

Abstract

The measurements of b -quark production cross sections in 7 and 13 TeV proton-proton collisions, and b -flavored hadron fragmentation fraction ratios in 13 TeV proton-proton collisions are presented using data taken with the LHCb detector located on the Large Hadron Collider (LHC). Both measurements are essential components of precision studies of beauty quark decays, which aim at probing the Standard Model of elementary particles and their interactions and possibly uncover evidence for new physics in rare decays or CP -violation asymmetries. In the former measurement, the absolute production cross sections are found to be consistent with next-to-leading-order (NLO) QCD calculations as a function of the pseudorapidity of the decaying b -hadron. The overall shape and normalization of the ratio between the cross section measured at 7 and 13 TeV is in agreement with theoretical expectations. The latter measurement quantifies the kinematic dependence of the fragmentation fraction ratios of the B_s^0 and the Λ_b^0 , with respect to the sum of B^0 and B^+ . The integrated ratio of the B_s^0 with respect to the sum of B^0 and B^+ is the most precise measurement to date. Additionally, measurements on (irradiated) prototype and production silicon micro-strip detectors for the LHCb Upstream Tracker (UT) upgrade are presented. These measurements are essential to the quality-assurance aspects of the UT project and provide a baseline measurement of irradiation properties for future radiation studies.

Measurements of Beauty Production Cross Sections and Fragmentation Fraction Ratios using the LHCb Detector

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Acknowledgments

Graduate studies in particle physics is not an easy road, and I deem myself lucky to have the knowledge and expertise of many others passed to me over the past six years.

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Dedicated to my parents and my partner, Claire.

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1 Introduction

Fundamental science has always aimed at a deeper understanding of the basic laws governing the universe. Nearly half a millennium ago scientists were inquiring where our place was within the celestial bodies. Giants such as Copernicus, Galileo, and Kepler questioned the assumption that our planet was the center of the universe. Later, Newton formulated the theory describing the motion of planets - the laws of gravity. Fast forwarding to the early 1900s, physicists discovered the quantized unit of electrical charge and the particle- and wave-like nature of matter [10] [11] [12]. Today, experimental physics is probing smaller and smaller features of matter, while also exploring the collisions of extremely massive black holes in distant corners of the universe.

Elementary particle physics is on the forefront of this march of scientific discovery probing the fundamental constituents of matter and the forces through which they interact. Over the past 100 years, many theoretical and experimental advancements on the electromagnetic, and weak and strong nuclear interactions led to what is called the *Standard Model* (SM). The SM has been extremely successful in predicting many features of nature that have been confirmed by experimental observation. On the other hand the standard model is not complete as it doesn't include the gravitation force. Also, many questions, such as the matter-antimatter asymmetry that we observe in today's universe, dark matter, and dark energy, still elude our understanding.

Experiments dedicated to studying elementary particle physics have grown evermore complex over the past 100 years. Early experiments, which snap images of particles passing through bubble chambers [13] would seem archaic compared to today's colossal detectors. The Large Hadron Collider at the European Organization for Nuclear Research (CERN), with its four experiments, is currently the largest machine designed for studying particle physics. One of these experiments, LHCb, is dedicated to studying particles containing b quarks - the heaviest quark able to form composite particles called hadrons. Studies of these particles may help us to answer questions such as what happened in the early universe to

produce a matter dominated world today.

Measurements of particle production properties at CERN is one of the essential prerequisite to many other studies that aim to answer fundamental questions. Production cross sections and fragmentation ratios of particles containing b quarks are necessary for studies to test for *beyond-the-standard-model* physics taking the form of CP -violation, rare decays, and lepton universality. This work focuses on these production properties.

The organization of this thesis is as follows: Chapter 2 provides an introduction to the Standard Model of particle physics and relevant topics such as mixing and CP -violation, and heavy quark production and fragmentation. Chapter 3 is dedicated to the definition of the LHC and the current LHCb detector. In Chapter 4, an overview of the LHCb upgrade is given, with a focus on the silicon micro-strip detectors for the Upstream Tracker (UT) upgrade, and measurements that I performed on prototype and production detectors. In Chapters 5 and 6, two physics measurements utilizing data recorded by the LHCb detector are described, namely the measurement of b -quark production cross section at 7 and 13 TeV center-of-mass energies, and the measurement of the b -flavored hadron fragmentation ratios at a center-of-mass energy of 13 TeV, respectively. Finally, Chapter 7 summarizes the conclusions from the work described. Throughout natural units are used, i.e., $\hbar=c=1$.

2 The Standard Model of particle physics

2.1 Overview

The *Standard Model* of particle physics (SM), first developed by Glashow, Salam, and Weinberg [14] [15] [16] [17], is a description of how the fundamental building blocks of nature and their interactions work. Since being formulated in the 1960's, the SM has been incredibly successful in predicting the existence of particles and how particles interact with each other.

The SM is a renormalizable quantum field theory that describes the electromagnetic (Quantum ElectroDynamics, QED), weak, and strong (Quantum ChromoDynamics, QCD) forces; Gravity is the only force not included in the SM. Two types of particles exist within the SM: *fermions* and *bosons*. The distinguishing factors between the two are the value of their intrinsic quantum number called *spin*; fermions have half-integer spin and bosons have integer spin (0 or 1).

Fermions are further split into two different types of particles called *quarks* and *leptons*. Quarks are the fundamental building blocks of particles, such as the familiar proton and neutron which form the nuclei of atoms making up ordinary matter. Due to a property of *quark confinement* [18], they cannot exist on their own and must be bound with other quarks. In the SM quarks carry a fractional electric charge. For example the *up* quark has an electric charge of $+\frac{2}{3}e$ (where $e=1.602\times 10^{-19}$ Coulombs). The other category of fermions, the leptons, consists of pairs of one electrically charged particle and a light neutrally charged partner. The familiar leptons are the electron, and its (electron) neutrino (ν_e) partner.

In the SM fermions are ordered in generations. The first generation of the leptons consists of the already mentioned electron and electron neutrino. Higher lepton generations, with similar properties to the first one but with higher masses, are made up by the muon and muon neutrino, and tau and tau neutrino. In all lepton generations the neutrinos are electrically neutral and their partners have an electric charge of $-1e$. In the quark sector, the first generation is made up of *up* (or *u*) and *down* (or *d*) quarks, with the up quark having an

electric charge of $+\frac{2}{3}e$ and the down quark having a charge of $-\frac{1}{3}e$. The second and third generations contain the *charm* (c) and *strange* (s), and *beauty* (b , and also called the *bottom* quark) and *top* (t) quarks, respectively. The charm and top quarks carry the same $+\frac{2}{3}e$ charge as the up quark, and the strange and beauty quarks carry the same $-\frac{1}{3}e$ charge as the down quark (hence the term “*up*-like” is used to describe the u , c , and t quarks, and “*down*-like” to describe d , s , and b quarks).

Bosons with spin=1 are the “force carriers” in the SM. There are four spin-1 bosons in the current SM that carry the forces of the three fundamental interactions: the photon (γ) is responsible for the electromagnetic force, gluons (g) are responsible for the strong force, and the $W^\pm$ and Z^0 are responsible for the weak force. Only particles that are “charged” under a force can interact with the respective force-carrying boson. Quarks and some leptons carry electromagnetic charge, and therefore can interact with photons. All quarks and leptons couple with the weak force, but only the left-handed “portion” can interact with the $W^\pm$ and Z^0 . Only quarks couple to the strong force and their coupling is called *color*. Three color charges are possible: red, blue, and green. Under the strong force gluons are also charged and can interact with other gluons.

The last SM building block is the scalar (spin=0) Higgs boson. Discovered by ATLAS and CMS in 2012 [19] [20], the Higgs boson is the final puzzle that completes the SM and is responsible for fermion masses [21] [22] [23].

Figure 1 summarizes the SM particles. In 1928 Paul Dirac predicted the existence of antimatter, which was experimentally confirmed in 1933 [13]. Therefore, for every particle listed in Figure 1 there is a corresponding antiparticle. Particles and their antiparticle partners have the same mass, but opposite charge and spin. For example, the anti-electron, the antiparticle to the electron and often called the positron, has a positive electric charge.

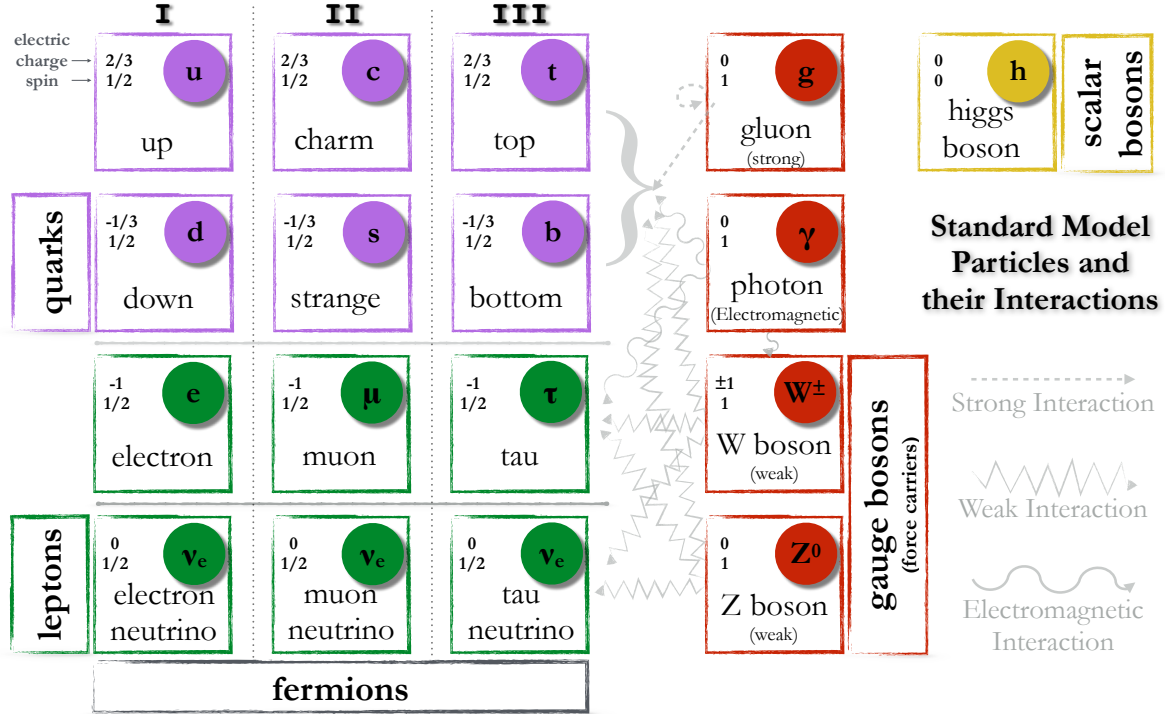


Figure 1: Summary of all elementary particles in the Standard Model (SM) and their interactions. The fermions, organized in three generations (denoted by the I, II, and III), comprise of quarks in the purple squares and leptons in the green squares. The bosons consist of the gauge bosons indicated by the red squares and the scalar boson indicated by the yellow square. The connecting lines indicate the interactions that the fermions couple to. The Higgs interacts with all particles except the neutrinos.

2.2 The role of heavy flavor

In QCD, the mass scale is set by Λ_{QCD} , which approximately is equal to 0.2 GeV. Thus, the first three quarks, the d , u , and the s quarks, are “light”, and the c , b , and the t quarks are “heavy”. This distinction actually plays an important role in hadron physics: At scales much above Λ_{QCD} , or small distances ($< 1\text{fm}$), hadron properties can be predicted using a perturbative expansion in the strong coupling constant α_s .

An exact analytical calculation of QCD-mediated processes is not possible in the low-energy non-perturbative regime. Lattice QCD [24], namely the use of lattice formulations of QCD in large scale numerical simulations, emerged as a technique with well defined and systematically uncertainties that can be improved upon, which can be applied to a wide range

of processes and physical quantities. Alternative approaches to non-perturbative processes are effective theories based on specific symmetries of QCD. The first such symmetry to be recognized was isospin symmetry, that this the basis of the chiral perturbation in which many low-energy properties are related to a few reduced matrix elements. Later, a new symmetry has been identified, applicable to system containing one heavy quark. It is due to the fact that once a quark becomes sufficiently heavy, its mass becomes irrelevant to the dynamics of the light, non-perturbative degrees of freedom in QCD. The associated effective theory, Heavy-Quark Effective Theory (HQET) [25] [26], provides the framework to systematically include non-perturbative corrections in computations involving hadrons containing heavy quarks. Predictions from the infinite heavy quark mass limit are useful as a check of several Lattice QCD calculations.

Direct observation of new physics depends upon the center-of-mass energy. However, sensitivity to higher mass scales is possible through indirect measurements of new particles in processes that occur via box or penguin diagrams (see Figure 6 for an example of a box diagram). For example, new particles such as charged Higgs or super-symmetric particles may enter as virtual particles in the loops along with the possible SM contributions, which would cause a discrepancy between measured data and SM expectation. Figure 2 shows the accessible energy scales of a few physics observables. LHCb alone has made a handful of measurements of this sort using decays of heavy flavored hadrons. Measurements of angular variables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays, which are forbidden at tree-level and must proceed via a penguin diagram, have deviations from the SM at the 3.4σ level [27], which may be a hint of contributions from new physics. Measurements of semileptonic CP -asymmetries in mixing (details in the next section), $a_{sl}^{d,s}$, can also contain new physics in the box-diagrams shown in Figure 6, which describe the mixing process for neutral mesons. Currently no deviation from $a_{sl}^{d,s}$ measurements and SM expectation has been found [28] [29]. Measurements of rare decays, such as $\overline{B}_s^0 \rightarrow \mu^- \mu^+$, which are predicted in the SM to be very small, may be enhanced by new physics. This branching fraction has been measured in a combined LHCb

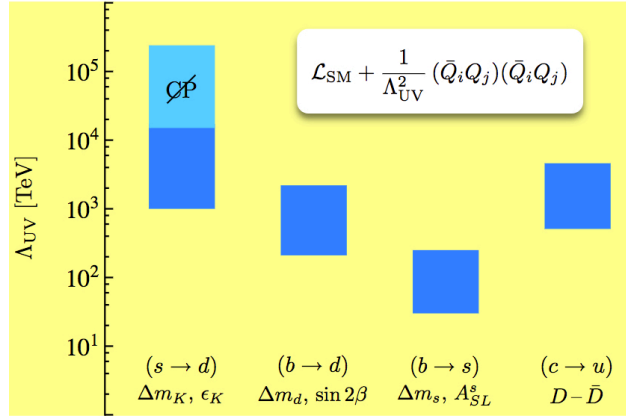


Figure 2: Energy scales probed by several physical observables [1].

and CMS analysis [30], and more recently by LHCb [31], and is found to be consistent, within current precision, with the SM prediction.

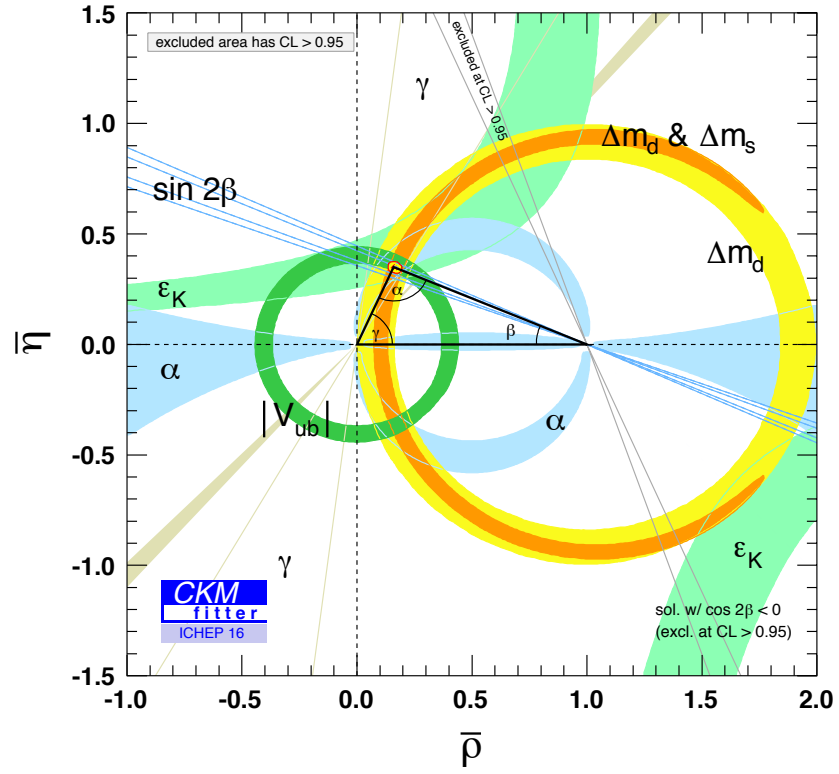


Figure 3: Overlapping constraints of the CKM unitarity triangle. The red hashed area shows the CKM fit to the apex with a 68% confidence interval [2].

2.3 Quark mixing

The SM charged weak currents allow the overall flavor content to change in processes where a left-handed quark couples to a W boson. Figure 4 shows for example the decay $B^+ \rightarrow \bar{D}^0 \mu^+ \nu_\mu$, in which a $\bar{b}$ quark decays into a $\bar{c}$ quark with the emission of a W^+ boson. The Lagrangian that describes quark couplings to W bosons is

$$\mathcal{L}_W = \frac{g_w}{\sqrt{2}} \sum_{j,k=1,2,3} [V_{jk} \bar{u}_{j,L} \gamma^\mu d_{k,L} W_\mu^+ + V_{jk}^* \bar{d}_{k,L} \gamma^\mu u_{j,L} W_\mu^-], \quad (1)$$

with g_w being the weak coupling constant and the u_L and d_L being the left-handed component of the up and down-like quark fields, with the subscript j running over the quark generations.

The V is the 3x3 unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{1,3}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}, \quad (2)$$

where $c_{ij} = \cos(\theta_{ij})$ and $s_{ij} = \sin(\theta_{ij})$ and the θ_{ij} are the mixing angles, and δ_{13} is a complex phase.

A useful parameterization of the CKM matrix is due to the Wolfenstein approximation [32] is

$$V = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}. \quad (3)$$

Where $\lambda = |V_{us}| \approx 0.22$ and $A \sim 1$. In this approximation only the parameters V_{ub} and V_{td} contain complex phases with the parameter η , which characterizes CP -violation (described below).

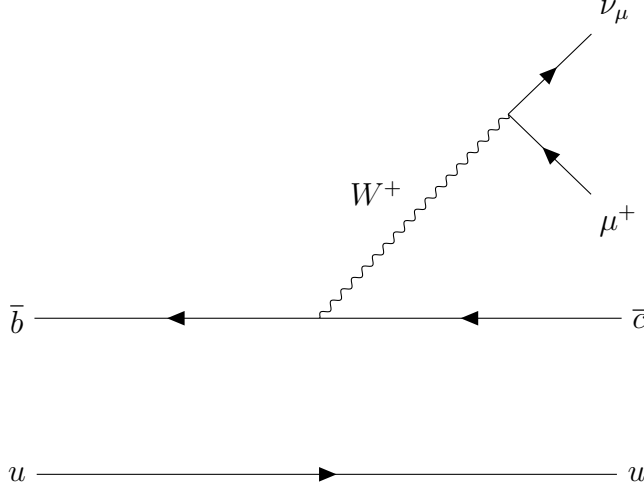


Figure 4: Tree-level $B^+ \rightarrow \bar{D}^0 \mu^+ \nu_\mu$ decay.

Unitarity of the CKM triangle imposes the following relations:

$$\begin{aligned} V_{1j}^* V_{1k} + V_{2j}^* V_{2k} + V_{3j}^* V_{3k} &= \delta_{jk} \\ V_{j1}^* V_{k1} + V_{j2}^* V_{k2} + V_{j3}^* V_{k3} &= \delta_{jk}. \end{aligned} \tag{4}$$

These relations, of which there are six, can be expressed as triangles in the complex plane. The most popular one used, and referred to as *the* unitarity triangle, is constructed from the relation

$$\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} + \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} + 1 = 0 \tag{5}$$

which is a rescaled version of Equation 4 with $j = b$ and $k = d$, and is illustrated in Figure 5. Here the triangle is completely constrained by the apex $(\bar{\rho}, \bar{\eta})$, with

$$\bar{\rho} + i\bar{\eta} = -\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}. \tag{6}$$

The angles α , β , and γ shown in Figure 5 are related to CP -violation, and are explicitly:

$$\begin{aligned}\alpha &= \arg\left[\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right], \\ \beta &= \arg\left[\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right], \\ \gamma &= \arg\left[\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right].\end{aligned}\tag{7}$$

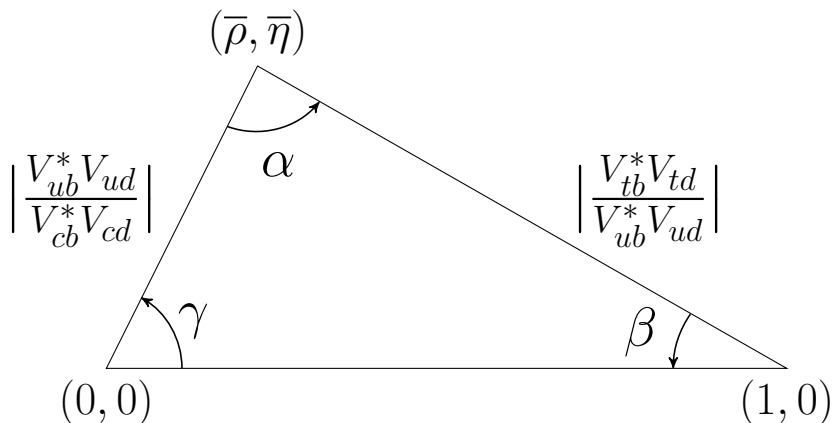


Figure 5: Sketch of the most commonly used unitarity triangle.

Heavy-flavored hadrons are used for precise measurements of the unitarity triangle sides and angles, which probe CP -violating properties of B decays. A key goal is the measurement of the least known CKM element, γ , which constrains the apex in the unitarity triangle, using tree level $B \rightarrow D^0 h$ decays, where the $D = D^0$ or $\overline{D^0}$. In this case the b quark can either transition into a c or u quark, and the interference of these two amplitudes is sensitive to γ . Measurements by LHCb [33] are the most precise determination of $\gamma = (73_{-10}^{+9})^\circ$. Measurements of the CKM elements $|V_{cb}|$ and $|V_{ub}|$ are possible with the tree-level $b \rightarrow (c, u)\mu\overline{\nu}_\mu$ semileptonic decays. One approach is an inclusive method where only the muon is detected, and the second being exclusive where a specific final state is detected. Currently the world averages for exclusive and inclusive determinations of $|V_{ub}|$ are at a 3σ tension and is a long-standing puzzle in flavor physics. LHCb recently reported the first determination of $|V_{ub}|$ using baryonic $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \overline{\nu}_\mu$ semileptonic decays [34], which confirms the inclusive-

exclusive puzzle. Figure 3 shows the overall status of the CKM unitarity triangle in the $\bar{\rho}, \bar{\eta}$ plane, with a global fit to the apex. Within current experimental uncertainties there are no significant deviations from the SM picture.

Another manifestation of the fact that the mass eigenstates are not the same as the weak eignestates is the phenomenon of flavor oscillation in neutral mesons (K^0 , D^0 , B^0 , and B_s^0). One can construct *box-diagrams* to describe this oscillation process, as shown in Figure 6 for the B_s^0 , that is fourth order in the weak couple constant. Mass eigenstates are written as superpositions of the flavor eigenstates, M and $\bar{M}$,

$$\begin{aligned} M_L &= p|M\rangle + q|\bar{M}\rangle \\ M_H &= p|M\rangle - q|\bar{M}\rangle, \end{aligned} \tag{8}$$

where the subscripts L and H represent the light and heavier mass eigenstates, respectively, and $|p|^2 + |q|^2 = 1$. Both p and q can be calculated using the box diagrams in Figure 6. The time evolution of the flavor eigenstates obeys the time-dependent Schrödinger equation

$$i\frac{d}{dt} \begin{pmatrix} |M(t)\rangle \\ |\bar{M}(t)\rangle \end{pmatrix} = H \begin{pmatrix} |M(t)\rangle \\ |\bar{M}(t)\rangle \end{pmatrix}, \tag{9}$$

where H is the 2x2 Hamiltonian matrix. Writing the time dependence of of the meson state

$$|M(t)\rangle = e^{-iE_M t - \frac{\Gamma}{2}t} |M\rangle, \tag{10}$$

where the first term in the exponential is the standard time evolution of a stable quantum state with energy $= E_M$, and the second term describes the decay of a particle with total width Γ . The probability to find an undecayed meson at time= t is

$$\langle M|M(t)\rangle = e^{-\Gamma t}. \tag{11}$$

Substituting the time-dependent meson states into Equation 9,

$$i \frac{d}{dt} \begin{pmatrix} |M(t)\rangle \\ |\bar{M}(t)\rangle \end{pmatrix} = \begin{pmatrix} M_{11} - i\frac{1}{2}\Gamma_{11} & M_{12} - i\frac{1}{2}\Gamma_{12} \\ M_{12}^* - i\frac{1}{2}\Gamma_{12}^* & M_{22} - i\frac{1}{2}\Gamma_{22} \end{pmatrix} \begin{pmatrix} |M(t)\rangle \\ |\bar{M}(t)\rangle \end{pmatrix}. \quad (12)$$

M_{11} and M_{22} are the masses of the meson states and come from the quark mass terms in the QCD Lagrangian, and all other elements are due to the weak interaction. CPT -symmetry (described in the next section) requires $M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$, so if the off-diagonal elements are equal to zero the meson states are exactly degenerate. However, even small values for the off-diagonal elements this can lead to large meson mixing.

The eigenvectors of the Hamiltonian matrix are

$$\begin{pmatrix} p \\ q \end{pmatrix}, \text{ and } \begin{pmatrix} p \\ -q \end{pmatrix}. \quad (13)$$

The Hamiltonian is now diagonalized as

$$Q^{-1}HQ = P = \begin{pmatrix} M_L - i\Gamma_L/2 & 0 \\ 0 & M_L - i\Gamma_H/2 \end{pmatrix}. \quad (14)$$

Where an auxiliary matrix, P , is introduced for simplicity, and the L, H are the two mass states. The Q matrices are

$$Q = \begin{pmatrix} p & p \\ q & -q \end{pmatrix} \text{ and } Q^{-1} = \frac{1}{2pq} \begin{pmatrix} p & q \\ p & -q \end{pmatrix}. \quad (15)$$

Finally writing the the time-dependence of the flavor states

$$\begin{pmatrix} |M(t)\rangle \\ |\bar{M}(t)\rangle \end{pmatrix} = QPQ^{-1} \begin{pmatrix} |M\rangle \\ |\bar{M}\rangle \end{pmatrix} = \begin{pmatrix} g_+(t) & \frac{q}{p}g_-(t) \\ \frac{p}{q}g_-(t) & g_+(t) \end{pmatrix} \begin{pmatrix} |M\rangle \\ |\bar{M}\rangle \end{pmatrix}, \quad (16)$$

where the parameters $g_{+,-}$ are

$$\begin{aligned} g_+ &= e^{-imt} e^{-\Gamma t/2} \left[\cosh\left(\frac{\Delta\Gamma t}{4}\right) \cos\left(\frac{\Delta Mt}{2}\right) - i \sinh\left(\frac{\Delta\Gamma t}{4}\right) \sin\left(\frac{\Delta Mt}{2}\right) \right] \\ g_- &= e^{-imt} e^{-\Gamma t/2} \left[-\sinh\left(\frac{\Delta\Gamma t}{4}\right) \cos\left(\frac{\Delta Mt}{2}\right) + i \cosh\left(\frac{\Delta\Gamma t}{4}\right) \sin\left(\frac{\Delta Mt}{2}\right) \right] \end{aligned} \quad (17)$$

with the following quantities:

$$\begin{aligned} m &= (M_L + M_H)/2 \\ \Gamma &= (\Gamma_L + \Gamma_H)/2 \\ \Delta M &= M_H - M_L \\ \Delta\Gamma &= \Gamma_L - \Gamma_H \end{aligned} \quad (18)$$

From the expressions in Equations 16 and 17 it is clear to see that as the meson states evolve in time they have finite probabilities to change into their anti-particle. To put things more transparently, the probabilities for M to mix into $\overline{M}$ and vice-versa are

$$\begin{aligned} P(M \rightarrow \overline{M}) &= \left| \frac{q}{p} \right|^2 |g_-(t)|^2 = \frac{e^{-\Gamma t}}{2} \left| \frac{q}{p} \right|^2 \left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) - \cos(\Delta Mt) \right], \\ P(\overline{M} \rightarrow M) &= \left| \frac{p}{q} \right|^2 |g_-(t)|^2 = \frac{e^{-\Gamma t}}{2} \left| \frac{p}{q} \right|^2 \left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) - \cos(\Delta Mt) \right]. \end{aligned} \quad (19)$$

Here it is clear that the mass difference drives the mixing frequency. If the ratio $\left| \frac{p}{q} \right|$ differs from 1 we have different mixing probabilities and CP -violation (more below).

2.4 Discrete symmetries and CP -violation

In the SM there are three discrete symmetries that are important. The first one is *parity*, P , which turns a right-handed coordinate system to a left-handed one. Put in other words

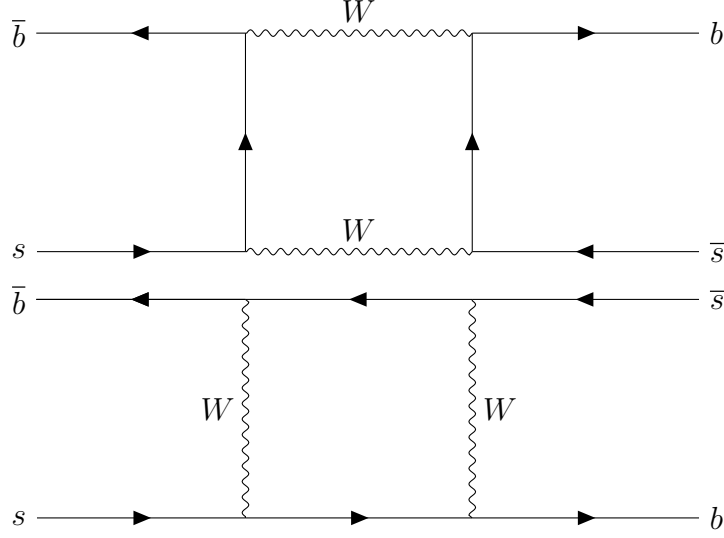


Figure 6: Box diagrams illustrating the mixing of B^0 mesons. In both cases virtual W bosons and quarks connect the four vertexes.

P inverts all spatial coordinates through the origin, i.e.,

$$P : \begin{pmatrix} x \\ y \\ z \end{pmatrix} \rightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}. \quad (20)$$

The second discrete symmetry is *charge conjugation*, C . Under C -transformations a particle is changed to its antiparticle, inverting quantum numbers such as electric and color charges. The final discrete symmetry is *time reversal*, T , which reverses the flow of time, which effectively changes the particle spin and momentum. Under these discrete symmetries, particles may have eigenvalues of 1 (even) or -1 (odd). For example a P -odd particles wavefunction may be of the form $\psi(x) \propto \sin(ax)$, which under P -transformations $P\psi(x) \propto \sin(a(-x)) = -\sin(ax)$.

Both the electromagnetic and strong interactions are invariant under P and C . The weak interaction, however, is known to violate both parity and charge conjugation symmetries. The first evidence of parity violation was measured using beta decays of cobalt-60 [35]; this experiment showed that parity is in fact violated maximally within the weak interaction. The

C -symmetry is violated by the fact that under charge conjugations helicity ¹ of a particle is unchanged (i.e., under C a left-handed neutrino would become left-handed anti-neutrino), but in nature only left-handed neutrinos and right-handed anti-neutrinos have been observed [36]. The combined CP symmetry was then thought to be symmetric under the weak interaction. CP -violation can manifest itself through:

- Direct CP -violation, in hadron decays
- CP -violation in neutral meson mixing
- CP -violation in the interference of mixing and decay

Direct CP -violation, also called CP -violation in decay, occurs where the decay amplitude $A_f = A(M \rightarrow f_{CP})$, for a generic particle (M) to decay into a CP -eigenstate (f_{CP}), differs from the CP -conjugate amplitude $\bar{A}_{\bar{f}} = A(\bar{M} \rightarrow \bar{f}_{CP})$. Direct CP -violation can occur both in charged and neutral mesons.

CP -violation in neutral meson mixing occurs when $|q|/|p| \neq 1$. In other words when the amplitude for a neutral meson M to mix into its anti-particle $\bar{M}$ is different than the amplitude for the reverse process ($A(M \rightarrow \bar{M}) \neq A(\bar{M} \rightarrow M)$).

CP -violation in the interference of mixing and decay occurs when imaginary part of the parameter

$$\lambda_f = \frac{p}{q} \frac{\bar{A}_f}{A_f} \quad (21)$$

deviates from zero, where the final state denoted as f reachable by both neutral meson and anti-meson under study.

Historically, first evidence of CP -violation has been experimentally measured in the observation of $K_{long} \rightarrow \pi^+ \pi^-$ decays [37], and since many other measurements have been done using b decays.

¹Helicity is defined as the projection of the a particles angular momentum on its momentum vector. Therefore a spin-1/2 particles helicity can take two values: +1 (“right-handed”) and -1 (“left-handed”).

2.5 Heavy quark production and fragmentation

The formation of heavy quarks in proton collisions can be generally seen as the convolution of hard and soft QCD processes, i.e., processes at high and low energy scales, respectively. The separation of these two components is possible by the factorization theorem. The hard process describes the interaction of two partons which produce heavy quarks, and can be calculated in perturbative QCD in terms of $\alpha_s(\mu_R^2, q^2/\Lambda_{QCD})$, where μ_R and q^2 are the renormalization scale and momentum transfer squared, respectively. The soft processes describe the quark and gluon densities (in terms of parton distribution functions, PDF) within the proton. Generally written, the heavy quark cross section has the form

$$\sigma^q \sim \sum_{partons} \int dx_1 dx_2 f_1(x_1) f_2(x_2) \sigma^{pert.}(p_1, p_2), \quad (22)$$

where f_i is the probability density function for finding parton i carrying the fractional momentum x within the projectile hadrons, and $\sigma^{pert.}(p_1, p_2)$ is the perturbative cross section in terms of initial parton momenta.

The translation of the unbound heavy quark to an observed final state hadron is also non-perturbative, and is described by a fragmentation function $f(z)$ that gives the probability of a quark to form a hadron with a fractional momenta z of the originally scattered quark. The cross section for a final state hadron has the following form

$$d\sigma(p_T)/dp_T \sim \sum_{partons} \int \frac{dz}{z} f(z) d\sigma^q(p_T/z)/dp_T. \quad (23)$$

In the following subsections hard parton scattering and hadron fragmentation will be described in more detail.

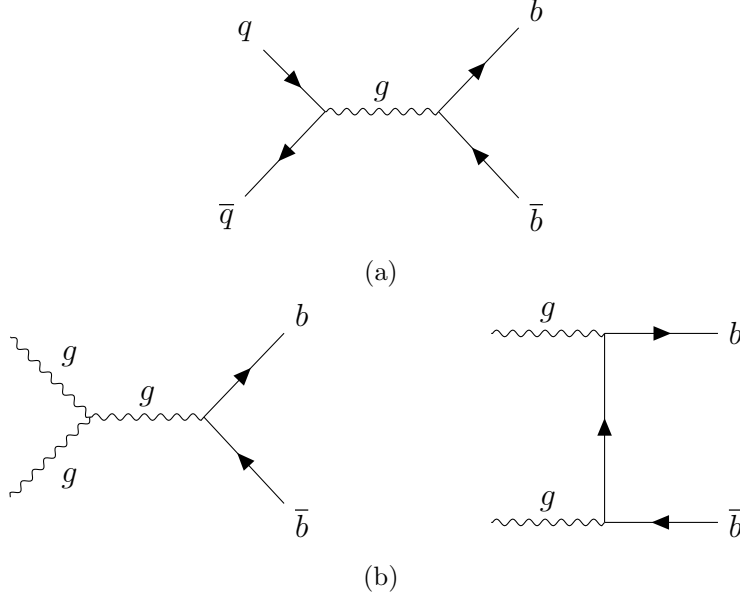


Figure 7: Lowest-order (LO) process that contribute to $q\bar{q} \rightarrow Q\bar{Q}$ (a) and $gg \rightarrow Q\bar{Q}$ (b).

2.5.1 Heavy quark production cross sections

At lowest-order (LO) in the strong coupling constant α_s ($\mathcal{O}(\alpha_s^2)$), the production of a heavy quark-antiquark pair ($Q\bar{Q}$) is dominated by

$$q\bar{q} \rightarrow Q\bar{Q} \text{ and } gg \rightarrow Q\bar{Q}, \quad (24)$$

which are illustrated by the four Feynman diagrams in Figure 7. At the TeV scale the dominant contribution to heavy quark production is $gg \rightarrow Q\bar{Q}$. In these LO diagrams there are no divergences in the propagators so the cross section is finite. The scale at which the strong coupling constant is evaluated is the minimum transverse momentum exchange in the t -channel diagram which is on the order of the quark mass. Since in the case of heavy quarks $m_q \gg \Lambda_{QCD}$, the production cross sections at LO can be reliably calculated using perturbation theory. However, to get accurate calculations, higher order contributions are needed.

Next-to-Leading-Order (NLO) effects are also important to evaluate heavy quark production; they are shown in Figure 8. In these processes an additional quark or gluon is

added to the final state, or the LO diagrams are altered with virtual corrections. At NLO it is possible to calculate the heavy-flavor cross section using due to the fact that the heavy b -quark mass removes collinear divergences. However at higher p_T , roughly 2-5 times the b -quark mass, convergence is spoiled due to large logarithms containing the ratio p_T/m_b , independent of the choice of renormalization or factorization scales. Explicitly, the perturbation expansion can be set in terms of the leading-log (LL), $\alpha_s^2[\alpha_s \log(p_T/m)]^k$, and the resummed next-to-leading logarithms (NLL), $\alpha_s^3[\alpha_s \log(p_T/m)]^k$.

The formalism of fixed-order plus next-to-leading-logs (FONLL) predicts the cross section exactly up to order α_s^3 (fixed-order) and includes the $\alpha_s^k \log(p_T/m)^k$ terms by merging the low p_T formalism up to a fixed-order (FO) and the high p_T formalism described by a resummation (RS) approach [38] which relies on the fragmentation function formalism.

In terms of the NLO, and resummed NLL, the cross section is

$$\begin{aligned} \frac{d\sigma}{dp_T^2} = & A(m)\alpha_s^2 + B(m)\alpha_s^3 \\ & + \left(\alpha_s^2 \sum_{i=2}^{\infty} a_i [\alpha_s \log(\mu/m)]^i + \alpha_s^3 \sum_{i=1}^{\infty} b_i [\alpha_s \log(\mu/m)]^i \right) \times G(m, p_T) + H.O. \end{aligned} \quad (25)$$

Here $\mu \approx p_T$ and the coefficients a_i and b_i depend on the center-of-mass energy, p_T , and μ . The function $G(m, p_T)$ is arbitrary but must approach 1 as m/p_T goes to zero, and comes from suppressed terms in the NLL part. The $H.O.$ stands for higher order terms which are suppressed by m/p_T and $\alpha_s^4[\alpha_s \log(p_T/m)]^k$. In the RS approach there are already FO order terms, and these are therefore subtracted. These terms are denoted as FO0M, which stands for fixed-order in the massless limit. In this simplified limit

$$A(m) = a_0, \text{ and } B(m) = a_1 \log(\mu/p_T) + b_0 \quad (26)$$

and the FO0M term is

$$FO0M = a_0\alpha_s^2 + (a_1\log(\mu/p_T) + b_0)\alpha_s^3. \quad (27)$$

A simplified formula for the FONLL formalism is

$$FONLL = FO + [RS - FO0M] \times G(m, p_T) \quad (28)$$

Uncertainties on the FONLL approach can be quite large ($\mathcal{O}(100\%)$) at transverse momenta near the quark mass and are dominated by the factorization and renormalization scales. Additional uncertainties are due to the heavy quark mass and parton distribution functions (PDF). The FONLL results used in Section 5 are given in [39], where the absolute 7 and 13 TeV cross sections are predicted with their ratio. In the ratio large theoretical systematic uncertainties cancel, as they are independent of beam energy, producing a total uncertainty on the order of 5-10%. Since these theoretical uncertainties on the ratio are on the order of experimental ones, a measurement of the 13 to 7 TeV ratio as a function of kinematic variables is now sensitive to constraining the gluon PDF used in the model.

2.5.2 Hadron fragmentation

QCD is able to predict hard process involving quarks and gluons because these are short distance processes and QCD is perturbative. At long distances, in which the quarks combine to form hadrons, perturbation theory cannot be used. Due to this there has been some development of phenomenological models to describe the non-perturbative fragmentation process. The most notable one being the string fragmentation model (Lund model), which is used by default in Pythia generators [40]. Other models are available, such as the cluster model, which is based of the pre-confinement property of parton showers [41].

The string, or Lund string model, starts from the concept of linear confinement. Two quarks, q and $\bar{q}$, moving apart from their production vertex will store potential energy

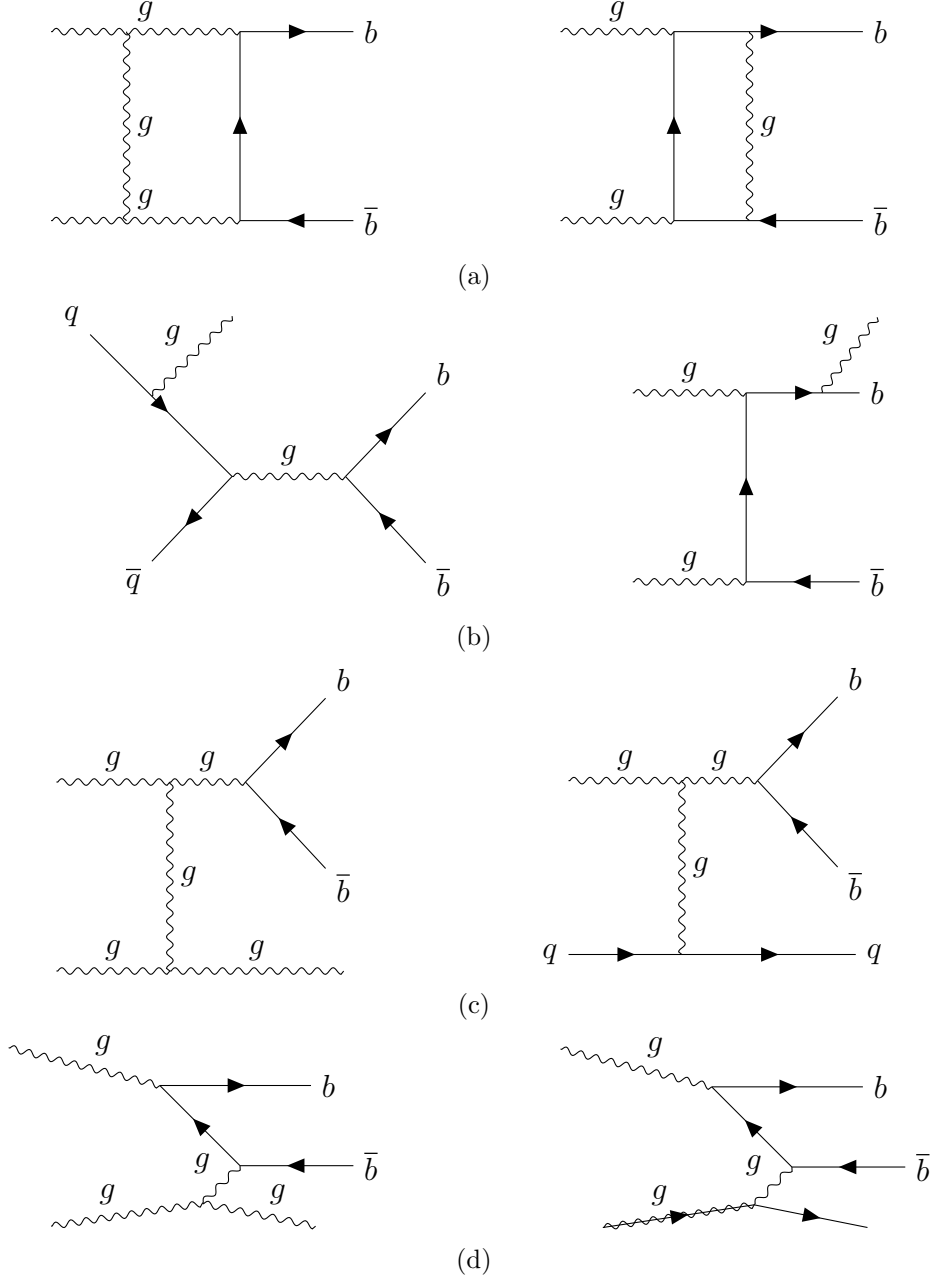


Figure 8: Next-to-Leading-Order (NLO) process that contribute to heavy quark production.

in a color flux tube, or string, that linearly increases as the distance between the quarks increases. At some point the string may break forming a new $q'\bar{q}'$ pair. The initial q -quark will combine with the $\bar{q}'$ to form a $q\bar{q}'$ meson, taking some fraction of available energy. The unpaired q' then form with another produced $q''\bar{q}''$ pair, and so on. This process will continue iteratively if the mass of the string is large enough. This fragmentation process is illustrated in Figure 9. Starting from the initial q -quark side is arbitrary and the opposite picture with the fragmentation starting on the initial $\bar{q}$ side is just as valid. This “left-right” symmetry constrains the fragmentation function and the Lund fragmentation function is symmetric and only has two free parameters determined from data.

Quantum mechanically the quarks produced by a string break are produced at the same point in space and pulled out by the color field. The Lund model involves quantum tunneling to compensate for the fact that the produced quarks with mass, m , in a linear force field with constant k , classically have to be produced at a distance $2l$ away from each other ($2m = 2lk$). Taking the overlap of the particles wave function inside the classically allowed region of $x > l$ (or $x < -l$), which behaves as a standard oscillator in a 1D linear potential, and the wavefunction in the classically forbidden region $|x| < l$, the amplitude is

$$A \propto \exp(-\pi m_q^2/k), \quad (29)$$

with m_q being the quark mass. From this tunneling process, production of a heavy quark is suppressed in the fragmentation process. The production ratios with respect to lighter quarks with a $k \approx 0.2 \text{ [GeV}/c]^2$ are $u : d : s : c = 1 : 1 : 1/3 : 10^{-11}$. Thus, heavy quarks are not produced in this soft fragmentation but only in the initial $g \rightarrow q\bar{q}$ hard process. This tunneling process also is responsible for producing a transverse momenta spectrum for the $q'\bar{q}'$ pair that is Gaussian and flavor independent.

Two models for baryon production exist in the Lund string model. The first being that baryon fragmentation occurs in the same way as meson fragmentation, except instead of

quark-antiquark pairs being produced from the color field diquark and antidiquark pairs are produced. The rate of diquark production is roughly 10% that of quark pairs. The second models assumes that two quarks are produced successively from the color field, hence earning the name “pop-corn” mechanism.

In the Lund model the fraction of remaining momentum z carried away by a produced hadron is given as the fragmentation function $f(z)$:

$$f(z) \propto \frac{1}{z^{1+m_q^2}}(1-z)^a \exp\left(-\frac{bm_\perp^2}{z}\right) \quad (30)$$

where the parameters a and b are free parameters, and $m_\perp$ is the transverse mass of the hadron. The factor m_q^2 is added if the mass of the quark is heavy. This equation holds if the remaining mass of the system is large enough; some tricks need to be applied at the end of the fragmentation process when using this model in generators.

The Lund string model has been successful in predicting the main features of hadronization. In particular in the string model, along with the two jets produced with the initial quark pair, a spray of hadrons will be produced. This is exactly what is observed in data. Measurements of particle multiplicities as a function of azimuthal angle in $e^+e^- \rightarrow 3$ jet events also provide a good test of fragmentation models. In [42] this was done with data collected by the TPC collaboration comparing Lund string, independent fragmentation, and Webber cluster models. In this analysis the Lund string model was able to reproduce the data the best.

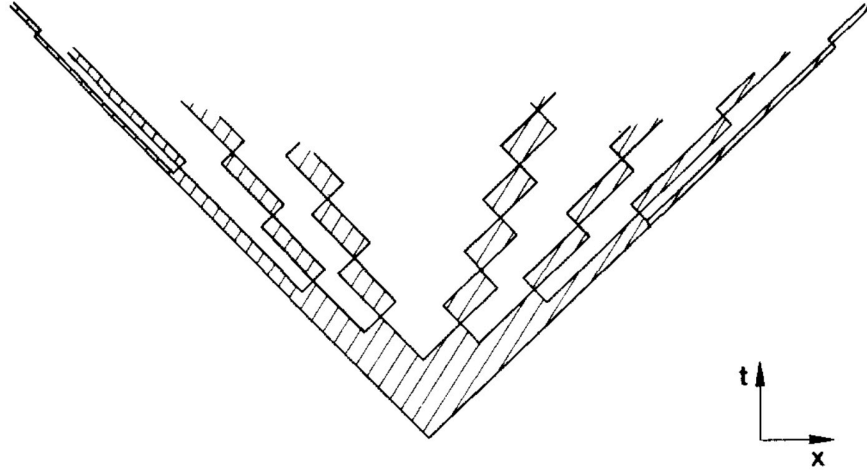


Figure 9: Illustration of the string fragmentation process with an initial $q\bar{q}$ produced at the initial vertex. The x -axis is spacial and the y -axis is time. Additional $q\bar{q}$ pairs are produced at subsequent vertexes where the strings break. Non-vanishing color fields are denoted by the hatched regions [3].

3 The LHCb experiment

3.1 The Large Hadron Collider

The Large Hadron Collider, or LHC for short, is currently the largest particle accelerator in the world located at the European Organization for Nuclear Research (CERN) on the Franco-Swiss border. The LHC is designed to accelerate beams of protons up to an energy of 7 TeV and to date the LHC has achieved beams with an energy of 6.5 TeV, producing collisions within the experimental halls with a center-of-mass energy of 13 TeV.

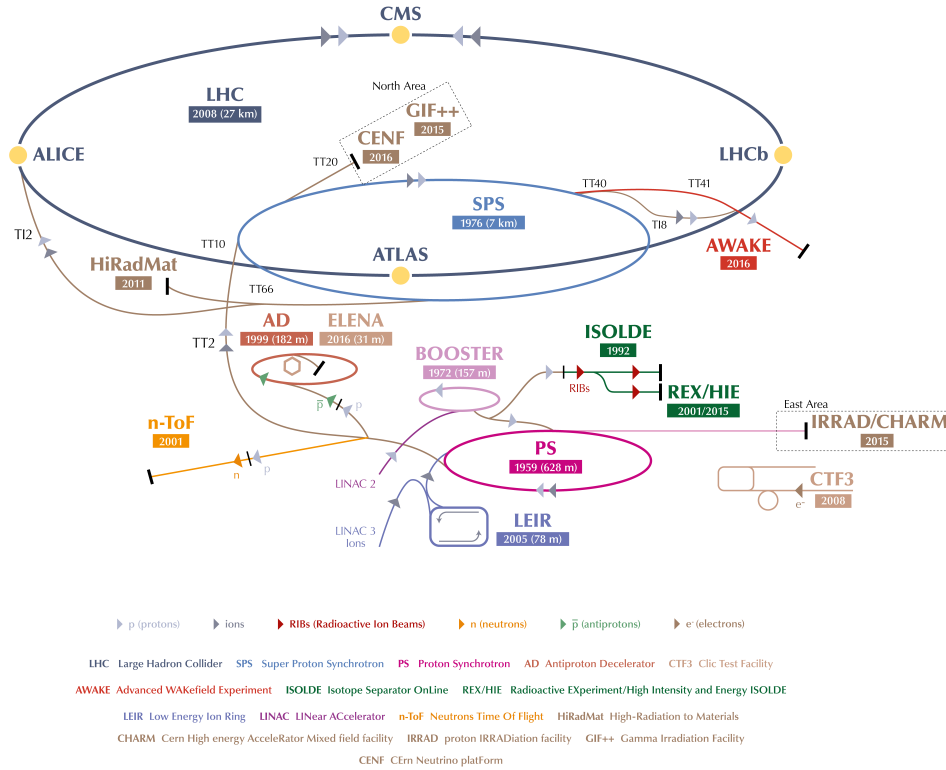


Figure 10: The CERN accelerator complex [4].

With a circumference of 27 km, the LHC is actually the last step of a chain of accelerators at CERN known as the *accelerator complex* shown in Figure 10. The accelerator

complex starts with the Linear Accelerator 2 (LINAC 2) which takes ionized hydrogen gas, i.e., protons, and accelerates them to 50 MeV with a series of alternating radiofrequency (RF) cavities. After LINAC 2, the proton beams are injected into the Proton Synchrotron Booster (PSB) made up of four superimposed synchrotron rings. Here the beams are further accelerated up to 1.4 GeV, before being fed into the Proton Synchrotron (PS). The PS, first operating in 1959, was once the worlds highest energy accelerator supplying protons and other heavy elements directly to experiments. Now, the PS supplies protons and other heavy elements, accelerated to 25 GeV, to the Super Proton Synchrotron (SPS), the second largest accelerator at CERN. Turned on in 1976, the SPS, capable of accelerating protons to 450 GeV, was the workhorse for CERN before the Large Electron-Positron (LEP) collider and the LHC. Most notably the W and Z bosons were discovered in proton-antiproton collisions delivered from the SPS [43] [44] [45] [46]. The SPS today acts as source of high-energy protons to current CERN experiments and as the final step before injecting beams into the LHC ring.

In the LHC, two opposite beams are accelerated up to unprecedented energies inside two ultra-vacuum tubes 100 meters underground. Beams are guided and focused around the ring with superconducting magnets - more than 1200 dipole magnets and almost 400 quadrupole magnets - cooled to -271.3° C with liquid helium. The LHC circulates beams containing over 2800 bunches during nominal operation, where each bunch contains about 10^{11} protons. Bunches are roughly 30 cm long with a transverse size on the order of a mm and in nominal operations, are separated by a time of roughly 25 ns. At four points along the LHC ring the beams are focused ever more to transverse sizes of around $10\text{ }\mu\text{m}$, and then collided at a rate of 40 MHz in the four LHC experiments: ATLAS (A Toroidal LHC ApparatuS [47]), CMS (Compact Muon Solenoid [48]), ALICE (A Large Ion Collider Experiment [49]), and the LHCb (LHC beauty) experiment.

3.2 The LHCb detector

The LHCb detector [5], shown in Figure 11, is a single-arm forward spectrometer dedicated to heavy flavor physics. The LHCb detector covers a pseudo-rapidity region of approximately $2 < \eta < 5$. This coverage was chosen because when $b\bar{b}$ quark pairs are produced in high energy pp collisions they tend to both fly into the same forward or backward cone.

The detector is designed to operate at a luminosity of $2 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$, which is two orders of magnitude less than the luminosity the LHC delivers ($10^{34} \text{cm}^{-2} \text{s}^{-1}$). Operating at a lower luminosity produces less interactions, or primary vertices (PVs), per bunch crossing. Having several PVs produces complications in physics analysis such as tracks being identified coming from the wrong PV. Additionally from a hardware point of view operating at lower luminosities produces less radiation damage in the detectors. To account for the high LHC luminosity, the beams at the interaction point are not collided head on, but are separated slightly in a process called *luminosity leveling*. Over the course of a physics run the beam separation is adjusted to produce a constant luminosity.

The first physics operations began in 2010, and ran till 2013 before long shutdown 1 (LS1). This corresponds to Run-I. During that time roughly 3 fb^{-1} worth of data was collected (approximately 1 fb^{-1} in 2011 and 2 fb^{-1} in 2012). LHCb started taking data again in 2015 and is scheduled to take data till the end 2018. This corresponds to Run-II. During which about 360 pb^{-1} , 1.67 fb^{-1} , and 1.82 fb^{-1} worth of data has been collected in 2015, 2016, and 2017, respectively.

The LHCb detector is composed of many sub-detectors which are dedicated to either tracking, particle identification, or trigger, and will be described in the following sub-sections in more detail.

3.2.1 Dipole magnet

The dipole magnet in the LHCb experiment is used to bend charged particles in the horizontal plane allowing a measurement of their momenta. Located after the Trigger Tracker (TT)

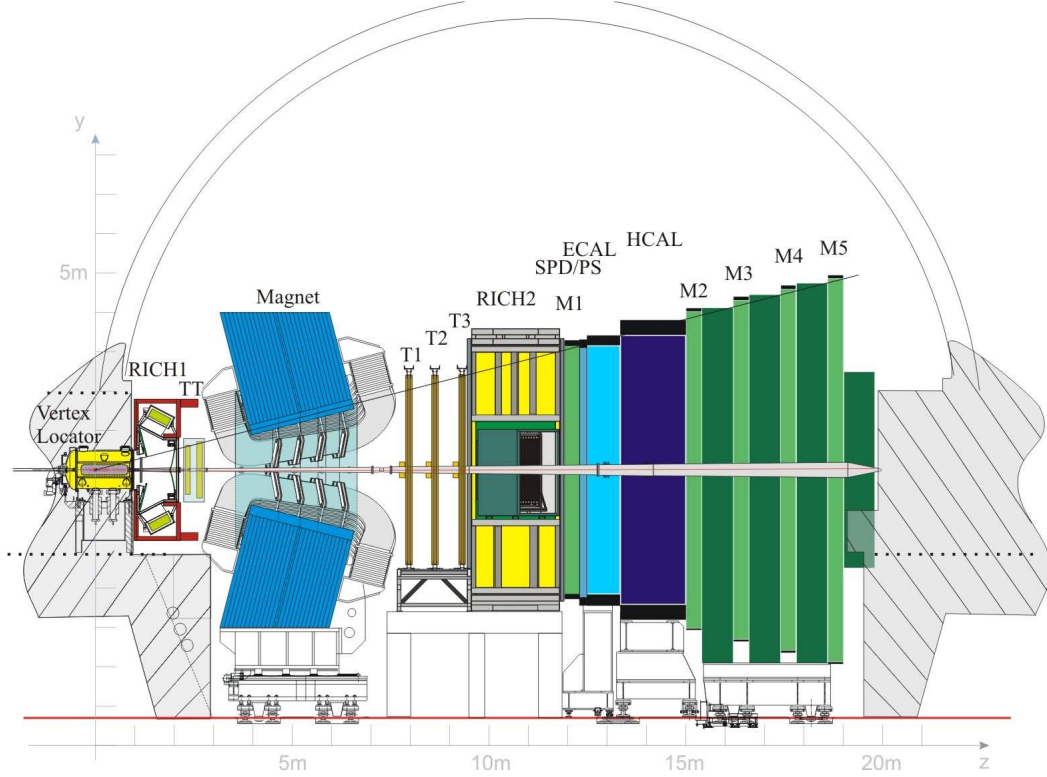


Figure 11: Layout of the LHCb detector [5].

and before the Tracking Stations (T Stations), the design of the magnet consists of two trapezoidal coils arranged symmetrically in the vertical direction inside a window-frame iron yoke. Figure 12 shows the design of the dipole magnet looking upstream towards the interaction region. The coils are made from 15 pure aluminum layers with a hollow center for water cooling. The magnet yoke is constructed with 100 mm plates of laminated low carbon steel having a maximum weight of 25 tons per plate. The design of the magnet produces an integrated magnet field of 4 Tm for traversing tracks that are 10 m long.

In order to achieve the required momentum precision for charged tracks the integrated magnetic field has to be known to $O(10^{-4})$, and the peak field to a few millimeters. Additionally the magnetic field direction is periodically reversed to cancel systematic uncertainties in physics analysis, so the field profile must be consistent in both polarities. An 80 mm x 80 mm grid of Hall probes were used to map the magnetic field in the volume of the magnet, inside the RICH, and between the TT and VELO. In total 60 sensor cards equipped with 3

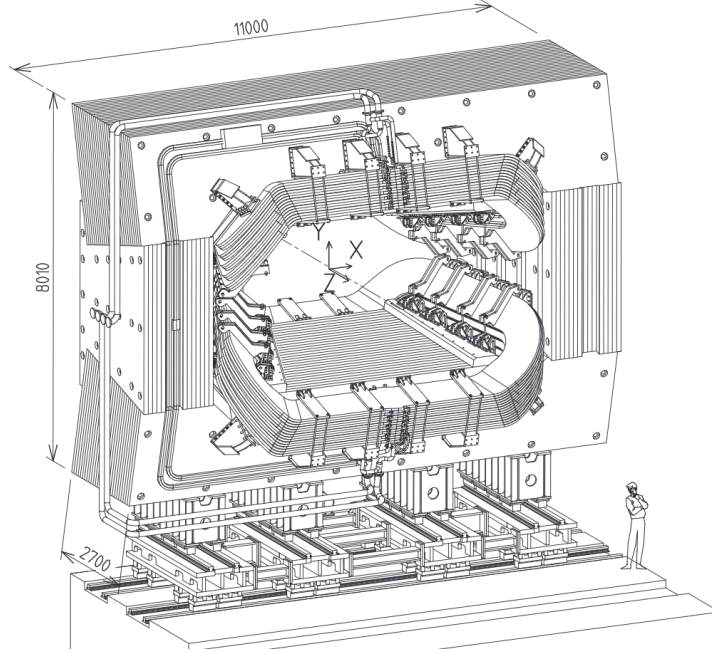


Figure 12: View of the LHCb dipole magnet looking from downstream the interaction region [5].

orthogonal Hall probes and necessary electronics are mounted on the 80 mm x 80 mm grid and the measurement was aligned to 1 mm with respect to the experiment reference frame. The final precision of the measured magnetic field was 4×10^{-4} and the absolute field is consistent with both magnetic polarities.

3.2.2 Vertex Locator

The VERtex LOcater (VELO) is used to measure track coordinates closest to the proton-proton interaction region, allowing the measurement of vertices displaced from the primary interaction vertex. This is crucial for identifying decays of c - and b -hadrons.

The entirety of the VELO detector is located in a vacuum and is constructed from 42 silicon modules. Each module consists of two n^+ -in- n silicon strip detectors measuring both the r - and ϕ -coordinates, carbon-fiber support, 32 front-end ASICs (Beetle chips [50]), and embedded cooling. There are an additional 4 modules placed upstream of the interaction region and comprise the *pile-up veto system*. Figure 13 shows a $x-z$ cross section of the

VELO at $y=0$. The VELO is split into two halves (21 modules each) that can move in the horizontal direction. During LHC injection the beam aperture is larger and the VELO has to retract (*open* position) to avoid damage to the sensors. During nominal physics running the VELO is then *closed* to provide closest coverage in the interaction region. When in the closed configuration modules on both halves overlap to avoid gaps in the azimuthal coordinate. Figure 13 sketches these *open* and *closed* configurations with two modules. In total the VELO is one meter in length along the beam direction and covers a pseudo-rapidity region of 1.9 to 4.9. The expected fluence in 1 MeV neutrons per year is around

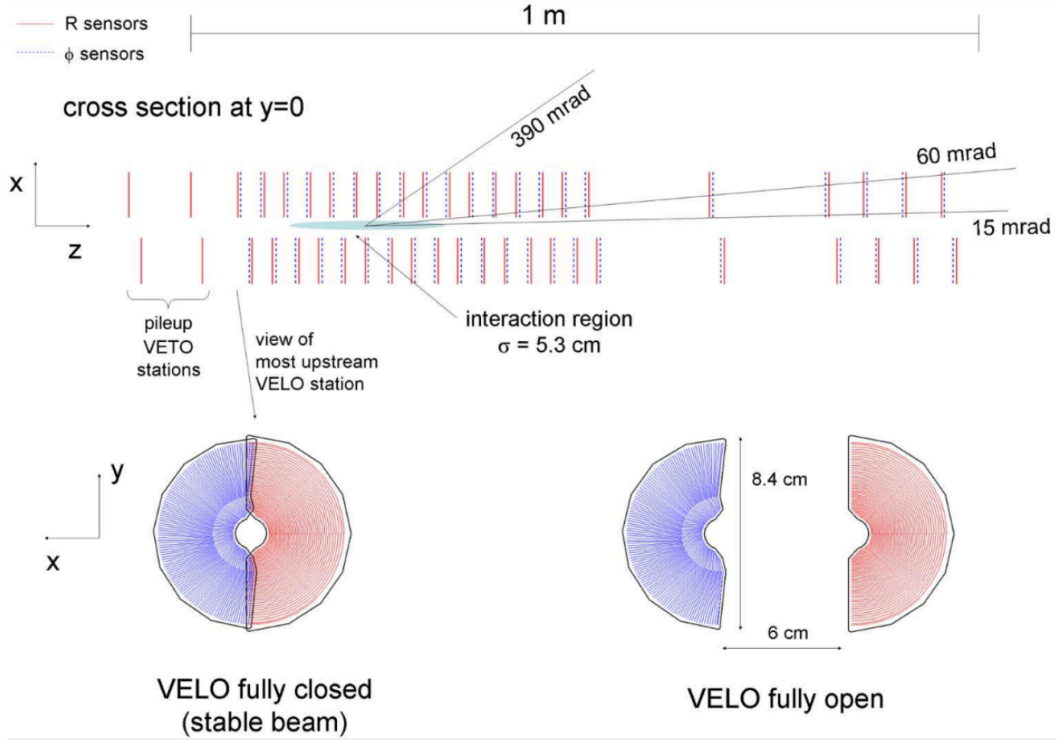


Figure 13: $x - z$ cross section of the VELO detector panes at $y=0$ with the detector in its closed position. The bottom two sketches show two VELO modules in the closed (left) and open (right) configurations [5].

$1.3 \times 10^{14} n_{eq}/\text{cm}^2$, and therefore a n^+ -in- n with p-spray detector technology was chosen with a thickness of $300 \mu\text{m}$. To mitigate the affects of radiation damage the sensors are kept at a temperature between -10 and 0 degrees Celsius and are continuously cooled to prevent

unwanted long-term annealing effects.

Two types of sensor geometries are used in the VELO: one that measures the r -coordinate and the other the ϕ -coordinate. Both geometries are sketched in Figure 14. This cylindrical coordinate system was chosen over a rectilinear system to improve reconstruction time. Sensors that measure the r -coordinate consist of semi-circle strip implants with the centers being the nominal center of the LHC beam. The pitch of the strips varies linearly from $38\text{ }\mu\text{m}$ at the inner most region to $101.6\text{ }\mu\text{m}$ along the outer most region. Furthermore, each R-sensor has strips segmented into four 45° regions to reduce occupancy and strip capacitance. Sensors that measure the ϕ -coordinate have strips that extend radially outward. Phi-sensors are split into an inner and outer region. The inner region has strips with a starting pitch of $78.3\text{ }\mu\text{m}$ that extend out to a radius of 17.25 mm , where the outer region begins. The outer region strips have a starting strip pitch of $39.3\text{ }\mu\text{m}$. To improve pattern recognition, the strips are further skewed so the inner strips make a 20° angle with the radial and the outer strips make a 10° angle with the radial. Readout of strips far from the sensor edge are done using a second metal layer isolated from the AC strips by a thin layer of SiO_2 .

During Run-I operations the VELO achieved a hit resolution from 4 to $20\text{ }\mu\text{m}$ at a strip pitch of 40 to $100\text{ }\mu\text{m}$, respectively. The impact parameter resolution, determined by test beams, is $\sigma_{IP} = (15 \pm 29/p_T)\text{ }\mu\text{m}$. The occupancy during normal running periods is less than 1% .

3.2.3 Trigger Tracker

The Trigger Tracker (TT) is located right before the dipole magnet and provides additional track coordinates. The TT consists of four 1.5 meters tall by 1.3 meters wide planes of silicon strip detectors and is housed in a light-tight box that electrically and thermally isolates the detector. Inside the detector volume the temperature is kept below 5° C and the detector box is continuously flushed with nitrogen gas. The four planes of silicon detectors are arranged in a x - u - v - x configuration where the first and last planes have strips aligned vertically with

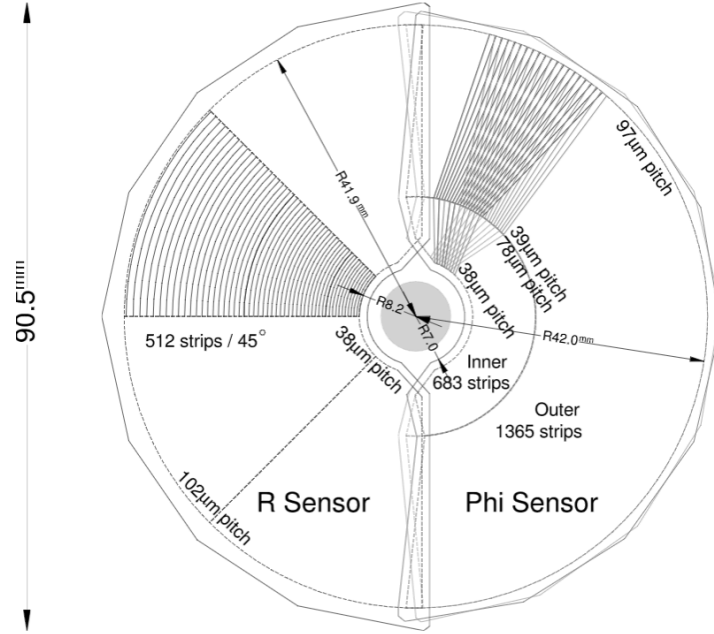


Figure 14: Sketch showing both r and ϕ sensor geometries. Only a portion of the strips are shown as an example [5].

the LHCb coordinate system, and the second and third layers are rotated at stereo angles of -5° and 5° , respectively. Figure 15 illustrates one TT layer.

Each layer is split into two halves that can retract away from the beam pipe and each half is constructed of 7 (first two layers) or 8 (last two layers) columns of silicon sensors that cover the entire LHCb acceptance in the vertical dimension. Columns are made up of two modules that are instrumented with seven silicon sensors each. Adjacent modules are staggered in z by about 1 millimeter, and in x by a few millimeters to avoid any gaps in the acceptance. Two additional modules are placed directly above and below the beam pipe at each detector layer.

Modules farther from the beam pipe (4-3 module) contain two readout hybrids at the end module. The first four silicon sensors have strips wire bonded together and are connected to the first readout hybrid via a Kapton cable. The remaining three silicon sensors have their strips wire-bonded together and are connected to the second readout hybrid via a Kapton cable. Modules close to the beam pipe (4-2-1 module), where the particle flux is larger, are

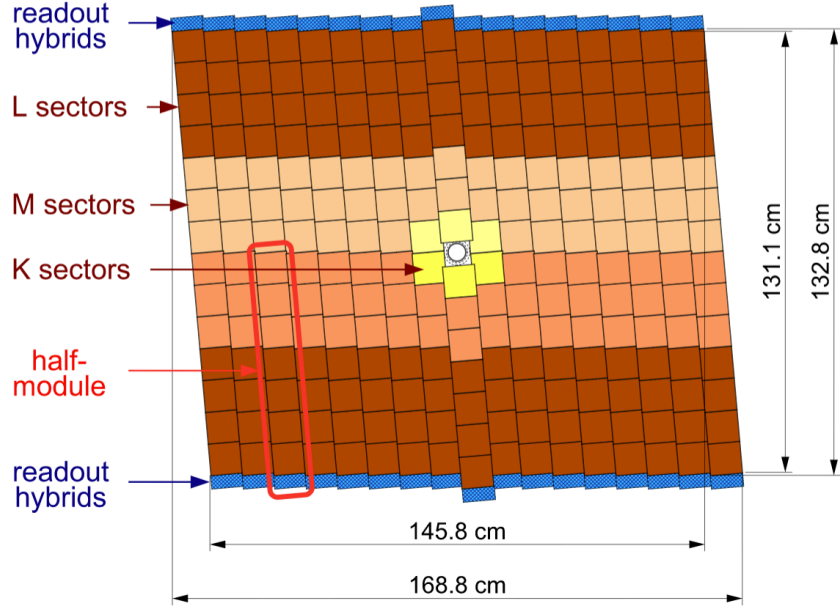


Figure 15: Layout of the third TT layer [5].

split into three readout regions with three readout hybrids at the end of the module. Like the former category, the first four silicon sensors are wire bonded and read out by the first readout hybrid connected by a Kapton cable. The remainder three silicon sensors are split into two readout regions with two wire bonded silicon sensors readout by one readout hybrid and the final silicon sensor at the end of the module readout by its own readout hybrid. Both regions are connect to the hybrid with Kapton cables.

All silicon sensors used in the TT are p-in-n technology and are $500\text{ }\mu\text{m}$ thick. Each sensor is 9.64 cm long by 9.44 cm long and contains 512 strips with a pitch of $183\text{ }\mu\text{m}$.

3.2.4 Inner Tracker

At each of the three tracking stations downstream of the dipole magnet are four inner tracker boxes that surround the beam pipe providing a measurement of track coordinates. Figure 16 shows a sketch of the one inner tracker layer surrounding the LHC pipe. Boxes above and below the beam pipe contain four layers of seven detector modules. Layers are arranged in a x - u - v - x configurations where the first and last layers have strips vertical in the LHCb

frame, and the second and third layers are rotated at stereo angles of -5° and 5° , respectively. Detector modules in these boxes consist of one silicon sensor and one readout hybrid. Boxes to the left and right of the beam pipe also contain four layers of seven detector modules. These modules contain two silicon sensors with strips wire bonded together and one readout hybrid and are kept at a temperature of 5°C and is continuously flushed with nitrogen gas. Two types of silicon detectors are used in the inner tracker. Both utilize single sided p-in-n

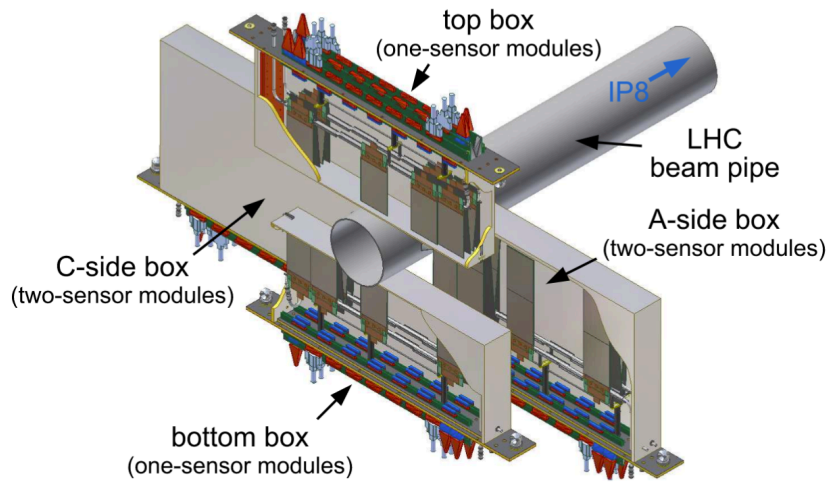


Figure 16: Layout of one IT station [5].

technology and have similar geometries containing 384 strips with a pitch of $198\ \mu\text{m}$ covering an area of 7.6 cm wide by 11 cm tall. Modules with one sensor have sensors that are $320\ \mu\text{m}$ thick and two-sensor modules have silicon sensors that are $410\ \mu\text{m}$ thick. Thicknesses were chosen to optimize the signal to noise ratio while maintaining an acceptable material budget.

3.2.5 Outer Tracker

The Outer Tracker (OT) consists of four layers of drift-tubes at each of the three tracking stations downstream of the dipole magnet. The four layers are arranged in a $x-u-v-x$ config-

urations where the first and last layers have drift-tubes vertical in the LHCb frame, and the second and third layers are rotated at stereo angles of -5° and 5° , respectively. Each station has an active area of 5.971 m by 4.850 m and covers the entire LHCb acceptance outside of the IT. Stations are composed of two retracting halves with each halve made of arrays of gas-tight modules. Modules contain 64 straw-tubes arranged in two staggered mono-layers. Drift-tubes are 4.9 mm in radius and contain a counting gas mixture of 70% Argon and 30% CO_2 which provide a fast drift time below 50 ns, and a overall spacial resolution of $200\ \mu\text{m}$.

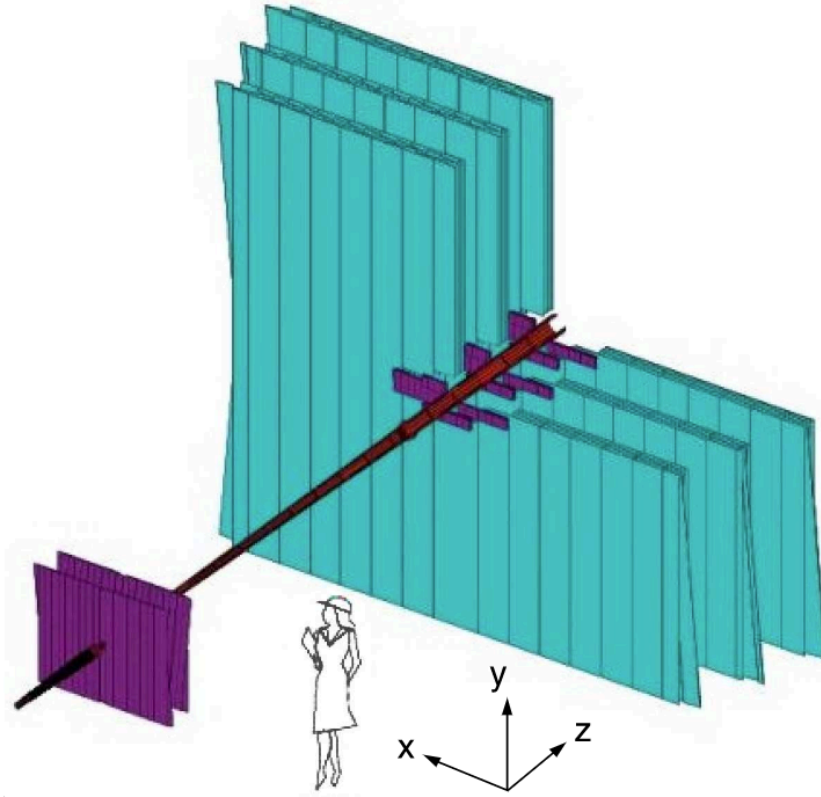


Figure 17: Layout of the three OT stations. Shown in the bottom left are the TT stations for comparison [5].

3.2.6 Calorimeters

The calorimeter system is located between the first and second muon station, downstream of the magnet. Three components comprise the calorimeter system: scintillating pad detector (SPD) and pre-shower (PS), electromagnetic calorimeter (ECAL), and hadronic calorimeter

(HCAL). All components of the calorimeter rely on scintillating material with wavelength-shifting fibers to transmit the photons to photo-multipliers. All calorimeter systems are segmented such that areas closer to the beam pipe have a finer granularity (see Figure 18)

The SPD and PS are located first on the calorimeter system moving downstream from the dipole magnet and consist of high-granularity scintillating pads separated by a lead converter. The SPD only detects charged tracks while the PS also detects both charged and neutral tracks by electromagnetic showers produced in the lead converter. With this backgrounds from neutral pions can be reduced by checking for hits in the SPD with an associated electromagnetic shower.

The ECAL, located right after the PS, is composed of alternating 4 mm thick scintillators and 2 mm thick lead absorbers spanning a total distance of 42 mm along the beam axis. Level 0 trigger requirements demanded that the ECAL fully contained the electromagnetic shower and therefore the ECAL was chosen to be 25 interaction lengths.

The HCAL, located right after the ECAL, is composed of 4mm thick scintillators and a 16 mm thick lead absorber. The HCAL does not fully contain the hadronic shower as it is only 5.6 interaction lengths. This was because trigger requirements were less stringent on the HCAL, and of space limitations.

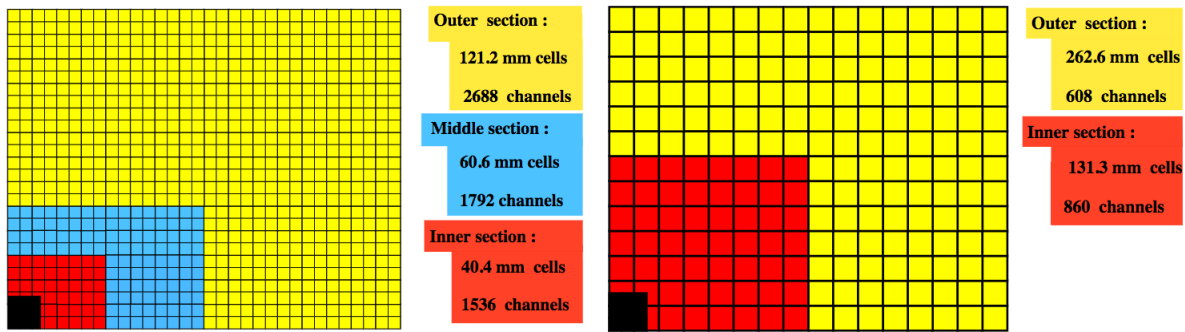


Figure 18: Segmentation of one quadrant of the calorimeters. The left sketch shows segmentation for the SPD/PS and ECAL while the right shows for the HCAL [5].

3.2.7 Ring imaging Cherenkov detectors

Two Ring Imaging Cherenkov (RICH) detectors are used for particle identification in LHCb: one before the TT detector (RICH1), upstream of the magnet, and one between the T stations and the first muon station (RICH2). RICH1 covers the entire LHCb acceptance and uses a C_4F_{10} radiator that allows discrimination of tracks with momenta between 1 and 60 GeV. RICH2 covers a reduced acceptance in the forward direction and can identify particles with a momentum of 15 to 100 GeV. In both RICH detectors Cherenkov photons are reflected outside the LHCb acceptance using both spherical and flat mirrors onto HPD detectors. The optical system for the RICH1 detector are located above and below the detector, whereas for RICH2 they are to the sides of the detector (see Figure 19). Figure 20 shows the reconstructed Cherenkov angles in the RICH1 detector for isolated hadron and muon tracks. Over the entire momentum range there is good π , K , and p separation, except for low momentum protons.

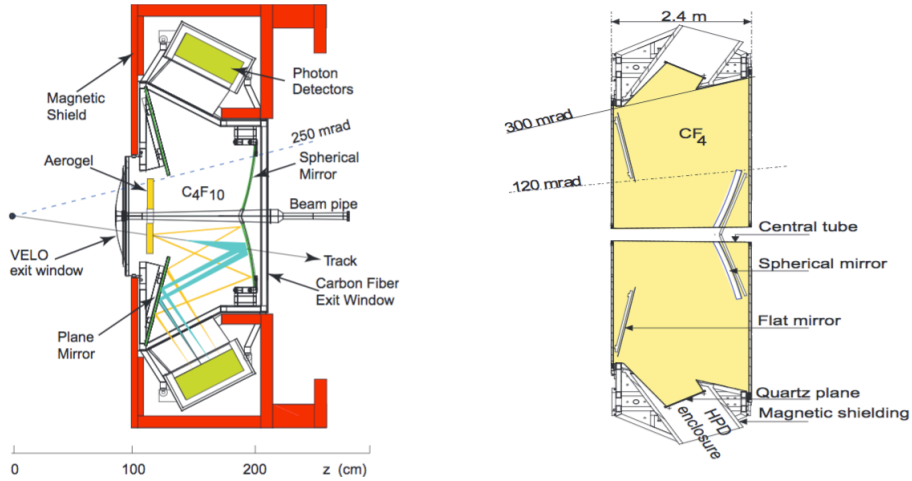


Figure 19: Schematic of RICH1 (left) and RICH2 (right). For RICH1 the perspective is looking from the side and for RICH2 the perspective is looking from the top [5].

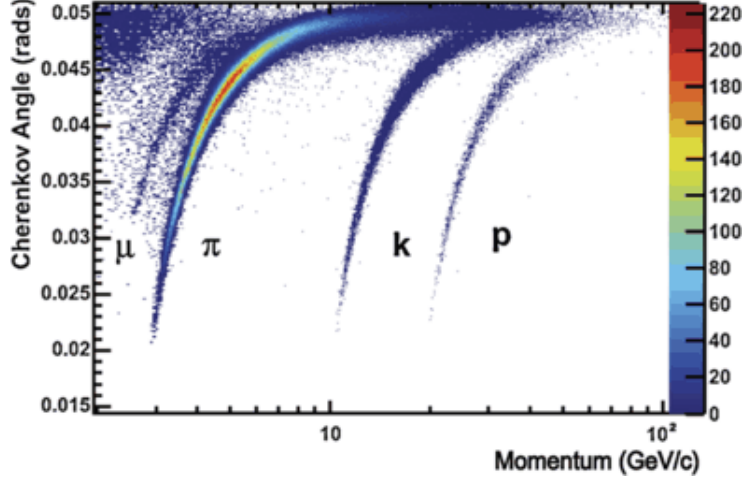


Figure 20: Detected Cherenkov angle as a function of particle momentum in the C_4F_{10} (RICH1) detector [6].

3.2.8 Muon system

The muon system is comprised of five rectangular stations (denoted M1, M2, etc.); one placed right before the calorimeters, and the rest downstream as shown in Figure 21. The M1 station is located before the calorimeters to improve the measurement of muon p_T used in the muon L0 trigger. Between each station 80 cm iron absorbers select muons with a minimum momentum of about 6 GeV. The muon stations are projective, meaning that station farther downstream is progressively larger to cover the full LHCb acceptance. Each station is partitioned into x and y *logical pads* which provide a yes/no signal for muon hits. Each station is split into four quadrants and each quadrant is split into four regions depending on the vicinity to the beam pipe. Figure 22 sketches the partitioning of logical pads for M1. Stations M1, M2, and M3, used for a stand-alone muon p_T trigger determination have a finer partitioning in the bending plane, where M4 and M5 are primarily to ensure tracks are penetrating muons and have a coarser partitioning. Most of the logical pads are constructed using 1368 multi-wire proportional chambers (MWPC) except the higher radiation environment of the inner-region of M1, which uses radiation-hard triple gas electron multipliers (GEM). The MWPC using a 40:55:5 gas mixture of Ar, CO_2 , and CF_4 , respectively. The same gas mixture is used on the GEM detectors but with a mixture of 45:15:40, respectively.

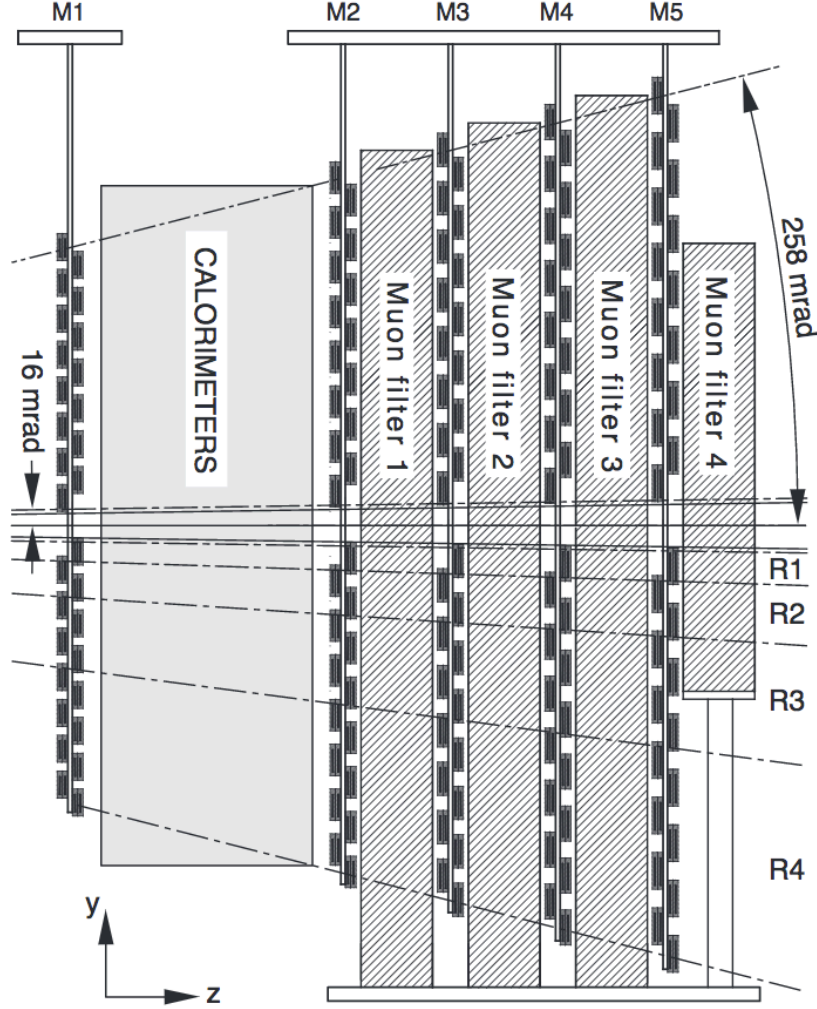


Figure 21: Layout of the muon stations as viewed from the side of the detector [5].

3.2.9 Trigger

The LHCb trigger is split into three components starting with a Level-0 (L0) hardware trigger and the two High-Level software Triggers (HLT1 and HLT2). The L0 trigger is based on custom electronics and reduces the 40 MHz bunch crossing frequency to 1 MHz. The First HLT1 trigger performs a partial reconstruction of events, which are then buffered to disk while a real-time detector calibration and alignment is performed, and then a full reconstruction is performed in HLT2; this reduces the rate to 12.5 kHz (see Figure 23 for

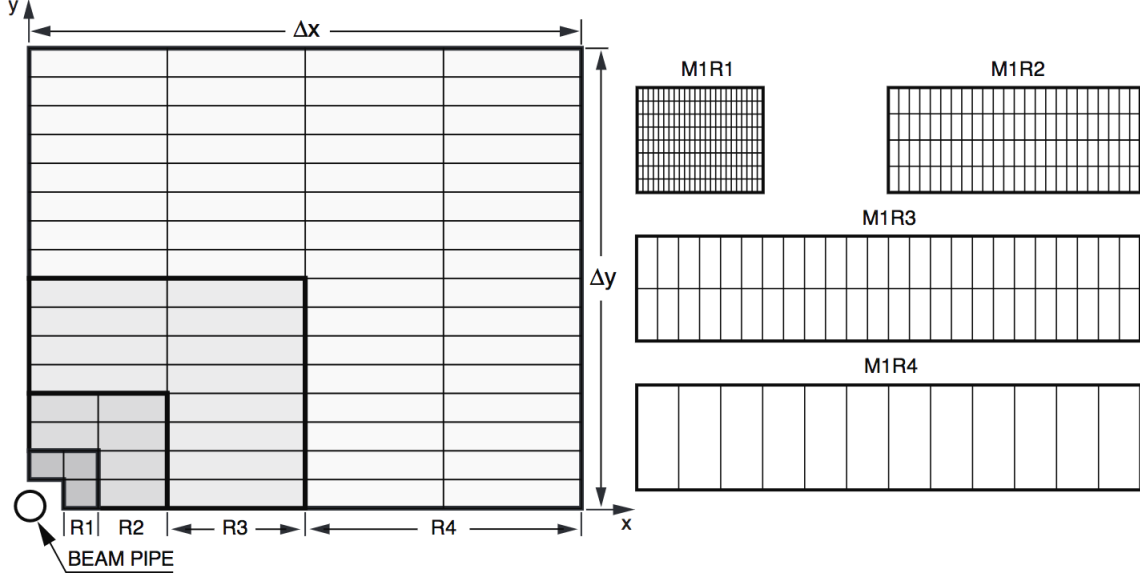


Figure 22: Layout of the segmentation in one quadrant of muon station 1 (M1). On the left are shown the chamber segmentation. Each station contains a total of 276 chambers. On the right are shown the logical segmentation of one chamber. Stations M2 and M3 (M4 and M5) have double (half) the number of logical pads in the vertical direction in each chamber [5].

a schematic outlying the trigger strategy). In Run-I, the high-level triggers was based on a simpler reconstruction and faster compared to high-level triggering strategy in Run-II. As a consequence in Run-I the online and offline reconstruction were different and the online did not use the latest calibration and alignment. Each trigger level will be described in more detail below.

The L0 trigger consists of three systems: The pile-up system, L0-Calorimeter, and L0-Muon trigger. The pile-up system was intended to measure the number of vertices in the bunch crossing using four R-coordinate VELO sensors placed upstream of the interaction region. The experiment ended up operating at a higher number of visible interactions and the pile-up system was not used in the L0 trigger and instead used for luminosity measurements. The L0-Calorimeter uses information from the calorimeter system to select events with electrons, photons, or hadrons with a transverse energy (E_T) above a set threshold. ECAL and HCAL clusters of 2 by 2 cells are used to calculate the E_T of particles. Photons above the E_T threshold are identified with hits in the PS but not not SPD, these events

correspond to the L0Photon candidates. Electrons are selected in the same way except they now require hits in the SPD. These events define L0Electron candidates. Finally the hadrons are selected with above threshold E_T in the HCAL and correspond to L0Hadron candidates. The L0-Calorimeter trigger can also VETO an event with a high multiplicity with a threshold on the number of SPD hits. The L0-Muon trigger relies on the five muon stations, which reconstruct muon transverse momenta with a precision of about 20%. Two muons with the highest transverse momentum (p_T) in each detector quadrant are looked for in the L0 trigger and are selected if the p_T of one track is above a set threshold or if the product of the two muons p_T is above a set threshold. All L0 components are then connected to a Level-0 Decision Unit (L0 DU) which makes the final trigger decision per bunch crossing. The output of the L0 DU is about 1 MHz.

The HLT runs on a computer farm with about 2000 computing nodes. Starting with the HLT1, L0 objects constructed using the VELO and TT stations are passed to the HLT1 algorithms. Due to CPU constraints the HLT1 only partially reconstructs the event to reject uninteresting events, reducing the total rate to about 30 kHz. At this point events are buffered to disk while a real-time detector calibration and alignment is performed in a few minutes on the trigger farm. The alignment task consists of an iterative procedure which reduces the residuals of the Kalman track fit and the alignment constants of the RICH mirrors. The calibration task consists of updating the RICH refractive index and the Hybrid Photon Detectors (HPD) images. The former can change due to environmental changes and monitoring systems are not precise enough to compute the expected refractive index with satisfactory precision. A scale factor is fit for using the measured and expected Cherenkov angles. The HPD images are affected by the magnetic and electric fields and offline images are enhanced, and a Sobel filter is applied to detect ring edges. Finally, a global time parameter is fitted for and used to calibrate the OT measured drift time. After the real-time calibration and alignment the HLT2 fully reconstructs events and stores events with a rate of 12.5 kHz.

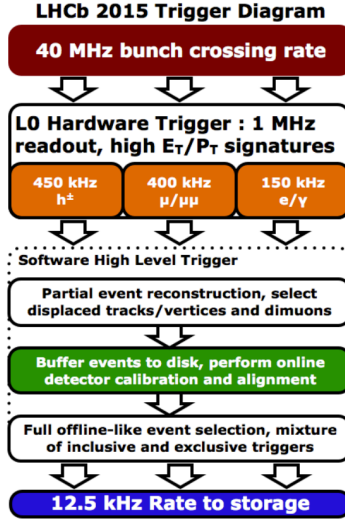


Figure 23: Schematic showing the trigger strategy in Run-II [7].

3.2.10 LHCb software

The LHCb software is built from a collection of *projects* based on the Gaudi framework [51]. Each project is made of a coherent set of software packages designed for a specific task.

Reconstruction is done with the BRUNEL package [52] which utilizes two independent tracking algorithms to construct tracks from either VELO and TT, or VELO and T-station detector hits (track segment definitions are shown in Figure 24). Tracks that have an overlap in detector hits with another higher quality track are suppressed with a Clone Killer algorithm. Ghost tracks, falsely reconstructed tracks built from track segments incorrectly associated in the reconstruction algorithm, are not explicitly removed from data but can be discriminated against using an algorithm that assigns a ghost probability per track.

After reconstruction a decay chain can be constructed, for example the $B_s \rightarrow D_s \mu \nu$ decay. However the size of the data is too large and therefore a set of centralized data criteria is used to minimize data storage. These centralized selections are known as *stripping* selections and each set of selections is called a stripping line. Stripping lines are organized into different LHCb working sectors (e.g., semileptonic decays, rare decays, charm decays, etc.) and many stripping lines contain similar selection criteria. Data stripping as described above is handled by the DaVinci package [52]. Stripped data is then processed offline by

users producing data tuples to be analyzed. Within the `DaVinci` package users can also implement various C++ analysis tools to further sort data (e.g, MVA analysis selections) or build more complicated decays chains by combining more tracks in the event.

There are several other LHCb software packages used for Monte Carlo (MC) simulations. Generation of pp collisions and the passage of particles through the experiment is achieved with the `Gauss` package [53], with `PYTHIA` [40] [54] as the primary pp generator and `EvtGen` [55] modeling non-coherent B -decays. The `Geant4` toolkit [56] [57] models the interaction of particles with the detector. The response of the detector is done by the `BOOLE` package and trigger emulation by the `MOORE` package [52]. At this point MC events are processed with the same reconstruction and stripping software as data.

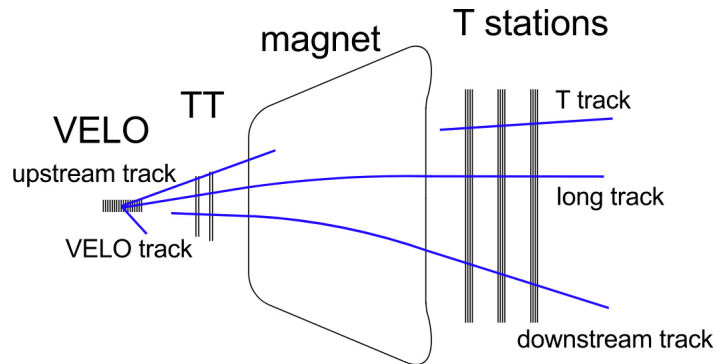


Figure 24: Schematic showing the LHCb tracking detectors and different types of track segments used in the tracking algorithm [8].

3.2.11 Definition of LHCb variables

Several abbreviations are used when describing event selections in physics analysis and will be defined here.

In trigger decisions events can be triggered independent of particular signal trigger decision, i.e., something else in the event fired a trigger decision. These events are classified as *TIS* on that particular signal trigger decision. Conversely, signal events that fired a particular trigger decision are called *TOS* on that trigger decision. In the two analyses presented

in this work, muon based trigger algorithms are used, and, additionally, the muon transverse momentum must exceed a minimum value (e.g., muon $p_T > 1100$ MeV). Additional topological decisions are used in HLT2 requirements [58].

Hadron particle identification variables are constructed using the log of the difference in likelihoods of a track being identified as one hadron specie against the hypothesis of the track being a different hadron. Likelihoods are constructed from information in the RICH detectors and track information. These are typically denoted as $DLLh$, where, h can be a pion, kaon, or proton, and these give the likelihood difference of h with respect to the default pion hypothesis. In the tables in this work, $DLLh$ is the same as $PIDh$.

Muon identification variables, DLL and $isMuon$, are constructed using the muon stations, and the calorimeter and RICH systems in the DLL variable [59]. $isMuon$ is a loose binary selection of muon candidates that is based on the penetration of muons through the calorimeters and iron filters. An additional variable, called $NShared$ and is defined as the number of identified muon tracks that share hits with the muon candidate, is used to reject false candidates.

Additional definitions used:

- DOCA: the distance of closest approach of a track with respect to a vertex
- DIRA: cosine of the angle between the momentum of the particle and the direction vector from some reference vertex
- IP: impact parameter of a track with respect to a vertex
- nLongTracks: number of tracks reconstruct as Long Tracks in the event
- GhostProb: probability assigned by the tracking algorithm that the track is constructed from fake combinations

4 The LHCb detector upgrade

4.1 Overview

The Run-II data-taking period will end in 2018 and at this point Long Shutdown 2 (LS2) will ensue that will last till around the end of 2020. During this time many substantial upgrades of the LHCb detector will be installed [9]. As depicted in Figure 25, each portion of the tracking system will be replaced: the new VELO will be instrumented with silicon pixel devices, the TT will be replaced with the Upstream Tracker (UT), which will improve granularity and acceptance, and the T-stations will be replaced with Scintillating Fiber (SciFi) tracking stations. The RICH1 detector will have the aerogel radiator removed as it is inefficient at the occupancy expected for high luminosity, and the HPD detectors will be replaced with multi-anode photomultipliers (MaPMTs). The first muon station (M1) will be removed.

The major change in the upgraded detector, however, is the complete elimination of the L0 trigger allowing every single bunch crossing to be fed into the LHCb computer farm for a full software trigger read-out. This means replacement of all read-out electronics of all detectors. The second major change for the upgraded LHCb detector is the increase in nominal operational luminosity by a factor of 5, with an expected instantaneous luminosity at $2 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$ achieved with a 25 ns bunch separation and a nominal number of (visible) interactions per bunch crossing of $\nu=7.6$ ($\mu=5.2$). The upgraded LHCb detector is expected to collect at least 50fb^{-1} worth of data over a period of 10 years.

4.2 The Upstream Tracker detector for the LHCb upgrade

The Upstream Tracker (UT) will replace the TT detector. Like the TT, the UT detector will be composed of four planes of silicon strip detectors as shown in Figure 26. The detector planes are arranged in a x - u - v - x orientation, with the second and third planes rotated at stereo angles of $+5^\circ$ and -5° with respect to the y -axis, respectively. Detector planes are split

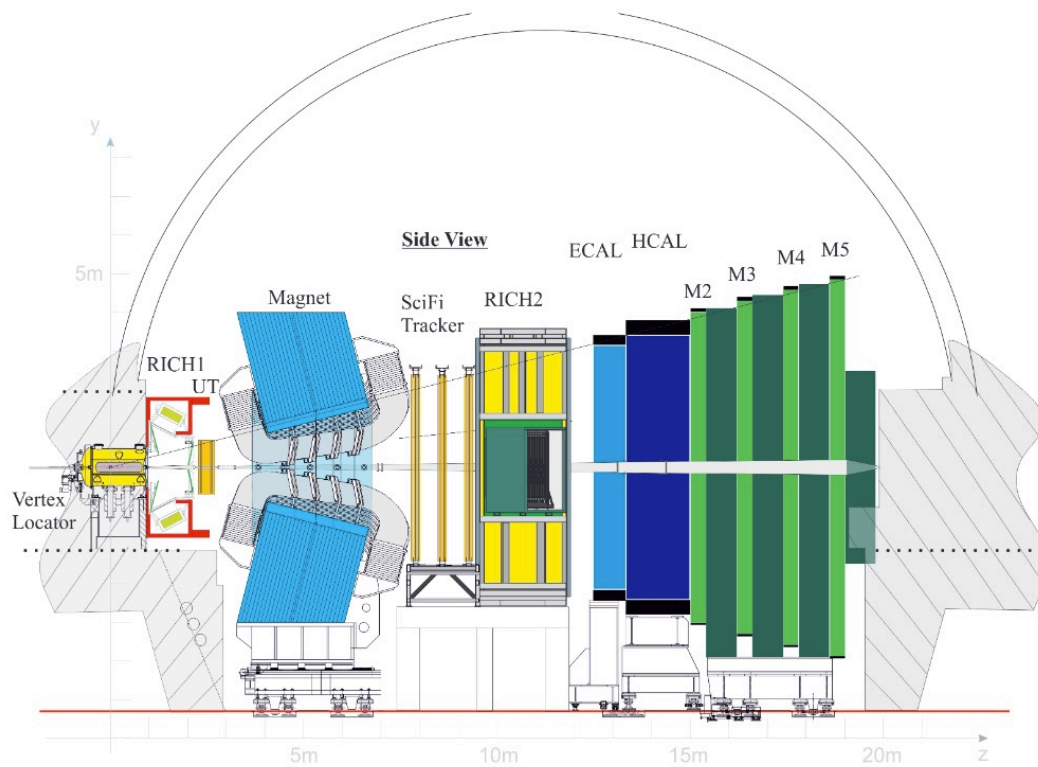


Figure 25: Layout of the LHCb detector with the upgraded tracking system [9].

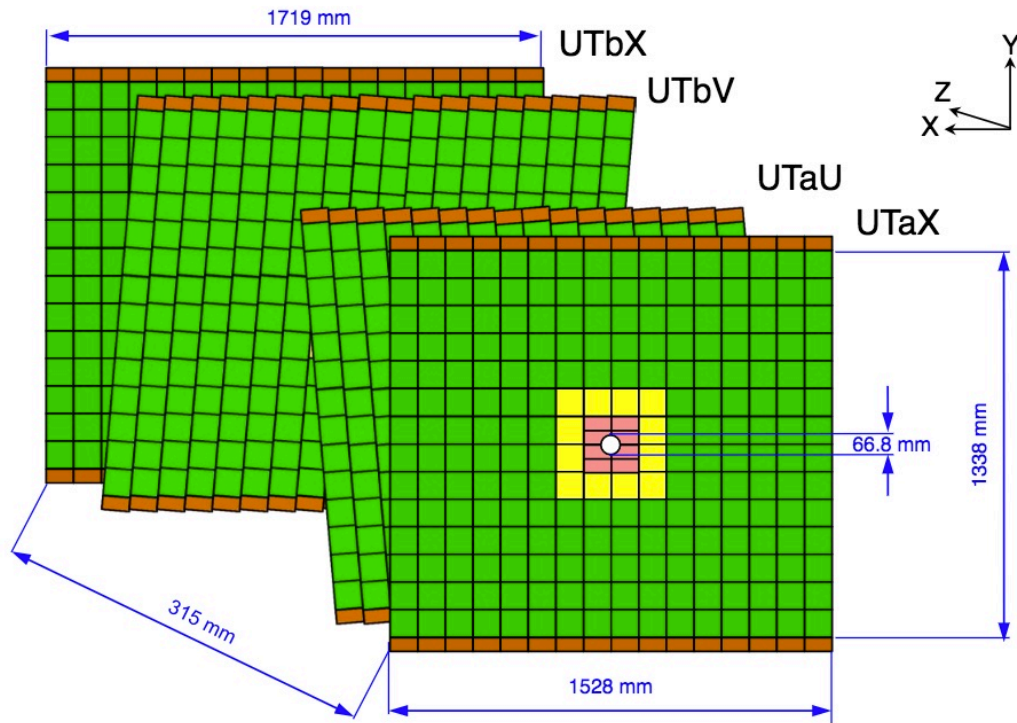


Figure 26: Layout of the four UT detector planes as looking downstream of the interaction point. Different Si sensor geometries are denoted as the green (A), yellow (B), red (C and D) squares [9].

into vertical components called *staves*, with the first two detector planes having 16 staves and the second two having 18. The concept of a stave is illustrated in Figure 27. Staves are equipped with modules comprising a ceramic stiffener hosting a silicon micro-strip detector and hybrid circuits with either four or eight dedicated ASIC front-end read-out circuits, called SALT (Silicon ASIC for LHCb Tracker) chips. Hybrid flexs are mounted, on both sides of the stave, on four power/data flex cables that provide high and low voltage to the hybrids, as well as read-out bus channels to electronics outside the detector volume.

The core mechanical and thermal structure of the staves are made of a thermally conductive carbon foam and rigid structural foam elements, sandwiched between two low-mass carbon fiber sheets. Embedded in the foam is a titanium tube that delivers cooling power via a bi-phase CO₂ vapor. The cooling tube is bent into a “snake” shape through each stave such that the tube is directly below the SALT chips, delivering the maximum cooling power directly to them.

The UT detector has an improved acceptance with respect to the TT by eliminating gaps between silicon sensors in the y direction by sufficiently overlapping the active areas of each detector with adjacent ones, and with the novel design of the silicon detectors near the beam pipe incorporating a quarter-circle cut-out to improve acceptance in the very forward region.

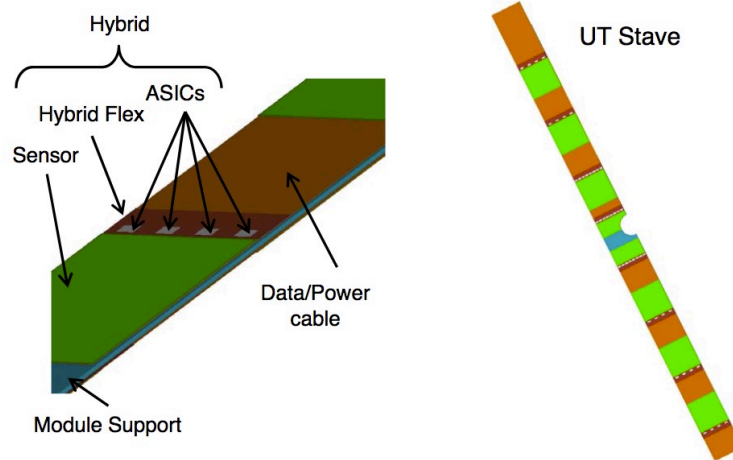


Figure 27: Schematic of the UT stave [9].

4.3 Silicon detectors for the UT upgrade

4.3.1 Sensor specifications

Four different sensors geometries, denoted type-A, B, C, and D, are used in the UT detector depending on proximity to the beam pipe, where the irradiation is highest. Illustrated in Figure 29 are the four detector types as produced from single wafers. Table 1 compiles the various specifications of each detector type. Detectors A and B are approximately 10 cm by 10 cm detectors and have 512 and 1024 read-out strips, respectively. Detectors C and D are approximately 10 cm by 5 cm with 1024 read-out strips, and are produced from the same wafer. Shown in Figure 28 is the expected irradiation dose after 50 fb^{-1} (including a safety factor of 4) as a function of the y coordinate. Most of the UT detector is expected to receive a fluence below $1 \times 10^{14} \text{ 1 MeV n}_{eq}/\text{cm}^2$, and corresponds to regions instrumented with type-A detectors. Therefore, the choice of technology for these silicon detectors is a less radiation hard p^+ -in- n technology. The rest of the silicon detectors are n^+ -in- p . The highest irradiation dose expected for type-D detectors is $4 \times 10^{14} \text{ 1 MeV n}_{eq}/\text{cm}^2$. To mitigate the effects of irradiation the cooling system is designed to provide a maximum operation temperature of the silicon detectors of -5° C .

Table 1: Summary of the four UT detector categories.

Type (#)	Technology	Thickness [μm]	Approx. physical size [cm^2]	# Strips	Strip pitch (μm)
A (888)	p^+ -in- n	320	10 x 10	512	≈ 190
B (48)	n^+ -in- p	320	10 x 10	1024	≈ 95
C (16)	n^+ -in- p	250	10 x 5	1024	≈ 95
D (16)	n^+ -in- p	250	10 x 5	1024	≈ 95

Besides the quarter circle cut-out of the type-D detectors, there are two other unusual features to the UT silicon detectors. The first are high voltage pads on the top of the detectors that couple to the backside metalization. Bringing in high voltage in this manner eliminates the need for high voltage directly to the backside metalization. The other unusual feature of the UT detectors is the on-sensor pitch adapters to accommodate for the sensor to SALT pitch differences ($\approx 190 \mu\text{m}$ to $\approx 73 \mu\text{m}$, respectively). The pitch adapters are realized

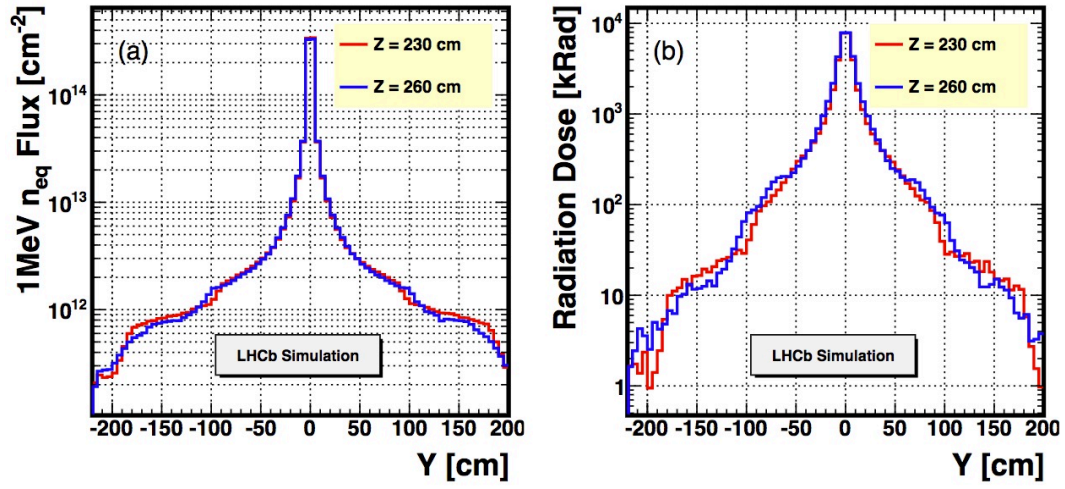


Figure 28: Expected fluence profile (left) and dose profile (right) after 50pb^{-1} of total integrated luminosity as a function of the vertical coordinate Y for $X=0$. This slice represents the highest fluence region throughout the UT system [9].

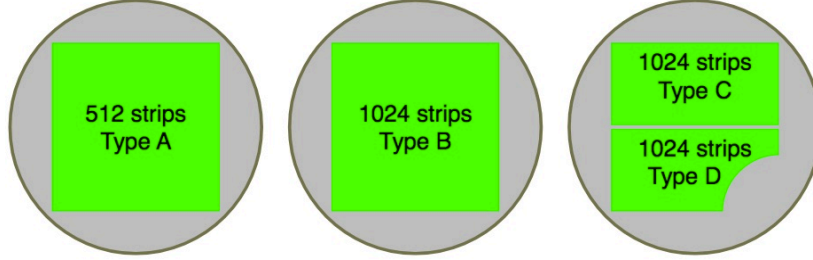


Figure 29: Sketch of the three mask designs for the UT upgrade. Sensors C and D are shorter and can be produced in a single 4 inch wafer, whereas sensors A and B require a full wafer.

through additional metal layers connecting the strip AC pads to a second set of pads $\approx 73 \mu\text{m}$ in pitch near the detector edge to be wire bonded to the SALT chip.

Prototype A-type detectors with approximate dimensions of 10 cm by 5 cm (1/2 # of strips) were produced with two different implementations of these pitch adapters illustrated in Figure 30. The first one (depicted on the top) is the *fan-in* pitch adapter, which routes the traces to bonding pads located within the active region. The second (depicted on the bottom) is the *fan-up* pitch adapter, which routes the traces over the guard ring to pads located out of the active area. A more recent version of the fan-up pitch adapter is shown in Figure 31.

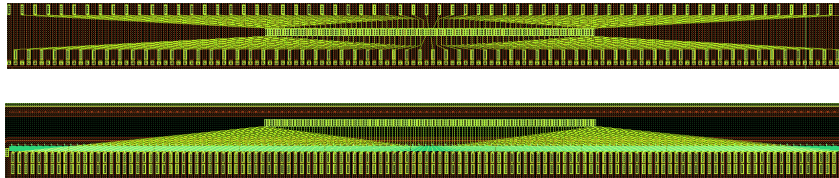


Figure 30: Two designs for the on-sensor pitch adapters. The *fan-in* design is shown on the top and the *fan-up* is shown on the bottom.

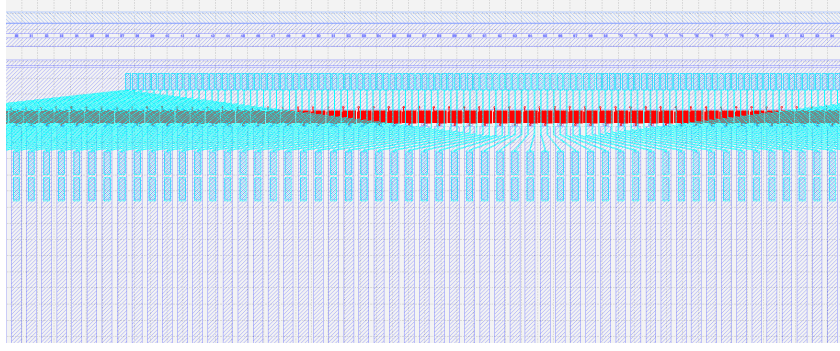


Figure 31: Recent design for the new fan-up pitch adapter.

4.3.2 Measurements on irradiated silicon detectors

An essential process to the detector quality assurance (QA) is the measurements of static properties of all silicon detectors. Namely, the measurements of the leakage current and bulk capacitance. Measurements of latter quantity are important as they extract at what voltage the silicon detector is fully depleted (i.e., the voltage which the detector achieves its maximum charge collection). For the UT upgrade it is a requirement that the depletion voltage does not exceed 500V during the lifetime of the detector. Additionally, a well behaved detector will have some finite leakage current when a reverse bias is applied that plateaus at a voltage near the depletion voltage. Increase leakage current as a function of voltage is an indication of the development of micro-discharges or the onset of breakdown. This increase may be sharp or gradual. Usually sharp increases, or “breakdowns”, are an indication of bad manufacturing processes.

What is just as critical are the measurements of detector properties after irradiating them to their expected doses over the lifetime of detector operation. As silicon detectors are expected to acquire more radiation their properties start to degrade. Thus, it is imperative to show a given detector technology will perform to satisfaction within its expected operation time.

Degradation of silicon sensors due to radiation effects occurs due to two categories of damage mechanisms. The underlying principle of both mechanisms is that particles travers-

ing the detector volume deposit some or all of their energy to the silicon crystal lattice. The first mechanism is the so-called “ionization damage”, when this deposited energy liberates charge carriers. This mainly affects the SiO₂ layers increasing the charge trapped at the Si-SiO₂ interface, and thus producing parasitic electric fields and, possibly, forming conducting channels between adjacent strips. The second damage mechanism is when the deposited energy is non-ionizing and can lead to variety of unwanted bulk effects such as increased leakage current, changes in effective doping concentrations, which changes the depletion voltage, and charge trapping.

The measurements presented here probe some of the effects listed above. Namely the changes in leakage current and depletion voltage due to irradiation, and the stability of the leakage current over large spans of time after irradiation. Another measurement presented is determination of the energy required to raise a charge carrier into the conduction band in silicon, called the energy band gap (E_b). This is measured on a variety of detectors over a range of irradiation levels.

The majority of measurements shown are from detector pre-prototypes from 2015 R&D phase. They are produced by Hamamatsu Photonics. The sections on leakage current, capacitance, and energy bandgap measurements summarize their observed properties. Detectors in these studies are both large area detectors that are either 1/2 or full size detectors, and “mini-sensor” which are detectors produced on the wafer periphery regions alongside of test structures. When evaluating the leakage current change versus fluence, sensors from all UT studies are combined. Additional sensors produced by Micron were tested after irradiation. Section 4.3.7 utilizes the latest prototype A and D type detectors.

4.3.3 Experimental setup

The irradiation of the majority of silicon detectors was carried out at the IRRAD facility at CERN [60]. The IRRAD facility delivers 24 GeV protons from the proton synchrotron (PS) in “spills” of approximately 3.5×10^{11} protons every 12 seconds with a beam profile

that is Gaussian in two dimensions and has a FWHM of $12 \times 12 \text{ mm}^2$. A few detectors were irradiated with 226 MeV protons from the Massachusetts General Hospital (MGH) proton irradiation facility [61].

Dosimetry measurements at IRRAD are performed using activated aluminum foil that was placed with the detectors during irradiation. In the case of large-size detectors the aluminum foil is segmented to measure the irradiation profile across the sensors. Figure 32 shows the profile across 1/2 A and D detectors in the 2015 irradiation. During this irradiation large-size sensors were irradiated at small angles with respect to the beam axis to irradiate the full length of the detector. Mini-sensors were irradiated perpendicular to the beam. In the 2017 irradiation campaign, a D type detector, presented in measurements here, was irradiated over the entire surface of the detector oriented perpendicular to the beam. Figure 33 shows the profile of this detector as measured by activated aluminum foil.

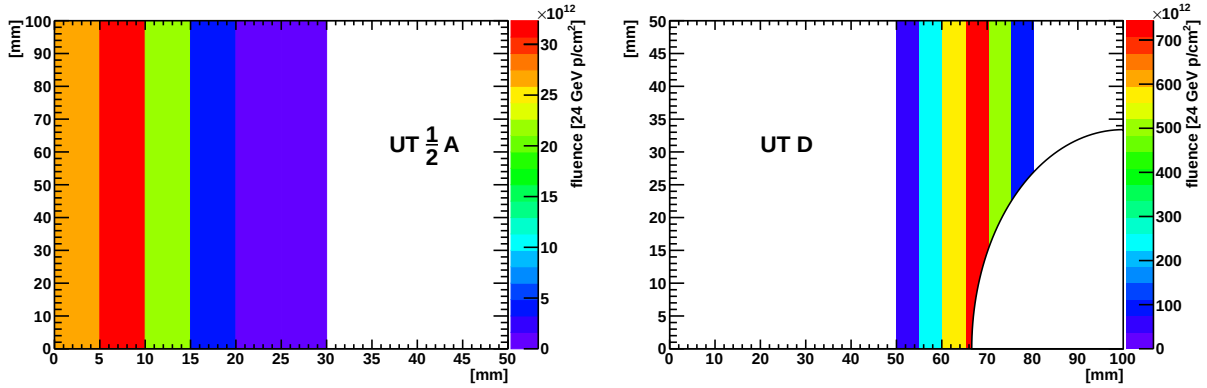


Figure 32: Measured irradiation profiles of 1/2 A (left) and full size D (right) sensors in units of 24GeV/c protons. Here the X-axis runs parallel with increasing strip number.

Measurements of pre-irradiation leakage currents and capacitance versus voltage were performed at the Syracuse University laboratory. The Syracuse probe station is enclosed in a light tight box. Sensors are held to the probe chuck using a vacuum pump. There is no temperature control of the Syracuse setup but the temperature is measured at each measurement for reference. Dry air is pumped into the box to produce a dry environment and the relative humidity is also monitored during each measurement. Leakage current

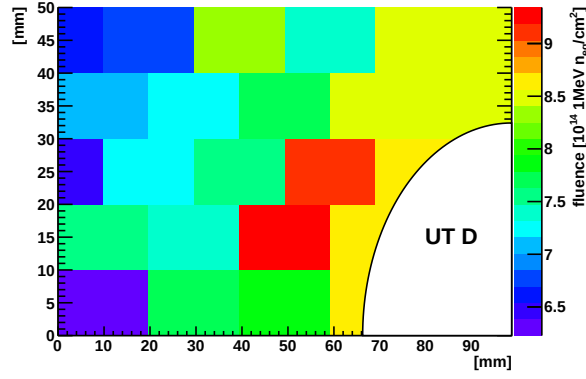


Figure 33: Measured irradiation profile of the D type detector in units of 24GeV/c protons. Here the X-axis runs parallel with increasing strip number.

measurements are done using a Keithley 237 SMU. Capacitance measurements are done using a Quadtech 7600 model b LCR meter, while the Keithley 237 is used to bias the detector. Measurements are automated using LabView software.

Most post-irradiation measurements were performed at the RD50 laboratory at CERN. The RD50 probe station is enclosed also in a light tight box. Sensors are held down to the probe chuck using a vacuum chuck. The chuck is manufactured by systems ATT and is liquid cooled, able to reach temperatures less than -20° C. Dry air is flushed in the box to produce a dry environment before and during cooling. Leakage currents are performed using a Keithley 237 SMU to bias the detector and a Keithley 2410 picometer to measure the leakage current. Capacitance measurements are performed using a Keithley 237 to bias the detector and an Agilent E4980A precision LCR meter. Measurements are automated using LabView software.

The final setup, used to measure the stability of leakage current, is located at the Syracuse University UT construction laboratory. This setup consists of gas-tight box within a light-tight box which also acts as a Faraday cage. The detector under test is housed inside the gas-tight box with a custom PCB board that provides bias voltage to the detector and coupling to the cooling system, consisting of a Peltier cooler, in a non-destructive manner. The detector volume is constantly flushed with ultra-high purity nitrogen gas. Inside the

gas-tight box environment variables are monitored with a RTD probe and relative humidity probe. On the PCB three RTD probes are placed in proximity to the detector under test to provide an estimate of the detector temperature. With this setup temperatures around 0-5° C are achievable. Readout of the detector leakage current is done via a precision 1 MΩ resistor in series in the bias circuit. Readout (every 300ms) of all environment and bias variables is automated with dedicated LabView software through a PCI-1713U ADVANTECH DAQ.

4.3.4 Leakage current

To compare leakage current measurements before and after irradiation, and between the Syracuse and RD50 laboratory measurements, leakage currents pre-irradiation are scaled to T=-5° C using the conventional leakage current scaling equation:

$$I_2 = I_1 \left(\frac{T_2}{T_1} \right)^2 \cdot e^{-\frac{E_{gap}}{2k_b} \left(\frac{1}{T_1} - \frac{1}{T_2} \right)}, \quad (31)$$

where $I_{1,2}$ and $T_{1,2}$ are the leakage current and temperature (in Kelvin), respectively, before and after scaling, and E_{gap} and k_b are the bandgap energy and Boltzmann's constant, respectively [62]. Here a value of 1.21 eV for the bandgap energy is used to scale leakage currents measurements. A temperature of T=-5°C was chosen for comparison because this is the nominal operating temperature of the sensors in the UT detector, and this is the temperature at which all post-irradiated detectors were measured. All measurements were made at a bias of at least 500V, as this is maximum operating voltage of the UT system.

Leakage current measurements of Hamamatsu mini, and 1/2 A and full size D sensors, before and after irradiation, are shown in Figures 34 and 35, respectively. All mini-sensor pre-irradiation currents were on the order of a few nA up to 500V, with the exception of a two detectors that had an onset of soft breakdown. 1/2 A and full size D detectors had a pre-irradiation current of around 10 nA up to the depletion voltage ($\approx 200V$) then have a slight turn on after 200V and increase almost an order of magnitude at 800V. After irradiation,

both 1/2 A and full size D, and all mini-sensors have leakage currents that scale as expected with the average dose received over the detector. There is no sign of (soft) breakdown in all the detectors up to the maximum operating voltage. The splitting of the leakage current of 1/2 A and full size D detectors shown in Figure 35 is assumed to be an effect of small differences in the vertical irradiation profile due to the stacking and rotating of detectors during irradiation. Otherwise, these detectors all shown the same post-irradiation leakage current properties.

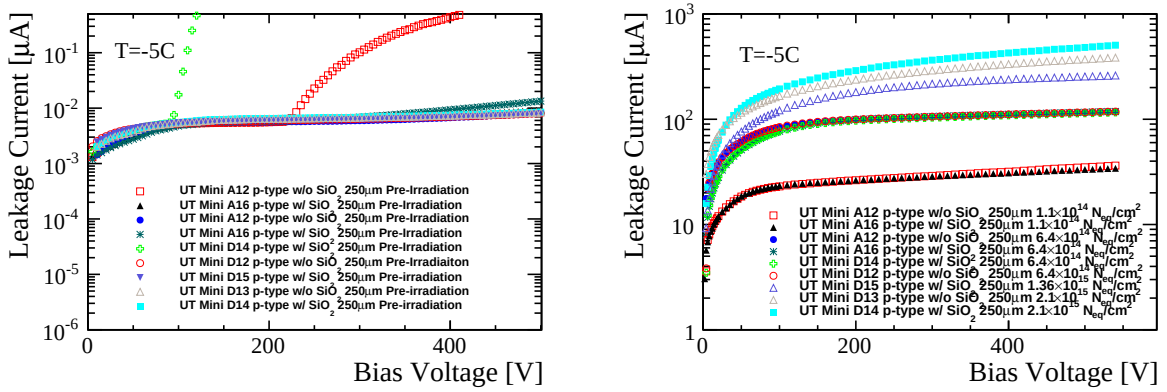


Figure 34: Leakage current of Hamamatsu 1/2 A (left) and D (right) sensors. Each plot shows the leakage current before and after irradiation. Here the post-irradiation leakage current is measured at $T = -5^\circ\text{C}$ where the pre-irradiation measurement is performed at room temperature and then scaled to $T = -5^\circ\text{C}$ using equation 31. In the post-irradiation plot, each band shows the different levels of irradiation ($1.1\text{E}14$, $6.4\text{E}14$, $1.36\text{E}15$, and $2.1\text{E}15$ $n_{\text{eq}}/\text{cm}^2$).

Leakage currents of Micron mini-sensors after irradiation are shown in Figure 36. Leakage currents per individual fluences are shown in Figure 38. One can see in general a better performance of the p-type detectors over n-type after irradiation, particularly at the highest fluence where the n-type detectors behave almost linearly after a bias voltage of 100V. This was expected as p-type detectors are known to be more radiation hard. All pre-irradiation currents ranged from a few nA to several 10 nA and nearly all mini-sensors had (soft) breakdown before 500V (See Figure 37).

To determine ΔI of each sensor as a function of fluence, a leakage current data point slightly above depletion was chosen. Additionally, to compare to previous measurements,

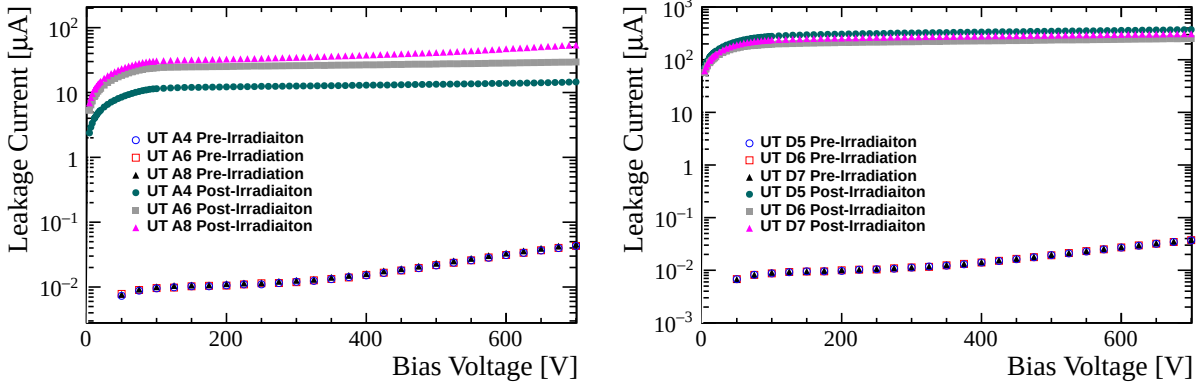


Figure 35: Leakage current of Hamamatsu mini-sensors before (left) and after (right) irradiation. Here the post-irradiation leakage current is measured at $T=-5^{\circ}\text{C}$ where the pre-irradiation measurement is performed at room temperature and then scaled to $T=-5^{\circ}\text{C}$ using equation 31. Type 1/2 A and full size D detectors were irradiated to a maximum fluence of $2.0\text{E}13$ and $4.6\text{E}14$ $n_{\text{eq}}/\text{cm}^2$, respectively.

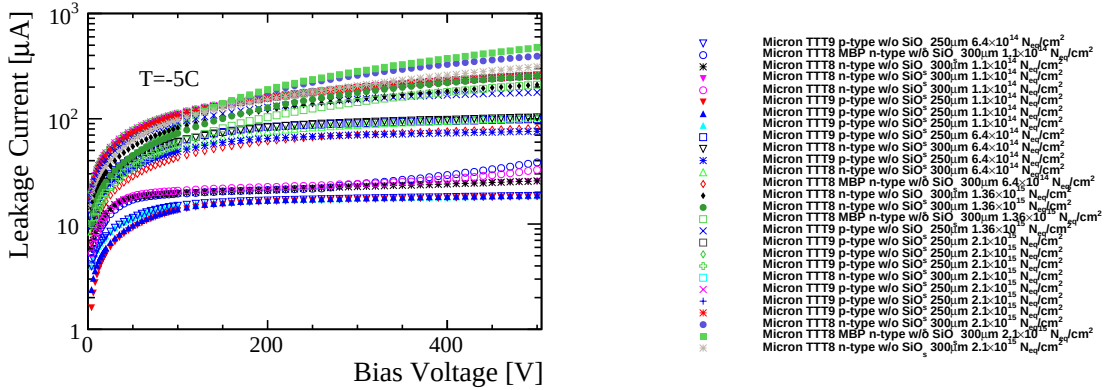


Figure 36: Leakage current of Micron mini-sensors after irradiation. Here the post-irradiation leakage current is measured at $T=-5^{\circ}\text{C}$ and all irradiation levels, and sensor geometries and technologies are shown.

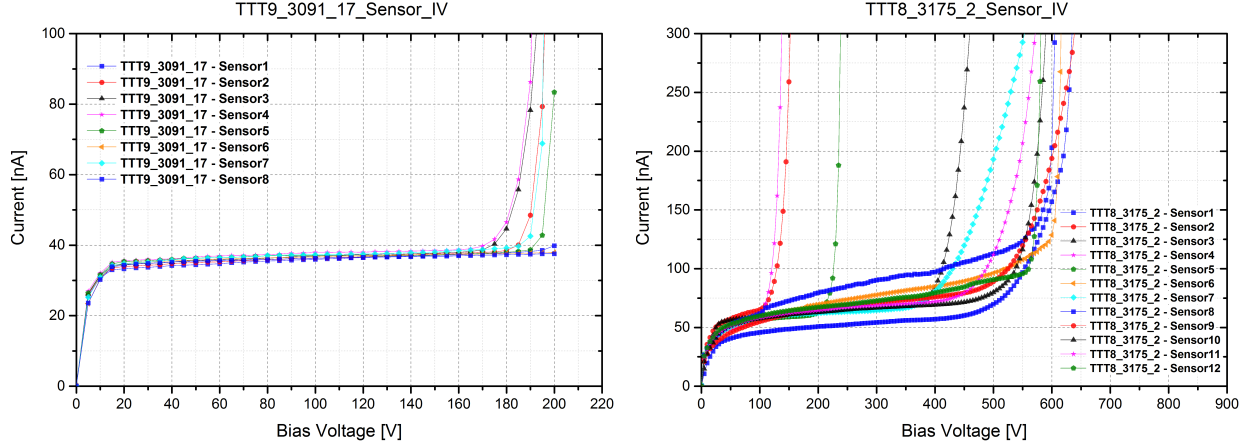


Figure 37: Pre-irradiation leakage current of Micron mini-sensors. Shown on the left is several TTT9 mini-sensors from one wafer and on the right TTT8 mini-sensors from one wafer.

sensors were scaled to 21° C using equation 31 where the value $E_{g,eff} = 1.180$ eV, determined later in Section 4.3.6, is used. Pre-irradiation current is considered negligible and set to zero as it is many orders of magnitude lower. For sensors irradiated to the highest dose the largest bias voltage data point was taken as they do not deplete within the given bias scans. There are a few other caveats to consider. Firstly for the larger area sensors, the dose is non-uniform, and thus the fluence was integrated over the entire detector, giving it a small average fluence. Secondly, several sensors have beampipe cutouts. These have to be taken into account carefully with calculated the volume of the detector and the integrated fluence.

Figure 39 shows the results of $\Delta I/V$ versus Φ for all detectors. The change in leakage current after irradiation is expected to scale linearly with fluence, and is parameterized by one free variable, α , called the current related damage rate. Explicitly,

$$\Delta I/V = \alpha V \Phi_{ave}, \quad (32)$$

where V is the volume of the detector under test and Φ_{ave} is average fluence in 1 MeV n_{eq}/cm^2 . From the fit to the data using this parameterization $\alpha = (7.5 \pm 0.1) \times 10^{-17}$ A/cm. This value for α is consistent for sensors with short term annealing [63], and with previous

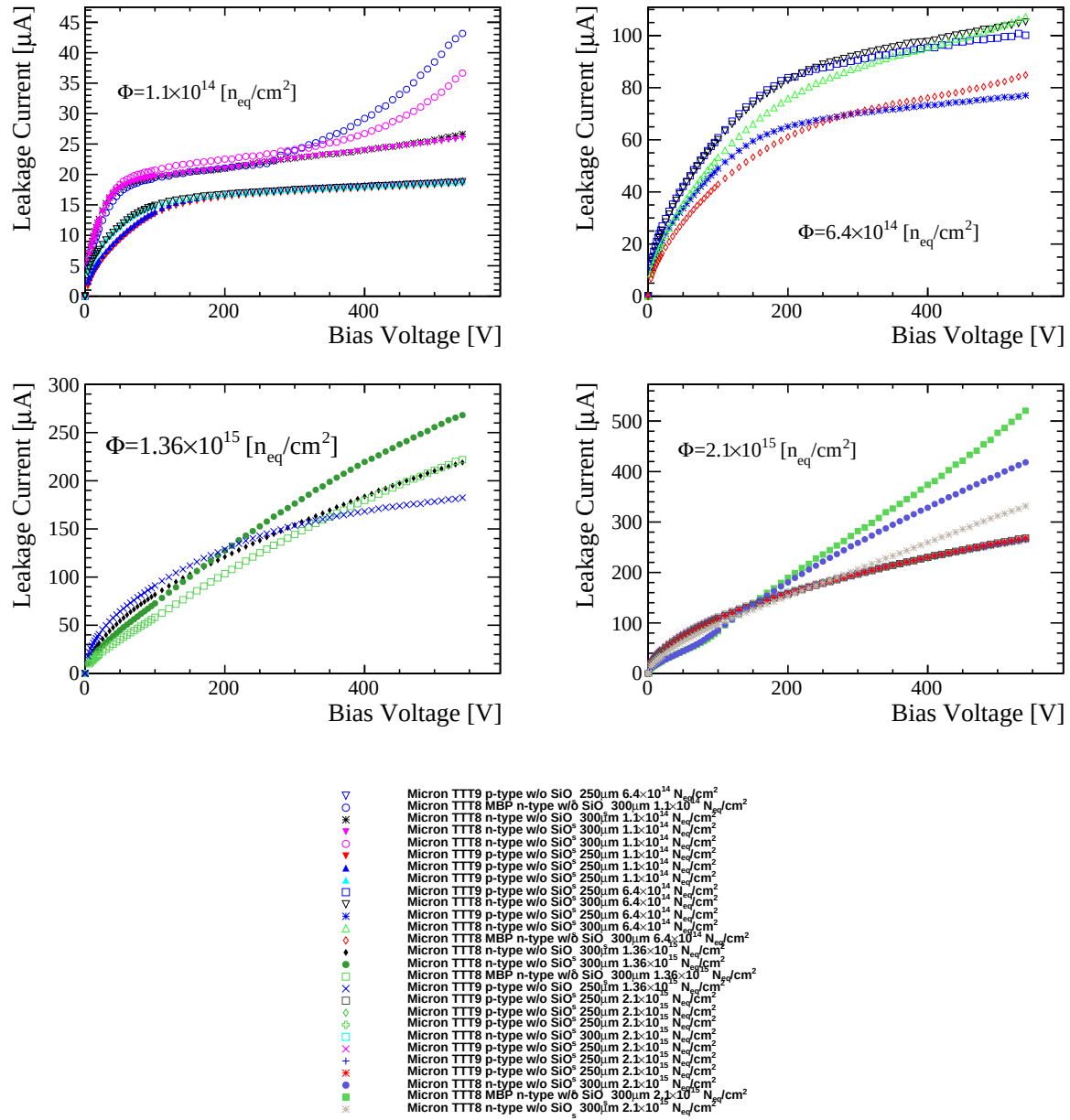


Figure 38: Leakage current of Micron mini-sensors after irradiation split into each fluence. Starting from top left to bottom right, the fluence shown (in 1 MeV neutron equivalent) is $1.1\text{E}14$, $6.4\text{E}14$, $1.36\text{E}15$, and $2.1\text{E}14$. Here the post-irradiation leakage current is measured at $T = -5^\circ\text{C}$ and all irradiation levels, and sensor geometries and technologies are shown.

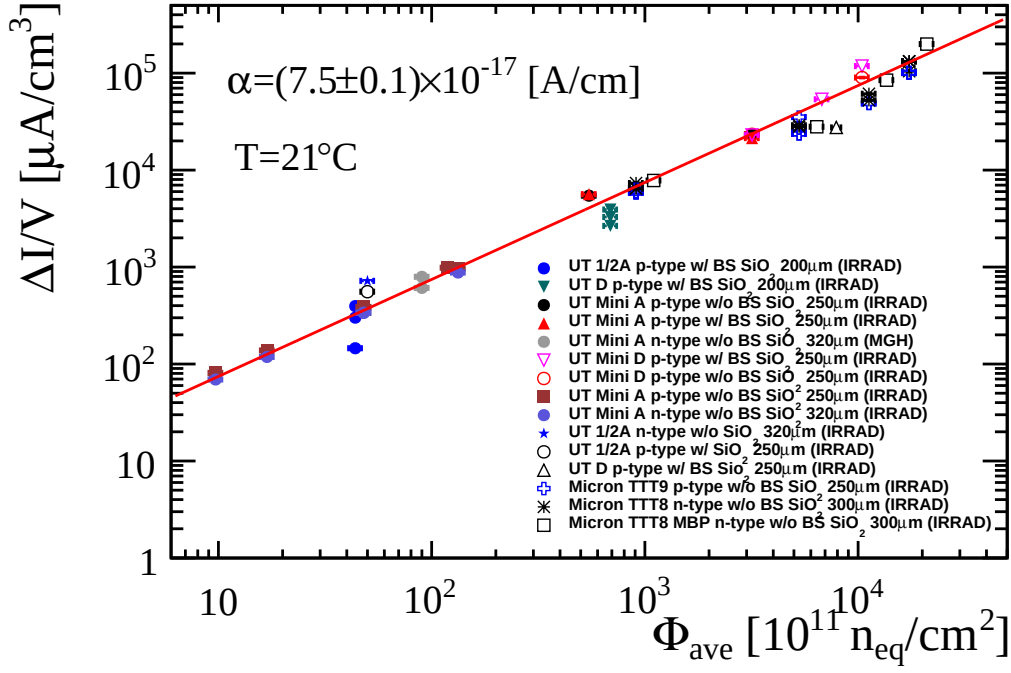


Figure 39: $\Delta I/V$ versus Φ for all Hamamatsu and Micron sensors. Here V indicates the detector volume. The red line shows a fit to all data.

measurements on Hamamatsu and Micron detectors [64].

4.3.5 Capacitance versus voltage

Capacitance versus voltage measurements were measured using a frequency of 1000 Hz at both Syracuse and RD50 laboratories. Shown in Figure 40 is the CV measurements made on pre and post-irradiated type 1/2 A and D detectors. In these detectors it is clear that they reach depletion around 145 V pre-irradiation, but post-irradiation curves don't show a clear indication when the detector is full depleted. This is expected since these detectors were irradiated non-uniformly and most of the detector is not irradiated at all. CV measurements of Hamamatsu mini-sensors irradiated to all fluences are shown in Figure 41. While the depletion voltage as a function of dose will be evaluated below for all sensors, one feature to be noted is the “inverse” behavior of capacitance versus bias voltage of sensors with backside passivation at moderate fluences. It is expected that capacitance decreases with

voltage due to the increase in space-charge region of the p-n junction, and levels off as the detector reaches full depletion, but sensors biased from the top rapidly drop off and slowly increase until leveling off at full depletion. This effect was tested and reproduced on an irradiated detector without backside passivation but biased from the topside contact. Figure 42 shows the this measurement on a Hamamatsu mini-sensor irradiated to 2.1×10^{15} 1 MeV n_{eq}/cm^2 . This effect is not completely understood and deserves more attention in future studies/simulations. CV measurements on Micron mini-sensors are shown in Figure 43.

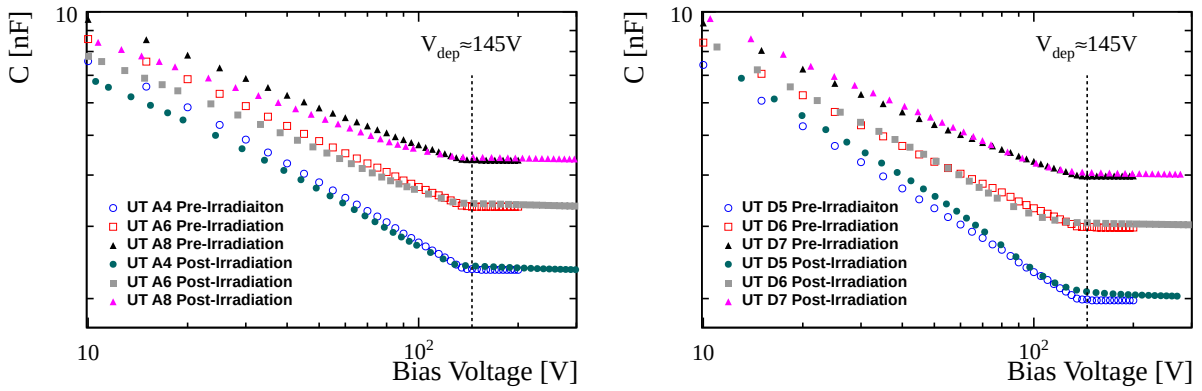


Figure 40: Capacitance versus voltage measurements of 1/2 A (left) and full size D (right) Hamamatsu detectors. Measurements were made at a frequency of 1000 Hz. Pre-irradiation it is clear that around 145V the detectors reach full depletion, but post-irradiation curves don't show a clear indication when the detector is full depleted. This is expected since these detectors were irradiated non-uniformly and most of the detector is not irradiated at all. Note in the plot individual sensor data are offset in Y from each other to make viewing easier.

The depletion voltage for each sensor type was estimated from fitting the $\log(C)$ versus $\log(V)$ curve with two linear functions before and after the “kink” in the curve, and then computing their intercept. While at lower fluences this method is straight forward, at higher fluences this becomes slightly difficult because the “kink” in the distribution is not as apparent. A conservative uncertainty of ≈ 40 V is estimated for these data points by varying the range of the fit. The depletion voltage is not reached for sensors irradiated to the highest fluence and are therefore not shown here. For sensors with backside passivation, and thus show the “inverse” effect described above, it is assumed that when full depletion is reached

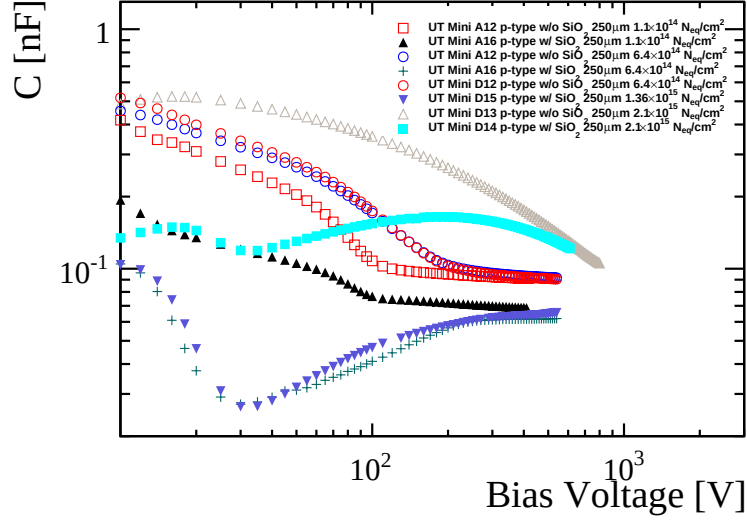


Figure 41: Capacitance versus voltage measurements of Hamamatsu mini-sensors measured at a frequency of 1000 Hz.

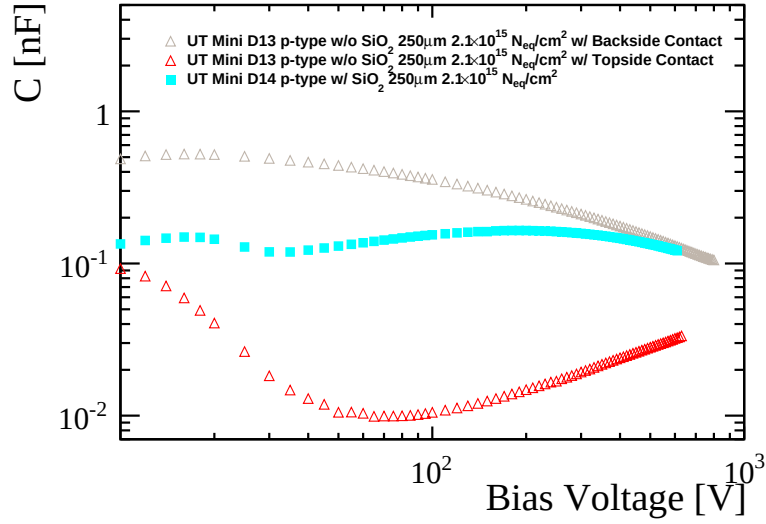


Figure 42: Capacitance versus voltage measurement on a Hamamatsu mini-sensor irradiated to $2E15 \text{ n}_{eq}/\text{cm}^2$. Measurements were made at a frequency of 1000 Hz. The gray data points show the CV dependence when biasing the detector through the backplane and the red data points shown when the same detector is biased via the topside contact. The cyan data points show a detector with backside passivation biased via the topside contact for reference.

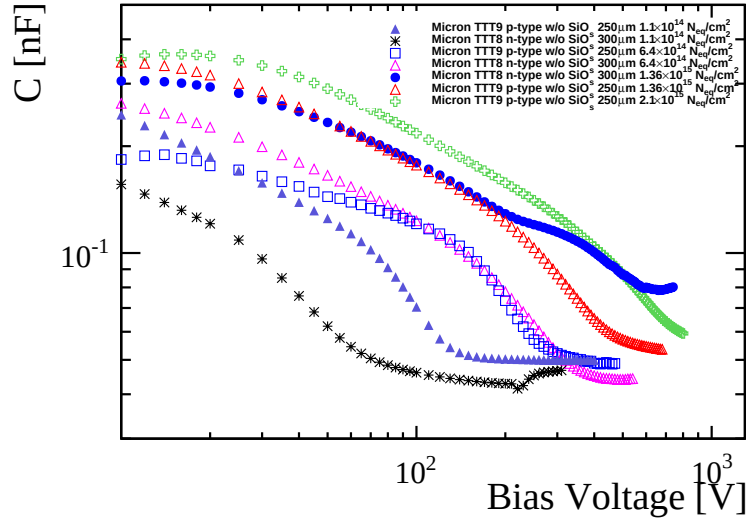


Figure 43: Capacitance versus voltage measurements of Micron mini-sensors. Measurements were made at a frequency of 1000 Hz.

the CV curve flattens out as in unpassivated detectors. 1/2 A and full size D detectors are not included here. A summary of all the depletion voltages as a function of fluence is shown in Figure 44 for all Hamamatsu and Micron mini-sensors.

4.3.6 Effective bandgap

Measurements of $E_{g,eff}$ on a subset of Hamamatsu and Micron mini-sensors were carried out at the RD50 lab at CERN, after irradiation. A measurement on each type of sensor at each fluence would of been ideal but due to testbeam priorities, Hamamatsu mini-sensors at the first two fluences were already being tested in 2015 testbeams. To determine the bandgap, leakage current measurements were measured at two temperatures. Rearranging Equation 31, we get

$$E_{g,eff} = -2k_b \frac{T_1 T_2}{T_1 - T_2} \cdot \ln\left(\frac{I_2 T_1^2}{I_1 T_2^2}\right), \quad (33)$$

where $I_{1,2}$ and $T_{1,2}$ are the leakage current and temperature (in Kelvin), respectively, at two different temperatures, and k_b is Boltzmann's constant. For this measurement $T=-5^\circ\text{C}$ and -20°C were used and correspond to I_1 and T_1 , and I_2 and T_2 , respectively.

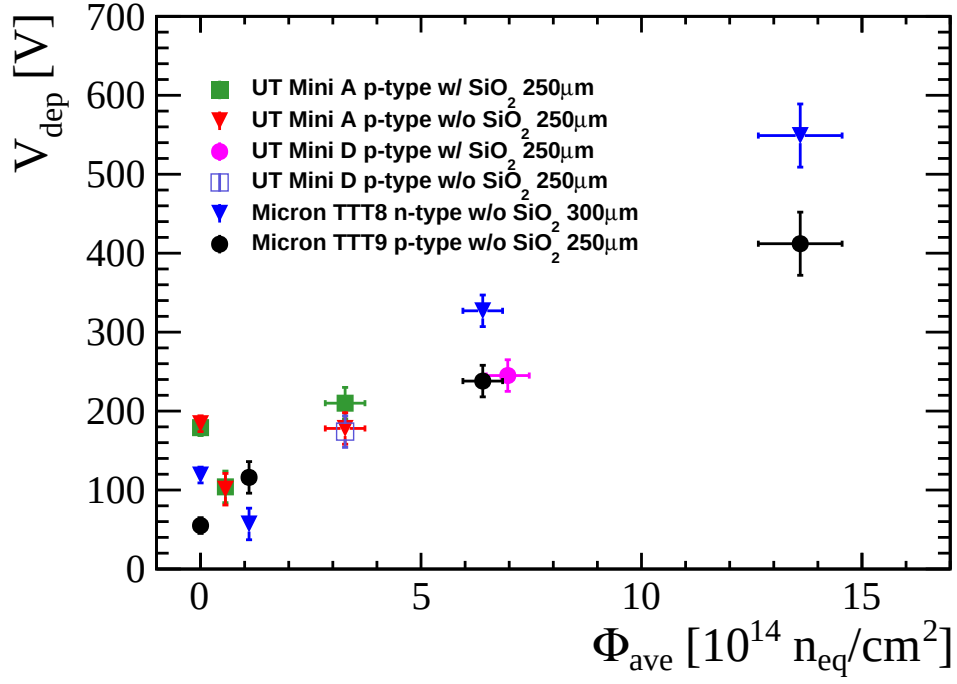


Figure 44: Summary of the depletion voltages as a function of fluence for all Hamamatsu and Micron mini-sensors.

Figure 45 shows the result of $E_{g,eff}$ as a function of bias voltage for all mini-sensors considered. For bulk generation current, $E_{g,eff}$ is expected to be independent of bias voltage. There are a few detectors in Figure 45 that seem not to constant over the bias scan. For low bias voltages ($< V_{dep}$) two explanations for the non-constant behavior of $E_{g,eff}$ can be due to other sources of current other than bulk current (e.g., surface current), which dominates after depletion, and the other being that the sensor temperature is not completely constant. Sensors cool exponentially and if they haven't sufficiently settled that would affect the measurement. Each data point along the bias scan was sufficiently delayed such that the temperature had enough time to settle after a few data points were taken. Therefore, for these detectors only data points above 100V are considered. There are three other curves that show non-uniformity over a large portion of the bias scan. One Micron sensor, irradiated to the highest fluence, which shows large changes at a bias larger than 400V. This is due to the sensor going into soft breakdown above 400V and for this particular sensor only data

points between 100 and 400V are considered. The the other two Hamamatsu detectors, one possible explanation is self-heating of the sensors, but seems unlikely since they level off at higher bias voltages. Given that these detectors are highly irradiated and below depletion for most of all of the scan, and are biased via the topside contact, it is possible there are other sources of current. For these detectors only biases above 200V are considered. In the collective determination of $E_{g,eff}$ these two Hamamatsu detectors are not considered as any unknown sources of current due to topside contact will bias the result, but are shown anyway for reference.

To determine $E_{g,eff}$ for each sensor, bias scan data points were projected onto $E_{g,eff}$ and the resulting histogram was fit with a Gaussian probability distribution function. The mean and sigma of the fit was then taken to be the central value and uncertainty for each sensor. The resulting fits can be seen in Figure 46. Finally, the measured value for $E_{g,eff}$ as a function of fluence for each sensor considered is shown in Figure 47. Also shown in green in Figure 47 is a combined fit to the data where the error represents the uncertainty in the fit. Combining both TTT8, TTT9, and mini-D sensors without backside passivation, the bandgap energy is measured to be $E_{g,eff} = 1.180 \pm 0.002 \pm 0.003$, where the first error is the uncertainty on the fit and the second is determined by changing the binning on individual sensor fits and seeing how far the central value shifts in the overall determination of $E_{g,eff}$. Figure 48 shows separate determination of $E_{g,eff}$ for TTT8 and TTT9 sensors. From these separate fits, and the one value of $E_{g,eff}$ for the Hamamatsu detector without backside passivation, there is no systematic bias when combining all the data points. There is also no significant deviation of $E_{g,eff}$ from the central value for sensors irradiated up to a fluence of $2.1\text{E}15 \text{ n}_{eq}/\text{cm}^2$

4.3.7 Long-term leakage current stability

Two goals for long-term leakage current stability measurement were to address the stability of the leakage current after irradiation over long spans of time, and if and how does grounding the guard ring affect the stability.

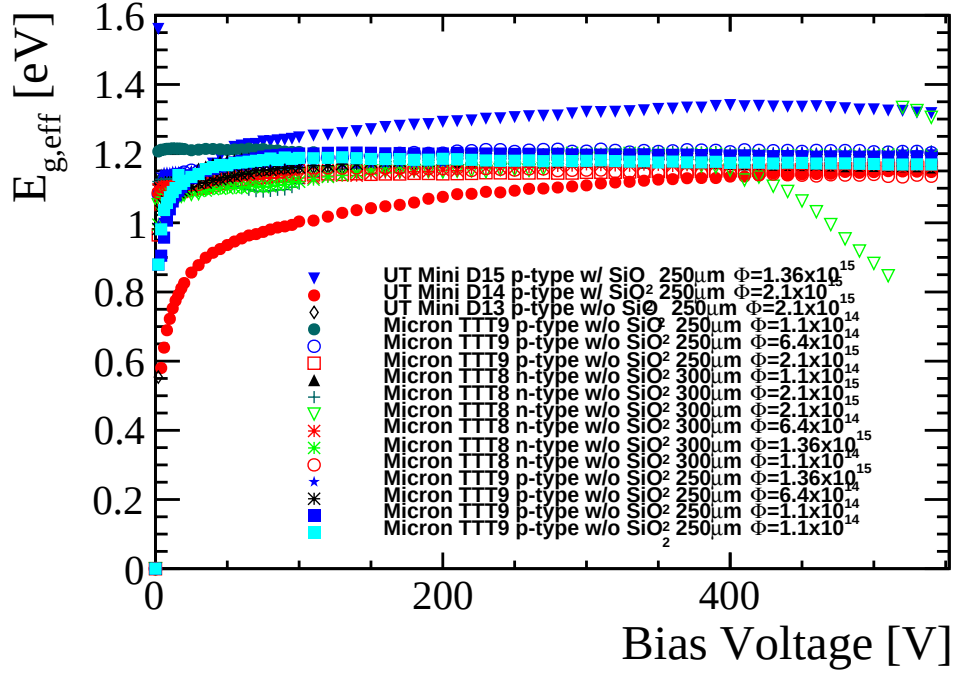


Figure 45: Summary of the $E_{g,eff}$ measurement as a function of voltage for all mini-sensors considered.

Measurements on three detectors were carried out to address these questions, one n-type 1/2 A and one p-type full size A, and one n-type D detector irradiated to 2x its expected dose.

Figure 49 shows the full size p-type detector with and without the guard ring grounded over a time of about 0.1 days with a bias of 370V. In the first measurement the temperature was ramped down over the course of the measurement. Besides small differences in the absolute leakage current values due to temperature differences, no difference between the two measurement schemes was observed. A longer measurement for roughly eight days was made with the guard ring grounded and is shown in Figure 50. In this measurement no instability was found, and the fluctuations in data reflect the daily temperature variations due to facility conditions. On the n-type 1/2 A detector a measurement spanning about three days at a bias of 330V without the guard ring grounded was made. Figure 51 shows the data from this measurement. The small spike around 2 days was due to a short intervention, not

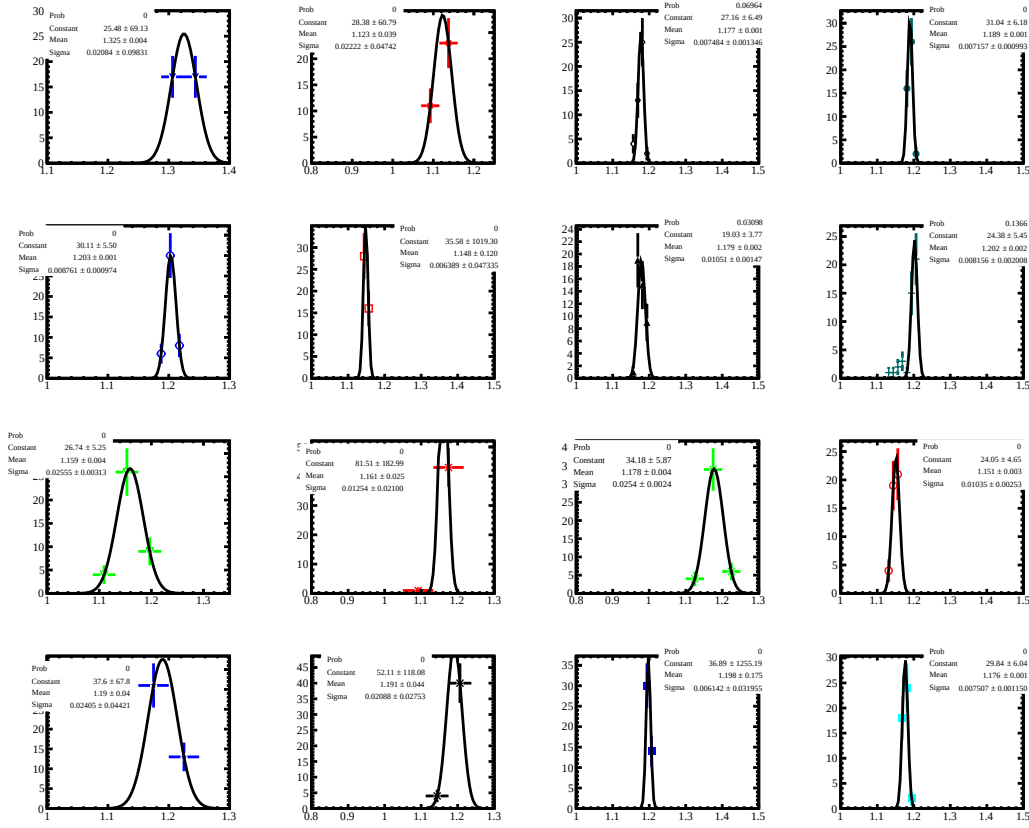


Figure 46: Fits of $E_{g,eff}$ for all mini-sensors measured. Note each histogram has the same data point style given in the legend shown in Figure 45.

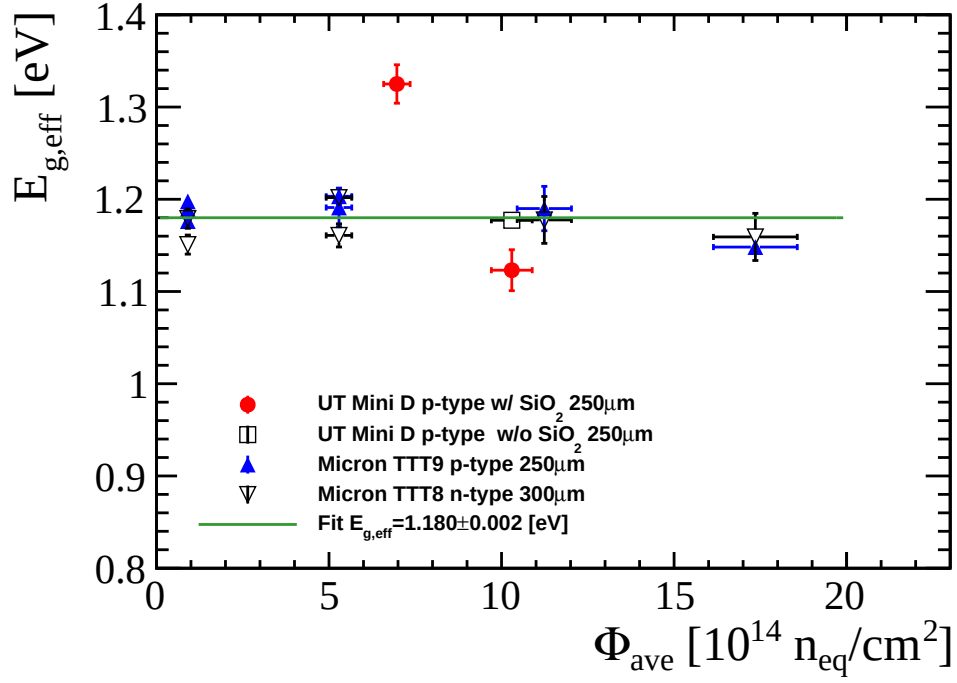


Figure 47: $E_{g,eff}$ as a function of fluence for all mini-sensors measured. A combined fit to the data is shown as the green line where the error represents the uncertainty of the fit.

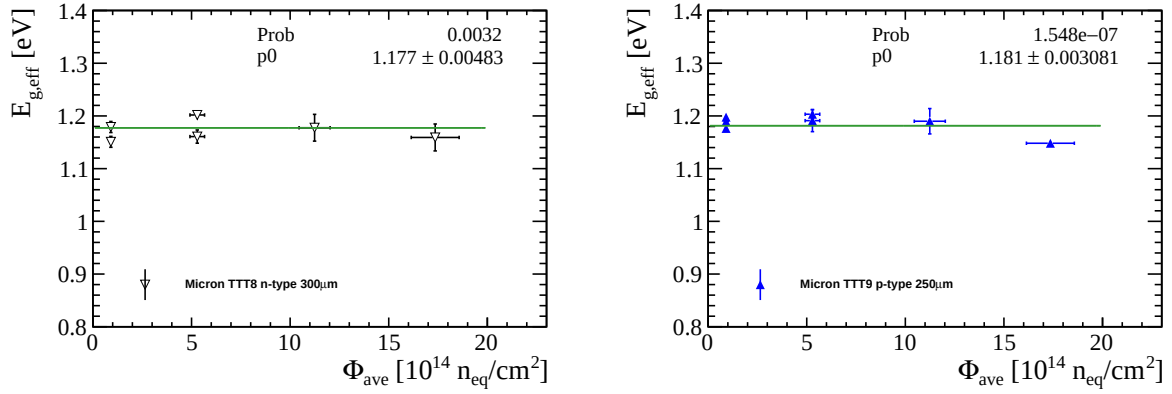


Figure 48: Measured values of $E_{g,eff}$ vs. fluence for TTT8 (left) and TTT9 (right) mini-sensors. Fits to the data is shown as the green line where the error represents the uncertainty of the fit.

from instability.

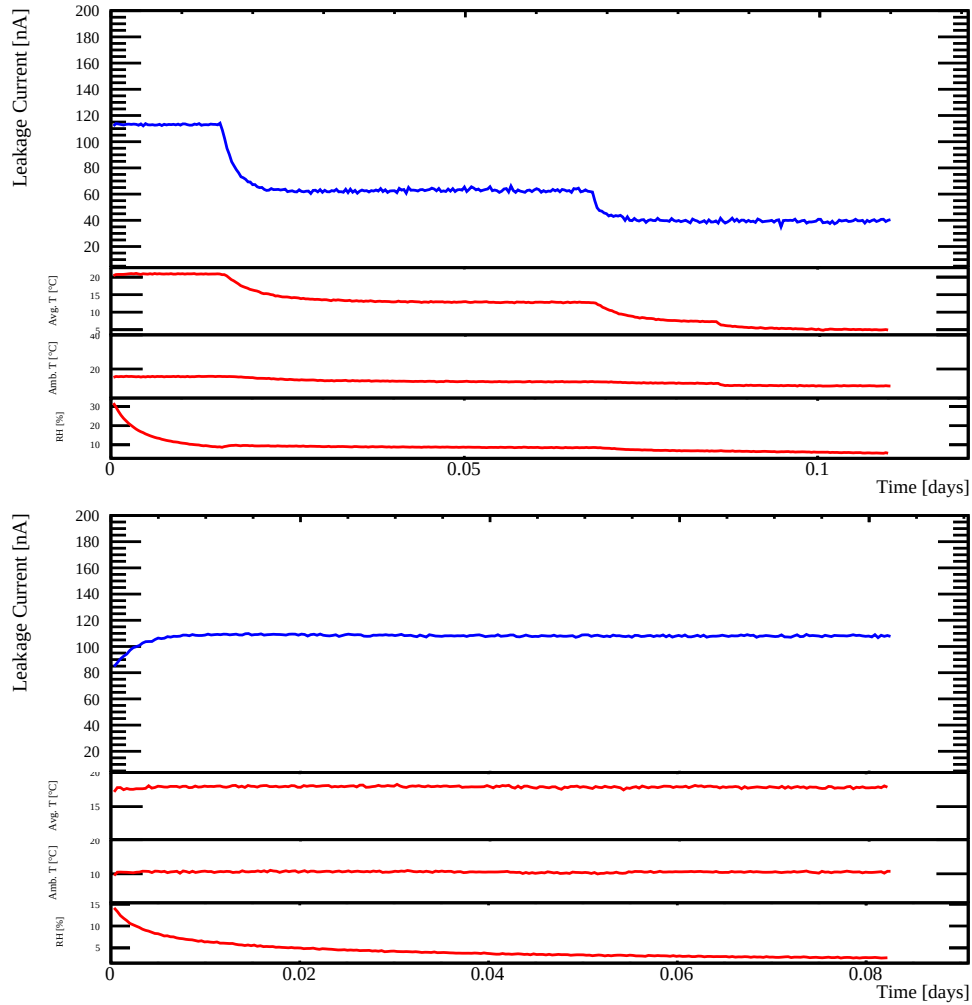


Figure 49: Measurement of the long-term leakage current stability on a p-type full size A detector. The top shows a nominal run and the bottom shows a run with the guard ring wire-bonded to ground. In both measurements the bias voltage was 370V. In the top plot the temperature was ramped down over the course of the measurement.

Two measurements were made on the irradiated D detector. The first one, shown in Figure 52, was made over the span of roughly five days at 220V. For the first day the relative humidity was kept slightly above 10%. Instabilities in the leakage current were observed whenever the relative humidity went above 11%. After lowering the relative humidity to 5% the leakage current stabilized and was constant for the remainder of the measurement. The second measurement grounded the guard ring and spanned for about 6 days. The first two

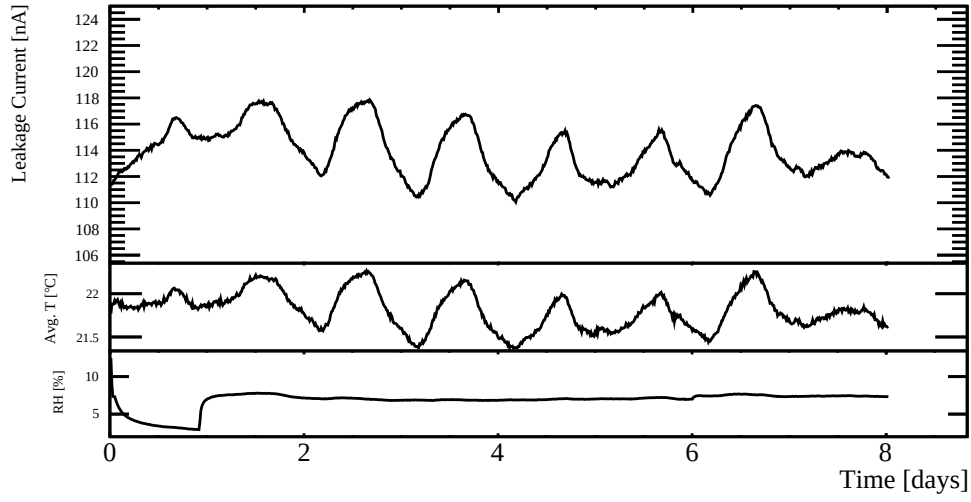


Figure 50: Measurement of the long-term leakage current stability on a p-type full size A detector. The daily oscillations in the data are due to facility day/night temperature changes.

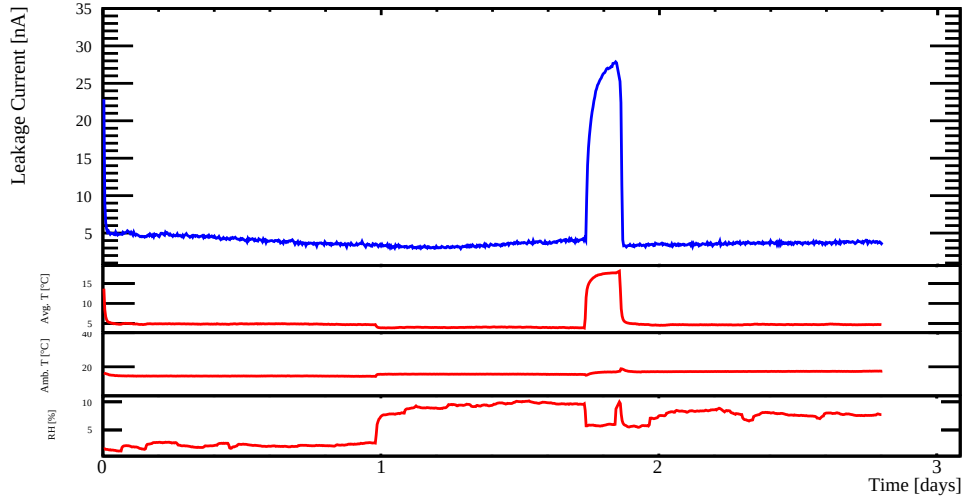


Figure 51: Measurement of the long-term leakage current stability on a n-type 1/2 A detector. The small spike around 2 days was due to a short intervention, not from instability.

days were with a bias of 220V and the remainder at 300V. The relative humidity was kept at a constant 5%. No instabilities were observed in this measurement, and the small jumps in the data are known to be a small baseline jump in the read-out chain, not from the detector.

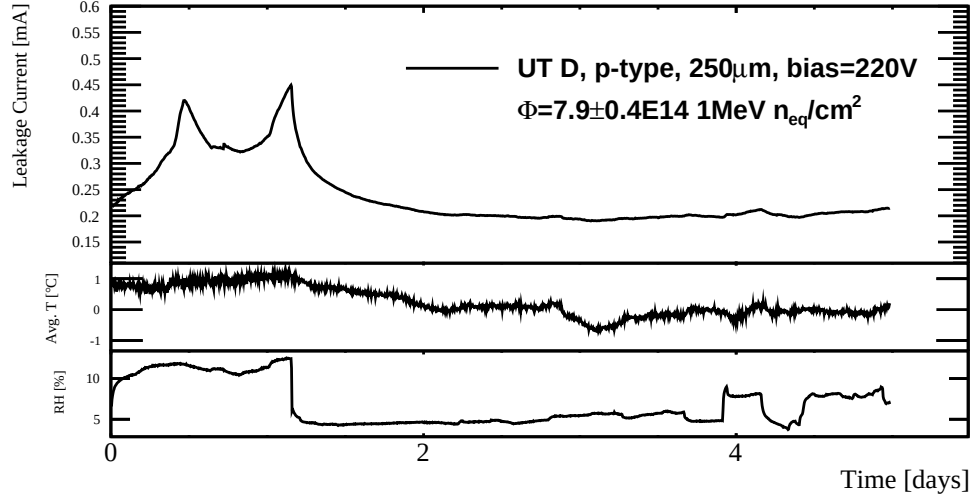


Figure 52: Measurement of the long-term leakage current stability of the full size D detector irradiated to 2x the expected dose. The increases in leakage current at the beginning of the measurement are due to the higher humidity environment.

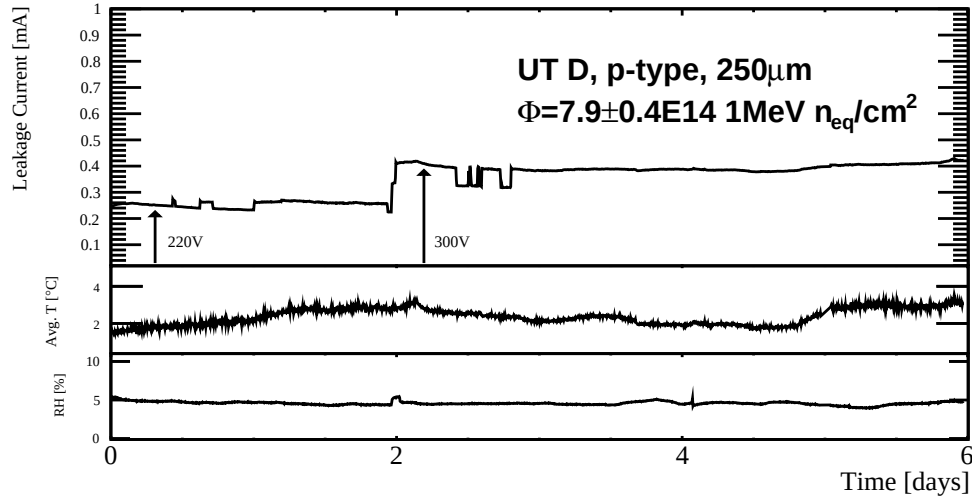


Figure 53: Measurement of the long-term leakage current stability of the full size D detector irradiated to 2x the expected dose. The small jumps in the data are known to be a small baseline jump in the read-out chain, not from the detector. In this measurement the guard ring is bonded to ground.

4.3.8 Conclusions

Measurements of the static properties and the leakage current stability were made on a variety of detectors related to the UT upgrade project.

Leakage current measurements on detectors irradiated at IRRAD and MGH to fluences ranging from 1×10^{12} 1 MeV n_{eq}/cm^2 to 2×10^{15} 1 MeV n_{eq}/cm^2 resulted in a ΔI vs. Φ curve that is linear with a slope consistent with previous measurements. Besides being a useful measurement on its own, measuring this curve provides a baseline for future UT irradiation studies as it can be used to corroborate irradiation dose measurements on detectors. Additional measurements of depletion voltages and bandgap energies were made as a function of fluence, for a variety of detectors in the 2015 irradiation campaign.

Measurements of long-term leakage stability on more recent prototype D and A detectors were performed to address the questions of stability over a span of a week, and changes in stability with the guard ring grounded. In all cases no difference was found in stability with and without the guard ring grounded. In the type A detectors no instability was observed over a span of six to eight days. In the case of the irradiated type D detector gradual increases of leakage current were observed when in an environment with a relative humidity greater than 11%. At a relative humidity of 5% no instabilities were observed throughout the measurement.

5 Measurement of the b -quark cross section in 7 and 13 TeV center-of-mass pp collisions

5.1 Introduction

Measurements of the production cross sections of heavy quarks are an excellent test of our understanding of models of quantum chromodynamics. Previous measurements of heavy quark cross sections have found good agreement between experiment and theoretical calculations [65] [66] [67] [68] [69] [70]. Additionally, precise measurements of heavy quark production cross sections are important for calculating experimental sensitivities to CP -violating processes and rare decays, and for estimating expected backgrounds in searches for physics beyond the standard model.

From an experimental point of view measurements of production cross sections need to be approached with caution as they deal with absolute quantities instead of ratios, where most systematic uncertainties cancel. For a generic physics process $a \rightarrow b$, the cross section can be written as

$$\sigma_{a \rightarrow b} = \frac{N_{a \rightarrow b}}{\mathcal{L} \times \epsilon_{a \rightarrow b}}, \quad (34)$$

where N , $\mathcal{L}$, and ϵ are the measured event rate, luminosity, and the detection efficiency for that particular physics process, respectively. The luminosity depends on the experimental setup and typically needs to be measured. For LHCb this is the product of the numbers of protons in oppositely colliding bunches, the revolution frequency, and the beam overlap integral. The efficiency that enters in Equation 34 contains multiple components such as selection, particle identification, trigger, etc. Systematic uncertainties such as kinematic mis-modeling in Monte Carlo simulations or tracking efficiencies, to name a few, which could normally be chosen to cancel in ratio measurements, can lead to a very drastic changes in any final cross section calculation. That is why it is essential to handle the absolute efficiency

in Equation 34 with care and to perform as many cross-checks as possible to ensure the absolute quantity is the right one.

5.2 Experimental method

The b -quark production cross section is measured at both 7 and 13 TeV center-of-mass energies with the LHCb detector using semileptonic decays of b -hadrons to ground state charmed hadrons in association with a muon. The cross section is determined in six equal bins of pseudorapidity, η , of the b -hadron between 2 and 5 ($\eta \equiv -\ln(\tan(\frac{\theta}{2}))$ where θ is the angle between the b -hadron flight path and the beam pipe), and thirteen bins of p_T of the charm-muon pair in the regions of $p_T(\text{charm} + \mu) \in [0, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 25]$ GeV. The $D^0\mu$, $D^+\mu^-$, $D_s^+\mu^-$, and $\Lambda_c^+\mu^-$ final states are reconstructed where the former two final states originate predominately from B^{+0} decays and the last two come from B_s^0 and Λ_b^0 decays, respectively. The charm hadrons are reconstructed in the decay modes listed in Table 24. The production cross section for one b -quark can be written as the sum of average cross section of each b -flavored hadron

$$\begin{aligned} \sigma(pp \rightarrow H_b X) = & \frac{1}{2}[\sigma(B^0) + \sigma(\bar{B}^0)] + \frac{1}{2}[\sigma(B^+) + \sigma(B^-)] \\ & + \frac{1}{2}[\sigma(B_s^0) + \sigma(\bar{B}_s^0)] + \frac{1+\delta}{2}[\sigma(\Lambda_b) + \sigma(\bar{\Lambda}_b)]. \end{aligned} \quad (35)$$

There are other b -hadrons (Ω_b , Ξ_b , ...) not explicitly measured here and the δ in Equation 35 takes these into account. The contribution from B_c is estimated using from $B_c \rightarrow \pi^\pm B_s$ decays [71] and is 0.8% the rate of B_s^0 and is therefore neglected. The value for

δ is estimated from [72] where two useful relations are given:

$$\Gamma(\Xi_b^- \rightarrow \Xi^- X \mu^- \bar{\nu}) = \Gamma(\Lambda_b^0 \rightarrow \Lambda X \mu^- \bar{\nu}), \quad (36)$$

$$\frac{\sigma(\Xi_b^-)}{\sigma(\Lambda_b^0)} = 0.11 \pm 0.03 \pm 0.03. \quad (37)$$

The former is based on flavor SU(3) symmetry and the latter is determined from Tevatron data and the assumption of SU(3) symmetry, which results in an estimated 30% systematic uncertainty. Since the lifetimes of the Λ_b^0 and Ξ_b^- are equal within their uncertainties [73], assuming that the two branching fractions are equal gives us an estimate of 0.11 for the Ξ_b^-/Λ_b^0 semileptonic decay fraction. However, this must be doubled, using isospin invariance, to account for the Ξ_b^0 . To this the Ω_b contribution must be added, thus arriving at an estimate of δ of 0.25 ± 0.10 , where the uncertainty is the one in Equation 36 added in quadrature to the estimate of the uncertainties from assuming isospin and lifetime equality.

Translated to the relevant reconstructed final state yields, efficiencies, and branching fractions, the equation for the b -quark cross section is

$$\begin{aligned} \sigma(pp \rightarrow H_b X) = \frac{1}{2\mathcal{L}} & \left(\left[\frac{n(D^0 \mu)}{\epsilon_{D^0} \times \mathcal{B}_{D^0}} + \frac{n(D^+ \mu)}{\epsilon_{D^+} \times \mathcal{B}_{D^+}} \right] \frac{1}{\mathcal{B}(B \rightarrow X_c X \mu \nu)} \right. \\ & + \left[\frac{n(D_s^+ \mu)}{\epsilon_{D_s^+} \times \mathcal{B}_{D_s^+}} \right] \frac{1}{\mathcal{B}(B_s \rightarrow D_s X \mu \nu)} \\ & \left. + \left[\frac{n(\Lambda_c^+ \mu)}{\epsilon_{\Lambda_c^+} \times \mathcal{B}_{\Lambda_c^+}} \right] \frac{1 + \delta}{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c X \mu \nu)} \right). \end{aligned} \quad (38)$$

The various $\mathcal{B}_{H_c}$ are the branching fractions for the charm hadron decays are listed in Table 24 with their sources and $\mathcal{B}(B \rightarrow X_c X \mu \nu)$ are the b -hadron semileptonic branching fractions.

The semileptonic b -hadron branching fractions for $B^{+/0}$ are taken from three measurements done by CLEO [74], BaBar [75], and Belle [76]. These latter two analyses charge tag B mesons and then measure the semileptonic decays of the other B . They do not cover the full momentum range so a correction has to be applied; this was done by the PDG [73]. The measurement from CLEO uses inclusive leptons taken at the $\Upsilon(4S)$ resonance and does

not distinguish between charged or neutral B decays. Furthermore the $\Upsilon(4S)$ does not have equal branching fractions into charged and neutral B s. The fraction into neutral B pairs is $\alpha = 0.486 \pm 0.006$ [73], with the remainder going into charged B pairs. Therefore to compute the $\overline{B}^0$ and B^- branching fractions the following coupled equations need to be used:

$$\begin{aligned} \alpha \mathcal{B}_{\text{SL}}^0 + (1 - \alpha) \mathcal{B}_{\text{SL}}^- &= (10.91 \pm 0.09 \pm 0.24)\% \\ \mathcal{B}_{\text{SL}}^0 / \mathcal{B}_{\text{SL}}^- &= 0.927 \pm 0.004 . \end{aligned} \tag{39}$$

The solution is listed in Table 3.

To derive the semileptonic branching fraction for B_s^0 and Λ_b^0 , their measured lifetimes are used along with the fact that the semileptonic widths are equal among all B species with only a small 4% correction to the baryons. the B_s^0 lifetime comes from measurements in the flavor-specific decay $\overline{B}_s^0 \rightarrow D_s^+ \pi^-$ from CDF [77] and LHCb [78]. the Λ_b^0 lifetime is taken from the HFLAV average [79].

As already mention, reconstructed $D^{0/+} \mu$ decays mostly originate from $B^{0/+}$ semileptonic decays, and $D_s \mu$ and $\Lambda_c \mu$ from B_s and Λ_b semileptonic decays, respectively. There are a few “cross-feed” decays, e.g., $\Lambda_b \rightarrow D^0 p \mu$, that are reconstructed in the inclusive $D \mu$ samples. All the cross-feed decays are $B_s \rightarrow D^{0(+)} K^{(0)} \mu$, $B^+ \rightarrow D_s K^{(0)} \mu$, and $\Lambda_b \rightarrow D^{0(+)} p(n) \mu$. These modes could be looked for and subtracted from the inclusive $B \rightarrow D \mu X$ samples, and added to the Equation 38 explicitly. However, the fact that the semileptonic branching fractions are almost equal and efficiencies between all b -hadron modes are very similar, this reduces to a percent level effect, which is beyond the precision of this measurement.

Table 2: Charm hadron branching fractions for the decay modes used in this analysis. The PDG average is used for the D^0 and D_s^+ modes. For the D^+ mode there is only one measurement by CLEO III, so that is used. For the Λ_c^+ the average measurements by CLEO and BESIII are used.

Particle and decay	$\mathcal{B}$ (%)	Relative error (%)	Source
$D^0 \rightarrow K^- \pi^+$	3.91 ± 0.05	1.3	PDG average [73]
$D^+ \rightarrow K^- \pi^+ \pi^+$	9.22 ± 0.17	1.8	CLEO III [80]
$D_s^+ \rightarrow K^- K^+ \pi^+$	5.44 ± 0.18	3.3	PDG average [73]
$\Lambda_c^+ \rightarrow p K^- \pi^+$	$5.84 \pm 0.27 \pm 0.23$		BES III [81]
	$6.84 \pm 0.24^{+0.21}_{-0.27}$		Belle [82]
	6.36 ± 0.35	5.5	Weighted average

Table 3: Measured semileptonic decay branching fractions for $\bar{B}^0$ and B^- mesons. The CLEO numbers result from solving Eq. 39.

Particle	Source	$\mathcal{B}_{\text{SL}}$ (%)
$\bar{B}^0$	CLEO	10.49 ± 0.27
$\bar{B}^0$	BaBar	9.64 ± 0.43
$\bar{B}^0$	Belle	10.46 ± 0.38
$\bar{B}^0$	Average	10.31 ± 0.19
B^-	CLEO	11.31 ± 0.27
B^-	BaBar	10.28 ± 0.47
B^-	Belle	11.17 ± 0.38
B^-	Average	11.09 ± 0.20

Table 4: Measured semileptonic decay branching fractions for B mesons and derived branching fractions for B_s and Λ_b based on the equality of semileptonic widths and the lifetime ratios.

Particle	τ (ps) measured	$\mathcal{B}_{\text{SL}}$ (%) measured	Γ_{SL} (ps^{-1}) measured	$\mathcal{B}_{\text{SL}}$ (%) to be used
$\bar{B}^0$	1.519 ± 0.005	10.30 ± 0.19	0.0678 ± 0.0013	10.30 ± 0.19
B^-	1.638 ± 0.004	11.09 ± 0.20	0.0680 ± 0.0013	11.09 ± 0.20
$< \bar{B}^0 + B^- >$		10.70 ± 0.19		10.70 ± 0.19
$\bar{B}_b^0$	1.533 ± 0.018			10.40 ± 0.30
Λ_b^0	1.467 ± 0.010			10.35 ± 0.28

5.3 Event selection

The 7 TeV dataset corresponds to $284.10 \pm 4.86 \text{ pb}^{-1}$ of integrated luminosity collected with the LHCb detector using pp collisions taken with trigger configuration key (TCK) 760037 [83] during 2011. All selected charm-muon candidates must satisfy the requirement that the muon is TOS on the following trigger lines: `L0Muon`, `Hlt1TrackMuon` and `Hlt2SingleMuon`. The events are selected by the `b2(D0|Dp|Ds|Lc)MuXB2DMuNuXLine` stripping lines in `Stripping 20r1` which corresponds to the summer 2012 full stripping and reprocessing with `Reco14`.

The 13 TeV dataset corresponds to $4.60 \pm 0.18 \text{ pb}^{-1}$ of integrated luminosity collected during the “early measurements” period of July and (one fill) August 2015. The muon must be flagged as TOS on the following lines: `L0Muon`, `Hlt1TrackMuon` and `Hlt2SingleMuon`. The events are selected by the `B2DMuNuX_(D0|Dp|Ds|Lc)Line` stripping lines in `Stripping 22` which corresponds to the prompt offline processing of the early measurements dataset.

The full list of stripping line selections is provided in Table 27 for both 7 and 13 TeV data. The offline analysis cuts for both 7 and 13 TeV data are given in Table 28. In 13 TeV data, the momentum and track η are chosen such that all data reside within the tracking correction calibration tables (described later).

For both 2011 and 2015 data, the muon requirements on the L0, HLT1, and HLT2 levels are listed for both years in Table 7. Note that the 2015 trigger selections are less restrictive as they were meant for early measurements.

Table 5: Stripping selections using Stripping20r1 for the 2011 data and Stripping22 for the 2015 data. Stripping selections for the $D^0\mu$ and $(D^+|D_s^+|\Lambda_c^+)\mu$ lines in 7 TeV data have some differences. The cuts in parentheses are for the $(D^+|D_s^+|\Lambda_c^+)\mu$ lines. The stripping selections for all 13 TeV lines are the same.

Item	7 TeV Stripping 20r1	13 TeV Stripping 22a
Muon		
Track fit χ^2/NDOF	< 3	< 3
Minimum χ_{IP}^2	> 9	> 9
p	$> 6 \text{ GeV}$	$> 6 \text{ GeV}$
p_T	$> 1.2(0.8) \text{ GeV}$	$> 1.0 \text{ GeV}$
PID for muons	$\text{DLL}(\mu - \pi) > 0$	$\text{DLL}(\mu - \pi) > 0$
Charm hadron daughter		
Track fit χ^2/NDF	< 3	< 3
Minimum χ_{IP}^2	> 9	> 4
p	$> 2 \text{ GeV}$	$> 2 \text{ GeV}$
Proton p	-	$> 8 \text{ GeV}$
Kaon p	-	$> 5 \text{ GeV}$
p_T	$> 0.3 \text{ GeV}$	$> 0.25 \text{ GeV}$
PID for pions	$\text{DLL}(K - \pi) < 4(10)$	$\text{DLL}(K - \pi) < 20$
PID for kaons	$\text{DLL}(K - \pi) > 4$	$\text{DLL}(K - \pi) > -2$
PID for protons	$\text{DLL}(p - \pi) > 4$	$\text{DLL}(p - \pi) > 0$
	$\text{DLL}(p-K) > 1e-10$	
Charm hadron		
Average of daughter $p_T/\#$ daughters (D^0)	$> 600(700) \text{ MeV}$	-
Vertex χ^2/NDOF	< 6	< 6
Flight distance χ^2	> 100	> 25
DIRA	> 0.99	> 0.99
b hadron		
Vertex χ^2/NDOF	< 6	< 9
B DIRA	> 0.999	> 0.999
z(charm)-z(b)	$> -9999(0)\text{mm}$	$> -0.05\text{mm}$
η	$\in [2, 5]$	$\in [2, 5]$
m(charm hadron + μ)	$\in [2.5, 6] \text{ GeV}$	$\in [2.2, 8.0] \text{ GeV}$
misc.		
NLongTracks	< 250	< 250
$D^0\mu^-$ prescale	factor of 0.5	none

Table 6: Offline selection criteria.

Item	Requirement
Muon	
L0	L0MuonDecision TOS
Hlt1	TrackMuonDecision TOS
Hlt2	SingleMuonDecision TOS
ISMUON	OK
N shared hit	=0
Charm hadron daughter	
PID for protons	$DLL(p - \pi) > 10$ and $DLL(p - K) > 0$
Charm hadron	
$Ln(IP/mm)$	$\in [-7, 2]$
b hadron	
$z(charm) - z(b)$	> 0
Invariant mass of $D^0(D^+) + \mu$	$3 < m(K\pi(\pi)\mu) < 5 \text{ GeV}$
Invariant mass of $D_s^+ + \mu$	$3.1 < m(KK\pi\mu) < 5.1 \text{ GeV}$
Invariant mass of $\Lambda_c\mu$	$3.3 < m(pK\pi\mu) < 5.3 \text{ GeV}$
Additional selections for 7 TeV data	
Muon p_T	$> 1300 \text{ MeV}$
Muon χ_{IP}^2	> 16
B flight radius	$< 4.8 \text{ mm}$
Additional selections for 13 TeV data	
Muon p_T	$> 1300 \text{ MeV}$
Sum of daughter $p_T/\#$ daughters (D^0)	$> 600 \text{ (700) MeV}$
Charm hadron daughter χ_{IP}^2	> 9
PID for kaons	$DLL(K - \pi) > 4$
PID for pion	$DLL(K - \pi) < 10$
B flight radius	$< 4.8 \text{ mm}$
Track η	$1.9 < \eta < 4.9$
Track p	$5 < p < 200 \text{ GeV}$

Table 7: Trigger selections for the 7 and 13 TeV datasets.

Item	7 TeV	13 TeV
TCK	760037	Various
L0	$n_{SPD} < 600$ $p_T > 1480 \text{ MeV}$	No global-event-cuts $p_T > 900 \text{ MeV}$
Hlt1	$p > 8000 \text{ MeV}$ $p_T > 1000 \text{ MeV}$ $IP > 0.1 \text{ mm}$ $IP-\chi^2 > 16$ Track fit $\chi^2 < 2$ isMuonTight	$p > 3000 \text{ MeV}$ $p_T > 800 \text{ MeV}$ — $IP-\chi^2 > 4$ Track fit $\chi^2 < 3$ isMuon
Hlt2	prescale = 0.5 $p_T > 1.3 \text{ GeV}$ $IP > 0.5 \text{ mm}$ track- $\chi^2 < 2$ $IP-\chi^2 > 200$ isMuon	prescale=0.5 $p_T > 1.3 \text{ GeV}$ — track- $\chi^2 < 3$ $IP-\chi^2 > 16$ isMuon

5.4 Signal fits

The method used to extract the charmed hadron- μ signal by using the $D^0 X \mu^- \bar{\nu}$ final state is described as an example; the same procedure is applied to the final states $D^+ X \mu^- \bar{\nu}$, $D_s^+ X \mu^- \bar{\nu}$, and $\Lambda_c X \mu^- \bar{\nu}$. Here, both charge conjugate states and data taken with magnet polarity up and down are combined. Extended maximum likelihood fits are performed to the two-dimensional distributions in $K\pi$ invariant mass over a region extending ± 75 MeV from the D^0 mass peak, and $\ln(\text{IP}/\text{mm})$. Shown here the integrated fits, but the actual event yields are extracted in bins of η and p_T .

The invariant mass signal PDF shape, shown as the green line in Fig. 54, is parameterized by a double Gaussian, where the means of each Gaussian are constrained to be the same and the widths are determined in the fit. The $\ln(\text{IP}/\text{mm})$ shape of the signal component, determined by examining MC, is a bifurcated Gaussian where the mean and widths are determined in the fit. The small prompt background component, shown as the purple dashed line is constrained to have the same shape as the signal in invariant $K\pi$ mass, and the $\ln(\text{IP}/\text{mm})$ shape, determined by studying a prompt enriched sample, is a bifurcated Gaussian. The combinatoric component, shown as the red dashed line is parameterized by a linear PDF in $K\pi$ invariant mass, and a bifurcated Gaussian plus a crystal ball in $\ln(\text{IP}/\text{mm})$. The combinatoric background $\ln(\text{IP}/\text{mm})$ PDF was chosen empirically by fitting events in the $K\pi$ invariant mass sidebands, and all $\ln(\text{IP}/\text{mm})$ shape parameters are determined bin-by-bin.

The figures for the other considered charmed hadrons are shown in Figs. 55, 56, and 57 for the 7 TeV data, and Figs. 58, 59, 60, and 61 for the 13 TeV sample.

The analysis of the $D_s^+ X \mu^- \bar{\nu}$ state includes one additional component coming from $D^{*+} \rightarrow D^0 \pi^+$ decays, where $D^0 \rightarrow K^+ K^-$. This component, shown in Figure 56 as the dashed yellow line around the $KK\pi$ invariant mass of 2010 GeV, is explicitly included in the fit. The shapes used to model this component are determined from a MC sample (see Figure 62), and are a double Gaussian in $KK\pi$ invariant mass and a bifurcated Gaussian in

$\ln(\text{IP}/\text{mm})$.

The fitting parameters are listed in Tables 8 and 9. These integrated fits are just examples of the procedure but show the overall statistical size of the data.

Table 8: Fitting parameters for the nominal fitting method described in the text for the $D^0\mu$, $D^+\mu$, $D_s^+\mu$, and $\Lambda_c^+\mu$ states in pseudorapidity region 2 to 5 in 7 TeV data.

Parameter	D^0	D^+	D_s^+	Λ_c^+
μ_{mass}	1866.49 ± 0.02	1870.92 ± 0.02	1969.81 ± 0.05	2288.04 ± 0.03
$\sigma_{1,mass}$	6.75 ± 0.06	6.1 ± 0.3	5.4 ± 0.1	4.82 ± 0.08
$\sigma_{2,mass}$	12.6 ± 0.2	10.5 ± 0.6	12.5 ± 0.9	10.55 ± 0.6
$frac_{1,mass}$	0.73 ± 0.02	0.59 ± 0.08	0.71 ± 0.03	0.75 ± 0.03
$\mu_{log(IP)}$	-0.610 ± 0.005	-0.638 ± 0.004	-0.66 ± 0.01	-0.791 ± 0.008
$\sigma_{L,log(IP)}$	0.920 ± 0.003	0.924 ± 0.004	0.924 ± 0.008	0.884 ± 0.006
$\sigma_{R,log(IP)}$	0.577 ± 0.003	0.573 ± 0.003	0.552 ± 0.006	0.561 ± 0.005
Signal Yield	205677 ± 486	161264 ± 516	42661 ± 381	57714 ± 319
Prompt Yield	1078 ± 46	1114 ± 47	245 ± 24	347 ± 27
Background Yield	22884 ± 229	77324 ± 427	89876 ± 485	48265 ± 305
D^* Yield	—	—	2529 ± 159	—

Table 9: Fitting parameters for the nominal fitting method described in the text for the $D^0\mu$, $D^+\mu$, $D_s^+\mu$, and $\Lambda_c^+\mu$ states in the pseudorapidity region of 2 to 5.0 in the 13 TeV data.

Parameter	D^0	D^+	D_s^+	Λ_c^+
μ_{mass}	1865.53 ± 0.04	1870.07 ± 0.06	1969.1 ± 0.1	2287.49 ± 0.08
$\sigma_{1,mass}$	6.4 ± 0.1	6.4 ± 0.3	5.5 ± 0.4	4.8 ± 0.3
$\sigma_{2,mass}$	11.0 ± 0.3	10.8 ± 1	11 ± 2	9 ± 1
$frac_{1,mass}$	0.63 ± 0.04	0.6 ± 0.1	0.7 ± 0.1	0.7 ± 0.1
$\mu_{log(IP)}$	-1.16 ± 0.01	-1.13 ± 0.02	-1.21 ± 0.05	-1.27 ± 0.03
$\sigma_{L,log(IP)}$	1.14 ± 0.01	1.17 ± 0.02	1.04 ± 0.05	$0.99 \pm .03$
$\sigma_{R,log(IP)}$	0.731 ± 0.007	0.710 ± 0.01	0.72 ± 0.03	0.69 ± 0.02
Signal Yield	50637 ± 264	16896 ± 177	4251 ± 83	5136 ± 83
Prompt Yield	1628 ± 108	946 ± 77	153 ± 25	77 ± 18
Background Yield	10664 ± 141	8992 ± 140	7462 ± 112	2420 ± 63
D^* Yield	—	—	103 ± 44	—

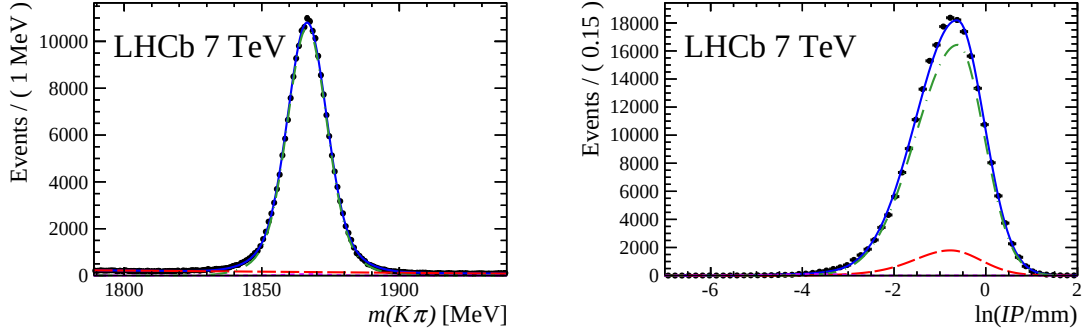


Figure 54: Fit to the D^0 invariant mass (left) and $\ln(\text{IP}/\text{mm})$ (right) distributions in the pseudorapidity range 2 to 5 in data taken at a center-of-mass energy of 7 TeV. The black points show the data, the blue curves the total fit, the green curves the signal, the purple dashed curves charm from the primary, and the red dashed curves the combinatorial background. The fitting procedure is described in the text.

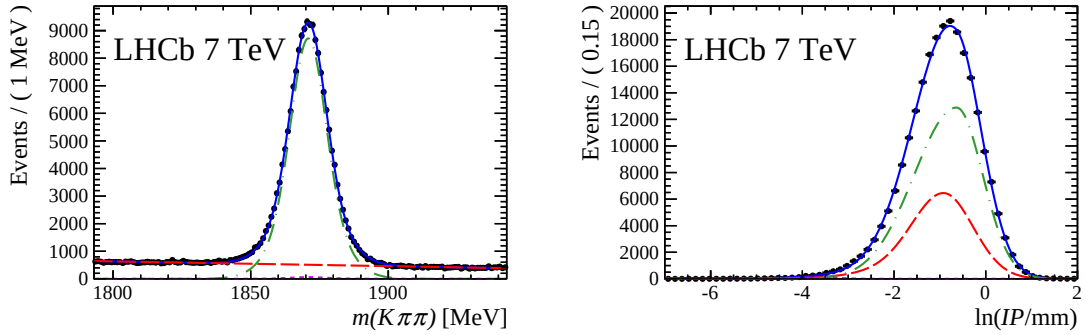


Figure 55: Fit to the D^+ invariant mass (left) and $\ln(\text{IP}/\text{mm})$ (right) distributions in the pseudorapidity region 2 to 5 in data taken at a center-of-mass energy of 7 TeV. The black points show the data, the blue curves the total fit, the green curves the signal, the purple dashed curves charm from the primary, and the red dashed curves the combinatorial background. The fitting procedure is described in the text.

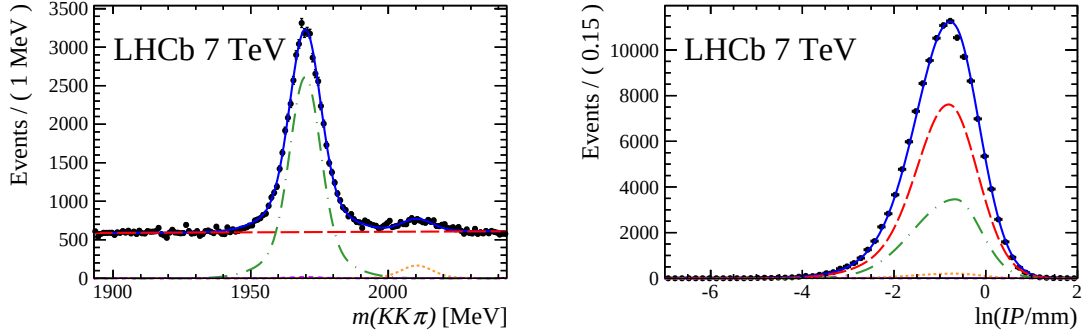


Figure 56: Fit to the D_s^+ invariant mass (left) and $\ln(IP/mm)$ (right) distributions in pseudorapidity region 2 to 5 in data taken at a center-of-mass energy of 7 TeV. The black points show the data, the blue curves the total fit, the green curves the signal, the purple dashed curves charm from the primary, the yellow dashed curves the D^{*+} component, and the red dashed curves the combinatorial background. The fitting procedure is described in the text.

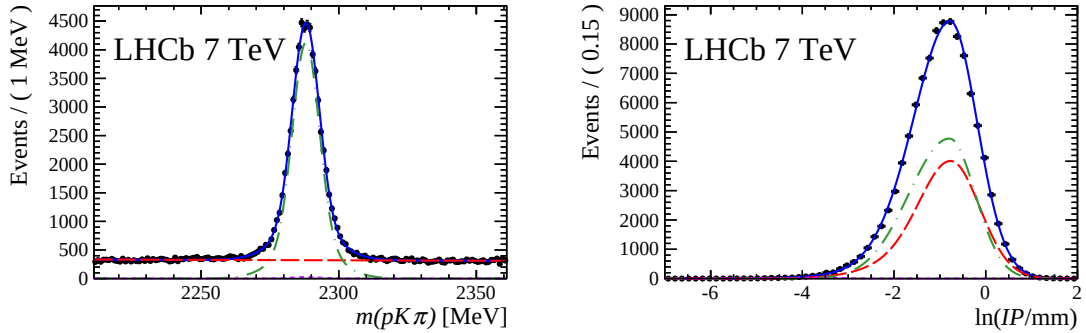


Figure 57: Fit to the Λ_c invariant mass (left) and $\ln(IP/mm)$ (right) distributions in pseudorapidity region 2 to 5 in data taken at a center-of-mass energy of 7 TeV. The same fits but with log scale are shown directly below. The black points show the data, the blue curves the total fit, the green curves the signal, the purple dashed curves charm from the primary, and the red dashed curves the combinatorial background. The fitting procedure is described in the text.

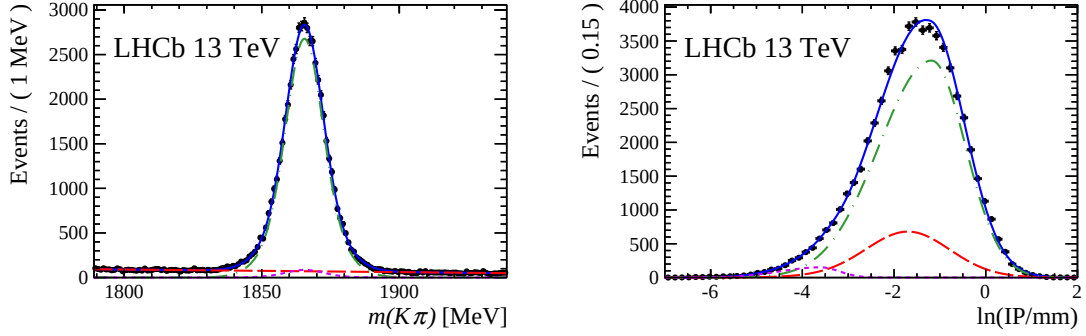


Figure 58: Fits to the D^0 invariant mass (left) and $\ln(\text{IP}/\text{mm})$ (right) distributions in the pseudorapidity region 2 to 5 in data taken at a center-of-mass energy of 13 TeV. The black points show the data, the blue curves the total fit, the green curves the signal, the purple dashed curves charm from the primary, and the red dashed curves the combinatorial background. The fitting procedure is described in the text.

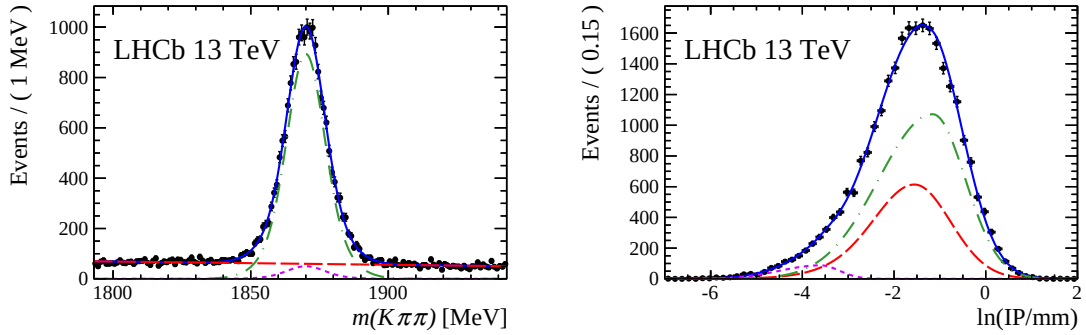


Figure 59: Fits to the D^+ invariant mass (left) and $\ln(\text{IP}/\text{mm})$ (right) distributions in the pseudorapidity region 2 to 5 from data taken at a center-of-mass energy of 13 TeV. The black points show the data, the blue curves the total fit, the green curves the signal, the purple dashed curves charm from the primary, and the red dashed curves the combinatorial background. The fitting procedure is described in the text.

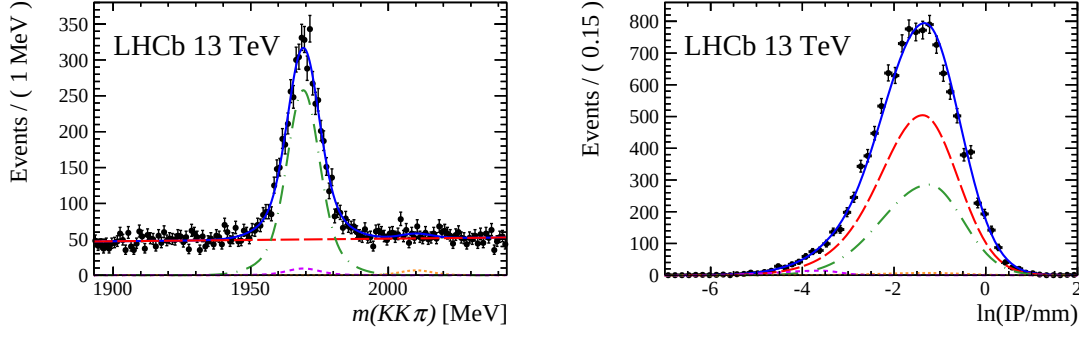


Figure 60: Fits to the D_s^+ invariant mass (left) and $\ln(\text{IP}/\text{mm})$ (right) distributions in the entire pseudorapidity region 2 to 5 in data taken at a center-of-mass energy of 13 TeV. The black points show the data, the blue curves the total fit, the green curves the signal, the purple dashed curves charm from the primary, the yellow dashed curves the D^{*+} component, and the red dashed curves the combinatorial background. The fitting procedure is described in the text.

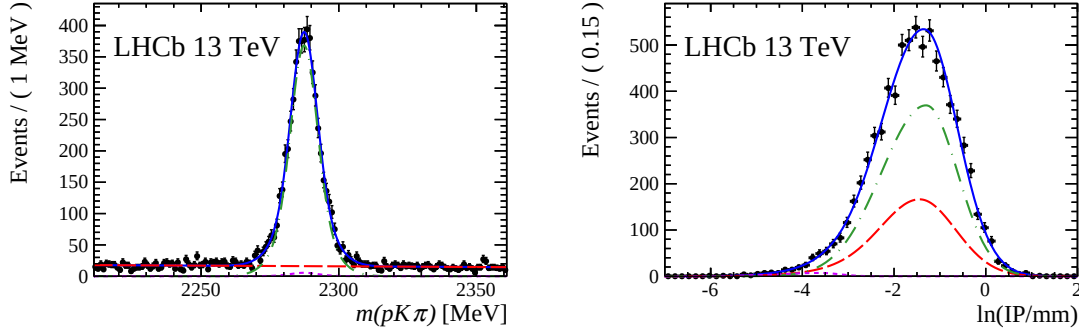


Figure 61: Fits to the Λ_c invariant mass (top left) and $\ln(\text{IP}/\text{mm})$ (top right) in the pseudorapidity region 2 to 5 in data taken at a center-of-mass energy of 13 TeV. The black points show the data, the blue curves the total fit, the green curves the signal, the purple dashed curves charm from the primary, and the red dashed curves the combinatorial background. The fitting procedure is described in the text.

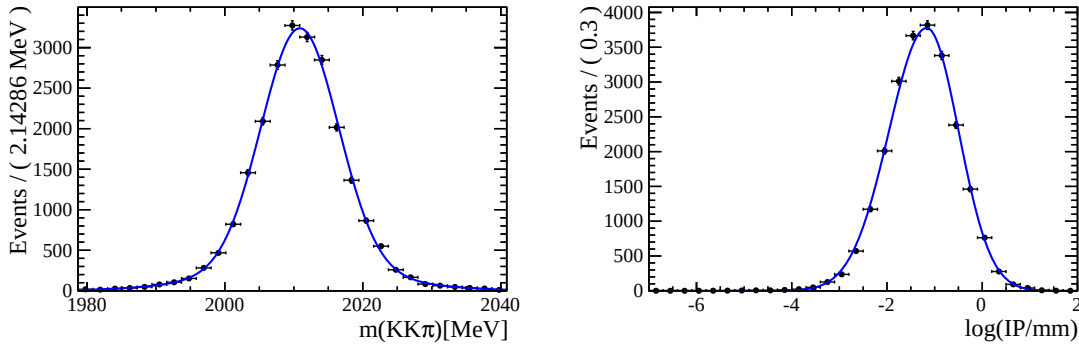


Figure 62: Fits to the $KK\pi$ invariant mass (left) and $\ln(\text{IP}/\text{mm})$ (right) using simulated D^{*+} events over the entire η and p_T range. The fit functions are described in the text.

5.5 Efficiency corrections

There are several sources of efficiency loss that need to be corrected for in the final determination of the b -quark cross section. The overall philosophy of the efficiency corrections is to use data-driven methods wherever available, and rely on Monte Carlo (MC) corrections for everything else. In this analysis MC is used to account for detector acceptance, event reconstruction, and stripping and offline selection efficiencies listed in Tables 27 and 28, respectively. Other efficiency corrections, namely hadron and muon identification, muon trigger, and global event cuts (GECs) are determined using dedicated calibration samples in data.

Additionally, since it is known that the tracking efficiency in MC is not perfectly modeled, a correction is applied to all final state MC particles. These corrections are determined with a dedicated data sample that measures the tracking efficiency of muons using a tag-and-probe method with $J/\psi \rightarrow \mu^+\mu^-$ decays in various tracking subdetectors. Taking the ratio of this tracking efficiency in data with the efficiency from MC provides a correction that can be applied per particle in other MC samples of the same data-taking conditions. Corrections are split into bins of particle momentum and η as reconstruction efficiency is highly dependent on these variables.

The presentation of efficiencies will be given first as an highlighted overview of the hadron identification, muon identification and trigger, and GECs, followed by sections on the tracking corrections, and MC efficiencies and integration of all components.

5.5.1 Hadron identification

Particle identification (PID) selection efficiencies for hadrons listed in Tables 27 and 28 are determined with a dedicated software package called PIDCalib [84], which utilizes data samples dedicated for PID efficiencies. Kaon and Pion efficiencies come from $D^{*+} \rightarrow D^0\pi^+$ decays were the D^0 decays into a $K^-\pi^+$ pair, and protons come from a sample of $\Lambda \rightarrow pK\pi$ decays. Backgrounds are subtracted off all calibration samples by using the sWeight method

with mass fits. The efficiency for a PID selection is then calculated in bins of particle kinematics and event variables. The PID binning scheme for this analysis was chosen to be as a function of particle transverse momentum, η , and track multiplicity. Figure 63 shows for example the kaon PID efficiencies in 2015 data as a function of these variables.

PID efficiencies are also determined separately for data taken with magnet polarity up and down. This is important because positively and negatively charged tracks are bent to different regions of the detector for a given magnet polarity, and the PID efficiencies may be different for different detector regions.

To propagate the efficiencies determined in the calibration samples to the semileptonic decays a weighted average is performed over the efficiencies according to the particle kinematics in the signal decay. This average is done in bins of semileptonic B pseudorapidity and transverse momentum of the charm plus muon pair. PID efficiencies for all modes in 2011 data are shown in Figure 64. Shown in Figure 66 are the PID efficiencies for 2015 data taken with magnet polarity down. There were inefficient calibration data taken with magnet polarity up so only the magnet down data were used. As a check, shown in Figure 65, using 2011 data the difference between magnet up and down efficiencies were calculated for all modes. The results show there are no differences between efficiencies in both magnet polarities.

Uncertainties on the hadron PID efficiencies come from the limited statistics of the calibration samples. To determine a systematic uncertainty on the final efficiencies a toy study was performed where the efficiencies per hadron were varied within bins of track kinematics according their statistical uncertainty with a Gaussian function when performing the weighted average. One hundred iterations were done in this manner and the width in the efficiency distribution was used as the systematic uncertainty.

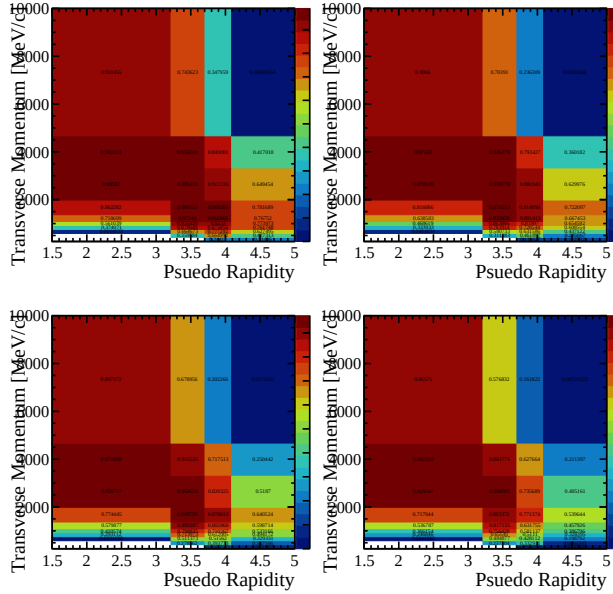


Figure 63: PID efficiencies for kaon identification in 2015 data as a function of kaon p_T and η split into four regions of track multiplicity.

5.5.2 Muon identification and trigger

Muon identification and trigger efficiencies are determined with a *tag-and-probe* method using a sample of $B^+ \rightarrow J/\psi K^+$ decays where the J/ψ decays into two muons. One of these muons is fully identified (called the “tag” muon), and the other muon (called the “probe” muon) is only loosely identified, i.e., no PID or trigger requirements. Probe muons are used to determine muon related efficiencies by attempting to fully identify the muon.

Explicitly the calibration sample is split into two categories, called *pass* and *fail*, depending whether the probe muon passes or fails the muon PID and trigger requirements, respectively. A fit in dimuon invariant mass is then performed in each category to separate background from true J/ψ decays.

As the muon PID and trigger efficiencies are highly dependent on muon kinematics these efficiencies are determined in a three-dimensional grid of muon transverse momentum, pseudorapidity, and absolute value of the muon tracks closest approach to the primary vertex, called the impact parameter (IP). One-dimensional projections of the muon PID and trigger

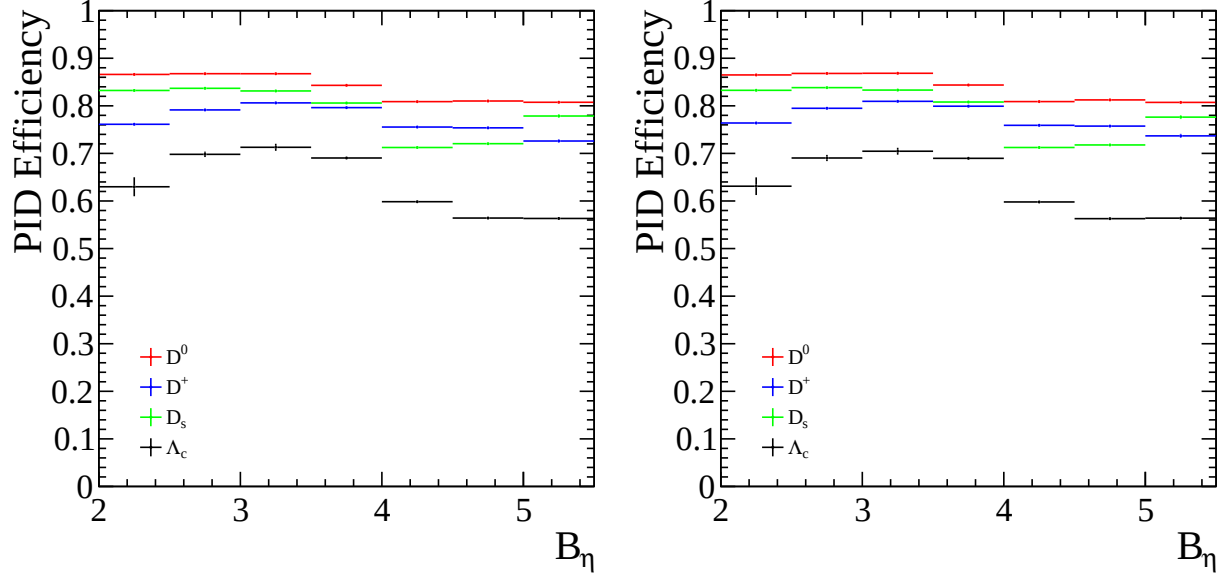


Figure 64: The PID efficiencies for the signal modes as a function of the pseudorapidity of the B hadron. 7 TeV data with magnet polarity down and up (left and right plots).

efficiencies are shown in Figures 67 and 68 for 2011 and 2015 data, respectively.

The muon PID and trigger efficiencies are propagated to the final semileptonic decay with a weighted average in the same manner as the hadron PID efficiencies and are given in Tables 10 and 11 for 2011 and 2015 data, respectively. Uncertainties given are the full muon PID and trigger systematic uncertainties described below.

There are three sources of systematic uncertainty considered in the tag-and-probe method for determining the muon PID and trigger efficiencies: statistical size of the calibration sample, choice of three-dimensional binning in muon kinematics, and any other source of bias in the method. The first one is determined with a toy study varying the efficiencies determined with the calibration sample with a Gaussian function according to the statistical uncertainty in each bin. The three-dimensional binning scheme is investigated in two ways. One where the signal MC is used where true trigger and PID efficiencies are compared to efficiencies determined with a finite three-dimensional grid from the same MC. The second method is varying the binning scheme in the calibration data with 18 different schemes and taking the maximum deviation in the final muon trigger and PID efficiency. The two methods

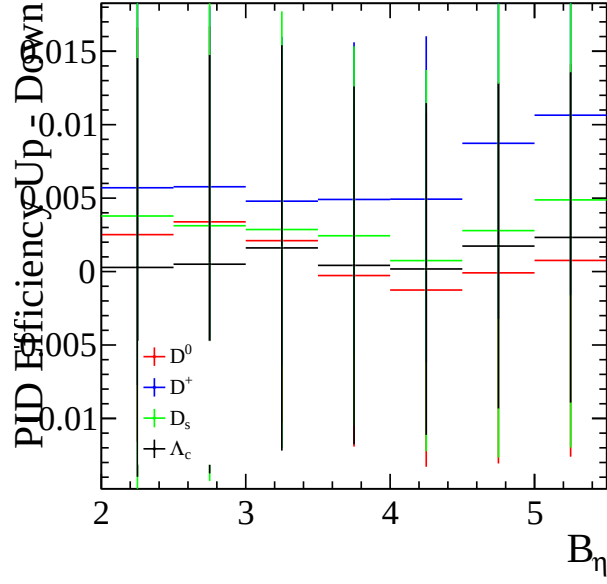


Figure 65: The difference in PID efficiencies between magnet up and magnet down 2011 data.

are not added together as they represent the same uncertainty; only the largest is taken. The final uncertainty on the bias of the tag-and-probe method is investigated by using the $B^+ \rightarrow J/\psi K^+$ and semileptonic MC samples. Comparing the efficiency using the tag-and-probe method on the $B^+ \rightarrow J/\psi K^+$ sample with the true efficiency from the semileptonic samples deviations up to 5% and 4% are seen in the 2011 and 2015 datasets, respectively. These comparisons, however, contain the effects of the finite binning in the tag-and-probe method and after considering this uncertainty, as determined in the previous systematic uncertainty, the final deviations are at most 3% in both datasets. This deviation is used to correct final efficiencies determined in data and is also taken as a systematic uncertainty as it is uncertain this effect in this MC study is present in the data. All systematic components are added in quadrature and included in the uncertainties shown in Tables 10 and 11 for the 2011 and 2015 datasets, respectively. For the 13 TeV to 7 TeV ratio, most trigger uncertainties cancel.

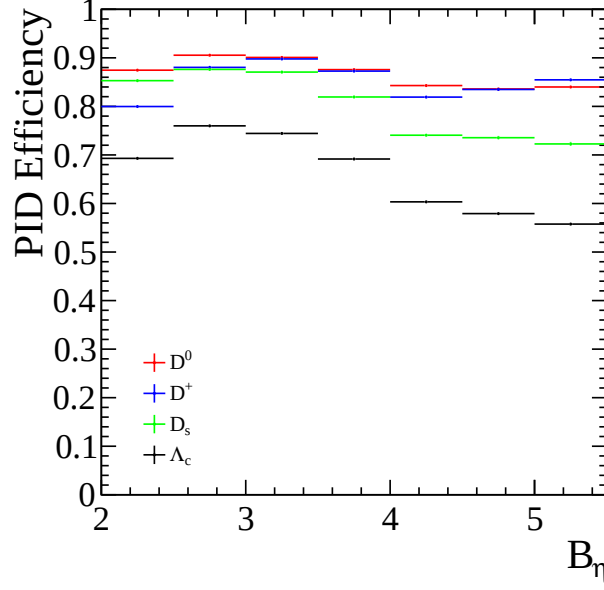


Figure 66: The PID efficiencies for the signal modes as a function of the pseudorapidity of the B hadron in 13 TeV data with magnet polarity down.

Table 10: 7 TeV single-muon trigger efficiencies for the various b species, with combined statistical and systematic uncertainties. The bottom row labeled as $b\bar{b}$ shows the average trigger efficiency, and the total trigger uncertainty per η interval.

	$2 < \eta < 2.5$	$2.5 < \eta < 3$	$3 < \eta < 3.5$	$3.5 < \eta < 4$	$4 < \eta < 4.5$	$4.5 < \eta < 5$
$D^0\mu$	15.3 ± 0.7	18.3 ± 0.7	19.8 ± 0.7	20.2 ± 0.6	19.2 ± 0.6	17.7 ± 0.6
$D^+\mu$	14.7 ± 0.7	18.7 ± 0.8	20.1 ± 0.5	19.8 ± 0.6	17.4 ± 0.5	16.2 ± 1.4
$D_s^+\mu$	16.2 ± 0.9	20.3 ± 0.9	21.7 ± 0.7	21.5 ± 0.7	20.9 ± 0.7	19.2 ± 1.4
$\Lambda_c^+\mu$	16.3 ± 1.3	20.4 ± 0.7	22.9 ± 0.8	23.9 ± 0.8	23.3 ± 0.9	21.2 ± 1.7
$b\bar{b}$	15.5 ± 0.8	19.0 ± 0.7	20.7 ± 0.7	21.0 ± 0.7	19.9 ± 0.7	18.3 ± 1.1

Table 11: 13 TeV single-muon trigger efficiencies for the various b species, with combined statistical and systematic uncertainties. The bottom row labeled as $b\bar{b}$ shows the average trigger efficiency, and the total trigger uncertainty per η interval.

	$2 < \eta < 2.5$	$2.5 < \eta < 3$	$3 < \eta < 3.5$	$3.5 < \eta < 4$	$4 < \eta < 4.5$	$4.5 < \eta < 5$
$D^0\mu$	73.2 ± 1.8	73.9 ± 1.3	71.9 ± 2.0	67.9 ± 2.2	63.1 ± 2.3	57.2 ± 2.5
$D^+\mu$	74.0 ± 2.3	73.7 ± 1.2	71.8 ± 2.0	67.8 ± 2.1	61.9 ± 2.2	55.7 ± 2.2
$D_s^+\mu$	72.6 ± 0.9	74.2 ± 1.2	71.8 ± 1.8	67.9 ± 2.0	62.0 ± 2.3	54.5 ± 2.0
$\Lambda_c^+\mu$	74.8 ± 1.7	75.5 ± 1.1	73.1 ± 1.7	68.9 ± 2.0	63.1 ± 1.9	56.7 ± 1.7
$b\bar{b}$	73.6 ± 1.8	74.3 ± 1.2	72.1 ± 1.9	68.1 ± 2.1	62.8 ± 2.2	56.6 ± 2.2

5.5.3 Global event cuts

Both 2011 and 2015 datasets contain global event cuts with the 2011 dataset having more restrictive cuts in comparison. In 2011 there are the cuts on the number of SPD hits less

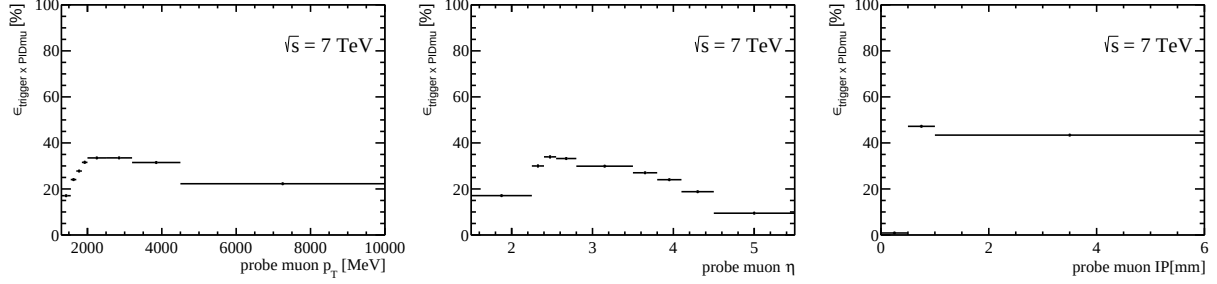


Figure 67: Efficiency due to single-muon trigger including PID requirements on the muon in bins of probe muon (left) p_T , (middle) η and (right) IP determined from detached J/ψ 's from B decays in 2011 data (note, that there is a factor of two prescale which is not included here).

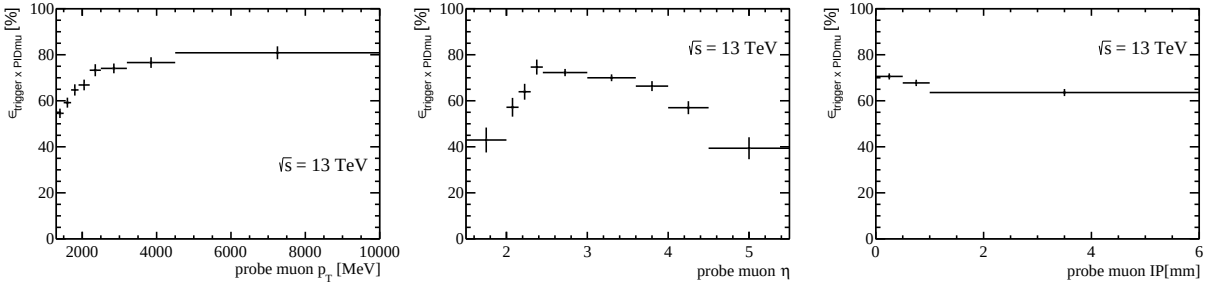


Figure 68: Efficiency due to single-muon trigger including PID requirements on the muon in bins of probe muon (left) p_T , (middle) η and (right) IP determined from detached J/ψ 's from B decays in 2015 data (note, that there is a factor of two prescale which is not included here).

than 600 in the trigger and the number of long tracks (nLongTracks) less than 250 in the stripping line. For 2015 the number of SPD hits was set less than 900 which only has about a 0.5% efficiency loss.

Both sets of GECs are determined using a sWeighted [85] sample of $B^+ \rightarrow J/\psi K^+$ decays triggered on the L0DiMuon line which cuts on the SPD hits less than 900 and a stripping line with no other GECs. An efficiency can be determined by fitting the SPD hit or nLongTrack distribution in the tail region and determining the fraction of events above the SPD or nLongTracks threshold. There is no reason that the SPD and nLongTrack distributions should agree between this sample and the semileptonic samples as the kinematics are different (as shown in Figure 69). Therefore, to produce the correct GEC efficiency, the $B^+ \rightarrow J/\psi K^+$ sample is reweighted in the distribution of total tracks in the event. This reweighting produces agreement in the SPD and nLongTracks distributions between the calibration and semileptonic samples.

The final GEC efficiencies are given in Table 12 and 13, for 2011 and 2015 data, respectively. The shape used to fit the tail of the SPD and nLongTrack distributions was a Gaussian. An example of the SPD distribution fit after reweighting the calibration sample to match the $D^0\mu X$ sample is shown in Figure 70.

Table 12: 2011 nSPD hits cut efficiencies at 600 for the $B \rightarrow D^0 X \mu \nu$ mode for all η bins

η	7 TeV nSPDcut efficiency
2-2.5	$95.17 \pm 0.13 \%$
2.5-3.	$94.98 \pm 0.07 \%$
3-3.5	$94.77 \pm 0.07 \%$
3.5-3.5	$94.58 \pm 0.08 \%$
4-4.5	$94.89 \pm 0.10 \%$
4.5-5.5	$95.60 \pm 0.17 \%$
5-5.5	$96.00 \pm 0.27 \%$

Table 13: 2015 number of long tracks cut efficiencies at 250 for the $B \rightarrow D^0 X \mu \nu$ mode for all η bins. There is an additional 0.5% inefficiency due to the SPD < 900 requirement.

η	13 TeV nLongTracks efficiency
2-2.5	$99.88 \pm 0.08 \%$
2.5-3.	$99.91 \pm 0.05 \%$
3-3.5	$99.91 \pm 0.05 \%$
3.5-3.5	$99.95 \pm 0.04 \%$
4-4.5	$99.95 \pm 0.05 \%$
4.5-5.5	$100.00 \pm 0.01 \%$
5-5.5	$99.85 \pm 0.20 \%$

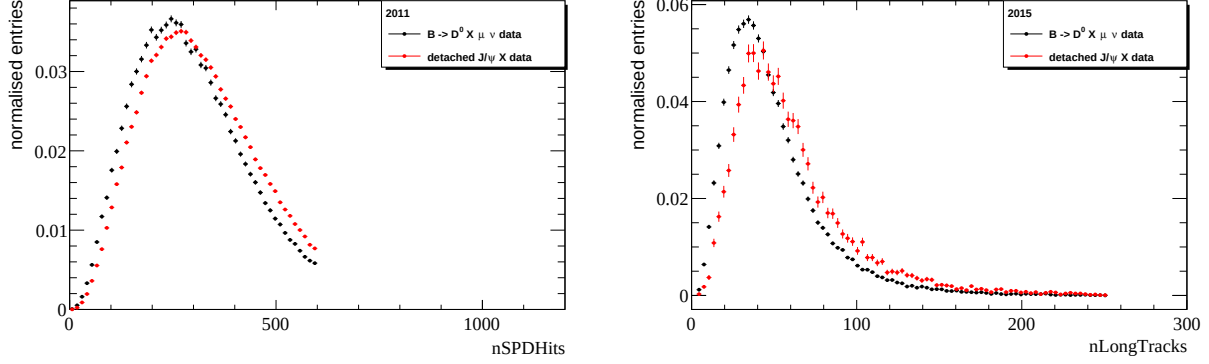


Figure 69: Comparisons of $B \rightarrow D^0 X \mu \nu$ (black) and $B^+ \rightarrow J/\psi K^+$ (red) of (left) 2011 number of SPD hits distributions and (right) 2015 number of long tracks distributions after applying the global events cut.

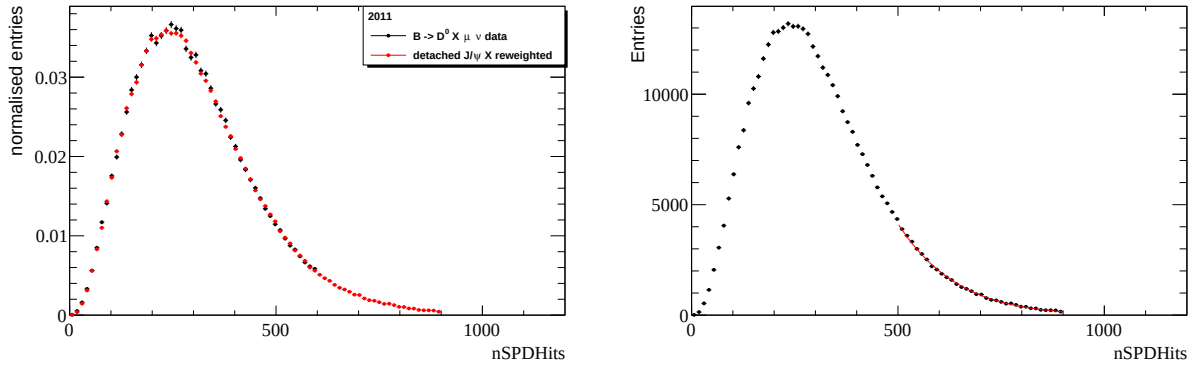


Figure 70: Left: Number of SPD hits for $B^+ \rightarrow J/\psi K^+$ (red) and the semileptonic b-hadron sample (black), after reweighting $B^+ \rightarrow J/\psi K^+$ for the total number of tracks in the event. Right: SPD distribution of $B^+ \rightarrow J/\psi K^+$ after reweighting for the total number of tracks in the event, the fitted pdf is the right side of a Gaussian.

5.5.4 Tracking corrections

To account for a tracking efficiency that is not modeled perfectly in simulation, a correction, that is provided by a dedicated LHCb working group [8], is applied to all MC samples. These corrections are derived using $J/\psi \rightarrow \mu\mu$ decays in data where the reconstruction of one muon track in the J/ψ candidate excludes one of the tracking sub-detectors (i.e., not in the VELO, TT, or downstream tracking stations). The efficiency can be determined by then attempting to reconstruct the muon track in the excluded detector, and then the correction factor is the ratio of this efficiency in data over the MC efficiency. Since the efficiencies depend on the momentum and angle of the track, the correction factors are determined in a grid of track momentum and η .

Corrections are determined for a specific data-taking condition, and therefore, for 2011 and 2015 data, different correction tables were used. Figure 71 shows the correction table for 2011 data. In all regions of track kinematics the correction is close to unity and therefore these corrections have little effect on the final results.

For 2015 two sets of corrections were derived for two different simulation versions used throughout the analysis. These versions correspond to Sim08h and Sim9b. All simulations corresponding to Run-II data incorporated a new parameterization of the efficiency loss as a function of track angle due to the double metal layer in the VELO silicon detectors. Sim08h had the first iteration of this parameterization and was found to produce distributions (e.g., the number of VELO hits per track) that are incorrect. The second iteration of this parameterization, corresponding to Sim09b, was more successful in producing the correct distributions compared to data. This effect is also illustrated in Figure 72, which shows the corrections tables for Sim08h/09b. Here the Sim08h tables have corrections up to 15% per track which shows how poorly this simulation produces the correct tracking efficiency. On the other hand the corrections for Sim09b are essentially unity and have little impact on the final results.

The systematic uncertainty due to the tracking corrections are determined differently for

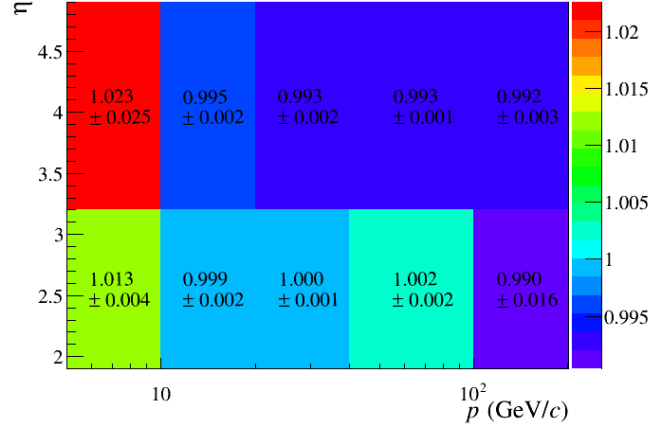


Figure 71: Tracking correction factors for 2011 data.

2011 and 2015. For 2011, three uncertainties are taken into consideration. The first being the statistical uncertainty on the calibration data and MC, and the second two, discussed in detail in [8], are from the MC reweighting and the uncertainty on hadronic interactions. The two latter are taken conservatively as 0.5% and 1.5% per track, respectively. To determine the statistical uncertainty on the corrections a toy study is performed by varying the corrections with a Gaussian function within their statistics. After 100 iterations, the final width on the distribution on the final efficiency is 0.8% and is taken as the uncertainty.

The uncertainty on the 2015 tracking corrections is determined in a separate analysis measuring the branching fraction ratio of $D^0 \rightarrow K3\pi$ to $D^0 \rightarrow K\pi$ and is highlighted in Section 5.6. To summarize, the results from this measurement corresponds to a total tracking systematic uncertainty of 6.3% in 2015 data.

5.5.5 Integration of all efficiencies

Offline selection and reconstructed efficiencies are determined using the simulated samples in Table 14. They were simulated using Run-I or II conditions (3.5 TeV or 6.5 TeV) using PYTHIA 8. The simulation was then reconstructed and stripped in the same manner as

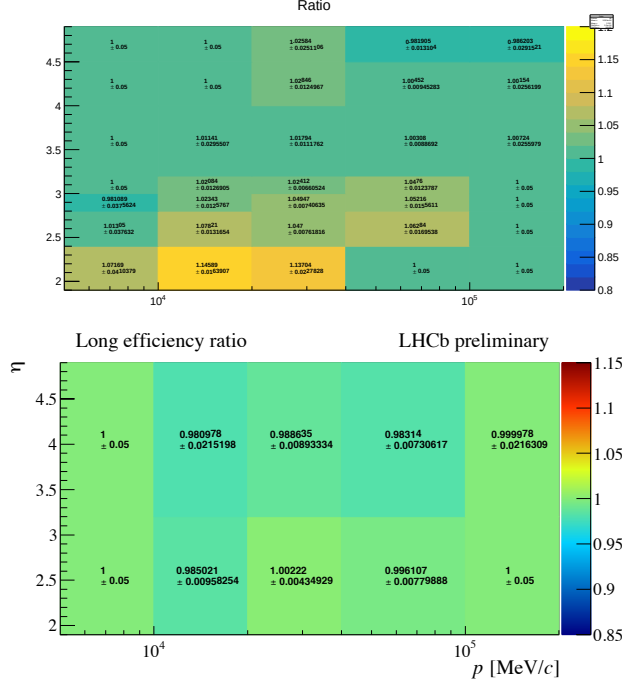


Figure 72: Tracking correction factors for 2015 data. The top plot shows the correction for Sim08h and the bottom for Sim09b.

real data. The only exception is that for simulation the particle identification is explicitly removed as this component is determined in calibration data. At the generator level the only requirement is that the b -hadron be produced with an angle between 0 and 400 mrad. An efficiency is then formed by taking the ratio of reconstructed and selected events to generated events. Explicitly,

$$\epsilon = \frac{n_{reco.,selected}}{n_{gen.}} \quad (40)$$

where the numerator is the reconstructed and selected events and denominator is the generated ones. The final efficiencies are produced in bins of b -hadron η and transverse momentum so the calculation above is repeated in each bin.

The final integration of all efficiencies is done in the above step by weighting MC events with the appropriate data-driven efficiencies. For each MC event the following weights are applied: 1) The muon p_T , IP, and η information are used to select the associated muon efficiency determined in the tag-and-probe method, 2) Each final state hadron p and η value

Table 14: Simulated samples used in the 2011 and 2015 cross section measurement.

EventType	DecFile	Conditions
11874091	Bd_D0Xmunu,D0=cocktail	MC2011/2015
11874401	Bd_D+Xmunu,D+=cocktail	MC2011/2015
12873441	Bu_D0Xmunu,D0=cocktail	MC2011/2015
12875401	Bu_D+Xmunu,D+=cocktail	MC2011/2015
13774003	Bs_Dsmunu=cocktail,hqet2	MC2011/2015
15874000	Lb_Lcmunu,pKpi=cocktail.dec	MC2011/2015

are used to select the associated PID efficiency determined from PIDCalib, 3) Each tracks p and η value are used to select the appropriate tracking correction. The final efficiency equation can be written as

$$\epsilon = \frac{\sum_i n_i^{reco.+sel.} \times W(tracking)_i \times [\epsilon_{trig.+\mu ID}(\eta^{\mu_i}, p_T^{\mu_i}) \times \sum_j \epsilon_{j,PID}(\eta^{hadron_{j,i}}, p^{hadron_{j,i}})]}{N_i^{gen}}. \quad (41)$$

Here the index i just runs over the number of events (generated or selected) in a particular b -hadron kinematic bin, and j runs over all final state hadrons in the event. The $W(tracking)$ is the product of all tracking corrections for all final state particles. The reconstructed and selected events in the numerator still contain non-peaking backgrounds (for example partially reconstructed decays, reflections, or events constructed with ghost tracks) that would be suppressed by trigger and particle identification selections. Since these selections are not explicitly imposed in the MC event, keeping them would bias the absolute efficiency. Therefore, truth information used on the charm candidate to require to be a true signal charm decay, removing all backgrounds that would otherwise bias the efficiency.

For $D^0\mu$ and $D^+\mu$ modes the average of efficiencies derived separately using B^0 and B^+ decays are used. The final b -hadron efficiencies incorporating all inputs are shown in Figures 73 and 74 as a function of the b -hadron for 2011 and 2015 data, respectively.

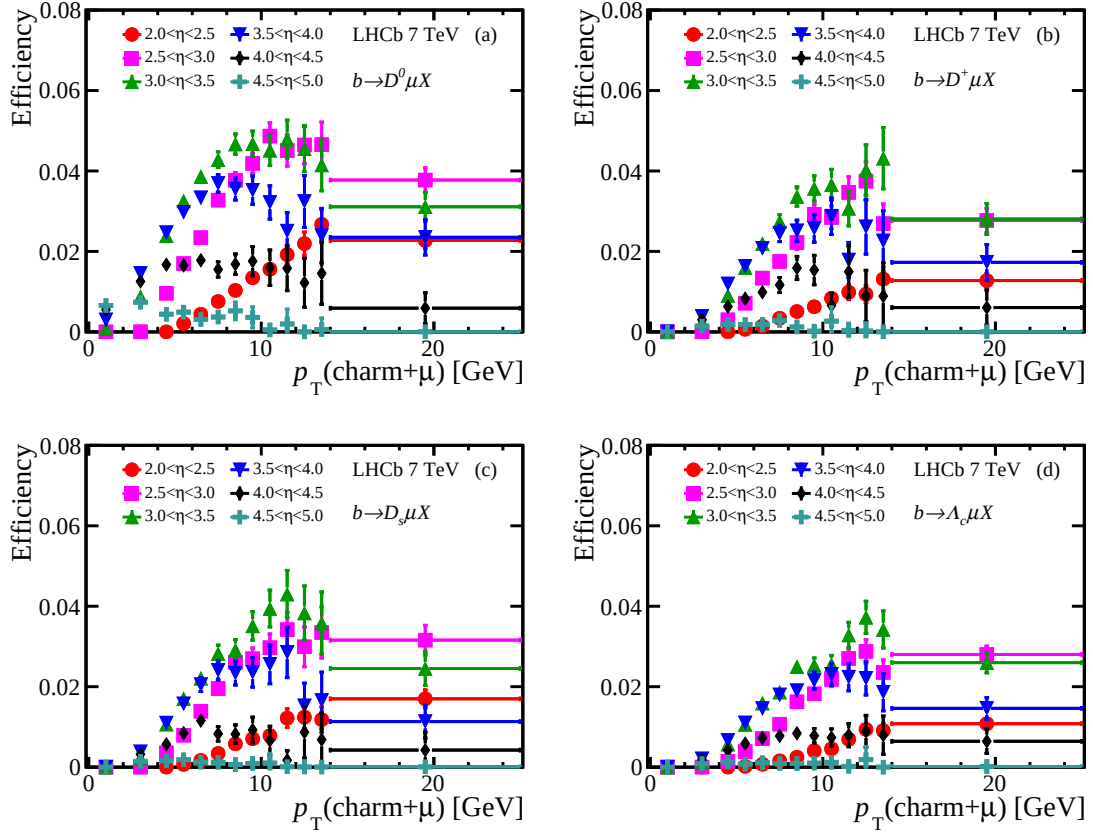


Figure 73: Final offline efficiencies for the 7 TeV data as a function of $p_T(\text{charm} + \mu)$ for the different η regions.

5.5.6 Efficiency correction at low $p_T(\text{charm} + \mu)$

An additional correction component not already discussed, and that is illustrated in Figure 73 or 74, is the essentially zero efficiency at low $p_T(\text{charm} + \mu)$. In this measurement it is intended to measure the cross section down to zero $p_T(\text{charm} + \mu)$. Therefore, some correction must be applied to account for the very low statistics in these regions.

In most bins of η there are inefficient regions at low transverse momentum of the charm plus muon up to approximately 2 GeV, and at low η this inefficiency region extends further out to about 6 GeV for the $\Lambda_c \mu$, and for the other charm 5 and 4 GeV, for $2.0 < \eta < 2.5$ and $2.5 < \eta < 3.0$, respectively. The only exception being the $D^0 \mu X$ mode, which has sufficient efficiency below 2 GeV at $\eta > 3.0$. When projecting the final cross section data onto η this

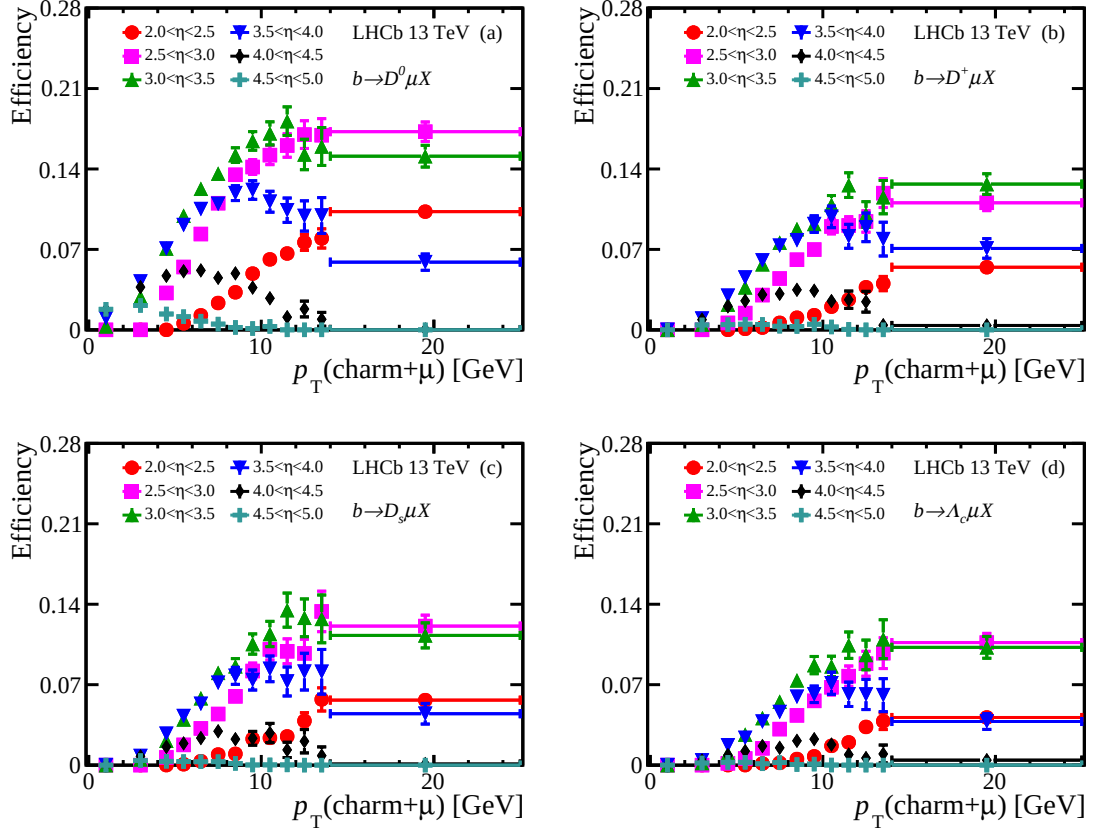


Figure 74: Final offline efficiencies for the 13 TeV data as a function of $p_T(\text{charm} + \mu)$ for the different η regions.

inefficiency is taken into account as an overall correction to the projected data. To derive a correction factor we use generator level Monte Carlo to calculate the fraction of events that fall within inefficient regions, labeled f_{miss} . The correction factors, explicitly $k_{\text{corr}} = 1/(1 - f_{\text{miss}})$, are calculated for each bin of η , charm mode for 7 TeV and 13 TeV data separately.

The systematic uncertainty on the correction factors are determined by changing the generated transverse momentum spectra and recalculating the fraction of events in the inefficient regions. First, the generated distribution is convoluted with a Gaussian with mean set to zero and a width determined from the transverse momentum resolution in reconstructed and selected Monte Carlo, which is on the order of 1%. This produces an overall effect that

is negligible. As a more conservative estimate this procedure is repeated using a Gaussian width of 10% to conservatively take into account any differences between data and simulation. This produces a relative change in the correction factor on the order of 5-10% which is assigned as the systematic uncertainty. Tables 15 and 16 lists the values for f_{miss} and the systematic uncertainties, for 7 TeV and 13 TeV data, respectively.

Table 15: Values for f_{miss} and their respective systematic uncertainties for 7 TeV data.

η	f_{miss} [%]			
	D^0	D^+	D_s^+	Λ_c^+
2.0-2.5	76 ± 5	77 ± 4	73 ± 4	68 ± 4
2.5-3.0	66 ± 4	68 ± 4	64 ± 4	59 ± 4
3.0-3.5	0 ± 0	35 ± 3	31 ± 3	25 ± 3
3.5-4.0	0 ± 0	39 ± 4	35 ± 3	28 ± 3
4.0-4.5	0 ± 0	38 ± 4	40 ± 4	33 ± 4
4.5-5.0	0 ± 0	42 ± 4	47 ± 4	39 ± 4

Table 16: Values for f_{miss} and their respective systematic uncertainties for 13 TeV data.

η	f_{miss} [%]			
	D^0	D^+	D_s^+	Λ_c^+
2.0-2.5	67 ± 4	69 ± 2	67 ± 4	73 ± 4
2.5-3.0	60 ± 4	59 ± 2	57 ± 4	53 ± 4
3.0-3.5	0 ± 0	27 ± 2	26 ± 3	23 ± 3
3.5-4.0	0 ± 0	30 ± 2	29 ± 3	25 ± 3
4.0-4.5	0 ± 0	33 ± 2	32 ± 3	28 ± 3
4.5-5.0	0 ± 0	38 ± 2	36 ± 4	33 ± 4

5.6 Standard candle measurement

In 2015 the first iteration of simulation was found to produce vastly incorrect efficiencies at low η due to poor modeling of the VELO reconstruction efficiencies. It is known the reconstruction efficiencies in LHCb simulation has to be corrected for (see Section 5.5.4), however the corrections used for Sim08h did not fully account for imperfections in VELO reconstruction efficiencies. Explanations for these corrections failing are the finite binning of the correction table coupled with the large and rapidly changing correction factors over the kinematic regions, and regions in which the tracking correction is not known due to statistics (thus, unity was used with a 5% uncertainty). Combined, both of these effects account for the differences seen between Sim08h and Sim09b efficiencies.

The final analysis utilizes Sim09b only and was necessary to check that the efficiencies derived with this simulation were correct, and had the proper systematic uncertainty assigned. Therefore, the measurement of $\mathcal{B}(D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-)/\mathcal{B}(D^0 \rightarrow K^- \pi^+)$ is used to validate the simulation used (namely the reconstruction efficiency) as this is sensitive to two times the reconstruction efficiency per pion. Additionally, this measurement is used to conservatively assign a tracking systematic per track.

Two things should be noted: firstly, the determination of the systematic per track using $\mathcal{B}(D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-)/\mathcal{B}(D^0 \rightarrow K^- \pi^+)$ also contains a PID uncertainty, and secondly the 2011 simulation is not effected by this because the parameterization of the double metal effect in the VELO was changed in 2015 in an incorrect manner.

5.6.1 Determination of $\mathcal{B}(D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-)/\mathcal{B}(D^0 \rightarrow K^- \pi^+)$

The ratio of the of $D^0 \rightarrow K3\pi$ and $D^0 \rightarrow K\pi$ branching fractions are measured using the semileptonic decay $b \rightarrow D^0 \mu X$. This branching fraction ratio has been measured precisely by CLEO as 2.11 ± 0.03 [80]. Explicitly defined as

$$R \equiv \frac{\mathcal{B}(D^0 \rightarrow K3\pi)}{\mathcal{B}(D^0 \rightarrow K\pi)} = \frac{n(D^0 \rightarrow K3\pi)/\epsilon(K3\pi)}{n(D^0 \rightarrow K\pi)/\epsilon(K\pi)}, \quad (42)$$

where the n 's correspond to the raw yields determined in data and the ϵ 's are the respective efficiencies incorporating acceptance, reconstruction, selection, PID, and muon identification and trigger.

The determination of the yields and efficiencies are the same as all the other semileptonic modes in the cross section determination and will therefore be omitted here. The only notable difference is in the $K3\pi$ mode the MC is reweighted in invariant mass of $m(\pi_L^-\pi^+)$ (m2piL), $m(\pi_S^-\pi^+)$ (m2piS), $m(\pi^-\pi^+\pi^-)$ (m3pi), $m(K^+\pi_L^-\pi^+)$ (mk2piL), $m(K^+\pi_S^-\pi^+)$ (mk2piS), $m(K^+\pi_L^-)$ (mkpiL) and $m(K^+\pi_S^-)$ (mkpiS). There are two π^+ mesons in the final state and here the one having the lower momentum is labeled “S”, and the other as “L”. A BDT is used to determine the correction weights for the MC sample. The data and the MC samples are taken as the signal and background in the BDT training and these 7 variables are taken as the training variables. The final BDT output distribution in data and MC is used to calculate the MC weights. Figure 75 shows the MVA output for both MC and data and Figure 76 shows these seven distributions in data and MC before and after re-weighting. It can be seen that the re-weighting procedure produces excellent data-MC agreement.

The value of R is determined in a two-dimensional grid of η and $p_T(charm + \mu)$ and the final results in η are the average of the transverse momentum bins. Several sources of systematic uncertainties are considered and tabulated in Table 17. The final result for R in bins of η of the parent B hadron, along with the expected value, is shown in Figure 77. From the plot all measured values of $\mathcal{B}(D^0 \rightarrow K^-\pi^+\pi^+\pi^-)/\mathcal{B}(D^0 \rightarrow K^-\pi^+)$ are consistent with the CLEO measurement within uncertainties. Averaging all data together the final value for $\mathcal{B}(D^0 \rightarrow K^-\pi^+\pi^+\pi^-)/\mathcal{B}(D^0 \rightarrow K^-\pi^+)$ is $2.15 \pm 0.07 \pm 0.03$ which is in excellent agreement with the CLEO results of 2.11 ± 0.03 .

5.6.2 Conclusions

The results of this measurement show that the tracking reconstruction for an addition two pion tracks is correct. Taking one half of the total uncertainty on the ratio represents the

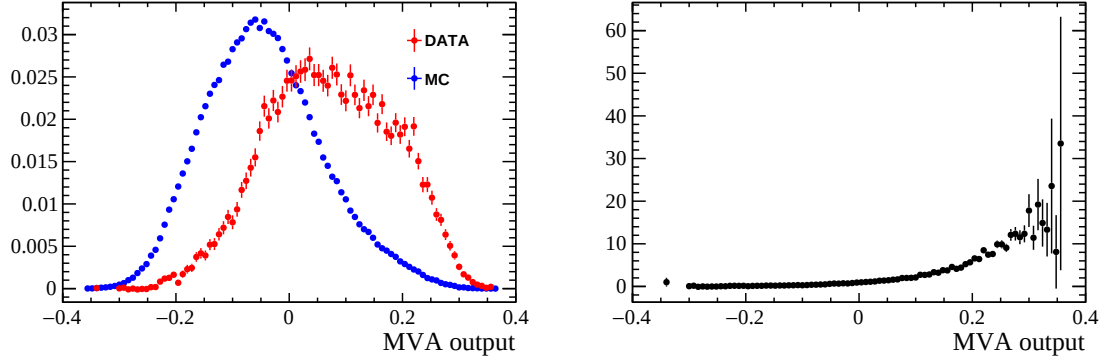


Figure 75: The BDT output (left) for the MC (blue) and data (red) samples and the correction weights for MC sample (right).

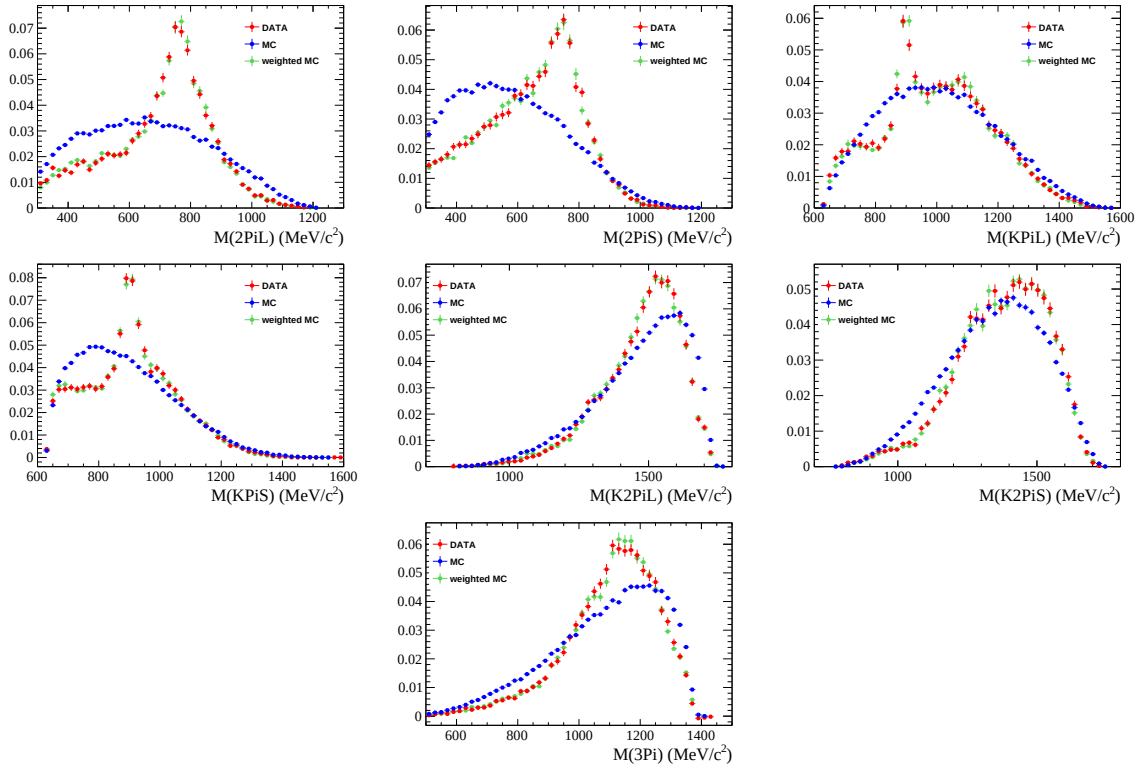


Figure 76: Comparison between data and MC distributions of different daughter combinations. Here the data are shown as the red points and the blue and green points show the simulation before and after re-weighting, respectively.

Table 17: Systematic uncertainty for $\mathcal{B}(D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-)/\mathcal{B}(D^0 \rightarrow K^- \pi^+)$ in percent.

Source/ η :	2.0 – 2.5	2.5 – 3.0	3.0 – 3.5	3.5 – 4.0	4.0 – 4.5	4.5 – 5.0
MC model	0.11	0.06	0.18	0.49	0.18	0.29
BKG shape in $m(D^0)$	1.38	0.31	0.28	0.68	0.00	0.81
BKG in $\ln(IP)$	0.04	1.90	0.25	2.24	3.08	1.67
Signal shape	2.46	1.39	1.05	1.90	3.05	0.11
MC statistics	1.71	0.82	0.74	0.92	1.70	6.36
Total	3.30	2.52	1.35	3.19	4.66	6.63

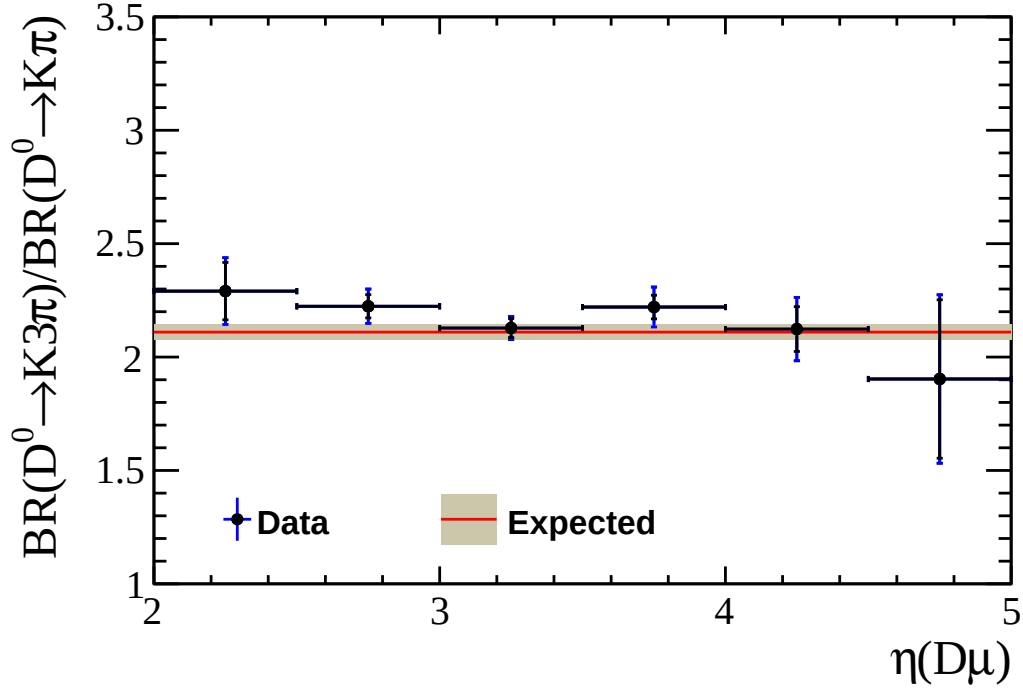


Figure 77: Results for $\mathcal{B}(D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-)/\mathcal{B}(D^0 \rightarrow K^- \pi^+)$ as a function of η . The black error bars show the statistical uncertainty and the blue ones have the systematic uncertainties added in quadrature. The red line with gray error band shows the CLEO result.

tracking plus PID systematic per track which multiplied by an average number of tracks in the cross section would give a total tracking systematic uncertainty. In the semileptonic modes used in $\sigma(b\bar{b})$ only the $D^0\mu$ mode has 3 tracks in the final state while all the other modes have 4. However the $D^0\mu$ contributes the most to the inclusive b -hadron cross section. To calculate the average number of tracks the measured b -hadron fractions [86] were used to weight the number of tracks in each final state ($\langle \# \text{ tracks} \rangle = f_{D^0} \times 3 \text{ tracks} + (1 - f_{D^0})$)

x 4 tracks). The calculated average number of final state tracks is 3.49. The final tracking systematic uncertainty is 6.3% (1.8×3.49).

5.7 Backgrounds

The fitting procedure removes explicitly backgrounds from prompt charm decays. However, two other sources remain that need to be estimated.

The first one comes from charm-muon combinations from two different b -hadron decays. These are determined in data by examining wrong-sign (WS) charm-muon combinations that come from the WS B2DMuNU stripping lines. WS charm-muon candidates are selected and triggered in the same way as nominal data and fits to the invariant charm mass and $\ln(\text{IP})$ are performed to determine this yield. WS fractions are then subtracted from the signal yield. This background is called “WS backgrounds”.

The second is from decays of the form $b \rightarrow DD\bar{X}$ where one of the charm hadron decays into the signal mode and the other decays into a muon. This background is called “DD” backgrounds and is estimated from simulation. Dedicated MC samples were produced that contain a cocktail of $b \rightarrow DD\bar{X}$ decays for all charm-muon final states. Using the efficiency for these backgrounds to be reconstruction in the signal mode with respect to the true signal efficiency, and ratios of relevant branching fractions, the fraction of DD backgrounds in signal data can be calculated and subtracted from the data. The $D_s\mu$ mode has the highest fraction of DD backgrounds due to the high probability of $W \rightarrow c\bar{s}$ transitions in the weakly decaying b -hadron. The dominant contributing modes simulated are $B^0 \rightarrow D_s D^- X$, $B^+ \rightarrow D_s D^0$, $B_s^0 \rightarrow D_s D_s$, and $\Lambda_b^0 \rightarrow D_s \Lambda_c$. In total these account for 15% of $D_s\mu$ events. However, the B_s has the smallest b -hadron fraction thus this only accounts for a 2% reduction in the final calculation. All other signal modes have a DD background fraction less than 1%.

Table 18 compiles the values of both background components for both 2011 and 2015 data. The final line in the table labeled $b\bar{b}$ shows the overall subtraction to the total cross section.

Table 18: Backgrounds (%) from $b \rightarrow DDX$ decays estimated from simulation and two separate b decays as estimated from wrong-sign (WS) rates. The bottom row denoted $b\bar{b}$ shows the overall effect of the backgrounds on the measurement by averaging over modes using the b-hadron fractions.

Source	7 TeV DD	7 TeV WS	13 TeV DD	13 TeV WS
$D^0\mu$	0.6	0.9	0.7	2.3
$D^+\mu$	0.5	0.6	0.4	2.1
$D_s^+\mu$	14.8	0.8	15.1	3.0
$\Lambda_c^+\mu$	0.6	0.1	1.0	0.6
$b\bar{b}$	1.9	0.7	1.8	2.0

5.8 Systematic uncertainties

Muon ID and trigger, PID, tracking systematic uncertainty determinations are described in detail in their respective sections. On the ratio, the trigger and muon ID systematic are taken to have a -50% correlated uncertainty.

The luminosity uncertainty in the ratio is obtained by assuming a -50% correlated error [87]. The various final states used to simulate the efficiencies, dubbed the b decay cocktail can contribute to an overall efficiency change. This is estimated by taking the difference between the efficiencies of the higher multiplicity $D^{**}\mu^-\nu$ and $D^*\mu^-\nu$ states and taking into account the uncertainties on the measured branching fractions. These are then added in quadrature.

The fraction of higher mass b baryon states with respect to the Λ_b^0 is given by $\delta = 0.25 \pm 0.10$, which represents a 40% relative uncertainty. The effect on the b cross section must be de-weighted by the fact that it represents a 25% correction on the Λ_b^0 fraction, which is only 21%, resulting in 2.0% uncertainty. In the ratio it contributes only if the number of heavy b -baryons changes which is assigned a 0.2% uncertainty since we do not expect the fraction to change by more than 10%. The b cross-feed uncertainty is estimated using the possible changes in efficiency for the cross-feed modes $B \rightarrow D_s K X \mu$, $\Lambda_b^0 \rightarrow D N X \mu$, and $B_s \rightarrow D K X \mu$. These are estimated to be at the level of 0.6% each, so adding them in quadrature gives $\sim 1\%$.

The uncertainties are listed in Tables 19 and 20. The first table gives results that are independent of η . The second table has three sections that describe the η dependent uncertainties for 7 TeV, 13 TeV and the ratio of 13/7 TeV, respectively. The selection efficiency is determined by simulation and the uncertainty on these η dependent numbers is given by the simulation statistics. These uncertainties are added in quadrature for the total systematic error.

Table 19: Systematic uncertainties independent of η on the $pp \rightarrow H_b X$ cross section at 7 and 13 TeV and their ratio.

Source	7 TeV	13 TeV	Ratio 13/7
Luminosity	1.7%	3.9%	3.8%
Tracking eff.	3.8%	6.3%	6.3%
b semileptonic $\mathcal{B}$	2.1%	2.1%	0
Charm hadron $\mathcal{B}$	2.6%	2.6%	0
b decay cocktail	1.0%	1.0%	0
Ignoring b cross-feeds	1.0%	1.0%	0
Background	0.2%	0.3%	0
$b \rightarrow u$ decays	0.3%	0.3%	0
δ	2.0%	2.0%	0.2%
Total	5.9%	8.9%	7.4%

Table 20: Systematic uncertainties (%) as a function of η on the $pp \rightarrow H_b X$ cross section at 7 and 13 TeV, and their ratio. The trigger efficiency includes the muon detection efficiency. “Selection” refers to the efficiency of event selection that depends on the kinematics resulting from the simulation. The bottom lines in each section give the total systematic uncertainty in each η bin.

7 TeV						
Source	$2.0 > \eta > 2.5$	$2.5 > \eta > 3.0$	$3.0 > \eta > 3.5$	$3.5 > \eta > 4.0$	$4.0 > \eta > 4.5$	$4.5 > \eta > 5.0$
Trigger	5.5	3.8	3.2	3.1	3.3	5.9
Selection	2.0	1.0	1.0	1.0	1.0	2.0
Hadron ID	1.9	1.7	1.6	1.5	1.7	1.8
Low ϵ regions	7.0	6.0	6.0	5.0	5.0	5.0
Sum η dependent	9.3	7.4	7.1	6.2	6.3	8.2
Total	11.0	9.4	9.2	8.5	8.6	10.1
13 TeV						
Source	$2.0 > \eta > 2.5$	$2.5 > \eta > 3.0$	$3.0 > \eta > 3.5$	$3.5 > \eta > 4.0$	$4.0 > \eta > 4.5$	$4.5 > \eta > 5.0$
Trigger	2.4	1.6	2.6	3.1	3.5	3.9
Selection	3.0	1.0	2.0	1.0	1.0	2.0
Low ϵ regions	5.0	6.0	4.0	4.0	4.0	4.0
Sum η dependent	6.3	6.3	5.2	5.2	5.4	5.9
Total	10.6	10.6	9.9	9.9	10.1	10.4
Ratio 13/7 TeV						
Source	$2.0 > \eta > 2.5$	$2.5 > \eta > 3.0$	$3.0 > \eta > 3.5$	$3.5 > \eta > 4.0$	$4.0 > \eta > 4.5$	$4.5 > \eta > 5.0$
Trigger	4.8	3.3	2.9	3.1	3.4	5.2
Selection	3.0	2.0	2.0	1.0	1.0	2.0
Sum η dependent	5.7	3.9	3.5	3.3	3.5	5.6
Total	9.3	8.4	8.2	8.1	8.2	9.3

5.9 Results

The inclusive b -hadron cross section at 7 TeV as a function of η is given in Figure 78, along with a theoretical prediction called FONLL [39]. The inclusive b -hadron cross section at 13 TeV as a function of η is given in Figure 79 and the 13 TeV/7 TeV ratio is shown in Figure. 80.

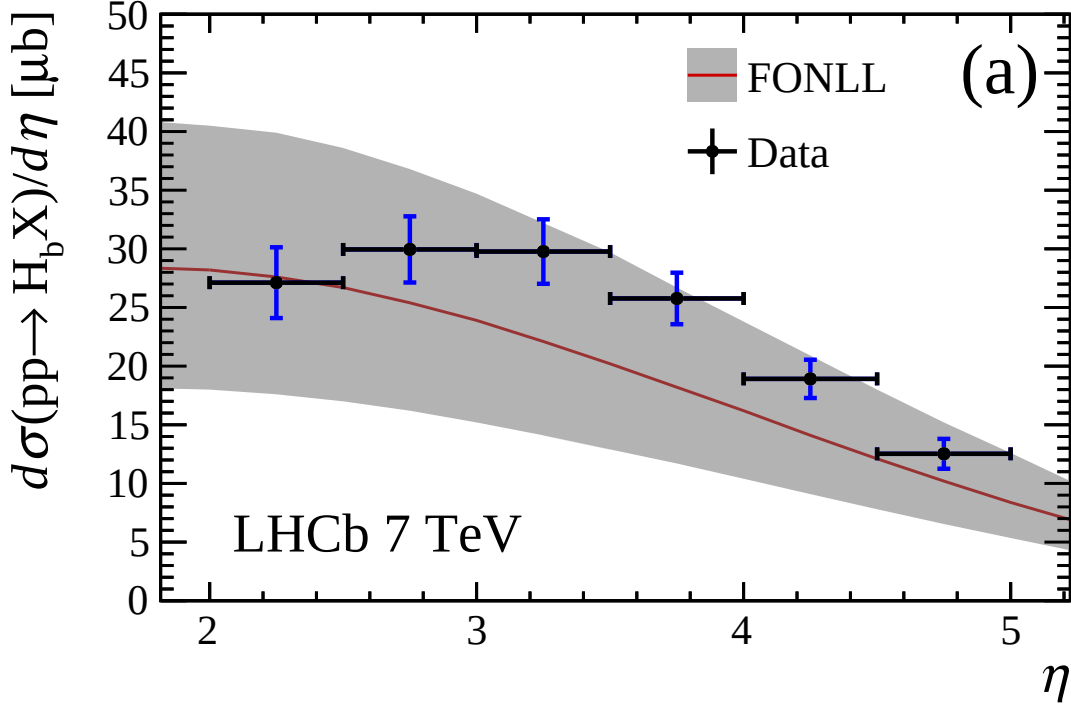


Figure 78: The cross section as a function of η for $\sigma(pp \rightarrow H_b X)$, where H_b is a hadron that contains either a b or an $\bar{b}$ quark, but not both, at 7 TeV center-of-mass energy. The black error bars show the statistical uncertainties only, and the blue ones have the systematic uncertainties added in quadrature. The solid line (red) gives the theoretical prediction, while the shaded band gives the estimated uncertainty on the prediction.

The results as a function of η are tabulated in Table 21. The total cross sections at 7 and 13 TeV integrated over $2 < \eta < 5$ are $72.0 \pm 0.3 \pm 7.3 \mu\text{b}$ and $144.0 \pm 1.3 \pm 20.6 \mu\text{b}$, respectively. The ratio is $2.00 \pm 0.02 \pm 0.26$. This agrees with theoretical predictions at 7 TeV and 13 TeV with values of $62^{+28}_{-22} \mu\text{b}$ and $111^{+51}_{-44} \mu\text{b}$, respectively. The measured ratio agrees with theoretical prediction in magnitude and shape as a function of η . Integrated over η the theoretical ratio is $1.79^{+0.21}_{-0.15}$ which is agreement with the data within uncertainties.

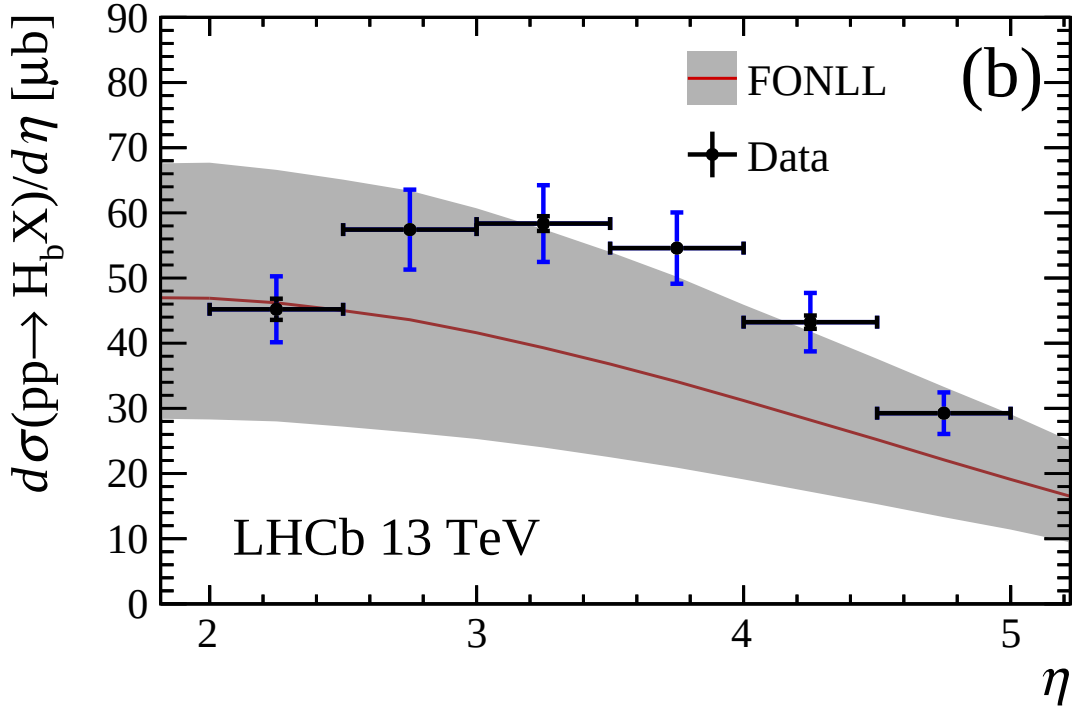


Figure 79: The cross section as a function of η for $\sigma(pp \rightarrow H_b X)$, where H_b is a hadron that contains either a b or an $\bar{b}$ quark, but not both, at 13 TeV center-of-mass energy. The black error bars show the statistical uncertainties only, and the blue ones have the systematic uncertainties added in quadrature. The solid line (red) gives the theoretical prediction, while the shaded band gives the estimated uncertainty on the prediction.

To estimate a factor to extrapolate the measurement from η between 2 and 5 to the entire phase space, PYTHIA 8 simulations were used. For 7 TeV, this corresponds to a multiplicative factor on the measured cross section of 4.1, and for 13 TeV 3.9. This corresponds to a total b-quark cross section of $\approx 295 \mu\text{b}$ and $\approx 562 \mu\text{b}$ for 7 and 13 TeV data, respectively.

5.9.1 Cross-checks

The overall goal of these cross-checks was to investigate any anomalous contributions from specific charm modes that may arise from the efficiency or data components. One example would be spurious over/under corrections from the tracking efficiencies in the 3-body charm modes with respect to the 2-body D^0 decay, or associated PID corrections. To investigate any of these effects, the data were split up into three categories: 1) $D^0\mu$ only, 2) $D^0\mu + D^+\mu$

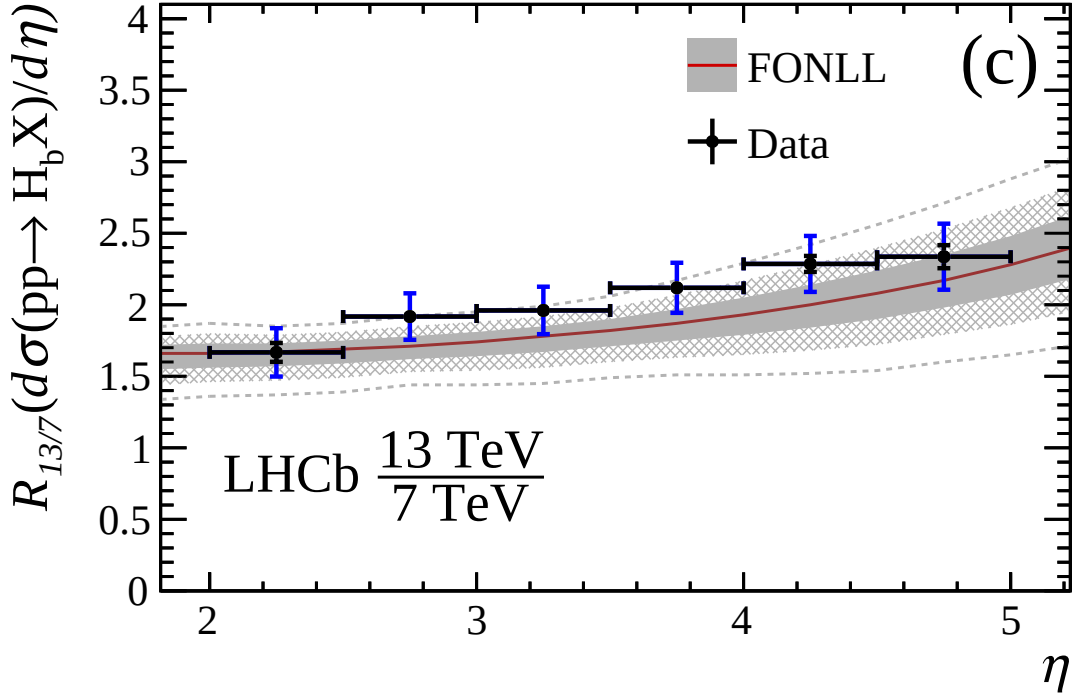


Figure 80: The cross-section ratio for 13 TeV/7 TeV as a function of η . The black error bars show the statistical uncertainties only, and the blue ones have the systematic uncertainties added in quadrature. The solid line (red) gives the theoretical prediction, while the shaded band gives the estimated uncertainty on the prediction.

only, and 3) $D^0\mu + D^+\mu + D_s\mu$ only. In principle all categories can be used to calculate the total inclusive b-quark cross section, but contain additional systematic uncertainties on the b-hadron fractions. (1) can be used by normalizing the efficiency and background corrected $D^0\mu$ yield to the total branching fraction of $b \rightarrow D^0\mu X$. This was the strategy in the early LHCb analysis [68] which included a large uncertainty from the $b \rightarrow D^0\mu X$ LEP fraction. For this cross-check an inclusive $b \rightarrow D^0\mu X$ fraction exclusively from LHCb measurements was used. (2) can be used by normalizing the efficiency and background corrected $D^0\mu$ and $D^+\mu$ yields with the $B^{0/+} \rightarrow D\mu X$ branching fraction and the light b-meson fraction [86]. (3) can be used in the same fashion as (2) by just adding the $D_s\mu$ component with the respective semileptonic branching fraction and total b-meson fraction (assuming B_c is negligible). All three categories, along with the nominal analysis method and theoretical predictions are shown in Figure 81 for 7 and 13 TeV, and their ratio. In all the plots black data points show

Table 21: $pp \rightarrow H_b X$ cross sections as a function of η for 7 TeV and 13 TeV collisions and their ratio. The first uncertainty is statistical and the second systematic.

η	7 TeV (μb)	13 TeV (μb)	Ratio 13/7
2.0–2.5	$13.6 \pm 0.2 \pm 1.5$	$22.6 \pm 0.8 \pm 2.4$	$1.67 \pm 0.07 \pm 0.16$
2.5–3.0	$15.0 \pm 0.1 \pm 1.4$	$28.7 \pm 0.4 \pm 3.0$	$1.92 \pm 0.03 \pm 0.16$
3.0–3.5	$14.9 \pm 0.1 \pm 1.4$	$29.2 \pm 0.6 \pm 2.9$	$1.96 \pm 0.04 \pm 0.16$
3.5–4.0	$12.9 \pm 0.1 \pm 1.1$	$27.3 \pm 0.4 \pm 2.7$	$2.12 \pm 0.04 \pm 0.17$
4.0–4.5	$9.5 \pm 0.1 \pm 0.8$	$21.6 \pm 0.5 \pm 2.2$	$2.29 \pm 0.06 \pm 0.19$
4.5–5.0	$6.3 \pm 0.1 \pm 0.6$	$14.6 \pm 0.5 \pm 1.5$	$2.34 \pm 0.08 \pm 0.22$

the nominal method with all uncertainties, the red line with shaded band show the theoretical prediction, and the colored show the cross-checks with only statistical uncertainties. In all plots there is excellent agreement between all charm combinations.

As a check on the low p_T corrections, the data was cut at a p_T above 6 GeV. In this region there are no p_T hole corrections therefore providing also a validation on the correction scheme by comparing the 13 TeV/7 TeV ratio with theory with and without corrections. However this can only be used to measure in the η region of 2 to 4.5 as there are no statistics at high p_T above an η of 4.5. Figure 83 shows these measurements for 7 and 13 TeV and their ratio and the tabulated results are in Table 22. While the theoretical corrections are cut at the same p_T their definition of p_T is of the parent b-hadron. Here there is the same data-theory agreement in the ratio measurement, affirming the analysis of the low p_T corrections used in the nominal analysis.

Integrated over η the values for the inclusive b-quark cross section above 6 GeV are $12.1 \pm 0.1 \pm 1.2 \mu\text{b}$ for 7 TeV data and $28.4 \pm 0.4 \pm 4.1 \mu\text{b}$ for 13 TeV data. The first uncertainty is statistical and the second is systematic. The integrated ratio is $2.35 \pm 0.04 \pm 0.31 \mu\text{b}$ with the first uncertainty being statistical and second systematic. The theoretical values are $13.6^{+6.1}_{-4.8}$ and 28.1^{+13}_{-11} for 7 and 13 TeV data, respectively. The theoretical 13 TeV to 7 TeV ratio is $2.07^{+0.24}_{-0.17}$. Both the theoretical absolute values and ratio are in agreement with data.

An addition check using the 7 TeV data was to compare the new data to the previous 7

Table 22: $pp \rightarrow H_b X$ cross sections as a function of η for 7 TeV and 13 TeV collisions and their ratio. Here all values are for a p_T above 6 GeV . The first uncertainty is statistical and the second systematic.

η	7 TeV (μb)	13 TeV (μb)	Ratio 13/7
2.0–2.5	$3.26 \pm 0.09 \pm 0.28$	$6.7 \pm 0.4 \pm 0.6$	$2.03 \pm 0.12 \pm 0.19$
2.5–3.0	$3.27 \pm 0.03 \pm 0.24$	$7.6 \pm 0.2 \pm 0.7$	$2.31 \pm 0.12 \pm 0.19$
3.0–3.5	$2.65 \pm 0.03 \pm 0.19$	$6.2 \pm 0.1 \pm 0.6$	$2.34 \pm 0.05 \pm 0.19$
3.5–4.0	$1.87 \pm 0.01 \pm 0.13$	$4.8 \pm 0.1 \pm 0.4$	$2.57 \pm 0.05 \pm 0.21$
4.0–4.5	$1.04 \pm 0.02 \pm 0.07$	$3.2 \pm 0.1 \pm 0.3$	$3.05 \pm 0.05 \pm 0.25$

TeV measurement [68]. The old data was scaled up by 14% to account for updates in the branching fractions used. Figure 82 shows this comparison. The agreement between both analysis is excellent.

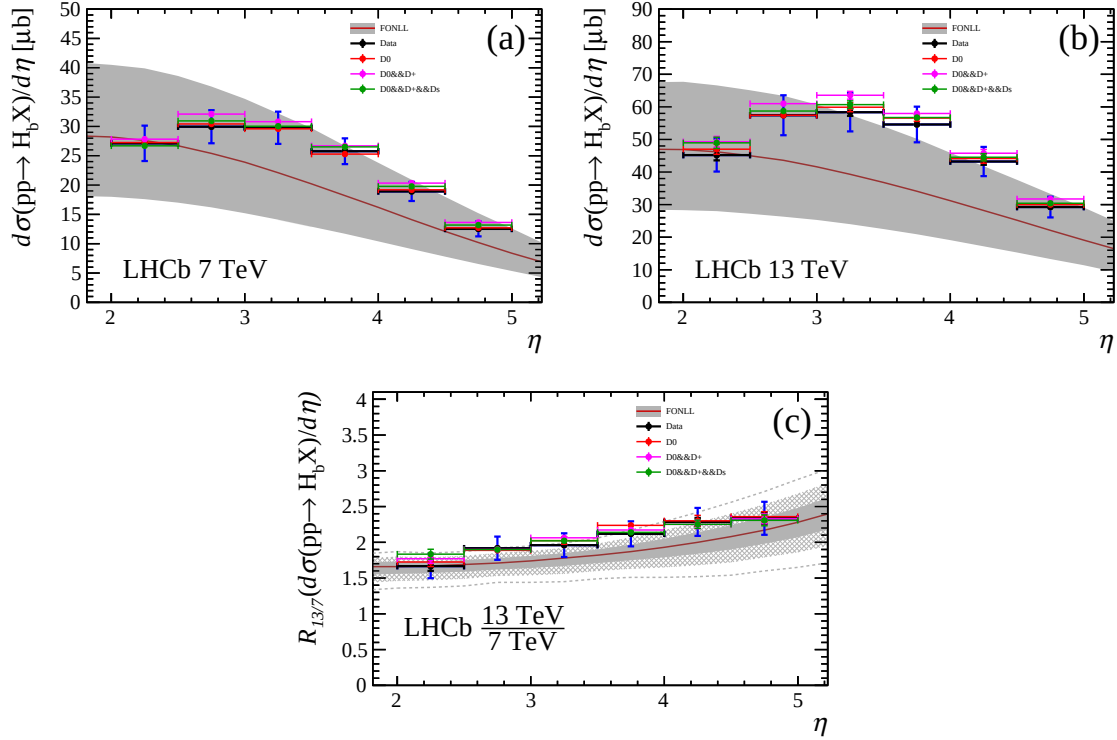


Figure 81: Inclusive b-quark cross section at 7 TeV (top left) and 13 TeV (top right) and their ratio (bottom). The black data points show the nominal data, while the colored data points show the individual charm checks described in the text. The solid line (red) gives the theoretical prediction, while the shaded band gives the estimated uncertainty on the prediction.

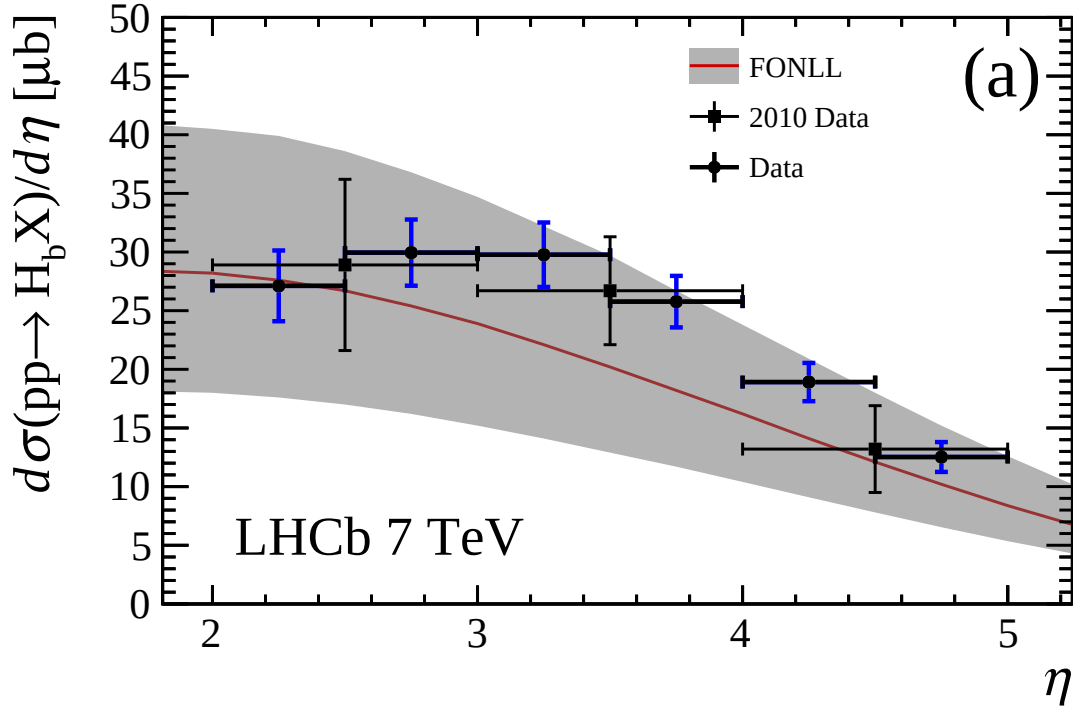


Figure 82: The cross section as a function of η for $\sigma(pp \rightarrow H_b X)$, where H_b is a hadron that contains either a b or an $\bar{b}$ quark, but not both, at 7 TeV center-of-mass energy for the new results compared with the results found in 2010 using only $b \rightarrow D^0 X \mu^-$ decays, where the results are interpreted using the LHCb measured b -fractions. The new results are shown by the circular points with the black error bars showing the statistical uncertainties only, and the blue ones have the systematic uncertainties added in quadrature. The older results have the statistical and systematic uncertainties added in quadrature and are the square data points.

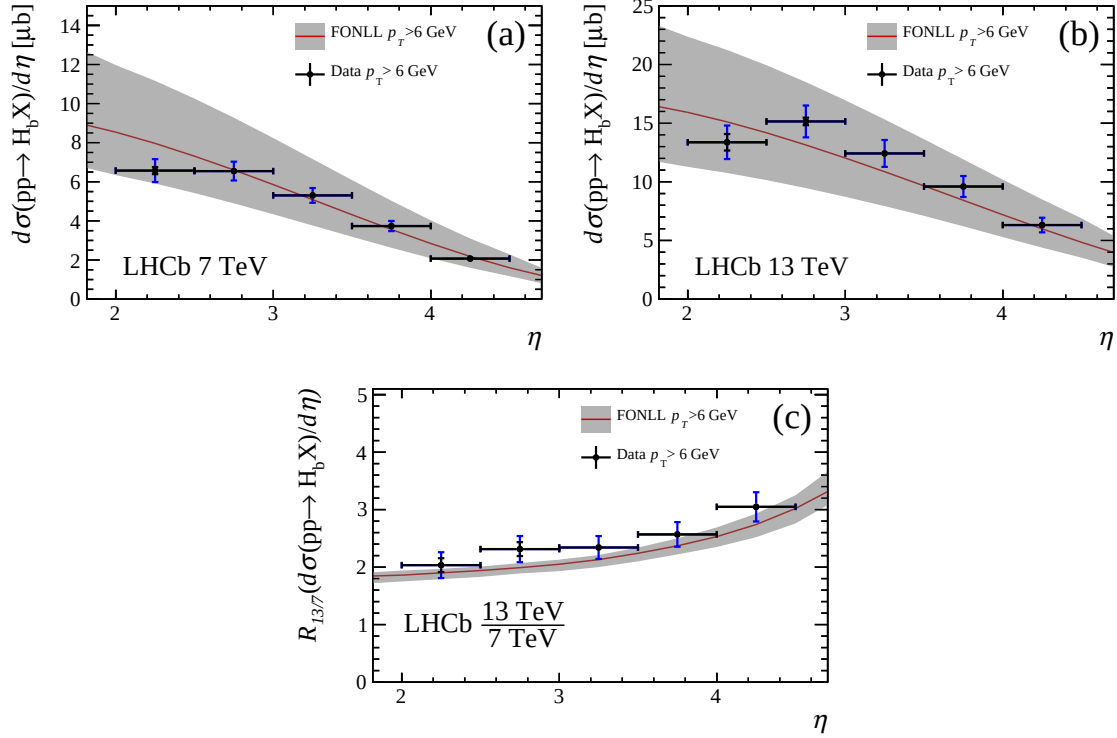


Figure 83: The cross section as a function of η for $\sigma(pp \rightarrow H_b X)$, where H_b is a hadron that contains either a b or an $\bar{b}$ quark, but not both, at a center-of-mass energy of 7 TeV (a) and 13 TeV (b), and the ratio of 13 TeV to 7 TeV (c). The black error bars show the statistical uncertainties only, and the blue ones have the systematic uncertainties added in quadrature. The solid line (red) gives the theoretical prediction, while the shaded band gives the estimated uncertainty on the prediction. Here there is a p_T cut on the charm plus muon system greater than 6 GeV in data thus eliminating the need for MC correction factors due to low efficiency at low p_T and η . The theoretical prediction also has a p_T cut of 6 GeV but this is on the b hadron.

6 Measurement of the b -hadron fragmentation ratios in 13 TeV center-of-mass pp collisions

6.1 Introduction

Measurements of the rate at which a b or $\bar{b}$ quark fragments with another quark or anti-quark to produce a meson, or two (anti-)quarks to produce a baryon, is essential to extract absolute branching fractions from data. These fractions are not perturbatively calculable in QCD and must be measured in experiments. The fragmentation fraction of a $\bar{b}$ -quark to combine with another lighter quark, q , is given as

$$\mathcal{B}(b \rightarrow B_q) \equiv f(b \rightarrow B_q) = f_q, \text{ with } q = u, d, s, \text{ or } c. \quad (43)$$

For the case of Λ_b baryon, the equivalent fraction is f_{Λ_b} .

Measurements of the absolute $B^{0/+}$ branching fractions have been measured at e^-e^+ colliders such as Belle and BaBar. Therefore measurements of the heavier b -flavored hadrons fractions with respect to the lighter b -hadrons provide an excellent way to determine absolute fractions for the B_s meson and Λ_b baryon. Measurements of these fractions are experimentally important for measuring rare processes and testing any CP -violating effects that may show up in the CKM sector. LHCb reports the branching fraction for the rare decay $B_s^0 \rightarrow \mu^+\mu^-$ which uses the measurement of f_s/f_d as an input. At the current uncertainty level there are no deviations with SM expectations but precise determinations of f_s/f_d may help probe contributions from new physics effects. Knowledge of the f_{Λ_b} fraction is similarly important for novel determinations of CKM elements $|V_{cb}|$ and $|V_{ub}|$.

Previous measurements of the production rates have been performed by LHCb in 7 TeV pp collisions [86] [88] [89]. The results of these measurements show a clear dependence on these fractions as a function of the decaying b -hadron. This is especially relevant for the b -baryon fraction as this has been shown to be exponentially dependent on the transverse momentum

of the b -hadron. These observations point out that combinations of measurements from different experiments with different kinematic sensitivities is not correct. Furthermore, measurements of the b -baryon spectrum provide useful inputs for tuning Pythia MC generators as it is well known that the modeling of Λ_b is not correct.

It is assumed that the b -hadron fractions are universal at high energies, which is plausible if the momentum transfer squared to the initial b quark is large compared to hadronization energy, i.e., $Q^2 \gg \Lambda_{QCD}^2$. However, the hadron fractions might depend on the initial b quark production mechanisms, which are different in hadron collisions compared to high p_T b jets at lepton colliders. In any case, there are no strong arguments for or against the universality of these fractions at different experiments, and must be determined with data.

f_s/f_d has been measured in hadron collisions by the CDF collaboration [90] in $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV, and ATLAS [91] in pp collisions at a center of mass energy of 7 TeV. The average f_s/f_d LEP fraction [79] is taken from measurements of high p_T b jets in Z^0 decays. In all measurements, including LHCb, the values for f_s/f_d are in agreement within uncertainties.

Measurements of f_{Λ_b}/f_d has been also measured by CDF [90] and LEP [79]. The LEP average is much small than the CDF average, and is explained by the large p_T dependence of the Λ_b fraction, and the fact that LEP only probes the high p_T region ($< p_T \leq 40$ GeV). The CDF and semileptonic LHCb measurements show similar p_T dependencies, and when averaged are consistent within uncertainties [79].

6.2 Master formula

To determine the b -hadron fraction ratios, semileptonic decays of B^+ , B^0 , B_s^0 , and Λ_b^0 are used (charge-conjugates are implied unless explicitly noted). The fragmentation fraction ratios are simply

$$\frac{f_s}{f_u + f_d} = \frac{N(\bar{B}_s^0 \rightarrow D\mu)}{N(\bar{B}^0 \rightarrow D\mu) + N(B^- \rightarrow D\mu)} \times \frac{\langle B_{SL}(B) \rangle}{B_{SL}(B_s^0)} \quad (44)$$

for the B_s^0 with respect to the lighter b -flavored hadrons, and

$$\frac{f_{\Lambda_b}}{f_u + f_d} = \frac{N(\Lambda_b^0 \rightarrow D\mu)}{N(\bar{B}^0 \rightarrow D\mu) + N(B^- \rightarrow D\mu)} \times \frac{\langle B_{SL}(B) \rangle}{B_{SL}(\Lambda_b^0)} \quad (45)$$

for the Λ_b^0 with respect to the lighter b -flavored hadrons. Here the shorthand $n(D\mu) \equiv n(DX\mu\nu)$ is used. $\langle B_{SL}(B) \rangle$ represents the average $B^{0/-}$ semileptonic branching fraction.

The main signal modes are reconstructed ground-state D^+ , D^0 , D_s^+ , and Λ_c^+ hadrons combined with a muon. Each of the final state modes can originate from different b -hadron decays. $B^{+/-}$ can decay semileptonically into a mixture of $D^0\mu X$ and $D^+\mu X$ final states. However, there is a small fraction of $D_s K\mu$ decays for both. The $\bar{B}_s^0$ decays predominately into $D_s^+\mu X$, with a small component of $D^0 K^+$ and $D^+ K_s^0$ that originate from non-resonant B_s decays or with intermediate excited D_s^{**} . Finally, the Λ_b decays mostly to $\Lambda_c\mu X$ with a small fraction going into $D^0 p\mu$ from higher Λ_c and non-resonant decays.

Suppressed $b \rightarrow u$ decays are ignored in the hadron fraction determinations as they constitute a roughly equal 1% to all b -hadron decays.

As it is impossible to separate reconstructed $D^0\mu$ events from B^0 or B^+ decays, as both can decay to the $D^0\mu$ final state with some intermediated D^* and/or with additional pions, and similarly for $D^+\mu$ events, the f_s and f_{Λ_b} fractions are measured relative to the sum of $f_u + f_d$. Besides small cross-feed contributions, which is explicit corrected for, it is assumed that the sum of $D^0\mu \equiv f_0$ and $D^+\mu \equiv f_+$ events are equivalent to the sum of the light b -flavored hadron fraction, i.e.,

$$f_0 + f_+ \equiv f_u + f_d. \quad (46)$$

Yields of charm plus muon events are measured in data and corrected for total efficiencies, charm branching fraction, and cross-feeds, and are labeled n_{corr} . The corrected yields for

the lighter b -hadrons, reconstructed through the $D^{+0}\mu$ modes, are

$$n_{corr}(B \rightarrow D^0 \mu \nu) = \frac{1}{\mathcal{B}(D^0 \rightarrow K^- \pi^+) \epsilon(B \rightarrow D^0)} \times \left[n(D^0 \mu) - n(D^0 K^+ \mu) \frac{\epsilon(B_s \rightarrow D^0)}{\epsilon(B^s \rightarrow D^0 K^+)} - n(D^0 p \mu) \frac{\epsilon(\Lambda_b \rightarrow D^0)}{\epsilon(\Lambda_b \rightarrow D^0 p)} \right], \quad (47)$$

$$n_{corr}(B \rightarrow D^+ \mu) = \frac{1}{\epsilon(B \rightarrow D^+)} \left[\frac{n(D^+ \mu)}{\mathcal{B}(D^+ \rightarrow K^- \pi^+ \pi^+)} - \frac{n(D^0 K^+ \mu)}{\mathcal{B}(D^0 \rightarrow K^- \pi^+)} \frac{\epsilon(B_s \rightarrow D^+)}{\epsilon(B_s \rightarrow D^0 K^+)} - \frac{n(D^0 p \mu)}{\mathcal{B}(D^0 \rightarrow K^- \pi^+)} \frac{\epsilon(\Lambda_b \rightarrow D^+)}{\epsilon(\Lambda_b \rightarrow D^0 p)} \right]. \quad (48)$$

Here ϵ is the total trigger and detection efficiencies. The ratios of efficiencies in the bracket terms accounts for the total efficiency of the cross-feed mode measured in data which includes an extra kaon or proton, and the efficiency to reconstruct this exclusive mode in the inclusive ground-state charm plus muon data.

The number of B_s resulting in $D_s X \mu \nu$ in the final state is given by

$$n_{corr}(B_s \rightarrow D_s \mu) = \frac{1}{\epsilon(B_s \rightarrow D_s)} \left[\frac{n(D_s \mu)}{\mathcal{B}(D_s \rightarrow K^+ K^- \pi^+)} - N(B^0 + B^+) \frac{\mathcal{B}(\bar{B}^0 \rightarrow D_s K \mu \nu) + \mathcal{B}(B^+ \rightarrow D_s K \mu \nu)}{2} \epsilon(B \rightarrow D_s \mu) \right], \quad (49)$$

where the last term subtracts yields of $D_s K X \mu \nu$ final states originating from B^0 or B^- semileptonic decays that are present in the inclusive $D_s \mu$ sample. The average branching fraction used for these decays is $\mathcal{B}(B \rightarrow D_s^{(*)+} K \mu \nu) = (6.1 \pm 1.2) \times 10^{-4}$ [73].

In addition, B_s decays semileptonically into $DKX \mu \nu$, and thus added to Equation 49 is

$$n_{corr}(B_s \rightarrow DK \mu) = \kappa \frac{n(D^0 K^+ \mu)}{\mathcal{B}(D^0 \rightarrow K^- \pi^+) \epsilon(B_s \rightarrow D^0 K^+ \mu)}, \quad (50)$$

where κ accounts for $B_s \rightarrow D^+ K^0 X \mu \nu$ semileptonic decays that are not measured. The total $n_{corr}(B_s \rightarrow D\mu)$ yield is therefore,

$$n_{corr}(B_s \rightarrow D\mu) = \left[\frac{n(D_s\mu)}{\mathcal{B}(D_s \rightarrow K^+ K^- \pi^+) \epsilon(B_s \rightarrow D_s)} + \kappa \frac{n(D^0 K^+ \mu)}{\mathcal{B}(D^0 \rightarrow K^- \pi^+) \epsilon(B_s \rightarrow D^0 K^+ \mu)} \right] - N(B^0 + B^+) \langle \mathcal{B}(B \rightarrow D_s K \mu \nu) \rangle \frac{\epsilon(B \rightarrow D_s \mu)}{\epsilon(B_s \rightarrow D_s \mu)}. \quad (51)$$

In this equation the terms in the brackets sum up all B_s semileptonic decays, and the last term subtracts off the $D_s K \mu$ component originating from light B decays that are reconstructed in the inclusive $D_s \mu$ sample.

The corrected yield for Λ_b is given as

$$n_{corr}(\Lambda_b \rightarrow D\mu) = \frac{n(\Lambda_c \mu)}{\mathcal{B}(\Lambda_c \rightarrow p K^- \pi^+) \epsilon(\Lambda_b \rightarrow \Lambda_c)} + 2 \frac{n(D^0 p \mu)}{\mathcal{B}(D^0 \rightarrow K^- \pi^+) \epsilon(\Lambda_b \rightarrow D^0 p)}, \quad (52)$$

where the factor 2 accounts for the isospin symmetric $D^+ n$ cross-feed state.

Taking the ratio of Equation 51 to the sum of Equations 47 and 48, the equation for the ratio $f_s/(f_u + f_d)$ is thus given as

$$\frac{f_s}{f_u + f_d} = \frac{n_{corr}(B_s \rightarrow D\mu)}{n_{corr}(B \rightarrow D^0 \mu) + n_{corr}(B \rightarrow D^+ \mu)} \frac{\tau_{B^-} + \tau_{B^0}}{2\tau_{B_s}} (1 + \xi_{B_s}) - \frac{\langle \mathcal{B}(B \rightarrow D_s K \mu \nu) \rangle}{\mathcal{B}_{SL}(B_s^0)} \frac{\epsilon(B \rightarrow D_s \mu)}{\epsilon(B_s \rightarrow D_s \mu)}. \quad (53)$$

This equation assumes equality of the semileptonic widths of all the b meson species ($B_{SL} = \Gamma_{SL}/\Gamma = \Gamma_{SL} \times \tau$), hence the ratio of semileptonic branching fractions in Equation 44 reduces to the ratio of lifetimes. This is a reliable assumption, as corrections in HQET arise only to order $1/m_b^2$ and the SU(3) breaking correction is quite small, of the order of 1% [92],

which is accounted for with $\xi_{B_s} = (1.0 \pm 0.5)\%$. The symbols τ_{B_i} indicate the B_i hadron lifetimes, that are all well measured [73]. The average B_s lifetime, 1.513 ± 0.019 ps [73] is used. The latter term on the right hand side of the equation, arising from $D_s K \mu$ cross-feed decays, is normalized by the semileptonic branching fraction of the B_s . Since this quantity is not measured it is derived using the equality of the semileptonic widths and the measured b -hadron lifetimes, and is listed in Table 23. This correction amounts to a $0.33 \pm 0.17\%$ subtraction to $f_s/(f_u+f_d)$, where the uncertainty is from the measured $B \rightarrow D_s K \mu$ branching fraction and the efficiency ratio determined from Monte Carlo simulations.

The Λ_b fraction is given as

$$\frac{f_{\Lambda_b}}{f_u + f_d} = \frac{n_{corr}(\Lambda_b \rightarrow D\mu)}{n_{corr}(B \rightarrow D^0\mu) + n_{corr}(B \rightarrow D^+\mu)} \frac{\tau_{B^-} + \tau_{B^0}}{2\tau_{\Lambda_b}} (1 - \xi_{\Lambda_b}). \quad (54)$$

Again, the assumption of equality of the semileptonic widths of different b hadrons is used, but with a small adjustment $\xi_{\Lambda_b} = (3.0 \pm 1.5)\%$, to account for the chromomagnetic correction, affecting b -flavored mesons but not b baryons [92]. The uncertainty is evaluated with very conservative assumptions for all the parameters of the heavy quark expansion.

Table 23 summarizes the b -hadron lifetimes and semileptonic branching fractions used.

Using the corrected yields of the $D^0\mu$ and $D^+\mu$, the ratio of $f_+/f_0 \equiv n_{corr}(D^+\mu)/n_{corr}(D^0\mu)$ serves as a useful systematic check to the analysis. Since this is a ratio of a four-body to

Table 23: Measured semileptonic decay branching fractions for B mesons and derived branching fractions for B_s and Λ_b based on the equality of semileptonic widths and the lifetime ratios.

Particle	τ (ps) measured	$\mathcal{B}_{SL}$ (%) measured	Correction	Γ_{SL} (ps ⁻¹) measured	$\mathcal{B}_{SL}$ (%)
B^0	1.520 ± 0.004	10.30 ± 0.19		0.0678 ± 0.0013	10.30 ± 0.19
B^-	1.638 ± 0.004	11.09 ± 0.20		0.0680 ± 0.0013	11.09 ± 0.20
$\langle \overline{B}^0 + B^- \rangle$		10.70 ± 0.19			10.70 ± 0.19
B_s	1.526 ± 0.015		$(1.0 \pm 0.5)\%$		10.3 ± 0.30
Λ_b	1.470 ± 0.010		$(3.0 \pm 1.5)\%$		10.35 ± 0.28

three-body final state tracks, due to the reconstructed charm meson modes, it is sensitive to the absolute tracking and PID efficiencies of one pion track from the D^+ decays, and any deviation of a flat kinematic distribution of this ratio would indicate systematic problems. Therefore, this ratio is also measured in data, in the same kinematic binning as the b -hadron fractions, to test for any problems in the analysis method. Additionally, this ratio is a convenient observable to constraint on the "unknown portion" of the hadron spectrum in semileptonic b decays. This ratio can be predicted with isospin extrapolations and using different extrapolation hypothesis for the missing semileptonic portion. Reference [93] gives predicted values for this fraction, and other observables, for a number of different extrapolation methods, and the data collected here are precise enough to constrain which extrapolation hypothesis best represents the data.

Table 24: Charm hadron branching fractions for the decay modes used in this analysis. $D^0 \rightarrow K^-\pi^+$ and $D_s^+ \rightarrow K^-K^+\pi^+$ are taken from Reference [73]. The $\Lambda_c^+ \rightarrow pK^-\pi^+$ fraction is a weighted average of direct measurements by BES III [81] and Belle [82]. $D^+ \rightarrow K^-\pi^+\pi^+$ is taken from Reference [80]

Particle and decay	$\mathcal{B}$ (%)
$D^0 \rightarrow K^-\pi^+$	3.93 ± 0.05
$D^+ \rightarrow K^-\pi^+\pi^+$	9.22 ± 0.17
$D_s^+ \rightarrow K^-K^+\pi^+$	5.44 ± 0.18
$\Lambda_c^+ \rightarrow pK^-\pi^+$	6.23 ± 0.33

6.3 Event selection

The 2016 dataset (Reco16) correspond to an integrated luminosity of approximately $1.67 fb^{-1}$, respectively, taken at a center-of-mass energy of 13 TeV. Data is processed with DaVinci v42r6p1 and corresponds to Stripping 28.

All b-hadron candidates are required to have the muon be L0Muon TOS and HLT1TrackMuon TOS, and to be TOS on one of the HLT2TopoMu(2|3|4)Body lines. The TCKs for both datasets are listed in Tab. 25. In the 2016 data there was a loose and tight configuration. Events are selected by the B2DMuNu_($D^0|D^+|D_s^+|\Lambda_c^+$) lines. A list of all stripping selections is provided in Tab. 27. Addition offline selections are listed in Tab. 28. These selections mimic those used in Section 5. In addition a charm hadron IP cut is applied to suppress the so called prompt-charm background, associated with charmed hadrons produced directly. The PID selection criteria are more stringent than in Section 5 in order to further reduce the background associated with mis-identified hadrons. In addition, potential reflections affecting the D_s^+ sample are suppressed by explicitly vetoing final states such as $K^+\pi^-\pi^+$ or $pK^-\pi^+$ that have an invariant mass close to the D^+ or Λ_c^+ masses, respectively, when either one π^+ or the p are misidentified as K^+ . Backgrounds from B decays to two charm hadrons, in which one decays into the signal channel and the other to a muon, are suppressed with cuts on corrected mass, defined as

$$m_{corr} = \sqrt{m_{H_c\mu}^2 + p_\perp^2} + p_\perp. \quad (55)$$

$m_{H_c\mu}$ is the mass of the charm hadron plus muon pair, and $p_\perp$ is momentum component of the charm hadron plus muon pair transverse to the b -hadron flight direction.

6.3.1 Removal of prompt charm

Figure 84 shows, for example, the 2-dimensional fit to the Λ_c invariant mass and natural log of the IP of the Λ_c with respect to the primary vertex, over the entire η and p_T regions. Here

the prompt contribution, shown in purple in both plots, is modeled as a double Gaussian in charm invariant mass, and as a bifurcated Gaussian in $\ln(IP/mm)$. The $\ln(IP/mm)$ shape is determined by examining a prompt enriched sample in MC. The prompt yield (13829 ± 205) determined in the fit is 0.92% of the signal yield (1498390 ± 1313). The fractional prompt component for the other modes is 1.45%, 1.94%, and 1.40% for the $D^0\mu$, $D^+\mu$, and $D_s\mu$ modes, respectively. The statistical uncertainty on these fractions are all 0.01%.

It is possible to remove the prompt component by cutting on the $\ln(IP/mm)$ of the charm-hadron without affecting the signal yield appreciably, and thus eliminating the need to do 2-dimensional fits in charm $\ln(IP/mm)$ and invariant mass. A cut on the $\ln(IP/mm) > -3$ of the charm hadron is found to reduce the prompt component to 0.06%, 0.09%, 0.07%, and 0.04%, for the $D^0\mu$, $D^+\mu$, $D_s\mu$, and $\Lambda_c\mu$ modes, respectively, while still being 97% efficient for all the signal decays.

At $\mathcal{O}(10^{-4})$ these prompt contaminations are beyond the sensitivity of the measurement, and thus the cut $\ln(IP/mm) > -3$ is used and signal fits for the main signal modes are performed in one dimension of the invariant charm mass.

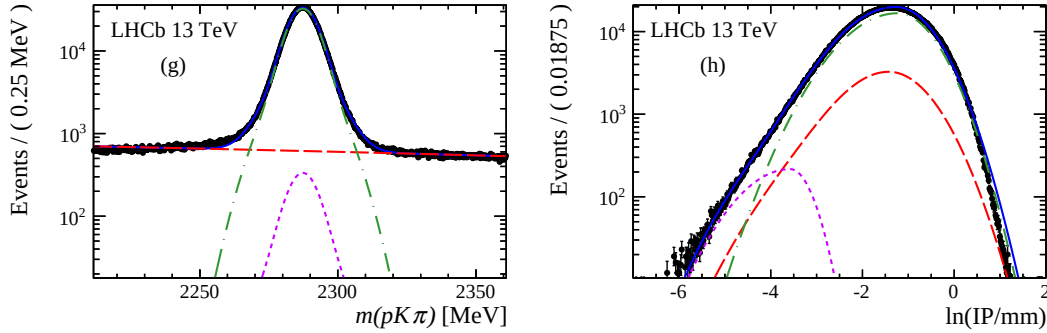


Figure 84: 2-dimensional fit to the Λ_c^+ invariant mass and natural log of the IP, integrated over $\eta(B)$ and $p_T(charm + \mu)$. Shown in green is the signal. The purple shows the prompt component and red shows the combinatorial background.

6.3.2 Suppression of reflections in the D_s^+ mass spectrum

In the $D_s^\pm \rightarrow K^\pm K^\mp \pi^\pm$ mass spectrum three sources of non-peaking backgrounds are identified. One of them is due to correctly identified $D^{*+} \rightarrow D^0(K^+K^-)\pi^+$ decays. The other two

are mis-identified $D^+ \rightarrow K^+\pi^-\pi^+$ and $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays, where the negatively charged pion or the proton is mis-identified as a kaon, respectively. Fig. 85 shows the $KK\pi$ mass spectrum in data, with the positive or negative kaon taken as a pion or proton, respectively. Here a clear peak at the Λ_c^+ or D^+ mass can be seen. Overlaid are also the MC distributions.

$D^{*+} \rightarrow D^0(K^+K^-)\pi^+$ decays could be explicitly fit for but to simplify the fit to data a VETO on the $\Delta m = m(KK\pi) - m(KK)$ spectrum is applied if the Δm is within 140 to 150 MeV. The $D^+ \rightarrow K^+\pi^-\pi^+$ contribution is cut out with a VETO to the $m(KK_{K \rightarrow \pi}\pi)$ mass within 20 MeV of the D^+ mass, where the negative kaon is taken as a pion. Finally the $\Lambda_c^+ \rightarrow pK^-\pi^+$ contribution, which was a considerable systematic in the previous b-fraction analysis using semileptonic decays, is subtracted with a VETO to the $m(K_{K \rightarrow p}K\pi)$ mass within 20 MeV of the Λ_c^+ mass, where the positive kaon is taken as a proton.

6.3.3 Reflections in other charm modes

Reflections in the D^+ and Λ_c^+ invariant mass spectra were also checked in the cases where one pion in the D^+ was mis-identified as a kaon, or the proton in Λ_c^+ was mis-identified as a kaon. In the former case no mis-identification backgrounds were seen. For mis-identified protons in Λ_c^+ , some small contributions from D^+ and D_s^+ to $KK\pi$ decays are present but are both very small compared to the combinatorial background (see Fig. 86), and therefore are not VETOed.

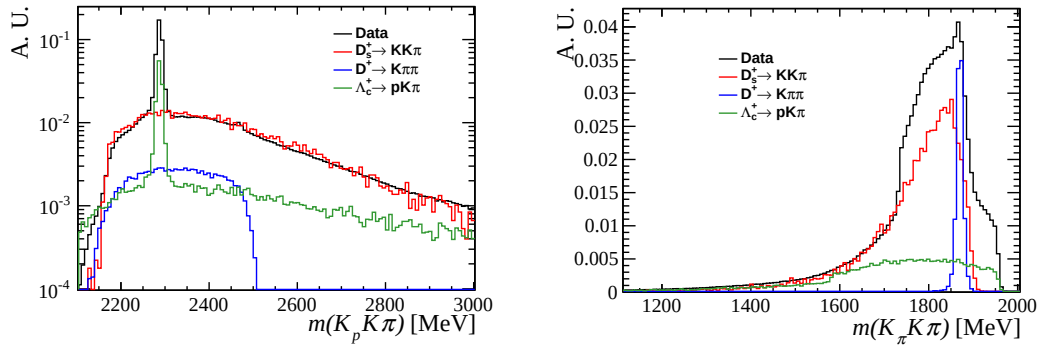


Figure 85: $KK\pi$ mass spectrum in data, with the positive (left) or negative (right) kaon taken as a pion or proton, respectively. Overlaid (with arbitrary normalizations) are the MC distributions.

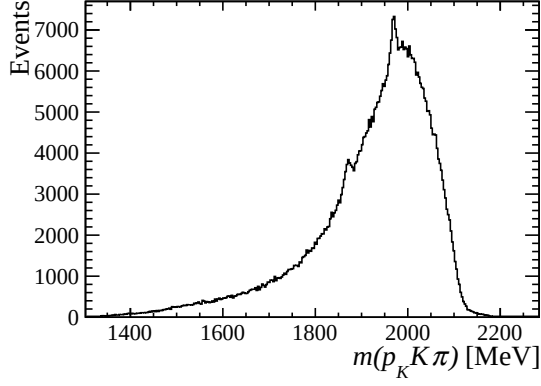


Figure 86: $pK\pi$ invariant mass in data where the proton taken to be a kaon. There are two small peaks corresponding to D^+ and D_s^+ to $KK\pi$ decays.

Table 25: HLT1 selections in TCKs for the 2016 dataset. For 2016 data there was a loose and tight configuration corresponding to “2016 HLT1Loose” and “2016 HLT1Tight” below.

TCKs	HLT1 requirements
2016 HLT1Loose	
0x11291600	$p_T > 910$ MeV
0x11291603	$p > 6000$ MeV
0x11291604	$IP_{\chi^2} > 10$
0x11291605	isMuon
0x11321609	
0x11341609	
2016 HLT1Tight	
0x11351609	$p_T > 1100$ MeV
0x11361609	$p > 6000$ MeV
0x11371609	$IP_{\chi^2} > 35$
0x1137160E	isMuon
0x11381609	GhostProb < 0.2
0x1138160E	
0x1138160F	
0x11381610	
0x11381612	
0x11381613	

Table 26: L0 selections for TCKs for the 2016 dataset. One ADC count translates to 50 MeV.

TCKs	Muon p_T [ADCs]
2016	
0x11291603	23
0x11291604	27
0x11291605	31
0x11371609	27
0x1137160e	27
0x11381609	31
0x1138160e	31
0x1138160f	37
0x11321609	27
0x11341609	27
0x11351609	27
0x11361609	27
0x11381611	31
0x11381612	33

Table 27: Stripping selection criteria applied to all charm modes

Item	Requirement
Muons	
Track χ^2	<3
p	>6 GeV
p_T	>1.0 GeV
IP χ^2	>9
PID	PIDmu >0
Ghost Prob.	<0.35
Pions	
Track χ^2	<3
p	>2 GeV
p_T	>250 MeV
IP χ^2	>4
PID	DLLK <20
Ghost Prob.	<0.35
Kaons	
Track χ^2	<3
p	>2 GeV
p_T	>250 MeV
IP χ^2	>4
PID	DLLK >-2
Ghost Prob.	<0.35
Protons	
Track χ^2	<3
p	>8 GeV
p_T	>250 MeV
IP χ^2	>4
PID	DLLp >0
Ghost Prob.	DLLp-DLLK >0 <0.35
Charm hadron	
Vertex χ^2/ndof	<6
BPVVDCHI2	>25
Invariant mass	Within 80MeV of nominal value
b hadron	
Vertex χ^2/ndof	<9
Invariant mass of charm+muon	$2.2 < m(H_c + \mu) < 8$ GeV
DIRA	>0.999
Event	
nLongTracks	<250

Table 28: Offline selection criteria

Item	Requirement
Trigger	
L0	L0MuonDecision TOS
Hlt1	TrackMuonDecision TOS
Hlt2	TopoMu(2 3 4)BodyDecision TOS
Muons	
ISMUON	OK
p_T	>1.3 GeV
N shared hit	$=0$
Track GhostProb	<0.2
Pions	
PID	$DLLK < 0$ & $DLLp < 0$
p_T	>300 MeV
Track GhostProb	<0.2
Kaons	
PID	$DLLK > 4$
p	>5 GeV
p_T	>300 MeV
Track GhostProb	<0.2
Protons	
PID	$DLLp > 10$
p_T	>300 MeV
Track GhostProb	<0.2
Charm hadron	
Charm impact parameter	$\ln(H_c \text{ IP}_{PV}/\text{mm}) > -3$
$D^0\mu X$	Scalar sum of daughter $p_T/2 > 600$ MeV
All other modes	Scalar sum of daughter $p_T/3 > 700$ MeV
b hadron	
Charm vertex downstream of b vertex	$z(\text{charm}) - z(\text{b}) > 0$
$p_T(\text{charm} + \mu)$	>3 GeV
B radius	<4.8 mm
Invariant mass of $D^0(D^+) + \mu$	$m(D^0(D^+) + \mu) \in [3, 5]$ GeV
Invariant mass of $D_s^+ + \mu$	$m(D_s^+ + \mu) \in [3.1, 5.1]$ GeV
Invariant mass of $\Lambda_c^+ + \mu$	$m(\Lambda_c^+ + \mu) \in [3.3, 5.3]$ GeV
B_s^0 corrected mass	>4.2 GeV
Λ_b^0 corrected mass	>4.5 GeV
VETOS	Veto if
D_s^+	
$D^{*+} \rightarrow D^0(KK)\pi_s$	$m(KK\pi) - m(KK) \in [140, 150]$ MeV
$D^+ \rightarrow K^+\pi^-\pi^+$	$ m(KK_{K \rightarrow \pi\pi}) - 1870 < 20$ MeV
$\Lambda_c^+ \rightarrow pK^-\pi^+$	$m(K_{K \rightarrow p}K\pi) \in [2267, 2309]$ MeV

Table 29: Total yields of all signal charm modes.

Mode	2016 Yield
$D^0\mu X$	13755200 ± 3911
$D^+\mu X$	4282650 ± 2396
$D_s^+\mu X$	845314 ± 1142
$\Lambda_c^+\mu X$	1753550 ± 1417

6.4 Signal fits

The method used to extract the charmed hadron- μ signal is described using the $D^0X\mu^-\bar{\nu}$ final state in 2016 data as an example; the same procedure is applied to the final states $D^+X\mu^-\bar{\nu}$, $D_s^+X\mu^-\bar{\nu}$, and $\Lambda_c^+X\mu^-\bar{\nu}$. Here data taken with magnet polarity up and down are combined. Extended maximum likelihood fits are performed to the $K^-\pi^+$ invariant mass over a region extending ± 75 MeV from the D^0 mass peak. Additionally, fits are performed in bins of pseudorapidity in 3 equal bins in the range $\eta \in [2, 5]$, and transverse momentum of the charm- μ pair in 18 bins in the range $p_T \in [0, 25]$ GeV. The invariant charm mass is fit with a signal component comprising of two Gaussian functions and combinatorial background component modeled as a linear function. Figure 87 shows the η and p_T integrated fits to the D^0 , D^+ , D_s^+ , and Λ_c^+ invariant masses. The black points show the data, the dotted green line shows the signal component, the dashed red line shows the combinatorial component, and the blue shows the whole fit.

The η and $p_T(\text{charm} + \mu)$ integrated yields are shown in Table 29 and the yields as function of η and $p_T(\text{charm} + \mu)$ are shown in Figures 88.

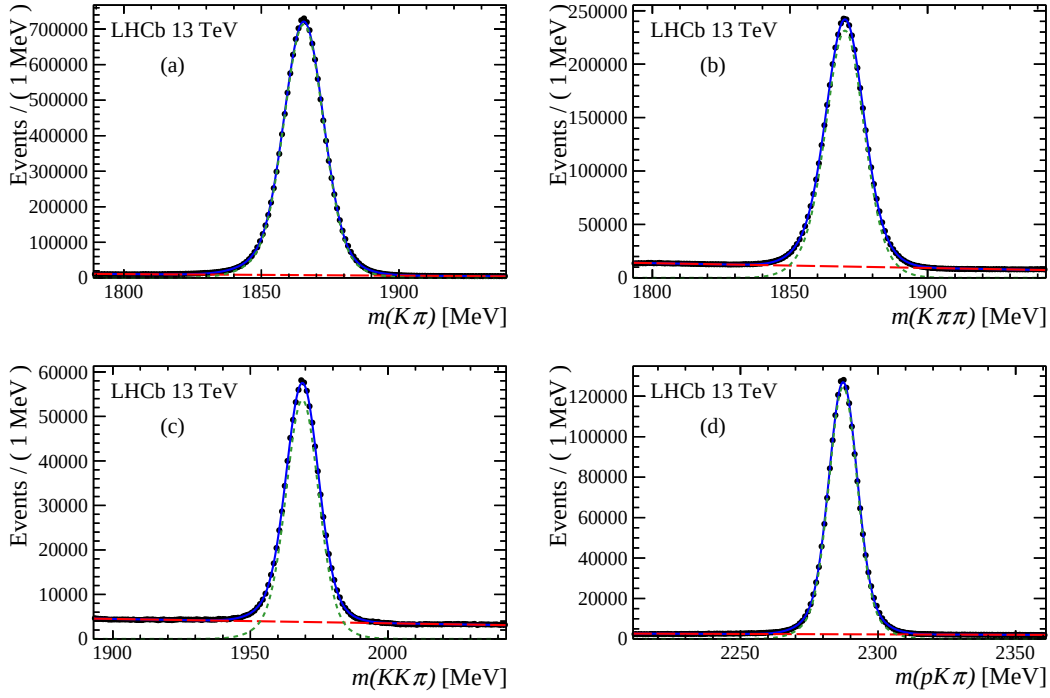


Figure 87: Fits to the $D^0 \rightarrow K\pi$ (a), $D^+ \rightarrow K\pi\pi$ (b), $D_s^+ \rightarrow KK\pi$ (c), and $\Lambda_c^+ \rightarrow pK\pi$ (d) mass spectra. The data is shown as the black points with error bars. The signal component is shown as the green dotted line and the combinatorial background component is shown as the dashed red line. The blue line shows all the fit components added together.

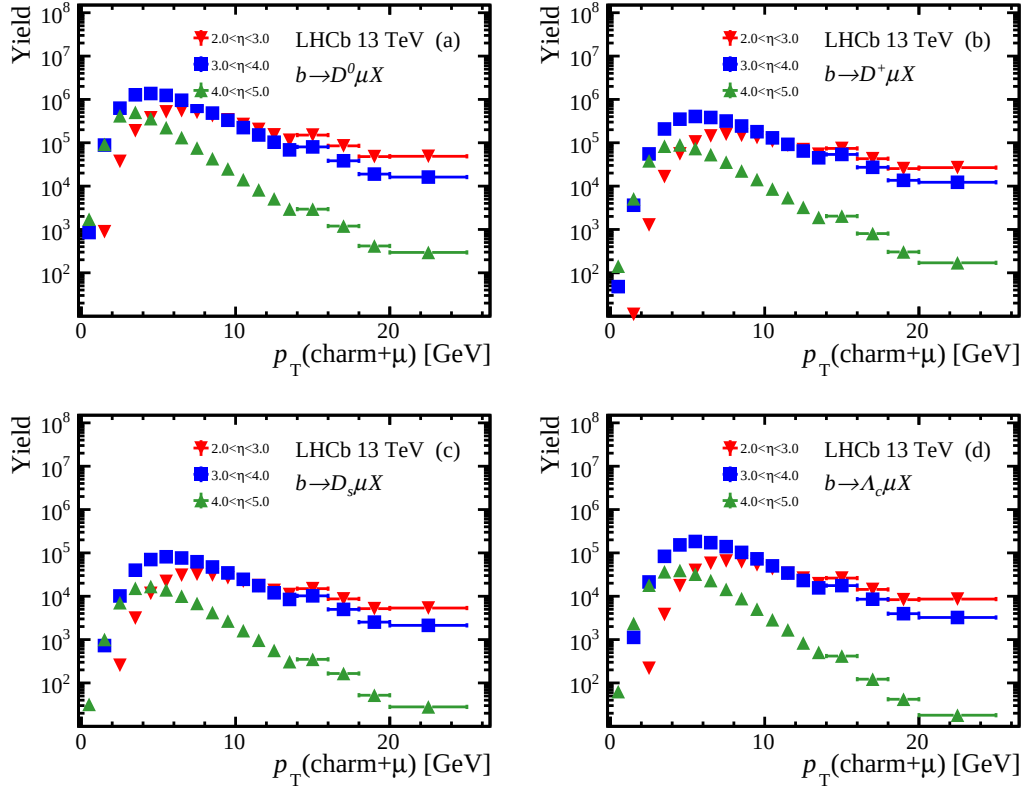


Figure 88: Yields of all the charm modes as a function of η and $p_T(\text{charm} + \mu)$ in 2016 data. Note the yields are determined in bins of $p_T(\text{charm} + \mu)$ that are not all equal in width.

Table 30: Fraction of wrong-sign to right-sign data integrated over $p_T(\text{charm} + \mu)$ and η .

Mode	WS/RS fraction [%]
$D^0\mu X$	0.93 ± 0.01
$D^+\mu X$	0.61 ± 0.01
$D_s^+\mu X$	0.60 ± 0.01
$\Lambda_c^+\mu X$	0.41 ± 0.01

6.5 Peaking backgrounds

Three other sources of peaking backgrounds, which are not already accounted for, are subtracted from signal yields by estimating their fractional contamination in the signal data sample. Two of them coming from the muon fake background combined with a real charm candidate and combinations of a real muon and charm from opposite side B decays. Both of which are, estimated from data with wrong charm- μ charge combinations. The third coming from $D\bar{D}$ decays where one charm decays into a signal channel and the other days into a muon. This background is estimated from dedicated MC simulations.

6.5.1 Fake muon

Data with wrong-sign (WS) charm- μ charge combinations are used to estimate the backgrounds coming from a fake muon combined with real charm decay (right-sign decays are denoted “RS”). Measuring the WS to RS fraction by performing fits to both samples estimates the fractional component of this background in the signal sample. These fractions integrated over p_T and η are listed in Table 30. While these fractions are all below 1% they may have some kinematic dependencies. Therefore they are further studied in bins of p_T . These are shown in Figure 89 for all charm modes in 2016 data. At lower p_T this fraction can increase above 1%. There is no significant dependence on η in a given interval of p_T . Therefore, the fractional WS/RS values, integrated over η , are subtracted from the raw signal yield in each bin of p_T for each mode, however there is little sensitivity to these backgrounds when calculating the final hadron fraction ratios.

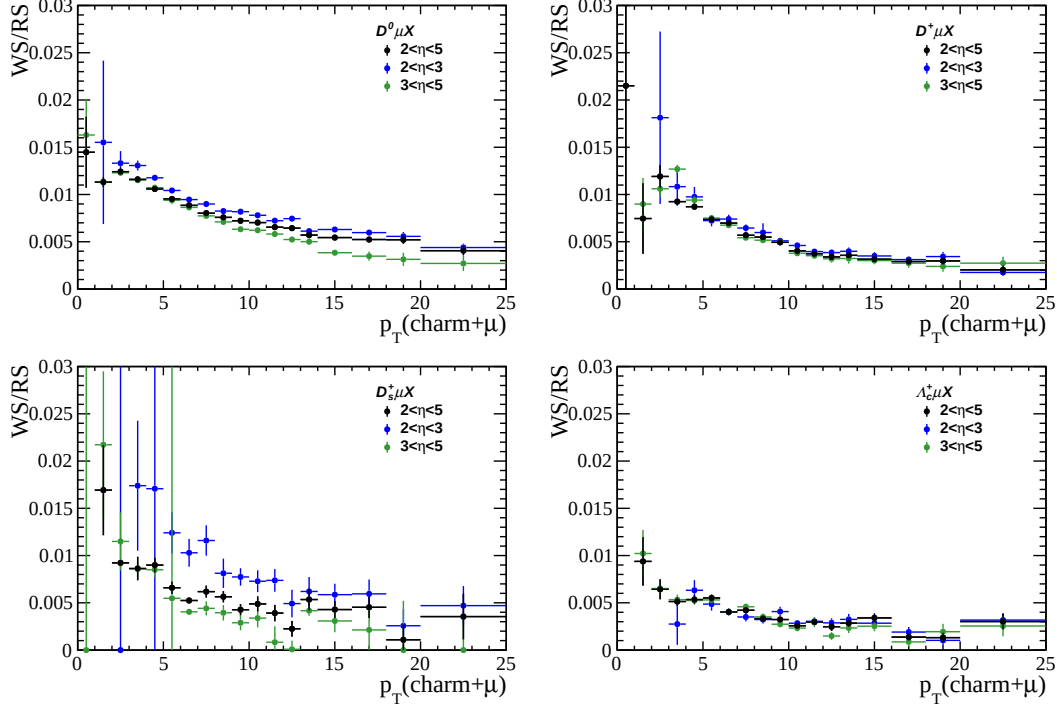


Figure 89: Fraction of wrong-sign data to right-sign data determined in bins of $p_T(\text{charm}+\mu)$ for all charm modes in 2016 data. The colored data points show the different η intervals. The uncertainties shown reflect the statistics of both samples added in quadrature.

6.5.2 $D\bar{D}$ decays

Backgrounds of the form $B \rightarrow DDX$, where one of the charm hadrons decays into a final state with a muon, and the other decays into the signal channel, will always produce right-sign decays and must be estimated using simulation. From Reference [94], the measured contribution in the $D_s^+\mu^-$ mode was $O(10\%)$. This large contribution is due to $W^+ \rightarrow c\bar{s}$. For the other signal channels, the double charm background is were measured to be about 1% for $\Lambda_c\mu$ and well below 1% for $D^{0/+}\mu$. Thus, backgrounds for $D_s\mu$ and $\Lambda_c\mu$ are estimated and subtract, but check their contributions in $D^0\mu$ and $D^+\mu$.

Figure 90 shows comparisons of the corrected mass in signal $B_s \rightarrow D_s\mu\nu$ MC and various simulated DD modes. Figure 91 shows the same for $\Lambda_b \rightarrow \Lambda_c\mu\nu$. In contrast to previous estimations of these background in Reference [94], dedicated MC are generated for each specific decay. Table 32 lists all the MC samples generated for these background estimations with

Table 31: Inclusive $c \rightarrow \mu$ branching fractions for all charm species taken from the PDG. For the D_s^+ and Λ_c^+ modes the values for the inclusive $\rightarrow eX$ were used and in the D_s^+ case the leptonic $\mu^- \bar{\nu}$ values were added.

Decay	$B(c \rightarrow \mu) [\%]$
$D^0 \rightarrow \mu X$	6.7 ± 0.6
$D^+ \rightarrow \mu X$	17.6 ± 3.2
$D_s^+ \rightarrow \mu X$	8.0 ± 0.4
$\Lambda_c^+ \rightarrow \mu X$	4.5 ± 1.7

number of generated events, final efficiency, branching fractions, and the final background contribution. The fraction of double charm events with respect to our signal is calculation as

$$f_{bkg}/f_{signal} = \frac{\epsilon(DD)}{\epsilon(Signal)} \times \frac{B(B \rightarrow DD X)}{B(B \rightarrow D\mu X)} \times \frac{f_{d,u,\Lambda_b}}{f_s} \times B(D \rightarrow \mu X) \quad (56)$$

where the first term is the efficiency ratio, the second is the ratio of the b-hadron branching fractions, the third term is the fragmentation fraction ratio, and the last term is the inclusive $c \rightarrow \mu$ branching fraction for the second charm hadron. The semileptonic branching fraction for the B_s^0 is listed in Table 23 and is $10.3 \pm 0.3\%$. In the efficiency ratio MC trigger efficiencies are used for both signal and double charm events. The total background fraction estimated in the $D_s\mu X$ yield is $2.7 \pm 0.6\%$, where the uncertainty is from MC statistics and uncertainties on the known branching fractions.

For $\Lambda_c\mu$ mode $\Lambda_b \rightarrow \Lambda_c D$ decays are simulated, where the D is a D^0 , D^+ , or a D_s that decays into a final state including a muon. The latter dominates the background (event number 15996201), and amounts to a $0.7 \pm 0.3\%$ background, where the uncertainty is from MC statistics and uncertainties on the know branching fractions. The former two where checked and do not contribute significantly.

The $D^0\mu$ mode was checked with $B^0 \rightarrow D^0 D^0$ and $B \rightarrow D_s D^0$ decays and the $D^+\mu$ mode was checked with $\Lambda_b \rightarrow \Lambda_c D^-$, $B^0 \rightarrow D_{(s)}^- D^+$, and $B^+ \rightarrow D^0 D^+$ decays. In both cases the background was negligible.

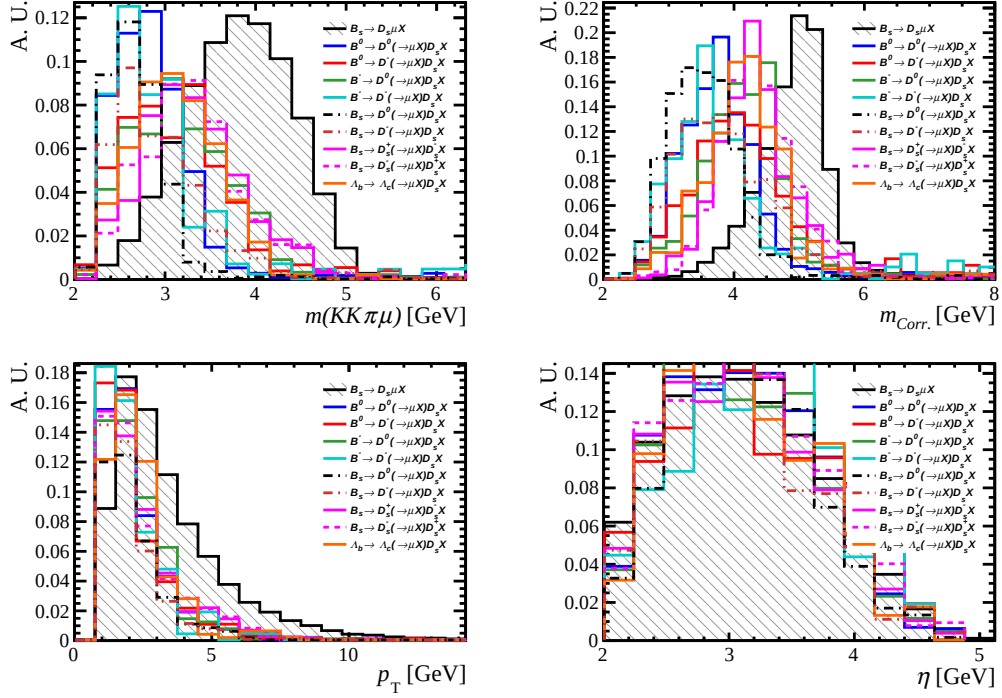


Figure 90: Comparison of the visible and corrected mass variables, and muon distributions between $B_s \rightarrow D_s \mu X$ and $b \rightarrow D D X$ background MC samples.

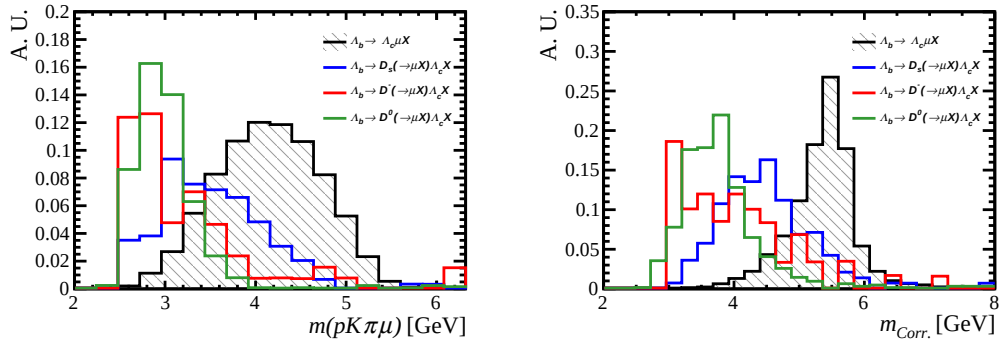


Figure 91: Comparison of the visible and corrected mass variables between signal $\Lambda_b \rightarrow \Lambda_c \mu X$ and $b \rightarrow D D X$ background MC samples.

Table 32: List of all $D_s^- \mu^+$ from double charm background simulated. f_{Λ_b}/f_s is taken as $2.34 \pm 0.31\%$ and $f_{u,d}/f_s$ is taken as $3.86 \pm 0.22\%$.

Decay	Event #	Gen. Events	Eff. Ratio [%]	BR_{BKG} [%]	$f_{bkg}/f_{sig.}$
$B^0 \rightarrow D^0(\rightarrow \mu X) D_s X$	11996000	200k	70 ± 19	5.7 ± 1.2	0.2 ± 0.1
$B^0 \rightarrow D^-(\rightarrow \mu X) D_s X$	11994601	200k	20 ± 3	4.6 ± 1.2	1.5 ± 0.5
$B^- \rightarrow D^0(\rightarrow \mu X) D_s X$	12995610	52k	93 ± 59	0.9 ± 0.09	0.1 ± 0.1
$B^- \rightarrow D^-(\rightarrow \mu X) D_s X$	12995300	200k	14 ± 2	7.9 ± 1.4	1.4 ± 0.4
$B_s \rightarrow D_s^{(*)\pm}(\rightarrow \mu X) D_s^{(*)\mp} X$	13994203/4	200k	8 ± 1	4.5 ± 1.4	0.2 ± 0.1
$\Lambda_b^0 \rightarrow D^0(\rightarrow \mu X) D_s X$	15996200	73k	60 ± 46	$0.1 \pm$	0.2 ± 0.1
$\Lambda_b^0 \rightarrow D^-(\rightarrow \mu X) D_s X$	15996400	81k	69 ± 80	$0.1 \pm$	0.2 ± 0.2
$\Lambda_b^0 \rightarrow \Lambda_c(\rightarrow \mu X) D_s X$	15994601	200k	16 ± 3	10.3 ± 2.1	0.8 ± 0.3
Sum					5.8 ± 0.9

6.6 Analysis of cross-feed channels

6.6.1 Selection criteria

$D^0\mu$ events that are selected with the B2DMuNu_D0 stripping line are combined with an additional kaon or proton to form $\overline{B}_s^0 \rightarrow D^0 K^- \mu^+ \nu_\mu$ or $\Lambda_b^0 \rightarrow D^0 p \mu^+ \nu_\mu$ candidates. A complete set of offline selections applied to candidates is tabulated in Tab. 33. The selection criteria is similar to the main signal channels, with a few additional requirements on the added kaon or proton track. Additionally, a $D^* \rightarrow D^0 \pi$ VETO is applied to B_s and Λ_b candidates with $m(h_{h \rightarrow \pi} K \pi) - m(K \pi) < 150$ MeV, where the h is the added kaon or proton, respectively. See for example Fig. 92 for $\overline{B}_s^0 \rightarrow D^0 K^- \mu^+ \nu_\mu$ data.

Combinatorial background in the $D^0 \rightarrow K \pi$ invariant mass spectrum is removed using sWeights [85] determined with a fit to the $K \pi$ mass. Figures 93 and 94 show an example fit to the D^0 invariant mass for $\overline{B}_s^0 \rightarrow D^0 K^- \mu^+ \nu_\mu$ and $\Lambda_b^0 \rightarrow D^0 p \mu^+ \nu_\mu$ candidates in the magnet down right-sign data, and the three wrong-sign categories (described below), respectively. It has been checked that $m(K \pi)$ is uncorrelated with the fit variables that are described below.

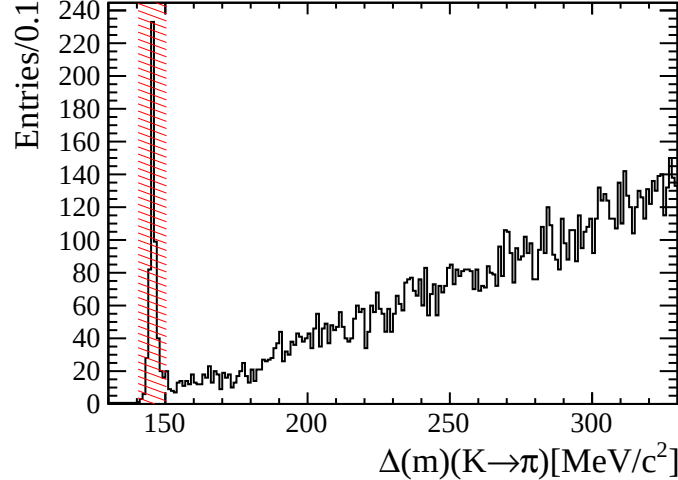


Figure 92: $m(h_{h \rightarrow \pi} K \pi) - m(K \pi)$ distribution in $\overline{B}_s^0 \rightarrow D^0 K^- \mu^+ \nu_\mu$ data. The peak at low Δm is $D^* \rightarrow D^0 \pi$ decays.

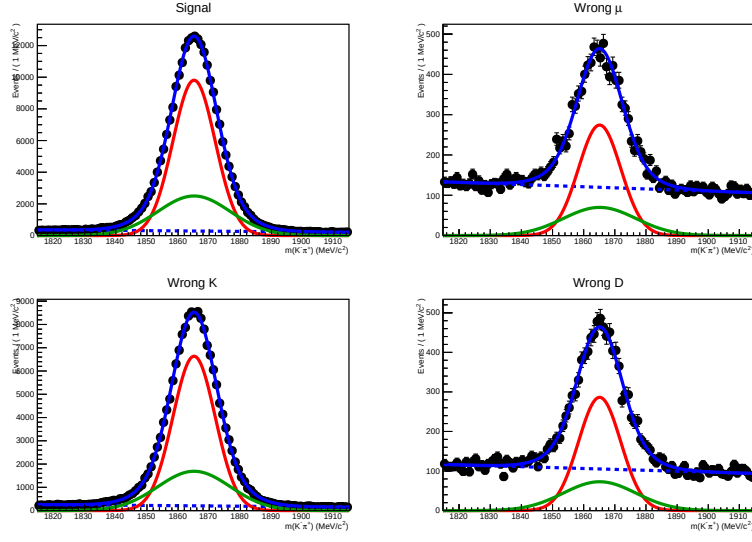


Figure 93: Fit to the D^0 invariant mass for $\bar{B}_s^0 \rightarrow D^0 K^- \mu^+ \nu_\mu$ candidates in the magnet down right-sign data, and the three wrong-sign categories. The red and green lines shown the two Gaussian components of the D^0 signal, the blue dotted line shows the combinatorial background, and the solid line shows all fit components added together.

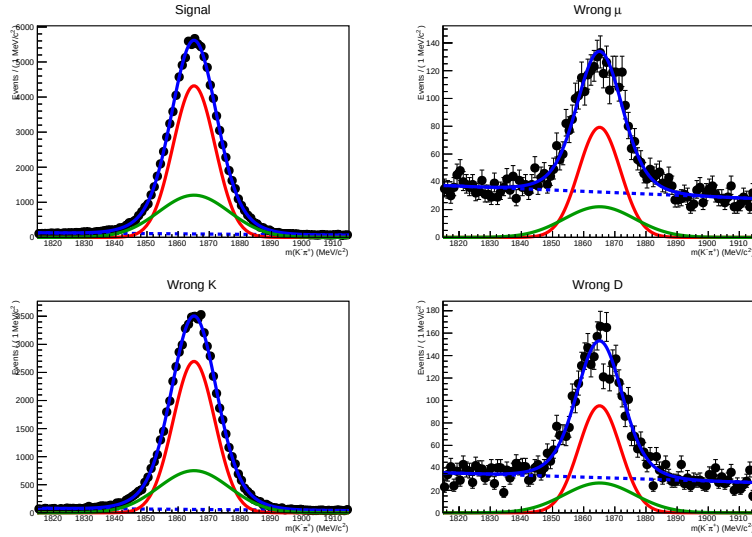


Figure 94: Fit to the D^0 invariant mass for $\Lambda_b^0 \rightarrow D^0 p \mu^+ \nu_\mu$ candidates in the magnet down right-sign data, and the three wrong-sign categories. The red and green lines shown the two Gaussian components of the D^0 signal, the blue dotted line shows the combinatorial background, and the solid line shows all fit components added together.

Table 33: Selection criteria for the cross-feed modes $\Lambda_b^0 \rightarrow D^0 p \mu$ and $B_s \rightarrow D^0 K \mu$.

Selection Quantity	Criteria
Trigger	Mu L0MuonDecision TOS Mu Hlt1TrackMuonDecision TOS B Hlt2TopoMu{2 3 4}BodyDecision TOS
Final state particles	Track GhostProb < 0.2 Track χ^2/ndoff < 3
Muon	isMuon==1 $p_T > 1300$ MeV, $p > 6000$ MeV $1.9 < \eta < 4.9$ NSHAREDMU == 0 χ_{IP}^2 Own PV > 9 PIDmu > 0
π from D^0	PIDK < 0, PIDp < 0 $p_T > 300$ MeV, $p > 5000$ MeV $1.9 < \eta < 4.9$ χ_{IP}^2 Own PV > 4
K from D^0	PIDK > 4 $p_T > 300$ MeV, $p > 5000$ MeV $1.9 < \eta < 4.9$ χ_{IP}^2 Own PV > 4
D^0	$ln(IP)$ Own PV > -3 $(p_T(K) + p_T(\pi))/2 > 600$ MeV χ_{FD}^2 Own PV > 25 (Duplicate of Stripping) End Vertex χ^2/ndoff < 6
K from B_s	PIDK > 4, PIDK-PIDp > 0 $p_T > 300$ MeV, $p > 5000$ MeV $1.9 < \eta < 4.9$ χ_{IP}^2 Own PV > 4
p from Λ_b^0	PIDp > 10 $p_T > 300$ MeV, $p > 8000$ MeV $1.9 < \eta < 4.9$ PIDp - PIDK > 0 χ_{IP}^2 Own PV > 4 $m(p_{p \rightarrow \pi} K \pi) - m(K \pi) > 150$ MeV
B_s or Λ_b^0 candidate	D^0 End Vertex z - X_b End Vertex $z > 0$ $p_T(D^0 + K)$ or $p_T(D^0 + p) > 2$ GeV X_b DIRA own pv > 0.999 $3000 < m(X_b) < 6000$ corrected B_s mass > 4.2 GeV or corrected Λ_b^0 mass > 4.5 GeV X_b EndVertex $z ==$ origin vertex (μD^0) z $log(\chi_{\text{End Vertex}}^2(X_b) - \chi_{\text{End Vertex}}^2(\mu D^0)) < 5$

6.6.2 Cross-feed signal fits

Both $\overline{B}_s^0$ and Λ_b^0 can decay into the $Dh\mu$ final state, where h is a kaon or proton, respectively, through the decays of higher charm states or non-resonantly. Simply performing a fit to the traditional $m(D^0h)_{const.} \equiv (D^0h) - m(D^0) + m(D^0)_{PDG}$ variable is not sufficient to ascertain the non-resonant signal yield as it is not distinguishable above the combinatoric background. Therefore, a two-dimensional fit to the $m(D^0h)_{const.}$ and $\ln(\chi_{IP}^2)$ of the added hadron track with respect to the $D\mu$ vertex is utilized (the latter variable is also seen as $\ln[\chi_{\text{vertex}}^2(D^0h\mu) - \chi_{\text{vertex}}^2(D^0\mu)]$). True resonant and non-resonant $\overline{B}_s^0 \rightarrow D^0 K^- \mu^+ \nu_\mu$ or $\Lambda_b^0 \rightarrow D^0 p \mu^+ \nu_\mu$ decays peak in the $\ln(\chi_{IP}^2)$ around a value of one while the background is smooth, thus allowing accurate determination of the non-resonant yield above background.

The signal shapes used in the fits are listed in Tables 34 and 35 for $\overline{B}_s^0 \rightarrow D^0 K^- \mu^+ \nu_\mu$ or $\Lambda_b^0 \rightarrow D^0 p \mu^+ \nu_\mu$, respectively. The shapes of the background component are determined by simultaneously fitting data with right-sign (RS) and wrong-sign (WS) charge combinations. The WS sample is defined as data with the sign of muon or added hadron track are inverted, or where the D^0 is reconstructed in the $K^+ \pi^-$ final state.

Table 34: Component shapes for the 2D fit to $m(D^0h)$ vs $\ln\chi_{IP}^2$ of h w.r.t $D^0\mu$ vertex. The shapes with shared parameters are labeled as such.

Shape	$m(D^0h)$	$\ln\chi_{IP}^2$ of h w.r.t. $D^0\mu$ vtx
D_{s1}	Double Gaussian	Double Bifurcated Gaussian
D_{s2}	Relativistic BW $\otimes$ Gaussian	Shared with D_{s1}
Non-resonant	Threshold Function	Double Bifurcated Gaussian
Background	Threshold Function	Gaussian

Figures 95 and 96 show the η and $p_T(\text{charm} + \mu)$ integrated fits to the RS and WS samples in $\overline{B}_s^0 \rightarrow D^0 K^- \mu^+ \nu_\mu$ or $\Lambda_b^0 \rightarrow D^0 p \mu^+ \nu_\mu$ decays, respectively. In both plots the data are shown as the black points with error bars, the fitted signal resonant components are shown as the red dashed lines and non-resonant component as the green dashed lines, the background is shown as the gray dotted lines. The combined fit model is shown as the blue

Table 35: Component shapes for the 2D fit to $m(D^0 h)$ vs $\ln\chi_{IP}^2$ of h w.r.t $D^0\mu$ vertex. The shapes with shared parameters are labeled as such.

Shape	$m(D^0 h)$	$\ln\chi_{IP}^2$ of h w.r.t. $D^0\mu$ vtx
$\Lambda_c^+(2860)$	RBW $\otimes$ Gaussian	Double Bifurcated Gaussian
$\Lambda_c^+(2880)$	RBW $\otimes$ Gaussian	Shared with $\Lambda_c^+(2860)$
$\Lambda_c^+(2940)$	RBW $\otimes$ Gaussian	Shared with $\Lambda_c^+(2860)$
Non-resonant	Threshold Function	Double Bifurcated Gaussian
Background	Threshold Function	Gaussian

line.

For each of the Λ_c^+ resonances considered in Table 35, the J^{PC} values are taken from Ref. [95], with the $\Lambda_c^+(2940)$ fixed to $l = 1$, as this is the most probable value. Changing the l parameter for the RBW does not have an effect on the fit quality.

The determined yields for the resonant and non-resonant components in $\bar{B}_s^0 \rightarrow D^0 K^- \mu^+ \nu_\mu$ or $\Lambda_b^0 \rightarrow D^0 p \mu^+ \nu_\mu$ decays are tabulated in Tables 36 and 37, respectively.

Table 36: Extracted yields of the fit to 2016 data for $B_s \rightarrow D^0 K \mu \nu_\mu$.

Fit Component	Yield
D_{s1}	22610 ± 210
D_{s2}	14290 ± 260
Non-resonant	38140 ± 460

Table 37: Extracted yields of the fit to 2016 data for $\Lambda_b^0 \rightarrow D^0 p \mu^+ \nu_\mu$.

Fit Component	Yield
$\Lambda_c(2860)$	6120 ± 460
$\Lambda_c(2880)$	2200 ± 220
$\Lambda_c(2940)$	1200 ± 260
Non-resonant	29770 ± 690

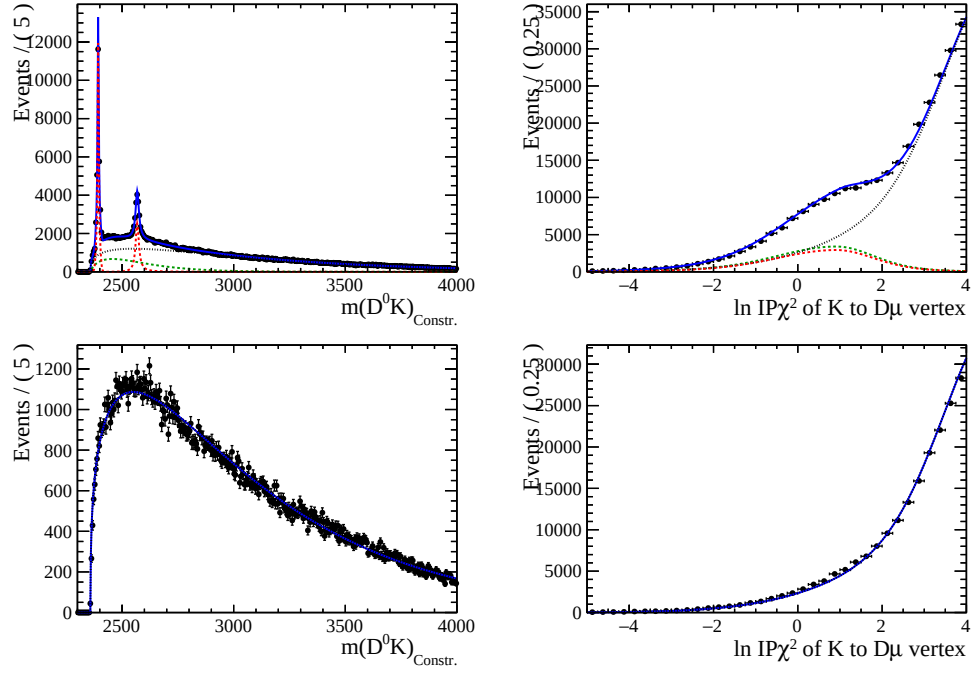


Figure 95: Projections of the 2D fit of the $\overline{B}_s^0 \rightarrow D^0 K^- \mu^+ \nu_\mu$ sample. The left side shows the constrained $m(D^0 K)$ projection, the right the $\ln \chi^2_{IP}$ of the K w.r.t. the $D^0 \mu$ vertex. The top row is RS and the bottom is WS. The red dashed line shows the peaking D_{s1} and D_{s2} components, the green dashed line shows the non-resonant component, the black dotted line is the background component, and the blue shows all components added together

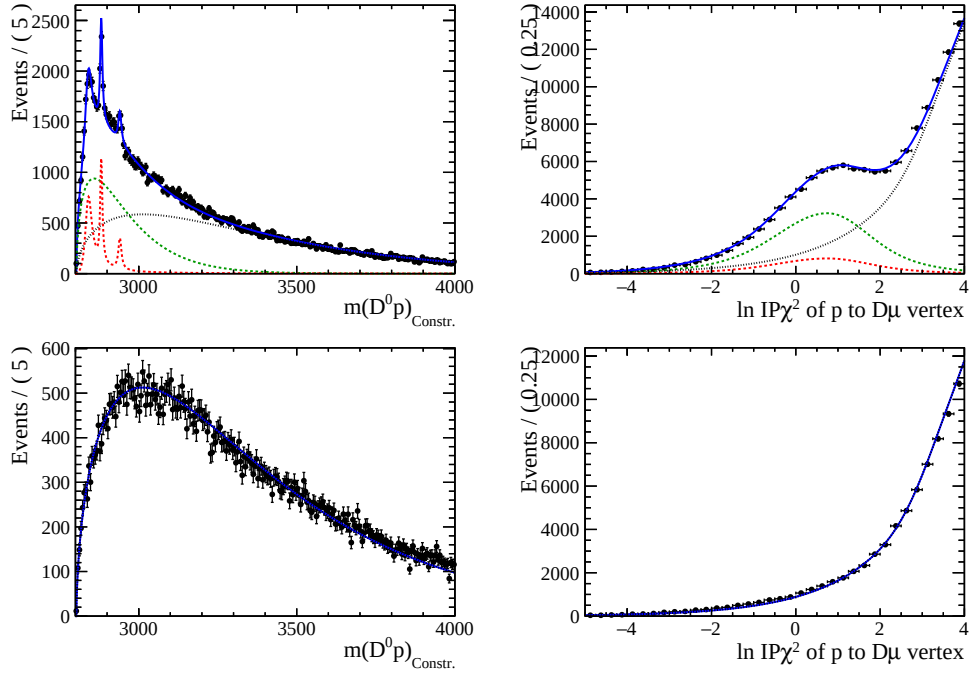


Figure 96: Projections of the 2D fit of the $\Lambda_b^0 \rightarrow D^0 p \mu \nu$ sample. The left side shows the constrained $m(D^0 p)$ projection, the right the $\ln \chi^2_{IP}$ of the p w.r.t. the $D^0 \mu$ vertex. The top row is RS and the bottom row is WS. The red dashed line shows the peaking components of the $\Lambda_c^+(2860)$, $\Lambda_c^+(2880)$ and $\Lambda_c^+(2940)$, the green dashed line is the non-resonant component, the black dashed line is the background and the blue line shows all components added together.

6.6.3 Backgrounds

In each reconstructed cross-feed mode, the added hadron track can be a mis-identified one and would still be treated as signal in the fit for the non-resonant yield. Mis-ID from pions is already removed in the VETO selections and the only mis-ID component is due to K - p mis-ID. In fact, the main source of these mis-ID rates in one cross-feed mode is due to the other reconstructed cross-feed mode. That is, for example the reconstructed $D^0 K \mu$ non-resonant yield is

$$N_{NR}^{reco}(D^0 K \mu) = N_{NR}^{true}(D^0 K \mu) \times \epsilon(K) + N_{NR}^{true}(D^0 p \mu) \times \epsilon(p \rightarrow K). \quad (57)$$

Where the true non-resonant yields are multiplied by the real kaon identification efficiency, $\epsilon(K)$, in the case of $D^0 K \mu$ decays, and the true $D^0 p \mu$ yield is multiplied by the mis-ID rate, $\epsilon(p \rightarrow K)$. To estimate the cross-contamination of these non-resonant yields, the same fitting procedure is performed on samples with tighter PID requirements. Using the efficiencies and mis-ID rates for the nominal samples and these tighter PID samples, the true yields are solved for using the above equation. The true yields are 10 and 9% smaller than the uncorrected non-resonant $D^0 p \mu$ $D^0 K \mu$ decays, respectively.

Another source of background is $b \rightarrow D D X$ decays. Using simulated $B \rightarrow D^0 D_s$ decays, where the D_s decays into $\phi(K K) \mu \nu$, the kinematic distributions in Figure 97 are constructed. These are the same as the combinatorial background model and are therefore absorbed in the total background model in the fit.

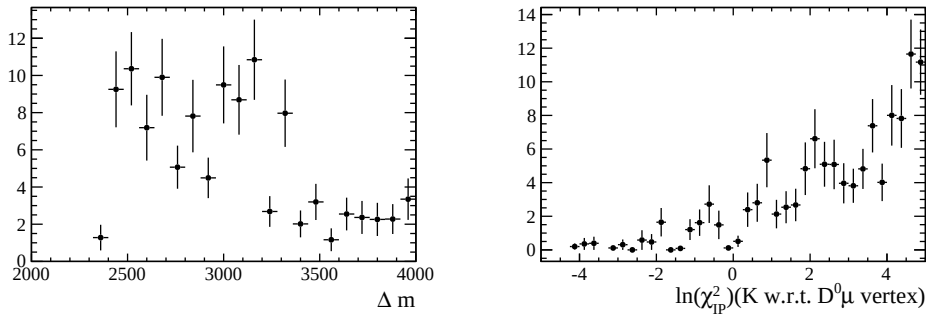


Figure 97: Reconstructed distributions of backgrounds coming from $B \rightarrow D^0 D_s$ decays.

Table 38: Simulated samples used for 2016 data. Samples for the $b \rightarrow DDX$ backgrounds are listed in their respective section.

EventType	DecFile	Generated 2016
<i>DμX</i> modes		
11874091	Bd_D0Xmunu,D0=cocktail	1M
11874401	Bd_D+Xmunu,D+=cocktail	1M
12873441	Bu_D0Xmunu,D0=cocktail	1M
12875401	Bu_D+Xmunu,D+=cocktail	1M
13774004	Bs_Dsmunu=cocktail,hqet2	3M
15874040/1	Lb_Lcmunu,pKpi.dec	1/2M
15576010	Lb_Lc2593munu,Lcpipi,pKpi	2M
15576011	Lb_Lc2625munu,Lcpipi,pKpi	2M
Cross-feed modes		
12575020	Bu_K+Ds-mu+nu,K-K+pi-=LHCbAcceptance	4M
15574080	Lb_D0pmunu,D0_Kpi=LHCbAcceptance	2M
13574440	Bs_Dsststmunu,D0=cocktail,LHCbAcceptance	1M/10M Filtered
13574441	Bs_Dsststmunu,D+=cocktail,LHCbAcceptance	1M/10M Filtered

6.7 Efficiency corrections

Efficiency corrections are determined using both Monte Carlo (MC) simulations and data-driven techniques. MC is used for reconstruction and selection efficiencies and data-driven techniques are used to derive trigger, muon ID, hadron particle ID (PID), and tracking efficiency corrections. The MC description is first given, then the data-driven techniques will be described in following sections, then reconstruction and selection and overall B hadron efficiencies will be derived.

6.7.1 MC samples

Signal and cross-feed MC samples are tabulated in Table 38 with their respective simulated statistics and conditions. Samples for $b \rightarrow DDX$ backgrounds are listed in a separate table in their respective section.

Table 39: Trigger and muon ID requirements

Item	Requirement
Trigger	
L0	L0Muon TOS
HLT1	HLT1TrackMuon TOS
HLT2	HLT2TopoMu{2 3 4}BodyDecision TOS
Muon ID	
PID	DLLmu>0
isMuon	OK
nShared	=0

6.7.2 Trigger and muon ID efficiencies

The efficiency for trigger and muon ID requirements listed in Tab. 39 are evaluated using two different data-driven methods. Efficiencies for requirements on the muon, i.e., L0 and HLT1 trigger and muon ID, are determined using a tag-and-probe method with a clean sample of detached J/ψ to dimuon decays. The HLT2 topological trigger requirements are determined using the TISTOS method on signal data. Both methods are described in the following sub-sections.

6.7.2.1 L0 and HLT1 trigger and muon ID To determine the L0 and HLT1 and muon ID efficiencies a data-driven tag-and-probe method is utilized. Detached $B^+ \rightarrow J/\psi(\rightarrow \mu^+\mu^-)K^+$ decays are used where one well-identified muon (tag) is in association with another track with no muon ID requirements (probe) both originating from the J/ψ vertex. The probe track is then sorted into “pass” or “fail” categories depending whether it passes or fails all muon trigger and/or ID requirements. From the yields within the respective categories the efficiency is calculated as $\epsilon = pass/(pass + fail)$.

B^+ candidates are selected from the PIDCalib Hlt2PIDB2KJPsiMuMu(Pos||Neg)Tagged calibration lines. Selections for muons and kaons, and combinations, are listed in Tab. 40. Tag and probe muons are then required to pass offline selections listed in Tab. 41. An additional selection of $nLongTracks < 250$ is applied.

As the trigger and muon ID efficiencies are highly dependent on muon kinematics the efficiencies are determined in intervals of probe muon transverse momentum and pseudo-

rapidity. The binning chosen is 20 bins in muon momentum in the intervals [1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, 2.1, 2.3, 2.5, 2.7, 2.9, 3.1, 3.3, 3.5, 4.5, 5.5, 10.0, 20.0, 30.0] GeV, and 21 bins of muon pseudo-rapidity spanning the intervals [1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, 2.1, 2.3, 2.5, 2.75, 3.0, 3.25, 3.5, 3.75, 4.0, 4.25, 4.5, 4.75, 5.0, 5.5, 6.0]. The binning in pseudo-rapidity covers regions outside the muon acceptance to make sure to include the full turn-off of the muon efficiency.

The yields above backgrounds of both pass and fail categories are ascertained by performing a simultaneous fit of the J/ψ invariant mass to both categories in bins of muon kinematics. As an example the fit to the entire muon momentum and pseudo-rapidity is shown in Fig. 98. Here the black data points show the data passing probe muon requirements and the black line shows the fit including signal and background. The red shows, respectively, candidates that fail the muon requirements. The J/ψ signal mass shape is described by 3 Gaussian functions and the background is described by a Chebychev polynomial. In total for 2016 data there are about 630k candidates above background after offline selections listed in Table 41 with 338362 ± 556 passing and 296575 ± 577 failing trigger and muon ID.

The muon trigger and ID efficiencies, in bins of transverse momentum and pseudo-rapidity, are shown in Fig. 99 for L0, HLT1, and muon ID in 2016 data. To propagate the muon trigger and ID efficiencies to bins of B pseudo-rapidity and transverse momentum MC are weighted with the muon trigger and ID efficiencies event-by-event according to the muon kinematics and average over the weights. The final muon trigger and ID efficiency per B mode in bins of pseudo-rapidity and transverse momentum, with systematic uncertainties due to the tag-and-probe method only (described in Section 6.9), are shown in Fig. 101. Comparisons between muon kinematics in data and MC are shown in Appendix B.1. Additionally Figure 100 shows the comparison of muon kinematics between all charm modes in data and MC.

Table 40: Stripping selection criteria applied to muons in the J/ψ to dimuon sample and addition cuts applied to kaons and the combined B^+ candidates.

Item	Requirement
Muons	
μ^- (probe)	
p_T	>0 MeV
p	>3000 MeV
χ^2/ndf	<5
Trigger	L0(Muon Dimuon) TIS
	Hlt1(TrackAllL0 TrackMuon SingleMuon DiMuon TrackMVA TwoTrackMVA) TIS
μ^+ (tag)	
p_T	>1200 MeV
p	>3000 MeV
χ^2/ndf	<3
GhostProb	<0.2
HasMuon	OK
isMuon	OK
$\mu^-\mu^+$	
χ^2 DOCA	<10
J/ψ	
Invariant mass	Within 200 MeV of nominal value
Kaons	
p_T	>300 MeV
p	>3000 MeV
Track χ^2/ndf	<3
IP χ^2 w.r.t. PV	>9
DLLK	>5
B^+	
Invariant mass	Within 500 MeV of nominal mass
DIRA	>0.9999
Vertex $\chi^2/ndof$	<25
χ^2_{VS}	>15
IP χ^2 w.r.t. PV	<25

Table 41: Offline Selection criteria applied to tag and probe muons in the J/ψ to dimuon sample.

Item	Requirement
Tag Muons	
p_T	>1300 MeV
p	>6000 MeV
IP χ^2	>16
Track χ^2	<3
PID	DLLmu >0
isMuon	OK
nSHared	$==0$
L0	L0Muon TOS
HLT1	HLT1TrackMuon TOS
Probe Muons	
p_T	>1300 MeV
p	>6000 MeV
IP χ^2	>9
Track χ^2	<3
HLT2	HLT2TopoMu2Body TIS

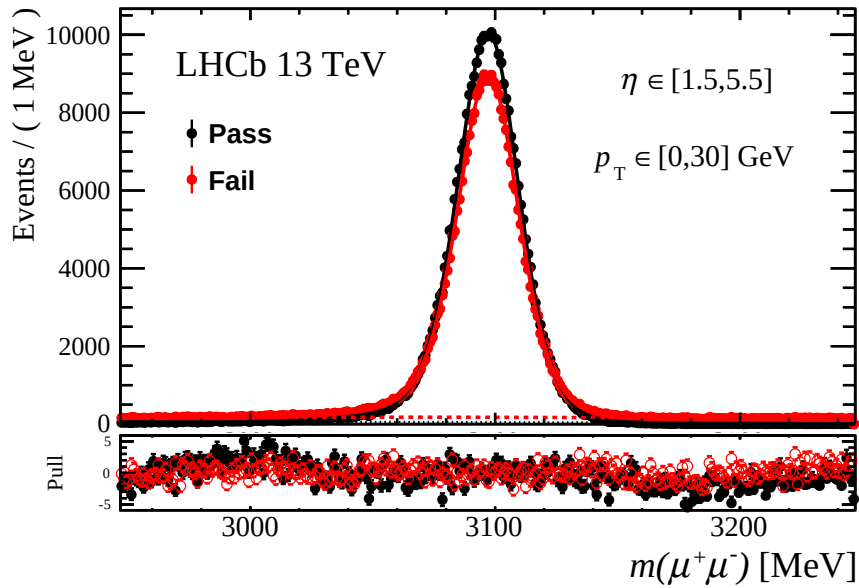


Figure 98: Fit to the dimuon invariant mass spectrum integrated over probe muon p_T and η . The black points show data where the probe muon passed L0 and HLT1 trigger requirements, and all muon ID cuts. The red points show probe muon that fail all these requirements. Both fail and pass categories are fit simultaneously and the functions are described in the text.

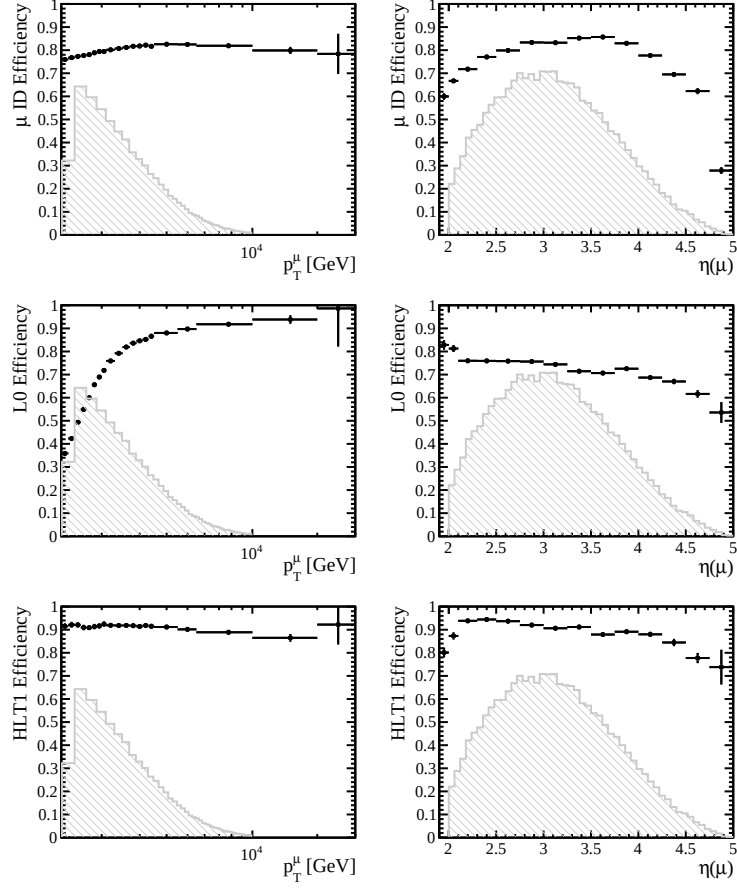


Figure 99: 2016 efficiencies for the muon ID (top), L0Muon (middle) and HLT1TrackMuon (bottom) trigger. The gray histogram shows the normalized average muon distribution. All error bars reflect statistics in the samples only.

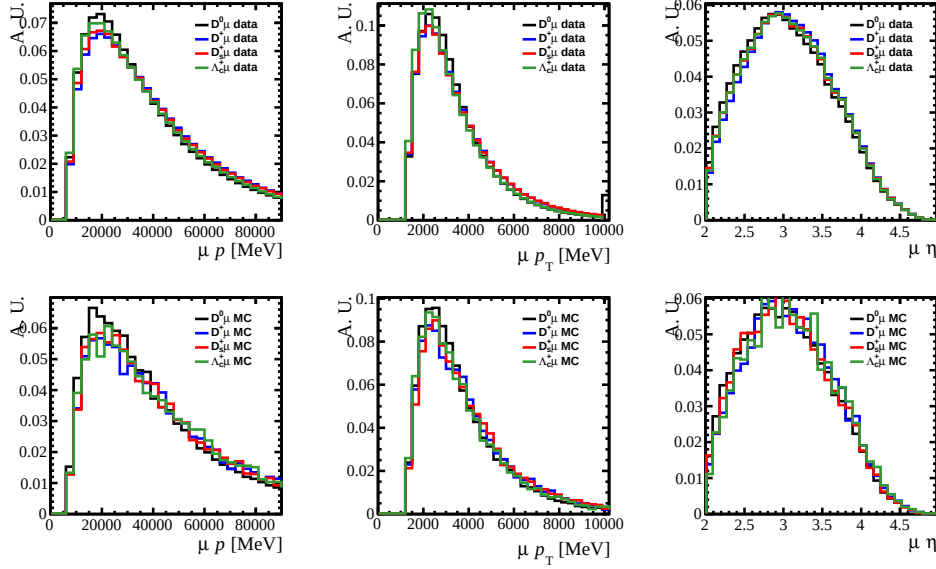


Figure 100: Comparison of muon kinematics in all charm modes in data (top) and MC (bottom)

6.7.2.2 HLT2 TISTOS efficiency The efficiency for the HLT2 topological triggers are determined with signal data using what is called the TISTOS method. In this method the data are required first (after all offline selections, and L0 and HLT1 trigger) to pass an *or* decision on the HLT2TopoMu{2|3|4}Body TIS and then calculate the efficiency as the number of events that are then *or* on the HLT2TopoMu{2|3|4}Body TOS. To make uncertainty calculations easier, the TIS sample is split into two samples that are TIS and TOS, and TIS and !TOS. Explicitly, the efficiency is

$$\epsilon = \frac{TIS \& TOS}{TIS} = \frac{TIS \& TOS}{(TIS \& TOS) + (TIS \& !TOS)} \quad (58)$$

The efficiencies are determined in the same B pseudo-rapidity and transverse momentum bins as the signal yields, and the yields above background are determined in the same way as the signal fits (see Sec. 6.4).

The efficiencies as a function of B pseudo-rapidity and transverse momentum, compared to MC, can be seen in Figures 102, 103, 104, and 105. The $D^+\mu$ mode has slightly less efficiency with respect to the other 4-body modes that is due to the longer D^+ lifetime.

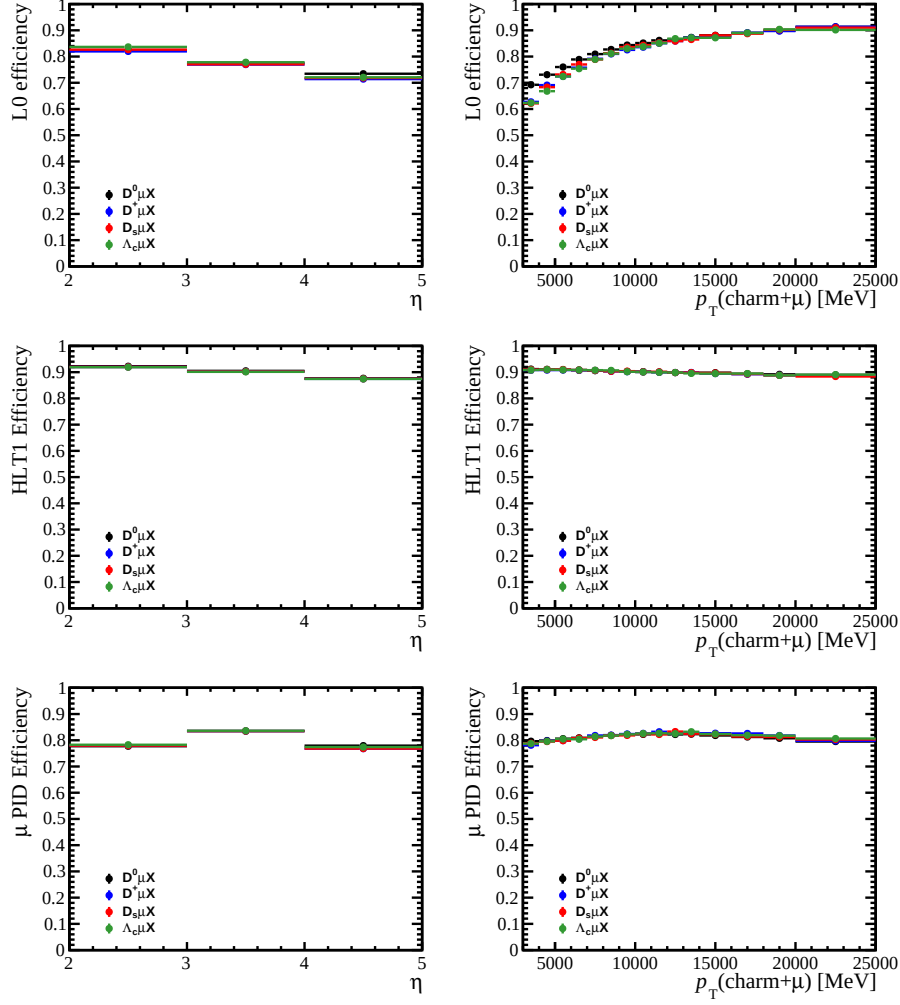


Figure 101: L0(top) and HLT1(middle) trigger and muon ID (bottom) efficiencies for all charm modes as a function of B kinematics. The efficiencies are determined by averaging over the muon L0, HLT1, or muon ID efficiencies determined in the calibration sample according to the muon distributions in MC in the respective signal samples. The (small) uncertainties shown are the diagonal errors associated with the $J/\psi \rightarrow \mu\mu$ calibration sample only.

Figure 106 shown are the data/MC ratios. Within uncertainties both data and MC show agreement.

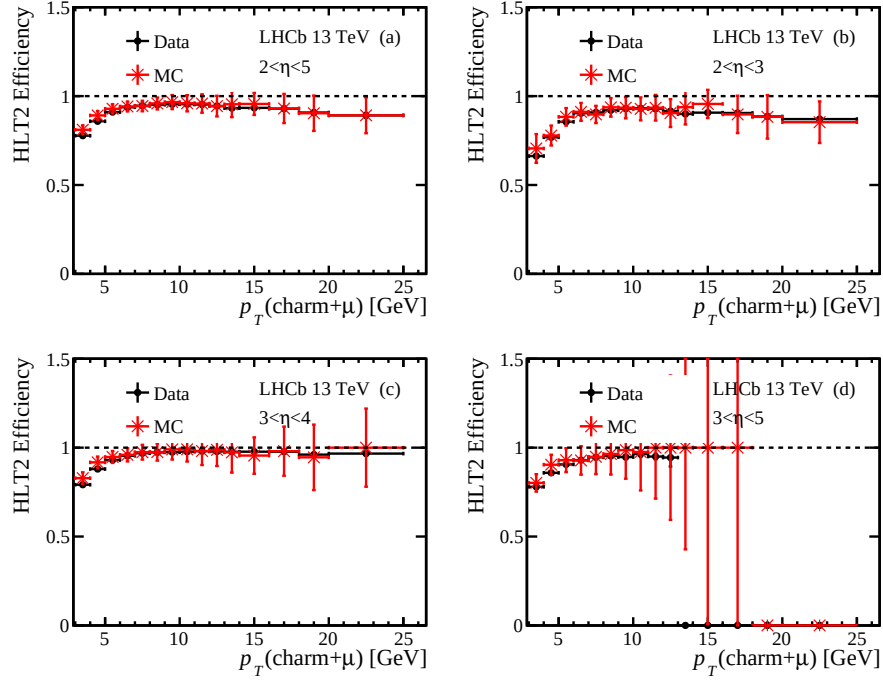


Figure 102: Efficiencies for the HLT2 topological triggers for $D^0\mu X$ mode determined using the TISTOS method in signal data compared to efficiencies derived from MC. Uncertainties shown reflect the statistics of the TIS/TOS samples or MC only.

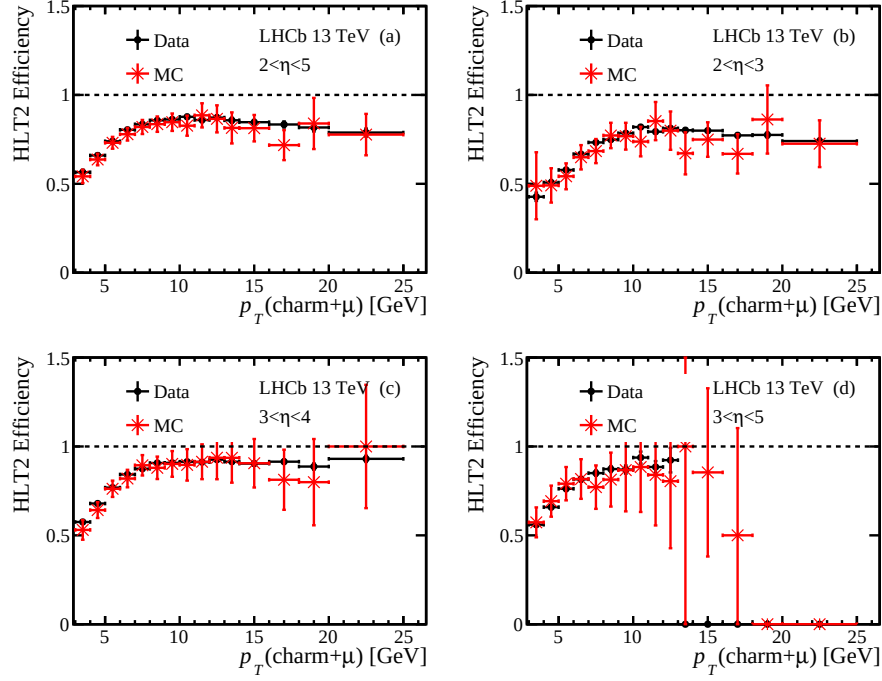


Figure 103: Efficiencies for the HLT2 topological triggers for $D^+\mu X$ mode determined using the TISTOS method in signal data compared to efficiencies derived from MC. Uncertainties shown reflect the statistics of the TIS/TOS samples or MC only.

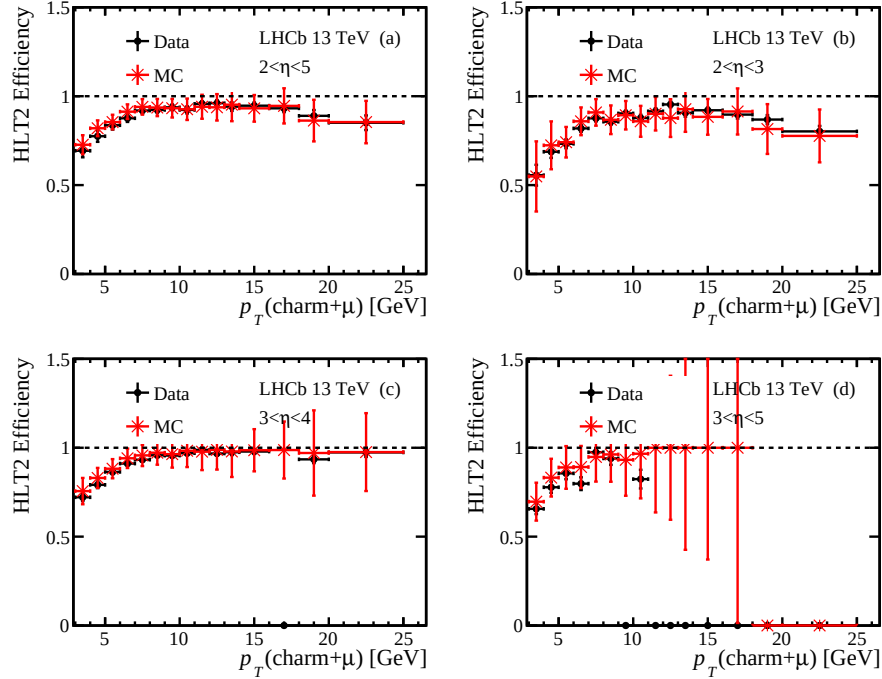


Figure 104: Efficiencies for the HLT2 topological triggers for $D_s^+\mu X$ mode determined using the TISTOS method in signal data compared to efficiencies derived from MC. Uncertainties shown reflect the statistics of the TIS/TOS samples or MC only.

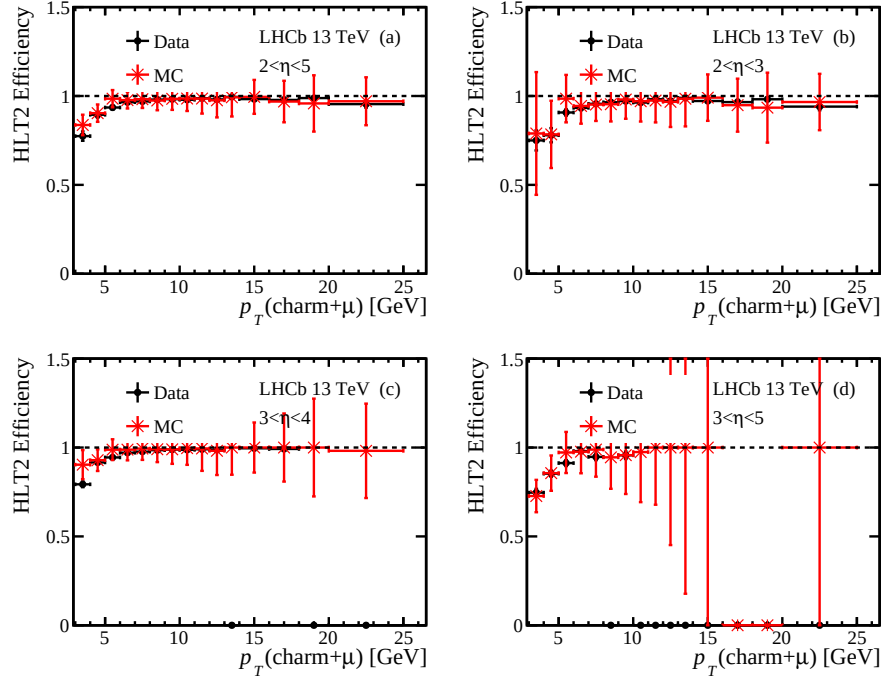


Figure 105: Efficiencies for the HLT2 topological triggers for $\Lambda_c^+ \mu X$ mode determined using the TISTOS method in signal data compared to efficiencies derived from MC. Uncertainties shown reflect the statistics of the TIS/TOS samples or MC only.

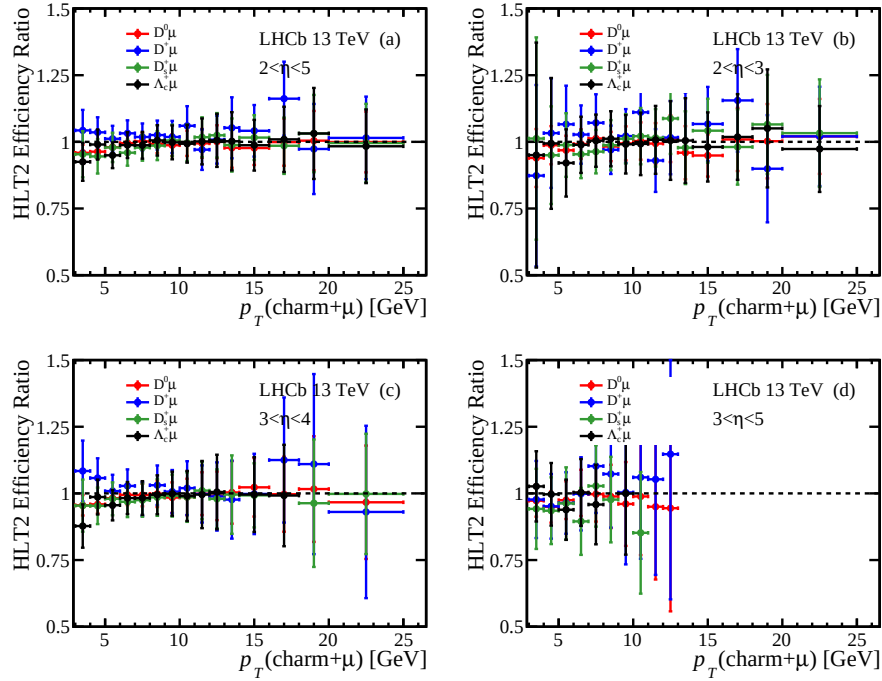


Figure 106: Data/MC efficiency ratios for the HLT2 topological triggers for all charm modes.

6.7.3 Hadron PID efficiencies

This section describes the determination of particle identification (PID) efficiencies for all final state hadrons with PID selections listed in table 28. As it is well known that Monte Carlo cannot be used to determine these efficiencies because the PID variable distributions are discrepant between Monte Carlo and data, data-driven methods are utilized to determine the final hadron efficiencies.

6.7.3.1 Single track efficiencies and mis-ID Before the final PID efficiency per b -hadron is discussed, here first briefly described are the single track efficiencies, e.g., the PID efficiency per Kaon, which come from dedicated *calibration* data samples. Kaon and Pion efficiencies come from $D^{*+} \rightarrow D^0 \pi_s^+$ decays where the D^0 decays into a $K^- \pi^+$ pair, and protons come from a sample of $\Lambda \rightarrow p K \pi$ decays. Backgrounds are subtracted off all calibration samples by using the sWeight method with mass fits.

To take into account the differences in calibration and signal kinematics the efficiencies are determined in a grid of particle momentum, η , and track multiplicity. The intervals in track momentum for pions and protons are (2, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18, 20, 25, 30, 35, 40, 45, 50, 55, 60, 70, 75, 80, 85, 90, 95, 100) [GeV]. For kaons the intervals are (5, 8, 9, 10, 12, 14, 16, 18, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100) [GeV]. For all particles, the intervals in η are (1.5, 3, 3.5, 4, 5) and (0, 250, 500) for track multiplicity.

In addition to studying the efficiencies per track, also studied are the hadron miss-ID rates. Figure 107 shows the Kaon track efficiency for a PID cut of $DLLK > 0$. Figure 108 shows the Pion track efficiency for a PID cut of $DLLK < 0$ and $DLLp < 0$. Finally, Figure 109 shows the proton track efficiency for a PID cut of $DLLp > 10$ and $DLLp - DLLK > 0$.

6.7.3.2 b -hadron PID efficiencies The PID efficiency for a given hadron daughter in a bin of $\eta - p_T(charm + \mu)$ is determined using a *reference* sample with the same kinematics as signal. Data or Monte Carlo before PID selections can be used and in this analysis MC is

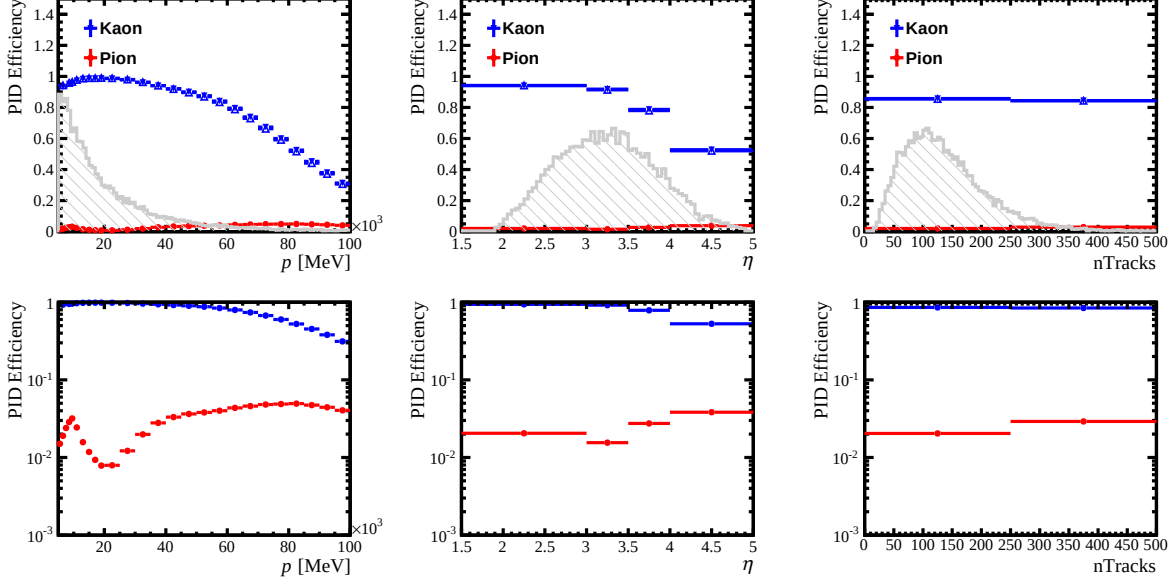


Figure 107: Single track PID efficiencies for kaons with $DLLK > 4$. The blue data points show the efficiency for the kaon for magnet down (closed down triangles) and magnet up (open triangles) data, and the red points show the mis-ID rates for pions. From left to right show the projections in particle momentum, η , and track multiplicity, and in all plots the gray histogram shows the kaon distributions in signal MC. The bottom set of plots show the same data on a log scale.

used. Comparisons between MC and data kinematics can be seen in 153, 161, 169, 173 for the D^0 , D^+ , D_s , and Λ_c daughters, respectfully. The efficiency for a particular $\eta - p_T(charm + \mu)$ bin i is determined as

$$\epsilon_i = \frac{\sum_j N_{i,j} \times \epsilon_j}{N_i}, \quad (59)$$

where N_i is the number of events in $\eta - p_T(charm + \mu)$ bin i without PID selections applied, and $N_{i,j}$ and ϵ_j are the number of events without PID selections and efficiency, respectively, in a bin of hadron kinematics j (i.e, momentum, η , and track multiplicity). It is observed that no difference in magnet polarity so the ϵ_j in the above equation are taken as the average between magnet up and down.

The final b -hadron PID efficiency is determined by multiplying all individual daughter PID efficiencies. Final PID efficiencies can be seen in 110, 111, 112, 113 for the D^0 , D^+ , D_s , and Λ_c modes, respectfully. Uncertainties shown in all PID plots are due to the PIDCalib

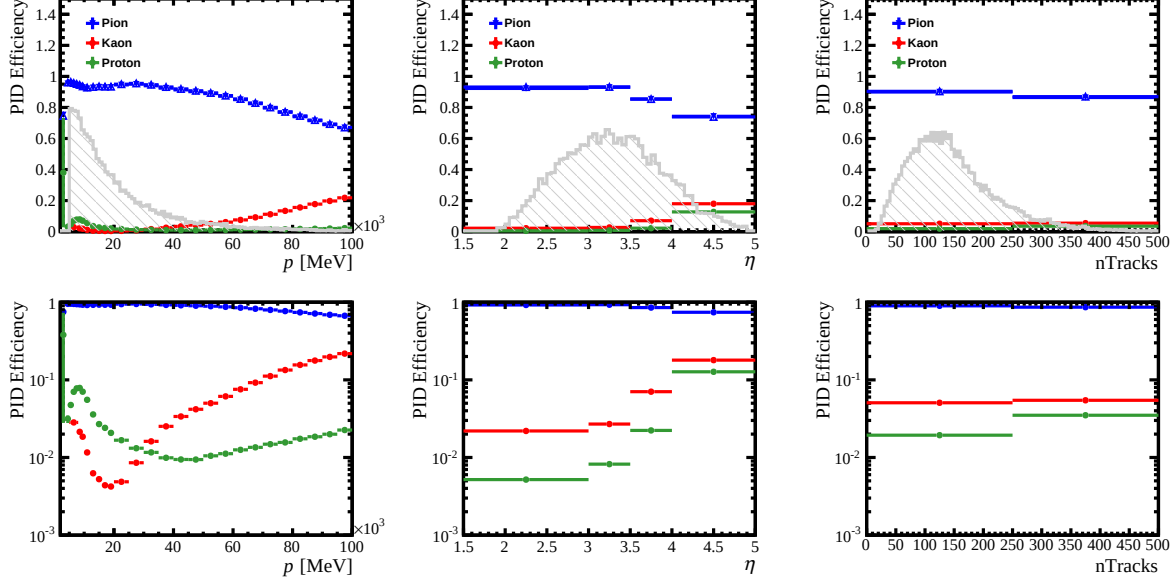


Figure 108: Single track PID efficiencies for pions with $DLLK < 0$ and $DLLp < 0$. The blue data points show the efficiency for the pion for magnet down (closed down triangles) and magnet up (open triangles) data, and the red and green points show the mis-ID rates for kaons and protons, respectively. From left to right show the projections in particle momentum, η , and track multiplicity, and in all plots the gray histogram shows the pion distributions in signal MC. The bottom set of plots show the same data on a log scale.

statistics and systematics, not MC, and are discussed in the Section 6.9. Additionally shown in the plots are the PID efficiencies determined in MC, and PID efficiencies determined by constructing a “PIDCalib-like” efficiency grid using MC and following the same procedure above. Both are used to assign a systematic uncertainty on the choice of PIDCalib track binning.

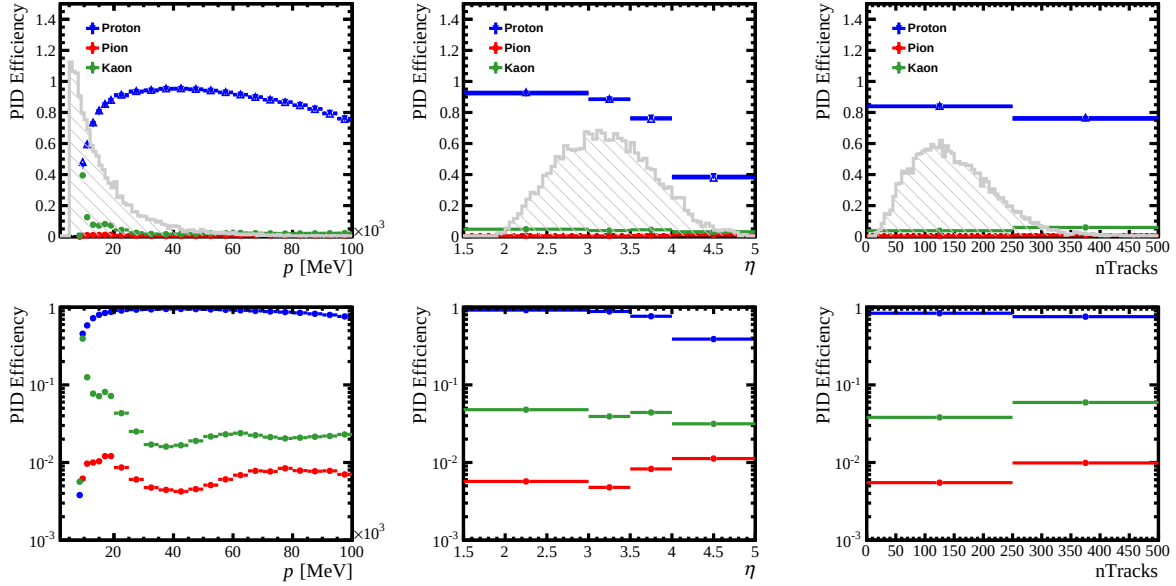


Figure 109: Single track PID efficiencies for protons with $\text{DLLp} > 10$ and $\text{DLLp-DLLK} > 0$. The blue data points show the efficiency for the proton for magnet down (closed down triangles) and magnet up (open triangles) data, and the red and green points show the mis-ID rates for pions and kaons, respectively. From left to right show the projections in particle momentum, η , and track multiplicity, and in all plots the gray histogram shows the proton distributions in signal MC. The bottom set of plots show the same data on a log scale.

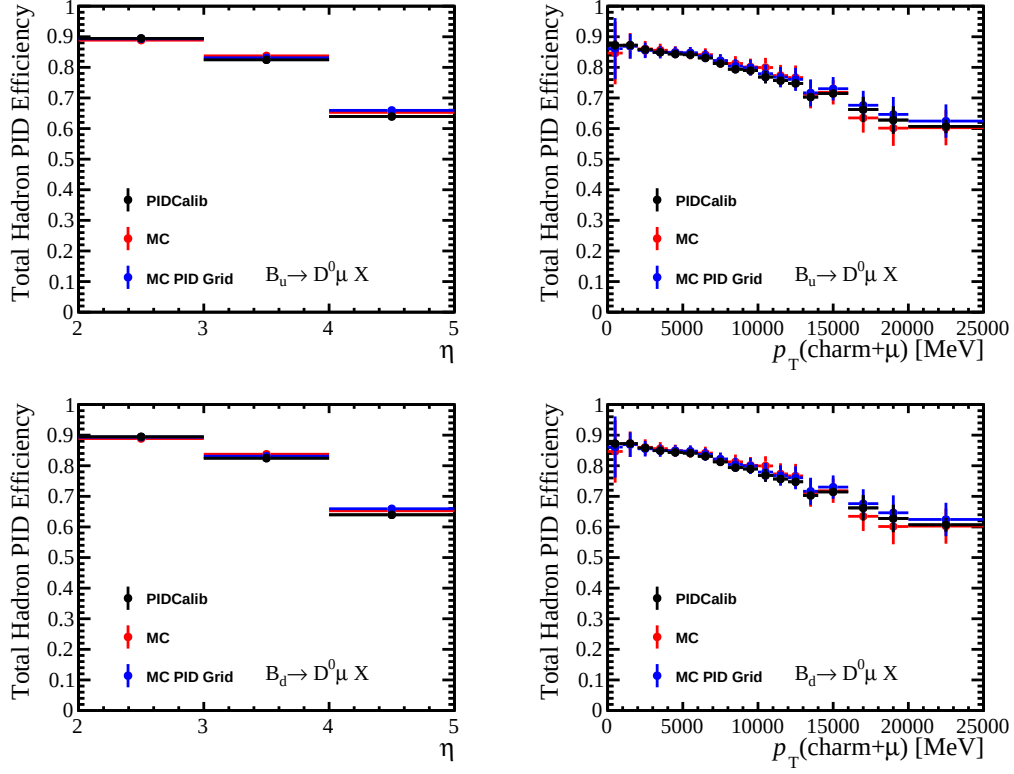


Figure 110: PID efficiency for the $D^0\mu X$ mode as a function of η of the b -hadron and charm+ μ p_T . The black points show the nominal PID efficiencies determined with PIDCalib while the red show MC PID efficiencies and the blue show PID efficiencies calculated in the same manner as the PIDCalib method but with track PID efficiency grids determined with MC. The first two plots correspond to efficiencies using the parent B^+ MC and the second two B^0 MC as reference samples. Black error bars have all systematic uncertainties added in quadrature. Uncertainties due to MC statistics are not included.

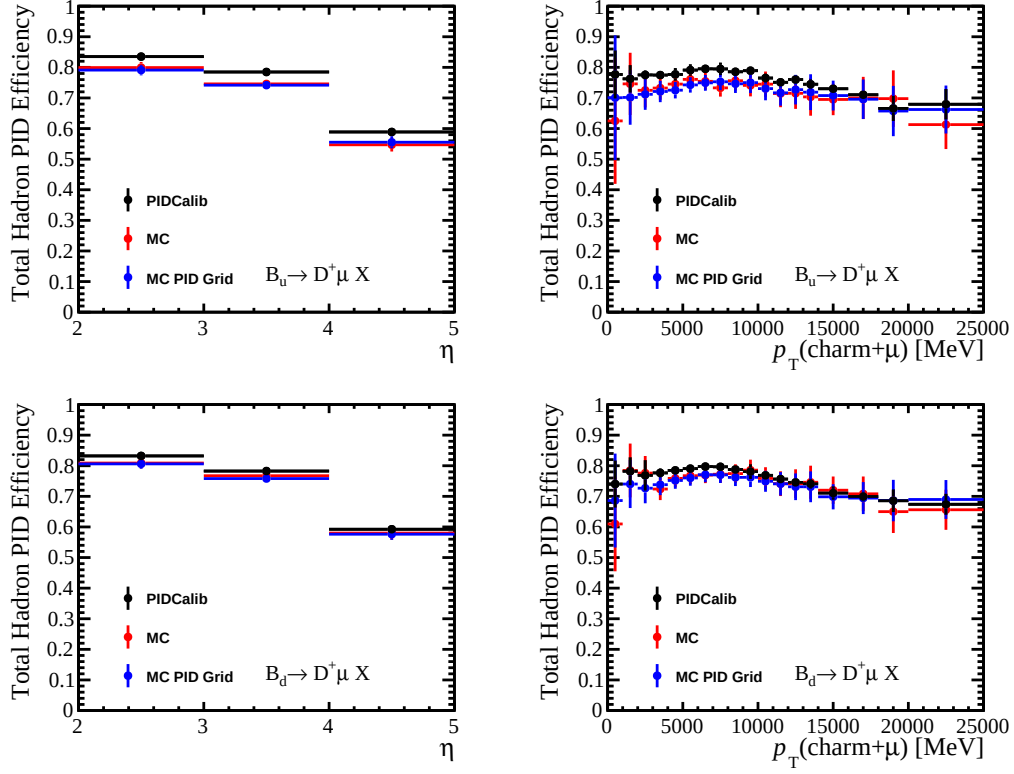


Figure 111: PID efficiency for the $D^+\mu X$ mode as a function of η of the b -hadron and charm+ μ p_T . The black points show the nominal PID efficiencies determined with PIDCalib while the red show MC PID efficiencies and the blue show PID efficiencies calculated in the same manner as the PIDCalib method but with track PID efficiency grids determined with MC. The first two plots correspond to efficiencies using the parent B^+ MC and the second two B^0 MC as reference samples. Black error bars have all systematic uncertainties added in quadrature. Uncertainties due to MC statistics are not included.

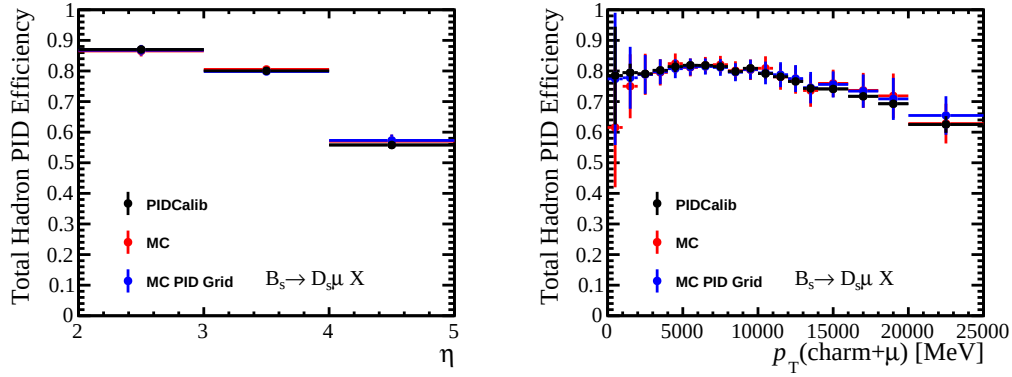


Figure 112: PID efficiency for the $D_s\mu X$ mode as a function of η of the b -hadron and charm+ μ p_T . The black points show the nominal PID efficiencies determined with PIDCalib while the red show MC PID efficiencies and the blue show PID efficiencies calculated in the same manner as the PIDCalib method but with track PID efficiency grids determined with MC. Black error bars have all systematic uncertainties added in quadrature. Uncertainties due to MC statistics are not included.

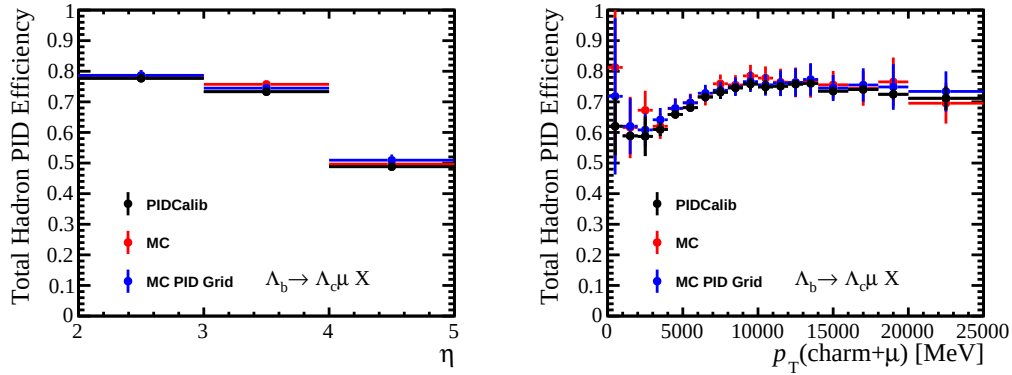


Figure 113: PID efficiency for the $\Lambda_c\mu X$ mode as a function of η of the b -hadron and charm+ μ p_T . The black points show the nominal PID efficiencies determined with PIDCalib while the red show MC PID efficiencies and the blue show PID efficiencies calculated in the same manner as the PIDCalib method but with track PID efficiency grids determined with MC. Black error bars have all systematic uncertainties added in quadrature. Uncertainties due to MC statistics are not included.

6.7.4 Tracking corrections

Tracking efficiencies are not well modeled in MC simulation and therefore the MC samples are corrected with tracking tables provided by the LHCb tracking group, which uses a tag-and-probe approach with $J/\psi \rightarrow \mu\mu$ decays to derive corrections. Muon Long tracks only are used for deriving the correction tables used in this analysis (as opposed to VELO or TT tracks). Figure 114 shows the standard data/MC corrections, in bins of particle momentum and η , in 2016 data. Here muons with a GhostProb less than 0.35 are used whereas in this analysis a cut of less than 0.2 is used. Using the TrackCalib package, new tables are generated with the correct GhostProb cut. Also produced are tables in bins of p_T and η and with a finer binning in η with respect to the standard table. Figure 115 shows these new correction tables in bins of particle p_T and η , and p and η . It should be noted that the choice of binning in η is such that it extends beyond the nominal region (1.9-4.9) as a check. For bins where the statistical uncertainty on the corrections are larger than 10% no corrections are applied to MC and a 5% uncertainty is assigned to tracks residing in that bin. Also shown in Figure 116 shows the 2016 data and MC tracking efficiencies in bins of momentum, η , number of PVs, and number of SPD hits with the tighter GhostProb cut.

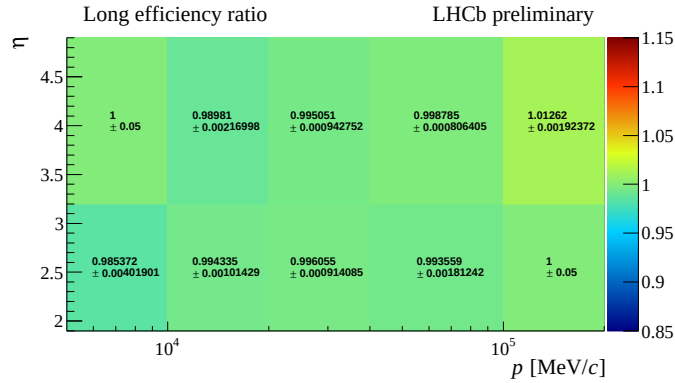


Figure 114: Standard (i.e., GhostProb<0.35 and coarse η binning) Data/MC correction table for 2016 data provided by the LHCb tracking group in bins of particle momentum and η .

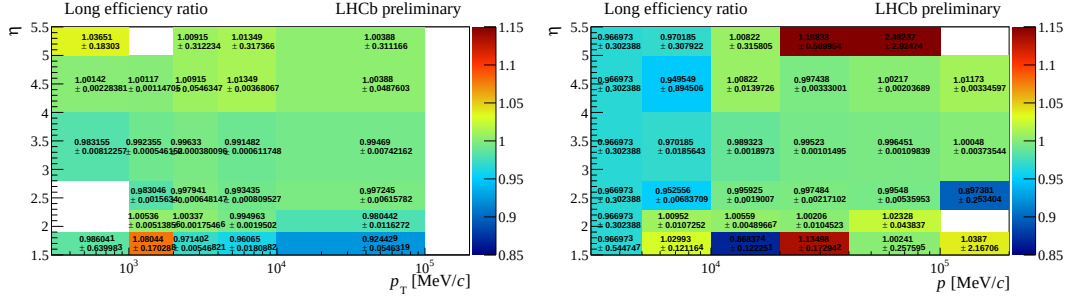


Figure 115: Data/MC correction table for 2016 data in bins of particle transverse momentum and η , and momentum and η , generated using the TrackCalib package. Here a tighter GhostProb cut of less than 0.2 is included.

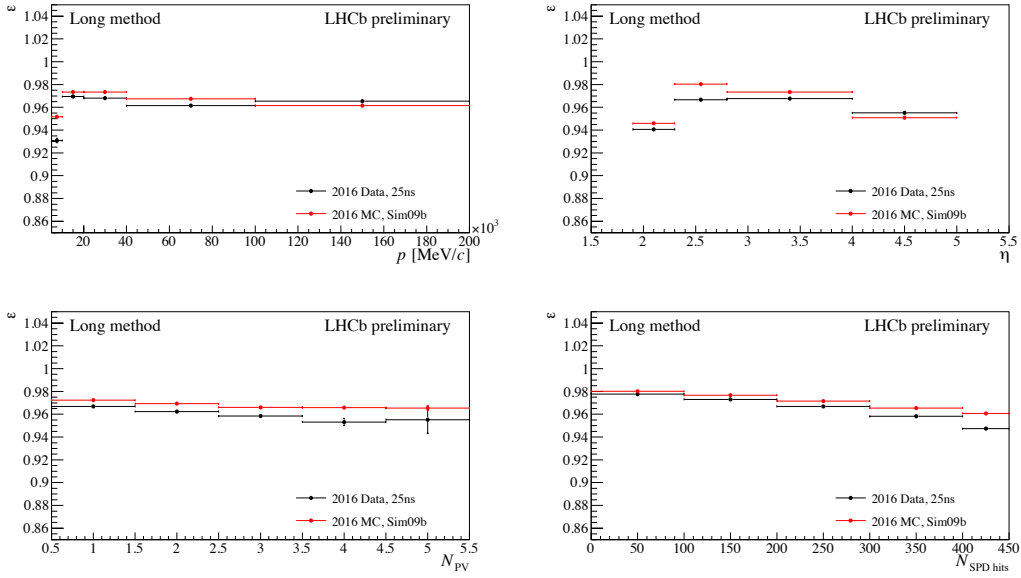


Figure 116: Data and MC tracking efficiencies for 2016 data in bins of particle momentum and η , number of PVs, and number of SPD hits, generated using the TrackCalib package. Here a tighter GhostProb cut of less than 0.2 is included.

6.7.5 Total b -hadron efficiency

Table 38 lists all signal MC samples used in this analysis. For each simulated sample ntuples are saved with the generator level events, which contain only a cut on the θ of the b -hadron to be less than 400mrad, and also the reconstructed and stripped events. These latter reconstructed events are first re-stripped to remove PID and trigger requirements, and are corrected with the tracking tables on a event-by-event basis. In each simulated sample the reconstructed decays are required to be a true signal event by requiring it to pass the $BKGCAT=0$ or 50 ($\parallel 20$ for D_s^+ $\parallel 10$ for Λ_c^+). Efficiencies are then calculated as the ratio of reconstructed and selected events to generated events, in bins of B hadron η and $p_T(charm + \mu)$. Integrated over b kinematics the efficiency after reconstruction and stripping is approximately 11% for all signal modes. After offline selections (no PID and trigger) it is reduced to roughly 5% for D^0 , 3% for D^+ , and 4% for D_s^+ and Λ_c^+ modes.

The overall b -hadron efficiency is calculated as the ratio of MC events, passing all selections and weighted with all data-driven efficiencies, to generated events. Explicitly, in a bin of B kinematics, the efficiency is calculated as

$$\epsilon = \frac{\sum_i n_i^{reco.+sel.} \times W^{track} \times [\epsilon_{trig.+\mu ID}(\eta^{\mu_i}, p_T^{\mu_i}) \times \sum_j \epsilon_{j,PID}(\eta^{hadron_{j,i}}, p^{hadron_{j,i}})]}{N_i^{gen}}. \quad (60)$$

Here the index i just runs over the number of events (generated or selected) in a particular b -hadron kinematic bin, and j runs over all final state hadrons in the event. Here, W^{track} is the product of all final state particle tracking corrections. For $D^0\mu$ and $D^+\mu$ modes we take the average of efficiencies derived using B^0 and B^+ decays. The final b -hadron efficiencies incorporating all inputs are shown in Figure 117 for all final state modes.

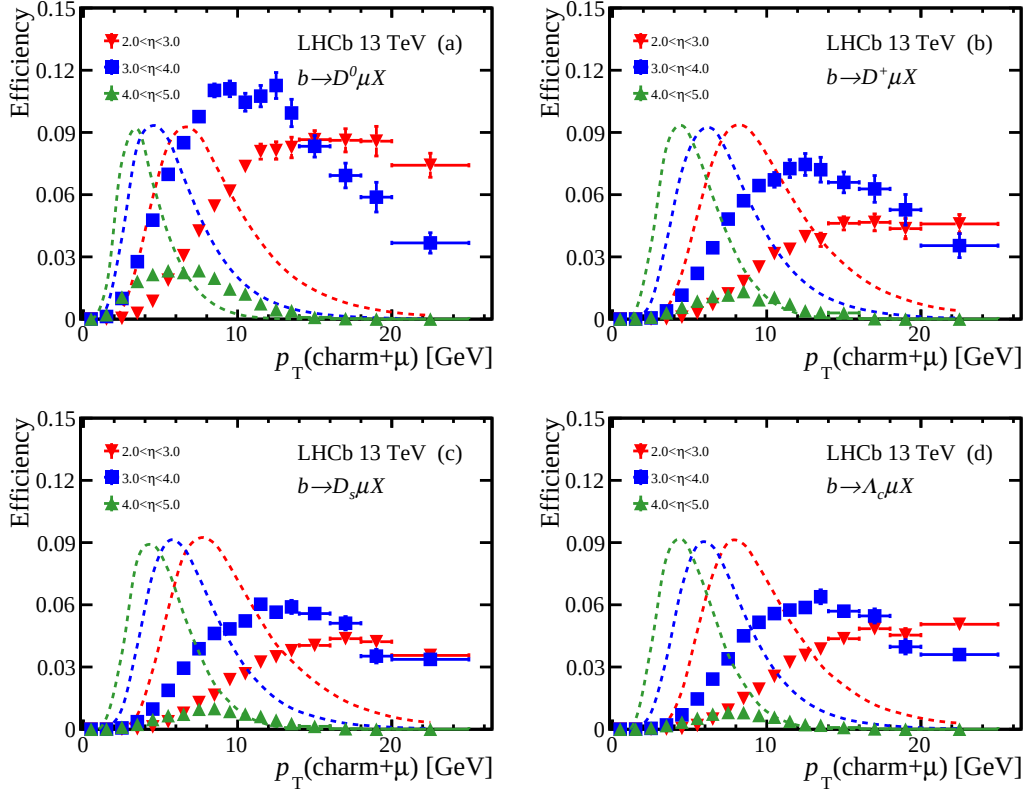


Figure 117: Overall b-hadron efficiencies for the main signal modes in bins of b -hadron η and $p_T(\text{charm} + \mu)$. Shown uncertainties reflect statistics on the MC samples only. The dotted lines show the signal distributions in data with arbitrary normalizations.

6.7.6 Efficiency corrected yields

Figure 118 shows the data corrected with efficiencies derived in the previous section, and as a check additionally shown are the same distributions with MC trigger requirements. This checks that no spurious corrections enter due to the data-driven trigger efficiencies. Figure 119 shows the same distribution integrated over η and normalized. Within uncertainties the normalized distribution of all B mesons agree on shape and the baryon spectrum is softer, as expected.

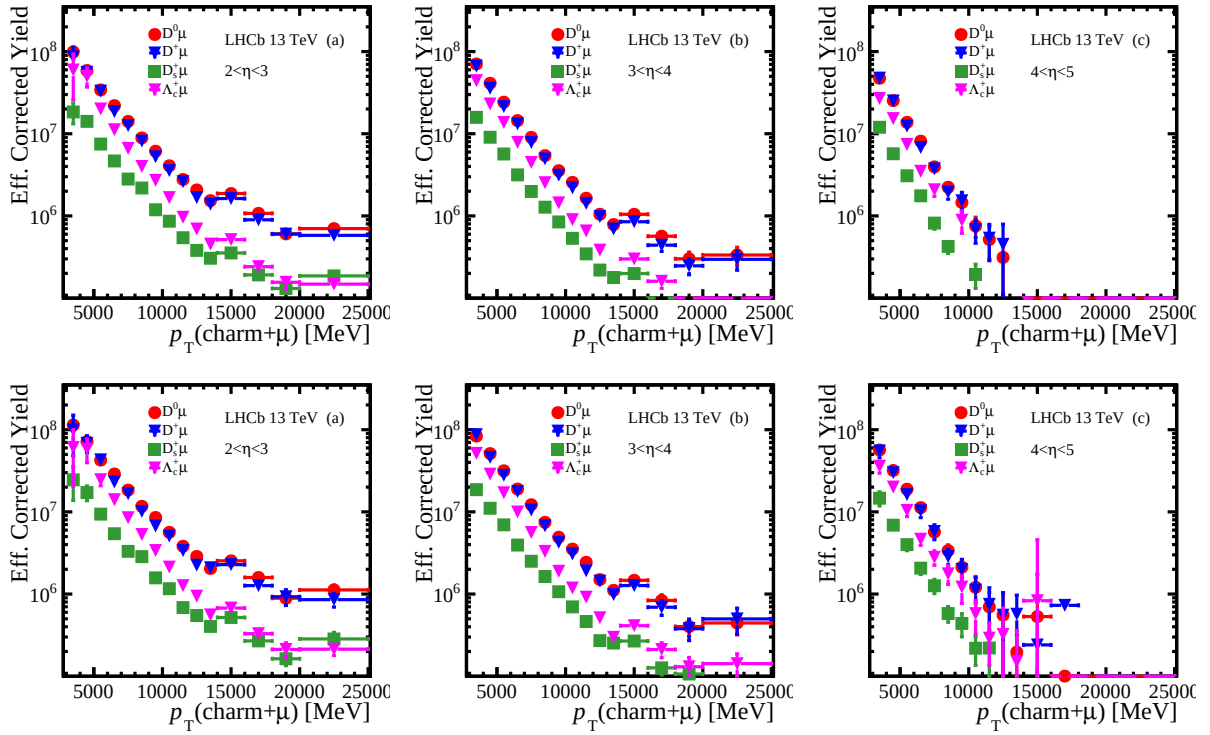


Figure 118: Yields in data corrected with the total efficiencies derived in previous sections. The top plots show the distributions in data corrected with trigger efficiencies determined in data-driven ways where the bottom plots show data corrected with MC trigger efficiencies.

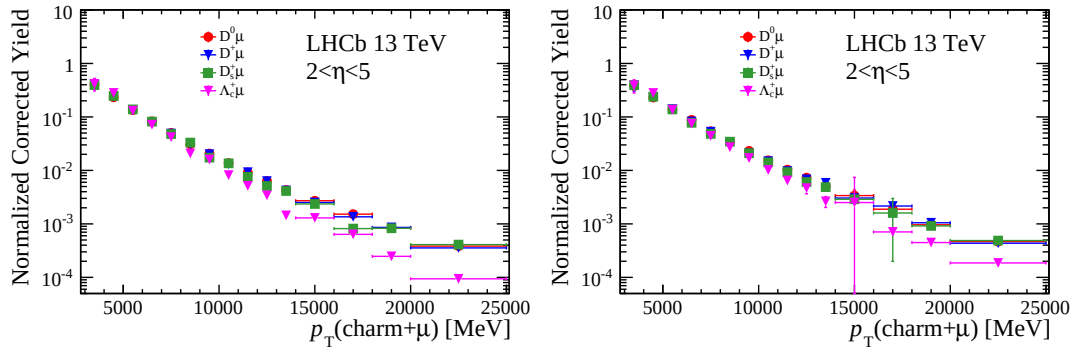


Figure 119: Normalized corrected yields in data integrated over η . The top plot shows the distributions in data corrected with trigger efficiencies determined in data-driven ways where the bottom plot shows data corrected with MC trigger efficiencies.

6.8 k -factor correction

Since the transverse momentum of the b -hadron cannot be determined experimentally due to the missing neutrino, a k -factor correction is applied to data to correct, on average, to the true b -hadron p_T . These corrections allow the comparison between the hadron distributions as a function of p_T of the charmed hadron plus muon and the b -hadron, and with previous 7 TeV LHCb analyses which utilize fully reconstructed b decays.

The k -factor used here is determined from MC simulation, and is defined as

$$k = \frac{p_T^{reco}}{p_T^{true}}, \quad (61)$$

which is different from the conventional momentum ratio, used to typically correct measured lifetime distributions. k -factor corrections are determined as a function of visible hadron plus muon mass which are shown in Figure 120 for the four charm modes. Shown as the black data points in these plots are the average k -factor per bin of visible invariant mass. A fit to the average data is performed with a second order polynomial, and is shown as the red lines. The fitted polynomial function is then used to correct the data and MC on an event-by-event basis. The MC is also corrected with these k -factors because MC studies show using this variable, instead of the B_TRUEPT, in the efficiency calculation better corrects the k -factor data to the true p_T distribution.

The yields in data, determined in bins of k -factor correct p_T (hereby called p_T of the b -hadron), are shown in Figure 121. The HLT2 TISTOS efficiencies are repeated also using k -factor corrected data, and the efficiencies as a function of p_T are shown in Figure 122, along with the HLT2 efficiency determined in MC. The total efficiencies in bins of p_T of the b -hadron are shown in Figure 123.

The systematic uncertainty associated with the k -factor correction is determined by performing toy studies varying the distributions in Figure 120 within their statistical uncertainty, and repeating the polynomial fit and re-calculating the efficiency corrections. The

final distribution of the efficiency calculations using toy polynomial fits are taken as the systematic uncertainty, and are on the order of 0.5% per mode. The k -factor corrections are nearly completely correlated between adjacent p_T bins, and therefore, these uncertainties are applied to the overall scale of the hadron fractions. The affect of varying the higher mass charm hadrons in the MC cocktails produces negligible changes in the final results.

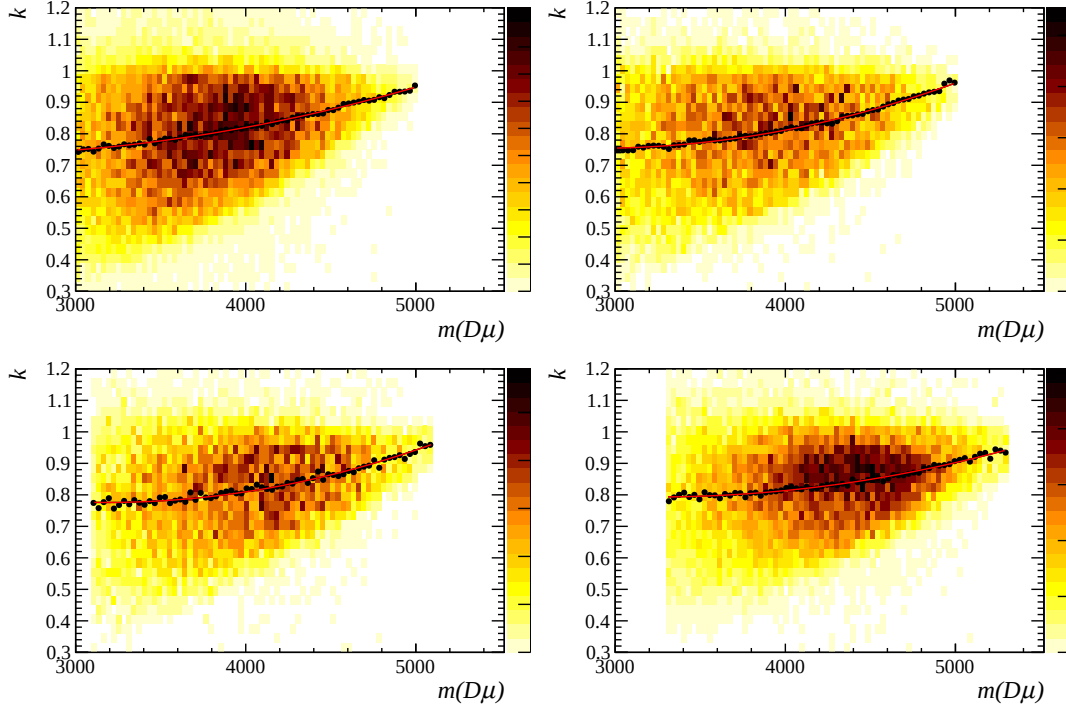


Figure 120: k -factor corrections as a function of visible hadron plus muon mass for the $D^0\mu$ (top left), $D^+\mu$ (top right), $D_s\mu$ (bottom left), and $\Lambda_c\mu$ (bottom right) modes. In all plots the black points are the average k -factor corrections, and the red line shows a polynomial fit to the average data.

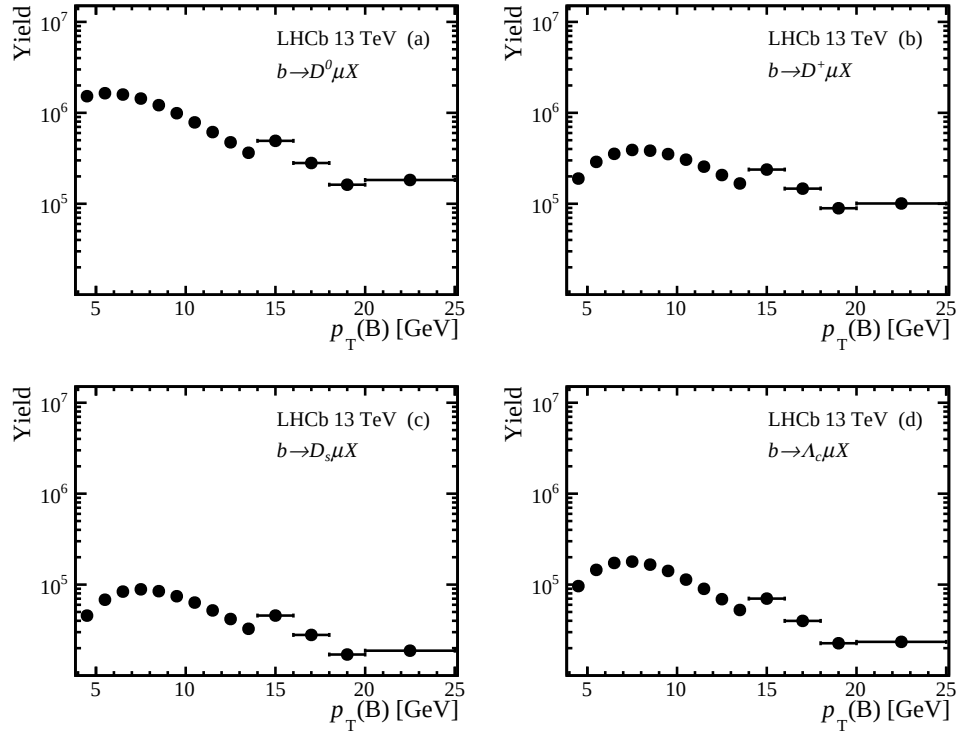


Figure 121: Yields determined in data for the four charm plus muon modes, in bins of p_T of the b -hadron. Note the bin widths are not constant and vary to account for the statistics.

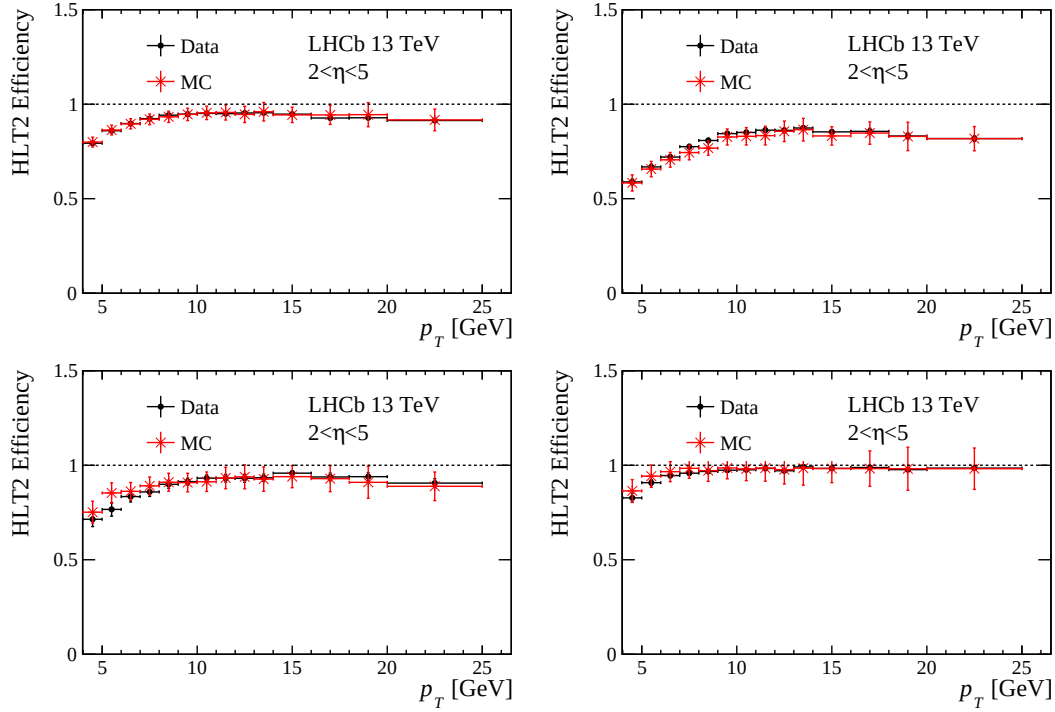


Figure 122: HLT2 TISTOS efficiencies determined in data for the four charm plus muon modes, in bins of p_T of the b -hadron for the $D^0 \mu$ (top left), $D^+ \mu$ (top right), $D_s \mu$ (bottom left), and $\Lambda_c \mu$ (bottom right) modes.

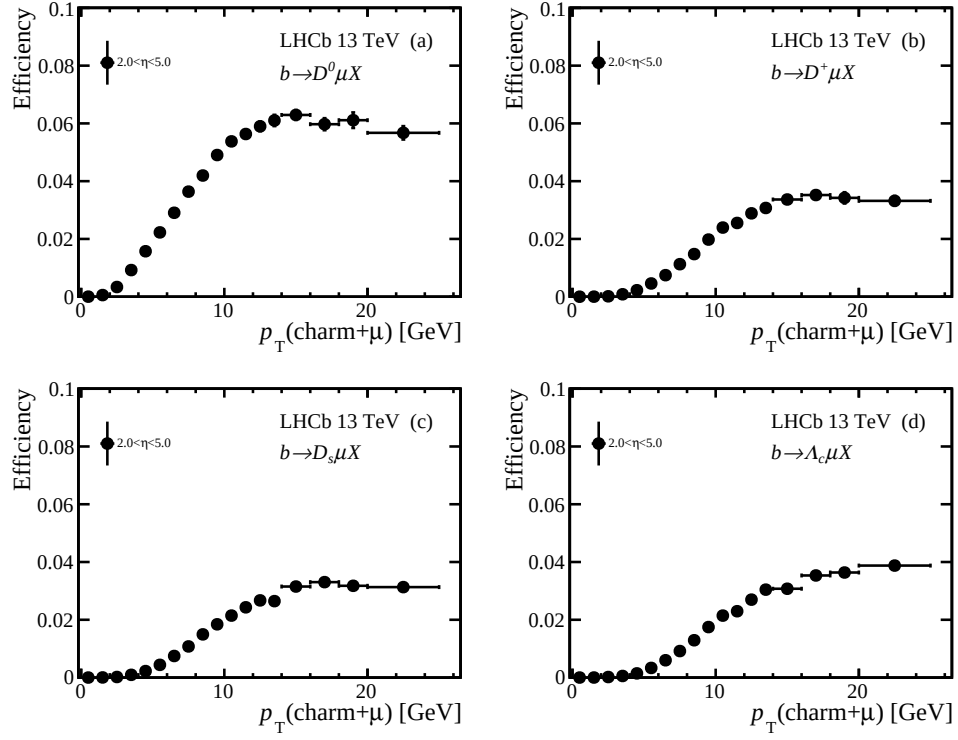


Figure 123: Total efficiencies for the four charm plus muon modes, in bins of p_T of the b -hadron.

6.9 Systematic uncertainties

Described in the sections below are the individual systematic uncertainties. In this section no kinematic correlations between modes are assumed therefore for some uncertainties, namely PID and tracking, the actual values used in the results are smaller. When incorporated into the final results, these correlations are taken into account.

Uncertainties that vary bin-by-bin and that are mostly uncorrelated between bins of b -hadron kinematics are described in the latter sections bellow. Uncertainties that are completely correlated are described first and are referred to as “Global” systematic uncertainties.

6.9.1 Global Systematics

Several sources of systematic uncertainty that don’t vary between bins exist. It is these uncertainties that will affect the overall scale of the ratios and are thus compiled separately.

The first ones are the charm branching fractions. In the f_+/f_0 measurement these are absolute and are in total 2.1%. In $f_s/(f_u + f_d)$ and $f_{\Lambda_b}/(f_u + f_d)$ the uncertainties on the denominator need to be taken according to the relative population of D^0 and D^+ . Therefore, these charm branching fraction uncertainties are weighted by the value of $1-f_+/f_0$ and f_+/f_0 , respectively, when computing the quadrature sum of all systematic uncertainties.

The second source is the lifetime ratios and come from the measured lifetimes and are listed in Table 23.

Thirdly, the uncertainty assigned to the corrections to Γ_{SL} in the B_s and Λ_b cases. This is 50% of the total correction and are 0.5% for f_s and 1.5% for f_{Λ_b} . These are also listed in Table 23.

A fourth source of global uncertainty is due to MC modeling. In the B_s^0 case, this is due to the higher D^* composition in the semileptonic spectrum, and its associated affect on the overall efficiency. This is estimated to be 1% with studies which vary the higher D^* composition in the MC. For f_{Λ_b} , this uncertainty is dominated by the Λ_b MC re-weighting describe in B.2, and is conservatively estimated to be 2.1%.

Table 42: Global systematic uncertainties on f_+/f_0 .

Source	Value [%]
Cross-feeds	0.2
$\mathcal{B}(D^0 \rightarrow K\pi)$	1.3
$\mathcal{B}(D^+ \rightarrow K\pi\pi)$	1.8
Total	2.2

Table 43: Global systematic uncertainties on $f_s/(f_u + f_d)$. It is noted that the D^0 and D^+ BF uncertainties do not add directly in quadrature. This is due to the fact that the denominator is mostly populated with D^0 decays. Therefore the $(1-f_+/f_0)$ and f_+/f_0 values are used to weight D^0 and D^+ uncertainties, respectively, in the total global uncertainty.

Source	Value [%]
MC modeling	1.7
Backgrounds	0.9
Cross-feeds	1.1
$\mathcal{B}(D^0 \rightarrow K\pi)$	1.3
$\mathcal{B}(D^+ \rightarrow K\pi\pi)$	2.1
$\mathcal{B}(D_s^+ \rightarrow KK\pi)$	3.3
Measured lifetime ratio	1.2
Γ_{sl} correction	0.5
Total	4.3

The final uncertainties are due to the background and cross-feed estimations. The fake muon estimations are all negligible and therefore carry no uncertainty. The backgrounds from $b \rightarrow DDX$ backgrounds estimated from MC have uncertainties associated with the relevant BFs used and MC statistics. These are negligible for $D^0\mu$ and $D^+\mu$, and are 0.7% and 0.3% for $D_s^+\mu$ and $\Lambda_c\mu$, respectively. The cross-feed uncertainties come from the uncertainties on the MC samples used to estimate the efficiency ratios needed, the statistics on the cross-feed yields measured in data and where applicable the branching fraction of the cross-feed modes (only relevant for $D_s\mu$ corrections). For the D^0 , D^+ , D_s^+ , and Λ_c modes this amounts to 0.1%, 0.2%, 0.8%, and 0.4%, respectively. To add them together the uncertainties associated with the D^0 and D^+ in the either $f_q/(f_u + f_d)$ denominator, the same weighting method is used as in the case of the charm branching fractions.

A tabulated list of all global systematic uncertainties on f_+/f_0 , $f_s/(f_u + f_d)$, and $f_{\Lambda_b}/(f_u + f_d)$ are given in Tables 42, 43, and 44, respectively.

Table 44: Global systematic uncertainties on $f_{\Lambda_b}/(f_u + f_d)$. It is noted that the D^0 and D^+ BF uncertainties do not add directly in quadrature. This is due to the fact that the denominator is mostly populated with D^0 decays. Therefore the $(1-f_+/f_0)$ and f_+/f_0 values are used to weight D^0 and D^+ uncertainties, respectively, in the total global uncertainty.

Source	Value [%]
Λ_b re-weighting	2.4
Backgrounds	0.3
Cross-feeds	0.4
$\mathcal{B}(D^0 \rightarrow K\pi)$	1.3
$\mathcal{B}(D^+ \rightarrow K\pi\pi)$	2.1
$\mathcal{B}(\Lambda_c^+ \rightarrow pK\pi)$	5.1
Measured lifetime ratio	0.7
Γ_{sl} correction	1.5
Total	6.1

6.9.2 MC statistics

Relative uncertainties from the statistical size of the MC samples used to calculate the efficiencies are shown in Figure 124.

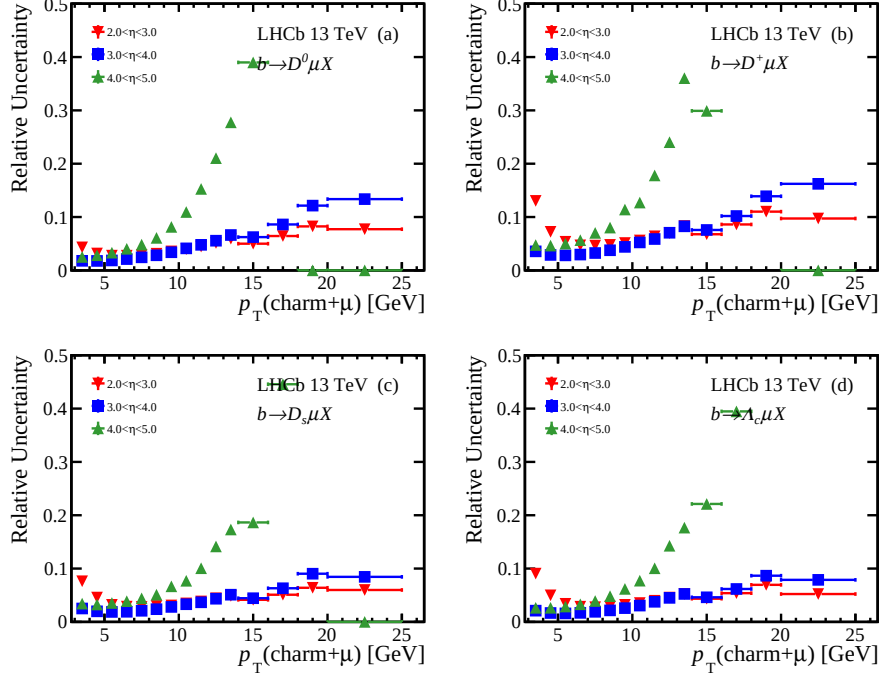


Figure 124: Relative uncertainties from the MC statistics used in the efficiency calculation per b -hadron mode as a function of p_T in three different η regions.

6.9.3 Tracking efficiency

The tracking tables used to correct the MC samples have statistical uncertainties related to the correction factors and this uncertainty is evaluated by performing toy studies. 100 iterations were done with MC where the efficiency was calculated with tracking corrections varied with a Gaussian function within their statistical uncertainties. The final width of this distribution in this toy study was used as the statical uncertainty in the correction tables. This was performed in bins of η and $p_T(\text{charm} + \mu)$ of the b-hadron. Figure 125 shows for example one toy distribution integrated over p_T and η for the $B_s \rightarrow D_s \mu X$ simulated decay.

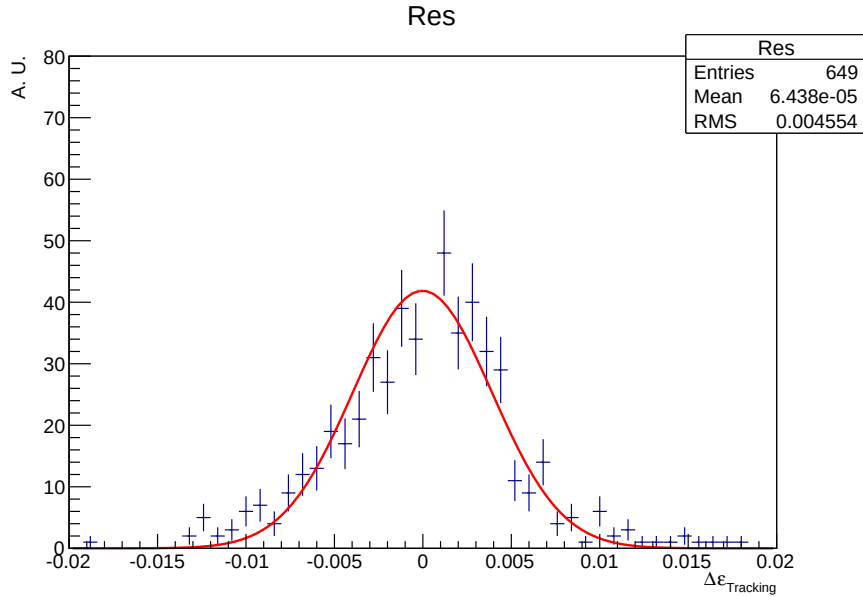


Figure 125: Example toy distribution from varying the tracking efficiencies within their statistical uncertainties for the $B_s \rightarrow D_s \mu X$ integrated over p_T and η .

The second uncertainty is due to hadronic interactions in the detector and a total material uncertainty in MC. The Tracking group calculates this uncertainty for pions and kaons with MC assuming a conservative 10% material uncertainty by calculating the efficiency loss due to hadronic interactions before the T-stations. For pions this adds up to a total 1.4% uncertainty, and kaons, a 1.1% uncertainty. To calculate this uncertainty for protons the studies in [96] are used. In these studies asymmetries in the interaction probabilities in varying thickness of Al. were done for protons, kaons and pions, and compared to experi-

mental data. However, for pions and kaons only interaction probabilities were given for 1mm thick Al. where protons several thicknesses were given. These 1mm interaction probabilities are used to scale up the pion tracking systematic of 1.4% given above for the proton. In the study the pion had an average interaction probability of 0.22% across the momentum region of 10 to 100 GeV. The proton had an average interaction probability of 0.29%, 0.25%, and 0.24% for 10, 20, 100 GeV momenta. The dependence is mostly related to the higher $\bar{p}$ hadronic cross section at lower momentum. Our proton momentum distribution peaks at around 20 GeV and falls off gradually at higher momenta, thus the 20 GeV interaction probability measurement is used as a suitable average. This corresponds to a 16% relative increase in the hadronic interactions for protons with respect to pions and, therefore, a 0.2% absolute increase in the tracking efficiency systematic, for a total of 1.6%. As a check, the same scaling procedure is used to derive an uncertainty for kaons using the 1.4% relative pion uncertainty, and the respective interaction probabilities, and results are 1.02% which is nearly the same as the 1.1% quoted.

6.9.4 Trigger and muon ID

Two systematic uncertainties are considered in the trigger and muon ID efficiencies. The first is the statistical uncertainty from the detached J/ψ calibration samples used for the L0 and HLT1 and muon ID efficiency corrections, and the choice of binning in probe muon kinematics. The statistical uncertainty on the sample is evaluated by performing 100 toy studies per b-hadron mode varying the efficiency corrections with a Gaussian distribution with the width set as the statistical uncertainty. Figure 126 shows for example one toy distribution for the $B_s \rightarrow D_s \mu X$ decay integrated over p_T and η . The second effect is evaluated by determining a 3D muon efficiency grid from the MC sample and recalculating the trigger and muon ID efficiency in the same manner as with data, then comparing to the MC efficiency by just cutting on the MC variables. The uncertainty from the statistics of the sample is all well below 1% for all modes, and the uncertainty due to the muon

binning is a few percent depending on the kinematic bin. The uncertainty from the probe muon binning is unreliable at low p_T because of low MC statistics, so large fluctuations are expected, and is overestimated because the absolute deviation between both methods is quoted as the uncertainty even though both are in agreement within MC statistics. From Figure 100 we derive the overlap in p_T and η of the muons between all modes, in both MC and data. For both MC and data comparisons this overlap is greater than 95%. Therefore, all systematics due to the muon trigger and PID completely correlated between modes and cancel in the final ratios. The second HLT2 trigger uncertainty is due to the statistical size of

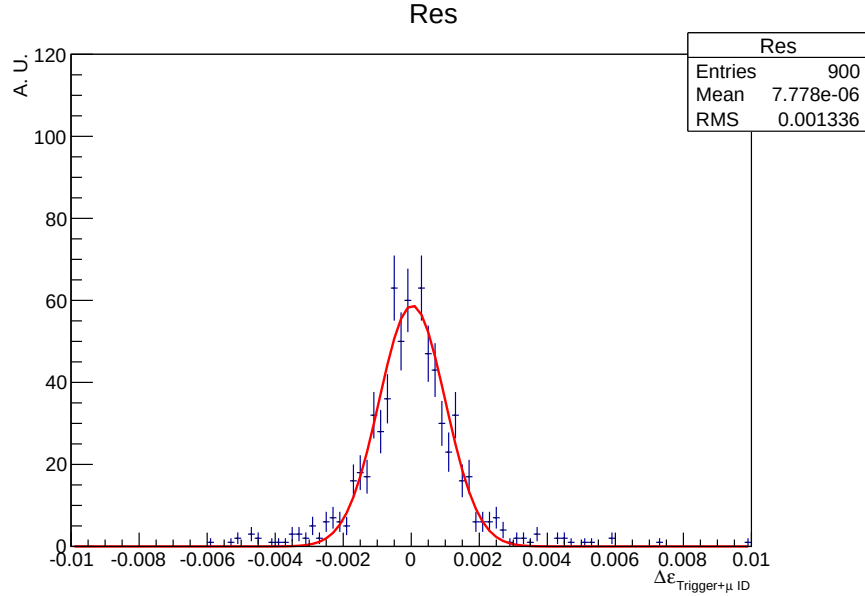


Figure 126: Example toy distribution from varying the trigger and muon ID efficiencies within their statistical uncertainties for the $B_s \rightarrow D_s \mu X$ integrated over p_T and η .

the HLT2TopoMuXBody TIS sample determined by the fits. These range from sub percent to a few 10% depending on the kinematic bin and are propagated to the final result.

6.9.5 Hadron PID

There are several sources of systematic uncertainties: One systematic uncertainty is from the statistical uncertainties of the calibration samples, a second from the choice of binning of track kinematics, and another 0.1% for each track due to the sWeight method used to

subtract background in the calibration samples. To estimate the uncertainty on the statics of the calibration sample 100 toy studies are performed for each mode where randomly varied are all particle efficiencies within a bin of particle momentum, η , and track multiplicity within their statistical uncertainty. The final spread on the total PID efficiency in a given bin of B p_T or η is taken as an uncertainty. These systematic uncertainties are mostly below 0.1% and are at maximum 1.12% in a few kinematic bins. Figure 127 shows for example the toy distributions for the pion, kaon, and proton PID efficiencies integrated over b -hadron kinematics. To determine the uncertainty that comes from the track binning, a study is performed where the PID efficiencies as a function of track kinematics are determined using MC PID variables, and then the overall PID efficiency in bins of b -hadron η and $p_T(charm + \mu)$ is calculated in the same manner as the PIDCalib track efficiencies. Then compared are the overall PID efficiencies by just cutting on the MC PID variables in bins of b -hadron η and $p_T(charm + \mu)$. Deviations between the two methods are assigned as a systematic and are on the order of 1% or less. These are added to the other two uncertainties in quadrature to produce an overall hadron PID uncertainty.

As a systematic check the PIDCalib efficiencies were produced in the default binning, which is finer in track η and nTracks. Propagating these efficiencies to the final result yielded no change in the integrated fraction for the f_s fraction within rounding, and changed the absolute f_{Λ_b} fraction by 0.002, which is well within the uncertainty. No significant changes were seen in the f_s and f_{Λ_b} fit results.

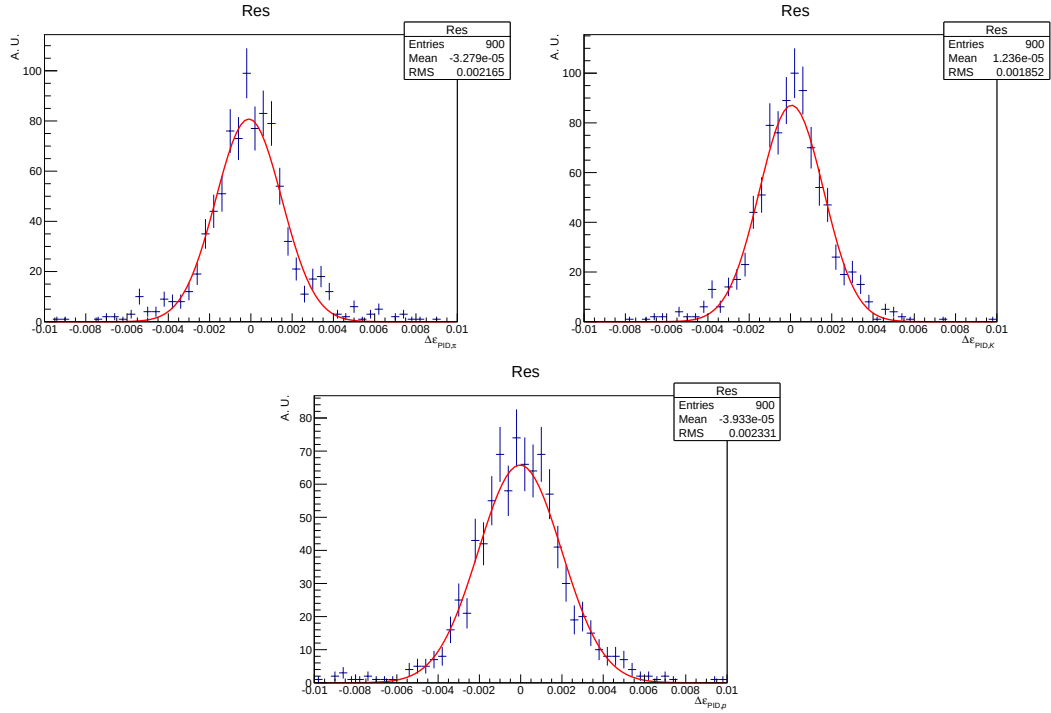


Figure 127: Example toy distributions from varying the PID efficiencies within their statistical uncertainties for the pion (top left), kaon (top right), and proton (bottom), integrated over p_T and η .

6.10 Results

6.10.1 $f_s/(f_u + f_d)$

The ratio $f_s/(f_u + f_d)$, as a function b -hadron kinematics are shown in Figure 128. A slight trend is seen as a function of $p_T(charm + \mu)$ while no trend as a function of η is evident. The individual projections shown in Figure 129, with the values in bins of p_T are calculated by taking a weighted average over the η values, and the η projection is generated by taking an average of the p_T values. Here the data shown as a function η are only for the $p_T(charm + \mu)$ region 3 to 14 GeV. This is done because in the region of $4 < \eta < 5$ there are no data above a p_T of 16 GeV. In these plots the black error bars include all bin-by-bin statistical and systematic uncertainties described in Sec 6.9. The blue error bars shows the bin-by-bin uncertainties added in quadrature with the global uncertainties, also listed in Sec 6.9. In the $p_T(charm + \mu)$ distribution the bin centers are the average $p_T(charm + \mu)$ of the B_s and $B^{0/-}$ determined from generator level MC.

The 7 TeV hadronic determination of f_s/f_d in Ref. [88] reports also a similar trend as a function of p_T of the B_s^0 hadron. They measure

$$f_s/f_d = (0.256 \pm 0.020) + (-2.0 \pm 0.6) \times 10^{-3}/\text{GeV} \times (p_T - \langle p_T \rangle), \quad (62)$$

where p_T is the transverse momentum of the b -hadron in GeV and $\langle p_T \rangle$ is an average p_T value of 10.4 GeV. Here the fit results are scaled to combined hadronic+semileptonic average (See Ref. [86] for the semileptonic results) reported in the paper. The pure hadronic average is $f_s/f_d=0.238$ (in any fit result comparison this number is used and not the reported average).

A linear χ^2 fit to the $p_T(charm + \mu)$ distribution is performed incorporating a full covariance matrix which takes into account the bin-by-bin correlations introduced from the kaon kinematics, and PID and tracking systematic uncertainties. The correlation matrix from the kaon with the same charge as the decays D_s is shown in Figure 130 (The pion and

opposite-sign kaon cancel in the ratio). The fit result is shown in Figure 131 and is

$$\frac{f_s}{f_u + f_d} = A \cdot [(0.124 \pm 0.002) + (-1.12 \pm 0.40) \cdot 10^{-3} \times \frac{p_T - \langle p_T \rangle}{1 \text{ GeV}}], \quad (63)$$

where the p_T is the charm-muon p_T in GeV, and $\langle p_T \rangle$ is the average measured $D_s\mu$ p_T , and is 8.46 GeV. The fit $\chi^2/\text{ndof} = 5.0/12$. The uncertainties on the constant and slope uncertainty contain all correlated bin-by-bin uncertainties. The pre-factor $A = 1.000 \pm 0.043$ and accounts for the global uncertainty. The correlation coefficient between the two fit parameters is 0.03. The solid gray uncertainty bands shown in Figure 131 are generated by producing toy datasets with the fit result, where the parameters are randomly varied within their uncertainties with a Gaussian. To take into account the correlation between the randomly generated variables, a Cholesky decomposition of the full covariance matrix is calculated using the NumPy package and dotted with the randomly generated error array to produce the shift in the central values in each toy iteration. The 1-sigma of the toy distribution in each p_T interval is used to set the upper and lower uncertainty limits of the fit. These limits do not contain the overall global uncertainty of the fractions, only bin-by-bin errors. The dotted lines show the total (bin-by-bin + global) uncertainties on the fit added in quadrature.

Performing the same fit to the k -factor corrected data in bins of p_T of the b -hadron, shown in Figure 132, the resulting parameters are

$$\frac{f_s}{f_u + f_d} = A \cdot [(0.119 \pm 0.001) + (-0.91 \pm 0.25) \cdot 10^{-3} \times \frac{p_T - \langle p_T \rangle}{1 \text{ GeV}}]. \quad (64)$$

Here $\langle p_T \rangle$ is the average measured B_s p_T , and is 10.1 GeV. The pre-factor has the definition as before. The correlation coefficient between the fit parameters is 0.20, and the uncertainty bands shown in Figure 132 are generated in the same way as for the charm+muon p_T fit. The fit $\chi^2/\text{ndof} = 9.2/11$.

To derive an average the yields in the numerator and denominator are integrated between

the $p_T(B)$ limits of 4 to 25 GeV. The result is

$$\frac{f_s}{f_u + f_d} = 0.122 \pm 0.006, \quad (65)$$

where the uncertainty contains both statistical and systematic sources. The total relative uncertainty is 4.8%.

The 7 TeV hadron fit and average (scaled by a factor of 0.5) from Ref. [88], and the average from Ref. [86] with the central value scaled to take into account updated charm branching fractions and b -hadron lifetimes, is plotted in Figure 133 with the data analyzed here.

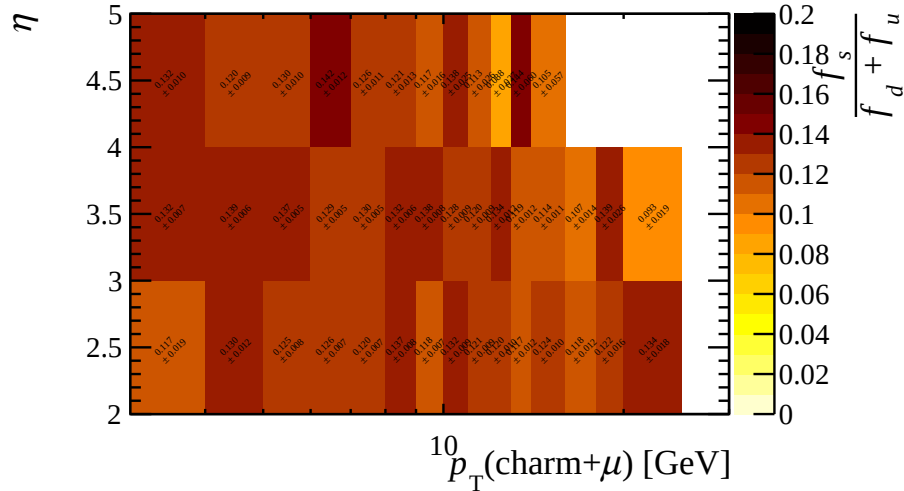


Figure 128: Values for $f_s/(f_u + f_d)$ in the 2-dimensional grid of $p_T(charm + \mu)$ and η . The uncertainties quoted show the bin-by-bin uncertainties only.

6.10.2 $f_{\Lambda_b}/(f_u + f_d)$

The results for $f_{\Lambda_b}/(f_u + f_d)$ are shown in Figure 134 as a function of b -hadron η and $p_T(charm + \mu)$. The data show a strong dependence on $p_T(charm + \mu)$ and no dependence on η within uncertainties. Figure 135 shows the two projections, calculated in the same way as the f_s case. In these plots the black error bars include all bin-by-bin statistical and systematic uncertainties described in Sec 6.9. In the $p_T(charm + \mu)$ distribution the bin

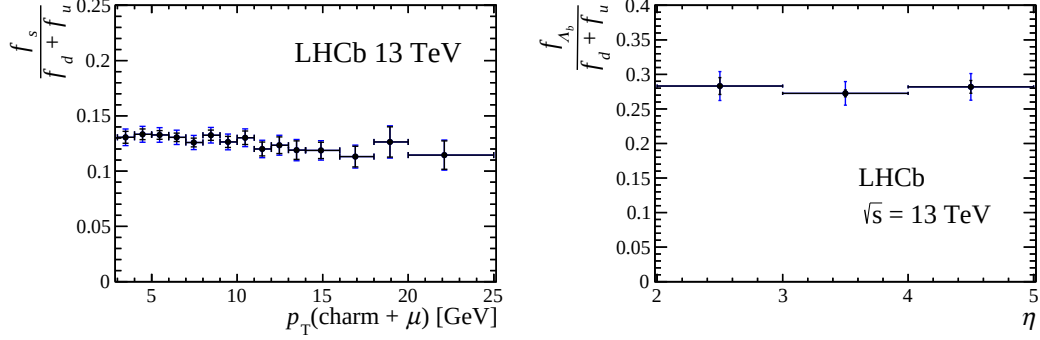


Figure 129: Values for $f_s/(f_u + f_d)$ in bins of $p_T(\text{charm} + \mu)$ (left) and η (right). The black error bars show the combined bin-by-bin statistical and systematic uncertainties, and the blue ones show the global systematics added in quadrature.

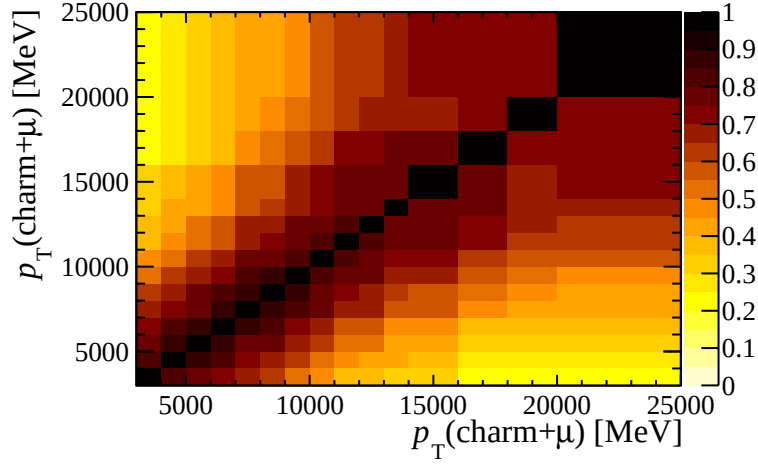


Figure 130: Correlation matrix induced by the same-sign kaon kinematics in D_s^+ decays in bins of $p_T(\text{charm} + \mu)$. The z -axis depicts the correlation coefficient.

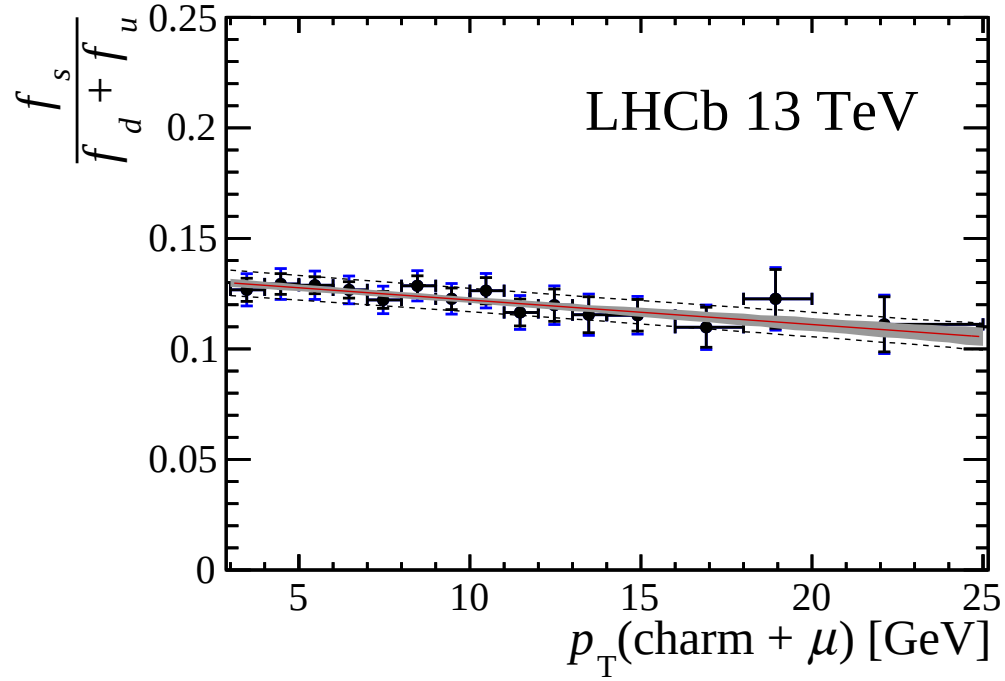


Figure 131: Values of $f_s/(f_u + f_d)$ in bins of $p_T(\text{charm} + \mu)$. The black error bars show the combined bin-by-bin statistical and systematic uncertainties, and the blue ones show the global systematics added in quadrature. A fit to the data is shown as the red solid line and the shaded area give the ± 1 sigma uncertainty limits on the fit result. The dotted lines show the bin-by-bin uncertainties on the fit added in quadrature with the global uncertainties.

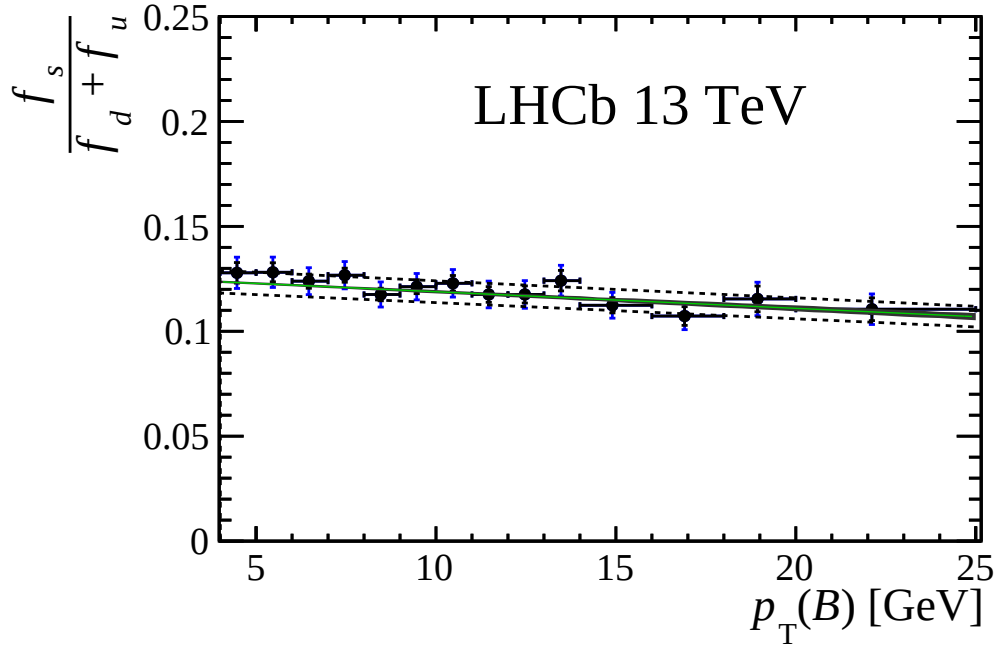


Figure 132: Values of $f_s/(f_u + f_d)$ in bins of $p_T(B)$. The black error bars show the combined bin-by-bin statistical and systematic uncertainties, and the blue ones show the global systematics added in quadrature. A fit to the data is shown as the green solid line and the shaded area give the ± 1 sigma uncertainty limits on the fit result. The dotted lines show the bin-by-bin uncertainties on the fit added in quadrature with the global uncertainties.

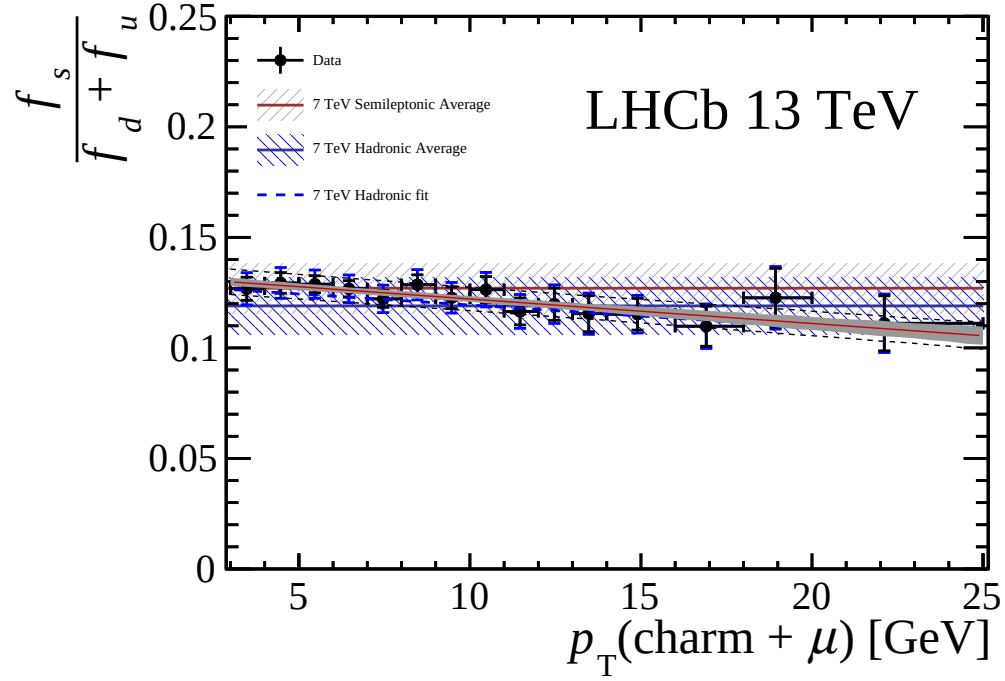


Figure 133: Values for $f_s/(f_u + f_d)$ in bins of $p_T(charm + \mu)$. The black error bars show the combined bin-by-bin statistical and systematic uncertainties, and the blue ones show the global systematics added in quadrature. The red line is the fit to the data, and upper and lower dashed lines give the ± 1 sigma uncertainty limits on the fit result. The dotted lines show the bin-by-bin uncertainties on the fit added in quadrature with the global uncertainties. The dark blue line with hashed error band shows the average 7 TeV hadronic value and the red shows the average 7 TeV semileptonic value. The dashed blue line shows the fit performed in the updated hadronic paper with the data scaled to include the hadronic+semileptonic averages.

centers are the average $p_T(\text{charm} + \mu)$ of the Λ_b and $B^{0/-}$ determined from generator level MC. Here the data shown as a function η are only for the $p_T(\text{charm} + \mu)$ region 3 to 14 GeV. This is done because in the region of $4 < \eta < 5$ there are no data above a p_T of 14 GeV.

A χ^2 fit to the $p_T(\text{charm} + \mu)$ distribution incorporating a full covariance matrix is done in the same manner as the f_s fraction above. However, here the proton correlations are taken into account, and the kaon and pion cancel in the ratio. The correlation matrix from the proton is shown in Figure 136. The function used in a fit is a constant plus an exponential term and is motivated by the 7 TeV hadron determination of f_{Λ_b}/f_d in Ref. [89]. Explicitly:

$$f = a + \exp[b + c \times \frac{p_T}{1 \text{ GeV}}], \quad (66)$$

with a, b , and c being the free parameters. The fit result is shown in Figure 137 and the result of the fit function is

$$\frac{f_{\Lambda_b}}{f_u + f_d} = A \cdot [(8.1 \pm 2.3) \cdot 10^{-2} + \exp[(-1.01 \pm 0.04) + (-0.102 \pm 0.018) \times \frac{p_T}{1 \text{ GeV}}]], \quad (67)$$

where p_T is the charm plus muon p_T in GeV. The fit $\chi^2/\text{ndof} = 9.8/11$. The the uncertainties on all the terms have all correlated bin-by-bin uncertainties included. The pre-factor $A = 1.000 \pm 0.061$ and accounts for the global systematic uncertainties. The correlation matrix of the fit parameters is (with the parameter array [a,b,c])

$$C = \begin{pmatrix} 1 & -0.06 & -0.96 \\ -0.06 & 1 & 0.21 \\ -0.96 & 0.21 & 1 \end{pmatrix} \quad (68)$$

The uncertainty bands shown in Figure 137 are generated in the same way as for the f_s case described in the above section.

The same fit is performed also to the k -factor corrected data. Figure 132 shows this fit.

The resulting parameters are

$$\frac{f_{\Lambda_b}}{f_u + f_d} = A \cdot [(7.93 \pm 1.41) \cdot 10^{-2} + \exp[(-1.022 \pm 0.047) + (-0.107 \pm 0.002) \times \frac{p_T}{1 \text{ GeV}}]]. \quad (69)$$

A is the same as above and the fit $\chi^2/\text{ndof} = 11/10$. The correlation matrix for this fit is

$$C = \begin{pmatrix} 1 & 0.40 & -0.95 \\ 0.40 & 1 & -0.63 \\ -0.95 & -0.63 & 1 \end{pmatrix} \quad (70)$$

The uncertainty bands shown in Figure 138 are generated in the same way as for the f_s case described in the above section.

To derive an average the yields in the numerator and denominator are integrated between the $p_T(B)$ limits of 4 to 25 GeV. The result is

$$\frac{f_{\Lambda_b}}{f_u + f_d} = 0.259 \pm 0.018, \quad (71)$$

where the uncertainty contains both statistical and systematic sources.

Figure 139 shows these results along with the 7 TeV semileptonic values [86], scaled to take into account the updated $\Lambda_c \rightarrow pK\pi$ branching fraction and b -hadron lifetimes, and the 7 TeV hadronic fit scaled by a factor of 0.5.

6.10.3 f_+/f_0

As a systematic check of the analysis method, and a useful measurement to test the knowledge of known semileptonic branching fractions and extrapolations used to saturate the unknown portion of the inclusive hadron spectrum, the ratio $f_+/f_0 \equiv n_{corr}(D^+\mu)/n_{corr}(D^0\mu)$ is measured in the same kinematic binning as the hadron fractions. Here the definition of $n_{corr}(D\mu)$ is given in Eqs. 47 and 48.

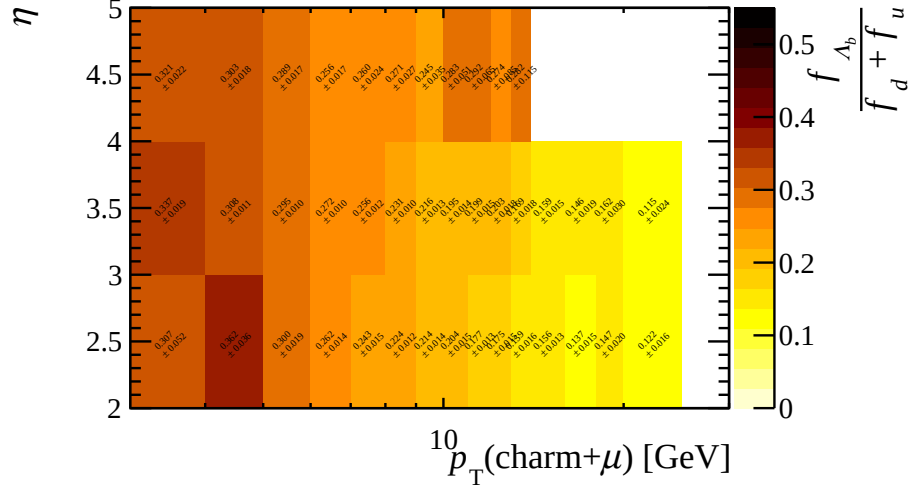


Figure 134: Values for $f_{\Lambda_b}/(f_u + f_d)$ in the 2-dimensional grid of $p_T(\text{charm} + \mu)$ and η . The uncertainties quoted show the bin-by-bin uncertainties only.

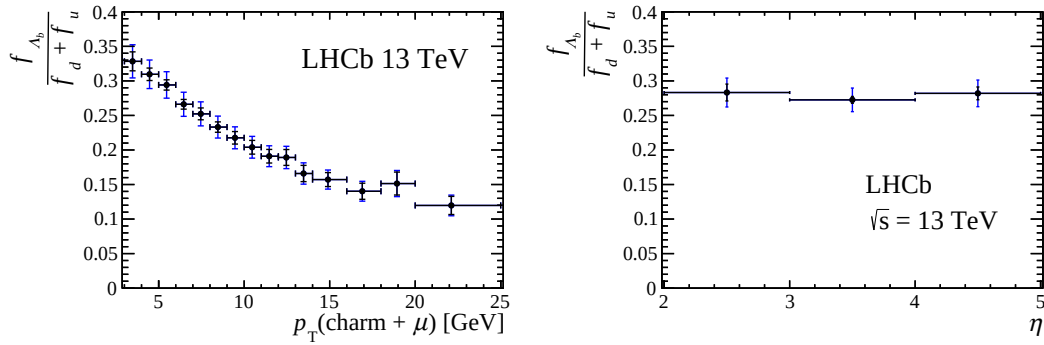


Figure 135: Values for $f_{\Lambda_b}/(f_u + f_d)$ in bins of $p_T(\text{charm} + \mu)$ (left) and η (right). The black error bars show the combined bin-by-bin statistical and systematic uncertainties, and the blue ones show the global systematics added in quadrature.

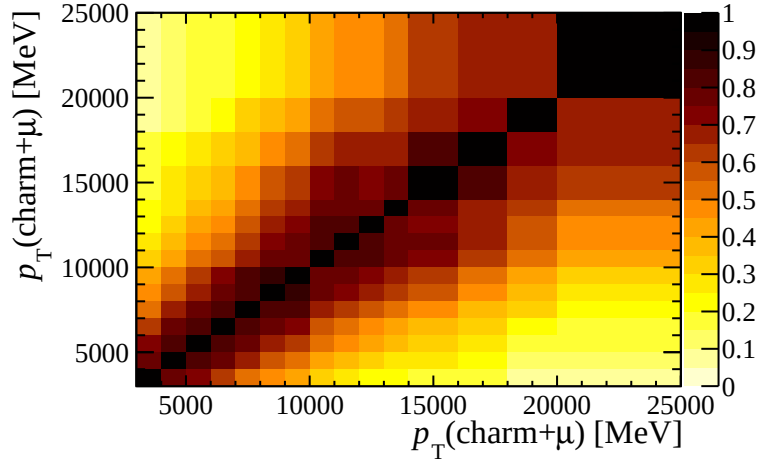


Figure 136: Correlation matrix induced by the proton kinematics in bins of $p_T(\text{charm} + \mu)$. The z -axis depicts the correlation coefficient.

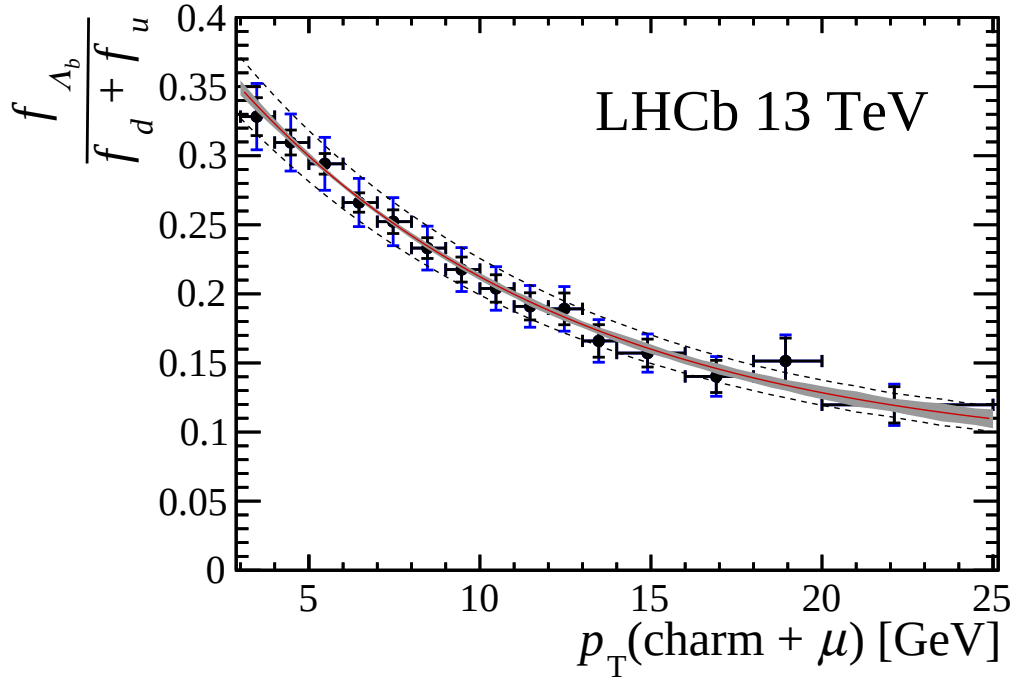


Figure 137: Values of $f_{\Lambda_b}/(f_u + f_d)$ in bins of $p_T(\text{charm} + \mu)$. The black error bars show the combined bin-by-bin statistical and systematic uncertainties, and the blue ones show the global systematics added in quadrature. A fit to the data is shown as the red solid line and the shaded area give the ± 1 sigma uncertainty limits on the fit result. The dotted lines show the bin-by-bin uncertainties on the fit added in quadrature with the global uncertainties.

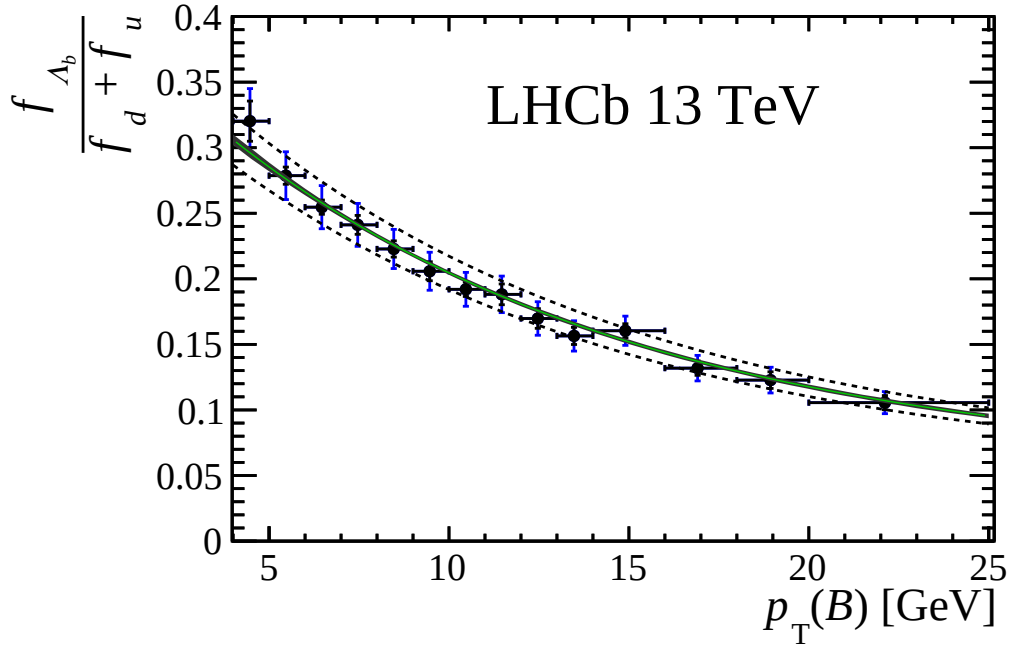


Figure 138: Values of $f_{\Lambda_b}/(f_u + f_d)$ in bins of $p_T(B)$. The black error bars show the combined bin-by-bin statistical and systematic uncertainties, and the blue ones show the global systematics added in quadrature. A fit to the data is shown as the green solid line and the shaded area give the ± 1 sigma uncertainty limits on the fit result. The dotted lines show the bin-by-bin uncertainties on the fit added in quadrature with the global uncertainties.

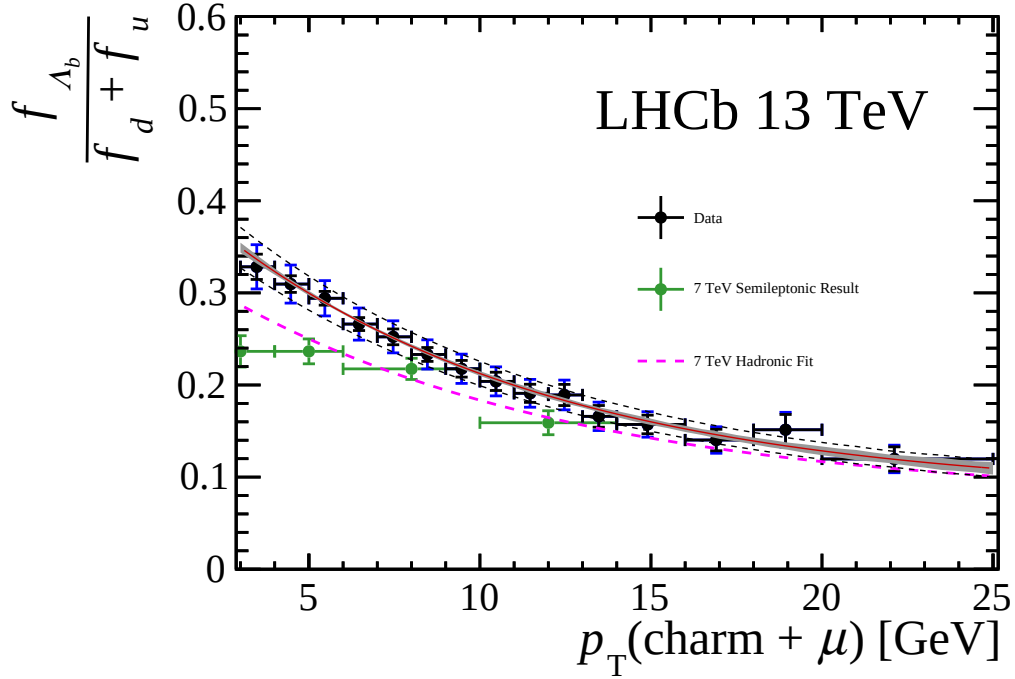


Figure 139: Comparisons of $f_{\Lambda_b}/(f_u + f_d)$ in bins of $p_T(charm + \mu)$ with the 7 TeV analysis. The black data points show the 13 TeV data and the black error bars show the combined bin-by-bin statistical and systematic uncertainties, and the blue ones show the global systematics added in quadrature. The red line is the fit to the data, and upper and lower dashed lines give the ± 1 sigma uncertainty limits on the fit result. The dotted lines show the bin-by-bin uncertainties on the fit added in quadrature with the global uncertainties. The green data points show the scaled 7 TeV semileptonic results, and the magenta dashed line shows the 7 TeV hadronic fit.

Assuming $f_u = f_d$, Reference [93] gives the expected fraction of $D^+\mu$ with respect to $D^0\mu$ from $B^{+/0}$ decays as $0.387 \pm 0.012(\text{exp.}) \pm 0.027(\text{syst.})$. The first uncertainty comes from the uncertainties on known measurements. The second uncertainty comes from the different extrapolations used to saturate the remaining portion of the inclusive rate, thus this uncertainty is an envelope of all possible solutions for f_+/f_0 depending on which extrapolation is used.

Figure 140 shows f_+/f_0 in bins of transverse momentum and η measured in 2016 data. Here, values shown on each 1-dimensional axis are weighted averages over the second variable. The black error bars include all bin-by-bin statistical and systematic uncertainties described in Sec 6.9. The blue error bars shows the bin-by-bin uncertainties added in quadrature with the global uncertainties, also listed in Sec 6.9. Figure 141 shows f_+/f_0 in bins of b -hadron transverse momentum via a k -factor correction.

To derive an overall value for f_+/f_0 , the $p_T(\text{charm} + \mu)$ distribution is fit to a constant. It has been checked that the kinematic distributions of the kaon on same-sign pion overlap in each p_T bin therefore the uncertainties associated with the PID and tracking cancel in the ratio. Therefore only the PID and tracking uncertainties on the second pion in the D^+ decay are considered. These uncertainties are also correlated between bins as the pion kinematics are similar in adjacent p_T bins. Figure 142 shows the correlation matrix for the second pion in D^+ decays. This correlation matrix is used to construct off-diagonal elements of the covariance matrix. Performing a χ^2 fit using the full covariance matrix the result is

$$f_+/f_0 = 0.360 \pm 0.008(\text{bin-by-bin}) \pm 0.009(\text{global}), \quad (72)$$

where the first uncertainty is from bin-by-bin statistical and systematic uncertainties determined in the fit, which include all correlations, and the second is due to the global systematics listed in Table 42. Performing the same fit to the data in bins of $p_T(B)$, the result is

$$f_+/f_0 = 0.359 \pm 0.006(\text{bin-bt-bin}) \pm 0.009(\text{global}), \quad (73)$$

where the first uncertainty is from bin-by-bin statistical and systematic uncertainties determined in the fit, which include all correlations, and the second is due to the global systematics listed in Table 42 plus an additional 0.5% uncertainty per charm mode on the k -factor correction. The χ^2/ndof of the fit is 8.7/13, consistent with a flat distribution. The total relative uncertainty on this result is f_+/f_0 is 3.0%. The average value from both fits are in agreement within uncertainties. All the data show no dependence as a function of kinematic variables and therefore show no systematic problems with the multiplicity dependent corrections (i.e., tracking and PID efficiencies).

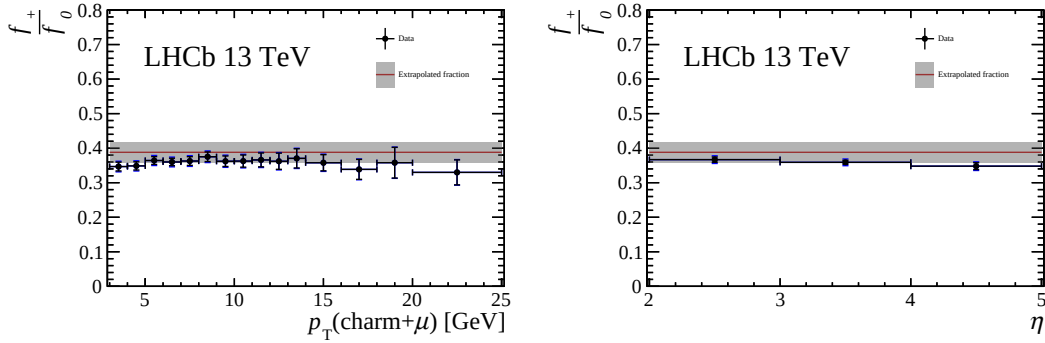


Figure 140: The measured value of $f_+/f_0 \equiv n_{corr}(D^+\mu)/n_{corr}(D^0\mu)$ in bins of transverse momentum (left) and η (right). Black error bars reflect data statistics and bin-by-bin uncertainties and the blue error bars contain the global uncertainties added in quadrature. The red horizontal line with the gray band shows the expected value and uncertainty.

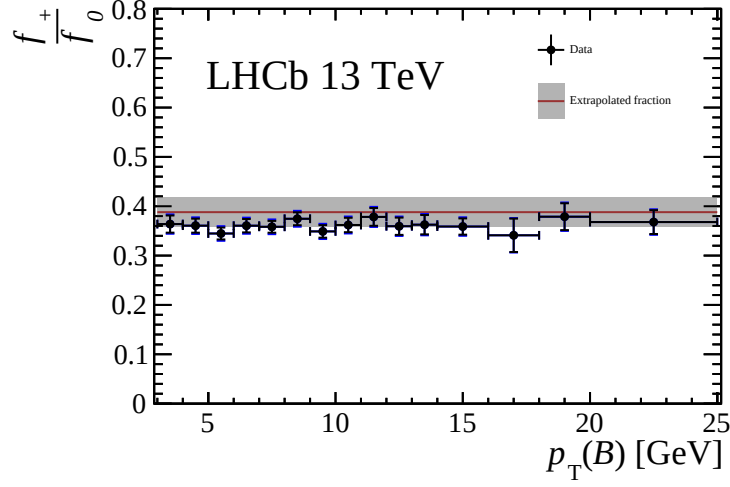


Figure 141: The measured value of $f_+/f_0 \equiv n_{corr}(D^+\mu)/n_{corr}(D^0\mu)$ in bins of b -hadron transverse momentum. Black error bars reflect data statistics and bin-by-bin uncertainties and the blue error bars contain the global uncertainties added in quadrature. The red horizontal line with the gray band shows the expected value and uncertainty.

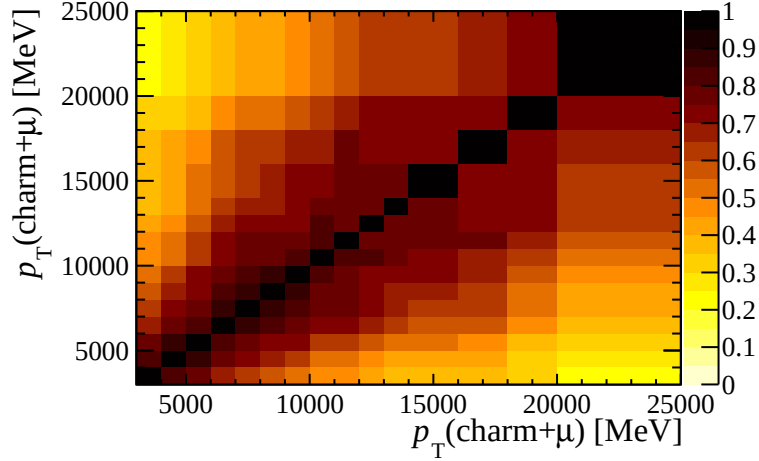


Figure 142: Correlation matrix induced by the second pion kinematics in D^+ decays in bins of $p_T(charm + \mu)$. The z -axis depicts the correlation coefficient.

7 Conclusions

The production cross section for b -quarks is measured in both 7 and 13 TeV pp collisions, as well as the 13 to 7 TeV ratio. All measurements are in the region $2 < \eta < 5$, where η is the pseudorapidity of the decaying b -hadron. The η integrated results for the absolute cross sections are:

$$\begin{aligned}\sigma(pp \rightarrow b\bar{b}X) &= 72.0 \pm 0.3 \pm 7.3 \text{ } \mu\text{b}, \sqrt{s} = 7 \text{ TeV} \\ \sigma(pp \rightarrow b\bar{b}X) &= 144.0 \pm 1.3 \pm 20.6 \text{ } \mu\text{b}, \sqrt{s} = 13 \text{ TeV},\end{aligned}$$

where the first uncertainties are statistical and the second are systematic. These measurements are in agreement with theoretical predictions at 7 TeV and 13 TeV with values of $62_{-22}^{+28} \text{ } \mu\text{b}$ and $111_{-44}^{+51} \text{ } \mu\text{b}$, respectively. The η integrated 13 to 7 TeV ratio is measured to be:

$$R_{13/7}(\sigma(pp \rightarrow b\bar{b}X)) = 2.00 \pm 0.02 \pm 0.26,$$

where the first uncertainty is statistical and the second systematic. Within uncertainties the measured 13 to 7 TeV ratio is consistent with the expectation of $1.79_{-0.15}^{+0.21}$.

The absolute cross section at 7 and 13 TeV, and their ratio are shown in Figures 78, 79, and 80, respectively. Within uncertainties, the expected 7 to 13 TeV increase is consistent with data in shape and normalization as a function of η .

The measurement of f_+/f_0 helps in constraining the knowledge of the unknown portion of the hadron mass spectrum in inclusive semileptonic b -hadron decays. The measured differential distributions, as a function of $p_T(\text{charm} + \mu)$ and η , and $p_T(B)$, are shown in Figure 140 and Figure 141, respectively. The value of f_+/f_0 in the $p_T(B)$ interval of 4 to 25 GeV, derived from fitting the data to a constant, is found to be:

$$f_+/f_0 = 0.359 \pm 0.006(\text{bin-by-bin}) \pm 0.009(\text{global}).$$

The total relative uncertainty on f_+/f_0 is 3.0%. The results of this measurement places some constraint on the D^+/D^0 fraction from B decays and suggest that the sum of exclusive measured branching fractions may indeed account for more of the total inclusive semileptonic width. This measurements also serves as a systematic check of the multiplicity depended corrections applied to the b-hadron fraction measurements, i.e., the tracking and PID efficiency corrections. No deviations from a flat distribution were found.

The values of the b -hadron fractions were measured as a function of b -hadron p_T by correcting the experimentally measured charm+muon p_T via k -factor correction. These corrections allow future measurements incorporating these results to use their measured spectra to derive an average b -fraction relevant to their kinematic acceptance. The ratio $f_s/(f_u + f_d)$ as a function of $p_T(B)$ is shown in Figure 132, along with a linear fit to the data. The values of the fit parameters are determined to be:

$$\frac{f_s}{f_u + f_d} = (1.000 \pm 0.043) \cdot [(0.119 \pm 0.001) + (-0.91 \pm 0.25) \cdot 10^{-3} \times \frac{p_T - \langle p_T \rangle}{1 \text{ GeV}}].$$

The ratio $f_{\Lambda_b}/(f_u + f_d)$ as a function of $p_T(B)$ is shown in Figure 138. This distribution is fit with an exponential function with the result being:

$$\frac{f_{\Lambda_b}}{f_u + f_d} = (1.000 \pm 0.061) \cdot [(7.93 \pm 1.41) \cdot 10^{-2} + \exp[(-1.022 \pm 0.047) + (-0.107 \pm 0.002) \times \frac{p_T}{1 \text{ GeV}}]].$$

The averages of the b-hadron fractions are

$$\begin{aligned} \frac{f_s}{f_u + f_d} &= 0.122 \pm 0.006 \\ \frac{f_{\Lambda_b}}{f_u + f_d} &= 0.259 \pm 0.018. \end{aligned}$$

The total relative uncertainty on the $f_s/(f_u + f_d)$ is 4.8%, and for $f_{\Lambda_b}/(f_u + f_d)$ the total relative uncertainty is 6.9%.

These measurements are currently the only ones existing for data taken at a center-of-

mass energy of 13 TeV, and they have an overall uncertainty reduced by almost a factor of two with respect to previous measurements. Their impact on several studies of B_s^0 and Λ_b^0 decays is expected to be significant.

Appendices

A b -quark cross section

A.1 Kinematic comparisons between data and MC

A.1.1 $D^0\mu X$

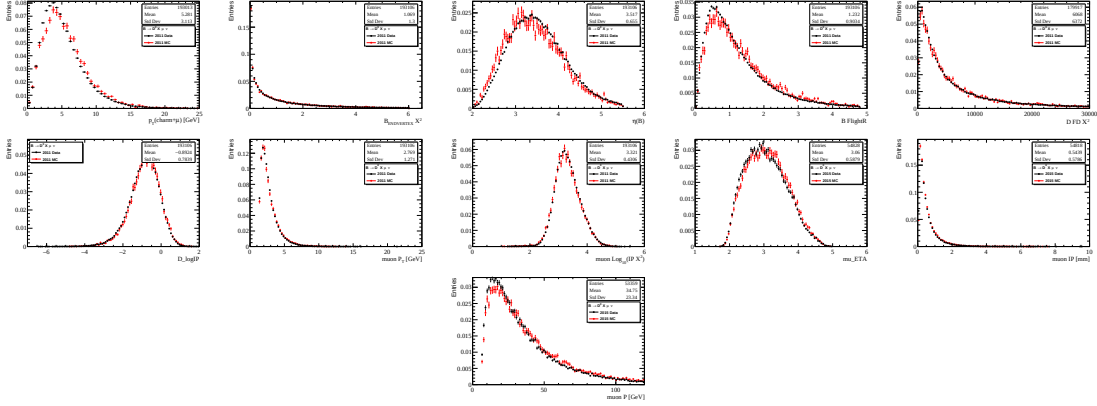


Figure 143: Kinematic comparisons for $B \rightarrow D^0 X \mu \nu$ decays in 2011 (black) data and (red) simulation.

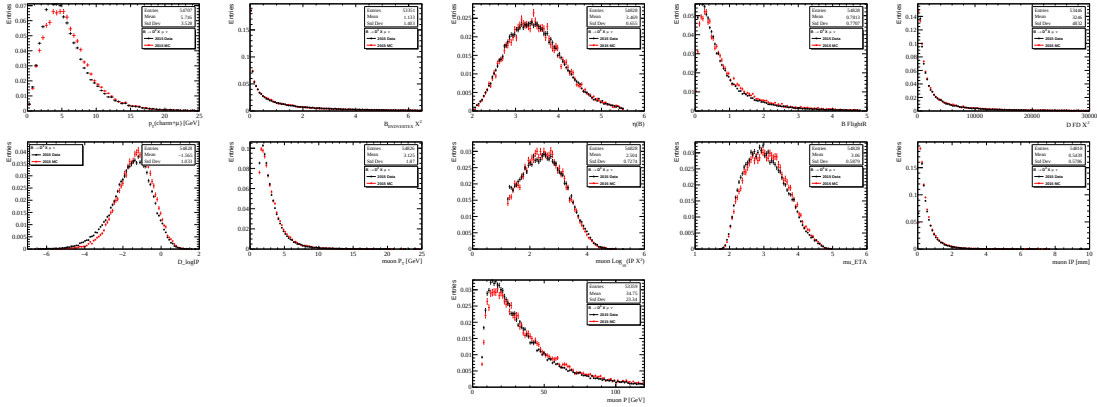


Figure 144: Kinematic comparisons for $B \rightarrow D^0 X \mu \nu$ decays in 2015 (black) data and (red) simulation.

A.1.2 $D^+\mu X$

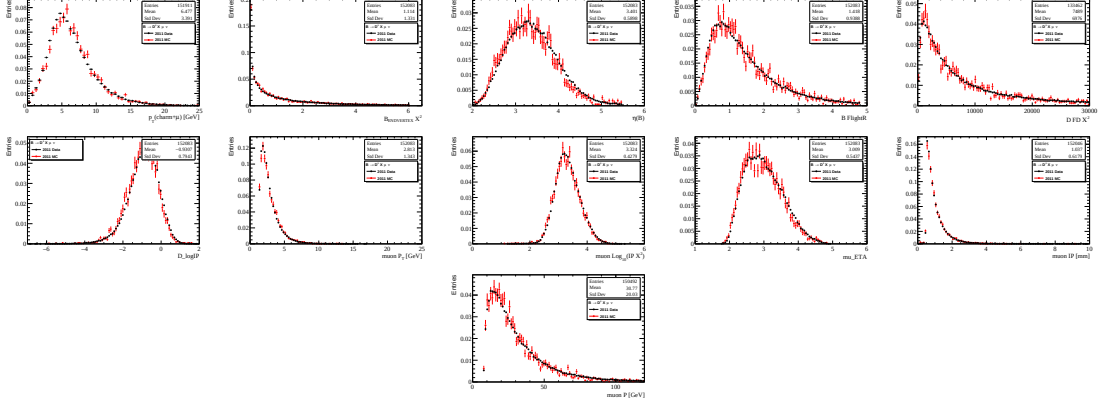


Figure 145: Kinematic comparisons for $B \rightarrow D^+X\mu\nu$ decays in 2011 (black) data and (red) simulation.

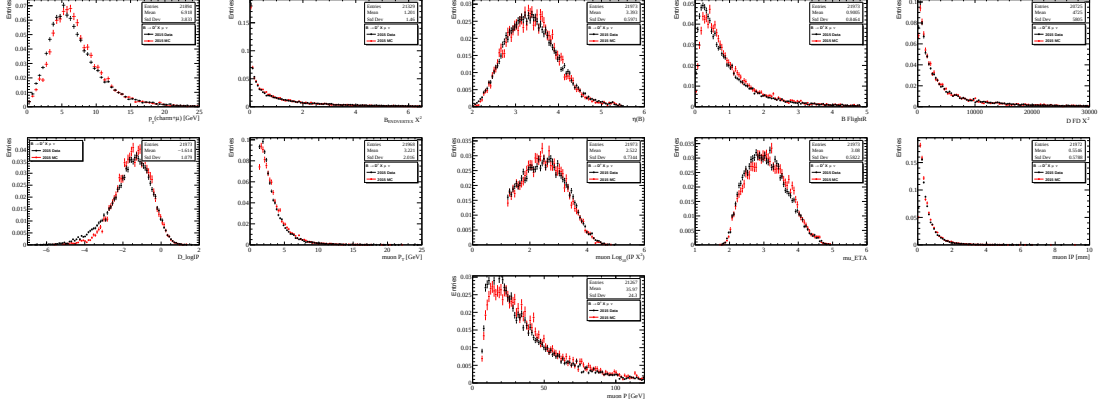


Figure 146: Kinematic comparisons for $B \rightarrow D^+X\mu\nu$ decays in 2015 (black) data and (red) simulation.

A.1.3 $D_s^+\mu X$

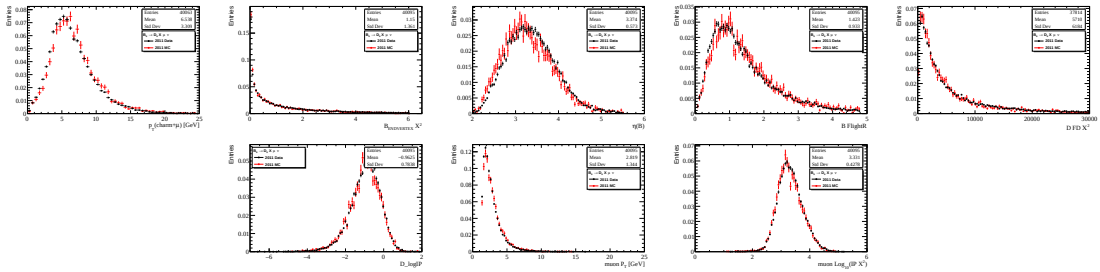


Figure 147: Kinematic comparisons for $B_s \rightarrow D_s^+X\mu\nu$ decays in 2011 (black) data and (red) simulation.

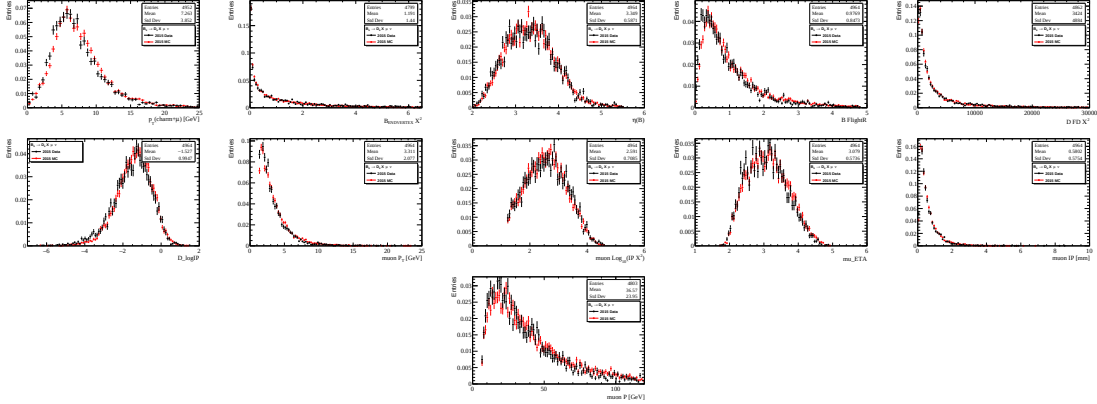


Figure 148: Kinematic comparisons for $B_s \rightarrow D_s X \mu \nu$ decays in 2015 (black) data and (red) simulation.

A.1.4 $\Lambda_c^+ \mu X$

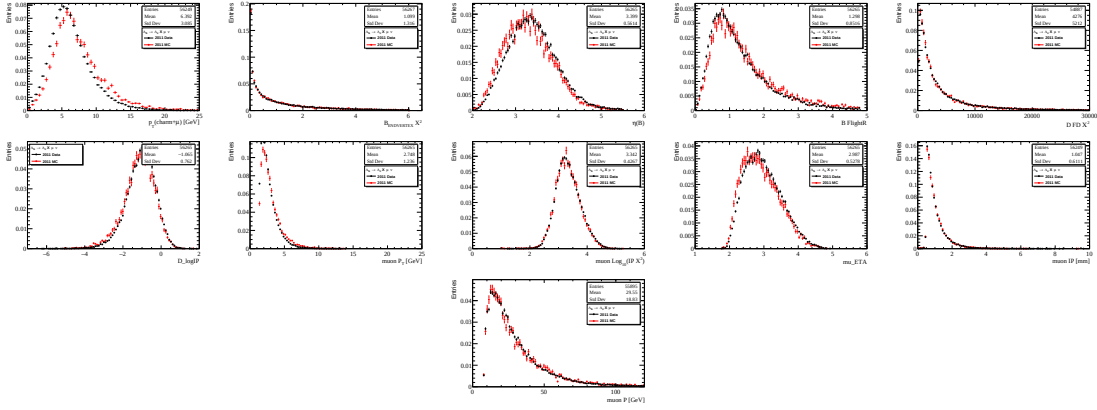


Figure 149: Kinematic comparisons for $\Lambda_b \rightarrow \Lambda_c X \mu \nu$ decays in 2011 (black) data and (red) simulation.

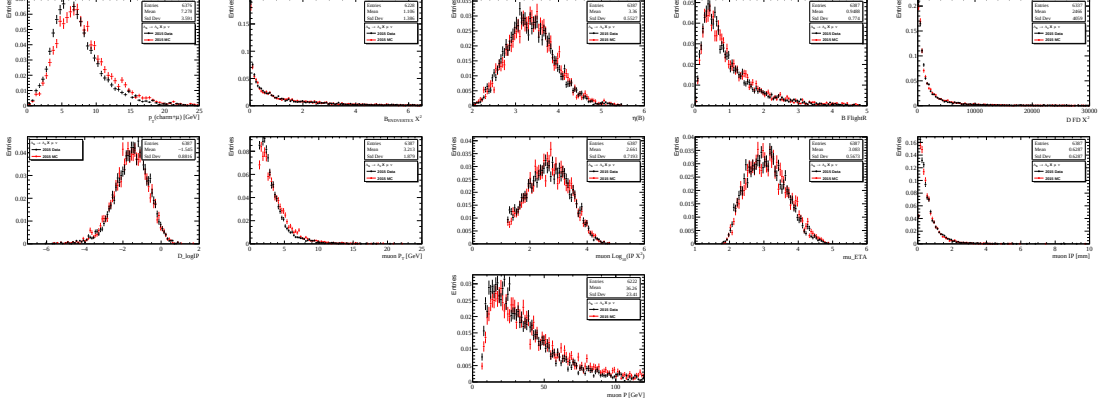


Figure 150: Kinematic comparisons for $\Lambda_b \rightarrow \Lambda_c X \mu \nu$ decays in 2015 (black) data and (red) simulation.

B b -hadron fragmentation ratios

B.1 Kinematic comparisons between data and MC

B.1.1 $D^0 \mu$

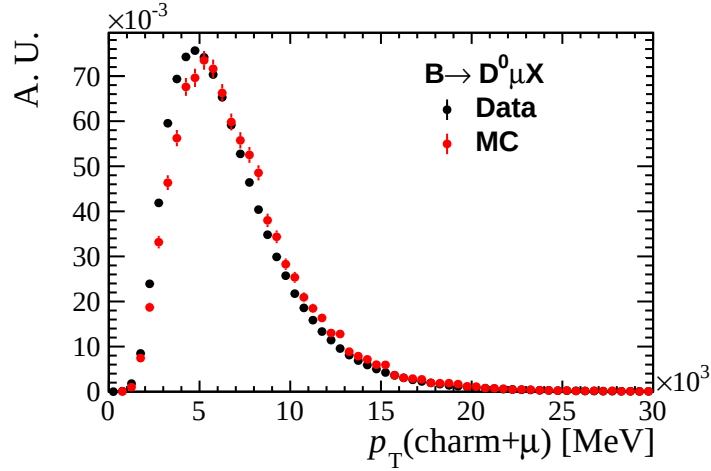


Figure 151: Data and MC comparisons of the $p_T(D^0 + \mu)$ spectrum integrated over b -hadron η .

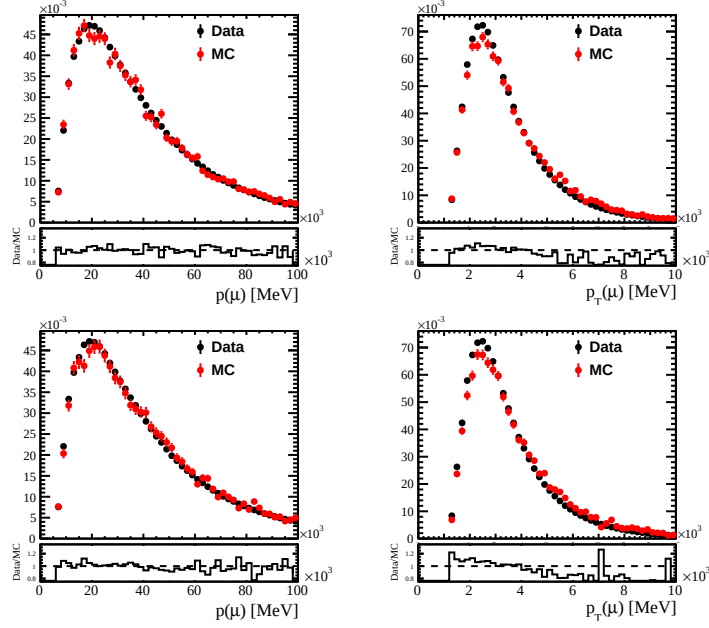


Figure 152: Data and MC distributions for muon in the $D^0\mu$ final state. Here the MC is from B^+ (top) and B^0 (bottom) decays. The data shown here is from the same TCK used in the simulation.

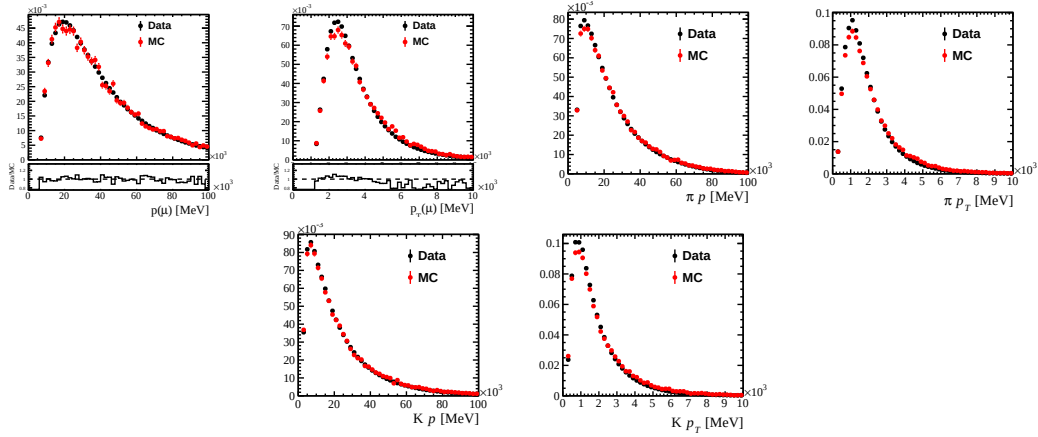


Figure 153: Data and MC distributions for the D^0 daughters. Here the MC is from B^+ decays.

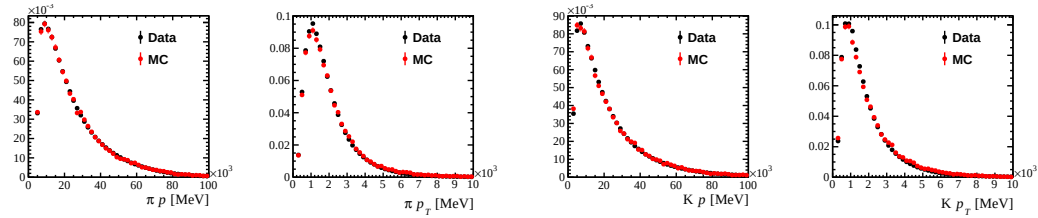


Figure 154: Data and MC distributions for the D^0 daughters. Here the MC is from B^0 decays.

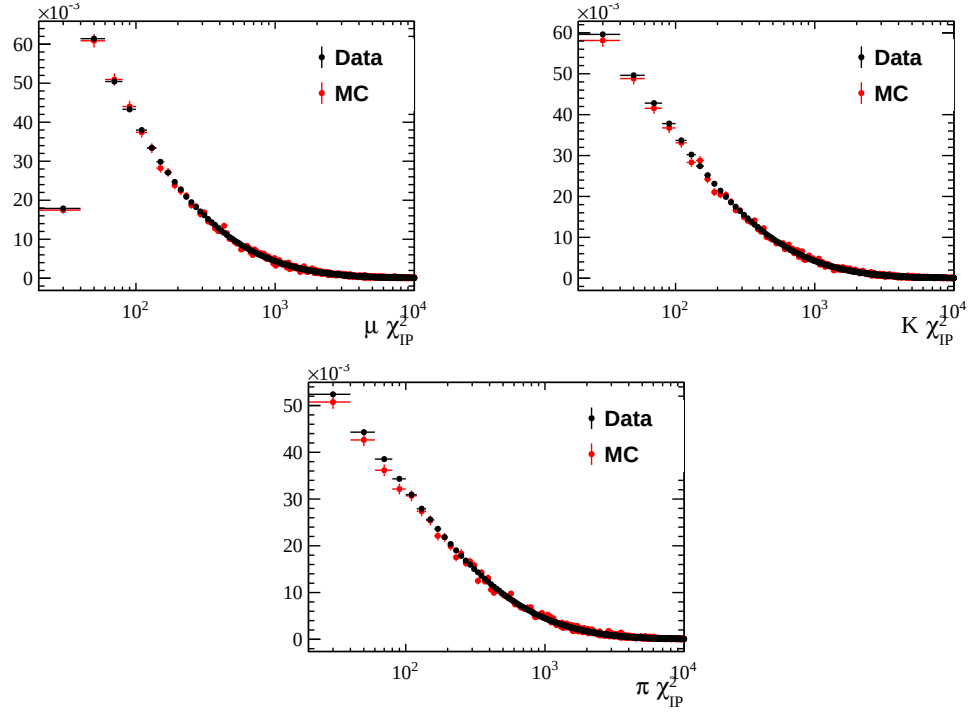


Figure 155: Data and MC IP χ^2 distributions for the D^0 daughters. Here the MC is from B^+ decays.

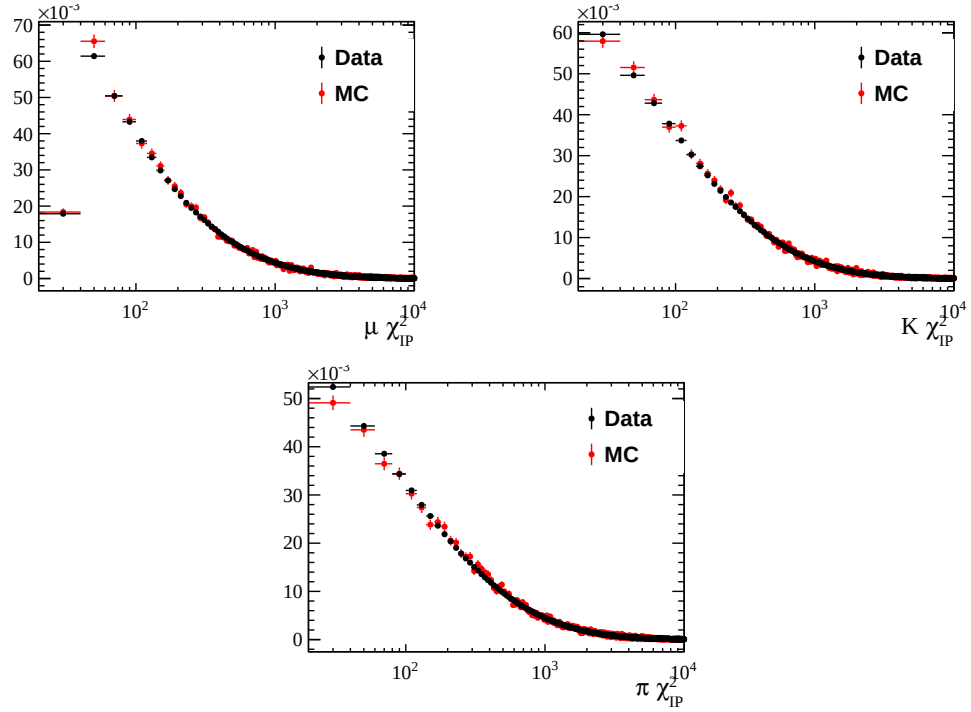


Figure 156: Data and MC IP χ^2 distributions for the D^0 daughters. Here the MC is from B^0 decays.

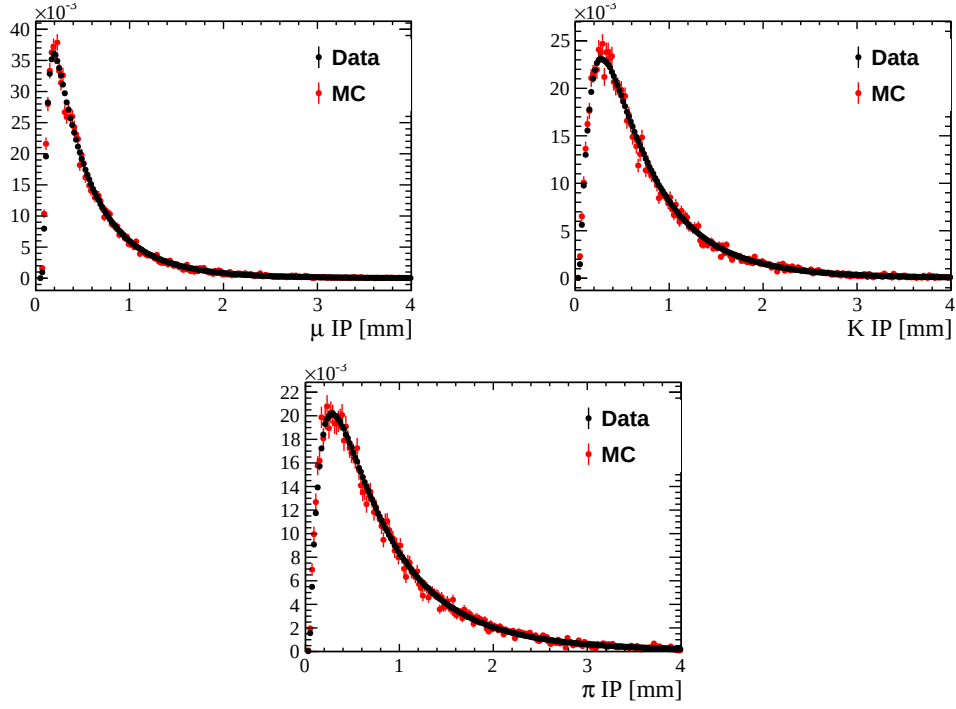


Figure 157: Data and MC IP distributions for the D^0 daughters. Here the MC is from B^+ decays.

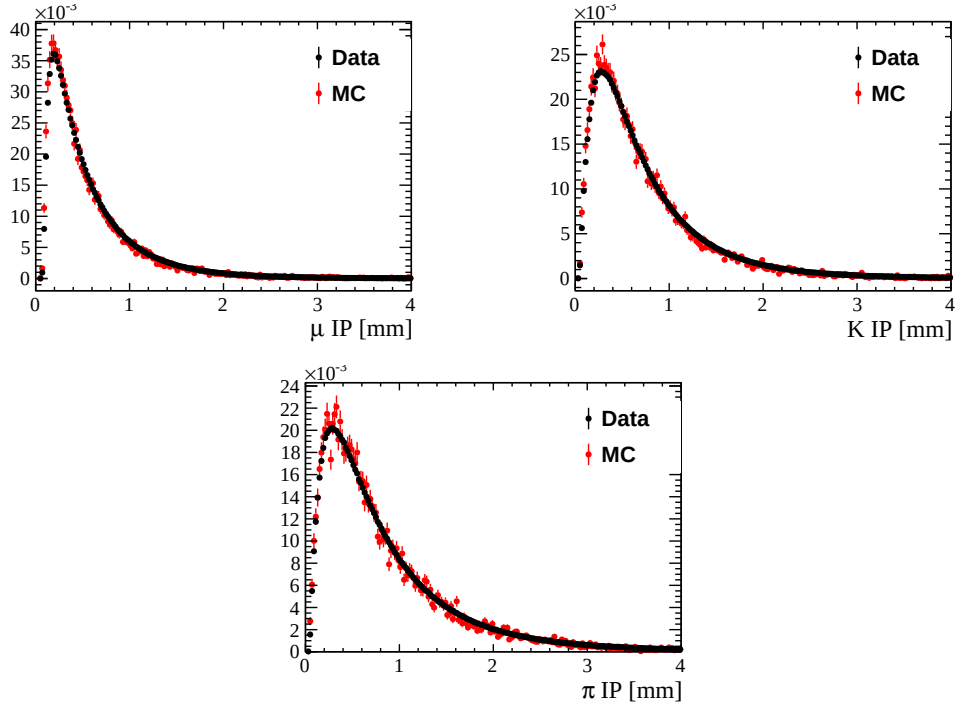


Figure 158: Data and MC IP distributions for the D^0 daughters. Here the MC is from B^0 decays.

B.1.2 $D^+\mu X$

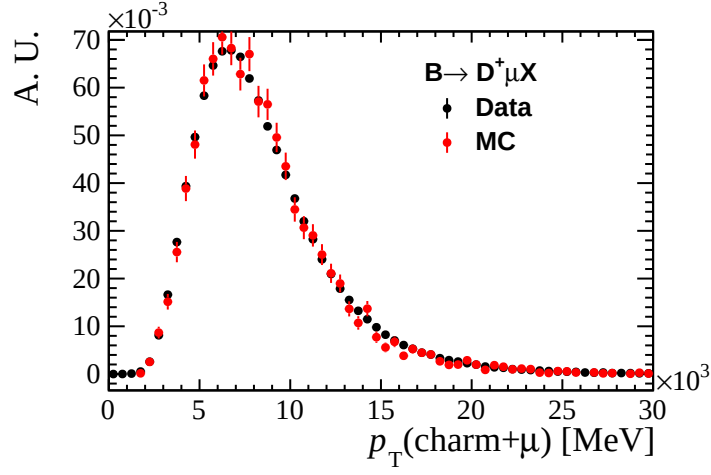


Figure 159: Data and MC comparisons of the $p_T(D^+ + \mu)$ spectrum integrated over b-hadron η .

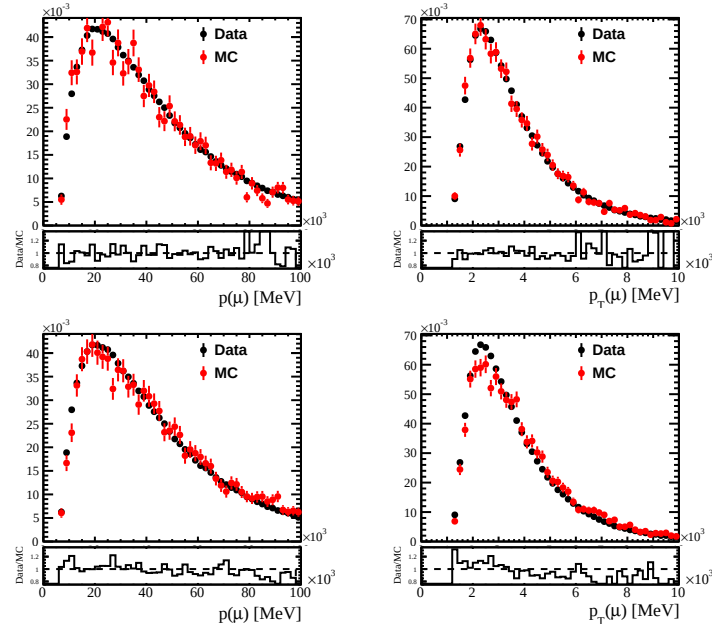


Figure 160: Data and MC distributions for muon in the $D^+\mu$ final state. Here the MC is from B^+ (top) and B^0 (bottom) decays. The data shown here is from the same TCK used in the simulation.

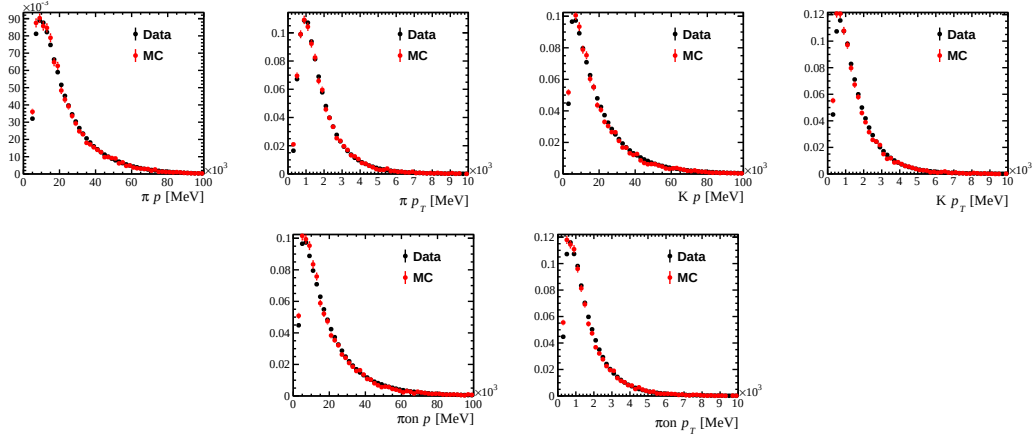


Figure 161: Data and MC distributions for the D^+ daughters. Here the MC is from B^+ decays.

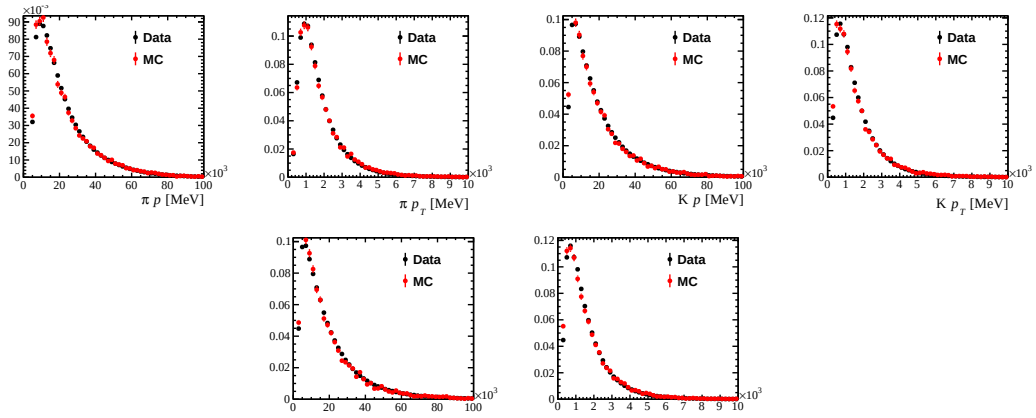


Figure 162: Data and MC distributions for the D^+ daughters. Here the MC is from B^0 decays.

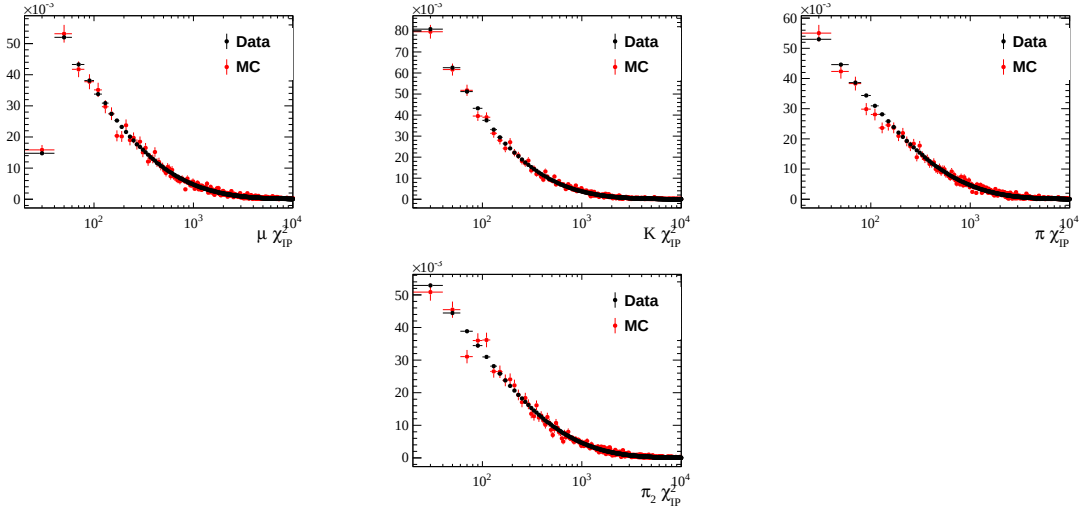


Figure 163: Data and MC IP χ^2 distributions for the D^+ daughters. Here the MC is from B^+ decays.

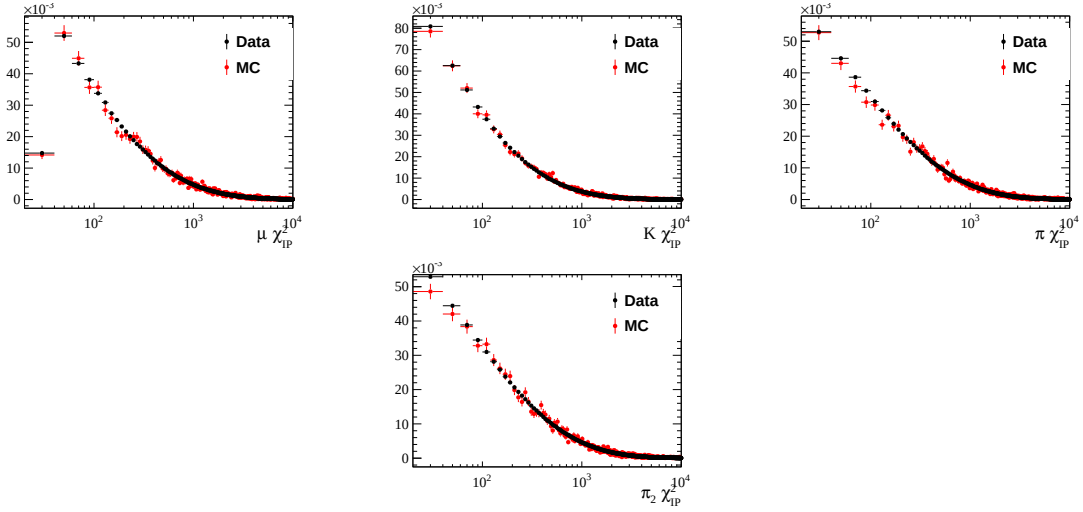


Figure 164: Data and MC IP χ^2 distributions for the D^+ daughters. Here the MC is from B^0 decays.

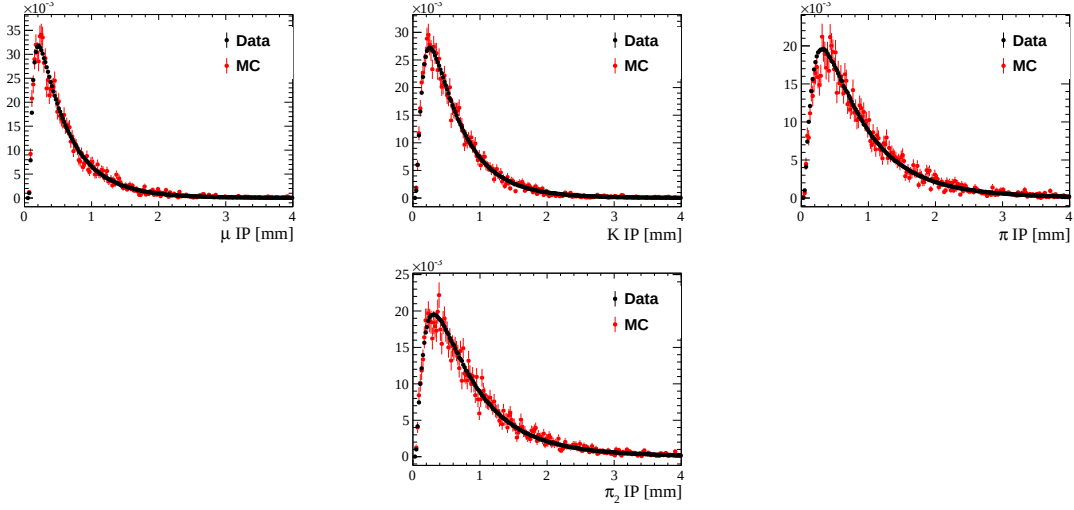


Figure 165: Data and MC IP χ^2 distributions for the D^+ daughters. Here the MC is from B^+ decays.

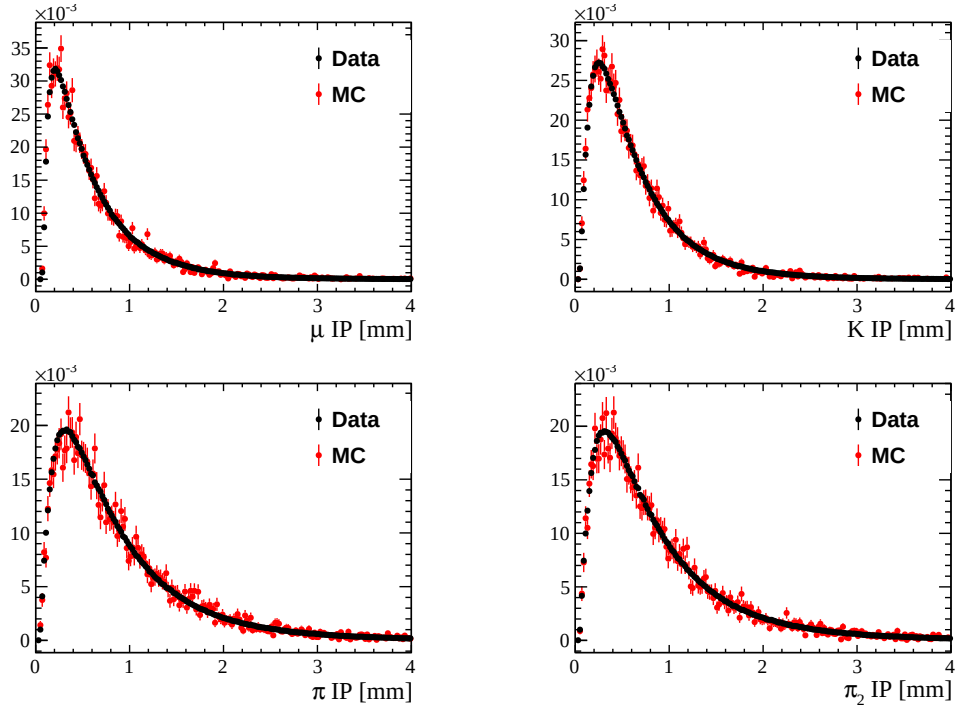


Figure 166: Data and MC IP distributions for the D^+ daughters. Here the MC is from B^0 decays.

B.1.3 $D_s^+ \mu X$

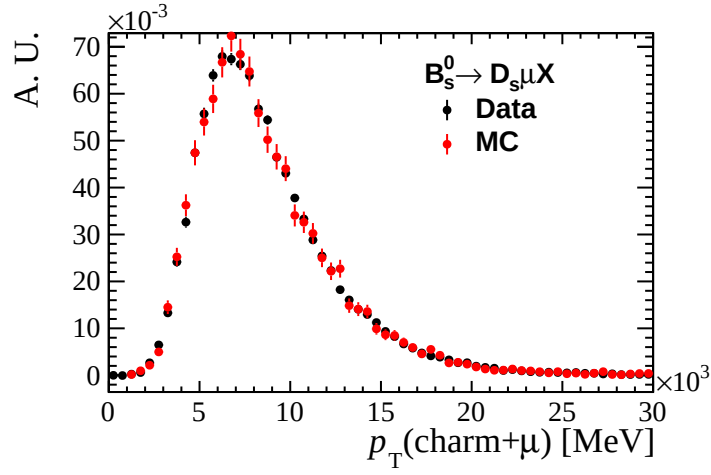


Figure 167: Data and MC comparisons of the $p_T(D_s^+ + \mu)$ spectrum integrated over b-hadron η .

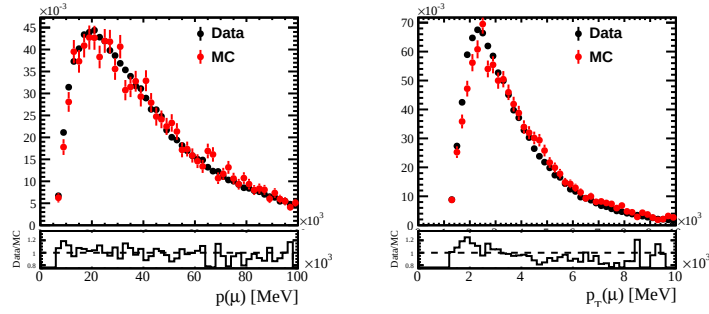


Figure 168: Data and MC distributions for the muon in the $D_s \mu$ final state. The data shown here is from the same TCK used in the simulation.

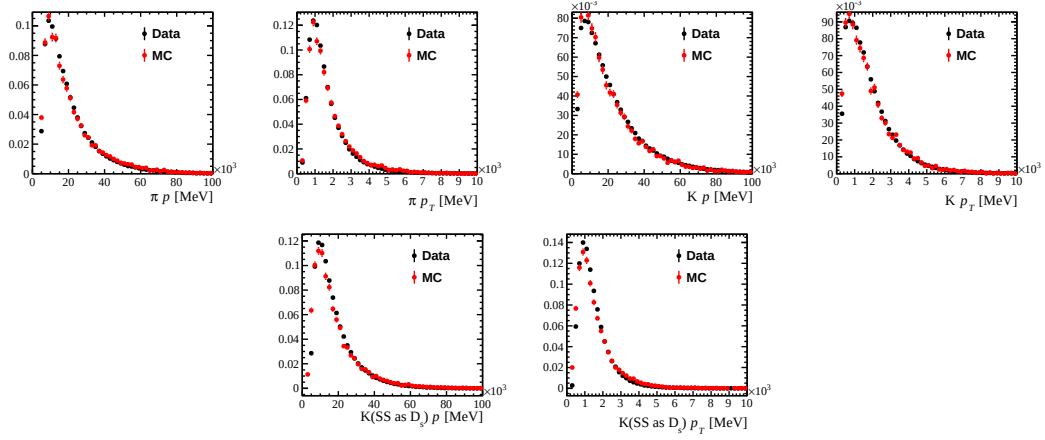


Figure 169: Data and MC distributions for the D_s daughters.

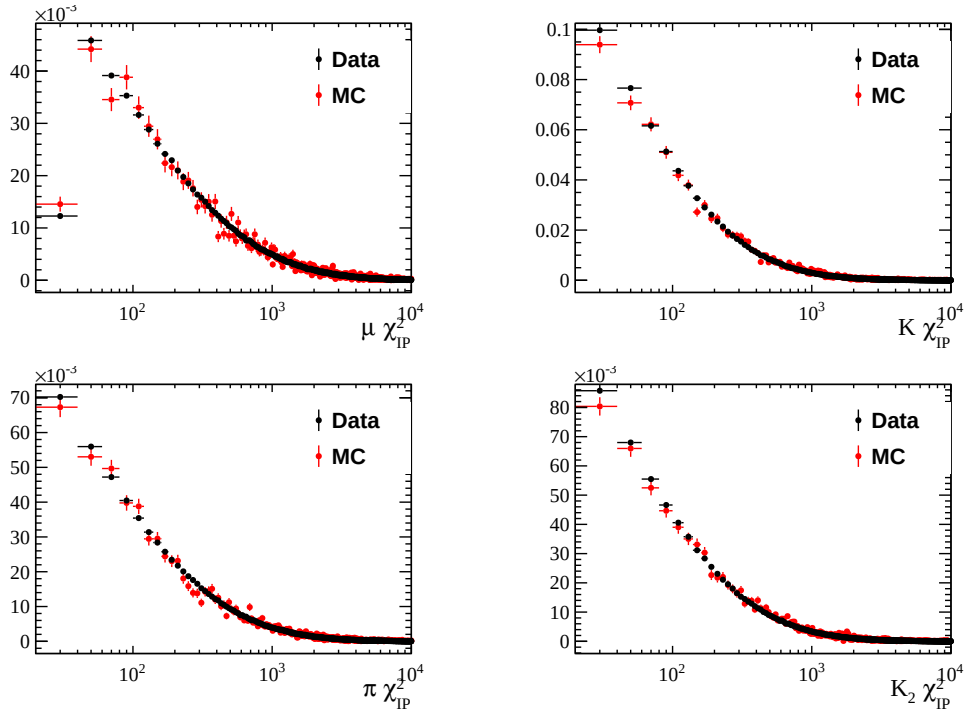


Figure 170: Data and MC IP χ^2 distributions for the D_s^+ mode.

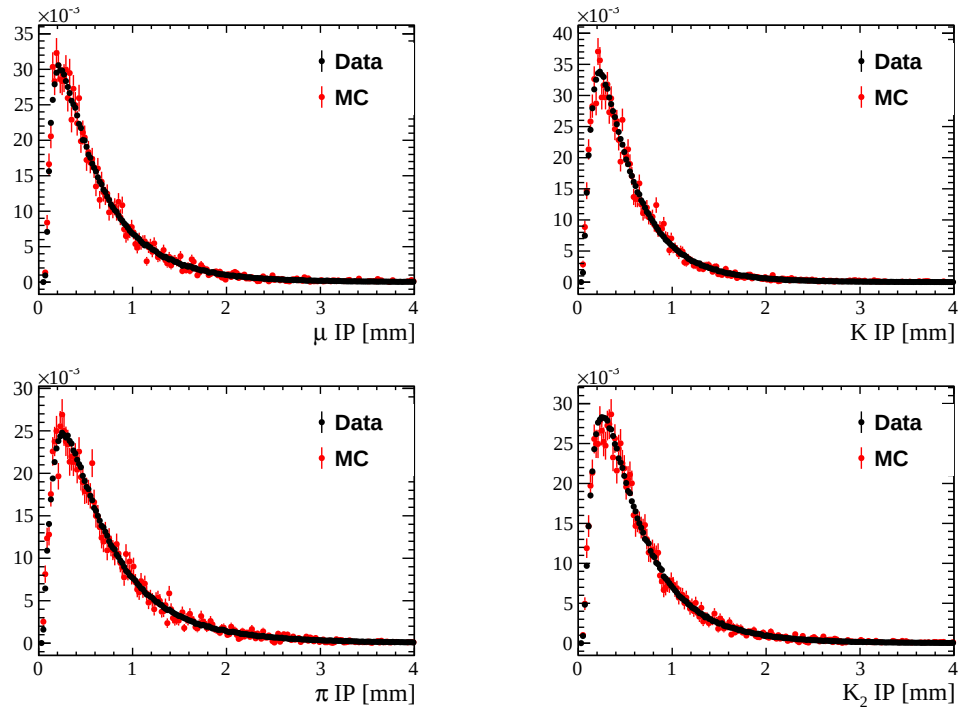


Figure 171: Data and MC IP distributions for the D_s^+ mode.

B.1.4 $\Lambda_c^+ \mu X$

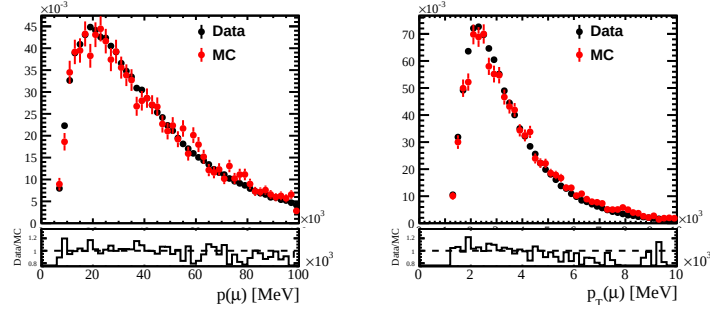


Figure 172: Data and MC distributions for the muon in the $\Lambda_c \mu$ final state. The data shown here is from the same TCK used in the simulation.

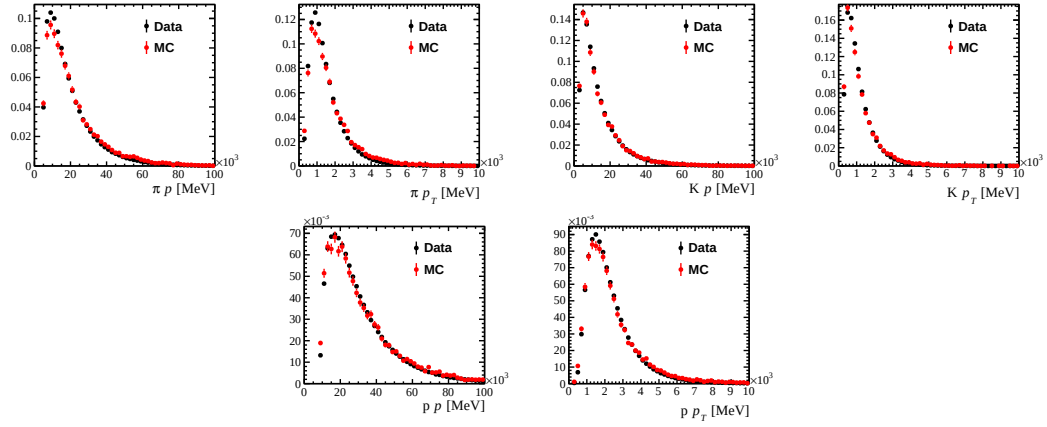


Figure 173: Data and MC distributions for the Λ_c daughters.

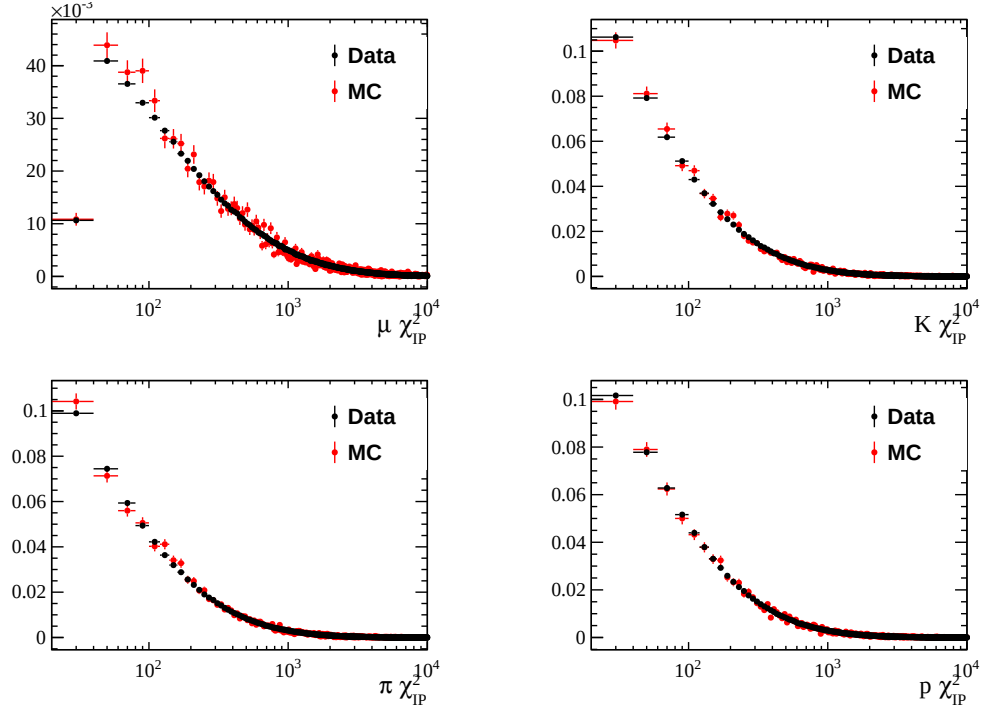


Figure 174: Data and MC IP χ^2 distributions for the Λ_c^+ mode.

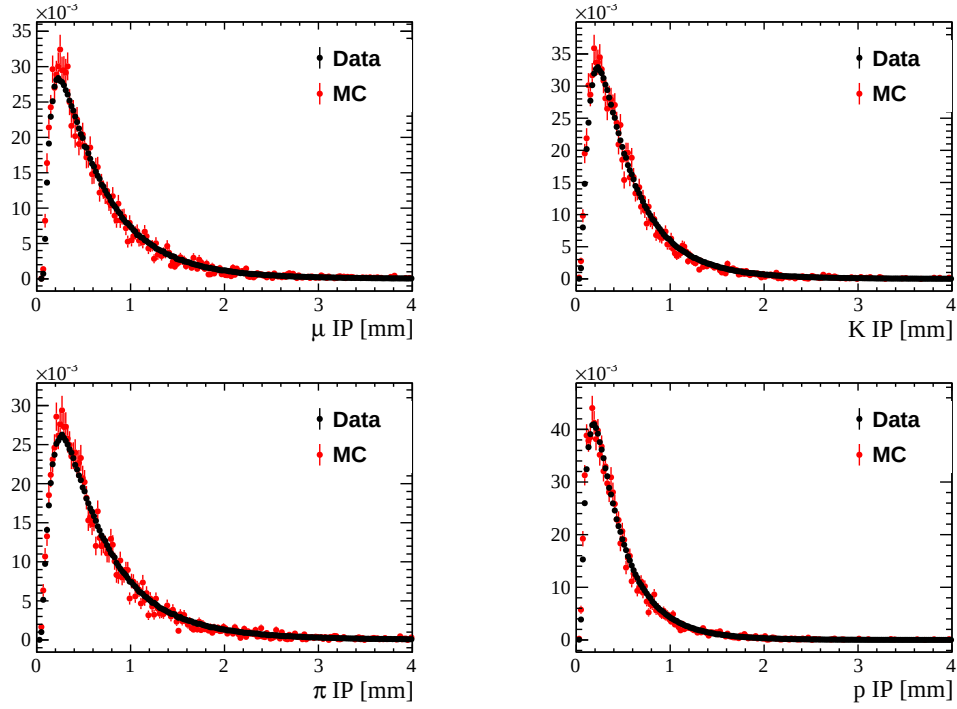


Figure 175: Data and MC IP distributions for the Λ_c^+ mode.

B.2 Λ_b Re-weighting

It is well known that the production kinematics for Λ_b^0 baryons are wrong in simulation, thus resulting to a p_T spectrum that is much harder in MC than data. Shown in Figure 182, in the top two plots, are the comparisons between data and MC of the $\Lambda_c^+ \mu$ p_T and p . To account for this MC mis-modeling we re-weight the Λ_b^0 $p_T(\Lambda_b)$ spectrum with weights determined with $\Lambda_b^0 \rightarrow J/\psi p K$ decays. Figure 176 shows the mass fit to the $J/\psi p K$ mass. There are roughly 36k events in the mass peak with a background contamination of about 2% within 20 MeV of the nominal Λ_b^0 mass. Shown in Figure 178 are the sideband-subtracted p_T and p spectra in both data and MC. Weights are determined in bins of p_T by taking the ratio of normalized data to MC events. Shown in Figure 179 are the weights. After re-weighting (shown in the bottom two plots in Figure 182) the p_T spectrum agree between MC and data.

As a check, a re-weighting of the Λ_b^0 p_T is done using weights determined with the theoretical p_T spectrum given in FONLL calculations in Ref. [39], and then correcting for the f_{Λ_b}/f_d fraction p_T dependence measured in Ref. [89]. Shown in Figure 180 are the corrected theoretical p_T shape and the shape from simulation, and the f_{Λ_b}/f_d p_T shape. After using this alternative shape to re-weight the middle two plots shown in Figure 182 show the results. Again using this alternative re-weighting procedure we find good agreement between data and MC. Agreement between the two re-weighted spectra is also found.

The uncertainty on the re-weighting procedure is determined by taking a weighted average of the statistical uncertainties on the weights according to the p_T spectrum in the semileptonic signal mode. This comes out to be 2.1% overall. To check the sensitivity to reweighting procedure the efficiency is determined in bins of $p_T(charm + \mu)$ with and without the re-weighting, and with the alternative weights calculated with the FONLL predictions corrected for the baryon spectrum. These efficiencies are all shown in Figure 181, with the respective pull distributions calculated as $(\epsilon_{alt.} - \epsilon_{nominal})/\sigma_{nominal}$. From the pull distributions nearly all efficiencies are in consistent with each other within uncertainties, even between efficiencies with and without re-weighting.

As a systematic uncertainty on the re-weighting procedure, the total 2.1% uncertainty due to the weights is used. This is a very conservative systematic uncertainty as these uncertainties will cancel because of the kinematic correlations between the generator level and reconstructed MC in the efficiency calculation. Additionally, it has been shown that the re-weighting procedure has only a small change in the final efficiency, and is very stable with respect to the alternative re-weighting procedure.

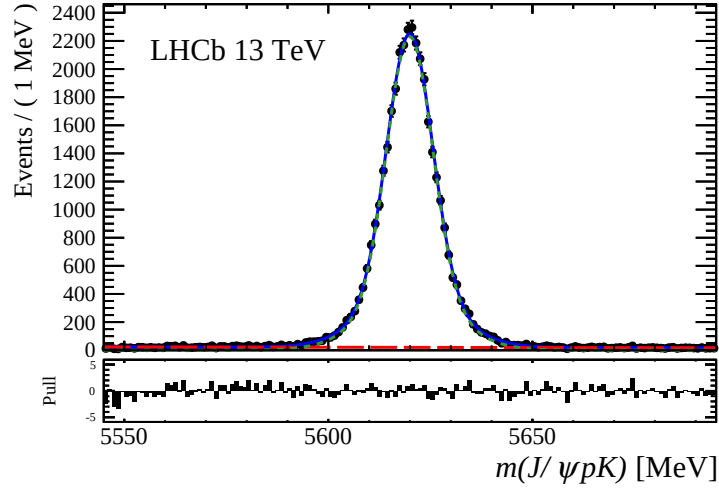


Figure 176: Fit to the $J/\psi pK$ invariant mass.

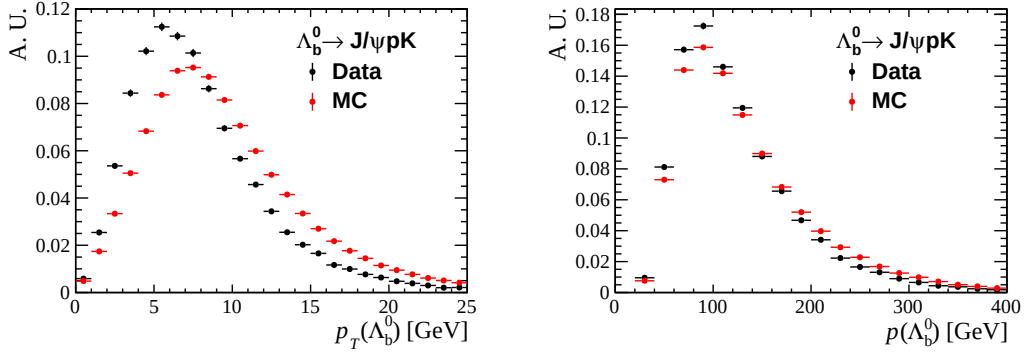


Figure 177: Comparisons of the Λ_b^0 p_T (left) and p (right) spectra in data and MC in $\Lambda_b^0 \rightarrow J/\psi pK$ decays.

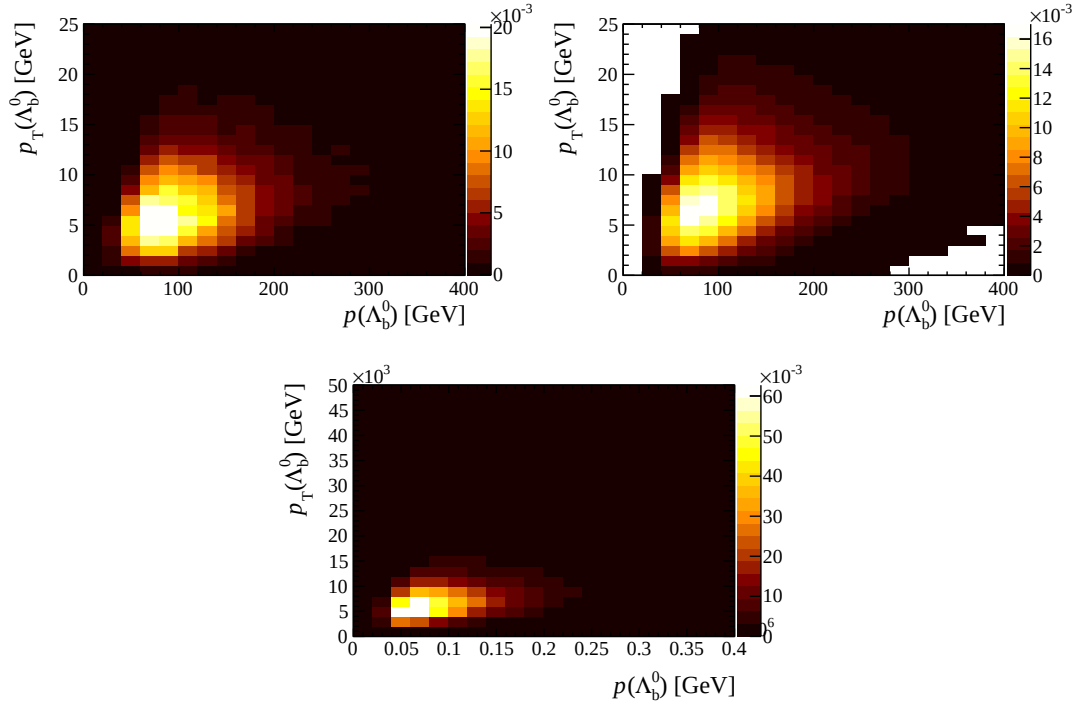


Figure 178: Comparisons of the Λ_b^0 p_T and p spectra in data (left) and MC (right) in $\Lambda_b^0 \rightarrow J/\psi p K$ decays and semileptonic decays (bottom).

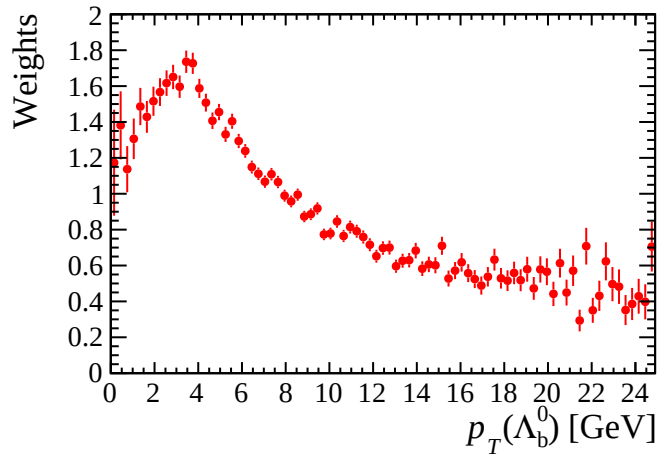


Figure 179: Weights determined from $\Lambda_b^0 \rightarrow J/\psi p K$ decays used to re-weight the semileptonic Λ_b^0 MC.

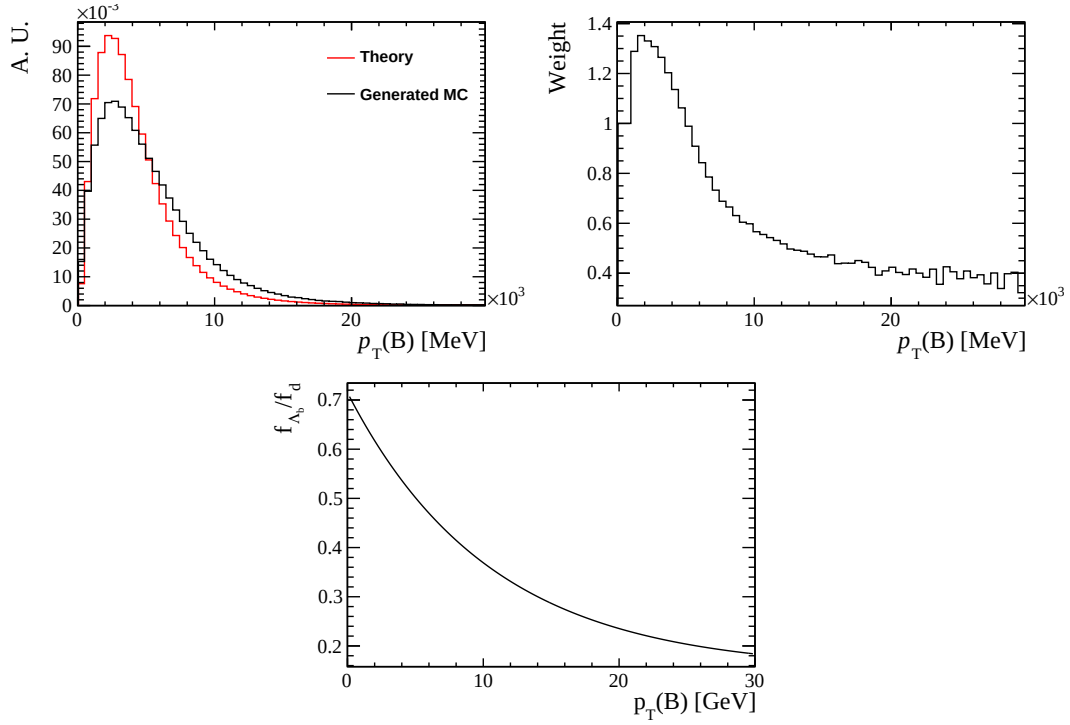


Figure 180: Comparisons of the Λ_b^0 p_T spectrum in simulations and predictions from FONLL (top left) and the ratio between the two (top right). The bottom plot shows the f_{Λ_b}/f_d p_T dependence as measured by LHCb in 7 TeV data.

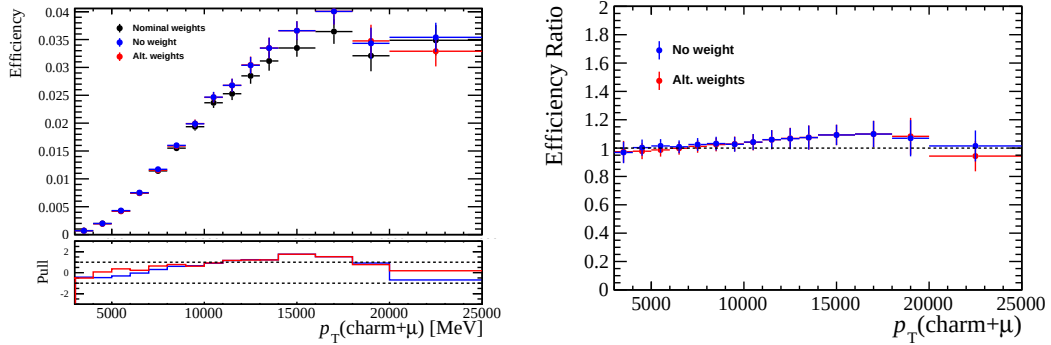


Figure 181: Efficiency (left) in bins of $p_T(\text{charm}+\mu)$ with MC re-weighted with $\Lambda_b^0 \rightarrow J/\psi p K$ decays (black) and weights determined with the corrected FONLL spectrum (red). The blue shows efficiencies with no re-weighting. The bottom section plot shows the pull distribution of the alternative re-weighting and no re-weighting methods with respect to the nominal re-weighting. In the right plot the ratios with respect to the nominal efficiencies are shown.

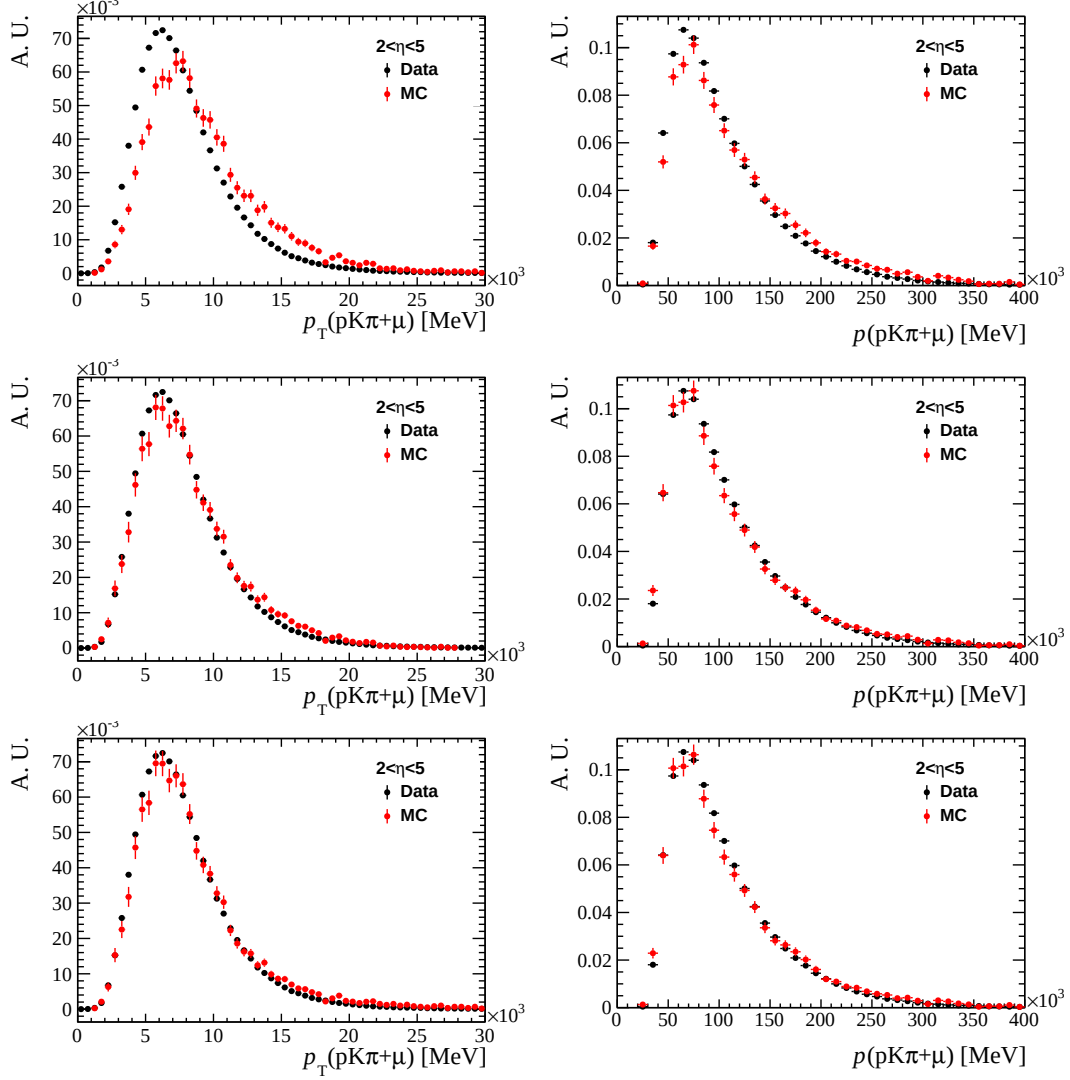


Figure 182: Data and MC comparisons of the $p_T(\Lambda_c^+ + \mu)$ spectrum integrated over b-hadron η (left). The right plot shows the data/MC comparisons in bins of $p(\Lambda_c^+ + \mu)$. The middle two plots show the same spectra but after re-weighting with the theoretical p_T spectrum and taking the f_{Λ_b}/f_d p_T dependence into account. The second to bottom two plots show also the same spectra but now after re-weighting with weights determined from the hadronic $\Lambda_b^0 \rightarrow J/\psi pK$ decays.

B.3 Re-weighting other modes

To assess if there is any systematic affect due to any residual data/MC differences in the other charm modes, a re-weighting procedure using weights determined from data and MC was performed. Weights are calculated in bins of $p_T(\text{charm} + \mu)$ by selecting sideband-subtracted data with the same TCK as MC, and taking the normalized ratio of data to MC. A fit to the the weight distribution is then performed using a third-order polynomial. The fit results are then used to re-weight the MC on an event-by-event basis according the charm+muon p_T . Weights and the resulting fits for the $D^0\mu$, $D^+\mu$, and $D_s\mu$ modes are shown in Figures 183, 184, and 185, respectively. The latter two modes have weights consistent with 1 in the 3-25 GeV interval, and therefore, have no differences in efficiency after re-weighting. The $D^0\mu$ mode shows some significant data-MC difference and to assess the effect of this the $D^0\mu$ MC was re-weighted event-by-event, and propagated through to the final calculation. Using these re-weighted efficiencies no change in the central values of the hadron fractions was seen within rounding.

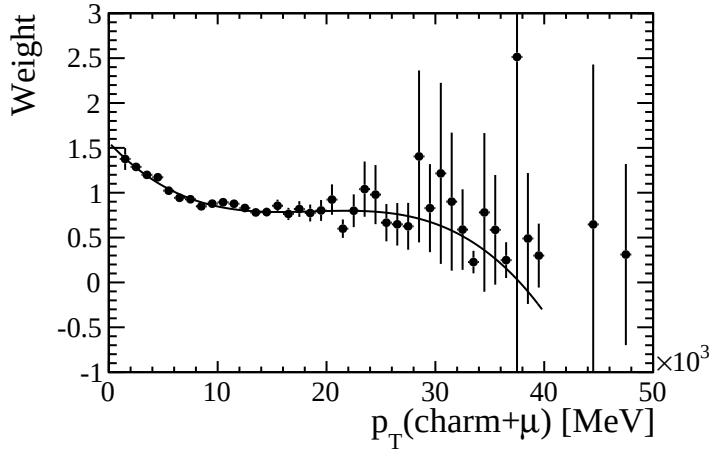


Figure 183: Data/MC weights determined from sideband-subtracted $D^0\mu$ data selected with the same TCK as MC. A fit is shown as the solid line.

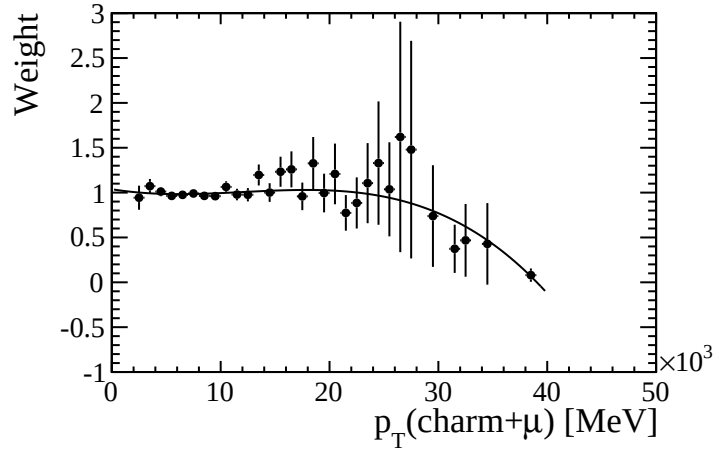


Figure 184: Data/MC weights determined from sideband-subtracted $D^+\mu$ data selected with the same TCK as MC. A fit is shown as the solid line.

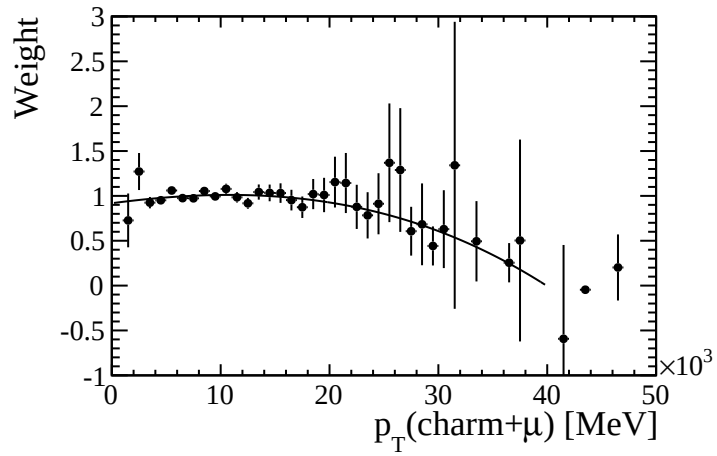


Figure 185: Data/MC weights determined from sideband-subtracted $D_s\mu$ data selected with the same TCK as MC. A fit is shown as the solid line.

B.4 Systematic studies on trigger efficiency

B.4.1 L0+HLT1+Muon ID

As a systematic check, instead of performing fits to the invariant J/ψ mass to determine the yield within the pass and fail categories, fits to the $J/\psi K^+$ were done. Figure 186 shows for example the fit to the B^+ mass integrated over probe muon kinematics. A triple Gaussian function and linear function is used to describe the signal and background shapes, respectively. Figure 187 then shows the projections of the efficiencies in bins of muon p_T and η . The red points in this plot show the efficiency determined with B^+ fits, and the black points show the efficiencies determined with J/ψ fits. Propagating the efficiency grid from the B^+ fit method to the final results had no visible effect to the central values within rounding.

A second systematic check was performed by producing the efficiency in a three-dimensional grid, with the added dimension being nLongTracks. Figure 188 shows these efficiency projections. When using this 3-dimensional efficiency grid to weight MC event-by-event, some bins have zero statistics due to the added dimension (roughly 10% of all MC events), and in these cases the efficiency is taken from the 2-dimensional grid. Propagating these efficiencies to the final calculation yielded consistent results within uncertainties. The fit result for the f_s fraction using these efficiencies is

$$\frac{f_s}{f_u + f_d} = (0.127 \pm 0.002) + (-1.05 \pm 0.20) \cdot 10^{-3} \times \frac{p_T - \langle p_T \rangle}{1 \text{ GeV}}. \quad (74)$$

The fit result for the f_{Λ_b} fraction is

$$\frac{f_{\Lambda_b}}{f_u + f_d} = (6.7 \pm 1.0) \cdot 10^{-2} + \exp[(-1.01 \pm 0.04) + (-0.100 \pm 0.010) \times \frac{p_T}{1 \text{ GeV}}]. \quad (75)$$

Both fits are in excellent agreement to the fits performed to data corrected with a 2-dimensional trigger efficiency grid. The integrated fractions are also in perfect agreement,

and the absolute change in the central values are both 0.001.

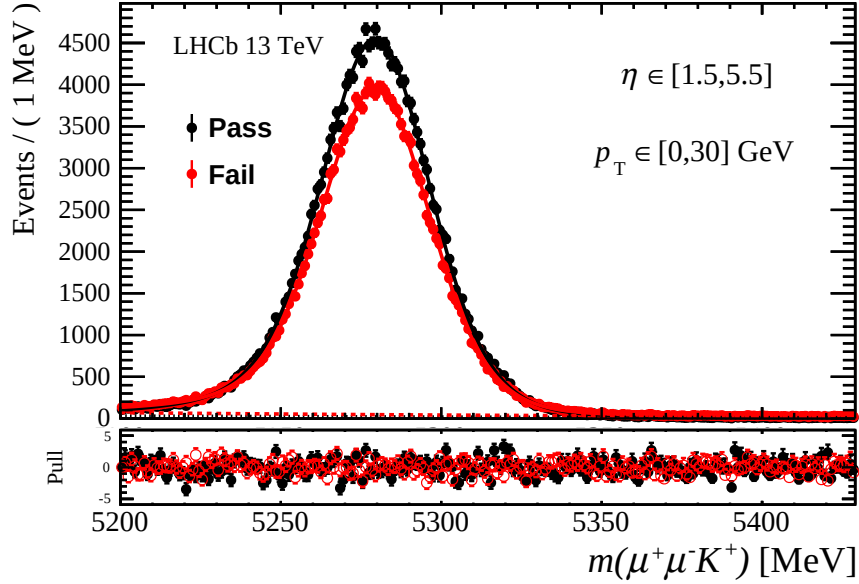


Figure 186: Fit to the $\mu\mu K^+$ invariant mass spectrum integrated over probe muon p_T and η . The black points show data where the probe muon passed L0 and HLT1 trigger requirements, and all muon ID cuts. The red points show probe muon that fail all these requirements. Both fail and pass categories are fit simultaneously and the functions are described in the text.

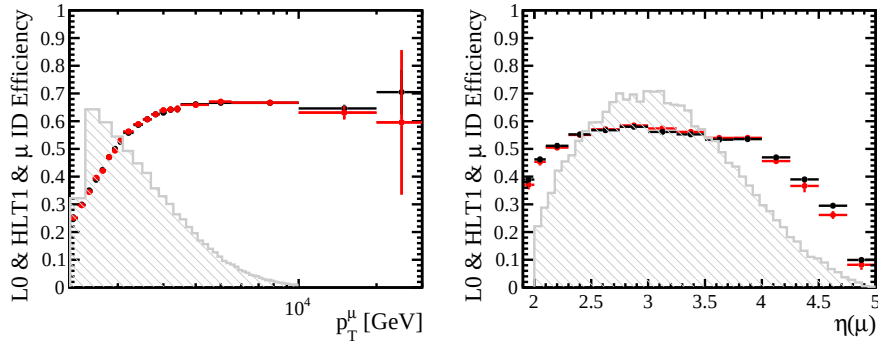


Figure 187: Comparisons between the total L0+HLT1+Muon ID efficiencies determined in the calibration sample by performing fits to the J/ψ mass (black) or $J/\psi K^+$ invariant mass (red). The gray histograms show the distributions in MC with arbitrary normalization.

B.4.2 HLT2

The TISTOS efficiencies for the HLT2 decision are different depending on the number of final state tracks, and also due to the lifetime of the D^+ . It is seen that the HLT2 TISTOS

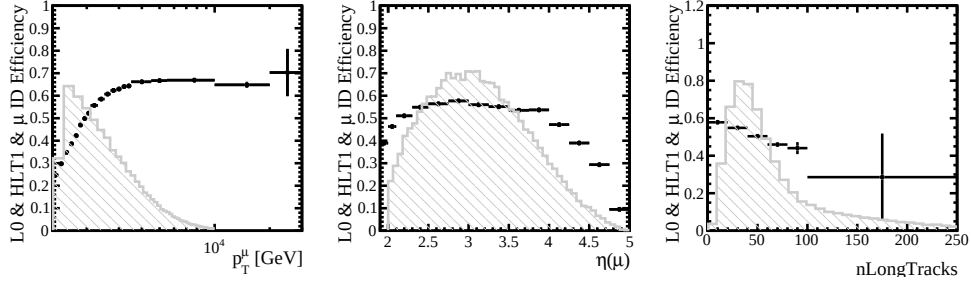


Figure 188: Total L0+HLT1+Muon ID efficiencies determined in the calibration sample in bins of muon p_T (left) and η (middle), and nLongTracks (right). The gray histograms show the distributions in MC before any trigger or muon ID with arbitrary normalization.

efficiencies in data are consistent with HLT2 absolute efficiencies in the signal MC. It is important to check these efficiencies wherever possible as they don't cancel in the ratio. There is also the question whether the TISTOSing works properly in this data due to a known software bug which affected the TISTOS trigger information stored in stripped data due to conflicts with the Turbo lines. This bug was known to influence data and MC equivalently.

To first order the integrated yields and HLT2 TISTOS efficiencies are compared in data processed with two separate DaVinci versions (v41r2p1 and v42r6p1; latter contains software fix). At this level it is quantified how much the bug affects the signal channels. In the case of the yields, it is found that they are consistent (but slightly higher in new DV) within 0.5% for the Λ_c mode and within 0.1% for all other modes. The largest relative uncertainty on the yield is for the $D_s^+ \mu^-$ mode which is 0.13%, and rounded up to 0.1% for the Λ_c mode. All the others are less than 0.1%. Thus, a 0.4% effect is seen in the Λ_c mode not accounted for within uncertainties. The HLT2 TISTOS efficiencies are evaluated in the same way for both DaVinci versions and are compiled for all modes in Figures 189 through 192. Here consistency in TISTOS efficiencies is found across all kinematic bins in all modes. At this level there little effect due to the software bug with the maximum effect being 0.4%.

As another check on TISTOSing, with MC compared are the absolute efficiency by cutting on the trigger decision on top of all other selections, and the TISTOS efficiency. This is done

with the HLT2 trigger in all modes. Figure 193 shows these comparisons in bins of b-hadron η and $p_T(\text{charm} + \mu)$. While the binning in $p_T(\text{charm} + \mu)$ have too few statistics the η projections shows consistency between both sets of efficiencies within statistics.

To further validate TISTOSing in data also compared are the absolute L0 (on top of selections+PID) and HLT1 (on top of L0) efficiencies with their respective TISTOS efficiencies in the same MC samples. These comparisons are shown in Figures 194 and 195 for L0 and HLT1, respectively. In these figures there are more statistics to make a useful comparison in both binning schemes. In all cases excellent agreement is found between the absolute efficiencies and TISTOS efficiencies.

To conclude in all MC checks at all trigger levels consistency is found between absolute and TISTOS efficiencies, and between TISTOS in data and both MC absolute and TISTOS efficiencies. TISTOS efficiencies in data processed with the two different DaVinci versions are identical within uncertainties. These tests are indicating no issues in the TISTOS method. The maximum effect seen due to the software bug as determined in the integrated data yields is 0.4%.

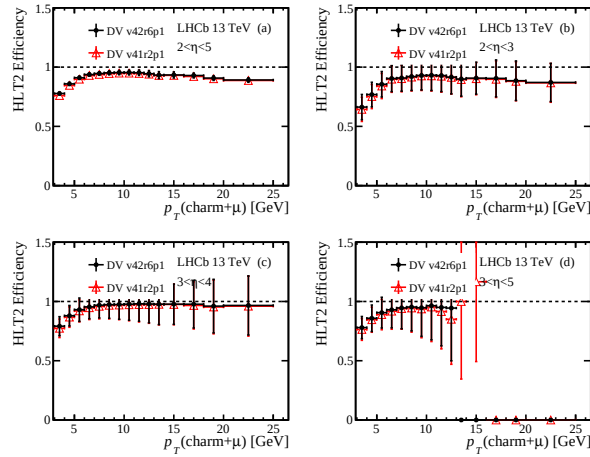


Figure 189: Efficiencies for the HLT2 topological triggers for $D^0\mu X$ mode determined using the TISTOS method in signal data compared between both DaVinci versions. DaVinci v42r6p1 contains the bug fix.

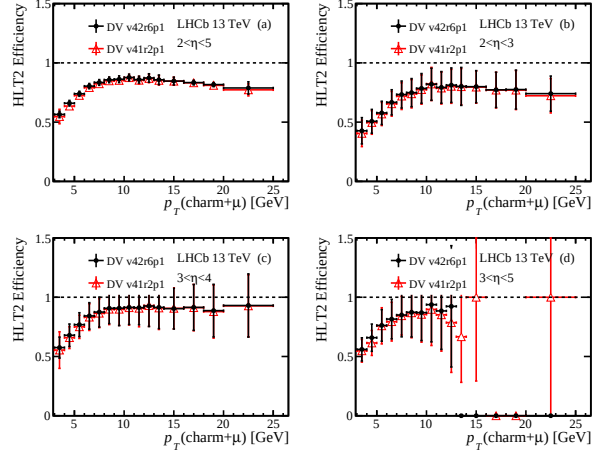


Figure 190: Efficiencies for the HLT2 topological triggers for $D^+\mu X$ mode determined using the TISTOS method in signal data compared between both DaVinci versions. DaVinci v42r6p1 contains the bug fix.

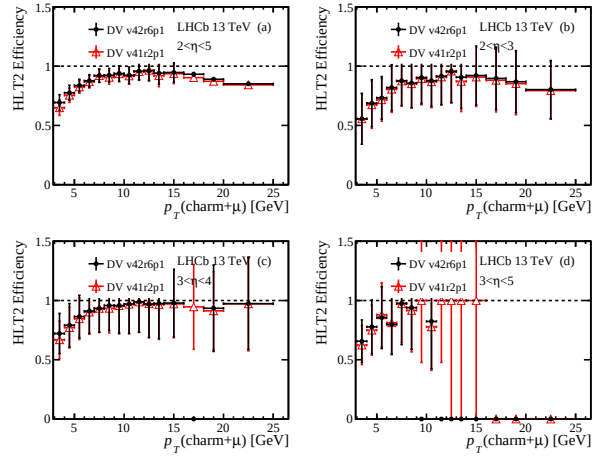


Figure 191: Efficiencies for the HLT2 topological triggers for $D_s^+\mu X$ mode determined using the TISTOS method in signal data compared between both DaVinci versions. DaVinci v42r6p1 contains the bug fix.

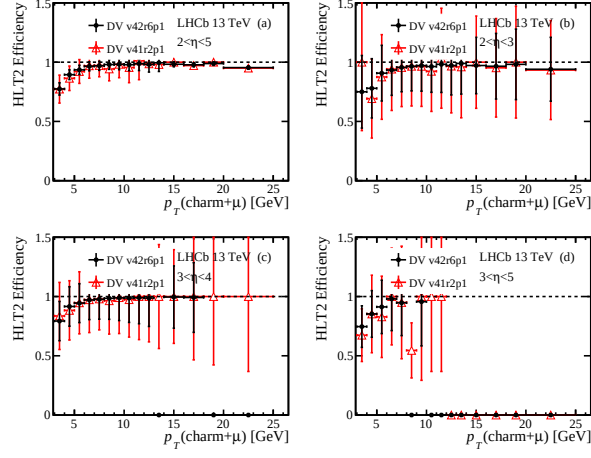


Figure 192: Efficiencies for the HLT2 topological triggers for $\Lambda_c^+ \mu X$ mode determined using the TISTOS method in signal data compared between both DaVinci versions.

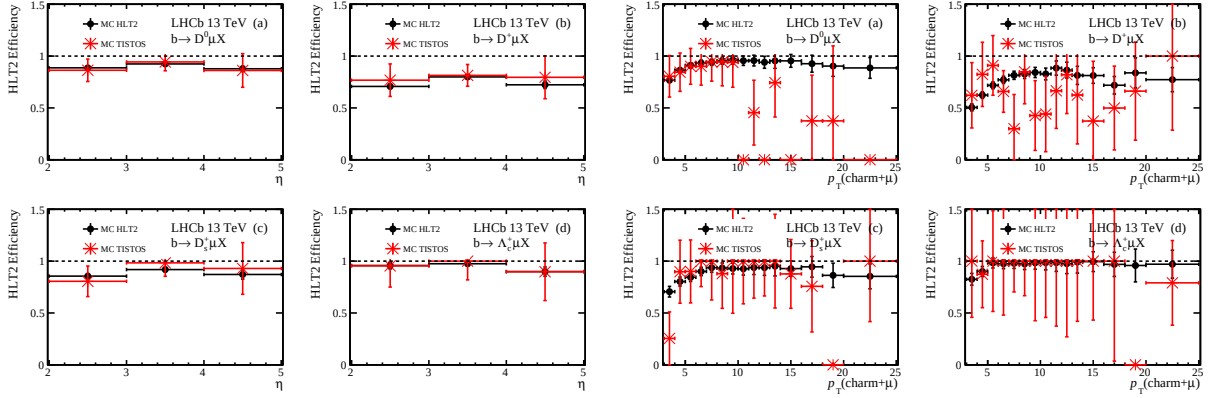


Figure 193: Comparisons between an absolute MC HLT2 efficiency by cutting on the HLT2 variables on top of all other selections, and the TISTOS efficiency using the same MC sample in bins of b -hadron kinematics.

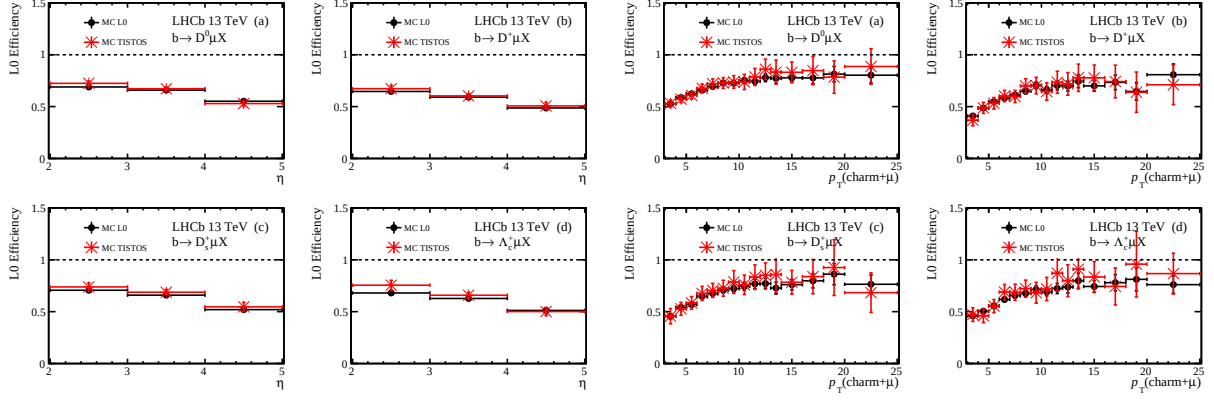


Figure 194: Comparisons between an absolute MC HLT2 efficiency by cutting on the L0 variables on top of offline and PID selections, and the TISTOS efficiency using the same MC sample in bins of b -hadron kinematics.

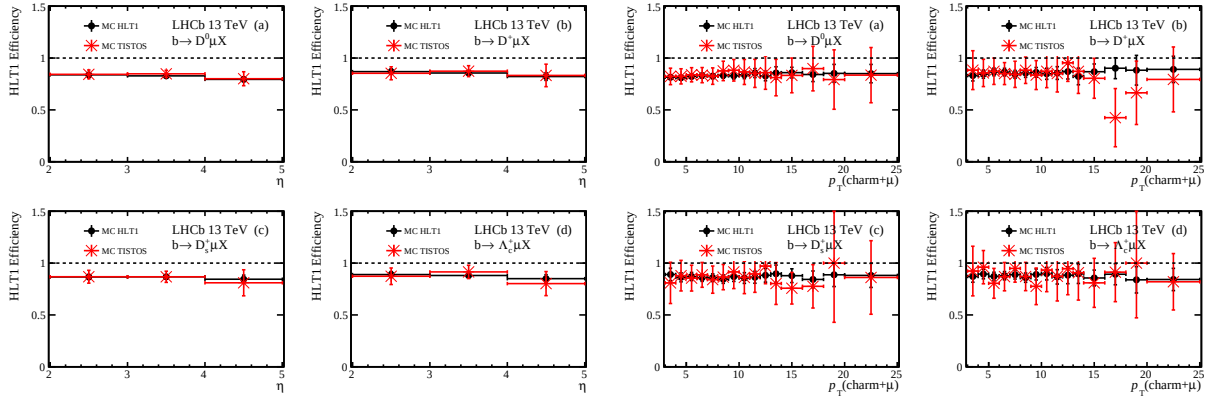


Figure 195: Comparisons between an absolute MC HLT2 efficiency by cutting on the HLT1 variables on top of L0, and the TISTOS efficiency using the same MC sample in bins of b -hadron kinematics.

B.5 Covariance matrix

Table 45: Values of $f_s/(f_u + f_d)$ and $f_{\Lambda_b}/(f_u + f_d)$ in each $p_T(B)$ bin. The first uncertainty is statistical and incorporates both the uncertainties due to the data sample size and the finite amount of simulated events, while the second is the overall systematic uncertainty, including global and bin-dependent systematic uncertainties.

$p_T(B)[GeV]$	$f_s/(f_u + f_d)$	$f_{\Lambda_b}/(f_u + f_d)$
4–5	$0.125 \pm 0.0007 \pm 0.0072$	$0.324 \pm 0.0012 \pm 0.0251$
5–6	$0.125 \pm 0.0006 \pm 0.0070$	$0.281 \pm 0.0008 \pm 0.0183$
6–7	$0.122 \pm 0.0005 \pm 0.0062$	$0.257 \pm 0.0007 \pm 0.0166$
7–8	$0.125 \pm 0.0005 \pm 0.0063$	$0.245 \pm 0.0006 \pm 0.0166$
8–9	$0.116 \pm 0.0005 \pm 0.0058$	$0.227 \pm 0.0006 \pm 0.0152$
9–10	$0.120 \pm 0.0005 \pm 0.0061$	$0.210 \pm 0.0006 \pm 0.0148$
10–11	$0.121 \pm 0.0006 \pm 0.0063$	$0.194 \pm 0.0006 \pm 0.0131$
11–12	$0.116 \pm 0.0006 \pm 0.0062$	$0.191 \pm 0.0007 \pm 0.0141$
12–13	$0.116 \pm 0.0007 \pm 0.0064$	$0.172 \pm 0.0007 \pm 0.0129$
13–14	$0.122 \pm 0.0008 \pm 0.0071$	$0.159 \pm 0.0007 \pm 0.0117$
14–16	$0.112 \pm 0.0006 \pm 0.0061$	$0.165 \pm 0.0006 \pm 0.0115$
16–18	$0.107 \pm 0.0007 \pm 0.0064$	$0.136 \pm 0.0007 \pm 0.0100$
18–20	$0.115 \pm 0.0010 \pm 0.0079$	$0.126 \pm 0.0008 \pm 0.0100$
20–25	$0.111 \pm 0.0009 \pm 0.0072$	$0.109 \pm 0.0007 \pm 0.0086$

Table 46: Covariance matrix of the measured ratio $f_s/(f_u + f_d)$ in bins of b -hadron p_T .

p_T [GeV]	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-16	16-18	18-20	20-25
4-5	2.30E-05	3.80E-06	1.84E-06	1.53E-06	9.28E-07	1.54E-06	1.77E-06	9.05E-07	7.47E-07	6.99E-07	6.46E-07	6.84E-07	5.47E-07	5.55E-07
5-6	3.80E-06	1.96E-05	2.37E-06	2.02E-06	1.23E-06	2.03E-06	2.36E-06	1.22E-06	1.04E-06	9.64E-07	8.94E-07	9.85E-07	8.04E-07	8.00E-07
6-7	1.84E-06	2.37E-06	1.10E-05	1.08E-06	6.71E-07	1.14E-06	1.32E-06	6.94E-07	5.83E-07	5.46E-07	5.18E-07	5.60E-07	4.67E-07	4.89E-07
7-8	1.53E-06	2.02E-06	1.08E-06	1.08E-05	6.46E-07	1.10E-06	1.27E-06	6.75E-07	5.73E-07	5.43E-07	5.08E-07	5.48E-07	4.80E-07	4.86E-07
8-9	9.28E-07	1.23E-06	6.71E-07	6.46E-07	8.73E-06	7.73E-07	9.09E-07	5.07E-07	4.26E-07	4.04E-07	3.79E-07	4.16E-07	3.77E-07	3.88E-07
9-10	1.54E-06	2.03E-06	1.14E-06	1.10E-06	7.75E-07	1.09E-05	1.66E-06	9.39E-07	8.03E-07	7.62E-07	7.24E-07	7.77E-07	7.01E-07	7.34E-07
10-11	1.77E-06	2.36E-06	1.32E-06	1.27E-06	9.09E-07	1.66E-06	1.33E-05	1.13E-06	9.90E-07	9.33E-07	9.37E-07	1.00E-06	9.03E-07	9.58E-07
11-12	9.05E-07	1.22E-06	6.94E-07	6.75E-07	5.07E-07	9.39E-07	1.13E-06	1.33E-05	5.94E-07	5.64E-07	5.74E-07	6.24E-07	5.73E-07	6.17E-07
12-13	7.47E-07	1.04E-06	6.94E-07	6.75E-07	5.07E-07	9.39E-07	1.13E-06	1.33E-05	5.94E-07	5.64E-07	5.74E-07	6.24E-07	5.73E-07	6.17E-07
13-14	6.99E-07	9.64E-07	5.43E-07	5.43E-07	4.04E-07	7.62E-07	9.33E-07	5.94E-07	5.42E-07	5.42E-07	5.31E-07	6.33E-07	5.98E-07	6.08E-07
14-16	6.46E-07	8.94E-07	5.18E-07	5.08E-07	3.79E-07	7.24E-07	9.37E-07	5.64E-07	5.42E-07	5.31E-05	1.32E-05	7.11E-07	6.66E-07	7.27E-07
16-18	6.84E-07	9.85E-07	5.60E-07	5.48E-07	4.80E-07	5.48E-07	1.00E-06	6.24E-07	6.33E-07	6.33E-07	7.11E-07	1.96E-05	8.08E-07	9.33E-07
18-20	5.47E-07	8.04E-07	4.67E-07	4.80E-07	3.77E-07	7.01E-07	9.03E-07	5.73E-07	5.73E-07	5.98E-07	6.66E-07	8.08E-07	3.71E-05	9.58E-07
20-25	5.55E-07	8.00E-07	4.89E-07	4.86E-07	3.88E-07	7.34E-07	9.58E-07	6.17E-07	6.08E-07	6.13E-07	7.27E-07	9.33E-07	9.58E-07	2.93E-05

Table 47: Covariance matrix of the measured ratio $f_{\Lambda_b}/(f_u + f_d)$ in bins of b -hadron p_T .

p_T [GeV]	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-16	16-18	18-20	20-25
6-20E-6	3.10E-6	2.60E-6	3.46E-6											
5-6	3.21E-5	4.34E-5	5.05E-6	1.30E-5	8.90E-6	1.12E-5	4.47E-6	9.65E-6	7.12E-6	3.73E-6	1.80E-6	9.11E-7	7.82E-7	1.12E-6
6-7	2.08E-5	5.05E-6	2.99E-5	9.39E-6	6.55E-6	8.41E-6	3.35E-6	7.43E-6	5.44E-6	2.86E-6	1.43E-6	7.04E-7	6.25E-7	8.96E-7
7-8	5.03E-5	1.30E-5	9.39E-6	5.32E-5	1.97E-5	2.56E-5	1.05E-5	2.26E-5	1.72E-5	9.14E-6	4.53E-6	2.33E-6	2.04E-6	3.01E-6
8-9	3.36E-5	8.90E-6	6.55E-6	1.97E-5	3.96E-5	2.10E-5	8.88E-6	1.95E-5	1.47E-5	7.91E-6	3.91E-6	2.03E-6	1.75E-6	2.75E-6
9-10	4.21E-5	1.12E-5	8.41E-6	2.56E-5	2.10E-5	5.44E-5	1.27E-5	2.81E-5	2.14E-5	1.21E-5	5.88E-6	3.11E-6	2.69E-6	4.44E-6
10-11	1.60E-5	4.47E-6	3.35E-6	1.05E-5	8.88E-6	1.27E-5	3.03E-5	1.33E-5	1.10E-5	6.15E-6	3.07E-6	1.67E-6	1.43E-6	2.48E-6
11-12	3.50E-5	9.65E-6	7.43E-6	2.26E-5	1.95E-5	2.81E-5	1.33E-5	6.41E-5	2.54E-5	1.42E-5	7.23E-6	3.98E-6	3.44E-6	5.86E-6
12-13	2.47E-5	7.12E-6	5.44E-6	1.72E-5	1.47E-5	2.14E-5	1.10E-5	2.54E-5	5.71E-5	1.36E-5	6.78E-6	3.85E-6	3.41E-6	6.10E-6
13-14	1.30E-5	3.73E-6	2.86E-6	9.14E-6	7.90E-6	1.21E-5	6.15E-6	1.42E-5	1.36E-5	4.37E-5	4.23E-6	2.47E-6	7.22E-6	3.88E-6
14-16	6.20E-6	1.80E-6	1.43E-6	4.53E-6	3.91E-6	5.88E-6	3.07E-6	7.23E-6	6.78E-6	4.23E-6	3.01E-5	1.35E-6	1.21E-6	2.24E-6
16-18	3.10E-6	9.11E-7	7.04E-7	2.33E-6	2.03E-6	3.11E-6	1.67E-6	3.85E-6	3.85E-6	2.47E-6	1.35E-6	3.17E-5	8.03E-7	1.54E-6
18-20	2.61E-6	7.82E-7	6.25E-7	2.04E-6	1.75E-6	2.67E-6	1.43E-6	3.44E-6	3.41E-6	2.22E-6	1.21E-6	8.03E-7	4.21E-5	1.62E-6
20-25	3.46E-6	1.12E-6	8.97E-7	3.01E-6	2.75E-6	4.44E-6	2.48E-6	5.83E-6	6.10E-6	3.88E-6	2.24E-6	1.54E-6	1.62E-6	3.09E-5

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