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Measurement of production asymmetries

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The knowledge of charm production asymmetries is an important prerequisite for many of the possible searches for CP violation in charm. Measurements of these asymmetries at hadron colliders can also help to improve our understanding of QCD. These proceedings review existing measurements and discuss some of the experimental challenges of determining charge asymmetries at the per-mille level.

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1 Introduction

The recent hints of CP violation (CPV) in singly Cabibbo suppressed D^0 decays to two-body final states from LHCb [1] and CDF [2] have heightened interest from theoreticians in charm physics. Despite the lack of confirmation of these hints by further studies [3], searches for direct CPV in charm remain well motivated. Measurements of charm production asymmetries have the potential to increase the number of possible techniques for CPV searches in charm, and also to make existing searches more precise.

For example, the most powerful search technique is currently the measurement of the ΔA_{CP} observable, which is the difference in CP-violating asymmetries between $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$. This quantity is equal to the difference between the measured raw asymmetries in these decay modes, where the raw asymmetry is defined for observed numbers of decays N as

$$A_{raw} = \frac{N(D^0) - N(\overline{D^0})}{N(D^0) + N(\overline{D^0})}. \quad (1)$$

The largest useable samples of these decays are those that originate from D^{*+} decays to D^0 and a charged pion, which tags the flavour of the D^0 . Unfortunately, the values of ΔA_{CP} expected in the Standard Model are difficult to calculate, partly due to the lack of a good understanding of the strong interaction effects and partly because the charge asymmetries in the individual decay modes are not known. Knowledge of the production asymmetry in D^{*+} decays would enable measurements of the charge asymmetries in $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ separately, solving the second of these problems. Furthermore, a precise production asymmetry measurement could in principle lead to a more precise measurement of CP violation in $D^0 \rightarrow K^- K^+$ than that in ΔA_{CP} , where the statistical uncertainty is limited by the $D^0 \rightarrow \pi^- \pi^+$ decay channel. Measurements of production asymmetries in the D^+ , D_s^+ and Λ_c^+ sectors are also worthy endeavours which will pave the way for more precise searches for CP violation in their Cabibbo-suppressed decay modes.

Measurements of charm production asymmetries are also interesting in their own right. The huge samples of charm decays from proton-proton collisions available at the LHC experiments can be used to improve our knowledge of the structure of the proton. It is conceivable that the charm samples at the B-factories could also be used to make precise tests of QCD symmetries via an investigation of the forward-backward asymmetry in charm meson production.

The forward-backward asymmetry in D^\pm production has been measured at the Belle experiment, and the D^+ and D_s^+ production asymmetries in pp collisions have been measured at LHCb. These measurements, discussed in the next sections, all use large Cabibbo-favoured charm samples, in which no CP violation is expected.

To make full use of the high statistical precision possible with these samples, careful studies of the systematic effects intrinsic to charge asymmetry measurements in particle physics detectors are required, and these are also discussed here.

2 Production asymmetry measurements at e^+e^- colliders

In the search for CPV in $D^+ \rightarrow K_S^0 \pi^+$ at the Belle experiment [4], the CP, detector and production asymmetries are intertwined. The raw measured charge asymmetry is

$$A_{\text{rec}}^{K_S^0 \pi^+} = A_{CP}^{K_S^0 \pi^+} + A_{FB}^{D^+}(\cos \theta_{D^+}^{\text{CMS}}) + A^{\pi^+}(p_{T\pi^+}^{\text{lab}}, \cos \theta_{\pi^+}^{\text{lab}}) + A_{\mathcal{D}}(p_{K_S^0}^{\text{lab}}) \quad (2)$$

where $A^{\pi^+}(p_{T\pi^+}^{\text{lab}}, \cos \theta_{\pi^+}^{\text{lab}})$ and $A_{\mathcal{D}}(p_{K_S^0}^{\text{lab}})$ are the detection asymmetries of charged pions and neutral kaons respectively. The quantities p^{lab} and $p_{\text{T}}^{\text{lab}}$ refer to momentum and transverse momentum in the laboratory frame. The angle θ is the angle of the pion with respect to the axis of the beam, in either the laboratory (lab) frame or the centre of mass (CMS) frame. $A_{FB}^{D^+}(\cos \theta_{D^+}^{\text{CMS}})$ is the forward-backward production asymmetry. $A^{\pi^+}(p_{T\pi^+}^{\text{lab}}, \cos \theta_{\pi^+}^{\text{lab}})$ is measured as the difference in raw charge asymmetries between $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^0 \rightarrow K^- \pi^+ \pi^0$ under the assumption that D^0 and D^+ have the same forward-backward asymmetry. $A_{\mathcal{D}}(p_{K_S^0}^{\text{lab}})$ is calculated as discussed in Sect. 4, and subsequently subtracted.

The asymmetries due to production and CP violation are then determined. In terms of the charge asymmetry after correction for detector effects, $A_{\text{rec}}^{K_S^0 \pi^+ \text{corr}}$, they are

$$A_{CP}^{K_S^0 \pi^+} = [A_{\text{rec}}^{K_S^0 \pi^+ \text{corr}}(+\cos \theta_{D^+}^{\text{CMS}}) + A_{\text{rec}}^{K_S^0 \pi^+ \text{corr}}(-\cos \theta_{D^+}^{\text{CMS}})]/2, \quad (3)$$

$$A_{FB}^{D^+} = [A_{\text{rec}}^{K_S^0 \pi^+ \text{corr}}(+\cos \theta_{D^+}^{\text{CMS}}) - A_{\text{rec}}^{K_S^0 \pi^+ \text{corr}}(-\cos \theta_{D^+}^{\text{CMS}})]/2 \quad (4)$$

respectively. The CP asymmetry is consistent with CPV in the neutral kaon system as expected: $D^+ \rightarrow K_S^0 \pi^+$ is a predominantly Cabibbo-favoured decay with no loop contribution at first order.

The assumption that the forward-backward asymmetries in charm meson production at e^+e^- colliders does not depend on the flavour of the other quark in the meson could be tested if the pion efficiency asymmetry could be determined using another method, for example the technique outlined in Sect. 4 that has been employed at LHCb.

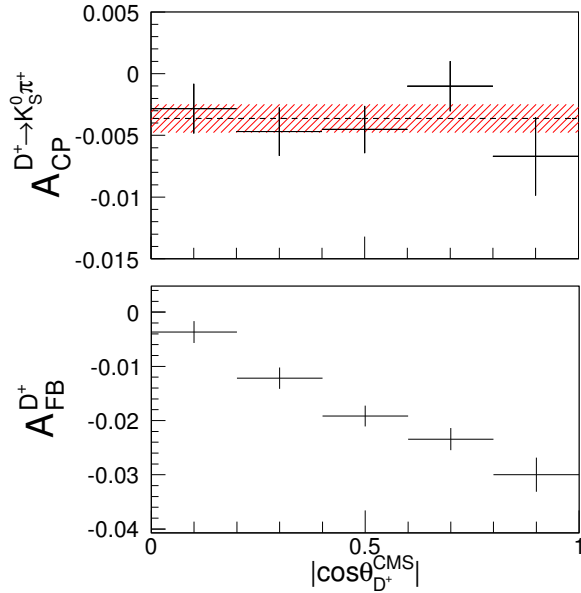


Figure 1: CP (top) and production (bottom) asymmetries measured in the $D^+ \rightarrow K_S^0 \pi^+$ channel with a data sample corresponding to an integrated luminosity of 977 fb^{-1} at the Belle experiment [4].

3 Production asymmetries at hadron colliders

When two protons collide, the baryon number conservation law implies that two more baryons than antibaryons will form in the final state. These will sometimes contain charm quarks, and thus one expects an excess of charmed baryons over charmed antibaryons, with the effect being more pronounced at high rapidity where the valence quarks tend to end up. The anticharm quark formed with the charm quark must form part of a meson, resulting in an excess of \bar{D}^0 over D^0 and of D^- over D^+ . It is helpful to define the Feynman momentum x_F as the fraction of the longitudinal momentum p carried by the relevant parton. This x_F is related approximately to rapidity η , transverse mass m_T and centre-of-mass energy \sqrt{s} by

$$x_F \sim 2m_T e^\eta / \sqrt{s} \quad (5)$$

for $\eta > 1$. Since the valence quarks are found at high rapidity, the production asymmetry is likely to increase with x_F .

In perturbative quantum chromodynamics (pQCD), charm quarks are produced by processes such as $q + \bar{q} \rightarrow c + \bar{c}$ and $g + g \rightarrow c + \bar{c}$, with the second dominating at high energy. Neither of these yield an overall excess of one quark type over the other,

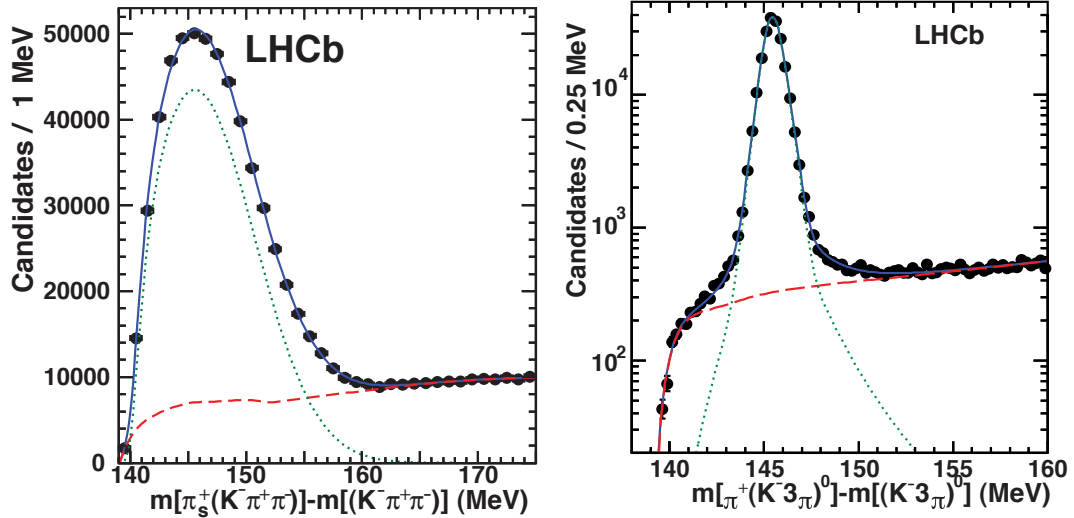


Figure 2: Mass distributions for the tagging $D^*(2010)^+$ particle in the partially (left) and fully (right) reconstructed D^0 decays to $K^-\pi^+\pi^-\pi^+$.

however. Such net production asymmetries cannot be explained with pQCD, nor with the string fragmentation model contained in the PYTHIA framework typically used to simulate pp interactions at collider experiments. More creative explanations must therefore be devised. Some models, for example the ‘meson cloud model’ [5], assume that the incoming proton fluctuates into a virtual charm meson - charm baryon pair which can sometimes escape and become real. Alternatively it has been proposed that $\bar{c}c$ pairs exist in the sea and have some probability to ‘recombine’ with valence quarks and hadronise [6]. These two models lead to different forecasts for the energy dependence of the production asymmetry, and Ref. [5] contains concrete predictions which are compared to LHCb measurements of the D^\pm asymmetry.

The LHCb collaboration has measured both the D^\pm and the D_s^\pm production asymmetries [7, 8]. The D_s^\pm asymmetry was determined using $D_s^+ \rightarrow \phi\pi^+$ decays. In this case, the raw measured asymmetry and the production asymmetry must be corrected by the detection asymmetry of the charged pion. This was determined using tagged D^0 decays to $K^-\pi^+\pi^-\pi^+$. Due to the large number of kinematic constraints provided by the four-body final state, it is possible to reconstruct $D^*(2010)^+$ -tagged decays of this type with one pion missing. The pion tracking efficiency is then the yield of fully reconstructed decays divided by the yield of decays partially reconstructed with a missing pion. The mass distributions for these two cases in the data recorded at LHCb in 2011 are shown in Fig. 2.

The tracking efficiencies are determined for D^{*+} and D^{*-} separately, and thus the charge asymmetry in the pion detection efficiency is obtained. When averaged

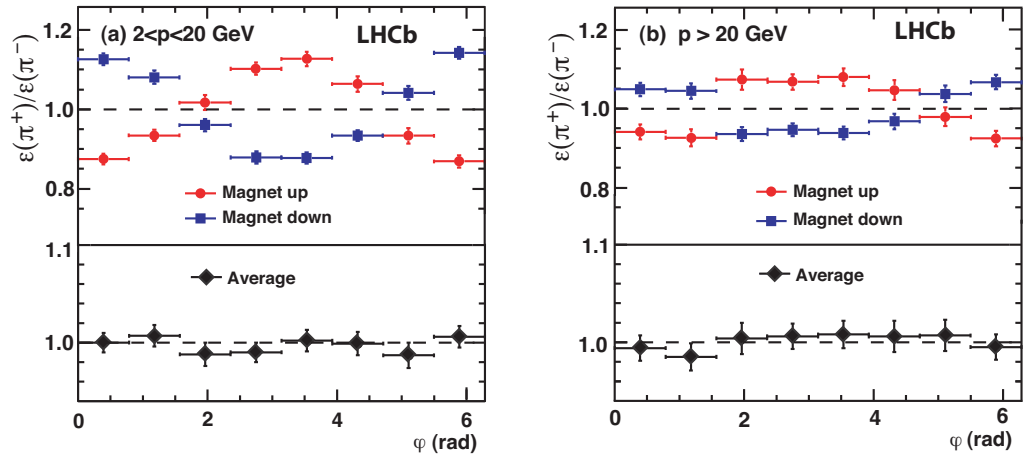


Figure 3: The variation of the asymmetry in the pion tracking asymmetry with the azimuthal angle ϕ made by the pion with a horizontal plane defined across the centre of the detector, which is the bending plane of the magnet. The causes and ramifications of the variation in the data split according to the polarity of the magnet are discussed in Sec. 4.

over the LHCb acceptance, the asymmetry is small, of order 0.1%. However, for a given polarity of the LHCb magnet, the asymmetry varies quite strongly according to where in the detector the pions end up, as shown in Fig. 3. This is discussed further in Sect. 4.

In a similar analysis, the D^+ asymmetry was measured using $D^+ \rightarrow K_S^0 \pi^+$ decays. Here

$$A_{prod} = A_{raw} - A_{\pi^+} - A_{K_S^0} \quad (6)$$

where the K_S^0 asymmetry $A_{K_S^0}$ is due to CP violation and material interactions in the neutral kaon system. There is assumed to be no CPV in the D^+ decay.

To determine the production asymmetries, the yields of $D_{(s)}^+$ and $D_{(s)}^-$ decays, and the average pion efficiency asymmetries, are determined in p_T and η bins. The overall yields are shown in Fig. 4. The raw asymmetries are thus corrected for the pion asymmetry on a per-bin basis. Measured raw asymmetries in bins of p_T and η are weighted by the reconstruction efficiency in these bins to determine an average asymmetry, and finally the charge asymmetry due to the neutral kaon is subtracted in the case of the D^+ measurement. This last quantity is very small because only neutral kaons with very short lifetimes are selected for use in the analysis, and thus its variation with p_T and η is negligible. The results are asymmetries for $D_{(s)}^+$ decays produced in pp collisions in the LHCb acceptance.

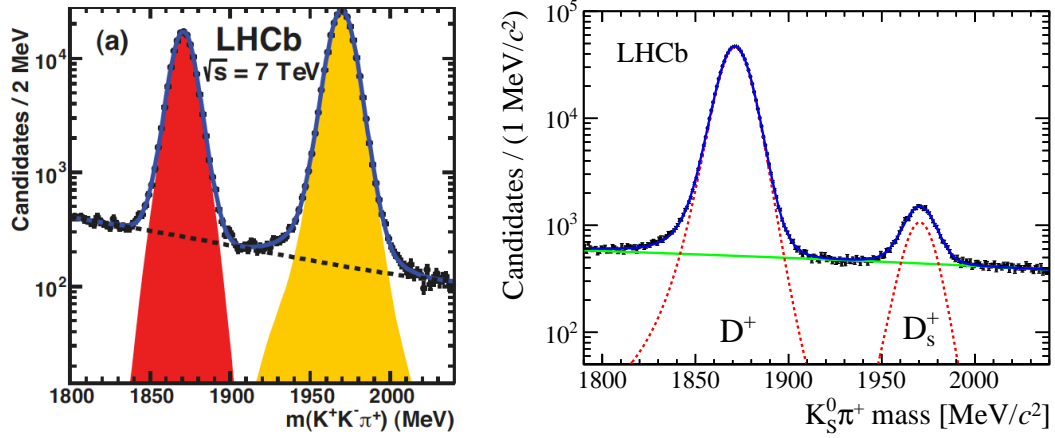


Figure 4: Invariant mass distributions of the two final state particle combinations used to measure the D_s^+ (left) and D^+ (right) production asymmetries. In both cases, the D_s^+ and D^+ mass peaks are visible.

The average asymmetries are

$$A_{prod}(D_{(s)}^+) = (-0.33 \pm 0.13 \pm 0.18 \pm 0.10)\% \quad (7)$$

$$A_{prod}(D^+) = (-0.96 \pm 0.19 \pm 0.18 \pm 0.18)\% \quad (8)$$

where the uncertainties are statistical on the $D_{(s)}^+$ decays, statistical on the pion efficiency asymmetry correction, and systematic. There are some hints of the expected dependence on p_T and η in the D^+ case, as shown in Fig. 5.

The comparison of the results with the theoretical model of Ref. [5] is shown in Fig. 6. It is clear that the effect is relatively small and the dependence on kinematic

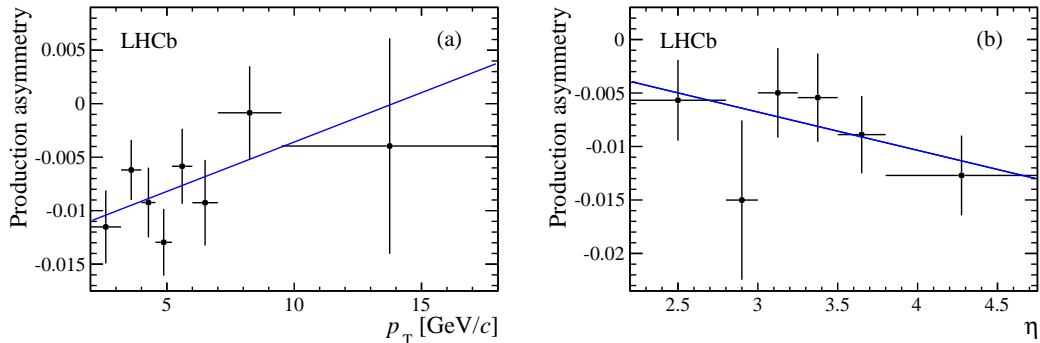


Figure 5: Dependence of the D^+ production asymmetry on p_T (left) and η (right).

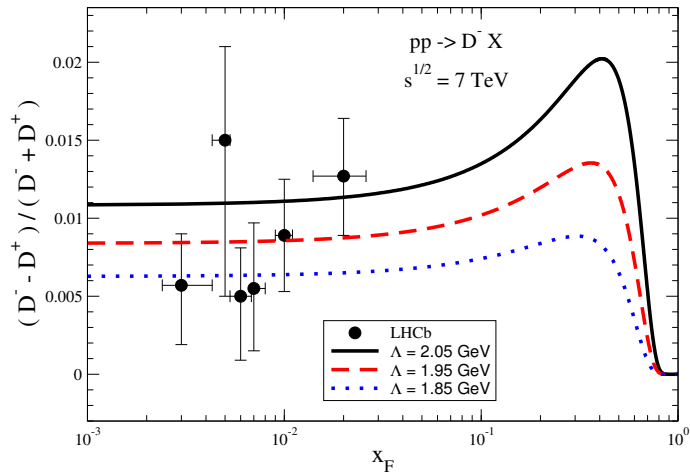


Figure 6: Comparison of production asymmetries measured at LHCb with the predictions of the meson cloud theory [5]. The parameter Λ is a cut-off. Note that the opposite convention is used here to define asymmetry, with an excess of D^- decays being defined as positive.

variables relatively weak, so more precise data will be needed before a fully rigorous test of the theory can be performed.

4 Experimental challenges

As data samples get larger and larger, systematic uncertainties are becoming increasingly important. It is a generally held view that systematics can be controlled at the level of the statistical uncertainty, but to achieve this they must be studied in ever more detail.

In charge asymmetry measurements, important systematic uncertainties arise from the fact that the magnetic field used to separate the charges bends oppositely-charged particles in opposite directions so they pass through different parts of the detector. The different detector elements could have different efficiencies. This is illustrated for the LHCb detector in Fig. 7. The different acceptance and efficiency in different radial directions is responsible for the large asymmetries seen in, for example, the pion detection efficiency as a function of azimuthal angle in Fig. 3 for data taken with one magnet polarity. This figure highlights the importance of taking data with both magnet polarities and averaging the results, as this leads to near-complete cancellation of the effects.

Other key systematic uncertainties in LHCb production and CP asymmetry measurements are associated with material interaction effects. The asymmetric interac-

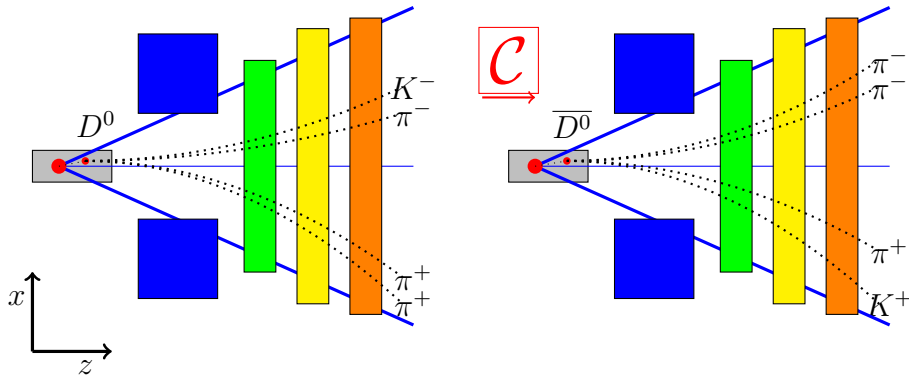


Figure 7: Schematic of the LHCb detector showing the path of charged particles from a $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decay and its charge conjugate. In this case, the raw asymmetry will be dominated by the material interaction effects of the charged kaon, but when the pion tracking efficiency is measured, this cancels between the numerator and the denominator.

tion of positive and negative pions with detector material are responsible for most of the angle-independent asymmetry in Fig. 3. Charged kaon material interactions lead to still larger asymmetries. There are also nuisance effects from neutral kaon mixing and CP violation. Neutral kaons are particularly interesting because they violate CP and their mixing can be affected by material interactions.

To parameterise neutral kaon material interactions, one usually defines a ‘regeneration parameter’ r in terms of forward scattering amplitudes f and \bar{f} for K^0 and \bar{K}^0 respectively,

$$r = -\frac{\pi \mathcal{N}(f - \bar{f})}{\Delta m - \frac{i}{2}(\Gamma_L - \Gamma_S)} \quad (9)$$

where \mathcal{N} is the number density of atoms in the material, Δm is the mass difference between K^0 and \bar{K}^0 , and $\Gamma_{L,S}$ are their lifetimes. The imaginary part of f is related to the cross section by the optical theorem and the real part of f is related to the imaginary part by dispersion integrals [9]. The difference between K^0 and \bar{K}^0 scattering amplitudes follows the scaling law

$$f - \bar{f} \propto -\frac{23.2 p A^{0.758}}{[p \text{ (GeV}/c)]^{0.614}} \text{ mb} \quad (10)$$

where A is the nucleon number of the material and p is the momentum of the neutral kaon [10]. Ko *et al* [11] model a detector as a series of layers of material, calculate r for each layer using measured cross sections, and solve a set of recursive equations to determine the asymmetry as a function of the kaon decay time and momentum.

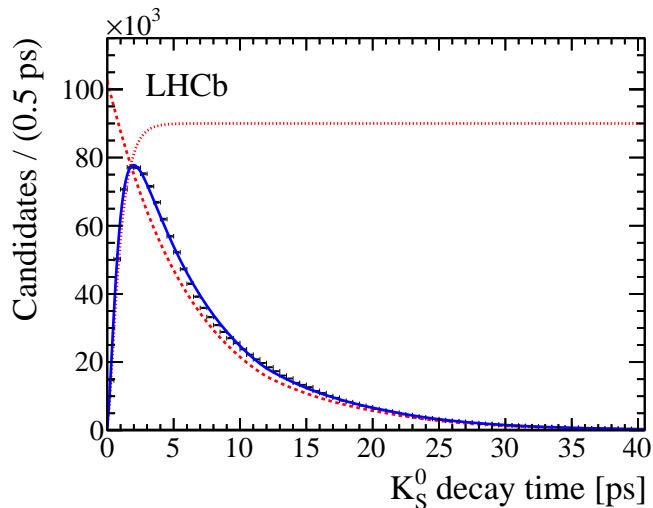


Figure 8: The K_S^0 decay time distribution for neutral kaons selected for use in the production asymmetry analysis.

The CPV in the neutral kaon system decouples from this regeneration at first order. Neglecting direct CPV, it is given by

$$A(t) = 2\text{Re}(\epsilon) - 2e^{-\frac{1}{2}\Delta\Gamma t} (\text{Re}(\epsilon) \cos \Delta mt + \text{Im}(\epsilon) \sin \Delta mt) \quad (11)$$

where the indirect CP violation parameter ϵ is approximately 2×10^{-3} .

The formalism has now been employed at LHCb, but to date both material interactions and CPV lead to small effects on the measured raw asymmetries in charm decays of a few times 10^{-4} . This is because kaons used in current analyses are very short-lived compared to K_S^0 lifetime of 89 ps, due to peculiarities in the trigger and selection criteria. The decay time distribution of the kaons is shown in Fig. 8.

5 Perspective

With production asymmetries under control, it is possible to search for CP-violation more precisely and in more different ways. Sometimes one can extract the production and CPV asymmetries together, as done in the analysis of $D^+ \rightarrow K_S^0 h^+$ by the Belle collaboration. Production asymmetries are also interesting for QCD and those measured in pp collisions should help theorists to develop non-perturbative models of the proton.

The prospects for the future include measurements of the Λ_c^+ and D^{*+} production asymmetries at LHCb. These are likely to be challenging but rewarding analyses and

the results will be highly pertinent to our understanding of both particle production and CP violation in charm decays.

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