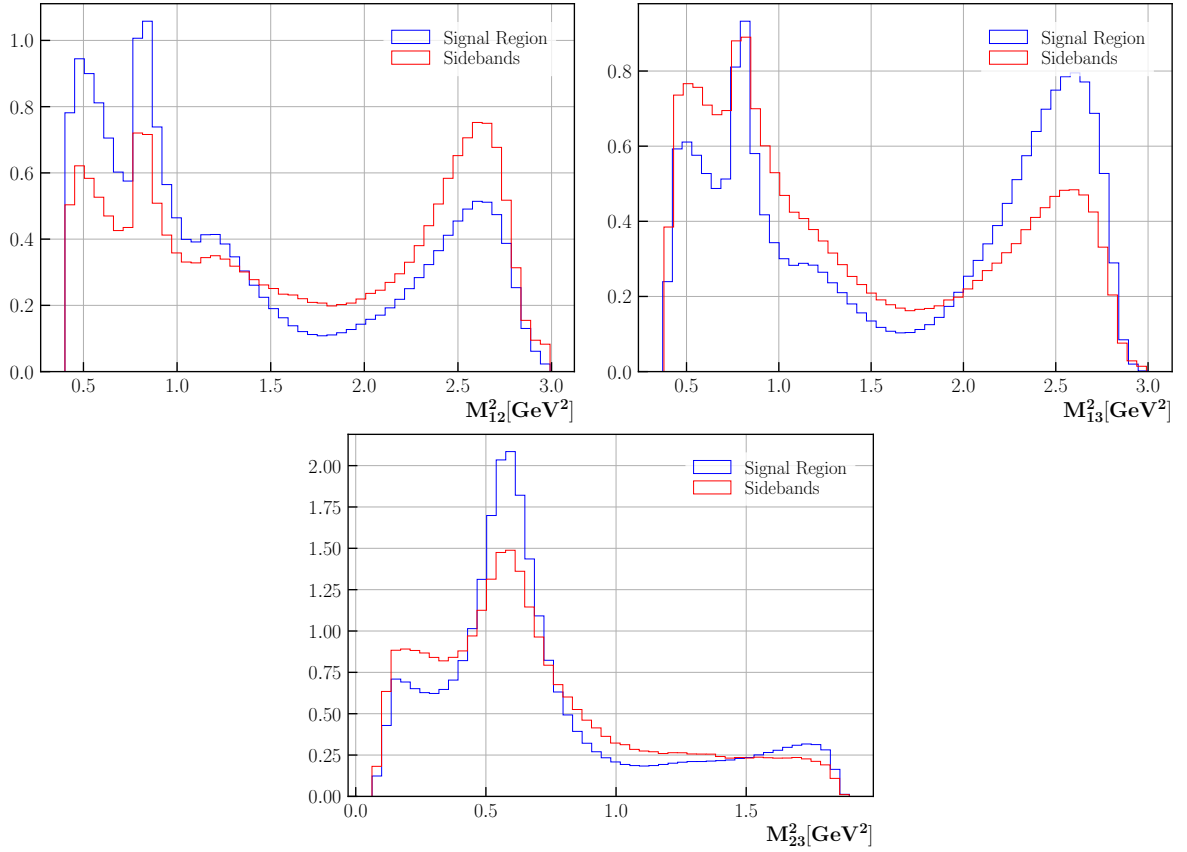


Figure 5.19: Control Channel Dalitz plot projections for m_{12}^2 (top left), m_{13}^2 (top right) and m_{23}^2 (bottom) for merged and resolved samples combined in the Δm signal region (blue) and Δm sidebands (red).

5.7 Equalising sample composition to suppress nuisance effects

Within a given magnet polarity, we can expect significant detector asymmetries to be present, for example due to geometrical effects where particles of one charge are swept out of acceptance, but not those of the opposite charge. Such effects may mimic the effects of genuine CP violation. By combining the two magnet polarity samples, such effects are removed to first order, but residual asymmetries can survive if the signal yields collected in each polarity are not equal.

To further suppress potential polarity-driven asymmetries in this analysis, the number of candidates collected in each magnet polarity is equalised by randomly rejecting candidates. This process is carried out in the same way for both signal and control channels, and separately for each data collection year.

Furthermore, the energy test is also sensitive to differences in phase space distributions of the merged and resolved samples, if they exhibit different global asymmetries, even in the absence of CP violation. To mitigate against this, the fraction of merged and resolved candidates is equalised in the two D^0 flavour samples that form the inputs for the energy test. Table 5.12 shows the fraction of candidates retained at each stage of the equalisation process for each year of data taking. The equalisation of the merged and resolved candidates is carried out after the equalisation of the candidates from each magnet polarity and thus a product of the two fractions represents the overall fraction of candidates retained.

In the control channel, there are 19,615,803 and 18,783,490 candidates before and after the equalisation process respectively. The corresponding numbers for the signal channel are 2,912,942 and 2,800,009 candidates before and after the equalisation process respectively. The equalisation procedure removes less than 5% of candidates.

Year	Efficiency [%]			
	$D^0 \rightarrow \pi\pi\pi^0$		$D^0 \rightarrow K\pi\pi^0$	
	Polarity	Fraction Merged & Resolved	Polarity	Fraction Merged & Resolved
2015	84.8	99.8	81.7	99.9
2016	97.40	99.90	95.80	99.98
2017	98.10	99.95	97.30	99.97
2018	95.70	99.98	96.40	99.99

Table 5.12: Efficiency of each equalisation stage for the signal and control channels. The efficiency is calculated with respect to the number of candidates after all selections for the polarisation equalisation and number of candidates after polarisation equalisation for the fraction of the merged and resolved equalisation.

Chapter 6

Cross-checks with data

Once the event selection has been performed and the final sample selected, the energy test can be applied to the data sample. However, before this is done, some cross-checks have to be carried out to ensure that the energy test is not sensitive to systematic effects that may bias the final measurement. These systematic effects primarily arise due to charge asymmetries in the detection efficiency of final state particles. Since the final state under consideration is symmetric with respect to charge conjugation, most such effects will cancel. Nevertheless, there can still be higher order effects due to particles being swept out of acceptance by the magnet which can lead to sizeable detection asymmetries in certain regions of phase space.

This chapter will describe how the control channel is used to assess the impact of various nuisance effects that may bias the energy test towards low p -values and can end up mimicking CP violation. Also presented in this chapter are tests performed on toy samples derived directly from the signal data sample, with random flavour (D^0 vs $\bar{D}^0$) allocations. Since these samples are CP symmetric by construction, different nuisance asymmetries can be emulated by rejecting candidates of specific flavour according to their properties to simulate asymmetries which are functions of kinematic quantities. The energy test can then be run over the asymmetry injected flavour randomised samples to generate a large ensemble of p -values. This is complementary to the approach with the control channel as it allows the impact of known nuisance asymmetries to be determined with high-statistics ensembles which is not possible with the test performed solely on the control mode. Before describing these data-driven studies, some sensitivity studies based on toy simulations are described for completeness.

6.1 Sensitivity Studies

The work carried out in this section has been carried out by a collaborator and is reported here for completeness.

Before running the energy test over the control channel or flavour randomised signal samples, the single parameter of the method, δ , must be chosen to optimise the sensitivity. The optimal value will

depend on the size of the dataset, which is known, the source of CP violation i.e. if it appears in only one intermediate resonance, and whether that is in the magnitude or phase of that resonance, and finally the distribution of candidates in the phase space.

Firstly, an amplitude model of the signal decay is used to produce a ‘toy’ phase space which is similar to the data. This model consists of several components from different intermediate resonances and a non-resonant term, each with a complex coefficient. This simulated phase space is produced by the **Laura++** package [103] with an amplitude model described by the isobar formalism. This model is taken from the BaBar amplitude analysis of this channel [104] with the amplitudes and phases of each component in the model given in Table 6.1. The generation of the toys produces D^0 and $\bar{D}^0$ mesons which can be CP symmetric by construction due to magnitude and phase being identical. D^0 and $\bar{D}^0$ samples can also be CP asymmetric by using different magnitudes or phases for particular resonances. For the studies used in this analysis, those are limited to the two dominant resonances ($\rho(770)^+\pi^-$) and ($\rho(770)^-\pi^+$), with CP asymmetries of up to 1% (1°) injected into the magnitude (phase) of the $\bar{D}^0$ samples.

The number of signal candidates is based on the LHCb Run 2 yield after all selections as described in Sec. 6.2, for the combination of merged and resolved samples (2.8 million events). This matches the analysis method as applied to real data.

Resonance	Magnitude a_n	Phase ϕ_n	Fit Fraction f_n (%)
$\rho(770)^+$	0.823	0	67.8
$\rho(770)^0$	0.512	16.2	26.2
$\rho(770)^-$	0.588	-2.0	34.6
$\rho(1450)^+$	0.033	-146	0.11
$\rho(1450)^0$	0.055	10	0.30
$\rho(1450)^-$	0.134	16	1.79
$\rho(1700)^+$	0.202	-146	0.11
$\rho(1700)^0$	0.055	10	0.30
$\rho(1700)^-$	0.134	16	1.79
$f_0(400)$	0.091	8	0.82
$f_0(980)$	0.050	-59	0.25
$f_0(1370)$	0.061	156	0.37
$f_0(1500)$	0.062	12	0.39
$f_0(1710)$	0.056	51	0.71
$f_2(1270)$	0.115	-171	1.32
non resonant	0.092	-11	0.84

Table 6.1: Amplitude model from BaBar analysis of $B^\pm \rightarrow D^0(\rightarrow \pi^-\pi^+\pi^0)K^\pm$ [104]. The listed parameters are used in Laura++ to simulate the signal phase space.

The toys produced in this way are termed ‘generator-level’ since they don’t include any detector effects or backgrounds. To make the toys more realistic, the non-uniform phase-space efficiency observed in data is emulated by randomly rejecting toy candidates from the sample. This is performed using a multivariate approach, as follows: a boosted decision tree (BDT) is trained on a randomly selected 80% of the combined merged and resolved signal sample (sWeighted to remove background) and a generator level toy without CP asymmetries. The BDT produces per-candidate weights such that the weighted generator level toy phase space matches the data sample phase space [105]. Using these weights, generated candidates are accepted or rejected randomly in order to produce a toy with a realistic phase space. When performing this rejection the number of initial candidates is increased so that the number of events remaining after rejection matches the yields observed in data.

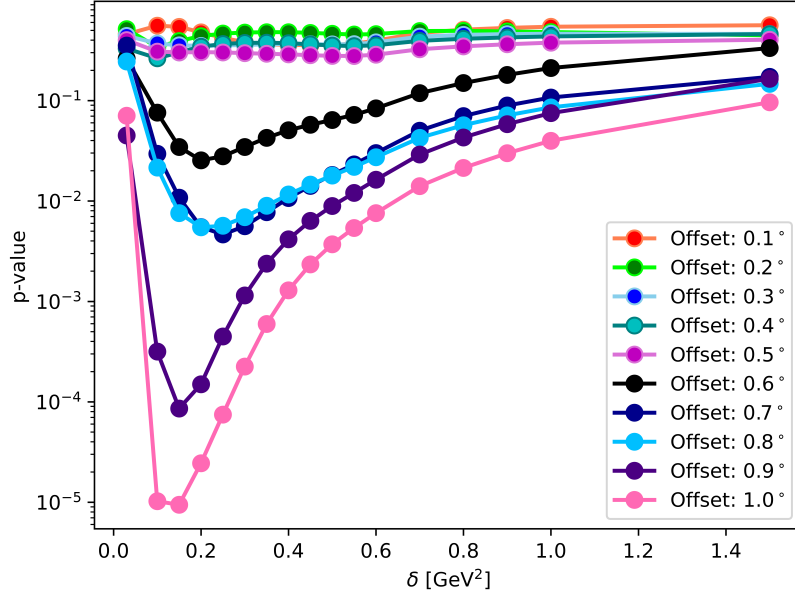
Backgrounds in the data sample can influence the results of the energy test. If there is a large local asymmetry from background candidates it can lead to small p -values even without any genuine CP violation in the signal. This will be checked using the control channel and signal channel sidebands in Sec. 6.2. However, even if background asymmetries do not influence the energy test results directly, background candidates could still dilute sensitivity to CP violation in the signal sample. This may shift the optimal value of δ , so should be investigated.

For these studies, we simulate charge symmetric backgrounds with realistic yields, and add them to the pure signal toy. The expected background yield in the final selected signal sample is 74,000 and 390,000 for merged and resolved categories, respectively.

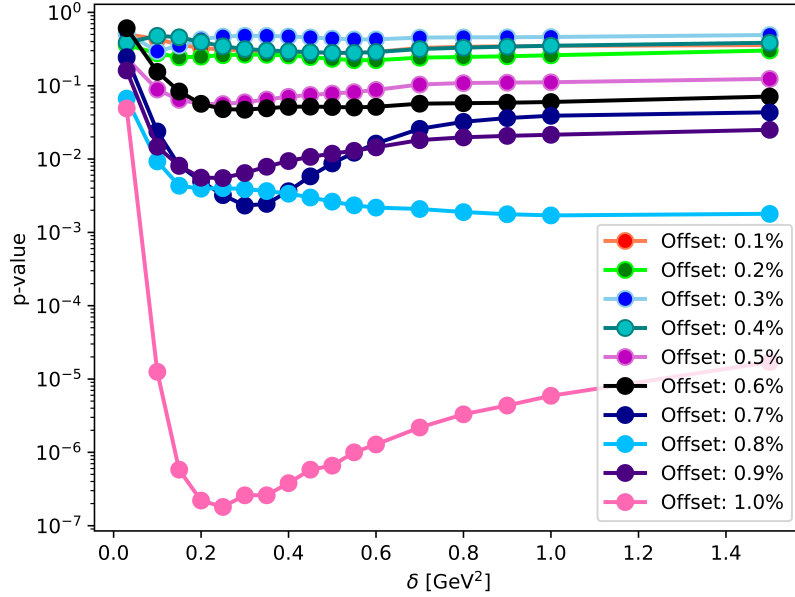
Background toy candidates are generated using a similar approach as developed for the efficiency emulation, with a BDT used to re-weight a uniform 3D phase space to the phase space of background candidates in the Δm sidebands.

The energy test is performed on each toy (comprising the combination of realistic signal and background toys) using different values of δ to establish the optimal choice. In principle this can differ for different CP violation scenarios. The corresponding p -value scans as a function of δ are shown in Figs. 6.1–6.2 for a range of magnitude and phase asymmetries injected into either the dominant or the sub-dominant resonance. There is a threshold with respect to the injected CP asymmetry below which there is no sensitivity to CP violating effects i.e. all p -value lines are greater than 10%. For the dominant resonance, this corresponds to a phase asymmetry of 0.5° or a magnitude asymmetry of 0.4%. Beyond this threshold, the p -values decrease rapidly with the size of the injected asymmetry i.e. a factor 10 decrease in p -value going from 0.9 to 1.0 degree offset). In all cases a value of $\delta = 0.2 \text{ (GeV}/c^2)^2$ is at or close to the minimum p -value. This is therefore chosen for the energy test to be performed on the real data sample. In principle, it is possible to pick more than one p -value for δ , and run the ET several times to determine a set of p -values. That was done for the Run 1 analysis (with two values selected). However, that leads to complications in interpreting the analysis, since the two p -values are not independent, and the look-elsewhere-effect needs to be taken into account. For this analysis, since a value $\delta=0.2 \text{ (GeV}/c^2)^2$ is optimal or close-to-optimal for a wide range of CPV

scenarios, we opt for the simplest approach of using a single δ value to produce a single p -value.

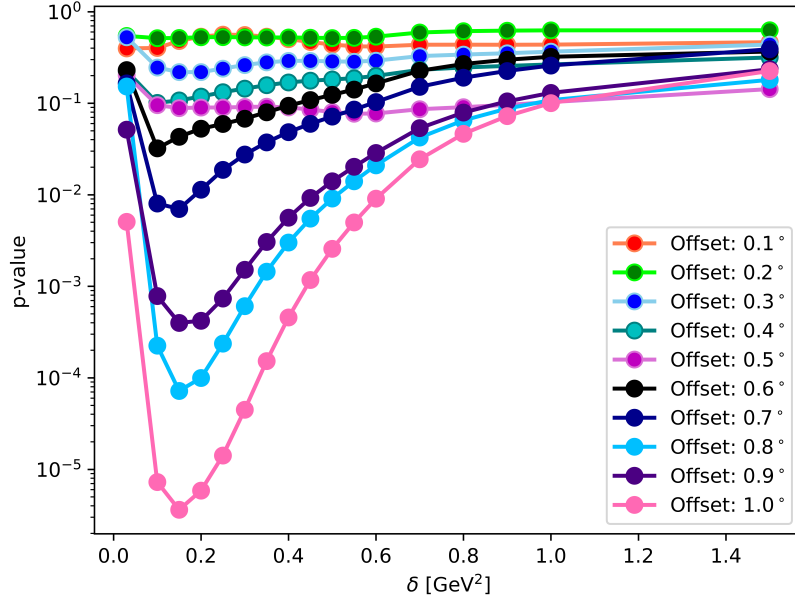


(a) Phase Asymmetries

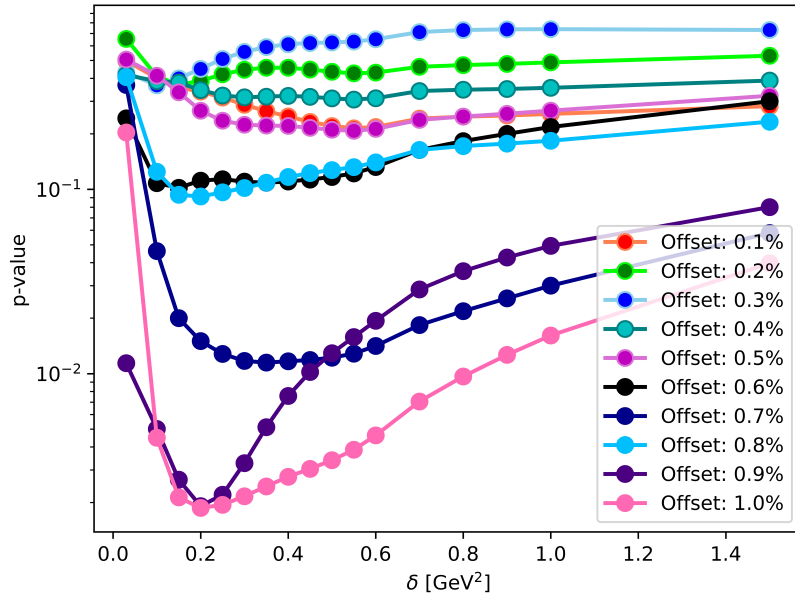


(b) Magnitude Asymmetries

Figure 6.1: Plots of average p -value as a function of delta for a set of five *realistic* toys per CP violation scenario. Here these are magnitude and phase asymmetries in the **dominant** $\rho(770)^+$ resonance.



(a) Phase Asymmetries



(b) Magnitude Asymmetries

Figure 6.2: Plots of average p -value as a function of delta for a set of five *realistic* toys per CP violation scenario. Here these are magnitude and phase asymmetries in the **sub-dominant** $\rho(770)^-$ resonance.

6.2 Control channel studies

For the control mode $D^0 \rightarrow K^- \pi^+ \pi^0$, the combined merged and resolved sample after all pre-selection requirements contains ~ 19 million events in the signal region of Δm ($143.6 < \Delta m < 147.2 \text{ MeV}/c^2$). Figure 5.18 shows the Dalitz plot for this combined sample. It is clear that there are contributions from the $\rho(770)^+ \rightarrow \pi^+ \pi^0$ and $K(892)^* \rightarrow K^- \pi^0$ resonances.

Compared to the signal decay, the control channel contains a $K^\mp\pi^\pm$ pair which introduces a global detection asymmetry caused by the presence of different hadrons that are oppositely charged. This is known as the $K - \pi$ detection asymmetry and it is not expected to contribute in the signal channel due to the presence of pairs of oppositely charged pions such that any charged detection asymmetries cancel to first order.

The energy test is performed over the control channel in the signal region of Δm . The sample is split into 8 independent sub-samples where each sub-sample contains approximately the same number of events found in the signal region of Δm in the $D^0 \rightarrow \pi^-\pi^+\pi^0$ channel. This enables a distribution of p -values to be obtained. If this is consistent with being uniformly distributed between zero and one, then we can conclude that any nuisance asymmetries from production or detector effects are sufficiently small that they can be neglected in the signal channel.

When performing this test, the number of candidates from each magnet polarity is equalised followed by the equalisation of the fraction of merged and resolved candidates for the different D^0 flavors in each sub-sample as explained in Sec. 5.7. The process of the two stages of equalisation is carried out for each year separately to account for the differences in data taking conditions.

The energy test is applied to each of the eight sub-samples. For each sub-sample, the null T-value distribution is determined using sets of 10,000 permuted samples, to convert the ET result into a p -value. The resulting p -value distribution is shown in Fig. 6.3 as well as the individual values presented in Table 6.2. The p -value distribution is consistent with a uniform distribution, and hence with the null hypothesis of CP symmetry in the control channel. We quantify the agreement with a uniform distribution by calculating the P -statistic defined as:

$$P = -2 \sum_i^N \log p_i \quad (6.1)$$

where p_i are the individual measured p -values (with $i=1,\dots,N=8$). The P -statistic follows a χ^2 distribution with $2N$ degrees of freedom if the individual p -values are distributed uniformly. Hence, a large departure of the P -statistic from the number of degrees of freedom would be indicative of a non-uniform distribution. As shown in the Fig. 6.3, the P -statistic for this eight sample test is 16.4 with 16 degrees of freedom, consistent with the null hypothesis of CP symmetry. Also shown in the figure is the result of performing an unbinned KS test, given as the probability that the p -values are sampled from a uniform distribution. Additionally, a linear fit is performed with the central values of the slope and offset shown in the green box in the figure with their associated uncertainties. The consistency of the slope with a value of zero aids in establishing whether the distribution is uniform or not.

As a further cross-check, the control channel sample is instead split into 4 independent sub-samples (rather than 8) where each sub-sample contains double the number of events found in the signal region of the $D^0 \rightarrow \pi^-\pi^+\pi^0$ channel. This cross-check confirms that the sensitivity to systematic effects caused by detection and production asymmetries is not present even with double the sample

size currently available. As such, they can be safely neglected. Figure 6.4 and Table 6.3 show that the distribution remains consistent with the null hypothesis of CP symmetry.

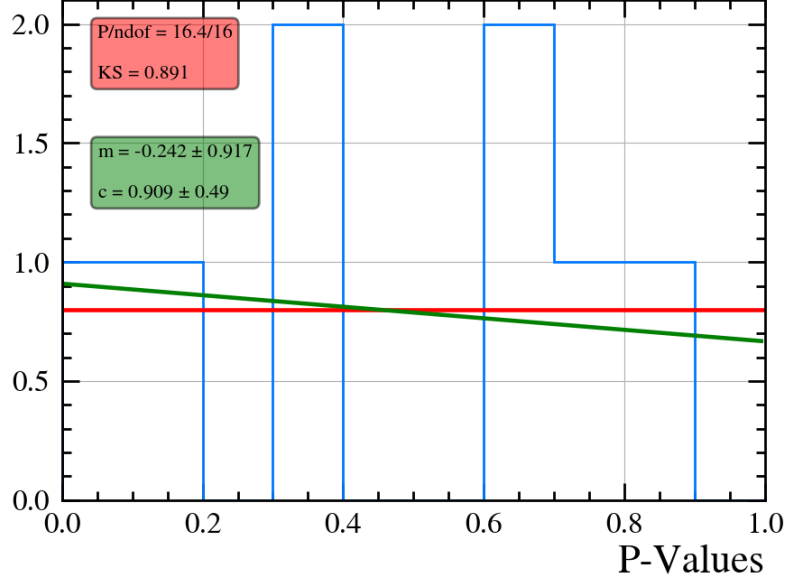


Figure 6.3: p -value distribution from applying the energy test to the eight independent samples in the control channel for $\delta=0.2 \text{ (GeV}/c^2)^2$. Also shown are the results of several statistical tests to evaluate the consistency of this distribution with the null hypothesis of CP symmetry (see text for details).

Sample	p -value
1	0.065
2	0.750
3	0.346
4	0.610
5	0.158
6	0.811
7	0.320
8	0.647

Table 6.2: p -values for the different control channel samples.

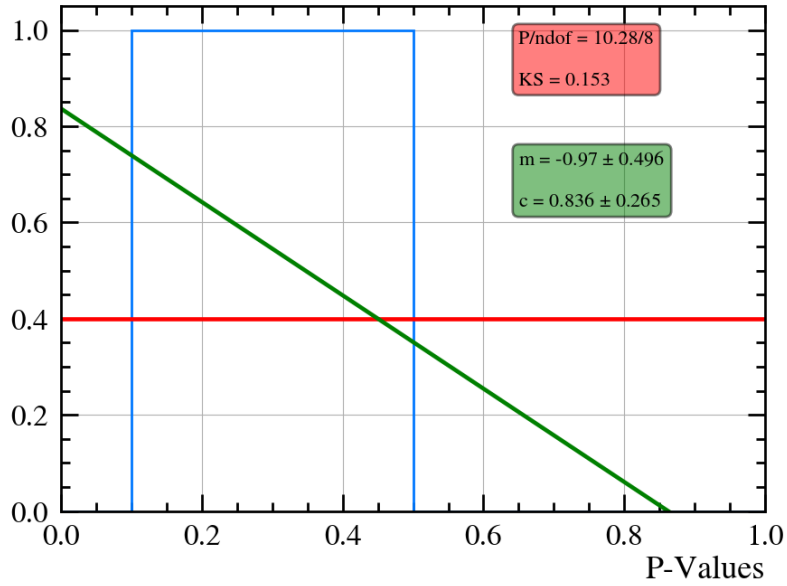


Figure 6.4: p -Value distribution from applying the energy test to four independent samples in the control channel for $\delta=0.2$ $(\text{GeV}/c^2)^2$. Each sub-sample has double the number of events found in the signal region of the signal channel.

Sample	p -value
1	0.477
2	0.323
3	0.175
4	0.216

Table 6.3: p -values for the different control channel samples with double the statistics expected in the signal region of the signal channel.

6.3 Background asymmetries

Despite the Δm signal region in $D^0 \rightarrow \pi^- \pi^+ \pi^0$ being quite pure (see Fig. 5.10), the presence of a background component can lead to an asymmetry which may affect the CPV search in the signal channel. Background asymmetries that are flat across the Dalitz distribution (global asymmetries) will not impact the energy test but locally varying Dalitz-dependent asymmetries can bias the measurement. Weighting the events is possible to account for the background contributions [94] but if there are no significant asymmetries in the background, their contribution can be neglected. As a cross-check of the possible influence of background contamination, the energy test is applied to the sidebands ($150 \text{ MeV}/c^2 < \Delta m < 155 \text{ MeV}/c^2 \parallel 139.5 \text{ MeV}/c^2 < \Delta m < 142 \text{ MeV}/c^2$) in the signal channel. The sample is formed from the combination of merged and resolved categories, as for the main analysis, and contains 810k candidates in total. A p -value of 0.5745 is obtained using 10,000 permutations. This shows that the peaking background visible in the m_{12}^2 projection (discussed in Sec. 5.5), which is most prominent in the sideband regions, is not causing discernible asymmetries at the sample yields being investigated here.

As a further cross-check, the energy test was applied to three independent sub-samples in the control channel sidebands where each sub-sample contains approximately the same number of background events found in the signal region of the signal channel. The number of background events in the signal region in Δm is found by performing an integral to the fit model which sets the yield of the individual control mode sideband samples. This check ascertains the sensitivity to background asymmetries using a much larger sample to derive a p -value distribution rather than a single p -value. Tab 6.4 shows that p -values aren't significant and thus the background distribution is consistent with the null hypothesis of CP symmetry.

Sample	p -value
1	0.7399
2	0.5021
3	0.6885

Table 6.4: p -values for the control channel sideband samples with each sample having the background yield expected in the signal region of the signal channel.

6.4 Detection asymmetries and fiducial cuts

The LHCb detector is designed to be as charge symmetric as possible when reconstructing decays of interest, but some differences in detection efficiency still occur. The magnetic field bends the trajectory of charged particles and breaks the left-right symmetry. The self-conjugate final state in the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ decay means that the detection asymmetry caused by oppositely charged hadrons can be ignored up to first order. However, as the D^0 is produced by the $D^{*+} \rightarrow D^0 \pi_s^+$ decay process,

the slow pion which tags the flavour of the D^0 can induce a detection asymmetry. Slow pions travelling near the edge of the magnet will either be swept out of acceptance, or swept towards the centre of the detector, depending on their charge. This effect leads to regions in kinematic space which have large detection asymmetries, in places up to $\pm 100\%$ for a given magnet polarity. Combining the two samples with opposite magnet polarities significantly reduces the asymmetries in these regions, but does not perfectly cancel them due to the different detector conditions when the magnet is in one polarity configuration compared to the other which can be down to inoperative or inefficient detector modules.

A common approach to mitigate this effect is to apply ‘fiducial’ cuts, which reject candidates where the slow pion travels through a region with large detection asymmetry. These regions include those close to the edges of the magnet, but also those around the beampipe. Figure 6.5 is a visual representation of the charge asymmetry caused by the slow pion for the 2015 resolved sample split between the two magnet polarities. This figure also shows separately the samples passing and failing the fiducial cuts (defined below). The charge asymmetry as a function of soft pion momentum along the x -axis and along the beam lines is shown in the plots. The regions of red and blue on the left side of the plots show particles passing close to the edge of the magnet. There is a large charge asymmetry which changes sign at $P_X=0$, and which has the opposite sign between the two magnet polarities. Figure 6.6 shows the corresponding plots for both magnet polarities combined. The asymmetric regions are still present but are less pronounced due to the combination of the two magnet polarities that cancels charge asymmetries.

For this analysis, we explicitly check to see whether applying a set of such fiducial cuts is beneficial. The drawback to applying the cuts is the loss of around 30 % of the signal, and hence a reduction in the sensitivity to CP violating effects. As such, they should only be applied if needed for the analysis.

We assess the following set of fiducial cuts:

$$|p_x| \leq \alpha(p_z - p_0) \quad (6.2)$$

where $\alpha = 0.317$ and $p_0 = 2400 \text{ MeV}/c$, and

$$p_1 - \beta_1 p_z < |p_x| < p_2 + \beta_2 p_z \quad (6.3)$$

where $p_1 = 418 \text{ MeV}/c$, $p_2 = 497 \text{ MeV}/c$, $\beta_1 = 0.01397$, and $\beta_2 = 0.01605$. The second requirement is only valid (and applied) for candidates with $|\frac{p_y}{p_z}| < 0.02$.

In this analysis, the control channel is used to study the impact of the fiducial cuts on the energy test, while the signal channel is still blinded. To assess a potential bias, eight samples are created containing events rejected by the cuts i.e. those events in the region of the highest charge asymmetry. Each sample is representative of the signal decay phase space. A p -value is then calculated from a distribution of 10,000 T -values. The p -value distribution is shown in Fig. 6.7

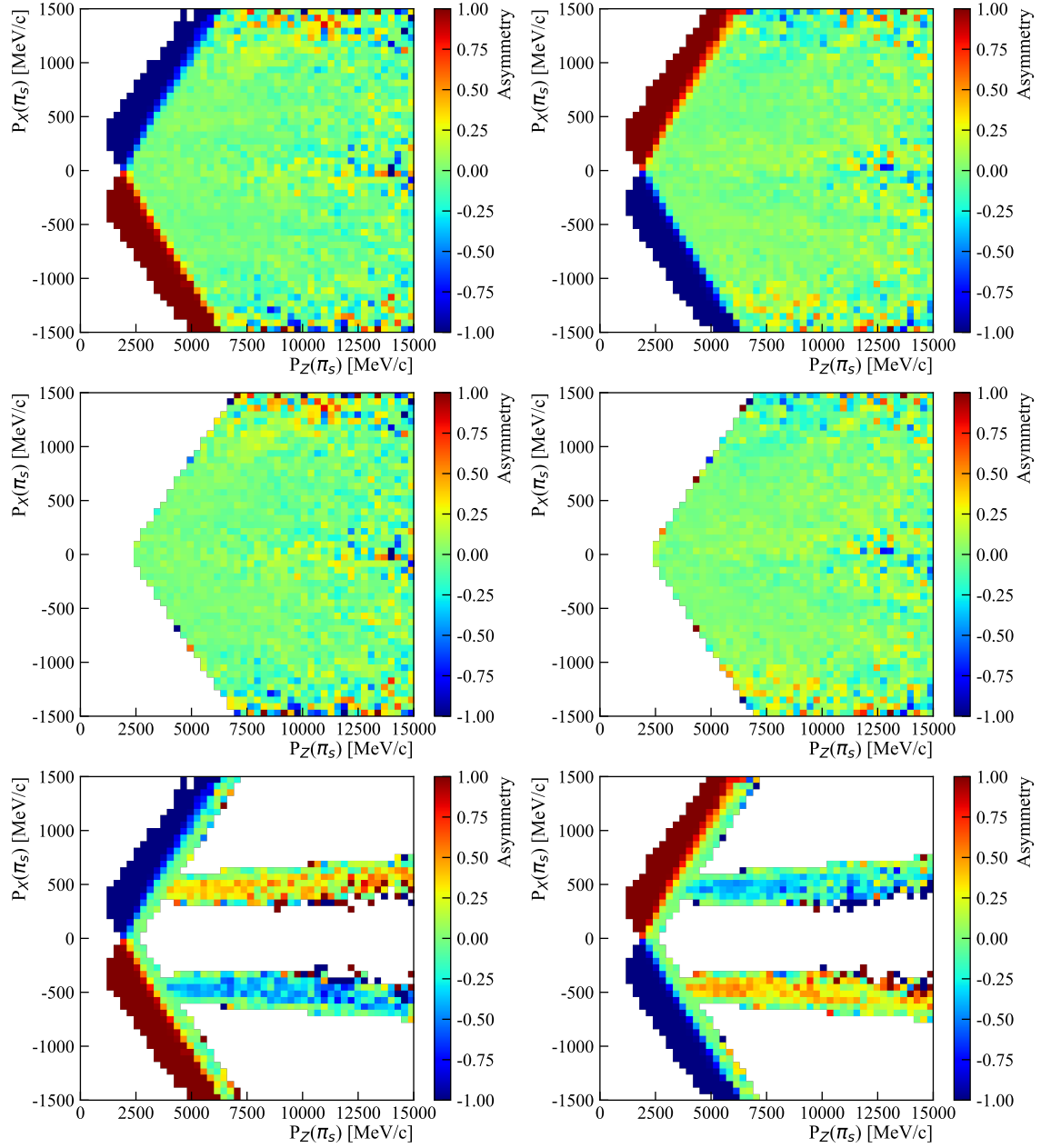


Figure 6.5: Charge asymmetry of the slow pion for the 2015 sample (Resolved & Merged combined) in the Magnet-Up (left) and Magnet-Down (right) polarities. The three rows show the total sample (top), the events that pass the fiducial cuts (middle) and the events that are rejected by the fiducial cuts (bottom).

If an underlying asymmetry is observed, the p -values will be enhanced towards low probabilities due to asymmetries between the D^0 and $\bar{D}^0$ mesons. In a CP symmetric case, a uniform distribution of p -values is expected. The uniformity of the distribution in Fig. 6.7 indicates that the regions with the greatest charge asymmetry are not inducing a bias in the energy test and can be included when performing the energy test on the signal sample.

The $\pi^+\pi^-$ pair originating from the D^0 can also induce detection asymmetry effects caused by the charged hadrons being bent out of the detector acceptance region. As stated previously, these effects

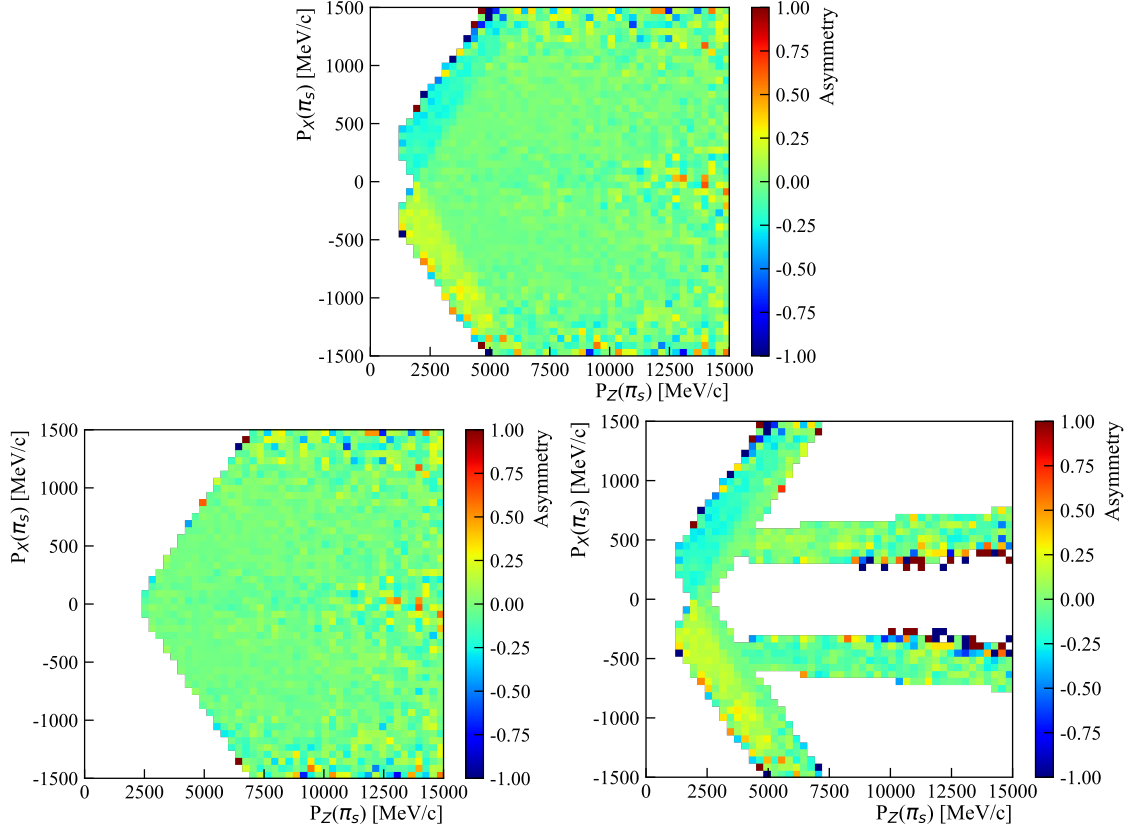


Figure 6.6: Charge asymmetry of the slow pion for the 2015 sample (Resolved & Merged combined) for both magnet polarities combined. The three plots show the total sample (top), the events that pass the fiducial cuts (bottom left) and the events that are rejected by the fiducial cuts (bottom right).

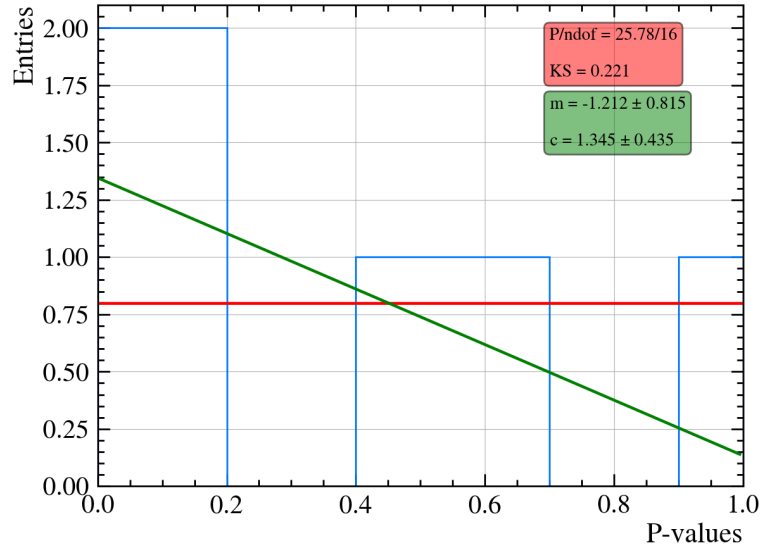


Figure 6.7: p -value distribution for the energy test run over the control mode, only for candidates with the greatest charge asymmetry i.e. events that would be rejected by the fiducial cuts of Eq. (9.1–9.2).

can be neglected up to first order due to the signal channel having a self conjugate final state. Table 6.5 shows the percentage of candidates retained in our signal sample as a result of applying fiducial cuts to the soft pion as well as the $\pi^+\pi^-$ pair. Additional configurations of various fiducial cuts applied to different pions in the final state are also shown. It is evident that a significant proportion of candidates are lost when applying the fiducial cuts to the soft pions ($\sim 27\%$) but imposing an additional constraint on the $\pi^+\pi^-$ pair doesn't diminish the statistics as drastically as only a further 3% of events are lost. From this we conclude that studying the impact of fiducial cuts as applied to the soft pion alone is a good proxy for alternative schemes (e.g. where all three charged pions are required to pass the cuts).

Sample	% Candidates Retained
All Candidates (No Fiducial cuts)	100
Soft pion passes (No requirement on $\pi^\pm$ from D^0)	73
Only one $\pi^\pm$ from D^0 passes (No requirement on soft pion)	97.9 / 95.9
Both $\pi^\pm$ from D^0 pass (No requirement on soft pion)	94.0
All pions pass	70
Both $\pi^\pm$ from D^0 pass and soft pion fails	23

Table 6.5: Percentage of candidates retained by applying various configurations of fiducial cuts to all pions.

6.5 Further Cross-Checks

The different hardware (L0) triggers used in this analysis can potentially induce different nuisance asymmetries. As such, it is useful to examine candidates from different L0 categories separately. It is possible to judge the impact of the hardware trigger on the analysis by running the ET over control channel sub-samples that pass a specific set of L0 trigger lines. This information is summarised in Tab. 6.6 where the sub-sample size is provided along with the trigger requirements placed on the sub-sample. The p -values are limited in precision by the number of permuted samples used to construct the null T-value distribution (10,000 permutations in this case). Here we use a shorthand notation to distinguish the three main L0 trigger paths: pi0_TOS refers to pi0_L0PhotonDecision_TOS; Hx_TOS refers to Hx_L0HadronDecision_TOS, where H1 is the kaon and H2 the pion for the control mode; L0_TIS refers to Dstr_L0_Global_TIS. Note, here the sub-samples are constructed such that they only pass the trigger line in question and fail to pass the other trigger lines in the nominal selection. For some trigger categories (pi0_TOS, and H2_TOS) it is not possible to create a sample with signal-like yield, simply due to the limited number of candidates.

For most samples, the observed p -values are not significant. The exception is the two samples collected with the hadron triggers, where either the charged pion or kaon are allowed to satisfy the line. These small p -values are caused by the charged kaon, which suffers from significant detector asymmetries from material interactions. For the signal channel this kaon is not present, so to emulate the signal

L0 Triggers	Size	p -value
pi0_TOS	1.5M (60% of signal)	0.5973
H1_TOS H2_TOS	2.9M	<0.00001
H1_TOS H2_TOS	2.9M	< 0.00001
H1_TOS H2_TOS (Tight momenta cut)	2.9M	0.0145
H2_TOS	1.8M (70% of signal)	0.9341
L0_TIS	2.3M	0.2491
L0_TIS	2.3M	0.8119
L0_TIS	2.3M	0.1979
L0_TIS	2.3M	0.2928
L0_TIS	2.3M	0.7074

Table 6.6: p -values for control channel samples that pass different L0 trigger requirements

situation more closely we also produce a subsample in which the charged pion (‘H2’ in the table) must by itself satisfy the L0 hadron trigger. For this sample, the p -value is not significant. To ensure that the L0 hadron trigger is not biasing our results for the signal channel, this cross-check is repeated on the signal channel upon unblinding. Another check for which the charged pion and kaon satisfy the hadron triggers is performed where the low momenta kaons are removed (denoted “Tight momenta cut” in the table) for which the charge asymmetry is largest. The kaons passing this trigger line must have momentum greater than 20GeV and transverse momenta greater than 3GeV. Imposing these requirements leads to a much larger p -value.

A second cross-check to better understand the impact of known detector charge asymmetries is to split the control channel sample according to the magnet polarity configuration. As fiducial cuts are not applied in this analysis (see Sec. 6.4), it is expected that running the Energy Test over the separate polarity-specific samples will show an asymmetry due to geometrical acceptance effects. Indeed, this is what is seen when looking at Tab. 6.7 where small p -values are seen for the Magnet Down configuration. Asymmetric values seen in one polarity configuration and not the other arise from the non-collinearity of the momentum vectors of the colliding protons. This causes some of the decay products to be swept out of acceptance in one polarity configuration and not the other, hence breaking the left-right symmetry of the detector. The small p -values disappear once fiducial cuts are applied as seen in Tab. 6.7. This is an expected result as the fiducial cuts remove regions in momentum space with the greatest asymmetry caused by the soft pion being bent out of the acceptance region of the detector.

However, Fig. 6.3 demonstrates that for the signal yields available for this analysis, any potential residual nuisance asymmetries after combining the two magnet polarities are sufficiently small to be neglected. They do not distort the p -value distribution significantly. From earlier studies, we observe that this is the case even without explicitly equalising the sample yields in each polarity.

Sample	MagUp	MagDown	MagDown with Fiducial Cuts
1	0.1101	0.0	0.0167
2	0.4078	0.0007	0.2997
3	0.0043	0.0017	0.0851
4	0.036	0.0104	0.0204

Table 6.7: p -values for control channel samples for the 2 different polarity configurations as well as the Magnet Down polarity configurations with Fiducial cuts applied.

As a third cross-check, we run the ET on the control channel over sub-samples split according to the data taking year. This information is summarised in Tab. 6.8 where the sub-sample size is also provided. No significant p -values are seen.

Year	No. of Events	p -value
2015	1M (40% of signal)	0.8991
2016	2.3M	0.7961
2016	2.3M	0.3494
2017	2.9M	0.3284
2017	2.9M	0.6102
2018	2.7M	0.1002
2018	2.7M	0.0847
2018	2.7M	0.7973

Table 6.8: p -values for control channel samples for the different data taking years.

6.5.1 Splitting control mode into kinematic subsamples

A common cross-check in measurements of fundamental quantities is demonstrating that they are consistent when determined in disjoint subsets of the data, split according to some meaningful scheme (e.g. low and high momentum). For the case of the energy test analysis something similar can be done, namely running the analysis over independent subsamples of the data to demonstrate that the results are consistent across these samples. While the signal analysis is blinded, the control mode is used to perform this check. This enables the data to be split into sets of eight independent subsamples, each with the same yield as the signal sample. Note, however, that a quantitative comparison of the the results between subsamples can not be done - these are p -values and not measurements with uncertainties. Instead, the metric of success is a set of p -values which are consistent with being drawn from a uniform distribution, and in particular where there are no obvious trends (e.g. very small p -values for subsamples with the lowest momentum).

For this test, as with all other signal and control mode studies, a requirement is imposed that the

number of candidates collected in each magnet polarity is consistent within each subsample. This is enforced by randomly rejecting candidates as necessary. Additionally, the merged and resolved samples have different kinematic distributions so ordering according to a kinematic quantity results in differing intervals for the two samples. The Energy test is run over the combined merged and resolved sub-samples where each sub-sample encapsulates two different kinematic intervals for the merged and resolved candidates. This is illustrated in Tabs. 6.9& 6.10 for each kinematic variable.

Figure 6.8 shows the p -values in bins ordered according to the transverse momenta and pseudorapidity of the D^0 meson. Figure 6.9 shows the corresponding plots for the soft pion. There are no discernible trends in p -values showing that regions of large charge asymmetry are not inducing a bias in the energy test.

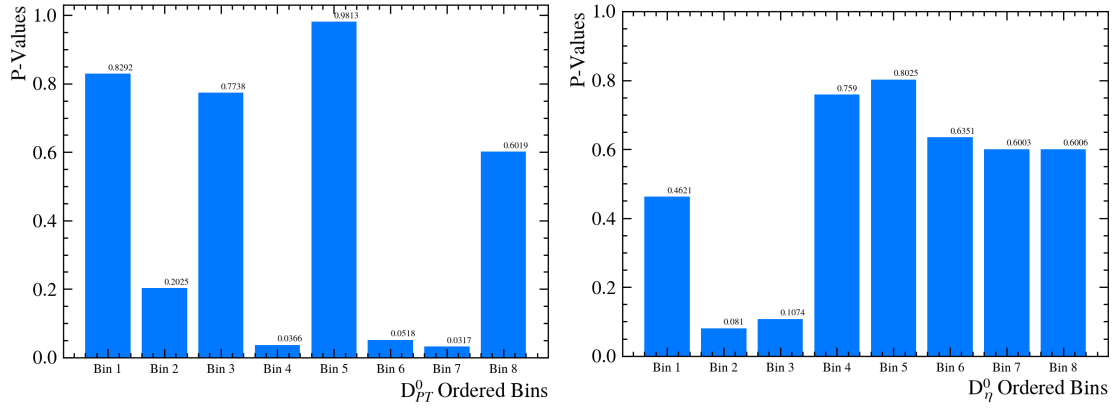


Figure 6.8: p -values in bins ordered by the transverse momenta (left) and pseudo-rapidity (right) of the D^0 meson.

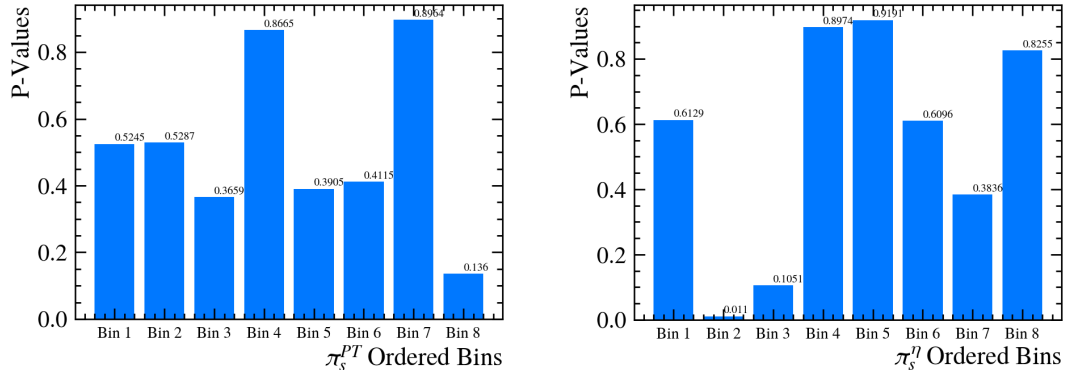


Figure 6.9: p -values in bins ordered by the transverse momenta (left) and pseudo-rapidity (right) of the soft pion.

Bin	Resolved Intervals			
	$p_T(D^0)[\text{GeV}/c]$	$\eta(D^0)$	$p_T(\pi_s)[\text{GeV}/c]$	$\eta(\pi_s)$
1	(2.80, 5.58)	(1.68, 2.33)	(0.30, 0.36)	(1.66, 2.36)
2	(5.58, 6.30)	(2.33, 2.51)	(0.36, 0.45)	(2.36, 2.54)
3	(6.30, 6.94)	(2.51, 2.66)	(0.45, 0.51)	(2.54, 2.70)
4	(6.94, 7.62)	(2.66, 2.80)	(0.51, 0.56)	(2.70, 2.84)
5	(7.62, 8.41)	(2.80, 2.95)	(0.56, 0.63)	(2.84, 2.98)
6	(8.41, 9.44)	(2.95, 3.11)	(0.63, 0.71)	(2.98, 3.14)
7	(9.44, 11.19)	(3.11, 3.31)	(0.71, 0.86)	(3.14, 3.35)
8	(11.19, 74.01)	(3.31, 4.48)	(0.86, 5.94)	(3.35, 4.56)

Table 6.9: Ordered kinematic intervals for the resolved sub-samples. Each bin corresponds to one of the bins in the plots shown in Figs. 6.8 & 6.9.

Bin	Merged Intervals			
	$p_T(D^0)[\text{GeV}/c]$	$\eta(D^0)$	$p_T(\pi_s)[\text{GeV}/c]$	$\eta(\pi_s)$
1	(3.97, 7.13)	(1.74, 2.34)	(0.30, 0.50)	(1.72, 2.35)
2	(7.13, 8.09)	(2.34, 2.51)	(0.50, 0.59)	(2.35, 2.53)
3	(8.09, 8.95)	(2.51, 2.67)	(0.59, 0.66)	(2.53, 2.70)
4	(8.95, 9.83)	(2.67, 2.84)	(0.66, 0.74)	(2.70, 2.86)
5	(9.83, 10.84)	(2.84, 3.02)	(0.74, 0.82)	(2.86, 3.05)
6	(10.84, 12.17)	(3.02, 3.25)	(0.82, 0.94)	(3.05, 3.27)
7	(12.17, 14.34)	(3.25, 3.52)	(0.94, 1.12)	(3.27, 3.55)
8	(14.34, 80.23)	(3.52, 4.73)	(1.12, 5.59)	(3.55, 4.72)

Table 6.10: Ordered kinematic intervals for the merged sub-samples. Each bin corresponds to one of the bins in plots shown in Figs. 6.8 & 6.9.

6.6 Nuisance asymmetry injection studies

The potential impact of nuisance asymmetries originating from the detection of the soft pion or the production of the $D^{*\pm}$ has been examined by running the ET over the control channel (see Sec. 6.2). No significant effects are found. However, the limited statistics in the control channel means that only eight p -values can be generated with each using a control channel sub-sample with signal-like yields. Further validation of the impact of nuisance asymmetries would require a large ensemble of p -values to be produced. This can be achieved by generating a set of flavour randomised signal samples and artificially injecting nuisance asymmetries by randomly rejecting candidates appropriately. The starting point for this procedure is the signal sample after all selection requirements have been applied. This is used to generate a ‘flavour-randomised’ sample, by randomly allocating the flavour (D^0 or $\bar{D}^0$) of each candidate in the sample with equal probability of each option. By repeating this process an ensemble of such samples is created. At this stage all such samples have exactly the same properties excepting the candidate flavour allocations. For each of these samples, the nuisance asymmetries are then injected using the procedure outlined below.

6.6.1 Soft pion asymmetry using $D^0 \rightarrow K_S^0 \pi^- \pi^+$ decays

For this study, realistic nuisance asymmetries are determined using a sample of $D^0 \rightarrow K_S^0 \pi^- \pi^+$ decays, where no direct CP violation is expected. The flavour at production is obtained by selecting $D(2010)^{*\pm} \rightarrow D^0 \pi^+$ decays. From this sample, the raw asymmetry in D^0 versus $\bar{D}^0$ candidates can be determined as a function of the reconstructed kinematics (transverse momentum and pseudorapidity) of different particles. Any non-zero asymmetry can be safely assumed to arise from instrumental effects, and those same effects could be present in the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ channel. The initial study derives this asymmetry in 2D bins of soft pion kinematics (p_T, η). This asymmetry is then injected into the flavour-randomised signal samples enabling a large ensemble of p -values to be collected by running the energy test separately over each ‘asymmetry-injected’ sample. As a second step, the corresponding asymmetries as a function of other particle kinematics can be compared between the $D^0 \rightarrow K_S^0 \pi^- \pi^+$ sample and the asymmetry-injected signal sample. If these are in good agreement, then we can conclude that by injecting the soft pion asymmetry we also indirectly include all other asymmetric effects (e.g. a possible production asymmetry of the $D(2010)^{*\pm}$ meson, or a charge asymmetry associated with the $\pi^+ \pi^-$ pair).

The $D^0 \rightarrow K_S^0 \pi^- \pi^+$ sample is selected using requirements optimised by a parallel energy test analysis, namely the search for CP violation in $D^0 \rightarrow K_S^0 K^+ \pi^-$ decays, for which it acts as the control mode. Selections similar to those imposed on the signal channel are applied, leading to a high purity $D^0 \rightarrow K_S^0 \pi^- \pi^+$ sample. Since all asymmetries are determined as a function of particle kinematics, it is not essential that the selections be completely aligned between this control mode and the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ signal channel. The resulting sample of $D^0 \rightarrow K_S^0 \pi^- \pi^+$ candidates has ~ 12 M signal candidates with 96% purity within the selected ΔM range as seen in Fig. 6.10.

A 2D map of the $D^0 \rightarrow K_S^0 \pi^- \pi^+$ charge asymmetry, as a function of the soft pion transverse momentum and pseudorapidity, is then extracted by counting candidates, neglecting the possible impact of the remaining residual background. The 1D and 2D maps of these asymmetries are shown in Fig. 6.11. A large global asymmetry (i.e. offset from $y = 0$) is clearly present, but the energy test is not sensitive to such global effects. No significant variation is seen as a function of the soft pion p_T , while a small but significant asymmetry trend in η is observed.

Since the 2D asymmetry map of Fig. 6.11 includes non-negligible uncertainties, we account for this explicitly by randomly sampling the per-bin asymmetry from the central values and uncertainties of the map, on a per-candidate basis. This works as follows. For each candidate i :

1. Assign a random number R_i distributed uniformly between 0 and 1.
2. Read the candidate flavour F_i . A D^0 is assigned $F = 1$ while $\bar{D}^0$ has $F = -1$
3. Determine the relevant bin in the 2D asymmetry map, based on the soft pion transverse momentum and pseudorapidity
4. Select the nuisance asymmetry from this bin using a Gaussian pdf with mean and width based on input from the 2D map. The resulting asymmetry for this candidate is then A_i . Since this number is determined from the asymmetry map, it's range is between -1 and 1.
5. Reject candidate if $R_i > (1 + 2F_i A_i)$.

In the final step, the use of the flavour tag ensures that only candidates of the appropriate flavour are rejected (since the condition $R > 1$ will never be fulfilled). The factor of 2 is included to fully inject an asymmetry since candidates from only one of the two flavours are rejected. This procedure is validated by examining the resulting asymmetry as a function of soft pion kinematics, which demonstrates that the asymmetry-injected signal samples reproduce the input asymmetry derived from the $D^0 \rightarrow K_S^0 \pi^- \pi^+$ sample. There are different approaches to inject asymmetry into an ensemble of flavour randomised samples. One such approach is to ignore the uncertainties and always assign the central values of the asymmetries in each bin. This will be referred to as the ‘central asymmetry value’ approach. An alternative is to re-sample the asymmetry map once and use the same map for all subsequent asymmetry injections. This will be referred to as the ‘fixed asymmetry map’ approach. This can be extended to re-sample the asymmetry map once only for a particular toy, so that all candidates see the same asymmetry map, but that map can change between toys. This will be referred to as the ‘re-sampled asymmetry map’ approach and will be the default approach unless stated otherwise. These approaches are used below for different purposes, as explained when relevant.

Running the energy test over the flavour randomised ensemble produces a p -value distribution shown in Fig. 6.12, in this case for an ensemble of 100 toys. The p -value distribution is uniform which is consistent with the the null hypothesis of CP symmetry.

The soft pion detection asymmetry differs for candidates with opposite magnet polarities as seen in

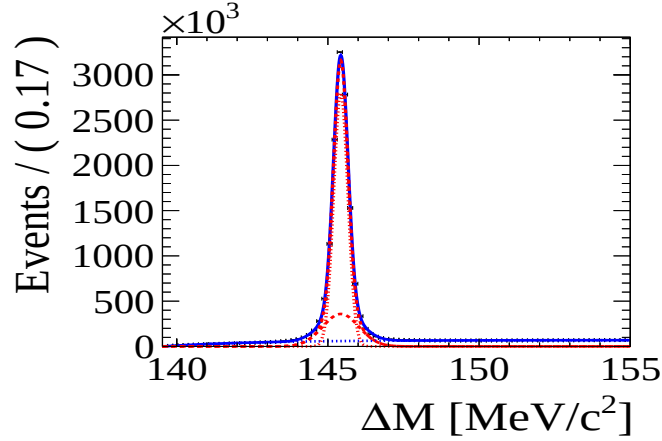


Figure 6.10: Δm distribution for the (D^{*+} -tagged) $D^0 \rightarrow K_S^0 \pi^- \pi^+$ sample, used as an additional control mode to determine nuisance asymmetries, which are then injected into the ensemble of flavour-randomised signal samples. A $\pm 3\sigma$ window is taken around the peak before the candidates are used in this analysis.

the top two plots in Fig. 6.5. The above study implicitly averages asymmetries over the two magnet polarities. We perform a further study in which the asymmetries are injected separately for the two polarities, before merging them, which is a more realistic reflection of reality. The general procedure is exactly the same as above. The only difference is that we now effectively have a 3D asymmetry map used in the injection, where the new dimension is the magnet polarity under which the candidate was collected. The 2D asymmetry maps as a function of soft pion (p_T, η) for the separate polarities are shown in Fig. 6.13 and presented in Tables. 6.11, 6.12. The resulting p -value distribution from running the energy test over the polarity dependent asymmetry-injected samples, before merging the two polarity samples, is shown in Fig. 6.14 and is consistent with the null hypothesis of CP symmetry.

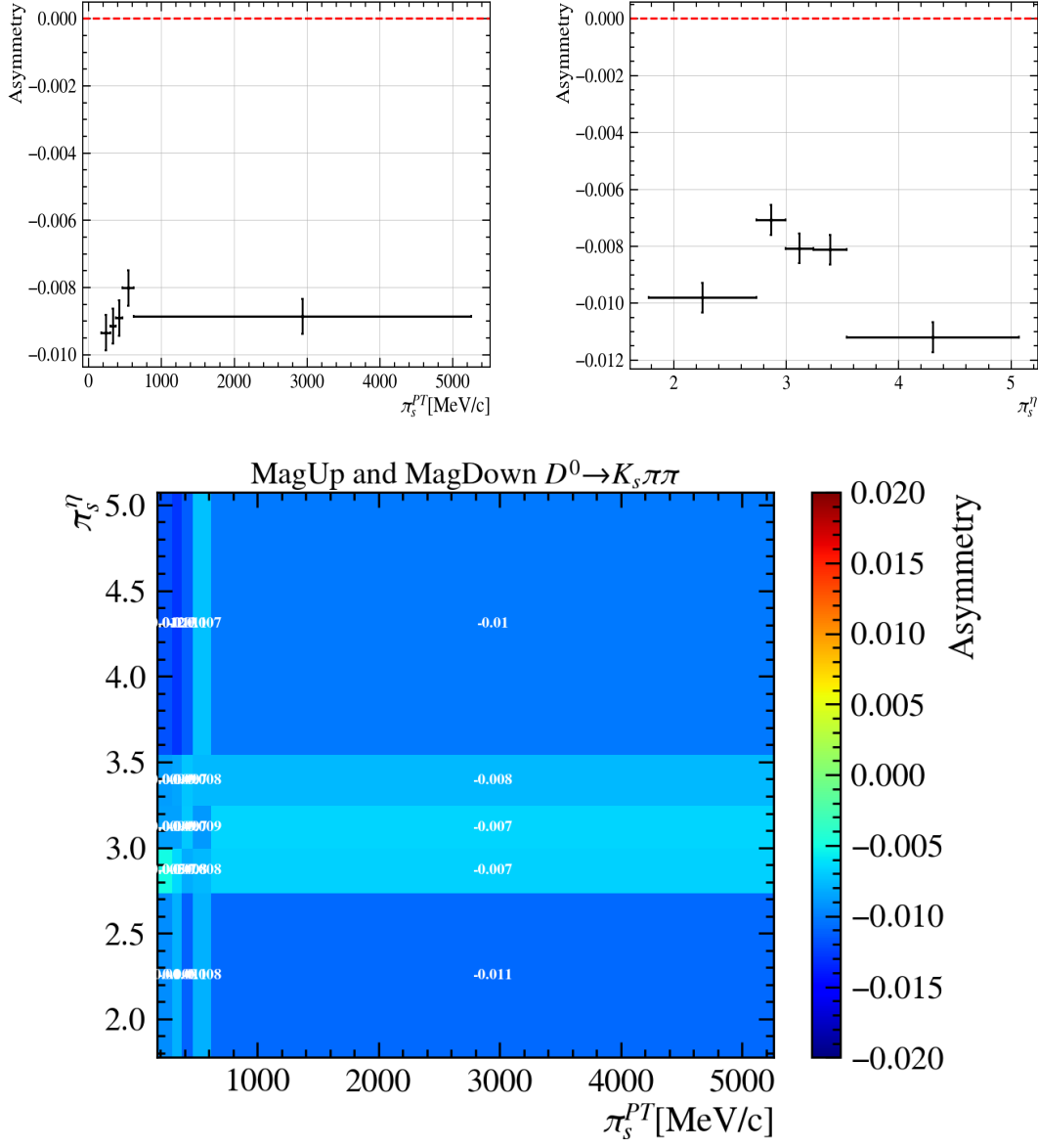


Figure 6.11: Asymmetry map for the soft pion transverse momenta (top left) and pseudorapidity (top right) from $D^0 \rightarrow K_S^0 \pi^- \pi^+$ channel. The corresponding 2D asymmetry map in these variables is also shown (bottom). The 2D map is used to inject asymmetries into the flavour randomised signal samples.

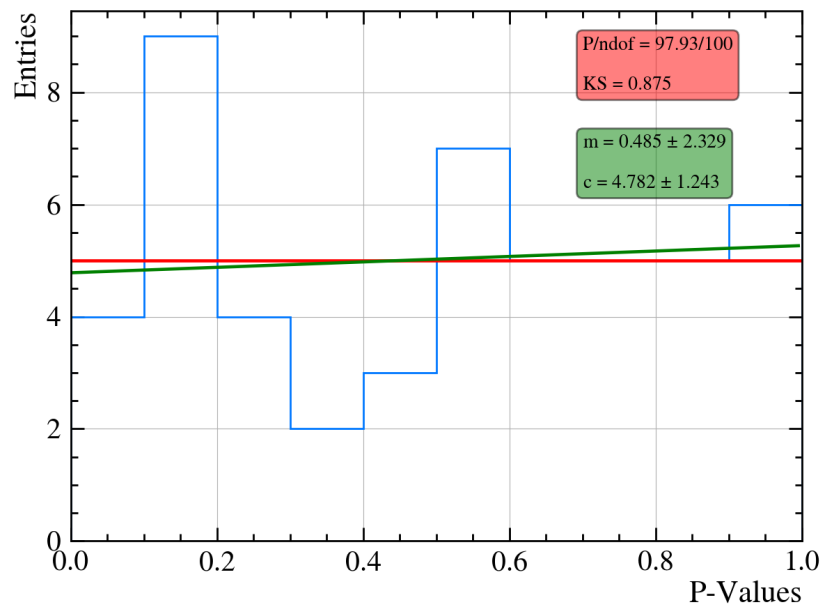


Figure 6.12: p -value distribution for an ensemble of flavour randomised signal samples where the soft pion asymmetry is artificially injected based on the asymmetry map from the $D^0 \rightarrow K_S^0 \pi^- \pi^+$ control mode. As before, the P -statistic and an unbinned KS test are calculated to show that the p -values are consistent with being drawn from a uniform distribution. This is further demonstrated by performing a linear fit with the slope of this fit being consistent with zero.

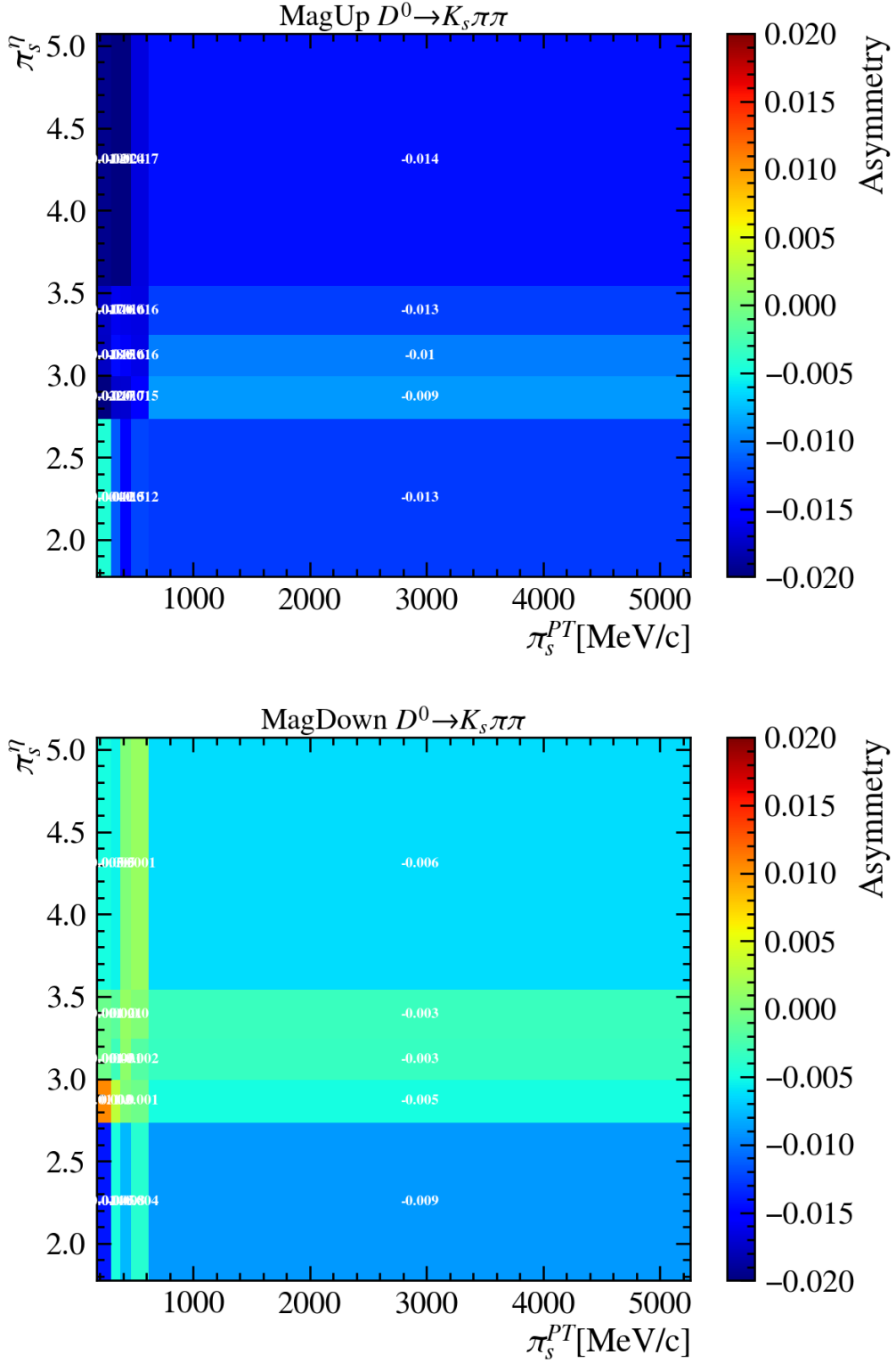


Figure 6.13: Asymmetry map for the soft pion transverse momenta and pseudorapidity from $D^0 \rightarrow K_s^0 \pi^- \pi^+$ channel for MagUp (top) and MagDown (bottom) polarities.

η					
$p_T(\text{GeV}/c)$	(1.78,2.73)	(2.73,3.0)	(3.0,3.24)	(3.24,3.54)	(3.54,5.07)
(0.174,0.30)	-0.4 ± 0.3	-1.2 ± 0.2	-1.5 ± 0.2	-1.2 ± 0.1	-1.3 ± 0.1
(0.30,0.377)	-2.2 ± 0.2	-1.7 ± 0.2	-1.7 ± 0.2	-1.5 ± 0.2	-0.9 ± 0.2
(0.377,0.47)	-1.8 ± 0.2	-1.5 ± 0.2	-1.6 ± 0.2	-1.6 ± 0.2	-1.0 ± 0.2
(0.47,0.621)	-1.7 ± 0.1	-1.6 ± 0.2	-1.6 ± 0.2	-1.6 ± 0.2	-1.3 ± 0.2
(0.621,5.26)	-1.9 ± 0.1	-2.1 ± 0.2	-2.4 ± 0.2	-1.7 ± 0.2	-1.4 ± 0.2

Table 6.11: Soft pion charge asymmetry from $D^0 \rightarrow K_S^0 \pi^- \pi^+$ in bins of soft pion transverse momenta and pseudorapidity for Magnet Up polarity configuration.

η					
$p_T(\text{GeV}/c)$	(1.78,2.73)	(2.73,3.0)	(3.0,3.24)	(3.24,3.54)	(3.54,5.07)
(0.174,0.30)	-1.4 ± 0.4	-0.5 ± 0.2	-0.8 ± 0.2	-0.4 ± 0.1	-0.9 ± 0.1
(0.30,0.377)	-1.1 ± 0.2	-0.3 ± 0.2	-0.005 ± 0.2	-0.06 ± 0.2	-0.5 ± 0.2
(0.377,0.47)	-0.06 ± 0.2	-0.3 ± 0.2	-0.09 ± 0.2	-0.2 ± 0.2	-0.3 ± 0.2
(0.47,0.621)	-0.08 ± 0.1	-0.2 ± 0.2	-0.1 ± 0.2	-0.03 ± 0.2	-0.3 ± 0.2
(0.621,5.26)	-0.5 ± 0.1	-0.5 ± 0.1	-0.03 ± 0.2	-0.1 ± 0.2	-0.6 ± 0.2

Table 6.12: Soft pion charge asymmetry from $D^0 \rightarrow K_S^0 \pi^- \pi^+$ in bins of soft pion transverse momenta and pseudorapidity for Magnet Down polarity configuration.

While the soft pion asymmetry is expected to be the largest, it is also possible that there are other sources of nuisance asymmetry, namely the $D^{*\pm}$ production asymmetry, and the $\pi^+\pi^-$ detection asymmetry. If these have significant variation as a function of the particle kinematics they could affect the energy test results. Our approach is first to compare the corresponding asymmetries from a post-injection signal sample with the $D^0 \rightarrow K_S^0 \pi^- \pi^+$ sample. Figure 6.15 shows that the raw flavour asymmetry as a function of D^0 kinematics is well described after injecting the soft pion detection asymmetry. Hence, there is no need for an additional asymmetry injection. Similarly, plotting the asymmetry versus the $\pi^+\pi^-$ squared-invariant-mass shows good agreement between the two samples, as shown in Fig. 6.16. We conclude that our procedure to inject the nuisance asymmetry as a function of soft pion kinematics results in a pattern of asymmetry consistent with the high-statistics $D^0 \rightarrow K_S^0 \pi^- \pi^+$ control mode. The fact that all resulting p -values are compatible with being drawn from a uniform distribution leads to the conclusion that we are insensitive to such nuisance asymmetries with the current signal yield.

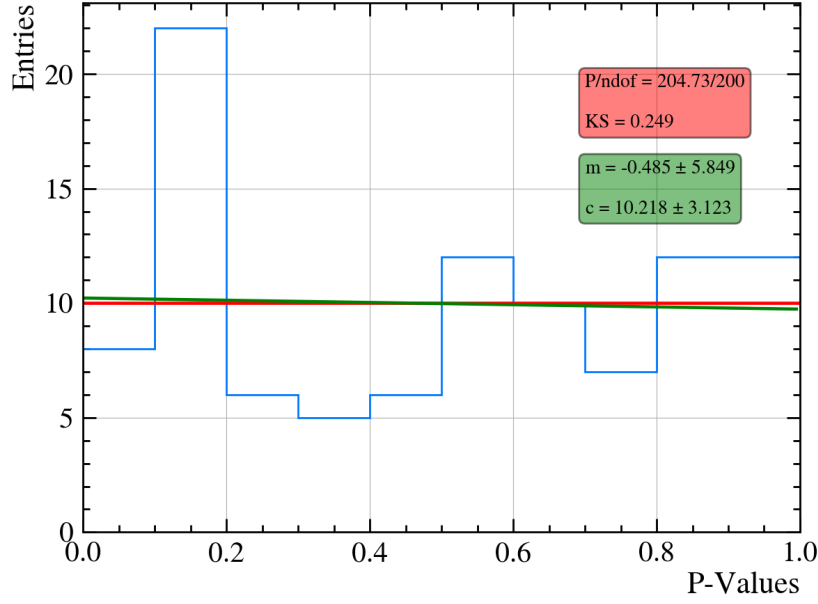


Figure 6.14: p -value distribution for an ensemble of flavour randomised signal samples where the soft pion asymmetry is artificially injected according to the magnet polarity of each candidate. As before, the P -statistic and an unbinned KS test are calculated to show that the p -values are consistent with being drawn from a uniform distribution. This is further demonstrated by performing a linear fit with the slope of this fit being consistent with zero. The injected asymmetry does shift the p -values to the lower half of the distribution but this is a non-significant systematic shift that doesn't impact the final conclusion.

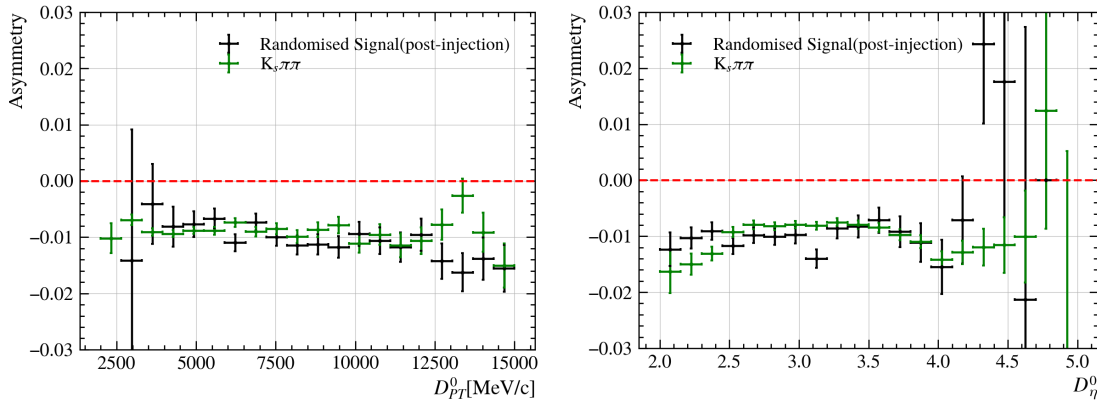


Figure 6.15: Asymmetry for the D^0 transverse momenta (left) and pseudorapidity (right) from $D^0 \rightarrow K_S^0 \pi^- \pi^+$ compared to a flavour randomised signal sample after the injection of the soft pion detection asymmetry.

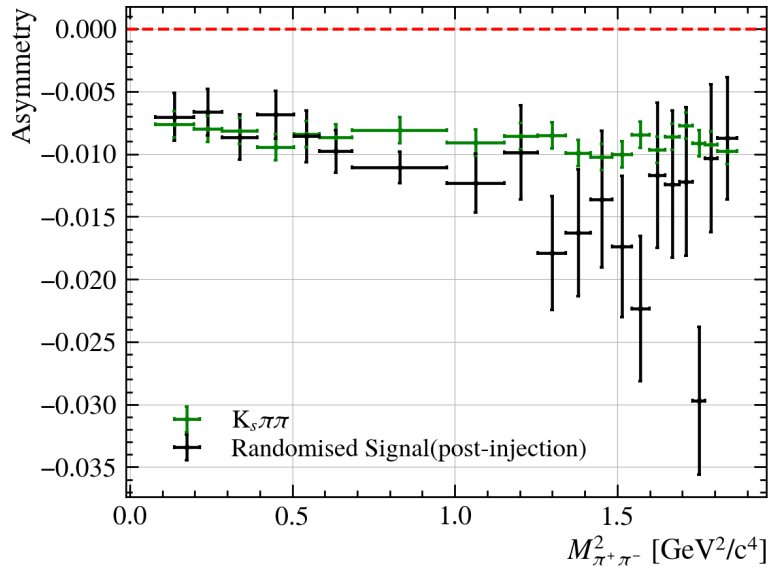


Figure 6.16: Asymmetry for the $M_{\pi^+\pi^-}^2$ from the $D^0 \rightarrow K_S^0 \pi^- \pi^+$ sample compared to a flavour randomised signal sample after the injection of the soft pion detection asymmetry. The higher $M_{\pi^+\pi^-}^2$ corresponds to regions in phase space where the D^0 momentum is highest and π_s momentum the lowest which explains the larger asymmetry seen in the latter half of the distribution.

6.6.2 Assessing shifts in p -values from nuisance asymmetries

A second, related method to assess the impact of nuisance asymmetries is to independently inject a nuisance asymmetry multiple times into the *same* underlying flavour randomised signal sample, and run the energy test over each post-injection sample. We can then compare the nominal p -value before any asymmetry is injected with the distribution of p -values post-injection. For this specific study we use the soft-pion asymmetry map as described above. In this case rather than looking for a p -value distribution which is uniform from zero to one, we are looking for a distribution which is closely clustered about the nominal pre-injection p -value, as an indication that the method is not sensitive to nuisance asymmetries (within the current sensitivity). For this test, a spread of the statistical significance is examined as this is easier to interpret than a spread of p -values. The p -values are converted into a statistical significance using an inverse error function.

When interpreting the results of this test, it is important to account for the fact that there will be some statistical variation independent of the impact of nuisance asymmetries, since in each case some candidates are removed from the base sample. To enable us to separate this purely statistical effect from a potential systematic shift in p -values due to the nuisance asymmetry, we perform a second related test, as follows. After each asymmetry injection, the number of candidates rejected is saved. Then starting with the same CP symmetric flavour randomised sample, the same fraction of candidates are rejected randomly without reference to phase-space. The energy test is performed after every random rejection to build an ensemble of p -values. In this case any shifts in the p -value will be purely statistical in nature.

Fig. 6.17 shows the variation in p -values in terms of the statistical significance for 6 independent flavour randomised samples where the injected soft pion asymmetry map is randomised for each entry in a single flavour randomised sample. This is analogous to the re-sampled asymmetry map approach but instead of re-sampling the asymmetry map between toys, it is re-sampled for each point within a given toy. Similarly, Fig. 6.18 shows the variation in p -values in terms of the statistical significance for the same 6 independent flavour randomised samples where the fixed asymmetry map approach is implemented. In order to induce a spread of p -values for each point in a given toy, the seed to select the random number that determines the rejection is randomised for each entry in a single flavour randomised sample. The two methods allow for the assessment of the impact of uncertainties on the asymmetry map since they are effectively ignored in the latter approach but included in the former approach. Since the distributions are broadly in agreement we can conclude that the details of the treatment of the asymmetry map do not influence the conclusions of the study.

The variation in p -values is shown for both approaches of injecting the soft pion asymmetry as well as randomly rejecting candidates. The red line shows the nominal significance before the injection of any asymmetry (or before any random rejection). In general the orange (random rejection) and blue (asymmetry injection) distributions are broadly similar, with a characteristic spread about the nominal significance. We conclude that any possible systematic variation from the nuisance asymmetry is negligible compared to the intrinsic statistical scatter, and so the p -values are not appreciably

changed by the nuisance asymmetries.

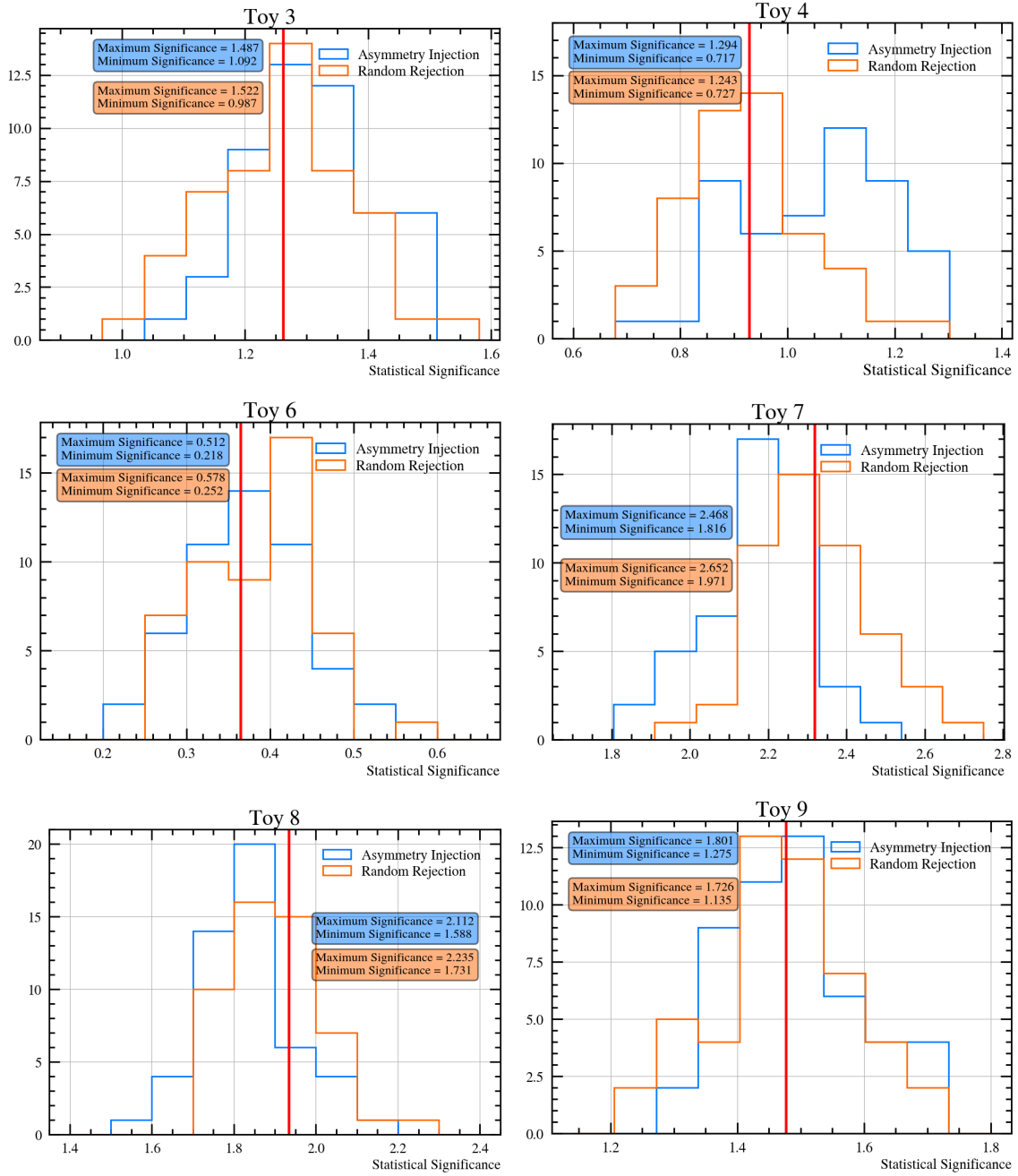


Figure 6.17: Six p -value distributions each based on a single flavour randomised sample, where the injected soft pion asymmetry is randomised 50 times to build an ensemble of p -values, then translated into a statistical significance. The variation in significance is shown for the nuisance asymmetry injection (blue) and the random rejection of candidates (orange) where the latter encapsulates the statistical noise resulting from asymmetry injection. The nominal significance (red) is shown prior to any candidate rejection.

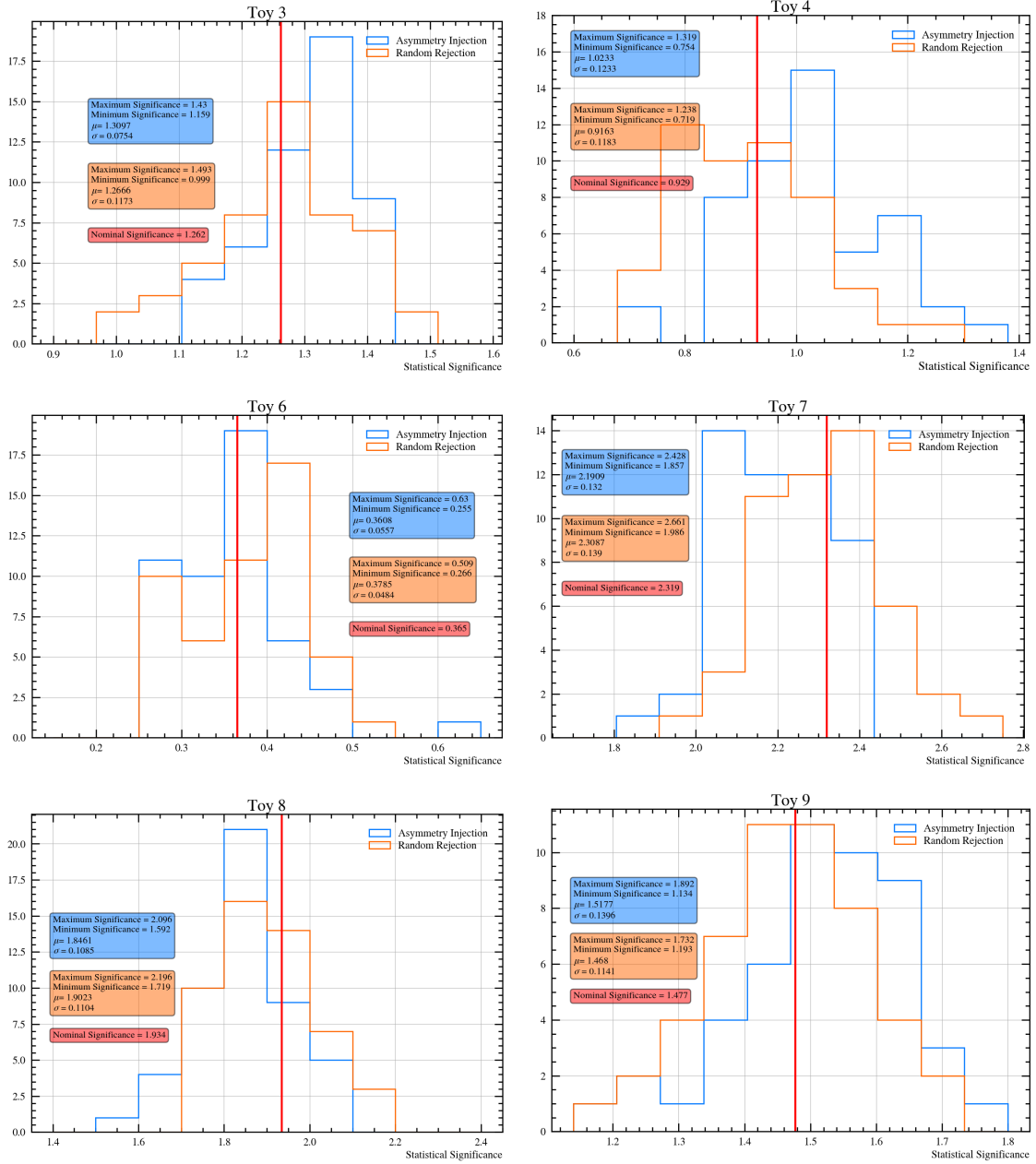


Figure 6.18: Six p -value distributions each based on a single flavour randomised sample, where the injected soft pion asymmetry is fixed but the seed to select the random number that determines the rejection is randomised 50 times to build an ensemble of p -values, then translated into a statistical significance. The variation in significance is shown for the nuisance asymmetry injection (blue) and the random rejection of candidates (orange) where the latter encapsulates the statistical noise resulting from asymmetry injection. The nominal significance (red) is shown prior to any candidate rejection.

6.6.3 $\pi^+\pi^-$ Detection Asymmetry

When injecting a nuisance asymmetry in bins of soft pion kinematics, it was shown that this leads to an asymmetry in $m^2(\pi^+\pi^-)$ consistent with the observed asymmetry from the $D^0 \rightarrow K_S^0\pi^-\pi^+$ channel. As such, we can be quite confident that any $\pi^+\pi^-$ asymmetry is implicitly accounted for in this study. However, we can also take an alternative approach by directly injecting the $\pi^+\pi^-$ detection asymmetry. Since there are two charged pions originating from the D^0 , we take an average of the momenta and pseudorapidity to build a 2D asymmetry map in bins of these kinematic quantities. The 2D asymmetry map is derived from $D^0 \rightarrow K_S^0\pi^-\pi^+$ channel and is shown in Fig. 6.19. These asymmetries are then injected into a flavour-randomised signal sample, as before, by randomly rejecting candidates in the bins of average bins of transverse momenta and pseudorapidity of the $\pi^+\pi^-$ pair.

Injecting these asymmetries into an ensemble of 150 flavour randomised signal samples and running the ET over these samples produces a p -value distribution shown in Fig. 6.20. We can conclude that the distribution is flat, based on the P -statistic and KS probability, further confirmed by the slope of the linear distribution being consistent with zero.

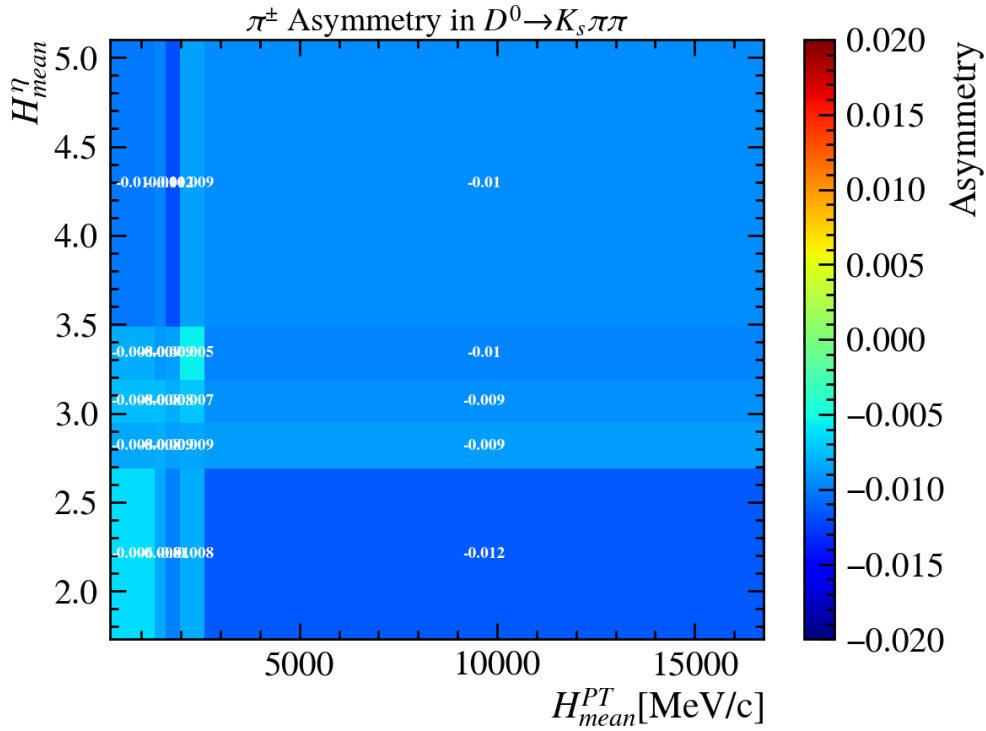


Figure 6.19: $\pi^+\pi^-$ asymmetry map from the $D^0 \rightarrow K_S^0\pi^-\pi^+$ in bins of the averaged pion transverse momenta and pseudorapidity. In this figure H_{mean}^{PT} and H_{mean}^η represent the mean transverse momenta and the mean pseudorapidity of the charged hadrons.

In the above test, the injected asymmetries are randomly sampled from the map in Fig. 6.19 using the re-sampled asymmetry map approach for each candidate in the sample. We can also use the central asymmetry value approach for asymmetry injections and the resulting p -value distribution is shown in Fig. 6.21 for an ensemble of 100 toys. The p -value distribution is again consistent with being uniform,

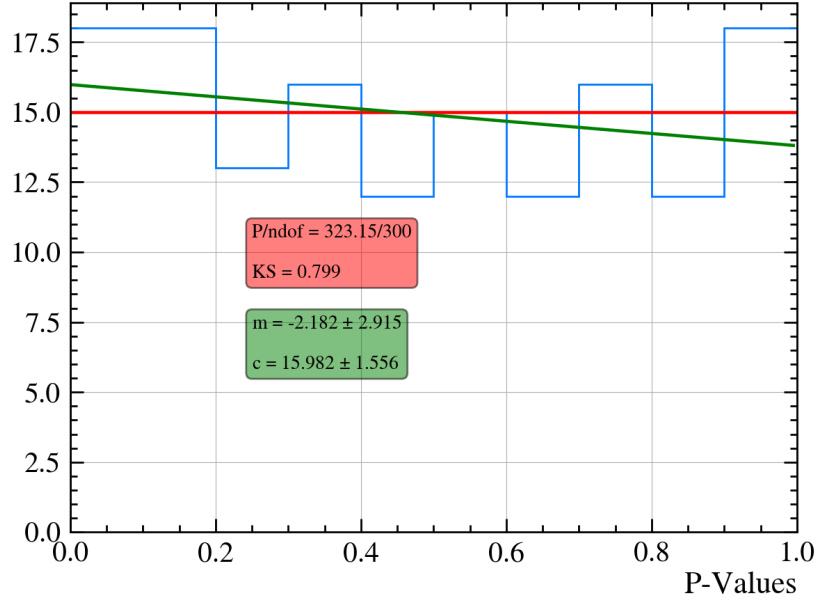


Figure 6.20: p -value distribution for an ensemble of flavour randomised signal samples where the charged pion asymmetry is artificially injected. As before, the P -statistic and an unbinned KS test are calculated to show that the p -values are consistent with being drawn from a uniform distribution. This is further demonstrated by performing a linear fit with the slope of this fit being consistent with zero.

showing no indication that the injected asymmetries are biasing the energy test results.

We then extend this approach to use the ‘fixed asymmetry map’ approach, by repeating several times with the asymmetry re-generated each time according to the known central values and uncertainties. Hence, within each ensemble of p -values a single asymmetry map is used, while between p -value ensembles the map is re-randomised. At present we have performed this for three distinct asymmetry maps, with the three p -value distributions shown in Fig. 6.22. Note that the same 100 flavour-randomised samples are used for each of the plots in Figs. 6.21 and 6.22, so any variation in p -values will be caused by the changes to the nuisance asymmetry map (and some statistical noise from the random rejection). The p -values in all three distributions are consistent with being drawn from a uniform distribution, and the variations between p -value distributions are quite small.

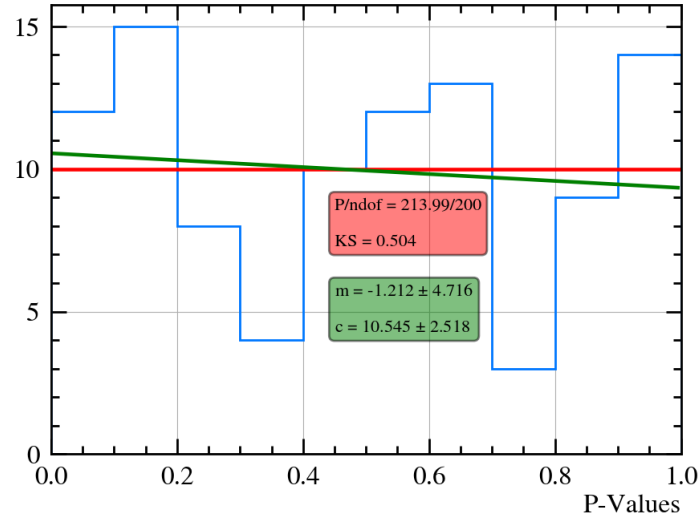


Figure 6.21: p -value distribution for an ensemble of flavour randomised signal samples where the injected charged pion asymmetries are fixed to the central values shown in Fig. 6.19. As before, the P -statistic and an unbinned KS test are calculated to show that the p -values are consistent with being drawn from a uniform distribution.

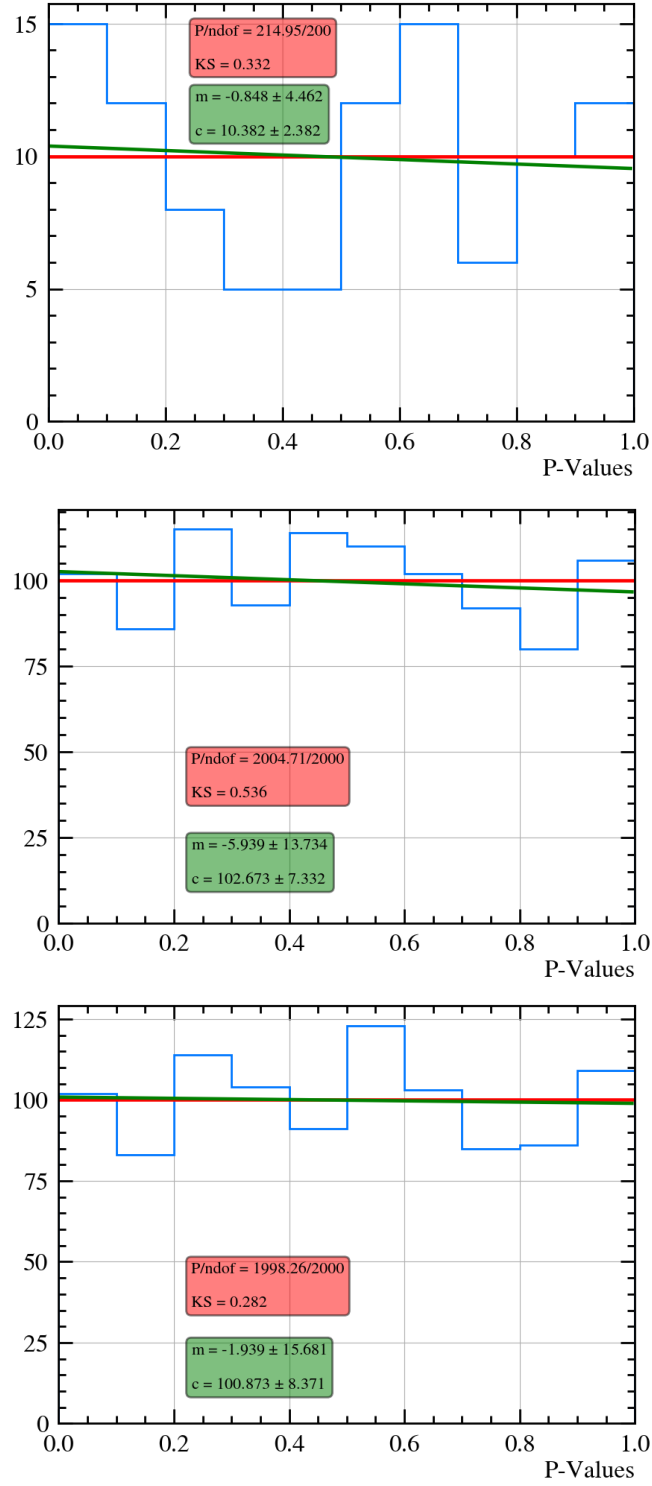


Figure 6.22: p -value distributions for an ensemble of flavour randomised signal samples where the injected charged pion asymmetry map is fixed for each toy in the ensemble. The three distributions correspond to different configurations of the asymmetry map. As before, the P -statistic and an unbinned KS test are calculated to show that the p -values are consistent with being drawn from a uniform distribution for all three p -value distributions.

Looking at asymmetry variations as a function of the helicity angle $\cos \theta$ is another method to assess the potential impact of a $\pi^+\pi^-$ detection asymmetry. Here the angle θ is the decay angle between the $\pi^-(\pi^+)$ and the $D^0(\bar{D}^0)$ in the $\pi^+\pi^-$ rest frame and is therefore dependent on the bachelor pion momenta. As previously, the asymmetry map for $\cos \theta$ is calculated from an independent sample of $D^0 \rightarrow K_S^0 \pi^- \pi^+$ decays and is shown in Fig. 6.23. The asymmetry is parameterised in terms of a second order polynomial and this is used for the injection rather than the bin by bin variation. This is done to avoid creating artificial discontinuities in the Dalitz coordinates which can mimic a fake asymmetry in the Energy Test.

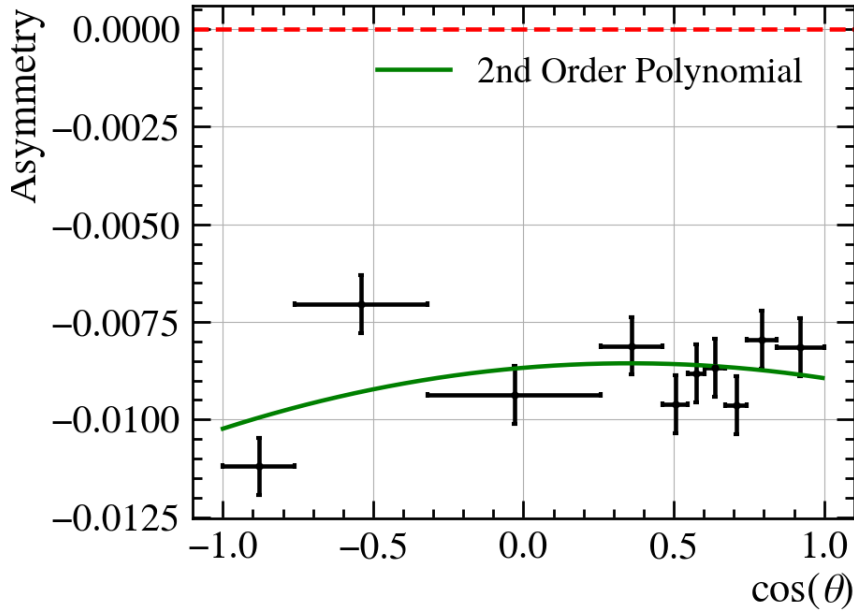


Figure 6.23: Asymmetry map from the $D^0 \rightarrow K_S^0 \pi^- \pi^+$ in bins of $\cos \theta$. The asymmetry is also parameterised in terms of a second order polynomial.

For the $D^0 \rightarrow K_S^0 \pi^- \pi^+$ decays, the angle is given by:

$$\cos \theta = \frac{m^2(K_S^0 \pi^+) - m^2(K_S^0 \pi^-)}{4pq} \quad (6.4)$$

where

$$p = \frac{\lambda^{1/2}(m^2(\pi^+\pi^-), m^2(D^0), m^2(K_S^0))}{2m(\pi^+\pi^-)} \quad q = \frac{\lambda^{1/2}(m^2(\pi^+\pi^-), m^2(\pi^+), m^2(\pi^-))}{2m(\pi^+\pi^-)} \quad (6.5)$$

and

$$\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2xy \quad (6.6)$$

Calculating $\cos \theta$ for $D^0 \rightarrow \pi^- \pi^+ \pi^0$ decays is done by replacing K_S^0 with π^0 in Eqs.6.4-6.6. Injecting the polynomial parameterised asymmetry into an ensemble of flavour randomised signal samples results in a p -value distribution shown in Fig. 6.24 and is consistent with the null hypothesis of CP symmetry.

The lowest p -value in this distribution is 0.4%, with just 2 of the 200 tests having a p -value below 1%. The results indicate that this analysis is insensitive to detection asymmetry variations as a function of $\cos \theta$.

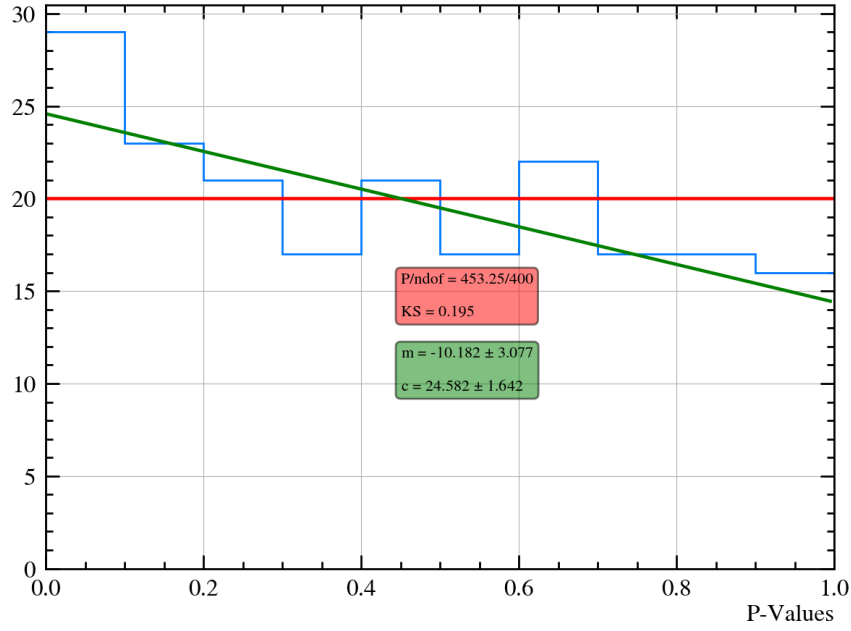


Figure 6.24: p -value distribution for an ensemble of flavour randomised signal samples where the injected $\cos \theta$ asymmetry is parameterised in terms of a second order polynomial. As before, the P -statistic and an unbinned KS test are calculated to show that the p -values are consistent with being drawn from a uniform distribution. The injected asymmetry does shift the p -values into the first bin of the distribution demonstrating a systematic shift. However the lowest p -values are non-significant and hence the final conclusion of p -values being drawn from a uniform distribution still stands.

6.6.4 Using externally-determined track detection asymmetries

The $\pi^+\pi^-$ detection asymmetry maps used for studies in the previous sections are determined using the control mode $D^0 \rightarrow K_S^0\pi^-\pi^+$ with cuts aligned to the signal requirements for this analysis. An alternative choice is to use externally-determined pion detection asymmetries from the analysis documented in Ref. [53]. The tracking asymmetry is calculated in bins of pion pseudorapidity and momentum from the underlying efficiencies to reconstruct the pions. The two approaches should give equivalent results, so this provides a cross-check of the conclusions derived from our default method using the $D^0 \rightarrow K_S^0\pi^-\pi^+$ control mode. The asymmetry maps from Ref. [53], as a function of pion momenta in separate regions of pseudorapidity, are shown in Fig. 6.25.

The resulting p -value distribution from running the energy test over these asymmetry-injected samples is shown in Fig. 6.26. The asymmetries are injected using the fixed asymmetry map approach. Two different methods are tested: In the first we use the polarity-averaged detection asymmetries to inject the asymmetry into our flavour-randomised pseudo-samples (“polarity averaged”). In the second approach we treat the two polarity-specific samples separately, injecting the corresponding detection asymmetries before merging the post-injection samples (“polarity specific”). In both cases the results are consistent with the null hypothesis of CP symmetry. This confirms that for this analysis we are not sensitive to pion track detection asymmetries.

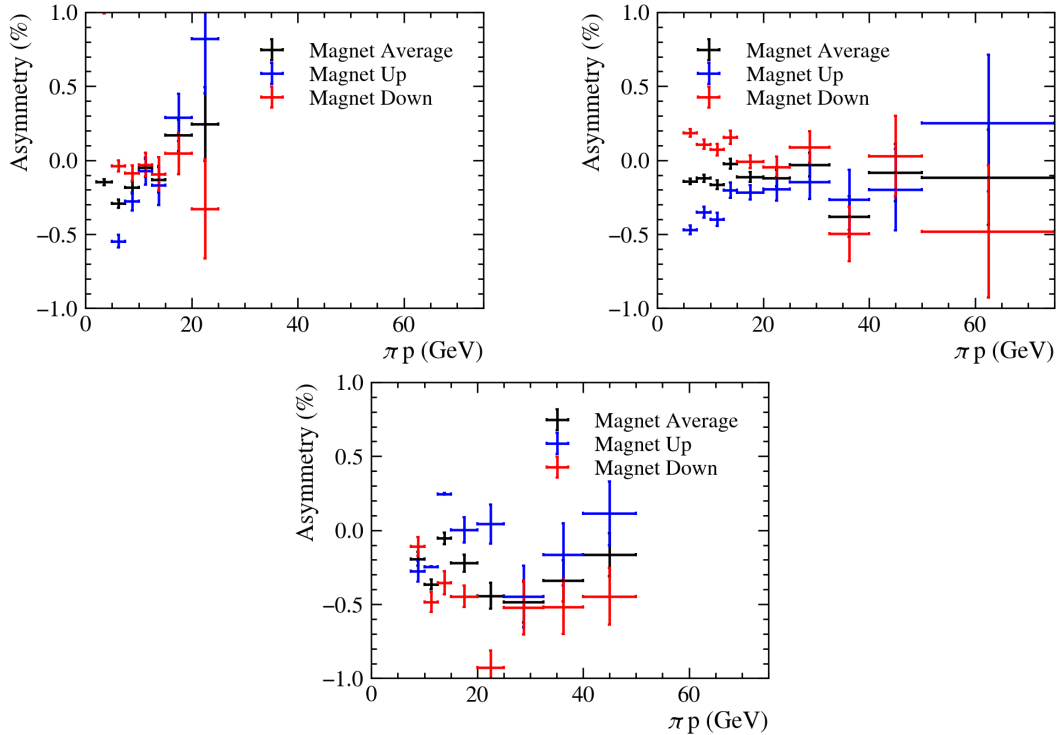


Figure 6.25: Track detection asymmetry calculated from the $D^0 \rightarrow K_S^0\pi^-\pi^+$ Bin-Flip analysis [53] as a function of single pion momenta shown in the following bins of η (left to right, top to bottom): [2.0, 3.0, 4.0, 5.0]

As previously, interpreting these results requires the disentanglement of statistical variation from

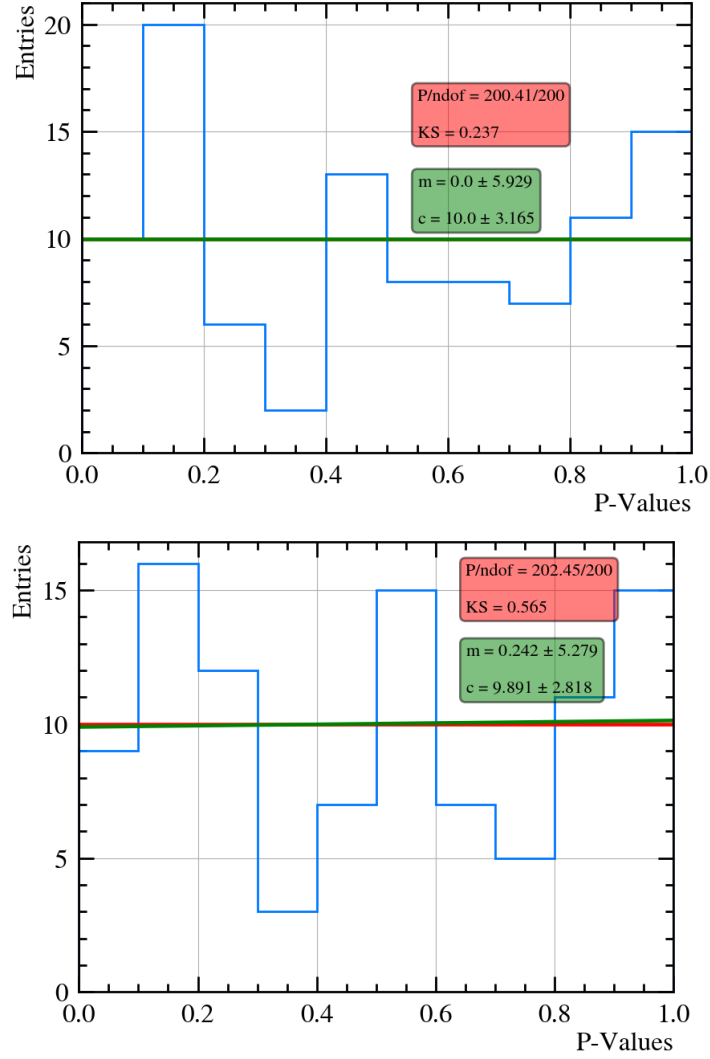


Figure 6.26: p -value distributions for polarity averaged (top) and polarity specific (bottom) charged pion asymmetries taken from Ref.[53] for an ensemble of flavour randomised signal samples. As before, the P -statistic and an unbinned KS test are calculated to show that the p -values are consistent with being drawn from a uniform distribution for both p -value distributions.

systemic shift in p -values due to nuisance asymmetries. This is tested as before by taking single CP symmetric toys and repeatedly injecting the nuisance asymmetry by randomising the asymmetry map to build an ensemble of p -values. The statistical fluctuation in p -values is estimated by randomly rejecting candidates without reference to kinematic quantities and the number of rejected candidates is based on the fraction of candidates rejected when injecting the nuisance asymmetry.

Fig. 6.27 shows the variation in p -values in terms of the statistical significance for 6 independent flavour randomised samples. This is shown for both approaches of injecting the single pion detection asymmetry as well as randomly rejecting candidates. The red line shows the nominal significance before the injection of any asymmetry (or before any random rejection). As before, we conclude that any possible systematic variation from the nuisance asymmetry is negligible compared to the intrinsic

statistical scatter, and so the p -values are not appreciably changed by the nuisance asymmetries.

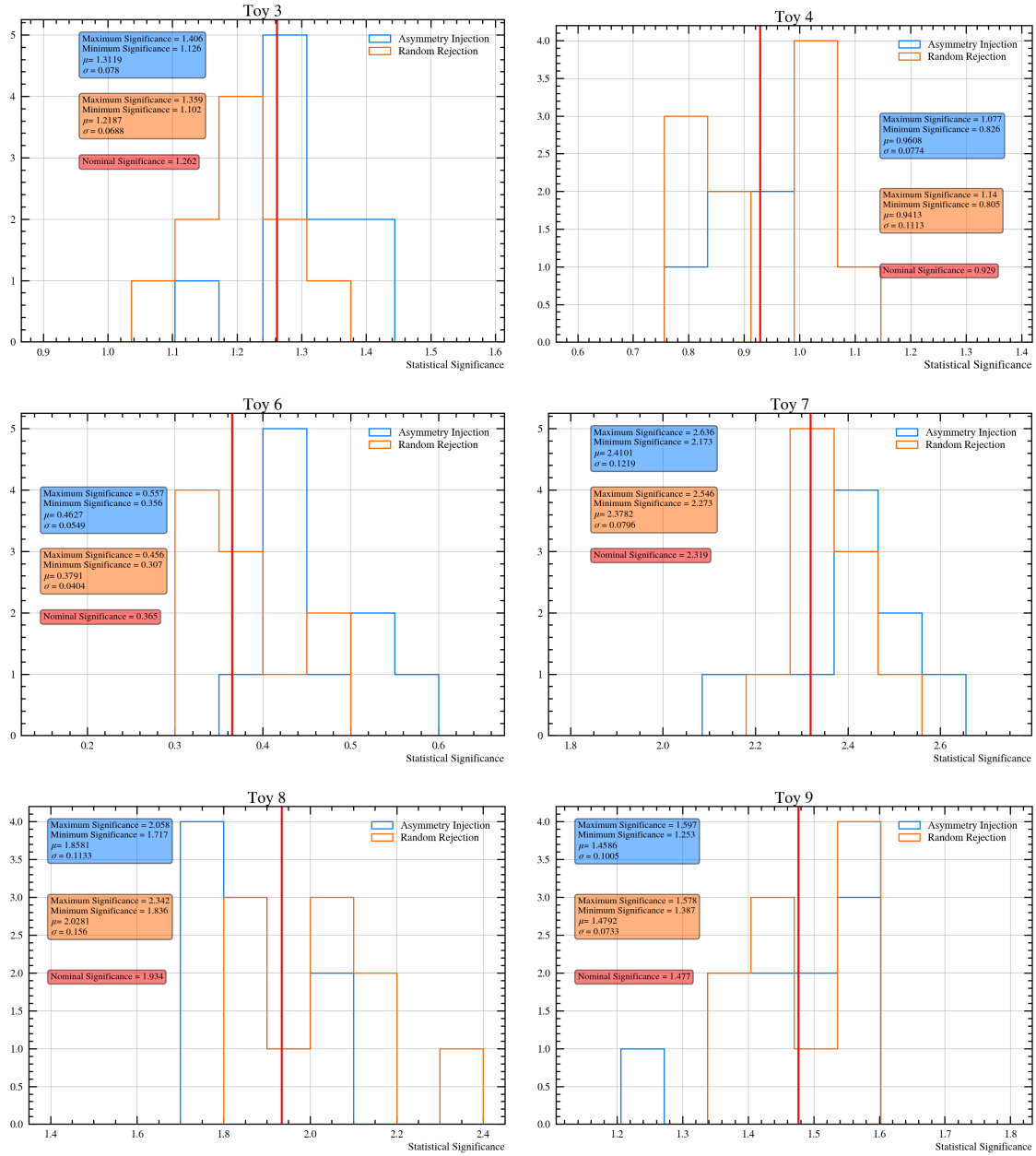


Figure 6.27: Six p -value distributions each based on a single flavour randomised sample, where the single pion detection asymmetry is randomised 10 times to build an ensemble of p -values, then translated into a statistical significance. The variation in significance is shown for the nuisance asymmetry injection (blue) and the random rejection of candidates (orange) where the latter encapsulates the statistical noise resulting from asymmetry injection. The nominal significance (red) is shown prior to any candidate rejection.

Chapter 7

Results of applying ET to the

$D^0 \rightarrow \pi^- \pi^+ \pi^0$ decays

The output of the ET is a single p -value testing the compatibility of the data with the null hypothesis of CP symmetry. If a significant p -value is observed, the test cannot be used to quantify the effect, or point to its origin. For this a more complex model-dependent analysis will be required, beyond the scope of this analysis. It is possible to apply the ET to the signal region of the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ sample once the method has been shown to be robust and insensitive to nuisance asymmetries such as those described in Chapter. 6.6. This is referred to as unblinding the analysis. Upon unblinding the analysis, a p -value of **0.622** is obtained which is consistent with the null hypothesis of CP symmetry. Figure. 7.1 shows the distribution of T -values constructed assuming the null hypothesis. Superimposed on the distribution is the nominal T -value obtained from running the ET on the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ channel.

A p -value that is compatible with the null hypothesis of CP symmetry in the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ channel means that CP violation is not entering the dominant or sub-dominant resonances at a phase asymmetry greater than 0.6° as demonstrated in Figs. 6.1 and 6.2. If CP violation is present in either the dominant or sub-dominant resonance, it is entering through a phase or magnitude asymmetry to which the Energy Test is insensitive at sample yields seen in the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ channel.

One cross-check that was proposed before unblinding was to check the impact of the L0 hadron triggers (H1_TOS || H2_TOS) on the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ sample. It had been observed in the control mode that events passing only the L0 hadron triggers and failing all other L0 trigger requirements produced small p -values which were attributed to the charged kaon in the final state of the control mode that induce significant detector asymmetries arising from material interactions. The absence of a kaon in the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ sample should mitigate against this effect. Imposing the L0 hadron trigger requirements results in the retention of 30% events compared with the full signal sample. Running the ET over this sample produces an alternative p -value of **0.206**. The compatibility of this value compared with the nominal p -value obtained from running over the full sample is determined by

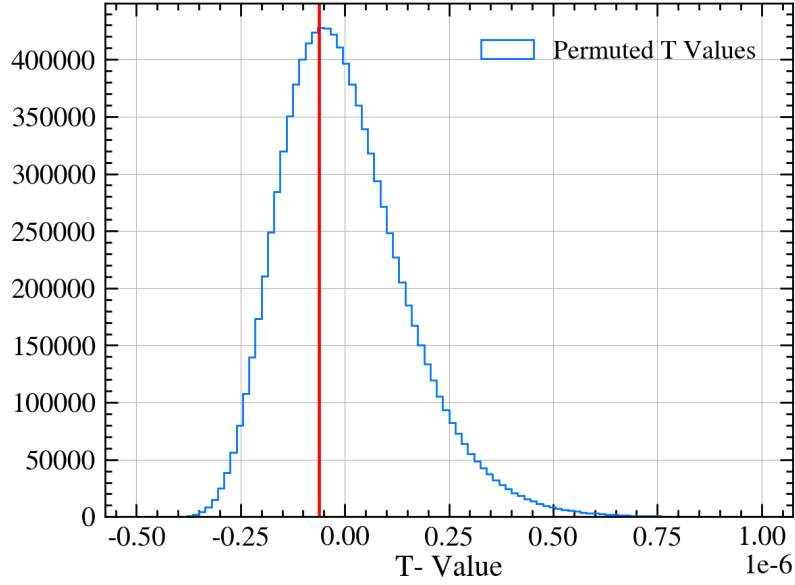


Figure 7.1: T -value distribution constructed from 10^7 permutations by assuming the null hypothesis of CP symmetry. The nominal T -value from running the ET over the signal sample is also shown in red.

performing a two sided test as follows:

1. The size of the sub-sample in question is determined as a fraction of the full sample.
2. A random set of candidates corresponding to this fraction of the total is drawn without reference to any of the candidate properties;
3. The ET is evaluated in this sample;
4. Steps 2-3 are repeated 100 times to obtain a distribution of p -values;

The alternative p -value is compared to this distribution, in a two-sided test. The test is passed if the alternative p -value is closer to the nominal than 5% (i.e. 5) or more of the random subsample p -values. Figure. 7.2 shows the distribution of p -values obtained from randomly sampling the fraction of events passing the L0 hadron trigger requirements. The alternative p -value is closer to the nominal p -value compared with 19 other values so the compatibility test is passed.

A similar test can be performed on events passing the fiducial cuts. The imposition that all pions in the final state pass the fiducial cuts stated in Eqs. 6.2 and 6.3, rejects 30% of the overall number of events in the signal region of the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ sample. Running the ET over this sub-sample produces a p -value of **0.940**. Compatibility with the nominal p -value is tested by performing the test described above. Figure. 7.3 shows the distribution of p -values obtained from randomly sampling the fraction of events passing the fiducial cuts for all pions in the final state. The compatibility test described above is performed on this sample and the alternative p -value is closed to the nominal p -value compared with 21 other values so the test is passed. The compatibility between the nominal p -value and both alternative p -values shows that the choice of L0 hadron triggers and excluding the

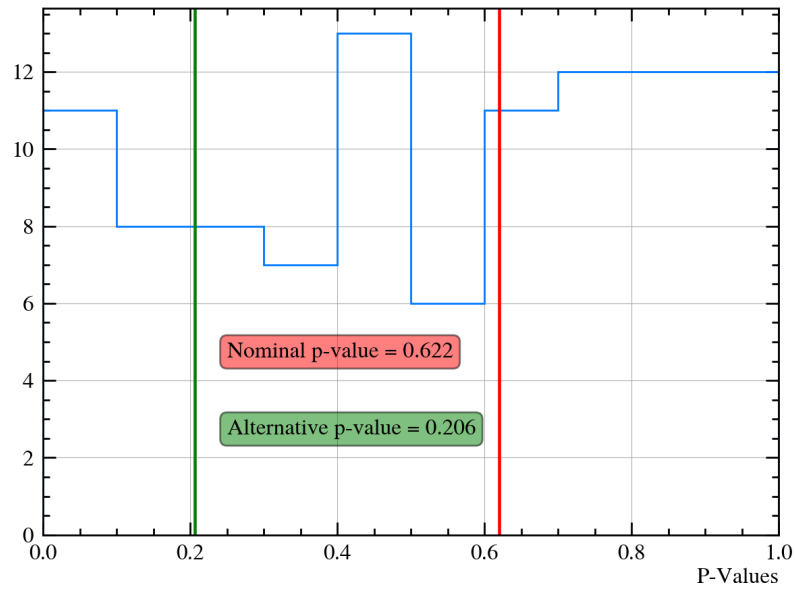


Figure 7.2: p -value distribution from randomly sampling the fraction of events passing the L0 hadron trigger requirements. The alternative and nominal p -values are shown in green and red respectively.

fiducial cuts in the analysis was well founded and did not bias the measurement in any way.

The analysis has passed through LHCb working group review, and assigned to a dedicated review committee. They approved the analysis for unblinding, and a paper draft is now in preparation which will enter LHCb collaboration-wide review in the next month.

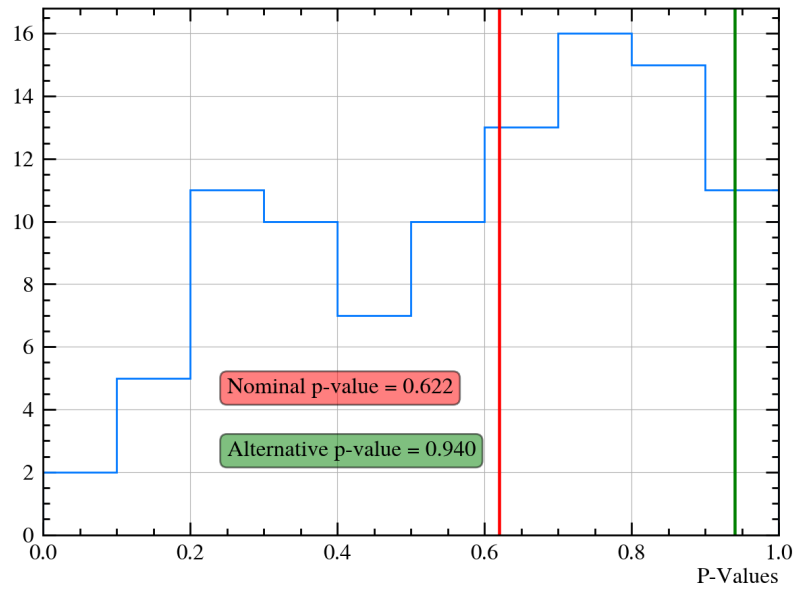


Figure 7.3: p -value distribution from randomly sampling the fraction of events passing the fiducial cuts requirements. The alternative and nominal p -values are shown in green and red respectively.

Part 2 - Analysis of $D^0 \rightarrow V\gamma$ decays

Chapter 8

Analysis Overview for $D^0 \rightarrow V\gamma$ decays

The $D^0 \rightarrow V\gamma$ ($V = \phi, \rho, K^*$) decays are a family of rare radiative charm decays. These decays present an opportunity to look for BSM physics complementary to other approaches at LHCb as outlined in Refs. [40, 106] and in Chapter 2. In some physics models, it is expected that the CP asymmetry in these channels can reach $\mathcal{O}(10^{-1})$ which would be indicative of undiscovered physics not accounted for in the SM as outlined in Chapter. 2.

Experimentally, the measurement of CP asymmetries and branching fractions for radiative charm decays is challenging at a hadron collider due to the disproportionate amount of background produced for every decay of interest. In this chapter, I will discuss some of the challenges associated with making such a measurement at a hadron collider, primarily the neutral pion background that can mimic the radiative decays. The methodology to measure CP asymmetries and branching fractions in these decays will also be outlined. Additionally, methods for dealing with nuisance asymmetries arising from differences in efficiencies of production of initial state particles and reconstruction of final state particles will be discussed.

8.1 Methodology

A parameter known as the CP asymmetry, defined in Eq. 2.36 for a generic final state, is used to quantify the amount of CP violation in a decay. It is defined for the final state under investigation in this analysis as:

$$\mathcal{A}_{CP}(D^0 \rightarrow V\gamma) = \frac{\Gamma(D^0 \rightarrow V\gamma) - \Gamma(\bar{D}^0 \rightarrow \bar{V}\gamma)}{\Gamma(D^0 \rightarrow V\gamma) + \Gamma(\bar{D}^0 \rightarrow \bar{V}\gamma)}, \quad (8.1)$$

where $\Gamma(D^0 \rightarrow V\gamma)$ and $\Gamma(\bar{D}^0 \rightarrow \bar{V}\gamma)$ are the decay rates of the D^0 meson to a final state and its CP conjugate process, respectively. Any deviation of this parameter from zero would be a manifestation of CP violation in decay as the decay rates of a process and its corresponding CP conjugate process

would be unequal. Experimentally, the raw asymmetry is measured instead:

$$\mathcal{A}_{\text{Raw}}(D^0 \rightarrow V\gamma) = \frac{N(D^0 \rightarrow V\gamma) - N(\bar{D}^0 \rightarrow \bar{V}\gamma)}{N(D^0 \rightarrow V\gamma) + N(\bar{D}^0 \rightarrow \bar{V}\gamma)}, \quad (8.2)$$

where $N(D^0 \rightarrow V\gamma)$ and $N(\bar{D}^0 \rightarrow \bar{V}\gamma)$ are the number of decays of D^0 and $\bar{D}^0$ respectively to the final state. The flavour of the D^0 is determined from the charge of the soft pion as explained in Chapter. 5. The raw asymmetry is the sum of CP asymmetry and all other nuisance asymmetries. Removing the nuisance asymmetries will be discussed in Sec. 8.2.

The branching fraction, $\mathcal{B}$, for a decay is the fraction of times a particle of interest decays into a particular final state. Experimentally, the branching fraction for the family of radiative decays will be measured with respect to the branching fraction of the $D^0 \rightarrow \bar{K}^{*0}\gamma$ channel. This is done because measuring absolute branching fractions relies on a precise and reliable knowledge of absolute efficiencies of the trigger, detector, reconstruction, and event selection, and also the luminosity. To simplify the analysis and reduce uncertainties, the relative branching fractions are instead measured using the $D^0 \rightarrow \bar{K}^{*0}\gamma$ state as a reference channel. The known $D^0 \rightarrow \bar{K}^{*0}\gamma$ branching fraction from other measurements can then be used to convert our measurements into absolute branching fractions for $D^0 \rightarrow \rho\gamma$ and $D^0 \rightarrow \phi\gamma$. The number of $D^0 \rightarrow V\gamma$ candidates can be written as:

$$N(D^0 \rightarrow V\gamma) = L * \sigma(pp \rightarrow D^0) * \mathcal{B}(D^0 \rightarrow V\gamma) * \varepsilon(D^0 \rightarrow V\gamma) * \varepsilon(\pi_s) \quad (8.3)$$

where L is the instantaneous luminosity of the pp collisions, $\sigma(pp \rightarrow D^0)$ is the cross-section of the pp collisions resulting in the formation of a D^0 meson and ε is the detection efficiency for these decays (see below). Thus, the ratio of the branching fractions with respect to the $D^0 \rightarrow \bar{K}^{*0}\gamma$ mode is:

$$\frac{\mathcal{B}(D^0 \rightarrow V\gamma)}{\mathcal{B}(D^0 \rightarrow K^{*}\gamma)} = \frac{N(D^0 \rightarrow V\gamma)}{N(D^0 \rightarrow K^{*}\gamma)} \frac{\varepsilon(D^0 \rightarrow K^{*}\gamma)}{\varepsilon(D^0 \rightarrow V\gamma)} \quad (8.4)$$

$$V = \rho, \phi$$

where $N(D^0 \rightarrow V\gamma)$ and $N(D^0 \rightarrow K^{*}\gamma)$ are the number of decays to the signal($V=\phi,\rho$) and K^{*} mode final states respectively. An accurate measurement of the branching fractions must also account for the efficiencies, ε , of the signal and K^{*} modes. The efficiency is a product of the geometric acceptance, reconstruction, detection, trigger and selection efficiencies. Efficiencies related to photon reconstruction and detection will be difficult to quantify but they will cancel in the ratio due to the presence of a photon in the signal and K^{*} mode final states. The other efficiencies can be determined using simulated samples. The measurement of the CP asymmetry and branching fractions in the $D^0 \rightarrow V\gamma$ channels is dependant on the yield of signal candidates, N in Eqs. 8.2, 8.4 in these channels. The signal yields are extracted from multidimensional unbinned maximum likelihood fits which are discussed further in Sec. 9.6.

What seems like a straightforward measurement is accompanied by a series of challenges. Firstly, the decay $D^0 \rightarrow V\gamma$ is swamped by the corresponding decay with a neutral pion in place of the photon, $D^0 \rightarrow V\pi^0$. The neutral pion will decay into two photons and this process can mimic the signal decay exactly if one of the photons is not detected or if the two photons are indistinguishable in

the electronic calorimeter due to the small separation angle between them. This is known as the neutral pion background due to its high branching fraction (See Tab. 8.1) compared with the signal mode and will be referred to as the π^0 background. A multivariate classifier has been developed to suppress this background. The classifier was trained on electromagnetic calorimeter and pre-shower detector variables that look at the energy deposits in calorimeter cells and shape of such deposits. The performance of the classifier was compared to a standard tool used to suppress the same background in beauty radiative decays [107]. Both tools were optimised by looking at the preliminary yields for the signal and neutral pion background found from a multidimensional fit to the data. These cuts are then applied to the data to obtain the signal significance from the signal and background yields. The tool with the greatest signal significance is chosen to suppress the neutral π^0 background.

Decay	Branching Fraction (%)
$D^0 \rightarrow \bar{K}^{*0}\pi^0$	1.95 ± 0.24
$D^0 \rightarrow \bar{K}^{*0}\gamma$	$(4.1 \pm 0.7) \times 10^{-2}$

Table 8.1: Table showing the branching fraction of the $K^{*}\gamma$ and the $K^{*}\pi^0$ channels [89]. The π^0 component has a branching fraction more than an order of magnitude greater than the γ component.

Another source of background, originating from random photons and misidentified vector mesons, is known as combinatorial background. Disentangling these sources of background from signal is necessary to make an accurate measurement of the CP asymmetry. A discussion on how to disentangle the different sources of background from the signal decays is presented in Sec. 9.6.

8.2 Correcting nuisance asymmetries

The raw CP asymmetry includes contributions from detector and particle production induced asymmetries. The raw asymmetry is related to $\mathcal{A}_{CP}$ through the following relation:

$$\mathcal{A}_{\text{Raw}}(D^0 \rightarrow V\gamma) = \mathcal{A}_{CP}(D^0 \rightarrow V\gamma) + \mathcal{A}_P(D^*) + \mathcal{A}_D(\pi_s) + \mathcal{A}_D(h'^+h^-) \quad (8.5)$$

where $\mathcal{A}_P(D^*)$ is the production asymmetry associated with the inherent matter-antimatter imbalance from the collision of protons at the primary vertex resulting in different cross sections for the D^{*+} and D^{*-} . Hence the production asymmetry can be defined as:

$$\mathcal{A}_P(D^*) = \frac{\sigma(D^{*+}) - \sigma(D^{*-})}{\sigma(D^{*+}) + \sigma(D^{*-})}, \quad (8.6)$$

where $\sigma(D^{*\pm})$ is the cross-section of the $D^{*\pm}$ production which is dependent on the kinematics of the decay.

$\mathcal{A}_D(\pi_s)$ is the detection asymmetry of the soft pion where the pion of a certain charge may be more efficiently reconstructed compared with its oppositely charged counterpart. Hence this detection

asymmetry can be defined as:

$$\mathcal{A}_D(\pi_s) = \frac{\epsilon(\pi_s^+) - \epsilon(\pi_s^-)}{\epsilon(\pi_s^+) + \epsilon(\pi_s^-)}, \quad (8.7)$$

where $\epsilon(\pi_s^\pm)$ is efficiency of the reconstruction of the $\pi_s^\pm$. As the charge of the soft pion tags the flavor of the D meson, any discrepancy between how oppositely charged soft pions are detected will induce a CP asymmetry.

$\mathcal{A}_D(h'^+h^-)$ represents the detection asymmetry from the decay of the vector meson into two hadrons as the presence of the vector meson is inferred from its decay into two hadrons. This asymmetry cancels to first order when the vector meson decays into a pair of oppositely charged kaons or pions i.e. $\phi \rightarrow K^+K^-$ or $\rho \rightarrow \pi^+\pi^-$. However, an asymmetry could be induced when a vector meson decays into a kaon and pion i.e. $\bar{K}^{*0} \rightarrow K^-\pi^+$. This originates from differences in how pairs of oppositely charged hadrons are detected. For instance, the detection asymmetry of oppositely charged pions will not necessarily cancel the detection asymmetry of oppositely charged kaons.

These additional contributions to $\mathcal{A}_{\text{Raw}}$ are difficult to measure so reference channels are used to study and correct for these nuisance asymmetries. The family of decays $D^0 \rightarrow h'^+h^-$, where $h = \pi, K$, serve as reference channels and their raw asymmetry can be parameterised as:

$$\mathcal{A}_{\text{Raw}}(D^0 \rightarrow h'^+h^-) = \mathcal{A}_{\text{CP}}(D^0 \rightarrow h'^+h^-) + \mathcal{A}_P(D^*) + \mathcal{A}_D(\pi_s) + \mathcal{A}_D(h'^+h^-) \quad (8.8)$$

where $\mathcal{A}_{\text{CP}}(D^0 \rightarrow h'^+h^-)$ is the CP asymmetry in the reference channel and all the other terms have their usual meaning. Each $D^0 \rightarrow V\gamma$ signal mode is matched to a reference channel with the same final state hadrons. For instance, when $V = \phi$, the reference channel is $D^0 \rightarrow K^+K^-$ since the ϕ mesons are reconstructed in the final state containing two kaons. Provided that the kinematics of the D^* , π_s and h'^+h^- follow similar distributions in the $D^0 \rightarrow V\gamma$ and reference channels, the nuisance asymmetries will cancel upon subtracting Eq. (8.8) from Eq. (8.5). Thus, re-arranging the obtained equation for $\mathcal{A}_{\text{CP}}(D^0 \rightarrow V\gamma)$ yields,

$$\mathcal{A}_{\text{CP}}(D^0 \rightarrow V\gamma) = \mathcal{A}_{\text{Raw}}(D^0 \rightarrow V\gamma) - \mathcal{A}_{\text{Raw}}(D^0 \rightarrow h^+h^-) + \mathcal{A}_{\text{CP}}(D^0 \rightarrow h^+h^-). \quad (8.9)$$

To ensure that the cancellation of nuisance asymmetries holds, the reference channels must undergo kinematic re-weighting to ensure that the decay kinematics match those in the $D^0 \rightarrow V\gamma$ channels. This process involves training an MVA over many variables in the reference and $D^0 \rightarrow V\gamma$ channels to provide a weight per candidate which can be applied to the kinematic distributions in the reference channel such that the corresponding distributions in the $D^0 \rightarrow V\gamma$ channels. A more explicit description of the method and its demonstration is provided in Sec. 9.7.1. Raw asymmetries are determined by simultaneously fitting the distribution of $\Delta m = m(D^0\pi_s) - m(D^0)$ for $D^0 \rightarrow h'^+h^-$ and $\bar{D}^0 \rightarrow h'^+h^-$ samples to calculate $\mathcal{A}_{\text{Raw}}(D^0 \rightarrow h'^+h^-)$. The samples share the same signal and background probability density functions (PDF's). The raw signal asymmetry, $\mathcal{A}_{\text{Raw}}$, and raw background

asymmetry, $\mathcal{A}_{\text{Raw}}^{\text{BKG}}$, can be calculated as:

$$\begin{aligned}\mathcal{A}_{\text{Raw}}(D^0 \rightarrow h'^+ h^-) &= \frac{S_+ - S_-}{S_+ + S_-} \\ \mathcal{A}_{\text{Raw}}^{\text{BKG}}(D^0 \rightarrow h'^+ h^-) &= \frac{B_+ - B_-}{B_+ + B_-}\end{aligned}\quad (8.10)$$

where $S_+(B_+)$ and $S_-(B_-)$ are the signal (background) yields from the $D^0 \rightarrow h'^+ h^-$ and $\bar{D}^0 \rightarrow h'^+ h^-$ samples respectively. The CP asymmetries for reference channels, needed as an input for Eq. 8.8, are taken from the world-averages as prepared by the heavy flavour averaging group (HFLAV). The world-averages combine the most accurate measurements of the CP asymmetry in the $D^0 \rightarrow h'^+ h^-$ channels and are very precisely known when compared to the experimental uncertainty on the raw asymmetries for the $D^0 \rightarrow V\gamma$ modes.

Instead of fitting for the yields in each sample, a fit to the signal and background raw asymmetries is performed using the signal and background yields,

$$\begin{aligned}S_{\pm} &= \frac{1}{2}S(1 \pm A_{\text{Raw}}(D^0 \rightarrow h^+ h^-)) \\ B_{\pm} &= \frac{1}{2}B(1 \pm A_{\text{Raw}}^{\text{Bkg}}(D^0 \rightarrow h^+ h^-))\end{aligned}\quad (8.11)$$

where $S = S_+ + S_-$ is the total signal yield and $B = B_+ + B_-$ is the total background yield from the two samples.

8.3 Experimental Status

A recent measurement of the CP asymmetry in the $D^0 \rightarrow \phi\gamma$ channel performed by the BELLE Collaboration show a mild tension with zero [108],

$$\mathcal{A}_{CP}(D^0 \rightarrow \phi\gamma) = 0.094 \pm 0.066 \pm 0.001 \quad (8.12)$$

where the first uncertainty is statistical and the second a source of systematic uncertainty. Measurements of CP asymmetry in the other modes are also dominated by the same analysis performed at the BELLE collaboration:

$$\begin{aligned}\mathcal{A}_{CP}(D^0 \rightarrow \rho\gamma) &= -0.03 \pm 0.020 \pm 0.000 \\ \mathcal{A}_{CP}(D^0 \rightarrow \bar{K}^{*0}\gamma) &= 0.056 \pm 0.151 \pm 0.006.\end{aligned}\quad (8.13)$$

The same analysis also performed absolute branching fraction measurements for the three radiative modes,

$$\begin{aligned}\mathcal{B}(D^0 \rightarrow \phi\gamma) &= (2.76 \pm 0.20 \pm 0.08) \times 10^{-5} \\ \mathcal{B}(D^0 \rightarrow \rho\gamma) &= (1.77 \pm 0.30 \pm 0.08) \times 10^{-5} \\ \mathcal{B}(D^0 \rightarrow \bar{K}^{*0}\gamma) &= (4.66 \pm 0.21 \pm 0.18) \times 10^{-4}.\end{aligned}\quad (8.14)$$

The larger data samples at LHCb are capable of reducing the statistical error on these measurements to potentially provide the first observation of CP violation in radiative charm decays as well as better constraining the branching fraction measurements.

Chapter 9

Event Selection for $D^0 \rightarrow V\gamma$

This analysis uses data collected at LHCb in 2012 and 2017-2018 at a centre of mass energy $\sqrt{s} = 8, 13$ TeV respectively. The Run 2 data will be discussed later in the chapter when discussing the future of the analysis. Unless otherwise specified the studies in this chapter are based on the Run 1 data sample only. In this chapter, I will describe the generic procedure to select $D^0 \rightarrow V\gamma$ decays where $V = \phi, \rho, K^*$. This will begin with the trigger and stripping requirements and move to the offline cuts applied to each mode. The vector resonances, V , all have different masses so different cuts are used for the three vector mesons to reflect their different masses and decay products. Section 9.6 describes the model building process for preliminary multi-dimensional fits to the data before a discussion in Sec. 9.7 on the development of the MVA to suppress the peaking π^0 background which sits on top of the signal peak. The development of the MVA is carried out in a partially data driven manner and it is compared to a corresponding tool in radiative beauty decays used to suppress the same background. This tool is called ‘IsPhoton’ and is used to suppress the π^0 background in this analysis.

9.1 Trigger Selection

As mentioned in Sec. 5.2, a trigger system is necessary to select the decays of interest from pp collisions occurring at 40MHz. The trigger requirements imposed in the analysis of the 2012 data are presented in Table 9.1.

Level	Trigger Line
L0	Dstr_L0_Global_TIS OR D_L0HadronDecision_TOS
HLT1	HLT1TrackAllL0Decision_TOS
HLT2	Dstr_Hlt2CharmHadInclDstr2PiD02HHXDst_hhXDecision_TOS

Table 9.1: Summary of the trigger requirements used in the analysis..

As mentioned previously, the L0 trigger decision is made using limited detector information, and in

particular it excludes information from the tracking system. As such, it is not possible to reconstruct the specific decays of interest for this analysis. The main purpose of imposing specific L0 requirements is to ensure a well-defined set of selection criteria are applied to our signal candidates at all stages of the trigger. To this end, a well defined L0 trigger strategy is necessary to provide a high signal efficiency as well as preventing the introduction of nuisance asymmetries. For this analysis we require that signal candidates satisfy either of the following two conditions:

1. The D^0 candidate passes the L0Hadron trigger as TOS, OR
2. the D^* candidate passes the L0Global trigger as TIS.

The former category provides most of the L0 efficiency, while the latter collects additional candidates while ensuring that there is no charge-bias introduced from the D^* requirement. At the HLT1 level, at least one of the children of the D^0 should fire the `HLT1TrackAllL0Decision_TOS` line. In Run1, this meant confirming the L0 decision by associating the track segments in the VELO or T-station to the energy deposit in the calorimeter [109].

At the HLT2 level, where the event is fully reconstructed, we require that the signal candidates pass an inclusive line which selects charm hadronic decays of the form $D^0 \rightarrow hhX$ where $h = K/\pi$ and X can be any neutral particle. The inclusive trigger line also requires that the D^0 originate from a $D^{*\pm}$ i.e. $D^{*+} \rightarrow D^0\pi_s^+$ and the charge conjugate process.

9.2 Stripping

Events passing the trigger requirements are stored on tape before the application of stripping. The cuts imposed during the stripping reduce the size of the data which needs to be stored and analysed. Table 9.2 shows the cuts imposed on the sample by the `StrippingDstarD2XGammaDstarD2[h,h]GammaLine` stripping lines. The selection cuts between the different radiative modes is identical other than the PIDK cut applied to mesons emerging from the vector resonances to distinguish between kaons and pions. The mass of the D^0 can be determined directly from the two-body invariant mass calculation of the vector resonance and the photon. Another method of determining the D^0 mass is through a three-body invariant mass calculation of the two hadrons and the photon without any consideration that the hadrons come from an intermediate resonance. The former is defined as m_{D^0} and latter as $m_{hh\gamma}$ in the cuts shown in Tab. 9.2. The indirect method ($m_{hh\gamma}$) is quicker to compute regardless of assumptions about the vector resonance, while the other is more precise but only relevant if we pick a resonance and hence has tighter cuts imposed. The same principle is extended to the determination of the mass of the $D^{*\pm}$ candidate where it can be calculated directly ($m_{D^{*\pm}}$) from the invariant mass combination of the D^0 and the soft pion. Alternatively, the mass can be determined from all final state particles i.e. the invariant mass of the two hadrons, the photon and the soft pion. This is called $m_{hh\gamma\pi_s}$. The cuts also remove any D^0 candidates with a negative reconstructed decay time which tend to be background dominated. All other variables used in the selection of $D^0 \rightarrow V\gamma$ decays are

described in Sec. 5.2.3.

Particle	Quantity	Cut
GEC	number of long tracks	<180
$\pi^\pm(K^\pm)$	p_T	> 250 MeV/c
	ghost probability	< 0.5
	PIDK	< 0 (>5)
	Track χ^2/dof	< 4
	$\min \chi_{\text{IP}}^2$	> 3
$h^\pm$ pair	DOCA χ^2	< 10
	$m_{\pi\pi}$	< 1865 MeV/c ²
	$\sum p_T$	> 0
$V(\phi, \rho, K^*)$	m_V	< 1865 MeV/c ²
	vertex χ^2/dof	< 16
	χ^2 w.r.t Best PV	> 100
γ	p_T	> 1700 MeV/c
D^0	vertex χ^2/dof	< 12
	p_T	> 2000 MeV/c
	χ_{IP}^2 w.r.t Best PV	< 35
	D^0 DIRA	> 0.9995
	Lifetime w.r.t Best PV	> 0.0001 ps
	$m_{hh\gamma}$	1610 < $m_{hh\gamma}$ < 2130 MeV/c ²
	m_{D^0}	1610 < m_{D^0} < 2100 MeV/c ²
	Track χ^2/dof	< 3
$D^{*\pm}$	$m_{D^{*\pm}} - m_{D^0}$	< 163 MeV/c ²
	vertex χ^2/dof	< 15
	DOCA χ^2	< 20
	$m_{hh\gamma\pi_s} - m_{hh\gamma}$	< 180 MeV/c ²

Table 9.2: Summary of selection criteria applied in the `StrippingDstarD2XGammaDstarD2[h,h]GammaLine` stripping lines where the hadron h can refer to K or π . Here π_s refers to the soft pion from the $D^{*\pm}$ decay. The PID cut for the pion and kaon are PIDK<0 and PIDK>5 respectively, giving completely independent samples.

9.3 Offline Selection

Following stripping, tighter cuts are applied to select the signal candidates for analysis. The customised offline cuts make use of kinematic, topological, and particle identification variables. Particle identification from the RICH detectors is used to identify hadrons originating from the vector meson.

The PIDK variable assigns a value to the hadron under the kaon hypothesis and hence a cut at higher (lower) value selects a $K^\pm(\pi^\pm)$. A cut is placed on the transverse momenta of the hadrons to eliminate low momenta hadrons responsible for inducing nuisance asymmetries which can bias the final measurement of CP asymmetry. A cut is imposed on the direction angle of the D^0 meson defined as the angle between the particle momentum vector and the displacement vector joining the production and decay vertices. Furthermore, tighter constraints are placed on the χ^2_{IP} of the D^0 with respect to best primary vertex which is defined as the difference in the χ^2 of the PV kinematic refit in the presence and the absence of the D^0 meson. This constraint eliminates many secondary D^0 mesons that come from the decay of beauty hadrons and hence don't originate from the primary vertex.

For the analysis of $D^0 \rightarrow V\gamma$ decays, π^0 veto is invoked which calculates the two-body invariant mass of the candidate photon combined with each of the other detected photons in the event. If the invariant mass is equal or close to the mass of the π^0 , then the candidate associated with the detected photon is rejected. This is a computationally expensive process and hence has to be carried out offline.

The presence of fake hadrons is also inferred from ghost probability cuts which use a multivariate classifier to eliminate fake hadron tracks produced from random combinations of hits in the VELO and tracking system. This is used to suppress fake tracks that pass track reconstruction requirements associated with a D^0 to build a D^* candidate. Finally, a mass cut to select the relevant resonances is applied for the three different vector particles. The mass cuts are different due to the width of the resonances i.e. ϕ is very narrow whereas ρ is wide. The mass cuts around the resonance are chosen to be $\pm 3\sigma$ around the mean mass of the resonance from the PDG values. Table 9.3 shows the summary of all cuts applied to the different $D^0 \rightarrow V\gamma$ modes.

Particle	Quantity	Cut
$K^\pm(\pi^\pm)$	PIDK	>10 (<10)
	p_T	$>800 \text{ MeV}/c$
D^0	$\text{acos}(\text{D_DIRA_OWN_PV})$	> 0.02
	$\log(\chi^2_{\text{IP}})$ w.r.t best PV	< 3
π_s	ghost probability	>0.8
γ	γ CL	>0.25
	$\pi^0 \rightarrow \gamma\gamma$ veto	$=0$
	p_T	$>2000 \text{ MeV}/c$
ϕ	$ m_{KK} - 1020 \text{ MeV}/c^2 $	$<10 \text{ MeV}/c^2$
ρ	$ m_{\pi\pi} - 770 \text{ MeV}/c^2 $	$<150 \text{ MeV}/c^2$
K^*	$ m_{K\pi} - 892 \text{ MeV}/c^2 $	$<60 \text{ MeV}/c^2$

Table 9.3: A table of offline selections applied to the Run 1 $D^0 \rightarrow V\gamma$ channels.

9.4 Fiducial Cuts

As mentioned in Sec. 6.4, the LHCb experiment can have different detection efficiencies for positively and negatively charged particles, leading to a detector-induced charge asymmetry despite the experiment being designed to be as charge symmetric as possible. In measurements of CP asymmetry, it is important to account for such effects that could inherently bias the final measurement. A common approach to mitigate this effect is to apply ‘fiducial’ cuts, which reject candidates where the slow pion travels through a region with large detection asymmetry. These regions include those close to the edges of the magnet, but also those around the beampipe. For this analysis, we apply the following fiducial cuts related to momenta of the slow pion as discussed in Sec. 6.3 for the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ analysis:

$$|p_x| \leq \alpha(p_z - p_0) \quad (9.1)$$

where $\alpha = 0.317$ and $p_0 = 2400 \text{ MeV}/c$, and

$$p_1 - \beta_1 p_z < |p_x| < p_2 + \beta_2 p_z \quad (9.2)$$

where $p_1 = 418 \text{ MeV}/c$, $p_2 = 497 \text{ MeV}/c$, $\beta_1 = 0.01397$, and $\beta_2 = 0.01605$. The second requirement is only valid (and applied) for candidates with $|\frac{p_y}{p_z}| < 0.02$ which corresponds to candidates with small vertical deflections around the beampipe. These cuts remove $\sim 25\%$ of the data in our sample but this is a necessary step for this analysis to ensure any significant CP asymmetry measurement can be attributed to the decay in question.

9.5 Decay Tree Fitter

As with the analysis of the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ channel the Decay Tree Fitter (DTF) is used to reconstruct the charm mesons from the final state. The DTF simultaneously considers all of the tracks within the decay topology, adjusting particle kinematics to give the best vertex fit, within a set of externally-imposed constraints. For this analysis, the full D^{*+} decay chain is reconstructed with a constraint imposed that the D^{*+} originates from the pp collision point. A constraint is not placed on the mass of the D^0 meson as this will be one of the distributions that will be modelled to extract the signal yields from an unbinned multi-dimensional fit and an understanding of how the resolution of the mass distribution is affected by the presence of photons in the final state is important to model the signal and background distributions in the fit.

9.6 Preliminary Fits

The measurements of the CP asymmetries and branching fractions in the $D^0 \rightarrow V\gamma$ channels takes as input the yield of signal candidates in these channels. The signal yields are extracted from an unbinned maximum likelihood fit to the invariant mass distribution of the D^0 candidates ($M(D^0)$), and the cosine of the helicity angle, θ_H . The helicity angle is defined as the angle between the momentum

vector of the D^0 and the π^+ , K^+ , or K^- in the rest frame of the ρ^0 , ϕ , or K^* respectively. This is a powerful variable to discriminate between signal and the π^0 background due to angular momentum conservation laws. The presence of a photon (a vector boson) in the signal channel as opposed to the neutral pion (a pseudo-scalar meson) results in the vector meson being polarised differently in the signal channel and the $D^0 \rightarrow V\pi^0$ channel. The cosine of the helicity angle will be referred to as the helicity distribution. Another variable, defined as $\Delta M \equiv M(D^*) - M(D^0)$, is added to the fit later once a better handle has been placed on the π^0 component within the two dimensional fit and the π^0 background suppressed sufficiently. These fits provide an initial separation of the different components, which later feeds into the development of the final fit model and event selection through the development of the MVA that suppresses the π^0 background.

The development of the multi-dimensional fit mainly exploits the 2012 $D^0 \rightarrow \phi\gamma$ and $D^0 \rightarrow \bar{K}^{*0}\gamma$ channels. The evolution of the multi-dimensional fit for the $D^0 \rightarrow \phi\gamma$ channel is described in the forthcoming section but a similar process has been followed for $D^0 \rightarrow \bar{K}^{*0}\gamma$ and $D^0 \rightarrow \rho\gamma$ channels albeit with slight variations.

9.6.1 2D Fits

The signal, π^0 background and the combinatorial background are the three most important components in the fit model. The combinatorial background arises from combining random photons with misidentified vector mesons to build a D^0 meson or combining random soft pions with D^0 mesons to build a fake D^* candidate. Furthermore, a source of background that can mimic the signal decay in a similar fashion to the π^0 background originates from the $D^0 \rightarrow V\eta$ channel where the η meson decays into two photons. This source of background will be referred to as the η component. The 2D fits will be performed in the ΔM signal region i.e. $\Delta M \in (143.02, 147.91)$ MeV/ c^2 where signal should be enhanced and the combinatorial background will be heavily suppressed.

Simulated Monte Carlo (MC) samples are used to fix or constrain parameters within the fit model before implementing the final multi-dimensional fit in data. The D^0 mass peak in the signal MC sample is parameterised by two Gaussian PDF's where the peak position and the width of the first/core part is free to float within the fit. The peak position of the second Gaussian shifts relative to the core Gaussian through an offset. Similarly, the width of the second Gaussian is the result of multiplying the width of the core Gaussian by a scale factor. Constraining the second Gaussian relative to the core Gaussian is done to model the mis-calibration of photons that results in asymmetric tails at higher mass. Both the scale factor and offset are free to float in the fit as well as the relative fraction between the two Gaussians and the result of the fit is shown in Fig. 9.1

The corresponding distribution in the $D^0 \rightarrow \phi\pi^0$ channel is parameterised similarly with the offset and scale factor constraining the core and second Gaussians fixed to the values obtained from the fit to the $D^0 \rightarrow \phi\gamma$ MC. Additionally, the fraction of the second Gaussian relative to the core Gaussian is also fixed from the fit to the mass in the $D^0 \rightarrow \phi\gamma$ MC. The peak position, the width and the relative fraction of the core Gaussian with the second Gaussian are allowed to float in the fit.

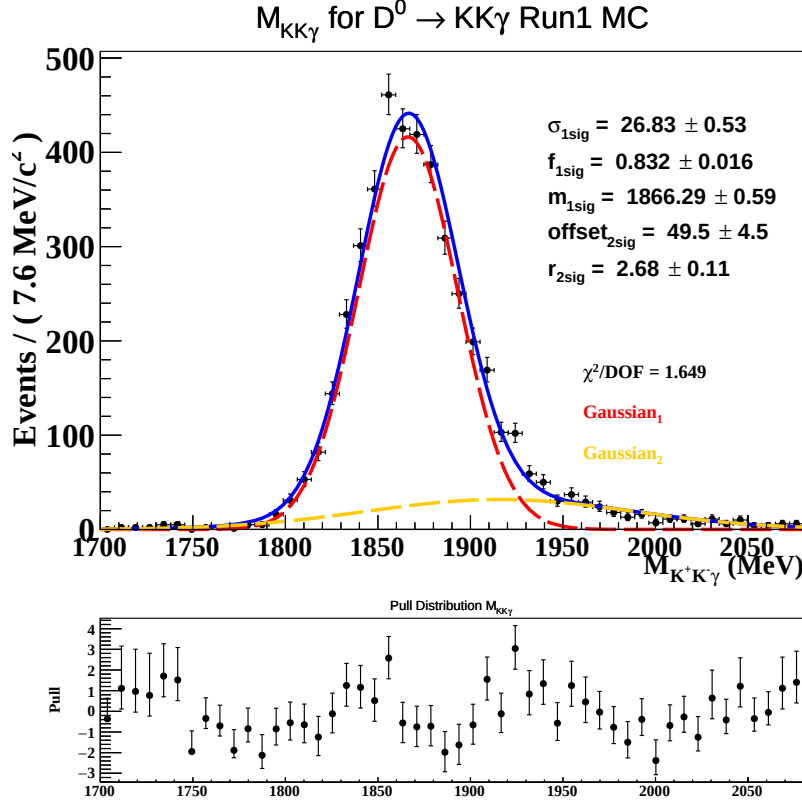


Figure 9.1: Fit to the $M(D^0)$ in the $D^0 \rightarrow \phi\gamma$ MC sample. The model comprises two Gaussians, the second of which is constrained to the core Gaussian (red) through an offset and scale factor (r_{2sig}). All other free parameters are shown in the fit

In the low mass region there is a second background component which must be modelled. This originates from low transverse momenta resolved photons that combine to create a π^0 candidate. The π^0 veto cut should in theory eliminate such events but is not 100% effective. A larger sample of these events can be obtained by inverting the π^0 veto cut and keeping all other cuts the same. Events passing this sets of cuts are known as the vetoed π^0 sample. The mass distribution of the vetoed π^0 sample is modelled through an asymmetric Gaussian which has the following empirical form:

$$\begin{aligned}
 f(x : \mu, \sigma_1, \sigma_2) &= A \exp\left(-\frac{(x - \mu)^2}{2\sigma_1^2}\right) & \text{if } x < \mu \\
 f(x : \mu, \sigma_1, \sigma_2) &= A \exp\left(-\frac{(x - \mu)^2}{2\sigma_2^2}\right) & \text{otherwise}
 \end{aligned} \tag{9.3}$$

where $A = \sqrt{\frac{2}{\pi}}(\sigma_1 + \sigma_2)^{-1}$, is a normalisation constant.

The asymmetric Gaussian PDF has three free parameters with an extra width compared with the nominal Gaussian PDF. The fit to the vetoed π^0 sample is shown in Fig. 9.2. The peak position and both the widths are then fixed when modelling the mass distribution in the $D^0 \rightarrow \phi\pi^0$ MC sample. The final fit to $D^0 \rightarrow \phi\pi^0$ mass distribution is shown in Fig. 9.2 with the default π^0 veto cut.

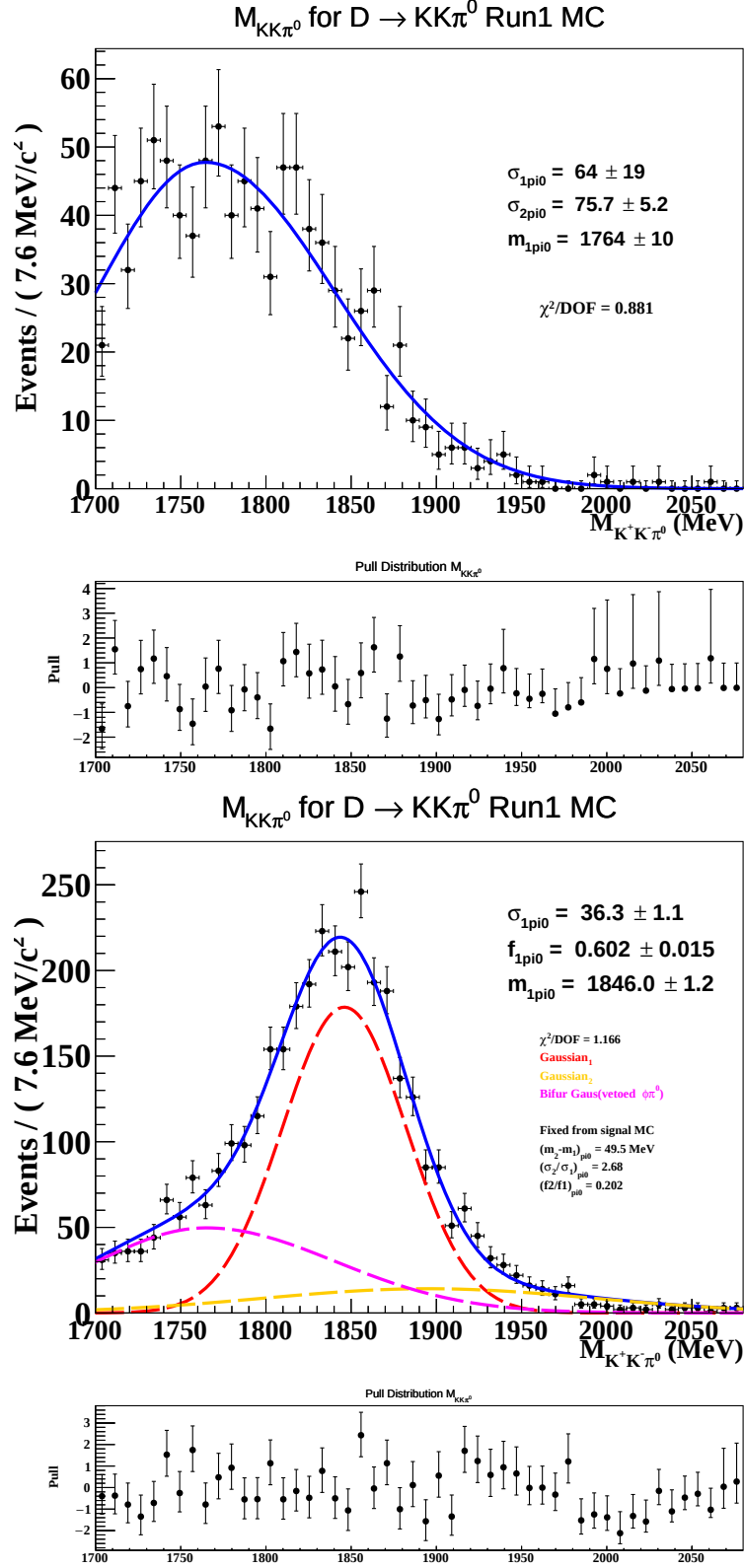


Figure 9.2: Fit to $M(D^0)$ in the $D^0 \rightarrow \phi\pi^0$ MC sample. The model for the fit to the vetoed sample (top) is an asymmetric Gaussian. The parameters of the asymmetric Gaussian are fixed in the fit to MC the sample with the nominal selection (bottom).

The corresponding mass distribution for the $D^0 \rightarrow \phi\eta$ MC sample utilises the full ΔM range unlike the other mass distributions because it doesn't peak sharply around the mass signal region. This is because η is reconstructed as a photon resulting in the mass not being fully reconstructed and hence the mass peaking around the lower mass region. The mass of the η component is parameterised using a Crystal Ball function which is ubiquitous in high energy physics to model non-Gaussian tails resulting from mis-calibration of the energy or radiative energy losses. The Crystal Ball function comprises a core Gaussian portion with a power law tail on one side. It has the following form:

$$f(x : \mu, n, \alpha, \sigma) = N \cdot \begin{cases} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) & \text{for } \frac{x-\mu}{\sigma} > -\alpha \\ A\left(B - \frac{x-\mu}{\sigma}\right)^{-n} & \text{for } \frac{x-\mu}{\sigma} \leq -\alpha \end{cases} \quad (9.4)$$

where $A = \left(\frac{n}{|\alpha|}\right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right)$, $B = \frac{n}{|\alpha|} - |\alpha|$ and N is a normalisation constant. The parameter α is chosen to be negative so that the power law is implemented in the high-mass tail, to reflect the shape of the observed distribution. All other parameters are left free in the fit. The range of the D^0 mass distribution is extended to lower masses ($1650 < M_{K+K-\eta} < 2080 \text{ MeV}/c^2$) to reduce the uncertainty on the width of the Gaussian portion of the function. Fig. 9.3 shows the mass distribution with the fit performed using the Crystal Ball function.

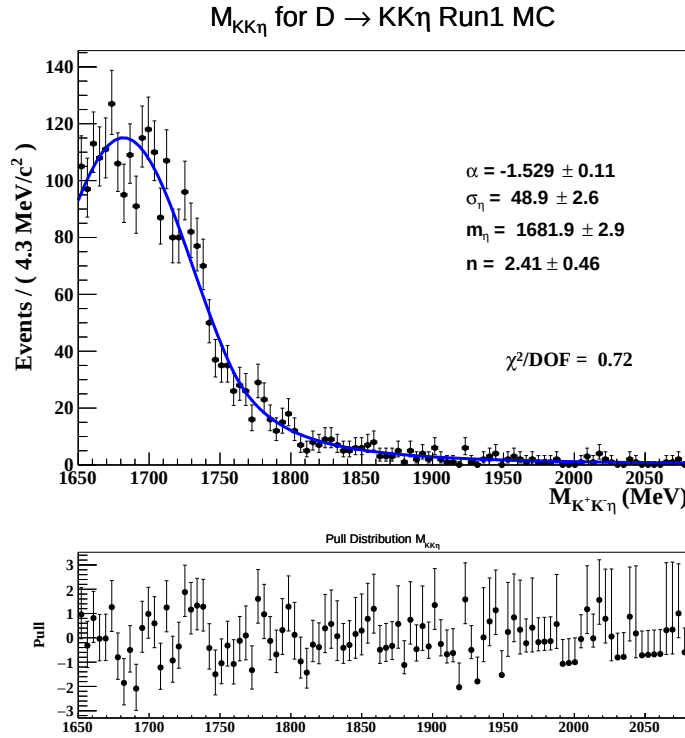


Figure 9.3: Fit to $M(D^0)$ in the $D^0 \rightarrow \phi\eta$ MC sample. The model comprises a Crystal Ball function where α is constrained to be negative. All other free parameters are shown in the fit.

The helicity distribution for the $D^0 \rightarrow \phi\gamma$ and $D^0 \rightarrow \phi\pi^0$ channels are parameterised by a theoretical parabolic shape, multiplied by a polynomial acceptance function. The theoretical parabolic shape is determined by the conservation of angular momentum in these decays. In the case of $D^0 \rightarrow \phi\gamma$ decays,

both the final state particles are vectors (spin=1) and hence the ϕ meson is transversely polarised and has a helicity state of ± 1 . For this reason the theoretical parabolic shape for the helicity distribution in $D^0 \rightarrow \phi\gamma$ decays can be modelled as:

$$F_{\phi\gamma}(\cos\theta_{hel}) = \cos^2\theta_{hel}. \quad (9.5)$$

Conversely, the presence of the π^0 (a scalar with spin=0) in the final state of $D^0 \rightarrow \phi\pi^0$ decays results in the ϕ meson being longitudinally polarised with a helicity state of 0. Therefore the theoretical parabolic shape for the helicity distribution in $D^0 \rightarrow \phi\pi^0$ decays can be modelled as:

$$F_{\phi\pi^0}(\cos\theta_{hel}) = 1 - \cos^2\theta_{hel}. \quad (9.6)$$

Furthermore, the theoretical parabolic shape is multiplied by a polynomial acceptance function to account for variations in the efficiency of reconstruction of the final state particles. The acceptance function used is determined from what is observed in data so a linear acceptance function is used when fitting edge helicity region and a quadratic acceptance function is used to fit the central helicity region in data. A fit to the edge helicity region ($0.8 < \cos(\theta_H) < 1.0$) in data is performed initially to check the parameterisation of the $D^0 \rightarrow \phi\pi^0$ component. The signal yield is negligible in this region and therefore any difference between data and MC is calibrated by an offset and scale factor that encapsulates a shift of the peak position and an enlargement/shrinking of the width of the distribution respectively. The same calibration is then applied in the fit to the signal candidates in data for the central helicity region ($-0.8 < \cos(\theta_H) < 0.8$) in data.

The helicity edge region is also used for a second independent purpose in the $D^0 \rightarrow \bar{K}^{*0}\gamma$ channel. It forms a high-purity $D^0 \rightarrow \bar{K}^{*0}\pi^0$ sample, which is used to calibrate the electromagnetic calorimeter variables and thereby improve $\gamma - \pi^0$ discrimination, as described later in Sec. 9.7.

The fits to the helicity edge region for the $D^0 \rightarrow \phi\gamma$ and the $D^0 \rightarrow \phi\pi^0$ MC samples are shown in Fig. 9.4 where the distribution is parameterised by a linear acceptance function multiplied by the theoretical parabolic shape. Hence the only free parameter in both fits is the coefficient for the linear term in the acceptance function.

The corresponding fit to the $D^0 \rightarrow \phi\eta$ helicity edge MC sample is shown in Fig. 9.5. The distribution is parameterised by a linear function since one of the photons from η is missed in the reconstruction so the D^0 momentum is underestimated and sensitivity to the theoretical parabolic shape is lost.

Finally, the combinatorial component is estimated by performing a two-dimensional extended maximum likelihood fit to the mass and helicity distributions in the data ΔM sidebands ($\Delta M \in [151, 161]$ MeV/ c^2). The η and π^0 components are included in this fit and their shapes are fixed to those from the MC distributions. The combinatorial component itself in mass is parameterised by an exponential function whereas in helicity it is parameterised by a quadratic function. The description is empirical based on the distributions observed in data so the lowest order term for the quadratic function is fixed to 1, leaving three free parameters. Additionally, the yields of the various components are floated leaving a total of 6 parameters free in the overall fit. Fig. 9.6 shows the 2D fit to the data ΔM

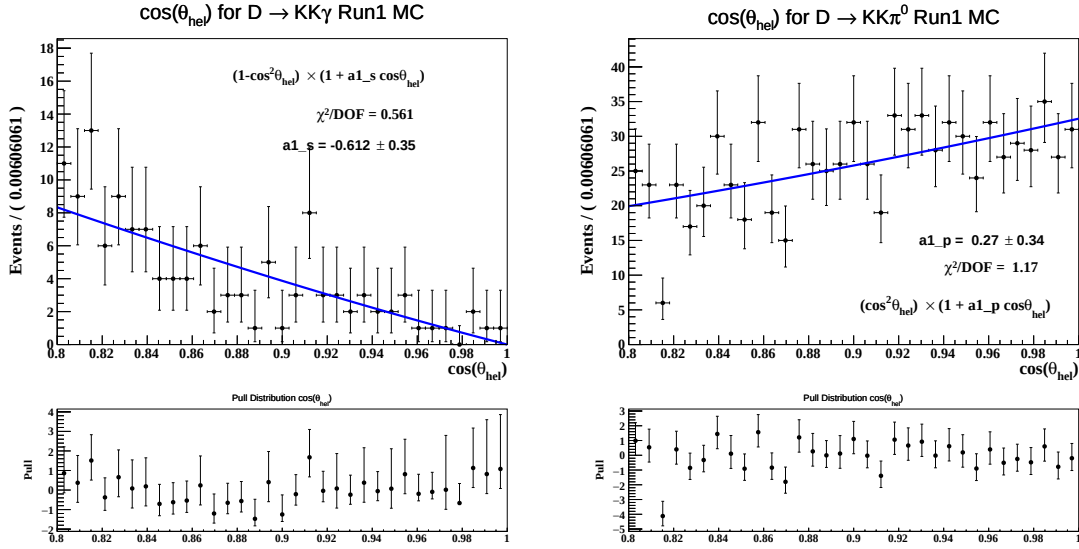


Figure 9.4: Fit to the $\cos(\theta_H)$ edge region for $D^0 \rightarrow \phi\gamma$ (left) and the $D^0 \rightarrow \phi\pi^0$ (right) MC samples. The model for the fit is the theoretical parabolic shape multiplied by a linear acceptance function.

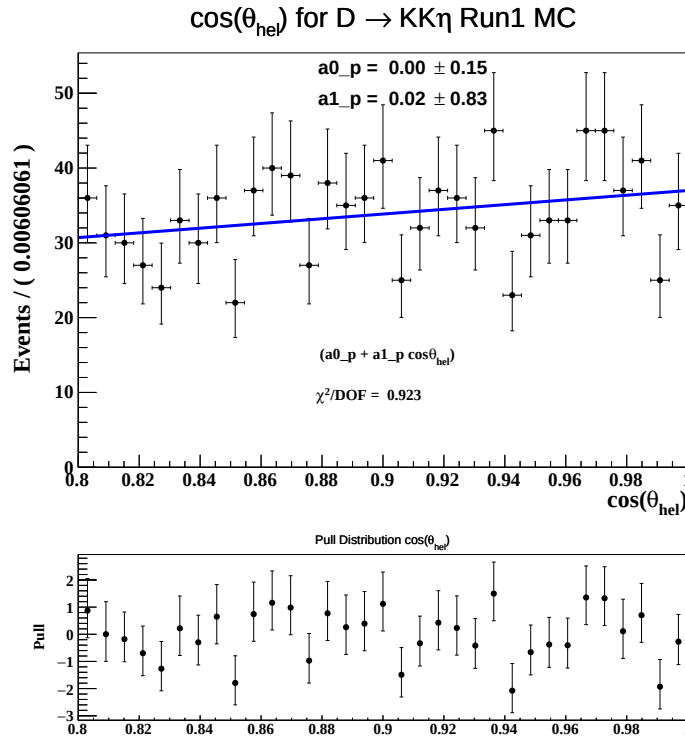


Figure 9.5: Fit to the $\cos(\theta_H)$ edge region for the $D^0 \rightarrow \phi\eta$ MC sample. The model for the fit is a linear acceptance function with two free parameters.

sidebands. The combinatorial parameters are then fixed when moving to the ΔM signal region in data.

Having established the shapes of the various components in both D^0 mass and $\cos(\theta_H)$, the fit to the selected $D^0 \rightarrow \phi\gamma$ candidates in data can be performed in the edge helicity region. The fit projections are shown in Fig. 9.7 where the yields of the different components (including signal) are free as well as

the offset and scale factor for the $D^0 \rightarrow \phi\pi^0$ mass distribution to calibrate any data-MC differences. The threshold Gaussian for the π^0 component is shown separately since this sub-component is the least well parameterised and it is interesting to see its interplay with η and combinatorial components at low mass. Table 9.4 summarises all the parameters that are either free or fixed in the fit to the helicity edge data.

Before moving to the central helicity region, the π^0 component must be suppressed using either a dedicated MVA or a generic tool developed in the analysis of rare decays of beauty hadrons known as IsPhoton [107]. The development of the MVA will be discussed in the next section compared with a tight IsPhoton cut which can be applied as a proxy for an MVA cut. This is also necessary as an intermediate step in building a 3-D fit model which also incorporates ΔM as the final dimension to the fit.

Parameter	Value
σ_{1sig}	26.83 MeV/c ²
f_{1sig}	0.832
m_{1sig}	1866.629 MeV/c ²
$offset_{2sig}$	49.5
r_{2sig}	2.68
σ_{1pi0}	36.3 MeV/c ²
f_{1pi0}	0.602
m_{1pi0}	1846.0
$offset_{2pi0}$	49.5
r_{2pi0}	2.68
$(f2/f1)_{pi0}$	0.202
$m_{1pi0thr}$	1764 MeV/c ²
$\sigma_{1pi0thr}$	64 MeV/c ²
$\sigma_{2pi0thr}$	75.7 MeV/c ²
α	-1.529
σ_η	48.9 MeV/c ²
m_η	1681.9 MeV/c ²
n	2.41
m (exponential)	-0.005765
$a1_s$	-0.612
$a1_p$	0.27
$a0_\eta$	0
$a1_\eta$	0.02
$p1$	-1.77
$p2$	4
$N_{\phi\eta}$	459 $\pm$ 62
$N_{\phi\gamma}$	90 $\pm$ 60
$N_{\phi\pi^0}$	2952 $\pm$ 131
N_{comb}	416 $\pm$ 145
$offset_{data}$	-0.41 $\pm$ 1.6
r_{data}	1.062 $\pm$ 0.049

Table 9.4: The values taken by the different parameters in the fit to the helicity edge data shown in Fig. 9.7. Values with no associated uncertainty are fixed and other values are floated in the fit.

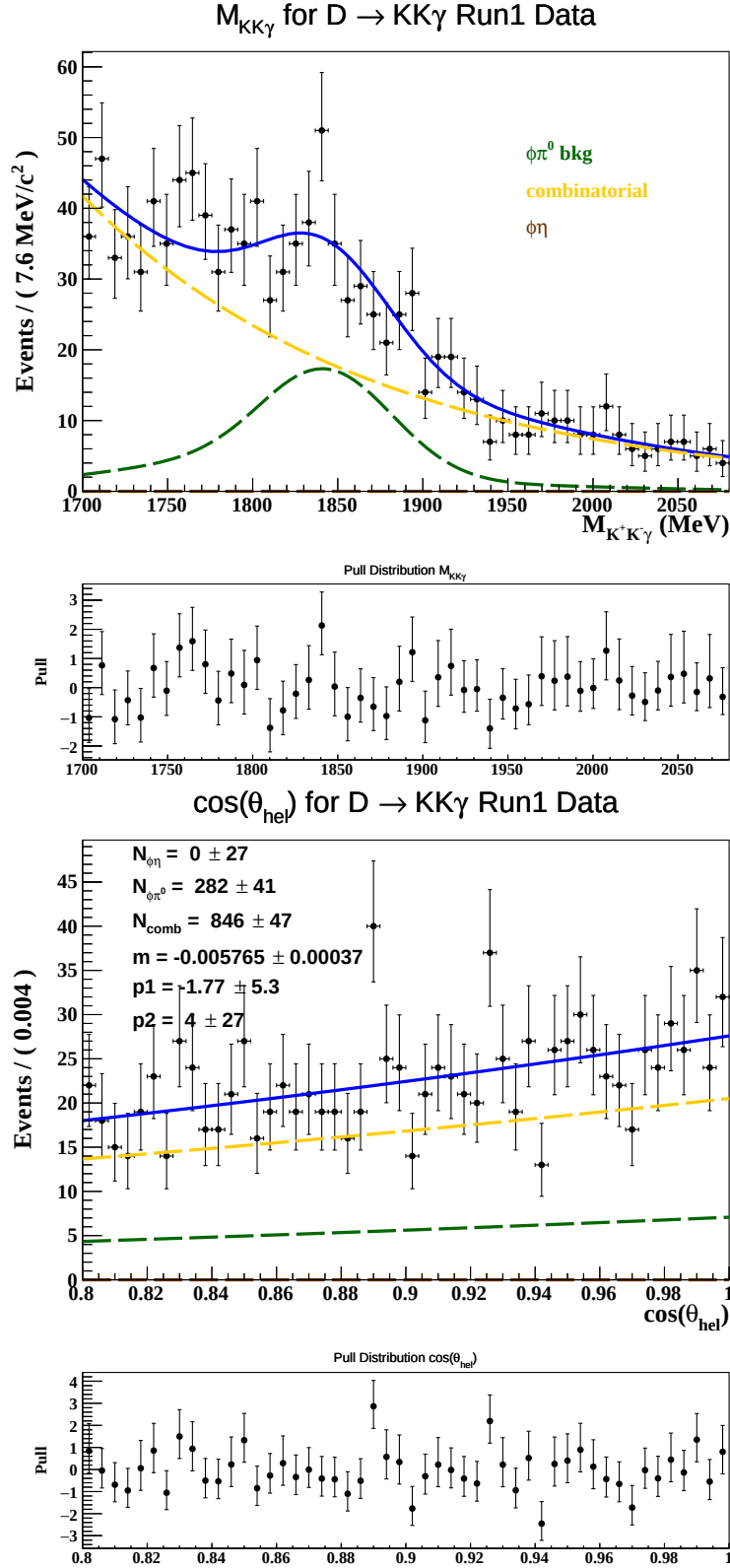


Figure 9.6: Fit to the mass (top) and $\cos(\theta_H)$ (bottom) edge region for data ΔM sidebands in 2012 data. The model for the η and π^0 components is taken from the MC fits and the combinatorial components in mass and helicity are free to float in the fit.

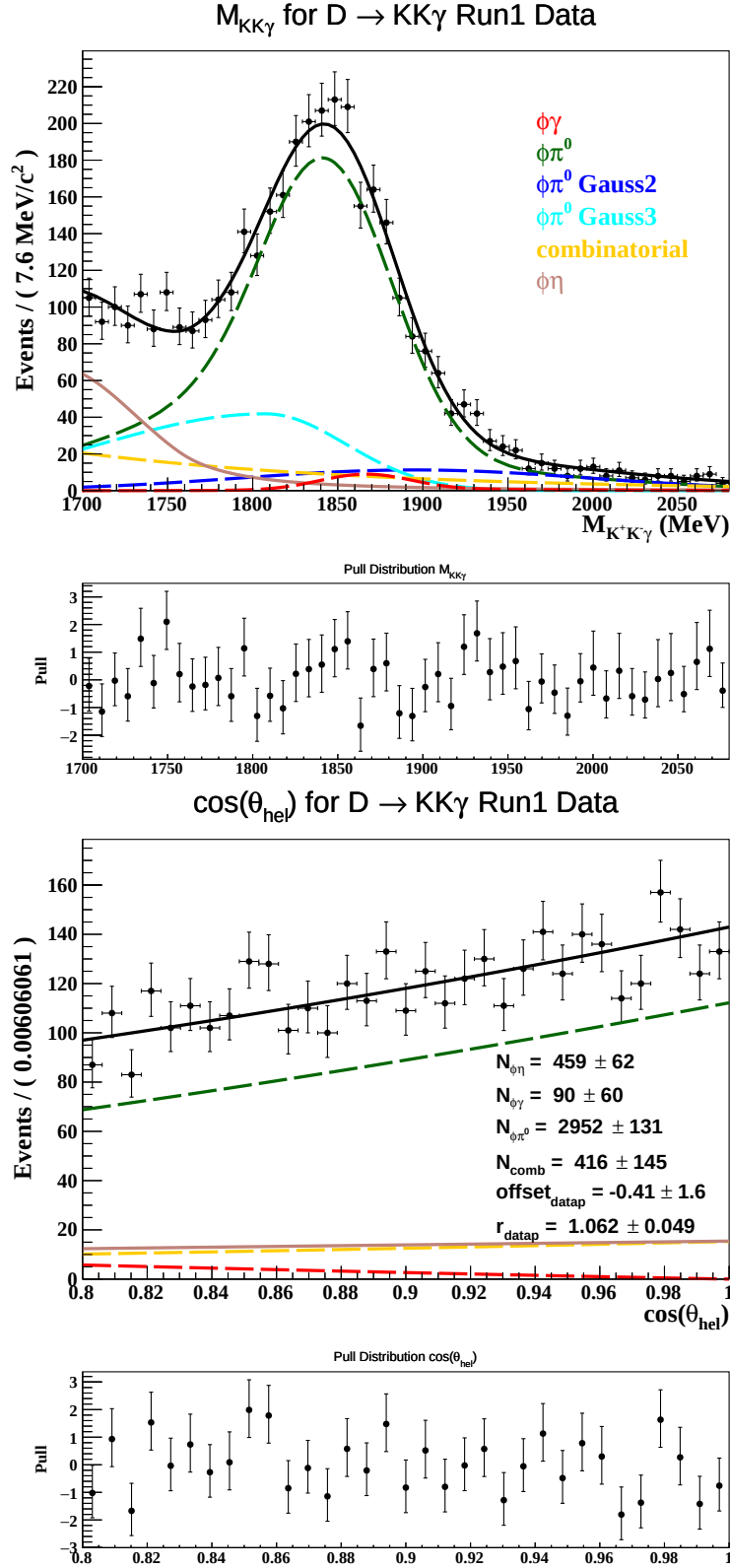


Figure 9.7: Fit to the mass and $\cos(\theta_H)$ edge region for the ΔM signal region in data. The model for the signal, η and π^0 components is taken from the MC fits whilst the combinatorial shape is taken from the ΔM sideband fit in real data. The second and threshold Gaussian shapes for the π^0 component in mass are shown in cyan and dark blue respectively.

9.7 MVA Classifier

As mentioned previously, multivariate analysis tools are ubiquitous in high energy physics and are commonly used to suppress any undesirable background for a decay of interest. In this analysis, the MVA was designed to suppress the peaking π^0 background that sits on the top of the signal peak. Typically, an MVA would be trained on MC samples but the large π^0 background in these channels and the limited yields in π^0 MC sample motivates an alternative data-driven approach to model the background. For this purpose, the **sPlot** [100] technique is used to obtain background and signal **sWeights** from a 2D maximum likelihood fit in the $D^0 \rightarrow \bar{K}^{*0}\gamma$ helicity edge distributions as shown in Fig. 9.8. The **sPlot** technique is a method to statistically disentangle different components in a sample based on a fit to a control variable or variables (in this case, it is extracted from a 2D fit of D^0 mass and helicity). This allows the distributions of each component to be determined for a range of other variables, provided they are not significantly correlated with the control variable(s). The $D^0 \rightarrow \bar{K}^{*0}\gamma$ data sample is used for the extraction of weights because it has high statistics and a low level of combinatorial background thus providing a high-purity π^0 sample.

The parameterisation of this fit is similar to what has been discussed for the $D^0 \rightarrow \phi\gamma$ channel. The helicity edge region ($-0.98 < \cos\theta_{hel} < -0.7$) covers a different range and the acceptance is derived by taking the ratio of the reconstructed distribution to the true underlying distribution. The former is obtained from full simulation samples which have been treated just like data, with all reconstruction effects included. The latter is taken from a different MC tool called RapidSim [110] which is lightweight MC generation tool used to model phase space of decays of charm and beauty hadrons as it excludes any detector or reconstruction effects.

In this fit, the π^0 yield is much larger than the yields from the corresponding MC sample. The π^0 **sWeights** assigned to each candidate are used as a proxy for the background sample when training the MVA. The signal for the MVA training was modelled using the $D^0 \rightarrow \bar{K}^{*0}\gamma$ MC sample since the statistics in the MC sample are comparable to what is expected in the data fits and the small signal yields in the helicity edge fit mean that the signal **sWeights** aren't reliable enough to model the signal distributions when training an MVA.

Since the MVA used to suppress the large π^0 background utilises signal simulated samples, it is necessary that the distribution of variables used for the training of the MVA match with the corresponding distributions in data. The Monte Carlo (MC) must be representative of data and hence matching the MC to data is necessary to ensure the best possible MVA performance, and also ensures that efficiencies derived from MC are accurate.

9.7.1 MC-Reweightings

The matching of these variables is performed by constructing a reweighting tool that transforms the MC distributions to match those from real data. This tool is developed using the π^0 background, as

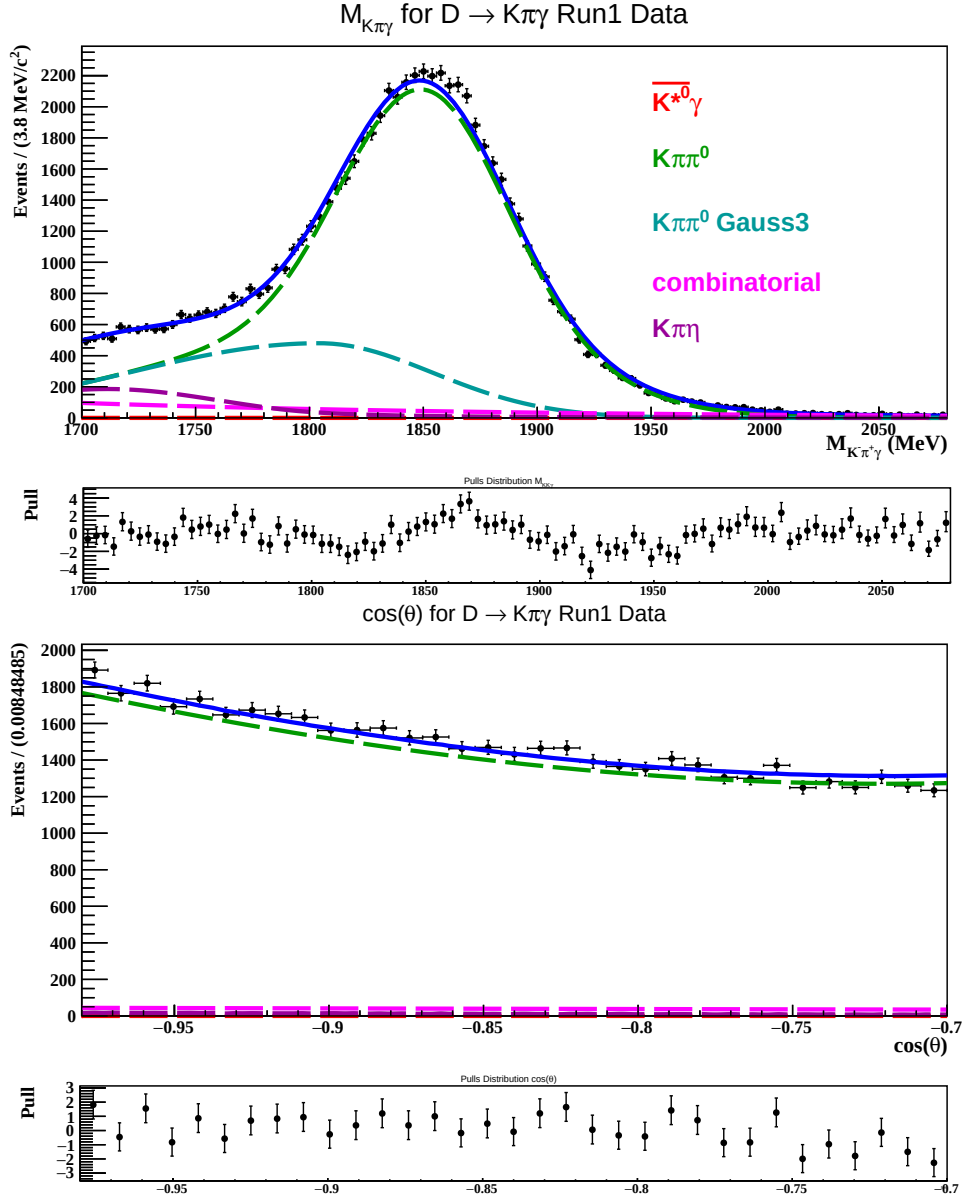
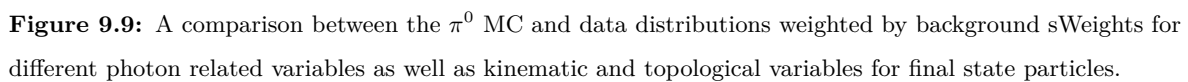


Figure 9.8: An unbinned maximum likelihood fit to the invariant mass distribution of the D^0 candidates ($M(D^0)$) and the cosine of the helicity angle in the $D^0 \rightarrow \bar{K}^{*0}\gamma$ channel. The fit is performed over the helicity edge region where the sample is dominated by the $D^0 \rightarrow \bar{K}^{*0}\pi^0$ component. This fit is used to derive sWeights and thereby inspect properties of the π^0 background relevant for the event selection.

the signal yields and purities in data are too low to achieve the required matching performance. A comparison of the π^0 MC and data distributions weighted by background sWeights for a variety of calorimeter, kinematic and topological variables is shown in Fig. 9.9. This is a visual summary of the agreement between a large set of variables. Those showing the largest data-MC differences are highlighted in Fig. 9.10. A gradient boosted reweighter which is a type of MVA was used to perform the matching over many variables simultaneously. The MVA learns how to distinguish between MC and data candidates. The MVA produces a single output quantity per candidate, which can then be applied to $D^0 \rightarrow \bar{K}^{*0}\gamma$ MC candidates as a weight which will ensure agreement with real data.



The following variables were matched to the background sWeighted data distribution:

- Gamma_PP_CaloPrsShapeFr2
- Gamma_PP_CaloPrsShapeEmax
- Gamma_PP_CaloPrsNeutralE4max
- Gamma_PP_CaloShapeKappa
- Gamma_PP_CaloPrsNeutralE49
- nSPDHits

nSPDHits refers to the number of hits left in the SPD in a given event. The definition of all other

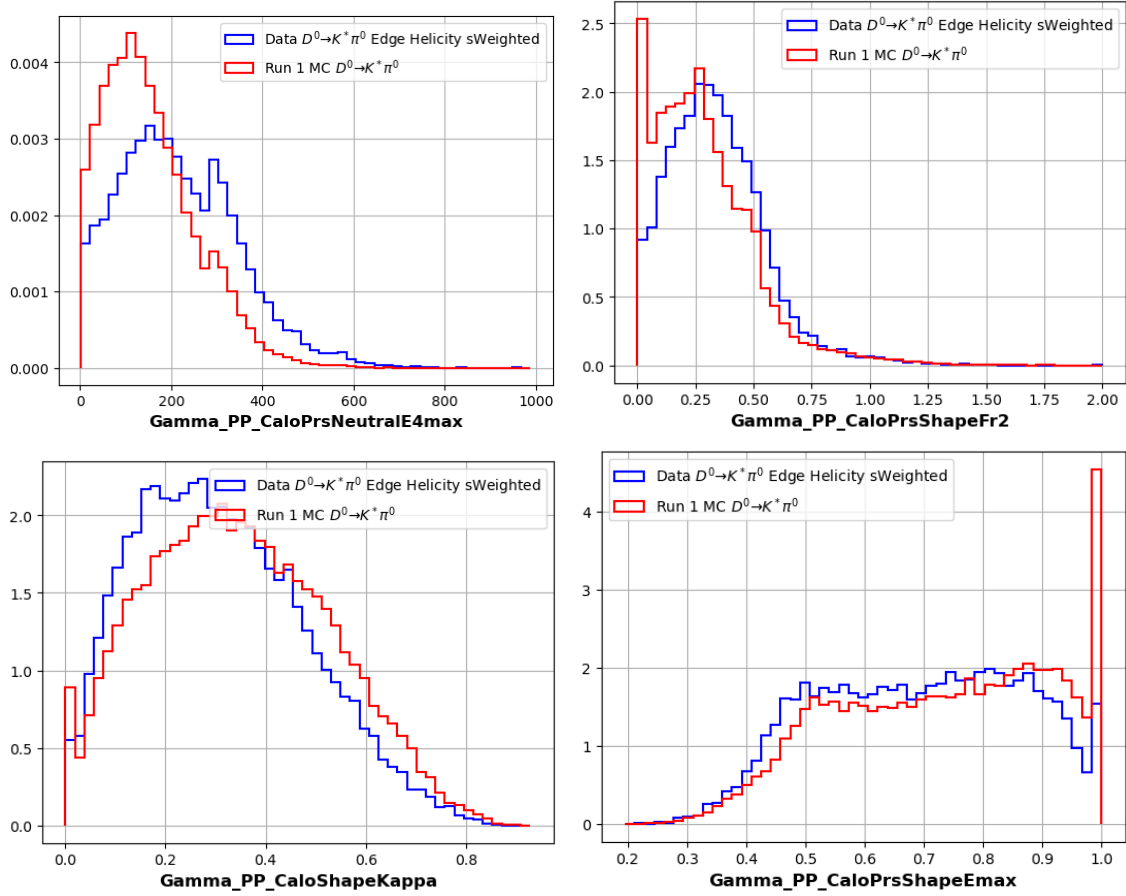


Figure 9.10: A comparison between the π^0 MC and data distributions weighted by background sWeights for a subset of the photon related variables shown in Fig. 9.9 that show the greatest data-MC discrepancy.

variables is provided in Sec. 9.7.2. Fig. 9.11 shows the distribution of the MC samples after undergoing reweighting compared with the sWeighted data distributions. Again, this is a visual representation for a large set of variables whereas Fig. 9.12 shows the effect of reweighting on the variables which previously had the greatest data-MC discrepancy. The data-MC differences are reduced substantially once the MC is reweighted to match the data distributions. The reweighter was applied to the signal simulated samples using a **Folding Reweigher** such that each event was reweighted independently.

9.7.2 Training MVA to suppress π^0 background

Having reweighted the MC to match real data, the next step is to train the classifier to discriminate between genuine photons and π^0 backgrounds. The set of discriminating variables used to train the classifier are variables associated with the calorimeter cluster shape of the energy deposits, distributed over many cells, and the corresponding variables in the Pre-Shower (PS) cells.

- **CaloShapeFr2r4** - Variable describing the tails of the cluster shape.
- **CaloShapeKappa** - The ratio of major to minor semi-axis of the cluster ellipse.

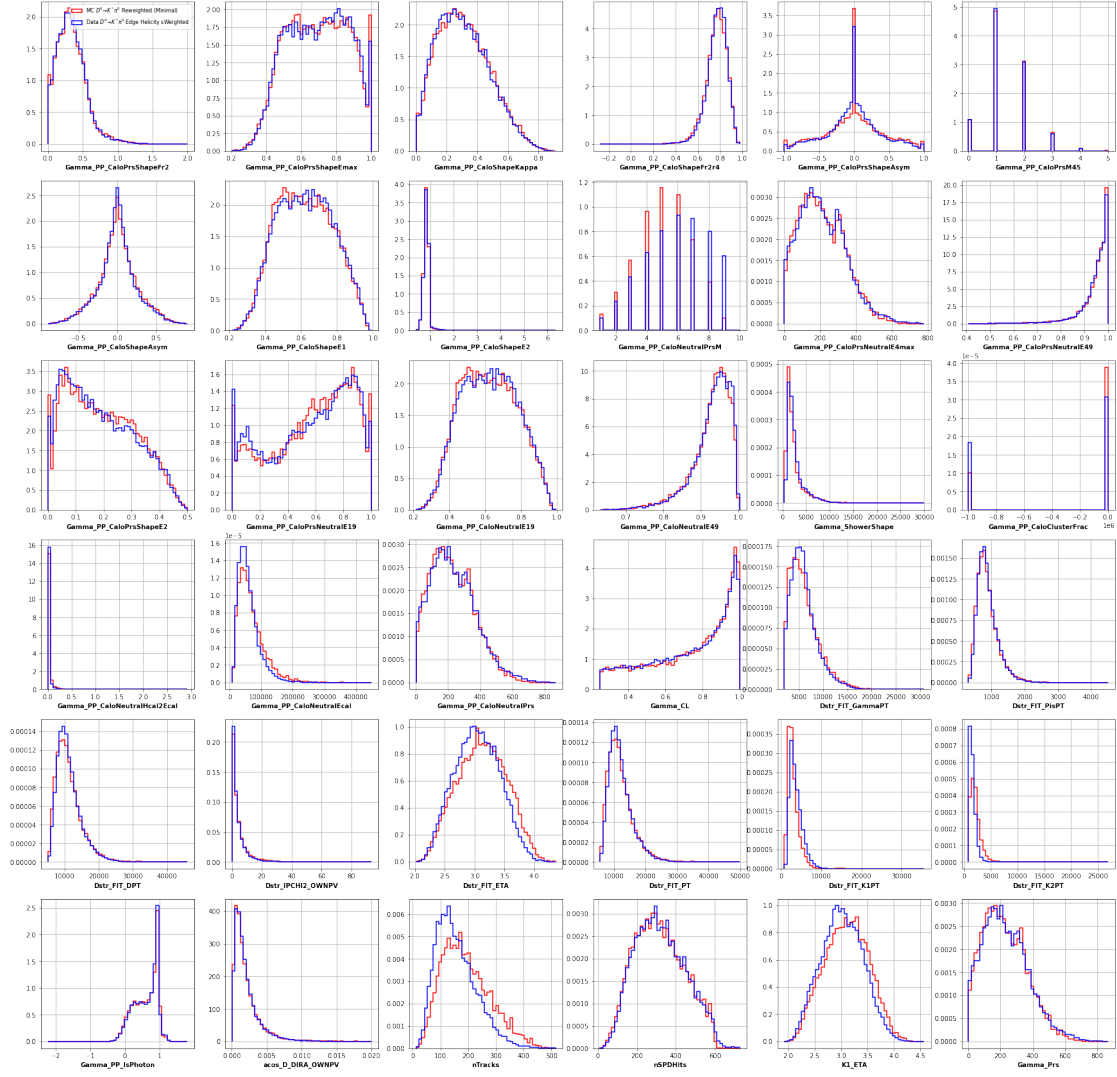


Figure 9.11: A comparison between the π^0 MC and data distributions weighted by background sWeights after reweighting the simulated samples.

- **CaloShapeAsym** - Orientation of the calorimeter cluster ellipse.
- **CaloShapeE1** - Ratio of the greatest energy deposited in a single cell in the cluster to the total energy in the cluster.
- **CaloShapeE2** - Ratio of the sum of the energies of the two most energetic cells in the cluster to the total energy in the cluster.
- **CaloNeutralE19** - Ratio of the greatest energy deposited in a single cell in the cluster to the total energy deposited in the outermost layers of cells in the cluster.
- **CaloNeutralE49** - Ratio of the energy deposited in the middle layer of cells to the total energy deposited in the outermost layers of cells in the cluster.
- **ShowerShape** - Variable describing the size of the cluster or the second order momenta for energy deposit.

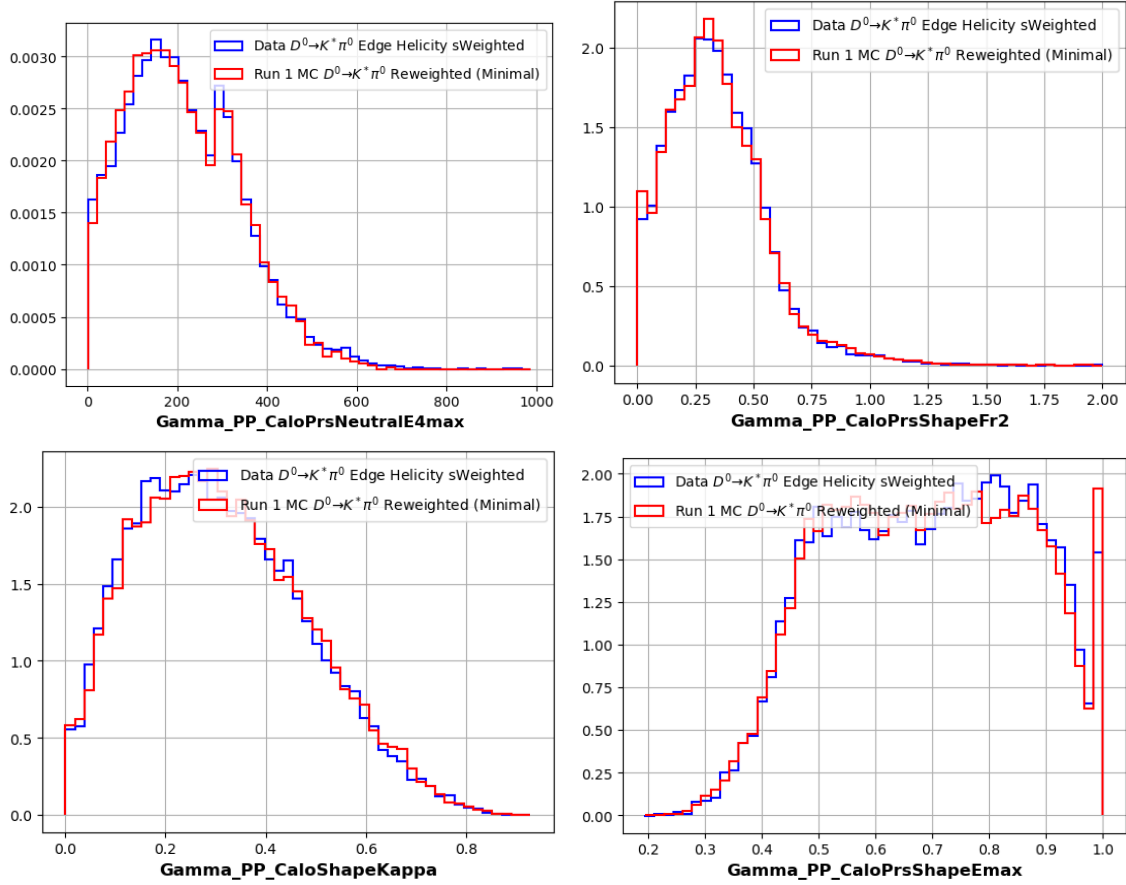


Figure 9.12: A comparison between the π^0 MC and data distributions weighted by background sWeights for a subset of the photon related variables shown in Fig. 9.11 after reweighting the simulated samples.

- **CaloPrsShapeEmax** - Ratio of the greatest energy deposited in a single cell in the cluster to the total energy in the cluster in the PS.
- **CaloPrsShapeE2** - Ratio of the total of the most energetic and second most energetic cells in the cluster to the total energy in the cluster in the PS.
- **CaloPrsShapeFr2** - Variable describing the size of the cluster or the second order momenta for energy deposit in the PS.
- **CaloPrsShapeAsym** - Orientation of the calorimeter cluster ellipse in the PS.
- **CaloPrsNeutralE4max** - Maximum energy deposited in the middle layer of cells in the PS.
- **CaloPrsNeutralE19** - Ratio of the greatest energy deposited in a single cell in the cluster to the total energy deposited in the outermost layers of cells in the cluster in the PS.
- **CaloPrsNeutralE49** - Ratio of the energy deposited in the middle layer of cells to the total energy deposited in the outermost layers of cells in the cluster in the PS.

Fig. 9.13 shows the separation of the discriminating variables for the signal and background samples. Several different types of classifiers were considered and the area under the receiver-operator charac-

teristic (ROC) curve was used as a figure-of-merit to select the final classifier to be used. The ROC curve shows the signal efficiency as a function of background rejection for a range of classifier cuts and hence the area under this curve is greatest for the best performing classifier i.e. one that optimises signal efficiency and background rejection. A variety of Boosted Decision Trees (BDTs) are considered. These comprise a decision tree that splits the data sample recursively based on the features provided to the tree as outlined in Sec. 5.4.2. Fig. 9.14 shows the ROC curve for the various BDTs that were trained to suppress the π^0 background. The Bagged BDT (BDTB) is chosen as this method has the largest area under the ROC curve. Bagging in this context involves sampling of training data with replacement so data points can be chosen more than once. This results in the generation of many sub-samples to create many weak models which are trained in parallel. The model with the greatest accuracy is chosen for classification problems such as the one in question for this analysis.

Signal and background distributions of the MVA output variable for the training and testing samples are superimposed on the same plot to check for over-training as shown in Fig. 9.15. Over-training occurs when the training sample has limited statistics and thus the classifier is trained to the point where random fluctuations in the training sample are used. The Kolmogorov-Smirnov (KS) test is also applied to the training and testing samples which quantifies the likelihood that the two samples are drawn from the same distribution. The KS probabilities for the signal sample are small, indicating some sign of over-training but this is expected due to the limited yields in the signal MC used in the training of the MVA.

The figure-of-merit to be optimised when choosing a cut value for the MVA is the signal significance, defined as $S/\sqrt{S+B}$, where S is the signal yield and B is the background yield in the signal region where the signal region is defined as:

$$\Delta M \in [143.15, 147.72)\text{MeV}/c^2 \quad \&\& \quad M(D^0) \in [1806.85, 1925.50)\text{MeV}/c^2. \quad (9.7)$$

The signal significance is maximised based on the preliminary signal and background yields in the signal region from a 2D fit to central helicity region in the $D^0 \rightarrow \bar{K}^{*0}\gamma$ channel. The optimal cut to optimise significance for the MVA is 0.33, giving a significance of 22.76.

A similar exercise can be carried out for the corresponding tool used in radiative decays of hadrons containing beauty quarks. This tool is called IsPhoton and information regarding its development can be found in Ref. [107]. The weights generated to reweight the MC to match data are also used to reweight the IsPhoton distribution. The signal and background efficiencies of the re-weighted MC IsPhoton distribution at many cuts can be calculated in MC and the signal significance optimised by using the preliminary signal and background yields in a similar manner to the dedicated MVA. Fig. 9.16 shows the efficiency and significance scan over the full range of IsPhoton cuts and an optimal cut of ~ 0.85 is found which gives a signal significance of 27.6. The optimal cut for both the MVA and IsPhoton tools can be applied to the data samples to suppress the π^0 background. A comparison of the signal significance after applying both cuts separately would provide an indication of the best tool for

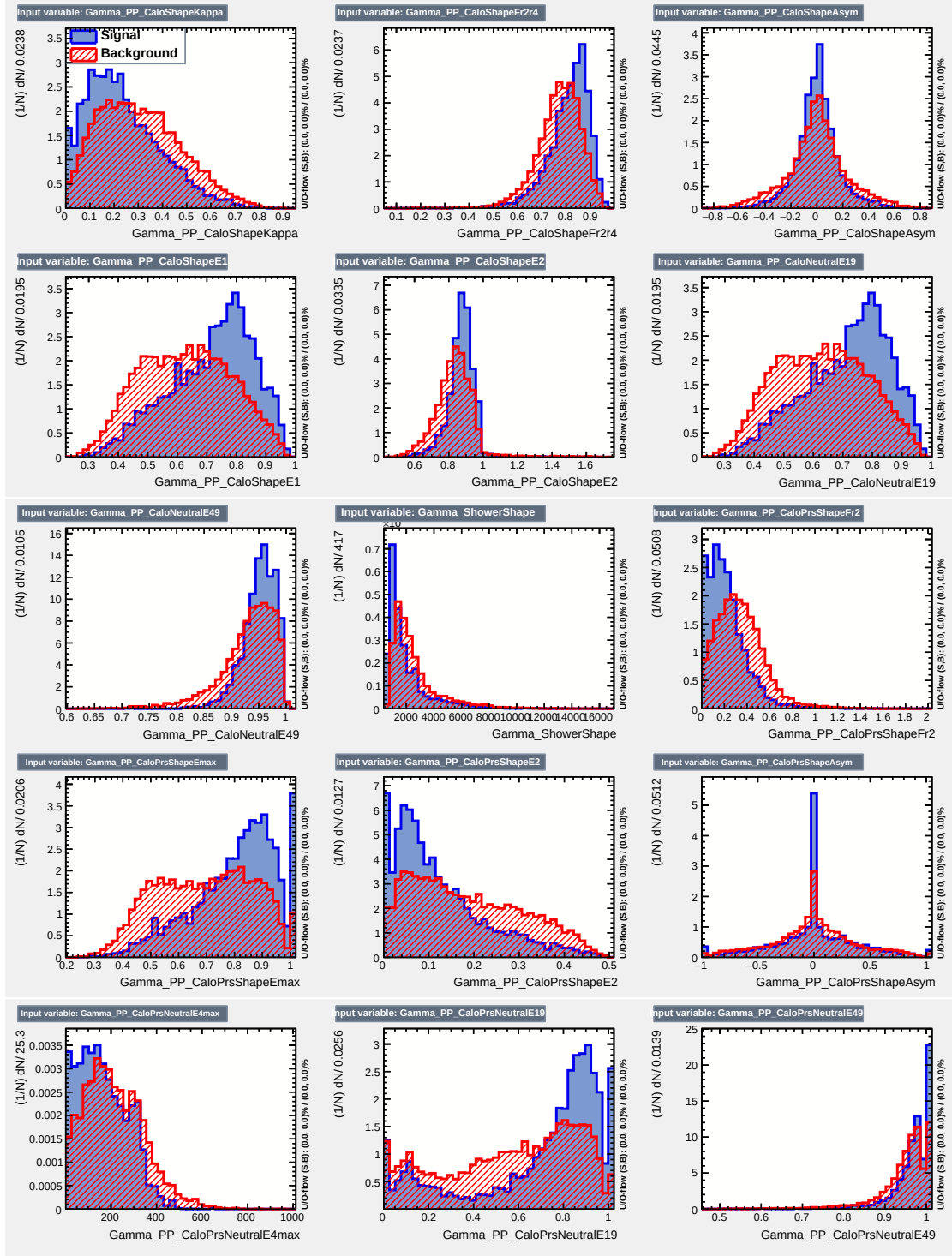


Figure 9.13: Normalised distributions of the signal and background samples used to train the MVA that discriminates between real photons and π^0 background. The signal and background samples used to train the MVA are described in the text.

reducing the π^0 background. The next chapter describes the evolution of the 2D fit for the $D^0 \rightarrow \phi\gamma$ channel with the optimal IsPhoton cut (>0.85) as this tool is found to give better suppression in the central helicity region of the $D^0 \rightarrow \bar{K}^{*0}\gamma$ channel. This could be because the IsPhoton tool is trained

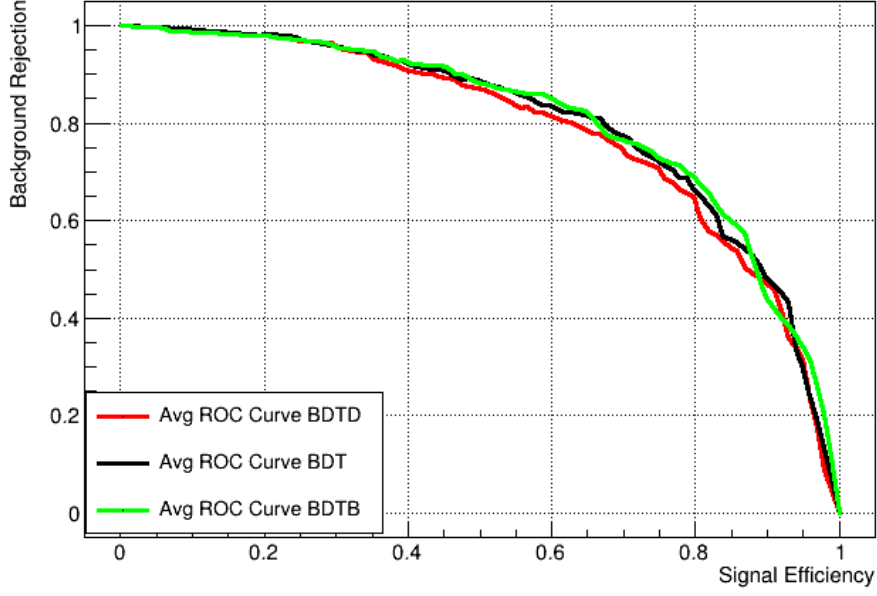


Figure 9.14: ROC curve for different BDTs trained to suppress the π^0 background.

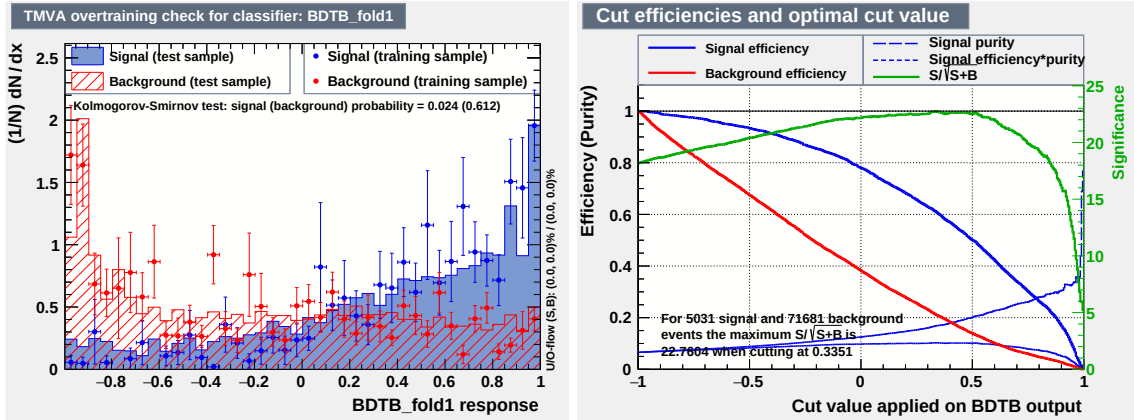


Figure 9.15: The BDT Output (left) and the significance/purity scans (right) for the samples used in the development of the MVA designed to separate photons from π^0 background.

over a larger sample whereas limited statistics available for the training of the dedicated MVA limits the performance of the classifier. Fundamentally, the IsPhoton tool is designed to suppress the π^0 background in radiative decays and the fact that it is trained on radiative decays of beauty hadrons is not important since photon and π^0 signatures are common to both beauty and charm decays.

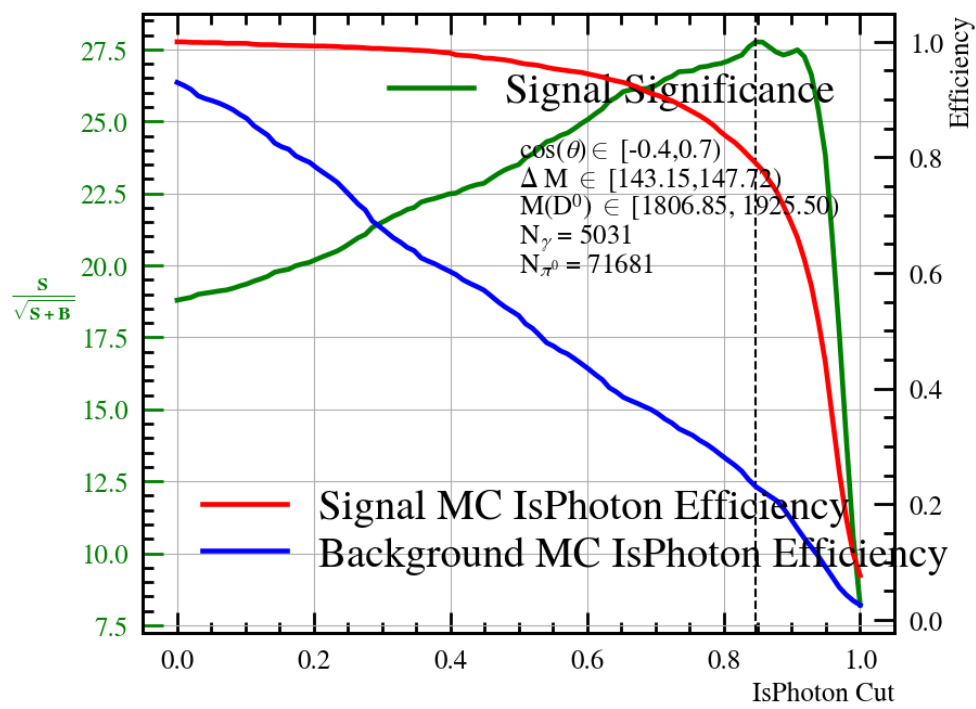


Figure 9.16: Significance/purity scans for the IsPhoton tool using the reweighted signal and background MC samples.

Chapter 10

Extracting Raw Asymmetry in

$D^0 \rightarrow \phi\gamma$ decays

In this chapter, the evolution of the multi-dimensional fits in the $D^0 \rightarrow \phi\gamma$ channel are described. These fits will enable the extraction of signal yields which, as described in Chapter 8, are needed as an input to measure CP asymmetries and branching fractions. Section. 10.1 presents the development of the two-dimensional fits after the application of the optimal IsPhoton cut used to suppress π^0 background. These fits initially exclude the ΔM variable but this is added in Sec. 10.2 once the models for the signal and π^0 components are better understood. The chapter concludes with suggestions for how the multi-dimensional fits can be improved further and a discussion of the future work needed for the analysis to make competitive CP asymmetry and branching fraction measurements.

10.1 2D Fits with IsPhoton cut

The preliminary fits to the helicity edge data presented in Sec. 9.6 are repeated after application of the additional requirement $\text{IsPhoton} > 0.85$. This includes fits to MC samples to derive updated fit parameters used in the data fit. The updated fits to the signal, π^0 and η components in mass for MC are shown in Figs. 10.1- 10.3. The fits to the helicity edge region for signal, π^0 and η components in MC are shown in Fig. 10.4.

The fit to the ΔM sidebands in the edge helicity region is shown in Fig 10.5. Instead of fixing the combinatorial parameters as before, they are constrained to be within $\pm 1\sigma$ through hard limits compared to their central values when performing the fit to the ΔM signal region in helicity edge data shown in Fig 10.6. The imposition of hard constraints is down to the combinatorial parameters having large uncertainties so fixing them wouldn't allow for enough freedom in the fit. Similar constraints are applied to the left width of the π^0 threshold Gaussian in the fit to the helicity edge data since it is least well parameterised with a large uncertainty. Table. 10.1 summarises all the parameters

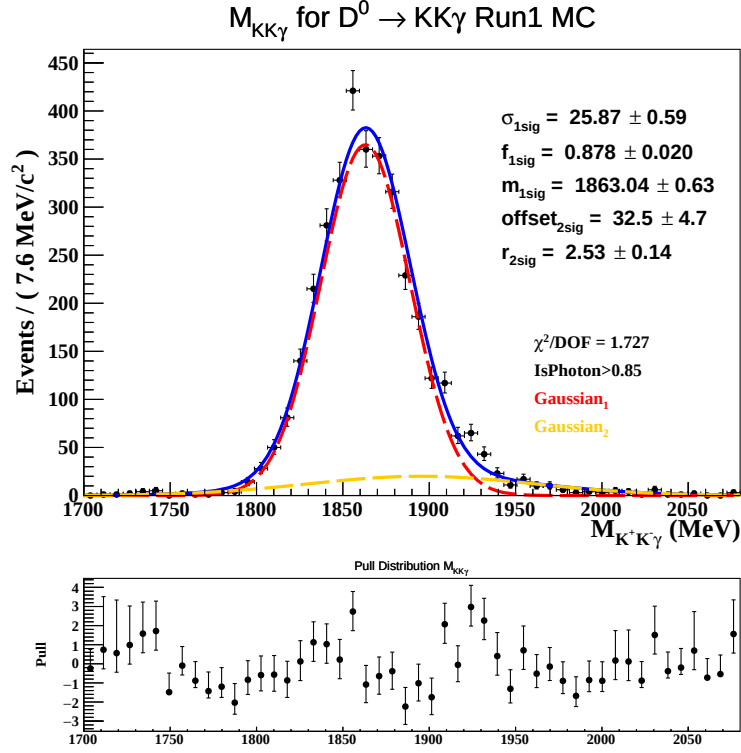


Figure 10.1: Fit to $M(D^0)$ in the $D^0 \rightarrow \phi\gamma$ MC sample after applying the IsPhoton cut. The model comprises two Gaussians, the second of which is constrained to the core Gaussian (red) through an offset and scale factor (r_{2sig}). All other free parameters are shown in the fit.

that are either free or fixed in the fit to the helicity edge data after applying the optimal IsPhoton cut.

Parameter	Value
σ_{1sig}	25.87 MeV/c ²
f_{1sig}	0.878
m_{1sig}	1863.04 MeV/c ²
$offset_{2sig}$	32.5
r_{2sig}	2.53
σ_{1pi0}	36.7 MeV/c ²
f_{1pi0}	0.601
m_{1pi0}	1838.2 MeV/c ²
$offset_{2pi0}$	32.5
r_{2pi0}	2.53
$(f2/f1)_{pi0}$	0.139
$m_{1pi0thr}$	1772.8 MeV/c ²
$\sigma_{1pi0thr}$	84 ± 15 MeV/c ²
$\sigma_{2pi0thr}$	60.2 MeV/c ²
α	-1.891
σ_η	42.7 MeV/c ²
m_η	1682.4 MeV/c ²
n	2.23
m (exponential)	-0.006639 ± 0.00028
$a1_s$	-0.13
$a1_p$	0.60
$a0_\eta$	-0.004
$a1_\eta$	0.04
$p1$	0
$p2$	-0.727 ± 0.46
$N_{\phi\eta}$	80 ± 26
$N_{\phi\gamma}$	19 ± 39
$N_{\phi\pi^0}$	1108 ± 71
N_{comb}	120 ± 163
$offset_{data}$	3.5 ± 2.8
r_{data}	1.054 ± 0.062

Table 10.1: The values taken by the different parameters in the fit to the helicity edge data shown in Fig. 10.6 after applying the optimal IsPhoton cut. Values with no associated uncertainty are fixed and other values are floated in the fit.

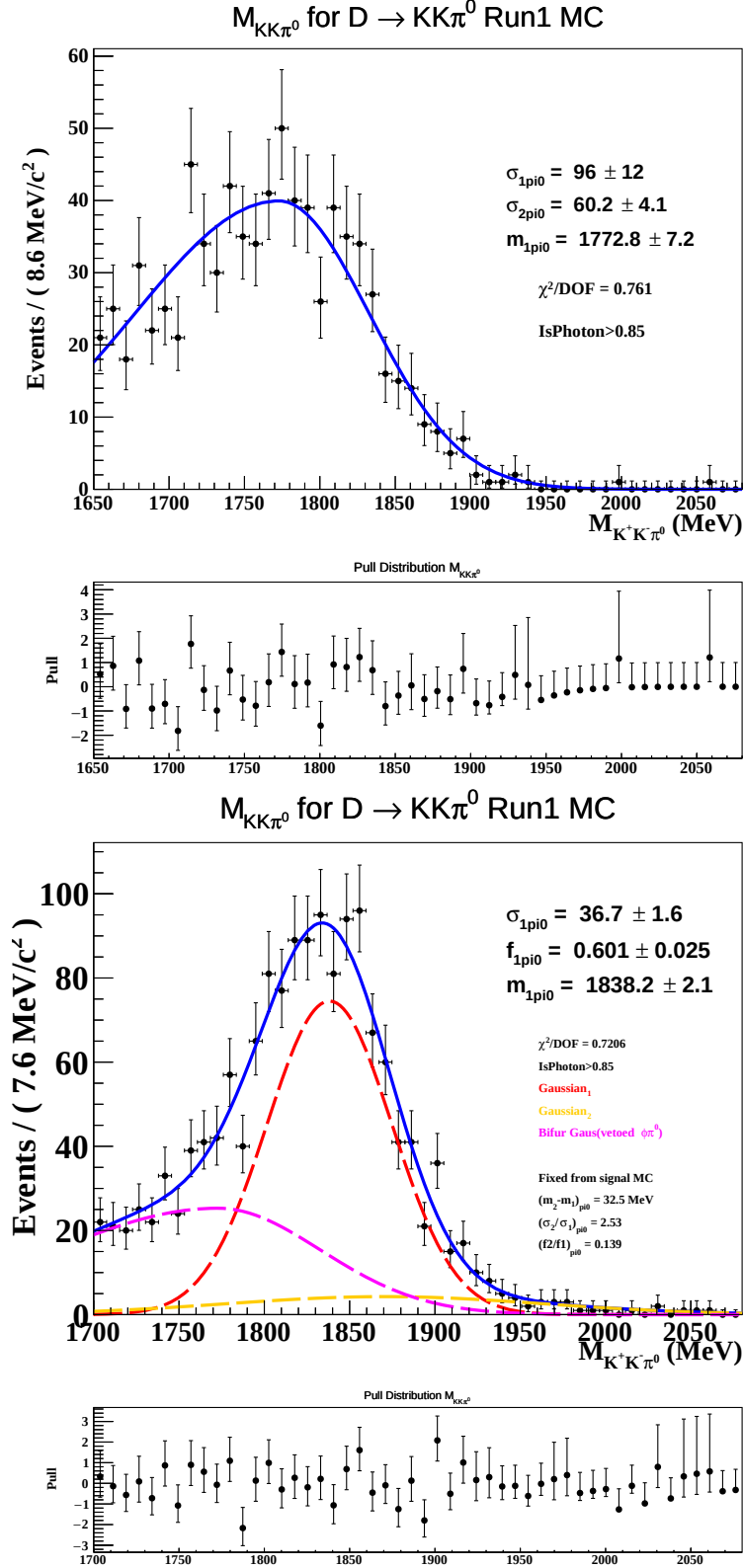


Figure 10.2: Fit to $M(D^0)$ in the $D^0 \rightarrow \phi\pi^0$ MC sample after applying the IsPhoton cut. The model for the fit to the vetoed sample (top) is an asymmetric Gaussian. The parameters of the asymmetric Gaussian are fixed in the fit to the sample with the nominal selection (bottom).

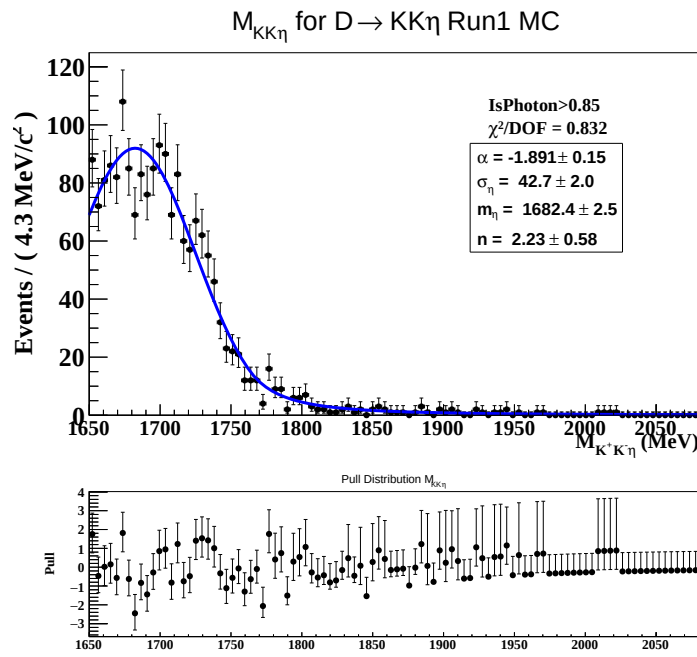


Figure 10.3: Fit to $M(D^0)$ in the $D^0 \rightarrow \phi\eta$ MC sample. The model comprises a Crystal Ball function where α is constrained to be negative. All other free parameters are shown in the fit.

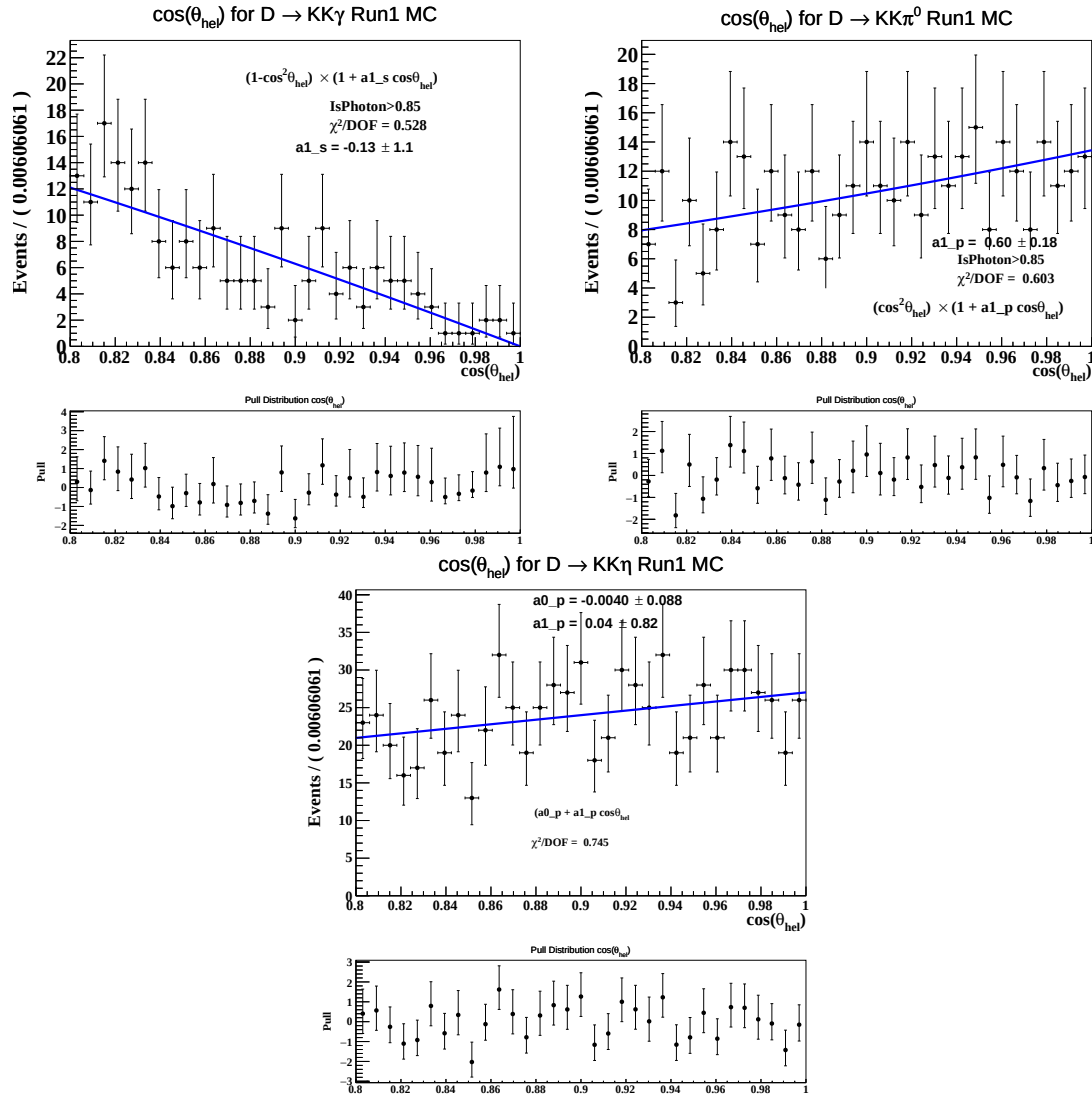


Figure 10.4: Fit to the $\cos(\theta_H)$ edge region for $D^0 \rightarrow \phi\gamma$ (top-left), $D^0 \rightarrow \phi\pi^0$ (top-right) and $D^0 \rightarrow \phi\eta$ (bottom) MC samples after applying the IsPhoton cut.

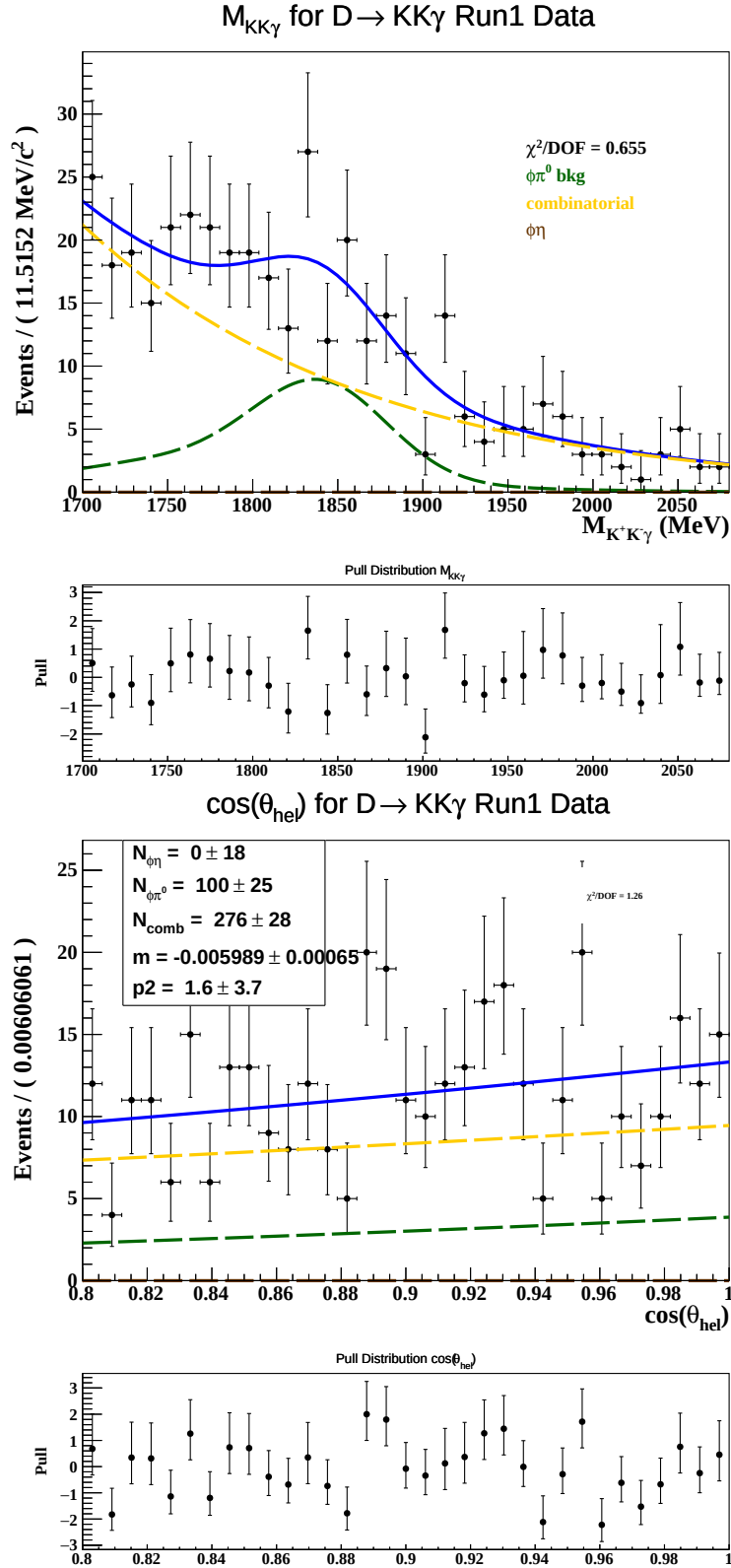


Figure 10.5: Fit to the mass and $\cos(\theta_H)$ edge region for data ΔM sidebands. The model for the η and π^0 components is taken from the MC fits and the combinatorial components in mass and helicity are free to float in the fit.

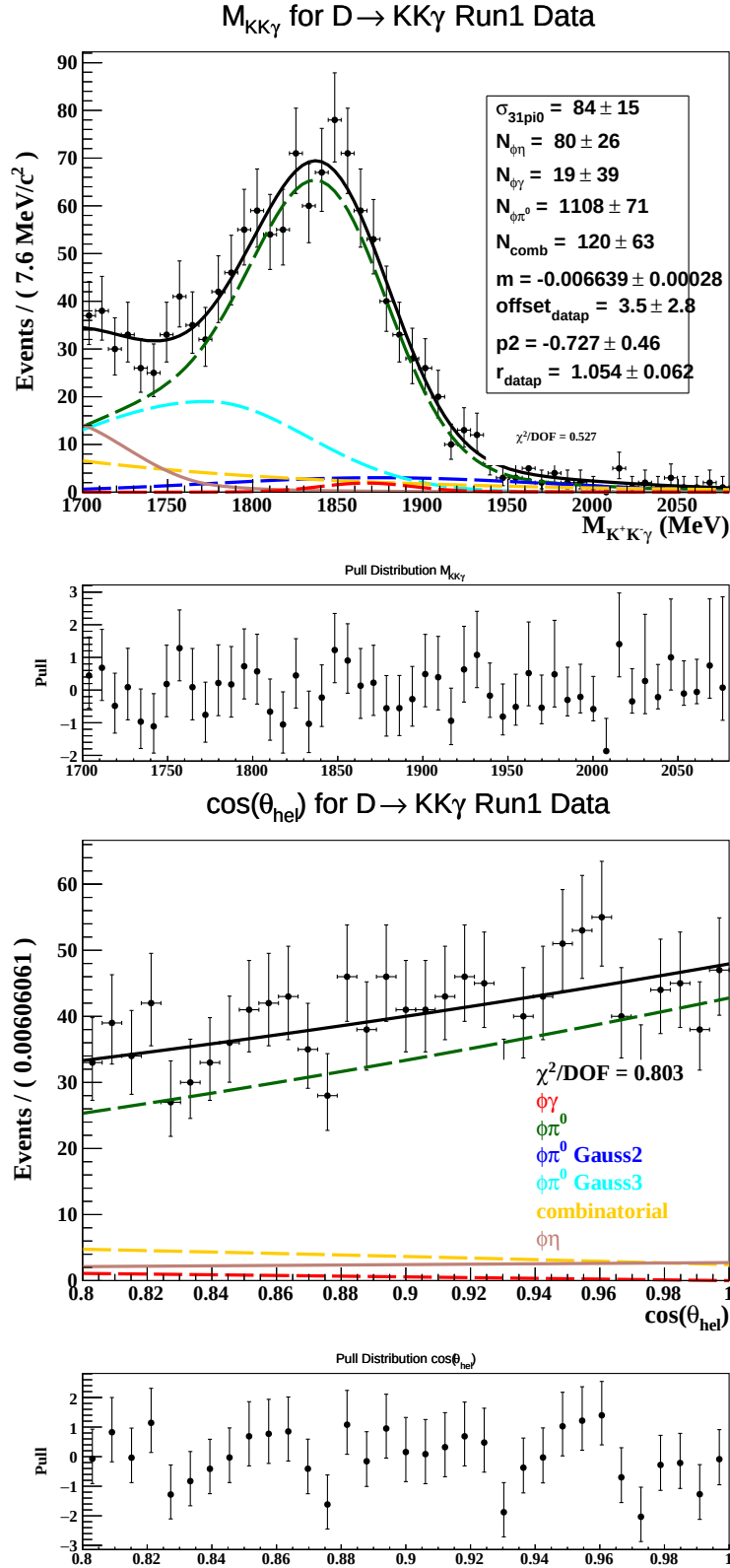


Figure 10.6: Fit to the mass and $\cos(\theta_H)$ edge region for the ΔM signal region in data. The model for the signal, η and π^0 components is taken from the MC fits whilst the combinatorial shape is taken from the ΔM sideband fit and constrained to be within $\pm 1\sigma$ through hard limits compared to their central values.

Before performing the fits to the central helicity region ($-0.8 < \cos(\theta) < 0.8$), helicity fits in the same region for the signal, π^0 and η components need to be performed. For the signal and π^0 components, the model comprises the theoretical parabolic shape multiplied by a quadratic acceptance where the linear term in the acceptance is fixed to zero following what is seen in data. As mentioned previously, sensitivity to the theoretical helicity shape for the η component is lost so the helicity distribution in the central helicity region for this component is parameterised using a quadratic function. The fits to the three components are shown in Fig. 10.7

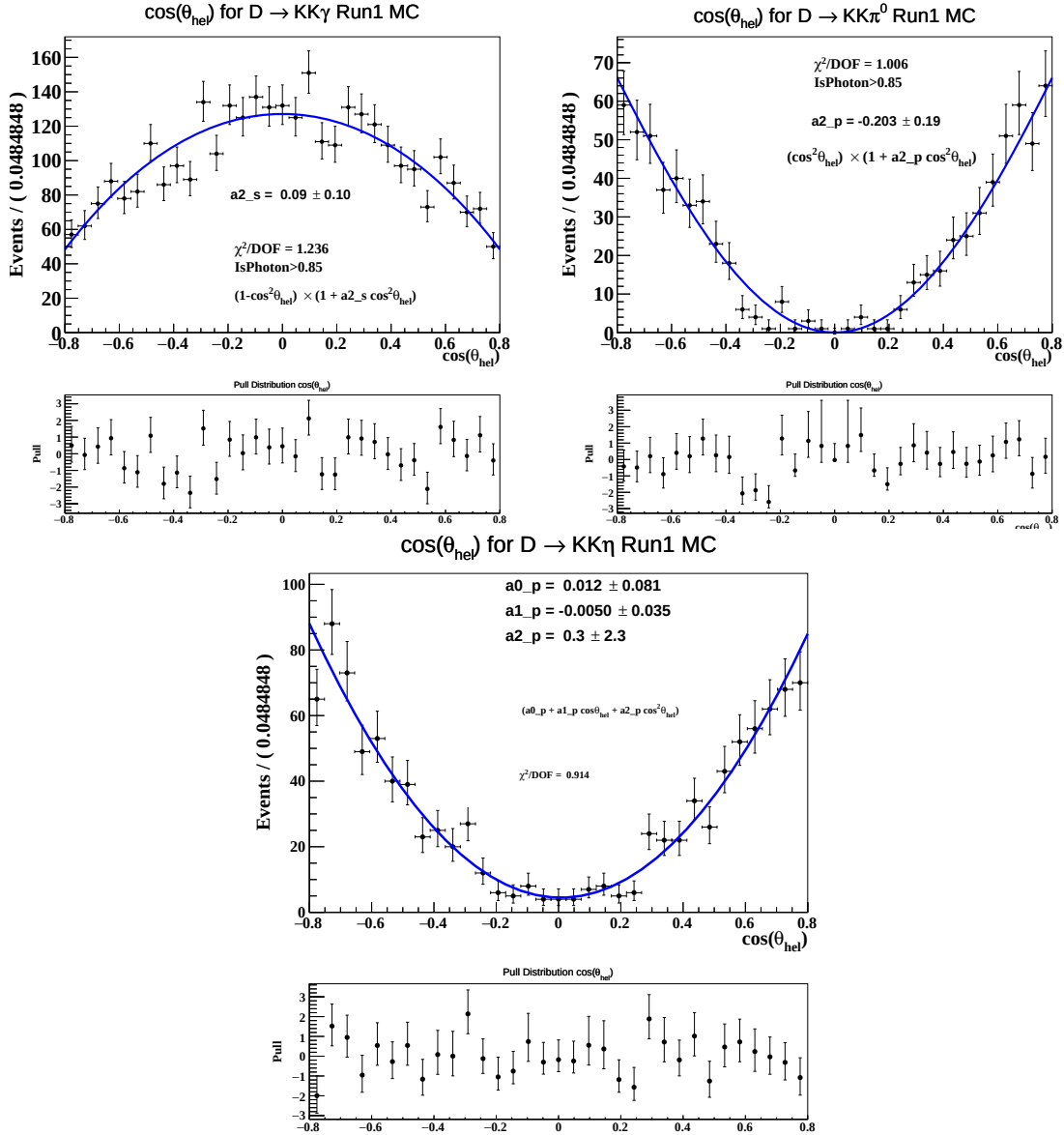


Figure 10.7: Fit to the $\cos(\theta_H)$ central region for $D^0 \rightarrow \phi\gamma$ (top-left), $D^0 \rightarrow \phi\pi^0$ (top-right) and $D^0 \rightarrow \phi\eta$ (bottom) MC samples.

Finally, the combinatorial component is parameterised as an exponential and second order polynomial in mass and helicity respectively. The parameters for these distributions are obtained by performing a fit to the central helicity ΔM sideband region where signal, π^0 and η components are fixed to

their respective MC values. The 2D fit to the central helicity ΔM sideband region is shown in Fig. 10.8.

A hard constraint is imposed on the combinatorial parameters such that they are forced to lie within $\pm 1\sigma$ of their central values in the fit to the ΔM signal region in the central helicity region in data as shown in Fig. 10.9. As previously, the yields of the four components are free as well as the offset and scale factor for the signal and π^0 components to calibrate any data-MC differences that will be common to both the peaking components. Additionally, an asymmetry in helicity is introduced for the π^0 component originating from the interference between the non-resonant $D^0 \rightarrow K^+K^-\pi^0$ and $D^0 \rightarrow \phi\pi^0$ diagrams. This isn't present in MC since the simulation only produces vector meson decaying into two hadrons as part of the full decay chain. The asymmetric term is introduced as the linear contribution to the helicity acceptance (a1_p) for the π^0 component. Table. 10.2 shows the values taken by the different parameters in the fit to the central helicity region in data as shown in Fig. 10.9.

The global projections show that the various components are well parameterised but mass (helicity) projections in helicity (mass) bins will show how the sub-components vary across different regions. Fig. 10.10 shows the mass and helicity projections in different bins of the other variables. From these projections and the global fit, we conclude that components within the fit model currently are sufficient to parameterise the data distributions in mass and helicity. Consequently, including ΔM as the third dimension in the fit is now possible and must be included to disentangle a potential asymmetry introduced by the tagging pion from the CP asymmetry in decay.

Parameter	Value
σ_{1sig}	25.87 MeV/c ²
f_{1sig}	0.878
m_{1sig}	1863.04 MeV/c ²
$offset_{2sig}$	32.5
r_{2sig}	2.53
σ_{1pi0}	36.7 MeV/c ²
f_{1pi0}	0.601
m_{1pi0}	1838.2 MeV/c ²
$offset_{2pi0}$	32.5
r_{2pi0}	2.53
$(f2/f1)_{pi0}$	0.139
$m_{1pi0thr}$	1772.8 MeV/c ²
$\sigma_{1pi0thr}$	84 $\pm$ 23 MeV/c ²
$\sigma_{2pi0thr}$	60.2 MeV/c ²
α	-1.891
σ_η	42.7 MeV/c ²
m_η	1682.4 MeV/c ²
n	2.23
m (exponential)	-0.00336 $\pm$ 0.0013
$a2_s$	0.09
$a1_p$	0.361 $\pm$ 0.047
$a2_p$	-0.203
$a0_\eta$	0.012
$a1_\eta$	-0.0050
$a2_\eta$	0.3
$p1$	0.18 $\pm$ 0.18
$p2$	0.3 $\pm$ 1.4
$N_{\phi\eta}$	158 $\pm$ 29
$N_{\phi\gamma}$	257 $\pm$ 33
$N_{\phi\pi^0}$	1198 $\pm$ 50
N_{comb}	298 $\pm$ 48
$offset_{data}$	2.2 $\pm$ 3.6
r_{data}	1.051 $\pm$ 0.046

Table 10.2: The values taken by the different parameters in the fit to the central helicity region in data as shown in Fig. 10.9 after applying the optimal IsPhoton cut. Values with no associated uncertainty are fixed and other values are floated in the fit.

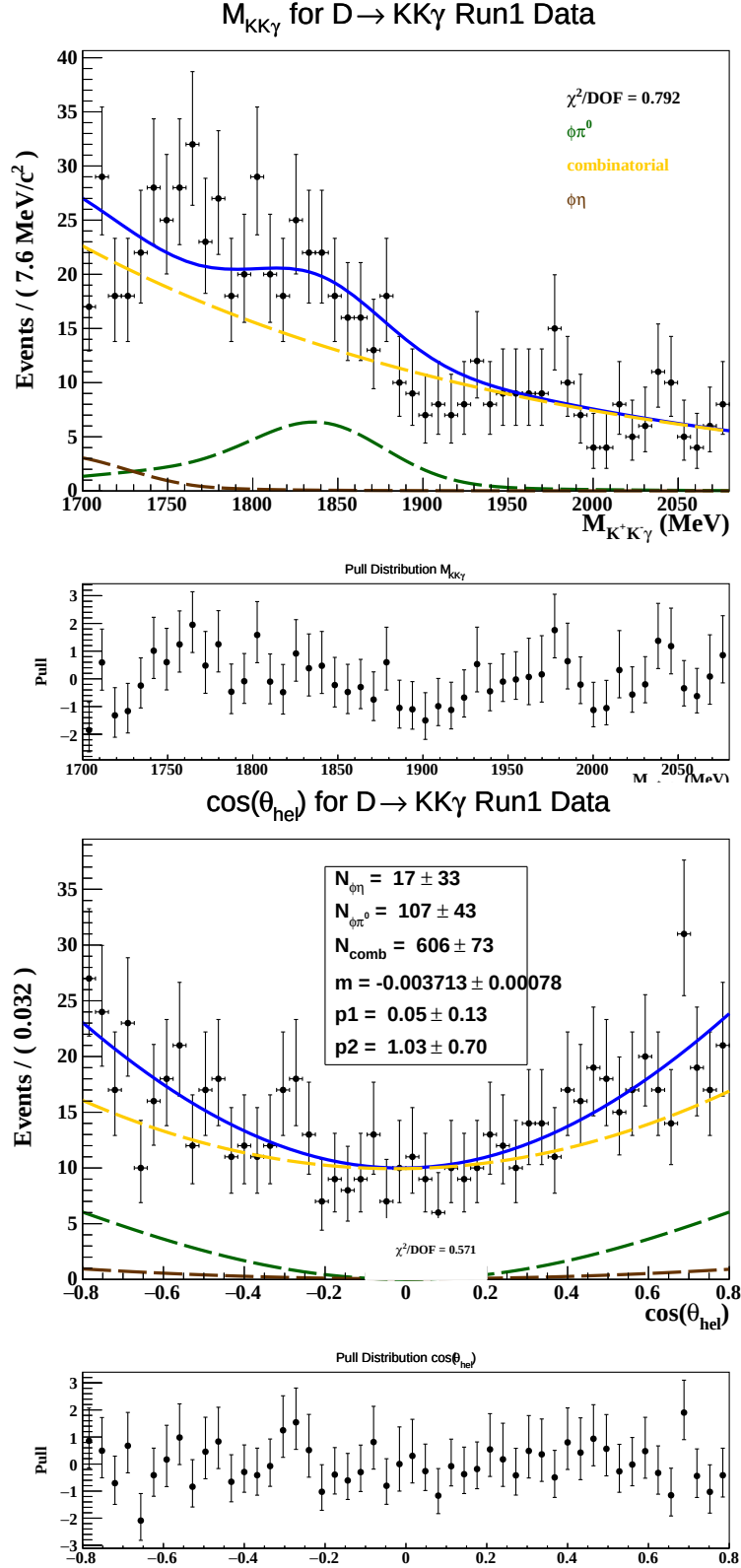
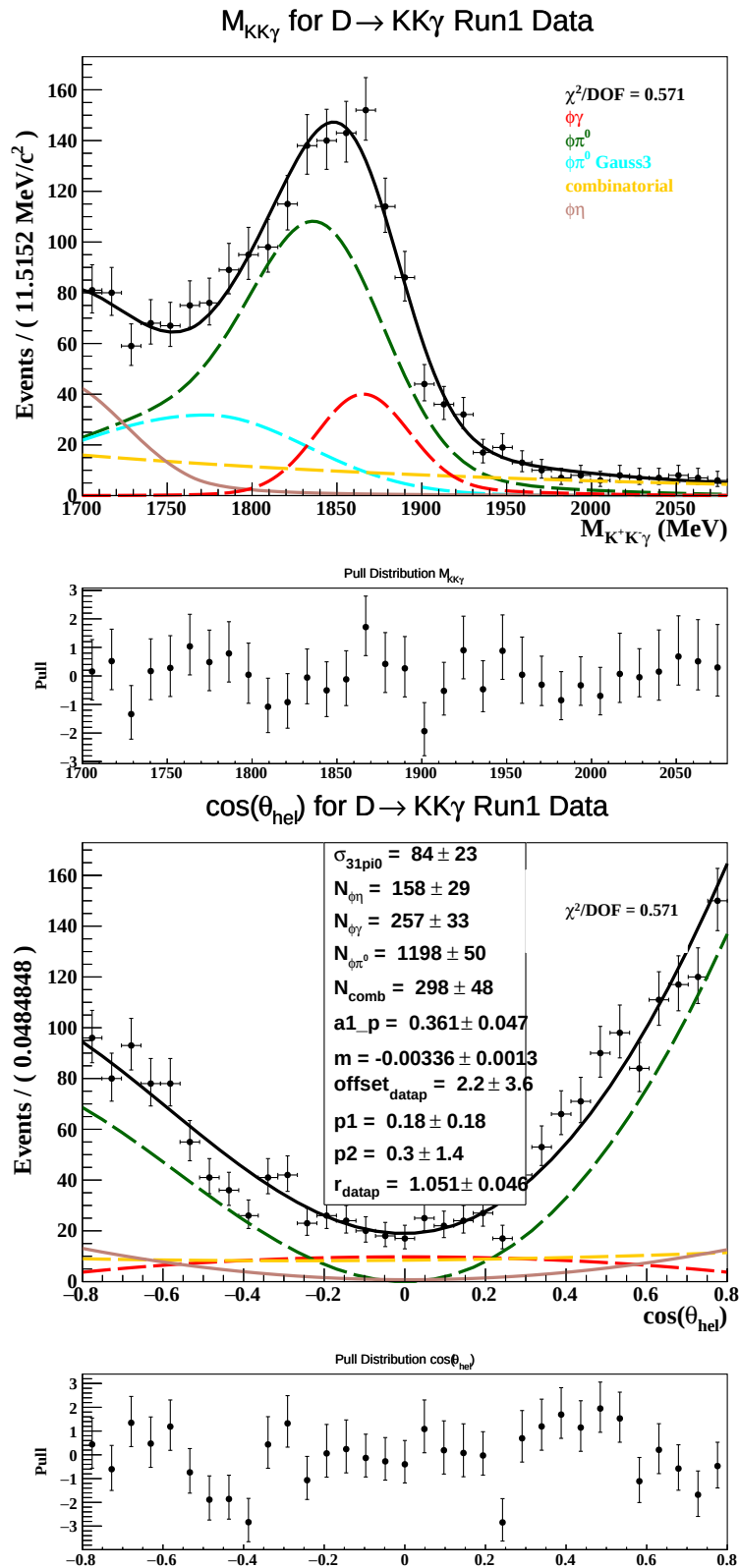


Figure 10.8: Fit to the mass and $\cos(\theta_H)$ central region for data ΔM sidebands. The model for the η and π^0 components is taken from the MC fits and the combinatorial components in mass and helicity are free to float in the fit.



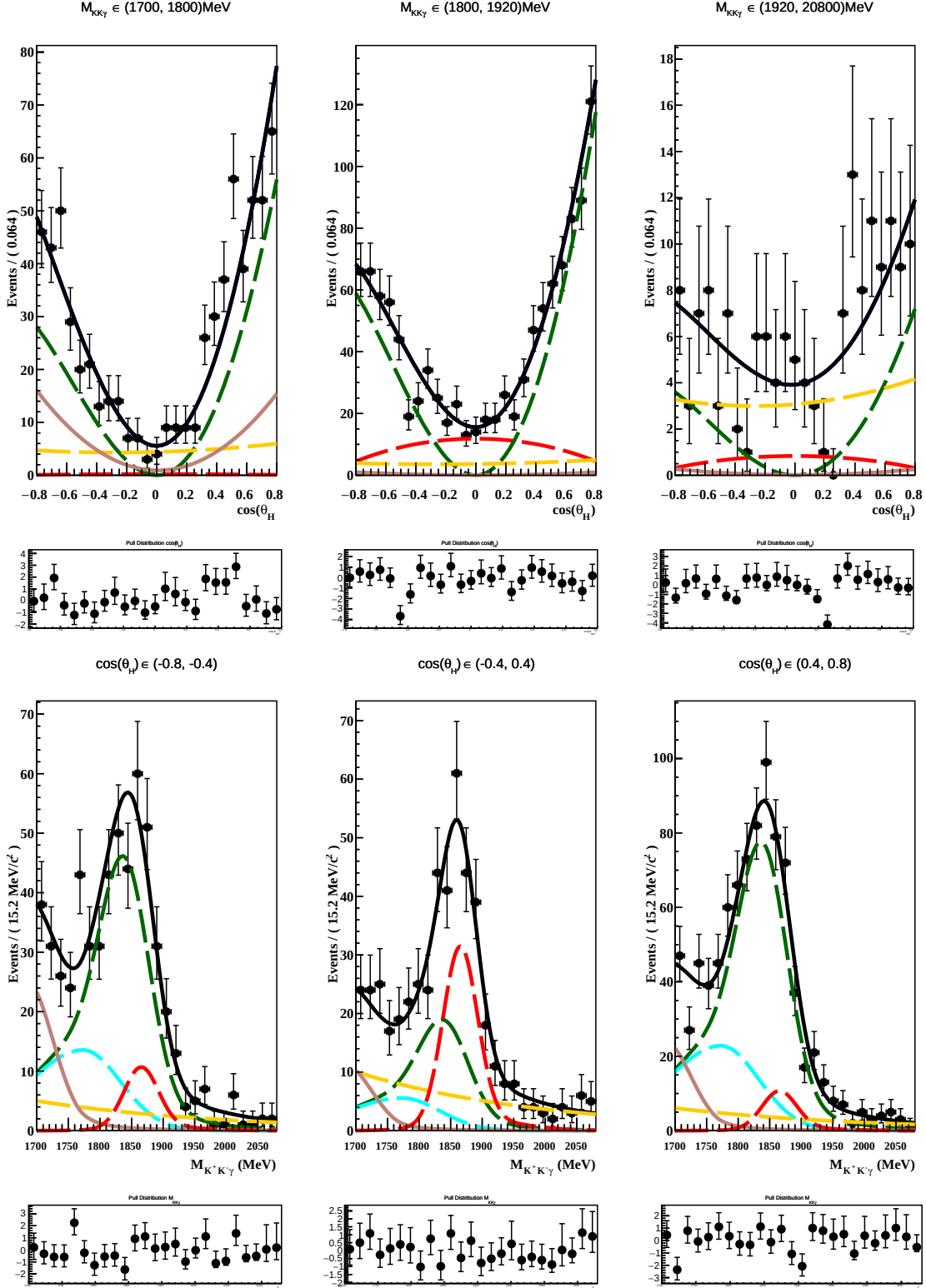


Figure 10.10: Helicity projection in 3 mass bins (top) as well as mass projections in 3 helicity bins (bottom). The χ^2 per degree of freedom for the helicity (mass) projections from left to right are: 0.797, 0.437, 0.821 (1.17, 1.06, 0.780).

10.2 3D Fits

Including ΔM as the third dimension in the fit is now possible and must be included to disentangle a potential asymmetry introduced by the tagging pion from the CP asymmetry in decay. Adding ΔM as an extra dimension in the fit requires a wider ΔM window of $\Delta M \in [139.5, 161)\text{MeV}/c^2$ for all subsequent fits. Fits to signal, π^0 and η components are performed again to derive updated fit parameters using the wider ΔM window. The components are modelled according to previously defined parameterisations. The fits to the mass and edge helicity distributions for these components are shown in Figs. 10.11, 10.12 and 10.13. The mass and helicity models for the η component already use the full ΔM window and can be utilised in their current form (Figs. 10.3 and 10.4).

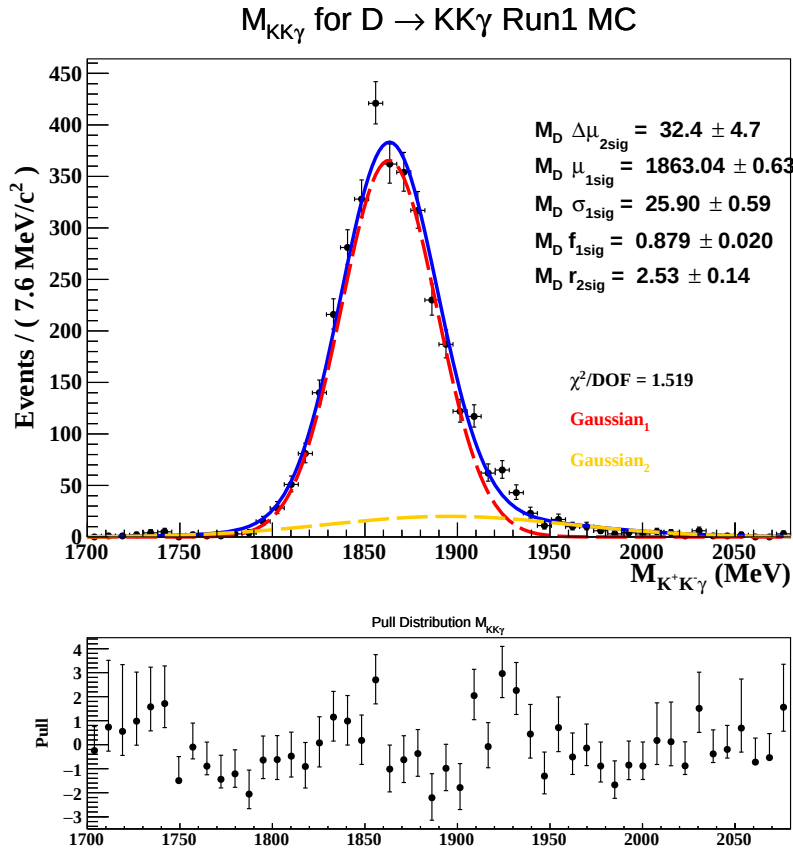


Figure 10.11: Fit to $M(D^0)$ in the $D^0 \rightarrow \phi\gamma$ MC sample for the full ΔM window after applying the IsPhoton cut. The model comprises two Gaussians, the second of which is constrained to the core Gaussian (red) through an offset and scale factor (r_{2sig}). All other free parameters are shown in the fit.

The various components in the fit model will each have a ΔM distribution that needs to be parameterised. As previously, MC samples are used to model ΔM distributions before fixing parameters in the final multi-dimensional fit to data.

The ΔM distribution in the $D^0 \rightarrow \phi\pi^0$ MC sample is modelled using 3 Gaussians. The core of the distribution is modelled by a broad and a narrow Gaussian which share a common mean. The width of the narrow Gaussian is free and is multiplied by a scale factor (r_{sigbrd}) to obtain the width of the

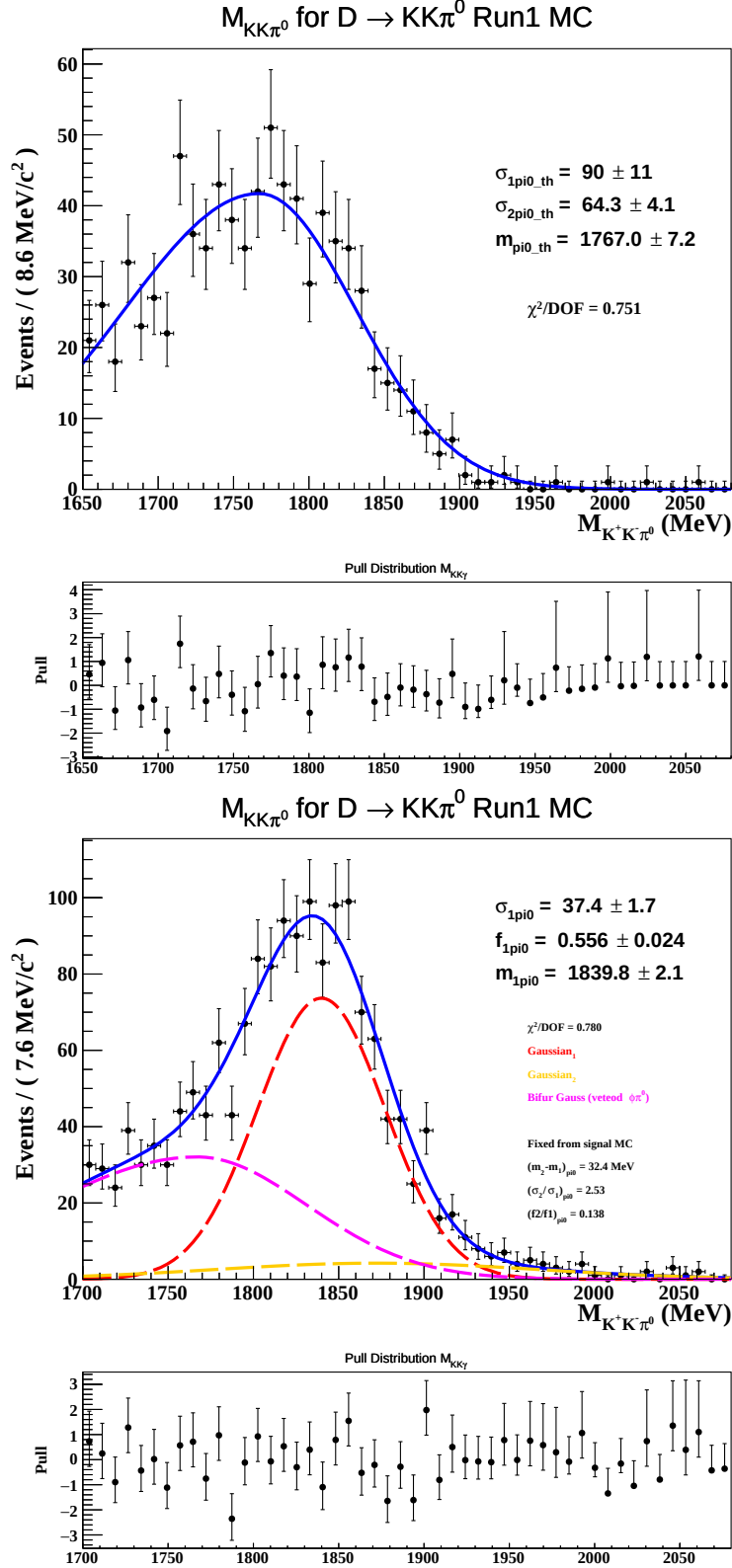


Figure 10.12: Fit to $M(D^0)$ in the $D^0 \rightarrow \phi\pi^0$ MC sample for the full ΔM window after applying the IsPhoton cut. The model for the fit to the vetoed sample (top) is an asymmetric Gaussian. The parameters of the asymmetric Gaussian are fixed in the fit to the sample with the nominal selection (bottom).

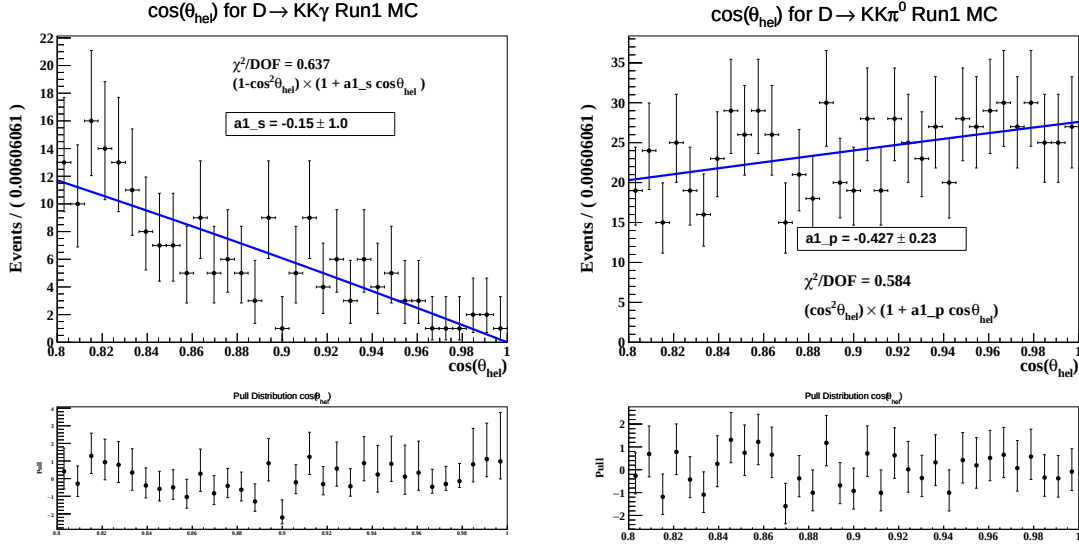


Figure 10.13: Fit to the $\cos(\theta_H)$ edge region for $D^0 \rightarrow \phi\gamma$ (left) and the $D^0 \rightarrow \phi\pi^0$ (right) MC sample for the full ΔM window after applying the IsPhoton cut. The model for the fit is the theoretical parabolic shape multiplied by a linear acceptance function.

broad Gaussian. The fraction ($f_{\phi\pi^0 nrw}$) between the two Gaussians is also free to float. The high mass region in the ΔM distribution is modelled by a tail Gaussian with a different mean and width to the core Gaussians. This is necessary in MC samples but the tail Gaussian will be dominated by and subsumed into the combinatorial background component in the data fits by combinatorial background. The relative fraction ($f_{\phi\pi^0 core}$) between the core and tail Gaussian is also free to float. The ΔM distribution for $D^0 \rightarrow \phi\gamma$ signal is parameterised similarly to $D^0 \rightarrow \phi\pi^0$ except that the three Gaussians (broad, narrow and tail) share a common mean rather than separate means for the core and tail parts of the distribution. Fig. 10.14 shows the result of the MC ΔM fits for signal and π^0 components.

The ΔM distribution in $D^0 \rightarrow \phi\eta$ MC is modelled by the sum of Crystal Ball and Gaussian functions with separate means and widths. The Crystal Ball models the higher ΔM tails whereas the Gaussian models the region intermediate between the core and the tails. The relative fraction between the two functions is kept free within the fit as shown in Fig. 10.15. The combinatorial component is modelled by an exponential PDF in mass and a quadratic polynomial PDF in helicity. The ΔM distribution of the combinatorial background is parameterised using a threshold exponential function with the following empirical form:

$$F_{bkg} = (\Delta m - m_{th})^{0.5} e^{-\beta(\Delta m - m_{th})}. \quad (10.1)$$

Here m_{th} is a fixed threshold parameter defined as the charged pion rest mass, and β is free parameter in the fit. As ΔM sidebands can't be used to constrain the combinatorial parameters, since ΔM is a dimension within the fit itself, the combinatorial parameters are kept free within the multi-dimensional fit.

The addition of ΔM as a fit variable enables an additional and important source of backgrounds to be

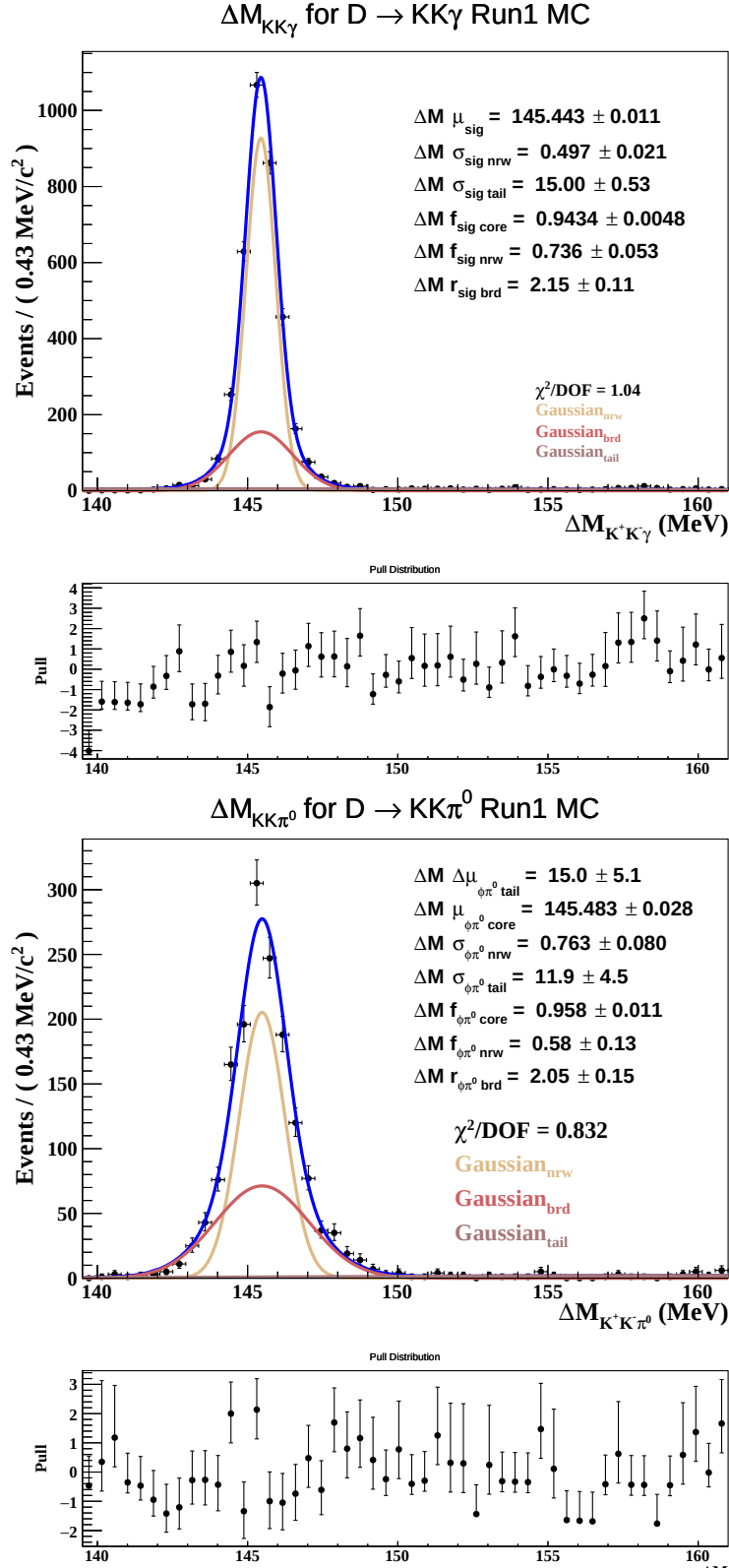


Figure 10.14: Fit to ΔM in the $D^0 \rightarrow \phi\gamma$ (top) and $D^0 \rightarrow \phi\pi^0$ (bottom) MC samples after applying the IsPhoton cut. All other free parameters are shown in the fit.

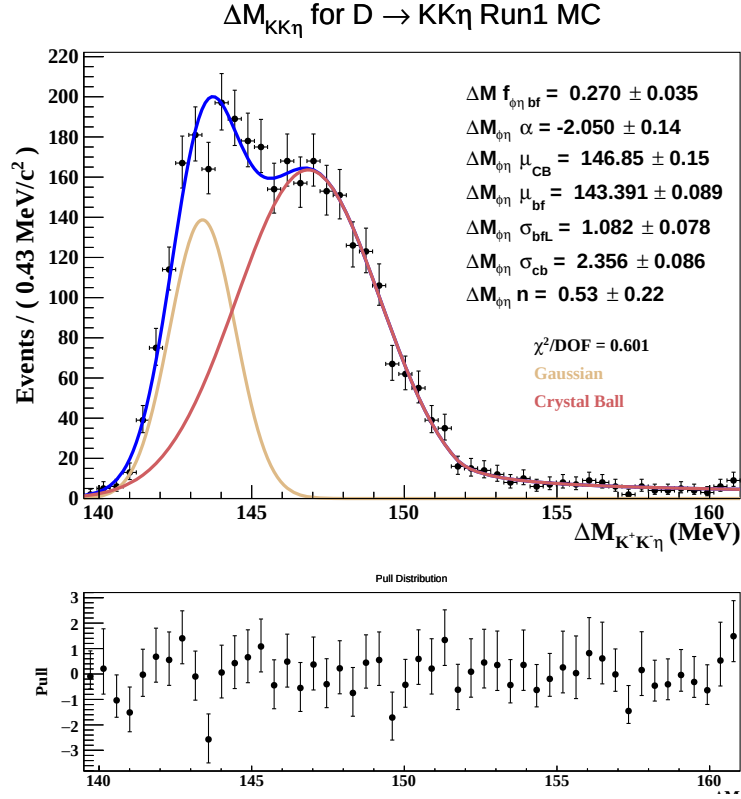
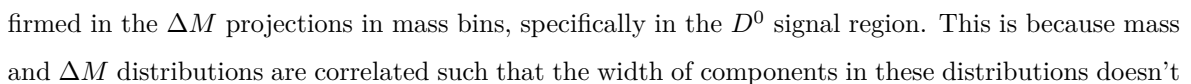


Figure 10.15: Fit to ΔM in the $D^0 \rightarrow \phi\eta$ MC sample after applying the IsPhoton cut. All free parameters of the Crystal Ball and Gaussian pdf's are shown in the fit.

included in the fit. This background corresponds to genuine D^0 mesons being combined with random unrelated soft pions. Not accounting for this could bias the CP asymmetry measurement since the charge of the soft pion tags the flavor of the D meson. Therefore the mis-association of the soft pion is included for the signal as well as the π^0 and η backgrounds as extra components in the fit. These extra soft pion components take on the shape of their corresponding nominal components in mass and helicity distributions because the reconstruction of the D^0 meson isn't affected by the mis-association of a random pion with real D^0 candidates. Conversely, this builds fake D^* candidates and hence the soft pion components are parameterised as combinatorial background in the ΔM distribution.

Combining all the components, a fit to the helicity edge region in data is performed as a cross-check to show that all components are parameterised sufficiently well. As previously, the yields of the components are free to float in the fit. The signal component is not included in this fit since it is found to be negligible in the helicity edge region. Consequently, the soft pion component associated with mis-associated signal decays is also not included. The left width of the threshold Gaussian for the π^0 component in mass is poorly constrained in MC so instead of imposing hard constraint, a Gaussian constraint is applied here such that the fit penalises any significant deviations from the central value found from MC fits. Similar constraints are applied to the η ($a0_e$, $a1_e$) and π^0 ($h1_p$) helicity parameters that model the linear polynomial and linear acceptance in those components respectively. The combinatorial parameters such as exponential decay factor in mass (m), the threshold polynomial in

From the global projections, the peak in the ΔM distribution is not well modelled and this is con-



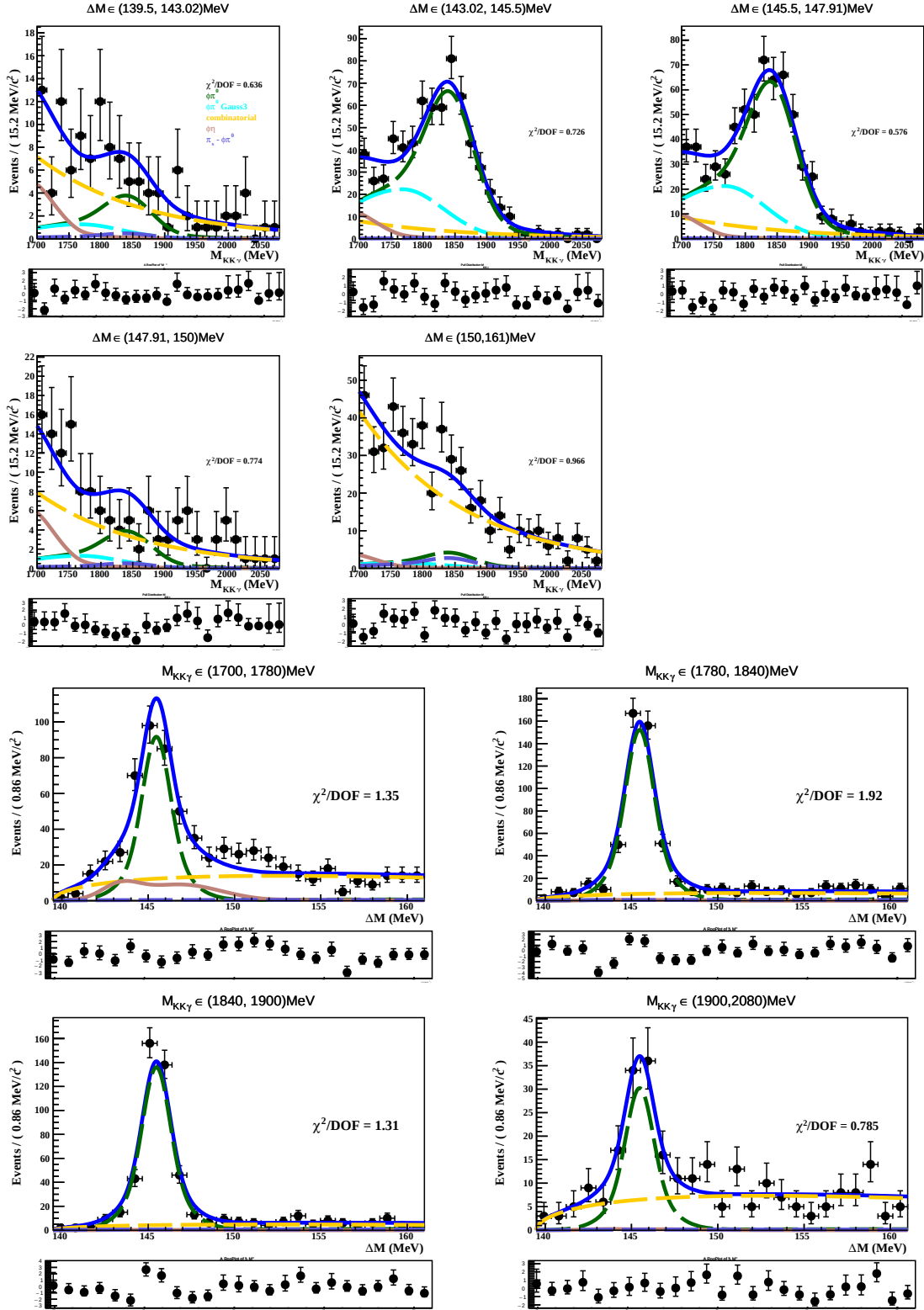


Figure 10.17: Mass projections in various ΔM bins (top-two rows) and ΔM projections in various mass bins (bottom-two rows) for the fit to the helicity edge region in data.

remain constant in bins of the other distribution. To account for these correlations, a simple model is employed whereby fits to the MC ΔM distribution are performed in many D^0 mass bins. The model

used for these fits is the same one used in the MC fits with the parameters fixed to the respective MC fit. To allow for some freedom in the fit, a scale factor, λ is allowed to float in these fits. The scale factor scales the widths of all core peak functions to fit the data. Since the π^0 background is the dominant component, correlations are first included here with Fig. 10.18 showing the corresponding fits to the ΔM distribution in D^0 mass bins. Correlations in the signal and η components are also included when moving to the central helicity region and are especially necessary for the signal component as any mis-modelling of the signal will alter its yield which could have a detrimental impact on any CP asymmetry or branching fraction measurement.

The scale factor, λ , is plotted as a function of the mass (in GeV/c^2) and a second order polynomial is used to model the relationship between the two variables as shown in Fig. 10.19. The parameters from the second order polynomial are shown in Tab. 10.3. To verify the correlations model, the multi-dimensional fit to the helicity edge data in $D^0 \rightarrow \phi\gamma$ is performed again with the correlations included in ΔM to account for the variation in width as a function of D^0 mass. Based on the uncorrelated fit, a Gaussian constraint is placed on the scale factor in mass ($\mathbf{r}_{\text{MD}}$) as well as the offsets in ΔM and mass. The global projections for the multidimensional fit are shown in Fig. 10.20 and mass (ΔM) projections in bins of ΔM (mass) are shown in Fig. 10.21. As previously, projections in bins of helicity are not shown for brevity. Table 10.4 shows the values parameters in the fit to the edge helicity region in data as shown in Fig. 10.20.

Including the correlations improves the modelling of the peak in ΔM as can be seen from the global projections and the peak description in bins of mass also improves, specifically the mass bin where signal is likely to enter. There is some mis-modelling of the π^0 component in ΔM in the lowest mass bin but this can be explained by imperfections in the correlation model due to the large uncertainty on the first two points in the correlation curve in Fig. 10.19.

Parameter	Value
a2	80.7 ± 10.2
a1	-298.7 ± 37.0
a0	276.9 ± 33.7

Table 10.3: Parameters of the second order polynomial from Fig. 10.19 such that $\lambda = a_0 + a_1 * M + a_2 * M^2$ where M is the reconstructed mass in GeV/c^2 of the $D^0 \rightarrow \phi\pi^0$ candidates in MC.

Mass Parameter	Value	ΔM Parameter	Value
σ_{1sig}	25.90 MeV/c ²	$\Delta M \mu_{sig}$	145.443 MeV/c ²
f_{1sig}	0.879	$\Delta M \sigma_{signrw}$	0.497 MeV/c ²
m_{1sig}	1863.04 MeV/c ²	$\Delta M f_{signrw}$	0.736
$\Delta\mu_{2sig}$	32.4	$\Delta M r_{sigbrd}$	2.15
r_{2sig}	2.53	$\Delta M \mu_{\phi\pi^0}$	145.483 MeV/c ²
σ_{1pi0}	37.4 MeV/c ²	$\Delta M \sigma_{\phi\pi^0nrw}$	0.763 MeV/c ²
f_{1pi0}	0.556	$\Delta M f_{\phi\pi^0nrw}$	0.58
m_{1pi0}	1839.8	$\Delta M r_{\phi\pi^0brd}$	2.05
offset _{2pi0}	32.4	$\Delta M_{\phi\eta} \mu_{CB}$	146.85 MeV/c ²
r_{2pi0}	2.53	$\Delta M_{\phi\eta} \mu_{bf}$	143.391 MeV/c ²
$(f2/f1)_{pi0}$	0.138	$\Delta M_{\phi\eta} \sigma_{CB}$	2.356 MeV/c ²
$m_{1pi0thr}$	1767.0 MeV/c ²	$\Delta M_{\phi\eta} \sigma_{bfL}$	1.082 MeV/c ²
$\sigma_{1pi0thr}$	91.7 $\pm$ 5.9 MeV/c ²	$\Delta M_{\phi\eta} \alpha$	-2.050
$\sigma_{2pi0thr}$	64.3 MeV/c ²	$\Delta M_{\phi\eta} f_{bf}$	0.27
α	-1.891	$\Delta M_{\phi\eta} n$	0.53
σ_η	42.7 MeV/c ²		
m_η	1682.4 MeV/c ²		
n	2.23		

Parameter	Value
m (exponential)	-0.005775 $\pm$ 0.00048
β	0.0430 $\pm$ 0.0072
a1_s	-0.15
a1_p	-0.427
a0 $_\eta$	0.0 $\pm$ 1.5
a1 $_\eta$	0.1 $\pm$ 1.1
p2	2.0 $\pm$ 6.7
h1_p	-0.48 $\pm$ 1.2
N $_{\phi\eta}$	91 $\pm$ 46
N _{slowπ($\phi\eta$)}	0 $\pm$ 17
N _{slowπ($\phi\pi^0$)}	118 $\pm$ 30
N $_{\phi\pi^0}$	1203 $\pm$ 38
N _{comb}	662 $\pm$ 44
offset _{MD}	3.5 $\pm$ 1.1
offset _{DM}	-0.0096 $\pm$ 0.018
r _{MD}	1.008 $\pm$ 0.029

Table 10.4: The values taken by mass (top-left), ΔM (top-right) and all other (bottom) parameters in the fit to the edge helicity region in data as shown in Fig. 10.20 after applying the optimal IsPhoton cut and incorporating correlations into the π^0 component. Values with no associated uncertainty are fixed and other values are floated in the fit.

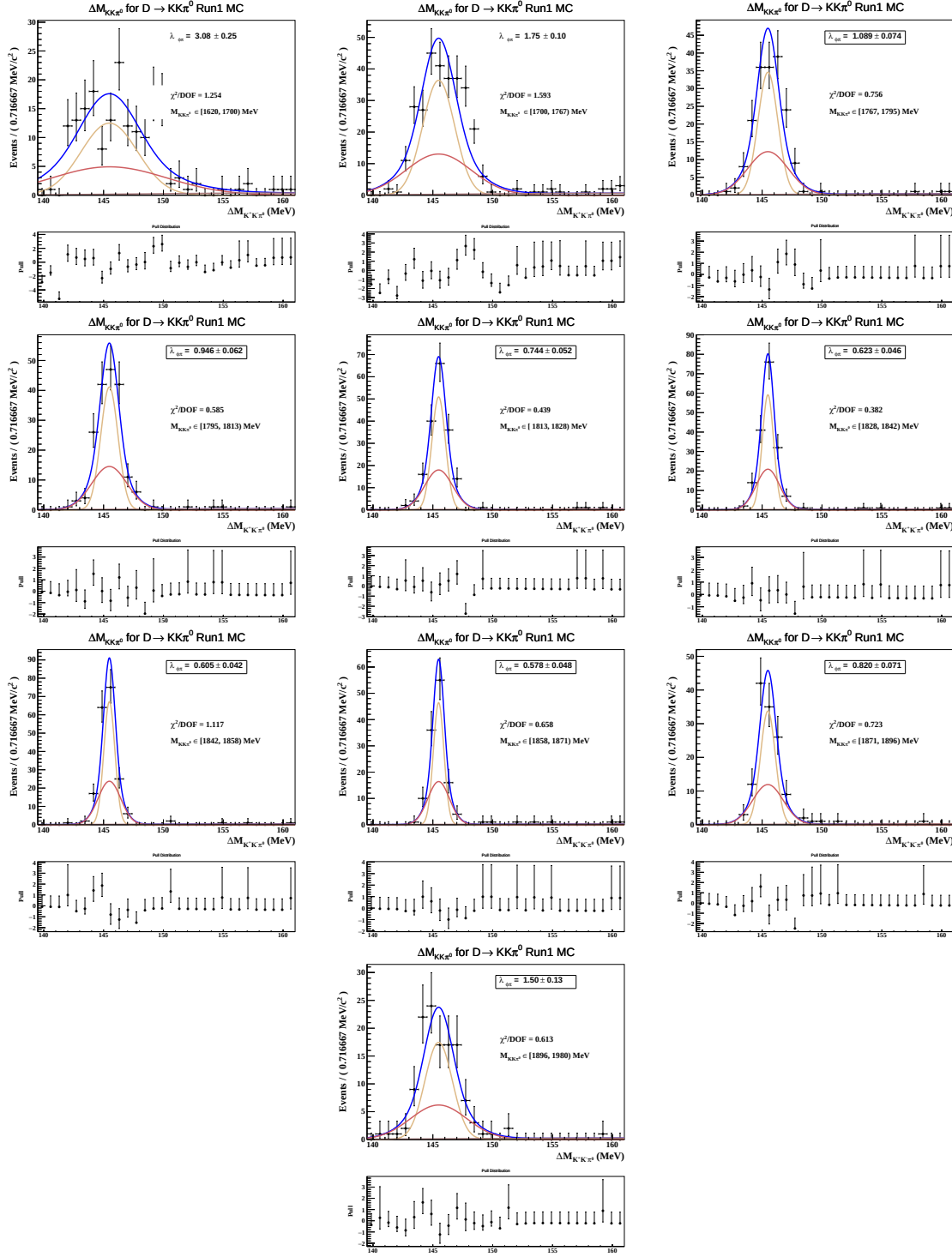


Figure 10.18: ΔM fits in mass bins where the scale factor, λ , scales the widths of the core Gaussians for the $D^0 \rightarrow \phi\pi^0$ simulation. The fits are performed to determine correlations between the parameters of the ΔM peak with the D^0 mass.

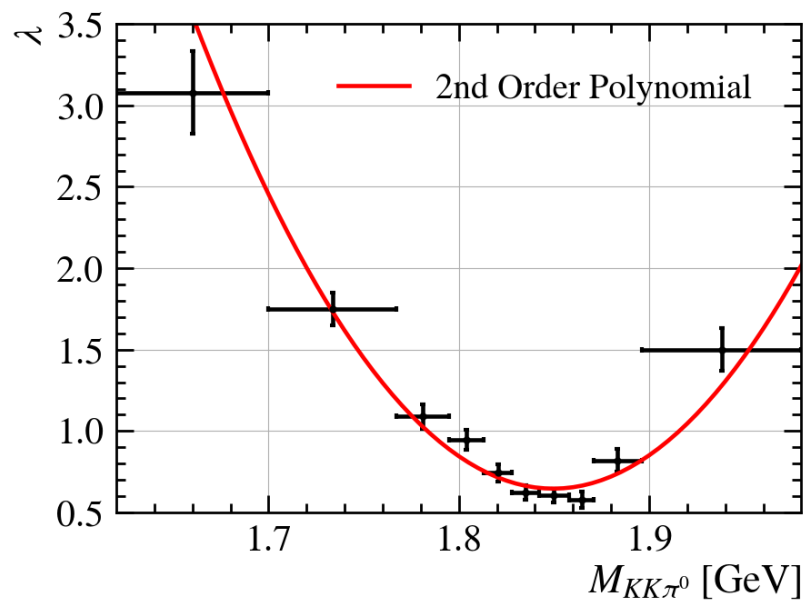


Figure 10.19: The variation of the ΔM width (parameterised by λ) as a function of the D^0 mass, showing a clear correlation for the π^0 MC. A second order polynomial is used to model the relationship between the scale factor λ and the reconstructed mass.

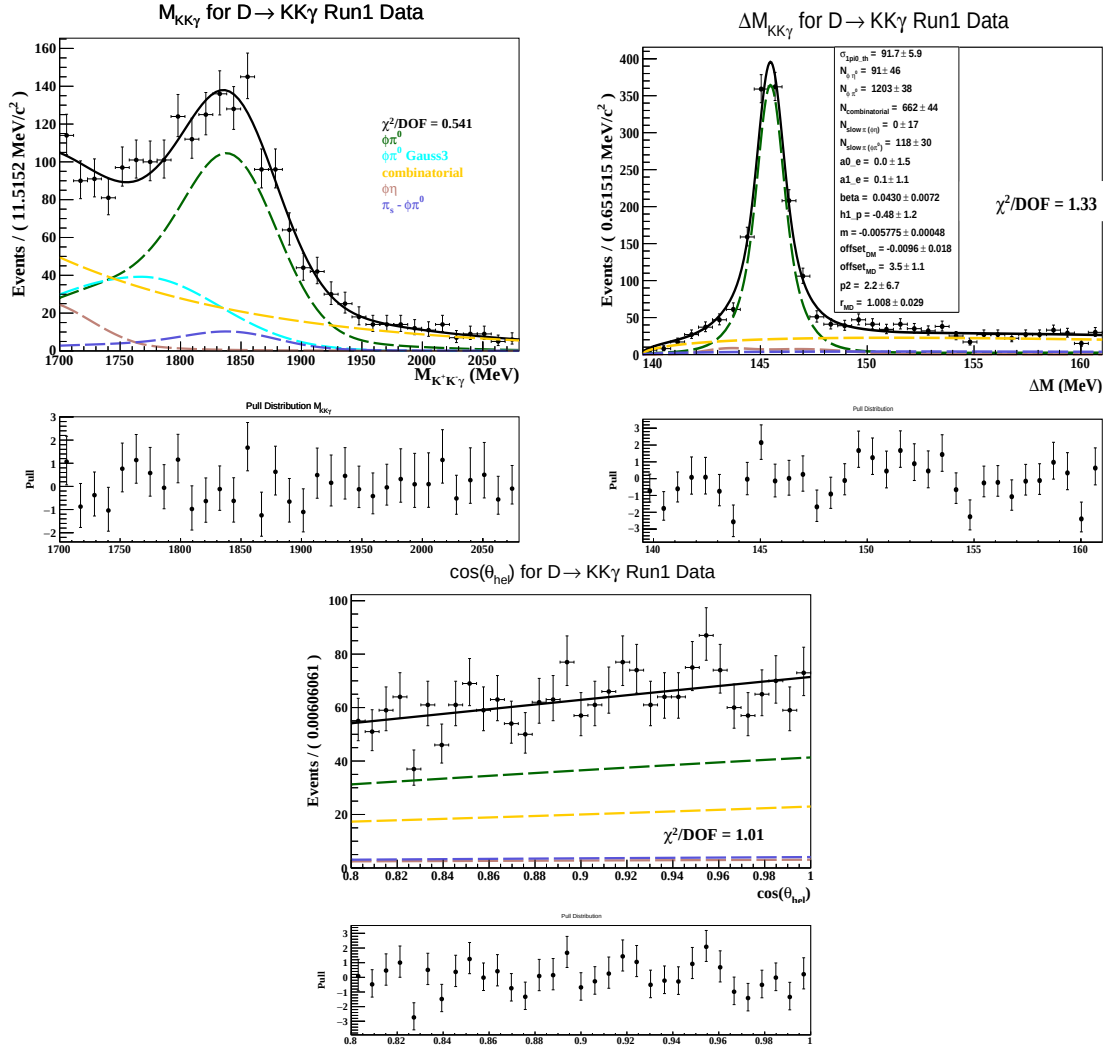


Figure 10.20: Multi-dimensional fit to mass (top-left), ΔM (top-right) and helicity (bottom) distributions for the $D^0 \rightarrow \phi\gamma$ helicity edge data sample after applying the IsPhoton cut and including the correlations in ΔM for the π^0 component. All free parameters of the fit are shown.

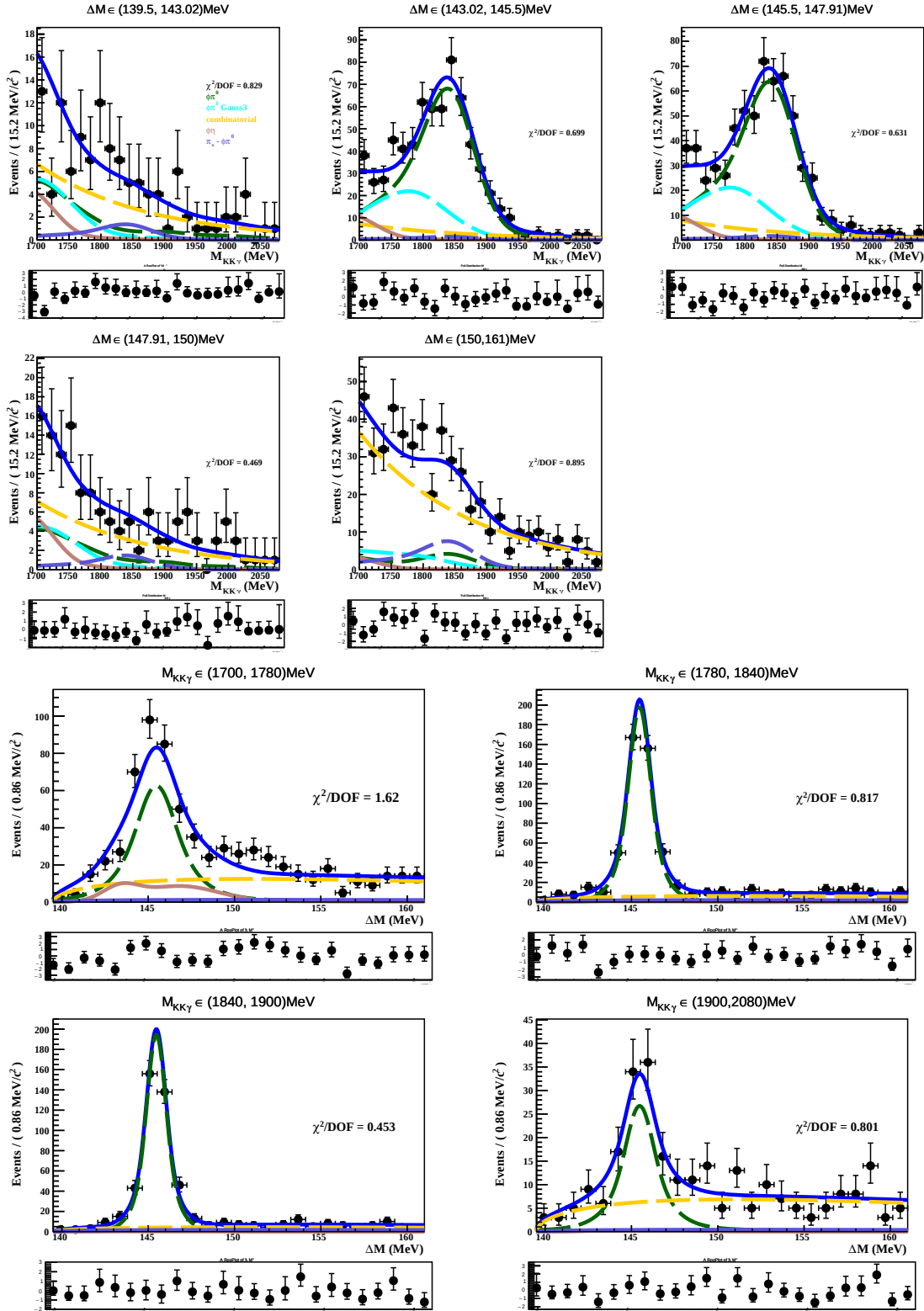


Figure 10.21: Mass projections in various ΔM bins (top-two rows) and ΔM projections in various mass bins (bottom-two rows) for the helicity edge region in data after adding correlations to the π^0 component.

10.2.1 Final Fits to the $D^0 \rightarrow \phi\gamma$ channel

The verification of the correlations model means that the fit to the central helicity region can now be performed. Before doing so, correlations in the signal and η components will have to be included in a similar manner to those in the π^0 component. The peak in signal ΔM distribution is narrower so when performing the fits in bins of mass, a narrower ΔM range ($\in[142,150]\text{MeV}$) is chosen in order to exclude the tail Gaussian from the fit altogether. The procedure is similar to the one outlined above for the π^0 component and fits in bins of mass are shown in Fig. 10.22 whilst the correlation curve is shown in Fig. 10.23. Corresponding parameters from the second order polynomial used to model the relationship between the two variables are shown in Tab. 10.5.

For the η component, only three fits in bins of mass are performed, shown in Fig. 10.24, owing to the lack of statistics in the mass region where the multi-dimensional fit will eventually be performed. The scale factor, λ , scales the widths of both the Crystal Ball and Gaussian p.d.f's. The relationship between the scale factor and mass is modelled by a flat distribution i.e. no evidence of correlation as shown in the correlation curve in Fig. 10.25.

Parameter	Value
a2	192.4 ± 21.3
a1	$-716.9 \pm 79.3.8$
a0	668.5 ± 73.9

Table 10.5: Parameters of the second order polynomial from Fig. 10.23 such that $\lambda = a0 + a1*M + a2*M^2$ where M is the reconstructed mass in GeV/c^2 of the $D^0 \rightarrow \phi\gamma$ decays in MC.

The helicity distributions for the signal and π^0 component in the central helicity region are modelled by multiplying the theoretical shape by a quadratic acceptance function where the linear coefficient is set to zero. As seen from the 2D fits to the central helicity data, an asymmetric term in helicity will need to be included. With this in mind, the MC is modelled using only symmetric terms. The fits to the central helicity region in MC for the two components are shown in Fig. 10.26. A Gaussian constraint is placed on all helicity parameters in the multi-dimensional fit to the central helicity region in data. The asymmetric helicity terms such as $\mathbf{h1}_p$ and $\mathbf{h1}_s$ for the π^0 and signal components are kept free in the fit.

Finally, as before, the combinatorial parameters are all kept free in the fit. This includes the exponential decay constant in mass ($\mathbf{m}$), the threshold polynomial in ΔM ($\mathbf{beta}$) and the quadratic polynomial in helicity ($\mathbf{p1}$, $\mathbf{p2}$). Fig. 10.27 shows the global projections for the multi-dimensional fit to the central helicity region in the $D^0 \rightarrow \phi\gamma$ data sample. Table 10.6 shows the values parameters in the fit to the correlated central helicity region in data as shown in Fig. 10.27. Mass (ΔM) projections in bins of ΔM (mass) are shown in Fig. 10.28 and the mass projections in bins of helicity are shown in Fig. 10.29. The mass projections in bins of helicity show the signal component dominating around the

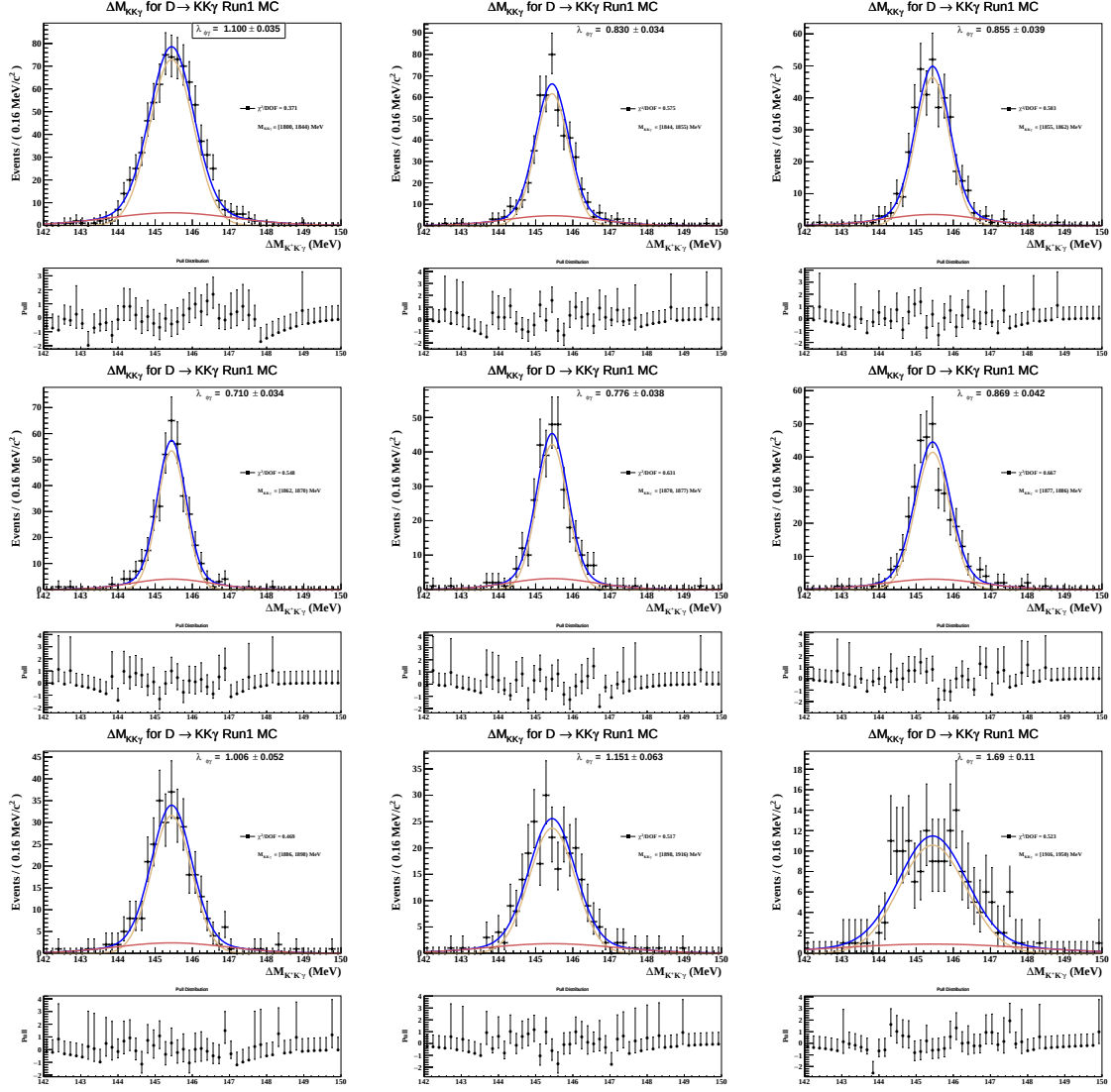


Figure 10.22: ΔM fits in mass bins where the scale factor, λ , scales the widths of the core Gaussians for the $D^0 \rightarrow \phi\gamma$ simulation. The fits are performed to determine correlations between the parameters of the ΔM peak with the D^0 mass.

most central helicity region ($-0.2 < \cos \theta_{hel} < 0.2$). There remains some mis-modelling of the ΔM peak in the lowest mass bin but this is again down to imperfections in the correlation model for the signal and π^0 components in the lower mass region. In fact, the ΔM peak is still modelled well in the mass region where the signal peaks and the ΔM projections are sensitive to this. Therefore it is possible to conclude that the signal is being modelled sufficiently well to extract the signal yield from such a fit. The final signal yield for the 2012 data $D^0 \rightarrow \phi\gamma$ channel is 254 ± 29 . Further improvements to multi-dimensional fit are presented in the following section and future work on this analysis to make a competitive measurements of the CP asymmetry and branching fraction in radiative charm decays is presented in Sec. 10.4.

Mass Parameter	Value	ΔM Parameter	Value
σ_{1sig}	25.90 MeV/c ²	$\Delta M \mu_{sig}$	145.443 MeV/c ²
f_{1sig}	0.879	$\Delta M \sigma_{signrw}$	0.497 MeV/c ²
m_{1sig}	1863.04 MeV/c ²	$\Delta M f_{signrw}$	0.736
$\Delta\mu_{2sig}$	32.4 MeV/c ²	$\Delta M r_{sigbrd}$	2.15
r_{2sig}	2.53	$\Delta M \mu_{\phi\pi^0}$	145.483 MeV/c ²
σ_{1pi0}	37.4 MeV/c ²	$\Delta M \sigma_{\phi\pi^0nrw}$	0.763 MeV/c ²
f_{1pi0}	0.556	$\Delta M f_{\phi\pi^0nrw}$	0.58 MeV/c ²
m_{1pi0}	1839.8 MeV/c ²	$\Delta M r_{\phi\pi^0brd}$	2.05
offset _{2pi0}	32.4	$\Delta M_{\phi\eta} \mu_{CB}$	146.85 MeV/c ²
r_{2pi0}	2.53	$\Delta M_{\phi\eta} \mu_{bf}$	143.391 MeV/c ²
$(f2/f1)_{pi0}$	0.138	$\Delta M_{\phi\eta} \sigma_{CB}$	2.356 MeV/c ²
$m_{1pi0thr}$	1767.0 MeV/c ²	$\Delta M_{\phi\eta} \sigma_{bfL}$	1.082 MeV/c ²
$\sigma_{1pi0thr}$	92.3 $\pm$ 9.7 MeV/c ²	$\Delta M_{\phi\eta} \alpha$	-2.050
$\sigma_{2pi0thr}$	64.3 MeV/c ²	$\Delta M_{\phi\eta} f_{bf}$	0.27
α	-1.891	$\Delta M_{\phi\eta} n$	0.53
σ_η	42.7 MeV/c ²		
m_η	1682.4 MeV/c ²		
n	2.23		

Parameter	Value
m (exponential)	-0.003171 $\pm$ 0.00053
β	0.0509 $\pm$ 0.0055
h1_s	0.56 $\pm$ 0.4
h2_s	0.093 $\pm$ 0.1
h1_p	0.288 $\pm$ 0.057
h2_p	-0.321 $\pm$ 0.12
a0 $_\eta$	0.0018 $\pm$ 0.0092
a1 $_\eta$	0.006 $\pm$ 0.027
a2 $_\eta$	0.09 $\pm$ 0.41
p1	0.03 $\pm$ 0.11
p2	0.62 $\pm$ 0.45
N $_{\phi\gamma}$	254 $\pm$ 29
N $_{\phi\eta}$	159 $\pm$ 38
N $_{slow\pi(\phi\eta)}$	76 $\pm$ 48
N $_{slow\pi(\phi\pi^0)}$	261 $\pm$ 71
N $_{slow\pi(\phi\gamma)}$	-7.7 $\pm$ 27
N $_{\phi\pi^0}$	1299 $\pm$ 53
N $_{comb}$	1233 $\pm$ 104
offset $_{MD}$	2.4 $\pm$ 1.2
offset $_{DM}$	-0.0216 $\pm$ 0.015
r $_{MD}$	1.037 $\pm$ 0.028

Table 10.6: The values taken by mass (top-left), ΔM (top-right) and all other (bottom) parameters in the fit to the central helicity region in data as shown in Fig. 10.27 after applying the optimal IsPhoton cut and incorporating correlations into the signal, π^0 and η components. Values with no associated uncertainty are fixed and other values are floated in the fit.

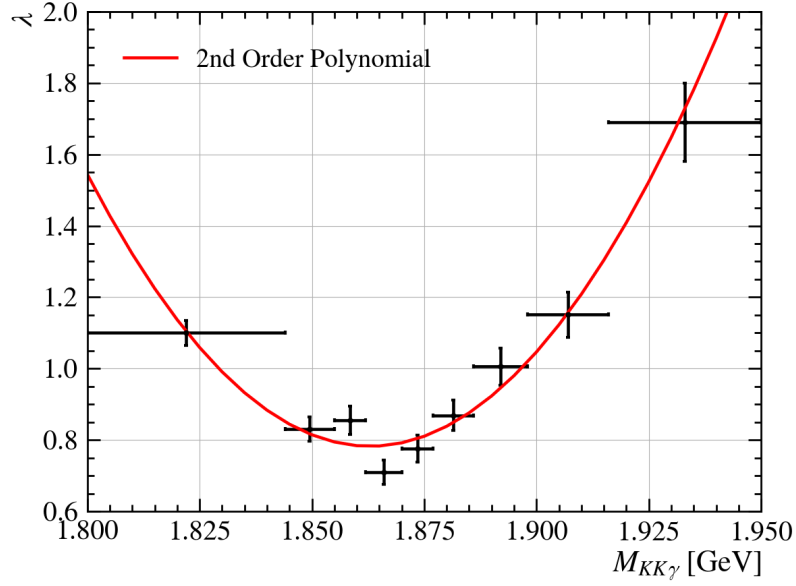


Figure 10.23: The variation of the ΔM width (parameterised by λ) as a function of the D^0 mass, showing a clear correlation for the signal MC. A second order polynomial is used to model the relationship between the scale factor λ and the reconstructed mass.

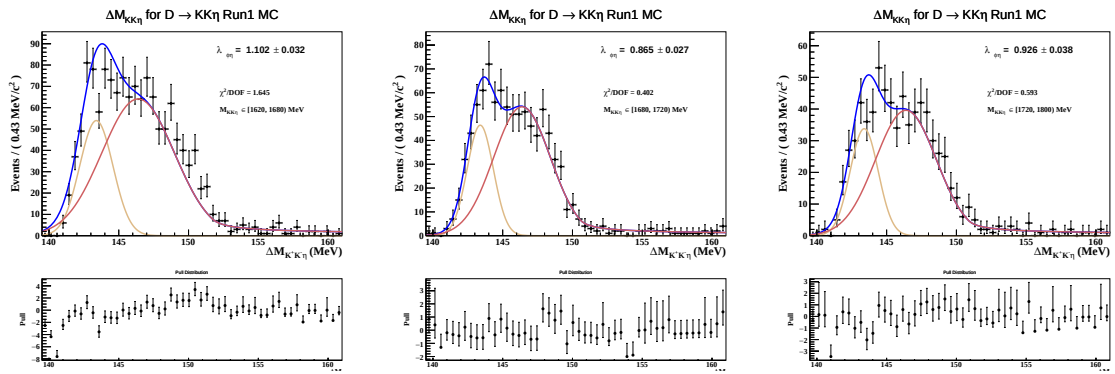


Figure 10.24: ΔM fits in mass bins where the scale factor, λ , scales the widths of the core Gaussians for the $D^0 \rightarrow \phi\eta$ simulation. The fits are performed to determine correlations between the parameters of the ΔM peak with the D^0 mass.

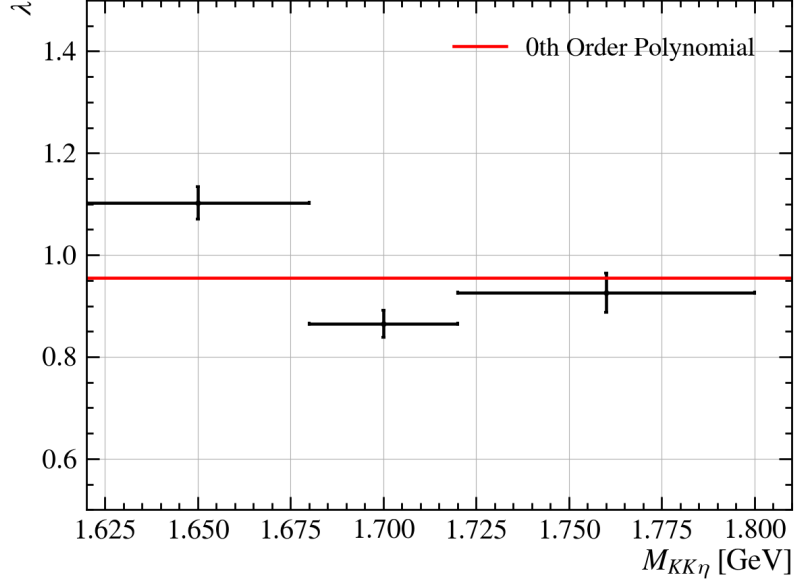


Figure 10.25: Correlation curve for the $D^0 \rightarrow \phi\eta$ MC where a flat distribution is used to model the relationship between the scale factor λ and the reconstructed mass. A flat distribution was an acceptable approximation here due to the limited data points available.

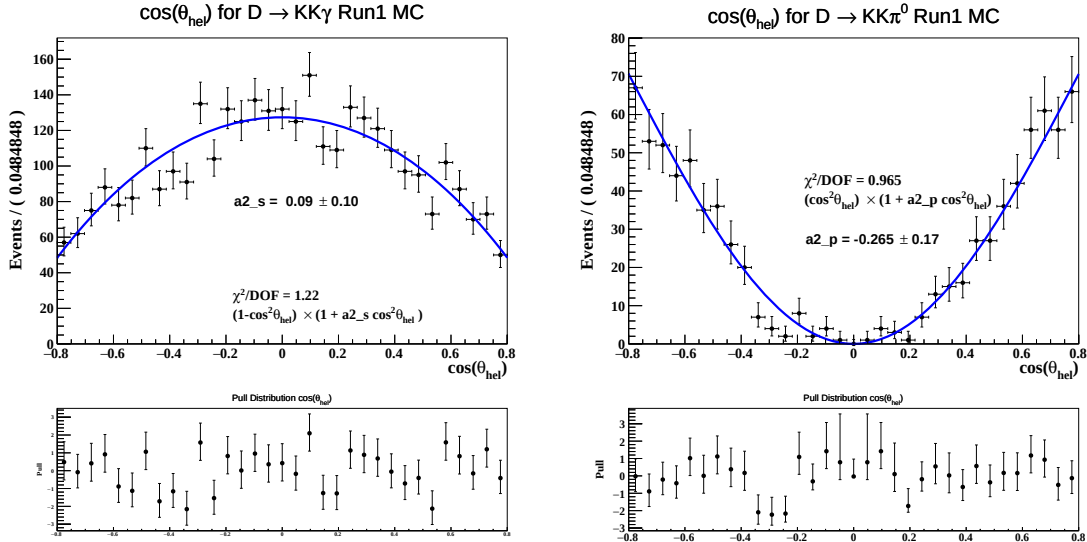


Figure 10.26: Fit to the $\cos(\theta_H)$ central region for $D^0 \rightarrow \phi\gamma$ (left) and the $D^0 \rightarrow \phi\pi^0$ (right) MC sample for the full ΔM window after applying the IsPhoton cut. The model for the fit is the theoretical parabolic shape multiplied by a quadratic acceptance function.

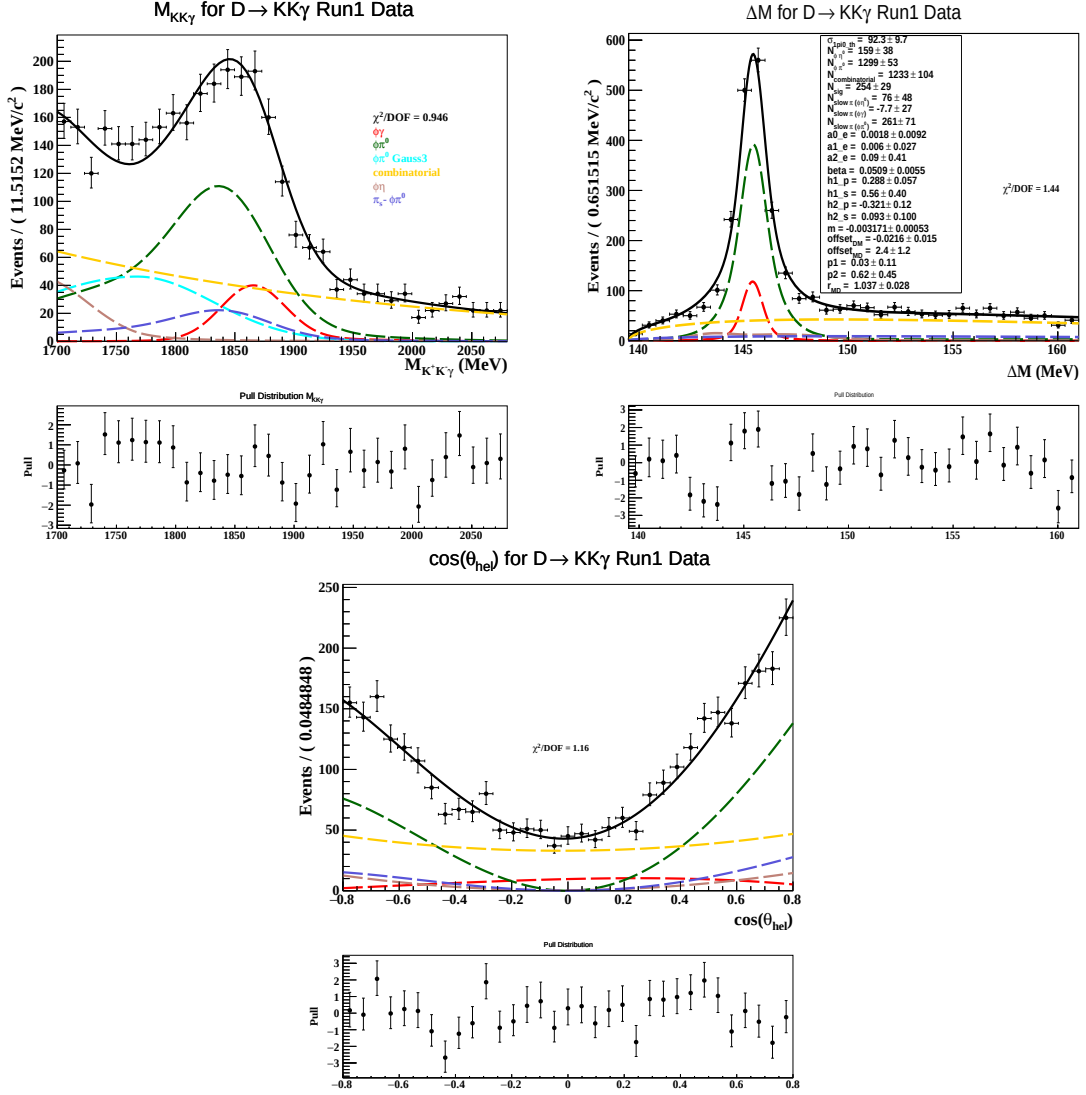


Figure 10.27: Multi-dimensional fit to mass (top-left), ΔM (top-right) and helicity (bottom) distributions for the $D^0 \rightarrow \phi\gamma$ central helicity region after applying the IsPhoton cut and including the correlations in ΔM for the signal, π^0 and η components. All free parameters of the fit are shown.

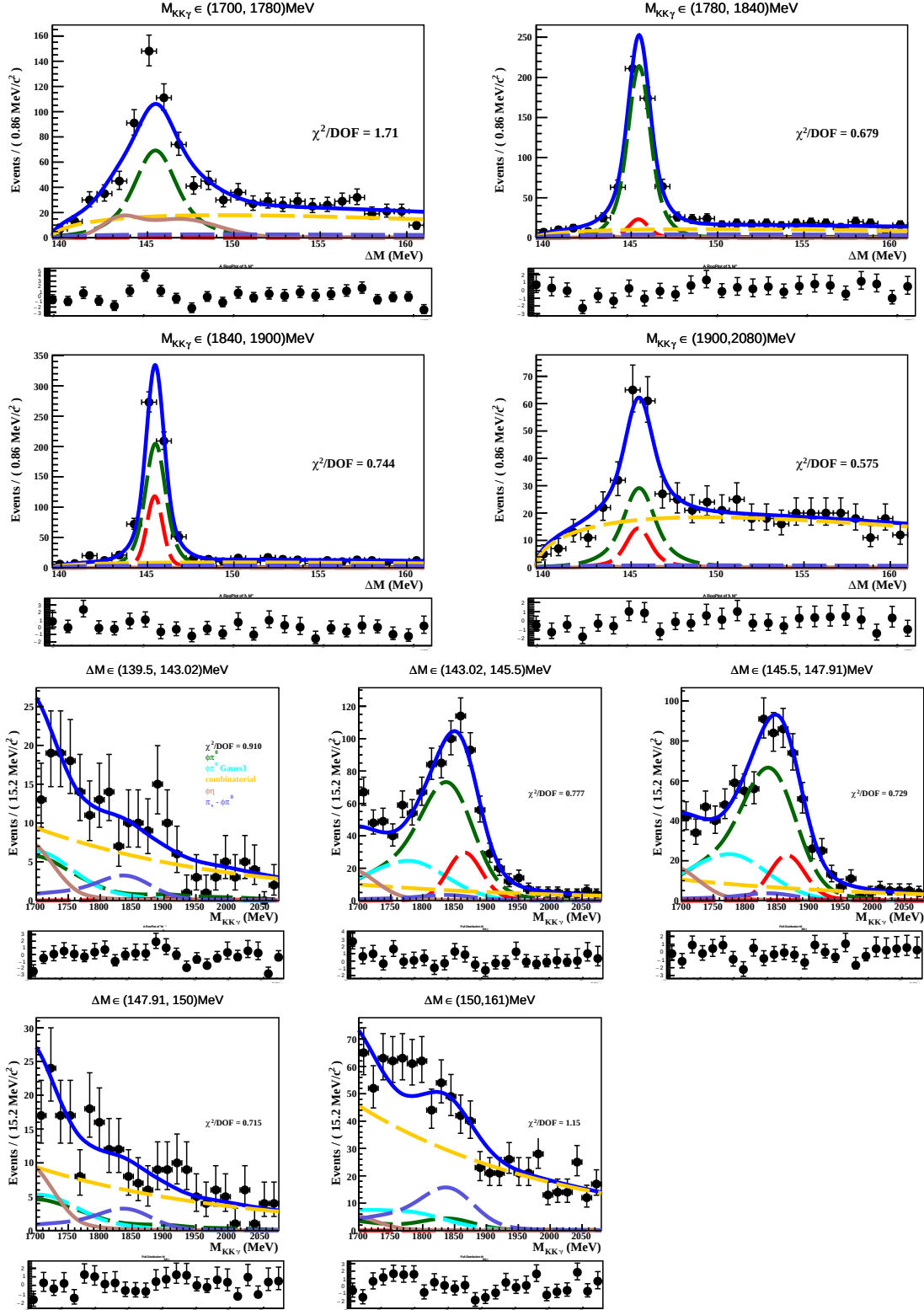


Figure 10.28: Mass projections in various ΔM bins (top-two rows) and ΔM projections in various mass bins (bottom-two rows) for the correlated fit in the central helicity region in data.

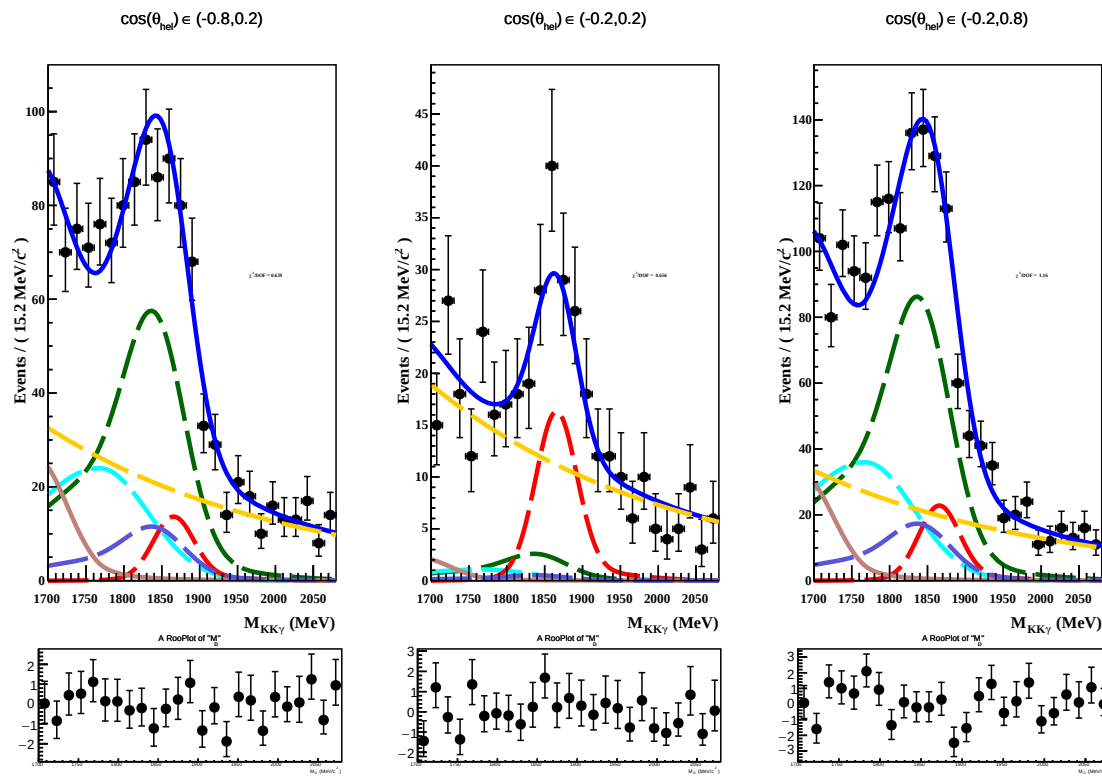


Figure 10.29: Mass projections in three helicity bins for the correlated fit in the central helicity region.

10.3 Further Improvements

Although the current parameterisation is sufficient to extract the signal yield from the multi-dimensional fit, certain improvements can still be made. Firstly, the MC fits are performed in a single dimension and correlations added once an initial multi-dimensional fit to data has been performed. A more holistic approach would entail performing a multi-dimensional fit in MC itself and adding the correlation to the MC samples. This fit is performed by integrating over the full $\cos\theta$ region to enhance yields and excluding the helicity distribution from the fit itself. The tail Gaussian from the ΔM distribution is excluded and absorbed into the combinatorial background component. The combinatorial component in both mass and ΔM is modelled by a first order Chebyshev polynomial. Ideally, the MC samples shouldn't have any combinatorial background but unphysical candidates can be present in the higher ΔM region and not modelling these events shifts the core part of distributions. To attenuate this effect, the ΔM fit is performed over a reduced range in MC ($139.5 < \Delta M < 152 \text{ MeV}/c^2$). Furthermore, the signal correlations calculated from the fits in the bins of ΔM shown in Fig. 10.22 can be applied here if the fraction and relative widths of the narrow and broad Gaussians is kept consistent. For this reason, the width of the narrow Gaussian is kept free but the relative widths between the narrow and broad Gaussian's is fixed to the model used in Fig. 10.22. All other parameters are free to float in the fit including the combinatorial parameters. Fig. 10.30 shows the multi-dimensional fit to the signal MC with correlations included. Mass (ΔM) projections in bins of ΔM (mass) are shown in Fig. 10.31.

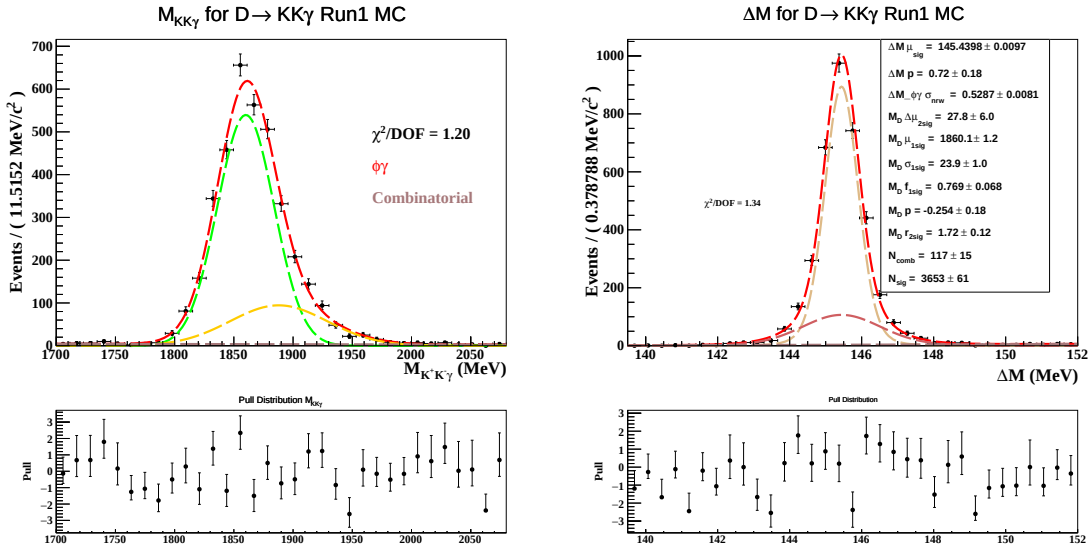


Figure 10.30: Multi-dimensional fit to mass and ΔM distributions in the signal MC with correlations included.

Similar fits can be carried out for the π^0 and η components with the correlations included. The parameters found from these fits can be used in fits to the three-dimensional data distributions with the inclusion of offsets and scale factors as before to account for data-MC differences.

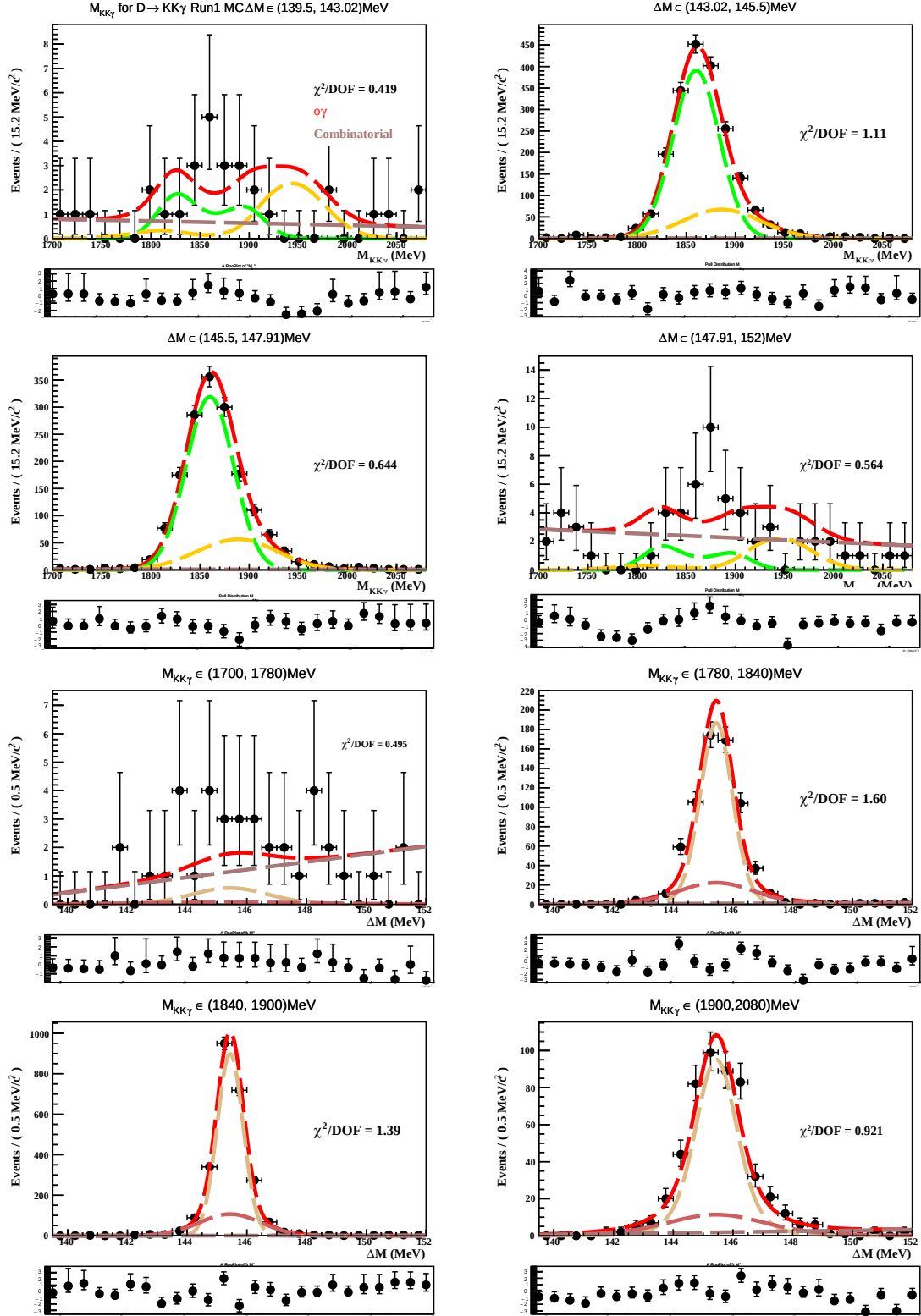


Figure 10.31: Mass projections in various ΔM bins (top-two rows) and ΔM projections in various mass bins (bottom-two rows) for the correlated fit to the signal MC sample. There is discrepancy between the fit and the data in the mass projections for the lowest and highest ΔM bins with the emergence of a double structure. The origin of the discrepancy in the fit is currently under investigation.

10.4 Future Work

With the extraction of the signal yield from a multi-dimensional fit to data, one of the components to make a CP asymmetry measurement for the $D^0 \rightarrow \phi\gamma$ channel is in place. The next step would be to divide the sample into D^0 and $\bar{D}^0$ sub-samples, and fit them simultaneously with all parameters except their yields common to the two samples. The raw asymmetry would also be one of the free parameters within the fit. This would be the input to calculate the raw asymmetry in this channel. To convert the raw asymmetry into a CP asymmetry measurement, raw asymmetries of the reference channel will have to be deducted from the raw asymmetry in the radiative channel. Work has been carried out already to determine the nuisance asymmetry inputs required to determine CP asymmetry using a reference sample ($D^0 \rightarrow h^+h^-$) where the kinematics of the reference sample are re-weighted to match the kinematics of the radiative channels.

Before making CP asymmetry and branching fraction measurements, an evaluation of systematic effects that could bias the results needs to be done. The dominant source of systematic uncertainty on the final measurement is foreseen to be the model used to describe the various components within the fit. It is possible to quantify this effect by generating many toys according to the baseline fit and fitting both the baseline and alternative models to these toys. An alternative fit model for example would account for the mass-dependence of variations in the ΔM width for the η background. The largest difference between the values of CP asymmetries and branching fractions obtained from using the baseline fit and alternative models could be assigned as the systematic uncertainty on these measurements. Another source of systematic uncertainty would include the effect of weighting the photon related distributions in the MC to match those in data as well as the reweighting of the kinematic variables in the reference channel to match those seen in the signal channels.

After the evaluation of the systematic uncertainties, the CP asymmetries and branch fractions can be measured in all the radiative channels but the signal yields from Run 1 are too small to be competitive with existing measurements from the BELLE collaboration [108]. Hence, data from Run 2 will have to be added to make a competitive measurement. As an example of how yields increased between the two operational runs at the LHC, the yields in the $D^0 \rightarrow \pi^-\pi^+\pi^0$ channel were more than four times greater in Run 2 compared to Run 1. The four fold increase in yields won't necessarily translate to the radiative channels but the evolution of exclusive trigger lines in the latter years of Run 2 for these channels should provide greater yields to make competitive measurements with perhaps the possibility of observing CP violation for the first time in these decays.

The branching fraction of the $D^0 \rightarrow \phi\gamma$ and $D^0 \rightarrow \rho\gamma$ channels can also be measured with the signal yields from these channels but also requires input from the $D^0 \rightarrow \bar{K}^{*0}\gamma$ channel. The wider resonance in the $D^0 \rightarrow \rho\gamma$ and $D^0 \rightarrow \bar{K}^{*0}\gamma$ channels makes it difficult to isolate the resonance of interest. Hence more sophisticated models in these modes will be required to extract the signal yields and work is ongoing to improve the parameterisation of data in these channels. Again, data from Run 2 will have to be added to the sample to make a competitive measurement of the branching fraction for the $D^0 \rightarrow \phi\gamma$ and $D^0 \rightarrow \rho\gamma$ channels. The greater yields from Run 2 will reduce the statistical

uncertainty on these measurements and therefore better constrain theoretical models where calculating the branching fraction of radiative decays is associated with large uncertainties.

Epilogue

In this thesis, a method to search for local CP violation in $D^0 \rightarrow \pi^- \pi^+ \pi^0$ decays is presented. The method used to search for local CP violation is known as the energy test and it produces a p -value that quantifies the consistency of the data with the null hypothesis of CP symmetry. Multi-body decays of hadrons containing the charm quark such as $D^0 \rightarrow \pi^- \pi^+ \pi^0$ decays are considered due to the many contributions from intermediate resonances which causes the strong phase to vary across the Dalitz space. This can provide additional sensitivity to CP violation. The method is shown to be insensitive to nuisance effects that can bias the final result as demonstrated on the control channel and signal toys. The energy test is applied to the $D^0 \rightarrow \pi^- \pi^+ \pi^0$ decays and yields a p -value of 0.62 which is consistent with the null hypothesis of CP symmetry. A cross-check upon unblinding the analysis showed that the nominal p -value is consistent with alternative p -value obtained from running the energy test over a sub-sample that pass the L0 hadron triggers and fail all other L0 trigger requirements in the default selection. A similar check is carried out for a sub-sample with the fiducial cuts imposed and the alternative p -value obtained is also found to be consistent with the nominal p -value.

A method to measure the CP asymmetries and branching fractions for a family radiative decays is presented in this thesis. These are radiative decays of hadrons containing a charm quark, of the form $D^0 \rightarrow V \gamma$ ($V = \phi, \rho, \bar{K}^{*}$) and can have CP asymmetries reaching up to $\mathcal{O}(10^{-1})$ in some BSM physics models. This would be indicative of undiscovered physics not accounted for in the Standard Model and makes charm radiative decays an attractive proposition when searching for new physics. Despite the difficulty in performing such measurements at a hadron collider, a proof of principle on how to extract the signal yield in the $D^0 \rightarrow \phi \gamma$ channel is provided through performing multi-dimensional fits to data recorded in the first operational run of the LHC. It is possible to make the most precise measurement of CP asymmetries and branching fraction for the family of radiative decays by including data from the second operational run at LHC and possibly observe CP violation for the first time in these decays.

Bibliography

- [1] Marian Stahl. Machine learning and parallelism in the reconstruction of lhcb and its upgrade. *Journal of Physics: Conference Series*, 898, 10 2017.
- [2] E. Fermi and C. N. Yang. Are mesons elementary particles? *Phys. Rev.*, 76:1739–1743, Dec 1949.
- [3] George Zweig. Concrete Quarks - The Beginning of the End. *EPJ Web Conf.*, 71:00146, 2014.
- [4] The hunting of the quark, michael riordan. 1987. simon and schuster, new york. 399 pages. index. isbn: 0-671-50466-5. \$21.95. *Bulletin of Science, Technology & Society*, 8(4):451–451, 1988.
- [5] J. Alcaraz et al. Search for antihelium in cosmic rays. *Physics Letters B*, 461(4):387–396, sep 1999.
- [6] M. et al Tanabashi. Review of particle physics. *Phys. Rev. D*, 98:030001, Aug 2018.
- [7] S. L. Glashow. Partial-symmetries of weak interactions. *Nuclear Physics*, 22(4):579–588, 1961.
- [8] Nicola Cabibbo. Unitary symmetry and leptonic decays. *Phys. Rev. Lett.*, 10:531–533, Jun 1963.
- [9] Murray Gell-Mann. Symmetries of baryons and mesons. *Phys. Rev.*, 125:1067–1084, Feb 1962.
- [10] Y. Ne’eman. Derivation of strong interactions from a gauge invariance. *Nuclear Physics*, 26(2):222–229, 1961.
- [11] Abdus Salam. Weak and Electromagnetic Interactions. *Conf. Proc. C*, 680519:367–377, 1968.
- [12] Steven Weinberg. A Model of Leptons. *Phys. Rev. Lett.*, 19:1264–1266, Nov 1967.
- [13] G. et al. Aad. Observation of a new particle in the search for the standard model higgs boson with the atlas detector at the lhc. *Physics Letters B*, 716(1):1–29, Sep 2012.
- [14] S. et al. Chatrchyan. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Physics Letters B*, 716(1):30–61, Sep 2012.
- [15] M. H. et al. Ahn. Measurement of neutrino oscillation by the K2K experiment. *Phys. Rev. D*, 74:072003, Oct 2006.

- [16] K. Abe, N. Abgrall, H. Aihara, T. Akiri, J. B. Albert, C. Andreopoulos, S. Aoki, A. Ariga, T. Ariga, S. Assylbekov, and et al. Evidence of electron neutrino appearance in a muon neutrino beam. *Physical Review D*, 88(3), Aug 2013.
- [17] Elementary Particle Interactions in the Standard Model. https://commons.wikimedia.org/wiki/File:Elementary_particle_interactions_in_the_Standard_Model.png. Accessed: 2022-07-22.
- [18] Standard Model. https://en.wikipedia.org/wiki/Standard_Model. Accessed: 2022-08-22.
- [19] E. Noether. Invariante variationsprobleme. *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse*, 1918:235–257, 1918.
- [20] C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson. Experimental test of parity conservation in beta decay. *Phys. Rev.*, 105:1413–1415, Feb 1957.
- [21] Richard L. Garwin, Leon M. Lederman, and Marcel Weinrich. Observations of the failure of conservation of parity and charge conjugation in meson decays: the magnetic moment of the free muon. *Phys. Rev.*, 105:1415–1417, Feb 1957.
- [22] Andrei D Sakharov. Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe. *Soviet Physics Uspekhi*, 34(5):392, 1991.
- [23] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay. Evidence for the 2π Decay of the K_2^0 Meson. *Phys. Rev. Lett.*, 13:138–140, Jul 1964.
- [24] K. et al. Abe. Observation of Large CP Violation in the Neutral B Meson System. *Phys. Rev. Lett.*, 87:091802, Aug 2001.
- [25] B. et al Aubert. Observation of CP Violation in the B^0 Meson System. *Phys. Rev. Lett.*, 87:091801, Aug 2001.
- [26] R. Aaij et al. (LHCb Collaboration). Measurement of CP Violation in the Phase Space of $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and $B^\pm \rightarrow K^\pm K^+ K^-$ Decays. *Phys. Rev. Lett.*, 111:101801, Sep 2013.
- [27] R. Aaij et al. Observation of CP Violation in Charm Decays. *Physical Review Letters*, 122(21), May 2019.
- [28] V. A. Kuzmin, V. A. Rubakov, and M. E. Shaposhnikov. On anomalous electroweak baryon-number non-conservation in the early universe. *Physics Letters B*, 155:36–42, May 1985.
- [29] Francis Muller, Robert W. Birge, William B. Fowler, Robert H. Good, Warner Hirsch, Robert P. Matsen, Larry Oswald, Wilson M. Powell, Howard S. White, and Oreste Piccioni. Regeneration and Mass Difference of Neutral K Mesons. *Phys. Rev. Lett.*, 4:418–421, Apr 1960.
- [30] H. Albrecht et al. Observation of B0-B0 mixing. *Physics Letters B*, 192(1):245–252, 1987.

- [31] S. L. Glashow, J. Iliopoulos, and L. Maiani. Weak Interactions with Lepton-Hadron Symmetry. *Phys. Rev. D*, 2:1285–1292, Oct 1970.
- [32] R. Aaij et al. Observation of $D^0 - \bar{D}^0$ Oscillations. *Physical Review Letters*, 110(10), March 2013.
- [33] Y. Amhis et al. Averages of B-Hadron, C-Hadron, and tau-lepton properties as of early 2012. 7 2012.
- [34] Yuval Grossman, Alexander L. Kagan, and Yosef Nir. New physics and CP violation in singly Cabibbo suppressed D decays. *Phys. Rev. D*, 75:036008, Feb 2007.
- [35] Damir Bečirević, Ilja Doršner, Svjetlana Fajfer, Darius A. Faroughy, Florentin Jaffredo, Nejc Košnik, and Olcyr Sumensari. On a model with two scalar leptoquarks $-R_2$ and S_3 . 6 2022.
- [36] Margarita Gavrilova, Yuval Grossman, and Stefan Schacht. The Mathematical Structure of U -Spin Amplitude Sum Rules. 5 2022.
- [37] Alexander Lenz and Guy Wilkinson. Mixing and cp violation in the charm system. *Annual Review of Nuclear and Particle Science*, 71(1), Apr 2021.
- [38] Measurement of the time-integrated CP asymmetry in $D^0 \rightarrow K^- K^+$ decays. Technical report, CERN, Geneva, 2022. All figures and tables, along with any supplementary material and additional information, are available at <https://cern.ch/lhcbproject/Publications/p/LHCb-PAPER-2022-024.html> (LHCb public pages).
- [39] Stefan de Boer and Gudrun Hiller. Rare radiative charm decays within the standard model and beyond. *JHEP*, 08:091, 2017.
- [40] S. Fajfer, Sasa Prelovsek, and P. Singer. Long distance contributions in $D \rightarrow V$ gamma decays. *Eur. Phys. J.*, C6:471–476, 1999.
- [41] The ATLAS Collaboration. The ATLAS experiment at the CERN large hadron collider. *Journal of Instrumentation*, 3(08):S08003–S08003, aug 2008.
- [42] The CMS Collaboration. The CMS experiment at the CERN LHC. *Journal of Instrumentation*, 3(08):S08004–S08004, aug 2008.
- [43] The ALICE Collaboration. The ALICE experiment at the CERN LHC. *Journal of Instrumentation*, 3(08):S08002–S08002, aug 2008.
- [44] The LHCb Collaboration. The LHCb detector at the LHC. *Journal of Instrumentation*, 3(08):S08005–S08005, aug 2008.
- [45] Roland Garoby. Upgrade issues for the cern accelerator complex. 09 2022.
- [46] CERN, “LHC report: record luminosity, well done LHC. <https://home.cern/news/news/accelerators/lhc-report-record-luminosity-well-done-lhc>. Accessed: 2022-08-01.

- [47] D Jacquet and F Follin. Implementation and experience with luminosity levelling with offset beam, 2014.
- [48] LHCb-Facts. <https://twiki.cern.ch/twiki/bin/view/Main/LHCb-Facts>. Accessed: 2022-08-01.
- [49] A Augusto et al. The LHCb detector at the LHC. *Journal of instrumentation*, 3(08):S08005, 2008.
- [50] Roel Aaij et al. Measurement of the $B_s^0 \rightarrow \mu^+ \mu^-$ decay properties and search for the $B^0 \rightarrow \mu^+ \mu^-$ and $B_s^0 \rightarrow \mu^+ \mu^- \gamma$ decays. *Phys. Rev. D*, 105(1):012010, 2022.
- [51] LHCb Collaboration, "LHCb discovers three new exotic particles". <https://home.cern/news/news/physics/lhcb-discovers-three-new-exotic-particles>. Accessed: 2022-09-04.
- [52] Roel Aaij et al. Test of lepton universality in beauty-quark decays. *Nature Phys.*, 18(3):277–282, 2022.
- [53] Angelo Di Canto, Laurent Dufour, Surapat Ek-In, Kamil Leszek Fischer, Martha Hilton, Nathan Philip Jurik, Maurizio Martinelli, Tara Nanut, Sascha Stahl, and Mark Richard James Williams. Run 2 analysis of prompt $D \rightarrow K_S^0 \pi^+ \pi^-$ decays with the bin-flip method. Mar 2020.
- [54] Roel Aaij et al. Updated measurement of time-dependent CP-violating observables in $B_s^0 \rightarrow J/\psi K^+ K^-$ decays. *Eur. Phys. J. C*, 79(8):706, 2019. [Erratum: Eur.Phys.J.C 80, 601 (2020)].
- [55] R Aaij et al. LHCb Detector Performance. *Int. J. Mod. Phys.*, A30(07):1530022, 2015.
- [56] R. Aaij et al. Performance of the LHCb Vertex Locator. *JINST*, 9:P09007, 2014.
- [57] G.A. Cowan. Performance of the lhcb silicon tracker. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 699:156–159, 2013. Proceedings of the 8th International â Hiroshimaâ Symposium on the Development and Application of Semiconductor Tracking Detectors.
- [58] Barbosa-Marinho et al. *LHCb outer tracker: Technical Design Report*. Technical design report. LHCb. CERN, Geneva, 2001.
- [59] S. et al Amato. *LHCb magnet: Technical Design Report*. Technical design report. LHCb. CERN, Geneva, 2000.
- [60] Marcello et al Losasso. Tests and Field Map of LHCb Dipole Magnet. Technical report, CERN, Geneva, Sep 2005.
- [61] The LHCb collaboration. Measurement of the track reconstruction efficiency at LHCb. *Journal of Instrumentation*, 10(02):P02007–P02007, feb 2015.

- [62] R. Frühwirth. Application of kalman filtering to track and vertex fitting. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 262(2):444–450, 1987.
- [63] Michel De Cian, Stephen Farry, Paul Seyfert, and Sascha Stahl. Fast neural-net based fake track rejection in the LHCb reconstruction. Technical report, CERN, Geneva, Mar 2017.
- [64] M Adinolfi et al. Performance of the LHCb RICH detector at the LHC. *Eur. Phys. J. C*, 73:2431. 25 p, 2013.
- [65] N. H. Brook et al. LHCb RICH 1 engineering design review report. 8 2004.
- [66] Cinthia Ambrosio, F. Metlica, A Papanestis, Mario Sannino, Paul Soler, Olav Ullaland, D Websdale, S Wotton, and K Wyllie. Lhcb note: Lhcb the lhcb rich detector control system requirements for monitoring and control of the rich detectors. 08 2022.
- [67] Yu. Guz. The LHCb calorimeter system: design, performance and upgrade. *Journal of Instrumentation*, 12(07):C07024–C07024, jul 2017.
- [68] P Perret and X Vilasis-Cardona. Performance of the LHCb calorimeters during the period 2010-2012. *J. Phys.: Conf. Ser.*, 587:012012. 6 p, Aug 2014. see LHCb-TALK-2014-236.
- [69] I. Belyaev, G. Carboni, N. Harnew, C. Matteuzzi, and F. Teubert. The history of LHCb. *The European Physical Journal H*, 46(1), mar 2021.
- [70] B Botchine, A Kashchuk, V A Lazarev, N Sagidova, A P Vorobev, and A Vorobyov. Wire pad chamber for LHCb muon system. Technical report, CERN, Geneva, Mar 2000.
- [71] G Bencivenni, G Felici, F Murtas, P Valente, W Bonivento, A Cardini, A Lai, D Pinci, B Saitta, and C Bosio. A triple-GEM detector with pad readout for the inner region of the first LHCb muon station. Technical report, CERN, Geneva, Jul 2001.
- [72] Pietro Albicocco, Wander Baldini, Samuel Belin, Valerio Bocci, Nikolay Bondar, Davide Brundu, Sandro Cadeddu, Alessandro Cardini, Maurizio Carletti, G. Chiodi, Alexsei Chubykin, Vladimir Chulikov, Paolo Ciambrone, Liliana Congedo, Andrea Contu, Francesco Debernardis, Marco Desideri, Marilisa Serio, Patrizia Simone, and Stefania Vecchi. A method based on muon system to monitor lhcb luminosity. *Symmetry*, 14:860, 04 2022.
- [73] Christian Lippmann. Particle identification. *Nucl. Instrum. Meth. A*, 666:148–172, 2012.
- [74] R. Aaij et al. Design and performance of the LHCb trigger and full real-time reconstruction in run 2 of the LHC. *Journal of Instrumentation*, 14(04):P04013–P04013, apr 2019.
- [75] Barbara Sciascia. LHCb Run 2 Trigger Performance. *PoS, BEAUTY2016:029*. 7, May 2016.
- [76] P Mato. GAUDI-Architecture design document. Technical report, CERN, Geneva, Nov 1998.

- [77] Antunes-Nobrega et al. *LHCb computing: Technical Design Report*. Technical design report. LHCb. CERN, Geneva, 2005. Submitted on 11 May 2005.
- [78] LHCb Collaboration, "The MOORE Project". <https://lhcbdoc.web.cern.ch/lhcbdoc/moore/>. Accessed: 2022-07-22.
- [79] LHCb Collaboration, "The BRUNEL Project". <https://lhcbdoc.web.cern.ch/lhcbdoc/brunel/>. Accessed: 2022-07-23.
- [80] LHCb Collaboration, "The DAVINCI Project". <https://lhcbdoc.web.cern.ch/lhcbdoc/davinci/>. Accessed: 2022-07-26.
- [81] R. Brun and F. Rademakers. ROOT: An object oriented data analysis framework. *Nucl. Instrum. Meth. A*, 389:81–86, 1997.
- [82] M Clemencic, G Corti, S Easo, C R Jones, S Miglioranza, M Pappagallo, and P Robbe and. The LHCb simulation application, gauss: Design, evolution and experience. *Journal of Physics: Conference Series*, 331(3):032023, dec 2011.
- [83] Torbjörn Sjöstrand, Stephen Mrenna, and Peter Skands. PYTHIA 6.4 physics and manual. *Journal of High Energy Physics*, 2006(05):026–026, may 2006.
- [84] D. J. Lange. The EvtGen particle decay simulation package. *Nucl. Instrum. Meth. A*, 462:152–155, 2001.
- [85] P. Golonka and Z. Was. PHOTOS monte carlo: a precision tool for QED corrections in z and w decays. *The European Physical Journal C*, 45(1):97–107, jan 2006.
- [86] Sea Agostinelli, John Allison, K al Amako, John Apostolakis, H Araujo, Pedro Arce, Makoto Asai, D Axen, Swagato Banerjee, GJN Barrand, et al. Geant4—a simulation toolkit. *Nuclear instruments and methods in physics research section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 506(3):250–303, 2003.
- [87] LHCb Collaboration, "The BOOLE Project". <https://lhcbdoc.web.cern.ch/lhcbdoc/boole/>. Accessed: 2022-08-04.
- [88] C. Burr, "The LHCb Starterkit". <https://lhcb.github.io/starterkit-lessons/first-analysis-steps/dataflow.html>. Accessed: 2022-08-04.
- [89] P.A. Zyla et al. Review of Particle Physics. *PTEP*, 2020(8):083C01, 2020.
- [90] Roel Aaij et al. Measurements of CP violation in the three-body phase space of charmless $B^\pm$ decays. *Phys. Rev. D*, 90(11):112004, 2014.
- [91] I. Bediaga, I. I. Bigi, A. Gomes, G. Guerrer, J. Miranda, and A. C. dos Reis. On a CP anisotropy measurement in the Dalitz plot. *Phys. Rev. D*, 80:096006, Nov 2009.

- [92] Roel Aaij et al. Search for CP violation in $\Xi_c^+ \rightarrow pK^-\pi^+$ decays using model-independent techniques. *Eur. Phys. J. C*, 80(10):986, 2020.
- [93] Chris Parkes, Shanzhen Chen, Jolanta Brodzicka, Marco Gersabeck, Giulio Dujany, and William Barter. On model-independent searches for direct CP violation in multi-body decays. *Journal of Physics G: Nuclear and Particle Physics*, 44(8):085001, 2017.
- [94] C. Parkes, S. Chen, J. Brodzicka, M. Gersabeck, G. Dujany, and W. Barter. On model-independent searches for direct CP violation in multi-body decays. *Journal of Physics G Nuclear Physics*, 44(8):085001, August 2017.
- [95] Mike Williams. Observing CP Violation in Many-Body Decays. *Phys. Rev.*, D84:054015, 2011.
- [96] W. Barter, C. Burr, and C. Parkes. Calculating p -values and their significances with the Energy Test for large datasets. *JINST*, 13(04):P04011, 2018.
- [97] R. Aaij et al. Search for CP violation in $D^0 \rightarrow \pi^+\pi^-\pi^0$ decays with the energy test. *Physics Letters B*, 740:158–167, 2015.
- [98] Bernard Aubert et al. Search for CP Violation in Neutral D Meson Cabibbo-suppressed Three-body Decays. *Phys. Rev. D*, 78:051102, 2008.
- [99] Daniel Berrar. Cross-validation. In *Encyclopedia of Bioinformatics and Computational Biology*, volume 1, pages 542–545. Elsevier, 2018.
- [100] Muriel Pivk and Francois R. Le Diberder. SPlot: A Statistical tool to unfold data distributions. *Nucl. Instrum. Meth. A*, 555:356–369, 2005.
- [101] Andreas Hocker et al. TMVA - Toolkit for Multivariate Data Analysis with ROOT: Users guide. TMVA - Toolkit for Multivariate Data Analysis. Technical report, CERN, Geneva, 2007. TMVA-v4 Users Guide: 135 pages, 19 figures, numerous code examples and references.
- [102] Andreas Hocker et al. TMVA - Toolkit for Multivariate Data Analysis. 3 2007.
- [103] John Back et al. LAURA⁺⁺: A Dalitz plot fitter. *Comput. Phys. Commun.*, 231:198–242, 2018.
- [104] B. Aubert, M. Bona, D. Boutigny, Y. Karyotakis, J. P. Lees, V. Poireau, X. Prudent, V. Tisserand, A. Zghiche, E. Grauges, and et al. Measurement of CP Violation Parameters with a Dalitz Plot Analysis of $B^\pm \rightarrow D\pi^+\pi^-\pi^0K^\pm$. *Physical Review Letters*, 99(25), Dec 2007.
- [105] Alex Rogozhnikov. Reweighting with Boosted Decision Trees. *Journal of Physics: Conference Series*, 762:012036, Oct 2016.
- [106] Stefan de Boer and Gudrun Hiller. Rare radiative charm decays within the standard model and beyond. *JHEP*, 08:091, 2017.

- [107] Miriam Calvo Gomez, Eric Cogneras, Olivier Deschamps, Mostafa Hoballah, Regis Lefevre, Stephane Monteil, Albert Puig Navarro, and Vicente Jose Rives Molina. A tool for γ/π^0 separation at high energies. Technical report, CERN, Geneva, Aug 2015.
- [108] A. Abdesselam et al. Observation of $D^0 \rightarrow \rho^0 \gamma$ and search for CP violation in radiative charm decays. *Phys. Rev. Lett.*, 118(5):051801, 2017.
- [109] Vladimir V Gligorov. A single track HLT1 trigger. Technical report, CERN, Geneva, Jan 2011.
- [110] G. A. Cowan, D. C. Craik, and M. D. Needham. RapidSim: an application for the fast simulation of heavy-quark hadron decays. *Comput. Phys. Commun.*, 214:239–246, 2017.