PROCEEDINGS OF SCIENCE

Beauty 2013: summary and outlook

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A selective summary is made of results presented at Beauty 2013, with emphasis on the first $\mathcal{O}(1\ \mathrm{fb}^{-1})$ analyses from the LHC. Consideration is given as to how some of these measurements may improve over the coming decade and a half.

14th International Conference on B-Physics at Hadron Machines
April 8-12, 2013
Bologna, Italy

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1. Introduction

This conference, although the fourteenth in the Beauty series, was the first occasion when results were available based on $\mathcal{O}(1\ \mathrm{fb}^{-1})$ data sets from the LHC. At the same time, the final analyses from the Tevatron experiments were presented. For these reasons, Beauty 2013 was a meeting of great significance for heavy flavour studies at hadron machines. The LHC and Tevatron talks were complemented by talks from e^+e^- facilities, theory talks, and presentations on future experiments. This rich programme of physics, unfolding in a beautiful location, with excellent food and wine to help stimulate discussion, made for a very rewarding conference. There follows a brief and selective tour through some of the most striking results.

2. Production and exotic spectroscopy

We were reminded this week [1] that theorists have had a long struggle to make reliable predictions of the cross-sections of heavy flavour production, with attempts in the early Tevatron era typically producing results much higher than the measurements. More recently, however, the situation has improved significantly. There now exist well developed and reliable tools, such as FONLL and NLO+PS, which yield predictions that are generally in good agreement with data. This progress is impressive, and opens up many possibilities in other areas of physics, such as the opportunity to use heavy flavour production to constrain parton density functions. Are there questions of specific relevance for flavour physics that can also be addressed? For example, LHC studies are now becoming sensitive to production asymmetries of charm and beauty hadrons, an issue which is important for *CP*-violation measurements. It would be interesting to learn what modern theoretical tools can tell us about the magnitude and kinematic dependence of such asymmetries.

It should also be remembered that there are observable which are still badly described by theory. One example is onia polarisation [2]. Studies of Υ polarisation at the Tevatron and the LHC have not found any significant degree of polarisation, in contrast to expectation. New results from the charmonium system are expected soon that may elucidate this puzzle [3, 4].

Exotic spectroscopy continues to be a subject which provides surprises, and this topic was tackled by many speakers during the conference [5]. Questions are eventually answered, but new ones inevitably emerge. In a recent analysis by LHCb of $B^\pm \to X(3872)K^\pm$ decays [6], the J^{PC} of this first-discovered of the 'exotics' has finally been established to be 1^{++}, a configuration which indeed favours a non-standard explanation for the nature of the particle. Even hotter news is the discovery of a new state, the Z(3900), in $J/\psi\pi^\pm$ decays, which has been seen in three separate data sets [7, 8, 9], the most recent observation being announced during the week of the conference. The mass peaks are presented in Fig. 1. Meanwhile, a signal first found by CDF in the $J/\psi K^+K^-$ spectrum [10], but later not confirmed by LHCb [11], has emerged once more in a CMS analysis [12], albeit with a broader form than reported at the Tevatron, and also with a sister feature higher in mass by around 200 MeV. A full amplitude analysis is required to establish whether these enhancements are indeed new particles, or have a more conventional explanation.

3. B_s^0 physics

Performing a thorough exploration of *CP* violation in the B_s^0 sector is one of the principal tasks

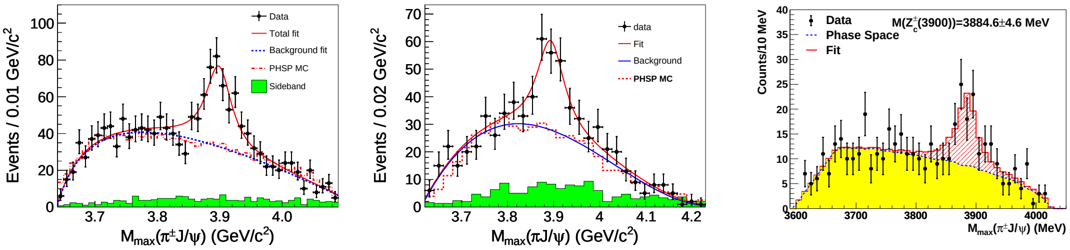

Figure 1: The $Z(3900)^\pm$ seen in the $J/\psi\pi^\pm$ invariant mass spectrum by BESIII (left) [7], Belle (middle) [8] and T. Xiao *et al.* (right) [9], the latter using data collected by CLEO-c.

in flavour physics studies at the LHC. This programme is now well underway, and the conference was told the satisfying news that for the first time a 5 sigma signal is observed, in the *CP*-asymmetry of $B_s^0 \to K\pi$ [13, 14].

The main focus of attention in B_s^0 studies over the last few years has been in the determination of the *CP*-violating phase between mixing and decay, often denoted ϕ_s, most usually accessed in the mode $B_s^0 \to J/\psi\phi$. The initial hints from the Tevatron for a large enhancement with respect to the Standard Model expectation have sadly not been confirmed at the LHC. The 1 fb^{-1} results from LHCb [15, 16], in both $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$, have a combined precision of 0.07 in ϕ_s and a central value that is in good agreement with the Standard Model prediction. A similar conclusion is arrived at by ATLAS, who presented at the conference their first flavour-tagged ϕ_s analysis [17, 18], a measurement that has a precision of 0.27 and a value that lies around half a sigma away from the Standard Model expectation. The impact of this result may be assessed in Fig. 2. Despite the disappointment that there are no sizable New Physics effects at play, the ϕ_s measurement will remain very important for the next LHC run, and into the upgrade era of LHCb, on account of its intrinsic high sensitivity to beyond-the-Standard-Model contributions. In parallel, studies of channels such as $B_s^0 \to \phi\phi$, where a gluon Penguin gives an additional opportunity for New Physics effects to enter, will become of increasing interest. The first time-dependent analysis of this mode has already been presented by LHCb [19, 20].

Another important observable in B_s^0 studies is the semileptonic (or flavour-specific) asymmetry, a_{sl}^s, which is non-zero if *CP* violation exists in the mixing itself. D0 have performed a measurement [21] exploiting dimuons that is sensitive to a linear combination of a_{sl}^s and a_{sl}^d, the corresponding observable in the B^0 system. This measurement has excited a great deal of interest because of its significant deviation from the essentially null value expected in the Standard Model. The conference heard reports from D0, LHCb and BaBar of individual measurements of a_{sl}^s and a_{sl}^d that have been performed to cast light on the dimuon anomaly [22, 23]. Frustratingly, all of these new measurements are so far compatible with *both* the Standard Model and the D0 dimuon result. More precise studies from LHCb and Belle-II are required to clarify this puzzle.

4. Precision CKM metrology

The great achievement of the *B*-factories has been to demonstrate that the CKM paradigm is the

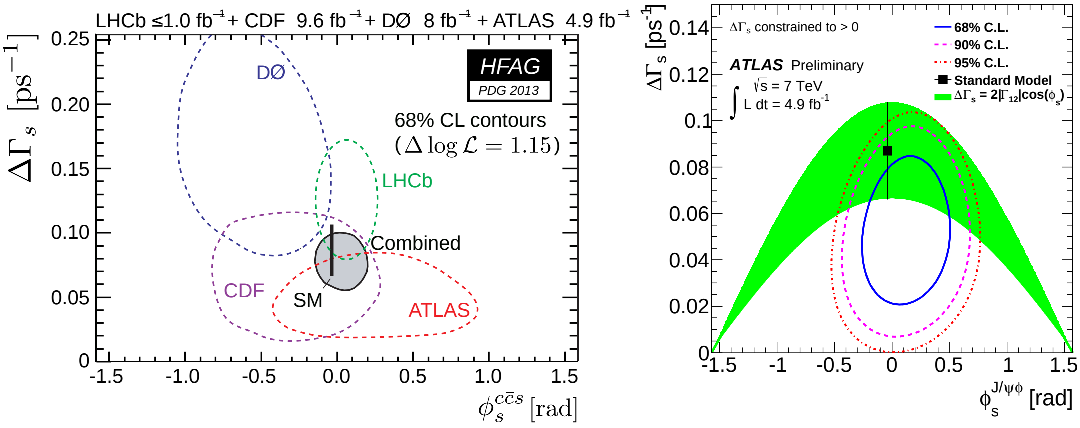

Figure 2: Constraints in $\phi_s - \Delta\Gamma_s$ space. Left: the situation immediately prior to Beauty 2013. When updating to the latest LHCb result [16] the LHCb error ellipse contracts by almost a factor of two, while the consistency with the Standard Model remains good. Right: the updated ATLAS result shown at the conference [18], which benefits from flavour tagging.

dominant mechanism for describing *CP* violation in the quark sector, a conclusion best appreciated by visualising the compatibility of the suite of measurements that map out the unitarity triangle in the complex $(\bar{\eta}, \bar{\rho})$ plane. However, it is still expected that in general any New Physics will perturb flavour-physics observables at the sub-dominant level, and therefore it is vital to improve the precision of these measurements. One observable for which improved precision is an imperative is the CKM triangle angle γ.

The parameter γ can be measured in $B^- \to DK^-$ decays, with D indicating either a D^0 or $\bar{D}^0$ reconstructed in a final state common to both. Examples include *CP* eigenstates such as K^+K^-, modes accessible by either Cabibbo favoured or doubly-Cabibbo suppressed decays such as $K^-\pi^+$, or self-conjugate final states such as $K^0_S\pi^+\pi^-$. The common final state means that interference occurs between the contributing tree-level $b \to c$ and $b \to u$ amplitudes, which leads to *CP* violating effects dependent on γ. Optimum sensitivity is achieved by combining together many measurements of this sort. As reported at the conference, each of the *B*-factory experiments has obtained a precision of around 16° by this approach [23], a sensitivity which has now been superseded by the combination of the first analyses from LHCb [24, 25, 26]. By the end of the operation of the current LHCb experiment an uncertainty of $\sim 4^\circ$ is expected. The LHCb upgrade [27] and Belle-II [28] aim to reach a precision of $\sim 1^\circ$ or better.

5. Suppressed FCNC decays

Suppressed FCNC decays have branching ratios which can be modified by New Physics effects. The most promising of these is the long sought-for decay $B^0_s \to \mu^+\mu^-$ which, with a Standard Model branching ratio of $3.56 \pm 0.30 \times 10^{-9}$ [29] [1], is not only ultra-rare, but rather precisely pre-

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[1] This value is modified with respect to the one reported in [29] through the inclusion of updated values of the B^0_s lifetime and width difference.

dicted. It is highly sensitive to models with an extended scalar Higgs sector and in SUSY has a $\tan^6\beta$ dependence. The first searches for this mode date back almost 30 years [30], but measurements able to access the $10^{-8}-10^{-9}$ regime have only been possible in recent years at the Tevatron and LHC. Reports were given on these later searches [31], the highlight being the first evidence for the decay by LHCb. An illustrative data plot from this analysis is presented in Fig. 3. This analysis [32] finds a branching ratio of $3.2^{+1.5}_{-1.2}\times 10^{-9}$ which, through its remarkable agreement with prediction, excludes any dramatic New Physics effects. Since the conference an updated measurement from LHCb [33] and one from CMS [34] have strengthened this conclusion, and together established the decay mode with a significance of over 5 sigma [35]. Much work remains to be done, however [36]. A precise measurement of the branching ratio is required to probe for more 'natural' New Physics effects than the spectacular enhancements that were initially hoped for. Moreover, the still rarer sister decay $B^0\to\mu^+\mu^-$ remains to be discovered, and the relative branching fraction of the two modes compared to expectation, since this ratio is a 'golden relation' which holds both in the Standard Model and Minimal Flavour Violation. Finally, when a sufficiently large sample of $B^0_s\to\mu^+\mu^-$ decays is available, a rich programme of lifetime and tagged time-dependent measurements may be performed.

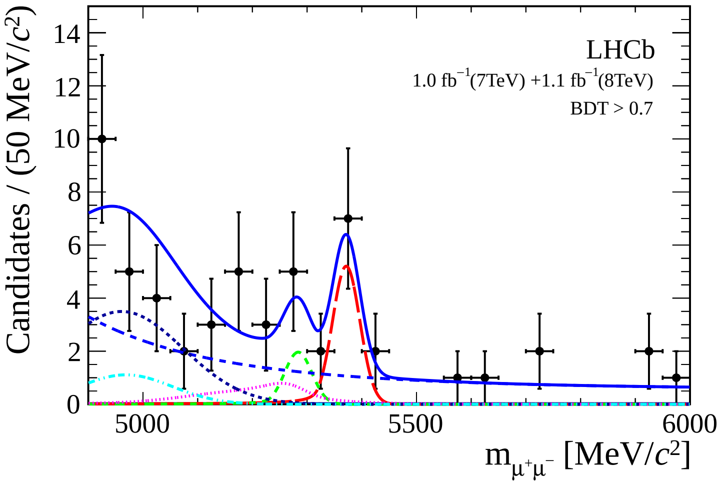

Figure 3: LHCb invariant mass spectrum for $B^0_s\to\mu^+\mu^-$ candidates in a region of high signal purity for the Boosted Decision Tree selection. The signal fit component is given by the red dashed line. See [32] for more information.

Another FCNC decay of great importance is $B^0\to K^{*0}\mu^+\mu^-$. Here the interest is not so much in the absolute branching ratio, but in studying the kinematical distributions of the final state particles, which are highly sensitive to the helicity structure of any New Physics [37]. The most well known observable in this system is the forward-backward asymmetry $A_{\rm FB}$ of the dimuons as a function of q^2, their invariant mass. The conference saw the exciting first results from ATLAS [38, 39] and CMS [40, 41]. These measurements have good sensitivity at high q^2 and complement the capabilities of LHCb [42, 43], which has good acceptance in the low q^2 region also. Results for $A_{\rm FB}$ against q^2 are shown in Fig. 4. The precision of the LHC experiments is now significantly in excess of what was achieved at the B-factories. Although the measured forward-backward asymmetry appears broadly consistent with the Standard Model expectation, there are a wealth of other observables to be studied which are sensitive to New Physics in complementary ways. Since the conference intriguing results from LHCb on these other observables [43, 44] have excited interest [45].

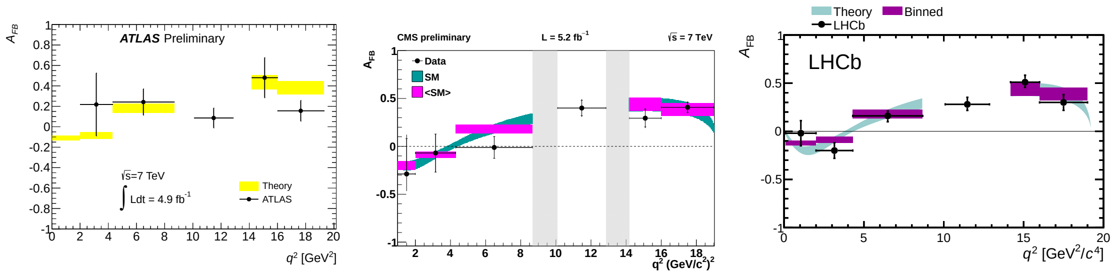

Figure 4: The forward-backward asymmetry $A_{\rm FB}$ as a function of the invariant-mass squared (q^2) of the dimuon system as measured by ATLAS (left) [39], CMS (middle) [41] and LHCb (right) [43].

Corresponding studies may be performed in the charm sector. The conference was told [46] of stringent limits by LHCb on the decays $D^+_{(s)} \to \pi^+\mu^+\mu^-$ [47] and $D^0 \to \mu^+\mu^-$ [48] which are significant improvements on previous results.

6. Charm mixing and *CP* violation

Although the accumulated evidence for charm mixing from the *B*-factories has become overwhelming, no single measurement achieved a 5 sigma observation. This step has now been taken with the 'wrong-sign $K\pi$' analyses performed by LHCb [49, 50] and CDF [51, 52], with the latter analysis being presented for the first time at the conference. Both these studies show compelling signatures of mixing, results obtained through the statistical power of hadron colliders, and the remarkable cleanliness of the data sets. Results are shown for both experiments in Fig. 5. The next challenge in this area is to increase the sensitivity in the search for *CP* violation in mixing.

Direct *CP* violation in charm is a topic which has received enormous attention over the past year [58], with the emerging evidence [53, 54, 55] for a non-zero signal in ΔA_{CP}, the difference between the *CP* asymmetry in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, and the most recent results which weaken this conclusion [49, 56, 57]. The accompanying theoretical discussion has been very valuable [58], with a growing acknowledgement that the Standard Model can generate larger *CP* violation in such modes than was previously thought possible. Future measurements from LHCb should be able to clarify the picture.

7. Outlook

The quality and breadth of flavour physics results now emerging from the LHC, and those from the final analyses still being performed at the Tevatron, are remarkable. Highlights include measuring for the first time the branching ratio of $B^0_s \to \mu^+\mu^-$, placing meaningful constraints on the B^0_s mixing phase ϕ_s, determining the zero point of the forward-backward asymmetry in

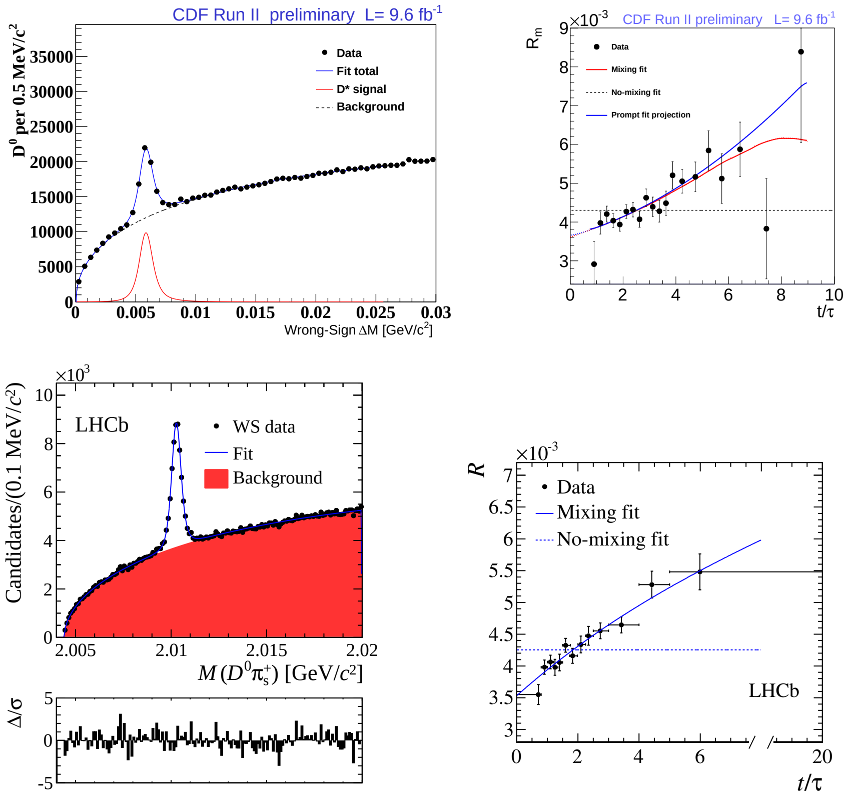

Figure 5: Wrong-sign $K\pi$ charm mixing analyses from CDF [52] and LHCb [50]. Signal peak in the $D^* - D^0$ invariant mass distribution from CDF (top left) and LHCb (bottom left). Measured ratio of wrong-sign to right-sign events as a function of decay time for CDF (top right) and LHCb (bottom right). In the absence of mixing these latter distributions would be consistent with a flat line.

$B^0 \to K^{*0}\mu^+\mu^-$ decays, and observing charm mixing in a single analysis. So far, most results are in agreement with the Standard Model expectation, but a few anomalies exist which require measurements of improved precision to resolve. The most prominent of these are the D0 dimuon *CP* asymmetry, the higher than expected branching ratios in $B^- \to \tau^-\bar{\nu}$ and $B \to D^{(*)}\tau^-\bar{\nu}$ [59], and the ΔA_{CP} enigma in charm.

Anomalies aside, there is not yet any clear signal of effects coming from beyond the Standard Model. The LHC, however, is only at the start of its measurement programme. The additional data already available from 2012, the data foreseen to be collected after the current technical stop, and the very large samples that will be collected at the LHCb upgrade [27] will enable many improvements to be made, in particular:

- A factor ∼10 reduction in the uncertainty on the CKM angle γ;
- A true precision measurement of ϕ_s;
- An extensive exploration of electroweak Penguins, with a thorough study of the available observables in $B^0 \to K^{*0}\mu^+\mu^-$ decays;

- A measurement of BR($B_s^0 \to \mu^+\mu^-$) to better precision than the theory uncertainty, a measurement of BR($B^0 \to \mu^+\mu^-$) and time dependent studies of the B_s^0 mode;
- Attaining sensitivity to direct *CP* violation in charm down to the Standard Model expectation, and performing an ultra-precise search for *CP* violation in charm mixing.

Complementary measurements will be performed at Belle-II [28]. By the end of the next decade, therefore, another order of precision will have been attained in most flavour observables, with many more being probed for the first time. These results, in conjunction with those from the direct searches for new particles at ATLAS and CMS, will be tremendously powerful in the hunt for physics beyond the Standard Model.

Acknowledgements

I thank the organsiers for their magnificent hospitality and an exceedingly well-run conference. I am also grateful to the participants for the high quality and stimulating presentations.

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