



Correction of simulation samples and studying effects of new physics on semileptonically-tagged $\Lambda_c \rightarrow pK\pi$ decays.

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Abstract

The report outlines the methods by which the model for the $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$ decay within the simulation of $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu_\mu^+$ at the LHCb experiment was corrected, where the simulation was generated using the data taking conditions for the year 2016. An incorrect model for this decay could impact both the efficiency of the signal selection as a function of the phase space as well as the distributions of the variables used in the extraction of the signal yield. The impact that the corrected $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$ model has on signal selection efficiency and the templates used in the extraction of signal yield is also discussed. Furthermore, the effect of new physics in the $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu_\mu^+$ decay on the phase space variables of $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$ decays is presented.

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1 Introduction and Motivation

This report focuses on studies of the $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu_\mu^+$ decay at the LHCb experiment at CERN. The analysis involved correcting the simulation sample for this decay as it was produced with an incorrect model for the $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$ decay. The use of the wrong model for this process within the decay could affect the efficiency of the signal selection as a function of the phase space as well as the distributions of the variables used in the extraction of the signal yield. The motivation for this study was to aid in the ongoing research in searches for New Physics (NP) beyond the Standard Model (BSM), including searches for additional currents in the weak decay process and lepton flavour universality violation.

While the SM is a very successful theory, there remains many observations that it does not explain. For example, the apparent asymmetry between matter and anti-matter in the universe, what is dark matter and how should general relativity be incorporated into the SM [1]. There have also been measurements hinting for lepton flavour universality violation [2]. This motivates the search for physics beyond the Standard Model. This decay process is useful for probing NP for a number of reasons. For example, compared to the b-meson decays, the studies of b-baryon decays provide complimentary information with regard to NP due to the different spin structures. Furthermore, large quantities of Λ_b baryons are produced in proton-proton collisions at the LHCb and the $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu_\mu^+$ decay has a large Branching Fraction (BF) compared to its mesonic counterpart ($B^+ \rightarrow \bar{D}^0 \mu^+ \nu_\mu$), therefore, the analysis can be optimised to study these decays [3].

The analysis for this semileptonic decay has been conducted using data from the 2016 sample from the LHC, however the simulation samples used to model the signal selection efficiency and the template distribution of certain variables (such as the corrected mass) have been generated with a preliminary model that required updating to a model that is obtained from investigating data. This report will discuss the new physics in the $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu_\mu^+$ decay as well as the modelling of the $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$ decay. We also go on to show how the corrected $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$ model affects the signal selection efficiency as well as the templates used in the extraction of signal yield. The report also presents the impact of new physics in the $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu_\mu^+$ decay on the phase space variables of $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$ decays [4].

2 Background

2.1 The Standard Model

The Standard Model of Particle Physics (SM) is a quantum field theory (QFT) that describes the fundamental particles of nature and the mechanisms by which they interact. It is a non-Abelian gauge theory governed by the gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$. The gauge group $SU(3)_C$ describes the symmetries of the theory of quantum chromodynamics (QCD) while the group $SU(2)_L \otimes U(1)_Y$ describes the symmetries of the unified electroweak theory (EW) [1, 5]. The elementary particles in the SM include the spin-1/2 particles called fermions and integer spin particles which act as force-carriers, for example, the spin-1 particles known as gauge bosons. These include gluons, photons, $W^\pm$ and Z bosons that are mediators of the three fundamental forces: strong, electromagnetic and weak respectively. There is a further neutral spin-0 scalar particle called the Higgs boson that is the force-carrier of the Higgs field. It is through the interaction with the Higgs field that these fundamental particles acquire their mass [6].

The weak interaction, specifically the charged-current weak interaction, differs from the strong and electromagnetic interactions in a number of ways, namely flavour and parity are not conserved in weak decays. The parity operator inverts the spatial components of a wavefunction. Fermionic particles have positive intrinsic parity whereas antiparticles and vector bosons have negative parity. Different quantities behave differently under parity transformation, for example, scalar quantities and axial vectors (formed via the cross product of two vectors) are invariant whilst vectors and pseudoscalars (formed via the scalar product of a vector and an axial vector) will change sign under parity transformation. An example of a pseudoscalar is helicity, h [6]. It is defined as the projection of the spin vector, $\vec{J}$, onto the 3-momentum vector of a particle, $\vec{p}$ [5]:

$$h = \frac{\vec{J} \cdot \vec{p}}{|\vec{p}| |\vec{J}|} \quad (1)$$

While the matrix element for QED and QCD interaction vertices (for a simple interaction involving only two vertices e.g. electron-quark scattering) can be written in terms of the scalar product of 4-vector currents of the form:

$$M \propto j_1 \cdot j_2 \quad (2)$$

$$j^\mu = \bar{u}(p') \gamma^\mu u(p) \quad (3)$$

where 1, 2 represent the two vertices in the Feynman diagram, p and p' represent the 4-momenta of the initial and final state particles in the decay, $u(p)$ is the Dirac spinor of the particle and γ^μ represents the Dirac γ matrices [6, 7]. These vector currents change sign under parity transformation and as such the matrix element is invariant under parity transformation. Since parity is not conserved in weak interaction processes the currents that arise due to the exchange of a $W^\pm$ boson take different forms:

$$j^\mu = \bar{u}(p') \Gamma^\mu u(p) \quad (4)$$

where Γ is a 4×4 matrix which can be constructed from the following combinations of the Dirac- γ matrices:

- Scalar: $\bar{\psi} \phi$
- Vector: $\bar{\psi} \gamma^\mu \phi$
- Pseudoscalar: $\bar{\psi} \gamma^5 \phi$
- Axial Vector: $\bar{\psi} \gamma^\mu \gamma^5 \phi$
- Tensor: $\bar{\psi} (\gamma^\mu \gamma^\nu - \gamma^\nu \gamma^\mu) \phi$

where $\bar{\psi}$ and ϕ represent the Dirac spinors. Within the SM, parity violation in the weak interaction enters through a combination of a vector minus an axial vector current (V-A) [6].

If NP terms are being investigated in these weak currents, they appear as quantum operators in the Hamiltonian or Lagrangian describing the decay process. The coefficients of these operators are called the Wilson Coefficients which can be measured to determine if NP is valid. This has been investigated in many papers, for example in [4], [8] .

2.2 The LHCb Experiment

The LHCb is a forward arm spectrometer designed to search for NP in Charge Parity violation (CPV) and decay processes involving beauty and charm hadrons. It covers an angular range of about 10mrad to 250-300mrad and consists of a variety of detector systems. The first detector is a vertex locator system called VELO which takes measurements of the coordinates of the particle's track near to the point of interaction such that the secondary vertices of the decay process can be measured. This allows for identification of beauty and charm hadronic decays. This is followed by a Ring Imaging Cherenkov detector (RICH1), a silicon microstrip Trigger Tracker (TT) and a spectrometer magnet. There are then a further three tracking detectors, another Ring Imaging Cherenkov detector (RICH2) along with a series of muon chambers with a calorimeter system (SPD/PS, ECAL, HCAL) located between M1 and M2. The combination of the two RICH detectors and the muon and calorimeter systems are very effective at identifying the charged particles: electron (e), muon (μ), pion (π), kaon (K) and proton (p) [9].

The precision of the p , K and π detection in the LHCb allows for the vertex of the $\Lambda_c \rightarrow p^+ K^- \pi^+$ decay being studied, to be fully reconstructed. Therefore, this decay process is very useful for studying the angular distributions that will be discussed in this report.

3 Methods

3.1 New Physics and the $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu_\mu^+$ Decay

In order to investigate NP models for this decay process, the effective Lagrangian for the process was extended to include currents not included in the SM. An effective Lagrangian for a four-fermion interaction such as in this semi-leptonic decay can be written as follows:

$$\mathcal{L} = \frac{4G_F}{\sqrt{2}} V_{cb} [(1 + C_{V_L}) \mathcal{O}_{C_{V_L}} + C_{V_R} \mathcal{O}_{C_{V_R}} + C_{S_L} \mathcal{O}_{C_{S_L}} + C_{S_R} \mathcal{O}_{C_{S_R}} + C_{T_L} \mathcal{O}_{C_{T_L}}] \quad (5)$$

where G_F is the Fermi constant, V_{cb} is the CKM matrix element, C_{V_L} , C_{V_R} , C_{S_L} , C_{S_R} and C_{T_L} are the Wilson coefficients. The operators are given by:

- Vector left-handed: $\mathcal{O}_{C_{V_L}} = \bar{c}_L \gamma^\mu b_L \bar{\ell}_L \gamma_\mu \nu_L$
- Vector right-handed: $\mathcal{O}_{C_{V_R}} = \bar{c}_R \gamma^\mu b_R \bar{\ell}_L \gamma_\mu \nu_L$
- Scalar left-handed: $\mathcal{O}_{C_{S_L}} = \bar{c}_R b_L \bar{\ell}_R \nu_L$
- Scalar right-handed: $\mathcal{O}_{C_{S_R}} = \bar{c}_L b_R \bar{\ell}_R \nu_L$
- Tensor left-handed: $\mathcal{O}_{C_{T_L}} = \bar{c}_R \sigma^{\mu\nu} b_L \bar{\ell}_R \sigma_{\mu\nu} \nu_L$

where the vector left-handed current vanishes during renormalisation. If any of the Wilson coefficients listed above are relatively large and non-zero then this would provide evidence for NP. In this decay the lepton flavour is that of the μ (or τ), $\ell = \mu$ (or τ).

The New Physics effects can be observed through the angular variables of the defined phase space. This Λ_b^0 decay can be parameterised in terms of the variables q^2 and $\cos(\theta_\mu)$ defined as:

$$q^2 = (P_{\Lambda_b^0} - P_{\Lambda_c})^2 \quad (6)$$

where P is the four-momentum and $\cos(\theta_\mu)$ is the angle between the three-momentum of μ and Λ_b^0 in the rest frame of the W^* boson [3, 4].

The probability density function for this model is defined as:

$$PDF(\vec{x}_R; \vec{\theta}) = \frac{1}{N} \times \int R(\vec{x}_R, \vec{x}_T) \epsilon(\vec{x}_T) f(\vec{x}_T; \vec{\theta}) d\vec{x}_T \quad (7)$$

where N is a normalisation factor, $\vec{x}_R = (q_R^2, \cos(\theta_\mu)_R)$ and $\vec{x}_T = (q_T^2, \cos(\theta_\mu)_T)$ are the reconstructed (R) and true (T) phase space observables. $\vec{\theta}$ represents the form factors and Wilson Coefficients (WCs) which are to be determined in the fit. $R(\vec{x}_R, \vec{x}_T)$ is the resolution function, it contains the probability that a reconstructed observable will migrate to a true observable. $f(\vec{x}_T; \vec{\theta})$ represents the dynamics of the model. Finally, the efficiency: $\epsilon(\vec{x}_T)$ represents the probability that a signal sample would pass the selection cuts as a function of the phase space variables. This equation reduces to the following for the binned fit, where i and j represent the bins of the reconstructed and true variables:

$$PDF(\vec{x}_R^i; \vec{\theta}) = \frac{1}{N} \times \sum_{ij} R(\vec{x}_R^i, \vec{x}_T^j) \epsilon(\vec{x}_T^j) F(\vec{x}_T^j; \vec{\theta}) \quad (8)$$

here $F(\vec{x}_T^j; \vec{\theta})$ is the integral of $f(\vec{x}_T; \vec{\theta})$ in the j^{th} bin of the true variable. It is through the efficiency term that the $\Lambda_c \rightarrow p^+ K^- \pi^+$ decay correction was implemented [4].

In the ongoing research conducted by A. Mathad et al. [4], the Wilson coefficients present in equation (5) are being determined from the fit to the corrected mass for the Λ_b^0 decay in bins of q^2 and $\cos(\theta_\mu)$ taking into account the efficiency and resolution effects. Where the corrected mass, M_{corr} , is defined as:

$$M_{corr} = \sqrt{m^2(\Lambda_c \mu) + p_\perp^2(\Lambda_c \mu) + p_\perp(\Lambda_c \mu)} \quad (9)$$

where $m^2(\Lambda_c \mu)$ represents the invariant mass of $\Lambda_c \mu$ and $p_\perp$ represents the magnitude of the perpendicular three momentum. This research is not sensitive to the absolute value of the efficiency but rather the shape of the efficiency distribution across the phase space. Therefore, the following analysis focused on the variation of the efficiency when the $\Lambda_c^+ \rightarrow p K^- \pi^+$ model was updated.

3.2 The $\Lambda_c^+ \rightarrow p K^- \pi^+$ decay

The analysis involved first reproducing the $\Lambda_c^+ \rightarrow p K^- \pi^+$ model used in the generation of the $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu_\mu$ simulation sample. This included the pure phase space decays and the decay channels: $K^* \rightarrow K^- \pi^+$, $\Delta^{++} \rightarrow p \pi^+$ and $\Lambda^* \rightarrow p K^-$ for the resonances $K^*(892)$, $\Lambda^*(1520)$ and $\Delta^{++}(1232)$. A data driven model of the $\Lambda_c^+ \rightarrow p K^- \pi^+$ decay was then built using the preliminary results from the ongoing amplitude analysis of semileptonically tagged Λ_c^+ decays. The model included the same decay channels used in the simulation sample, however, it included the following resonances: $K^*(892)$, $K_0^*(700)$, $K_0^*(1430)$, $\Delta^{++}(1232)$, $\Delta^{++}(1600)$, $\Delta^{++}(1700)$, $\Lambda^*(1405)$, $\Lambda^*(1405)$, $\Lambda^*(1520)$, $\Lambda^*(1600)$, $\Lambda^*(1670)$, $\Lambda^*(1690)$, $\Lambda^*(2000)$. The simulation samples were then corrected such that the Λ_c phase space distribution followed that of the data-driven model. The effect of the correction to the simulation samples on the efficiency maps and template shapes was also investigated.

The phase space for the $\Lambda_c^+ \rightarrow pK^-\pi^+$ process is five dimensional. The variables chosen to represent this phase space varied depending on the formalism used when modelling the complex amplitude. In this study the Dalitz Plot Decomposition (DPD) formalism was investigated. The Helicity formalism was also investigated and can be found in A.1, however, the results will be presented for the DPD formalism [10].

3.2.1 DPD Formalism

The phase space variables used in this analysis were chosen to be the invariant mass of the Λ^* resonance ($m_{pK^-}^2$), the invariant mass of the K^* resonance ($m_{K\pi}^2$), $\phi_p^{[\Lambda_c]}$ and $\cos \theta_p^{[\Lambda_c]}$ which are the azimuthal angle and cosine of the polar angle representing the negative of the direction of the proton's momentum in the rest frame of Λ_c and finally $\phi_{K\pi}$ which represents the azimuthal angle between the plane containing the proton momentum and that defined by the kaon and pion momentum (ϕ_{23} in the space-fixed CM in Fig. 1) [10].

An image of the coordinate system for the phase space variables described previously is depicted below, where particle 1 is the proton, particle 2 is the kaon and particle 3 is the pion:

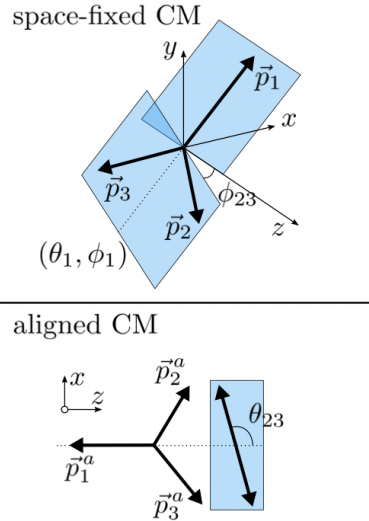


Figure 1: The figure depicts the coordinate systems used in the DPD formalism analysis. $\vec{p}$ represents the three-momentum of each of the particles 1, 2 and 3 which in turn represent the proton, kaon and pion. It was taken from the paper [10].

The transition amplitude for the $\Lambda_c \rightarrow pK^-\pi^+$ decay through DPD formalism is given by:

$$A_{\lambda_p}^{M_{\Lambda_c}} = \sum_{\nu} D_{M_{\Lambda_c}, \nu}^{J_{\Lambda_c^*}}(\phi_p^{[\Lambda_c]}, \theta_p^{[\Lambda_c]}, \phi_{(K\pi)}) O_{\lambda_p}^{\nu} \quad (10)$$

where ν represents the spin of Λ_c in the aligned CM frame and M_{Λ_c} is the orbital angular

momentum of Λ_c in the space fixed frame of reference as depicted in Fig. 1. $O_{\lambda_p}^\nu$ is given by:

$$\begin{aligned}
O_{\lambda_p}^\nu = & \sum_{\lambda_{K^*}} \sqrt{2} n_s \delta_{\nu, \lambda_{K^*} - \lambda_p} (-1)^{J_p - \lambda_p} R(m^2(K\pi)) d_{\lambda_{K^*}, 0}^{J_{K^*}}(\theta_{K\pi}) H_{\lambda_{K^*}, \lambda_p}^{J_{\Lambda_c}, J_{K^*}} \\
& + \sum_{\Delta, \lambda_p'} \sqrt{2} n_s \eta_{\lambda_p'} (-1)^{J_p - \lambda_p'} (-1)^{\nu - \lambda_\Delta} d_{\nu, \lambda_\Delta}^{1/2}(\hat{\theta}_{p(K)}) R(m^2(p\pi)) H_{\lambda_\Delta}^{J_{\Lambda_c}, J_\Delta} d_{\lambda_p', \lambda_p}^{1/2}(\zeta_{K(p)}^p) \\
& + \sum_{\Lambda^*, \lambda_p''} \sqrt{2} n_s \eta_{\lambda_p''} (-1)^{J_p - \lambda_p''} (-1)^{\nu - \lambda_{\Lambda^*}} d_{\nu, \lambda_{\Lambda^*}}^{1/2}(\hat{\theta}_{\pi(p)}) R(m^2(pK)) H_{\lambda_{\Lambda^*}}^{J_{\Lambda_c}, J_{\Lambda^*}} d_{\lambda_p'', \lambda_p}^{1/2}(\zeta_{\pi(p)}^p)
\end{aligned} \tag{11}$$

where $n_s = \sqrt{2J_i + 1}$, J_i is the intrinsic spin of the resonance and λ_i represents the helicity of particle i . The factor η_{λ_p} enforces parity conservation in the strong decay of $\Delta \rightarrow p\pi^+$ and $\Lambda^* \rightarrow pK^-$ through:

$$\eta_{\lambda_p} = \begin{cases} 1 & \text{when } \lambda_p = 1/2 \\ (-1)^{\frac{3}{2} - J_i} \eta_i & \text{when } \lambda_p = -1/2 \end{cases}$$

where η_i is the parity of the resonance i . R is the lineshape of the different resonances, it represents the invariant mass dependence of each of the resonances. For $K_0^*(700)$ and $K_0^*(1430)$ the lineshape discussed in [11] was used and the $\Lambda^*(1405)$ lineshape was taken to be the Flatté function as it peaks below the pK^- threshold [12]. All other resonances were parametrised with a relativistic Breit-Wigner function modified to include the Blatt-Weisskopf form factors as discussed in [13]. $\theta_{K\pi}$ is the polar angle of the kaon's three-momentum in the rest frame of $K\pi$ as depicted in Fig. 1 (θ_{23} in the aligned CM frame). The calculations for the angles used in this formalism can be found in the paper [10]. D and d represent the Wigner-D and Wigner-d functions. Furthermore, H represents the complex helicity couplings of which there is one for each helicity state for which angular momentum is conserved. These couplings describe the dynamics of the decay for each channel, they were altered to match with the very preliminary fit fractions of the ongoing LHCb analysis [14], [15].

The total amplitude of the decay was determined by incoherently summing the amplitude multiplied by its complex conjugate and the polarization density matrix for Λ_c , ρ , over the external quantum numbers; the helicity of the proton and the orbital angular momenta of Λ_c (M_{Λ_c} , M_{Λ_c}'):

$$d = \sum_{M_{\Lambda_c}', M_{\Lambda_c}, \lambda_p} A_{\lambda_p}^{M_{\Lambda_c}} \times A_{\lambda_p}^{*, M_{\Lambda_c}'} \times \rho_{M_{\Lambda_c}, M_{\Lambda_c}'} \tag{12}$$

3.3 The Old model and Efficiency

The simulation sample used in this analysis was obtained using the data taking conditions for the year 2016. It consisted of two samples; one in which no cuts were made on the simulation sample and one in which the simulation sample was subjected to a variety of cuts. It was known that the model used the decay channels of the pure phase space and the resonances $K^*(892)$, $\Delta^{++}(1232)$ and $\Lambda^*(1520)$, however, the exact implementation and the values of the helicity couplings used were not known. The exact form of the model was approximated by altering the equation (11).

A fit was conducted once the model had been constructed to determine these helicity couplings. The masses and widths of the resonances were floated during this fit to allow for any unknown factors that may have been included in the simulation model. This involved performing a minimization of the negative log likelihood using the MINUIT library [16]. The results from this fit can be found in A.2. Once a valid model was established for the $\Lambda_c \rightarrow pK^-\pi^+$ decay for the simulated sample, the weights were calculated to convert the 2016 simulation sample to the corrected form. These were determined by dividing the new data-driven model for the probability density function which was formed of the normalised total amplitude in equation (12) by the normalised total amplitude of the generated 2016 simulation model containing just three resonances. The probability density function (PDF) for the simulation model had to be edited to the following form in order to prevent discontinuities in the weights when the PDF approached zero:

$$pdf = N_{K^*} \times pdf_{K^*}(\vec{\Omega}) + N_{\Delta^{++}} \times pdf_{\Delta^{++}}(\vec{\Omega}) + N_{\Lambda^*} \times pdf_{\Lambda^*}(\vec{\Omega}) + N_{phsp} \times pdf_{phsp}(\vec{\Omega}) \quad (13)$$

where N_i is the fraction of the data sample that consisted of data generated from each of the decay channels specified by i and pdf_i is the normalised total amplitude of the model calculated individually for each of the resonances i ($phsp$ refers to the pure phase space which was the dominant term). $\vec{\Omega}$ represents the five phase variables. The 2016 simulated data used to determine the normalised total amplitudes for both models was first truth matched to ensure that each value corresponded to the correct decay channel and fixed to being inside the defined phase space. If either of the truth matching or phase space requirements failed then that value was assigned a weight of zero.

These weights were then used to modify the signal selection efficiency of the full decay and the differences in its distribution over the binned q^2 and $\cos(\theta_\mu)$ observed. The efficiency is a two-dimensional variable that was calculated by dividing the binned $(q^2, \cos(\theta_\mu))$ values for the simulation sample that had undergone selection cuts by that which had not.

4 Results

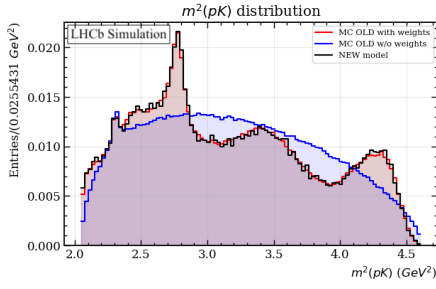
The following results depict the overall effectiveness of the weights in correcting the 2016 simulation sample to the new model for the $\Lambda_c \rightarrow pK^-\pi^+$ decay for the sample that was subjected to selection cuts and that which was not. The signal selection efficiency distribution, calculated using these two data samples, is also presented for the weighted and un-weighted samples. The effects of NP on the Λ_c phase space variables for the decays $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu \nu_\mu$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \tau \nu_\tau$ are presented in Section 4.5.

4.1 The Fit Results

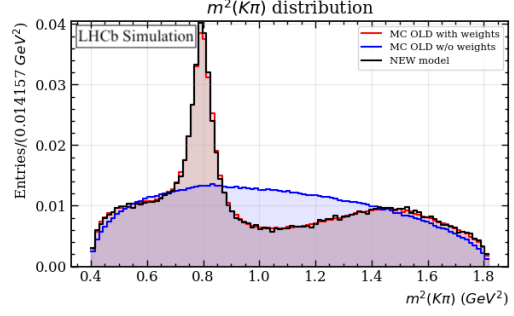
4.1.1 Generated sample without selection cuts

The normalised histograms for the five phase space variables for a Monte-Carlo (MC) sample generated using the updated data-driven model described in equations (10), (11), (12) are shown in black. The blue line depicts the phase space distributions for the generated 2016 simulation sample that was not subjected to selection cuts, whilst the red line depicts the same sample but with the weights described previously assigned to each value.

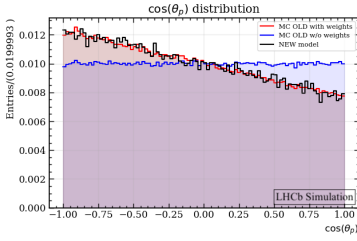
It can be seen in Fig. 22 that the weighted 2016 simulation sample matches well with the new data-driven model for the $\Lambda_c \rightarrow pK^-\pi^+$ decay.



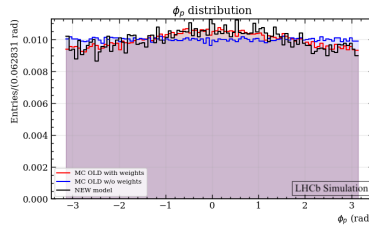
(a) The figure depicts the invariant mass squared of pK (Λ^*)



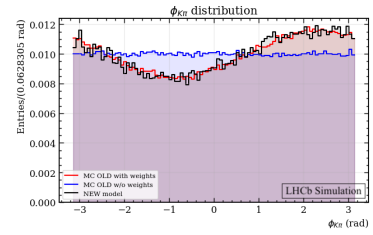
(b) The figure depicts the invariant mass squared of $K\pi$ (K^*)



(c) The figure depicts the $\cos(\theta_p)$ distribution.



(d) The figure depicts the ϕ_p distribution.



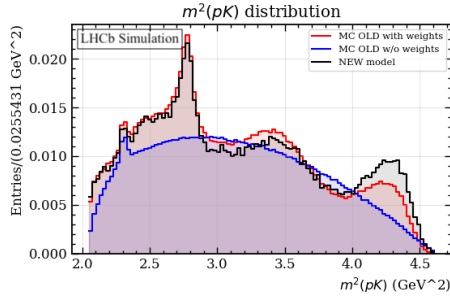
(e) The figure depicts the $\phi_{K\pi}$ distribution.

Figure 2: The plots depict the five phase space variables for the generated MC sample (without selection cuts) with (red) and without weights (blue) and the distributions for the new model (black).

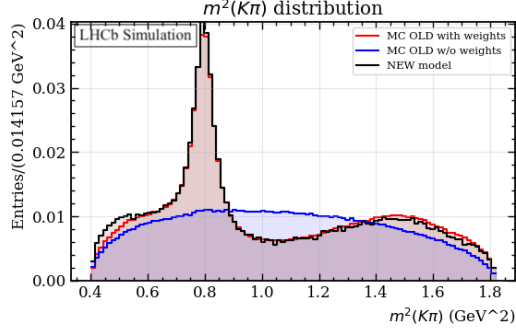
4.1.2 Generated sample with selection cuts

The following normalised histograms have the same definitions as those outlined in Fig. 22, however, the blue and red histograms were generated using the 2016 simulation sample that had been subjected to selection cuts. These selection cuts included fixing the pseudo-rapidity of the Λ_b baryon to be in the range of the LHCb, ensuring only reconstructed decays are retained as well as some kinematic and topological cuts pertaining to the Stripping line: "Strippingb2LcMuXB2DMuForTauMuLine" [3].

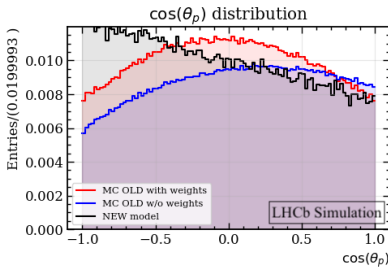
The weighted distribution for the 2016 simulation sample could not be made to exactly match the new model. This was due to the selection cuts that this sample has been subjected to affecting the angular distributions. However, the invariant mass and ϕ_p phase space variables were still improved from their previous shape (shown in blue).



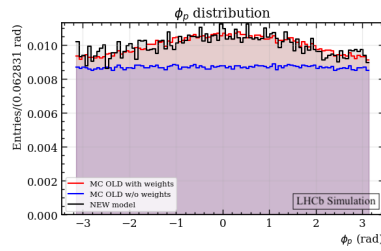
(a) The figure depicts the invariant mass squared of pK (Λ^*)



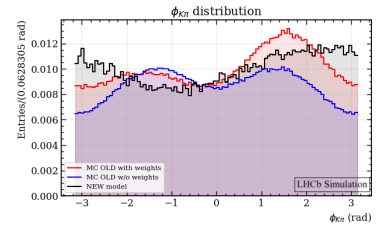
(b) The figure depicts the invariant mass squared of Kπ (K^*)



(c) The figure depicts the ϕ_p distribution.



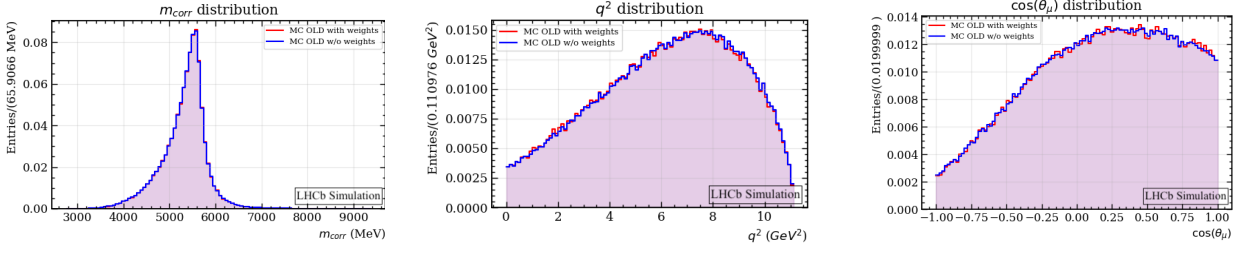
(d) The figure depicts the ϕ_p distribution.



(e) The figure depicts the $\phi_{K\pi}$ distribution.

Figure 3: The plots depict the five phase space variables for the generated MC sample (with selection cuts) with (red) and without weights (blue) and the distributions for the new model (black).

Fig. 4 below, depicts the normalised distributions of the corrected mass defined in equation (9), q^2 and $\cos\theta_\mu$ for the 2016 simulation sample with selection cuts with no extra weights added (blue) and with the weights outlined in Section 3.3 assigned to each value (red). Observations of the corrected mass were conducted as the ongoing NP analysis involves extracting the $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu_\mu$ yield as a function of the reconstructed q^2 and $\cos\theta_\mu$ variables through the fit to the corrected mass distribution that provides a good discrimination between signal and background [3], [4]. It can be seen that these three variables are virtually unaffected by the weighting suggesting that there is not a significant correlation between the Λ_c phase space variables and q^2 and $\cos\theta_\mu$.



(a) The figure depicts the corrected mass distribution.

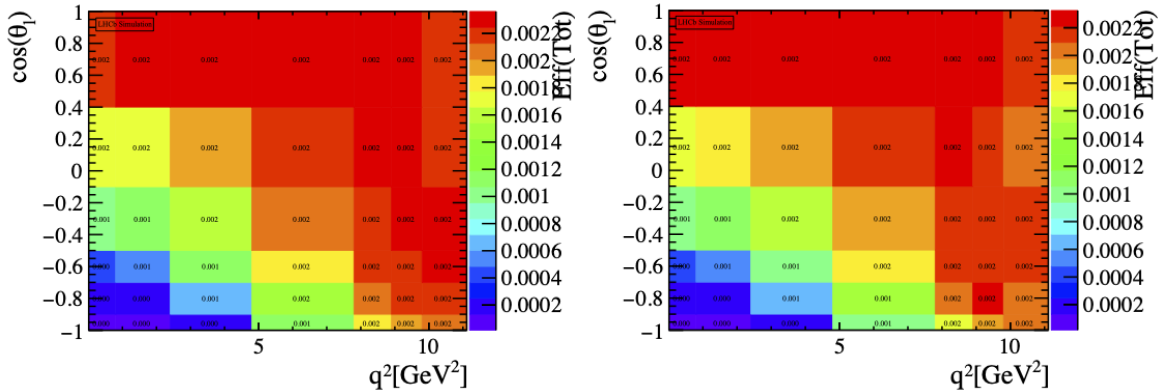
(b) The figure depicts the q^2 distribution.

(c) The figure depicts the $\cos \theta_\mu$ distribution.

Figure 4: The three figures depict the comparison between the weighted and un-weighted distributions of the three variables: the corrected mass, q^2 and $\cos \theta_\mu$ for the 2016 MC sample that had been subjected to selection cuts.

4.2 The signal selection efficiency

Fig. 5 (a) depicts the total signal selection efficiency calculated using the true variables in the two 2016 simulation samples (that which was subjected to selection cuts and that which was not) whilst Fig. 5 (b) depicts the same variables but with the two samples subjected to the extra weights discussed in Section 3.3.

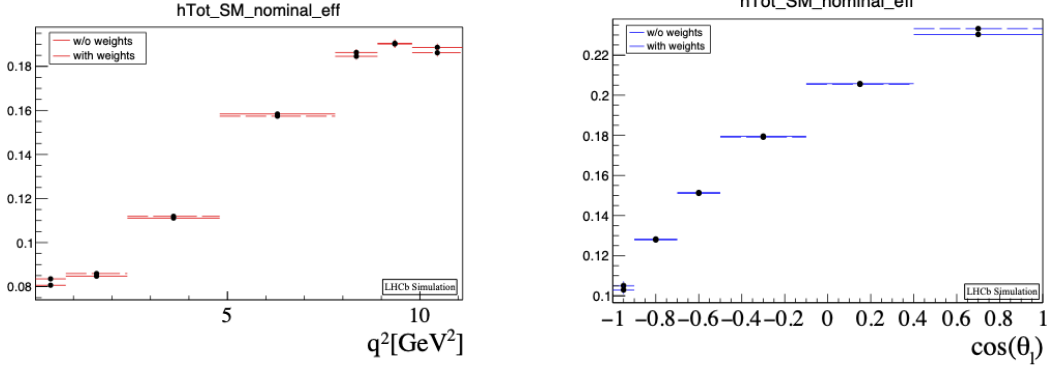


(a) Un-weighted signal selection efficiency in bins of q^2 and $\cos \theta_{mu}$.

(b) Weighted signal selection efficiency in bins of q^2 and $\cos \theta_{mu}$.

Figure 5: Signal selection efficiency for the weighted and un-weighted 2016 generated MC sample.

The following figures depict the projections of the normalised efficiency, with and without the correction weights applied, onto the q^2 (Fig. 6 (a)) and $\cos \theta_\mu$ (Fig. 6 (b)) axes.



(a) Projection of the signal selection efficiency onto the q^2 axis.

(b) Projection of the signal selection efficiency onto the $\cos \theta_m u$ axis.

Figure 6: The figures depict the projection of signal selection efficiency onto the q^2 and $\cos \theta_m u$ axes.

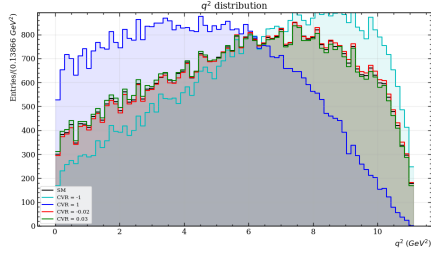
Fig. 5 and 6 confirmed the assumption that changing the model for the $\Lambda_c \rightarrow pK^- \pi^+$ decay does not have a significant impact on the signal selection efficiency map of the full $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu_\mu^+$ decay. This shows that despite the fact that the signal selection efficiency as a function of the $\Lambda_c \rightarrow pK^- \pi^+$ is not flat, corrections to this model have little impact on the efficiency map as a function of the $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu_\mu$ phase space. The average total efficiency for Fig. 5 (a) was measured to be 0.165% with a variation of 141.9% and was measured to be 0.162% with a variation of 142.6% for Fig. 5 (b). These again show a small difference, again confirming the assumption.

4.3 Angular Analysis of Wilson Coefficients

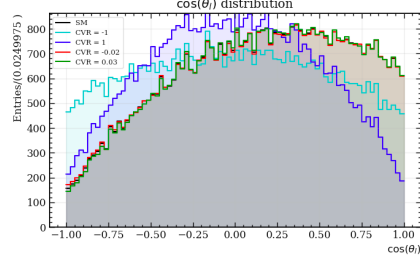
A further analysis was conducted into the effects of the Wilson coefficients, introduced in equation 5, on the observables q^2 , $\cos \theta_l$, $\cos \theta_p$, ϕ_p and $\phi_{K\pi}$. This was conducted for both the full decay of: $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu \nu_\mu$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \tau \nu_\tau$. The results are presented for the Wilson coefficient, C_{V_R} , as seen in equation 5, with all other Wilson coefficients set to zero. The results for the other coefficients: C_{S_L} , C_{S_R} and C_T can be found in A.3.

4.3.1 The $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu \nu_\mu$ decay

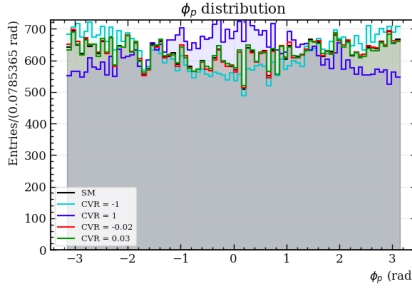
The distribution of the five observables listed above for the C_{V_R} values 0 (SM - black), 1 (blue), -1 (light blue), -0.02 (red) and 0.03 (green) are depicted in the figure below. The limiting values of -0.02 and 0.03 for C_{V_R} were taken from the paper [17]. A C_{V_R} value of 1 or -1 is large and as such the effect on the distributions are more pronounced for these values. It can be seen that the q^2 and $\cos \theta_l$ (where the flavour here is $l = \mu$) distributions vary significantly with the large values of C_{V_R} and slightly for the smaller values indicating that these distributions change with the NP effects. There are also less pronounced changes in the angular variables: $\cos \theta_p$, ϕ_p and $\phi_{K\pi}$ from the Λ_c phase space when the C_{V_R} values are altered. All of these variables vary when NP terms are introduced and as such would be useful variables for studying NP effects in this such semileptonic decays.



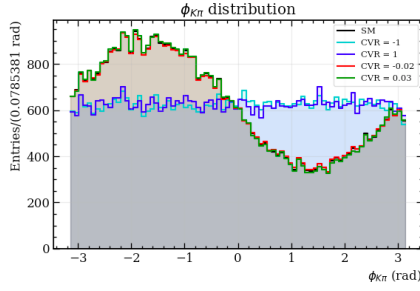
(a) The figure depicts the q^2 distribution.



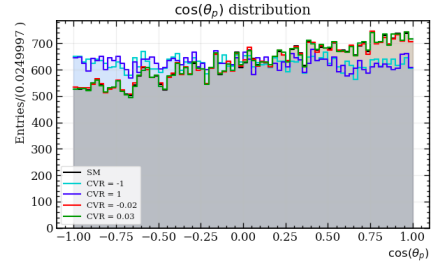
(b) The figure depicts the angular distribution of the μ .



(c) The figure depicts the ϕ_p distribution.



(d) The figure depicts the $\phi_{K\pi}$ distribution.

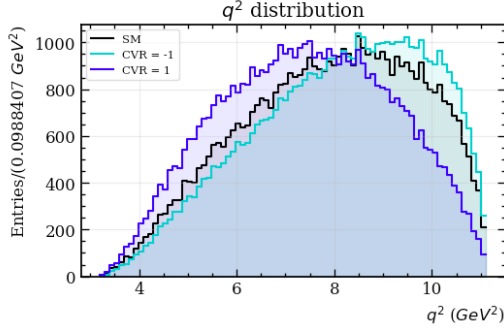


(e) The figure depicts the $\cos\theta_p$ distribution.

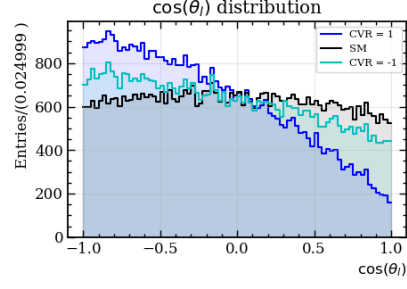
Figure 7: The figures depict the q^2 , $\cos\theta_\mu$, ϕ_p , $\phi_{K\pi}$ and $\cos\theta_p$ distributions for four different values of the Wilson Coefficient, C_{V_R} , for the decay: $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu \nu_\mu$

4.3.2 The $\Lambda_b^0 \rightarrow \Lambda_c^+ \tau \nu_\tau$ decay

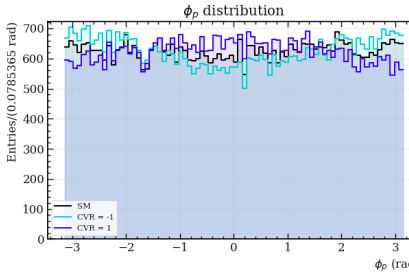
The distribution of the same five variables listed above for the C_{V_R} values: 0 (SM - black), 1 (blue), -1 (light blue) are depicted below for the $\Lambda_b^0 \rightarrow \Lambda_c^+ \tau \nu_\tau$ decay. As before the q^2 and $\cos\theta_\tau$ variables varied significantly when the values of C_{V_R} were altered. The angular variables for the Λ_c phase space also changed as the value of C_{V_R} was altered.



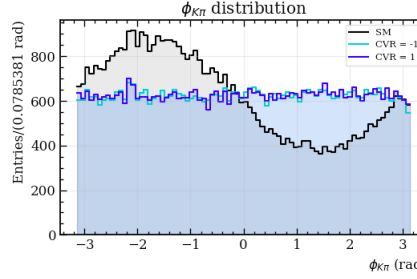
(a) The figure depicts the q^2 distribution.



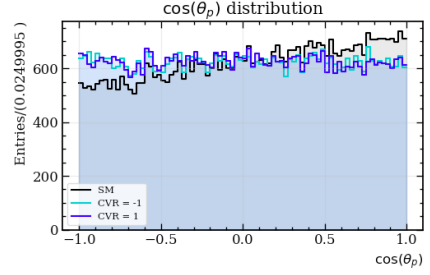
(b) The figure depicts the angular distribution of the μ .



(c) The figure depicts the ϕ_p distribution.



(d) The figure depicts the $\phi_{K\pi}$ distribution.



(e) The figure depicts the $\cos\theta_p$ distribution.

Figure 8: The figures depict the q^2 , $\cos\theta_\tau$, ϕ_p , $\phi_{K\pi}$ and $\cos\theta_p$ distributions for four different values of the Wilson Coefficient, C_{V_R} , for the decay: $\Lambda_b^0 \rightarrow \Lambda_c^+ \tau \nu_\tau$

The variation of these observables as the value of the Wilson coefficient, C_{V_R} , was altered gives a useful insight into how these NP variables affect the dynamics of the decay, specifically the $\Lambda_c \rightarrow pK^-\pi^+$ process that was being investigated.

5 Conclusions

The phase space distributions for the data-driven model outlined Section 3.2.1 varied quite significantly from the 2016 simulation model and the weights which were determined to correct the phase space of the $\Lambda_c \rightarrow pK^-\pi^+$ decay in the generated simulation sample worked effectively. It was shown that the efficiency map as a function of the $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \nu_\mu$ phase space did not vary significantly when the corrected form of the $\Lambda_c \rightarrow pK^-\pi^+$ model was implemented in the simulation sample despite the fact that the efficiency as a function of the $\Lambda_c \rightarrow pK^-\pi^+$ is not a flat distribution. This shows that the signal selection procedure designed to improve the signal purity is fairly independent of the Λ_c phase space. Furthermore, it was observed that both the q^2 , $\cos\theta_\mu$ and ϕ_p , $\phi_{K\pi}$ and $\cos\theta_p$ phase space variables varied under the influence of NP operators, where the latter group of observables varied less significantly. Therefore, these observables could be useful for probing the effects of NP on these semileptonic decays.

A Appendices

A.1 Helicity Formalism

The variables chosen to represent the five-dimensional phase space in the Helicity formalism were the invariant mass of the K^* resonance ($m_{K\pi}^2$), the polar and azimuthal angles of the K^* resonance in the rest frame of Λ_c and the polar and azimuthal angles of K in the rest frame of K^* . The transition amplitude was determined by coherently summing over the complex amplitudes of each of the three decay channels where the proton helicities, λ_p , were defined in the K^* rest frame:

$$A_{\lambda_p}^{M_{\Lambda_c}} = \sum_{K^*} A_{M_{\Lambda_c}, \lambda_p}^{K^*} + \sum_{\Delta, \lambda'_p} D_{\lambda'_p, \lambda_p}^{1/2}(\alpha_1, \zeta_{K(p)}^p, \phi_K^{[K^*]}) A_{M_{\Lambda_c}, \lambda'_p}^{\Delta} + \sum_{\Lambda^*, \lambda''_p} D_{\lambda''_p, \lambda_p}^{1/2}(\alpha_2, \zeta_{\pi(p)}^p, \phi_K^{[K^*]}) A_{M_{\Lambda_c}, \lambda''_p}^{\Lambda^*} \quad (14)$$

$$\alpha_1 = \begin{cases} 2\pi & \text{when } |\phi_p^{[\Lambda_c]} - \phi_{\pi}^{[\Lambda_c]}| > \pi \\ 0 & \text{otherwise} \end{cases}$$

and

$$\alpha_2 = \begin{cases} 2\pi & \text{when } |\phi_p^{[\Lambda_c]} - \phi_K^{[\Lambda_c]}| > \pi \\ 0 & \text{otherwise} \end{cases}$$

D here represents the Wigner-D function which ensures the helicity of the proton as defined in the Δ^{++} (λ'_p) and Λ^* (λ''_p) rest frames are correctly rotated to the rest frame of K^* . $A_{M_{\Lambda_c}, \lambda_p}^{K^*}$, $A_{M_{\Lambda_c}, \lambda'_p}^{\Delta}$ and $A_{M_{\Lambda_c}, \lambda''_p}^{\Lambda^*}$ are the complex amplitudes for the individual decay channels. They are given by the following equations:

$$A_{M_{\Lambda_c}, \lambda_p}^{K^*} = C_1 \times R(m^2(K^- \pi^+)) \times \sum_{\lambda_{K^*}} \left(D_{M_{\Lambda_c}, \lambda_{K^*} - \lambda_p}^{J_{\Lambda_c}, *}(\phi_{K^*}^{[\Lambda_c]}, \theta_{K^*}^{[\Lambda_c]}, 0) \times D_{\lambda_{K^*}, 0}^{J_{K^*}, *}(\phi_K^{[K^*]}, \theta_K^{[K^*]}, 0) \times \epsilon_{\lambda_p} \times H_{\lambda_{K^*}, \lambda_p}^{J_{\Lambda_c}, J_{K^*}} \right) \quad (15)$$

$$A_{M_{\Lambda_c}, \lambda_p}^{\Lambda^*} = C_2 \times R(m^2(pK^-)) \times \sum_{\lambda_{\Lambda^*}} \left(D_{M_{\Lambda_c}, \lambda_{\Lambda^*}}^{J_{\Lambda_c}, *}(\phi_{\Lambda^*}^{[\Lambda_c]}, \theta_{\Lambda^*}^{[\Lambda_c]}, 0) \times D_{\lambda_{\Lambda^*}, \lambda_p}^{J_{\Lambda^*}, *}(\phi_p^{[\Lambda^*]}, \theta_p^{[\Lambda^*]}, 0) \times \eta_{\lambda_p} \times H_{\lambda_{\Lambda^*}}^{J_{\Lambda_c}, J_{\Lambda^*}} \right) \quad (16)$$

$$A_{M_{\Lambda_c}, \lambda_p}^{\Delta} = C_3 \times R(m^2(p\pi^+)) \times \sum_{\lambda_{\Delta}} \left(D_{M_{\Lambda_c}, \lambda_{\Delta}}^{J_{\Lambda_c}, *}(\phi_{\Delta}^{[\Lambda_c]}, \theta_{\Delta}^{[\Lambda_c]}, 0) \times D_{\lambda_{\Delta}, -\lambda_p}^{J_{\Delta}, *}(\phi_p^{[\Delta]}, \theta_p^{[\Delta]}, 0) \times \epsilon_{\lambda_p} \times \eta_{\lambda_p} \times H_{\lambda_{\Delta}}^{J_{\Lambda_c}, J_{\Delta}} \right) \quad (17)$$

where C_i are constants, θ_i^j and ϕ_i^j are the polar and azimuthal angles of particle i defined in the rest frame of particle j , J_i is the spin of particle i , M_i and λ_i represent the orbital angular momentum and helicity of particle i . R is the lineshape of the different resonances, it represents the invariant mass dependence of each of the resonances. For $K_0^*(700)$ and $K_0^*(1430)$ the lineshape discussed in [11] and the $\Lambda^*(1405)$ lineshape was taken to be the Flatté function as it peaks below the pK^- threshold [12]. All other resonances were parametrised with a relativistic Breit-Wigner function modified to include the Blatt-Weisskopf form factors as discussed in [13]. Furthermore, H represents the helicity coupling amplitudes these were altered to match with the fit fractions of the recent LHCb paper that is in the process of being published [18, 19, 13].

A.2 The fit results of the generated 2016 Monte-Carlo sample

The following plots depict the normalised histograms for the invariant mass distributions for the 2016 simulation sample with (A.2.2) and without (A.2.1) selection cuts (blue) and a generated Monte-Carlo sample using the constructed model for the simulated sample (red). (Note that no fit was conducted for these plots).

A.2.1 2016 simulation sample without selection cuts

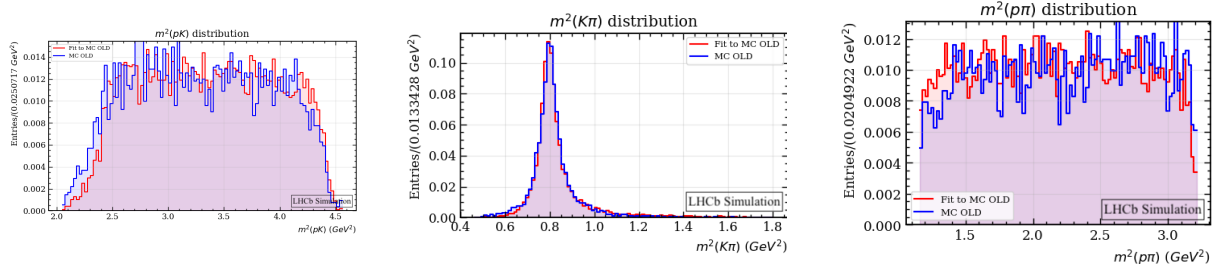


Figure 9: The figure depicts the normalised invariant mass distributions for the K^* resonance for the model formed to represent the 2016 generated MC data plotted with the true values from the data.

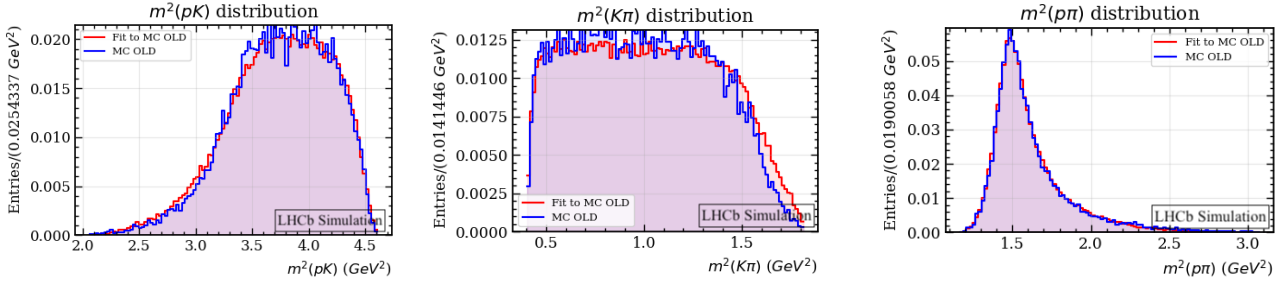


Figure 10: The figure depicts the normalised invariant mass distributions for the Δ^{++} resonance for the model formed to represent the 2016 generated MC data plotted with the true values from the data.

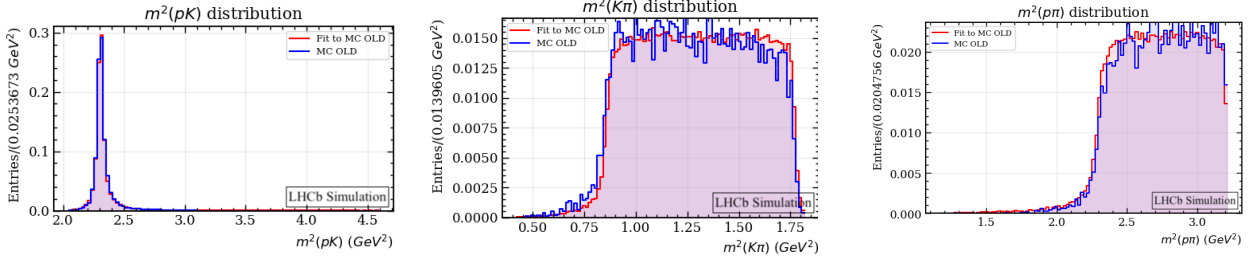


Figure 11: The figure depicts the normalised invariant mass distributions for the Λ^* resonance for the model formed to represent the 2016 generated MC data plotted with the true values from the data.

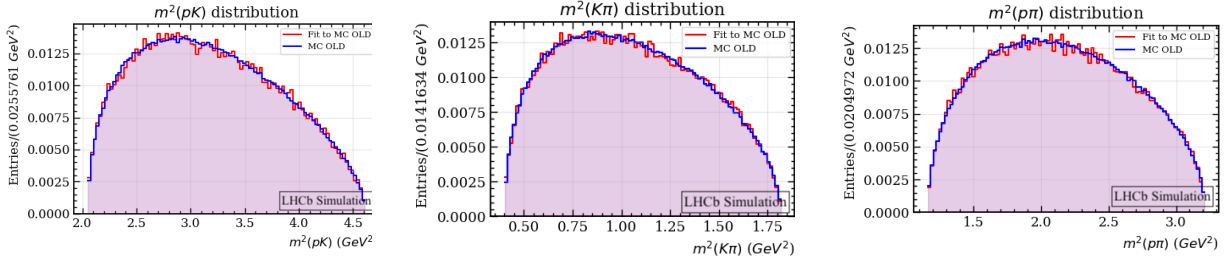


Figure 12: The figure depicts the normalised invariant mass distributions for the phase space of the model formed to represent the 2016 generated MC data plotted with the true values from the data.

A.2.2 2016 simulation sample with selection cuts

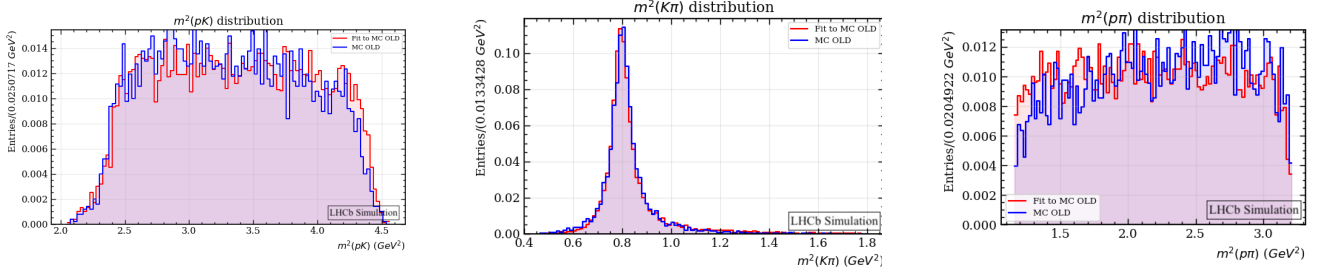


Figure 13: The figure depicts the normalised invariant mass distributions for the K^* resonance for the model formed to represent the 2016 generated MC data with selection cuts plotted with the true values from the data.

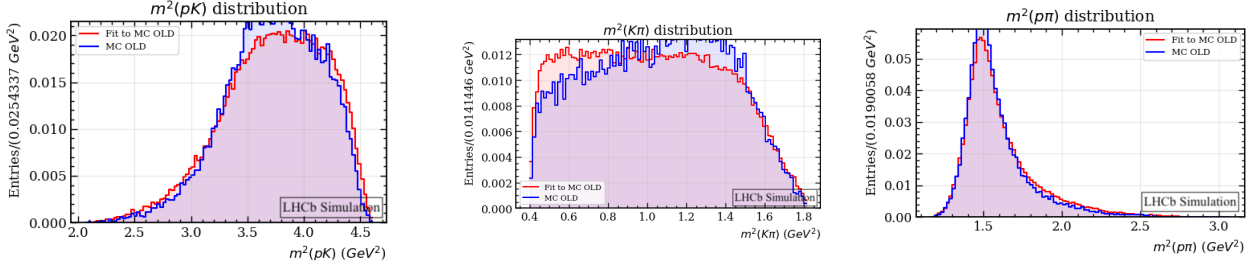


Figure 14: The figure depicts the normalised invariant mass distributions for the Δ^{++} resonance for the model formed to represent the 2016 generated MC data with selection cuts plotted with the true values from the data.

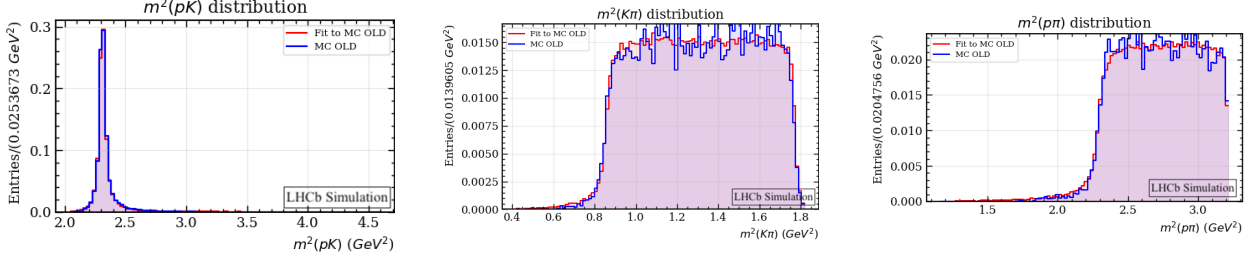


Figure 15: The figure depicts the normalised invariant mass distributions for the Λ^* resonance for the model formed to represent the 2016 generated MC data with selection cuts plotted with the true values from the data.

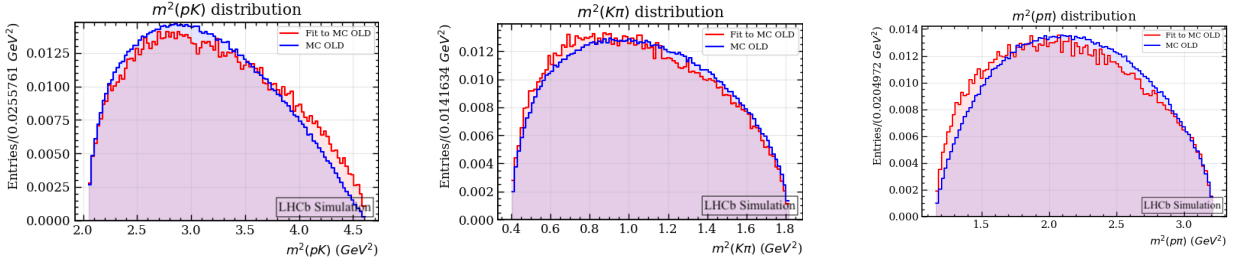


Figure 16: The figure depicts the normalised invariant mass distributions for the phase space contribution for the model formed to represent the 2016 generated MC data with selection cuts plotted with the true values from the data.

A.3 The C_T , C_{S_L} and C_{S_R} Results

The following figures present the variation of the q^2 , $\cos\theta_\tau$, ϕ_p , $\phi_{K\pi}$ and $\cos\theta_p$ distributions for different values of the Wilson Coefficient, C_T , C_{S_L} and C_{S_R} .

A.3.1 The $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu \nu_\mu$ decay

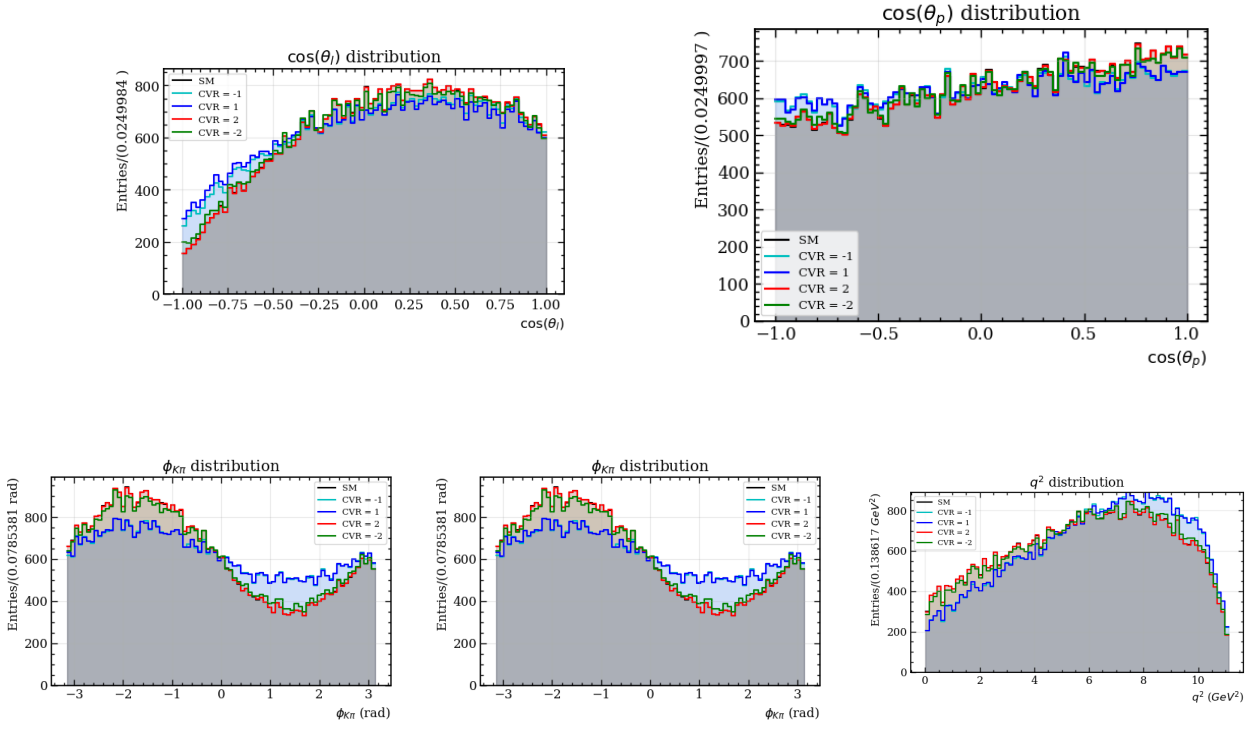


Figure 17: The plots depict the variations of the q^2 , $\cos\theta_\mu$, ϕ_p , $\phi_{K\pi}$ and $\cos\theta_p$ variables when the C_{S_L} Wilson coefficient was altered.

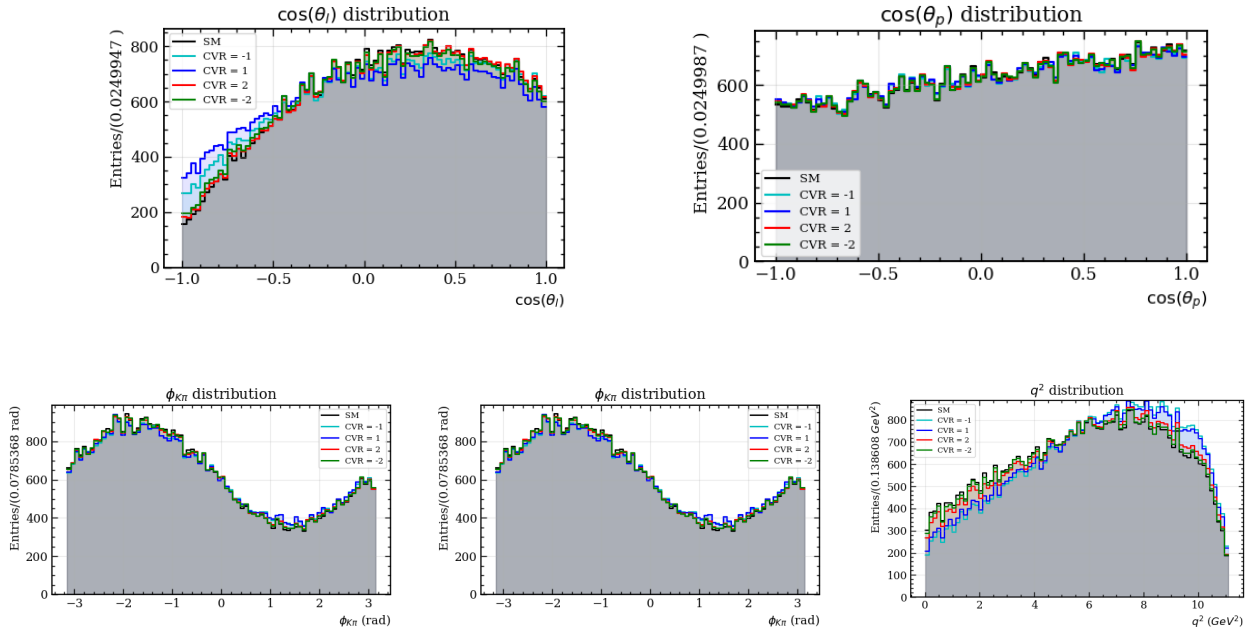


Figure 18: The plots depict the variations of the q^2 , $\cos\theta_\mu$, ϕ_p , $\phi_{K\pi}$ and $\cos\theta_p$ variables when the C_{S_R} Wilson coefficient was altered.

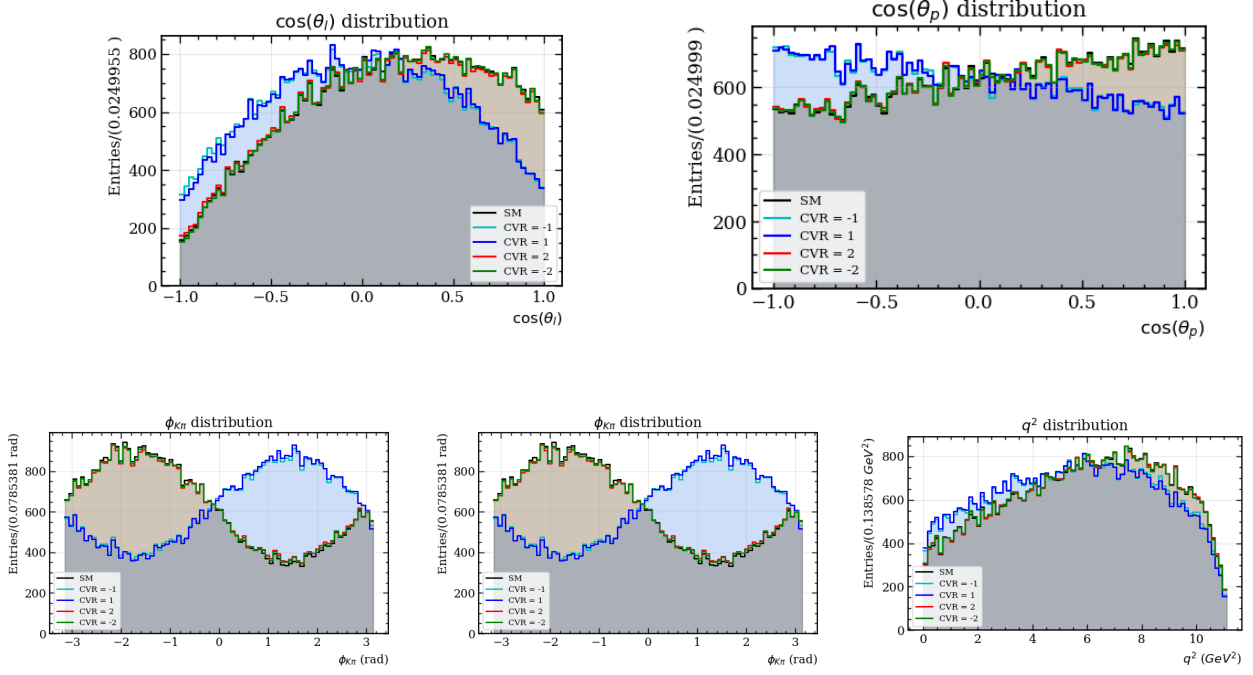


Figure 19: The plots depict the variations of the q^2 , $\cos\theta_\mu$, ϕ_p , $\phi_{K\pi}$ and $\cos\theta_p$ variables when the C_T Wilson coefficient was altered.

A.3.2 The $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu \nu_\mu$ decay

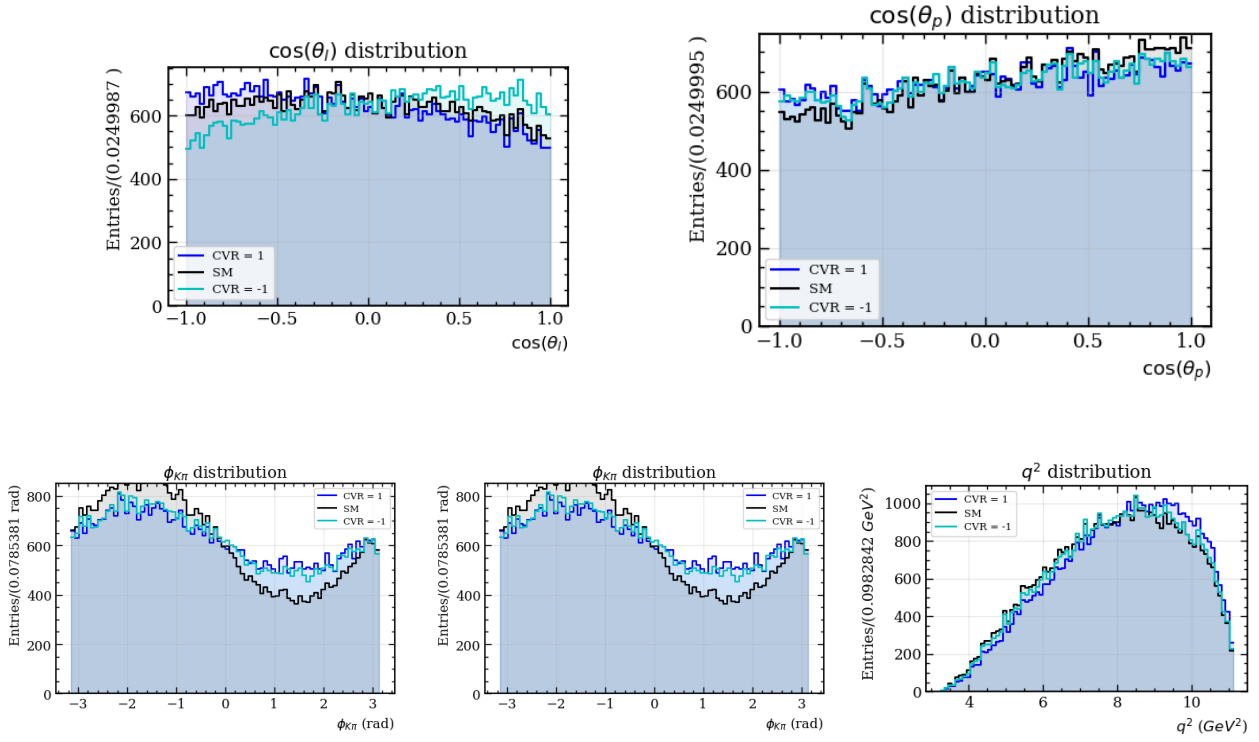


Figure 20: The plots depict the variations of the q^2 , $\cos\theta_\mu$, ϕ_p , $\phi_{K\pi}$ and $\cos\theta_p$ variables when the C_{S_L} Wilson coefficient was altered.

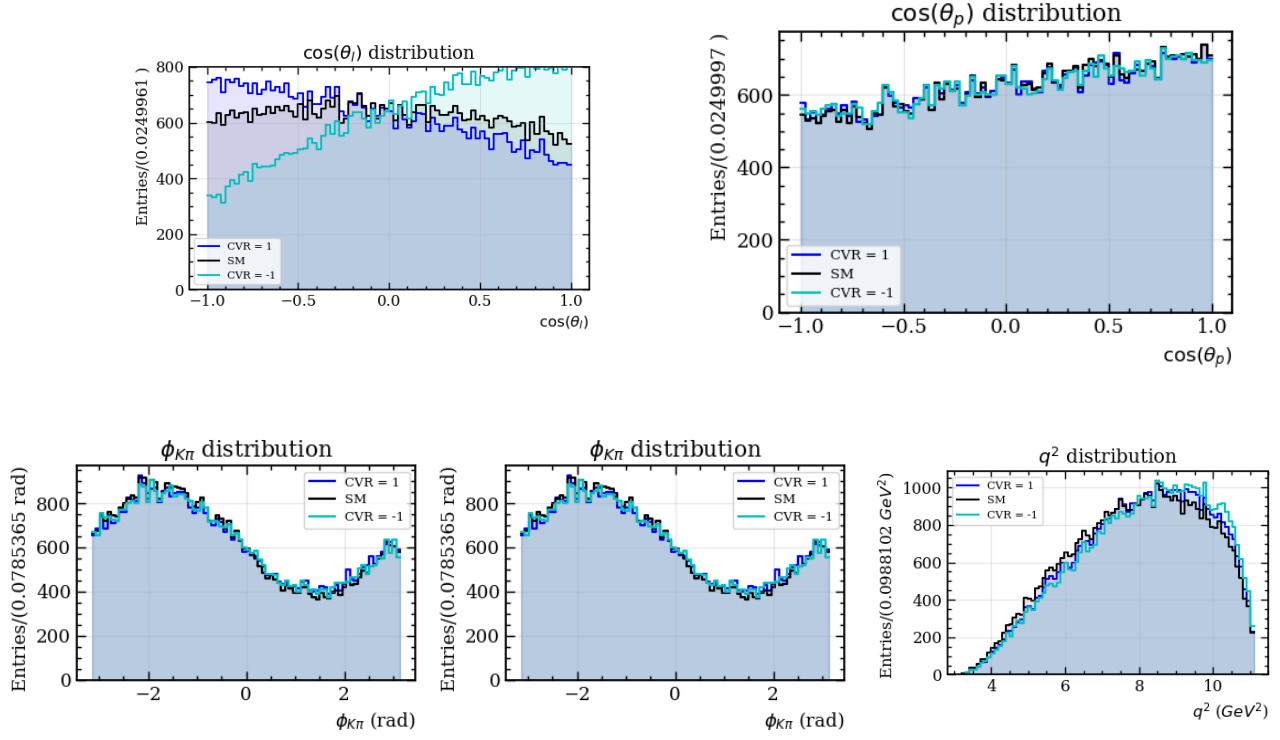


Figure 21: The plots depict the variations of the q^2 , $\cos\theta_\mu$, ϕ_p , $\phi_{K\pi}$ and $\cos\theta_p$ variables when the C_{SR} Wilson coefficient was altered.

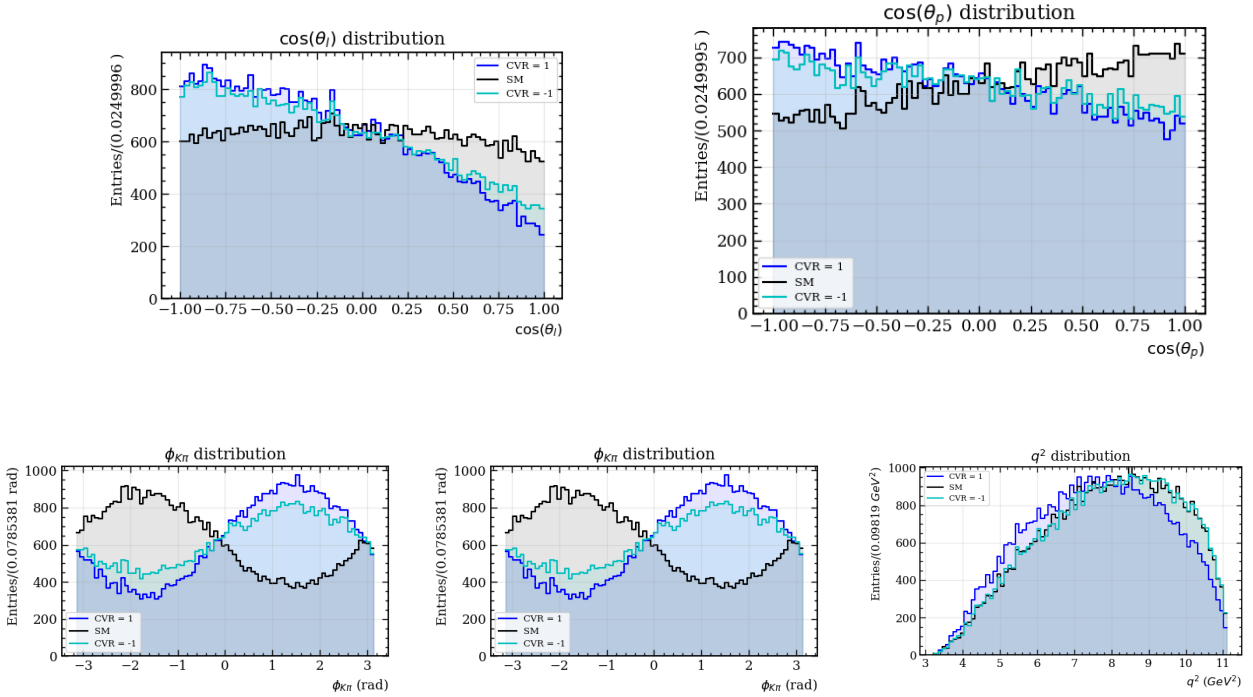


Figure 22: The plots depict the variations of the q^2 , $\cos\theta_\mu$, ϕ_p , $\phi_{K\pi}$ and $\cos\theta_p$ variables when the C_T Wilson coefficient was altered.

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