CP violation in heavy-flavour hadrons

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Measurements of CP-violating observables in B meson decays can be used to determine the angles of the Unitarity Triangle and hence probe for manifestations of New Physics beyond the Cabibbo-Kobayashi-Maskawa Standard Model paradigm. Of particular interest are precise measurements of the angles $\gamma$ and $\beta$. Also of great importance are studies of CP-violation involving $B^0_s$ mesons, in particular the phase $\phi_s$, which is a golden observable in flavour physics at the LHC. Complementary to these studies is the continuing search for direct and indirect CP-violation in the charm system, where the experimental precision is now at the $10^{-3}$ level. I will present new and recent results in these topics, and in CP-violation searches in baryon decays, with specific emphasis on the measurement programme at the LHC.

Keywords: Flavour physics; CP violation; LHC

1. Introduction

The violation of CP symmetry, the combination of the discrete symmetries of charge-conjugation (conjugation of all internal quantum numbers) and parity (reversing spatial coordinates), is a necessary condition to generate the baryon asymmetry of the Universe. However, the level of CP violation allowed within the quark sector of the SM is many orders of magnitude too small to explain astronomical observations, demanding experimental searches for new sources of violation. Heavy-quark hadrons provide an excellent laboratory to perform such searches as they allow the exploration of high energy scales well beyond the direct reach of the LHC. This approach has been successfully applied in the past with, for example, the observation of $B^0$ meson mixing leading to the first estimates of the top quark mass before it was directly discovered. The large heavy-quark production cross-sections at the LHC lead to large samples of exclusively reconstructed $b$ and $c$ hadron decays that have been used to make precision measurements of CP violating observables. These proceedings summarise the latest of these measurements, focussing on those using 3 fb$^{-1}$ of data collected by the LHCb experiment in $pp$ collisions at the LHC during 2011 and 2012, unless otherwise stated. Recent comprehensive reviews can be found in Refs. and references therein.

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2. CP violation in the Standard Model

The only source of CP violation within the SM is due to the non-zero value of the phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix, to which all CP-violating observables are related. The unitarity of the matrix leads to relations between elements (e.g., $V_{ub}V_{cb}^* + V_{cd}V_{tb}^* + V_{td}V_{tb}^* = 0$), which are convenient to visualise as a triangle in the complex plane. For the triangle (the Unitarity Triangle) where all sides are of a similar magnitude, the angles are defined as

$$\alpha \equiv \arg \left[ -\frac{V_{td}V_{tb}^*}{V_{ub}V_{cb}^*} \right], \quad \beta \equiv \arg \left[ -\frac{V_{cd}V_{cb}^*}{V_{ub}V_{cb}^*} \right], \quad \gamma \equiv \arg \left[ -\frac{V_{ud}V_{ub}^*}{V_{ub}V_{cb}^*} \right].$$

These angles can be measured using a variety of different CP violating observables covering both tree-level quark transitions, where the impact of New Physics (NP) contributions is expected to be small, and loop-level transitions, which are sensitive to new higher-mass particles. One of the goals of studying the heavy-quark sector is to compare measurements of these quantities to check for the overall consistency of the CKM mechanism. Figure 1 shows the latest global fit of the CKM matrix parameters to experimental measurements and Lattice QCD calculations, showing that the SM is working well. However, there is still room for NP contributions at the level of $\sim 10\%$, implying that a new set of precision measurements is required.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{unitarity_triangle.png}
\caption{Global fit to the CKM matrix parameters, showing consistency between measurements when interpreted in terms of SM quark transitions.}
\end{figure}

In the quark sector, the neutral mesons ($P^0$) can oscillate into their antiparticles ($\bar{P}^0$), resulting in the physical states ($P^0_{H,L}$) being admixtures of the flavour eigenstates: $P^0_H = pP^0 + q\bar{P}^0$ and $P^0_L = pP^0 - q\bar{P}^0$, where $p$ and $q$ are complex coefficients ($|p|^2 + |q|^2 = 1$). The physical states have well defined masses and lifetimes, and the parameters $\Delta m = m_H - m_L$, $\Delta \Gamma = \Gamma_L - \Gamma_H$ and $\Gamma = (\Gamma_L + \Gamma_H)/2$ control the
decay-time-dependent decay rates of the mesons. In particular, $\Delta m$ controls the oscillation frequency.

$CP$ violation depends on the quantity $\lambda_f = \frac{\gamma_f}{p/A_f}$. Here, $f$ is the final state that the $P$ hadron decays to with amplitude $A_f$ and the $\bar{P}$ hadron decays to with amplitude $\bar{A}_f$. Three types of $CP$ violation are allowed: in neutral meson mixing ($|q/p| \neq 1$); in the interference between neutral meson mixing and decay ($\arg(\lambda_f) \neq 0$) and in hadron decay ($|\bar{A}_f/A_f| \neq 1$). Only $CP$-violation in decay is allowed for charged mesons and baryons.

3. $CP$ violation in $B$ meson mixing

Semileptonic $B^0_{(s)}$ decays are dominated by tree-level quark transitions, implying that there should be no $CP$ violation in decay, and therefore provide a clean system to search for $CP$ in mixing. The so-called semileptonic (or flavour-specific) asymmetry is defined as $A_{sl} = \frac{\Gamma(\pi^0 \to B^0 \to f) - \Gamma(\pi^0 \to B^0 \to \bar{f})}{\Gamma(\pi^0 \to B^0 \to f) + \Gamma(\pi^0 \to B^0 \to \bar{f})} \approx \frac{\Delta \Gamma}{\Delta m} \tan \phi_M$, where $\phi_M$ is the mixing phase from the $B^0_{(s)}$ mixing matrix. These asymmetries are predicted to be very small in the SM, at the level of $10^{-4}$ or less\textsuperscript{14} and therefore any measurement of a significantly non-zero effect would be a clear sign of beyond-the-SM physics.

Experimentally, the quantity measured is the untagged decay-time, $t$, dependent charge asymmetry between semileptonic $B^0_{(s)}$ decays with a positive or negatively charged muon, defined as $A_{\text{meas}}(t) = \frac{N(D^- \mu^+, \nu) - N(D^+ \mu^-, \nu,t)}{N(D^- \mu^+, \nu,t) + N(D^+ \mu^-, \nu,t)} \approx A_D + \frac{4}{3} \frac{\Delta \Gamma}{\Delta m} \cos(\Delta m t)$. This is sensitive to $A_{sl}$ along with other production, $A_P$, and particle detection, $A_D$, asymmetries. In the case of the measurements from the LHCb collaboration\textsuperscript{17,18} these asymmetries can be controlled to high precision using data calibration samples and by reversing the LHCb dipole magnet, thereby allowing a precision measurement of the $CP$ asymmetries in both the $B^0$ and $B^0_{(s)}$ systems.\textsuperscript{14} Figure 2a shows the current experimental situation for $CP$ violation in $B$ meson mixing. The global average values are $A_D = (-0.21 \pm 0.17)\%$ and $A_{sl} = (-0.06 \pm 0.28)\%$, consistent with SM expectations.

The left-most green ellipse in Figure 2a corresponds to the dimuon asymmetry measured by the D0 collaboration\textsuperscript{19}, which is a measurement of a linear combination of $A_{sl}$ and $A_{sl}^s$. Although it is inconsistent with SM expectations at $\sim 3\sigma$ it has been proposed\textsuperscript{20} that there may be additional contributions from a non-zero value of $\Delta \Gamma_d/\Gamma_d$, which is expected to be very small in the SM. The most precise measurement of this quantity has recently been made by the ATLAS collaboration\textsuperscript{21} (Figure 2b), obtaining $\Delta \Gamma_d/\Gamma_d = (-0.1 \pm 1.1 \pm 0.9) \times 10^{-2}$. An update of the 1 fb\textsuperscript{-1} measurement\textsuperscript{22} of $\Delta \Gamma_d/\Gamma_d$ from the LHCb collaboration is eagerly anticipated.

\textsuperscript{a} For the $B^0_{(s)}$ system, the time-integrated rate can be measured as the fast $B^0_{(s)}$ oscillations wash out the production asymmetry.
4. CP violation in the interference of B meson mixing/decay

In the case where the $B^0(s)$ or $\bar{B}^0(s)$ mesons decay to the same final state, $f$, the decay-time-dependent CP asymmetry is given by

$$\frac{\Gamma_{\overline{B}^0 \to f}(t) - \Gamma_{B^0 \to f}(t)}{\Gamma_{\overline{B}^0 \to f}(t) + \Gamma_{B^0 \to f}(t)} = \frac{S_f \sin(\Delta m t) - C_f \cos(\Delta m t)}{\cosh(\Delta \Gamma t/2) + A_{\Delta \Gamma} \sinh(\Delta \Gamma t/2)},$$

where $|S_f|^2 + |C_f|^2 + |A_{\Delta \Gamma}|^2 = 1$ by definition.

4.1. The $B^0$ system

In the $B^0$ system, $\Delta \Gamma_d \approx 0$ and only the numerator of Eq. 1 needs to be considered. The canonical decay mode used by the B-factories to measure this asymmetry is $B^0 \to J/\psi K^0_S$, which proceeds predominately via a tree-level $b \to c\bar{c}s$ transition. In the case where the sub-dominant penguin diagrams can be neglected\(^25-28\), $S_{J/\psi K^0_S} \approx \sin 2\beta$.

The LHCb collaboration has recently used its Run 1 data to measure $S_f$ and $C_f$ in $B^0 \to J/\psi (\mu^+\mu^-)K^0_S$, $B^0 \to J/\psi (e^+e^-)K^0_S$ and $B^0 \to \psi(2S)(\mu^+\mu^-)K^0_S$ decays\(^30\) using a flavour-tagged\(^31\) decay-time-dependent analysis. The asymmetry for $B^0 \to J/\psi (\mu^+\mu^-)K^0_S$ decays can be seen in Figure 3a. The individual measurements and their combination are shown in Figure 3b, where the systematic uncertainty is dominated by background tagging asymmetry. The LHCb-averaged values are $S_{[\pi]K^0_S} = 0.760 \pm 0.034$ and $C_{[\pi]K^0_S} = -0.017 \pm 0.029$. Together, these measurements reduce the tension between the world average value for $\sin 2\beta$ and the indirect determination from global fits\(^15,16\). The consistency between the results
Signal yield asymmetry

\[ t (\text{ps}) \]

\[ LHCb \]

\[ -0.4 \]
\[ -0.3 \]
\[ -0.2 \]
\[ -0.1 \]
\[ 0 \]
\[ 0.1 \]
\[ 0.2 \]
\[ 0.3 \]
\[ 0.4 \]

\[ LHCb \]

\[ (a) \]

\[ (b) \]

Fig. 3. (a) CP asymmetry as a function of decay time for \( B^0 \rightarrow J/\psi K^0_S \) decays\(^{29}\), showing a clear oscillation. (b) LHCb combination of CP violation parameters as measured using \( B^0 \rightarrow J/\psi (\mu^+ \mu^-) K^0_S \), \( B^0 \rightarrow J/\psi (e^+ e^-) K^0_S \) and \( B^0 \rightarrow \psi(2S) (\mu^+ \mu^-) K^0_S \) decays.

Fig. 4. HFLAV average of CP parameters in \( B^0 \rightarrow D^+ D^- \) decays\(^{19}\).

using the electron and muon channels for charmonium reconstruction also help to build confidence in the electron reconstruction performance of LHCb, which is particularly relevant when viewed through the prism of recent anomalies in \( b \rightarrow s \ell^+ \ell^- \) transitions\(^{32}\).

Decays such as \( B^0 \rightarrow D^+ D^- \) are governed by \( b \rightarrow c \bar{c} d \) quark transitions and therefore measurements of the decay-time-dependent asymmetry gives complimentary information about \( \sin 2\beta \) that can be used to constrain the size of potential penguin contributions to the decay\(^{25,26}\). Figure 3 summarises the current situation with these measurements from the BaBar, Belle and LHCb\(^{33}\) collaborations. The
Belle result is outside of the physical region \((S_{2DD}^2 + C_{2DD}^2 < 1)\), which may have been an indication of large hadronic effects. However, the latest LHCb measurement shows that these terms are small and consistent with zero, with the phase shift induced by the penguin diagrams measured to be \(\Delta \phi = -0.16^{+0.19}_{-0.21}\) rad.

### 4.2. The \(B_s^0\) system

Decay-time-dependent \(CP\) asymmetries in the \(B_s^0\) system using \(b \to c\bar{s}s\) transitions are sensitive to the CKM phase \(\beta_s \equiv \arg \left(\frac{V_{ts}^* V_{tb} V_{cs}^* V_{cb}}{V_{ts} V_{tb}}\right)\). Typically measurements are made of the experimentally observable phase \(\phi_s\), which is equal to \(-2\beta_s\) if the penguin contributions to the decay can be neglected. Global fits give a precise Standard Model prediction for \(\phi_s\) of \(-36.5 \pm 1.3\) mrad\(^{13}\). Deviations from this value would be a clear sign for NP, strongly motivating the need for more precise experimental measurements.

The golden mode for measuring \(\phi_s\) is using a flavour-tagged decay-time-dependent angular analysis of the \(B_s^0 \to J/\psi \phi\) decay. This channel has a high branching fraction and the presence of two muons in the final state leads to a high trigger efficiency at hadron colliders. An angular analysis is necessary to disentangle the interfering \(CP\)-odd and \(CP\)-even components in the final state, which arise due to the relative angular momentum between the two vector resonances. In addition, there is a small \((\sim 2\%)\) \(CP\)-odd \(K^+K^-\) S-wave contribution that must be accounted for.

The CDF\(^{34}\), D0\(^{35}\), ATLAS\(^{36}\), CMS\(^{37}\) and LHCb\(^{38}\) collaborations have all measured \(\phi_s\) (in addition to other mixing-related parameters of the \(B_s^0\) system) using the \(B_s^0 \to J/\psi \phi\) decay. Additional information can be obtained by utilising the region of the \(K^+K^-\) invariant mass spectrum above the \(\phi(1020)\) meson, where higher spin \(K^+K^-\) resonances are expected to contribute. Such a flavour-tagged decay-time-dependent amplitude analysis has just been performed by the LHCb collaboration\(^{39}\), which finds the dominant component of the high-mass spectrum comes from the \(f_0^0(1525)\) meson (Figure 5) and measures \(\phi_s = 119 \pm 107 \pm 34\) mrad. The LHCb detector has excellent time resolution \((\sim 45\) fs\) and tagging power \((\sim 4\%)\), both of which are crucial to the measurement. Combining the LHCb results from \(B_s^0 \to J/\psi \phi\) (low mass), \(B_s^0 \to J/\psi K^+K^-\) (high mass) and \(B_s^0 \to J/\psi \pi^+\pi^-\) decays\(^{39}\) gives \(\phi_s = 1 \pm 37\) mrad.

The global combination of \(\phi_s\) and \(\Delta \Gamma_s\) using the measurements referenced above in addition to \(B_s^0 \to \psi(2S)\phi\)\(^{41}\) and \(B_s^0 \to D_s^+ D_s^-\)\(^{42}\) decays gives average values of \(\Delta \Gamma_s = 0.090 \pm 0.005\) ps\(^{-1}\) and \(\phi_s = -21 \pm 31\) mrad. The combination is dominated by the statistical uncertainty from the LHCb \(B_s^0 \to J/\psi \phi\) result and are consistent with the SM prediction\(^{10,15}\). However, there remains space for new physics contributions at \(O(10\%)\) and as the experimental precision improves it is essential that there is good control over hadronic effects\(^{13,14}\) that could mimic the signature of beyond-the-SM physics.

A related \(CP\)-violating phase, \(\phi_s^{ass}\), can be measured by applying similar anal-
ysis methods to $B^0_s$ meson decays that occur via $b \rightarrow s\bar{s}s$ transitions. The LHCb collaboration has performed such an analysis using $B^0_s \rightarrow \phi\phi$, measuring $\phi_s = -0.17 \pm 0.15 \pm 0.03$ rad, which is consistent with the SM predictions, all of which are very close to zero.\textsuperscript{46–48} Updated measurements of $CP$-violating parameters in charmless $B^0_s \rightarrow K^+K^-$ decays have also recently been reported by the LHCb collaboration\textsuperscript{49}, including a first measurement of $A_{\Delta\Gamma}^{K^+K^-}$.

5. $CP$ violation in $b$ hadron decay

5.1. The CKM angle $\gamma$

The CKM angle $\gamma$ is the only $CP$ violating parameter that can be measured from tree-level decay\textsuperscript{50} and the uncertainty on its theoretical prediction is constrained to be $< O(10^{-7})$. Together these make measurements of $\gamma$ a “standard candle” within the SM with which other loop-level determinations can be compared in order to look for the effects of new $CP$ violating contributions. The canonical technique to measure $\gamma$ is to exploit the interference between the different decay paths in $B \rightarrow DK$ decays. Depending on the final state of the $D^0$ meson there are different analysis methods (e.g., GLW\textsuperscript{50,51} ADS\textsuperscript{52,53} and GGSZ\textsuperscript{54}) that vary in their sensitivity to $\gamma$ and the other hadronic parameters that describe the strong dynamics of the $B$ and $D$ meson decays. Unlike the measurement of $\beta(s)$, there is no dominant channel in which to measure $\gamma$ and a combination of several modes is required to achieve the maximal sensitivity.

A new result\textsuperscript{55} from the LHCb collaboration is an update, using Run 2 data, of the measurements of the $CP$-violating observables in $B^\pm \rightarrow D^{(*)0}K^\pm$ and $B^\pm \rightarrow D^{(*)0}\pi^\pm$ decays using the GLW method. Figure 6 shows the invariant mass

\textsuperscript{b}There are some caveats.
distribution of the $D^0h$ system. In the case of $B^\pm \to D^0K^\pm$ decays a clear asymmetry is visible between the oppositely-charged modes. After controlling for small detector and production asymmetries using the Cabibbo-favoured $B^\pm \to [K^\pm \pi^\mp]_D \pi^\pm$ mode, the $CP$ asymmetry is measured to be $A^K_{DK} = +0.126 \pm 0.014 \pm 0.002$, where the first uncertainty is statistical and the second systematic.

For the first time the collaboration has also used a partial reconstruction technique to measure the $CP$ observables using the modes with excited $D^{*0} \to D^{0}\gamma$ and $D^{*0} \to D^{0}\pi^0$ decays where the photon or $\pi^0$ is not reconstructed. This approach avoids the efficiency penalty that would need to be paid to fully reconstruct these channels. The partially reconstructed decays correspond to the structures at lower mass in Figure 5 where the different shapes for the $D^{*0} \to D^{0}\gamma$ and $D^{*0} \to D^{0}\pi^0$ contributions allow the decay rates and $CP$ asymmetries to be measure separately for each. The $CP$ asymmetry in the $B^\pm \to (D^{*0} \to D^{0}\pi^0)K^\pm$ channel is measured as $A^K_{CP,\pi^0} = -0.151 \pm 0.033 \pm 0.011$, which is different from zero at $4.3\sigma$. The corresponding asymmetry for the $\gamma$ mode is $A^K_{CP,\gamma} = +0.276 \pm 0.094 \pm 0.047$.

Another new result is the measurement of the $CP$-violating observables in $B^\pm \to DK^{*\pm}$ decays, with $K^{*\pm} \to K^0\pi^\pm$. This updates Ref.\cite{55} using two- and four-body $D$ meson final states\cite{56} in addition to Run 2 data. The branching ratio of the $B^\pm \to DK^{*\pm}$ decay is of similar magnitude to $B^\pm \to DK^+$ (described above), but the overall event yield in LHCb is lower due to the efficiency for reconstructing $K^0_s$ mesons. Figure 7 shows the invariant mass distributions of the $DK^*$ systems for the two-body Cabibbo-favoured and ADS $D^0$ decay modes. The decays are isolated with high signal purity and this result corresponds to the first $4.2\sigma$ evidence of the ADS mode, with the rate measured to be $R_{K^+} = 0.020 \pm 0.006 \pm 0.001$. The measurements for the decay rates and $CP$ asymmetries are consistent with and more precise than the corresponding analysis from the BaBar collaboration\cite{57}. In the future they will help to further constrain $\gamma$ and the related hadronic parameters for this system.

5.2. $\gamma$ combination

As stated above the best precision on $\gamma$ is obtained by combining information from many $B \to DK$ decay modes. An updated combination from LHCb has recently been performed\cite{58} that utilises 85 observables and contains 37 parameters. It includes the $B^\pm \to D^{(*)0}K^\pm$ and $B^\pm \to DK^{*\pm}$ results described above\cite{55} and an updated decay-time-dependent measurement of the $CP$ asymmetry in $B^0_s \to D^+_s K^+$ decay\cite{59}. The final measurement is $\gamma = 76.8^{+5.1}_{-5.0}$. The HFLAV collaboration have combined this with existing measurements from the B-factories to obtain $\gamma = 76.2^{+4.7}_{-5.0}$, where the precision is dominated by the LHCb measurement. Many more updates of $B \to DK$ channels can be expected with Run 2. The aim is to have sub-degree-level precision at the end of the LHCb phase 1 upgrade in 2024 by

\footnote{In fact, only the $B^\pm \to DK^{*\pm}$ results from Ref.\cite{55} are used.}
Fig. 6. Distribution of invariant mass of the $Dh^\pm$ system for (left) $B^-$ and (right) $B^+$ decays. The bachelor hadron is a (top) kaon and (bottom) pion. In the case of the $B^\pm \rightarrow [K^+ K^-]_C h^\pm$ decays a clear asymmetry is visible between the distributions. The structures at lower masses is due to partially reconstructed $D^{*0} \rightarrow D^0 \gamma$ and $D^{*0} \rightarrow D^0 \pi^0$ decays where the $\gamma$ or $\pi^0$ particle is missed.

Fig. 7. Distribution of invariant mass of the $DK^*$ system for (left) $B^-$ and (right) $B^+$ decays. Both the (top) Cabibbo-favoured and (bottom) ADS $D^0 \rightarrow K \pi$ decay modes are visible.

which point LHCb will have collected 50 fb$^{-1}$.

5.3. First evidence of CP violation in the baryon system

So far there has been no observation of CP violation in $b$ baryon decays. However, since they are governed by the same quark-level transitions as meson decays there is potential for non-zero effects in the SM$^{61-63}$. For example, charmless decays of $b$ baryons have contributions of similar magnitude from both tree and penguin decays, which give rise to sensitivity to the CKM angle $\alpha$. No sign of CP violation has been found in such charmless two$^{64}$ or three-body$^{65,66}$ $\Lambda^0_b$ or $\Xi^0_b$ baryon decays,
Fig. 8. 1-CL plot, using the profile likelihood method, for the $\gamma$ combinations split by analysis method. (yellow) GGSZ methods, (orange) GLW/ADS methods, (blue) other methods and (green) the full combination.

Fig. 9. (a) The invariant mass distributions for $A_{b}^{0} \rightarrow p\pi\pi\pi$ used to extract the asymmetries. (b) The $P$-odd and $CP$-odd asymmetries as a function of $|\Phi|$, the magnitude of angle between the $p\pi_{\text{fast}}^{-}$ and $\pi_{\text{slow}}^{-}\pi^{+}$ decay planes in the $A_{b}^{0}$ rest frame.

however, a recent study of four-body $A_{b}^{0} \rightarrow ph^{-}h^{+}h^{-}$ decays has revealed the first evidence for $CP$-violation in the baryon sector.

The measurement is performed by using the four-body decay topology to compute triple products, which are odd under the motion reversal operator, $\hat{T}$. The triple products are defined as $C_{T} = \vec{p}_{p} \cdot (\vec{p}_{h_{1}^{-}} \times \vec{p}_{h_{2}^{-}})$ and $\overline{C}_{T} = \vec{p}_{p} \cdot (\vec{p}_{h_{1}^{+}} \times \vec{p}_{h_{2}^{+}})$ for $A_{b}^{0}$ and $\overline{A}_{b}^{0}$ decays, respectively. The corresponding $\hat{T}$-odd asymmetries are $A_{T}(C_{T}) = \frac{N(C_{T}>0) - N(C_{T}<0)}{N(C_{T}>0) + N(C_{T}<0)}$ and $\overline{A}_{T}(\overline{C}_{T}) = \frac{N(\overline{C}_{T}>0) - N(\overline{C}_{T}<0)}{N(\overline{C}_{T}>0) + N(\overline{C}_{T}<0)}$, where $N$ refers to the number of observed $A_{b}^{0} \rightarrow ph^{-}h^{+}h^{-}$ candidates. From these $\hat{T}$-odd asymmetries is possible to build $P$-odd and $CP$-odd observables, defined$^4$

$^4$The $\hat{T}$ operator is equivalent to the parity operation for spinless particles.
as $a_{T-\text{odd}}^{CP} = \frac{1}{2}(A_T + \bar{A}_T)$ and $a_{T-\text{odd}}^{CP} = \frac{1}{2}(A_T - \bar{A}_T)$, respectively. The CP-odd observable is insensitive to production and detection asymmetries that affect standard CP-asymmetries (e.g., those based on event yields) and is also formed from a different combination of strong and weak phases.

Figure 9a shows the $\Lambda_0^b \to p\pi\pi\pi$ invariant mass from Ref.\textsuperscript{67} that has been used to measure $a_{T-\text{odd}}^{CP}$. The global measurement is consistent with CP symmetry but it has been noted\textsuperscript{68} that there is increased sensitivity to CP-violating effects by looking at differential distributions. Figure 9b shows $a_{T-\text{odd}}^{CP}$ as a function of the phase space of the $\Lambda_0^b \to p\pi\pi\pi$ decay. Using this and an alternative binning scheme, the p-value for the CP-symmetry hypothesis is evaluated as $9.8 \times 10^{-4}$, which is equivalent to a $3.3\sigma$ deviation of $a_{CP}^{T-\text{odd}}$ from zero. This constitutes the first evidence of CP violation in baryon decays. With the larger data samples to be collected in Run 2 and beyond it will be possible to perform a full amplitude analysis of the $\Lambda_0^b \to p\pi\pi\pi$ channel to understand where the CP asymmetry arises in the phase space of the decay.

Similar methods using $\hat{T}$-odd observables have been used to search for CP violation in rare $\Lambda_0^b$ decays\textsuperscript{69,70} and the charm system\textsuperscript{71}. In each case the results are consistent with the hypothesis of CP conservation.

6. Study of $b$-baryon oscillations

As noted in Section 1 the origin of the baryon asymmetry in the Universe is unclear. Baryon number violation (BNV) has never been seen experimentally, with strong constraints imposed by the measured proton and bound-neutron lifetimes. However, beyond-the-SM models containing flavour-diagonal six-fermion vertices\textsuperscript{72–75} could permit BNV without violating existing constraints. Unambiguous experimental observation of such BNV would be the observation of baryon-antibaryon oscillations of hadrons containing quarks of all three generations (i.e., $u_s b$), such as the $\Xi_b^0$ baryon.

A new result\textsuperscript{76} from the LHCb collaboration measures the decay-time-dependent ratio between the rates of same-sign (SS) and opposite-sign (OS) decays of the $\Xi_b^0$ baryon. The ratio is defined as $R(t) = \frac{\Gamma(\Xi_b^0 \to \Xi^0 \pi^-)}{\Gamma(\Xi_b^0 \to \Xi^0 \pi^+)} \approx (\omega t)^2$, where $\omega$ is the mixing frequency. Here, SS (OS) means that the charge of the proton from the charged $\Xi_c \to pK \pi$ decay is the same (opposite) to the charge of the pion from the strong decay of the excited $\Xi_b^{*}$ baryons that tags the initial flavour of the $\Xi_b^0$ candidate. Figure 10 shows the mass difference distribution for the LHCb data. The two narrow peaks visible near threshold in the OS-tag sample are due to the excited $\Xi_b^{*}$ baryons. The red histogram shows the corresponding distribution for the SS tags, which is consistent with the background-only hypothesis. In seven bins of decay time the ratio $R(t)$ is evaluated using a likelihood fit to the mass distribution, which allows an upper limit to be set on the mixing frequency. The limit is $\omega < 0.08 \text{ ps}^{-1}$ at 95% CL, determined using a likelihood ratio test and the CLs method.
Fig. 10. Spectra of the mass difference $\delta m = m(\Xi^0_b\pi) - m(\Xi^0) - m_\pi$ for the OS-tagged (black points with error bars) and SS-tagged (red, hatched histogram) decays. Inset: detail of the region $2.0 < \delta m < 5.5$ MeV/c$^2$.

7. Charm

Studies of the charm system provide the only way to investigate CP violation using up-type quarks. As in the neutral B meson system, neutral D mesons undergo oscillations, but in this case they are dominated by long-distance effects and the mixing parameters ($x = \Delta m/\Gamma$, $y = \Delta\Gamma/(2\Gamma)$) are expected to be small. Likewise, very small CP-violating effects are expected. As yet there is no evidence for CP violation in the charm system, but the very large data samples being collected by the LHCb experiment provide an ideal place to precisely test theoretical predictions and search for new sources of CP violation.

At hadron colliders it is possible to tag the initial flavour of $D^0$ mesons using two different methods, depending on how they were produced. The flavour is determined either by the charge of the pion from promptly-produced $D^+ \to D^0\pi^+$ decays or the charge of the muon from semileptonic $B$ decays ($B \to D^0\mu^-X$). These independent samples have different properties in terms of background and reconstruction efficiencies, leading to different systematic uncertainties in the final measurements.

The large yields available in the charm system can also be used to search for CP violation in strong interactions. The LHCb collaboration has recently used $D^{+}_{(s)} \to \pi^+\pi^+\pi^-$ decays to search for CP violating $\eta^{(')} \to \pi^+\pi^-$ decays, finding no signal in the $\pi^+\pi^-$ mass spectrum. This constrains the branching fractions to be less than $\sim 10^{-5}$ at 90% CL, which are comparable with or better than existing limits. 

7.1. Direct CP violation in the charm system

Direct CP violation in the charm system can be explored by measuring the asymmetries in the decay of $D^0$ mesons to CP eigenstates (i.e., $D^0 \to h^+h^-$). Experimentally the raw yield asymmetry is measured, $A_{\text{raw}} \equiv N(D^0 \to h^+h^-) - N(D^0 \to h^-h^+)$, and subsequently corrected for small production and detection asymmetries using data control modes in order to determine the CP asymmetry, $A_{CP}(D^0 \to h^+h^-) = A_{\text{raw}}(D^0 \to h^+h^-) - A_P(D^{*+}) - A_P(\pi_s^+)$. The LHCb collaboration has recently measured $A_{CP}(D^0 \to K^+K^-)$ using a prompt-tagged sample (Figure 11). While still statistically limited, the dominant systematic uncertainty in the result relates to control of the nuisance asymmetries. Combining $A_{CP}(D^0 \to K^+K^-)$ with an earlier measurement of the difference in CP asymmetries between the kaon and pion modes, $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$, allows $A_{CP}(D^0 \to \pi^+\pi^-)$ to be extracted. Figure 11b shows the result for the two CP asymmetries, which are consistent with CP symmetry. These results have been combined with independent measurements from the semileptonic-tagged sample to provide an overall LHCb result of $A_{CP}(D^0 \to K^+K^-) = (0.04 \pm 0.12 \pm 0.10)$% and $A_{CP}(D^0 \to K^+K^-) = (0.07 \pm 0.14 \pm 0.11)$%, where the first uncertainty is statistical and the second systematic. These results are now approaching the per-mille level of uncertainty but still do not show any signs of CP violation. Likewise, there are no indications of CP violation in other modes such as $D^\pm \to \eta'\pi^\pm$ and $D_s^\pm \to \eta'\pi^\pm$. A search for CP violation in $D^0 \to \pi^+\pi^-\pi^+\pi^-$ decays using an energy test reports a mild tension with CP-symmetry that requires further exploration with Run 2 data.
Fig. 12. Measured asymmetry $A(t)$ in bins of $t/\tau_D$, where $\tau_D$ is the world average value for the $D^0$ lifetime$^{19}$, for (a) $D^0 \rightarrow K^+K^-$ and (b) $D^0 \rightarrow \pi^+\pi^-$ decays. The solid line shows a linear fit to the data, with a slope equal to the best estimate of $-A_{\Gamma}$.

7.2. Indirect CP violation

As discussed in above, the mixing parameters and decay-time-integrated CP asymmetries in the charm system are small. Based upon this, a measurement of the decay-time-dependent CP asymmetry of $D^0$ decays to CP eigenstates is sensitive to the indirect CP violating parameter $A_{\Gamma}$. Here, $A_{\Gamma} \equiv \frac{\Gamma_{D^0 \rightarrow f} - \Gamma_{D^0 \rightarrow f'}}{\Gamma_{D^0 \rightarrow f} + \Gamma_{D^0 \rightarrow f'}}$, is the asymmetry between the inverse effective lifetimes of the $D^0$ meson and its antiparticle.

Within the SM, its magnitude is expected to be $\lesssim 5 \times 10^{-3}$ and independent of the final state, $f$, owing to the small CP violation in decay.

The LHCb collaboration has recently measured $A_{\Gamma}$ using a prompt-tagged sample of $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays$^{84}$. Two different methods are used to measure the asymmetry, an approach that is binned in the $D^0$ decay time and an unbinned method. Both approaches use the large sample of $D \rightarrow K\pi$ decays to control production and detection asymmetries. They each give consistent measurements, with the binned result being slightly more precise and chosen as the nominal result. Figure 12 shows the binned asymmetries as a function of decay time for the kaon and pion decay modes. The value of $A_{\Gamma}$ is given by the gradient of the linear fit to these asymmetries. These values are combined to give $A_{\Gamma} = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3}$. They have subsequently been combined with the semileptonic-tagged sample$^{85}$ to obtain $A_{\Gamma} = (-0.29 \pm 0.28) \times 10^{-3}$. This is the most precise measurement of a CP-violating observable in the charm system ever made.

7.3. Charm mixing and indirect CP violation

The measurement of charm mixing parameters and a search for CP violation can be performed by studying the decay-time-dependent ratio of yields of Cabibbo-suppressed to Cabibbo-favoured $D^0 \rightarrow K\pi$ decays. This ratio is defined separately for $D^0$ and $D^0$ decays and is related to the mixing parameters via a second-order expansion of the mixing equations (assuming small mixing) given by

$$R(t)^\pm = R_D^\pm + \sqrt{R_D^+} y'^\pm + \frac{(y'^\pm)^2 - (y'^\mp)^2}{4} \left(\frac{t}{\tau}\right)^4,$$

where $\tau$ is the average $D^0$ lifetime.
and the $x', y'$ have been rotated from the nominal mixing parameters by the strong phase in the $D \rightarrow K\pi$ decay. A recent result\textsuperscript{86} from the LHCb collaboration uses a double-tagged (DT) technique (using the charge of the pion and the muon from the semileptonic $B$ decays ($B^0 \rightarrow (D^{*+} \rightarrow D^0\pi^+)\mu^- X$)) to provide a very pure sample of events (Figure 13a and b) that cover a complementary region of the decay time spectrum than has been previously studied using a prompt-sample\textsuperscript{87}. Figure 13c shows the ratios for $D^0$ and $\bar{D^0}$ decays and their difference for both the DT and prompt samples. The ratios increase as a function of time, consistent with charm mixing, allowing $x', y'$ to be measured for the DT sample alone and both samples combined. The complementary coverage of the DT and prompt sample gives an improved precision, by 10–20%, for the charm mixing parameters from the combined fit even though the DT analysis is based on almost 40 times fewer candidates than the prompt analysis. The data are consistent with the hypothesis of $CP$ conservation (both for decay and interference of mixing and decay).

8. Looking to the future

The majority of beauty and charm sector measurements are statistically limited, which strongly motivates the case for a new set of precision measurements of $CP$-violating observables to constrain the size of (or perhaps find) new physics contributions. The LHCb collaboration recently submitted an expression of interest\textsuperscript{88} regarding future phase 1b and 2 upgrades that would operate during LHC runs 4 and 5, respectively. It is expected that using the data collected with the improved detector it will be possible to improve the precision on $\gamma$ to 0.4$^\circ$, $\phi_s$ to 9 mrad (see
Fig. 14. Projection of how precision on $\phi_s$ from LHCb measurements will scale as a function of time for different decay modes. Information taken from Refs. 89, 90.

Figure 14 and achieve precision on charm mixing and $CP$ violation parameters at the level of $10^{-4}$. These will allow unprecedented sensitivity to the small effects of new physics. Crucially, as the precision improves it is essential to control hadronic effects that can hide small non-Standard Model effects. Other studies can be found in Refs. 89, 90.

9. Summary

This year is the 40th anniversary of the discovery of the $b$ quark 91. In that time there has been huge progress in using the physics of heavy-flavour hadrons to make detailed studies of $CP$-violation, both experimentally and theoretically. So far all measurements are consistent with Standard Model predictions, confirming validity of the CKM mechanism. The LHCb experiment is now leading the way in terms of precision measurements in the $b$ and $c$ sectors, with new explorations of $CP$ violation in baryons just beginning. It will be fascinating to observe how the SM is able to withstand the next round of precision measurements that will be made over the next decade.

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