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PRECISION MEASUREMENT OF TIME-DEPENDENT CHARM OBSERVABLES AT HIGH-LUMINOSITY LHCb

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Ai miei genitori

PREFACE

LHCb is an experiment dedicated to the study of heavy-flavor processes at the Large Hadron Collider at CERN. The large production cross section for heavy quarks (bottom and charm) available at LHC, and the excellent performance of the detector, have allowed the LHCb collaboration to publish many new results in the field during the past two data taking runs of the LHC. In particular, measurements in the charm sector have been able to exploit unprecedented samples of up to $\mathcal{O}(10^9)$ fully reconstructed decays, leading to many precision measurements, including the first observation of CP violation in the up-quark sector, published in 2019.

Precision measurements of this kind are of great importance in advancing our understanding of fundamental physics, particularly regarding the breaking of fundamental symmetries like CP , the combined transformation of charge-conjugation (C) and parity (P). CP violation is allowed in the Standard Model (SM) by the existence of a complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix, but has no known fundamental explanation, and its observed strength in known phenomena seems unable to account for cosmological observations like the matter-anti-matter abundance ratio. This puts into question our real understanding of the phenomenon, and strongly motivates further experimental explorations, that might reveal the existence of new fundamental dynamics. This is particularly true in the charm sector, given the limited experimental knowledge currently available.

It is therefore hardly surprising that the precision study of charm observables keeps a prominent position in the LHCb physics plans throughout the end of the LHC program, when a factor thirty larger samples are expected. However, implementation of this plan requires keeping extremely small systematic uncertainties, while operating the LHCb detector at larger and larger beam luminosities and data rates. It cannot therefore be achieved just by passive data accumulation, but requires an effort to upgrade the analysis methodology and the online data selection to levels of precision that have not been attained in the field before.

In this thesis, I consider the precision measurement of the y_{CP} parameter in neutral charm meson oscillations, and study the ways in which the analysis methodology could be improved to make it successfully applicable also to future data, starting from the very next run beginning in the current year. Given the decay to the CP -even final state $D_0(\bar{D}_0) \rightarrow h^+h^-$ ($h = K, \pi$) and the flavor

specific decay $D_0(\bar{D}_0) \rightarrow K^-\pi^+$, it can be written:

$$y_{CP} \approx \frac{\hat{\Gamma}(D^0 \rightarrow h^+h^-) + \hat{\Gamma}(\bar{D}^0 \rightarrow h^+h^-)}{\hat{\Gamma}(D^0 \rightarrow K^-\pi^+) + \hat{\Gamma}(\bar{D}^0 \rightarrow K^+\pi^-)} - 1,$$

with $\hat{\Gamma}$ being the *effective decay width* concerning the process of interest. The measurement of the parameter y_{CP} is of considerable interest in the context of CP -violation in the charm sector. In case of CP -violation, y_{CP} is expected to deviate from the value of the mixing parameter $y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$, where $\Gamma_{1,2}$ represent decay widths of the CP eigenstates $D_{1,2}$ (respectively CP -even and CP -odd) of the charmed neutral meson, and Γ their mean value. Knowledge of the parameter y_{CP} with good precision, and its incompatibility with y , would not only shed light on this symmetry-violating mechanism, but would also offer better constraints on the other CP -violating parameters regarding the charm sector.

With y_{CP} defined this way, its value can be accessed through a ratio of decay time distributions, meaning that many systematic effects cancel out. This is the route taken by the last LHCb measurement of such parameter, that has just been published. It was measured $y_{CP} = (6.96 \pm 0.26_{stat.} \pm 0.13_{syst.}) \times 10^{-3}$.

This came four years after the previous Run 1 based measurement, released in 2018, and required the formulation of a different analysis approach. The issue lies in how precise the determination of the efficiency map, for the tracks of the final state particles produced in the two-body neutral D meson decay, can be, for it constitutes the greatest contribution to the systematic uncertainty. As a matter of fact, this efficiency presents enough difference between the $D^0 \rightarrow hh$ and $D^0 \rightarrow K\pi$, that it manifests even in the ratio between the decay widths and the Monte Carlo simulations of the detector cannot reproduce these effects with enough accuracy. In the current measurement, this issue has been faced by equalizing the selection efficiencies, with a kinematic matching between the different decay modes (hh and $K\pi$), and equalizing the detection efficiencies through a kinematic re-weighting of the distributions. In spite of the progress achieved with this new method, this analysis approach is not guaranteed to be of use for further measurements in the future.

First and foremost, this technique relies completely on the existence of a special trigger line dedicated to lifetime measurements (LTUNB). In exchange for a reduced bias on decay time measurements, this selection yields a considerably less pure sample, in comparison with “standard” charm trigger lines. As a consequence, it has a pretty high rate of accepted events, that had to be manually reduced by randomly discarding a significant fraction of events (“prescale”), already at the luminosity of Run 2. At higher luminosities, starting already from the next run, this kind of selection would need even higher prescale factors, and most likely will not be implemented at all, as it will do little to increase the size of current sample. Second, as the luminosity increases, so does the Primary Vertex (PV) multiplicity per beam crossing. This increases the probability of PV misassignment, resulting in a bias on the lifetime measurement. Third, the uncertainty in the determination of the efficiency map in the current measurement does not scale down with increasing samples, and its contribution to the systematic uncertainty will overwhelm the statistical power offered by Run 3. This uncertainty will be much larger when analyzing a sample of data collected by the regular charm trigger. The future data will necessarily have much tighter cuts and much larger

inefficiencies; and yet we need to further lower our uncertainty if we are to further improve this measurement.

Therefore, a whole new methodology needs to be introduced. Obviously, this is relevant not only for the measurement of y_{CP} , but also for many other measurements relying on precision determination of lifetimes. The aim of this thesis is forging a pathway secure enough to allow charm time-dependent measurements in a high-luminosity scenario.

Regarding the issue of PV misassignment, I demonstrate, via extensive use of Monte Carlo simulations, that negligible loss of accuracy and precision ($< 4 \times 10^{-4}$) arise on lifetime measurements if purely transverse variables are used in computing the flight-distance of the charmed meson, and an average PV transverse position is used instead of an event-by-event PV. This provides a robust method of measuring lifetimes, insensitive to the occurrence of mismatches between PV and decay candidates.

Moving on to the point concerning the efficiency map, I investigate whether the reconstruction efficiency can be extracted with a completely data-driven approach. A self-calibration of the efficiency is indeed possible, exploiting the conspicuous size of the available data samples and observing correlations between the distributions of a “standard-candle” decay. Such “standard-candle” can be identified as the two-body decay of a scalar particle: analyzing the correlations between the kinematic distributions of the decay products allows to extract constraints on the efficiency responses among different detector regions, leading to an accurate efficiency map. Another advantage of this method is that it can also be applied to the same data set used for the lifetime measurement, an *in-situ* calibration is then possible, as for the $D^0 \rightarrow hh, K^- \pi^+$ decays.

This new approach has therefore significant advantages over the methodology used in the current measurement, that requires Monte Carlo simulations for its validation. Being completely data-driven, it is virtually devoid of limits on its precision: the greater the sample, the more precise is the efficiency extraction.

In order to validate the analysis strategy, the efficiency extraction technique is first tested on Toy Monte Carlo simulations, with arbitrarily injected detection efficiencies. It is proved that the simulated mean lifetime is correctly retrieved with an accuracy $< 5 \times 10^{-4}$, along the simulated efficiency shape. Then, the test is repeated with LTUNB Official LHCb Monte Carlo simulations. Again, the extracted lifetime is in agreement with the simulated one within 1σ of the statistical uncertainty reachable with the statistical power of the samples themselves, both for the $D^0 \rightarrow \pi^- \pi^+$ and $D^0 \rightarrow K^- K^+$ processes. Finally, the methodology is tested on real data from the LTUNB trigger line. The test quantity

$$\Delta\tau_{KK-\pi\pi} \equiv \tau(D^0 \rightarrow \pi^- \pi^+) - \tau(D^0 \rightarrow K^- K^+)$$

is measured and found to be compatible with the expected value of zero within 1σ of the statistical uncertainty ($\sim 1\% \tau_{D^0}$ with 1 fb^{-1} of integrated luminosity).

This validates the new analysis approach on the same LTUNB sample used by the current analysis. However, the goal is to establish its usability with the “standard” charm triggers. I tested the procedure using the Run 2 sample from the regular charm trigger, and again found good agreement with the expected zero value within 1σ of the statistical uncertainty - this time with a precision of $\sim 0.25\% \tau_{D^0}$, due to larger yields available in this sample, in spite of the larger efficiency corrections. This proves that the new technique is applicable beyond of

the special limits of the special LTUNB trigger.

I have also researched an alternative technique for the subtraction of the secondary decays backgrounds, that is another current source of systematic uncertainty. All charm samples in LHCb are contaminated by secondary production of charm in decays of B hadrons. These decays are affected by a bias on the decay time due to the production point of the charm particle being erroneously assigned to the PV. Rather than relying on the Monte Carlo model for subtracting the contribution of the secondary decays in the fit of the ratio of lifetimes, as it was done in the last LHCb measurement, I determined the relationship between the true D^0 mean lifetime and the reconstructed decay time, by simulating different values for $\tau(D^0)$. Finding a linear relation between them, with coefficient α , implies that in the measurement of lifetime differences the model-dependent impact of “secondaries” can be suppressed to a degree dependent on α . This means that the extraction of y_{CP} from the difference of lifetimes instead of their ratio, enabled by our new technique of determining efficiency separately for each process, allows for a less model-dependent measurement also for what concerns the secondary contribution.

Taken all together, the studies discussed in this work indicate the existence of a viable path to the highest precision measurements of the y_{CP} observable, up until the end of the LHC program many years from now.

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PART I

INTRODUCTION

CHAPTER

1

TIME-DEPENDENT CHARM OBSERVABLES

In order to understand what time-dependent charm observables are and how they relate to the concept of CP violation and possible New Physics (NP), I will have, firstly, to briefly explain the Standard Model (SM) of particle physics, what CP violation is and how it is modeled within the SM. Only then I can introduce charm physics, its observables and the current state of art – and common issues – about measuring such parameters.

1.1 The Standard Model

The Standard Model (SM) is a theory of particle physics, describing the strong and electro-weak interactions between elementary particles. It stems [1] from the work of notable physicists, who across the 20th century have vastly contributed to the comprehension of this branch of physics, spanning from Weyl’s first gauge concept in 1918 [2,3] to the Quantum Chromodynamics Lagrangian (Fritzsh, Gell-Mann and Lautweyler), published in 1973 [4], and including at-the-time innovative ideas such as Dirac’s predicted anti-particles [5], Yukawa’s coupling [6], Yang-Mills theory [7], Lee and Yang’s work on parity violation in weak currents [8], Brout-Englert-Higgs’s mechanism [9,10], existence of quarks and their color charge [11–14], electroweak unification [15–17], ’t Hooft’s renormalizability of gauge theories with Spontaneous Symmetry Breaking¹ [18].

Essentially, the SM is a local, gauge-invariant quantum field theory defined by a non-abelian group of symmetry, under whose action the Lagrangian is invariant. This gauge group of symmetry is

$$G_{SM} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y,$$

¹ For a more in-depth discussion of the various contributions in theoretical physics leading to the final structure of the Standard model, and its history, we refer the reader to the source [1].

where $SU(3)_C$ describes the phenomenology of strong interaction [11–14], with C being the color charge of the fields on which the group transformation acts; $SU(2)_L \otimes U(1)_Y$ refers to the electroweak interaction as Salam-Weinberg-Glashow have modeled it with their unified theory [15–17], here L stands for the *chirality* of the weak interaction and y is the *hypercharge*.

In the current view, all matter is made out of three kinds of elementary particles: leptons, quarks and mediators [19]. While the latter transform as the adjoint representation of G_{SM} , the first two are representations of the same group and the dimension of such representations can compactly indicate the transformation properties of the fields under G_{SM} , and, therefore, how the particle interacts through a certain fundamental force [1, 20]. Adopting the notation $f_{\xi i}^I (n_{SU(3)}, n_{SU(2)})_Y$, where f is the spinor field, or the multiplet of spinor fields, describing the fermions, whether they be quarks or leptons, $\xi = R, L$ is the chirality, I is the interaction eigenstate and $n_{SU(N)}$ is the dimension of the representation of the expressed group, the quarks and the leptons can be described with:

$$Q_{Li}^I(3, 2)_{+1/6}, \quad u_{Ri}^I(3, 1)_{+2/3}, \quad d_{Ri}^I(3, 1)_{-1/3}, \quad L_{Li}^I(1, 2)_{-1}, \quad l_{Ri}^I(1, 1)_{-1},$$

with $i = 1, 2, 3$ as the flavor eigenstate, for each quark, lepton field is replicated in three generations.

Were it be the end of the constituents building the SM, then the model would have failed long ago. In fact, the gauge bosons, mediators of the weak interaction, arising from the $SU(2)_L$ symmetry, would be massless, whereas they were expected to be massive in order to accommodate for the fact that the weak interaction is short range. Artificially adding a mass term to the theory is out of question as, then, the gauge symmetry would be violated and the theory would become non-renormalizable due to the bad ultraviolet behavior for the gauge boson propagator, induced by its mass [21]. The masses, then, need to spontaneously arise from within the theory itself, a feat made possible thanks to the Brout-Englert-Higgs (BEH) mechanism which involves spontaneous symmetry breaking [9, 10].

As the BEH mechanism has to generate the $W^\pm$ and Z masses, a weak isospin $SU(2)$ doublet is introduced as follows

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}. \quad (1.1.1)$$

Its Lagrangian term is

$$\mathcal{L}_{Higgs} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi) \quad (1.1.2)$$

where the Higgs potential is

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2. \quad (1.1.3)$$

If $\mu^2 < 0$, the potential has an infinite set of degenerate minima satisfying

$$\phi^\dagger \phi = \frac{1}{2}(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = \frac{v^2}{2} = -\frac{\mu^2}{2\lambda}. \quad (1.1.4)$$

Choosing one of those minima means breaking the symmetry, and as the photon needs to remain massless, once the symmetry is broken, the minimum has to be

chosen so that only the charge-less component ϕ_0 of the field acquire a non-zero vacuum expectation value v , that is

$$\langle 0|\phi|0\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}. \quad (1.1.5)$$

With an appropriate choice of gauge in order to take out the Goldstone boson produced by the symmetry breaking, and once the complex scalar field is expanded about the physical vacuum, one finds [22]

$$\phi = \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}. \quad (1.1.6)$$

Having defined the gauge symmetry, the primary constituents and the BEH mechanism, the Lagrangian of the SM can now written as [23]:

$$\mathcal{L} = \mathcal{L}_{kinetic} + \mathcal{L}_{gauge} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa} \quad (1.1.7)$$

where the interaction between bosons and fermions is described by the kinetic term

$$\mathcal{L}_{kinetic} = \bar{\psi} \gamma^\mu i D_\mu \psi, \quad (1.1.8)$$

with ψ ($\bar{\psi} = \psi^* \gamma^0$) being the Dirac spinor (adjoint spinor), γ are the Dirac matrices and D_μ is the covariant derivative, which is

$$D_\mu = \partial_\mu + \frac{ig}{2} W_\mu^\alpha \sigma_\alpha + \frac{ig'}{2} B_\mu Y + \frac{ig_s}{2} G_\mu^a \lambda_a. \quad (1.1.9)$$

Here the $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$ generators appear respectively as Y, σ_α and λ_a ; g, g' and g_s are the coupling constants. Moving on, the gauge kinetic term is

$$\mathcal{L}_{gauge} = -\frac{1}{4} \left(G_{\mu\nu}^a G_{\mu\nu}^a + W_{\mu\nu}^b W_{\mu\nu}^b + B_{\mu\nu} B_{\mu\nu} \right), \quad (1.1.10)$$

with $G_{\mu\nu}^a$ as the tensor representing the gluon fields ($a = 1, \dots, 8$) mediating the strong interaction, $W_{\mu\nu}^b$ as the tensor representing the three weak mediators ($b = 1, 2, 3$) and $B_{\mu\nu}$ the electromagnetic tensor. As $\mathcal{L}_{Higgs}$ has already been described in Eq. 1.1.2, it remains to be defined only

$$\mathcal{L}_{Yukawa} = -Y_{ij}^d \bar{Q}_{Li}^I \phi d^{Rj} - Y_{ij}^u \bar{Q}_{Li}^I \tilde{\phi} u^{Rj} - Y_{ij}^l \bar{L}_{Li}^I \phi \ell^{Rj} + h.c. \quad (1.1.11)$$

describing how the Higgs fields affects the fermion masses, with $i, j = 1, 2, 3$ being again the flavor (generation) index and $\tilde{\phi} = i\sigma_2 \phi^\dagger$.

One last fundamental missing piece must be illustrated before moving on charm physics. In fact, until 1957 with the experiment of Madame Wu [24], spatial parity P , which is the inversion of the spatial coordinates, and charge conjugation C , reversing all discrete additive quantum numbers of the particle, were presumed to be conserved and the Lagrangian be symmetric under such discrete transformations. The experiment, however, proved that β -decays violated C -parity. This result was promptly confirmed by another experiment conducted by Garwin, Lederman and Weinrich, who by observing the magnetic moment of muons produced in pion decays reached the same conclusion [25]. The phenomenon could still have been attributed to some unknown propriety of leptons if not for the work of Conversi *et al.*, who in the same year demonstrated parity

non-conservation in hyperon decays [26], thus promoting the effect from a possible lepton anomaly to a characteristic of the weak interaction.

After these experiments, it was assumed that at least CP , which is the combined action of P and C thus transforming a particle in its antiparticle, was conserved. However, in 1964 Christenson, Cronin and Fitch found that the weak decay $K_L \rightarrow 2\pi$ violated CP . A question, then, arises: how can CP violation (CPV) enter the Standard Model?

The answer is simpler than expected². When the coupling of weak interaction seemed not to comply to the principle of universality, providing different strengths between reactions with $\Delta S = 0$ and $\Delta S \neq 0$, with S being the *strangeness* of the initial/final state, Cabibbo, in 1963, proposed the concept that, for at-the-time known quarks (u , d and s), the d mass eigenstates and the weak interaction eigenstates were not the same, but that the passage from one to the other was possible through a rotation, introducing the Cabibbo angle θ_c . This way universality was saved as the observed different strength of interaction were due to the multiplicative $\sin \theta_c$ or $\cos \theta_c$ term coming from the rotation [27]. Cabibbo focused on weak charged currents but later in 1970, in order to explain the apparent absence of strangeness-changing neutral currents, Glashow, Iliopoulos and Maiani proposed the existence of a forth quark s' , orthogonal to the d' rotated one, obtaining [28]

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos \theta_c & \sin \theta_c \\ -\sin \theta_c & \cos \theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}. \quad (1.1.12)$$

In 1974, the charm quark was indeed discovered.

Armed with the knowledge of this rotation matrix which transforms mass eigenstates in weak interaction eigenstates, the concept could be extended to the three hitherto known generations of quarks.

In 1973 Kobayashi and Maskawa introduced a 3×3 unitary mixing matrix [29], later known as the Cabibbo–Kobayashi–Maskawa (CKM) matrix

$$V_{\text{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \quad (1.1.13)$$

so that once $SU(2)_L \otimes U(1)_Y$ symmetry is broken to $U(1)_{em}$ and the charge eigenstates of the weak gauge bosons emerge as $W_\mu^\pm = (W_\mu^1 \mp W_\mu^2)/\sqrt{2}$, then the charged current interactions can be expressed in the mass basis with the following form

$$\mathcal{L}_{W^\pm} = -\frac{g}{\sqrt{2}} \bar{u}_L^i \gamma^\mu (V_{\text{CKM}})_{ij} d_L^j W_\mu^\pm + h.c. . \quad (1.1.14)$$

This matrix allows for the existence of CPV : in fact, a general complex matrix would have $2n^2$ degrees of freedom, but unitary condition imposes n^2 constraints, leaving behind n^2 free parameters. Of these $n(n-1)/2$ are real, whereas $n(n+1)/2$ are complex phases. From eq. 1.1.14, it can be observed that the Lagrangian is invariant under the redefinition of the phases of each quark field, which are, generally $2n$, taking out $2n$ complex phases from the matrix. However, the Lagrangian is also invariant for a redefinition of the global phase of V_{CKM} , therefore one phase is “replugged-in”. In the end, $n(n-1)/2$ real parameter and $(n-2)(n-1)/2$ complex phases remain. In the case $n = 3$, there are therefore three real rotation

² Simpler if compared to the work necessary to account for massive gauge boson and discussed above.

angles and one complex phase, which permits the violation of CP^3 . Therefore, the CKM matrix can be rewritten as [30]

$$V_{\text{CKM}} = \begin{bmatrix} c_{12}c_{13} & s_{12}s_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{-i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{-i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{-i\delta} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{-i\delta} & c_{23}c_{13} \end{bmatrix}. \quad (1.1.15)$$

If the matrix is expressed in the Wolfenstein parametrization [31], the contribution of the various components is made manifest. Defining

$$\lambda = s_{12}, \quad A\lambda^2 = s_{23}, \quad A\lambda^3(\rho - i\eta) = s_{13}e^{-i\delta},$$

with $\lambda = |V_{us}| \approx 0.22$ and expanding to the order $\mathcal{O}(\lambda^5)$, it can be written

$$V_{\text{CKM}} = \begin{bmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + \frac{1}{2}\lambda^5 A^2 [1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) & A\lambda^2 \\ A\lambda^3 [1 - (\rho + i\eta)] + \frac{1}{2}\lambda^5 A(\rho + i\eta) & -A\lambda^2 + \frac{1}{2}\lambda^4 A [1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}\lambda^4 A^2 \end{bmatrix} + \mathcal{O}(\lambda^6).$$

It appears to be close to the identity matrix with small off-diagonal contributions. This leads to conclude that mixing between generation is allowed, but suppressed with respect to transitions within the same generation. From the expansion it can also be read that mixing between the first and second generation is of order $\mathcal{O}(10^{-1})$, between the second and third generation, $\mathcal{O}(10^{-2})$, and, finally, for the first and third ones, $\mathcal{O}(10^{-3})$.

As of 2020, from a global fit to all experimental observables, the magnitudes of the CKM elements are known to be [32]

$$V_{\text{CKM}} = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & (3.82 \pm 0.24) \times 10^{-3} \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & (41.0 \pm 1.4) \times 10^{-3} \\ (8.0 \pm 0.3) \times 10^{-3} & (38.8 \pm 1.1) \times 10^{-3} & 1.013 \pm 0.030 \end{bmatrix}.$$

From these measurements, focusing on the first line, a tension of about 3σ appears to be present between $|V_{ud}| + |V_{us}| + |V_{ub}| = 0.9985 \pm 0.0005$ and the expected value of 1, required by the unitarity condition of the matrix. Addressing also the fact that the observed strength of CPV cannot account for the dominance of matter against antimatter, it is only natural to consider the SM only a low-energy of a more complex unified theory, where gravitation could also find its place among the other fundamental forces. Consequently, sources of CPV outside those foreseen by the SM are thoroughly investigated. For such studies, the charm sector offers an interesting landscape due to its unique position among the up-type quarks, given that it can decay through many processes useful for probing CPV , differently from the t quark, that hadronizes before decaying, and the u quark that, being the lightest one, does not offer processes of interest. Considering the CKM matrix, for charmed meson the relevant unitary equation is $V_{cd}^* V_{ud} + V_{cs}^* V_{us} + V_{cb}^* V_{ub} = 0$, implying that the approximate estimate of CPV is $\leq \mathcal{O}(V_{cb}^* V_{ub} / V_{cs}^* V_{us}) \sim \mathcal{O}(10^{-3})$.

The smallness of such effect, combined with the very limited knowledge currently available about the charm CPV , results in precision study of charm observables keeping a prominent position in LHCb physics plans, in the quest of searching for possible discrepancies with SM, that might reveal the existence of a new fundamental dynamics.

³ It can be observed that from these relations, CPV is allowed only for $n \geq 3$.

1.2 CP violation in the charm sector

1.2.1 Neutral charm meson system

Oscillation of neutral charm meson between charge conjugates states is a familiar phenomenon arising from the eigenstates of the Hamiltonian, governing the time evolution, being superpositions of the flavor eigenstates:

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle, \quad (1.2.1)$$

with p and q two non-zero complex numbers, satisfying $|p|^2 + |q|^2 = 1$. The phase is chosen so that $CP|D^0\rangle = -|\bar{D}^0\rangle$ and $CP|\bar{D}^0\rangle = -|D^0\rangle$, leading to D_1 being CP -odd and D_2 being CP even, in the case CP were not violated ($p = q$).

The Hamiltonian describing the system can be expressed as [32]

$$\mathcal{H} = \mathbf{M} - i\frac{\mathbf{\Gamma}}{2}. \quad (1.2.2)$$

$\mathbf{M}$ and $\mathbf{\Gamma}$ are two hermitian matrices, with $M_{11} \equiv M_{22}$ and $\Gamma_{11} \equiv \Gamma_{22}$ as required by CPT invariance⁴. The off-diagonal elements of $\mathbf{M}$ and $\mathbf{\Gamma}$ respectively refer to the dispersive and absorbing part of the mixing. The dynamics of the oscillations can be described introducing the two following parameters

$$x = \frac{m_1 - m_2}{\Gamma} \quad \text{and} \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}, \quad (1.2.3)$$

where $m_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths of the $|D_{1,2}\rangle$ eigenstates, and the average decay width has been defined as $\Gamma = (\Gamma_1 + \Gamma_2)/2$.

The decay amplitudes of the $\bar{D}^0$ meson to the final states f and $\bar{f}$ are

$$\begin{aligned} A_f &= \langle f|\mathcal{H}|D^0\rangle, & A_{\bar{f}} &= \langle \bar{f}|\mathcal{H}|D^0\rangle, \\ \bar{A}_f &= \langle f|\mathcal{H}|\bar{D}^0\rangle, & \bar{A}_{\bar{f}} &= \langle \bar{f}|\mathcal{H}|\bar{D}^0\rangle. \end{aligned} \quad (1.2.4)$$

The discrete CP operator acts on the final states as

$$CP|f\rangle = e^{i\nu_f}|\bar{f}\rangle = \rho_f|\bar{f}\rangle, \quad CP|\bar{f}\rangle = e^{-i\nu_f}|f\rangle = \rho_f^*|f\rangle, \quad (1.2.5)$$

ν_f in an arbitrary phase⁵.

The decay amplitudes can be expanded

$$A_f = \sum_k |A_f^k| e^{i\delta_f^k} e^{i\phi_f^k}, \quad \bar{A} = \sum_k |A_{\bar{f}}^k| e^{i\delta_{\bar{f}}^k} e^{-i\phi_{\bar{f}}^k}, \quad (1.2.6)$$

where A_f^k are the magnitudes of the magnitudes relative to each k element. The ϕ_f^k , arising from the CKM mixing matrix, changes sign under CP transformation, whereas δ_f^k are strong phases appearing due to the contribution of intermediate states, but as they originate from the strong interaction they are invariant under CP . Considering not more than two amplitudes, one can write

$$|A_f|^2 - |\bar{A}_f|^2 = -4|A_f^1||A_f^2| \sin(\delta_f^1 - \delta_f^2) \sin(\phi_f^1 - \phi_f^2). \quad (1.2.7)$$

⁴ T is a discrete operator inverting the arrow of time and, whereas CP is proven violated, CPT is assumed to be conserved, due to the CPT theorem.

⁵ For CP -even final states as K^+K^- and $\pi^+\pi^-$ we have $f = \bar{f}$. Then $CP|f\rangle = \eta_{CP}|f\rangle$ with $\eta_{CP} = 1$.

In the case of CPV $|A_f| \neq |\bar{A}_f|$; a variable encapsulating all the possible manifestation of this type of violation is

$$\lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f} = -\eta_f^{CP} R_m R_f e^{i\phi_{\lambda_f}}, \quad (1.2.8)$$

with

$$R_m = \left| \frac{p}{q} \right|, \quad R_f = \left| \frac{\bar{A}_f}{A_f} \right|, \quad \phi_{\lambda_f} = \arg \left(\frac{q}{p} \frac{\bar{A}_f}{A_f} \right). \quad (1.2.9)$$

CP violation occurring in the mixing implies $R_m \neq 1$, when $R_f \neq 1$ then CPV in decay is manifested and then $\phi_{\lambda_f} \neq 0$ probes CPV in the interference between mixing and decay.

1.2.2 CP violation from time-dependent observables

Focusing on Cabibbo suppressed (CS) decays into CP final states, which are the subjects on which the measurement discussed in this thesis will focus, the following observables can be introduced⁶

$$x_{12} \equiv \frac{2|M_{12}|}{\Gamma}, \quad y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma}, \quad \phi_{12} \equiv \arg \left(\frac{M_{12}}{\Gamma_{12}} \right) \quad (1.2.10)$$

and

$$\lambda_f^M \equiv \frac{M_{12}}{|M_{12}|} \frac{A_f}{\bar{A}_f} \equiv \eta_f^{CP} \left| \frac{A_f}{\bar{A}_f} \right| e^{i\phi_f^M} \quad (1.2.11)$$

where the weak phases ϕ_f^M and ϕ_f^Γ abide by $\phi_{12} = \phi_f^M - \phi_f^\Gamma$. In case of no CP violation these phases are equal to the dispersive and absorptive mixing phases ϕ_2^M and ϕ_2^Γ , defined as the phases of M_{12} and Γ_{12} w.r.t. the dominant $\Delta U = 2$ (U -spin) contributions.

Time-dependent asymmetries

As D^0 and $\bar{D}^0$ mesons produced initially in their flavor eigenstate and decaying to final state f after a time t could have oscillated in the meantime, the contribution to the amplitude of the process is twofold:

$$\begin{aligned} A(D^0 \rightarrow f, t) &= \langle D^0 | D^0(t) \rangle A_f + \langle \bar{D}^0 | D^0(t) \rangle \bar{A}_f, \\ A(\bar{D}^0 \rightarrow f, t) &= \langle D^0 | \bar{D}^0(t) \rangle A_f + \langle \bar{D}^0 | \bar{D}^0(t) \rangle \bar{A}_f. \end{aligned} \quad (1.2.12)$$

The time dependent decay rates can be expressed as follows [33]

$$\begin{aligned} \Gamma(D^0 \rightarrow f, t) &\equiv e^{-\Gamma t} |A_f|^2 \left[1 + c_f^+ \Gamma t + c_f'^+ (\Gamma t)^2 \right], \\ \Gamma(\bar{D}^0 \rightarrow f, t) &\equiv e^{-\Gamma t} |\bar{A}_f|^2 \left[1 + c_f^- \Gamma t + c_f'^- (\Gamma t)^2 \right] \end{aligned} \quad (1.2.13)$$

with

$$\begin{aligned} c_f^\pm &\approx \eta_f^{CP} \left[\mp x_{12} \sin \phi_f^M - y_{12} \cos \phi_f^\Gamma (1 \mp a_f^d) \right], \\ c_f'^\pm &\approx \frac{1}{2} \left[y_{12}^2 \pm x_{12} y_{12} \sin \phi_{12} \mp (x_{12}^2 + y_{12}^2) a_f^d \right], \\ a_f^d &\equiv \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2} \approx 1 - \left| \frac{\bar{A}_f}{A_f} \right|. \end{aligned}$$

⁶ This section sources from various works, but, mainly, it closely follows the framework presented in [33].

We can, finally, define the more convenient experimental observables

$$\begin{aligned} y_{CP}^f &\equiv -\frac{c_f^+ + c_f^-}{2} \approx \eta_f^{CP} y_{12} \cos \phi_f^\Gamma, \\ \Delta Y_f &\equiv \frac{c_f^+ - c_f^-}{2} \approx \eta_f^{CP} (-x_{12} \sin \phi_f^M + y_{12} a_f^d). \end{aligned} \quad (1.2.14)$$

In the CP -conserving case, $y_{CP}^f = \eta_f^{CP} y_{12}$ and $\Delta Y_f = 0$.

y_{CP}^f and ΔY_f in experiments

The decay rates expressed in eq. 1.2.13 can be modeled as exponential functions [34, 35]

$$\begin{aligned} \Gamma(D^0 \rightarrow f, t) &= |A_f|^2 e^{-\hat{\Gamma}_{D^0 \rightarrow f} t}, \\ \Gamma(\bar{D}^0 \rightarrow f, t) &= |\bar{A}_f|^2 e^{-\hat{\Gamma}_{\bar{D}^0 \rightarrow f} t} \end{aligned} \quad (1.2.15)$$

with $\hat{\Gamma}_{D^0, \bar{D}^0 \rightarrow f} \approx \Gamma(1 - c_f^\pm)$. Then a manifest experimental interpretation of y_{CP}^f and ΔY_f arises and they can be measured as

$$\begin{aligned} y_{CP}^f &\approx \frac{\hat{\Gamma}_{D^0 \rightarrow f} + \hat{\Gamma}_{\bar{D}^0 \rightarrow f}}{2\Gamma} - 1, \\ \Delta Y_f &\approx \frac{\hat{\Gamma}_{D^0 \rightarrow f} - \hat{\Gamma}_{\bar{D}^0 \rightarrow f}}{2\Gamma}. \end{aligned} \quad (1.2.16)$$

Contribution from $y_{CP}^{K\pi}$

Previous measurement [34–36] relying on two body decay approximated Γ as the effective decay width of the $D^0 \rightarrow K^- \pi^+$ Cabibbo Favoured (CF) process. As indicated in [33, 37], at the first order

$$\frac{\hat{\Gamma}_{D^0 \rightarrow f} + \hat{\Gamma}_{\bar{D}^0 \rightarrow f}}{\hat{\Gamma}_{D^0 \rightarrow K^- \pi^+} + \hat{\Gamma}_{\bar{D}^0 \rightarrow K^- \pi^+}} - 1 \approx y_{CP}^f - y_{CP}^{K\pi}, \quad (1.2.17)$$

where, once defined the quantity R_D as the ratio between CF and Doubly Cabibbo Suppressed (DCS) branching ratio as

$$R_D = \frac{\text{BR}(D^0 \rightarrow K^+ \pi^-)}{\text{BR}(D^0 \rightarrow K^- \pi^+)} \quad (1.2.18)$$

and the strong phase difference between CF and DCS decays as $\Delta_{K\pi}$, then [37]

$$y_{CP}^{K\pi} \approx \sqrt{R_D} (x_{12} \cos \phi_2^M \sin \Delta_{K\pi} - y_{12} \cos \phi_2^\Gamma \cos \Delta_{K\pi}). \quad (1.2.19)$$

Similarly,

$$\frac{\hat{\Gamma}_{D^0 \rightarrow f} - \hat{\Gamma}_{\bar{D}^0 \rightarrow f}}{\hat{\Gamma}_{D^0 \rightarrow K^- \pi^+} + \hat{\Gamma}_{\bar{D}^0 \rightarrow K^- \pi^+}} \approx \frac{\Delta Y_f}{1 + y_{CP}^{K\pi}}. \quad (1.2.20)$$

All the previous literature reported y_{CP} as the measured quantity, while in truth it was $y_{CP}^f - y_{CP}^{K\pi}$, due to the above correction being negligible at the available statistic precision. In this work y_{CP} and $y_{CP}^f - y_{CP}^{K\pi}$ will be used interchangeably, due

to the changed nomenclature being not widespread and different sources adopting different lettering. Regarding ΔY_f , another variable related to it, has been adopted in previous measurements:

$$A_\Gamma^f \equiv \frac{\hat{\Gamma}_{D^0 \rightarrow f} - \hat{\Gamma}_{\bar{D}^0 \rightarrow f}}{\hat{\Gamma}_{D^0 \rightarrow f} + \hat{\Gamma}_{\bar{D}^0 \rightarrow f}} \approx -\frac{\Delta Y_f}{1 + y_{CP}^f}, \quad (1.2.21)$$

given the smallness of y_{CP}^f , $A_\Gamma^f \approx -\Delta Y_f$ within 1% [33].

1.3 State of the art of charm physics

As mentioned before, charm physics is a branch of the SM of which we have limited experimental knowledge. However, in recent times, some light has been shed at least on some of its aspects. Mixing is a well-known and established phenomenon. From the experimental data the point $x = y = 0$ is now excluded at more than 11σ . However, CPV in mixing, or from a phase difference between the amplitudes of mixing and a direct decay, remains unobserved (Fig. 1.1).

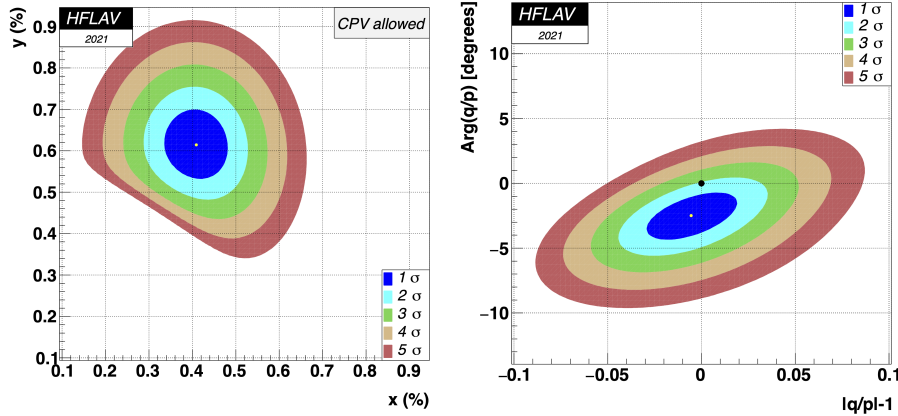


Figure 1.1: Left: values of x and y mixing parameters. Right: values of $R_m - 1$ (probe for CPV in mixing) and $\arg(R_m)$, probe of CPV in interference between mixing and decay. Both values arise from a global fit of all the available measurements [38].

Direct CPV in the decay has been observed only in 2019 by LHCb. Selecting $D^0 \rightarrow h^+ h^-$, with $h = \pi, K$, the observable $\Delta \mathcal{A}^{CP}$ has been measured. This observable is defined as $\mathcal{A}^{CP}(K^+ K^-) - \mathcal{A}^{CP}(\pi^+ \pi^-)$, where $\mathcal{A}^{CP}(f)$ is the time-integrated asymmetry between D^0 and $\bar{D}^0$ mesons decaying to the same CP -even state

$$\mathcal{A}^{CP}(f) = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f)} = \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2} = \frac{1 - R_f^2}{1 + R_f^2}. \quad (1.3.1)$$

Direct CP violation can be explicitly expressed if $\Delta \mathcal{A}^{CP}$ is rewritten as

$$\Delta \mathcal{A}^{CP} \approx \Delta a_{CP}^{dec} - \frac{\Delta \langle t \rangle}{\tau(D^0)} A_\Gamma, \quad (1.3.2)$$

where Δa_{CP}^{dec} is the difference of the decay asymmetry between the two final states and $\Delta \langle t \rangle$ is the difference of the mean lifetimes. The LHCb result [39]

$\Delta\mathcal{A}^{CP} = (-15.4 \pm 2.9) \times 10^{-4}$, corresponding to 5.3σ standard deviations from zero, proved the existence of CPV in the decay of charm hadrons. In Figure 1.2 a global fit showing the measured CPV violating effects through the decay (direct) and due to interference and mixing (indirect). Regarding time-dependent observ-

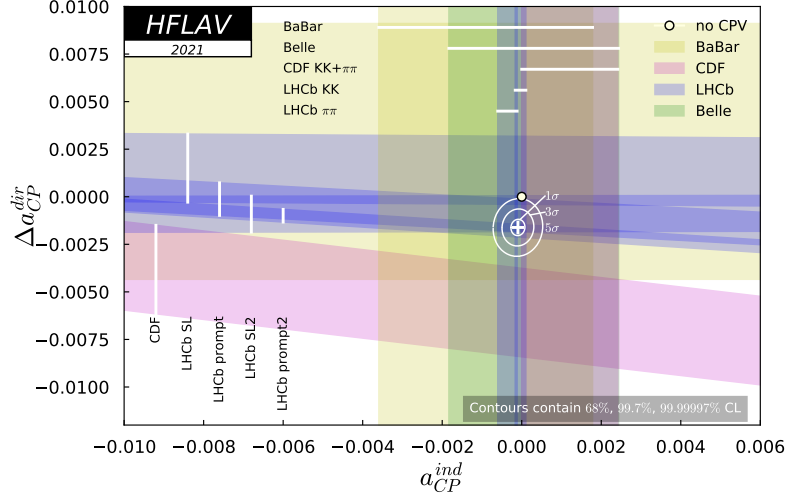


Figure 1.2: Values of Δa_{CP}^{dir} and $a_{CP}^{ind} \propto A_\Gamma$. From Ref. [38].

ables, in Figure 1.3 it is shown how the average of the measurements [35, 40–43] in the graphics is compatible with zero, thus CPV is not manifesting through this mechanism, at the current sensitivity. Finally, let us consider y_{CP} , the observable on which this thesis is focused. It is clear from Figure 1.3 that at the current level of sensitivity y_{CP} is indistinguishable from y [35, 36, 40, 44–48], and no further CPV effect seem to arise. However the SM, combined with the observed measurements on related variables, predicts that $|y_{CP} - y| < 3.4 \times 10^{-5}$ [37], therefore there is still quite a long road before surrendering to the absence of discrepancies between these observables. With such difference being so small, at the current level of available precision, which is a order of magnitude larger than the predicted effect, the value of a y_{CP} measurement is also used as estimation for y . Lowering the uncertainty, however, is not an easy task. Considering the 2018 LHCb measurement [36], the main (almost unique), contributor to the systematic uncertainty was the uncertainty on detection efficiencies as a function of the decay time. That was a measurement performed on LHC Run 1 samples, and even if much more data, sixty times larger was available from Run 2, no further analysis had been successfully completed for a long time, as no methods was known to significantly reduce that systematic uncertainty. This was the status until very recently, when a new measurement has been recently published by LHCb Collaboration [37]. The new results (Figure 1.4) are $y_{CP} - y_{CP}^{K\pi} = (0.696 \pm 0.020_{stat.} \pm 0.013_{syst.}) \times 10^{-2}$, that is, four times more precise than the current world-average value.

From this quick glimpse at the current state of art, it can be seen how LHCb takes a leading role in this sector of measurements, and how often it has improved the precision on some observables. With the start of the Run 3 of the LHC, that LHCb is facing with a extensively renovated detector capable of sustaining higher luminosities (see next Chapter), it might be expected that further improvements of these measurements will easily come out. At the end of Run 4, foreseen in 2030, LHCb is predicted to have accumulated 50 fb^{-1} of integrated luminosity, about

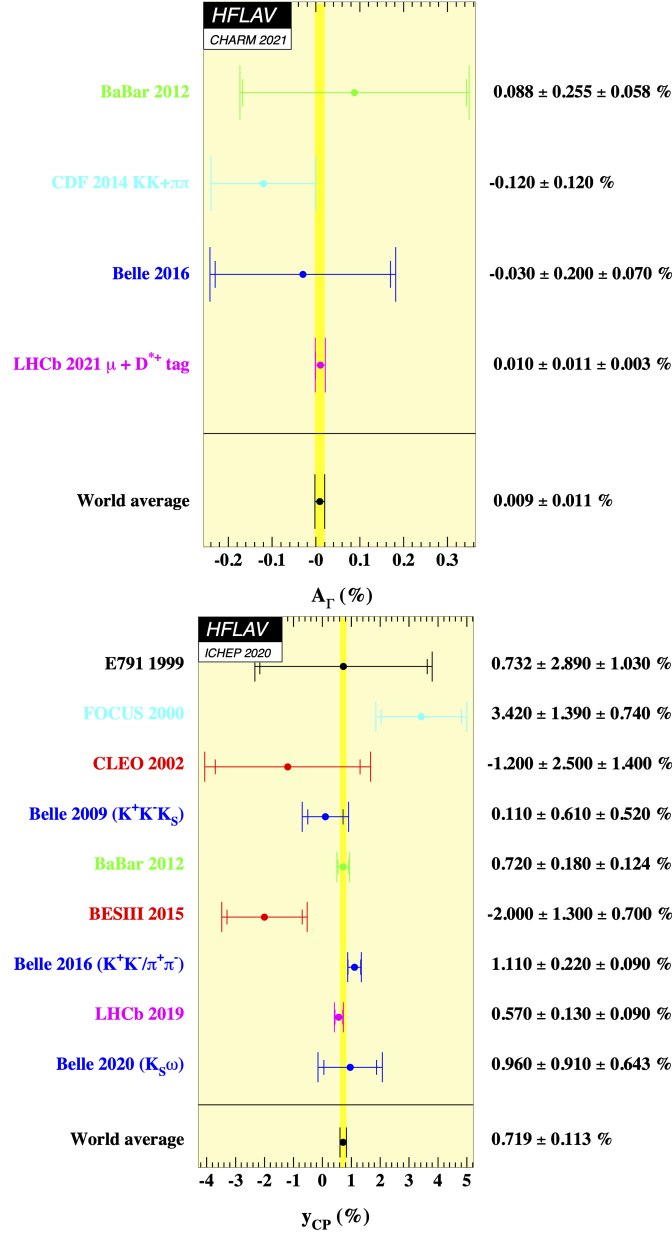


Figure 1.3: Above: values of A_Γ . Below: values of y_{CP} . Both values arise from a global fit of all the available measurements [38].

20 times larger than the current available datasets. In addition, the fact that LHCb is already planning for a further upgrade [49], with expected integrated luminosity of 300 fb^{-1} , makes for very optimistic expectations about the future improvements in the precision with which these observables will be known.

However, if one looks in more detail at the current measurements and at the evolution in the running conditions of the LHCb experiment in the future, extrapolation of the future precision from the current status is far from obvious. As it will be discussed in detail in the coming chapters, the techniques utilized in the current y_{CP} measurement will not be viable in the future, starting already from this year's run. This is because neither the data selection (a special sample, initially designed only for calibration purposes), nor the analysis methodology will

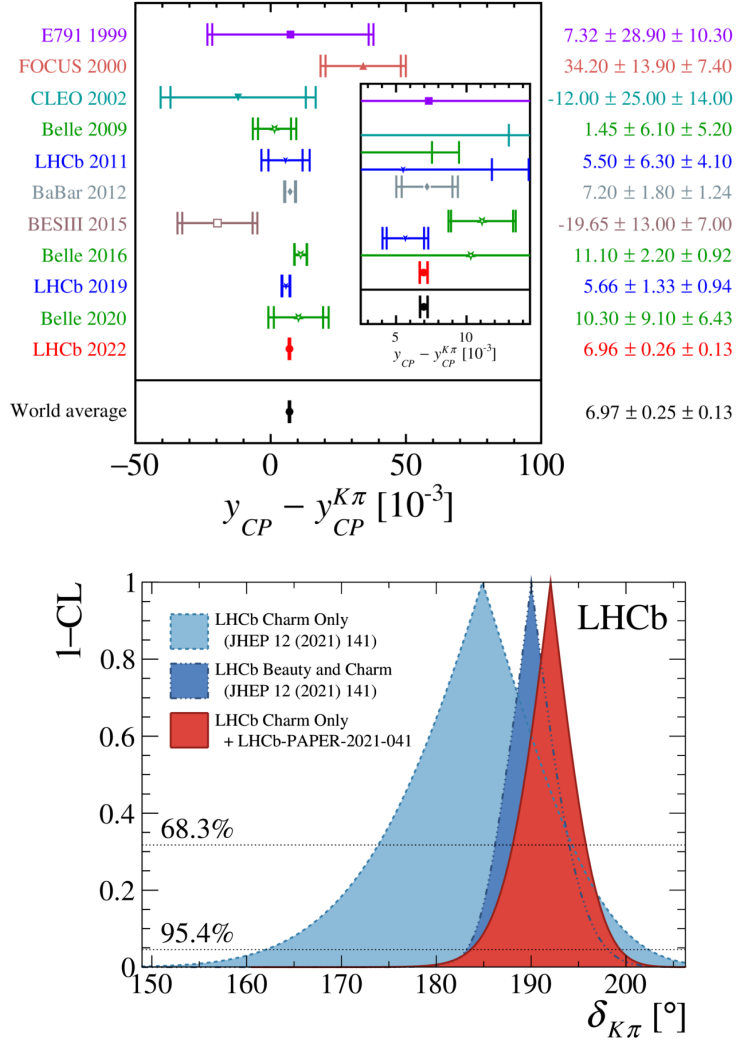


Figure 1.4: Above: values of y_{CP} . Below: value of $\Delta_{K\pi}$. Both values are from [37].

be repeatable with Run 3 data.

Therefore, while the success of the Run 2 measurement does strongly encourage us in thinking that further improvement will be possible, we know already that the development of a totally new approach will be absolutely necessary for this to happen. This is precisely the aim of this thesis: to study the possibility of performing high precision measurements of y_{CP} (and other similarly time-dependent charm observables) in the experimental conditions of future LHCb runs.

We will start in the next chapter by describing the evolution in the detector, data acquisition system, and running conditions – and how they affect the current measurement methodology. We will then move on to describe our studies of new analysis methodologies that are viable in the new conditions, the tests performed, and the possible prospects they open.

CHAPTER

2

THE LHCb EXPERIMENT TOWARDS HIGH-LUMINOSITY

The Large Hadron Collider beauty (LHCb) experiment was born with the specific intent of performing bottom and charm flavor physics research at the Large Hadron Collider (LHC), aiming at precisely measuring CP asymmetries in a hadronic environment and possibly discovering Beyond Standard Model (BSM) physics. This chapter provides a brief description of the LHCb detector, starting from its Run 2 configuration and then considering its upgrade path to handle increasingly higher LHC luminosities.

2.1 The LHCb detector in Run 2

The design of the LHCb detector [50] is that of a single-arm spectrometer with a forward angular coverage from 10 mrad to 300(250) mrad in the bending (non bending) plane, which corresponds to a pseudorapidity range of $1.8 < \eta < 4.9^1$. This is motivated by b -hadrons and c -hadrons being produced with high boosts and therefore having their production cross section peaking at high values of $|\eta|$; the pseudorapidity coverage, moreover, is complementary to the one of the other general-purpose detectors, ATLAS and CMS, operating at the Large Hadron Collider (LHC), a proton-proton and heavy-ions collider located at the European Organization for Nuclear Research (CERN) laboratory, on the French-Swiss border [51].

At the LHC, two proton – or ion beams – are accelerated in opposite direction by two separate dipole cavities, sharing the same iron yoke. NbTi superconducting dipole magnets, which are maintained at a temperature of 1.9 K by a liquid helium cooling system and produce a field of 8.3 T, take care of bending the beam around the LHC circumference. Proton beams are not continuous, but gathered

¹ The pseudorapidity is defined as $\eta = -\log[\tan(\theta/2)]$ and θ is the polar angle with respect to the beam direction.

in bunches of about 10^{11} protons each, which are time-spaced by multiples of 25 ns, resulting to a maximum bunch-crossing rate of 40 MHz. The bunches are necessary because the charged particles need to be synchronous with the correct wavefront of the accelerating radiofrequency (RF). Not all particles can be perfectly synchronous with the accelerating field, however a volume around a virtual synchronous particle, where the charged particles exhibit an oscillatory motion around the synchronous one, can be defined and is commonly named *bucket* [52]. Due to the presence of empty buckets² the average rate of bunch crossings is about 30 MHz. Four instrumented points of interactions are present along the LHC circumference, one for each detector of the four LHC experiments: ATLAS, CMS, LHCb and ALICE. The collider is designed to operate with a centre-of-mass energy (E_{cm}) of 14 TeV for the pp collisions, with instantaneous luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Initially $E_{cm}(pp)$ was fixed at 7 TeV during years 2010 and 2011, then raised at 8 TeV in 2012 and finally reached 13 TeV all through Run 2 (2015-2018).

The LHCb detector is carefully designed for highly precise measurements of particle decaying via weak interaction. As b -hadrons and c -hadrons have lifetimes of $\mathcal{O}(0.1\text{--}1 \text{ ps})$, their distinctive long flight distance is a key feature for distinguishing them from the huge background of a hadron machine. This requires high vertex resolution, which is crucial in measuring time-dependent CP asymmetries and neutral meson oscillation phenomena. Another essential observable is the invariant mass of the analyzed process: residual background can be reduced through a selection on this variable, this asks for sufficient momentum resolution.

The detector comprises a charged particle tracking system and a particle identification system. A dipole magnet and three different detectors make up the tracking system, with the three different detectors being the vertex locator (VELO), the tracker turicensis (TT), both upstream of the magnet, and three tracking stations (T1–T3), downstream of the magnet. The particle identification system is formed by two ring imaging Cherenkov (RICH) detectors, the calorimeter detectors and the muon detectors. The layout of the LHCb detector is shown in Figure 2.1. The right handed coordinate system has the x axis pointing toward the center of the LHC ring, the y axis pointing upwards, and the z axis pointing along the beam direction.

At the nominal LHC luminosity, multiple primary pp interactions may occur when the beams collide, causing high particle occupancy in the detector. This constitutes an issue for the online system as the detector readout cannot operate at a higher rate than 1 MHz, as well as the high particle density causes relevant radiation damage. Therefore, by transversally defocusing the beams at the LHCb intersection, the instantaneous luminosity is decreased to $2\text{--}4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, thus lowering the average number of primary pp interaction per bunch crossing to one. The recorded LHCb integrated luminosity in Run 1 and in Run 2 is shown in Figure 2.2.

2.1.1 The tracking system

With its tracking system providing accurate spatial measurements of charged particle tracks, LHCb can determine the momentum of these particles with a

²At least one bucket needs to be empty, functioning as a reference point for all the other bucket to be numbered. Due to technical reasons, *i.e.* injection procedure, managing the heat load to the cryogenics system, more than one bucket is left empty [53].

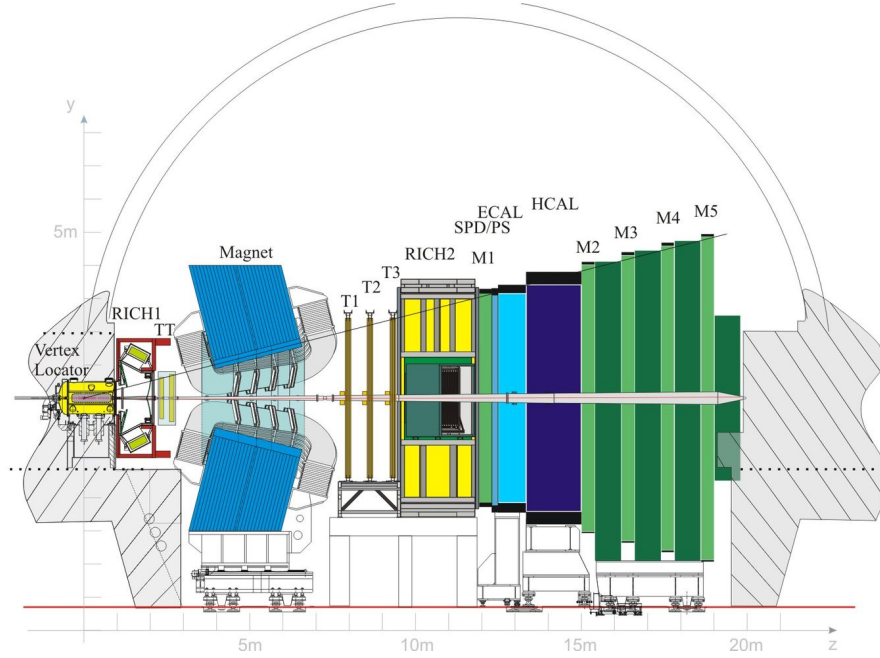


Figure 2.1: The LHCb layout.

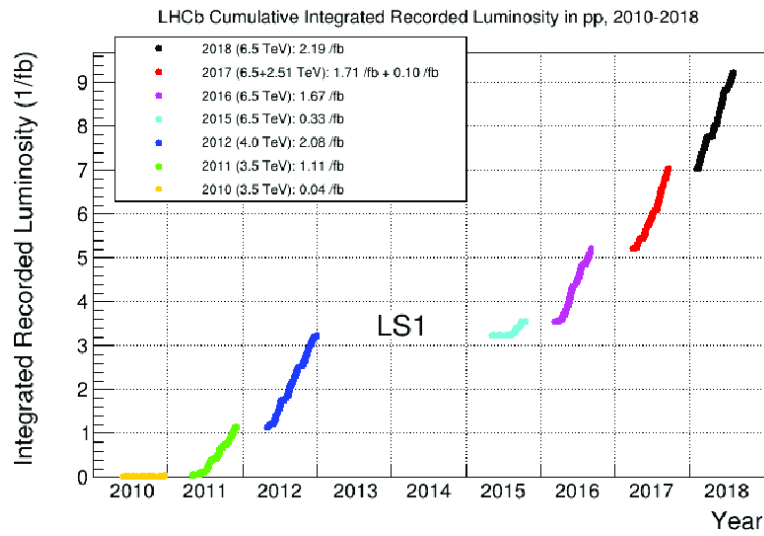


Figure 2.2: The cumulative integrated luminosity at LHCb in Run1 and Run2.

relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/ c . Here it follows a description of the various components of the tracking system.

The Vertex Locator detector The VERtex LOcator (VELO) [54] is a silicon-strip vertex detector and measures charged particle trajectories in the region closest to the interaction point. Its main purpose is to reconstruct primary vertices and displaced secondary vertices, the latter being essential in b -tagging algorithms and, more in general, heavy flavor decays identification. As b -hadrons have typically a decay length $c\tau \approx 500 \mu\text{m}$ at LHCb, and for neutral (charged) c -hadrons $c\tau \approx 100(300)\mu\text{m}$, the vertex detector spatial resolution is therefore required to be much lower than these values in order to distinguish the displaced secondary vertexes from the primary ones.

Both upstream and downstream of the nominal interaction point, 21 disk-shaped tracking stations, which form the vertex locator, are positioned. Each tracking station is divided in two semicircular retractile halves, named modules, each one consisting of two silicon strip sensors, one for radial measurements and the other for azimuthal ones, as shown in Figures 2.3 and 2.4. Both r and ϕ sensors are centered around the nominal beam position and have a sensitive area covering the region from $r = 8.1 \text{ mm}$ to $r = 41.9 \text{ mm}$. The arrangement of the modules is such that every track within the LHCb acceptance intersects at least four of them. The r -sensors measure the radial distance from the beam with semicircular-shaped strips. In order to lower detector occupancy, they are subdivided into four 45° regions. The pitch increases linearly with the radial distance from $38 \mu\text{m}$ up to $102 \mu\text{m}$ at the outer radius, ensuring that the multiple measurements along the track contribute with equal weights to the precision on its IP. The ϕ -sensor is subdivided in inner region and outer region, with the border between the two being located at 17.25 mm from the center. In the inner region, the strip pitch increases linearly from 38 to $78 \mu\text{m}$, while in the outer region from 39 to $97 \mu\text{m}$. At the innermost radius, the inner strips are arranged with angle of $\sim 20^\circ$ w.r.t. the radial direction; for the outer strips this angle is $\sim 10^\circ$. The modules are installed in such a way that adjacent ϕ -sensors have opposite skew w.r.t. each other; the resulting stereo view allows for a better discrimination of ghost hits from true ones, when compared to a configuration where all azimuthal sensors are placed along the radial direction.

The VELO detector is placed as close as possible to the collision point in order to maximize the precision on vertex localization. The sensors are mounted on a remote-controlled positioning system which permits to retract them by 3 cm in the x direction at injection time and all the other instances of non-stable beam, in order to avoid damages to the sensors. There is no beampipe through this detector; instead, a thin aluminium foil – the RF-foil, with RF standing for radiofrequency – separates the beam vacuum from the VELO modules and shield these from electromagnetic effects induced by the high-frequency beam structure. The foils have a corrugated shape (Figure 2.5) to allow the overlap between the two module of the same VELO stations when it is in closed configuration; moreover, they are as thin as possible to avoid worsening of resolution due to the elastic scattering of particles.

Dedicated test beams led to an estimation of the VELO performance. Raw hit resolution ranges from $\sim 10 \mu\text{m}$ to $\sim 25 \mu\text{m}$. Introducing the Impact Parameter as the smallest distance between the particle trajectory and the Primary

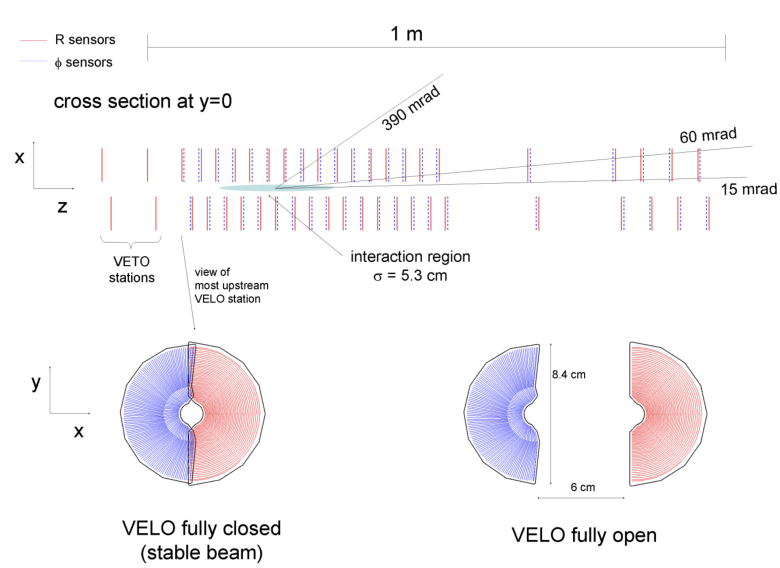


Figure 2.3: Transverse (top) and front (bottom) view of a single station of the VELO detector.

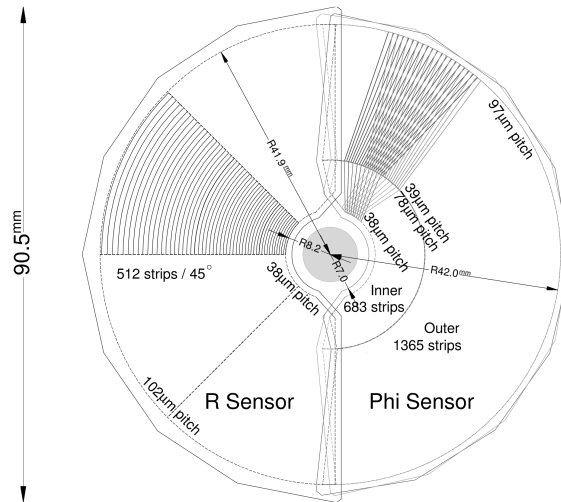


Figure 2.4: Geometrical scheme of the r and ϕ VELO sensors. Only a portion of the strips is shown; in the ϕ -sensor, the strips on two adjacent modules are represented to highlight the stereo angle.

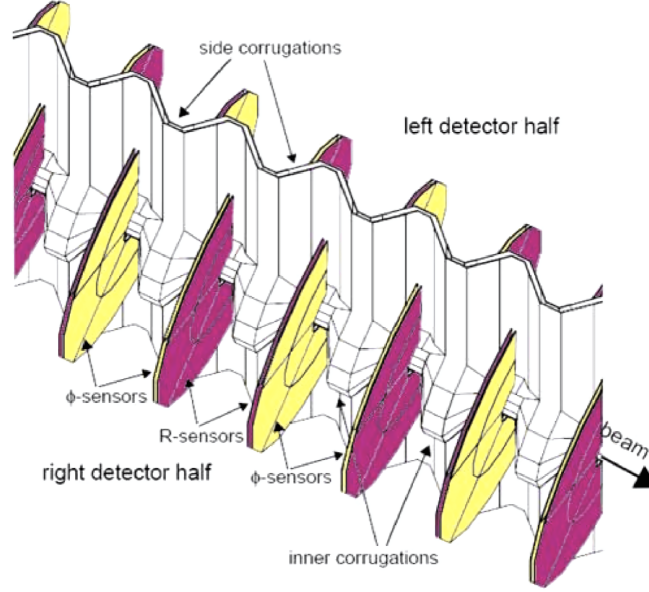


Figure 2.5: The inside of an RF-foil with the detector halves in the fully closed position. The edges of the box are cut away to show the overlap with the staggered opposing half. The r -sensors and ϕ -sensors are illustrated with alternate shading.

Vertex (PV), particles originating from secondary vertices can be identified by the IP of their tracks. From the tests the IP is measured with a resolution of $(15 + 29/p_T)\mu\text{m}$, where p_T is the component of the momentum transverse to the beam, in GeV/c . The high precision on the IP measurement makes the VELO essential for the success of LHCb.

The dipole magnet The LHCb warm-dipole magnet provides bending to the charged particles, necessary for measuring their momentum. The magnet is formed by two saddle-shaped coils slightly inclined w.r.t. the beam axis. This is to increase the opening window as z increases, matching the acceptance of the LHCb detector (Figure 2.6). The maximum magnetic field strength is 1.1 T, with the field having its main component along the y direction. This results in the bending plane being approximately the (x, z) -plane. The total bending power is $\int Bdl = 4 \text{ Tm}$. The magnetic dipole is located between the TT and the T-stations. The magnetic field is measured with a relative resolution of 4×10^{-4} before the data-taking periods. A precise map is so obtained, which implies having a good momentum resolution and consequently a good mass resolution. A unique feature of the the LHCb detector consists into the possibility of reversing the polarity of the magnetic field (*MagUp* or *MagDown*). Charge asymmetries introduced by the detector can therefore be accurately studied and accounted for in the analyses. In fact, as particles hit some specific regions of the detector, large charge detection asymmetries can arise. If data samples of the same size are collected with *MagUp* and *MagDown*, effects of detection charge asymmetries are expected to cancel out, as long as operating conditions remain stable between the two polarities.

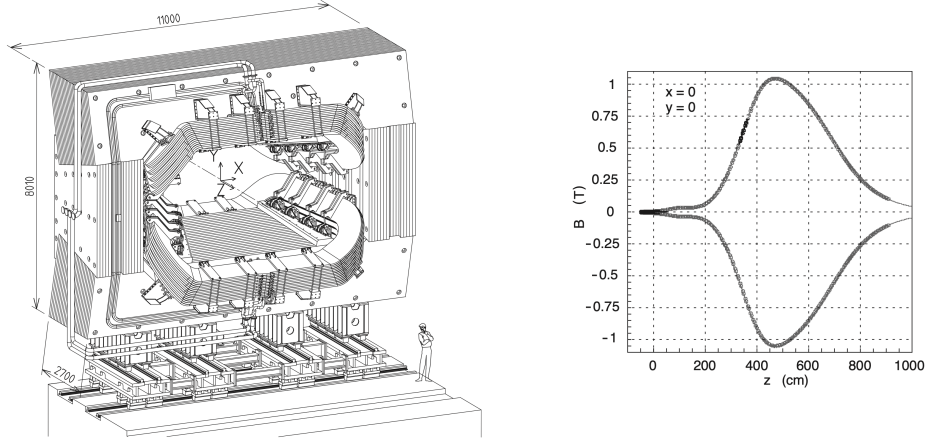


Figure 2.6: Left: perspective view of the LHCb dipole magnet (lengths in mm). Right: vertical magnetic field measured on the z axis, as a function of the z coordinate.

Silicon Tracker: Tracker Turicensis and Inner Tracker The silicon tracker [55] consists of two detectors with same technology: the tracker turicensis (TT), upstream of the magnet, and the inner tracker (IT), downstream of it.

The TT is a silicon microstrip detector with the purpose of reconstructing the trajectory of low-momentum particles, bent away from the LHCb detector acceptance by the dipole magnet, and to reconstruct long-lived particles, whose decay is likely to occur outside the VELO. The TT is formed by four layers, which are grouped in two stations at the distance of 30 cm one from the other along the beam line. The four layers are positioned in a $x - u - v - x$ stereo arrangement, Figure 2.7.

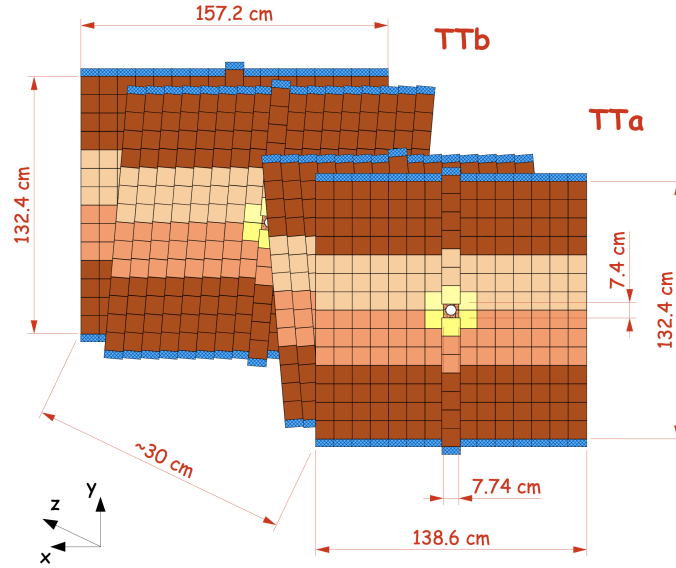


Figure 2.7: The TT detector; different readout sectors are indicated by different colours.

The first and last layers consist of vertical strips, measuring the x coordinate of the particle, while the second and third layers are rotated by $\pm 5^\circ$ w.r.t. the

vertical strips, respectively being the u and v layers. This slight rotation is for avoiding the ambiguities that would arise with an horizontal orientation providing a measurement in y -direction, which would cause ghost hits, Figure 2.8.

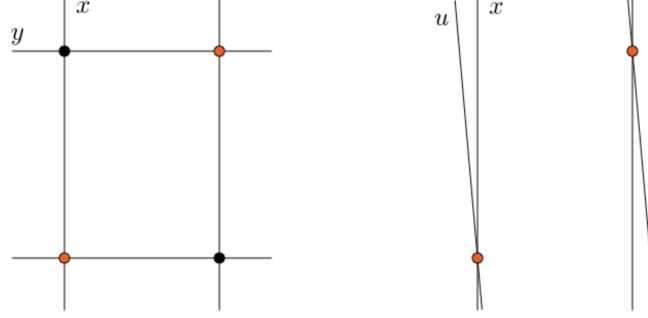


Figure 2.8: Comparison of two different strip arrangements: hits of the same two particles in a $(x - y)$ configuration (left) and $(x - u)$ configuration (right). The smaller the angle between the two strips' layers, the lower the number of intersections of the strips between different layers, such that reconstruction of ghost hits can be avoided.

While the TT covers the full acceptance of the experiment, the IT, placed downstream of the magnet, covers a range of $\sim 150 - 200$ mrad in the bending plane and $\sim 40 - 60$ mrad in the $y - z$ plane. The IT, consisting in a micro-strip silicon detector, is mounted in three tracking stations, called T-stations, each one with four overlapped detection planes. The planes configuration is the same of TT sub-detectors ($x - u - v - x$). The purpose of the IT is to reconstruct tracks that have passed through the magnetic field region near the beam axis. The IT layout is shown in Figure 2.9. Single-hit resolution of both TT and IT detectors is $\sim 50 \mu\text{m}$.

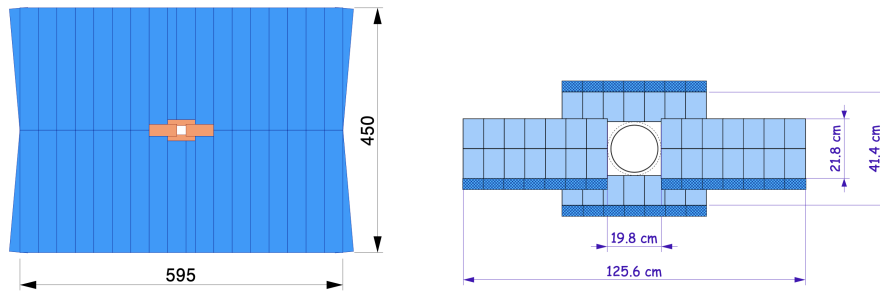


Figure 2.9: Left: front view of one of the T-stations (lengths in cm); the inner tracker is drawn in orange, the outer tracker in blue. Right: front view of a x plane of the inner tracker.

The Outer Tracker Still located in the T-stations but covering the area further from the beam line w.r.t. the IT, the Outer Tracker (OT) [56] is a gaseous ionization detector consisting of straw tubes operating as proportional counters. This design allows the system to cover a large area at a much smaller cost than a full silicon tracker. As the IT, the OT is composed of four detection planes and

the planes configuration is equal to the IT and the TT ones ($x - u - v - x$). Each layer is made up of two rows of 2.4 m long drift tubes, with an inner diameter of 4.9 mm. The tubes are filled with a gas mixture of Ar/CO₂/O₂ in order to achieve a drift time of 50 ns. The detector occupancy is lower than 10%, with a hit efficiency above 99%. The OT Layout is shown in Figure 2.10.

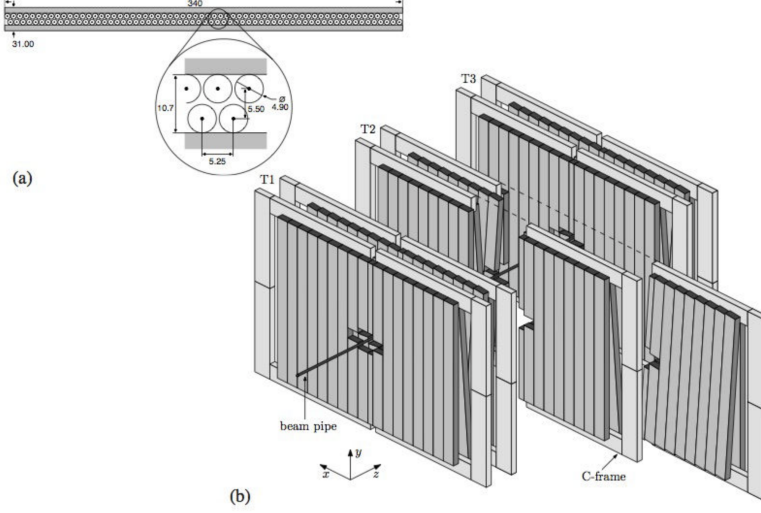


Figure 2.10: (a) Section of an OT detection plane. (b) Arrangement of OT straw-tubes modules in planes and stations; the second station is partially opened.

Track reconstruction The trajectories of charged particles, or simply tracks, are reconstructed through pattern recognition on a sequence of hits in the tracking sub-detectors [57]. Depending which sub-detectors the particle has crossed, different types of tracks can be defined, as shown in Figure 2.11:

- **Long tracks** are those for which particles have traveled across the entire tracking system. They are reconstructed by combining hits from the VELO and the T-stations, and, when possible, hits from TT.
- **Downstream tracks** are those reconstructed only in the TT and in the T-stations, typically long-lived particles as K_S^0 decaying outside the VELO region.
- **VELO tracks** are tracks with only VELO hits. They are used in the primary vertex reconstruction and contribute to reconstruct long and upstream tracks.
- **Upstream tracks** are low-momentum tracks whose hits are only in the VELO and TT, they are bent away from the LHCb acceptance by the magnetic field.
- **T tracks** are formed using only hits into the T-stations.

Most tracks at LHCb typically have hits in the VELO, TT and forward tracking detectors, being, therefore, reconstructed as long tracks, as they are created within less than 1 cm from the PV. However, a significant amount of neutral long-lived particles cannot produce hits in the VELO, thus cannot be long tracks, with

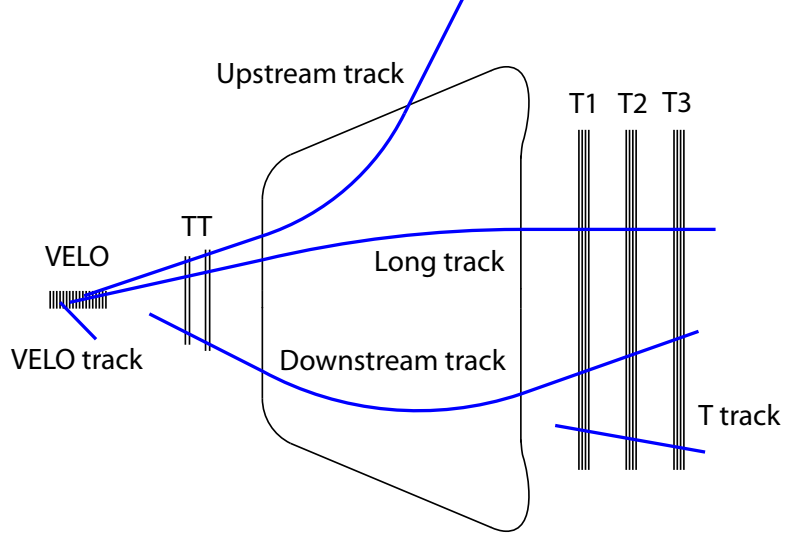


Figure 2.11: Definition of different types of tracks.

their typical decay lengths being $\mathcal{O}(1 - 10)\text{cm}$. This commonly happens for K_S^0 and Λ particles, which can be reconstructed as downstream tracks only if they decay before the TT.

2.1.2 Particle identification and calorimetric system

In order to correctly reconstruct the decays, particle identification occupies a key role. This is achieved at LHCb through Cherenkov detectors, which are able to separate between charged kaon and pions, and calorimeter detectors taking care of the identification of electron, photon and hadrons. Muon chambers are dedicated, as the name may suggest, to the identification of muons.

The Cherenkov detectors

As charged particles, in a dielectric medium with refractive index n , traveling at superluminal speed ($\beta > 1/n$) emit Cherenkov radiation at a precise angle

$$\cos \theta_c = \frac{1}{\beta n} = \frac{1}{n} \sqrt{1 + \left(\frac{m}{p}\right)^2}, \text{ with } c = 1, \quad (2.1.1)$$

then, once the particle momentum is known, the mass m can be inferred from θ_c , thus allowing for the identification of different particles. In order to discriminate particles either at low and high momentum, different, and mutually exclusive, constraints on n would be required, respectively to be high (for low momenta) and to be close to one (for high momenta). Thus LHCb deploys two different Ring Cherenkov detectors, RICH1 and RICH2 [58], permitting the discrimination of charged particles over a momentum range 1–100 GeV/ c .

The geometry of the two Cherenkov detectors is shown in Figure 2.12. Each detector has a spherical mirror for ring-imaging and a set of flat mirrors that guide photons onto the Hybrid Photon Detectors (HPDs), able to detect photons in the 200–600 nm wavelength range and placed outside the detector acceptance either to reduce material costs and, at the same time, protecting them from the magnetic field.

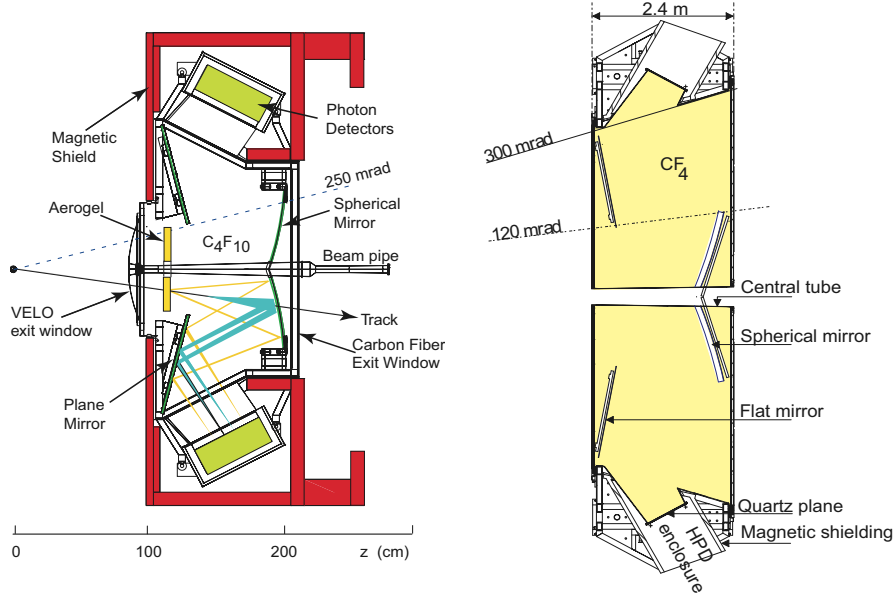


Figure 2.12: Schematic view of RICH1 (left) and RICH2 (right) detectors.

The RICH1 sub-detector is located between the VELO and the TT, covers the full detector acceptance, and deploys aerogel ($n = 1.03$) and C_4F_{10} ($n = 1.0014$) as radiators in order to discriminate low momentum particles (1–60 GeV/ c). The RICH2 is downstream the magnet, after the last T-station, and covers angular acceptance from 15 to 120(100) mrad in the bending (non-bending) plane. In this case, the gas radiator is CF_4 ($n = 1.0005$) which lets the sub-detector properly distinguish particles with momentum ranging from 15 to ≥ 100 GeV/ c . The $\pi - K$ separation is 90% efficient for momenta up to 30 GeV/ c . In Figure 2.13 is shown the relation between the Cherenkov angle and particle momentum for different particles and radiators.

Calorimeters

Calorimeter detectors offer fast information for the low-level trigger and provide identification of electrons, photons, and hadrons, along with a raw measurement of their energies and positions.

The calorimetric system is formed by an electromagnetic calorimeter (ECAL) [59] and a hadron calorimeter (HCAL) [60]. Their angular acceptance is from 25 mrad to 300(250) mrad in the bending (non bending) plane and both are placed between the first and the second muon station. In addition to the ECAL, two more sub-detectors are present: a Pre-Shower detector (PS) and a Scintillator Pad Detector (SPD), which are placed in front of it and are separated by a 2.5-radiation-length-thick lead converter. The low level electron trigger uses them to reject charged and neutral pions, in order to improve electron identification; the

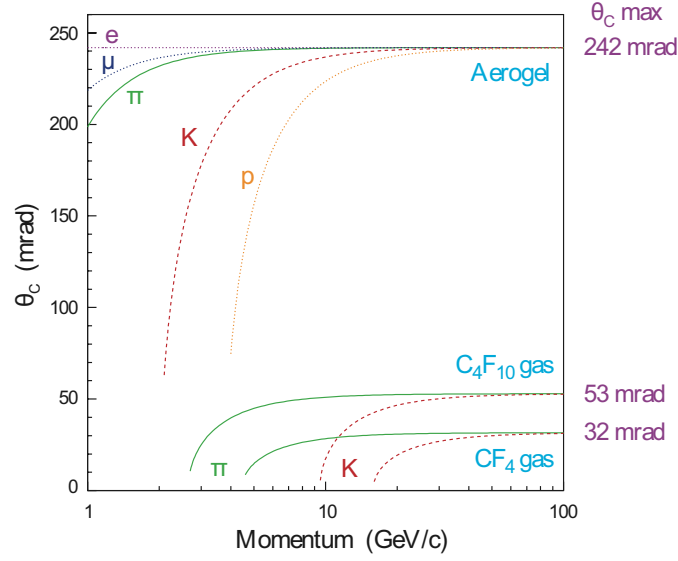


Figure 2.13: The Cherenkov angle dependence on the particle momentum, for various mass values and for the different radiators deployed in RICH1 and RICH2.

SPD distinguishes charged particles from neutral ones, while the PS discriminates between electromagnetic and hadronic showers. By looking at the longitudinal development of the electromagnetic shower in the PS, charged π can be rejected, while neutral π are rejected using the information provided by the SPD. The SPD can also measure the number of tracks per event, allowing for imposing an online veto against overpopulated events. Both sub-detectors are as thick as 2 radiation lengths (X_0) and 0.1 nuclear interaction lengths (λ_{int}). All calorimeter detectors are subdivided in four quadrants, each one with a lateral segmentation in cells of different sizes, depending on the distance from the beam axis. The lateral segmentation is finer in the ECAL, PS and SPD than in the HCAL, as shown in Figure 2.14.

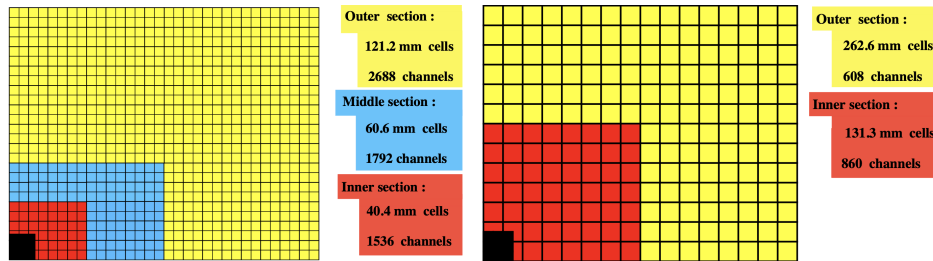


Figure 2.14: Segmentation of one quadrant of ECAL (left) and of the HCAL (right). The black sector, corresponding to the beam pipe, is outside of the LHCb acceptance.

ECAL, comprising alternating layers of lead (2 mm thick) and scintillator tiles (4 mm thick), has overall thickness of $25 X_0$ and $1.2 \lambda_{int}$, in order to nearly contain all the electromagnetic shower and to exhibit an energy resolution of $\sigma_E/E(\text{GeV}) = 1\% \oplus 10\%/\sqrt{E(\text{GeV})}$. The total thickness of HCAL, which is made up of 16 mm thick iron layers alternated with 2 mm scintillating fibres, corresponds to $5.6 \lambda_{int}$ and is limited by the space available inside the LHCb cavern. The energy resolution of the HCAL is $\sigma_E/E(\text{GeV}) = 9\% \oplus 70\%/\sqrt{E(\text{GeV})}$.

While this poor resolution, combined with the incapability of containing the full hadronic shower, makes the HCAL unsuitable for offline analysis, it is still used in the estimation of hadron energy for the low level trigger. The readout system, common to all detectors, uses wavelength-shifter fibres to deliver scintillation light to photomultipliers.

Muon chambers The muon detectors [61], comprising five rectangular stations denoted M1-M5, provide transverse momentum measurement of penetrating muons either for both low-level and high-level triggers, and also for offline analysis. Station M1, placed in front of the calorimeters, improves the p_T measured in the following stations, thus feeding a more precise measurement to the trigger. Stations M2-M5, placed downstream of the calorimeters, are interleaved with 80 cm thick iron absorbers, with the whole muon system thickness amounting to a total of $\sim 20 \lambda_{int}$ and allowing only muons with $p > 6 \text{ GeV}/c$ to cross all the stations.

The stations are composed of four quadrants, surrounding the beampipe; each quadrant comprises four regions, R1-R4, installed at increasing radii from the beampipe. A side view of the muon detectors and a station layout are shown in Figure 2.15.

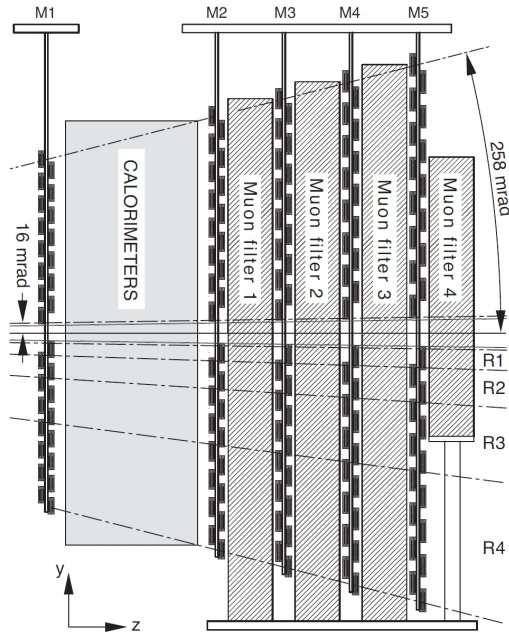


Figure 2.15: Side view of the muon system.

While M1 station employs triple-GEM detectors in the R1 region, due to higher particle rate that is present near the beam pipe, the rest of the detector is equipped with Multiwire Proportional Chambers (MPCs). The gas mixture used in both cases, but with varying mixing proportions, is one of Ar, CO₂, and CF₄. The first three stations, M1-M3, deal with transverse momentum measurements, whereas the last two stations, M4 and M5, detect whether the particle has traveled across the whole system or not. The detection efficiency of muon detectors is 95%, and the system can be included in the low-level trigger thanks to the signal being

collected in less than 20 ns. An average transverse momentum resolution of 20% is achieved in stand-alone muon reconstruction, which is also used in the trigger.

2.1.3 The trigger system

Designed to efficiently select heavy flavor decays from far larger background comprising exclusively light quarks, the LHCb trigger [62] exploits the long decay distance of b and c -hadrons and their higher p_T w.r.t. the background processes. Its aim is to reduce the event rate from 30 MHz, which is the average bunch-crossing rate, to 12.5 kHz, the maximum permitted rate for data to be stored. Events containing a b -hadron decay represent a small fraction, approximately 15 kHz, and the decays-of-interest rate is even smaller, $\mathcal{O}(\text{Hz})$. Charm decays are ~ 20 times more frequent. It is, then, imperative to reject background events as soon as possible in the acquisition chain. In order to do so, the trigger is organized in three stages. Firstly, the Level-0 trigger (L0), synchronously operating with the bunch crossing, is hardware-based and uses information from the calorimeters and the muon chambers to perform a fast selection reducing the rate to 1.1 MHz, which is the maximum readout rate the detector can handle. Then, selected events encounter the High-Level Trigger 1 (HLT1) and the High-Level Trigger 2 (HLT2). These software-based trigger stages run asynchronously on dedicated computers and perform more refined selections, taking information from all detectors and, in case of HLT2, also reconstructing the decay. After this step the event rate has been reduced to the safe-storage threshold rate of 12.5 kHz, mentioned above. In Figure 2.16 the LHCb trigger flow is shown, with typical rates for the accepted events at each stage.

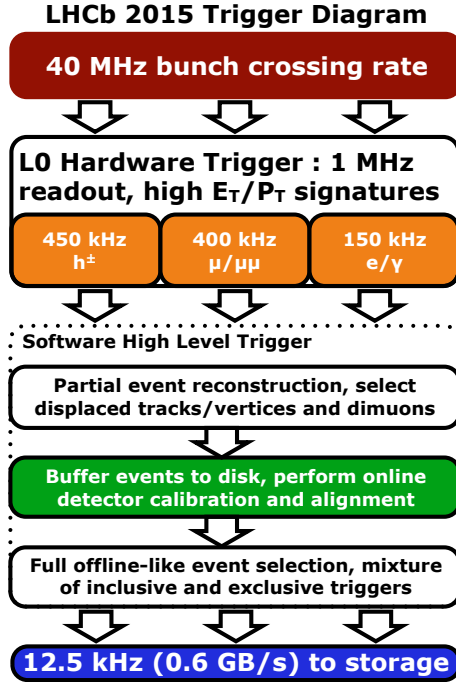


Figure 2.16: LHCb Run 2 trigger scheme (left). From [63]. The bunch crossing rates refers to the nominal one and not the average one, as if all buckets were filled.

The L0 Trigger

The Level-0 trigger, as already stated, has task of reducing the rate from 30 MHz to 1.1 MHz, value at which the LHCb detector can be readout. To achieve this goal the fast selection has a fixed latency of 4 μ s. To accomplish this, the L0 trigger is entirely based on custom-built electronic boards, relying on FPGA technology, and deploys parallelism and pipelining to respect the fixed latency limit. Therefore, at this stage, selections can only involve basic information, simple and immediately available quantities, like those provided by calorimeter and muon detectors.

L0 muon The *L0 muon* trigger identifies highly energetic muons, using the information from the five muon stations. Once the two muons with highest p_T , per quadrant, are identified, the trigger decision depends on two thresholds: one on the highest p_T and the other on the product of the two highest transverse momenta.

L0 calorimeter The *L0 calorimeter* trigger uses as seed the ECAL, HCAL, PS, and SPD information. It calculates the transverse energy deposited in a cluster of 2×2 cells of the same size, for both the electromagnetic and hadron calorimeters. This quantity is combined with information on the number of hits on PS and SPD in order to define three types of trigger candidates: photon, electron and hadron. The event is retained if the most energetic particles has reached the E_T threshold of 3.5, 2.4 and 2.8 GeV respectively for hadrons, electrons and photons.

L0 hadron The *L0 hadron* aims at better discriminating signal from background, as, in case of c and b -decays, final state particles have on average higher transverse momenta than particles originated from light quark processes.

The High Level Trigger

Once selected by the L0 trigger, the events, with all their detector information, are transferred to the Event Filter Farm (EFF). Here, the HLT, which is implemented through a C++ executable, performs a fast reconstruction of the events and selects them. The HLT stage is split in two different levels: the first one, which is HLT1, and the second one, HLT2.

HLT1 At the HLT1 level, only tracks in the VELO are fully reconstructed in the 3D space with the purpose of finding all the PVs produced. Information from the TT and T-stations is used to fully reconstruct the tracks, only if these exhibit high IPs. The selection depends on their probability of being compatible with heavy flavor decays: at least one good-quality track, large IP w.r.t. all the reconstructed PVs, and high p_T . The output rate of this stage is 150 kHz.

HLT2 At this stage, the event is fully reconstructed, using either the tracking and particle identification detectors. Due to the quite relaxed time constraints at this step (~ 800 ms), the trigger reconstruction is in line with the quality reached offline. Depending on their topology and the identified detected particles, different decays are selected, with various selection thresholds, and each selection is assigned to a different *trigger line*.

Turbo Stream Lines As the main limit is the maximum storage rate, and this particularly affects charm physics, the implementation of the *Turbo Stream* [64], a novelty of Run 2, has led to the possibility of using just 5 kB per events, instead of the canonically 70 kB. This is possible considering that HLT2 trigger already offers reconstructed candidates suitable for the analysis, thus bypassing the need of an offline reconstruction. Then only a compact summary of physics objects containing the information necessary for the analyses is preserved and the rest of the event can be discarded to save bandwidth and storage resources. This results in an increased output rate and higher average efficiencies.

2.2 The LHCb Upgrade I

In 2011, the interest of upgrading LHCb was expressed with the aim of increasing both the data rate and the trigger efficiency, leading to higher signal yields [65]. The target was, and still is, to accumulate 50 fb^{-1} by the year 2030, thus improving the majority of measurements whose precision at the end of Run 2, with an integrated luminosity of 9 fb^{-1} , is statistically limited. Therefore, during the Long Shutdown 2 (LS2) in 2019-2021, the upgrade has been implemented, in order for LHCb to function at the increased instantaneous luminosity of $\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. Currently, the Run 3 of data-taking is just in the process of commencing during this year (2022).

With the average number of primary interactions per collision increasing from 1 to 7.6, most of the sub-detectors were replaced, as well as all the data-acquisition system and the front end electronics: a totally new silicon pixel VELO has been developed, along with a silicon strips upstream tracker (UT) and Scintillating Fibres detector (SciFi) downstream to the magnet, respectively substituting the TT and the T-stations.

The SPD and PS were completely removed, as their purpose was strictly circumscribed to L0 trigger decisions. In fact, the L0 trigger has been eliminated, as this trigger's yield would have reached saturation for hadronic channels at the increased luminosity regime. Thus, it was decided that the trigger system be fed the full event information, moving from the L0+HLT approach of Run 1+2 to Full HLT of Run3.

Apart from the new readout electronics, the particle identification system remains unmodified, except for the M1 muon station being removed and the RICH1 being deprived of its aerogel radiator. In Figure 2.17 the schematic layout of the upgraded LHCb detector.

2.2.1 The silicon pixel VELO

In order to improve its performance at the nominal readout rate of 40 MHz, the new VELO [66] comprises a silicon pixel detector, a new radiation hard ASIC (Application Specific Integrated Circuit), dubbed VeloPix, capable of coping with the data rates, and an improved cooling system, using evaporative CO_2 , integrated within the module.

The VELO is composed of 26 stations, 19 of which are placed in the forward region and 7 in the backward region with respect to the interaction point; each of them are made of two modules, one on the left-hand side of the detector, the

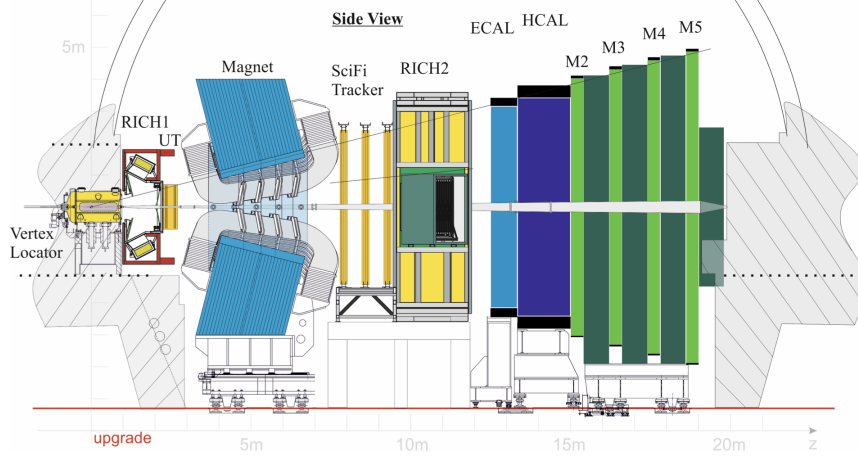


Figure 2.17: Schematic layout of the upgraded LHCb detector.

other on the right-hand side, with the beampipe running between them (Figure 2.18).

Each module contains four silicon sensors, two for each side, with a thickness of $200\text{ }\mu\text{m}$ and an active area of $42.46 \times 14.08\text{ mm}^2$. The sensor is bump-bonded to a row of three VeloPix ASICs. The ASICs, with an active area of $14.08 \times 14.08\text{ mm}^2$, consist in blocks of silicon, $200\text{ }\mu\text{m}$ thick. A $400\text{ }\mu\text{m}$ thick silicon slab make the microchannel cooling substrate (Figure 2.19).

The VELO again implements RF foils to preserve the vacuum for the beamline, as in Run 2; the foils are still made of aluminum, but with a reduced *uniform* thickness of $250\text{ }\mu\text{m}$ (against the old $300\text{ }\mu\text{m}$, which exhibited local variations). The longitudinal layout was modeled so that the majority of tracks in LHCb

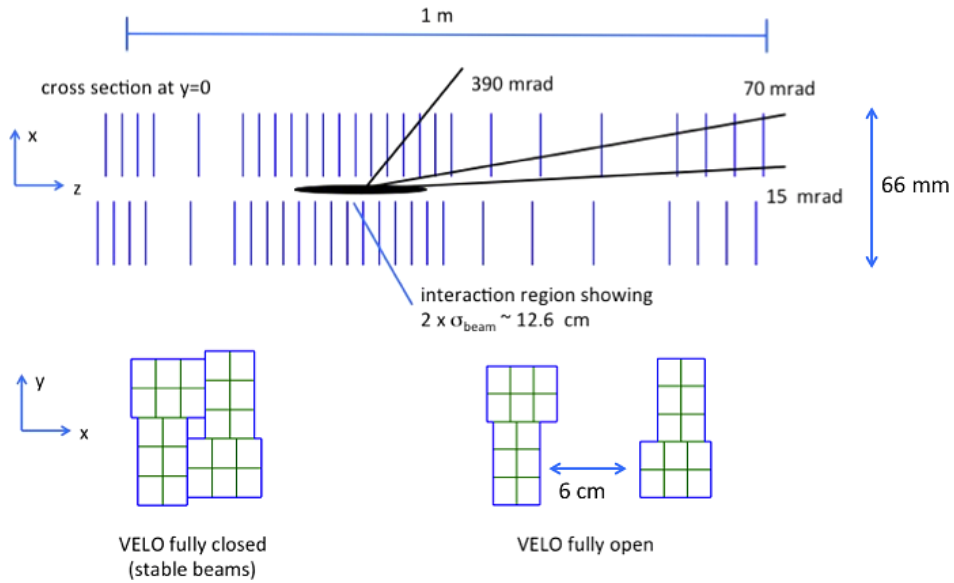


Figure 2.18: Schematic layout of the upgraded VELO.

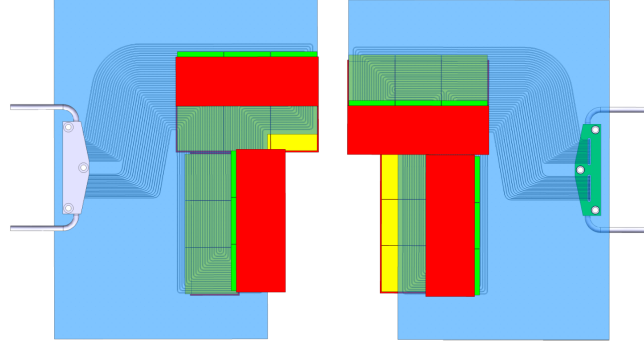


Figure 2.19: Front and rear side of a module. Sensors are drawn in red and the microchannel cooling substrate in blue. The bottom sides of the ASICs are drawn in yellow, while the area where the bond pads are located is made green. The overall horizontal and vertical dimensions of the substrate are 80 and 104 mm, respectively.

geometrical acceptance cross at least four VELO stations.

The new VELO is only 5 mm distant from the beamline, 8 mm being the distance of the old detector. For this reason the resolution of IPs should increase. The single hit resolution is expected to be $\sim 12 - 15 \mu\text{m}$ for both x and y coordinates.

2.2.2 The Upstream Tracker

The Upstream Tracker (UT) has replaced the TT [67,68]. In fact, the TT offered insufficient radiation hardness and incompatible readout geometry and technology for the expected event rate. The UT is a micro-strip silicon detector made of four layers (as the old TT) in the $x-u-v-x$ arrangement. Each UT sensor is composed of $250 \mu\text{m}$ thick silicon and a $10 \mu\text{m}$ metalization layer. The segmentation is finer than the TT, with near-beam sensor pitch of $95 \mu\text{m}$ and dimension of $98 \times 49 \text{ mm}$, against the TT sensor pitch of $183 \mu\text{m}$. In Figure 2.20 a view of the detector is shown. Further from the center, sensor pitch and length double.

2.2.3 The Scintillating Fibre tracker

As at the new luminosity value some regions of the OT would have exhibited a too large occupancy level, along the need to replace all the readout technology for both the IT and OT, a complete overhaul for the T-stations has been decided, substituting the OT and IT with a Scintillating fibre (SciFi) tracker [67, 69], which will cover the full acceptance of the magnet. It comprises three stations, each composed of four $x-u-v-x$ layers, made of 12 modules of $5 \text{ m} \times 52 \text{ cm}$. The two modules closer to the beam have 6 fibre layers, whereas all the other contain 5 layers. The fibres are 2.5 m long with a diameter of $250 \mu\text{m}$, and are read out by Silicon Photomultipliers (SiPMs) contained in the so-called “Read-out Boxes” at the top and bottom of the detector.

The optical photons, constituting the signal, are produced through a multi-step process. Ionization energy is deposited in the polymer core of the fibre; a few eV suffice to produce an excitation of the polymer. However, due to the relaxation

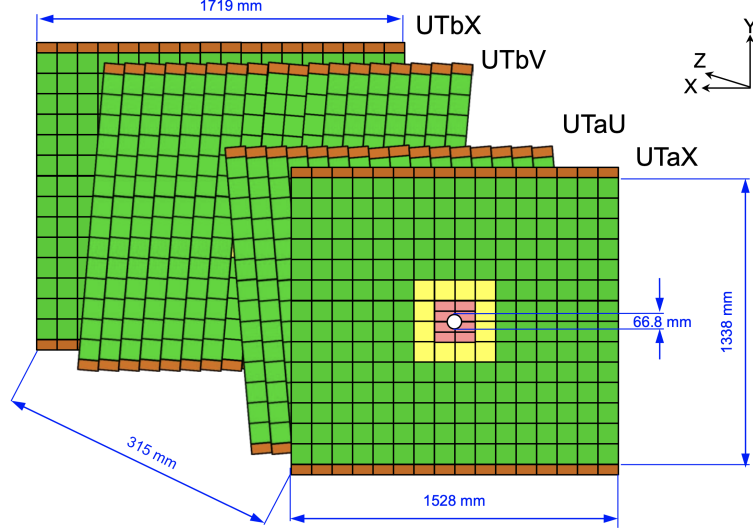


Figure 2.20: Overview of the UT schematic layout. The different sensor geometries are color coded: in yellow the sensors with double length w.r.t. the pink ones, and in green sensor of double length and pitch w.r.t. those coded in pink.

time and light yield of the base material being quite poor, an organic fluorescent dye, with matching excitation energy-level structures, is added to the polystyrene base ($\sim 1\%$ of its weight) to improve the efficiency of the scintillation mechanism.

At the end of its lifetime, the simulated hit efficiency of the detector is estimated to be above 97%. Raw hit resolution is expected to be $\sim 42\mu\text{m}$. The schematics of the SciFi detector and its structure are shown in Figure 2.21.

2.2.4 Data acquisition and trigger

As previously stated, with the dismissal of the L0 trigger, the challenge of processing online full reconstructed events at the expected rate of 30 MHz resides in implementing a data acquisition and trigger system that can deal with the onslaught of expected information from all the sub-detectors. What has been developed is a trigger-less readout system backed by a purely software trigger [70,71]. While the two-step HLT structure is maintained (Figure 2.22), the first stage runs on GPUs [72]. This calls for a separated computer cluster where the events are built, hence the name Event Builder (EB), where HLT1 runs. Events are then passed on to the EFF where HLT2 runs on CPUs. Multiple EB nodes are assigned to each sub-detector: as every event will be processed by a large number of nodes, fast data exchange is required as all the information relative to the event need to be transferred to an EB node, as this gets reconstructed. The network connecting the nodes is called Event Builder Network.

The data-flow is as follows (Figure 2.23): the detector front-end, with no suppressions whatsoever, sends data to the EB farm through optical fibres; each node receives the data through PCIe40 FPGA card, which can write data directly to the memory through Direct Memory Access (DMA) by implementing the PCIe Gen3 protocol [73]. The writing peak rate is 100 Gbit/s. The network card then lets the node communicate with the others, sharing the information, and the GPU

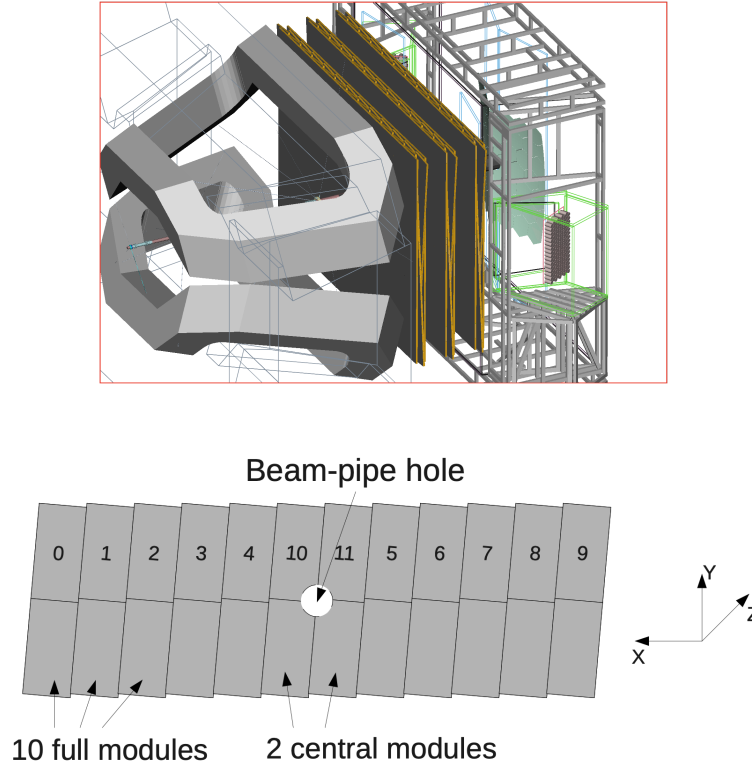


Figure 2.21: Above: the three stations of the scintillating fibre tracker shown between the dipole magnet on the left and RICH2 on the right. Below: the structure of one detection layer is made up of 12 fibre modules. The modules 10 and 11 have a cut-out to allow the beam-pipe to pass through the detector.

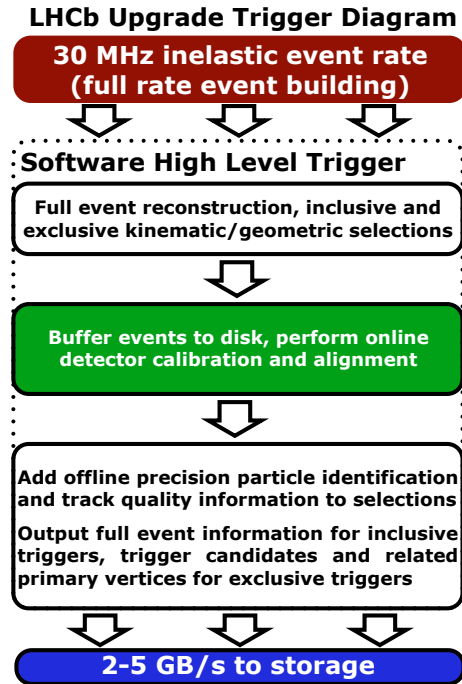


Figure 2.22: LHCb trigger system in Run 3, with disk-buffering between HLT1 and HLT2 for online alignment and calibration purpose. From [63].

card(s) – they can be either one or two – mounted in the node perform(s) the event reconstruction and HLT1 selection; the output is sent to the EFF through the 10G network present on the GPU itself (Figure 2.24).

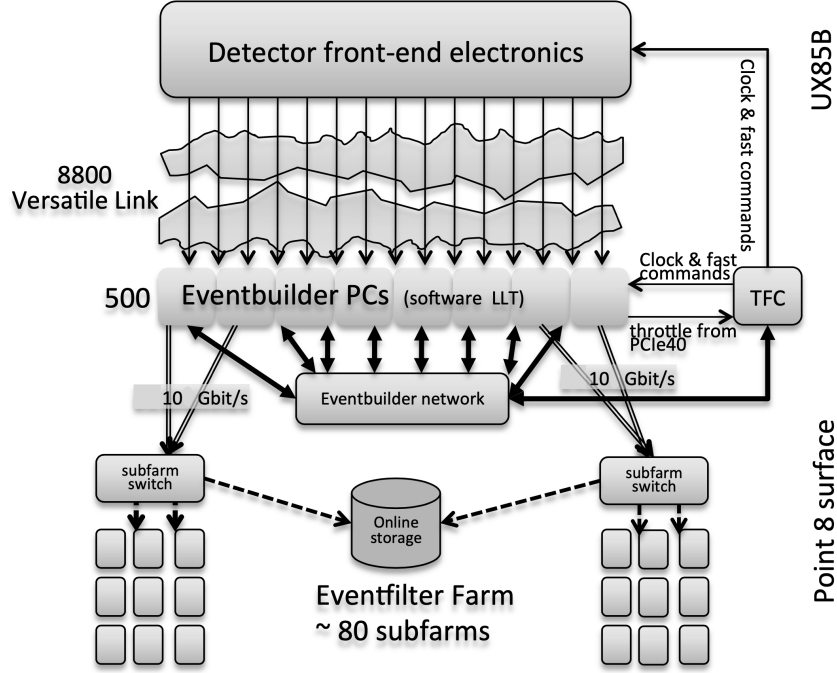


Figure 2.23: The architecture of the upgraded LHCb readout-system.

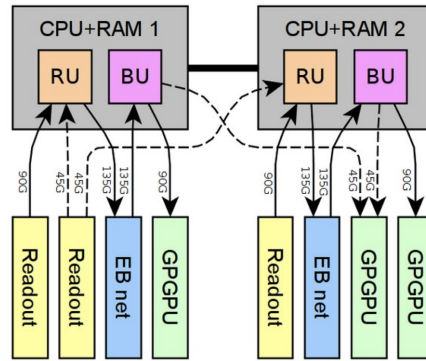


Figure 2.24: Diagram of data flow inside an EB node and its architecture. RU and BU are respectively the readout-unit and building-unit.

The new software will handle an overall data flow of 40 Tbit/s at the rate of 30 MHz, and as the only relevant part of the event will be preserved, much of data selection will be performed online. Maintaining high efficiency for the interested processes and good quality of the samples in such conditions, especially in the charm sector, is proving to be challenging. While some trigger lines have been simply inherited from the Run 2, others are yet-to-be finalized at the current time.

2.3 The LHCb Upgrade II: HL-LHC era

By the end of LHC Run 4, in 2030, 50 fb^{-1} of data will have been accumulated. Further data taking without ulterior upgrades will not be attractive as many of the components in the detector will have reached the end of their natural life span due to radiation exposure. Moreover, the time for doubling the size of the samples will become unappealing [49]. While the LHCb Upgrade I will improve the sensitivity of many flavor studies, the precision on a host of measurements will still be limited by statistics, and other observables, associated with rare processes, will still be poorly known. New physics models need to be further and more thoroughly investigated, as recent measurements seem to indicate BSM physics, an example being the measured tension with the SM, regarding lepton flavor universality [74]. The Upgrade II will allow the experiment to accumulate a minimum of 300 fb^{-1} at the end of Run 6 of data-taking, exploiting the full potential of the High-Luminosity LHC (HL-LHC) era, where LHCb is estimated to be operating at an instantaneous luminosity of $1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The installation of such upgrade will happen during the LS4 (2033-2034), with the first run at high luminosity, Run 5, scheduled to start in 2035. In Figure 2.25 the prospected maximum luminosity values and the integrated luminosity at LHCb through the Run 1-6.

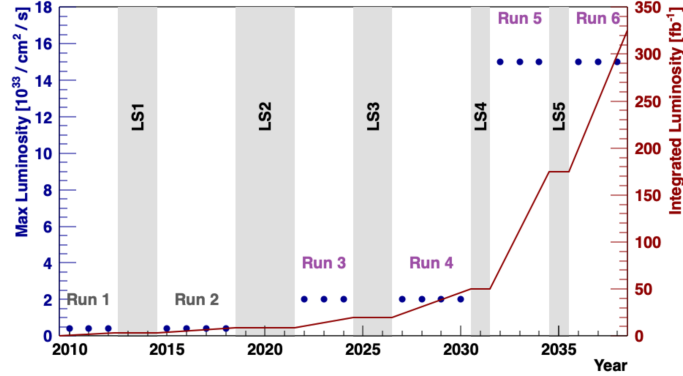


Figure 2.25: Integrated luminosity profile for the original LHCb, Upgrade I (Run 3 and 4) and Upgrade II (Run 5 and 6) experiments, in the context of the official LHC schedule of 2021 (extensions of Run 3 and LS3 by one year and six months, respectively, have been deliberated in January 2022). The blue points and the left scale indicate the anticipated maximum instantaneous luminosity whilst the red line and right scale indicate the accumulated integrated luminosity. From [49].

In these conditions, the number of PVs per pp bunch-crossing are expected to be ~ 56 , which makes the correct matching between tracks and their own PV particularly challenging, not to mention the difficulties in identifying secondary vertices [75]. Detectors need to level up in order to address the increased particle multiplicity, rates and radiation damage.

In the current proposal, the detector will overall preserve the existing layout of the spectrometer, without turning the current arrangement of the sub-detectors upside-down. The tracking system will be composed of a new VELO and tracking stations both upstream the magnet, a new Upstream Tracker, and downstream, the Mighty Tracker (MT). The last one comprises a Silicon Tracker for the inner region and a SciFi Tracker for the outward regions. At the side of the magnet walls,

the Magnet Stations (MS) will be located, for additional tracking. Concerning the particle identification system, the Cherenkov detectors, ECAL and muon stations M2-M5 will be kept in a similar fashion as Upgrade I, however the HCAL will be no more included, replaced with additional shielding, and a time of flight detector (TORCH) will be positioned in front of the RICH2. Differently from pre-HL-LHC era, time resolution will be essential, as at the increased PV multiplicity timing information from the sub-detectors can help in matching the tracks with their own PV. In Figure 2.26 the layout of the detector after the HL Upgrade.

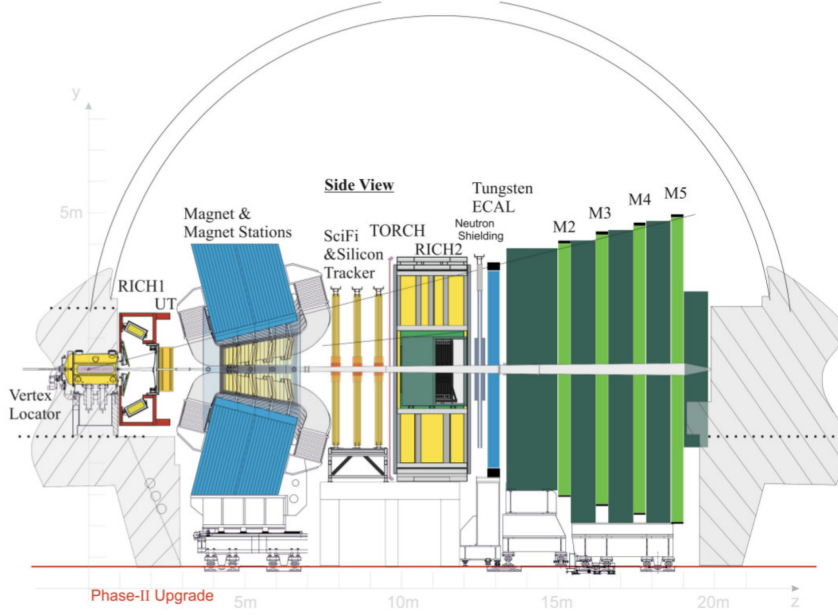


Figure 2.26: The proposed layout for the LHCb detector Upgrade II. From [49].

2.3.1 The tracking system

The vertex detector

With the Upgrade II, the increased luminosity poses significant challenges which necessitate the construction of a new VELO with enhanced capabilities. To cope with the large increase in pile-up, new methods for PV identification, assignment and real time track pattern recognition must be developed. As previously anticipated equipping the VELO with timing capabilities would partially address such challenges. In fact, preliminary studies show that, in the Upgrade II, PV mis-association levels may reach $\sim 20\%$, but it can be reduced to $\sim 5\%$ with a timing precision of $50 - 100$ ps [75]. In Figure 2.27 is shown how timestamps on the track can facilitate the identification of the correct PV.

Another aspect to take in consideration is the expected radiation levels, that the detector will be exposed to, requiring improvements in the mechanical design in order to allow for module replacement. The detector need also to cover the nominal acceptance of LHCb and providing a minimum of four hits per track.

The target value for for the IP resolution is $12 \oplus 24/p_T$, with p_T as the track transverse momentum. With the aim of significantly reducing the multiple scattering term of the IP resolution, scenarios with Ultra Thin RF Foils or with

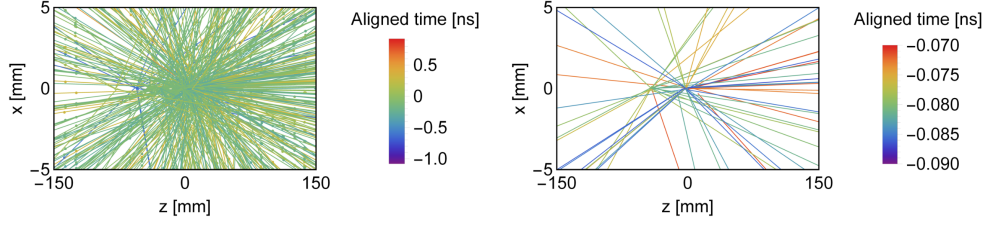


Figure 2.27: The track density generated by 42 collisions spread over a bunch crossing. On the left the whole bunch crossing time period is considered (~ 1 ns). If a time cut of 20 ps would be applied, only a few collisions and corresponding tracks remain, as shown by the plot on the right.

no foils are currently under investigation, and the outcome of such R&D will have great impact on the VELO development and final design.

Upstream tracking

The higher occupancies, expected for Upgrade II, call for a higher granularity Upstream Tracker (UT) than the one developed for Upgrade I. Moreover the innermost silicon sensors are not qualified to sustain a radiation dose exceeding the one expected from 50 fb^{-1} of integrated luminosity [75].

It can be potentially be implemented as a four-plane pixel detector using Monolithic Active Pixel Sensors (MAPS). As this technology offers a time resolution of 5 ns, then, if R&D manages to reduce it to 3 ns, the rate of mis-match between the the upstream and the downstream track segment can be reduced. Moreover the pixel approach would offer for the first time unambiguous precision measurements in the y -direction and hence opening to the possibility of stand-alone track reconstruction [49].

Downstream tracking

The inner part of the Upgrade I SciFi tracker cannot withstand the radiation dose estimated in the high-luminosity runs, then it has been proposed to replace the scintillating fibres of its inner part with high granularity silicon detector, implementing CMOS or HV-CMOS technology. This hybrid tracker has been named Mighty Tracker (MT) and was it to deploy MAPS as its CMOS technology for the silicon part it would be equipped with timing information, thus coordinating the track matching with the upgraded UT. With pixel of size $100 - 200 \mu\text{m}$ in x and 1 cm in y , then the occupancy requirements would be satisfied. Still under discussion is the decision on the number of layers, between 6 and 12 [75].

The Magnet Station

The Magnet Station (MS) is a scintillating-based tracking subsystem proposed to be located inside the magnet to measure the position and direction of particles hitting the magnet side walls. This improves the momentum resolution of upstream tracks to a sub-percent level. The MS will also help to reconstruct tracks at the outer edges of the MT [75].

The improvement of low-momentum particle tracking can be achieved if a spatial resolution of $\mathcal{O}(\text{mm})$ in the bending-plane is offered. The preliminary design

proposes four $350 \times 100 \text{ cm}^2$ panels, each composed of four layers of scintillating bars, with the scintillating light being collected by 1 mm wavelength shifters embed inside the bars and guided outside the magnet with clear fibres [49].

2.3.2 The particle identification system

Hadron identification: the RICH detectors and the TORCH

Regarding the Cherenkov detectors and the increased track multiplicity, the main concern is replacing the current Multi-Anode PhotoMultipliers Tubes (PMTs) with a higher granularity photodetector, possibly Silicon PhotoMultiplier (SiPM). Other contending candidates for such replacement are still under investigation [75].

A complete redesign of the optics, resulting in a shifted response of the photodetectors towards longer wavelengths, may be necessary in order to improve the Cherenkov angle resolution by a factor of three w.r.t. Upgrade I.

The prospect of installing a Timing Of internally Reflected CHerenkov photons (TORCH) detector is taking shape. This detector aims to provide particle identification for particles with momentum $2 - 10 \text{ GeV}/c$, a range not currently covered by the RICH detectors [76]. The detector exploits prompt Cherenkov light produced when charged particles traverse a 10 mm thick quartz plate. Once propagated via total internal reflection to the edge of the plate, the photons are focussed onto a detector plane made of micro-channel plate photomultipliers (MCP-PMTs). Measuring the time-of-flight of the internally reflected Cherenkov light allows for inferring the particle mass as follows. In Figure 2.28 the schematics of a TORCH module showing possible reflection paths.

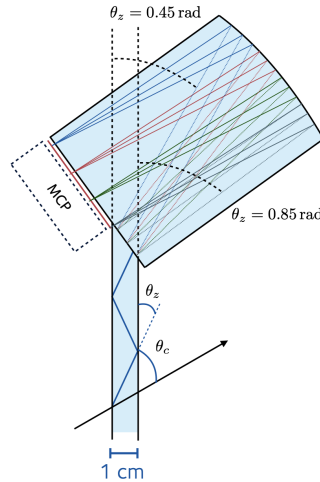


Figure 2.28: Schematics of a TORCH module showing possible reflection paths.

Charged particles passing through the quartz plane emit Cherenkov photons propagating to the edges via total internal reflection. Then, the arrival time of the photon at the edge of the plane equals to the sum of the time-of-flight of the particle to the emission point, t , and the time for the propagation of the photon

in the medium. τ_γ . It can be calculated:

$$t + \tau_\gamma = \frac{x}{c} \sqrt{1 + \left(\frac{m}{p}\right)^2} + \frac{d_\gamma n_g}{c}, \quad (2.3.1)$$

where x is the position where the particle starts emitting Cherenkov radiation, d_γ is the photon path length inside the medium and $n_g = n - \lambda dn/d\lambda$ is the *group index*, with λ being the photon wavelength and n being the refractive index of the medium, which can be determined from Equation 2.1.1. The characteristic photon patterns are reconstructed from the MCP-PMT photon detectors and, for testing and calibration purposes, the expected distributions for $\pi/K/p$ hypotheses are compared to the measured MCP-PMT photon spatial hits and arrival times in order to distinguish the different particle species. The target is to measure individual photons with an angular precision of 1 mrad and 70 ps time resolution with ~ 30 detected photons [77]. Kaons can so be identified in the $p < 10 \text{ GeV}/c$ region, thus enhancing flavor-tagging and reconstruction of multi-body final states. A suitable location for the TORCH within LHCb would be upstream of RICH2.

ECAL

The main challenges the ECAL will face at HL-LHC are three. First, the expected total radiation dose of around 200 MGy for the inner modules will constrain the technology choice towards particularly radiation-hard solutions. Secondly, the high luminosity will result in overlapping showers, degrading the energy resolution and worsening shower finding efficiency. Smaller cell size can solve this problem. Thirdly, due to the high number of particles per event, the combinatorial background is expected to be extremely large, hence the need of fast timing information. Current proposals involve a homogeneous crystal calorimeter with longitudinal segmentation or a sampling calorimeter solution with tungsten-alloy converter, where the fast-timing signal would be produced by an additional crystal component [75].

Muon system

To account for the increased luminosity and radiation degradation, the main effort in the muon system will be focused in the innermost regions of all the stations, which will require, once again, higher granularity. Possibly μ -RWELL detector, which is a new type of Micro-Pattern Gaseous Detector, will be exploited [49]. Extra shielding will also be needed: the HCAL (whose main purpose is contributing to the L0 trigger, which already in Upgrade I is removed) will then be replaced with a 1.7 m thick iron wall.

2.3.3 Data acquisition and online processing

Readout and data acquisition

With the ability of handling at least 200 Tbit/s the readout and data acquisition system will be similar to the Run 3 one. Some enhancement will have to be implemented as using either Ethernet 400 Gbit/s or PCIe Gen5 for the readout board interfacing with the EB, instead of the Run3 PCIe40, thus increasing the bandwidth four times. The EB is foreseen to implement a 400 Gbit/s, if not

800 Gbit/s, or PCIe Gen6, for its EB network between nodes. Such nodes currently offer space for up to 480 accelerators (GPUs), if more are required the number of nodes will be increased. Moreover the accelerators themselves could be either GPUs, FPGA cards or some new technology, as long as they interface with the PCIe standard [49].

Trigger and online processing

With the high PV multiplicity per bunch crossing, a traditional trigger strategy of selecting said bunch crossings based on interesting inclusive topologies, will no longer significantly reduce data rate at the first stages of the trigger. The focus will be on reducing the pile-up, hence the importance of timing information across the majority of the sub-detectors.

From a technological standpoint, the trigger will maintain a Run 3-like structure, with full software HLT split in two stages, the first running on GPUs (in the EB nodes) and the second either in CPUs or GPUs, depending on the architectures available and the costs of such technology. Currently, R&D is focusing on downstream tracking with FPGAs. A testbed in which this technology can already be tested in a Run 3 readout environment is being finalized to allow better integration in the future Upgrade II. It is the case of the Retina project [78], which proposes a very fast and parallel track reconstruction algorithm. Similarly to what happens in the eyes of mammals, where some neurons are sensitive to particular properties of the sensed visual stimulation, so this algorithm recognizes track properties comparing the detector response with stored track patterns; a continuous output (non binary), gauging the distance of the track from the patterns, is then returned. The RETINA concept is applicable, separately, to the different tracking detectors in LHCb. Other parallel projects for online processing, most of them implementing FPGAs are being pursued, from 4D tracking to developing new type of parallel processing units.

Every single investigated enhancement will provide important information for ensuring that the LHCb's trigger and reconstruction algorithms take the best advantage of the most affordable architecture in the future upgrade.

2.4 Opportunities for Charm CP -violation during Run 3 and upcoming HL-LHC era

The Upgrade I and II frameworks described above are expected to take full advantage of the enormous rate of charm hadrons in the upcoming years. At the end of Run 6 a sample of charm decays two order of magnitude greater than Belle II will offer potential unprecedented precision on charm observables [75].

2.4.1 CP violation in mixing

The SM predicts CP violation effects in mixing of charm meson at the level of $\mathcal{O}(10^{-4})$ [79]. While signs of new physics can be uncovered in the upcoming Run 3, precision measurements of these observables at the level predicted by the SM can only occur only in the HL-LHC era, when LHCb will reach the sensitivity of $\mathcal{O}(10^{-5})$.

Measurements involving $D^0 \rightarrow K^\mp \pi^\pm$ will gain great benefits from the implementation of the Magnet Stations (MS). In fact, in such decays the flavor of the D^0 is tagged from the charge of the low-momentum pion (π_s standing for soft pion) produced in the decay $D^{*+} \rightarrow D^0 \pi^+$. These π_s are heavily deflected by the magnetic field and the addition of the MS would allow to flavor-tag previously discarded D^0 mesons, due to lost tagging π_s . In Figure 2.29 is shown how the sample can be increased in size by 40% with the inclusion of MS.

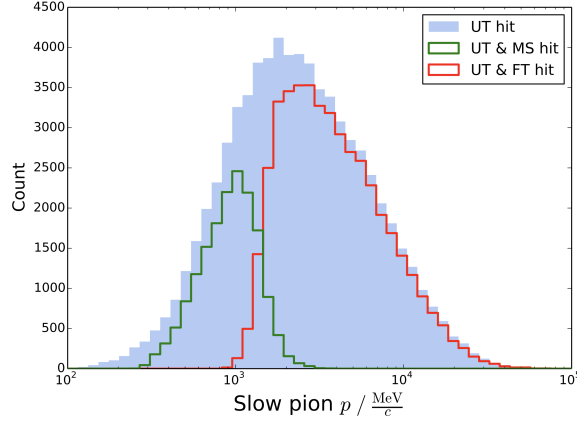


Figure 2.29: The momentum spectra in LHCb simulation of π_s from the decay $D^{*+} \rightarrow D^0 \pi^+$ that leave hits in the UT. The soft π_s observed in the SciFi in Upgrade I and those that will be added by the Magnet Stations (MS) for Upgrade II are indicated respectively in red and green.

In order to have an idea of the reachable precision with the upcoming samples, few observables, not previously discussed in Section 1.2, must now be defined. Labeling as Right Sign (RS) decays those Cabibbo-favoured processes $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$ and as Wrong Sign (WS) the doubly-Cabibbo-suppressed $D^{*+} \rightarrow D^0(\rightarrow K^+\pi^-)\pi^+$, then the time-dependent ratio of WS-to-RS rates can be approximated as

$$R_{K\pi}(t) \approx R_D^{K\pi} + \sqrt{R_D^{K\pi}} y'_{K\pi}(\Gamma t) + \frac{x'^2_{K\pi} + y'^2_{K\pi}}{4} (\Gamma t)^2 \quad (2.4.1)$$

with t being the D^0 meson proper decay time, $R_D^{K\pi}$ is the rate ratio WS-to-RS at $t = 0$ and

$$\begin{pmatrix} x'_{K\pi} \\ y'_{K\pi} \end{pmatrix} = \begin{pmatrix} \cos \delta_{K\pi} & \sin \delta_{K\pi} \\ -\sin \delta_{K\pi} & \cos \delta_{K\pi} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix},$$

where $\delta_{K\pi}$ is the strong phase difference between WS and RS.

In case of CP violation $R^+(t)$ and $R^-(t)$, respectively relative to D^0 and $\bar{D}^0$, would depend on different sets of $(R_D^{K\pi+}, x'^+_{K\pi}, y'^+_{K\pi})$ and $(R_D^{K\pi-}, x'^-_{K\pi}, y'^-_{K\pi})$. It can be defined

$$A_D^{K\pi} = \frac{R_D^{K\pi+} - R_D^{K\pi-}}{R_D^{K\pi+} + R_D^{K\pi-}},$$

which departs from zero in case of direct CP violation [75]. Whereas if CP is violated in mixing or interference between mixing and decay, then no differences arise between

$$\begin{pmatrix} x'^+_{K\pi} \\ y'^+_{K\pi} \end{pmatrix} = \left| \frac{q}{p} \right| \begin{pmatrix} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{pmatrix} \begin{pmatrix} x'_{K\pi} \\ y'_{K\pi} \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} x'^-_{K\pi} \\ y'^-_{K\pi} \end{pmatrix} = \left| \frac{q}{p} \right|^{-1} \begin{pmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{pmatrix} \begin{pmatrix} x'_{K\pi} \\ y'_{K\pi} \end{pmatrix},$$

as $|q/p|$ would be one and ϕ would equals to zero. In Table 2.1 is shown the expected precision on the above defined observables at increasing integrated luminosity.

Sample ($\mathcal{L}$)	Yield($\times 10^6$)	$\sigma(x'_{K\pi})$	$\sigma(y'_{K\pi})$	$\sigma(A_D)$	$\sigma(q/p)$	$\sigma(\phi)$
Run 1-2 (9 fb^{-1})	1.8	1.5×10^{-5}	2.9×10^{-4}	0.51%	0.12	10°
Run 1-3 (23 fb^{-1})	10	6.4×10^{-6}	1.2×10^{-4}	0.22%	0.05	4°
Run 1-4 (50 fb^{-1})	25	3.9×10^{-6}	7.6×10^{-5}	0.14%	0.03	3°
Run 1-6 (300 fb^{-1})	170	1.5×10^{-6}	2.9×10^{-5}	0.05%	0.01	1°

Table 2.1: The expected yields for the $WS D^{*+} \rightarrow D^0(\rightarrow K^+\pi^-)\pi^+$ decay sample at the end of the scheduled data-taking Runs, and the expected statistical precision on charm CPV observables. From [75].

Analogously to the two-body decay, the processes $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$ and $D^0 \rightarrow K^+\pi^-\pi^-\pi^+$ constitutes a pair of RS and WS decays, offering high sensitivity to charm mixing. The increased signal yield, but also the future TORCH detector, can help in fully capture the rich structure of the five dimensional phase space describing this multi-body decay. As the strong phase difference varies across the phase space, $x'_{K\pi\pi\pi}$ and $y'_{K\pi\pi\pi}$ can be measured, providing high precision to the parameters $|q/p|$ and ϕ . In Table 2.2 is shown the expected precision on these variables at increasing integrated luminosity. For these multi-body pro-

Sample ($\mathcal{L}$)	Yield($\times 10^6$)	$\sigma(x'_{K\pi\pi\pi})$	$\sigma(y'_{K\pi\pi\pi})$	$\sigma(q/p)$	$\sigma(\phi)$
Run 1-2 (9 fb^{-1})	0.22	2.3×10^{-4}	2.3×10^{-4}	0.020	1.2°
Run 1-3 (23 fb^{-1})	1.29	0.9×10^{-4}	0.9×10^{-4}	0.008	0.5°
Run 1-4 (50 fb^{-1})	3.36	0.6×10^{-4}	0.6×10^{-5}	0.005	0.3°
Run 1-6 (300 fb^{-1})	22.5	0.2×10^{-4}	0.2×10^{-5}	0.002	0.1°

Table 2.2: The expected yields for the $WS D^0 \rightarrow K^+\pi^-\pi^-\pi^+$ decay sample at the end of the scheduled data-taking Runs, and the expected statistical precision on charm CPV observables. From [75].

cesses, however, the systematic uncertainty arising from the assumed amplitude model would compromise the statistical power of the samples. Model-independent approaches will be needed [75].

With higher signal yields for the $D^0 \rightarrow K_S^0\pi^+\pi^-$ process, more precise measurements of x , y , $|q/p|$ and ϕ can be performed reaching the statistical uncertainty values shown in Table 2.3, where SL tag stands for semi-leptonic production $B^- \rightarrow D^0\mu^-\bar{\nu}_\mu$ and *Prompt* for $D^{*+} \rightarrow D^0\pi^+$. Once again the the strong phase evolution across the phase space and the detection asymmetries, play a significant role in limiting the systematic precision. Model independent approaches will have to be developed along model-dependent ones in order to avoid uncertainty bottlenecks.

A_Γ and y_{CP}

The time evolution of D^0 mesons decaying in CP eigenstates gives sensitive probe to indirect CP violation. Regarding the A_Γ observable, already defined in Section 1.2, its statistical precision depends on the size of the two-body decay samples

Sample ($\mathcal{L}$)	Tag	Yield($\times 10^6$)	$\sigma(x)$	$\sigma(y)$	$\sigma(q/p)$	$\sigma(\phi)$
Run 1-2 (9 fb^{-1})	SL	10	0.07%	0.05%	0.07	4.6°
	Prompt	36	0.05%	0.05%	0.04	1.8°
Run 1-3 (23 fb^{-1})	SL	33	0.036%	0.030%	0.036	2.5°
	Prompt	200	0.020%	0.020%	0.017	0.77°
Run 1-4 (50 fb^{-1})	SL	78	0.024%	0.019%	0.024	1.7°
	Prompt	520	0.012%	0.013%	0.011	0.48°
Run 1-6 (300 fb^{-1})	SL	490	0.009%	0.008%	0.009	0.69°
	Prompt	3500	0.005%	0.005%	0.004	0.18°

Table 2.3: The expected yields for the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decay samples (SL for semi-leptonic tag with D^0 produced from B^- and Prompt for $D^{*+} \rightarrow D^0 \pi^+$) at the end of the scheduled data-taking Runs, and the expected statistical precision on charm mixing observables. From [75].

$D \rightarrow K^+ K^-$ and $D \rightarrow \pi^+ \pi^-$, from which the measurement has been hitherto inferred [42, 43], with D^0 flavor tagging from the $D^{*\pm}$ decay. Systematic effects inducing correlation between momentum and proper decay time must however be studied and controlled with high precision. In Table 2.4 is shown the expected yields of the KK and $\pi\pi$ samples and the precision expected on A_Γ at increasing integrated luminosity.

Sample ($\mathcal{L}$)	Yield KK	$\sigma(A_\Gamma)$	Yield $\pi\pi$	$\sigma(A_\Gamma)$
Run 1-2 (9 fb^{-1})	60M	0.013%	18M	0.024%
Run 1-3 (23 fb^{-1})	310M	0.0056%	92M	0.0104%
Run 1-4 (50 fb^{-1})	793M	0.035%	236M	0.0065%
Run 1-6 (300 fb^{-1})	5.3G	0.0014%	1.6G	0.0025%

Table 2.4: The expected yields for KK and $\pi\pi$ samples at the end of the scheduled data-taking Runs, and the expected statistical precision on A_Γ . From [75].

Similarly, the precision on the y_{CP} observable, or precisely y_{CP}^{hh} can be extrapolated from the expected signal yields of the KK and $\pi\pi$ above mentioned samples, and from the current precision and signal yields of the last published measurement of y_{CP}^{hh} at LHCb [37]. In Table 2.5 is shown the expected yields of the KK and $\pi\pi$ samples and the precision expected on y_{CP} in the future runs. The main concern regarding limits on the precision of y_{CP} is handling the

Sample ($\mathcal{L}$)	Yield KK	$\sigma(y_{CP})$	Yield $\pi\pi$	$\sigma(y_{CP})$
Run 2 (6 fb^{-1}) [37]	18.2M	0.30×10^{-3}	5.82M	0.53×10^{-3}
Run 1-3 (23 fb^{-1})	310M	0.72×10^{-4}	92M	0.13×10^{-3}
Run 1-4 (50 fb^{-1})	793M	0.45×10^{-4}	236M	0.83×10^{-4}
Run 1-6 (300 fb^{-1})	5.3G	0.17×10^{-4}	1.6G	0.32×10^{-4}

Table 2.5: The expected yields for KK and $\pi\pi$ samples at the end of the scheduled data-taking Runs, and the expected statistical precision on y_{CP} . From [37, 75].

time-dependent biases that detection efficiency and selections can introduce in the sample. It can, moreover, be noted that already at the end of Run 4 the expected

sensitivity is $\mathcal{O}(10^{-5})$, at the same order of magnitude predicted by the SM for the difference $y_{CP} - y$ [37].

The necessity of being able to perform such measurement in the upcoming runs is, therefore, of great importance and for this reason this thesis focuses on developing a new methodology for extracting y_{CP} at high luminosities.

For sake of completeness, before moving on to discuss the recent published y_{CP} measurement of LHCb [37] and the procedure studied in this thesis, in order to overcome the challenges that the upcoming runs will arise when such a high precision measurement is pursued at the expected luminosities, the predicted precision for direct CPV observables in the charm sector are briefly reported.

2.4.2 CP violation in decay

The $D \rightarrow K^+K^-$ and $D \rightarrow \pi^+\pi^-$ are also useful in extracting the observable $\mathcal{A}^{CP}(hh)$ defined in Equation 1.3.1. Of particular interest is the variable $\Delta\mathcal{A}^{CP} = \mathcal{A}^{CP}(K^+K^-) - \mathcal{A}^{CP}(\pi^+\pi^-)$, which is robust against systematic effects, whose uncertainties are expected all to have reducible contributions [75]. The signal yields would be again those shown in Table 2.4, however reweighting procedures necessary to carry out the measurement, will slightly affect the samples resulting in yield variations w.r.t. those already shown. In Table 2.6, an overview of $\sigma(\Delta\mathcal{A}^{CP})$ and $\mathcal{A}^{CP}(hh)$ in the future.

Sample ($\mathcal{L}$)	Yield KK	Yield $\pi\pi$	$\sigma(\Delta\mathcal{A}^{CP})$	$\sigma(\mathcal{A}^{CP}(hh))$
Run 1-2 (9 fb^{-1})	52M	17M	0.03%	0.07%
Run 1-3 (23 fb^{-1})	280M	94M	0.013%	0.03%
Run 1-4 (50 fb^{-1})	1G	305M	0.007%	0.015%
Run 1-6 (300 fb^{-1})	4.9G	1.6G	0.003%	0.007%

Table 2.6: The expected yields for KK and $\pi\pi$ samples, usable for direct violation analyses, at the end of the scheduled data-taking runs, and the expected statistical precision on $\Delta\mathcal{A}^{CP}$ and $\mathcal{A}^{CP}(hh)$. From [75].

Also multi-body decays are good channels for direct CPV measurements: the resonances of intermediate states produce overlap and interference patterns in the Dalitz plots, due to strong phase differences. Comparing the Dalitz plot of a three body decay, such as $D^+ \rightarrow K^-K^+\pi^+$ and $D^+ \rightarrow K^-K^+\pi^+$, with their respective charge conjugated ones, a sensitivity on phase differences up to 0.13° , 0.083° and 0.032° can be achieved respectively at 23 fb^{-1} , 50 fb^{-1} and 300 fb^{-1} of integrated luminosity, by observing the $f_0(500)\pi$ resonance, thus unveiling CPV at a 5σ level [75]. This type of analysis is also model-independent and asymmetries in detection efficiency can be accurately extracted from control channels.

Four-body decays offer the possibility of measuring T violating effects (T being the time-inverting operator), and indirectly CP , under the assumptions of the CPT theorem, which implies CPT conservation. With $D^0 \rightarrow K^+K^-\pi^+\pi^-$ and $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ it will be possible to probe T -violation with a sensitivity on T_{odd} asymmetries of $\mathcal{O}(10^{-4})$ at the end of Run 3, $\mathcal{O}(10^{-4} - 10^{-5})$ at the end of Run 4, before the HL-HLC era, and finally $\mathcal{O}(10^{-5})$ at the end of Run 6 with 300 fb^{-1} of integrated luminosity [75].

CHAPTER

3

THE MEASUREMENT OF y_{CP} AT LHCb IN RUN 2

In this chapter it is discussed how LHCb Collaboration has overcome the systematic issue concerning the knowledge of time-dependent track efficiency, mentioned in Chapter 1, in performing the recently published measurement of y_{CP} . In order to fully understand the effort of such endeavor, but also the limitations this methodology is foreseen to have in view of future runs, a brief description needs to be offered, regarding the Run 2 LHCb available samples deployed in the analysis, with their trigger selections, the procedure itself, and how the remaining systematic effects have been addressed. Only then the work developed for this thesis can be explained and the choices, made along the way, be fully understood. This entire chapter is based on References [37, 80].

3.1 Methodology

Once defined the time-dependent decay time ratio between $D^0 \rightarrow f$ and $D^0 \rightarrow K^-\pi^+$ as

$$R^f(t) = \frac{N(D^0 \rightarrow f)}{N(D^0 \rightarrow K^-\pi^+)}, \quad (3.1.1)$$

where the final state f is a CP eigenstate, then $y_{CP}^f - y_{CP}^{K\pi}$ can be retrieved from it, as it is

$$R^f(t) \propto e^{-(y_{CP}^f - y_{CP}^{K\pi})t/\tau_{D^0}} \frac{\varepsilon(f, t)}{\varepsilon(K^-\pi^+, t)}, \quad (3.1.2)$$

with τ_{D^0} the measured lifetime of the D meson equal to 410.1 ± 1.5 as per [32] and ε is the time-dependent efficiency for the particular final state analysed (f is either KK or $\pi\pi$). It is so made manifest how discrepancies between the efficiencies for the process at the numerator and the one at the denominator of Equation 3.1.2 affects the estimation of the desired observable by the mean of an exponential fit.

Those efficiencies comprise two contributions each. One is the *selection efficiency* which depends on the requirements imposed on the reconstructed observables of the particles, both online (trigger selection) and offline (analysis selection). The other is the *detector efficiency*, arising from the interaction of the produced particles with the detector, and its response. With the sensitivity available using Run 1 data-sets, the contribution of these effects was negligible in the ratio [42], but with the statistical power offered by Run 2 data-taking period, this issue had to be addressed. The approach used here entails artificially equalizing the efficiencies between the two processes ($D^0 \rightarrow f$ and $D^0 \rightarrow K^- \pi^+$) such as that they cancel out in the ratio.

The *selection efficiencies* exhibits discrepancies between the two final states because the different mass values of the final particles, K and π , lead to different kinematic distributions thereof. However, the momentum p of the D^0 meson and the decay angle θ^* , between the momentum of the negatively charged particle h^- in the D^0 center-of-mass frame and the D^0 momentum in the laboratory frame, are independent of the final state. To equalize efficiencies then a *kinematic matching procedure* has been developed, consisting in boosting the product particles in the D^0 center-of-mass frame, where both final-state particles have the same momentum, recomputing such momentum substituting the mass value of m_{K^+} with m_{π^+} for the $K^+ K^-$ process, and vice-versa for the $\pi^+ \pi^-$ final state. This way the same phase space is covered by both $D^0 \rightarrow K^- K^+ (\pi^- \pi^+)$ and $D^0 \rightarrow K^- \pi^+$ (Figure 3.1).

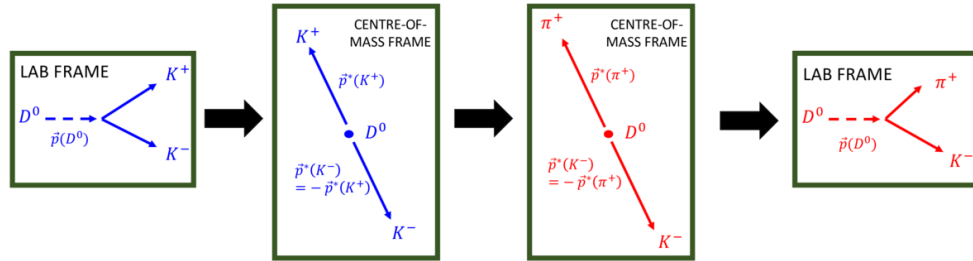


Figure 3.1: The kinematic matching procedure for $D^0 \rightarrow K^- K^+$ to $D^0 \rightarrow K^- \pi^+$, where the mass value of the K^- is substituted with $m(\pi^-)$ and the momentum recomputed in the center-of-mass (w.r.t. D^0) frame, then the reference system is reverted back to the laboratory frame.

Regarding the *detection efficiencies* a *kinematic reweighting procedure* is carried out on the p , p_T and η of the D^{*+} and the final-state particles, after they both undergo the *kinematic matching procedure*.

The accuracy of the method is checked through Monte Carlo Simulations. As full simulation of the pp interaction would have required extremely large computing resources, a lighter simulation generating only the desired decay chain, instead of the whole underlying event, is used. This however implies that particle identification (PID) variables affected by the local occupancy of the detector will be not exactly simulated¹. As in the simulations the mean decay time is set to be the

¹ Even if a Full Simulation were used, accurately reproducing PID information in simulation is a difficult task, and residual discrepancies between data and simulation exists.

same for both $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$, then the measured y_{CP} is expected to be zero. The success of such test with a level of precision of 2.4×10^{-4} (KK channel) and 4.4×10^{-4} ($\pi\pi$ channel) on the extracted y_{CP} , is used to validate the employed strategy. This however means that the simulation is assumed to be reliable and accurate, thus making the methodology not completely data-driven.

For a cross-check on real data, a new observable defined as

$$R^{CC}(t) = \frac{N(D^0 \rightarrow \pi^- \pi^+, t)}{N(D^0 \rightarrow K^- K^+, t)} \propto e^{-y_{CP}^{CC} t / \tau_{D^0}} \frac{\varepsilon(\pi^- \pi^+, t)}{\varepsilon(K^- K^+, t)}, \quad (3.1.3)$$

where y_{CP}^{CC} is expected to be compatible with zero, for the strong phase for both processes is approximated to be the same. It was found $y_{CP}^{CC} = -0.43 \pm 0.54$, proving the validity of the method even on data.

Before reporting the results it is imperative to discuss the charm trigger lines used by LHCb for collection of D^0 two-body decay. Knowledge of the selections that shape the available samples is of essence for understanding the landscape this last measurement found itself operating in, how the new methodology proposed by this work interplays with the Run 2 trigger lines and what decisions concerning online selections are being taken in the imminent Run 3.

3.2 Data sample and selection

“Standard” sample During the Run 2 of data taking, years 2015-2018, LHCb accumulated 6 fb^{-1} of integrated luminosity. Each year two samples of approximately the same size were collected, with opposite orientation of the magnetic field (*MagUp* and *MagDown*). The “kinematic and reweighting technique” successfully works only in presence of dedicated, lifetime unbiased (LTUNB) trigger line, as selections biasing the decay time distributions (or even their ratio) prevent the accurate retrieval of the desired observable. It is to be noted that the LTUNB lines did not exist in Run 1, and are not in the plans for the future Run 3, for reasons that will be discussed in this section. This foreshadows how extending this measurement in the future is anything but trivial. In the following paragraphs the Run 2 trigger selections at various stage of the LHCb trigger system will be discussed in detail.

L0 trigger

A selection on the L0 trigger is necessary otherwise the logic OR of all the lines would be selected resulting in a complex selection, not entirely known with accuracy. For such analysis, one would want a “simple” well known selection demanding that the daughter particles have been reconstructed as hadrons and that they have sufficient transverse energy for them being compatible with a D^0 decay. Requiring that at least one of the two tracks satisfies this conditions means that the `D0_LOHadron_TOS` has been fired. The label TOS stands for *Trigger-On-Signal*, it is assigned after the offline reconstruction and means that the candidate particle, or at least one of its decay products, had been accepted by the L0 trigger selection. A candidate is labeled TIS (*Trigger-Independent-Signal*) w.r.t. a L0 trigger line if neither the candidate itself or its decay products are responsible for the event to having been selected by the L0 trigger line.

However, requiring `D0_LOHadron_T0S` does not guarantee to select particles with E_T over a certain threshold, due to the approximated algorithm the L0 trigger employs. Moreover the E_T thresholds has been changed more than 20 times over the four years of Run 2, highly increasing the complexity of the analysis method. Deciding to select D^0 mesons produced in the decay of $D^* \rightarrow D^0 \pi_s$, where the pion π_s is considered *soft* due to the narrow phase space allowed by the decay and is used as tag, then it can be required `Dst_LOGlobal_TIS`. This way, as the events that trigger L0 are the *non-signal* ones, biases on the signal candidates are avoided.

High Level Triggers

Analyses involving two-body decays of the D^0 meson, such as ΔA_{CP} [39] and ΔY [81], make use of what is informally called within the LHCb charm group the “standard two-body selection”. That selection requires high-quality tracks and good background suppression.

At the HLT1 level, one of the daughter particles has to fire the `Hlt1TrackMVA` line or the combination of the two need to be selected by `Hlt1TwoTrackMVA`. The former requires that the single track satisfies

$$\left[(p_T > 25.0) \wedge (\chi_{IP}^2 > 7.4) \right] \vee \left[(p_T \in [1.0, 25.0]) \wedge \left[\ln(\chi_{IP}^2) > \left(\ln(7.4) + \frac{1.0}{(p_T - 1.0)^2} + \lambda \left(1 - \frac{p_T}{25.0} \right) \right) \right] \right], \quad (3.2.1)$$

where p_T is the transverse momentum of the track expressed in GeV/ c , λ is a constant varying during the years between 1.1 and 2.3, and χ_{IP}^2 is the difference of the χ^2 vertex fit, before and after removing the track from the fit. It stands as consequence that a track not belonging to the vertex has larger χ_{IP}^2 .

The `Hlt1TwoTrackMVA` consists in the output of a Boosted Decision Tree (BDT) based on the significance of the flight distance χ_{FD}^2 between the PV and the Decay Vertex (DV), the sum of the transverse momenta of the two tracks, the number of tracks having $\chi_{IP}^2 < 16$ and the χ^2 of the vertex fit of both tracks

The HLT2 trigger, which is based on fully reconstructed event data, selects the decay $D^{*+} \rightarrow D^0(\rightarrow h^+ h^-) \pi_s^+$ via the `Hlt2CharmHadDstp2D0Pip_D02xxTurbo` line, with `xx` being either `KmPip`, `KmKp` or `PimPip`, depending on the final state of interest being respectively $K^- \pi^+$, $K^- K^+$ or $\pi^- \pi^+$. The acceptance requirements are shown in Table 3.1, where DOCA is the Distance Of Closest Approach between two tracks, θ_{DIRA} is the DIRectional Angle defined as the angle between the momentum of the particle and its displacement vector, which is the oriented distance between the PV and its EV, also known as *flight distance*. The $DLL_{K-\pi}$ is defined as the difference of the log-likelihoods between the kaon and the pion hypotheses. The quantity $P_{\text{Ghost}}^{\text{track}}$ is the probability of the track being the product of random hits in the detector instead of being created by a real particle. Some caveats apply to the samples selected through these trigger lines. Events are, in fact, heavily lifetime-biased by the selection on the χ_{FD}^2 and χ_{IP}^2 , being them highly correlated with the decay time. While the efficiency of the χ_{FD}^2 cut is expected be the same across the different decay channels of interest, canceling out in the time decay ratio, the same cannot be said for χ_{IP}^2 . The issue resides in both variables arising from complex vertex fits and being very difficult to reproduce in

Hlt2CharmHadDstp2D0Pip_D02xxTurbo		
Candidate	Quantity	Requirement
D^{*+}	fit of D^{*+} vertex χ^2/ndf	< 25
	$\Delta m = m(h^+h^-\pi_{tag}^+) - m(h^+h^-)$	$\in [130, 160]\text{MeV}/c^2$
π_{tag}^+	track χ^2/ndf	< 3
	$P_{\text{Ghost}}^{\text{track}}$ (2015,2016)	< 0.4
	$P_{\text{Ghost}}^{\text{track}}$ (2017,2018)	< 0.25
	p_T (2015,2016)	$> 100 \text{ MeV}/c$
	p_T (2017,2018)	$> 200 \text{ MeV}/c$
	p	$> 1 \text{ GeV}$
D^0	$p_T(h^+h^-)$	$> 2 \text{ GeV}$
	$m(h^+h^-)$	$\in [1715, 2015]\text{MeV}/c^2$
	fit of D^0 vertex χ^2/ndf	< 10
	χ_{FD}^2	> 25
	θ_{DIRA}	$< 17.3 \text{ mrad}$
Daughters	track χ^2/ndf	< 3
	$P_{\text{Ghost}}^{\text{track}}$	< 0.4
	$p_T(h^\pm)$	$> 800 \text{ MeV}/c$
	$p(h^\pm)$	$> 5 \text{ GeV}/c^2$
	$\chi_{IP}^2(h^\pm)$	> 4
	$\text{DLL}_{K-\pi}(K)$	> 5
	$\text{DLL}_{K-\pi}(\pi)$	< 5
	$\max\{p_T(h^+), p_T(h^-)\}$	$> 1 \text{ GeV}/c$
	$\text{DOCA}(h^+h^-)$	$< 0.1 \text{ mm}$

Table 3.1: The Hlt2CharmHadDstp2D0Pip_D02xxTurbo line requirements.

simulation. Thus the kinematic matching is doomed to fail at some point, as it cannot exactly equalize efficiencies for different particle like kaons and pions and it cannot be reproduced by simulation with arbitrary precision.

LTUNB sample During Run 2, another high-level trigger line strategy was available for two-body D^0 decays. The LifeTime UNBiased (LTUNB) sample is built via the `Hlt2CharmHadDstp2D0Pip_D02xxLTUNBTurbo` line which require its corresponding `HLT1CalibTrackingHH` (HH=KK, PiPi or KPi) line to be fired as well. The requirements of the HLT1 line are shown in Table 3.2, while the ones of the HLT2 are in 3.3.

HLT1CalibTrackingHH		
Quantity	Requirement	
Daughters	track χ^2/ndf	< 2
	p (2015,2016)	$> 4 \text{ GeV}/c$
	p (2017,2018)	$> 5 \text{ GeV}/c$
	p_T	$> 600 \text{ MeV}/c$
	$\max\{p_T(h^+), p_T(h^-)\}$	$> 900 \text{ MeV}/c$
D^0	p_T	$> 1.5 \text{ GeV}/c$
	$m(h^+h^-)$	$\in [1764, 1964] \text{ MeV}/c^2$
	fit of D^0 vertex χ^2/ndf	< 10
	θ_{DIRA}	$< 451 \text{ mrad}$
	decay time t	$> 200 \text{ ps}$

Table 3.2: The HLT1CalibTrackingHH line requirements.

Events collected in this way are less pure in comparison to the “standard” sample, with a much larger combinatorial background. Given this, due to bandwidth limitations to save the triggered events, the Cabibbo-favored $D^0 \rightarrow K^-\pi^+$ channel was subjected to a *prescale*² factor of 0.5 for years 2017 and 2018, 0.2 in year 2016 and 1.0 during 2015.

Additional offline selections were added, both for reducing backgrounds and for determining a kinematic region where the kinematic matching and reweighting procedure properly works. Requirements on the $DLL_{K-\pi}$ quantity were tightened in order to reduce misidentification, transverse flight distance L_{xy} of the D^0 bounded to a maximum value of 4 mm for removing signal-like events produced from the interaction of hadrons with the RF-foils. The contribution of secondary decays, which are D^0 produced in decays of B hadrons instead of originating from the PV, is minimized by imposing that the impact parameter of the D^0 w.r.t the PV does not exceed 50 μm . These decays are affected by a bias on the decay time due to the production point of the charm particle being erroneously assigned to the PV, biasing the flight distance of the D^0 meson and thus being a source of systematic uncertainty. The D^0 mass window is constrained within 2σ from the known D^0 mass and similarly the $\Delta m = m(D^{*+}) - m(D^0)$ is selected within 2σ from the known π mass. The combinatorial background is reduced by sideband subtraction using the Δm distribution. Finally a decay time window is deter-

² Meaning that only a fraction of events passing the selection requirements was randomly retained.

Hlt2CharmHadDstp2D0Pip_D02xxLTUNBTurbo		
Candidate	Quantity	Requirement
D^{*+}	fit of D^{*+} vertex χ^2/ndf	< 25
	$\Delta m = m(h^+h^-\pi_{tag}^+) - m(h^+h^-)$	$\in [130, 160]\text{MeV}/c^2$
π_{tag}^+	track χ^2/ndf	< 3
	$P_{\text{Ghost}}^{\text{track}}$ (2015,2016)	< 0.4
	$P_{\text{Ghost}}^{\text{track}}$ (2017,2018)	< 0.25
	p_T (2015,2016)	$> 100 \text{ MeV}/c$
	p_T (2017,2018)	$> 200 \text{ MeV}/c$
	p	$> 1 \text{ GeV}$
D^0	$p_T(h^+h^-)$	$> 2 \text{ GeV}$
	$m(h^+h^-)$	$\in [1804, 1924]\text{MeV}/c^2$
	fit of D^0 vertex χ^2/ndf	< 10
	decay time t	$> 250 \text{ ps}$
	θ_{DIRA}	$< 141 \text{ mrad}$
Daughters	track χ^2/ndf	< 3
	$P_{\text{Ghost}}^{\text{track}}$	< 0.4
	$p_T(h^\pm)$	$> 800 \text{ MeV}/c$
	$p(h^\pm)$	$> 5 \text{ GeV}/c^2$
	$\text{DLL}_{K-\pi}(K)$	> 10
	$\text{DLL}_{K-\pi}(\pi)$	< 0
	$\max\{p_T(h^+), p_T(h^-)\}$	$> 1.2 \text{ GeV}/c$
	$\text{DOCA}(h^+h^-)$	$< 0.1 \text{ mm}$

Table 3.3: The Hlt2CharmHadDstp2D0Pip_D02xxLTUNBTurbo line requirements.

mined in the range $[1 - 8]\tau_{D^0}$. The lower bound is defined by the inability to recover, even in the simulation, the correct lifetime ratio below $1\tau_{D^0}$; the upper is to limit the contribution of surviving secondary decays, which have larger impact at greater decay times. Additional requirements on the re-matched kinematic variables of the daughter particles (not discussed in detail because deeply interconnected with the kinematic matching procedure and outside the scope of this work) are then applied, resulting in a final offline selection efficiency of 22%, 16% and $\sim 5\%$ respectively for the $K^-\pi^+$, K^-K^+ and $\pi^-\pi^+$ samples.

3.3 Results and systematic uncertainties

The cross-check observable defined previously is found to be

$$y_{CP}^{CC} = (-0.43 \pm 0.53) \times 10^{-3},$$

thus validating the methodology on real data. Then $y_{CP}^{KK} - y_{CP}^{K\pi}$ and $y_{CP}^{\pi\pi} - y_{CP}^{K\pi}$ are independently measured

$$y_{CP}^{\pi\pi} - y_{CP}^{K\pi} = (6.57 \pm 0.53_{\text{stat.}} \pm 0.16_{\text{syst.}}) \times 10^{-3}$$

$$y_{CP}^{KK} - y_{CP}^{K\pi} = (7.08 \pm 0.30_{\text{stat.}} \pm 0.14_{\text{syst.}}) \times 10^{-3}.$$

The main source of systematic uncertainty for $y_{CP}^{\pi\pi} - y_{CP}$ is the combinatorial background subtraction and the reweighting procedure itself, while concerning the $y_{CP}^{KK} - y_{CP}$ observable the main contributor is the *peaking background*, comprising partially reconstructed $D^{*+} \rightarrow D^0\pi^+$ decays, and, again, the combinatorial background subtraction.

Of particular interest is how the contribution of remaining secondary decays is handled in order for them contributing with an effect an order of magnitude lower the total systematic uncertainty. The ratio $R^f(t)$ is rewritten accounting for the prompt and secondary components contributing separately

$$R^f(t) = [1 - f_{\text{sec}}(t)] R_{\text{prompt}}^f(t) + f_{\text{sec}}(t) R_{\text{sec}}^f(t), \quad (3.3.1)$$

with

$$R_{\text{sec}}^f(t) \propto e^{-(y_{CP}^f - y_{CP}^{K\pi})(t_D(t))/\tau_{D^0}},$$

where $\langle t_D(t) \rangle$ is the average true D^0 decay time as a function of the reconstructed decay time for secondary decays. Both $f_{\text{sec}}(t)$ and $\langle t_D(t) \rangle$ are determined via simulated samples.

When $y_{CP}^{KK} - y_{CP}^{K\pi}$ and $y_{CP}^{\pi\pi} - y_{CP}^{K\pi}$ are combined, the final result is

$$y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26_{(\text{stat.})} \pm 0.13_{(\text{syst.})}) \times 10^{-3},$$

exhibiting a precision four times lower than at-the-time WA. It is proposed again in Figure 3.2, already shown in Chapter 1, the great improvement this measurement has produced, well after three years from the last Run 1 LHCb measurement of the same parameter, when the incapability of addressing the issue of selection and detection efficiencies and its contribution to the systematic uncertainty halted any further analysis with higher statistical power.

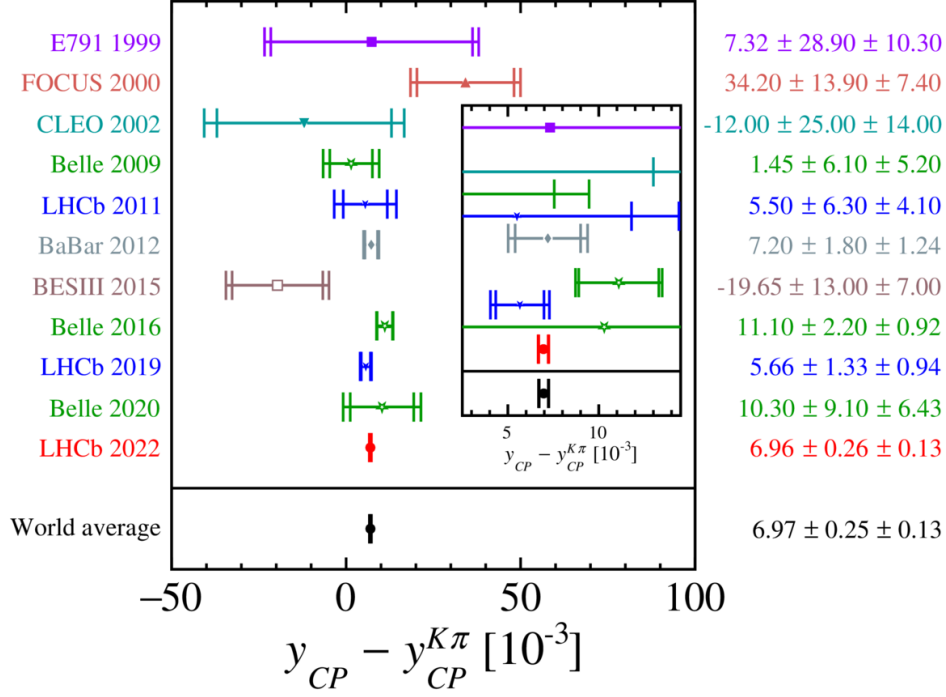


Figure 3.2: The new $y_{CP} - y_{CP}^{K\pi}$ World Average after the last published LHCb measurement.

3.4 Repeating the measurement at higher luminosity

This methodology, as it has been illustrated, heavily relies on the presence of a LTUNB trigger line for the samples of interest. This not only prevents it to being applied to the Run 1 data sets which are devoid of such unbiased selection, but also impedes the applicability at future runs. In fact, it has been discussed that even at the Run 2 luminosity this trigger line needed to be prescaled and, as a higher luminosity run is just starting, higher prescale factor would be needed, causing the collected samples to rapidly reach statistical precision saturation. Moreover, large quantities of combinatorial background would continue to be accepted, creating a bottleneck in reducing its contribution to the systematic uncertainty. For this reason, in the Run 3, while the “standard” Hlt2CharmHadDstp2D0Pip_D02xxTurbo line has been incorporated in the new HLT system, the Hlt2CharmHadDstp2D0Pip_D02xxLTUNBTurbo has been discontinued.

Currently, a *low bias* trigger line is being finalized, with HLT1 and HLT2 selections working coordinately, implementing $IP(h^\pm)$ selections, that while biasing the lifetime they involve a quantity that can be computed offline accurately, contrary to $\chi_{IP}^2(h^\pm)$. However, the kinematic matching and reweighting technique is not guaranteed to properly work in such conditions. Moreover, the “reweighting bit” of the above discussed strategy only sidesteps the need of extracting the time-dependent detection efficiency for every decay channel by equalizing them within a certain precision. The systematic uncertainty related to this equalization does not scale with the growing samples as the integrated luminosity increases, as it is not of statistical nature. For one thing, the method cannot account in any way

for the different efficiency of the particle-identification requirements applied to K and π . In addition the issue of higher vertex multiplicity and greater probability of PV/track mismatch expected at Run 3 needs to be addressed.

Therefore, now that the limits of the analysis methodology explained in this chapter have been discussed in depth, equipped with a background framework necessary to understand CP violation in the charm sector, its state of art and what are the possibilities of the LHCb in the future regarding these observables, the characteristics of the detector in the previous runs of data-taking and the changes it has already undertaken for the Upgrade I, along with those it will encounter for Upgrade II, the new proposed analysis strategy for measuring y_{CP} from Run 3 forward will be discussed starting from the next chapter. The presented studies are expected to be useful not only to the y_{CP} measurements, but also for other time-dependent measurements.

PART II

ANALYSIS STRATEGY AND TESTS ON TOY MONTECARLO

CHAPTER

4

OVERCOMING PRIMARY VERTEX BIAS AND MISMATCHING

As stated in Section 2.2 and Section 2.3, the increased instantaneous luminosity equals to higher PV multiplicity along the beam line, while at Run 2 there was, on average, one PV per beam crossing. This poses two issues: differentiating the PVs and assigning the track to the correct PV. While in Run 3 differentiating PVs may still be manageable, with the PV separation being of 4.2 mm and the resolution along the z axis being expected to be $60 - 100\mu\text{m}$ [82], this separation is calculated to drop up to 1.5 mm after Upgrade II. However even in the case the PVs are properly differentiated, it remains the problem of possible mismatch between PV and tracks. Currently, it has been proposed for the Upgrade II that applying track timestamps reduces the number of PV candidates to each track [83].

Two paths have, to this day, been suggested in order to achieve such implementation: moving to full 4D-tracking, by adding precise timing to every hit, or, instead, adding dedicated timing plates. As the former option offers best results concerning PV efficiency, it imposes strict requirements on the radiation hardness of the timing detectors due to the increased luminosity, it has never been implemented on such scale and it is extremely expensive. The timing plates approach would collocate these detectors further away from the interaction region, and while in this case the material budget can be more easily controlled, the PV efficiency would suffer [49]. This upgrade, however, would benefit only Run 5 and 6, leaving Run 3 and 4, expected to last up until 2030, vulnerable to such issue.

What it is explored in this chapter is an analysis method circumventing the necessity of correctly assign the decay to its true PV. The lifetime is calculated using only transverse variables; then the flight distance of the particle whose lifetime is being measured is computed w.r.t. the mean PV instead of the own

PV of every event.

4.1 The need of a custom simulation

In order to prove the feasibility of the proposed approach, a custom simulation, “Toy Monte Carlo” (ToyMC), is created from scratch. The sample produced with this ToyMC, or a statistically independent one with the same configuration, is then re-used for testing all the methods proposed through all the Part II of this thesis’ work.

The choice of a “hand-made” ToyMC resides with the necessity of having large enough samples in reasonable time, with the additional feature of full flexibility, which is highly coveted at the initial stage of a research regarding a new methodology with unknown systematic effects. In such manner, variables can be easily redefined from scratch throughout the development of the method, and momentum and lifetime generated distributions can be modified without difficulty. This, while at this stage can be under-appreciated, will be of great usefulness in the upcoming chapters.

This ToyMC is loosely based on the kinematic distributions of the LHCb Official MC Full Simulation using the LTUNB trigger line for the process $D^{*+} \rightarrow D^0 \pi^+ \rightarrow (K^+ K^-) \pi^+$, already mentioned in Chapter 3.

The PV is generated as follows:

- the true PV position is modeled with a 3-D Gaussian function with $\mu_x = \mu_y = \mu_z = 0 \mu\text{m}$ and $\sigma_x = \sigma_y = 27 \mu\text{m}$, $\sigma_z = 44 \text{ mm}$;

As the D^{*+} decays to D^0 via strong interaction, instead of simulating the former meson and its decay vertex, which is the origin point of the latter meson, the D^0 is directly originated in the PV. This also reflects the fact that in the analysis of real data the flight distance of such particle is computed from the PV instead of its origin vertex, which has far less precision than the PV position. Regarding the D^0 momentum:

- the magnitude of D^0 momentum distribution is approximated with a Landau distribution, estimated from the fit of the Official MC Full Simulation;
- the pseudorapidity η of the D^0 is approximated with a Gaussian shape whose mean and variance are those of the η distribution extracted from the Official MC Full Simulation;
- the azimuthal angle ϕ distribution of the D^0 is assumed isotropic.

Then the D^0 meson is allowed to fly for a time t extracted randomly from an exponential distribution with $\tau = 410.1 \text{ fs}$ [32], thus determining the vector flight distance $\vec{L}_{3D}$ and, using the PV as the origin vertex of the D^0 , univocally defining the decay vertex (or end vertex) EV as $\vec{EV} = \vec{PV} + \vec{L}_{3D}$. At this point the D^0 decays in two kaons of opposite charge, with the kinematic of a two-body decay.

In this first instance, resolution effects are simulated by a Gaussian smearing on PV and EV coordinates, and the momentum magnitude of the two kaons - from which the momentum of the D^0 is then recalculated. All the effects are assumed statistically independent.

The resolution effects amount to:

- $\sigma_x = \sigma_y = 10 \mu\text{m}, \sigma_z = 54 \mu\text{m}$ on the PV coordinates;
- $\sigma_x = \sigma_y = 30 \mu\text{m}, \sigma_z = 56 \mu\text{m}$ on the EV coordinates;
- $\sigma_P/P = 1\%$ on the K momentum magnitude.

Using this configuration, 3×10^8 events have been generated - this number will acquire a clearer meaning in the following chapter, when the issue of track efficiencies will be addressed.

4.2 Moving to transverse variables

When the problem, arising at high luminosities, of assigning the correct PV to the decay has been introduced, it was explained as consequence of high PV density along the beam line. If we now consider the dispersion of the PV true positions in the transverse plane, mentioned above in the ToyMC input parameters, it can be noted that the Gaussian-like profile has $\sigma_x = \sigma_y = 27 \mu\text{m}$, thus assigning the wrong PV to the decay is comparable with the resolution effects¹, whereas in longitudinal direction it has been stated that PV separation is expected to be 4.2mm in Run 3 and 1.5mm at HL-LHC, meaning that a mismatch between the tracks and their PV has far greater effects than the ones due to resolution. Exploiting the compactness of the beam in the plane transverse to the beamline is, therefore, what allows sidestepping the issue of PV misassignment. From here on when transverse plane or transverse variable will be mentioned it will always be implied “transverse w.r.t. the beamline” unless stated otherwise. Then, instead of computing the absolute lifetime of a particle as

$$\tau_{3D} = \frac{\vec{L}_{3D} \cdot \vec{p} m}{|\vec{p}|^2 c} \quad \text{it is here proposed} \quad \tau_T = \frac{\vec{L}_{xy} \cdot \vec{p}_T m}{|\vec{p}_T|^2 c}, \quad (4.2.1)$$

where $\vec{L}_{3D}$ ($\vec{L}_{xy}$) and $\vec{p}$ ($\vec{p}_T$) are respectively the 3D (transverse) flight distance and momentum of the measured particle, m its mass and c the speed of light in vacuum (Figure 4.1). Projecting the flight distance on the momentum helps with partly reabsorbing resolution effects of particle momentum and PV, EV positions.

With the support of the Toy MC described in the previous section it can be studied whether the choice of using transverse variables produces significant effects on the lifetime measurements. A binned likelihood fit is performed of both τ_{3D} and τ_T observables, based on the full ToyMC without any selections. Results are shown in Figure 4.3 for a few choices of fit range. An example plot of one such a fit is shown in Figure 4.2. The first thing to be noted in Figure 4.2 is the deviation of the pulls from zero at low decay times. The suspect is that resolution effects producing a smearing on the decay time resolution need to be modeled and their contribution accounted for in the fit. Further ahead this will be properly investigated, for now the region below 1 ps will not be considered for the evaluations carried out in this instance.

Considering now the values extracted and shown in Figure 4.3, it can be noted that above the mentioned threshold there is no loss of accuracy or precision in using transverse variable instead of the 3D ones, as long as the range is restricted

¹ The resolution effects has been previously discussed in describing the creation of the ToyMC.

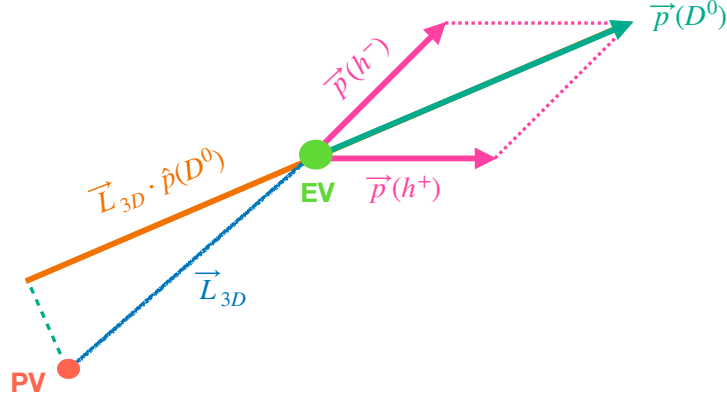


Figure 4.1: A pictorial representation of the D^0 flight distance and its momentum reconstructed from momenta of its products. $\vec{L}_{3D}$ and $\vec{p}(D^0)$ are not collinear due to detection smearing effects on the position of the vertices and the direction of the D^0 momentum vector. These effects have been overemphasized for representational purpose.

to decay times above 1 ps. Moreover the value extracted are in agreement with the simulated one proving not only that the simulation is correct, but also that the reconstruction algorithm is valid. However even at higher decay time regions, the χ^2 of the fit is far larger than the expected value ($\chi_{exp.}^2 = ndf$, with ndf being the number of degree of freedom). It was then investigated whether the resolution smearing effects could be the cause. The effect, in fact, is expected to dominate at low decay times, where shorter flight distances, more influenced by vertex position resolution, lie, but at this precision level one wonders if it can also cause “inflated” χ^2 values in fit at higher decay time ranges. In order to test this assumption the decay time was recomputed from *non smeared* variables.

The results of the fits to the decay time distribution with no resolution effects for various fit ranges are shown in Figure 4.4. Now, good values of χ^2 are obtained even at low decay times, so it can be proven that even at low temporal windows, using transverse variables results in no loss of accuracy or precision.

Because the mean lifetime of the particles does not necessarily need to be extracted with a fit to the distribution and one would want to leave open as many viable pathways as possible, another test is comparing the arithmetic means of τ_{3D} and τ_T unbinned distributions. It is found:

$$\bar{\tau}_{3D} = (410.145 \pm 0.024)\text{fs} \quad \text{and} \quad \bar{\tau}_T = (410.151 \pm 0.024)\text{fs},$$

This values are not only compatible with each other, but are also only 2σ away from the simulated value. This validates the simulation and the reconstruction algorithm, and proves that τ_T can be used in place of τ_{3D} for measuring the mean lifetime of the particle. Moreover, we see that resolution effects do not bias the arithmetic mean.

4.3 No need for a Primary Vertex

Using only the transverse variable to compute the decay time provides another advantage. Further exploiting the compactness of the beam bunch in the transverse plane, it can be argued that as the true PV position is Gaussian-like dispersed

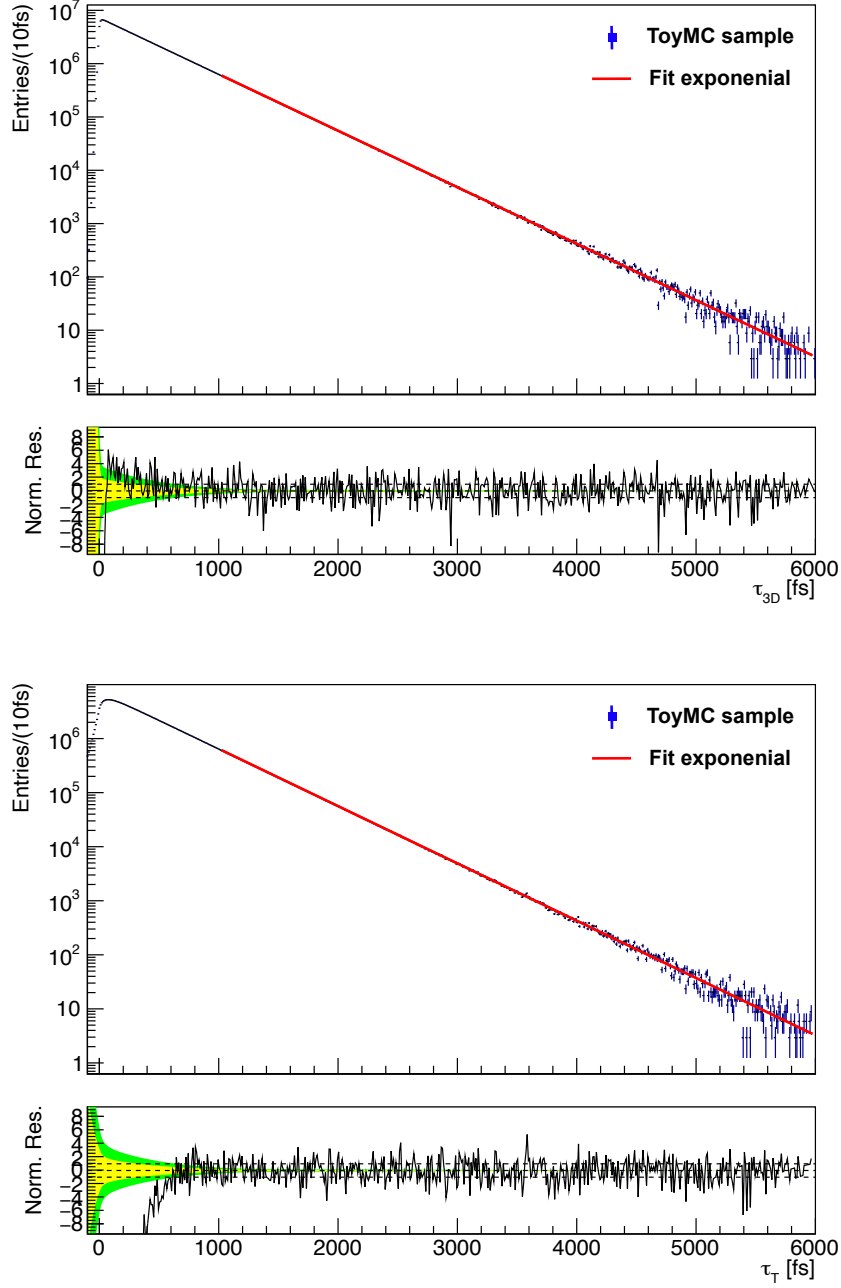


Figure 4.2: Above: binned likelihood exponential fit in the range $[1.0, 6.0]$ ps of the lifetime computed with 3D variables. Below: binned likelihood exponential fit in the range $[1.0, 6.0]$ ps of the lifetime computed with transverse variables. The sample distribution is represented in blue with the poissonian uncertainty of each bin being drawn. The fitted function is plotted in red and below each plot the pulls are shown (even outside the fit range).

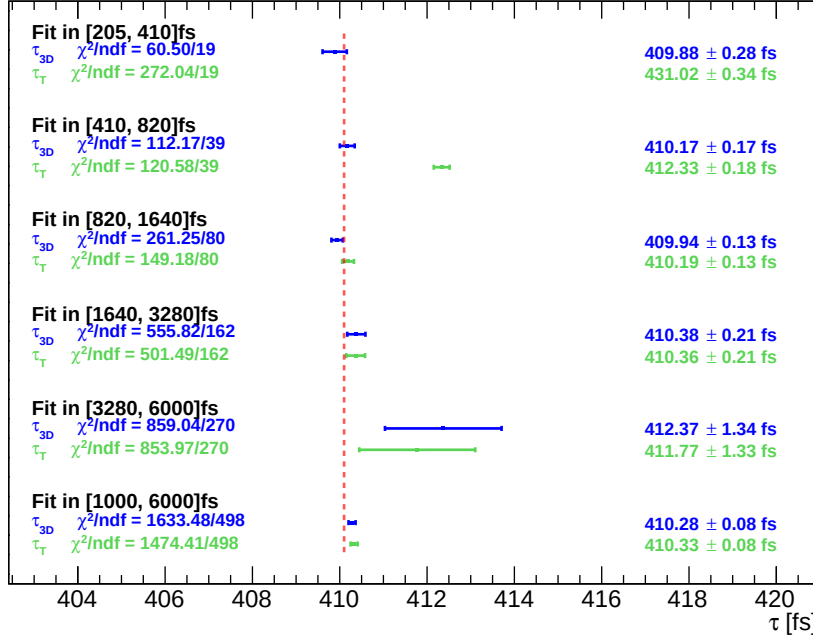


Figure 4.3: Comparison between τ_{3D} and τ_T exponential fits in various ranges. The Baker-Cousin χ^2 can be interpreted as goodness-of-fit-indicator and it is indicated over the degrees of freedom of the fit. The plot of extracted τ_T from the [205,410]fs fit range would have made all the other values unreadable: on the right the explicit value returned by the fit is thus reported, with its uncertainty. The red dotted line represents the simulated mean lifetime.

with a $\sigma_{x,y}$ comparable, in magnitude, with the resolution effect, then the issue of assigning to one decay its correct PV can be completely evaded in the following way: instead of employing the event-by-event PV position in the computation of the transverse flight distance, the beam spot position in the transverse plane can be used as the starting point of the D^0 meson. As already stated, this choice is expected to produce effects of comparable size to the resolution of the PV itself. However, at least during Run 2, LHCb could not rely on a Beam Position Monitor², meaning that this quantity need to be inferred from the mean PV transverse position extracted from the sample itself. This way the transverse flight distance is calculated w.r.t the mean PV, instead of the own PV of the decay; explicitly, for every event i :

$$\vec{L}_{xy}^i = \vec{DV}_{xy}^i - \vec{PV}_{xy}^i \quad \rightarrow \quad \vec{L}_{xy}^{i,PV} = \vec{DV}_{xy}^i - \langle \vec{PV}_{xy} \rangle,$$

where $\vec{X}_{xy}$ denotes the 2-D projection of the original 3-D vector on the transverse plane, and $\langle \vec{PV}_{xy} \rangle$ is the mean PV position also on the transverse plane.

This approach also mitigates any biases that the algorithm of PV reconstruction and matching might introduce in the overall event reconstruction. Including the tracks of the signal candidates in the PV fit, would pull the PV position to-

² LHCb is equipped with a Beam Control Monitor, but its aim is detecting possible LHC malfunction and protecting the detector components in case of unstable beams. It does not provide precise measurement of the beam position for analysis purpose [84].

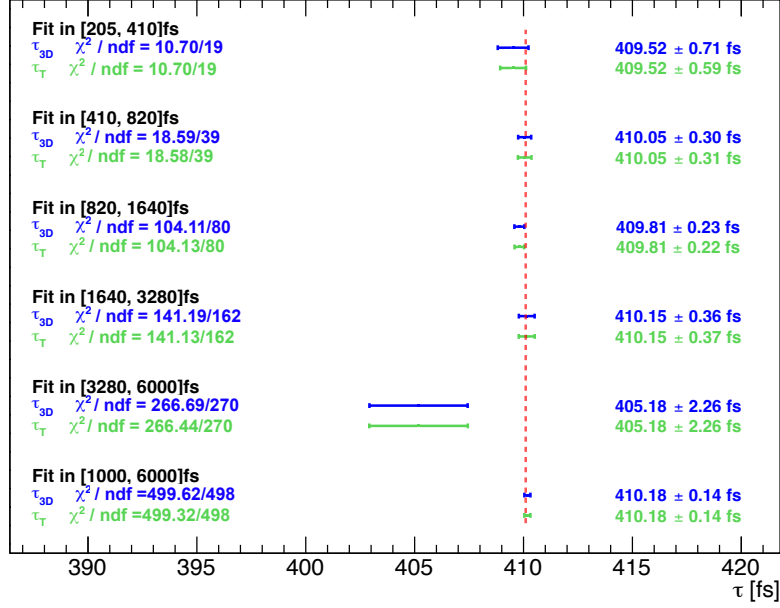


Figure 4.4: Comparison between τ_{3D} and τ_T exponential fits in various ranges with resolution smearing effects turned off in the simulation. The Baker-Cousin χ^2 can be interpreted as goodness-of-fit-indicator and it is indicated over the degrees of freedom of the fit. Where the error bars appears to be absent, the uncertainty of the point is simply too small to be visualized: on the right the explicit values returned by the fit are thus reported, with their uncertainty. The red dotted line represents the simulated mean lifetime.

wards these tracks, biasing any displacement variables. At LHCb, in Run 2 and in the upcoming Run 3, PVs are then refitted without the signal tracks when an unbiased measure of a particle w.r.t its PV (*i.e.* flight distance, decay time,...) is pursued. However this can produce limited improvements. In fact, when few tracks contribute to the PV fit, excluding the signal can cause a pull of the PV position in the opposite direction of the candidate tracks, thus overestimating the displacement variables [85].

To measure the effect of using the mean PV on the accuracy of the measured lifetime, once again a test on the ToyMC is carried out.

The mean PV position is extracted from a subsample of 10^6 events out of the 3×10^8 simulated ones, while the remaining sample is left for measuring the lifetime. This is done so that the mean PV extraction and the lifetime measurements are carried out on statistically independent data sets. The choice of the number of events destined to the mean PV position estimation was in order to achieve $\sigma_{xy}/10^3 = 2.7 \times 10^{-2} \mu\text{m}$ precision on its position, where σ_{xy} is the variance of the generated PV position distribution in the transverse plane, thus resulting in a totally negligible uncertainty when compared with highest PV transverse position resolution achievable at LHCb detector, which is $10 \mu\text{m}$. Given also that the real data sample size amounts to $> 5 \times 10^7$ events, then 10^6 events for mean PV evaluation is a reasonable choice. After recomputing the transverse flight distance of the D^0 meson w.r.t. this mean PV, the arithmetic mean of τ_T and τ_T^{PV} unbinned

distributions have been computed and found to be:

$$\bar{\tau}_T = (410.151 \pm 0.024)\text{fs} \quad \text{and} \quad \bar{\tau}_T^{\overline{PV}} = (410.149 \pm 0.024)\text{fs},$$

showing their respective compatibility and still 2σ apart from the simulated value, exhibiting no biases nor loss of accuracy when using the mean PV. Then the value is extracted again through repeated binned likelihood fits on the remaining sample, with a simple exponential function as model, in the same time ranges described in the previous section. An example fit is shown in Figure 4.5 for the the fit range $[1.0, 6.0]\text{ps}$. All results are summarized in Figure 4.6.

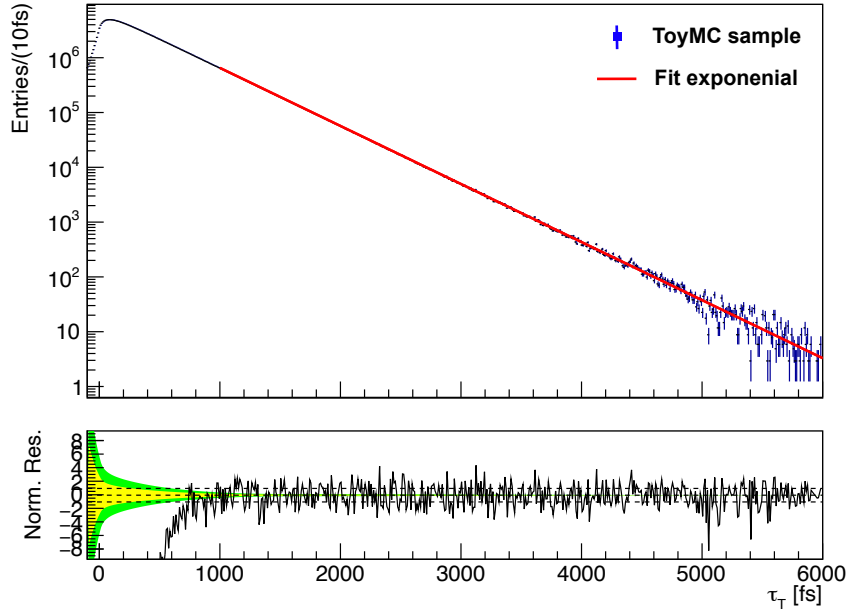


Figure 4.5: Binned likelihood exponential fit in the range $[1.0, 6.0]\text{ps}$ of the lifetime computed with transverse variables and w.r.t. the mean PV.

The exponential shape is still not a perfect match to the data at low decay times, however no evidence of discrepancy between τ_T and $\tau_T^{\overline{PV}}$ is found, and no loss of precision in the decay time window above $2\tau_{D^0}$. Once more the same test is reiterated turning off the resolution effects in order to find assurance that the inflated χ^2 and the behavior at low decay times are still imputable to the resolution smearing, as it was done in the previous section. In Figure 4.7 the results of the fits to the decay time distribution with no resolution effects are shown for various fit ranges. Here some criticality still arises below $1\tau_{D^0}$. It was reiterated several times that the passage from the own PV of the event to a mean PV was equivalent, as effect, to a resolution smearing. From Figure 4.8 it appears that even in case of perfect resolution, the distribution still exhibits departure from the simple exponential. Given this, one would want, at least on ToyMC where all aspects of the generation are under control and perfectly known, to be capable of recovering the simulated mean lifetime even at lower decay time windows.

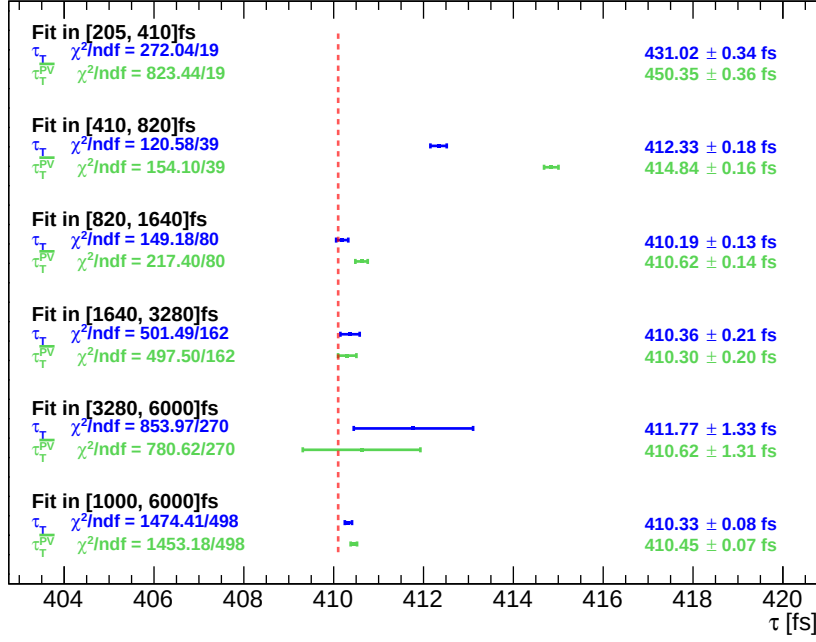


Figure 4.6: Comparison between τ_T and τ_T^{PV} exponential fits in various ranges. The Baker-Cousin χ^2 can be interpreted as goodness-of-fit-indicator. The fit results for the [205,410]fs lie outside the plotted axis range as their inclusion would have made the other points unreadable: on the right the explicit values returned by the fit are thus reported, with their uncertainty. The red dotted line represents the simulated mean lifetime.

4.4 Modeling the resolution effects

As discussed in previous sections, resolution effects and the use of the mean PV cause a smearing on the exponential distribution so that in extracting the mean lifetime measure via an exponential fit, a cut on low decay times is necessary. The goal of this section is to develop a fit procedure that explicitly accounts for the smearing effects, and is therefore capable of a correct extraction of lifetime in the wider possible range. This will be done by extracting a smearing template, convoluting it with the exponential function and finally fitting the decay time distribution of the ToyMC with this convolution.

With the resolution effects turned on, for every observable τ_{3D} , τ_T and τ_T^{PV} we can define, respectively $\Delta\tau_{3D}$, $\Delta\tau_T$ and $\Delta\tau_T^{\text{PV}}$, which are the differences between the reconstructed variable and the true decay time of the event. On the distribution of each of this differences a Kernel Density Estimation (KDE) procedure is performed, using Gaussian kernel and adaptive bandwidth, employing a small subsample of 2×10^5 events, which afterwards will be discarded in the extraction of the mean lifetime in order to avoid statistical correlation.

Initially, it was researched if the $\Delta\tau_x$ distributions could be fitted with an analytical function or a combination of them. When such approach failed, KDE offered the solution for modeling the smearing template. The KDE method, however, limits the size of the subsample from which extracting such resolution templates because of the excessive computational load ($> 24h$ of computing time)

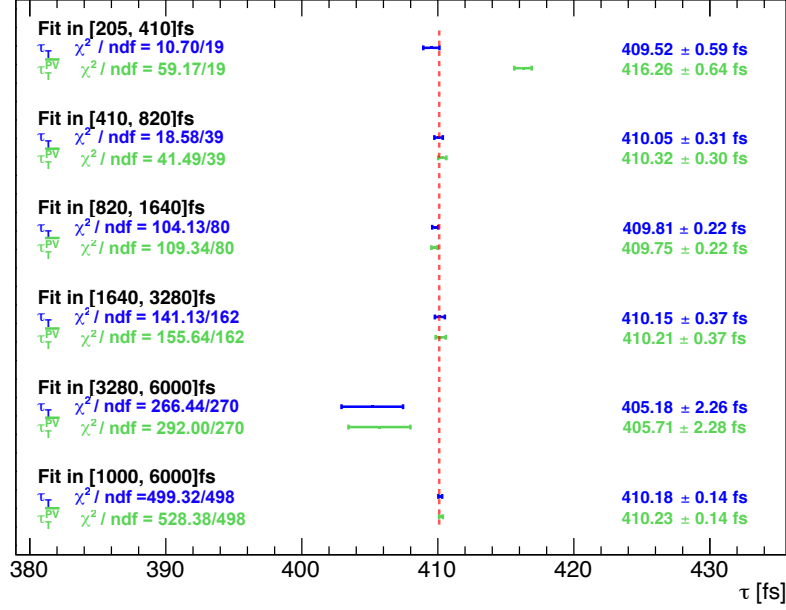


Figure 4.7: Comparison between τ_{2D} and τ_{2D}^{PV} exponential fits in various ranges with resolution smearing effects being turned off in the simulation. The Baker-Cousin χ^2 can be interpreted as goodness-of-fit-indicator and it is indicated over the degrees of freedom of the fit. Where the error bars appears to be absent, the uncertainty of the point is simply too small to be visualized: on the right the explicit values returned by the fit are thus reported, with their uncertainty. The red dotted line represents the simulated mean lifetime.

KDE causes when the threshold of 2×10^5 events is superseded. The tool used for achieving this is ROOFIT, a library available in ROOT, which provides several tools for modeling distributions.

In Figure 4.9 the three distributions are plotted, with their KDE superimposed. The smearing effects appear to have greater impact in the passage from 3D to 2D variables and than to the mean PV. While removing the longitudinal information has significant consequences on the precision of the single decay time, it has been already previously shown that the effect on the slope of the exponential distribution of the decay times is negligible. In addition, the smearing effect caused by the use of the mean PV is clearly observable.

In order to extract the mean lifetime, three fit models are defined:

$$\mathcal{T}_{3D}(t) = \exp\left(-\frac{t}{\tau_{3D}}\right) * \text{KDE}_{3D}^{\text{res.}} \quad (4.4.1)$$

$$\mathcal{T}_{2D}(t) = \exp\left(-\frac{t}{\tau_{2D}}\right) * \text{KDE}_{2D}^{\text{res.}} \quad (4.4.2)$$

$$\mathcal{T}_{2D}^{\overline{PV}}(t) = \exp\left(-\frac{t}{\tau_{2D}^{\overline{PV}}}\right) * \text{KDE}_{2D, \overline{PV}}^{\text{res.}}, \quad (4.4.3)$$

where $\text{KDE}_{xx}^{\text{res.}}$ is the kernel density estimation of the respective reconstructed variable shown in Figure 4.9. An unbinned maximum likelihood fit is then per-

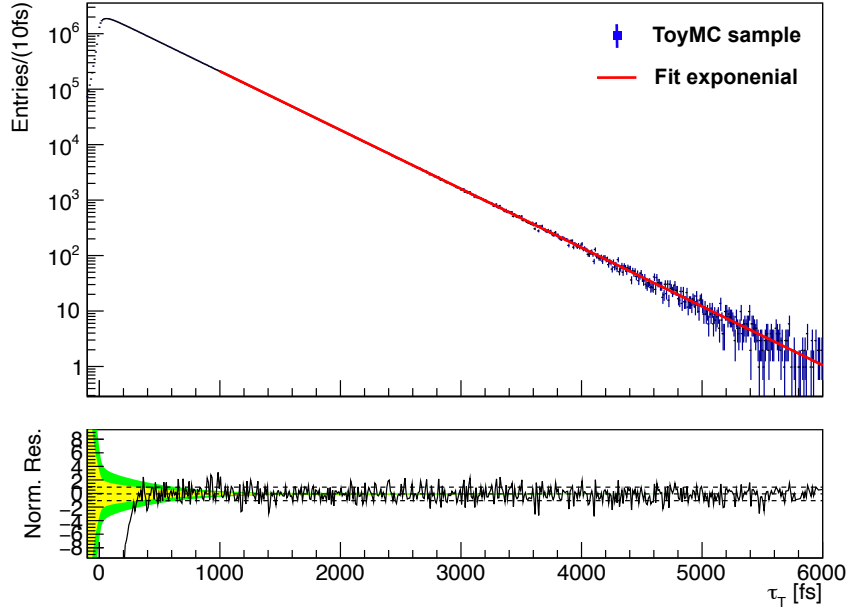


Figure 4.8: Binned likelihood exponential fit in the range $[1.0, 6.0]$ ps of the lifetime computed with transverse variables and w.r.t. the mean PV, when resolution effects are turned off in the simulation.

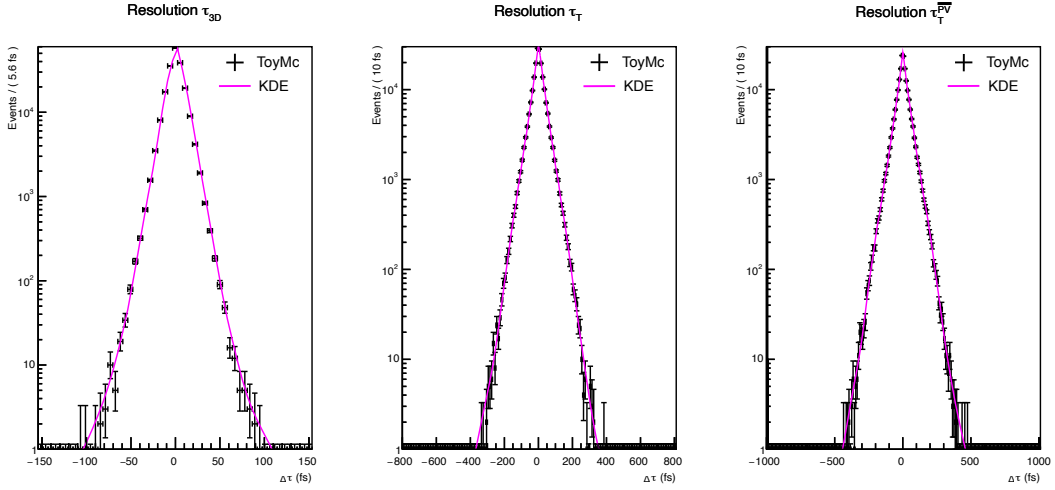


Figure 4.9: The distributions of the difference $\Delta\tau$ between the reconstructed decay time and the true one for τ_{3D} (left), τ_T (center) and τ_T^{PV} (right), with their own KDE superimposed.

formed on the ToyMC sample, discarding those events used for estimating both the mean PV and the resolution KDE. With a fit range from 0.205ps, which

corresponds to $0.5\tau_{D^0}$, up to 6 ps, it is found:

$$\begin{aligned}\tau_{3D} &= (410.059 \pm 0.056) \text{ fs} \\ \tau_{2D} &= (410.067 \pm 0.055) \text{ fs} \\ \tau_{2D}^{\overline{PV}} &= (410.027 \pm 0.055) \text{ fs}.\end{aligned}$$

Comparison with the results for the same fit range (Figures 4.3 and 4.6) clearly shows how modeling the resolution effects has been successful, and that the use of transverse variables and the mean PV does not compromise the precision of the lifetime determination nor introduce systematic biases at the simulated level of sensitivity, even at lowest accessible decay times. This tests are carried out at a precision level a factor 30 greater than the last absolute lifetime measurement of the D_s^- meson published by LHCb [86]. It is also an order of magnitude greater than the resolution of the last Belle II D^0 lifetime measurement [87] which extracted $\tau(D^0) = 410.5 \pm 1.1_{stat.} \pm 0.8_{syst.}$ fs. This means that possible biases introduced by the method are negligible up to a statistical precision level yet-to-be reached.

When the values obtained with the arithmetic mean are taken in consideration, it can be concluded that using mean PV and transverse variables still produce an unbiased measurement within a statistical uncertainty 60 times smaller than the just mentioned LHCb most precise lifetime measurement of D_s^- meson (20 times w.r.t. the Belle II statistical precision).

Consequently, from here onwards transverse variables will be used and all displacement variables will be computed w.r.t. the mean PV position, unless stated otherwise. In the next chapter we will address the issue of recovering time-dependent track efficiencies.

CHAPTER

5

RETRIEVING TRACK EFFICIENCIES

Reconstructing the efficiency map w.r.t. the particle decay time has been the main hurdle in lifetime measurements [86, 88, 89], as the main contributor to systematic uncertainties. In previous y_{CP} measurements [36, 42] the effects of these efficiencies were absorbed in the ratio of decay time distributions between $D^0 \rightarrow hh$ and $D^0 \rightarrow K^- \pi^+$, denoted $R(hh/K\pi)$. However, with the precision arising from the larger samples now available, the differences in efficiencies between the $D^0 \rightarrow hh$ and $D^0 \rightarrow K\pi$ manifested at a non-negligible level even in the ratio between the effective decay widths. In Section 3 it has been reported how the latest y_{CP} measurement [37] produced by LHCb has handled this issue by lowering the efficiency differences through kinematic matching and reweighting, and a MonteCarlo-based confirmation of the result.

In view of the upcoming Run 3 and the high-luminosity scenario, we discuss here an approach based on a completely data-driven determination of the two individual efficiencies separately. This approach could in principle be applied also to absolute lifetime measurements; but in the context of this work we are mostly interested in its use as a way of boosting the precision of the determination of the efficiency ratio.

The introduction of a completely new technique for efficiency determination is motivated by the existence of hard-to-overcome limitations in the methods currently in common use: Monte Carlo Simulation and the tag-and-probe approach. The former relies on a precise knowledge of the detector response, but it is in practice impossible to have a perfect knowledge of every detector detail; for one thing, the detector response varies with time, due to fluctuations of the electronic response, small component failures, and other ageing effects. The level of accuracy attained by the current official LHCb simulation has essentially reached a point of saturation, where further progress is extremely difficult and uncertain. At the same time, even simply producing Monte Carlo samples of sufficient size is hitting the wall of limited available computing power. Already in the Run 2 analysis era,

Monte Carlo simulations used the majority of computing power available to the LHCb collaboration (this include online computing resources as well, that have been exploited for Monte Carlo generation every time they were free from online processing tasks) [90].

The tag-and-probe method, while being data-driven and in principle improvable with larger samples, also suffers from some hard limitations. It requires the availability of a sufficiently pure source of known particles, and them being reconstructed in different detector regions, such that a relative efficiency between the events registered in the probed detector region w.r.t those events registered in the tagged detector section, can be extracted. This requires the tag information to be extremely reliable to exclude background contamination, a non-destructive detection process, and perfectly uncorrelated efficiencies between the probe and tag regions. All those criteria are not easily met at high precision, and are far from easy to improve beyond a certain saturation point.

The approach proposed here could be said to have some conceptual similarity with the tag-and-probe approach, but its applicability goes significantly beyond it. It might be seen as a kind of a “double-probe” method: two different particles, whose correlation is accurately known, hit two different regions of the same detector. With this premise the relative efficiency between two detector regions can be measured, and a map can be reconstructed, if accurate relationships between the two particles are somehow known. In this chapter the theoretical framework is introduced first, then various tests of efficiency extraction on simulated data are discussed and their result reported.

5.1 Theoretical framework

For the sake of the present work, a two-body decay of a scalar particle is considered: if the momentum and mass of the parent particle are precisely known, then the kinematic of the two daughter particles is uniquely determined, leading to accurate knowledge of the correlation between the two tracks. From the description given above of the two-body decay case, it is not difficult to see how it could be extended to other settings that are not of direct interest for the present work.

Let us start with the following definitions:

- x, x' respectively the true and measured value of an observed quantity;
- $\vec{\mathbf{P}}$ the vector of the parent particle observables defining its initial state, *i.e.* its mass, position and momentum in case of a scalar particle;
- $\mathcal{D}(\vec{\mathbf{P}})$ the probability density function (pdf) of $\vec{\mathbf{P}}$. We will separately consider the case of $\mathcal{D}(\vec{\mathbf{P}})$ being a known or an unknown function;
- $\vec{d}_{1,2}$ kinematic coordinates of the two daughter particles. The efficiency will be parameterized as function of these variables;
- $\varepsilon_i(\vec{d}_i)$ ($i = 1, 2$) the detection efficiency for the final state particle observed in the *measured* state $\vec{d}_i$ - an important assumption is for it to be independent from the other particle;
- $\mathcal{M}(\vec{d}_1, \vec{d}_2 | \vec{\mathbf{P}})$ the observed *conditional* pdf of $\vec{d}_1$ and $\vec{d}_2$, given $\vec{\mathbf{P}}$;

- $\mathcal{P}(\vec{d}_1, \vec{d}_2 | \vec{\mathbf{P}})$ the *conditional* pdf of the daughters particles phase space given $\vec{\mathbf{P}}$
- $\mathcal{A}(\vec{d}_1, \vec{d}_2, \vec{\mathbf{P}})$ the *joint* acceptance function, determined by the detector geometry and the selections applied to the sample, and dependent on the measured quantities;
- $s(\vec{d}_i | \vec{d}_i)$ the resolution smearing pdf – that is, the conditional distribution for measuring $\vec{d}_i$ given $\vec{d}_i$.

Now it can be written:

$$\mathcal{M}(\vec{d}_1, \vec{d}_2 | \vec{\mathbf{P}}) = \varepsilon(\vec{d}_1) \varepsilon(\vec{d}_2) \mathcal{A}(\vec{d}_1, \vec{d}_2, \vec{\mathbf{P}}) \int d\vec{d}_1 d\vec{d}_2 \mathcal{P}(\vec{d}_1, \vec{d}_2 | \vec{\mathbf{P}}) s(\vec{d}_1 | \vec{d}_1) s(\vec{d}_2 | \vec{d}_2), \quad (5.1.1)$$

and once defined

$$\mathcal{K}(\vec{d}_1, \vec{d}_2 | \vec{\mathbf{P}}) = \int d\vec{d}_1 d\vec{d}_2 \mathcal{P}(\vec{d}_1, \vec{d}_2 | \vec{\mathbf{P}}) s(\vec{d}_1 | \vec{d}_1) s(\vec{d}_2 | \vec{d}_2), \quad (5.1.2)$$

which is the probability distribution for the apparatus to measure the values $\vec{d}_1$ and $\vec{d}_2$ without considering efficiencies and acceptance, Eq. 5.1.1 can be rewritten as

$$\mathcal{M}(\vec{d}_1, \vec{d}_2 | \vec{\mathbf{P}}) = \varepsilon(\vec{d}_1) \varepsilon(\vec{d}_2) \mathcal{A}(\vec{d}_1, \vec{d}_2, \vec{\mathbf{P}}) \mathcal{K}(\vec{d}_1, \vec{d}_2 | \vec{\mathbf{P}}), \quad (5.1.3)$$

then

$$\mathcal{M}(\vec{d}_1, \vec{d}_2) = \varepsilon(\vec{d}_1) \varepsilon(\vec{d}_2) \int d\vec{\mathbf{P}} \mathcal{D}(\vec{\mathbf{P}}) \mathcal{A}(\vec{d}_1, \vec{d}_2, \vec{\mathbf{P}}) \mathcal{K}(\vec{d}_1, \vec{d}_2 | \vec{\mathbf{P}}), \quad (5.1.4)$$

and integrating over $\vec{\mathbf{P}}$

$$\mathcal{M}(\vec{d}_1, \vec{d}_2) = \varepsilon(\vec{d}_1) \varepsilon(\vec{d}_2) \mathcal{A}(\vec{d}_1, \vec{d}_2) \mathcal{K}(\vec{d}_1, \vec{d}_2). \quad (5.1.5)$$

It should be noted that $\mathcal{K}(\vec{d}_1, \vec{d}_2 | \vec{\mathbf{P}})$ depends only on the dynamics of the two-body decay, which is perfectly known. Conversely, $\mathcal{K}(\vec{d}_1, \vec{d}_2)$ also depends on $\mathcal{D}(\vec{\mathbf{P}})$ - which might be known only up to a certain precision.

5.1.1 Case of known $\mathcal{D}(\vec{\mathbf{P}})$

Let us start from the simpler case, with the distribution of $\vec{\mathbf{P}}$ being known. Let us also restrict to the case of $\vec{d}_1, \vec{d}_2$ being a one-dimensional parameter. This corresponds to mapping the efficiency w.r.t. only two parameters and averaging over all the rest. From Eq. 5.1.5 it can be derived

$$\varepsilon(d'_1) \varepsilon(d'_2) = \frac{\mathcal{M}(d'_1, d'_2)}{\mathcal{A}(d'_1, d'_2) \mathcal{K}(d'_1, d'_2)}, \quad (5.1.6)$$

having meaning when both $\mathcal{M}$ and $\mathcal{K}$ differ from zero; that is, being in a region of parameter space accessible to our signal. The $\mathcal{A}$ function and the $\mathcal{K}$, $\mathcal{M}$ distributions can be extracted from an unbinned fit from the samples or alternatively can be estimated via Kernel Density Estimation, then binned and the efficiency extracted as a ratio between the integral over each bin; however the chosen route

is to directly bin them. Dividing the $\vec{d}_1 \times \vec{d}_2$ space in $n \times n$ bins and averaging in each one of them, it can be obtained

$$\varepsilon_{1i}\varepsilon_{2j} = \frac{1}{V_{d'}^2} \int_{[ij]} dd'_1 dd'_2 \frac{\mathcal{M}(d'_1, d'_2)}{\mathcal{A}(d'_1, d'_2) \mathcal{K}(d'_1, d'_2)} = \mathbb{E}_{ij} \left[\frac{1}{\mathcal{A}(d'_1, d'_2) \mathcal{K}(d'_1, d'_2)} \right], \quad (5.1.7)$$

where $V_{d'}$ is the normalizing volume for the variable d' w.r.t the ij bin, $\mathbb{E}_{ij}$ is the expected value of its argument and $\varepsilon_{\ell i}$ is the mean value of ε_ℓ in the bin i . Then applying the Law of Large Numbers it can be shown that:

$$\varepsilon_{1i}\varepsilon_{2j} = \mathbb{E}_{ij} \left[\frac{1}{\mathcal{A}(d'_1, d'_2) \mathcal{K}(d'_1, d'_2)} \right] \simeq \frac{n_{ij}}{N} \frac{1}{\mathcal{A}(d'_1, d'_2) \mathcal{K}(d'_1, d'_2)}, \quad (5.1.8)$$

where N is the true total number of events that produced the sample, and n_{ij} is the number of events measured in the bin ij . N can be unknown without interfering with correct the *relative* efficiency extraction. In order to extract the efficiency vector, the matrix $\mathcal{E}$ can be constructed as

$$\mathcal{E}_{ij} = \frac{n_{ij}}{N} \frac{1}{\mathcal{A}(d'_1, d'_2) \mathcal{K}(d'_1, d'_2)}. \quad (5.1.9)$$

As the efficiencies factorize, then $\mathcal{E}$ is the dyadic product:

$$\mathcal{E} = \varepsilon_1 \otimes \varepsilon_2 = \varepsilon_1 \varepsilon_2^T, \quad (5.1.10)$$

from which ε_1 can be extracted as the unique non-zero right-eigenvector of $\mathcal{E}$ and ε_2 as the unique non-zero left-eigenvector of $\mathcal{E}$. Concerning the eigenvalues, all are zero except for the one corresponding to the non-zero eigenvector. As there will be Poisson noise contaminating the bin population, what is expected is one large eigenvalue, while the others being small and compatible with Poisson fluctuations. A deviation from this behavior should arise concerns and cast doubts on the correctness of the assumptions, and offers a way to perform crosschecks.

5.1.2 Case of unknown $\mathcal{D}(\vec{\mathbf{P}})$

From Eq. 5.1.3, one can write:

$$\varepsilon(d'_1)\varepsilon(d'_2) = \frac{\mathcal{M}(d'_1, d'_2 | \vec{\mathbf{P}})}{\mathcal{A}(d'_1, d'_2, \vec{\mathbf{P}}) \mathcal{K}(d'_1, d'_2 | \vec{\mathbf{P}})}, \quad (5.1.11)$$

leading to a whole different scenario with respect to the one in Eq. (5.1.6). Here, in fact, the equation does retain meaning when both $\mathcal{M}(d'_1, d'_2 | \vec{\mathbf{P}})$ and $\mathcal{A}(d'_1, d'_2, \vec{\mathbf{P}}) \mathcal{K}(d'_1, d'_2 | \vec{\mathbf{P}})$ differ from zero, as opposed to the $\mathcal{D}(\vec{\mathbf{P}})$ known method where if one of the two function equals zero implicates it corresponds simply to a non-signal region. Here if the right member of Eq. 5.1.11 is not defined, the same cannot be said for the left member, in fact what is being hidden in Eq. 5.1.11 is that the left member is not simply defined in a 2-D space, but in a $(2+K)$ -D space with $K = \dim(\vec{\mathbf{P}})$, and $\varepsilon(d_i)$ should truly be $\varepsilon(d_i | \vec{\mathbf{P}})$. The relative efficiency is assumed to actually be independent from $\vec{\mathbf{P}}$, hence the notation without this argument. It is then here defined the concept of 0/0 regions, which are those regions where both $\mathcal{M}(d'_1, d'_2 | \vec{\mathbf{P}})$ and $\mathcal{A}(d'_1, d'_2, \vec{\mathbf{P}}) \mathcal{K}(d'_1, d'_2 | \vec{\mathbf{P}})$ are 0. Then, it is not that the efficiencies in general are not defined in this 0/0 regions, as they shall be

called onwards, but they will not be defined for some given $\vec{\mathbf{P}}$. The issue can be addressed by dividing the $(2+K)$ -D space in well-defined sub-regions.

So, instead of using

$$\varepsilon_{1i}\varepsilon_{2j} = \frac{1}{V_{d'}^2} \int_{[ij]} dd'_1 dd'_2 \frac{\mathcal{M}(d'_1, d'_2)}{\mathcal{A}(d'_1, d'_2) \mathcal{K}(d'_1, d'_2)} \quad (5.1.12)$$

where the conditional probability distribution $\mathcal{M}$ is unknown for $\vec{\mathbf{P}}$ is unknown itself, the equation of interest is

$$\varepsilon_{1i}\varepsilon_{2j} = \frac{1}{V_{d'}^2} \int_{[ij]} dd'_1 dd'_2 \int_{I(d'_1, d'_2)} d\vec{\mathbf{P}} \frac{1}{V_I(d'_1, d'_2)} \frac{\mathcal{M}(d'_1, d'_2 | \vec{\mathbf{P}}) \mathcal{D}(\vec{\mathbf{P}})}{\mathcal{A}(d'_1, d'_2, \vec{\mathbf{P}}) \mathcal{K}(d'_1, d'_2 | \vec{\mathbf{P}})} \quad (5.1.13)$$

which allows to go from the conditional probability distribution to the joint

$$\mathcal{M}(d'_1, d'_2 | \vec{\mathbf{P}}) \mathcal{D}(\vec{\mathbf{P}}) = \mathcal{M}(d'_1, d'_2, \vec{\mathbf{P}}), \quad (5.1.14)$$

with $I(d'_1, d'_2)$ being the region in the $(2+K)$ -D space without “0/0” contributions and $V_I(d'_1, d'_2)$ the normalization factor for $\mathcal{D}(\vec{\mathbf{P}})$ on the $V_I(d'_1, d'_2)$ region. Now $\mathcal{M}(d'_1, d'_2, \vec{\mathbf{P}})$ can be estimated even without knowing $\mathcal{D}(\vec{\mathbf{P}})$; instead $V_I(d'_1, d'_2)$ should require such knowledge but requiring that the region is devoid of “0/0” cases, which can be done by defining the region with the knowledge of $\mathcal{K}(d'_1, d'_2 | \vec{\mathbf{P}})$, then $V_I(d'_1, d'_2)$ is simply a multiplicative constant that can be omitted, as the overall normalization is of no interest. Such a region is not necessarily easy to determine, and it may end up being too small and scarcely populated, and therefore a compromise must sometimes be sought.

Once this is done, the function can be binned as in the “ $\mathcal{D}(\vec{\mathbf{P}})$ known” method, to write:

$$\varepsilon_{1i}\varepsilon_{2j} = \mathcal{E}_{ij} = \sum_{\vec{\mathbf{P}}} \frac{n_{ij}(\vec{\mathbf{P}})}{N} \frac{1}{\mathcal{A}(d'_1, d'_2, \vec{\mathbf{P}}) \mathcal{K}(d'_1, d'_2 | \vec{\mathbf{P}})}, \quad (5.1.15)$$

where $n_{ij}(\vec{\mathbf{P}})$ is the number of observed events with given $\vec{\mathbf{P}}$ in the ij bin. With $\mathcal{K}(d'_1, d'_2 | \vec{\mathbf{P}})$ usually lacking an analytical expression, a K -D grid is built. High dimensionality however disperses the population and brings another issue: $n_{ij}(\vec{\mathbf{P}})$ could have not enough population even if initially a large sample was produced, so that in the carefully defined regions devoid of “0/0” the numerator is still zero and thus producing an estimation of efficiency with one-hundred per-cent of uncertainty. For this reason while “ $\mathcal{D}(\vec{\mathbf{P}})$ unknown” takes power in not requiring an a-priori knowledge of $\mathcal{D}(\vec{\mathbf{P}})$, it is far more fragile and need greater care in its deployment. Once $\mathcal{E}$ is obtained then the efficiency vectors can be retrieved exactly as in Eq. 5.1.10, as eigenvectors of the matrix.

An important point about this method is that the quantities $\varepsilon(d_i)$ must not necessarily be intended just as detection efficiencies. The requirement is just that $\varepsilon(d_1)$ factorizes with $\varepsilon(d_2)$. Therefore, any selection requirements concerning a single track, can be included in $\varepsilon(d_1)$ rather than taken out with $\mathcal{A}$, allowing the algorithm to extract their true efficiencies directly from the data. This does not work for track-correlating selection efficiencies, (the D^0 flight distance is an example), that must be accounted for in the $\mathcal{A}$ acceptance function, in order for them not to pollute the extraction. But it allows a much greater freedom in the choice of selection cuts, and as a consequence, a much greater freedom in choosing the trigger sequence for the measurement. Important examples of this are cuts on

particle identification ($DLL_{K-\pi}$), track χ^2/ndf , particle IP or even particle χ^2_{IP} , that now can be used in selecting samples for time-dependent analysis, unlike previous measurements. This opens the door to using samples of data not coming from the highly restrictive LTUNB trigger lines.

In the next sections, we will put this approach to the test in concrete examples to verify its actual practical applicability,

5.2 Test of efficiency extraction

With the aim to test this efficiency extraction technique, the already known ToyMC presented in the previous chapter is used. The track efficiencies are modeled as a function depending on the Transverse Impact Parameter (TIP) of the track, defined as:

$$TIP_h = |L_{xy} \sin(\phi_{xy} - \phi_h)|, \quad (5.2.1)$$

where L_{xy} is the magnitude of the D^0 transverse flight distance, ϕ_{xy} is the azimuthal coordinate of the same vector and ϕ_h is the azimuthal angle of the track of interest. Figure 5.1 shows a pictorial representation of these quantities.

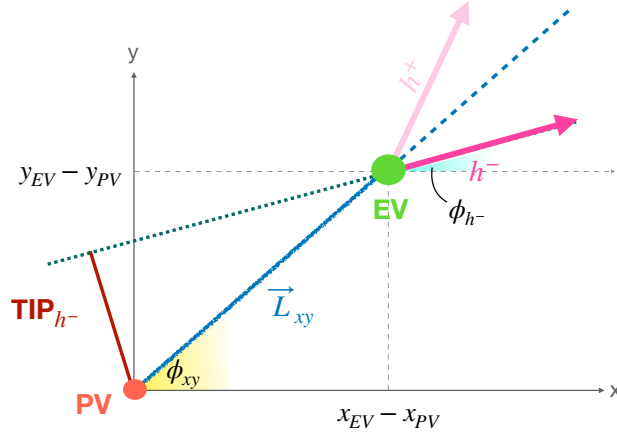


Figure 5.1: Graphical representation of the TIP definition, where $h^\pm$ are the momenta of the decay products originated from the D^0 meson and $\vec{L}_{xy}$ is the D^0 transverse flight distance.

This variable offers the advantage of being a single-track observable and, at the same time, being highly correlated with the decay time of the D^0 meson through the dependence on its flight distance. In case of extracting the efficiency where the two tracks are identical particles, two K or two π , then the binned function $\mathcal{E}$ will be symmetrized under the assumption that the time-dependent *relative* efficiency is charge-independent.

5.2.1 $\mathcal{D}(\vec{P})$ known

Starting with the simplest case, and remembering the formula in case of $\mathcal{D}(\vec{P})$ known, which is

$$\mathcal{E}_{ij} = \frac{n_{ij}}{N} \frac{1}{\mathcal{A}(TIP_1, TIP_2) \mathcal{K}(TIP_1, TIP_2)}.$$

Firstly, both $\mathcal{K}$ and $\mathcal{A}$, get binned as 2-D histograms $TIP_1 \times TIP_2$, obtaining

$$\mathcal{E}_{ij} = \frac{n_{ij}}{N} \frac{1}{A_{ij} K_{ij}}, \quad (5.2.2)$$

where ij is the 2-D bin index of the histograms, i being the index for TIP_1 and j for TIP_2 . Then it can be easily recognized that $N K_{ij}$ is anything but the number of events generated by the simulation belonging to the ij bin. If the generated events undergo a selection process, a 2-D histogram can be constructed for the filtered events f_{ij} . Now, A_{ij} is the binned acceptance function, which can be estimated as

$$\mathcal{A}_{ij} = \frac{f_{ij}}{N K_{ij}}, \quad (5.2.3)$$

and it easily follows that

$$\mathcal{E}_{ij} = \frac{n_{ij}}{f_{ij}}. \quad (5.2.4)$$

Therefore the ToyMC can be divided in two subsamples of equal size, one supplying the n_{ij} term, named ToyMC_{data} and performing as simulated data, the other used for f_{ij} term and called ToyMC_{KA}. At this point, one might argue that simulation is being used in order to extract the efficiencies, and that the method is not truly data-driven. However, this is not the case, because the simulation being used is a ToyMC and not a detector simulation; it is employed only as a numerical tool to facilitate the computation of the functions $\mathcal{A}(TIP_1, TIP_2)$ and $\mathcal{K}(TIP_1, TIP_2)$. These functions can be determined with essentially arbitrary precision, as the latter is the kinematic distribution of a two body decay and the former is supposed to only include selections that the analyst can easily reproduce offline. This last point however is not a given, and must be carefully guarded when formulating the design of the trigger line - we will return on this issue later on.

Concerning the selections entering the $\mathcal{A}$ function, let us start with the Run 2 LTUNB cuts, reproducing them with the kinematic variables available from the ToyMC. Those selections are summarized in Table 5.1.

Quantity	Requirement
$p_T(D^0)$	$> 2 \text{ GeV}/c$
$\tau_{3D}(D^0)$	$> 250 \text{ fs}$
$p_T(K^\pm)$	$> 800 \text{ MeV}/c$
$p(K^\pm)$	$> 4 \text{ GeV}/c$
$\max\{p_T(K^+), p_T(K^-)\}$	$> 1.2 \text{ GeV}/c$

Table 5.1: The selection imposed on the ToyMC.

After applying these selections on both ToyMC_{KA} and ToyMC_{data}, various efficiency shapes, as function of TIP, are injected on ToyMC_{data}, and retrieved with the technique described in previous sections. From the 1.5×10^8 generated events in each subsample, the yield after the selection is 5.9×10^7 . The efficiency matrix is then reconstructed with 100×100 bins, in the TIP range $0.0 - 0.4 \text{ mm}$, due to the bin population over this threshold being too small. The signal yield drops to 5.6×10^7 .

Flat efficiency case The first tested efficiency shape is uniform across the entire TIP region. Our procedure is then expected to yield a constant function. The resulting $\mathcal{E}$ matrix is shown in Figure 5.2.

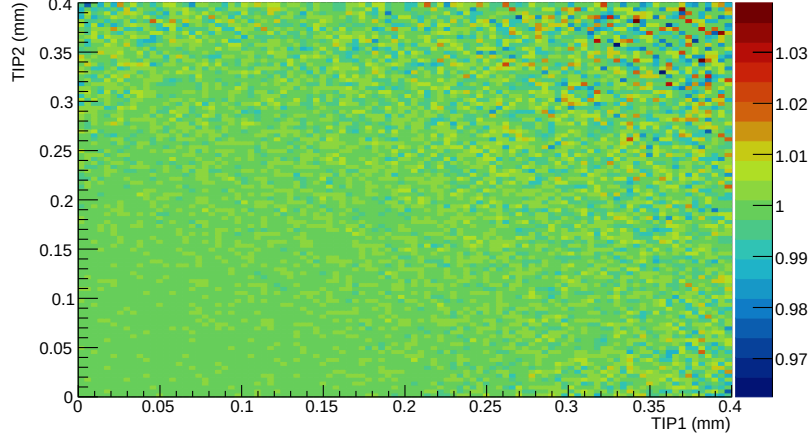


Figure 5.2: The $\mathcal{E}$ matrix in case of simulated flat efficiency.

The matrix appears flat as expected, with a slight instability in the ratio starting to appear where TIP is simultaneously high for both kaons. The eigenvector extraction procedure leads to the efficiency shape shown in Figure 5.3

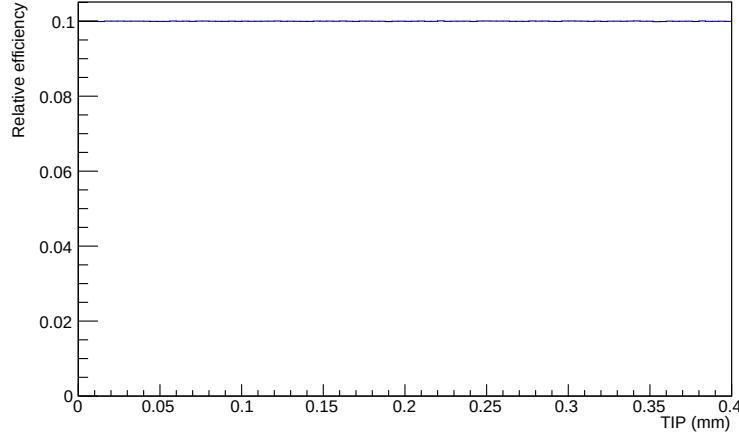


Figure 5.3: The efficiency eigenvector in case of simulated flat efficiency.

A Least Square (LS) fit is performed with a linear function $\alpha x + \beta$, yielding to an angular coefficient value:

$$\alpha = (0.24 \pm 3.57) \times 10^{-5} \text{ mm}^{-1}$$

in agreement with the uniform input model where $\alpha \equiv 0$. A look at the secondary eigenvalues, which has been normalized w.r.t. the first one, shows that they never exceed 0.15%. Their departure from zero arise from the Poisson fluctuations of bin population. Their smallness confirms the assumption of factorization of track efficiencies (Figure 5.4).

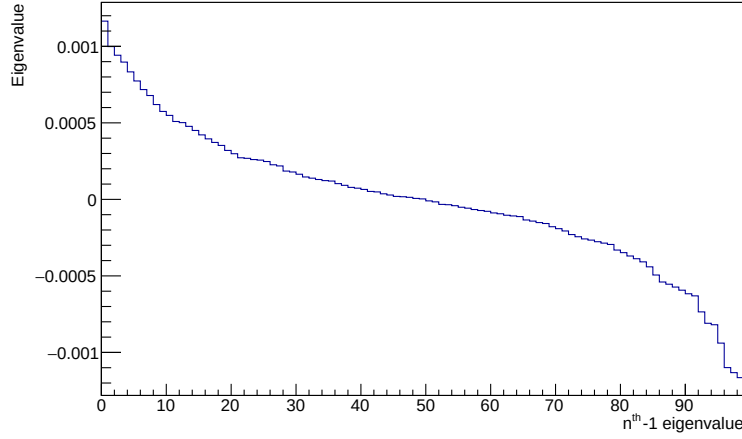


Figure 5.4: The secondary eigenvalues, normalized w.r.t. the first one, in case of simulated flat efficiency.

Linear efficiency shape The second tested shape is a linear decreasing efficiency as function of TIP:

$$\varepsilon(TIP) = 1 - \alpha TIP[\text{mm}],$$

where $\alpha = 1 \text{ mm}^{-1}$. In Figures 5.5 and 5.6 the efficiency matrix and efficiency vector are respectively illustrated. From a LS fit with a linear model $\alpha x + \beta$ it

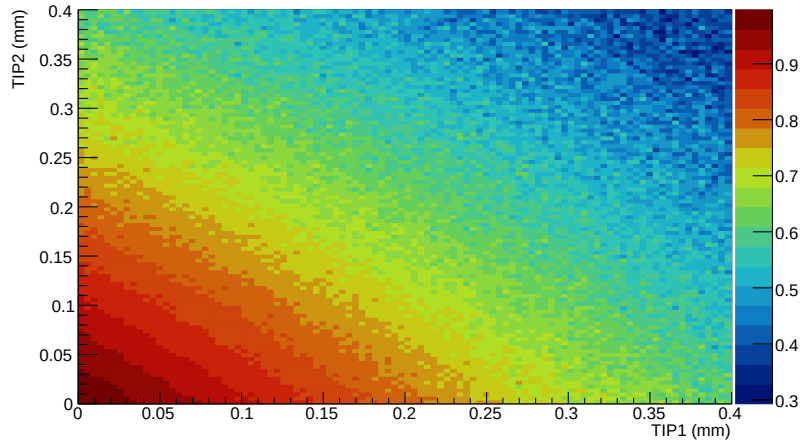


Figure 5.5: The $\mathcal{E}$ matrix in case of simulated decreasing linear efficiency.

is now found:

$$\frac{\alpha}{\beta} = (-1.01 \pm 0.01) \text{ mm}^{-1},$$

that compares well with the expected value $\alpha/\beta = -1 \text{ mm}^{-1}$. This confirms the success of the method in this less trivial example. Secondary eigenvalues again turn out small, never exceeding 1% of the main eigenvalue.

Sinusoidal efficiency shape To check the correct behavior of the procedure, we need to test it also on more complicated efficiency functions. We decided to

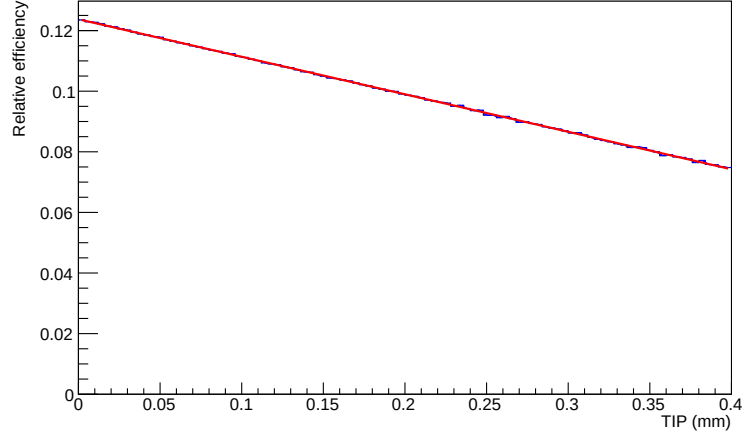


Figure 5.6: The efficiency eigenvector in case of simulated decreasing linear efficiency, with the vector shown in blue and the LS fit function in red.

perform a test with a sinusoidal efficiency shape:

$$\varepsilon(TIP) = \frac{1 - \sin(2\pi TIP[\text{mm}]/\lambda[\mu\text{m}])}{2}, \quad \text{with } \lambda = 40 \mu\text{m}.$$

Again in the efficiency matrix $\mathcal{E}$ and the extracted efficiency function are shown in Figure 5.7 and in Figure 5.8. The fit model is

$$\varepsilon(TIP) = a \frac{1 - \sin(2\pi x/\lambda + c)}{2},$$

with a being a multiplication factor with no physical meaning as the method loses an overall normalisation factor along the way, λ the simulated wavelength and c a phase introduced to stress the test model. The results from the LS fit are

$$\lambda = (40.003 \pm 0.003) \mu\text{m} \quad \text{and} \quad c = 0.002 \pm 0.003,$$

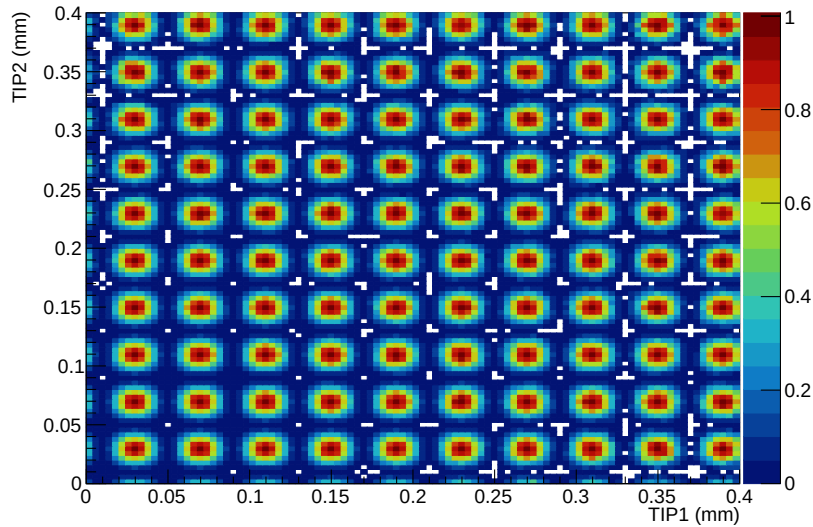


Figure 5.7: The $\mathcal{E}$ matrix in case of simulated sinusoidal efficiency shape.

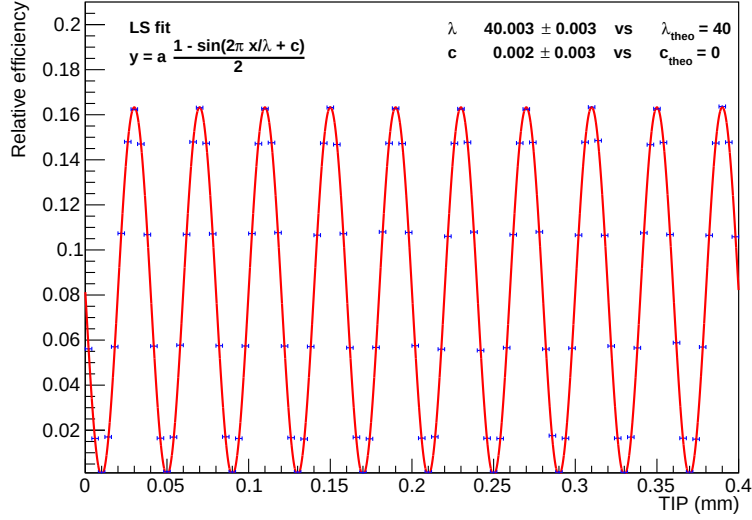


Figure 5.8: The efficiency eigenvector in case of simulated sinusoidal efficiency shape, with the vector shown in blue and the LS fit function in red.

again in good agreement within 1σ with the values input to the simulation. Secondary eigenvalues also stay below $\sim 1\%$ of the main.

Non parametric efficiency shape As a further test, a non parametric function was picked in order to simulate an efficiency with sharp variations, to check the ability of the algorithm to reproduce sudden efficiency jumps. Every $5 + 7n$ TIP bin, with $n \in \mathbb{N}$, the efficiency drops to 0%, while it stands at 100% in all other bins. In Figure 5.9 is shown the reconstructed efficiency where it is clearly visible how the retrieved shape, filled in blue, agrees with the expected one (red dashed lines). The secondary eigenvalues are of order 10^{-3} , relative to the main one.

These examples should be convincing that the technique works as intended with efficiency functions of very different and quickly varying shapes - at least under the assumption of $\mathcal{D}(\vec{\mathbf{P}})$ being known.

Before moving on to the extraction of lifetimes, let us consider the case of unknown $\mathcal{D}(\vec{\mathbf{P}})$.

5.2.2 $\mathcal{D}(\vec{\mathbf{P}})$ unknown

For the $\mathcal{D}(\vec{\mathbf{P}})$ unknown method it is necessary to recover Equation 5.1.15, with the parameterizing variable of the single i track being again TIP_i

$$\varepsilon_{1i}\varepsilon_{2j} = \mathcal{E}_{ij} = \sum_{\vec{\mathbf{P}}} \frac{n_{ij}(\vec{\mathbf{P}})}{N} \frac{1}{\mathcal{A}(TIP_1, TIP_2, \vec{\mathbf{P}}) \mathcal{K}(TIP_1, TIP_2 | \vec{\mathbf{P}})}, \quad (5.2.5)$$

and then the $\mathcal{A}$, $\mathcal{K}$ function is to be binned again. What is different now is their dependence on additional variables with respect to only TIP_1 , TIP_2 of the $\mathcal{D}(\vec{\mathbf{P}})$ known method. First let $\mathcal{K}$ be rewritten as a joint distribution instead of a

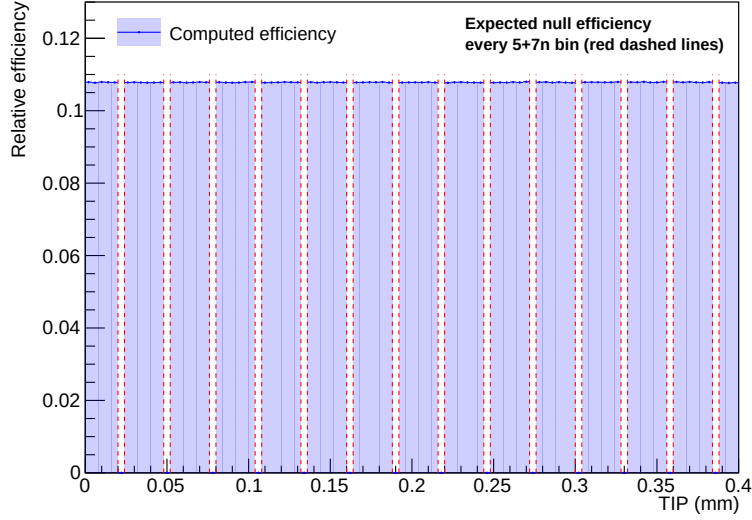


Figure 5.9: The efficiency eigenvector in case of simulated non-parametric efficiency shape, with the reconstructed efficiency filled in blue and the expected one depicted with red dashed lines.

conditional

$$\mathcal{K}(TIP_1, TIP_2 | \vec{\mathbf{P}}) = \frac{\mathcal{K}(TIP_1, TIP_2, \vec{\mathbf{P}})}{\mathcal{D}_{gen.}(\vec{\mathbf{P}})} = \frac{\mathcal{K}(TIP_1, TIP_2, \vec{\mathbf{P}})}{\iint \mathcal{K}(TIP_1, TIP_2, \vec{\mathbf{P}}) dTIP_1 dTIP_2}, \quad (5.2.6)$$

where $\mathcal{D}_{gen.}(\vec{\mathbf{P}})$ is the D^0 $\vec{\mathbf{P}}$ distribution generated in the ToyMC_{KA} for the computation of $\mathcal{A}$ and $\mathcal{K}$. Now these functions can be binned, picking the D^0 3D momentum p and the D^0 transverse momentum p_T for the $\vec{\mathbf{P}}$ parametrization. Here it is assumed that the azimuthal angle of the D^0 does not carry any relevance in the time-dependent track efficiencies. A 4-D grid $TIP_1 \times TIP_2 \times p(D^0) \times p_T(D^0)$ is therefore built, with $100 \times 100 \times 30 \times 15$ bins whose indexes are respectively i, j, k and l . While TIP_i still ranges between 0.0 mm and 0.4 mm, p is bound between 10 GeV and 80 GeV, and p_T start from 2 GeV up to 17 GeV. This boundaries retain $\sim 75\%$ of the events w.r.t. the $\mathcal{D}(\vec{\mathbf{P}})$ known method, without overwhelming the grid with 0/0 regions. From Equation 5.2.5 and 5.2.6, and making the binning explicit:

$$\varepsilon_{1i}\varepsilon_{2j} = \mathcal{E}_{ij} = \sum_{k,l} \frac{1}{N} \frac{n_{ijkl}}{A_{ijkl} \frac{K_{ijkl}}{\sum_{i,j} K_{ijkl}}}, \quad (5.2.7)$$

and considering that the binned acceptance function can be estimated as

$$A_{ijkl} = \frac{f_{ijkl}}{NK_{ijkl}}, \quad (5.2.8)$$

with f_{ijkl} being the number of generated events which have passed the selections in the bin $ijkl$ and NK_{ijkl} the number of generated event previous to any selection in the bin $ijkl$. Finally all these calculations give

$$\varepsilon_{1i}\varepsilon_{2j} = \mathcal{E}_{ij} = \sum_{k,l} \frac{n_{ijkl}}{\frac{f_{ijkl}}{\sum_{i,j} K_{ijkl}}} = \sum_{k,l} \frac{n_{ijkl}}{N \frac{f_{ijkl}}{\sum_{i,j} NK_{ijkl}}}, \quad (5.2.9)$$

from which the efficiency can be extracted.

Flat efficiency As with the $\mathcal{D}(\vec{\mathbf{P}})$ known method, a uniform efficiency is again used for the first test. The efficiency matrix extracted via Equation 5.2.9 is reported in Figure 5.10. The first most noticeable characteristic is that this matrix

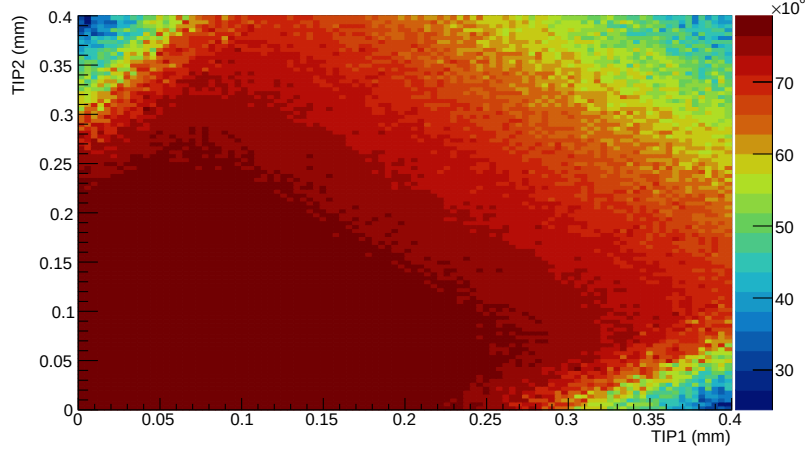


Figure 5.10: The $\mathcal{E}$ matrix in case of simulated flat efficiency shape with the $\mathcal{D}(\vec{\mathbf{P}})$ unknown method. The z coloured scale has no physical meaning due to a normalisation constant being lost.

is anything but flat. The 0/0 regions, in fact, have contaminated this matrix, resulting in an underestimation of the efficiencies in those region where the statistic is lower, which is at both TIPs being higher and, also, well outside the bisector zone. In such conditions extracting the efficiency eigenvector accomplish next to nothing: a region less polluted by 0/0 bins must be identified. We restrict the TIPs boundaries between 40 μm and 200 μm , which result in the surviving samples, both ToyMC_{data} and ToyMC_{KA} , remaining with 8.4×10^6 events, a $\sim 15\%$ retention rate on the yields available to the $\mathcal{D}(\vec{\mathbf{P}})$ known method. Now the $\mathcal{E}$ matrix appears far less worrying (Figure 5.11) and the efficiency can attempt to be extracted (Figure 5.12). Comparing the z scale of Figure 5.10 and Figure

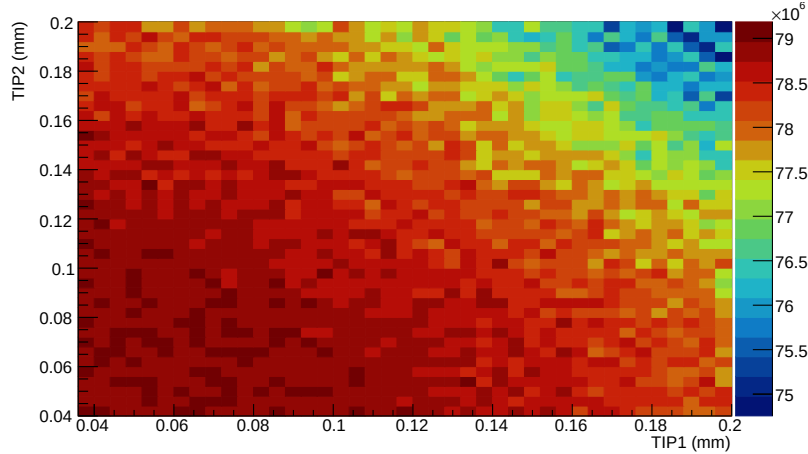


Figure 5.11: The $\mathcal{E}$ matrix in case of simulated flat efficiency shape with the $\mathcal{D}(\vec{\mathbf{P}})$ unknown method, in the reduced region $\text{TIP}_{1,2} \in [40, 200] \mu\text{m}$.

5.11, even if its absolute value is devoid of physical meaning, allows for estimating the impact of 0/0 regions being less than an order of magnitude lower in the $TIP_{1,2} \in [40, 200]\mu\text{m}$ region than in the $TIP_{1,2} \in [0, 400]\mu\text{m}$ one. The Least

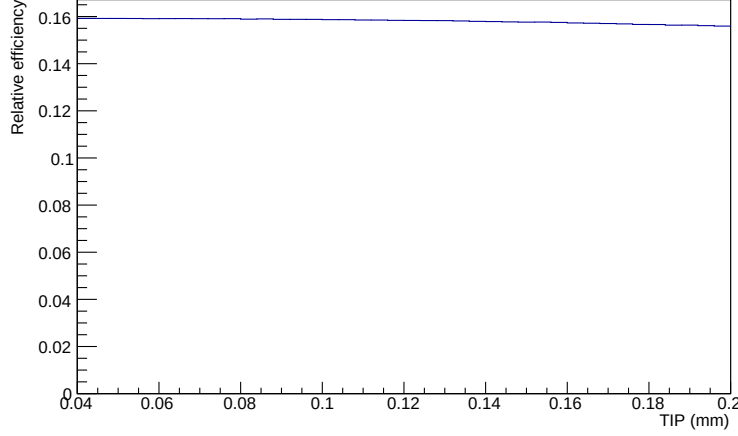


Figure 5.12: The efficiency eigenvector in case of simulated flat efficiency with the $\mathcal{D}(\vec{\mathbf{P}})$ unknown method, in the reduced region $TIP_{1,2} \in [40, 200]\mu\text{m}$.

Square (LS) fit employing a linear model $\alpha x + \beta$ returns an angular coefficient

$$\alpha = (-2.06 \pm 0.09) \times 10^{-2} \text{ mm}^{-1}$$

diverging from the flat hypothesis where $\alpha \equiv 0$, by more than 5σ . Restricting the region is then not sufficient in order to recover the simulated efficiency. The secondary eigenvalues in this case are smaller than 0.3% of the main one, but are not a good indicator for gauging the success of the algorithm, just signaling that the efficiencies between the two track are not correlated. Before addressing this issue a further efficiency model is tested to get a firmer grasp on what is happening.

Linear efficiency The same linear efficiency model presented in the previous subsection is injected in the simulated data sample ToyMC_{data} , already restricting the TIP region to the $TIP_{1,2} \in [40, 200]\mu\text{m}$ range. The extracted efficiency is in Figure 5.13. From the parameter values returned by the LS fit with a linear model $\alpha x + \beta$ it is obtained

$$\frac{\alpha}{\beta} = (-1.09 \pm 0.01) \text{ mm}^{-1},$$

which is not in agreement with the expected value of $\alpha/\beta = -1 \text{ mm}^{-1}$ within the quoted uncertainties. At this point it is clearly necessary to look for a way to resolve this issue without further compromising the already low yields with additional cuts.

5.2.3 Improving the $\mathcal{D}(\vec{\mathbf{P}})$ unknown algorithm

The loss of accuracy in extracting the efficiency shape can be traced back to the presence of low acceptance 0/0 regions. In Figure 5.14 the distribution of these regions, reweighted for $1/\sum_{i,j} NK_{ijkl}$, is plotted showing how they contribute in the $\mathcal{E}$ matrix and to what extent. From a comparison of this distribution with the

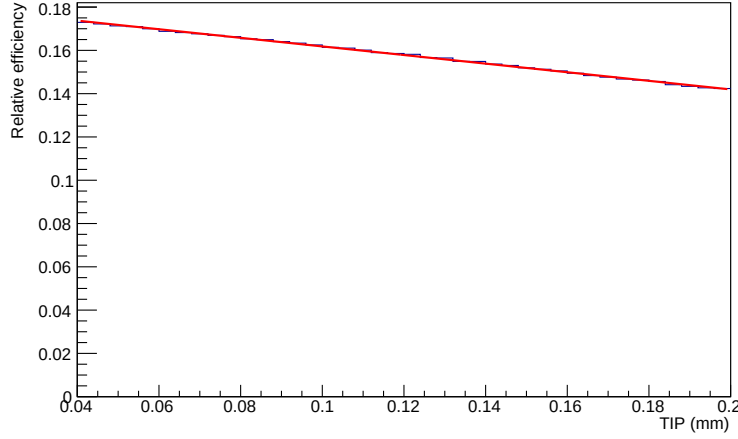


Figure 5.13: The efficiency eigenvector in case of simulated linear efficiency shape with the $\mathcal{D}(\vec{\mathbf{P}})$ unknown method, in the reduced region $TIPs \in [40, 200]\mu\text{m}$. The vector is shown in blue and the LS fit function in red.

flat efficiency matrix shown in Figure 5.11, it can be inferred how the simple sum of these two matrices would return the correct expected flat efficiency. Moreover the contribution of 0/0 regions, dangerously mimic the effect of decreasing almost linear factorizing efficiency, rendering the method blind to such problem and resulting in the secondary eigenvalues remaining small, as if all is functioning well, which is obviously not the case. Having the tangible evidence of the cause of the problem, and how it hides within the algorithm, two routes can be taken. The first is restricting the signal region further, by lowering the upper TIP bound. This is not really feasible for two reason: first the yields would suffer further, which is not ideal when the aim is building an analysis methodology for a high-luminosity scenario where the statistic power of the sample is then compromised by extremely tight selections; second it has been shown how this effect did not show up through altered values of the secondary eigenvalues, which would otherwise signal other anomalies. Tightening the TIP boundaries would not change this behavior, therefore the second route is taken: changing the binning.

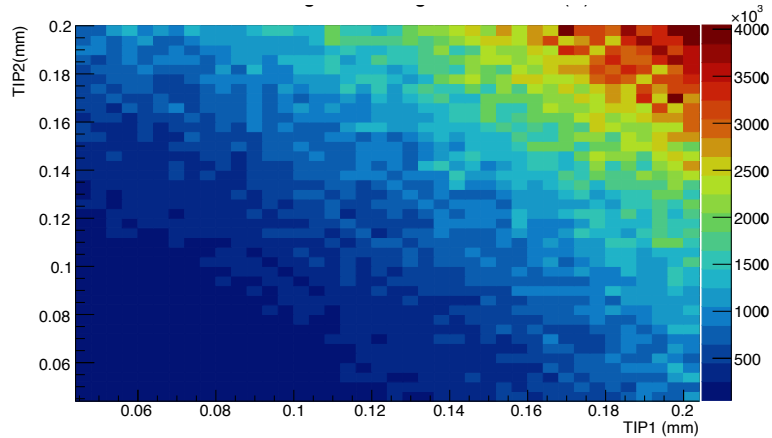


Figure 5.14: The distribution of 0/0 regions reweighted for $1/\sum_{i,j} NK_{ijkl}$, in order to account for their correct contribution to the efficiency matrix.

Variable-bin approach Instead of using a fixed bin width for the TIP_1 and TIP_2 observables, a geometric series of progressively increasing widths has been generated, where every bin is 5% wider than the previous, in a way that the $[0, 400]\mu\text{m}$ TIP range still fit a number of 100 bins. Without dwelling too much on the matter, suffice to say that the $TIP_{1,2} \in [0, 400]\mu\text{m}$ region still exhibits issues. In fact the 0/0 phenomenon arises both at high tip values on the bisector and far away from it when the TIP of one track is at the lower (higher) bound and the other at the higher (lower). This time the range $[48, 200]\mu\text{m}$ is chosen with the retain rate dropping slightly from the $\sim 15\%$ of the $[40, 200]$ case to $\sim 11\%$ of this one.

Flat efficiency shape The retrieval of the flat efficiency shape is performed again, this time obtaining from the $\alpha x + \beta$ LS fit

$$\alpha = (-1.0 \pm 0.5) \times 10^{-3} \text{ mm}^{-1},$$

which is in good agreement with the zero expected value within 2σ . In Figure 5.15 the extracted efficiency matrix, while in Figure 5.16 the efficiency eigenvector. The secondary eigenvalues are less than 5×10^{-4} of main eigenvalue.

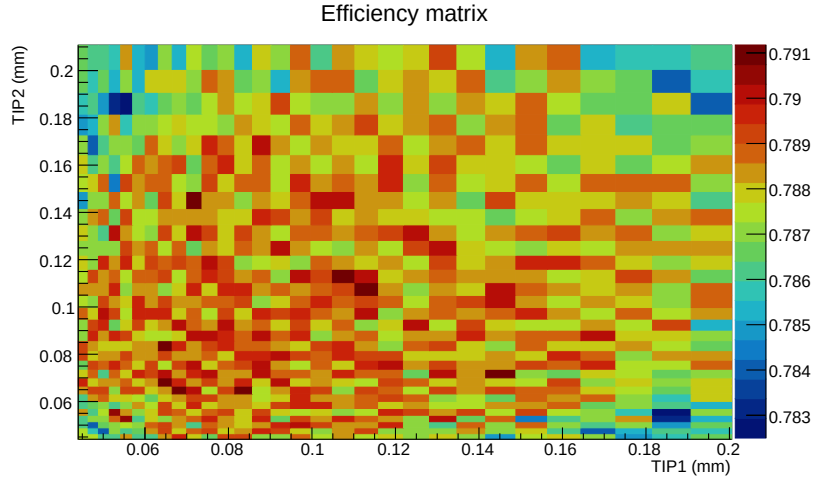


Figure 5.15: The $\mathcal{E}$ in case of simulated flat efficiency shape with the $\mathcal{D}(\vec{\mathbf{P}})$ unknown method and the variable bin width approach, in the reduced region $TIP_{1,2} \in [48, 200]\mu\text{m}$.

While the matrix appears far from flat at first sight, the z scale, giving quantitative interpretation to the colors, helps in understanding that such fluctuations from a perfect flat behavior are of the order of 1%. Let the distribution of 0/0 regions be addressed. In Figure 5.17 is shown the equivalent of Figure 5.14, using the variable bin width approach. While the z axis are not directly comparable due to different normalization constant, it can be noted that while the effects of 0/0 regions amounted to a variation in the flat efficiency matrix equal to 5% by comparing the z scales of Figures 5.11 and 5.14, here the effect is reduced to an impact of $< 1\%$ (z scales of 5.11 and 5.17). Another advantage gained is that the shape of this 0/0 regions contribution does not imitate any longer the behavior of factorizing efficiencies. The distribution in Figure 5.17 exhibit a correlation pattern between TIP_1 and TIP_2 , therefore if the 0/0 regions were to significantly impact the efficiency matrix $\mathcal{E}$, then the secondaries eigenvalues would inflate and provide a clear warning to the analyst.

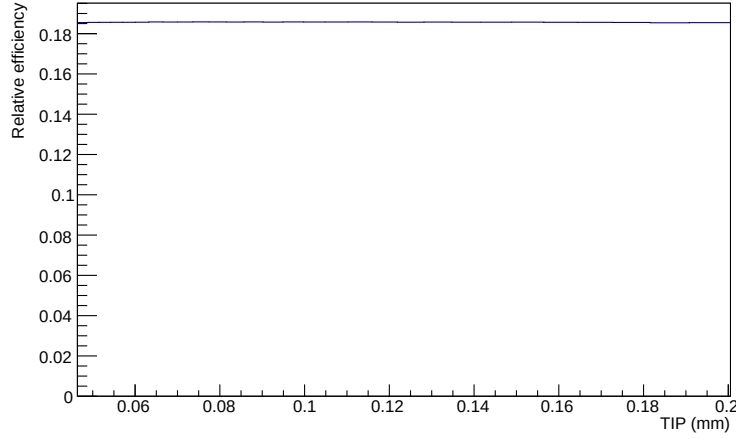


Figure 5.16: The efficiency eigenvector in case of simulated flat efficiency with the $\mathcal{D}(\vec{\mathbf{P}})$ unknown method and the variable bin width approach, in the reduced region $TIP_{1,2} \in [48, 200]\mu\text{m}$.

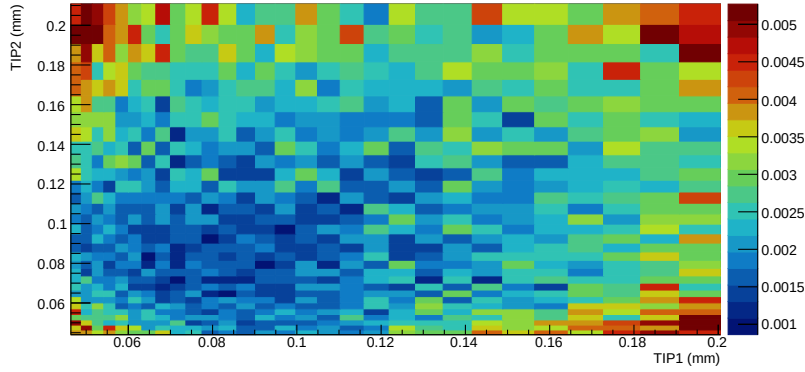


Figure 5.17: The distribution of 0/0 regions reweighted for $1/\sum_{i,j} NK_{ijkl}$, in order to account for their correct contribution to the efficiency matrix, with the variable bin width approach.

Linear efficiency shape Now that the 0/0 regions issue has been managed, the linear efficiency shape test is repeated in order to verify that all is indeed under control. Using the same variable width binning just described previously, the efficiency matrix and eigenvector are extracted (Figures 5.18 and 5.19). The secondary eigenvalues normalized to the main one are $< 0.2\%$.

From the LS fit with $\alpha x + \beta$ model it is now attained

$$\frac{\alpha}{\beta} = (-1.000 \pm 0.003) \text{ mm}^{-1},$$

in good agreement with the simulated value of $\alpha/\beta = -1 \text{ mm}^{-1}$, finally proving not only that the $\mathcal{D}(\vec{\mathbf{P}})$ unknown method works in principle in extracting the correct simulated efficiency models from the data, but also that a way of managing the 0/0 regions has been found that successfully works in practice.

Summarizing the work achieved in this chapter, it has been proved that the data-driven technique for extracting efficiencies that factorize between the two tracks, functions correctly and manages to retrieve several efficiency shapes, both analytic and non-parametric. The $\mathcal{D}(\vec{\mathbf{P}})$ unknown method has been thoroughly

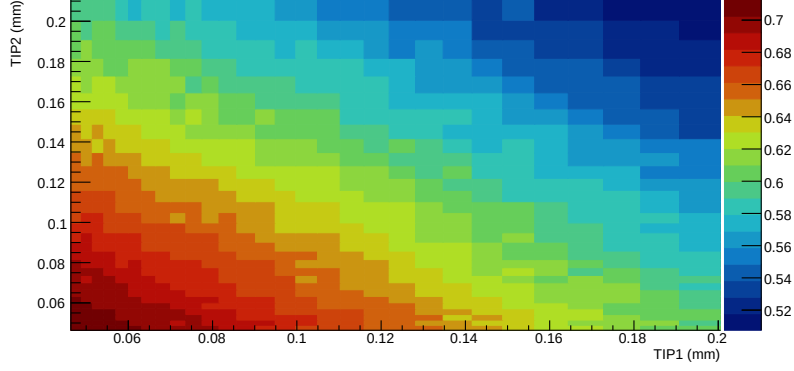


Figure 5.18: The $\mathcal{E}$ in case of simulated linear efficiency shape with the $\mathcal{D}(\vec{\mathbf{P}})$ unknown method and the variable bin width approach, in the reduced region $TIP_{1,2} \in [48, 200]\mu\text{m}$.

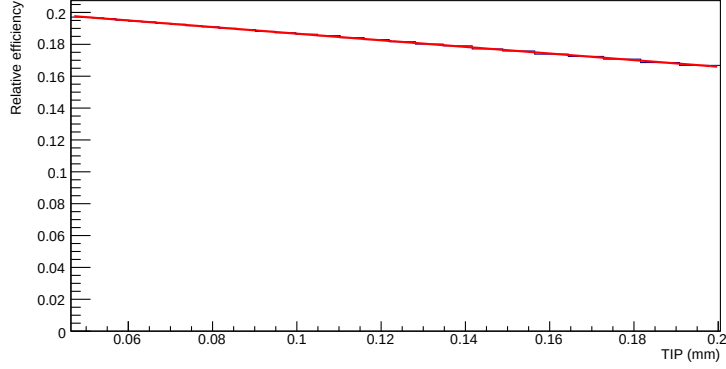


Figure 5.19: The efficiency eigenvector in case of simulated linear efficiency with the $\mathcal{D}(\vec{\mathbf{P}})$ unknown method and the variable bin width approach, in the reduced region $TIP_{1,2} \in [48, 200]\mu\text{m}$. In blue the extracted eigenvector and in red the LS fit function.

investigated and the conditions for it to return accurate values even from critic regions have been presented. Even if the choice may preferably fall on the $\mathcal{D}(\vec{\mathbf{P}})$ known method, far less “fragile”, having at disposal a tool which permits to measure track efficiency even not knowing the production distribution of the D^0 is a too great advantage to discard so early in the road of building the analysis strategy for y_{CP} at high luminosities.

In the next chapter, we deal with incorporating the efficiency extraction methodology in performing lifetime measurements.

CHAPTER

6

MEASURING ABSOLUTE LIFETIMES

It stands to reason that if the sample from which the lifetime shall be extracted undergoes selections and the final product tracks are subjected to detection efficiencies biasing the decay time, then the measured decay time distribution $\mathcal{D}(\tau)_{raw}$ will be

$$\mathcal{D}(\tau)_{raw} = \mathcal{S} \varepsilon_1 \varepsilon_2 \mathcal{D}(\tau)_{decay} \quad (6.0.1)$$

where the $\mathcal{D}(\tau)_{decay}$ is the reconstructed decay time distribution without any selection and with 100% detection efficiency, from which the unbiased mean lifetime can be measured, $\mathcal{S}$ is a function containing the selection efficiency and the geometric acceptance of the detector, and ε_i ($i = 1, 2$) is the single track detection efficiency, that we proved in the previous chapter to be obtainable through a fully data-driven method.

As consequence, by assigning to each event a weight

$$w = \frac{1}{\mathcal{S} \varepsilon_1 \varepsilon_2},$$

it should be possible to extract $\mathcal{D}(\tau)_{decay}$ from $\mathcal{D}(\tau)_{raw}$.

6.1 Correcting lifetimes for acceptance effects

In the previous chapter the function $\mathcal{A}$ was introduced, that contains selection and acceptance efficiencies. While not mandatory, it is a possibility that the sample from which the track efficiency is extracted is the same employed for the mean lifetime measurement. In that case the $\mathcal{A}$ function can also be used here for the reweighting of the decay time distributions (*in-situ* calibration). However, a few clarification are necessary.

Both $\mathcal{A}$ and ε are defined only within their respective limited domains. In the $\mathcal{D}(\vec{\mathbf{P}})$ known (unknown) method the ε domain used was $TIP \in [0, 400]\mu\text{m}$

$([48, 200]\mu\text{m})$, while $\mathcal{A}(TIP_1, TIP_2)$ of the $\mathcal{D}(\vec{\mathbf{P}})$ known method (Figure 6.1) is defined inside the

$$TIP_1 \in [0, 400]\mu\text{m} \times TIP_2 \in [0, 400]\mu\text{m}$$

region and $\mathcal{A}(TIP_1, TIP_2, p^{D^0}, p_T^{D^0})$ of the $\mathcal{D}(\vec{\mathbf{P}})$ unknown method inside

$$TIP_1 \in [48, 200]\mu\text{m} \times TIP_2 \in [48, 200]\mu\text{m} \times p^{D^0} \in [10, 80]\text{GeV} \times p_T^{D^0} \in [2, 17]\text{GeV}.$$

Due to this, it cannot be simply $\mathcal{A} = \mathcal{S}$ as the selections imposed by restriction

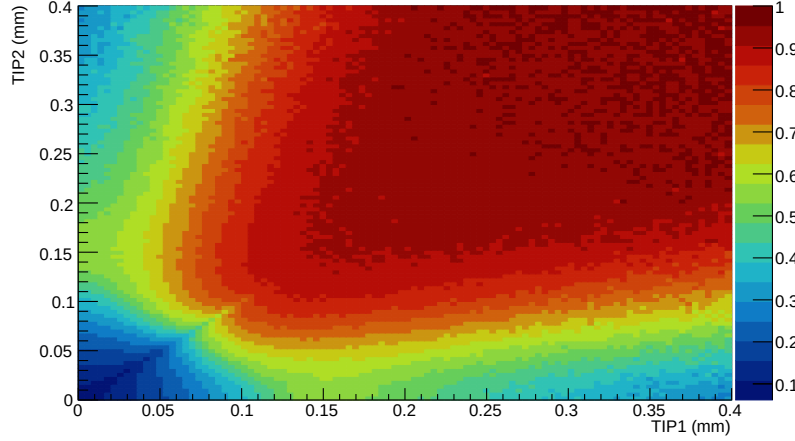


Figure 6.1: The $\mathcal{A}(TIP_1, TIP_2)$ of the $\mathcal{D}(\vec{\mathbf{P}})$ known method.

of the data to those domains would not be accounted for. A new function $\mathcal{C}(\tau)$ is then defined in order to have

$$\mathcal{S} = \mathcal{A}\mathcal{C}(\tau),$$

which operates as a corrective factor to $\mathcal{A}$ in order to correctly model the efficiency of all the selections.

With the goal of having $\mathcal{C}(\tau)$ independent on the lifetime value, a further Monte Carlo sample is built via the same ToyMC mentioned in the previous chapters, where the D^0 decay time distribution is not sampled from an exponential but from a uniform distribution between 0 and 5 ps. The sample is then filtered with the same selections imposed before and illustrated in the previous chapter (Table 5.1). No track efficiency is injected (resulting in a 100% flat efficiency) and every event is reweighted for $1/\mathcal{A}$, obtaining the distribution $\mathcal{D}_{\mathcal{A}}^{flat}(\tau)$ shown in Figure 6.2. Its ratio with the initial simulated decay time distribution return the corrective factor $\mathcal{C}(\tau)$ that factorizing with $\mathcal{A}$ gives $\mathcal{S}$ and hence the correct reweighting for extracting the unbiased mean lifetime. However, it can be noted that as the initial unfiltered decay time distribution of this sample was simulated flat, then $\mathcal{C}(\tau) = \mathcal{D}_{\mathcal{A}}^{flat}(\tau)$ but for a trivial multiplicative factor. In fact, this last equality hides the effects of resolution smearing, absorbing it in the correction function. It is the true decay time distribution to be simulated as uniform, not the reconstructed decay time one. There are edge effects due to resolution smearing that cause the reconstructed decay time distribution to not be flat. Writing $\mathcal{C}(\tau) = \mathcal{D}_{\mathcal{A}}^{flat}(\tau)$ implies that the resolution smearing effects are being absorbed inside the $\mathcal{C}(\tau)$ function. For this reason the following fits are performed with a simple exponential function as model. As a further note, in this chapter all instances of τ or τ_T will stand for $\tau_T^{\overline{PV}}$, to simplify the notation.

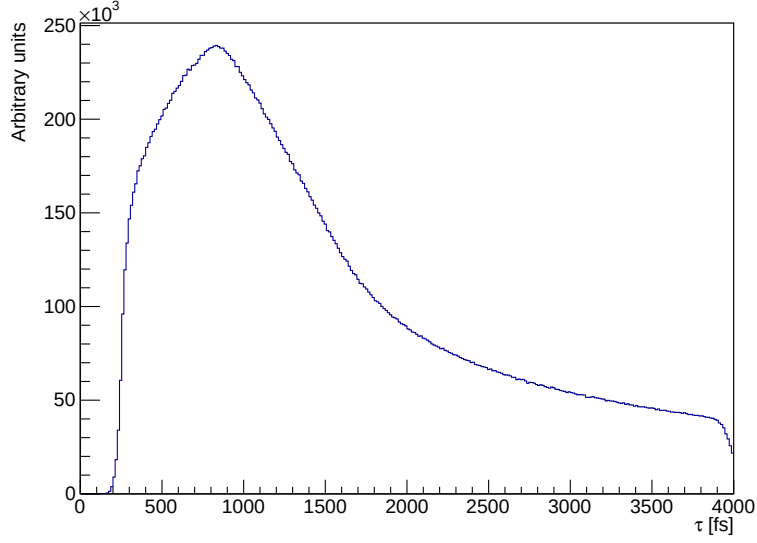


Figure 6.2: The $\mathcal{D}_{\mathcal{A}}^{flat}(\tau)$ distribution, also known as $\mathcal{C}(\tau)$ corrective factor.

6.2 Retrieving lifetimes, case of known $\mathcal{D}(\vec{\mathbf{P}})$

The algorithm described above is implemented using the already presented linear model for the track efficiency. Binned likelihood fit are performed in various fit ranges both on the decay time distribution after reweighting for

$$w_{\mathcal{A}\mathcal{C}} = \frac{1}{\mathcal{A}(TIP_1, TIP_2)\mathcal{C}(\tau)} \quad (6.2.1)$$

and again after correcting for the efficiency with the weight

$$w_{\mathcal{A}\mathcal{C}\varepsilon} = \frac{1}{\mathcal{A}(TIP_1, TIP_2)\mathcal{C}(\tau)\varepsilon_1(TIP_1)\varepsilon_2(TIP_2)}. \quad (6.2.2)$$

The results are shown in Figure 6.3. The fit in the range $[0.4, 4]$ ps with the reweighting $w_{\mathcal{A}\mathcal{C}}$ is shown in Figure 6.4, and the one after correcting for the track efficiencies in Figure 6.5. From Figure 6.3 it is apparent how the method for extracting the efficiency proves to be useful in reweighting the decay time distribution and extracting a measurement in good agreement with the simulated D^0 lifetime of 410.1 ps with a precision of 0.05% the nominal τ_{D^0} . The χ^2/ndf values are good, testifying that the simple exponential is a good model for the data. The value extracted from the fit with wider range is

$$\tau = (410.20 \pm 0.20) \text{ fs},$$

which is compatible with the simulated one within 0.5σ .

Comparing Figures 6.4 and 6.5, it is explicitly shown how the efficiency correction “straightens” the data distribution towards an exponential shape. The pulls distribution appears well behaved above 400 fs. Below this threshold a discrepancy can be seen, and from Figure 6.3 it can be noted that no fit is performed under this value. This is due to how the resolution smearing effect have been incorporated in the $\mathcal{C}(\tau)$ function: while it helps in regularizing the distribution at

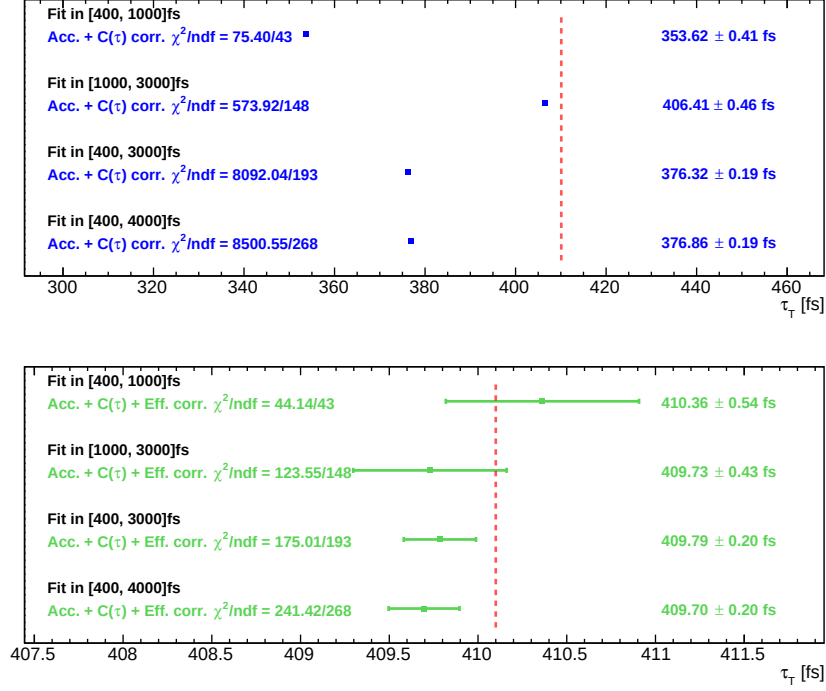


Figure 6.3: The mean D^0 lifetime extracted at various fit ranges, comparing the results before (above) and after (below) the track efficiency correction extracted with the $\mathcal{D}(\vec{P})$ known method. Before efficiency correction (above) representation of the bias has been deemed priority over the precision, which is reported on the right next to the value. The dashed red line is the simulated mean life time used in creating the sample.

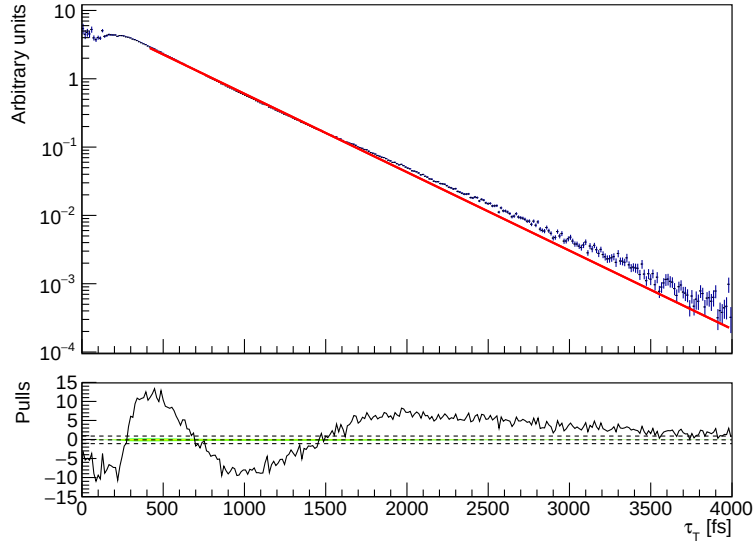


Figure 6.4: The decay time distribution of the filtered sample subjected to loss of track efficiency with a linear shape, corrected just for the selection efficiency (in blue). In red the exponential distribution fitted to the data in the range $[0.4, 4]$ ps, with the pulls being displayed below.

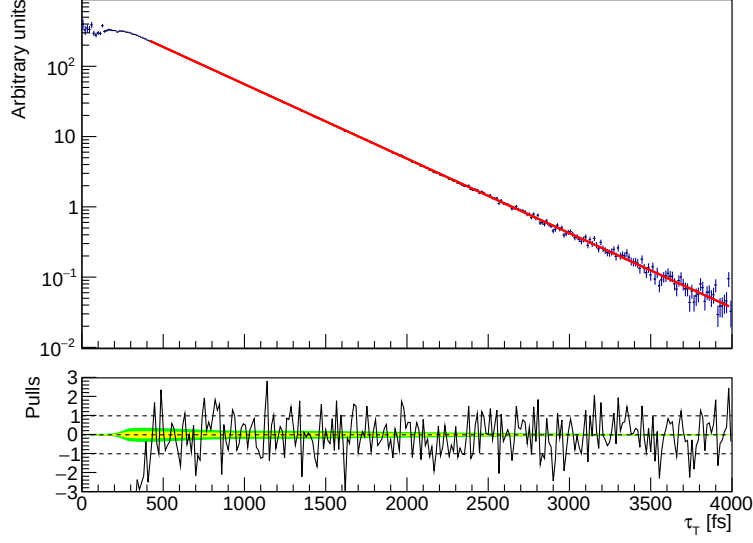


Figure 6.5: The decay time distribution of the filtered sample subjected to loss of track efficiency with a linear shape, corrected for both the selection and detection efficiencies (in blue). In red the exponential distribution fitted to the data in the range $[0.4, 4]$ ps, with the pulls being displayed below.

higher decay times, it must be emphasized that the edge deformation caused by the smearing is quite different between a uniform distribution starting at 0 fs and an exponential distribution. Therefore this discrepancy is expected at low decay time. It has been previously shown that the resolution model can be incorporated in the fit via an appropriate template, as of consequence this current issue does not raise concerns, as its cause is understood and can be avoided should low decay time be not discarded.

Summarizing what has been reported, the correct mean lifetime has been extracted with no bias evident at the statistical precision of 5×10^{-4} the nominal τ_{D^0} , this precision an order of magnitude smaller than the precision on the most recent LHCb D_s^- lifetime measurement [86]. It is also five times smaller than the one of the current most precise measurement of D^0 absolute lifetime performed at Belle II [87]). Recovering the track detection efficiency from data has enabled achieving this result.

6.3 Retrieving the lifetime with $\mathcal{D}(\vec{\mathbf{P}})$ unknown ε

The entire procedure has been repeated using the track efficiency extracted with the $\mathcal{D}(\vec{\mathbf{P}})$ unknown method and substituting in the reweight $\mathcal{A}(TIP_1, TIP_2)$ with $\mathcal{A}(TIP_1, TIP_2, p^{D^0}, p_T^{D^0})$. The binned likelihood fit results with a simple exponential as model are reported in Figure 6.6. Plots of the decay time distribution with the fitted function and the pulls distribution appear to be with no dissimilarity from those already shown in the previous section, concerning the $\mathcal{D}(\vec{\mathbf{P}})$ known method; hence, they are not reported.

From Figure 6.6 it is noticeable the loss of precision by a factor ~ 2 on the extracted mean lifetime w.r.t. the $\mathcal{D}(\vec{\mathbf{P}})$ known scenario, due to the tighter selection required for the $\mathcal{D}(\vec{\mathbf{P}})$ unknown method to function. Apart from this,

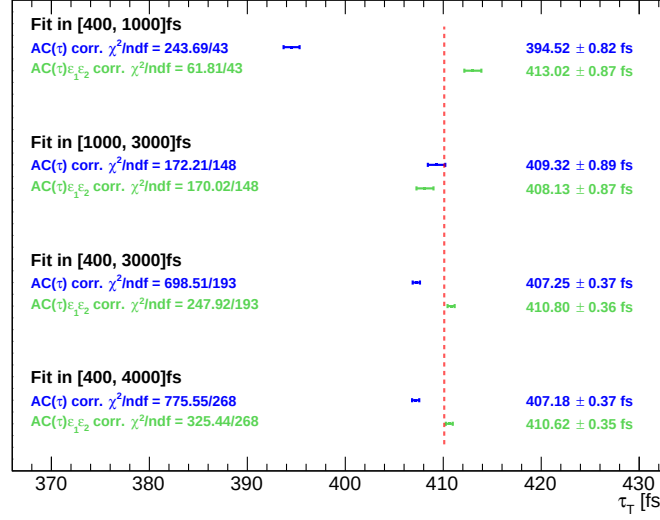


Figure 6.6: The mean D^0 lifetime extracted at various fit ranges, comparing the results before and after the track efficiency correction extracted with the $\mathcal{D}(\vec{\mathbf{P}})$ unknown method. The dashed red line is the simulated mean life time used in creating the sample.

good agreement with the simulated value is always found at all fit ranges after the sample distribution has been corrected for both the selection the detection efficiencies. From the fit between 0.4 and 4 ps it is obtained

$$\tau = (410.62 \pm 0.35) \text{ fs},$$

which is compatible with the simulated value within 1.5σ .

This result is indeed of great relevance. Being capable of extracting the track detection and factorizing selection efficiencies from the data means that the absolute mean lifetime of the particle of interest can be measured, even if the distribution $\mathcal{D}(\vec{\mathbf{P}})$ is not known. So, while the statistical precision, being 5×10^{-4} for the $\mathcal{D}(\vec{\mathbf{P}})$ known method and 10^{-3} in case of $\mathcal{D}(\vec{\mathbf{P}})$ unknown, has suffered passing from one method to the other, it appears that systematic effects producing bias on the mean lifetime are smaller than the statistical precision in both methods. Moreover, as the efficiency extraction technique is completely data-driven, the precision on the efficiencies themselves are expected to scale with the size of the sample, thus providing a solid strategy to be employed in the future runs, where the accumulated integrated luminosity will open the path to unprecedented achievable precision on time-dependent observables.

PART III

OFFICIAL

FULL-SIMULATION AND

REAL DATA

CHAPTER

7

APPLICATION TO REAL DATA

In this chapter the results obtained with the LTUNB samples, both Official Monte Carlo Full Simulation and real data, are presented. The absolute D^0 lifetimes $\tau_{D^0}^{\pi\pi}$ and $\tau_{D^0}^{KK}$ will be extracted from the Monte Carlo simulation respectively from the $D^0 \rightarrow \pi^-\pi^+$ sample and $D^0 \rightarrow K^-K^+$, while for real data a test observable $\tau_{D^0}^{KK} - \tau_{D^0}^{\pi\pi}$ will be checked to be compatible with zero, as expected from theory.

7.1 Official generator-level simulation

When faced with the choice of using the $\mathcal{D}(\vec{\mathbf{P}})$ known method or the $\mathcal{D}(\vec{\mathbf{P}})$ unknown one, it has been taken in consideration that in case of $\mathcal{D}(\vec{\mathbf{P}})$ unknown a loss of precision happens. Given that the 0/0 regions are an issue waiting around the corner to manifest itself, it has been decided to use the $\mathcal{D}(\vec{\mathbf{P}})$ known method, not only more precise, due to looser selections, but also tamer.

However, this implies that the $\vec{\mathbf{P}}$ distribution is to be well known, therefore in order to minimize differences between the simulated $\mathcal{K}$ production distribution and the effective one, we asked LHCb for a production of a generator level simulation of the decay $D^{*+} \rightarrow D^0\pi_s^+ \rightarrow (K^-K^+)\pi_s^+$ and its c.c. with 2.5×10^8 events simulating the 2018 *MagUp* beam conditions. This number was chosen to be roughly at the same order of magnitude of the real data sample, after the trigger selections are applied.

This way the D^0 meson is produced using the PYTHIA Event Generator, which is tuned to the LHC data and it is capable of modeling complex particle physics phenomena. Its accuracy and reliability is thoroughly tested at LHCb [91], therefore providing an accurate $\mathcal{D}(\vec{\mathbf{P}})$, which enables the use of the $\mathcal{D}(\vec{\mathbf{P}})$ known method. As the provided generator level simulation used as input parameters the 2018 *MagUp* beam conditions, the samples analyzed will be of the 2018 *MagUp* data taking period as well.

However, the produced sample only contains the true value of the kinematic observables concerning the particles in the decay. In fact any reconstruction sim-

ulation would implicitly also include the detection efficiency, which would render the data set useless as what is wanted is the distribution of the decay phase space before any selection or detection efficiency intervenes on the observables' distributions. Ideally, as it has been illustrated in Chapter 4 and Chapter 6, the resolution effects should be modeled separately and not included in the reweighting procedure may it be $\mathcal{A}$, $\mathcal{C}(\tau)$ or the track efficiency function. Therefore all these reweighting should be computed not with respect to the true observables' distributions, but the reconstructed ones. In order to do so the generator level simulation provided by LHCb needs to be subjected to a "hand-made smearing process", where the vertices and momenta of the particles are simulated to withstand the reconstruction process, without encountering the detection efficiency.

7.2 Custom smearing template for the generator-level simulation

Simulations called Particle Gun(s) are employed in extracting the smearing templates on the PV, EV and momentum of the decay products particles. These Particle Guns are a type of fast simulation where, given a decay chain, instead of simulating the whole pp collision, the 3D momentum of the particle at the top of the decay is sampled from a stored p_T , η 2D distribution, then the decay of interest computed from these initial conditions and the detector response are simulated. The choice of using such simulations was simply to extract the resolution smearing template from a sample statistically independent from the Official Full Simulation, used for the tests.

Therefore from the mentioned samples the following distributions are extracted:

- $\delta PV_i = PV_i^{reco.} - PV_i^{true}$, $i = x, y, z$, the resolution smearing on the PV coordinates;
- $\delta EV_i = EV_i^{reco.} - EV_i^{true}$, $i = x, y, z$, the resolution smearing on the EV coordinates;
- $\delta p_z^K / p_z^K = \frac{p_z^{reco.}(K) - p_z^{true}(K)}{p_z^{true}(K)}$, the resolution smearing on p_z of the K particle over its true value;
- $\delta \theta^K / \sqrt{\theta^K} = \frac{\theta^{reco.}(K) - \theta^{true}(K)}{\sqrt{\theta^{true}(K)}}$, the resolution smearing on the polar angle θ of the K particle over the square root of its true value;
- $\delta \phi^K = \phi^{reco.}(K) - \phi^{true}(K)$ the resolution smearing on the azimuthal angle θ of the K particle.

Such parametrizations are chosen in an entire empirical way, so that the smearing templates remain approximately constant for any given value of the true observable.

Performing binned likelihood fits of these observables it is decided that:

- δPV_i can be modeled with a Gaussian profile with $\mu_x = \mu_y = \mu_z = 0$ and $\sigma_x = \sigma_y = 10 \mu\text{m}$ and $\sigma_z = 54 \mu\text{m}$;
- δEV_x and δ_x^{EV} are also Gaussian-like with zero mean and $\sigma_x = 25 \mu\text{m}$ and $\sigma_y = 18 \mu\text{m}$;

- δEV_z is Lorentzian-like centred in zero and with $\Gamma = 365 \mu\text{m}$;
- $\delta p_z^K / p_z^K$ is again Gaussian-like with mean zero and $\sigma = 0.4\%$;
- $\delta\theta^K / \sqrt{\theta^K}$ can be described with a Gaussian of zero mean and $\sigma = 0.5 \text{ mrad}^{1/2}$;
- $\delta\phi^K$ modeled with a Gaussian with zero mean and $\sigma = 1.2 \text{ mrad}$.

Using these described templates then the detection smearing effects are applied to the PVs, EVs and momentum of the two K , from which the D^0 momentum is then recomputed.

The resolution effects are approximated to be independent from each other; this assumption was backed up by the fact that no variables arising from decay-tree fitter were used. A decay-tree fitter takes a complete decay chain, parameterizes it in terms of vertex positions, decay lengths and momentum parameters, and then fits these parameters simultaneously, taking into account the relevant constraints, such as the measured parameters of the final state tracks and four-momentum conservation at each vertex. Obviously, this way, smearing effects of all the refitted observables would correlate with each other, with different degrees of course, but still correlated they would be. Using instead variables calculated starting from the most downstream observables and moving upwards in order to reconstruct the decay, with the vertices fit performed separately from the momenta computation ensures a high degree of independence.

With this simulation available, providing produced distribution of the reconstructed observables, without any selection bias, the track efficiency can be extracted from the Official Simulation with the technique of Chapter 5 and then the D^0 mean lifetime can be measured.

7.3 LTUNB Official Full Simulation

7.3.1 $D^0 \rightarrow K^- K^+$

Efficiency extraction The “smeared” LHCb generator level simulation is filtered using the selections of Table 7.1, which are the same of the LTUNB trigger line. However, if compared with Table 3.3 which comprises all the selec-

Quantity	Requirement
$p_T(D^0)$	$> 2 \text{ GeV}/c$
$\tau_{3D}(D^0)$	$> 250 \text{ fs}$
$p_T(K^\pm)$	$> 800 \text{ MeV}/c$
$p(K^\pm)$	$> 5 \text{ GeV}/c$
$\max\{p_T(K^+), p_T(K^-)\}$	$> 1.2 \text{ GeV}/c$
$p_T(\pi_{tag}^+)$	$> 200 \text{ MeV}/c$
$p(\pi_{tag}^+)$	$> 1 \text{ GeV}/c$

Table 7.1: The selection imposed on the on the “smeared” generator level LHCb simulation.

tions of this trigger line, it can be seen that there are selections on the π_{tag}^+ , $\Delta m = m(D^{*+}) - m(D^0)$ and $m(D^0)$ that are not here reproducible as the mass

resolution effects should also be modeled and injected in the provided generator level simulation.

It is not an impossible feat, only a time consuming one, therefore in order to accommodate for such missing selections, the 2D distribution p_T, η of the D^0 meson from the generator level simulation after the selections of Table 7.1 is reweighted to the same distribution from the Official Full Simulation. The discrepancy in the D^0 3D momentum distribution between the filtered “smeared” generator and the Official Simulation before this reweighting is shown in Figure 7.1. The variable-bin approach, discussed in Section 5.2.3, has been employed

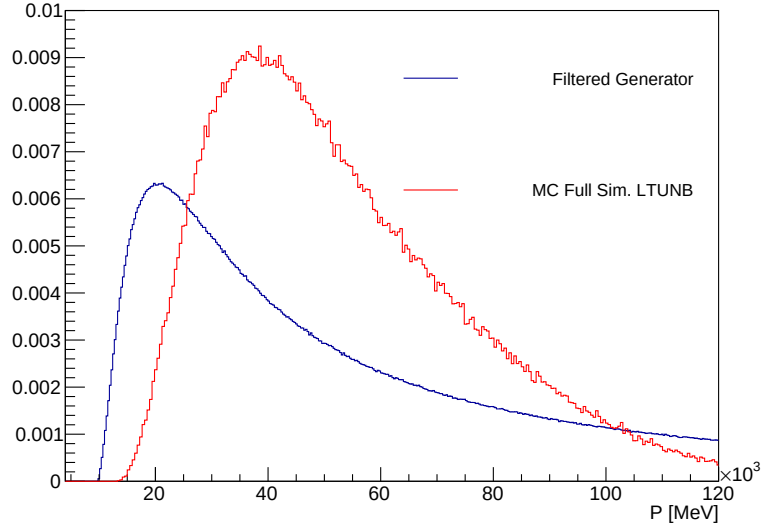


Figure 7.1: The D^0 momentum distribution of the filtered generator level simulation and the Official Simulation. The y axis is in arbitrary units as the distributions have been re-scaled for shape confrontation.

due to the Official Simulation amounting only to 1.1×10^6 events. The efficiency matrix $\mathcal{E}$ is shown in Figure 7.2. The extracted efficiency eigenvector is reported

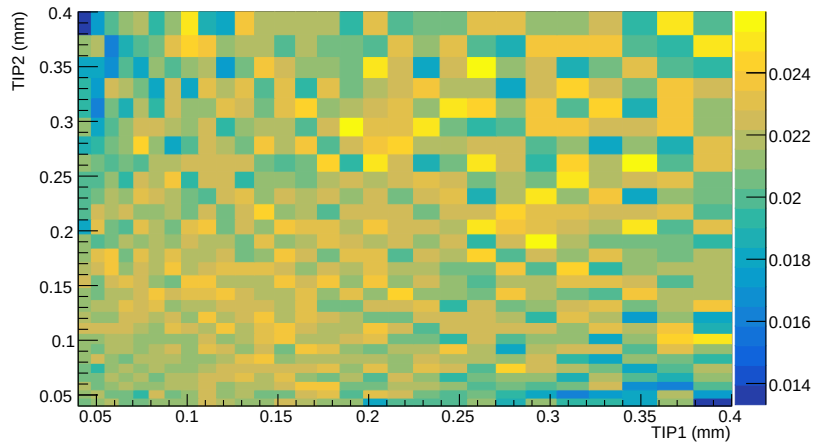


Figure 7.2: The $\mathcal{E}$ matrix from the Official Full Simulation LTUNB sample for $D^0 \rightarrow K^- K^+$.

in Figure 7.3 and the secondary eigenvalues are smaller than 3% of the main one,

indicating good factorizing behavior from the single track efficiencies. Armed with

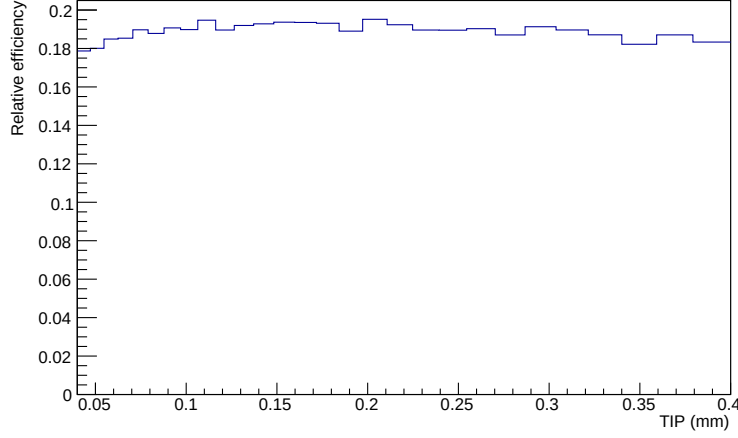


Figure 7.3: The extracted efficiency eigenvector from the Official Full Simulation LTUNB sample $D^0 \rightarrow K^- K^+$.

this result, the absolute D^0 lifetime can now be measured.

Lifetime extraction Reached this point, if the same procedure employed on the custom simulations (ToyMC) were to be followed (Chapter 6), the $\mathcal{A}$ function would be employed in order to partially correct the selection efficiency, then the $\mathcal{C}(\tau)$ function, factorizing with $\mathcal{A}$ by construction, would be extracted by a separate simulation with flat decay time distribution. The product of these two function provides the inverse weight that correct the bias on the decay time distribution caused by the selection (Equation 6.2.1). However, this time a flat decay time generator level simulation is not available, unless one recurs again to custom simulation. Another reason for not following this approach is tied to how the “standard” sample will be handled. This will be explained more in depth in Section 8.3; for now, it suffices to say that building $\mathcal{A}$ and then a factorizing $\mathcal{C}(\tau)$ is not possible for such samples, due to some selections difficult to reproduce offline. As one would want not to revolutionize the methodology too much between LTUNB and “standard” samples, implementing only the strictly necessary changes, here it is proposed another approach. This way the validation achieved on the LTUNB samples still stands when the analysis strategy is applied to the “standard” data sets.

Using the provided generator level simulation a $\mathcal{S}(\tau)$ function is directly computed depending on the decay time from the ratio between the decay time distribution after the selection of Table 7.1 and the reweighting of the $D^0 P_{T,\eta}$ mentioned in the previous paragraph, and the original decay time distribution with no selections whatsoever (Figure 7.4). Now as the ratio is between distribution of *reconstructed* decay times, smearing effects need to be explicitly modeled in the lifetime fit. The smearing template is extracted from the generator level simulation and it is shown in Figure 7.5, along with its modeling through KDE, as it was done in Chapter 4.

Using the convolution of this KDE and an exponential distribution as model, three unbinned likelihood fits are performed in the range $[0.41, 4]$ ps on the raw decay time distribution with no correction (Figure 7.6), on the events reweighted

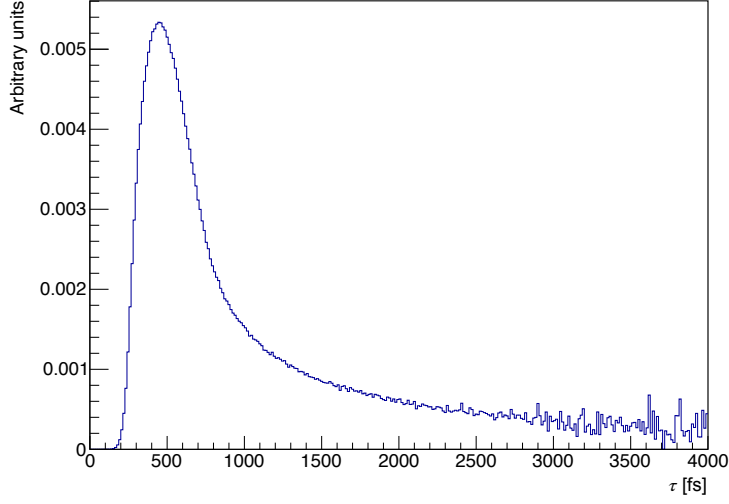


Figure 7.4: The $S(\tau)$ function which corrects the lifetime distribution for the selection efficiency.

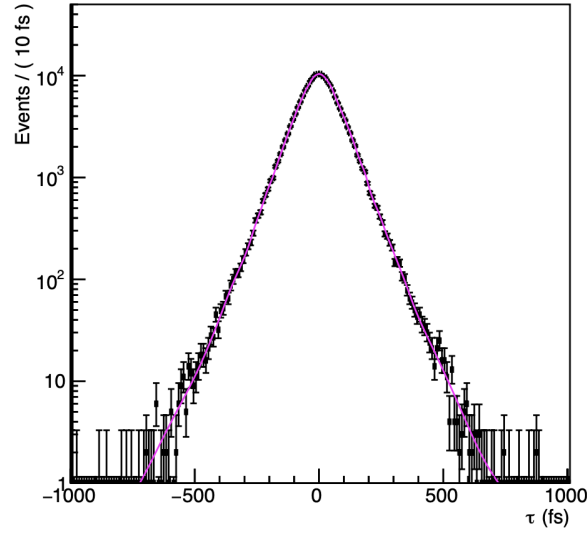


Figure 7.5: The decay time smearing template extracted from the “smeared” generator level simulation. In magenta the KDE.

for the selection efficiency with $w = 1/S$ (Figure 7.7) and finally on the distribution corrected for both the selection and single track efficiencies (Figure 7.8).

The lower bound on the decay time for the fit is chosen both in accordance on what has been done in the most recent LHCb y_{CP} measurement and the fact that the S correction does not correctly work at very low decay times as it can be seen from Figure 7.7.

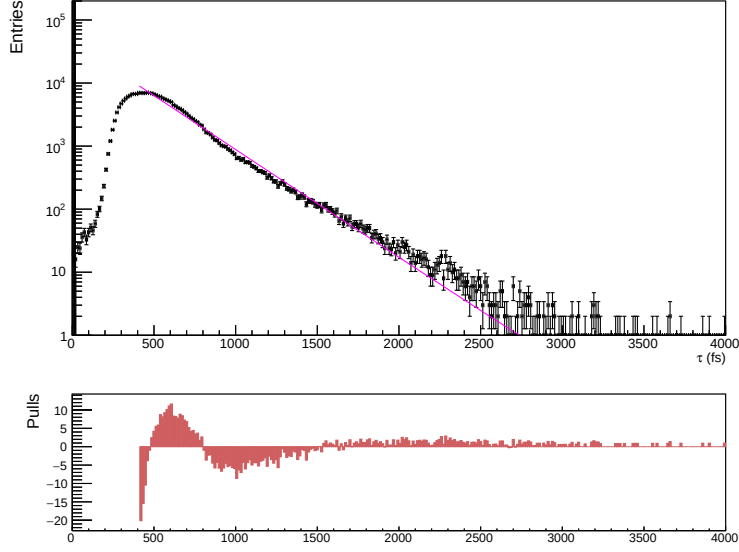


Figure 7.6: The decay time raw distribution from the Official Simulation LTUNB sample $D^0 \rightarrow K^- K^+$ and the fit model described in the text. The sample and the fitted distributions are binned for representational purpose and the pulls distribution for every bin is shown below.

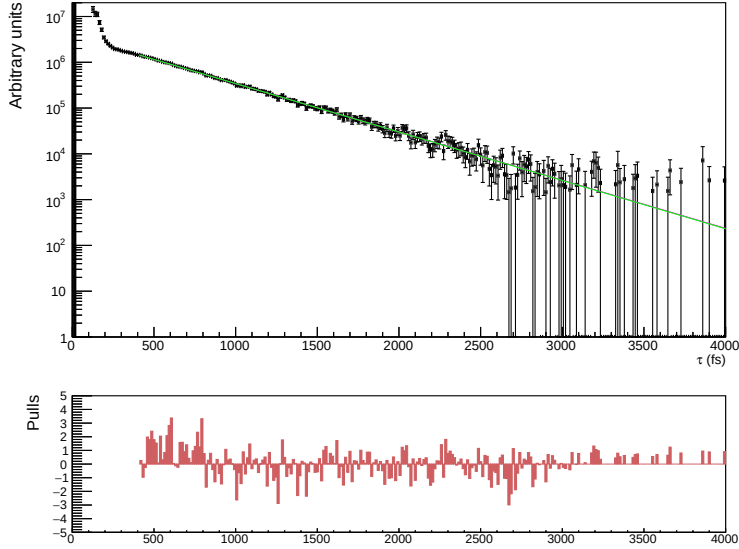


Figure 7.7: The decay time distribution corrected for the selection efficiency from the Official Simulation LTUNB sample $D^0 \rightarrow K^- K^+$ and the fit model described in the text. The sample and the fitted distributions are binned for representational purpose and the pulls distribution for every bin is shown below.

The extracted values are

$$\begin{aligned}\tau_{raw}^{KK} &= (253.18 \pm 0.62) \text{ fs before any reweighting,} \\ \tau_S^{KK} &= (411.1 \pm 1.8) \text{ fs after } 1/s(\tau) \text{ reweighting,} \\ \tau_{S\varepsilon}^{KK} &= (410.6 \pm 1.8) \text{ fs after } 1/s(\tau)\varepsilon_1\varepsilon_2 \text{ reweighting.}\end{aligned}$$

The greatest biasing effects are then due to the imposed selections, as it can be seen from the three fits that most of the correction is carried out by the $S(\tau)$

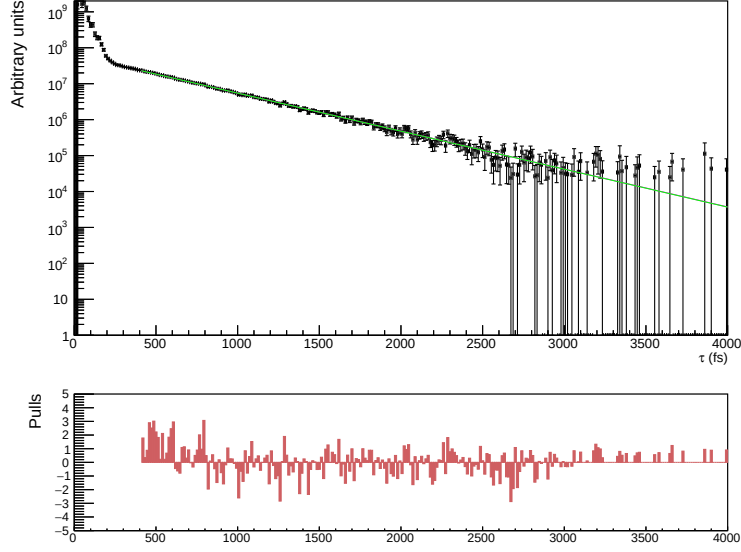


Figure 7.8: The decay time distribution corrected for both the selection and detection efficiency from the Official Simulation LTUNB sample $D^0 \rightarrow K^- K^+$ and the fit model described in the text. The sample and the fitted distributions are binned for representational purpose and the pulls distribution for every bin is shown below.

function. The track efficiency only contributes as a marginal effect. This is in accordance with the efficiency eigenvector extracted (Figure 7.3), which exhibited small variations across the TIP range. Another necessary observation is that a slight tension on the pulls distribution is visible for decay times under $2\tau_{D^0}$ (820fs). It must be remembered that $\mathcal{S}$ struggles at low decay times, as already stated, but also that the smearing template is assumed independent on the true decay time, which is an approximation: either one of these issues, if not both, can explain this tension. However, notwithstanding these pulls distribution's behavior, the extracted value $\tau_{\mathcal{S}\varepsilon}$ is in good agreement with the simulated one within 0.3σ (having started from a raw spectrum that was far off the mark) indicating that the analysis chain works properly. The statistical uncertainty overwhelms the effects of the efficiency correction, which however has shifted the central value of the extracted parameter towards the simulated mean lifetime by 0.5 fs, exhibiting a correct behavior.

7.3.2 $D^0 \rightarrow \pi^- \pi^+$

The exact same procedure adopted in the previous subsection for the $D^0 \rightarrow K^- K^+$ sample, is now applied to the $D^0 \rightarrow \pi^- \pi^+$ decay. We used the same generated D^0 events of the KK simulation, and re-simulated the decay into the $\pi\pi$ mode. This was accomplished with the same principle of the kinematic matching (Chapter 3) meaning that the two kaons are brought in the D^0 centre-of-mass frame, and maintaining the θ^* decay angle in such frame their mass values are switched to the one of the pions, the momenta recomputed and then they are boosted back in the laboratory frame, thus obtaining a generator level simulation of $D^0 \rightarrow \pi^- \pi^+$.

Efficiency extraction The efficiency matrix $\mathcal{E}$ (Figure 7.9) is extracted and the efficiency eigenvalue (Figure 7.10) computed from it, with the secondary eigen-

values not larger than 2% the main one. From the extracted efficiency function,

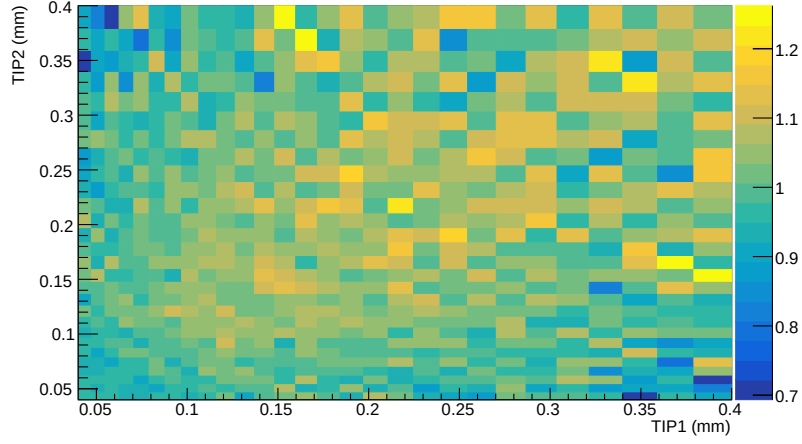


Figure 7.9: The $\mathcal{E}$ matrix from the Official Full Simulation LTUNB sample for $D^0 \rightarrow \pi^- \pi^+$.

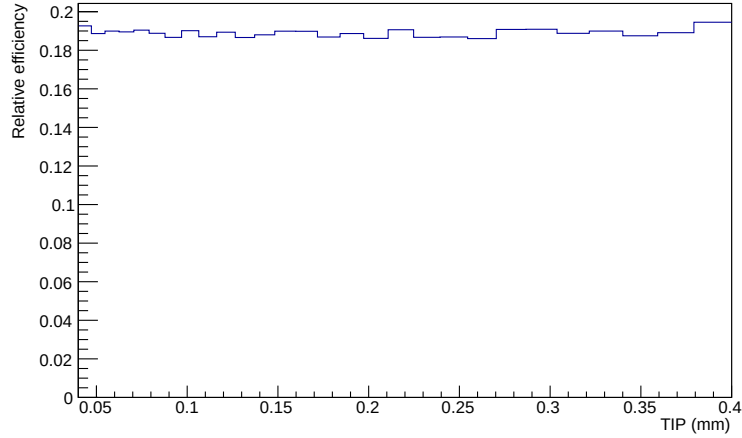


Figure 7.10: The extracted efficiency eigenvector from the Official Full Simulation LTUNB sample for $D^0 \rightarrow \pi^- \pi^+$.

which appears almost flat then it is expected that its impact on the lifetime correction will be smaller than the one seen in $D^0 \rightarrow K^- K^+$.

Lifetime extraction After extracting the $S(\tau)$ function from the $D^0 \rightarrow \pi^- \pi^+$ generator level simulation, three unbinned maximum likelihood fit are performed in the same fit range on the Official Simulation 2018 *MagUp* sample, before any correction (Figure 7.11), after the selection efficiency correction (Figure 7.12) and after detection and selection efficiency correction (Figure 7.13), using as model a simple exponential convoluted with the KDE smearing template extracted again from the generator level simulation.

In this case, the extracted values are

$$\begin{aligned}\tau_{raw}^{\pi\pi} &= (227.04 \pm 0.62) \text{ fs before any reweighting,} \\ \tau_s^{\pi\pi} &= (412.1 \pm 2.2) \text{ fs after } 1/s(\tau) \text{ reweighting,} \\ \tau_{s\varepsilon}^{\pi\pi} &= (412.5 \pm 2.2) \text{ fs after } 1/s(\tau)_{\varepsilon_1 \varepsilon_2} \text{ reweighting,}\end{aligned}$$

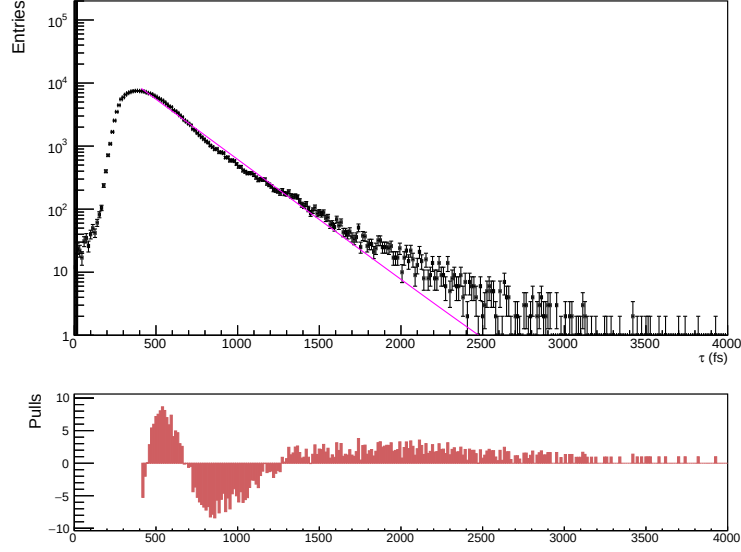


Figure 7.11: The decay time raw distribution from the Official Simulation LTUNB sample $D^0 \rightarrow \pi^- \pi^+$ and the fit model described in the text.

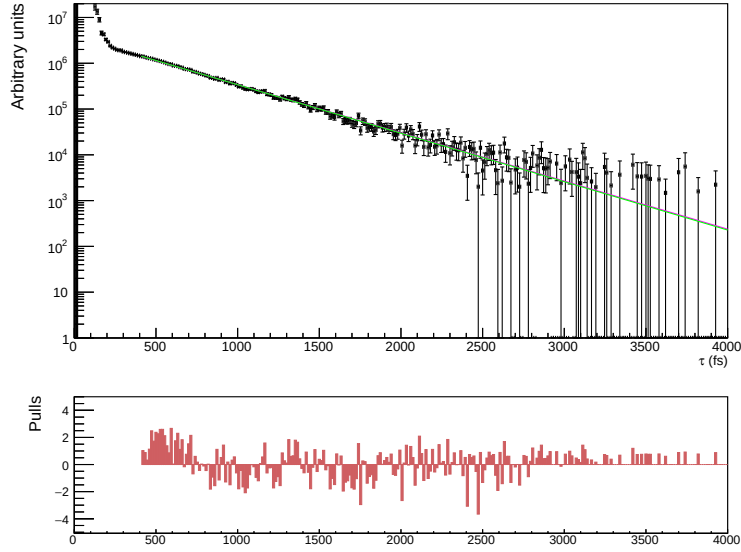


Figure 7.12: The decay time distribution corrected for the selection efficiency from the Official Simulation LTUNB sample $D^0 \rightarrow \pi^- \pi^+$ and the fit model described in the text.

with τ_{se} in agreement with the simulated value of $\tau = 410.1$ fs within 1.1σ . As it was expected from the previous paragraph, the efficiency correction has little effect indeed, however it confirms that the algorithm works as expected. From the pull distribution of the fits it is noticed the same tension below $2\tau_{D^0}$. This will be kept in mind when moving to real data - it suggests imposing a cautious low decay time bound at such threshold when evaluating the results.

7.4 Real Data from the LTUNB trigger

Instead of focusing on $D^0 \rightarrow K^- K^+$ process before and then analysing $D^0 \rightarrow \pi^- \pi^+$, both samples will be displayed in parallel, first presenting the efficiency extraction

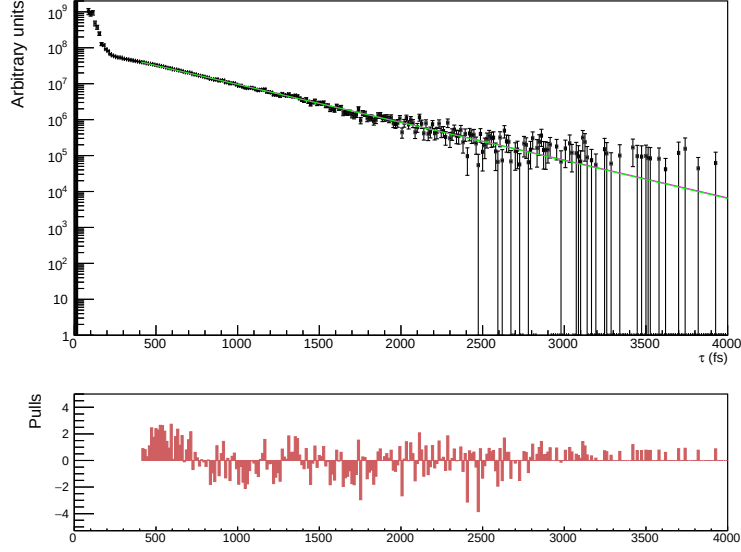


Figure 7.13: The decay time distribution corrected for both the selection and detection efficiency from the Official Simulation LTUNB sample $D^0 \rightarrow \pi^- \pi^+$ and the fit model described in the text.

and then the lifetime measurement, which obviously will be blinded. This allows for an easier comparison between the two samples at each step.

Due to the generator level simulation being available only for the 2018 *MagUp* conditions, the analysis will be restricted to the same year and magnetic field orientation, in other words of the 6 fb^{-1} of Run 2 data taking, only 1 fb^{-1} will be analysed.

Efficiency extraction The `Dst_LOGlobal_TIS` flag is required for the reasons explained in Subsection 3.2, with a retain rate of $\sim 83\%$ for both KK and $\pi\pi$ samples. To extract efficiencies on real data, background contamination must be accounted for. Selections on $\Delta m = m(D^{*+}) - m(D^0)$ and $m(D^0)$ in order to suppress this background have been employed, imposing $|\Delta m - m_\pi| < 1.5 \text{ MeV}/c^2$, where m_π is the nominal mass of the charged pion, and $|m(D^0) - m_{D^0}| < 20 \text{ MeV}/c^2$ where m_{D^0} is the nominal mass of the D^0 meson. These selections result in a combined relative retention rate of $\sim 40\%$ for the $D^0 \rightarrow K^- K^+$ sample and $\sim 18\%$ for the $D^0 \rightarrow \pi^- \pi^+$ sample. An ulterior selection $\log(\chi^2_{IP}(D^0)) < 3$ is employed in order to reduce the contribution of secondary decays [37] which halves the sample size available previous to performing this cut.

Due to the background contamination (either residual combinatorial, secondary decays or peaking background from mis-reconstructed D^*), it was necessary to limit the efficiency extraction to the domain of $TIP \in [100, 200] \mu\text{m}$, as a wider range exhibits shapes suggesting correlation between the tracks were visible. This is a very tight cut with a 4% retention rate for KK and 2.5% on $\pi\pi$. Much more elegant approaches, as sideband subtraction of combinatorial background, can be implemented when the final measurement will be performed in order to avoid this large drop in signal yields - however, what is searched here is a validation of the technique, to understand whether the proposed methods are a viable pathway for high precision measurement of y_{CP} in the upcoming runs. For this purpose, even these very low retention rates are acceptable. The resulting

signal yields are 5×10^5 events for the KK channel and 2.8×10^5 events for the $\pi\pi$ sample.

In Figures 7.14 and 7.15 the efficiency matrices $\mathcal{E}$ are shown respectively for the KK and $\pi\pi$ samples.

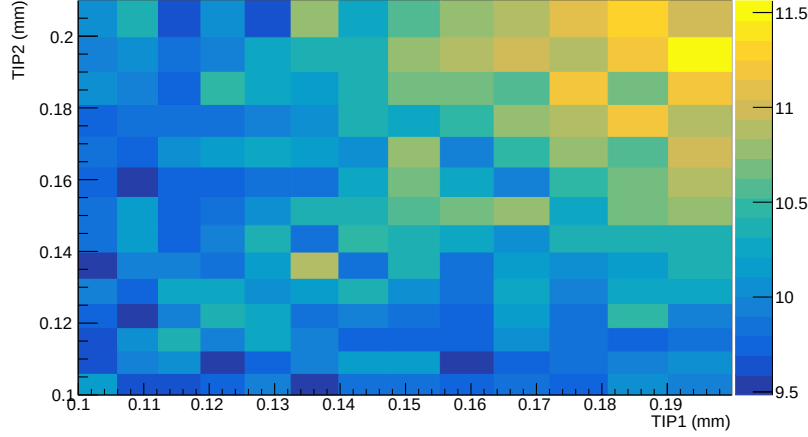


Figure 7.14: The $\mathcal{E}$ matrix from the real data 2018 MagUp LTUNB sample for $D^0 \rightarrow K^- K^+$.

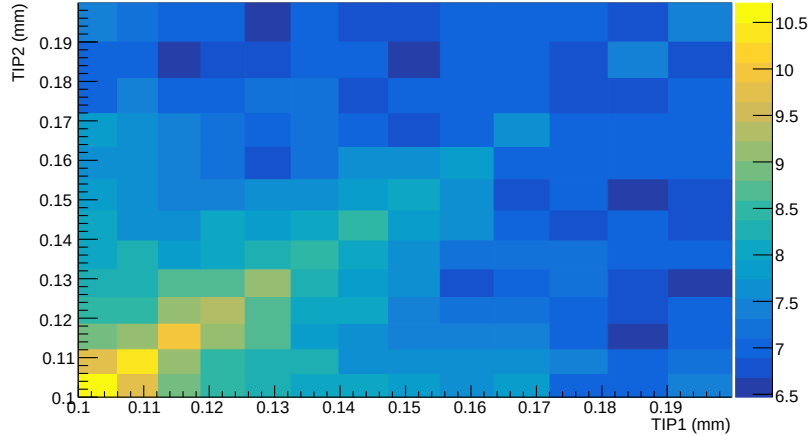


Figure 7.15: The $\mathcal{E}$ matrix from the real data 2018 MagUp LTUNB sample for $D^0 \rightarrow \pi^- \pi^+$.

The extracted efficiencies can be seen superimposed in Figure 7.16. It is useful to compare these extracted efficiencies with the relative efficiencies w.r.t. the $D^0 \rightarrow K^- \pi^+$ channel extracted in the 2019 LHCb y_{CP} measurement [36] shown in Figure 7.17. Even if the efficiencies of the LHCb paper are relative to the $K\pi$ process and the ones extracted in this section are absolute (w.r.t. the process), the relative efficiencies between KK and $\pi\pi$ can be deduced from the comparison of the two plots. This comparison shows that our results qualitatively agree with past LHCb results that were obtained independently: the opposite curve trend between KK and $\pi\pi$ is found, and the effects are of similar size.

Lifetime extraction In case of the decay time distribution, the combinatorial background has been taken out via sideband subtraction. Imposing the selection

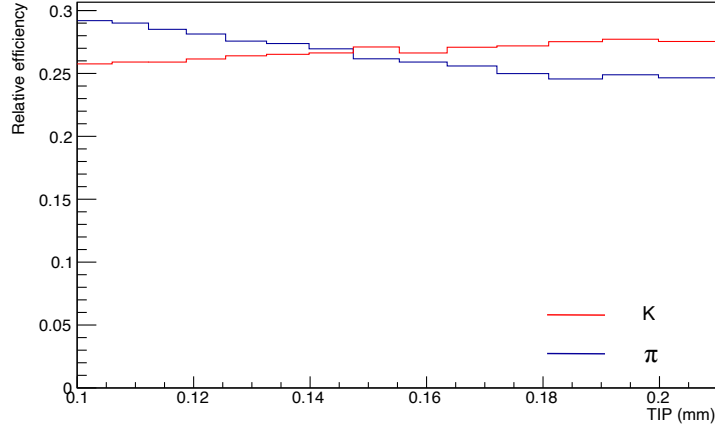


Figure 7.16: The extracted efficiency eigenvector from the real data 2018 MagUp LTUNB sample for $D^0 \rightarrow K^- K^+$ in red and $D^0 \rightarrow \pi^- \pi^+$ in blue.

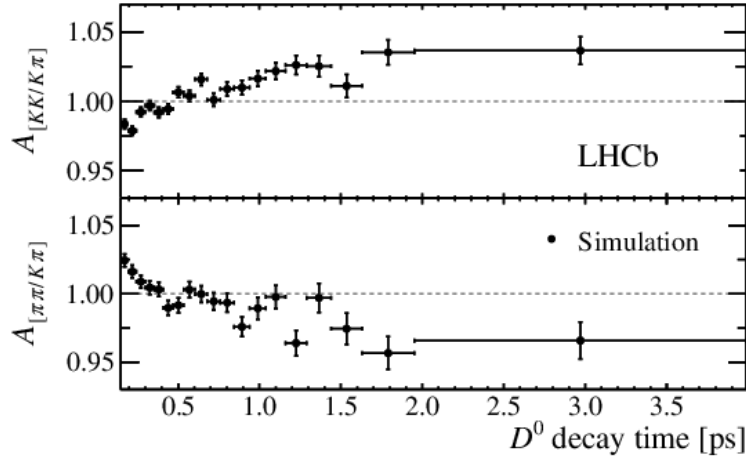


Figure 7.17: Ratio of decay-time efficiencies from simulation for (top) $D^0 \rightarrow K^- K^+$ over $D^0 \rightarrow K^- \pi^+$ decays and (bottom) $D^0 \rightarrow \pi^- \pi^+$ over $D^0 \rightarrow K^- \pi^+$ decays. From [36].

$|\Delta m - m_\pi| < 1.5 \text{ MeV}/c^2$, the D^0 mass distribution has been fitted with the following model

$$\mathcal{F}(m; \vec{s}) = f_{sig.} [f_1 \mathcal{G}(m; \mu, \sigma_1) + (1 - f_1) \mathcal{G}(m; \mu, \sigma_2)] + (1 - f_{sig.}) \mathcal{Exp}(m; \lambda), \quad (7.4.1)$$

where $\vec{s}$ is the vector of parameters, $\mathcal{G}_1$, $\mathcal{G}_2$ are two Gaussian distribution with same mean and different σ modeling the signal, and $\mathcal{Exp}$ is an exponential distribution modeling the background. Such fit is shown in Figure 7.18 for the KK channel and in Figure 7.19 for $\pi\pi$. The signal region is defined between $[\mu - 2\sigma_1; \mu + 2\sigma_1] \text{ GeV}/c^2$, where σ_1 is the smaller of the two sigmas, and it is indicated in green. The sidebands are bounded between $[1808; \mu - 30] \text{ GeV}/c^2$ and $[\mu + 30; 1920] \text{ GeV}/c^2$.

The decay time distributions are extracted from the sideband regions (Figure

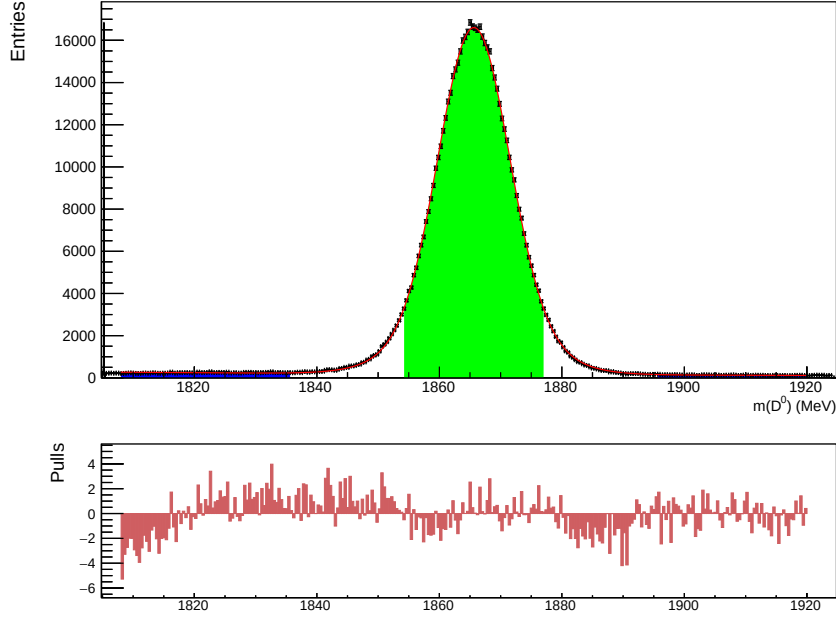


Figure 7.18: The D^0 mass fit for the KK channel, with the signal region in green and the sidebands in blue.

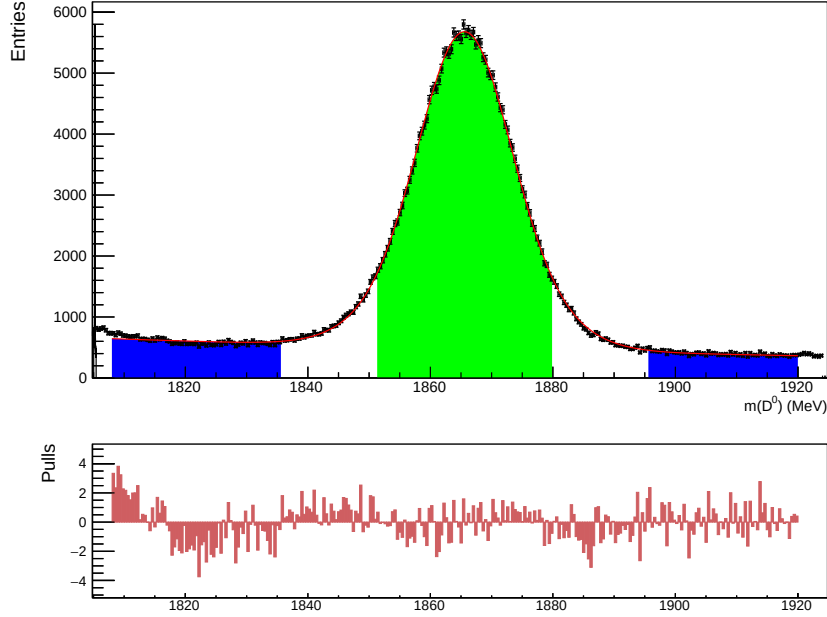


Figure 7.19: The D^0 mass fit for the $\pi\pi$ channel, with the signal region in green and the sidebands in blue.

7.20 reporting the $\pi\pi$ channel) and reweighted for

$$\frac{\int_{[Sig.]} \mathcal{E}xp(m; \hat{\lambda}) dm}{\int_{[Side]} \mathcal{F}(m; \hat{s}) dm}, \quad (7.4.2)$$

where $[Sig.]$ stands for the signal region and $[Side]$ the sidebands. Then such weighted distributions are subtracted from the decay time distributions of the samples selected in the signal regions just defined.

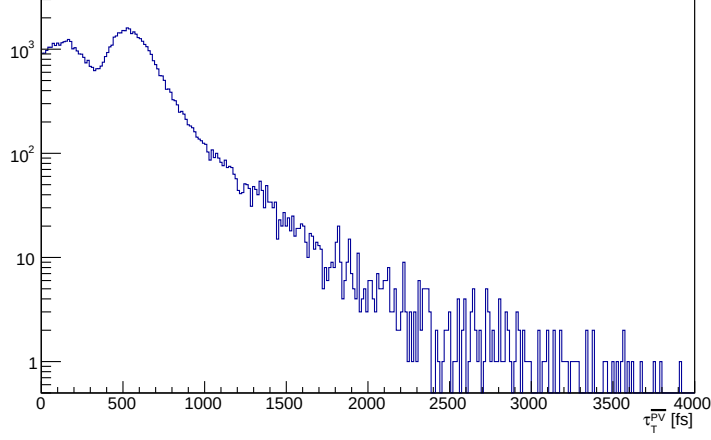


Figure 7.20: The decay time distribution of the events in the sideband region for the $D^0 \rightarrow \pi^- \pi^+$ sample.

Then the selection efficiency $\mathcal{S}(\tau)$ function is extracted from the generator level simulation by the decay time ratio between the filtered simulation and the unfiltered one (Figure 7.21).

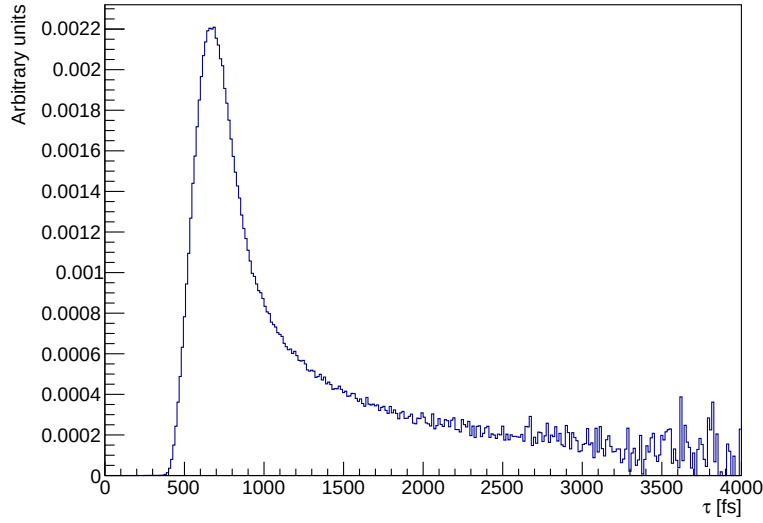


Figure 7.21: The $\mathcal{S}(\tau)$ selection efficiency function for the KK channel.

Finally, the decay time distributions, with the subtracted combinatorial background component, are fitted with a convolution of a simple exponential and the KDE smearing template extracted from the generator level simulation, in various fit ranges, before any efficiency correction, after the $\mathcal{S}(\tau)$ correction and after $\mathcal{S}(\tau)\varepsilon_1\varepsilon_2$ correction. The τ parameter of the exponential component is blinded by a shift in fs sampled from a uniform distribution $U[-25, 25]$, which is the same across all fits. In Figures 7.22, 7.23 and 7.24 respectively each one of the mentioned distribution with their fit and the pulls distribution below are shown for the process $D^0 \rightarrow K^- K^+$. The fits are performed with unbinned likelihood maximization - the binning is used just for display purpose. The fit range shown is

$[0.615, 4]\text{ps}$, corresponding to $1.5 - 9.8\tau_{D^0}$. The lower bound is chosen due evident discrepancy between reweighted data and fit model shown by the pull distribution nearing the decay time value of 615 fs.

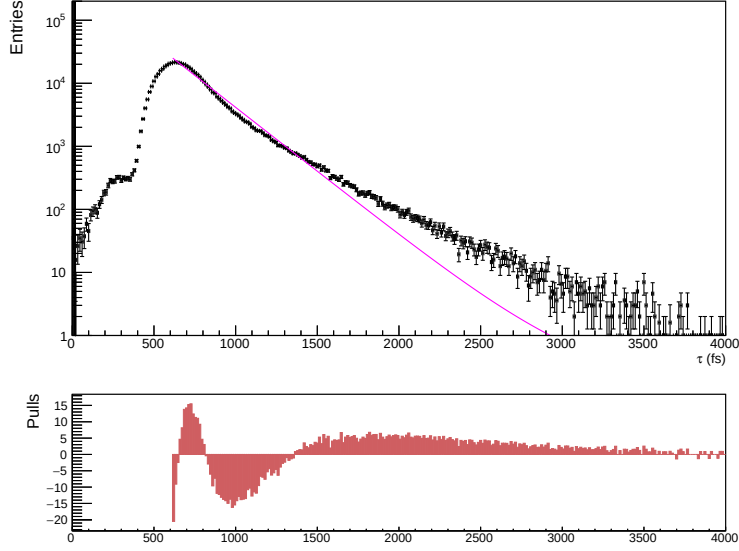


Figure 7.22: The decay time raw distribution from the real data 2018 MagUp LTUNB sample $D^0 \rightarrow K^- K^+$ and the fit model described in the text.

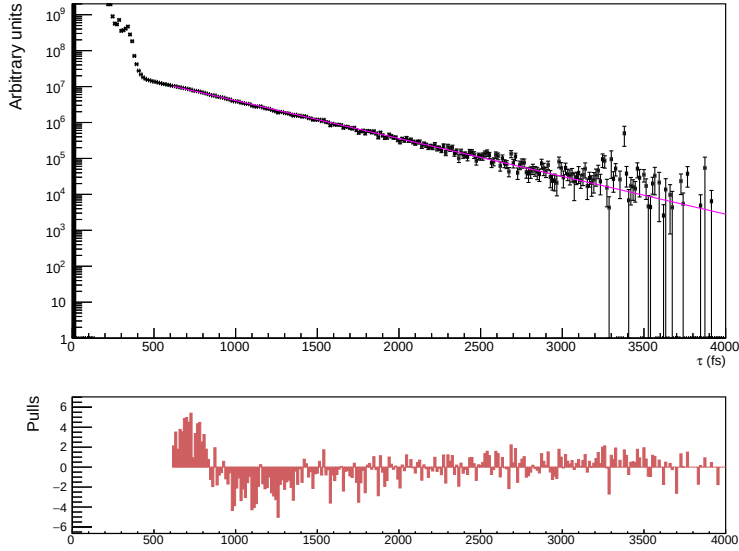


Figure 7.23: The decay time distribution corrected for the selection efficiency from the real data 2018 MagUp LTUNB sample $D^0 \rightarrow K^- K^+$ and the fit model described in the text.

The measured values are

$$\begin{aligned}\tau_{raw}^{KK} &= (152.59 \pm 0.43) \text{ fs before any reweighting,} \\ \tau_s^{KK} &= (392.1 \pm 1.9) \text{ fs after } 1/s(\tau) \text{ reweighting,} \\ \tau_{s\varepsilon}^{KK} &= (392.1 \pm 1.9) \text{ fs after } 1/s(\tau)_{\varepsilon_1 \varepsilon_2} \text{ reweighting.}\end{aligned}$$

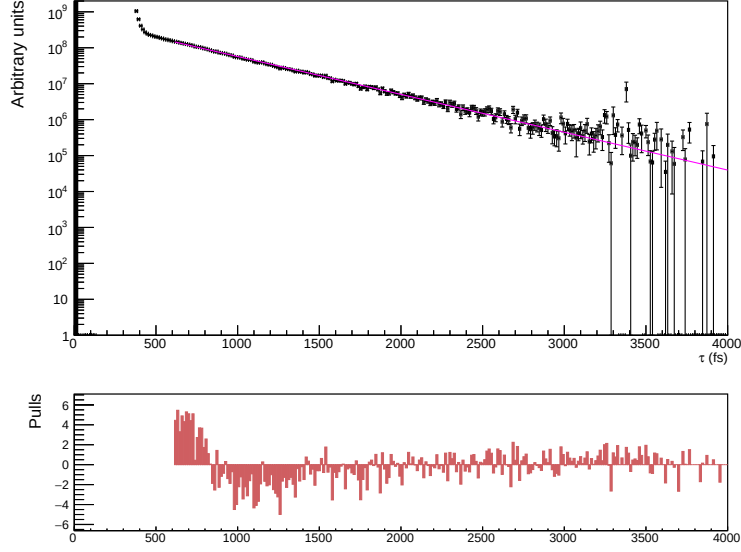


Figure 7.24: The decay time distribution corrected for both the selection and detection efficiency from the real data 2018 MagUp LTUNB sample $D^0 \rightarrow K^- K^+$ and the fit model described in the text.

From these figures appears evident how the detection efficiency effects still have secondary relevance against the selection efficiency, in this fit range. As a matter of fact the efficiency correction seems to produce no effect. Similar results have been achieved on the $D^0 \rightarrow \pi^- \pi^+$ sample, and for a more comprehensible visualization of the extracted lifetime, these are shown alongside the KK channel in various fit ranges starting with the lower bound 615 fs and then progressively raise it. The measured mean lifetimes after only the selection efficiency correction are shown in Figure 7.25, while the results after applying also the detection efficiency correction be seen in Figure 7.26. From Figure 7.26 the good agreement between $\tau_{D^0}^{KK}$ and

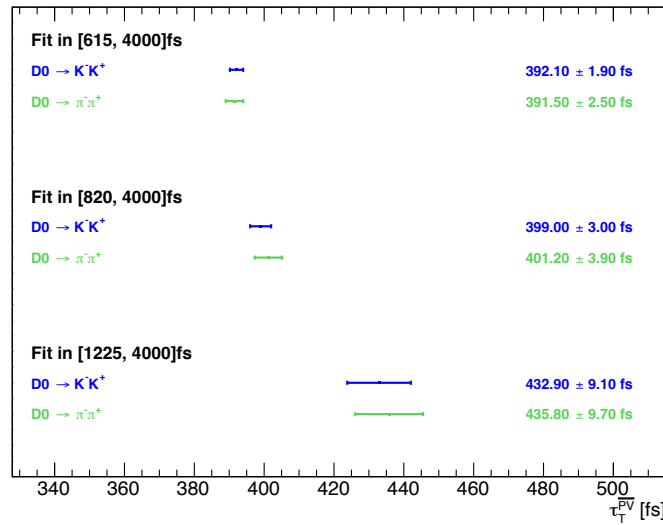


Figure 7.25: Comparison between the mean lifetime of the D^0 meson extracted from the $D^0 \rightarrow K^- K^+$ sample (blue) and $D^0 \rightarrow \pi^- \pi^+$ (green), after only the selection efficiency correction.

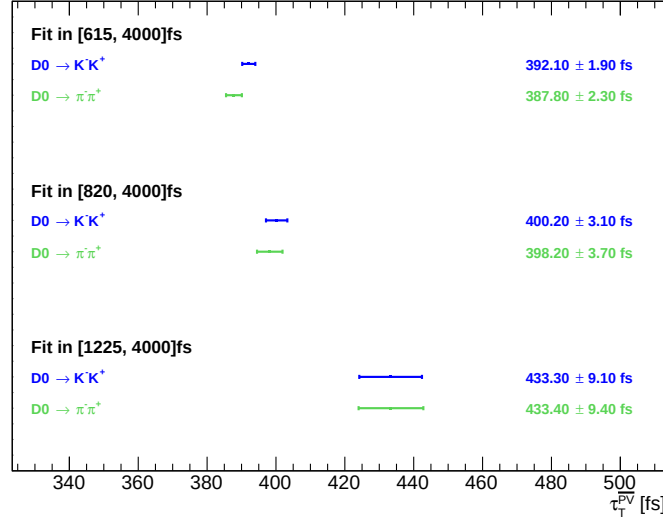


Figure 7.26: Comparison between the mean lifetime of the D^0 meson extracted from the $D^0 \rightarrow K^- K^+$ sample (blue) and $D^0 \rightarrow \pi^- \pi^+$ (green), after both the selection and detection efficiency correction.

$\tau_{D^0}^{\pi\pi}$ is evident at every range. This is a successful achievement for the method that this way proves its reliability, obtaining its validation on real data. It can be seen how at higher fit ranges the measurements shift to higher values: while a cut on $\log(\chi_{IP}^2(D^0))$ was imposed, contamination from remaining secondary decays still biases the measurement. In fact defining $\Delta\tau_{fit}^{range}$ the difference between the [1.225, 4]ps time fit range result and the one obtained from the [0.615, 4]ps fit range, it can be seen how $\Delta\tau_{fit}^{range}$ varies by modifying the threshold of the $\chi_{IP}^2(D^0)$ selection the results (Table 7.2).

Upper $\log(\chi_{IP}^2(D^0))$ threshold	$\Delta\tau_{fit}^{range}(D^0 \rightarrow K^- K^+)$	$\Delta\tau_{fit}^{range}(D^0 \rightarrow \pi^- \pi^+)$
4.00	(45 ± 10) fs	(50 ± 12) fs
3.50	(44 ± 10) fs	(44 ± 10) fs
3.00	(41.1 ± 9.4) fs	(46 ± 10) fs
2.50	(37.2 ± 7.7) fs	(34.7 ± 8.4) fs
2.00	(35.1 ± 7.7) fs	(28.1 ± 7.7) fs
1.50	(35.9 ± 8.5) fs	(25.5 ± 7.8) fs

Table 7.2: The $\Delta\tau_{fit}^{range}$ observable defined in the text at different $\log(\chi_{IP}^2(D^0))$ upper thresholds for secondary decays suppression.

By restricting this selection in fact the gap between fit results with lower bound at high decay times and low decay times, shrinks by a factor 25% for the KK channel and 50% for the $\pi\pi$ one, suggesting that indeed secondary decays are plausibly the cause.

The test observable $\tau_{D^0}^{KK} - \tau_{D^0}^{\pi\pi}$ can be evaluated and from the [0.615, 4]ps range fit, after the single track efficiency correction, is found

$$\tau_{D^0}^{KK} - \tau_{D^0}^{\pi\pi} = (4.3 \pm 3.0) \text{ fs}$$

in good agreement with $\tau_{D^0}^{KK} - \tau_{D^0}^{\pi\pi} = 0$ within 1.4σ . This results means that a statistical precision of 0.7% the nominal D^0 mean lifetime has been achieved with 1 fb^{-1} of integrated luminosity on the difference of mean lifetimes, and systematic effects biasing the measurement appears to be smaller than the statistical precision. With the precision on the extracted efficiency scaling with the signal yields, given that the method is data-driven, it is expected to attain a precision of 0.3% with the whole Run 2 sample, with no systematic biases. If on the other hand absolute lifetime measurements are to be carried out then a precision comparable with the one of Belle II is attainable already with the Run 2 data.

7.4.1 The measurement of y_{CP}^{CC}

In the previous decay time fits, the pulls distribution hinted that residual bias effects still influence the measurement of absolute lifetime. These effects mainly imputable to the accuracy of the $\mathcal{S}$ function and background contamination can be dealt with by further research and additional time for working on these aspects, much more that what a master thesis is granted. When these remaining issues will have been overcome, then it is plausible that high precision measurement of *absolute* lifetimes will be manageable to carry out. However, for what concerns this work, the target is a valid strategy for future y_{CP} measurements, while absolute lifetimes were just a mean to understand the strengths and the weaknesses of the employed methods. What really matters is the ratio of decay time distributions from which y_{CP} can be inferred (Equation 3.1.2). In such ratio this lingering imperfections of the new methodology, due to $\mathcal{S}$ and residual background, cancel out for the most part, leaving the ratio of the detection efficiency, whose retrieval has been perfected, between KK and $\pi\pi$ channels as the main focus for correctly determining y_{CP} . Therefore, in order to test if the developed method works correctly on the y_{CP} parameter extracted from the ratio, the same test variable y_{CP}^{CC} defined in Equation 3.1.3 is here measured, and its agreement with the expected result of zero evaluated.

So, from the decay time binned distributions of the KK and $\pi\pi$ sample, their bin-à-bin ratio is computed and fitted with a simple exponential shape, before any correction (Figure 7.27), after reweighting for $1/\mathcal{S}(\tau)$ (Figure 7.28) and after the final correction accounting for the single track efficiency (Figure 7.29).

The extracted values y_{CP}^{CC} values are

$$\begin{aligned} y_{CP}^{CC} &= (-16.658 \pm 0.092) \times 10^{-2} \text{ before any reweighting,} \\ y_{CP}^{CC} &= (-10.4 \pm 1.1) \times 10^{-3} \text{ after } 1/\mathcal{S}(\tau) \text{ reweighting,} \\ y_{CP}^{CC} &= (-0.6 \pm 1.1) \times 10^{-3} \text{ after } 1/\mathcal{S}(\tau)_{\varepsilon_1 \varepsilon_2} \text{ reweighting.} \end{aligned}$$

This result is of particular significance. It gives a direct demonstration on the y_{CP} control check variable of the algorithm validity, without going through absolute lifetime measurements. Initially, y_{CP}^{CC} after only the $\mathcal{S}(\tau)$ correction is definitely in strong disagreement with the expected value of zero, being $\sim 10\sigma$ apart; the single track efficiency correction, obtained from a completely data-driven method, turns out to bring it in precise agreement with zero, within $\sim 0.5\sigma$. From the figures it can be seen how the ratio function get progressively straightened.

Moreover, when the result of the same test observable retrieved from the last

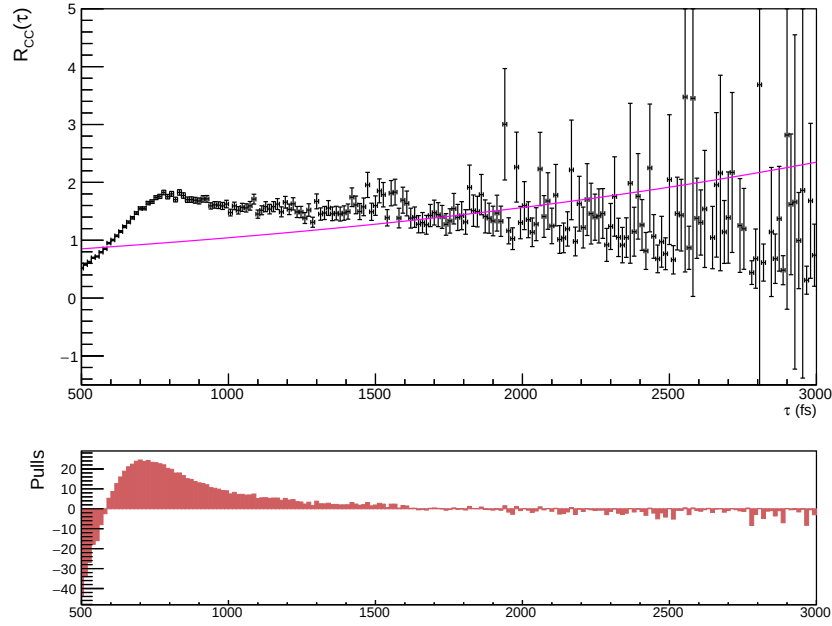


Figure 7.27: The ratio of the decay time raw distributions from the real data 2018 MagUp LTUNB sample $D^0 \rightarrow K^- K^+$ over $D^0 \rightarrow \pi^- \pi^+$ sample, and the fit model described in the text.

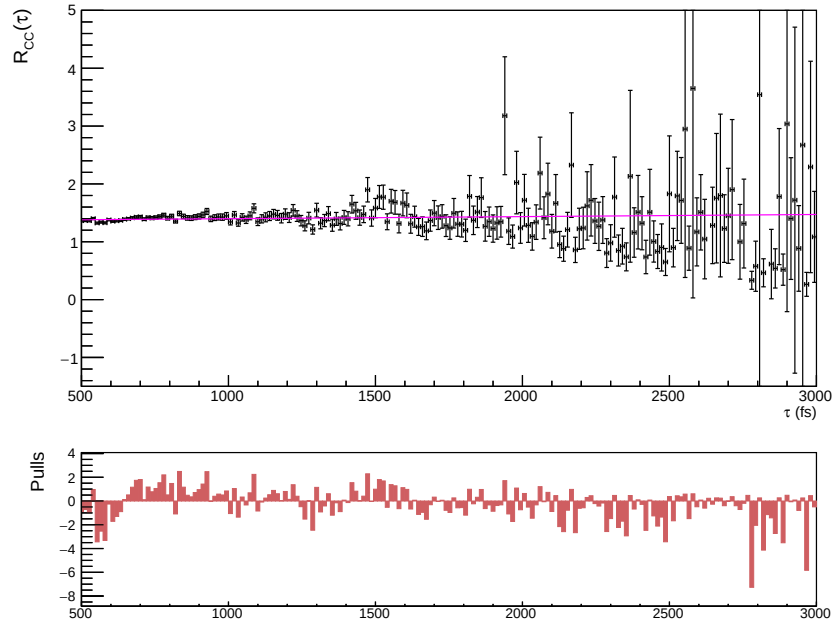


Figure 7.28: The ratio of the decay time distributions corrected for the selection efficiency from the real data 2018 MagUp LTUNB sample $D^0 \rightarrow K^- K^+$ over $D^0 \rightarrow \pi^- \pi^+$ sample, and the fit model described in the text.

LHCb publication

$$y_{CP}^{CC}{}_{pub.} = (-1.15 \pm 1.30) \times 10^{-3}$$

using the same 2018 MagUp sample (Figure 7.30) is taken in consideration, it can be seen that compatible values are found and even better precision is achieved in

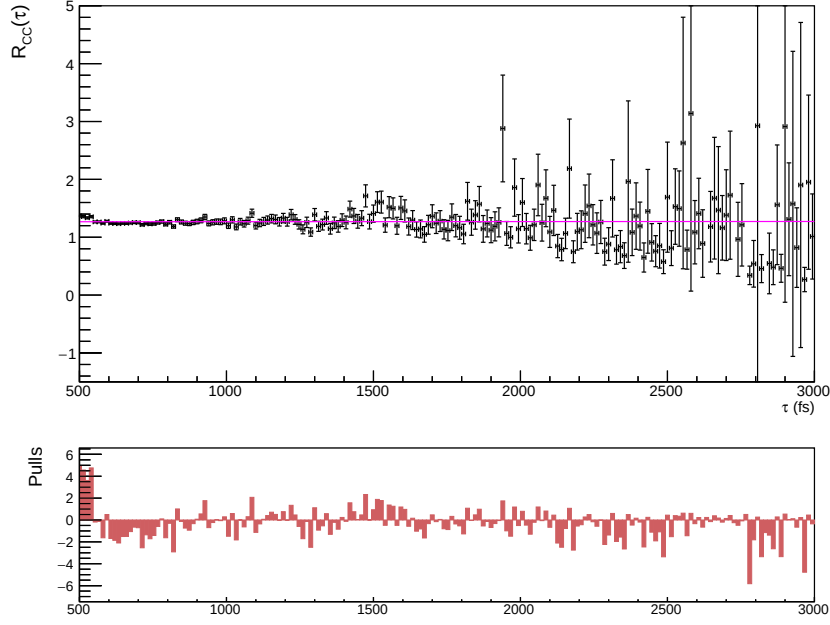


Figure 7.29: The ratio of the decay time distribution corrected for both the selection and detection efficiency from the real data 2018 MagUp LTUNB sample $D^0 \rightarrow K^- K^+$ over $D^0 \rightarrow \pi^- \pi^+$ sample, and the fit model described in the text.

this thesis, having measured

$$y_{CP}^{CC} = (-0.6 \pm 1.1) \times 10^{-3},$$

meaning that the methodology discussed in this work can reproduce the same results recently published by LHCb at the same level of precision; and in a completely data-driven way.

Having reached this objective, in the next chapter we will focus on going further beyond, towards a further improved measurement.

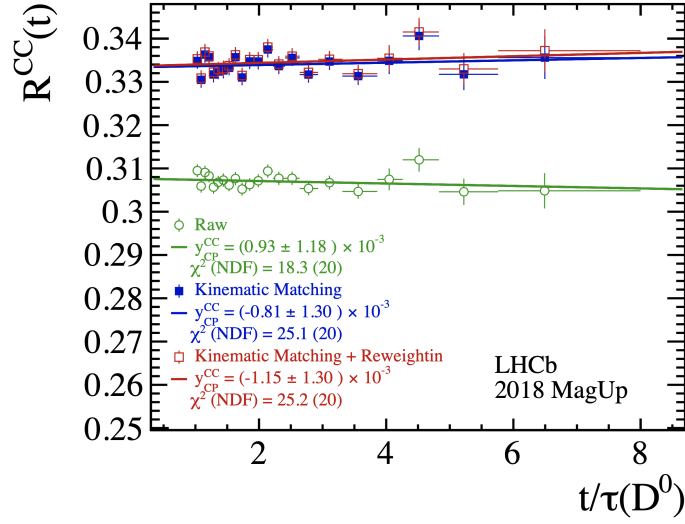


Figure 7.30: The ratio of the decay time distribution from the real data 2018 MagUp LTUNB sample $D^0 \rightarrow K^- K^+$ over $D^0 \rightarrow \pi^- \pi^+$ sample, published in the most recent y_{CP} measurement by LHCb [37].

CHAPTER

8

TOWARDS AN IMPROVED y_{CP} MEASUREMENT

It must be remembered that the purpose of this thesis is securing an analysis methodology for y_{CP} for the upcoming runs. It has been already stated in Section 3.4 that the LTUNB trigger line will be no longer available. Applying the procedure hitherto described on such sample, while providing further validation, does not prove that it is capable of working on biased trigger lines. Further tests and analysis need to be carried on less restrictive data samples. They however are not free from other issues, with the `H1t2CharmHadDstp2D0Pip_D02xxTurbo` line performing selections on variables difficult to simulate, highly lifetime-biasing and also correlating the track efficiencies. Therefore, leaving the safe haven of lifetime-unbiased trigger lines and landing on the far less safe shores of time-biasing ones is anything but trivial, and some aspects must be discussed before moving on to work with those data sets.

8.1 Issues with the “standard” charm trigger line

Among the selections of the `H1t2CharmHadDstp2D0Pip_D02xxTurbo` line (Table 3.1) there are a few that are cause for concern, due to their complexity in being simulated with good accuracy, as mentioned in Subsection 3.2: the χ^2_{IP} of the single track, the $\chi^2_{FD}(D^0)$, the χ^2/ndf of the vertices fit and the χ^2/ndf of the track fit. Among these, however, χ^2_{IP} and χ^2/ndf of the track fit are selections applied to individual tracks, that factorize. Here the power of the presented efficiency extraction method manifests itself: even if some selections efficiencies cannot be accurately modeled through simulation, then as long as these factorize between the tracks, they can be recovered with the data-driven technique.

It then remains the issue concerning $\chi^2_{FD}(D^0)$ and the χ^2/ndf of the vertices fit. The latter is only a false concern as its threshold is loose enough that its effect is negligible on signal events, the former instead remains a hurdle, as it correlates

the track efficiencies strongly.

Therefore, it is researched whether a further selection on individual tracks can absorb the effects of the $\chi_{FD}^2(D^0) > 25$. The procedure consists in taking the LTUNB Monte Carlo Full Simulation sample for the year 2018 with magnetic field of the detector oriented upwards (*MagUp*), simulating the decay $D^0 \rightarrow K^+ K^-$, and observing the $\chi_{FD}^2(D^0)$ distribution imposing various selections. The studied selections are:

- the **Hlt10neTrackMVA** trigger line (Equation 3.2.1);
- $\chi_{IP}^2(h^\pm) > 12$, thus tightening the already present selection on the “standard” sample which is $\chi_{IP}^2(h^\pm) > 4$;
- $IP(h^\pm) > 60 \mu\text{m}$ which is a possible threshold for the $IP(h^\pm)$ selection to be implemented in the Run 3 low bias trigger line for such decay.

Such distributions are shown in Figure 8.1, from which it can be deduced that $IP(h^\pm) > 60 \mu\text{m}$ does not absorb $\chi_{FD}^2(D^0) > 25$ and therefore cannot be employed for making the Run 2 “standard” sample available to the technique discussed in this thesis, in order to perform the desired tests and analysis. Between $\chi_{IP}^2(h^\pm) > 12$ and the **Hlt10neTrackMVA** trigger line the former is to be preferred as it has higher efficiency (Table 8.1).

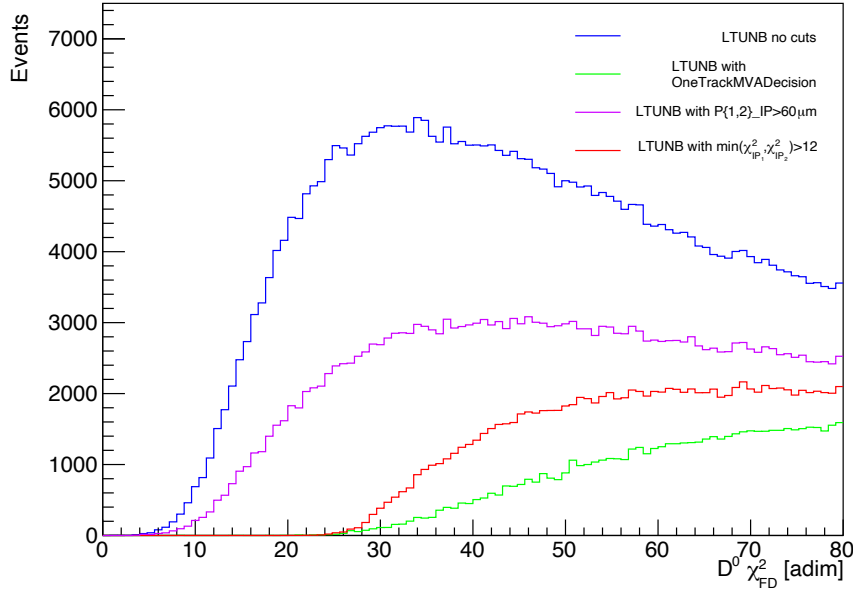


Figure 8.1: The 2018Up LTUNB Official Monte Carlo $\chi_{FD}^2(D^0)$ distributions with different selections.

In order to find assurance that $\chi_{IP}^2(h^\pm) > 12$ really absorbs $\chi_{FD}^2(D^0) > 25$ not only on the prompt decay $D^0 \rightarrow K^+ K^-$ simulation, but also on the real data, the same test is performed on the 2018 *MagUp* real collisions samples. From Figure 8.2 it is ascertained that indeed $\chi_{IP}^2(h^\pm) > 12$ is a good solution for the problem posed by $\chi_{FD}^2(D^0) > 25$. While its efficiency seems now to be on par with **Hlt10neTrackMVA**, it must be remembered that this sample also contains

MC LTUNB 2018Up	
Selection	Retention Rate
$\min(IP_1, IP_2) > 60\mu m$	76.8%
$\min(\chi_{IP_1}^2, \chi_{IP_2}^2) > 12$	64.8%
Hlt10neTrackMVA	55.6%

Table 8.1: The retention rates of the Official Monte Carlo Full simulation LTUNB sample, employing various selections in order to overcome $\chi_{FD}^2(D^0) > 25$.

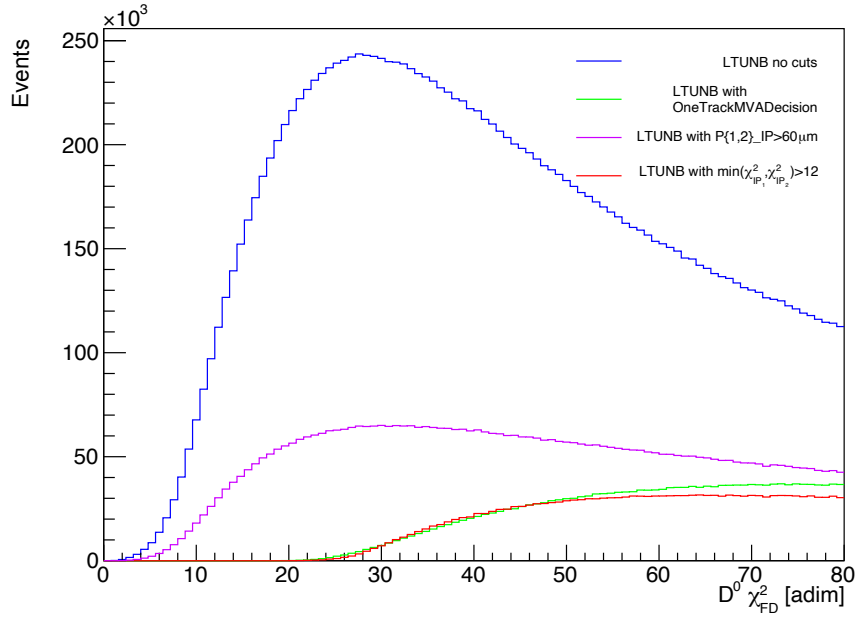


Figure 8.2: The 2018Up LTUNB Real Data $\chi_{FD}^2(D^0)$ distributions with different selections.

background. The reason the test was reiterated on real data is to validate that $\chi_{IP}^2(h^\pm) > 12$ absorbs $\chi_{FD}^2(D^0) > 25$ independently from the process studied.

What is interesting is instead looking at the retain rates of such selection on the “standard” sample, as this is the data set the selection will be imposed on. These can be found in Table 8.2 and Table 8.3, showing respectively the retention rates for the “standard” Official Monte Carlo 2018Up sample and “standard” real data 2018Up sample. From the above tables it can be inferred that $\chi_{IP}^2(h^\pm) > 12$ has better retention rate than Hlt10neTrackMVA when applied on the “standard” sample, for both the Official Monte Carlo simulation and the real data events.

Therefore, in conclusion, a method which allows exploitation of the “standard” sample, by making it compatible with this thesis’ technique of extracting track efficiency, has been found. This requires sacrificing some efficiency when applying it to the Run 2 sample - but a redesign of this trigger selections, informed by what has been learned here, could lead to a more optimized trigger line for Run 3.

MC Standard 2018Up	
Selection	retention Rate
$\min(IP_1, IP_2) > 60\mu m$	83.1%
$\min(\chi_{IP_1}^2, \chi_{IP_2}^2) > 12$	75.3%
Hlt10neTrackMVA	65.3%

Table 8.2: The retention rates of the Official Monte Carlo Full simulation “standard” sample, employing various selections in order to overcome $\chi_{FD}^2(D^0) > 25$.

Data Standard 2018Up	
Selection	Retention Rate
$\min(IP_1, IP_2) > 60\mu m$	82.98%
$\min(\chi_{IP_1}^2, \chi_{IP_2}^2) > 12$	75.03%
Hlt10neTrackMVA	61.36%

Table 8.3: The retention rates of the Real Data “standard” sample, employing various selections in order to overcome $\chi_{FD}^2(D^0) > 25$.

8.2 Considerations on trigger-lines planned for Run 3

Before finally testing the analysis method on the “standard” samples, a few lines commenting the Run 3 trigger lines based what has just been discussed are necessary. In fact it has been shown that while $IP(h^\pm) > 60\mu m$ exhibits a higher retention rate, selections based on χ_{IP}^2 tends to produce purer samples [37]. A similar selection is being considered to be implemented in upcoming Run 3 low bias trigger line for $D^0 \rightarrow h^- h^+$. At this point one could wonder if the $\chi_{IP}^2(h^\pm) > 12$ selection would be advantageous for producing a purer sample, given that with the efficiency extraction technique these type of cuts can be corrected for. In Figure 8.3 the decay time distributions of the Official Monte Carlo LTUNB sample are shown with the selections studied above in order to overcome $\chi_{FD}^2(D^0) > 25$. The most time-biasing selection results to be Hlt10neTrackMVA. This, coupled with its retain rate being the smallest one, pushes towards its final discard in such analysis. The selection $IP(h^\pm) > 60\mu m$ appears to be less biasing and if its higher retain rate is taken in consideration than it is the best candidate among these three to be indeed implemented in the future trigger system. Moreover, the IP is a simple enough observable to be accurately simulated, offering more control in its handling. The conclusion of this Section is then that $IP(h^\pm) > 60\mu m$ is the most preferable choice for future implementations, while the $\chi_{IP}^2(h^\pm) > 12$ selection lets Run 2 “standard” sample be of use in time-dependent measurements, thanks to the technique for retrieving factorizing efficiencies of Chapter 5.

8.3 A small tweak: the on-top efficiency

As already forewarned in Paragraph 7.3.1, the methodology needs to be slightly tweaked in order to be applicable to the “standard” data set. While it is true

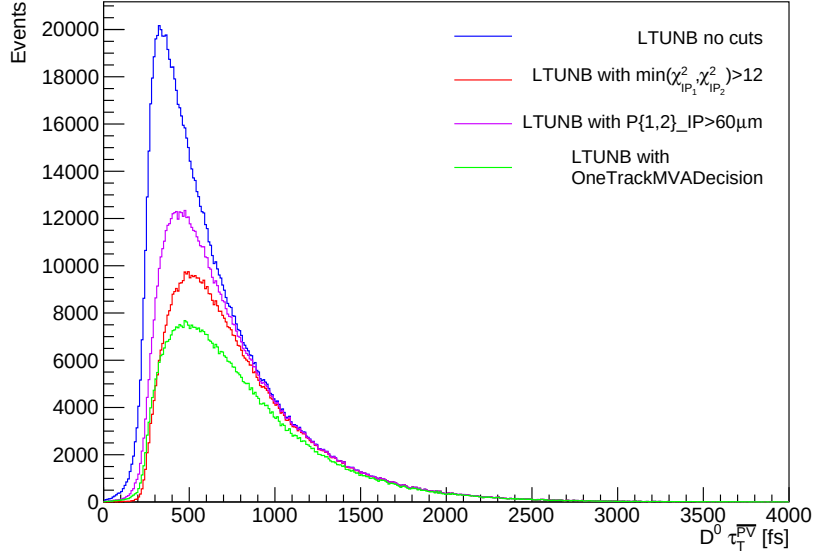


Figure 8.3: The 2018Up LTUNB Official Monte Carlo simulation τ_T^{PV} distributions with different selections.

that $\chi_{IP}^2(h^\pm) > 12$ is a single track selection, small correlating effects may still remain due to them being computed w.r.t. the same PV. If these χ_{IP}^2 cuts are included inside the single track efficiency then one must rely on their complete factorization. It is decided then to further employ the Official Monte Carlo Full Simulation. In fact, even if these observables are not easily reproducible offline, the Official Monte Carlo still simulates them up to a certain degree of accuracy. It is then deemed advantageous to fully exploit this Simulation and extracting a hybrid acceptance function

$$\mathcal{A}_{hyb.}(TIP_1, TIP_2) = \frac{\text{Full Simulation}(TIP_1, TIP_2 | \text{Hlt2Standard})}{\text{Smeared Generator Level Simulation}(TIP_1, TIP_2)} \quad (8.3.1)$$

where “Full Simulation($TIP_1, TIP_2 | \text{Hlt2Standard}$)” is TIP_1, TIP_2 distribution of the Official Monte Carlo Full Simulation sample whose events have passed the Hlt2 trigger line selections which characterize the charm “standard” sample (Table 3.1) and “Smeared Generator Level Simulation(TIP_1, TIP_2)” is the same distribution extracted from the generator level simulation without any selections. The on-top single track efficiencies then can be defined as follows:

$$\varepsilon_1^{top}(TIP_1) \varepsilon_2^{top}(TIP_2) = \mathcal{E}(TIP_1, TIP_2) = \frac{\text{Real Data}(TIP_1, TIP_2 | \text{Hlt2Standard})}{\text{Full Simulation}(TIP_1, TIP_2 | \text{Hlt2Standard})}, \quad (8.3.2)$$

which can be extracted via the eigenvector technique once the functions and distributions are binned. It must be emphasized that the Full Simulation accounts also for single track detection efficiency, therefore $\mathcal{A}_{hyb.}$ is defined *hybrid*: because it contains both selection and detection efficiencies as modeled by the Full Simulation. If such simulation were perfect, then $\mathcal{A}_{hyb.}$ would provide all the information necessary regarding the efficiency and $\varepsilon_{1,2}^{top}$, which is a correction to all efficiency effects already included in the simulation, would be flat because no discrepancy would manifest between real data and simulation. As it is not the case $\varepsilon_{1,2}^{top}$ will

help in bridging the gap between real samples and simulation. For $\varepsilon_{1,2}^{top}$ are relative efficiencies w.r.t. those modeled in the Official Monte Carlo, then in the lifetime extraction the function $\mathcal{S}(\tau)$ which in Chapter 7 corrected for the selection efficiency, must now incorporate all the effects contained in $\mathcal{A}_{hyb.}$, in addition it must account also for the $\varepsilon_{1,2}^{top}$ function domain $[TIP_{min}, TIP_{max}]$. Therefore it is now defined

$$\mathcal{S}_{hyb.}(\tau) = \frac{\text{Full Simulation}(\tau | \text{Hlt2Standard} \cdot TIP_{1,2} \in [TIP_{min}, TIP_{max}])}{\text{Smeared Generator Level Simulation}(\tau)}. \quad (8.3.3)$$

Reweighting every event in the signal region for

$$w = \frac{1}{\mathcal{S}_{hyb.}(\tau) \varepsilon_1^{top}(TIP_1) \varepsilon_2^{top}(TIP_2)} \quad (8.3.4)$$

is expected to unbiased the D^0 decay time distribution for the “standard” sample.

8.4 The “Standard” Real Data sample

We have finally gathered all the ingredients needed to tackle the analysis of the mainstream data sample for charm physics.

Once again, we take the sample of the 2018 *MagUp* data taking period for our study, in order to match the simulation conditions of the available generator level sample.

On-top efficiency extraction As it was done for the LTUNB real data samples (Section 7.4), the efficiency functions are extracted for both channels $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$. It is required $\chi_{IP}^2(h^\pm) > 12$ with a retain rate of 96% events, then it is asked the event to be flagged as `Dst_LOGlobal_TIS` (retain rate of 75% for KK and 65% for $\pi\pi$). Selections as $|\Delta m - m_\pi| < 1.5 \text{ MeV}/c^2$ and $|m(D^0) - m_{D^0}| < 20 \text{ MeV}/c^2$ are imposed on the real data sample with the aim of rejecting much of the combinatorial background. The combined retain rates are, for these cuts, 30% (KK) and 9% ($\pi\pi$). And then, on top, the secondary decays rejection selection $\log(\chi_{IP}^2(D^0)) < 3$ along with the $TIP_{1,2}$ window $[100, 400] \mu\text{m}$ in order to reduce the contribution of residual combinatorial background at low TIP values, leaves at the end 4% (KK) and $< 1\%$ ($\pi\pi$) of the events contained in the initial samples, from 7.5×10^7 to 2.8×10^6 for the KK channel and from 1.2×10^8 to 9.1×10^5 in case of $\pi\pi$. The on-top efficiency matrices $\mathcal{E}$ are reported in Figures 8.4 and 8.5.

The extracted K and π on-top efficiency functions are shown respectively in Figures 8.6 and 8.7, with the secondary eigenvalues being $< 4\%$ the main one. Some considerations can be derived from these extracted on-top efficiency functions, which are a correction to the efficiencies (selection and detection) modeled in the Full Official Simulation. First, the trend and size of the shape are similar between the K and π , hinting that the simulations err in similar way and same “direction” between the two processes. This is somewhat in agreement with intuition, as most of the K - π differences are arguably accounted for by the simulation, leaving out some residual tracking-related effects, that are mostly common to both particles. This justify how within a certain precision, it was tolerable in the 2019 LHCb measurement of y_{CP} [36] to assume that such contributions elided

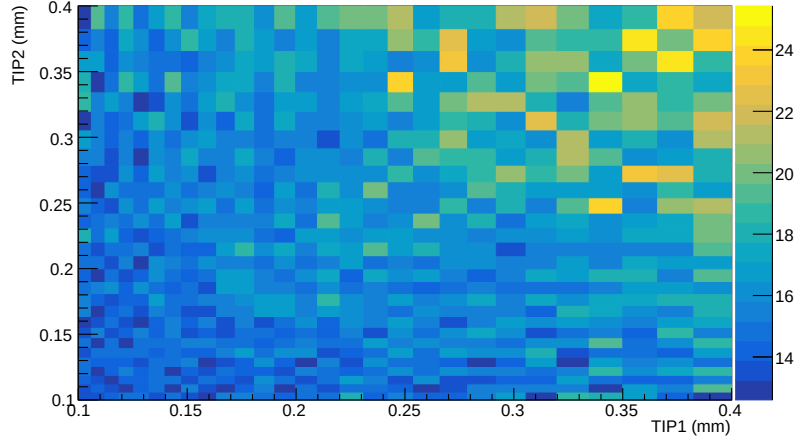


Figure 8.4: The $\mathcal{E}$ matrix from the real data 2018 MagUp “standard” sample for $D^0 \rightarrow K^- K^+$.

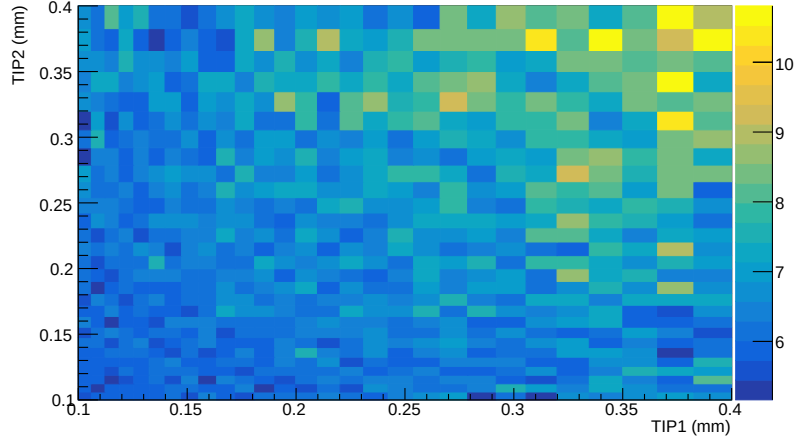


Figure 8.5: The $\mathcal{E}$ matrix from the real data 2018 MagUp “standard” sample for $D^0 \rightarrow \pi^- \pi^+$.

in the ratio and the simulated acceptance function were sufficient for correcting the selection bias, given the at-the-time attainable precision.

Second, the comparison between Figures 8.6 and 8.7 and Figure 7.16 which reports the LTUNB single track efficiencies, is of interest. The single track efficiencies extracted from the LTUNB sample in fact were “absolute” efficiencies, incorporating detection track efficiency and selection efficiency due to the $DLL_{K-\pi}$ and χ^2/ndf of the track fit cuts. The size of the effect shown by those shapes is larger than what is seen here, where a wider range is shown. This leads to concluding that the official simulation is wrong on the modeled efficiency by an amount smaller than the efficiency effects - that is, it is at least partially correct.

Lifetime extraction Tackling the $D^0 \rightarrow K^- K^+$ sample first, the combinatorial background was subtracted with the same procedure discussed in Paragraph 7.4, by defining the signal and sidebands regions on D^0 mass invariant distribution after imposing $|\Delta m - m_\pi| < 1.5 \text{ MeV}/c^2$. The binned maximum likelihood fit, with the model of Equation 7.4.1, is performed on the distribution

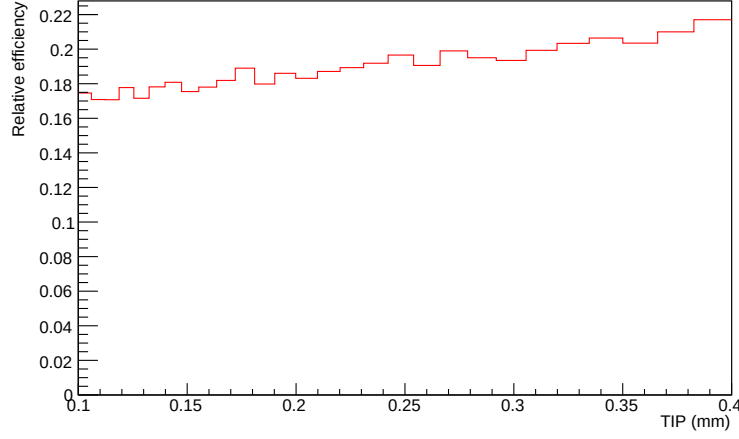


Figure 8.6: The kaon single track efficiency eigenvector extracted from the real data 2018 MagUp “standard” sample for $D^0 \rightarrow K^- K^+$.

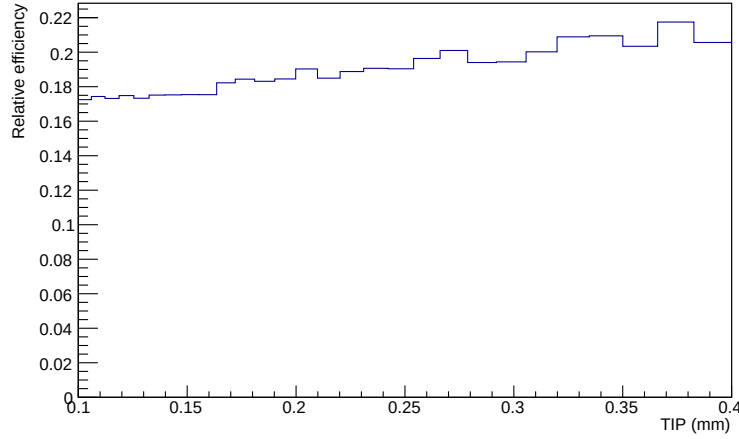


Figure 8.7: The pion single track efficiency eigenvector extracted from the real data 2018 MagUp “standard” sample for $D^0 \rightarrow \pi^- \pi^+$.

in order to extract the correct weight (Eq. 7.4.2) used in order to subtract the background component in the signal region from the decay time distribution. The $\mathcal{S}_{hyb.}(\tau)$ (Eq. 8.3.3) is extracted from the Official Monte Carlo Simulation (Figure 8.8), presenting now a broader shape than the one for the LTUNB sample (Figure 7.21) due to the higher upper bound for the TIP efficiency domain. Then, at various ranges, unbinned maximum likelihood fits are carried out on the decay time distributions with the same model of an exponential distribution convoluted with the KDE resolution template extracted from the generator level simulation.

The τ parameter of the exponential component is again blinded by a shift sampled from a uniform distribution $U[-25, 25]$ fs, common to all fits and decay channels. In Figures 8.9, 8.10 and 8.11 are respectively shown the decay time distributions before any correction, after reweighting for $1/\mathcal{S}_{hyb.}(\tau)$, and finally after the $1/\mathcal{S}_{hyb.}(\tau)\varepsilon_1\varepsilon_2$ correction with their fit in the $[615, 4000]$ fs range and the pulls distribution below (computed from the plotted binned representations) for the

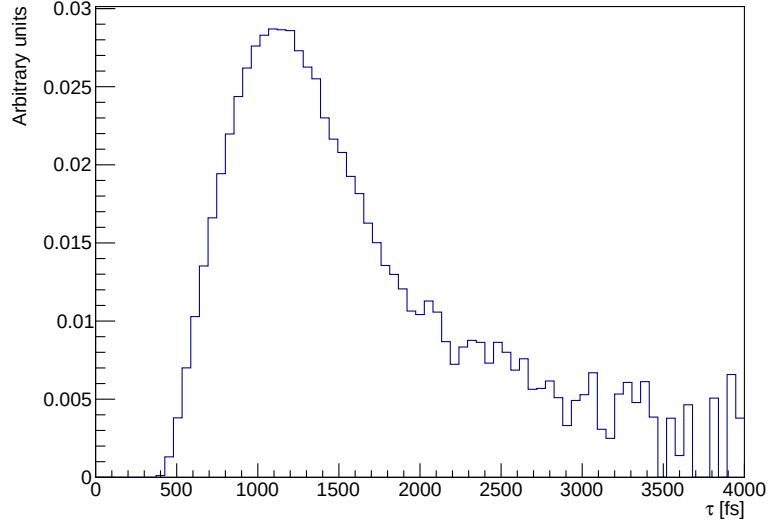


Figure 8.8: The $S_{hyb.}(\tau)$ hybrid selection efficiency function for the KK channel on the Standard sample.

process $D^0 \rightarrow K^- K^+$.

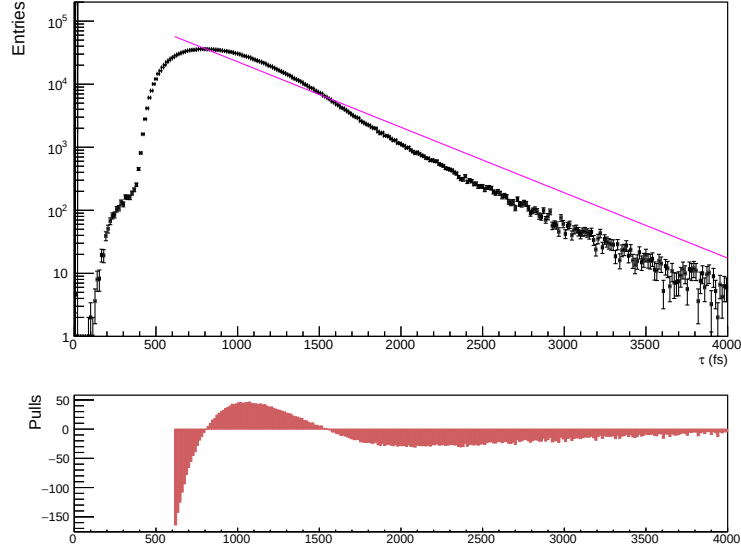


Figure 8.9: The decay time raw distribution from the real data 2018 MagUp “standard” sample $D^0 \rightarrow K^- K^+$ and the fit model described in the text.

The measured values are

$$\begin{aligned}\tau_{raw}^{KK} &= (397.00 \pm 0.27) \text{ fs before any reweighting}^1, \\ \tau_S^{KK} &= (409.01 \pm 0.36) \text{ fs after } 1/s(\tau) \text{ reweighting,} \\ \tau_{S\varepsilon}^{KK} &= (388.59 \pm 0.31) \text{ fs after } 1/s(\tau)\varepsilon_1\varepsilon_2 \text{ reweighting.}\end{aligned}$$

Including events with $TIP_{1,2}$ up to 400 μm permits to better appreciate the correction due to the on-top efficiency which produces a shift on the measured mean

¹ This results has little meaning due to the shape of the distribution being evidently different from the fitted model.

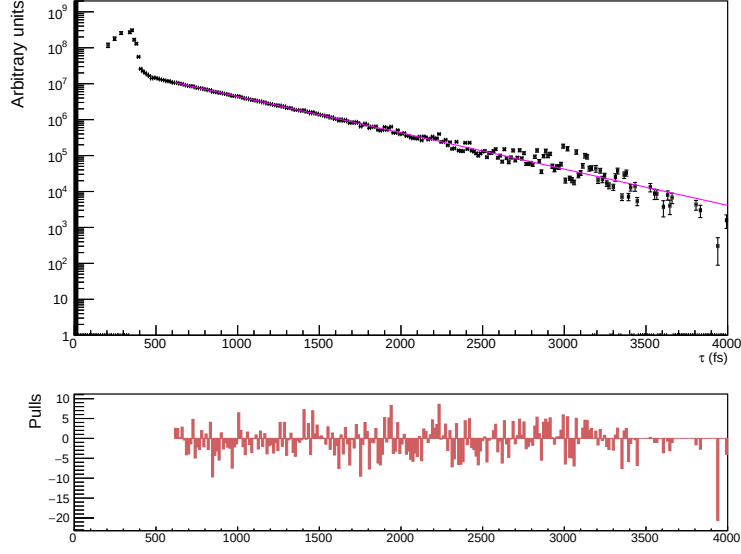


Figure 8.10: The decay time distribution corrected for the selection efficiency from the real data 2018 MagUp “standard” sample $D^0 \rightarrow K^- K^+$ and the fit model described in the text.

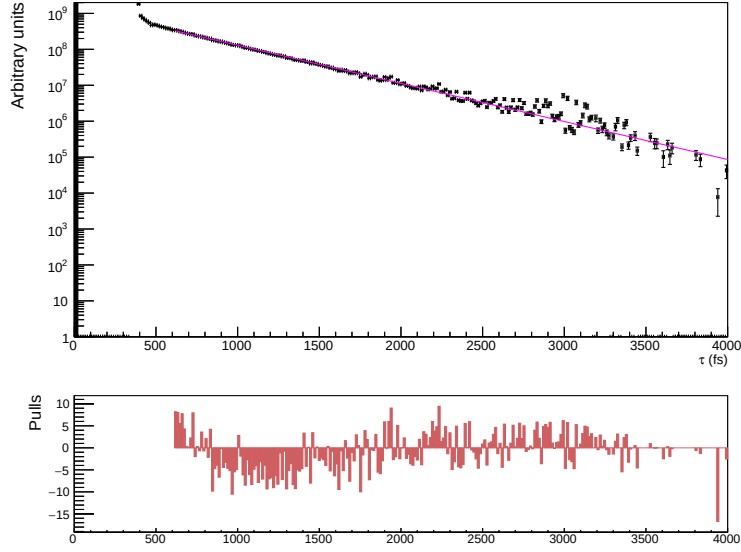


Figure 8.11: The decay time distribution corrected for both the selection and detection efficiency from the real data 2018 MagUp “standard” sample $D^0 \rightarrow K^- K^+$ and the fit model described in the text.

lifetime equal to $\sim 5\%$ the nominal D^0 lifetime. In fact, in the LTUNB sample, with efficiency variations of smaller size, the effect on the extracted lifetime was less impacting. Moreover the attained statistical precision is $< 0.1\%$ the nominal D^0 lifetime. This leads to the conclusion that indeed the “standard” sample is advantageous in terms of statistical power and a methodology permitting to exploit it for time-dependent measurements means unprecedented precision on such observables.

The results are blinded, therefore offer little validation on whether the strategy works on biased lines for absolute lifetime measurements. Tests on Official

Monte Carlo Simulation were unfeasible as it is the basis on which the on-top efficiency corrections are built. What can be checked is if the $D^0 \rightarrow \pi^- \pi^+$ sample produce compatible results with these one, similarly to what it was carried out in the real data LTUNB samples, as it is expected $\tau_{KK} - \tau_{\pi\pi} = 0$ from theory.

The same steps are then repeated for the $\pi\pi$ decay channel and for sake of conciseness the final results are shown in comparison with the ones obtained from $D^0 \rightarrow K^- K^+$. The measured mean lifetimes after only the selection efficiency correction are shown Figure 8.12, while the results after applying also the detection efficiency correction be seen in Figure 8.13.

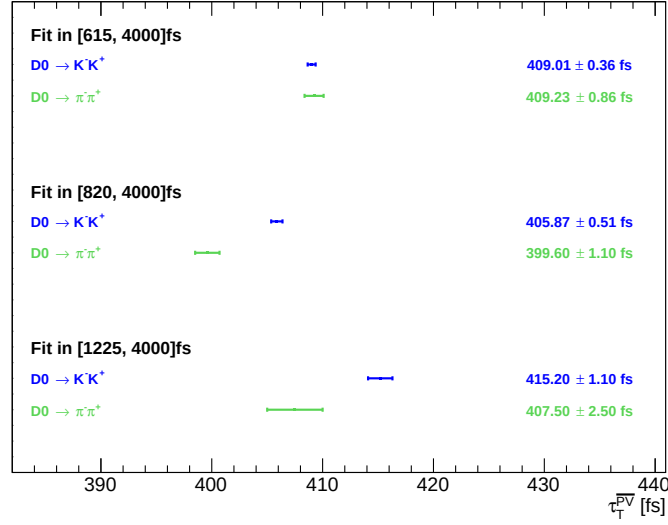


Figure 8.12: Comparison between the mean lifetime of the D^0 meson extracted from the $D^0 \rightarrow K^- K^+$ sample (blue) and $D^0 \rightarrow \pi^- \pi^+$ (green), after only the selection efficiency correction.

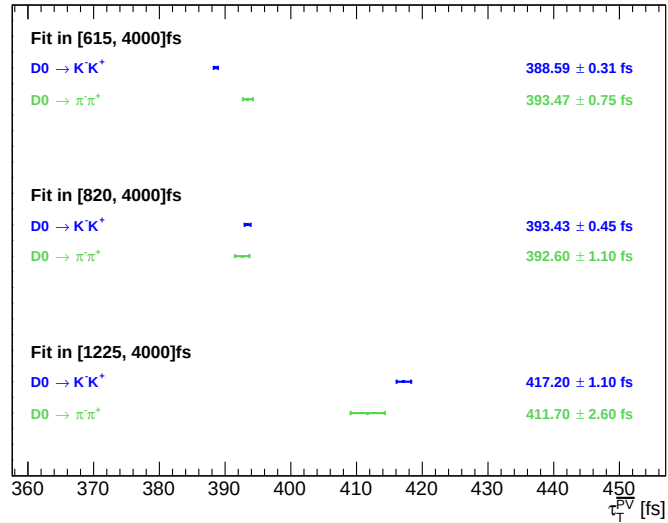


Figure 8.13: Comparison between the mean lifetime of the D^0 meson extracted from the “standard” $D^0 \rightarrow K^- K^+$ sample (blue) and $D^0 \rightarrow \pi^- \pi^+$ (green), after both the selection and detection efficiency correction.

From Figure 8.13 it can be seen that using 615 fs as the lower bound for the fit range, does not returns the expected results, in fact while before the single track efficiency correction τ_{KK} appears in good agreement with $\tau_{\pi\pi}$ (Figure 8.12), the same cannot be said after the efficiency correction, obtaining $\tau_{KK} - \tau_{\pi\pi} = (4.98 \pm 0.81)$ fs over 5σ from the expected zero value. From the pull distribution of the decay time fit in Figure 8.11, and also from the one of the LTUNB sample in Figure 7.24, it can be seen how at low decay time some discrepancy between data and model arises, while above $2\tau_{D^0}$ (820 fs) the situation starts to improve. A possible explanation is that the residual combinatorial background pollutes the efficiency matrix $\mathcal{E}$, causing slight bias on the extracted efficiency function. The combinatorial background mainly affects low TIP (IP) regions, for this reasons trigger lines adopt selections rejecting low IPs or low χ^2_{IP} ; it is plausible that with a bias on the efficiency at low TIPs then low decay time windows are the most affected, as low TIPs are inextricably bound to low transverse flight distances, especially after a cut $p_T(D^0) > 2$ GeV, as implemented in all the reported trigger lines. This seem supported by the fact that after applying the efficiency correction the pulls distribution worsen at low decay time w.r.t. the fits performed only with the $1/s(\tau)$ correction, shown in Figures 7.23 (LTUNB) and 8.10 (“standard”). The issue can be addressed by operating a sideband subtraction also in the TIP_1, TIP_2 data distribution, from which the $\mathcal{E}$ matrix is extracted. While it is an advantageous approach to be taken in consideration when performing the measurement, thus recovering low decay time windows, here, at the moment, higher decay time windows are taken in consideration such as [820, 4000]fs, where these issues seems negligible.

From Figure 8.13 of the comparison between τ_{KK} and $\tau_{\pi\pi}$, the behavior of the single track efficiency correction seems consistent between the two higher fit ranges, where both results shows how τ_{KK} and $\tau_{\pi\pi}$ are brought nearer to each other.

From the fit range [820, 4000]fs it is computed

$$\tau_{KK} - \tau_{\pi\pi} = (0.8 \pm 1.2) \text{ fs},$$

in good agreement with $\tau_{KK} - \tau_{\pi\pi} = 0$ within 0.7σ .

Even imposing a tighter cut on low decay times results in obtaining a precision on the difference of mean lifetimes equal to $\sim 0.25\%$ the nominal τ_{D^0} value.

This proves that the analysis methodology works even on biased trigger lines, which can finally be employed also for measurement of time-dependent charm observables.

8.5 The measurement of y_{CP}^{CC}

The test observable y_{CP}^{CC} defined in Equation 3.1.3 is here measured again as done with the LTUNB sample.

The ratio of the KK decay time distribution over the $\pi\pi$ one is computed and fitted with a simple exponential shape, before any correction (Figure 8.14), after reweighting for $1/s_{hyb.}(\tau)$ (Figure 8.15) and then after correcting for the single track efficiency (Figure 8.16).

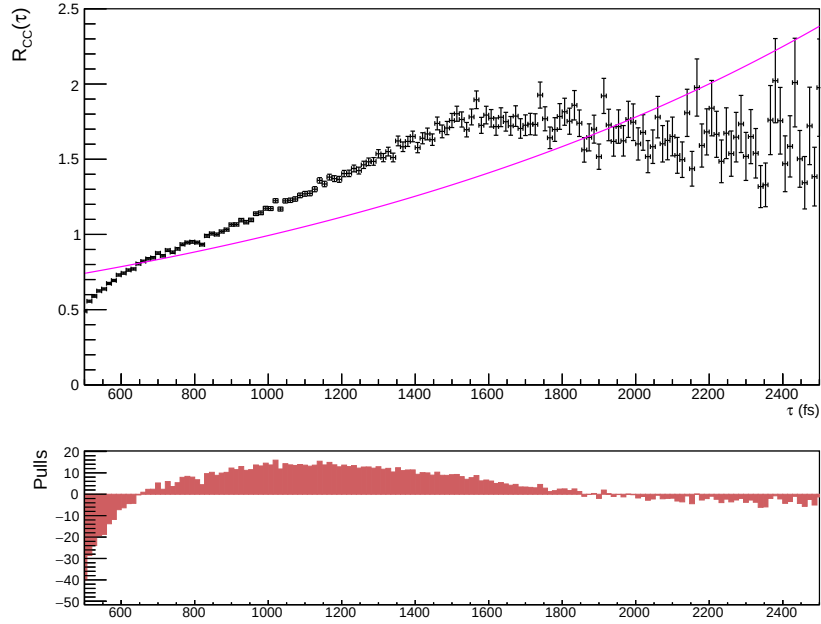


Figure 8.14: The ratio of the decay time raw distributions from the real data 2018 MagUp “standard” sample $D^0 \rightarrow K^- K^+$ over $D^0 \rightarrow \pi^- \pi^+$ sample, and the fit model described in the text.

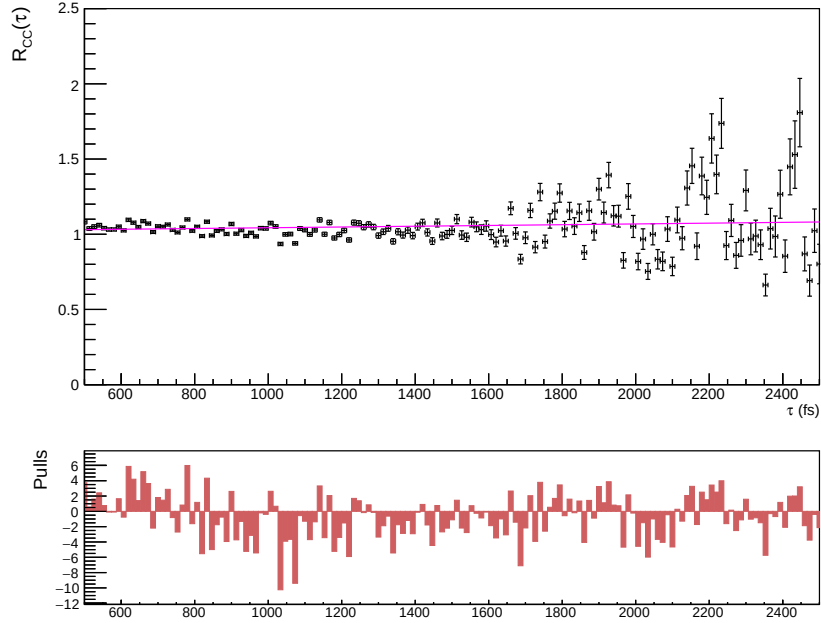


Figure 8.15: The ratio of the decay time distributions corrected for the selection efficiency from the real data 2018 MagUp “standard” sample $D^0 \rightarrow K^- K^+$ over $D^0 \rightarrow \pi^- \pi^+$ sample, and the fit model described in the text.

The y_{CP}^{CC} values from the fits are

$$y_{CP}^{CC} = (-23.042 \pm 0.058) \times 10^{-2} \text{ before any reweighting,}$$

$$y_{CP}^{CC} = (-11.41 \pm 0.77) \times 10^{-3} \text{ after } 1/s(\tau) \text{ reweighting,}$$

$$y_{CP}^{CC} = (-0.46 \pm 0.77) \times 10^{-3} \text{ after } 1/s(\tau)_{\varepsilon_1 \varepsilon_2} \text{ reweighting.}$$

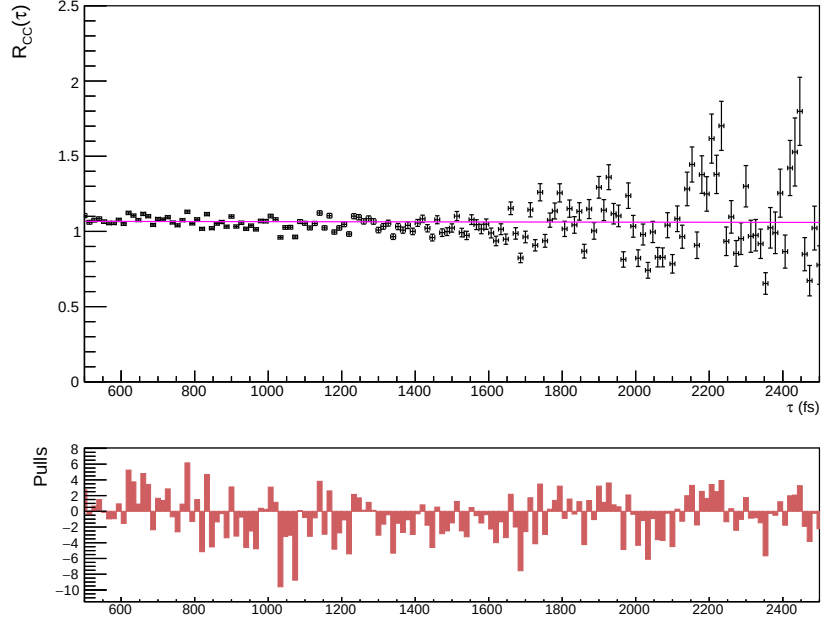


Figure 8.16: The ratio of the decay time distribution corrected for both the selection and detection efficiency from the real data 2018 MagUp “standard” sample $D^0 \rightarrow K^- K^+$ over $D^0 \rightarrow \pi^- \pi^+$ sample, and the fit model described in the text.

Even with the use of the “standard” sample corresponding to 1 fb^{-1} it was managed to find the y_{CP}^{CC} test observable in extremely good agreement with zero, after all efficiency and acceptance correction are applied. A better statistical precision than the last published LHCb paper [37] with $y_{CP}^{CC} = -1.15 \pm 1.30$ is achieved. This proves that with our developed method, a significantly better measurement can in principle be obtained already on the Run 2 data set.

CHAPTER

9

REDUCING UNCERTAINTY IN SECONDARY DECAYS SUBTRACTION

In Chapter 3 it was described how the systematic effects caused by secondary decays has been handled in the y_{CP} measurement recently published by LHCb [37]. In the studies presented in this thesis a simple rejection was instead carried out, by imposing the selection $\log(\chi^2_{IP}(D^0)) < 3$. However, we have seen in Table 7.2 that a remaining fraction of secondary decays still affects the measurement. Modeling and including in the fit this residual component, as it was done in the last published measurement, implies a reliance on the decay model incorporated in physics generators. This brings in an associated systematic uncertainty, that is another significant contribution to the measurement uncertainty that cannot be easily reduced when going to larger samples. Coherently with the fully data-driven approach we have pursued in the determination of detector efficiencies, we have developed an alternative method for dealing also with this issue in a way that, if not completely eliminates, at least strongly reduces the reliance on simulation. While we have not directly applied it to data in the current work, we describe it here in the following to provide an argument that such procedure is viable, so that the contamination from secondaries will not defeat our efforts towards a purely data-driven, high-precision measurement of y_{CP} in the future.

9.1 Secondary decays

Secondary decays have previously been mentioned only in passing, without fully discussing their features, or why selecting on $\chi^2_{IP}(D^0)$ affects their presence. Such selection has been justified based on previous strategies cited in the bibliography, as in [37], but not explicitly discussed. Hereby we illustrate the phenomenology of such processes.

As previously stated, secondary decays are those events where the D^0 meson, or more accurately the D^{*+} decaying in D^0 , is produced not in the PV from the pp interaction (prompt decay), but as decay product of a B^0 or B^+ meson, hence the label *secondary decay*. A pictorial representation of these two types of processes is shown in Figure 9.1.

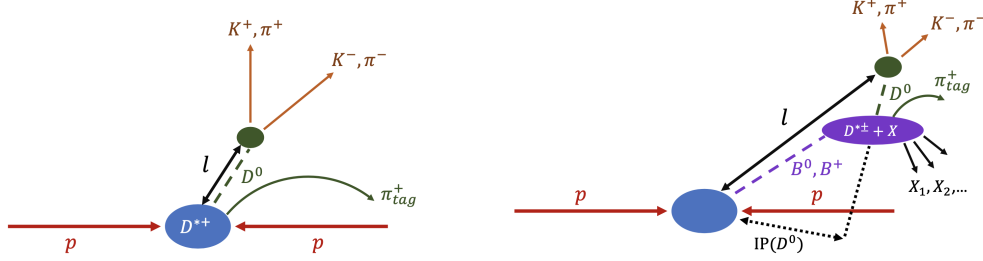


Figure 9.1: The production schemes for prompt (left) and secondary (right) decays, where l stands for the reconstructed flight distance used in decay time computation. How the $IP(D^0)$ in case of secondary decay reaches non zero values is shown. From [80].

From this representation it can be understood why selecting low values of $IP(D^0)$ reduce the contribution of secondary decays, although it does not eliminate it. The reconstructed flight distance l , or transverse flight distance L_{xy} as used in this work, computed as the distance between the DV of the D^0 and the PV (or mean PV), would still be affected by the contribution of the b meson flight distance, with $\tau_B \approx 1.57 \text{ ps} = 3.83\tau_{D^0}$. This obviously biases the reconstructed D^0 decay time calculated from

$$\tau_T = \frac{\vec{L}_{xy}^{\langle PV \rangle} \cdot \vec{p}_T m}{|\vec{p}_T|^2 c}.$$

Different strategies can be adopted to address such contribution. Similar to the combinatorial background, their fraction can be extrapolated via simulations and their contribution subtracted from the decay time distribution. Another is tightening the $IP(D^0)$ or $\chi_{IP}^2(D^0)$ selection in order to further suppress them, paying the price of also rejecting signal events which due to the finite resolution on the momenta direction and vertices position can result in $IP(D^0) \neq 0$. Otherwise their contribution can be included in the fit for extracting the y_{CP} parameter from the ratio of decay time distributions, as it was done in the last LHCb measurement and mentioned in Chapter 3. Below we present a further alternative.

9.2 Reconstructed lifetimes of secondary decays

Exactly as it was done in [37] the reconstructed decay time for secondary decays as function of the mean true D^0 decay time $\tau_{true}(D^0)$ was studied. In order to accomplish this, custom simulations were employed injecting different D^0 mean lifetime values from 390 fs to 430 fs.

9.2.1 Custom simulation for secondary decays

The secondary decay was simulated through an approximated model extracted from a PGun simulation for B^0 to D^0 decays. The PV position is generated in

exactly the same way and with the same values as the previous custom simulation of Chapter 4. Then, the 3D B^0 true flight distance vector is extracted from the PGun 3D distribution and the B^0 η and ϕ calculated from it. Exploiting the additivity of the rapidity y and with $y \sim \eta$ approximation, the $\eta(D^0) - \eta(B^0)$ quantity is sampled as well, and $\eta(D^0)$ computed accordingly given the value of the already simulated $\eta(B^0)$ (from the B^0 flight distance). The azimuthal angle does not offer the additivity advantage, therefore it is extracted randomly from the conditional probability distribution

$$\mathcal{D}(\phi(D^0), \phi(B^0) | \phi(B^0))$$

and finally the $|\vec{P}(D^0)|$ generated independently still employing the distributions provided by the PGun simulation. All these quantities undergo resolution smearing effects as modeled in Chapter 4.

9.2.2 The secondary decay lifetimes as function of $\tau_{true}(D^0)$

The secondary decays samples generated as described above, with different values of true D^0 mean lifetime injected, are processed as it was done with the custom simulation in Chapter 6. The selection are the same of Table 7.1, and the track efficiency simulated with a linear decreasing shape, the same used for prompt decays. This way the single track efficiencies already extracted from prompt decays could be re-used. This is the same as assuming that detection efficiencies, or correction to the efficiency simulated by the Official Simulation, do not depend on the process, but only on the tracks' properties. The $\mathcal{C}$ function correcting for the selection efficiencies and factorizing with $\mathcal{A}$, is extracted from another custom simulation for secondary decays with uniform decay time distribution for the D^0 meson. Resolution effects are again incorporated in $\mathcal{S}(\tau)$, then a simple exponential fit on the lifetime between 0.4 fs and 4 ps is carried out. The extracted mean D^0 lifetimes are plotted in Figure 9.2 as function of the true injected values, both after the $\mathcal{AC}(\tau)$ reweighting and also after correcting for the track efficiency. A minimum χ^2 fit is carried on on these results using a linear model $\alpha x + \beta$ and it is found after all efficiency correction are applied

$$\begin{aligned}\alpha &= 0.812 \pm 0.007 \\ \beta &= (202 \pm 2) \text{ fs},\end{aligned}$$

with $\chi^2/ndf = 1.9/12$.

The data are in good agreement with a linear model. Moreover it is to be noted that α is closer to one than to zero. These two aspects will gain significance in the following subsection.

The test is repeated at various lower threshold for the θ_{DIRA} variable which is the angle between the D^0 momentum and its flight distance. In secondary decays θ_{DIRA} is expected to acquire larger values, as the reconstructed flight distance it is not the D^0 true one. The results of this scan for both the α and β parameters are shown in Figure 9.3 (α parameter) and Figure 9.4 (β parameter).

From this, it can be seen how at trigger line θ_{DIRA} thresholds (~ 17 mrad for LTUNB and ~ 140 mrad for the “standard” charm line) α take a value roughly between 0.85 and 0.9. This is of great use in a y_{CP} measurement, as it will be discussed. Moreover an expected behavior is found: tighter thresholds corresponds

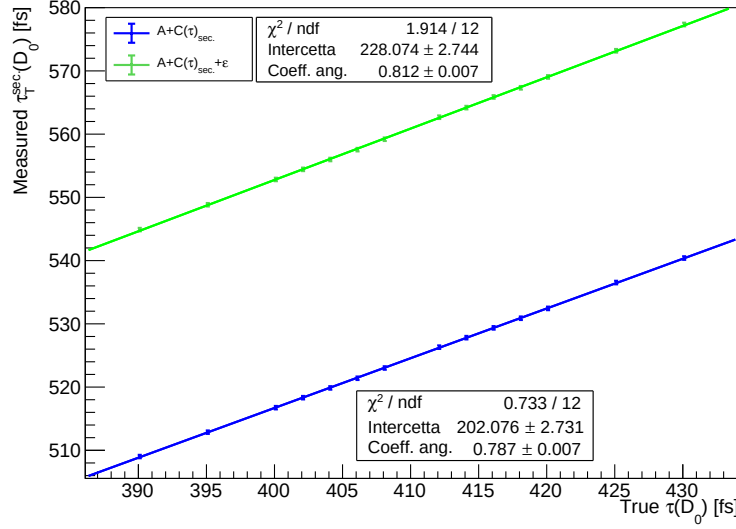


Figure 9.2: Relationship between measured mean lifetime and true $\tau(D^0)$ injected in the simulation for secondary decays. In blue before correcting for the simulated detection efficiencies and in green after accounting for them.

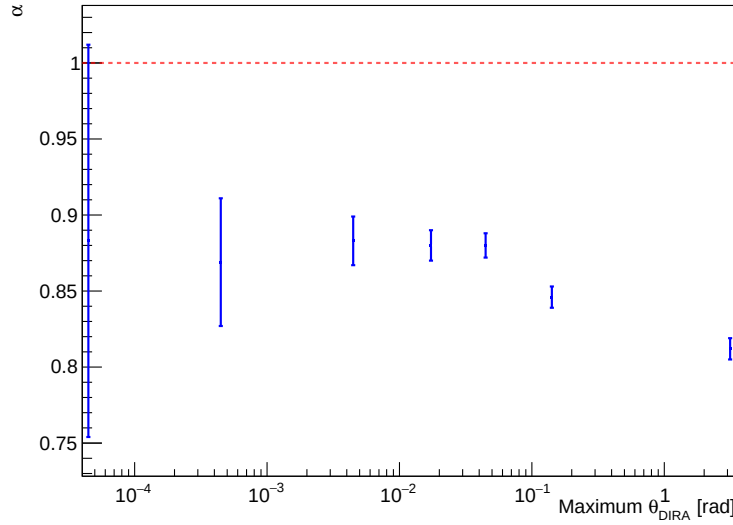


Figure 9.3: The variation of the parameter α at various lower thresholds of the observable θ_{DIRA} .

on selecting D^0 mesons pointing to the PV, this happens with very short B^0 flight distances; then the decay it is almost a prompt decay and thus $\alpha \rightarrow 1$ and $\beta \rightarrow 0$. These limit values are not however reached due to a portion of B^0 almost collinear with the D^0 which pass the θ_{DIRA} selection and continues to bias the lifetime measurement.

9.2.3 Consequences on the y_{CP} measurement

Besides from the ratio of decay time time distribution, or the ratio of absolute lifetime between hh and $K\pi$ decay channels, the observable y_{CP} can also be

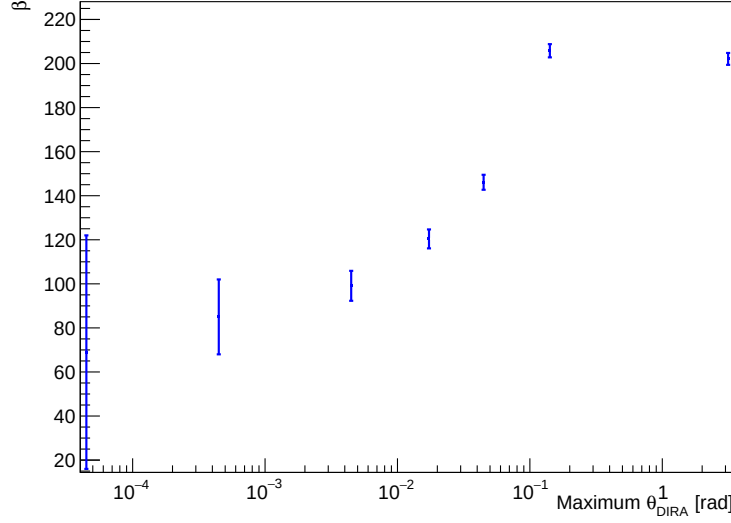


Figure 9.4: The variation of the parameter β at various lower thresholds of the observable θ_{DIRA} .

extracted from the measured difference of such absolute lifetimes. In fact

$$y_{CP} \approx \frac{\hat{\Gamma}_{CP}}{\hat{\Gamma}_{K\pi}} - 1 = \frac{\tau_{K\pi}}{\tau_{CP}} - 1 = \frac{\tau_{K\pi} - \tau_{CP}}{\tau_{CP}} = \frac{\tau_{K\pi} - \tau_{CP}}{\tau_{K\pi} - (\tau_{K\pi} - \tau_{CP})}, \quad (9.2.1)$$

where τ_{CP} is the absolute lifetime measured for the hh decay channel and $\tau_{K\pi}$ for the $K\pi$ channel. If the difference $\Delta\tau = \tau_{K\pi} - \tau_{CP}$ is measured then y_{CP} can be extracted as

$$y_{CP} \approx \frac{\Delta\tau}{\tau_{K\pi} - \Delta\tau}, \quad (9.2.2)$$

and using the nominal D^0 mean lifetime for $\tau_{K\pi}$.

If $\langle\tau_{D^0}^{K\pi}\rangle_{measured} - \langle\tau_{D^0}^{hh}\rangle_{measured}$ can be measured from a sample contaminated with secondary decays, then

$$\begin{aligned} \langle\tau_{D^0}^{K\pi}\rangle_{measured} - \langle\tau_{D^0}^{hh}\rangle_{measured} &= ((1-f)\langle\tau_{D^0}^{K\pi}\rangle_{prompt} + f\langle\tau_{D^0}^{K\pi}\rangle_{sec.}) \\ &\quad - ((1-f)\langle\tau_{D^0}^{hh}\rangle_{prompt} + f\langle\tau_{D^0}^{hh}\rangle_{sec.}) \end{aligned} \quad (9.2.3)$$

as the average value of the sum of different exponential distribution is equal to the sum of the averages. Here f is the fraction of secondary decays in the signal region, $\langle\tau_{D^0}^{xx}\rangle_{prompt}$ is the measured mean lifetime contribution to the sample from prompt decays, and $\langle\tau_{D^0}^{xx}\rangle_{sec.}$ is the measured mean lifetime contribution to the sample from secondary decays.

However it has been proved that $\langle\tau_{D^0}\rangle_{sec.} = \alpha\langle\tau_{D^0}\rangle_{prompt} + \beta$, then

$$\begin{aligned} \langle\tau_{D^0}^{K\pi}\rangle_{measured} - \langle\tau_{D^0}^{hh}\rangle_{measured} &= (1-f+f\alpha)\langle\tau_{D^0}^{K\pi}\rangle_{prompt} + f\beta \\ &\quad - (1-f+f\alpha)\langle\tau_{D^0}^{hh}\rangle_{prompt} - f\beta, \end{aligned} \quad (9.2.4)$$

thus obtaining:

$$\langle\tau_{D^0}^{K\pi}\rangle_{prompt} - \langle\tau_{D^0}^{hh}\rangle_{prompt} = \frac{\langle\tau_{D^0}^{K\pi}\rangle_{measured} - \langle\tau_{D^0}^{hh}\rangle_{measured}}{1-f(1-\alpha)}. \quad (9.2.5)$$

As $\langle \tau_{D^0}^{K\pi} \rangle_{prompt} - \langle \tau_{D^0}^{hh} \rangle_{prompt}$ is an estimate of $\Delta\tau$, then by plugging it in Equation 9.2.1 it can be seen how the contribution of secondary decays on the y_{CP} measurement is not dependent simply on their fraction f in the signal region, as it was in the method adopted by the last LHCb measurement of Chapter 3 (Equation 3.3.1), but now the fraction f is suppressed by a factor $(1 - \alpha)$. Remembering that from the custom simulations, with trigger-like selections on θ_{DIRA} , it was $\alpha \sim 0.85 - 0.90$, then f is multiplied by a factor $\sim 10^{-1}$.

The systematic effects due to the secondary decays contribution and the uncertainty on the f parameter, are here reduced by almost an order of magnitude, improving the handling of such source of systematic uncertainty.

9.2.4 Moving from exponential fits to weighted means for lifetimes extraction

It can be argued that in the custom simulation for secondary decays the decay time distributions were reweighted with a function correcting the selection efficiency purposely built for them, whereas on real data, the $\mathcal{S}(\tau)$ function is modeled after the prompt decays. If secondary decays are reweighted with $\mathcal{S}(\tau)_{prompt}$ their decay time distribution get deformed and an exponential fit, which already was an approximation, would not work anymore. The solution is moving from fitting the decay time distribution to computing the arithmetic mean. If the whole decay time range would be available, like it is common at lepton colliders, no issues would arise, however due to trigger selections some lower bound is always imposed at LHCb. This means that the distribution are truncated, and this must be accounted for as it introduces biases on the estimated mean lifetime if computed through the arithmetic mean. In the following subsection is presented an example of this issues and how it can be resolved.

Bias on truncated mean: systematic contribution and correction

For sake of simplicity let us consider a truncated exponential distribution with decay time τ , bounded in the $[a, b]$ range. Then it can be computed that its expected value is

$$E[x] = \tau + a - \frac{(b - a)e^{a/\tau}}{e^{b/\tau} - e^{a/\tau}}, \quad (9.2.6)$$

and for a sample large enough $E[x] \sim \langle t \rangle$, with $\langle t \rangle$ being the sample arithmetic mean.

When measuring a difference of mean lifetimes originating from two exponential distributions with different decay time τ_{hh} and $\tau_{K\pi}$, truncated with the same bounds $[a, b]$, then the difference of the arithmetic means can be expressed as

$$\langle t_{K\pi} \rangle - \langle t_{hh} \rangle = \Delta\tau + (b - a) \overbrace{\frac{e^{-\frac{b-a}{\tau_{K\pi}-\Delta\tau}} - e^{-\frac{b-a}{\tau_{K\pi}}}}{\left(1 - e^{-\frac{b-a}{\tau_{K\pi}}}\right) \left(1 - e^{-\frac{b-a}{\tau_{K\pi}-\Delta\tau}}\right)}}^{\text{trunc. bias } B(\Delta\tau, \tau_{K\pi})}, \quad (9.2.7)$$

where $\Delta\tau = \tau_{hh} - \tau_{K\pi}$.

In case of secondary decay contamination by a fraction f the left member of Equation 9.2.7 must be rewritten as

$$\frac{\langle t_{K\pi} \rangle - \langle t_{hh} \rangle}{1 - f(1 - \alpha)}.$$

Then once $\langle t_{K\pi} \rangle - \langle t_{hh} \rangle$ is measured, $\Delta\tau$ can be computed by inverting Equation 9.2.7 and then plugged in Equation 9.2.2 in order to extract y_{CP} .

The question is whether this truncation bias can be neglected at the current level of precision. In Figure 9.5 are reported both the truncation bias part $B(\Delta\tau, \tau_{K\pi})$ showing in the second member of Equation 9.2.7, and the same quantity over $\Delta\tau$ - the relative bias - in the range $\Delta\tau \in [-8, 8]$ fs. The range widely covers the $\Delta\tau$ value expected from the SM. The nominal $\tau_{K\pi}$ is fixed at the upgraded WA value of (410.3 ± 1.0) fs, after the last Belle II measurement [87].

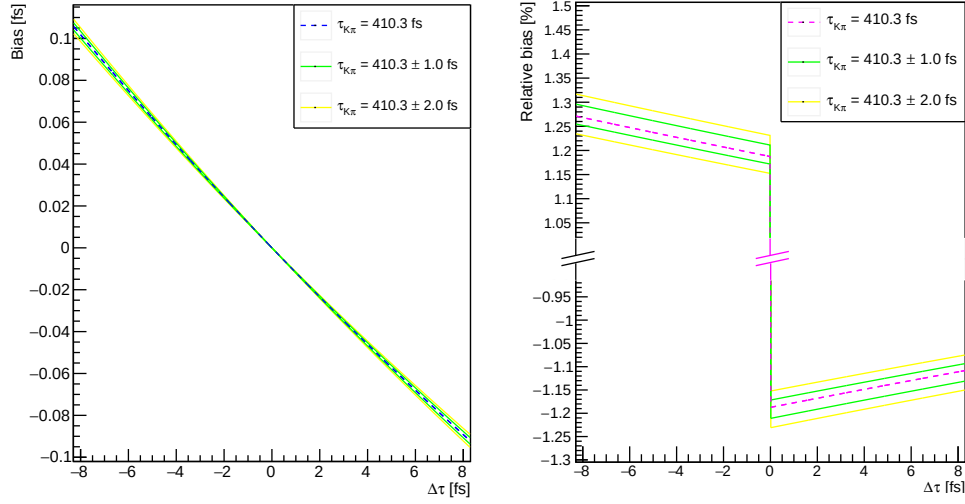


Figure 9.5: The bias (left) and relative bias (right) on the difference of lifetime calculated from the averages due to truncation of the distributions. In green and yellow the same functions with the value of $\tau_{K\pi}$ varied by $\pm 1\sigma$ and $\pm 2\sigma$ respectively.

The effects of neglecting such truncation bias amount up to 1.3% the values of $\Delta\tau$, which roughly translates in 1.3% bias on y_{CP} . The last LHCb measurement of y_{CP} reports a total systematic uncertainty of 1.8% (3.8% statistical), therefore if this approach is chosen for carrying out the analysis in the future this bias must be corrected.

As the nominal $\tau_{K\pi}$ value has its uncertainty, in Figure 9.5 the recomputed biases with $\tau_{K\pi} \pm 1\sigma$ and $\tau_{K\pi} \pm 2\sigma$ are reported. The coverage conservation for the uncertainty intervals between the $B(\Delta\tau, \tau_{K\pi})$ quantity and $\tau_{K\pi}$ is verified by checking $B(\Delta\tau, \tau_{K\pi})$ be monotonic function of $\tau_{K\pi}$ once $\Delta\tau$ is fixed (Figure 9.6).

As last point, it is checked if Equation 9.2.7 is invertible in order to be able of extracting $\Delta\tau$ from $\langle t_{K\pi} \rangle - \langle t_{hh} \rangle$. Therefore Eq. 9.2.7 is plotted as function of $\Delta\tau$ and shown in Figure 9.7. From Figure 9.7 the function displays monotonic behavior thus it is invertible. The test is repeated at a wider range of $\Delta\tau \in [-25, 25]$ fs producing the same result. Therefore $\Delta\tau$ can be always extracted from $\langle t_{K\pi} \rangle - \langle t_{hh} \rangle$.

All these conclusions are reached taking in consideration exponential distributions. In presence of resolution effects disturbing this simple exponential shape,

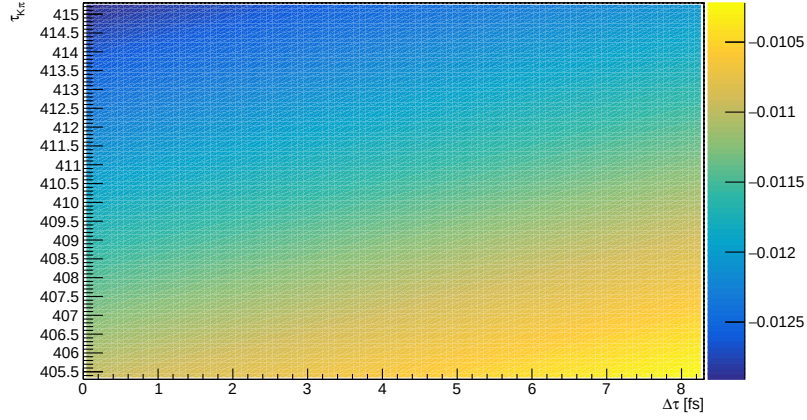


Figure 9.6: $B(\Delta\tau, \tau_{K\pi})$ function displaying monotonic trend as function of $\tau_{K\pi}$ for fixed values of $\Delta\tau$.

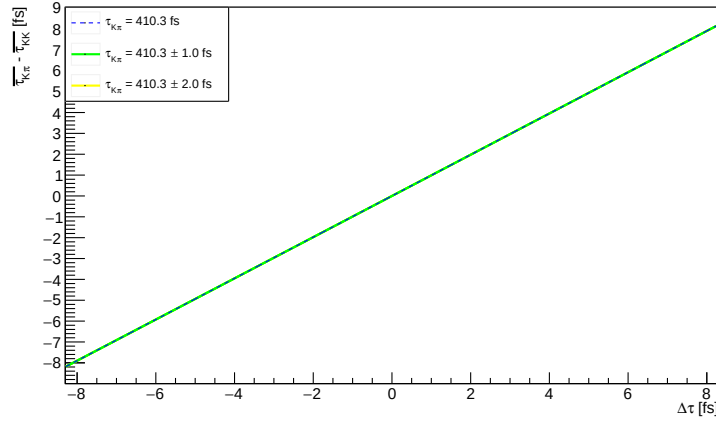


Figure 9.7: The function in Eq. 9.2.7 displaying monotonic behaviour in function of $\Delta\tau$.

the method and tests can be easily generalized to more complex distributions. In case of KDE as resolution smearing template, this algorithm must be adjusted for numerical evaluation, instead of analytic.

In conclusion to this chapter then, a method for extracting y_{CP} from the difference of lifetimes has been presented, promising to suppress the effects of secondary decays by a factor $1 - 1.2 \times 10^{-1}$ w.r.t. other algorithms depending only on the f_{sec} contamination fraction. Additional research is carried out for extracting the mean lifetime through methods other than fitting the sample distribution. Finally it has been checked if this method is feasible at increasing level of precision and at which conditions.

CHAPTER

10

CONCLUSIONS

The new analysis methodology developed in this work indicate a viable path to the highest precision measurements of the y_{CP} observable in the upcoming years, starting from the imminent Run 3. The issues arising at higher intensities have been addressed and shown to be solvable.

The adverse effects of primary vertex misassignments can be effectively avoided by computing the decay time with transverse variables only, and utilizing the mean primary vertex position (beam axis) in place of the event-by-event primary vertex. It has been shown that this change can be done without introducing any bias or loss of precision on the absolute lifetime measurement, up to a statistical precision level of 10^{-4} of the nominal D^0 mean lifetime τ_{D^0} , which surpass the projected precision attainable at the end of Run 6 with 300 fb^{-1} .

The central core of the analysis strategy is the fully data-driven track efficiency determination engine, which has been discussed in-depth from its theoretical foundation up to its various application aspects. This algorithm allows to accurately correct for the discrepancy between the efficiency of the $D^0 \rightarrow h^- h^+$ decay channel and $D^0 \rightarrow K^- \pi^+$, removing another roadblock arising when higher precisions on y_{CP} are pursued. No visible systematic effects on the retrieved absolute lifetime have been detected in the present work, up to a statistical precision of $5 \times 10^{-4} \tau_{D^0}$, securing the unbiasedness of the measurement up to $\sim 80 \text{ fb}^{-1}$ of integrated luminosity. This has been validated with the official LHCb Full Simulator, showing no visible bias on lifetime measurements up to a precision of $5 \times 10^{-3} \tau_{D^0}$, in both KK and $\pi\pi$ channels. These results have general applicability to all lifetime-related measurements at LHCb.

The procedure has then been applied to a substantial sample of real LHCb data from the past run (1 fb^{-1} of integrated luminosity). The main crosscheck quantity y_{CP}^{CC} used as validation of the recently published measurement has been remeasured to be:

$$y_{CP}^{CC LTUNB} = (-0.6 \pm 1.1) \times 10^{-3},$$

on par with the last LHCb measurement based on the same subsample

$$y_{CP}^{CCpublished} = (-1.15 \pm 1.30) \times 10^{-3},$$

thus proving that the whole algorithm here proposed can reproduce the measurement just published, with a statistical precision even improved by 20%.

Moving beyond the current measurement, that relies heavily on the availability of a very special, lifetime-unbiased sample, it has been proved that our analysis strategy is capable of producing reliable results on samples obtained from much less restrictive selections, as per our initial goal. This is a crucial step to enable improving this measurement with future data samples, collected in luminosity conditions that do not allow the use of lifetime-unbiased triggers due to their huge bandwidth cost. The reliability of this conclusion has been tested directly on real data, based on the “standard” charm trigger line that already existed in Run 2. The result is:

$$y_{CP}^{CCStandard} = (-0.46 \pm 0.77) \times 10^{-3},$$

showing that our novel method could in principle produce a better measurement already with past samples of data. Extrapolating to the 6 fb^{-1} sample of Run 2, it is obtained

$$\sigma(y_{CC})_{Standard}^{6 \text{ fb}^{-1}} = 0.31 \times 10^{-3}.$$

The precision on the y_{CP} observable attainable with this methodology can be projected at various values of integrated luminosity, obtaining the results shown in Table 10.1.

Sample	Luminosity [fb^{-1}]	Statistical $\sigma(y_{CP})$
Published LTUNB Run 2	6 fb^{-1}	2.6×10^{-4}
Projected LTUNB Run 2	6 fb^{-1}	2.2×10^{-4}
Projected Standard Run2	6 fb^{-1}	1.5×10^{-4}
Projected Standard Run 3	23 fb^{-1}	0.8×10^{-4}
Projected Standard Run 4	50 fb^{-1}	0.5×10^{-4}
Projected Standard Run 6	300 fb^{-1}	0.2×10^{-4}

Table 10.1: The projected statistical precision attainable with this work’s methodology at various values of integrated luminosity.

By the end of Run 3, the experimental precision is expected to reach the same level of the predicted effect by the SM.

In addition, a technique for suppressing the systematic effects of secondary decays up to a factor $\sim 1.2 \times 10^{-1}$ their current contribution on the statistical uncertainty, has been developed.

The potential systematic uncertainties in these future measurements have been considered, and it was shown that with these new tools they will not dominate up to a level of precision attainable at $\sim 80 \text{ fb}^{-1}$. In fact, there are good reasons to expect them to further decrease with the increase of the signal yields.

By looking at Table 10.2 where the systematic uncertainties of the published measurement are reported, it then can be concluded that the contribution due to

kinematic weighting procedure, which was the primary contribution concerning the KK channel, is totally excised.

Systematic	$\sigma(y_{CP}^{\pi\pi})$ [10^{-3}]	$\sigma(y_{CP}^{KK})$ [10^{-3}]
Combinatorial background	0.12	0.07
Treatment of secondary decays	0.03	0.03
Kinematic weighting procedure	0.08	0.02
Input D^0 lifetime	0.03	0.03
Residual nuisance asymmetries	0.03	< 0.01
Peaking background	0.02	0.11
Fit bias	0.03	0.03
Total	0.16	0.14

Table 10.2: The systematic uncertainties on the last LHCb y_{CP} published measurement.

Taking into account our arguments in Chapter 9 showing that the secondary decay uncertainty can be further suppressed by an order of magnitude, it can be concluded that a clearly marked pathway exists for performing very high precision y_{CP} measurements in all future planned LHCb runs, that will be able to detect and measure even the very small effect predicted by the SM.

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