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News from the flavour frontier - heavy quark physics at the LHC

Guy Wilkinson[∗†]
University of Oxford
E-mail: guy.wilkinson@cern.ch

Results are presented on heavy flavour results from LHC data collected in 2010 and the early months of the 2011 run. All experiments have contributed to studies of heavy flavour production, where a wide range of measurements are now available. In the domain of heavy flavour decays there exist many observables which are highly sensitive to physics beyond the Standard Model. Here several benchmark analyses of LHCb already match or surpass in precision those of the *B*-factories and Tevatron. The other experiments, in particular CMS with its search for the rare decay $B_s^0 \to \mu^+\mu^-$, are now augmenting this programme.

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[∗]Speaker.
[†]On behalf of the LHC collaborations.

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1. Introduction

Many of the open questions in the Standard Model (SM) are found in the flavour sector. Why are there three generations (and is it only three)? What determines the extreme hierarchy of fermion masses and the distinctive structure of the CKM matrix? What is the origin of *CP* violation? Furthermore, flavour physics is a proven tool of discovery. Notable examples include pointing the way to charm (through e.g. kaon mixing and study of the decay $K^0_L \to \mu^+\mu^-$), demonstrating the need for a third generation of quarks (through *CP* violation), and indicating the high mass scale of the top quark (through $B^0 - \bar{B}^0$ mixing). This lesson from history remains valid in the LHC era: processes that are suppressed in the SM, and in which box and Penguin loop diagrams play a significant role, are a priori sensitive to the contribution from new, heavy particles. Precise measurements of flavour observables provide a very promising probe for New Physics (NP) beyond the SM, in a manner which is complementary to the searches for direct production of new particles that are being performed at ATLAS and CMS.

The last decade has witnessed a golden period for flavour physics, with the great success of the BABAR and Belle experiments at the *B*-factories. An important factor behind the achievements of these facilities has been the cleanliness of the e^+e^- environment, which has been very beneficial in allowing for a wide range of beautiful and sophisticated measurements. For this reason, it is forgivable to consider the $\Upsilon(4S)$ the 'one true home' of heavy quark studies, and the initiatives to plan for projects (Belle II, SuperB) at new generation, very high luminosity e^+e^- machines are certainly well motivated. Nonetheless, the Tevatron experiments have vividly demonstrated over the past five years or so that high quality flavour physics is also possible at hadronic machines. Indeed, hadron colliders offer the advantages of a much higher production cross-section for heavy quark events, and a full spectrum of *b*-hadrons, include B^0_s mesons and *b*-baryons, which opens up a wide vista of new studies that cannot be pursued at the $\Upsilon(4S)$.

The example of the Tevatron is now being followed at the LHC, which has three main advantages over the Fermilab facility in the field of heavy flavour studies. Firstly, the higher collision energy results in a larger production cross-section. Secondly, the very high luminosity of the LHC is an definite advantage for certain analyses, for example the search for the very rare decay $B^0_s \to \mu^+\mu^-$. Finally, the CERN collider has a dedicated flavour physics experiment, LHCb, at one interaction point. LHCb has a trigger system (almost) fully devoted to flavour physics that allows for the collection of large samples of charm decays and *b* decays to hadronic final states, as well as *b* decays to dimuons, for which the general purpose detectors ATLAS and CMS also have high efficiency. LHCb has a forward acceptance, optimised for the production kinematics of heavy quarks, a very good proper time resolution ($\sim$ 50 fs) that is invaluable for studying observables in the fast oscillating $B^0_s - \bar{B}^0_s$ system, and hadron identification over the momentum range $2 - 100$ GeV/c, provided by a RICH system. As most flavour physics measurements are best suited to a low pileup environment, LHCb does not operate above luminosities of 4×10^{32} cm^{-2}s^{-1}, whereas ATLAS and CMS run at the highest luminosity that the machine can deliver. (The machine is able to operate with different luminosities at each interaction point, both through the use of different β^* settings, but also by steering the beams so that they do not collide head on. An advantage of the latter strategy is that by reducing the beam offset as the currents diminish, a constant luminosity can be delivered throughout the fill. This technique of 'luminosity leveling' has been exploited by LHCb

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throughout the 2011 run.)

In this review selected flavour physics highlights from 2010 (the first full year of LHC running), and from the first few months of 2011 (the first year of operation at luminosities of $10^{32}-10^{33}$ cm^{-2}s^{-1}) are reported. The discussion is focused on those results which were available at the time of the conference, but updates are mentioned where these are available. Most attention is devoted to heavy quark decays, as it is this topic which has highest sensitivity to NP. The report begins, however, with a brief review on heavy flavour production in pp collisions and the study of quarkonia exotics which is now underway at the LHC.

2. Heavy flavour production

2.1 Onia

The study of onia production has been a natural early topic in heavy flavour studies at the LHC, on account of the distinctive dilepton signature and the difficulties that theory has had in satisfactorily describing onia measurements performed at the Tevatron [1]. Consequently a wide range of measurements have now been performed, all so far based on 2010 data. Studies of J/ψ production have been published by the four large LHC experiments [2, 3, 4, 5, 6]. These have been joined by measurements of $\psi(2S)$ production by CMS [5] and LHCb (preliminary) [7], and upsilon production by ATLAS [8], CMS [9] and LHCb (preliminary) [10]. Example signal peaks from these studies are shown in Fig. 1. In general the measurements of the differential cross-sections are more precise than the theoretical predictions, with the caveat that there remain significant uncertainties arising from the unknown polarisation. New observables are required to discriminate between models, and these are now appearing. ALICE has published the first study of the J/ψ polarisation [11], while LHCb has made the first observation of double J/ψ production [12], and measured the ratio of χ_{c2} to χ_{c1} production (preliminary) [13]. In Fig. 2 can be seen preliminary χ_c signals produced by ATLAS [14] and CMS (2011 data) [15]. In the ATLAS analysis the photon from the χ_c decay is identified in the calorimeter system, whereas in the CMS analysis it is reconstructed through photon conversions, which provides sufficient resolution that the χ_{c2} and χ_{c1} states can be clearly distinguished.

2.2 Exotics

It is hoped that the LHC can help in elucidating the nature of some of the exotic states which have been discovered at the B-factories and the Tevatron. The most famous of these exotics is the $X(3872)$ and this has now been observed in its decay to $J/\psi\pi^+\pi^-$ by both CMS and LHCb. Preliminary measurements of its inclusive production rate have been presented by both experiments using 2010 data [16, 17]. A preliminary determination of the mass performed by LHCb with the same data set yields the result $3871.96\pm0.46\,(\mathrm{stat})\pm0.10\,(\mathrm{syst})$ MeV/c^2 [18], which is about a factor of two less precise than the current world average [19]. As the total uncertainty is dominated by the statistical error there are good grounds to expect that the LHC will be able to improve significantly the precision of the world average with the much larger data set of 2011. Figure 3 shows $X(3872)$ signals isolated by CMS [20] and LHCb with early data from the 2011 run. Here the CMS signal is inclusive, whereas that shown from LHCb is reconstructed as part of the decay

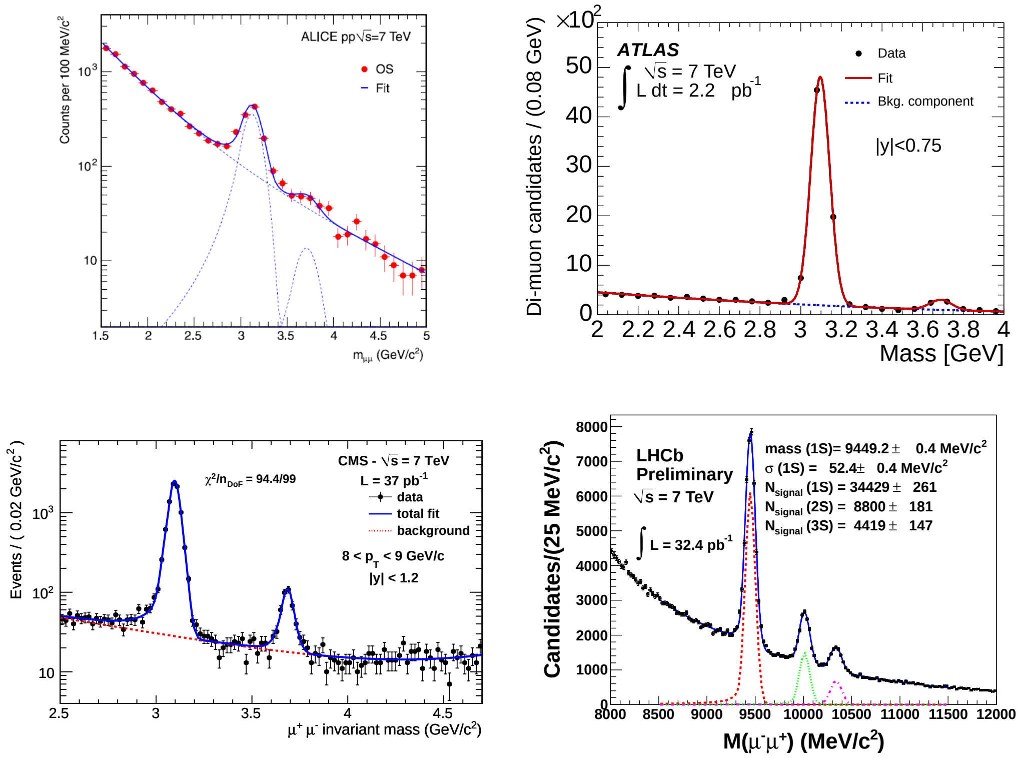

Figure 1: LHC results on onia decaying to dimuons. Top left: ALICE J/ψ and $\psi(2S)$ (2010 data) [2]. Top right: ATLAS J/ψ and $\psi(2S)$ (2010 data) [3]. Bottom left: CMS J/ψ and $\psi(2S)$ (2010 data) [5]. Bottom right: LHCb Υ spectrum (preliminary, 2010 data) [10].

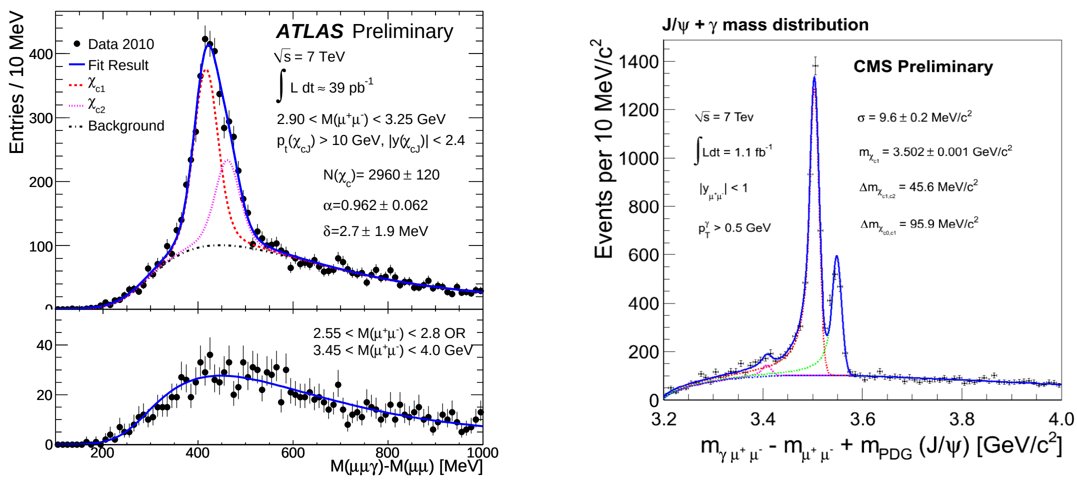

Figure 2: Preliminary LHC χ_c signals. Left: ATLAS signal from calorimeter based analysis (2010 data) [14]. Right: CMS signal from photon conversion based analysis (2011 data) [15].

chain $B^+ \to X(3872)K^+$. Not only is the exclusive signal clean but, with a larger sample, the constraints of this production process will allow the J^{PC} of the $X(3872)$ to be determined [21]. This information will be invaluable in attempting to understand better the true nature of the particle.

Results are also emerging on other possible exotics. The CDF Collaboration has reported the observation of a narrow structure in the $m(J/\psi\phi) - m(J/\psi)$ spectrum, obtained from a sample of $B^+ \to J/\psi\phi K^+$ decays [22]. This feature is labelled the $X(4140)$. At this conference LHCb presented a preliminary search for the $X(4140)$ with a data set of around 380 pb^{-1}, containing approximately twice as many $B^+ \to J/\psi\phi K^+$ decays as that studied by CDF [23]. When analysing the $m(J/\psi\phi) - m(J/\psi)$ spectrum and assuming the same background model as CDF, a fit to the $X(4140)$ region returns 7 ± 5 events, whereas $39 \pm 9 \pm 6$ events are expected when scaling the published CDF results. Therefore LHCb is not able to confirm the existence of the $X(4140)$ with the present data set.

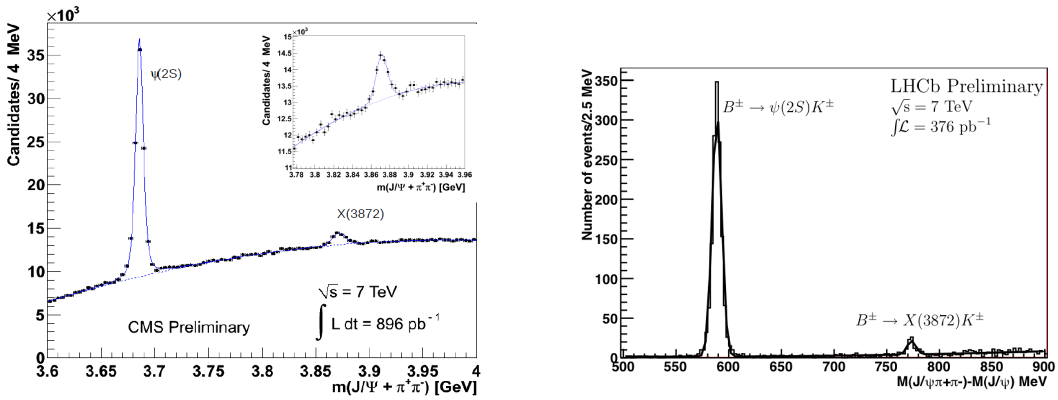

Figure 3: Preliminary LHC X(3872) signals. Left: CMS inclusive $J/\psi\pi^+\pi^-$ spectrum showing $\psi(2S)$ and $X(3872)$ peaks (2011 data) [20]. Right: fully reconstructed $B^\pm \to \psi(2S)K^\pm$ and $B^\pm \to X(3872)K^\pm$ decays at LHCb (2011 data).

2.3 Open heavy flavour

It is necessary to measure the properties of b and c-hadron production at the LHC both to test QCD predictions and as a natural first step in the flavour physics programme. To this end, the LHC collaborations have used the 2010 data samples to perform a wide variety of measurements.

Using lifetime information to isolate the secondary component of the J/ψ and $\psi(2S)$ samples discussed above provides a convenient tag of b-hadron decays from which the differential cross-section may be extracted. This technique has been exploited by ATLAS [3], CMS [4, 5] and LHCb [6]. Complementary approaches include: the selection of events containing displaced D mesons together with muons, as pursued by LHCb [24]; the selection of events with inclusive leptons, as demonstrated by ALICE (preliminary) [25], ATLAS [26] and CMS [27]; the use of dilepton tags, as performed by CMS [28]; the use of leptons together with b-tagged jets, as presented by CMS soon after the conference (preliminary) [29]; and with b-tagged jets alone (CMS, preliminary) [30]. Analyses have also been performed by CMS [31, 32, 33] and LHCb (preliminary) [34] which measure the separate cross-sections of B^+, B^0 and B^0_s production, using exclusive decays of the sort $B \to J/\psi X$. All the measurements tell a consistent story: that the production is broadly compatible with NLO QCD. Integrated over the full acceptance, the cross-section in pp collisions at $\sqrt{s} = 7$ TeV is found to be approximately 300 μb [24].

Having established the scale of b-hadron production at the LHC, the experiments are now seeking to learn more about the nature of the production process and make up of the events. CMS has studied the angular correlation between pairs of displaced secondary vertices to gain insight into the dynamics of the underlying hard scattering subprocesses [35]. A sizable fraction of b-hadron pairs are found to be produced at small opening angles. LHCb has measured the fragmentation fractions of the different b-hadrons. This information is necessary in many flavour physics studies, for example exploiting normalisation modes in the search for the decay $B^0_s \to \mu^+\mu^-$ (see Sec. 3.7). The relative production rate of B^0_s to B^0 and B^+ mesons has been measured both by reconstructing hadronic decays [36] and through displaced D hadrons in combination with muons [37]. From these studies the rate of B^0_s to B^0 mesons is found to be $f_s/f_d = 0.267^{+0.021}_{-0.020}$ [37]. It is interesting to note that although there is no reason to believe that f_s/f_d is a universal quantity, the value measured by LHCb is consistent with the average of those results obtained at LEP and the Tevatron (0.271 ± 0.027 [38]). LHCb has also measured the ratio of Λ^0_b production to that of B^0 and B^+ mesons and observed that, in contrast to f_s/f_d, this quanity has a p_T dependence [37].

ALICE [39], ATLAS (preliminary) [40] and LHCb (preliminary) [41] have also studied the production of charm hadrons. The rate of open charm production is determined to be around 20 times higher than that of beauty.

3. Heavy flavour decays

A selection of topics are reviewed where there have been new measurements presented at this conference or (in the case of ϕ_s) where results appeared soon after. Discussed first are those measurements involving D, B^0 and $B^\pm$ mesons, where comparisons can be made with the results of the B-factories, and then those studies that concern B^0_s mesons and b-baryons.

3.1 Charm physics

For many years charm was regarded as the poor relation of heavy quark physics, on account of the very small rate of mixing and levels of CP violation expected in this sector, and the difficulty of evaluating QCD contributions at the charm mass scale when attempting to make predictions for the observables of interest. Recently however there has been a resurgence of interest, mainly driven by the observation of $D^0 - \bar{D}^0$ mixing [42]. The goal now is to discover CP violation, either associated with the mixing, or of a direct nature. In both cases the effect is expected to be very small in the SM, but it can be enhanced by NP. When searching for direct CP violation it is advantageous to look in singly Cabibbo suppressed decays where the non-negligible contribution from Penguin amplitudes gives an opportunity for NP effects to manifest themselves [43].

The enormous rate of $c\bar{c}$ production at the LHC makes this an ideal facility to make high precision searches for CP violation in charm, and the attributes of LHCb are well suited to this task. During the 2011 run LHCb wrote charm decays to tape at a rate of around 1 kHz, providing samples of unprecedented size for offline analysis. The challenge then is to control the possible

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sources of systematic bias such that these high statistics can be fully exploited. Several studies from the 2010 data set presented at the conference show that the outlook is promising.

In time dependent charm measurements the difficulties lie in correctly describing the shape of the decay time acceptance induced by the cuts in the High Level Trigger, and in understanding what effect the few percent contamination from secondary D mesons produced in B decays has on the prompt charm dominated sample. Secondary production is a possible source of bias in these measurements because the decay time of the D mesons is not correctly reconstructed. First measurements with $D^0 \to K^-K^+$ and $D^0 \to K^-\pi^+$ decays of the CP violating observable A_Γ [44] and the mixing parameter y_{CP} [45] (the latter appearing soon after the conference) demonstrate that these systematic challenges are under control.

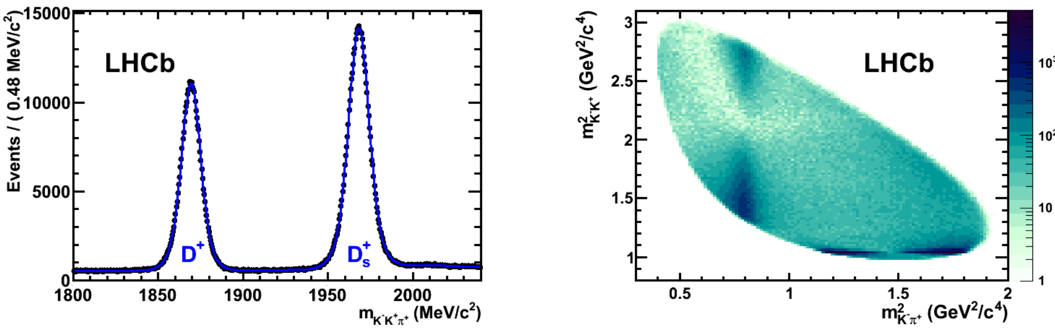

Figure 4: LHCb results on $D^+ \to K^+K^-\pi^+$ (2010 data) [46]. Left: mass spectrum showing both $D^+ \to K^+K^-\pi^+$ and $D_s^+ \to K^+K^-\pi^+$. Right: $D^+ \to K^+K^-\pi^+$ Dalitz plot.

LHCb has searched for direct CP violation in a sample of around 370,000 singly Cabibbo suppressed $D^+ \to K^+K^-\pi^+$ decays [46]. The cleanliness of the sample can be seen from the signal peak in Fig. 4 (left). Note also the presence of the Cabibbo favoured $D_s^+ \to K^+K^-\pi^+$ decay which can, to an excellent approximation, be considered CP conserving and thus serves as a very useful control sample to probe for possible detector biases. Further checks can be performed with the Cabibbo favoured mode $D^+ \to K^-\pi^+\pi^-$. The analysis proceeds by looking in bins of the Dalitz plot (Fig. 4 right) for differences between D^+ and D^- decay. The contents of each bin are effectively normalised by the integrated yield of the Dalitz plot in order to suppress any biases associated with production asymmetries. No fake asymmetry is observed in the control channels, and no evidence of CP asymmetry is found in the signal decay.

As these proceedings are being written LHCb has released its first charm result from the 2011 data [47]. This is from a search for (essentially) direct CP violation in the time-integrated $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decay rates. In order to cancel out detector and production asymmetries the difference between the CP asymmetries in the two decays is constructed. The measurement returns a result which lies 3.5σ away from the CP conservation hypothesis. Interesting times now lie ahead.

3.2 Precise CKM metrology

The principal achievement of the B-factory experiments has been to perform measurements of the angles and sides of the CKM unitarity triangle which demonstrate that the CKM paradigm is the dominant mechanism of *CP* violation in nature (at least for those systems described by the conventional unitarity triangle). Nonetheless, second order contributions from NP are still possible and, in most beyond-the-SM theories, indeed expected. For this reason more precise measurements of the triangle parameters are required, in particular of the angle γ (also denoted ϕ_3), which at present is only known with a precision of around 10° [48].

A powerful way to gain sensitivity to γ is to use the 'ADS' [49] approach and measure the *CP* asymmetries in the suppressed mode $B^{\pm} \to (K^{\mp}\pi^{\pm})_D K^{\pm}$ (where the 'D' subscript indicates that the $K^{\mp}\pi^{\pm}$ pair comes from either a D^0 or $\bar{D}^0$ decay). Here the final state can be reached either by a suppressed $b \to u$ transition followed by a Cabibbo favoured D decay, or a favoured $b \to c$ transition followed by a doubly Cabibbo suppressed D decay. The amplitudes of these two paths are similar in magnitude and hence interference effects are large. Since the interference involves γ, which is the *CP* violating phase difference between the two B decay amplitudes, a significant asymmetry is expected between the B^- and B^+ decay rates. Measurement of this asymmetry, in combination with other observables, can be used to extract γ. The visible branching ratio is however 10^{-7}, and it was only by analysing its full data set that the Belle experiment has recently been able to announce 4.1σ evidence for the existence of this decay [50]. The sample sizes collected at the B-factories are therefore inadequate to exploit the ADS strategy for a meaningful measurement of γ.

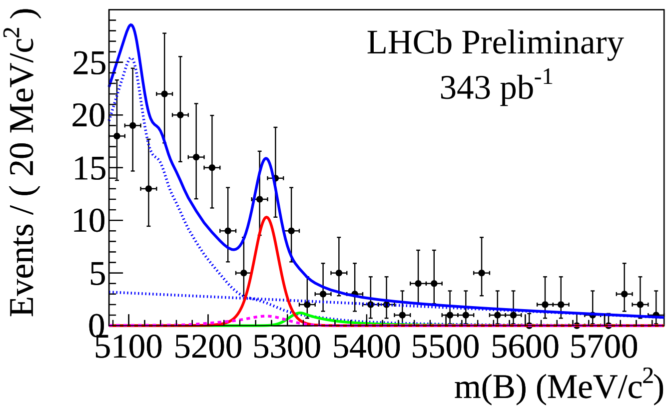

Figure 5: Preliminary LHCb mass peak in the suppressed ADS mode $B^{\pm} \to (K^{\mp}\pi^{\pm})_D K^{\pm}$ (2011 data). The red curve shows the signal contribution in the fit, the blue line the sum of all contributions in the fit, and the other lines indicate various background contributions [51].

LHCb has analysed around 340 pb^{-1} of data collected in early 2011 and obtained a 4.0σ signal, which is shown in Fig. 5 [51]. The measured decay rate with respect to the favoured decay $B^{\pm} \to (K^{\pm}\pi^{\mp})_D K^{\pm}$ is $R^{DK}_{ADS} = (1.66 \pm 0.39\,(\mathrm{stat}) \pm 0.24\,(\mathrm{syst})) \times 10^{-2}$. The *CP* asymmetry is determined to be $A^{DK}_{ADS} = -0.39 \pm 0.17\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})$, which is the most precise result yet obtained for this observable. With the analysis of the full 2011 sample LHCb will be able to improve the precision of these quantities and make measurements in related modes, which will allow γ to be determined with a precision better than the current world average.

3.3 $\mathbf{B^0 \to K^{*0}\mu^+\mu^-}$

A host of observables are available in the decay $B^0 \to K^{*0}\mu^+\mu^-$ that are sensitive to the helicity structure of any NP contributions [52]. The forward-backward asymmetry of the dimuon system (A_{FB}) as a function of the dimuon invariant mass (q^2) has attracted particular attention. Until now the samples available in this mode have not been large enough to ascertain whether the shape of the asymmetry is consistent with SM expectation, but those measurements available from the *B*-factories [53, 54] and CDF [55, 56] have hinted at an unexpected behaviour at low q^2, with the asymmetry showing a tendency to have the opposite sign to that predicted in the SM.

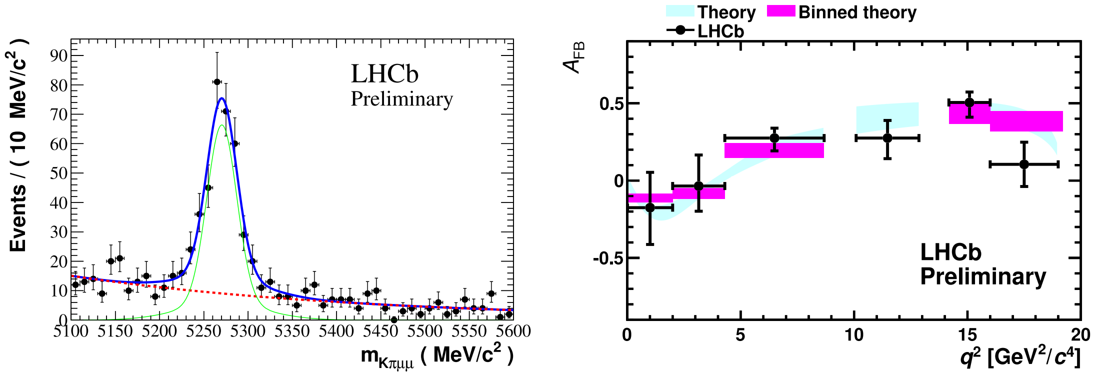

Figure 6: Preliminary LHCb results on $B^0 \to K^{*0}\mu^+\mu^-$ (2011 data) [57]. Left: mass peak. Right: forward-backward asymmetry.

At this conference LHCb has shown preliminary results from approximately 300 pb^{-1} of 2011 data [57]. Around 300 signal events are selected over a low background (Fig. 6 left). This is the largest individual sample of these decays yet collected. The values of A_{FB} measured in q^2 bins are shown in Fig. 6 (right). There is excellent consistency with the SM expectation, with no sign of anomalous behaviour at low q^2. The analysis of more data will allow the SM prediction to be tested to higher precision. In particular the location of the theoretically clean 'crossing point', where $A_{FB} = 0$, will be determined. In addition, other observables will be studied, such as $A_T^{(2)}$, which has sensitivity to contributions from right-handed currents [58].

3.4 Two body charmless b-hadron decays

Decays of *b*-hadrons into two-body hadronic final states (e.g. $B^0 \to \pi^+\pi^-$, $B_s^0 \to K^+\pi^-$ etc, generically referred to as '$B \to hh$' decays) are an important topic of study in flavour physics, as the tree diagrams responsible for these decays are $b \to u$ transitions, which means that certain observables are sensitive to the CKM angle γ. Moreover, Penguin loop diagrams also play a significant role, giving an entry point for NP to contribute. A wide range of observables, including branching ratios, time-dependent *CP* asymmetries and time-independent direct *CP* asymmetries, allow these effects to be disentangled.

The principal experimental challenge in $B \to hh$ physics is that of separating the many final states, which are topologically very similar. LHCb overcomes this problem by exploiting both its good invariant mass resolution, and the particle identification capabilities of the RICH system. In a preliminary analysis [59], based on around 320 pb^{-1} of data, LHCb has used these attributes to isolate a pure sample of $B^0_{d,s} \to K\pi$ events and has measured the direct *CP* asymmetries

$$A_{CP}(B^0 \to K\pi) \equiv \frac{\Gamma(\bar{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\bar{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)} \quad (3.1)$$

and

$$A_{CP}(B^0_s \to K\pi) \equiv \frac{\Gamma(\bar{B}^0_s \to K^+\pi^-) - \Gamma(B^0_s \to K^-\pi^+)}{\Gamma(\bar{B}^0_s \to K^+\pi^-) + \Gamma(B^0_s \to K^-\pi^+)}. \quad (3.2)$$

In performing these measurements it is necessary to account for both a possible asymmetry between the number of B and anti-B mesons produced in the detector acceptance, and a detection asymmetry for the $K\pi$ final state. Both of these effects turn out to be small compared with the intrinsic *CP* asymmetry. Values of $A_{CP}(B^0 \to K\pi) = -0.088 \pm 0.011\,(\text{stat}) \pm 0.008\,(\text{syst})$ and $A_{CP}(B^0_s \to K\pi) = 0.27 \pm 0.08\,(\text{stat}) \pm 0.02\,(\text{syst})$ are determined, which are the most precise measurements of these observables performed to date. The latter result constitutes the first evidence of *CP* violation in B^0_s decays. The invariant mass spectra, shown separately for the $K^-\pi^+$ and $K^+\pi^-$ final states, and focusing on the B^0_s region, is shown in Fig. 7. The raw *CP* asymmetry can be seen through the different signal sizes in the two plots.

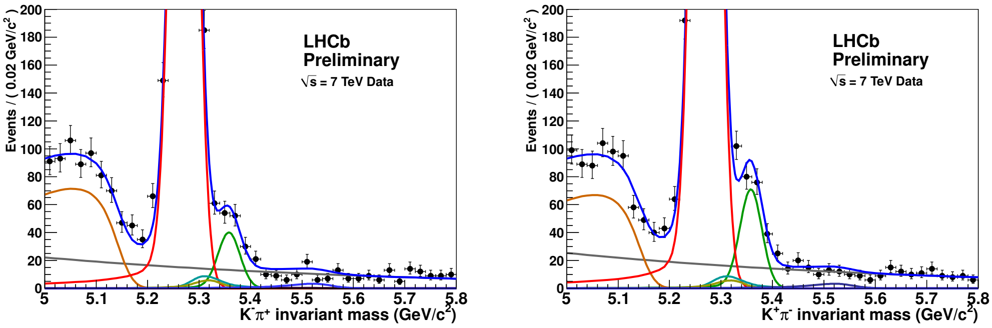

Figure 7: Preliminary LHCb results for the CP asymmetry measurement in $B^0_s \to K\pi$ (2011 data) [59]. Left: $B^0_s \to K^-\pi^+$. Right: $\bar{B}^0_s \to K^+\pi^-$. For both the fitted signal component is shown in green. The large, truncated signal at lower mass comes from the $B^0 \to K\pi$ decay.

LHCb has also searched for the rare decay $B^0_s \to \pi^+\pi^-$. This decay can only proceed through Penguin annihilation and W exchange diagrams, and so the branching ratio of this decay helps set the scale at which these graphs contribute to the other $B \to hh$ decays. A signal is found corresponding to a branching ratio of $BR(B^0_s \to \pi^+\pi^-) = (0.98^{+0.23}_{-0.19}\,(\text{stat}) \pm 0.11\,(\text{syst})) \times 10^{-6}$, which is in agreement with a measurement performed by CDF [60].

3.5 New observations in b-baryon decays

The B-factories operated at too low an energy to produce b-baryons and hence study of these particles is an important responsibility of experiments at hadron colliders. Just before the conference the CDF collaboration reported the first observation of the Ξ^0_b baryon (quark content *udb*) [61]. LHCb has begun its own programme of b-baryon studies. In a preliminary analysis of around 330 pb^{-1} of data [62] the experiment has made the first observation of the decay mode

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$\Lambda_b^0 \to D^0 p K^-$, which is a potentially useful channel for measurements of the unitarity triangle angle γ. The observed peak is clearly seen in the right plot of Fig. 8. The signal is normalised to the Cabibbo favoured mode $\Lambda_b^0 \to D^0 p \pi^-$ (Fig. 8 left) and the relative branching ratio between the two modes is determined to be $0.112 \pm 0.019\,(\mathrm{stat})\,^{+0.011}_{-0.014}\,(\mathrm{syst})$. Also visible in Fig. 8 (right), at around 5800 MeV/c^2, is a peak of 2.6σ in significance which is taken to be the Ξ_b^0, that is the same baryon discovered by CDF, but here reconstructed in the decay mode $D^0 p K^-$. The mass of this signal is 14 ± 8 MeV/c^2 above that value reported by CDF.

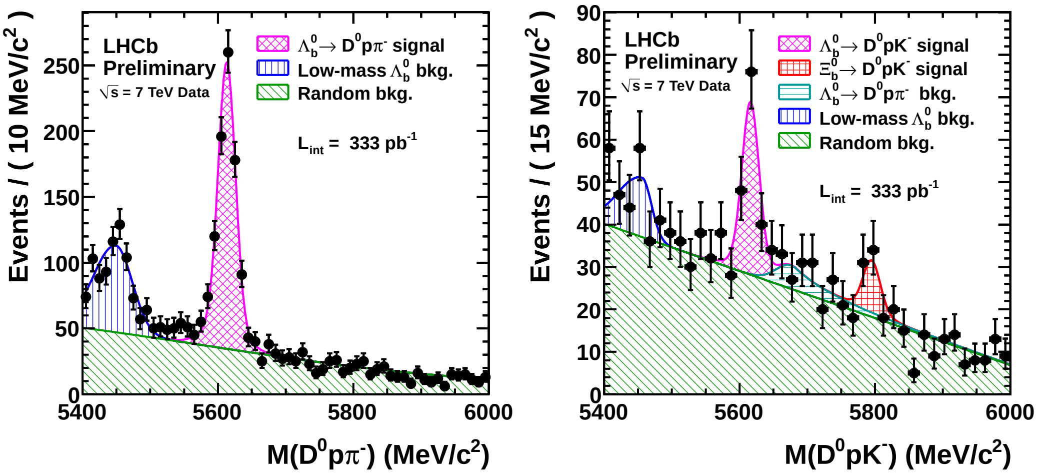

Figure 8: Preliminary LHCb results on b-baryons (2011 data) [62]. Left: $D^0 p \pi^-$ mass spectrum. Right: $D^0 p K^-$ mass spectrum.

Since the conference LHCb has presented preliminary measurements of the masses of the Ξ_b^- and Ω_b^- baryons [63].

3.6 CP violation in $\mathbf{B_s^0 - \bar{B}_s^0}$ mixing

The study of *CP* violation in the interference between mixing and decay in the B_s^0 system is one of the most promising ways in which to search for NP in heavy flavour studies, since the box diagram responsible for $B_s^0 - \bar{B}_s^0$ mixing is susceptible to NP contributions which could induce a *CP* violating phase, ϕ_s, significantly different to the very small value predicted in the SM. For this reason the measurements of ϕ_s performed at the Tevatron by CDF [64] and D0 [65] using the decay $B_s^0 \to J/\psi\phi$ are intriguing. Although both results are compatible with the SM, the central values returned by both analyses hint at a value that is much larger in magnitude than is expected within the established theory.

No new ϕ_s studies from the LHC were presented at the conference, but more recently LHCb has released preliminary results using both $B_s^0 \to J/\psi\phi$ [66] and $B_s^0 \to J/\psi f_0(980)$ [67]. These measurements, both individually and when combined [68], show good consistency with the SM. It seems, therefore, that there are no *very* large NP effects in the B_s^0 sector. Nonetheless, ϕ_s remains an excellent observable to look for contributions from beyond the SM, and significant improvements in precision are expected from the LHC over the coming years. Along with LHCb, ATLAS and CMS are expected to contribute to this measurement programme. A plot demonstrating the potential of ATLAS in time-dependent studies is shown in Fig. 9, which presents a measurement of the B_s^0 lifetime in $J/\psi\phi$ events [69].

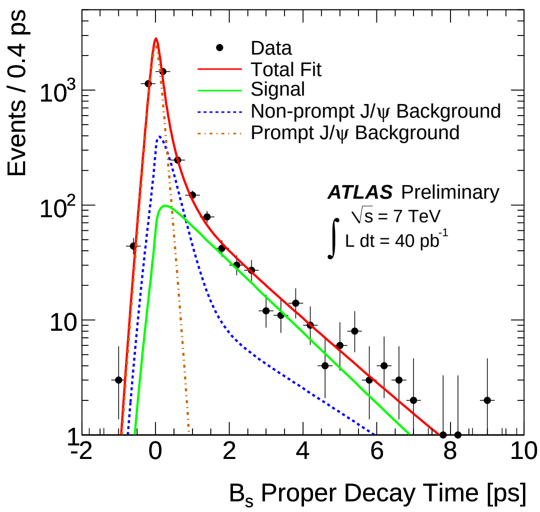

Figure 9: ATLAS preliminary results on fit to proper decay time of reconstructed $B_s^0 \to J/\psi\phi$ candidate (2010 data) [69].

3.7 The search for $\mathbf{B_s^0} \to \mu^+\mu^-$

The importance of the search for $B_s^0 \to \mu^+\mu^-$ has long been recognised. In the SM this decay is extremely rare, but also precisely predicted, with a expected branching ratio of $(3.2 \pm 0.2) \times 10^{-9}$) [70]. When considering extensions to the SM this decay rate can be perturbed significantly. An example is minimal supersymmetry, in which case the branching ratio is approximately proportional to $\tan^6\beta$, where $\tan\beta$ is the ratio of the vacuum expectation value of the two neutral *CP*-even Higgs fields. Until this summer the most restrictive 95% confidence level upper bound on this decay was 4.3×10^{-8} from the CDF experiment, obtained with 3.7 fb^{-1} [71]. In the weeks before the conference, however, interest has been raised by the 7 fb^{-1} update from CDF, which sees a small excess above background, corresponding to a branching ratio of $1.8^{+1.1}_{-0.9} \times 10^{-8}$ [72]. At this conference first results have been presented from the 2011 LHC run from CMS [73] and LHCb [74].

The CMS search makes use of 1.14 fb^{-1} of data. The events are triggered at L1 by the dimuon trigger, with track information being employed in the High Level Trigger. The offline analysis applies cuts based on quantities such as the alignment between the flight direction of the candidate and the direction between the primary and secondary vertices, the flight length significance, the fit quality, and certain isolation criteria. One muon is required to have a p_T greater than 4.0 GeV/c, the other a p_T above 4.5 GeV/c and the b-hadron candidate itself a p_T above 6.5 GeV/c. The signal efficiency is measured on Monte Carlo, with the distribution of the key variables validated in data on the control channels $B^+ \to J/\psi K^+$ and $B_s^0 \to J/\psi\phi$. The analysis is very robust against pileup, with the efficiency found to be stable up to a high number of multiple interactions (checked up to 12 primary vertices). A search window of width 150 MeV/c^2 is imposed in dimuon invariant mass, centred around the B_s^0 mass. The background level in this signal region is interpolated from the sidebands, with additional consideration given to a possible peaking component from B meson decays to two-body hadronic final states, in which the hadrons are misidentified as muons. In converting the number of observed signal events into a branching ratio, the mode $B^+ \to J/\psi K^+$ is used as a normalisation channel.

A data set of 300 pb^{-1} is analysed by LHCb in a preliminary measurement (since the conference the study has been updated to 370 pb^{-1} and submitted for publication [75]). Dimuon events are selected in which at least one muon candidate fired the earliest level trigger with p_T above 1.5 GeV/c. After a loose preselection the candidates are classed according to their invariant mass and the output of a boosted decision tree (BDT). The expected invariant mass resolution of the signal is 25 MeV/c^2. The decision of the BDT is based on kinematical and topological variables. The BDT is trained on Monte Carlo but its performance is calibrated on data using decays of B mesons to two-body hadronic final states, which have the same topology as the signal. The background level is estimated from side-bands and evaluating the feed-down from two-body hadronic B decays. Rather than defining a single signal region, a grid of 4×6 cells is considered in the two-dimensional space of the BDT output against dimuon invariant mass. The final results are obtained by comparing the observed to expected number of events, cell-to-cell. Normalisation is provided by the three decay modes $B^+ \to J/\psi K^+$, $B_s \to J/\psi \phi$ and $B^0 \to K\pi$, which are found to given consistent results.

CMS observe 3 events passing the selection cuts, with an expected background of around 1.5 events. LHCb finds 5 events in its two most sensitive BDT cells, integrated over an invariant mass interval of 120 MeV/c^2, with an expected level of background of around 4 events. The upper limit at 95% confidence level set by CMS and LHCb is 1.9×10^{-8} and 1.5×10^{-8}, respectively, where the 2011 LHCb result has been combined with that from the 37 pb^{-1} analysis from 2010 [76]. The two experiments have also produced a combined result [77]. The combined upper limit at the 95% confidence level is found to be 1.1×10^{-8}, which is lower than, but not yet inconsistent with, the central value reported by CDF. This limit already places severe constraints on SUSY parameter space (see, e.g. [78]). It is interesting to note that both experiments are becoming sensitive to signal decays, even at the SM branching ratio, as in both samples around one event would be expected from a signal of this source. In other words the number and distribution of events in data and the expectation match better if this signal contribution is allowed for (Fig. 10, right), but this improved agreement is not yet very significant. A clearer picture will emerge with the analysis of the remainder of the 2011 data set.

Both CMS and LHCb have also searched for the even rarer $B^0 \to \mu^+\mu^-$ decay and have not seen a signal. Further information can be found in [73, 75].

4. Conclusions

LHC flavour physics has come very far, very quickly. In little over a year of data analysis a comprehensive series of measurements has been performed over a wide range of topics, both involving production and decay. For many benchmark analyses in the domain of decay studies, the sensitivity attained by the B-factories and Tevatron has been matched or overtaken. Here the broad programme of study being conducted at LHCb is now being augmented in specific areas

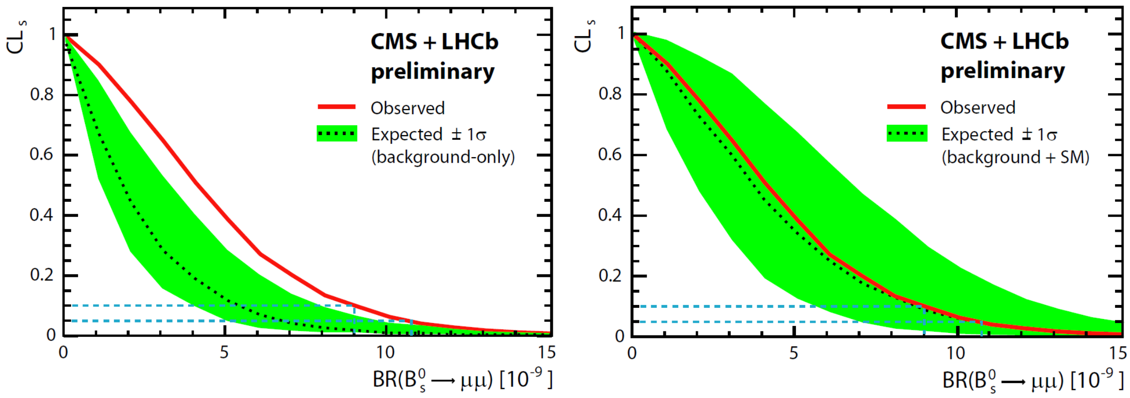

Figure 10: Observed and expected CLs values for the combination of CMS (2011) [73] and preliminary LHCb (2010 and 2011) [74] $B_s^0 \to \mu^+\mu^-$ search results [77]. Left: expectation with background only hypothesis. Right: expectation with SM signal and background hypothesis. The dashed blue lines indicate the 90% and 95% confidence levels.

by the other experiments, most notably by CMS in the search for $B_s^0 \to \mu^+\mu^-$. Although the measurements performed up to the time of the conference are all compatible with SM expectation, the much higher precision expected over the coming few years will provide some of the most sensitive probes of NP at the LHC. Plans are also underway to improve the trigger of the LHCb experiment, and equip it to run at higher luminosity, in order to increase its physics reach still further [79]. Without question, LHC has become the flavour frontier, and will remain so for many years to come.

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