

WG5 summary: direct CP violation in B decays

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These proceedings summarise new results shown at the 2016 CKM workshop in Working Group 5. Time-integrated charge asymmetry measurements in $B \rightarrow Dh$ and charmless b -hadron decays are core themes of the group but several ancillary topics are reported. Vital to understanding $B \rightarrow D^0 K$ charge asymmetries in multibody D^0 decays is knowledge of the CP content of the D^0 decay and two important developments are described. Also reported is a number of searches for new hadronic B decay signatures. Experimental results are dominated by LHCb at this time though, results from Belle are still forthcoming.

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1. Introduction

These proceedings summarise the the study of direct CP violation in hadronic B decays as presented at the conference. The results are fall into three categories: measurements of CP observables from the $B \rightarrow DK$ family of decays; studies of direct CP violation in charmless decays; searches for new hadronic modes which may be later studied in the context of CP violation.

There is an emphasis on open charm decays of B^+ and B^0 mesons to the $D^{(*)}K^{(*)}$ final states because these decays have tree-level sensitivity to the Unitarity Triangle angle γ . The importance of the tree-level sensitivity is that these decays suffer negligible corrections from higher-order loop contributions. In contrast to the charmed case, CP -violation in charmless decays requires the interference of tree and loop (penguin) amplitudes. The separation of the hadronic (strong) parameters from the CKM (weak) information is not trivial.

2. $B \rightarrow D^0 K^{(*)}$

The sensitivity to the CP -violating weak phase of the CKM matrix is achieved in $B \rightarrow D^0 K^{(*)}$ decays because the rates for B and \bar{B} decays depend on $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$, which is closely related to the CKM phase. Decays of this type are dominated by $b \rightarrow c\bar{u}s$ tree-level transitions but receive a significant contribution from $b \rightarrow u\bar{c}s$ transitions, also a tree decay. The interference of these amplitudes allows sensitivity to the phases between them which can be further separated into CP -violating and CP -conserving parts. The CP -violating phase is that of the weak force where the CP -conserving part is associated with the dynamics of the strong forces in the formation of the mesons. Inspection of the contributing CKM elements identifies the weak phase in $B \rightarrow D^0 K^{(*)}$ decays as $\gamma \cong \arg(-V_{ub}^*/V_{cb}^*)$. To be sensitive to interference effects the charm meson must be reconstructed in final state accessible (with similar magnitude) from both D^0 and \bar{D}^0 . Conceptually this is simplest where the charm meson is reconstructed in a CP eigenstate as this is equally accessible to both D^0 and \bar{D}^0 (in the absence of direct CP violation in the charm decay) as advocated in the GLW method [1]. It can be shown that the rates for B^+ and B^- thus differ,

$$\Gamma(B^\pm \rightarrow D_{CP}K^\pm) = \left| 1 + r_B e^{i(\delta_B \pm \gamma)} \right|^2 = 1 + r_B^2 + 2r_B \cos(\delta_B \pm \gamma), \quad (2.1)$$

where the magnitude of the $b \rightarrow u\bar{c}s$ amplitude compared to that of the $b \rightarrow c\bar{u}s$ transition is the factor r_B and the CP -conserving phase between the two amplitudes is labelled δ_B . The ADS method [2] is a generalisation that can include non- CP eigenstate decays of the D^0 by included a factor relating \bar{D}^0 and D^0 to a common final state, $r_D e^{-i\delta_D}$. In the charm meson decay only a CP -conserving phase is needed as CP -violating effects are neglected; the minus sign needed by convention. For example $K^- \pi^+$ which doubly-Cabibbo-suppressed in the case that it comes from a \bar{D}^0 but favoured from a D^0 . By choosing combinations where the charge of the kaon from the B and D are of opposite charge, the two interfering amplitudes represented in Eq. 2.1 become similar in size and thus much larger interference effects (asymmetries) are possible. The B^\pm decay rate becomes,

$$\Gamma(B^\pm \rightarrow [\pi^\pm K^\mp]_D K^\pm) = \left| r_D e^{-i\delta_D} + r_B e^{i(\delta_B \pm \gamma)} \right|^2 = r_D^2 + r_B^2 + 2\kappa r_D r_B \cos(\delta_B - \delta_D \pm \gamma), \quad (2.2)$$

where $\kappa = 1$ for two-body D -decays. Note that in the case of a CP -eigenstate decay, $r_D = 1$ and $\delta_D = 0$ and Eq. 2.2 reverts to Eq. 2.1. This formula generalises to three- or four-body final states

by a non-unity value of the dilution parameter, κ , in the interference term of Eq. 2.2. In the special cases that a self-conjugate charm decay is used, notably $D^0 \rightarrow K_s^0 \pi^+ \pi^-$, the dilution factor is approximately zero and so, taken inclusively, the CP information washes out. In this case, it is preferable to measure CP asymmetries across the D decay Dalitz plane with the GGSZ method [3].

2.1 Combination of results for γ

With so many techniques and no overall golden mode for the measurement of γ in $B \rightarrow D^0 K^{(*)}$ decays, a statistical combination is made. This inference must take into account correct treatment of nuisance parameters and consideration for coverage. Two techniques are common,

- A **Frequentist** statistical approach starts from a likelihood function, built from the product of probability density functions (PDFs). The PDFs are calculated from the experimental observables and their uncertainties assuming that these uncertainties describe a multidimensional Gaussian distribution.
- A **Bayesian** statistical approach calculates probability regions in the multi-parameter space by finding the highest posterior probability density, integrating over the nuisance parameters. The posterior probability density is related to the likelihood by the prior probability of the parameters. In all work described here, the prior probability are assumed to be uniform.

The most precise measurements of the CP observables from $B \rightarrow DK$ decays come from LHCb and that collaboration have performed a statistical inference using their published results [4]. Using results from the ADS/GLW and GGSZ analyses of $B^+ \rightarrow DK^+$ decays and $B^0 \rightarrow DK^0$ decays, plus time-dependent asymmetries in $B_s^0 \rightarrow D_s^+ K^-$ decays, LHCb infer values of γ using both a Frequentist and Bayesian approach,

$$(72.2^{+6.8}_{-7.3})^\circ \text{ Frequentist LHCb and } (70.3^{+7.1}_{-7.9})^\circ \text{ Bayesian LHCb,}$$

which are considered compatible, given the assumptions made by the competing techniques.

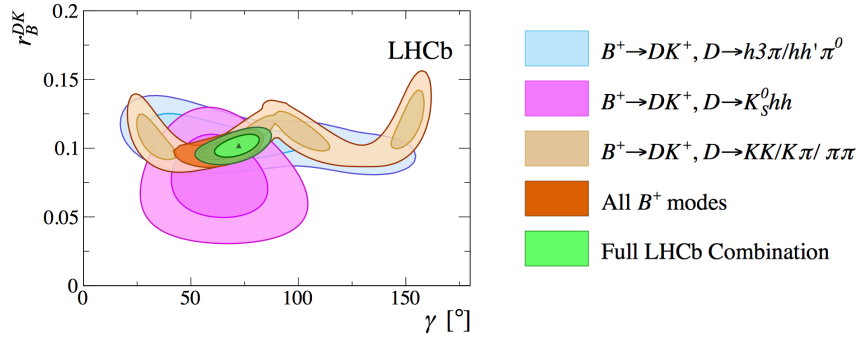


Figure 1: Profile likelihood contours for r_B vs. γ , where r_B is the ratio of suppressed to favoured amplitudes contributing to $B^+ \rightarrow DK^+$ decays. The measurements that contribute to each contour are described in the legend. The full frequentist LHCb combination is shown in green. In each case the dark and light regions show the intervals containing 68.3% and 95.5% respectively.

The profile likelihood contours for $B^+ \rightarrow DK^+$ decays are shown in Fig. 1. The full LHCb combination illustrates the important contribution from $B^+ \rightarrow DK^+$ modes. A further combination

which includes CP observables in the ADS/GLW analyses of $B^+ \rightarrow D\pi^+$ decays with the effect of D -mixing properly taken into account shows negligible improvement in the uncertainty of γ . Dedicated proceedings describe the contributing LHCb analyses from $B \rightarrow D^{(*)}K^*$ decays [5] and $B \rightarrow Dhh'$ decays [6].

Global combinations, which include legacy measurements from the B -factories are also available from the CKMfitter [7] and UTFit [8, 9] groups with updates presented at conference; these results are seen to be similar to, and dominated by, the LHCb measurements,

$$(72.2^{+5.3}_{-5.8})^\circ \text{ Global Frequentist (CKMfitter) and } (70.5 \pm 5.7)^\circ \text{ Global Bayesian (UTFit).}$$

2.2 $B^+ \rightarrow DK^{*+}$

An important new result, presented for the first time from LHCb, is a preliminary ADS/GLW analysis of $B^- \rightarrow DK^{*-}$ [10]. This is the first time that this mode has been reconstructed at a hadron collider though results have been available from the Babar for some time [11]. The analysis

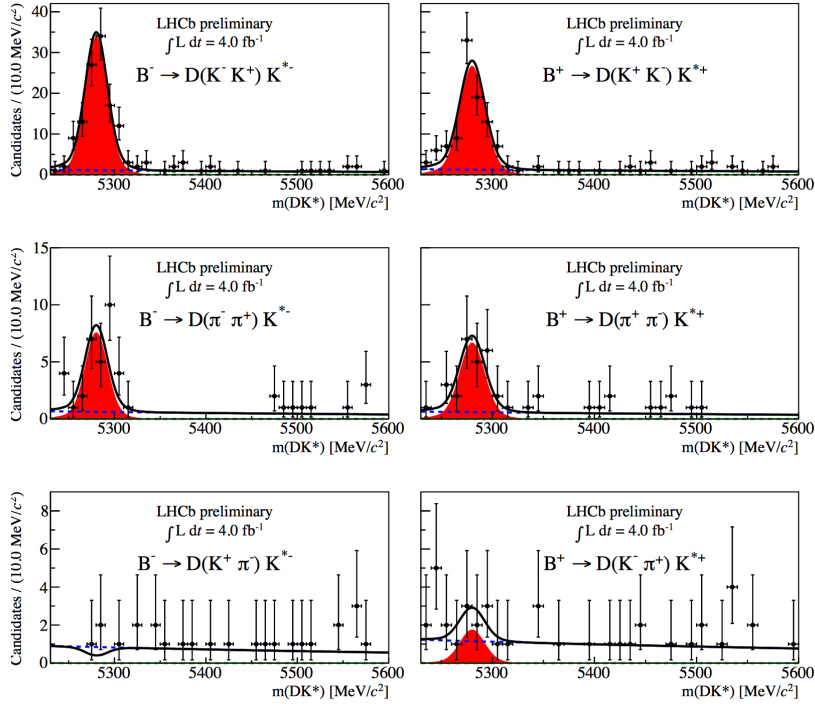


Figure 2: Invariant mass distributions to $B^- \rightarrow DK^{*-}$ decays (left) and $B^+ \rightarrow DK^{*+}$ decays (right) from LHCb. From top to bottom the D^0 decay modes are K^+K^- , $\pi^+\pi^-$ and suppressed $K\pi$ combinations. The signal component is represented by the red area.

reconstructs $K^{*-} \rightarrow K_S^0 \pi^-$ which means the number of events with respect to an analysis of $B^- \rightarrow DK^-$ decays is lower by the branching fraction of $K^{*-} \rightarrow [\pi^+\pi^-]_{K_S^0} \pi^-$ ($\approx \frac{2}{3}$) and the efficiency of reconstructing and selecting a K_S^0 in the experiment ($\approx 12\%$ for LHCb). The DK^{*+} final state has the advantage that there is no large misidentified physics background, like $B^- \rightarrow D^0 \pi^-$ in the case of $B^- \rightarrow D^0 K^-$. The CP observables are ratios of branching fractions and charge asymmetries,

$$R_{CP+} = \frac{2\Gamma(B^- \rightarrow D_{CP} K^{*-}) + \Gamma(B^+ \rightarrow D_{CP} K^{*+})}{\Gamma(B^- \rightarrow D^0 K^{*-}) + \Gamma(B^+ \rightarrow \bar{D}^0 K^{*+})} = 1.21 \pm 0.10, \quad (2.3)$$

$$A_{CP+} = \frac{\Gamma(B^- \rightarrow D_{CP} K^{*-}) - \Gamma(B^+ \rightarrow D_{CP} K^{*+})}{\Gamma(B^- \rightarrow D_{CP} K^{*-}) + \Gamma(B^+ \rightarrow D_{CP} K^{*+})} = 0.11 \pm 0.07, \quad (2.4)$$

$$R_{ADS} = \frac{\Gamma(B^- \rightarrow [\pi^- K^+]_D K^{*-}) + \Gamma(B^+ \rightarrow [\pi^+ K^-]_D K^{*+})}{\Gamma(B^- \rightarrow D^0 K^{*-}) + \Gamma(B^+ \rightarrow \bar{D}^0 K^{*+})} = 0.003 \pm 0.004. \quad (2.5)$$

The observables with the CP subscript are taken from the weighted sum of the results in the $K^+ K^-$ and $\pi^+ \pi^-$ D -meson modes. R_{ADS} is the rate of the suppressed mode, where the kaon from the D decay is of opposite charge to that of the K^* , compared to the favoured mode. These suppressed mode data are shown in the third row of Fig. 2 from which an intriguing charge asymmetry is seen. As non-resonant $K_S^0 \pi^-$ can contribute non-negligibly to the signal due to the necessarily large mass window of the K^{*-} selection. This introduces a dependence on a coherence factor κ as described in Eq. 2.2, estimated to be 0.95 ± 0.06 within the K^{*-} mass and helicity window requirements. The parameter κ is estimated by generating many amplitude models for $B \rightarrow DK_S^0 \pi$ decays consisting of resonant components whose relative amplitudes and phases are varied within limits according to branching ratio measurements.

2.3 B -factories and γ

Though most $B \rightarrow DK$ analyses were first made at Belle and Babar, the large LHCb dataset means that experiment's results currently provide for most information on γ . The B -factory data nevertheless continues to make new contributions, especially in with modes that involve neutral particles. It is known that a useful addition to the $B \rightarrow DK$ suite of analyses is that of $B^+ \rightarrow D^* K^+$ decays with $D^{*0} \rightarrow D^0 \pi^0$ and $D^{*0} \rightarrow D^0 \gamma$. Belle report an analysis of this mode using 711 fb^{-1} , or 7.72 million $B\bar{B}$ events, with CP observables,

$$\begin{aligned} R_{CP+} &= 1.19 \pm 0.13 \pm 0.03, & R_{ADS}(D\pi^0) &= (1.0_{-0.7}^{+0.8} \text{ }_{-0.2}^{+0.1}) \%, \\ R_{CP-} &= 1.03 \pm 0.13 \pm 0.03, & R_{ADS}(D\gamma) &= (3.6_{-1.2}^{+1.4} \pm 0.2) \%, \\ A_{CP+} &= -0.14 \pm 0.10 \pm 0.01, & A_{ADS}(D\pi^0) &= +0.4_{-0.7}^{+1.1} \text{ }_{-0.1}^{+0.2}, \\ A_{CP-} &= +0.22 \pm 0.11 \pm 0.01, & A_{ADS}(D\gamma) &= -0.5 \pm 0.3 \pm 0.1. \end{aligned}$$

A 3.5σ signal is claimed for the $D^{*0} \rightarrow D\gamma$ ADS mode. Full details and implications for γ are anticipated soon [12].

From late 2018, the new $e^+ e^-$ B -factory, Belle II, starts collecting data. The benefits of the higher efficiency, especially for neutral particles, means Belle II will bring significant competition to LHCb in the pursuit of degree-level precision on γ . A comparison of the expected uncertainty on γ for LHCb and Belle II is shown in Fig. 3, reproduced from the dedicated proceedings [12]. These projections, based on extrapolating uncertainties from two-body GLW/ADS analyses plus $K_S^0 \pi^+ \pi^-$ GGSZ analyses, suggest that the two experiments will approach statistical uncertainties of less than 2° within eight years. This prediction is conservative because there are a large number of additional modes that both experiments can exploit.

2.4 Limitation for precision measurements

The culmination of $B \rightarrow D^0 K$ analyses over the next decade will be a precision on γ around 1° . At this level, γ will be known to a similar precision as with the measurement of the Unitarity Triangle β from $B^0 \rightarrow J/\psi K^0$. The theoretical uncertainty on the value of γ from $B \rightarrow DK$ decays is far beyond this experimental limit because there is a negligible loop contribution in $B \rightarrow DK$

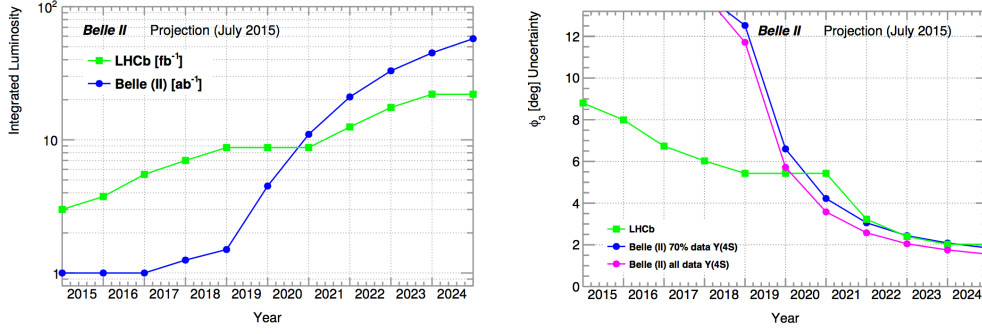


Figure 3: Projected dataset size (left) and projected uncertainty on γ (right) as a function of time.

decays and the hadronic parameters can be fitted from data. In recent work the ultimate limitations, from a theoretical point of view, are identified:

- Measurements of γ are biased by D mixing effects though these can be entirely corrected for with precise knowledge of the D mixing parameters and the lifetime acceptance [13].
- The CP violation in K^0 mixing can cause the biases in modes involving a K_S^0 . Uncorrected, the bias is of the order ϵ_K/r_B where $\epsilon_K \approx 2 \times 10^{-3}$ so can be a significant bias for GGSZ analyses with $B \rightarrow D\pi$ decays [14].
- The CP -violating phase measured from the interference in $B \rightarrow DK$ decays is not exactly γ , as defined from the Unitarity Triangle. The difference is due to sub-leading terms that are considered to be without an imaginary component. To correct for this effect requires precise knowledge of the ratio $V_{cd}V_{cs}^*/V_{ud}V_{us}^* \sim 2.6 \times 10^{-3}$ [15].
- The irreducible theoretical uncertainty in γ comes from the contribution from alternative Feynmann diagrams with *different* CKM elements. Second-order box diagrams can contribute to the $b \rightarrow c\bar{u}s$ amplitude with different CKM elements (the $b \rightarrow u\bar{c}s$ amplitude is safe) resulting in a limiting theoretical uncertainty $|\delta_\gamma/\gamma| \leq 10^{-7}$ for $B \rightarrow DK$ decays and $\leq 10^{-4}$ in the case of $B \rightarrow D\pi$ decays [16].

In a related study [17], the assumption of no new physics at tree-level is reviewed. It is found that a universal New Physics contribution to tree-level B decays is not excluded by the data. The intrinsic, model-independent, theoretical uncertainty on γ in this paradigm is $|\delta_\gamma| \approx 4^\circ$ so this speculative possibility will soon be constrained by direct measurement. It is also noted that $B \rightarrow DK$ decays have a built-in test for New Physics in the presumption that the ratio of amplitudes r_B is the same for b - and \bar{b} -quark transitions. Tests for New Physics should thus retain sensitivity to $r_{B-} \neq r_{B+}$.

3. Charm inputs for $B \rightarrow DK$ analyses

The understanding of CP -violation in $B \rightarrow DK$ in anything other than the simplest GLW analysis requires external information on the hadronic parameters of the neutral charm decay that is produced from the B decay. As discussed above, the ADS and GLW modes can be generalised to

three or more particles in the final state by including a dilution parameter. Where the dilution parameter is small, it is not useful to approximate to a two-body and a GGSZ (or GGSZ-like) analysis is used. In this case, the CP content of the D^0 decay is described by n (c_i, s_i) parameters ($1 < i < n$) defined in n bins across the Dalitz space of the multibody D^0 decay.

$$c_i + is_i = \frac{\int_i A_f(\mathbf{p}) \bar{A}_f(\mathbf{p})^* d\mathbf{p}}{\sqrt{\int_i |A_f(\mathbf{p})|^2 d\mathbf{p} \cdot \int_i |\bar{A}_f(\mathbf{p})|^2 d\mathbf{p}}},$$

where the amplitude for the \bar{D}^0 going to final state f at point \mathbf{p} on the Dalitz space is $\bar{A}_f(\mathbf{p})$. In the GGSZ analysis of $D \rightarrow K_S^0 \pi^+ \pi^-$, symmetric binning around the $y = x$ diagonal of the Dalitz plot ensures a simple relation between the CP -conjugate bins either side of this divide, $c_{-i} = c_i$, $s_{-i} = -s_i$. In recent work, these ideas have been expanded to four-body self-conjugate final states.

3.1 $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$

In analysis of $B^+ \rightarrow [\pi^+ \pi^- \pi^+ \pi^-]_D K^+$ decays by LHCb [18] demonstrates event yields similar to the primary GGSZ mode, $B^+ \rightarrow [K_S^0 \pi^+ \pi^-]_D K^+$ [19]. Furthermore, the overall CP -fraction in this mode is only $F_+ = 0.737 \pm 0.028$ [20]. In terms of an overall, total phase-space averaged c_0, s_0 , this is $c_0 = 2F_+ - 1 = 0.474 \pm 0.056$, $s_0 = 0.0$, which means that there is a potential factor of two increase in sensitivity with a binning of c_i, s_i measurements.

A four-body amplitude analysis of $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ has recently become completed using data collected by the CLEO-c detector [21]. Prominent contributions are found from the decay modes $D^0 \rightarrow a_1(1260)^+ \pi^-$, $D^0 \rightarrow \sigma f_0(1370)$ and $D^0 \rightarrow \rho^0(770) \rho^0(770)$. From this model, an adaptive binning scheme is developed [22] to find an appropriate granularity to adequately partition the five-dimensional Dalitz space for the purposes of measuring c_i, s_i for this mode.

Preliminary results for c_i, s_i in $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ decays using CLEO-c quantum-correlated data are also presented. The quantum-correlated technique tags the flavour or CP content of a $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ decay from the flavour or CP content of the *other* neutral D mesons from a $\psi(3770)$ decay. In this preliminary work, only flavour and CP eigenstate tags are used and not the mixed-tag from $D \rightarrow K_S^0 \pi^+ \pi^-$ decays. This means the preliminary result, shown in Fig. 4 gives only c_i , and not s_i , information. However, a projection is also shown in the figure of the eventual precision on both ordinates. Once the binning definition and the c_i and s_i measurements are published, LHCb and Belle II will be able to perform a binned GGSZ-like analysis of $B^+ \rightarrow [\pi^+ \pi^- \pi^+ \pi^-]_D K^+$.

3.2 $D^0 \rightarrow K_S^0 \pi \pi \pi^0$

A similar analysis is presented for another self-conjugate mode, $D^0 \rightarrow K_S^0 \pi \pi \pi^0$. This mode has, so far, not been used in analysis of $B \rightarrow DK$ decays, but this important work shows it to have excellent sensitivity to γ with sufficient statistics. Three conclusions are drawn: a first measurement of the CP fraction is made from analysis of the CLEO-c dataset, $F_+ = 0.246 \pm 0.018$, the small fraction means this mode approximates as a CP -odd final state. Second, an eight-bin scheme is devised around the expected intermediate resonances (in the absence of a full amplitude model) and measurements of the c_i, s_i parameters are made, again using the CLEO-c data. Third, a sensitivity study of a $B^- \rightarrow [K_S^0 \pi^+ \pi^- \pi^0]_D K^-$ analysis at Belle II concludes that this mode may have a single-mode sensitivity to γ of 3.5° with 50 ab^{-1} . This study and the graphical representation of the c_i, s_i results are shown in Fig. 5. A dedicated proceedings is available [23].

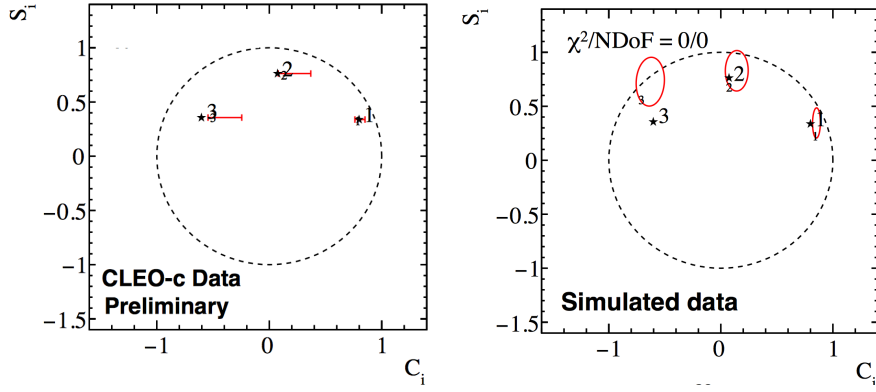


Figure 4: Preliminary measurement of the CP content of $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ decays using CLEO-c data (left) and projected accuracy from simulation once the analysis includes $K_S^0\pi^+\pi^-$ tags (right). In both cases the black star marks the centre of the bin and the red line(oval) is the measurement(projection).

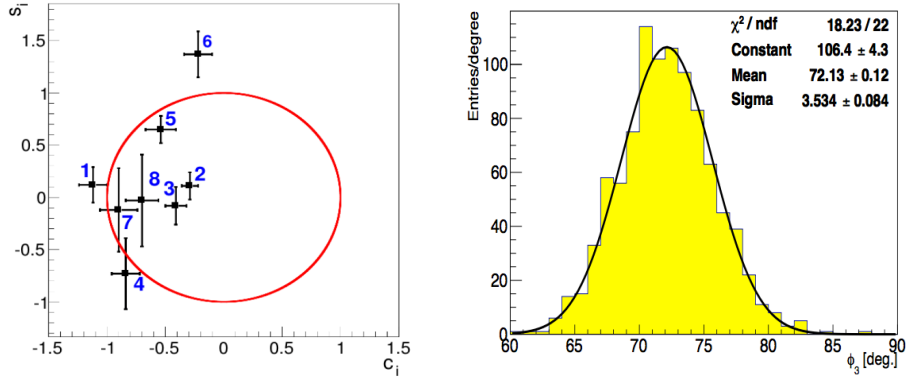


Figure 5: Preliminary measurement of c_i , s_i from an analysis of $D^0 \rightarrow K_S^0\pi^+\pi^-\pi^0$ decays using CLEO-c data (left) and projected precision on γ from this mode with 50 ab^{-1} of Belle II (right).

4. Direct CP violation in charmless b -hadrons

CP violation in charmless B^+ , B^0 and B_s^0 decays arises from the interference of tree and penguin contributions. Extracting CKM information from experimental measurements depends upon the theoretical understanding of the hadronic dynamics. The perturbative calculations for two-body B decays is complete up to $\mathcal{O}(\alpha_s^2)$ [24, 25, 26] and resulting predictions of CP asymmetries agree with experiment [27], though large theoretical uncertainties from long-distance effects persist. Increasingly, multibody decays of b -hadrons are being examined by experiments though the associated theory calculation is a challenge.

4.1 Multibody phenomenology

The theoretical understanding of multibody charmless decays is hindered by the increased complexity of the multibody kinematics and a larger variety of final states. Some efforts to extend the framework of QCD factorisation to B decays into three light mesons has been made [28] but a full NLO calculation of three-body B decays remains a future challenge.

A phenomenological study of $B \rightarrow K\pi\pi$ is presented at conference and later published [29]. It combines Belle and Babar analyses for $B^0 \rightarrow K^*\pi$ and $B^+ \rightarrow K^*\pi$ decays in an isospin analysis, which allows to express these decays in terms of CKM parameters and 6 complex hadronic amplitudes: colour allowed tree and penguin; annihilation and colour suppressed tree; colour allowed and colour suppressed electroweak penguin amplitudes. Conclusions are drawn from setting upper bounds on the assumed-small electroweak penguin to make measurements of the Unitarity angle α . A conclusion of this work is that the bound on the electroweak penguin amplitude is not precise from the theoretical point of view and doubt is cast on the potential of this method to constrain α . The logic is then reversed, drawing conclusions about the hadronic factors by holding CKM-elements to their best fit externally determined values [7]. They find that the Babar analysis of $B^0 \rightarrow K^+\pi^-\pi^0$ is important in predicting a large contribution from electroweak penguin amplitudes, and conclude that new analysis with more data from LHCb and Belle II is motivated.

4.2 Confirmation of large CP violation in regions of the $B^+ \rightarrow K^+K^-\pi^+$ Dalitz space

Belle report an examination of $B^+ \rightarrow K^+K^-\pi^+$ decays that have been shown in a prior LHCb analysis to exhibit large CP violation in certain regions of the decay phase space [30]. With the whole Belle dataset of 711 fb^{-1} , 715 ± 48 events are selected, and are seen to be concentrated at low $m(K^+K^-)$ and exhibit a large CP asymmetry, similar to the LHCb data. This result is shown in Fig. 6, which is reproduced from the dedicated proceedings [31].

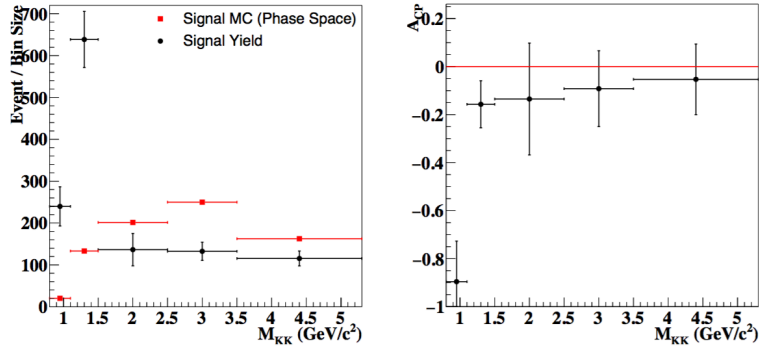


Figure 6: left: $B^+ \rightarrow K^+K^-\pi^+$ event yields as a function $m(KK)$. right: The corresponding asymmetry.

4.3 Evidence of CP violation in $\Lambda_b^0 \rightarrow p^+\pi^-\pi^+\pi^-$

With CP violation well established in B mesons, it is natural to search for CP asymmetries in b -baryons. Large, $\mathcal{O}(20\%)$ asymmetries are postulated in multibody Λ_b^0 decays but are as yet unobserved. To search for CP violation, LHCb measure CP -odd observables by studying asymmetries in a sample of $6646 \pm 105 \Lambda_b^0 \rightarrow p^+\pi^-\pi^+\pi^-$ decays.

The asymmetries are built from scalar triple products of three of the Λ_b^0 daughters in such a way as to form two quantities, $a_P^{\hat{T}\text{-odd}}$ and $a_{CP}^{\hat{T}\text{-odd}}$ that are sensitive to P and CP violation respectively [32]. These asymmetries are measured in bins in two schemes. The first bins across the Dalitz space of the 4-body decay, the second as a function of angle between the decay plane of the

proton and the fastest π^- compared to the decay plane of the two other pions. The resulting asymmetry is shown in Fig. 7. A permutation test of the CP violating effect concludes the significance of the CP violation is 3.3σ and thus represents the first evidence of CP violation in baryons. An alternative description is available in these proceedings [33].

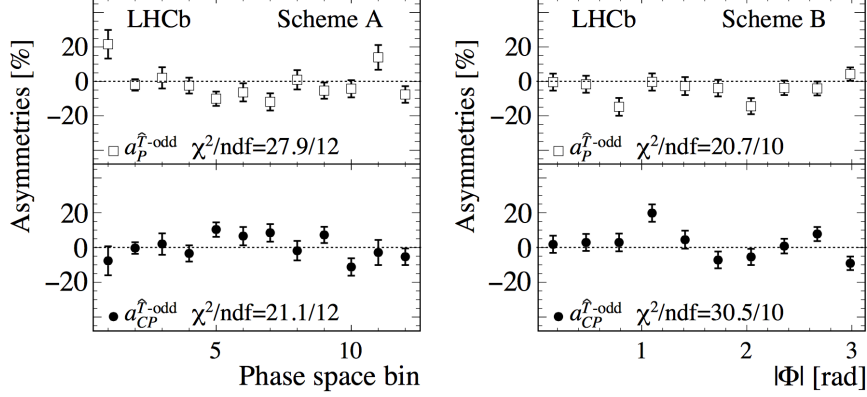


Figure 7: The results for each of the two binning schemes described in the text. The asymmetries $a_p^{\hat{T}-\text{odd}}$ and $a_{CP}^{\hat{T}-\text{odd}}$ for $\Lambda_b^0 \rightarrow p^+ \pi^- \pi^+ \pi^-$ decays are represented by open boxes and filled circles, respectively. The values of the χ^2/ndf are quoted for the P - and CP -conserving hypotheses for each binning scheme. Reproduced from [32].

5. New searches

The pursuit of a comprehensive understanding of CP violation needs new hadronic modes of b -hadrons. A number of new decay modes are reported, albeit without CP violation investigations.

5.1 $B \rightarrow$ charmless

Searches for two charmless B_s^0 decays are reported by LHCb: $B_s^0 \rightarrow \phi \pi^+ \pi^-$ and $B_s^0 \rightarrow \phi \eta'$. Both are mediated, in part, by gluonic penguin diagrams with potential sensitivity to the B_s^0 mixing-phase, β_s , with an eventual time-dependent analysis. These searches however, are untagged and time-integrated, searching for signals in the 3 fb^{-1} samples from 2011 and 2012. An event yield of 697 ± 30 $B_s^0 \rightarrow \phi \pi^+ \pi^-$ candidates are observed with little background. A study of the $\pi^+ \pi^-$ invariant mass distribution in Fig. 8 show that it is dominated by the light strangeless combinations $f_0(980)$, $f_2(1270)$ and the $f_0(1500)$. A total branching fraction is measured:

$$\mathcal{B}(B_s^0 \rightarrow \phi \pi^+ \pi^-) = (3.48 \pm 0.23 \pm 0.17 \pm 0.35) \times 10^{-6},$$

where the third uncertainty is due to the normalisation with respect to $B_s^0 \rightarrow \phi \phi$. Around a third of the $\pi^+ \pi^-$ combinations are found in the narrow $f_0(980)$ resonance. A dedicated proceedings is available [34].

From Belle, two new signals are presented. The first is an observation of $B_s^0 \rightarrow K^0 \bar{K}^0$ with branching fraction,

$$\mathcal{B}(B_s^0 \rightarrow K^0 \bar{K}^0) = (19.6_{-5.1}^{+5.8} \pm 1.0 \pm 2.0) \times 10^{-6},$$

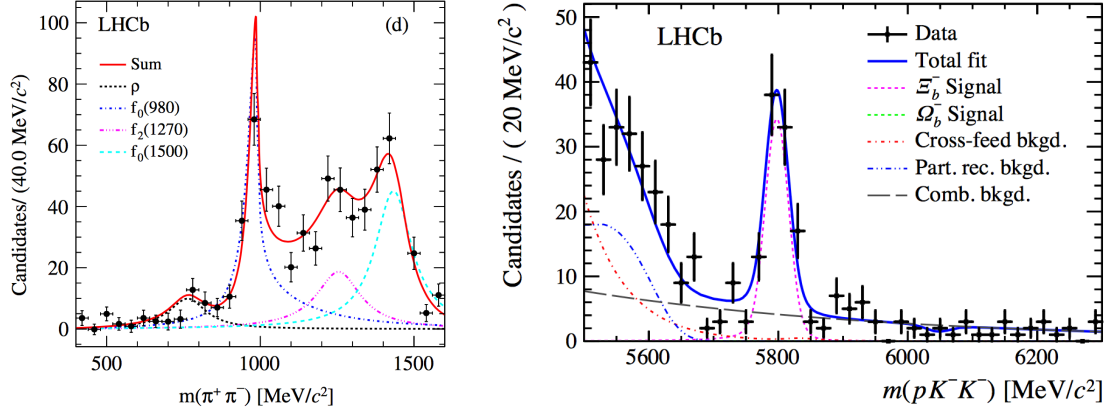


Figure 8: left: background-suppressed invariant mass distribution on $m(\pi^+\pi^-)$ in $B_s^0 \rightarrow \phi\pi^+\pi^-$ decays. The contributing intermediate $\pi^+\pi^-$ resonances, as deduced by an angular analysis, are shown in the legend. right: Mass distributions for b -hadron candidates in the pK^-K^- final state. The Ξ_b^- signal decays are shown with pink dashed lines and partially reconstructed backgrounds are shown with dark dashed lines.

from an analysis of 6.5M $B_s^0\bar{B}_s^0$ pairs accumulated at the $e^+e^- \rightarrow \Upsilon(5S)$ resonance. This decay mode is of similar interest as the previously-observed two-body mode, $B_s^0 \rightarrow K^+K^-$. Evidence of $B^0 \rightarrow \eta\eta$ is also presented from the analysis of 753M $B\bar{B}$ pairs accumulated at the $e^+e^- \rightarrow \Upsilon(4S)$ resonance with branching fraction,

$$\mathcal{B}(B^0 \rightarrow \eta\eta) = (7.6_{-2.3}^{+2.7+1.4}) \times 10^{-7}.$$

This decay receives contributions from $b \rightarrow u$ tree and $b \rightarrow d$ penguin amplitudes and could contribute to Unitarity angle α measurements at Belle II. A dedicated proceedings is available [31].

5.2 $\Xi_b^- \rightarrow pK^-K^-$

The evidence of CP violation in the baryonic sector [32] summarised in Sec. 4.3 motivates the development of hadronic decays of b -baryons. CP -asymmetry parameters are measured in three-body Λ_b^0 baryon decays to $K_s^0 p\pi^-$ [35], ΛK^+K^- and $\Lambda K^+\pi^-$ [36] and found to be consistent with zero. In the search of CP -violation effects the pK^-K^- final state is reconstructed by LHCb. The decay $\Xi_b^- \rightarrow pK^-K^-$ proceeds via the combination of $b \rightarrow u$, colour-suppressed tree decays and $b \rightarrow s$ penguin decays. LHCb observe 83 ± 10 events of this mode, the data is shown in Fig. 8 [37].

5.3 Baryonic B decays

Branching fraction of charmless baryonic B decays are $\mathcal{O}(10^{-6})$ and have been observed in several modes of B^+ and B^0 mesons, but not previously in B_s^0 decays. As two-body baryonic decays are suppressed with respect to multibody decays, LHCb reports a search for baryonic B_s^0 decays into three-body final state, $B_s^0 \rightarrow p\bar{\Lambda}h^-$ where $h \in \{\pi, K\}$ [38]. The result of this successful search is an observation of 260 ± 21 $B_s^0 \rightarrow p\bar{\Lambda}K^-$ decays. The distribution of these events is investigated on the Dalitz plane. No significant intermediate structure is seen except for a threshold enhancement at low $m(p\bar{\Lambda})$, see Fig. 9. A branching fraction for this baryonic decay of the B_s^0 meson is quoted,

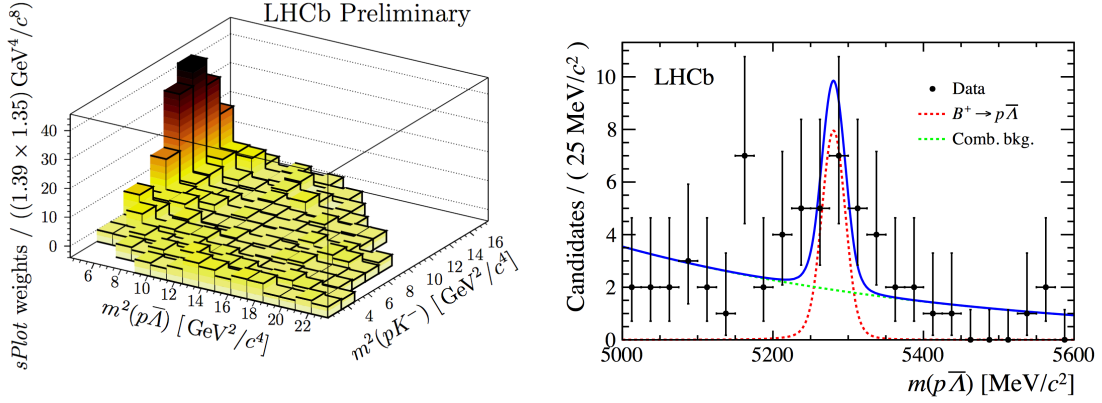


Figure 9: left: Dalitz plot of $p\bar{\Lambda}K^-$ combinations consistent with a B_s^0 mass, a threshold enhancement is observed but no resonances. right: Invariant mass distribution of $p\bar{\Lambda}$ combinations that exhibit evidence of the $B^+ \rightarrow p\bar{\Lambda}$ decay mode.

$$\mathcal{B}(B_s^0 + \bar{B}_s^0 \rightarrow p\bar{\Lambda}K^-) = (5.48_{-0.80}^{+0.82} \pm 0.85) \times 10^{-6}.$$

These final states have been postulated to manifest a $\mathcal{O}(10\%)$ T violation [39] and should be investigated with larger datasets.

LHCb also report the first evidence (4.1σ) of the rare two-body baryonic decay mode, $B^+ \rightarrow p\bar{\Lambda}$. This mode is analogous to the two-body mesonic decay $B^+ \rightarrow K\pi$ but with a different arrangement of quarks in the final state. $B^+ \rightarrow p\bar{\Lambda}$ is expected to be dominated by a $b \rightarrow s$ penguin transition with contribution from suppressed $b \rightarrow u$ tree and annihilation processes. That collaboration report a branching fraction of,

$$\mathcal{B}(B^+ \rightarrow p\bar{\Lambda}) = (2.4_{-0.8}^{+1.0} \pm 0.3) \times 10^{-7},$$

normalising to $B^+ \rightarrow K_s^0\pi^+$ decays, assuming half of the K^0 B -decay products mix to K_s^0 mesons. This evidence is reproduced from [40] in Fig. 9. A dedicated proceedings is available [41].

5.4 $B_c^+ \rightarrow D^0K^+$

The B_c^+ meson is the only meson to contain two heavy flavour quarks of different flavour. It has been observed in a number of decay modes with a J/ψ , which is expected from a $b \rightarrow c$ external W -emission tree decay. The lifetime of the B_c^+ meson has recently been measured, $\tau(B_c^+) = 0.513 \pm 0.012$ ps [42], which is significantly shorter than the lifetimes of the other B mesons which all lie in the interval 1.50 – 1.64 ps [43]. The shorter lifetime is attributed to a large fraction ($\sim 60\%$) of its partial width being due to Cabibbo favoured $c \rightarrow s$ transitions of the charm quark, with only $\sim 20\%$ from cross-generation $\bar{b} \rightarrow \bar{c}$ transition. The first observation of a charm quark decay in a B_c^+ meson was $B_c^+ \rightarrow B_s^0\pi^+$ with an approximate branching fraction of around 10% [44]. The third classification of B_c^+ decay, with around 10% of the total width, is the annihilation topology. Annihilation decays are unambiguously probed in B mesons with searches for final states that contain no quark from the initial state; in the case of B_c^+ decays, this is charmless decays. LHCb has conducted searches for charmless B_c^+ decays in the $p\bar{p}\pi^+$ final state

but found no signal, setting an upper limit on $\sigma(B_c^+)/\sigma(B^+) \times \mathcal{B}(B_c^+ \rightarrow p\bar{p}\pi^+) < 3.6 \times 10^{-8}$ for $m(p\bar{p}) < 2.85 \text{ GeV}/c^2$ where σ symbolises the production cross section [45]. A similar search is conducted in the $\bar{K}^{*0}K^+$ final state where a 2.4σ excess is reported with $\sigma(B_c^+)/\sigma(B^+) \times \mathcal{B}(B_c^+ \rightarrow \bar{K}^{*0}(\rightarrow K^-\pi^+)K^+) \sim [0.1, 1.7] \times 10^{-8}$ for $m(K^-\pi^+) < 1.834 \text{ GeV}/c^2$. The low values of these quantities indicates a small decay constant for B_c^+ mesons and, in turn the annihilation topology. Another decay that may receive a large, though not unique signature from $\bar{b} + c$ annihilation is $B_c^+ \rightarrow D^0K^+$. At the conference LHCb reported an observation of $B_c^+ \rightarrow D^0K^+$ [46] with with a

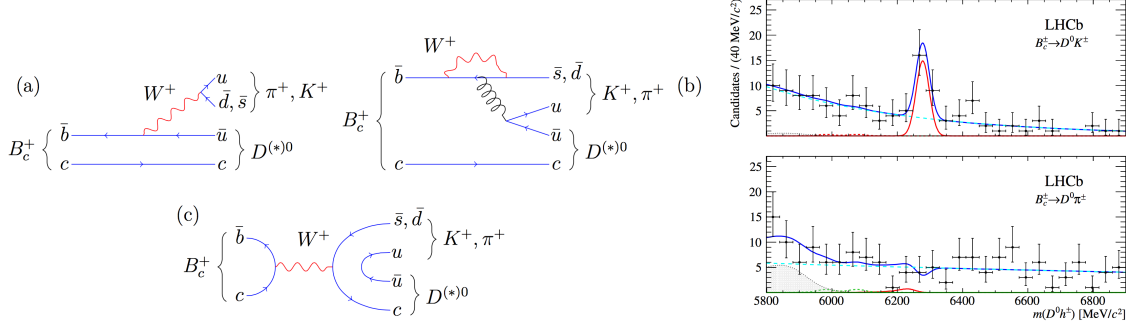


Figure 10: left: Feynman diagrams of processes contributing to $B_c^+ \rightarrow D^0 h^+$ decays (a) $b \rightarrow u$ transition, (b) $b \rightarrow s$ penguin, (c) $\bar{b} + c$ annihilation. right: Invariant mass of $m(D^0 K^+)$ and $m(D^0 \pi^+)$ combinations.

branching fraction multiplied by the ratio of cross-sections,

$$\frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \rightarrow D^0 K^+) = (9.3_{-2.5}^{+2.8} \pm 0.6) \times 10^{-7},$$

as shown in Fig. 10. The ratio of cross sections is expected to be between 0.003 and 0.011, implying that the B_c^+ branching fraction is $\mathcal{O}(10^{-4})$, which is higher than predicted [47].

6. Conclusions

Direct CP violation in B decays remains a vibrant topic. With only a quarter of the total LHCb dataset analysed and with Belle II imminent, the interest will continue. The measurement of γ is becoming more accurate, and a relative precision similar to that of β is a realistic target within the next decade. Multibody charmless decays of b -hadrons have a rich phenomenology but the separation of CKM information from the hadronic parameters remains a theoretical challenge. Finally, several new modes have been observed and reported to the conference, and we anticipate measurements of CP asymmetries with them in the future, from the datasets of Belle II and the LHCb upgrade.

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