CKM studies from $b$ physics at hadron machines

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In absence of direct signs of new physics at the LHC, flavour physics provides an ideal laboratory to look for deviations from the Standard Model and explore an energy regime beyond the LHC reach. Here, new results in $CP$ violation and rare decays are presented.

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1 Introduction

The first run of the Large Hadron Collider with 7 and 8 TeV pp collisions has allowed to discover the Higgs boson [1], but not to find any hint of the existence of new particles. Neither supersymmetry nor any other sign of new physics has popped out of the LHC. This situation may change during Run II with higher centre-of-mass energies of 13 TeV. In the meantime it is worth investigating what the data at the lower energies involved in the decays of $b$ hadrons can tell us about new physics.

Studies of $CP$ violation in heavy flavour decays are both sensitive to the above-mentioned high mass scales and to potential new phases beyond the phase of the CKM matrix. Also of particular interest are rare decays that are strongly suppressed in the Standard Model (SM), where new physics amplitudes could be sizable.

2 $CP$ violation measurements

Owing to the legacy of the $B$ factories [2], we have entered the era of precision tests of the Cabibbo-Kobayashi-Maskawa (CKM) paradigm [3]. Precise measurements of the angles of the unitarity triangle(s) are needed to search for new sources of $CP$ violation beyond the single phase of the CKM matrix.

The LHC is often considered as a $B^0_s$ meson factory, owing to its large cross-section and the unprecedented capabilities of the LHC experiments to precisely resolve its oscillations. This opens the door to precision measurements of the $CP$-violating phase $\phi_{cs s}$, which is equal to $-2\beta_s = -2 \arg \left(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*\right) = -0.0363 \pm 0.0013$ in the SM, neglecting sub-leading penguin contributions. It was measured at the LHC using the flavour eigenstate decays $B^0_s \rightarrow J/\psi \phi$ with $J/\psi \rightarrow \mu^+\mu^-$ and $\phi \rightarrow K^+K^-$ [4] and $B^0 \rightarrow J/\psi \pi^+\pi^-$ [5]. Recently LHCb used the decay $B^0_s \rightarrow J/\psi K^+K^-$ for the first time in a polarisation-dependent way [6]. Combined with $B^0 \rightarrow J/\psi \pi^+\pi^-$, LHCb obtains $\phi_{cs s} = -0.010 \pm 0.039$ rad. The constraints on $\phi_{cs s}$ and the decay width difference $\Delta \Gamma_s$ are shown in Fig. 1 (left). The same quantity was also measured with a fully hadronic final state using the decay $B^0_s \rightarrow D_s^+D_s^-$ with $D_s^\pm \rightarrow K^\pm K^-\pi^\pm$, yielding $0.02 \pm 0.17 \pm 0.02$ [7]. The effective tagging power $\epsilon D^2$ in excess of 5% for this channel is unprecedented at a hadron collider.

With the precision on some CKM phases reaching the degree level, the effects of suppressed penguin topologies cannot be neglected any more [8,9]. Cabibbo-suppressed decay modes, where these topologies are relatively more prominent can be used to constrain such effects. This programme has started with studies of the decays $B^0_s \rightarrow J/\psi K^0_s$ [10], $B^0_s \rightarrow J/\psi K^{*0}$ [11] and more recently with $B^0 \rightarrow J/\psi \pi^+\pi^-$ [12]. The measurement of $\sin 2\beta_{\text{eff}}$ in the latter mode allows to constrain the shift to $\phi_{cs s}$ due to penguin topologies to the range $[-0.018, 0.021]$ radians at 68% CL. Considering the present uncertainty of $\pm 0.039$ radians, such a shift needs to be to constrained
Figure 1: (left) Constraints on $\Delta \Gamma_s$ and $\varphi_s^{cs}$ from various experiments. (right) Fitted values of $x$ and $y$ for $B^-$ and $B^+$ in $B^\pm \to DK^\pm$ with $D \to K^0_s h^+ h^-$ decays [17].

further.

An interesting test of the Standard Model is provided by the measurement of the mixing phase $\varphi_s^{cs}$ with a purely penguin-induced mode as $B^0_s \to \phi \phi$. In this case the measured value is $-0.17 \pm 0.15 \pm 0.03$ [13], which is compatible with the SM expectation.

Similarly, the decays $B \to hh$ with $h = \pi, K$ are also sensitive to penguin topologies (as well as trees) and are sensitive to the CKM phases $\gamma$ and $\beta_s$. LHCb for the first time measured time-dependent CP-violating observables in $B^0_s$ decays using the decay $B^0_s \to K^+ K^-$ [14]. Using methods outlined in Refs. [9, 15], a combination of this and other results from $B \to hh$ modes allows to determine $-2\beta_s = -0.12^{+0.14}_{-0.16}$ rad using as input the angle $\gamma$ from tree decays (see below), or $\gamma = (63.5^{+7.2}_{-6.7})^\circ$ constraining $-2\beta_s$ to the SM value [16]. These values are in principle sensitive to the amount of U-spin breaking that is allowed in this decay and are given here for a maximum allowed breaking of 50%.

This value of $\gamma$ can be compared to that obtained from tree-dominated $B \to DK$ decays, where the CP-violating phase appears in the interference of the $b \to c$ and $b \to u$ topologies. It is the least precisely known angle of the unitarity matrix, and its determination from tree decays is considered free from contributions beyond the Standard Model and unaffected by hadronic uncertainties. Yet its precise determination is important to test the consistency of the CKM paradigm, and to allow comparisons with determinations from modes dominated by penguin topologies.

The most precise determination of $\gamma$ from a single decay mode is achieved with $B^+ \to DK^+$ followed by $D \to K^0_s h^+ h^-$ with $h = \pi, K$ [17]. Here the interference of the $D^0$ and $\bar{D}^0$ decay to $K^0_s h^+ h^-$ is exploited to measure CP asymmetries [18]. The method needs external input in the form of a measurement of the strong phase over
the Dalitz plane of the $D$ decay, coming from CLEO-c data [19]. The determined $CP$-violating parameters are shown in Fig. 1 (right), and the value of $\gamma$ is $(62^{+15}_{-14})^\circ$. The same decay mode is also used in a model-dependent measurement [20] using an amplitude model.

An experimentally very different way of determining $\gamma$ is provided by the decay $B_0^s \to D_s^+K^\pm$ [21,22]. In this case the phase is measured in a time-dependent tagged $CP$-violation analysis. Using a dataset corresponding to 1 fb$^{-1}$, LHCb determines $\gamma = (115^{+28}_{-43})^\circ$, which is not competitive with other methods but will provide important cross-checks with more data.

The $\gamma$ measurements of Refs. [17,22,24] are then combined in an LHCb combination prepared for the CKM conference [23]. Using only $B \to DK$ decay modes one finds $\gamma = (73^{+9}_{-10})^\circ$, which is more precise than the corresponding combination of measurements from the $B$ factories [2]. The likelihood profile is shown in Fig. 2 (left).

The same-sign dimuon asymmetry measured by the D0 collaboration [25] and interpreted as a combination of the semileptonic asymmetries $A_{sl}^d$ and $A_{sl}^s$ in $B^0$ and $B_0^s$ decays, respectively, remains puzzling. The measured values differ from the SM expectation by 3$\sigma$. So far LHCb has not been able to confirm or disprove this. The measurement from LHCb follows a different approach, looking at the $CP$ asymmetry between partially reconstructed $B \to D_s^+\mu\nu$ decays, where the flavour of the $D$ identifies that of the $B$. The measured value of $A_{sl}^s$ [26] and the newly reported $A_{sl}^d$ [27] are both consistent with the SM and the D0 value. The world average including measurements from the $B$ factories and D0 is not more conclusive. See Fig. 2 (right).

Large $CP$ violation has also been found in charmless $b$-hadron decays like $B^+ \to h^+h^-h^\pm$ [28] ($h = \pi,K$) and $B^+ \to pph^+$ [29]. In the former case $CP$ asymmetries, integrated over the phase-space, ranging from $-12\%$ ($B^\pm \to \pi^\pm K^+K^-$) to $+6\%$
\( (B^\pm \to \pi^\pm K^+K^-) \) are measured. Particularly striking features of these decays are very large asymmetries in small regions of the phase-space not related to any known resonance, which are of opposite sign for \( B^\pm \to h^\pm K^+K^- \) and \( B^\pm \to h^\pm \pi^\pm \pi^- \) decays. These could be a sign of long-distance \( \pi^\pm \pi^- \leftrightarrow K^+K^- \) rescattering.

Finally, another important field is the study of \( CP \) violation in beauty baryons. The \( \Lambda_b^0 \) hadronisation fraction was measured to be surprisingly large at the LHC in the forward region \( [30] \), almost half of that of \( B^0 \) mesons. These baryons can be used for measurements of \( CP \) violation with better precision than \( B^0 \) mesons. Searches have been performed by LHCb with the decays \( \Lambda_b^0 \to J/\psi p\pi^- \) \( [31] \), \( \Lambda_b^0 \to K^0 p\pi^- \) \( [32] \), and by CDF with \( \Lambda_b^0 \to ph^- \) \( [33] \). It is to be noted that to date no evidence of \( CP \) violation in any decay of a baryon has ever been reported.

### 3 \( B^0_s \to \mu^+\mu^- \) and \( B^0 \to \mu^+\mu^- \)

The rare decay \( B^0_s \to \mu^+\mu^- \) proceeds in the SM by a box-type annihilation diagram involving the \( W \) boson and the \( t \) quark. It is furthermore helicity-suppressed. The most recent standard model prediction of its branching fraction is \( (3.66 \pm 0.23) \times 10^{-9} \) \( [34] \), where the uncertainty is dominated about equally by CKM matrix elements and the \( B^0_s \) decay constant. In this calculation the branching fraction is evaluated as an average over all decay times, see Refs. \( [35] \) for more details.

The decay \( B^0_s \to \mu^+\mu^- \) has been searched for over three decades, with most recent results from the Tevatron \( [36] \) and the LHC \( [37] \). The first evidence was reported in Summer 2012 by LHCb \( [38] \) using 2 fb\(^{-1}\) from the 2011 and half of the 2012 data. A year later LHCb and CMS updated their results to the full Run I dataset \( [39] \).

The data-sets in these two publications were then combined in a joint fit to the data of both experiments \( [40] \). This is the first time such a joint fit is done at the LHC. The selections (and thus the data-sets) are left unchanged, but the fit models are aligned to be based on the same assumptions. Notably the treatment of the \( \Lambda_b^0 \to p\mu^+\nu \) background was different between the two experiments, and the effect of the lifetime acceptance on the admixture of heavy and light \( B^0_s \) states had been neglected in the CMS publications. As for the individual publications, the fits are performed in each bin of boosted-decision-tree output. An example fit is shown in Fig. 3 (left). The result of the combination is a clear first observation of the \( B^0_s \to \mu^+\mu^- \) decay and a 3\( \sigma \) excess over the background for the \( B^0 \to \mu^+\mu^- \) decay. In the latter case, the significance obtained from Wilk’s theorem is 3.2\( \sigma \), while a likelihood scan following the Feldman-Cousins method \( [41] \) yields 3.0\( \sigma \). This is a deviation from the SM expectation by 2.2\( \sigma \). The measured \( B^0 \to \mu^+\mu^- \) and \( B^0_s \to \mu^+\mu^- \) branching fractions are compared to the SM expectation in Fig. 3 (right). More data from Run II and III will tell if the excess of \( B^0 \to \mu^+\mu^- \) is a statistical fluctuation or the indication of new physics.
4 Rare electroweak decays

The family of decays $b \to s \ell^+ \ell^-$ is a laboratory of new physics on its own. In particular the exclusive decay $B^0 \to K^{*0} \ell^+ \ell^-$ ($\ell = e, \mu$) provides a very rich set of observables with different sensitivities to new physics and for which the theoretical predictions are available and affected by varying levels of hadronic uncertainties. In the case of some ratios of observables most of these uncertainties cancel, thus providing a clean test of the SM [42,43].

The differential decay width with respect to the dilepton mass squared $q^2$, the well-known forward-backward asymmetry $A_{FB}$, and the longitudinal polarisation fraction $F_L$ of the $K^*$ resonance have been measured by many experiments [44, 45] with no significant sign of deviations from the SM expectation.

In a second analysis of the already published [45] 2011 data, LHCb published another set of angular observables [46] suggested by Ref. [43]. In particular a $3.7\sigma$ local deviation of the $P'_5$ observable from the Standard Model expectation was observed in one bin of $q^2$, shown in Fig. 4 (right).

This measurement triggered a lot of interest in the theory community, with interpretation articles being very quickly submitted to journals. See Refs. [48] for a small subset. It is not clear if this discrepancy is an experimental fluctuation, is due to under-estimated form factor uncertainties (See Ref. [49]), or the manifestation of a heavy $Z'$ boson, among many other suggested explanations. The contribution of $c \bar{c}$ resonances is also being questioned [50] after the LHCb observation of $B^+ \to \psi(4160)K^+$ with $\psi(4160) \to \mu^+ \mu^-$ [51], where the $\psi(4160)$ and its interference with the non-resonant component accounts for 20% of the rate for dimuon masses above 3770 MeV/$c^2$. Such a large contribution was not expected.

Given the hint of abnormal angular distributions, LHCb tried to look for other
deviations in several asymmetry measurements. The $CP$ asymmetry in $B^0 \rightarrow K^\ast \mu^+ \mu^-$ and $B^\pm \rightarrow K^\pm \mu^+ \mu^-$ turns out to be compatible with zero as expected \[52\], as does the isospin asymmetry between $B^0 \rightarrow K^{(*)0} \mu^+ \mu^-$ and $B^+ \rightarrow K^{(*)+} \mu^+ \mu^-$. The lepton universality $R_K = \frac{B(B^+ \rightarrow K^+ \mu^+ \mu^-)}{B(B^0 \rightarrow K^0 \mu^+ \mu^-)}$ is measured to be $0.745^{+0.099}_{-0.074} \pm 0.036$ \[47\] in the $1 < q^2 < 6 \text{ GeV}/c^2$ range, which indicates a $2.6\sigma$ tension with unity. Unlike at the $B$ factories, where electrons and muons contribute equally to $b \rightarrow s \ell^+ \ell^-$ modes, at hadron colliders only muonic modes are normally used. Yet, LHCb has demonstrated its ability to use rare decays to electrons \[54\]. The use of electrons is difficult due to the lower trigger efficiency and the poorer mass resolution due to bremsstrahlung. Figure 4 shows the $K^+ e^+ e^-$ mass distribution for candidates with $1 < q^2 < 6 \text{ GeV}/c^2$, which is safely far from the radiative tail of the $J/\psi \rightarrow e^+ e^-$ decay. This result is being interpreted as an indication of a new vector current ($Z'$?) that would couple more strongly to muons and interfere destructively with the SM vector current \[55\].

5 Conclusions

The LHC is the new $b$-hadron factory and will be dominating flavour physics until the start of Belle II, and beyond in many decay modes. Atlas, CMS and LHCb have presented interesting new results in rare decays, that set strong constraints on models beyond that SM and exhibit some discrepancies with the SM predictions. It is not yet clear whether these are fluctuations, poorly understood form factors, or new physics. The upcoming Run II, with its higher centre-of-mass energy translating into higher $bb$ cross-sections, may tell us.
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