

Experimental prospects for B physics and discrete symmetries at LHC and future projects

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Abstract. The experimental prospects for B physics (with brief mentions of charm and τ physics) at the Large Hadron Collider experiments are reviewed, with particular attention to the LHCb experiment. The main focus is on CP (a)symmetry, though the usefulness of rare decays to probe the symmetries of nature is also discussed. The need for upgrades and new facilities to continue the investigations beyond the first few years of LHC operations is emphasised.

1. Current status

A great deal has been learnt about heavy flavour physics over the past decade. In particular, the achievements of the B factory experiments, the Tevatron, the kaon experiments NA48 and KTeV as well as several other experiments have confirmed that the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1, 2] is the origin of CP violation within the Standard Model (SM). This is often shown in the form of constraints on the so-called “Unitarity Triangle”, as seen in Fig. 1. The strongest constraints come from the measurement of $\sin(2\beta)$ in $B^0 \rightarrow J/\psi K_S^0$ and related processes¹ from BaBar [3] and Belle [4], the value of Δm_d normalised to that obtained for Δm_s by CDF [5], the CP violation parameter in neutral kaon mixing ϵ_K and combinations of many measurements from BaBar and Belle that constrain $|V_{ub}|$, α and γ (for detailed reviews containing all original citations, see Refs. [6, 7, 8]). All measurements overlap (within a few standard deviations) at a single point, illustrating their consistency with the CKM paradigm.

However, a closer scrutiny of the situation reveals several intriguing hints of non-standard effects in flavour observables that demand further investigation. These include evidence for an inclusive same-sign dimuon asymmetry from D0 [11, 12], anomalous results for the CP violating phase in B_s^0 oscillations [13, 14, 15, 16], possible deviations from the expected behaviour of the forward-backward asymmetry in $B \rightarrow K^* l^+ l^-$ decays [17, 18, 19], a larger than expected rate for $B \rightarrow \tau \nu$ [20, 21] and tension in the CKM fit [22]. Moreover, the existing constraints do not rule out the possibility of large contributions from non-SM processes in various flavour physics observables that can be tested in the next few years.

Tab. 1 presents an alternative method of summarising the current knowledge of CP violation. Definitions of the three different categories of CP violation, namely (i) CP violation in mixing, (ii) CP violation in the interference between mixing and decay, (iii) CP violation in decay (also known as direct CP violation), can be found in the review by D. Kirkby and Y. Nir

¹ The inclusion of charged conjugated processes is implied throughout.

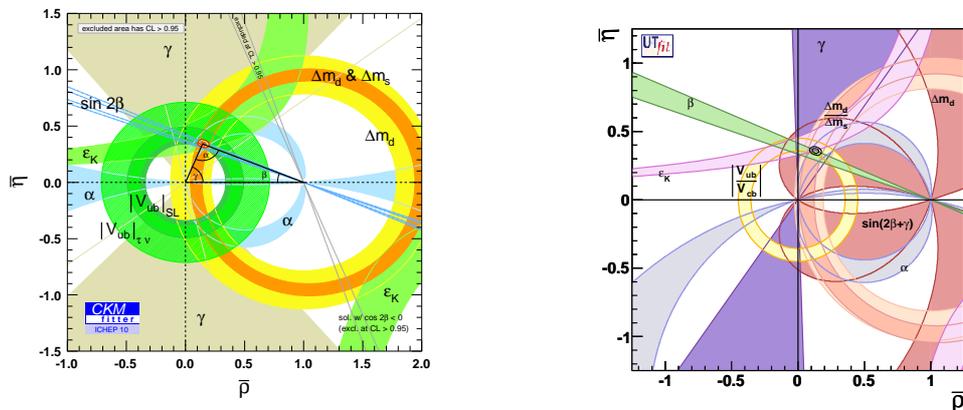


Figure 1. Constraints on the Unitarity Triangle compiled by (left) the CKMfitter collaboration [9], using frequentist methods; (right) the UTfit collaboration [10], using a Bayesian approach.

in Ref. [8]. All three categories have been observed in the neutral kaon system,² while some sizable effects in the B_d^0 system have been observed as expected in the SM (including direct CP violation [23, 24, 25]). Yet it is clear that despite the huge progress made by the B factory experiments, there is much that remains to be experimentally tested. Consequently, next generation experiments have enormous discovery potential. As will be discussed in the following sections, there are several sectors where large CP violation effects are expected in the SM but have not yet been investigated with sufficient precision. On the other hand, in some of the others the Standard Model prediction is for negligibly small levels of CP violation – these therefore provide sensitive “null tests” that can be used to search for the effects of physics beyond the SM.

Table 1. Summary of the systems where CP violation effects have been observed. A five standard deviation (σ) significance threshold is required for a \checkmark . Note that CP violation in decay is the only possible category for particles that do not undergo oscillations. Further details can be found in the review by D. Kirkby and Y. Nir in Ref. [8].

| | K^0 | D^0 | B_d^0 | B_s^0 | Charged mesons | Baryons | Charged leptons |
|---|--------------|----------|--------------|----------|----------------|----------|-----------------|
| CP violation in mixing | \checkmark | \times | \times | \times | – | – | – |
| CP violation in mixing/decay interference | \checkmark | \times | \checkmark | \times | – | – | – |
| CP violation in decay | \checkmark | \times | \checkmark | \times | \times | \times | \times |

2. The Large Hadron Collider and its experiments

The year 2010 was a remarkably successful start of the LHC era. As shown in Fig. 2, the delivered luminosity per experiment approached 50 pb^{-1} , and the peak instantaneous luminosity exceeded

² I am grateful to Marco Sozzi for a clarification on this point.

$10^2 \text{ Hz}/\mu\text{b} \equiv 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. This roughly corresponds to the design luminosity of the LHCb experiment, and is only two orders of magnitude below the anticipated peak luminosity that will be delivered to the ATLAS and CMS experiments before a major upgrade of the machine.

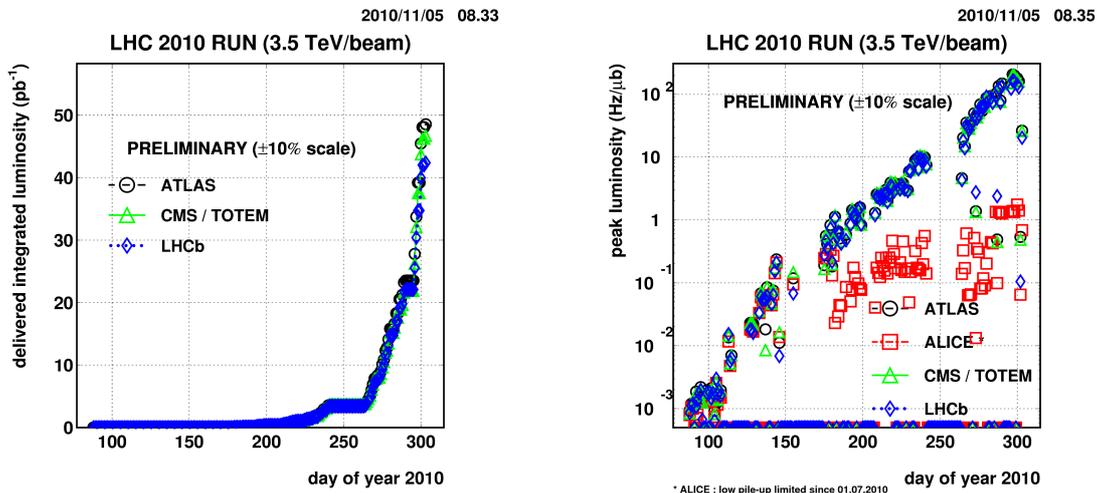


Figure 2. Performance of the LHC during 2010: (left) integrated delivered luminosity; (right) peak instantaneous luminosity.

Details of the LHCb [26], ATLAS [27] and CMS [28] experiments can be found elsewhere; the salient difference between LHCb and the general purpose detectors is that the former is instrumented to cover the forward region ($2 < \eta < 6$) where the $b\bar{b}$ production cross-section is strongly peaked. All achieved excellent operational efficiency during 2010. Among results pertinent to flavour physics, at the time of the conference, all three experiments have produced results on the J/ψ production cross-section [29, 30, 31], while LHCb has in addition measured the open charm production cross-section [32] and has published the first measurements of $b\bar{b}$ production in pp collisions at 7 TeV [33]. The first observation of the decay $B_s^0 \rightarrow D_{s2}^{*-} X \mu^+ \nu$ [34] illustrates that LHCb is already moving into a phase where it is competitive with previous B physics experiments.

3. CP violation effects expected in the Standard Model

One of the most striking features of Tab. 1 is that CP violation has not yet been observed in the decay of any charged meson. The Standard Model predicts large effects in several channels, and indeed several measurements show evidence for the predicted effects [7, 8], but none at the 5σ level.

One of the theoretically cleanest predictions in CP violation phenomenology is that direct CP violation will occur in $B^+ \rightarrow DK^+$ decays, when the neutral D meson is reconstructed in a final state that is accessible to both D^0 and \bar{D}^0 decays, at a rate that is governed by the angle of the CKM Unitarity Triangle γ . Since only tree-level decay amplitudes are involved, and all the hadronic parameters can be determined from the data, there is negligible associated theoretical uncertainty [35]. At present γ is only weakly constrained [9, 10], and therefore improving the knowledge of this quantity is one of the key goals of LHCb, as described in the recent roadmap document [36].

Already in the data accumulated in 2010, LHCb has observed signals of $B^+ \rightarrow DK^+$ and the related $B^+ \rightarrow D\pi^+$ decays, where the D meson is reconstructed in two track final states, as shown in Fig. 3. The yields are broadly in line with the Monte Carlo simulation based

expectations. The yield of $B^+ \rightarrow D\pi^+$, $D \rightarrow K^+K^-$ events (1035 ± 54) exceeds that of CDF in their publication based on 1 fb^{-1} (780 ± 36 events) [37]³ but is somewhat less than in the final B factory datasets. Signals have also been seen in the related channels with the D meson reconstructed from $K_S^0\pi^+\pi^-$ or $K_S^0K^+K^-$, as also shown in Fig. 3. Measurements from the B factories have shown that these have high sensitivity to γ [38, 39].

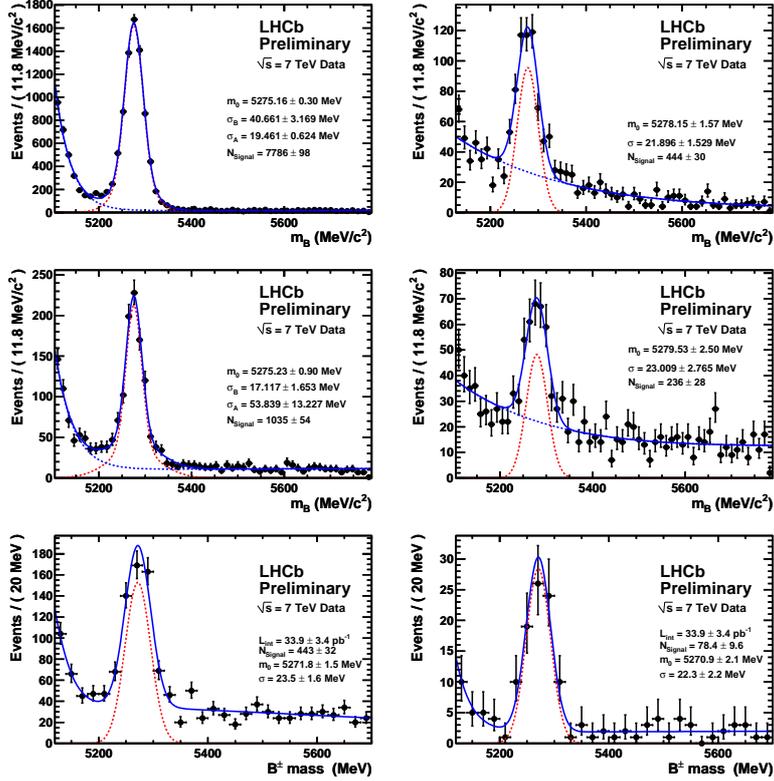


Figure 3. Signals in $\sim 34 \text{ pb}^{-1}$ of LHCb data for (top to bottom; left to right) $B^+ \rightarrow D\pi^+$, $D \rightarrow K^+\pi^-$; $B^+ \rightarrow DK^+$, $D \rightarrow K^+\pi^-$; $B^+ \rightarrow D\pi^+$, $D \rightarrow K^+K^-$; $B^+ \rightarrow D\pi^+$, $D \rightarrow \pi^+\pi^-$; $B^+ \rightarrow D\pi^+$, $D \rightarrow K_S^0\pi^+\pi^-$; $B^+ \rightarrow D\pi^+$, $D \rightarrow K_S^0K^+K^-$.

It should also be noted that several other channels are in competition for the first observation of direct CP violation in charged B decay. One notable example is $B^+ \rightarrow \rho^0 K^+$. This decay can be studied via Dalitz plot analysis of the $\pi^+\pi^-K^+$ final state, giving heightened sensitivity to CP violation effects, as demonstrated by analyses from Belle and BaBar [40, 41].

Several other decays of the type $B \rightarrow DK$ (not only those of the charged B meson) can be used to determine γ . A time-dependent analysis of $B_s^0 \rightarrow D_s^\mp K^\pm$ is sensitive to the combination $2\beta_s - \gamma$. Since this quantity is not small in the SM, this channel has the potential to make a measurement of CP violation in the interference between mixing and decay in the B_s^0 system. Signals for the related decay $B_s^0 \rightarrow D_s^- \pi^+$ are apparent in the 2010 data, as shown in Fig. 4 (this channel will be used to measure Δm_s). As before, the yields are consistent with expectation, indicating that LHCb is on track to produce the world's best measurement of γ , with estimated sensitivity $\sim 7^\circ$, with the data expected to be accumulated in 2011 ($\sim 1 \text{ fb}^{-1}$ from collisions at $\sqrt{s} = 7 \text{ TeV}$).

³ Any such comparison must be taken “*cum grano salis*” due to the different trigger, reconstruction and selection efficiencies.

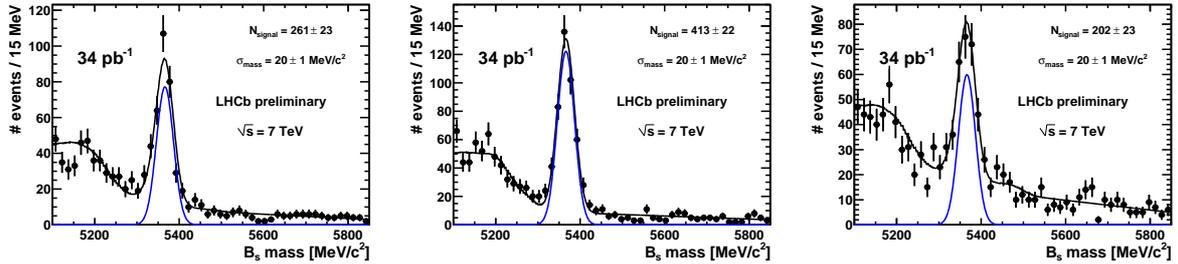


Figure 4. Signals in $\sim 34 \text{ pb}^{-1}$ of LHCb data for (left to right) $B_s^0 \rightarrow D_s^- \pi^+$, $D_s^- \rightarrow K^{*0} K^-$; $B_s^0 \rightarrow D_s^- \pi^+$, $D_s^- \rightarrow \phi \pi^-$; $B_s^0 \rightarrow D_s^- \pi^+$, $D_s^- \rightarrow K^+ K^- \pi^-$ (excluding $K^{*0} K^-$ and $\phi \pi^-$).

Another channel which may provide the first observation of CP violation in the interference between mixing and decay in the B_s^0 system is $B_s^0 \rightarrow K^+ K^-$. The measurement is again sensitive to γ , with somewhat larger theoretical uncertainties (compared to $B^+ \rightarrow DK^+$) that can, however, be controlled exploiting the U-spin relation to the $B_d^0 \rightarrow \pi^+ \pi^-$ decay. Since the decays contain loop (“penguin”) contributions, new physics particles may appear in the loops, leading to deviations from the SM predictions.

Fig. 5 shows the signals for $B_s^0 \rightarrow K^+ K^-$ (254 ± 20 events) and $B_d^0 \rightarrow \pi^+ \pi^-$ (229 ± 23 events) in the 2010 LHCb data.³ These yields can be compared to those from CDF in their analysis of 1 fb^{-1} : 1307 ± 64 and 1121 ± 63 events respectively [42]. As is clear from Fig. 5, the particle identification capability provided by the RICH detectors of LHCb is provides a powerful tool to distinguish the different b -hadron decays to two track final states.

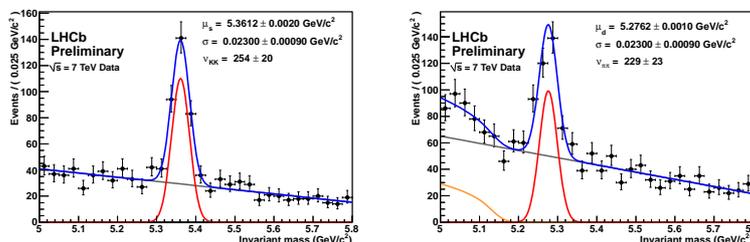


Figure 5. Signals in $\sim 35 \text{ pb}^{-1}$ of LHCb data for (left to right) $B_s^0 \rightarrow K^+ K^-$; $B_d^0 \rightarrow \pi^+ \pi^-$.

Two track final states offer other notable discovery possibilities. Direct CP violation in B decay was first seen in $B_d^0 \rightarrow K^+ \pi^-$ decays [23, 24], and the same final state may reveal the first direct CP violation in B_s^0 decay. Fig. 6 shows the yields in the $K\pi$ final state split into the two charge conjugate modes. Raw asymmetries are clearly visible in existing data. The central values are consistent with expectations and previous measurements. Corrections due to production or detection asymmetries are being evaluated together with the other systematic uncertainties necessary to quote a meaningful quantitative measurement.⁴

Similarly, two body Λ_b decays offer excellent prospects for the first discovery of CP violation in the baryon sector. Fig. 7 shows the yields of these decays in LHCb 2010 data, illustrating that such effects are likely to become observable with the data expected to be accumulated in 2011. Charmed Λ_b decays are also being investigated.

⁴ While these proceedings were in preparation, the first results including systematic uncertainties were presented [43].

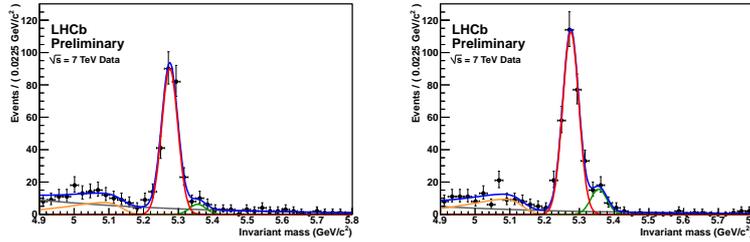


Figure 6. Signals in $\sim 35 \text{ pb}^{-1}$ of LHCb data for (left to right) $\bar{B} \rightarrow K^- \pi^+$; $B \rightarrow K^+ \pi^-$.

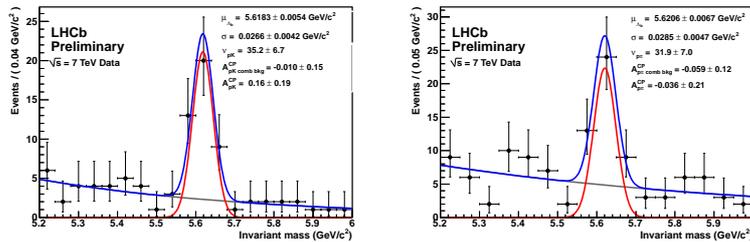


Figure 7. Signals in $\sim 35 \text{ pb}^{-1}$ of LHCb data for (left to right) $\Lambda_b^+ \rightarrow pK^+$; $\Lambda_b^+ \rightarrow p\pi^+$.

4. CP violation effects not expected in the Standard Model

While it is of undoubted importance to search for all the manifestations of CP violation that are predicted by the SM, it is perhaps even more fundamental to search for effects that would clearly indicate CP violating amplitudes that cannot be accommodated within the SM. Inconsistencies in the CKM fit that could be revealed by more precise measurements, and direct comparisons of the value of γ (for example) measured in different processes, provide exciting potential to search for “new physics” (NP) beyond the SM. These are complemented by searches for CP violation effects in processes where the SM prediction is small, and which therefore serve as “null tests” for NP.

One such process is the decay channel $B_s^0 \rightarrow J/\psi\phi$. This is the B_s^0 system counterpart to the B factory “golden mode” $B_d^0 \rightarrow J/\psi K_S^0$, and probes CP violation in the interference between mixing and decay parameterised by $2\beta_s$, which is small in the SM ($\beta_s^{\text{SM}} \sim 2^\circ$). Since the final state contains two vector-mesons, an angular analysis is required to disentangle the CP -even and CP -odd components.⁵ Moreover, the width difference $\Delta\Gamma_s$ cannot be neglected, unlike the case for the B_d^0 system. Consequently, the full tagged, time-dependent angular analysis is rather complicated (for full details, see Ref. [36]). First such measurements have been performed by CDF [13, 14] and D0 [15, 16] giving exciting hints of non-standard contributions, albeit with very large statistical uncertainties.

In the data collected in 2010, LHCb has already accumulated a large sample of $B_s^0 \rightarrow J/\psi\phi$ decays, as shown in Fig. 8, where the related mode $B_d^0 \rightarrow J/\psi K^{*0}$, that is used to cross-check the angular acceptance, is also shown. The number of $B_s^0 \rightarrow J/\psi\phi$ events is 877 ± 32 , which can be compared to ~ 6500 in the CDF analysis based on 5.2 fb^{-1} [14] or ~ 3500 in the D0 analysis based on 6.1 fb^{-1} [16].³ Another important aspect of the analysis is the flavour tagging, which is a serious challenge in the hadronic environment. Fig. 9 shows that the performance of the tagging algorithms was already sufficient to observe oscillations in the decay $B_d^0 \rightarrow D^{*-} X \mu^+ \nu$ in the

⁵ Such an angular analysis is not necessary for CP -eigenstate decays. While these proceedings were in preparation, the first observation of $B_s^0 \rightarrow J/\psi f_0(980)$ was reported by LHCb [44] and rapidly confirmed by Belle [45].

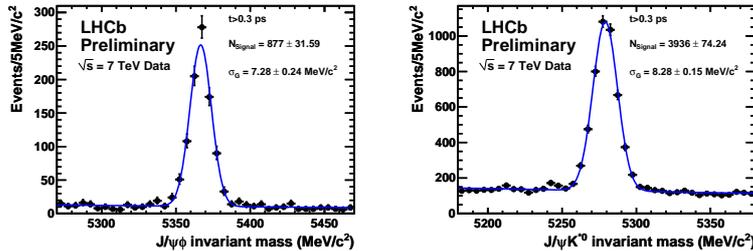


Figure 8. Signals in $\sim 34 \text{ pb}^{-1}$ of LHCb data for (left to right) $B_s^0 \rightarrow J/\psi\phi$; $B_d^0 \rightarrow J/\psi K^{*0}$.

first 1.9 fb^{-1} of data. These provide confidence that LHCb is well on the way to significantly improve the constraints on CP violation effects in B_s^0 oscillations with the data that will be accumulated in 2011. If large, non-standard effects are present in this system, this could be established with relatively little data, but in order to establish CP violation at the SM level much larger datasets (and hence an upgraded LHCb experiment) will be required.

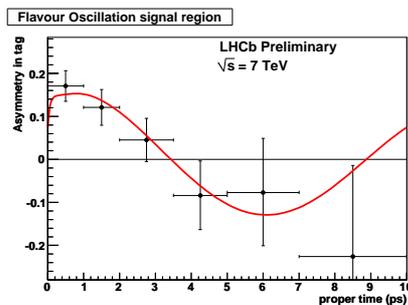


Figure 9. Raw asymmetry between $N(\text{unmixed})$ and $N(\text{mixed})$ as a function of proper time in the decay $B_d^0 \rightarrow D^{*-} X \mu^+ \nu$ in the first 1.9 fb^{-1} of LHCb 2010 data.

A complementary approach to search for New Physics effects in B_s^0 oscillations is through the measurement of CP violation that arises in the mixing amplitude itself. This can be measured using flavour-specific decays where the quantity determined is the so-called flavour-specific asymmetry, $A_{\text{fs}}(B_s^0)$. Inclusive semileptonic decays provide a convenient high-statistics sample with which to search for this form of CP violation. The SM prediction is $A_{\text{fs}}(B_s^0) = (2.06 \pm 0.57) \times 10^{-5}$ [46], and hence any asymmetry larger than $\mathcal{O}(10^{-4})$ could only be a consequence of NP.

The A_{fs} observable has received a lot of attention recently due to the (3σ) evidence for an anomalous effect measured by the D0 collaboration [11, 12]. This result is based on an inclusive reconstruction, and hence probes a linear combination of the flavour-specific asymmetries in B_d^0 and B_s^0 decays. One urgent goal of the first phase of LHCb is to confirm or rule out this anomaly. Due to the high precision required, it is necessary to use methods with intrinsically low levels of systematic uncertainty. The favoured approach in early data taking is to examine the difference between the B_d^0 and B_s^0 flavour-specific asymmetries, identifying B_d^0 and B_s^0 by their decays to $D^- \mu^+ X$ and $D_s^- \mu^+ X$ respectively, using the identical final state $K^+ K^- \pi^-$ for both D^- and D_s^- decays. Fig. 10 shows the anticipated sensitivity in the $A_{\text{fs}}(B_s^0) - A_{\text{fs}}(B_d^0)$ plane, compared to the D0 result.

The charm system provides unique opportunities to search for flavour-changing effects in flavour changing transitions of up-type quarks. All three categories of CP violation of Tab. 1 are extremely small in the SM, while current experimental constraints [7] are generally at least

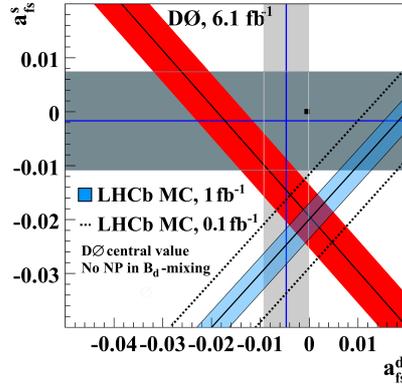


Figure 10. Anticipated sensitivity of LHCb to flavour-specific asymmetries caused by CP violation in mixing. The band shown assumes the SM value of $A_{fs}(B_d^0)$. The D^0 result [11, 12] is also shown.

an order of magnitude away from the interesting region.⁶ As well as direct CP violation, the recent evidence for charm mixing [47, 48] has opened the door to the possibility of studying mixing-induced CP violation effects.

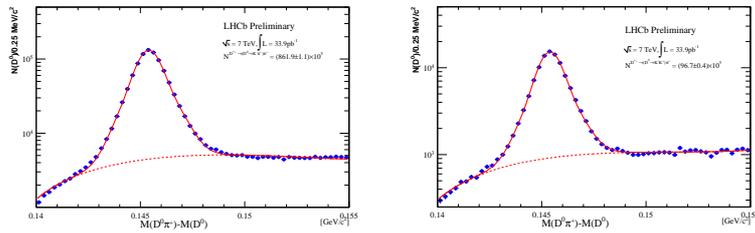


Figure 11. Signals in $\sim 34 \text{ pb}^{-1}$ of LHCb data for (left to right) $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K^- \pi^+$; $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K^+ K^-$.

Owing to the large cross-section for charm production in the LHCb acceptance [32], copious samples of charm decays are already available for analysis. Fig. 11 shows the $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^+ K^-$ samples in the LHCb 2010 dataset, where the charm meson is tagged using the $D^{*+} \rightarrow D^0 \pi^+$ decay. These already compare well to the total samples available at previous experiments: for example there are $\sim 10^5$ $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K^+ K^-$ events in Fig. 11, comparable to the number used by Belle in an analysis based on 540 fb^{-1} of $e^+ e^-$ collision data [48]. A similar picture emerges among charged charmed mesons, as shown in Fig. 12 for the decays $D_{(s)}^+ \rightarrow K^+ K^- \pi^+$.

Before leaving the subject of null tests of discrete symmetries, it is worthwhile to briefly consider the potential of LHCb to search for CPT violation. Although no detailed sensitivity studies have been performed, it can be foreseen that the studies of B_d^0 , B_s^0 and D^0 oscillations are extendable to allow searches for such effects, as has been done in B_d^0 sector by the B factories [49, 50].⁷ It will also be possible to test the equivalence of heavy flavoured particle and

⁶ An exception is for the decays $D_{(s)}^+ \rightarrow K_S^0 \pi^+$ and $D_{(s)}^+ \rightarrow K_S^0 K^+$, where CP violation in kaon mixing leads to an apparent direct CP violation effect of $\mathcal{O}(10^{-3})$ in charm decays that is, however, still too small to be observed with current experiments.

⁷ Recent results on CP violation in the B_s^0 system can be interpreted in terms of constraints on CPT violation [51].

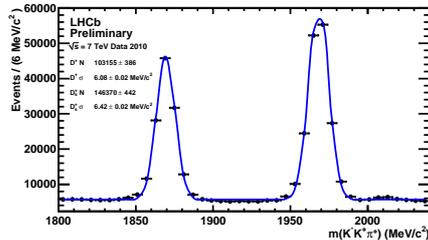


Figure 12. Signals in $\sim 10 \text{ pb}^{-1}$ of LHCb data for $D_{(s)}^+ \rightarrow K^+ K^- \pi^+$.

antiparticle masses and lifetimes.

5. Global symmetries and rare decays

The flavour sector of the Standard Model possesses a number of accidental global symmetries that are not necessarily protected in extensions of the SM. For example, lepton universality is affected by models with extended Higgs sectors. Therefore “rare” decays (with branching fractions that are highly suppressed or even zero in the SM) that probe these symmetries provide sensitive methods to search for NP. Among the channels that can be studied in B physics, the golden channels include $B_s^0 \rightarrow \mu^+ \mu^-$ and $B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$.

The prospects for the study of $B_s^0 \rightarrow \mu^+ \mu^-$ (and the counterpart $B_d^0 \rightarrow \mu^+ \mu^-$ decay) at LHCb are shown in Fig. 13. Note that this figure is based on a small subsample of the total 2010 LHCb dataset – the full dataset will be analysed in a blind manner. The signal yield will be determined from the two dimensional distribution of the dimuon invariant mass and the “geometrical likelihood” (GL), which combines information about the geometry of the event (exploiting the displaced vertex of the B candidate relative to the primary vertex). More details about the analysis strategy can be found in Ref. [36]. The background, which consists mainly of combinations of muons from semileptonic decays of different B hadrons, peaks sharply at low values of the GL and is distributed linearly in invariant mass. The signal is flat in GL (by construction of the variable) and peaks at the relevant B meson mass with an approximately Gaussian distribution.

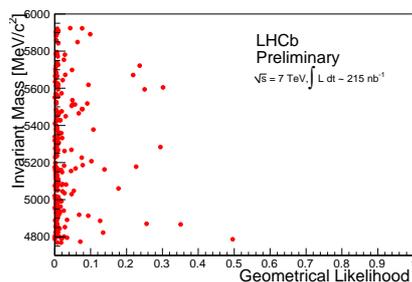


Figure 13. Invariant mass distribution of $B_s^0 \rightarrow \mu^+ \mu^-$ candidate invariant mass *vs.* the geometrical likelihood from 215 nb^{-1} of LHCb 2010 data.

An extrapolation of the LHCb sensitivity shows that the existing limits [52, 53] can be surpassed with less than 100 pb^{-1} of integrated luminosity. The 90% confidence level exclusion limit is predicted to approach the Standard Model prediction of $\mathcal{B}^{\text{SM}}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.2 \pm 0.2) \times 10^{-9}$ [54] with around 1 fb^{-1} .

The general purpose detectors ATLAS and CMS are also expected to have excellent sensitivity to this rare decay. A direct comparison of the sensitivity of the different experiments is difficult since it depends on many factors, such as the integrated luminosity of each experiment, the angular acceptance (and the variation of the $b\bar{b}$ production cross-section with rapidity), the trigger efficiency, the invariant mass resolution, and so on. Definitive statements on the relative sensitivities of the experiments will only be possible once the keenly anticipated first results are publicly available. Nevertheless, it is clear that the data that will be accumulated in 2011 will provide excellent discovery potential in this channel.

One of the characteristic features of the $B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay is the forward-backward asymmetry in the angular distribution of the muons in the dimuon rest-frame (relative to the B^0 direction) as a function of the dimuon invariant mass, q^2 . This asymmetry arises as a consequence of interference between the contributing electroweak diagrams. Since the relative amplitudes of these diagrams vary as a function of q^2 , there is a point at which the forward-backward asymmetry crosses zero, usually denoted $q^2 = s_0$. Due to a cancellation of hadronic uncertainties, the value of s_0 is cleanly predicted in the SM to be $s_0 = (4.36^{+0.36}_{-0.33}) \text{ GeV}^2$ [55, 56]. First measurements of the differential distributions have been made by the B factories and CDF, with results providing an exciting hint of a deviation from the SM prediction [17, 18, 19].

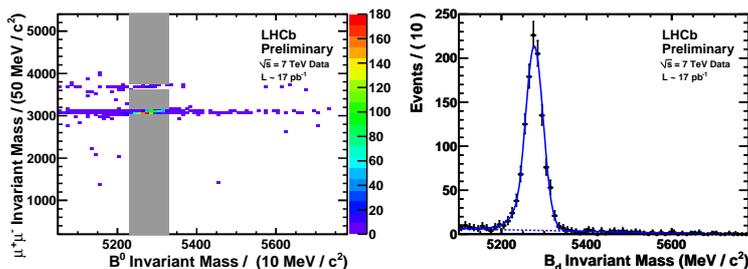


Figure 14. (Left) $K^{*0} \mu^+ \mu^-$ candidates reconstructed from $\sim 17 \text{ pb}^{-1}$ of 2010 LHCb data as a function of dimuon invariant mass and the B_d^0 candidate invariant mass. The horizontal bands correspond to dimuons from J/ψ and $\psi(2S)$. Note that the $B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$ signal region is blinded. (Right) projection onto the B_d^0 candidate invariant mass for events with the dimuon pair consistent with the J/ψ hypothesis. Note the much smaller background compared to Fig. 8 due to the tighter selection requirements in this analysis.

LHCb has excellent potential to improve dramatically the available sample of $B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays. The analysis is currently blinded, but as shown in Fig. 14 the backgrounds are very low, and large yields are seen in the control channel $B_d^0 \rightarrow J/\psi K^{*0}$. First results on the forward-backward asymmetry can be expected within the next year. With larger data samples it will be possible to extend the analysis to include additional kinematic observables and thereby further improve the sensitivity to new physics [57, 58, 59].

The $b \rightarrow s \gamma$ transition provides another sensitive probe of the effects of virtual particles contributing to the loop amplitude. The SM predicts that the emitted photon is highly polarised, due to the $V-A$ structure of the weak interaction, while different results are possible in NP models. Although many measurements of $b \rightarrow s \gamma$ processes exist, none have yet provided strong constraints on the photon polarisation. Several methods have been proposed to test this SM prediction, the most promising of which is based on measurements of time-dependent asymmetries of decays such as $B_s^0 \rightarrow \phi \gamma$ [60, 61, 62]. While reconstruction of neutral particles such as photons presents a challenge in the hadronic environment, LHCb has already observed a signal for the decay $B_d^0 \rightarrow K^{*0} \gamma$, as shown in Fig. 15.

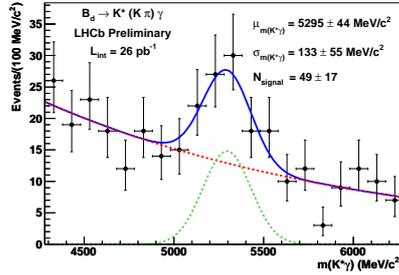


Figure 15. Signal for $B_d^0 \rightarrow K^{*0}\gamma$ in $\sim 26 \text{ pb}^{-1}$ of 2010 LHCb data.

6. Future projects

The LHCb experiment requires the instantaneous luminosity from the LHC to not exceed a value of about $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$. This will be achieved by displacing the LHC beams to produce only a fraction of the maximum collision rate once the available luminosity exceeds this value. The cause of the limitation is the level 0 (hardware) trigger, which has a maximum output rate of 1 MHz. Higher rates necessitate tighter cuts at level 0, particularly for hadronically triggered decay modes, so there is no overall gain in yield. In order to overcome this, a fully flexible software trigger using the readout of the whole detector at 40 MHz is necessary.

The implementation of a software trigger is the main objective of the proposed upgrade to LHCb [63]. This will enable the full physics programme of LHCb as a general purpose detector in the forward region. The upgraded experiment has unique discovery potential that is not restricted to flavour physics – for example, several new physics models introduce new long-lived particles that will produce displaced vertices that could only be observed by LHCb. In the flavour sector, the role of the upgraded LHCb experiment will depend on the outcome of the first years of operation. In the case that NP is discovered in early data, the task will be to understand what is the correct model describing the new phenomena and to measure its parameters. In the less favourable scenario that there is no early discovery at the LHC that is inconsistent with the SM, it will be necessary to maximise the possibility of the discovery of NP, leaving no stone unturned in the search. In either case, an upgraded LHCb experiment will be essential.

However, there are certain important flavour observables that cannot be studied in the hadronic environment. Two important examples that are only accessible in e^+e^- collisions are the decay $B^+ \rightarrow \tau^+\nu$ and the lepton flavour violating decay $\tau^+ \rightarrow \mu^+\gamma$. In the context of Tab. 1, e^+e^- facilities provide unique potential to search for CP violation in charged lepton decays (for example in $\tau^+ \rightarrow K^+\pi^0\nu$ and $\tau^+ \rightarrow K_S^0\pi^+\nu$ decays). Inclusive decays, and decays with missing energy, can also be reconstructed, allowing several interesting rare decays to be studied.

Two next generation e^+e^- colliders have been proposed. Belle2/SuperKEKB is an upgrade of the Belle detector and KEKB accelerator at KEK in Japan. This project has recently been approved, and commissioning of the upgraded machine and detector is expected to commence in 2014. SuperB is a new Italy-based project that achieves significant cost savings by reuse of hardware from BaBar/PEP-II. Very recently, SuperB was approved for funding by the Italian government. The two projects share much in common in terms of machine and detector designs (for more details, see Ref. [64]), though one notable difference is the potential for beam polarisation in the SuperB design.

7. Summary

The LHC machine and detectors performed superbly during the 2010 run. The data accumulated has already demonstrated the potential to make groundbreaking measurements in B physics, and to test the symmetries of the Standard Model. LHCb has excellent potential for major discoveries in many sectors of flavour physics, with strong competition expected from ATLAS and CMS in some modes, most notably $B_s^0 \rightarrow \mu^+ \mu^-$. The next few years promise to be extremely exciting – if large non-standard effects are present, the LHC data will point the way to progress beyond the Standard Model. Upgrades and new experiments in B physics are being planned and are necessary to ensure progress in understanding flavour physics and discrete symmetries throughout the LHC era.

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