Heavy Flavour Physics at the LHC

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Abstract

A summary of results in heavy flavour physics from Run 1 of the LHC is presented. Topics discussed include spectroscopy, mixing, $CP$ violation and rare decays of charmed and beauty hadrons.

Keywords: quark flavour physics, spectroscopy, $CP$ violation, rare decays, Large Hadron Collider

1. Introduction

The high energy proton-proton collisions at the Large Hadron Collider are the world’s most copious source of heavy flavoured particles. For example, the production cross-sections for $c\bar{c}$ and $b\bar{b}$ production are $\mathcal{O}(1\text{ mb})$ and $\mathcal{O}(100\mu\text{b})$ respectively. (Studies of the heaviest flavoured particle, the top quark, are not within the scope of this review.) Specific values depend on the kinematic region in which the measurement is made, with the production peaking at pseudorapidity values $|\eta| \sim 3$, and are an increasing function of centre-of-mass energy. Therefore, per $\text{fb}^{-1}$ of data collected at, for example, LHCb, over $10^{11}$ $b\bar{b}$ quark pairs are, in principle, available, with the corresponding number for charm pairs an order of magnitude larger. The number that is actually recorded by each experiment depends critically on the trigger used for online selection.

The availability of such large samples enables a new era of precision flavour physics and discovery. Measurements of the properties of heavy flavoured hadrons – including those of states that had not previously been observed – provide tests of QCD in a regime where it is not well understood. In addition, heavy flavour phenomena such as mixing, $CP$ violation and rare decays are mediated by loop processes involving virtual particles, and are sensitive to possible non-Standard Model physics at high scales. In fact, precision measurements in the quark sector can be sensitive to new particles with masses much higher than the reach of the LHC collisions. Studies of these processes therefore provide a complementary approach to discover “new physics”, and form a key part of the LHC programme to search beyond the Standard Model.
2. Detectors

All the main LHC detectors have considerable potential to study heavy flavour physics, and ATLAS [1], CMS [2] and LHCb [3] have extensive programmes in this area. Although ALICE can study production at low luminosity, it cannot perform competitive studies of the processes that are the main focus of this review, and therefore is not discussed further.

Precision tracking is a key requirement in a hadronic environment in order to reduce combinatorial background to an acceptable level. All the LHC detectors have well aligned and calibrated tracking detectors delivering performance close to design expectations. An important performance indicator of the tracking system is the mass resolution for the $\Upsilon$ resonances decaying to the dimuon final state, shown in Fig. 1. ATLAS, CMS and LHCb have $\Upsilon(1S)$ mass resolutions of $\sim 120 \text{ MeV}/c^2$, $\sim 70 \text{ MeV}/c^2$ and $\sim 45 \text{ MeV}/c^2$ respectively.

The key signatures that allow decays of heavy flavoured particles to be distinguished from random combinations of tracks are the presence of muons with comparatively large transverse momentum, and a displaced vertex due to the non-negligible lifetimes of the weakly decaying hadrons. ATLAS and CMS exploit only the former in their online selections, while LHCb makes extensive use in its trigger [7] of information from its vertex locator [8]. This, together with the particle identification capability provided by its ring-imaging Cherenkov detectors [9], gives LHCb a broader heavy flavour physics programme than ATLAS and CMS. However, ATLAS and CMS benefit from higher integrated luminosities ($\sim 5 \text{ fb}^{-1}$ of $\sqrt{s} = 7 \text{ TeV}$ and $\sim 20 \text{ fb}^{-1}$ of $\sqrt{s} = 8 \text{ TeV}$ $pp$ collisions collected in 2011 and 2012, respectively, for each experiment) and are therefore highly competitive for final states containing dimuon signatures. LHCb operates at a lower instantaneous luminosity to avoid saturating its trigger and causing over-occupancy of its subdetectors: the corresponding integrated luminosities are $1 \text{ fb}^{-1}$ (2011) and $2 \text{ fb}^{-1}$ (2012). The LHCb upgrade [10] will enable higher luminosity operation.

Figure 1: Dimuon invariant mass resolution in the region of the $\Upsilon$ resonances for (left) ATLAS [1] (middle) CMS [2] (right) LHCb [3].
3. Spectroscopy

The large datasets collected at the LHC have allowed studies of the properties of $b$-hadrons with unprecedented precision. This is a wide field of research, in which three particularly interesting areas, discussed below, are exotic spectroscopy, the $B^+_c$ meson and $b$-baryons.

In addition to conventional mesons and baryons, the QCD Lagrangian allows for more exotic possibilities such as tetraquark and molecular states. The unexpected discovery of the $X(3872)$ state by the Belle collaboration [11] led to a resurgence of interest in exotic spectroscopy and subsequently many new “XYZ” states have been claimed.

The $X(3872)$ state has been studied in detail both at the $e^+e^-$ $B$ factories [12, 13] and the Tevatron [14, 15] but the nature of this particle remains unclear. Its properties do not match the predictions for the conventional charmonium states and it has been interpreted as a candidate for a tetraquark state or a loosely bound deuteron-like $D^* D^0$ “molecule” (reviews can be found in Refs. [16, 17]). At the LHC the $X(3872)$ is produced both directly in $pp$ collisions and also in $b$-hadron decays. Inclusive studies are challenging due to the large combinatorial background from other particles produced in the $pp$ interaction. Nevertheless, both LHCb and CMS have studied inclusive $X(3872)$ production in $pp$ collisions at $\sqrt{s} = 7$ TeV [18, 19]. The cross-sections measured by both experiments are significantly less than those expected from leading-order NRQCD predictions [20], as shown in Fig. 2.

In addition, LHCb has measured the $X(3872)$ quantum numbers by performing a five-dimensional angular analysis of the $B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ decay chain [21]. To distinguish between the possible hypotheses for the quantum numbers a likelihood ratio test is performed. The data favour the $J^{PC} = 1^{++}$ hypothesis and the $2^{-+}$ hypothesis is rejected with a significance of...
8.4σ. This assignment favours the hypothesis that the $X(3872)$ is exotic in nature. However, the relative decay rates of the $X(3872)$ to the $\psi(2S)\gamma$ and $J/\psi\gamma$ final states \cite{22} are inconsistent with the prediction for a pure molecule. Further studies are still needed to understand the nature of the $X(3872)$ particle.

The large datasets collected by the LHC experiments have allowed studies of other “XYZ” states. One very important result is the confirmation by LHCb \cite{23} of the existence and resonant nature of the $Z(4430)^+$ state first seen by the Belle collaboration \cite{24}–\cite{26}. As this state is charged its minimal quark content is $cud$, and thus it provides clear evidence for the existence of non-$q\bar{q}$ mesons. A puzzle that remains open concerns the existence of the $X(4140)$ state. Evidence for this putative $J/\psi\phi$ resonance was reported by the CDF collaboration based on studies of the $B^+ \rightarrow J/\psi\phi K^+$ decay chain \cite{27}. However, a subsequent LHCb study found no evidence for this state and set upper limits on its existence \cite{28}. An analysis by CMS \cite{29} confirmed the existence of a peaking structure in the same region, and in addition found evidence for a second structure with $m(J/\psi\phi) \sim 4300$ MeV/$c^2$, in same decay mode. Further study is needed to clarify whether these structures are resonant in nature.

The $B_c^+$ meson, the ground state of the $\bar{b}c$ system, is unique as it is the only weakly decaying heavy quarkonium system. It was first observed by the CDF collaboration \cite{30}–\cite{31}, but with the advent of the LHC studies of the $B_c^+$ meson have entered a new precision era. LHCb has reported observations of many new decay modes \cite{32}–\cite{37}, while signals for the $B_c^+ \rightarrow J/\psi \pi^+\pi^+\pi^-$ decay have also been reported by ATLAS \cite{38} and CMS \cite{39}. One particularly important observation is that of the decay $B_c^+ \rightarrow B_s^0 \pi^+$ \cite{40}, which is mediated by the decay of the constituent $c$ quark. Such decays are expected to dominate the $B_c^+$ width, but had never previously been observed. It will be of interest to search for decay modes in which the $b$ and $c$ annihilate in the near future. The fundamental properties of the $B_c^+$ meson have also been determined, with significant improvements in precision compared to prior results. The most precise measurement of the $B_c^+$ mass to date is obtained by LHCb in the $J/\psi D_s^+$ decay mode \cite{34},

$$m(B_c^+) = 6276.28 \pm 1.44 \text{ (stat)} \pm 0.36 \text{ (syst)} \text{ MeV}/c^2.$$

In addition, LHCb has used semileptonic $B_c^+$ decays to measure the lifetime \cite{41}

$$\tau(B_c^+) = 509 \pm 12 \text{ (stat)} \pm 8 \text{ (syst)} \text{ fs}.$$

The observation of a candidate $B_c(2S)^+$ state by ATLAS \cite{42}, shown in Fig. 3(left), demonstrates the possibility for more detailed understanding of the spectroscopy in the $B_c^+$ sector.

The large data samples collected by the LHC experiments has also allowed to explore in detail the properties of the $b$-baryon sector for the first time. One puzzle from studies at LEP and the Tevatron concerned the lifetime of the $\Lambda_b^0$ baryon. Theoretical predictions based on the Heavy Quark Expansion (HQE) give the ratio of the $\Lambda_b^0$ and $B^0$ lifetimes to be consistent with unity at the level of a few percent \cite{43}–\cite{45}. However, early measurements gave considerably
smaller values. ATLAS, CMS and LHCb have all made measurements of this quantity [46–48] and find values more consistent with theory. The most precise measurements of the $Λ_b^0$ lifetime are obtained by LHCb with decays to the $J/ψ Λ$ [49] and $J/ψ pK^- [50]$ final states. These give

$$\tau(Λ_b^0) = 1.468 \pm 0.009 \pm 0.008 \text{ ps},$$

within a few percent of the measured $B^0$ lifetime [51] as predicted by the HQE. Measurements of the lifetimes of other $b$-baryons also start to approach the percent level [52, 53].

First observations of excited $b$-baryons have also been made. CMS has observed an excited $Ξ_b$ state [54] whilst LHCb has observed two excited $Λ_b^0$ states [55], as shown in Fig. 3(right). Further new discoveries in this area can be anticipated with more data and refined analysis techniques.

4. Mixing

There are four ground-state neutral flavoured mesons: the $K^0 (\bar{s}d)$, $D^0 (\bar{c}u)$, $B^0 (\bar{b}d)$ and $B_s^0 (\bar{b}s)$ particles. Each of these can mix with its antiparticle, through diagrams that either contain virtual heavy particles or have on-shell intermediate states. These are often referred to as short-distance (or dispersive) and long-distance (or absorptive) processes, respectively.

As a result of the mixing, physical states with definite masses and lifetimes are formed. When the amplitudes of the mixing processes are calculated, theoretical predictions for the mass and width differences ($Δm$ and $ΔΓ$), and for the parameter of $CP$ violation in the mixing ($a_sl$), are obtained. Since, at least for the short-distance diagrams, the uncertainties related to the theory prediction are under good control, comparison of the measurements (particularly $Δm$ and $a_sl$) to the predictions provide strong tests of the Standard Model.

The first data from the LHC has led to significant improvement in knowledge of the $D^0$ and $B^0_s$ mixing parameters. The measurement of the mass difference in the $B_s^0$ system, $Δm_s$, had proved challenging for previous experiments because
its large value causes fast oscillations between $B^0_s$ and $\bar{B}^0_s$ that are hard to resolve. The CDF collaboration did, however, succeed to determine the value of $\Delta m_s$ with 5$\sigma$ significance [56].

Due to the LHCb detector’s excellent vertex resolution, which allows to resolve the oscillations, and flavour tagging capability [57, 58], from which initial state $B^0_s$ and $\bar{B}^0_s$ mesons can be distinguished, major improvement in the determination of $\Delta m_s$ has been achieved [59–61]. The single most precise result, based on a sample of $B^0_s \rightarrow D^- \pi^+$ decays selected from LHCb’s 2011 data sample, illustrated in Fig. 4 (left), gives [60]

$$\Delta m_s = (17.768 \pm 0.023 \text{ (stat)} \pm 0.006 \text{ (syst)}) \text{ ps}^{-1}.$$ 

The width difference in the $B^0_s$ system, $\Delta \Gamma_s$, can be measured either by comparing the lifetimes for CP-even (e.g. $K^+K^-$ [62, 64] or $D^+_sD^-_s$ [65]) and CP-odd (e.g. $J/\psi\pi^+\pi^-$ [66] or $J/\psi K^0$ [67]) final states or from analysis of decays to a final state that contains an admixture of both (e.g. $J/\psi\phi$). The most precise measurements come from the latter approach [68–72], which also has the advantage that it is not necessary to make assumptions concerning CP violation parameters since they can be determined simultaneously (as discussed below). The single most precise measurement gives [72]

$$\Delta \Gamma_s = (0.663 \pm 0.005 \text{ (stat)} \pm 0.006 \text{ (syst)}) \text{ ps}^{-1}.$$ 

In stark contrast to the large values of $\Delta m_s$ and $\Delta \Gamma_s$, the mixing parameters in the charm sector are small. Indeed, while previous experiments had seen evidence for charm oscillations [74–76], no single measurement exceeded the 5$\sigma$ threshold for discovery. LHCb has taken the precision of the measurements far past that threshold using $D^0 \rightarrow K^\pm \pi^\mp$ decays [77, 78] as shown in Fig. 4 (right). The world averages of the charm mixing parameters are now [79]

$$x_D = \frac{\Delta m_D}{\Gamma_D} = (0.39^{+0.16}_{-0.17})\%, \quad y_D = \frac{\Delta \Gamma_D}{(2\Gamma_D)} = (0.67^{+0.07}_{-0.08})\%,$$

where $\Gamma_D$ is the average width of the neutral charm mesons. As the value of $x_D$ is still consistent with zero, further improvement of precision is well motivated.

5. Mixing-related CP violation

CP violation phenomena in charm oscillations are expected to be negligible. Now that charm mixing is definitively established, precise experimental searches to test this Standard Model prediction are imperative. Results from LHCb with the $D^0 \rightarrow K^\pm \pi^\mp$ [78] and $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ [80] decays have significantly improved the precision of prior measurements, but not yet revealed any discrepancy with the Standard Model. Further improvements in precision
Figure 4: Mixing in (left) the $B^0_s$–$\bar{B}^0_s$ system [60]; (right) the $D^0$–$\bar{D}^0$ system [77].

are anticipated as all measurements are updated to the full Run I data sample, and results from additional channels such as $D^0 \to K^0\pi^+\pi^-$ become available.

Mixing-induced $CP$ violation in the $B^0$ sector has been studied extensively by the $e^+ e^-$ $B$ factories. The benchmark measurement is from the asymmetry in $B^0 \to J/\psi K^*_0$ decays, which gives $\sin 2\beta = 0.665 \pm 0.024$ [79, 81, 82], where $\beta \equiv \arg [-V_{td} V_{tb}^*/(V_{cd} V_{cb}^*)]$ is an angle of the Cabibbo-Kobayashi-Maskawa (CKM) [83, 84] unitarity triangle. Using its 2011 dataset LHCb has measured $\sin 2\beta = 0.73 \pm 0.07$ (stat) $\pm 0.04$ (syst) [85], in agreement with the world average though less precise. Results with the full Run I precision should be competitive with the individual measurements from BaBar and Belle.

The LHC era has allowed the first high precision searches for $CP$ violation in the $B^0_s$ sector. In the Standard Model the prediction for the $CP$ violation effect in $B^0_s \to J/\psi \phi$ decays is $\phi_s \equiv -2\arg [-V_{ts} V_{tb}^*/(V_{cs} V_{cb}^*)] = -0.036 \pm 0.002$. Extensions of the Standard Model typically give additional phases which can make the measured value of $\phi_s$ differ from this prediction. Hence, precise measurements of $\phi_s$ test models of new physics. Prior to LHC running, first measurements from the Tevatron experiments hinted towards a deviation with the Standard Model, though with large uncertainties [86, 87]. Significant improvement in precision has been achieved by LHCb with the $B^0_s \to J/\psi \phi$ channel [71, 72]. ATLAS [69] and CMS [70] have also released preliminary measurements from flavour-tagged time-dependent angular analyses of $B^0_s \to J/\psi \phi$ decays, using their 2011 and 2012 data samples, respectively.

It is of interest to make $\phi_s$ measurements using additional channels. LHCb has released results based on the $B^0_s \to J/\psi \pi^+\pi^-$ decay [88, 90]. This final state has a large contribution from $J/\psi f_0(980)$ decays, but the whole phase-space can be used inclusively since it has been shown to be dominantly $CP$-odd [91, 92]. The most recent LHCb analysis of $B^0_s \to J/\psi \pi^+\pi^-$ using the full Run I data sample gives currently the single most precise measurement [88]

$$\phi_s = 0.07 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad}.$$
edge of $\phi_s$: the measurements are consistent with the Standard Model, suggesting that any new physics effects are small.

In addition, LHCb has measured $\phi_s$ with the $B^0_s \rightarrow \phi\phi$ channel [93, 94]. As this decay is dominated by the $b \rightarrow s$ loop transition, it can be used to search for new physics effects in the decay amplitude as well as in mixing. In the near future it will be interesting to obtain also values of $\phi_s$ from $B^0_s \rightarrow K^{*0}\overline{K^{*0}}$ which is similarly sensitive to possible new physics effects.

The semileptonic (or flavour-specific) asymmetry $a_{sl}$ is sensitive to CP violation in mixing. It is expected to be negligibly small in the Standard Model, but the D0 collaboration has reported an anomalous asymmetry between positive and negative like-sign muon pairs [95]. The effect, which deviates from the Standard Model predictions by $3.6\sigma$, could be caused by non-zero $a_{sl}$ in either or both the $B^0$ and $B^0_s$ systems. LHCb has measured $a_{sl}(B^0_s)$ using $B^0_s \rightarrow D^-\mu^+X$ decays reconstructed in its 2011 data sample [96]. The result is the single most precise measurement of this quantity, and is in agreement with the Standard Model prediction, as are all other measurements of $a_{sl}(B^0)$ and $a_{sl}(B^0_s)$ individually. The current situation is summarised in Fig. 6. Further improvements in precision are needed to shed light on whether the D0 result indicates new physics.

6. Direct CP violation and the determination of $\gamma$

The term “direct CP violation” is used to refer to asymmetries that cannot be caused by CP violation in the mixing amplitude. Historically, this categorisation was important to test so-called “superweak” models. Direct CP violation can be observed as a difference in mixing-related CP violating effects in neutral meson decays to different final states, as seen in the kaon system [97, 98]. Alternatively,
Figure 6: Compilation of data on $a_{sl}$ in the $B^0$ and $B^0_s$ system \cite{79}. The vertical and horizontal bands show the averages of $a_{sl}(B^0)$ and $a_{sl}(B^0_s)$ measured individually, the green ellipse is the D0 measurement with inclusive same-sign dileptons, and the red ellipse is the world average of all measurements. The Standard Model prediction (red point) is indistinguishable from the origin.

If $a_{sl}$ is known to be small, direct $CP$ violation can be seen in flavour-specific decays of neutral mesons, for example as an asymmetry in the yields of $B^0 \to K^+\pi^-$ and $B^0 \to K^-\pi^+$ decays \cite{99,100}. This approach allowed LHCb to make the first observation of $CP$ violation in the $B^0_s$ system \cite{101,102}

$$A_{CP}(B^0_s \to K^-\pi^+) = 0.27 \pm 0.04 \text{ (stat)} \pm 0.01 \text{ (syst)}.$$  

Among other results on direct $CP$ violation, particularly striking are the phase-space dependent effects seen in $B^+$ decays to the final states $\pi^+\pi^-K^+$, $K^+K^-K^+$, $\pi^+\pi^-\pi^+$ and $K^+K^-\pi^+$ \cite{103,104}, illustrated in Fig. 7. The asymmetries are larger than 50% in some regions away from resonant peaks. This appears to indicate that interference effects play a crucial role in generating the asymmetries, although further investigation is necessary to obtain a clear understanding.

The main objective in $CP$ violation studies is to understand whether all observed effects arise from the complex phase of the CKM quark mixing matrix. To interpret results such as those in charmless $B$ meson decays mentioned above, it is necessary to have a benchmark determination of the Standard Model phase \(\gamma \equiv \arg [-V_{ud}V_{ub}^*/(V_{cd}V_{cb}^*)]\). This can be achieved using decays such as $B \to DK$, where interference between amplitudes leading to final state $D^0$ and $\bar{D}^0$ mesons is possible when they are reconstructed in a common final state such as $K^+K^-$. As no loop contributions are possible these decays are very clean theoretically, and moreover all hadronic parameters can be determined from the data by considering several different $D$ meson decays. LHCb has reported results.
Figure 7: Direct CP violation effects in the phase space of (left) $B^+ \rightarrow \pi^+\pi^+\pi^+$ and (right) $B^+ \rightarrow K^+K^-\pi^+$ decays \cite{104}. The z-axis (y-axis on inset) shows the raw asymmetry, without correction for background, or instrumental efficiencies and asymmetries.

on $B^+ \rightarrow DK^+$ using $D \rightarrow K^+K^-, \pi^+\pi^-, K^{+}\pi^{\pm}$ \cite{105}, $K^{0}\pi^{+}\pi^{-}, K^{0}_\text{S}K^{+}K^{-}$ \cite{107,108} and $K^{0}_\text{S}K^{0}\pi^{+}$ \cite{109} decays. The combination of these results gives \cite{110,111}

$$\gamma = (67 \pm 12)^\circ.$$  

Since most of the inputs are yet to be updated to include all Run I data, and results on $B^0 \rightarrow DK^{*0}$ \cite{112,113}, $B^+ \rightarrow DK^{+}\pi^+\pi^-$ \cite{114} and $B^0 \rightarrow D^{+}_s K^{\pm}$ \cite{115} can also be included, there are excellent prospects for further improvement.

Since the Standard Model predicts only small or vanishing CP asymmetries in charm decays, searches for direct CP violation provide useful null tests. A measurement of the parameter $\Delta A_{CP}$, describing the difference between the asymmetries for $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays, that differed from zero by 3.5 standard deviations \cite{116}, prompted a great deal of theoretical activity (reviewed in Ref. \cite{117}) to examine whether or not a percent level asymmetry could be accommodated within the Standard Model. More recent measurements, however, bring the world average closer to zero \cite{118,119}. In addition searches for $CP$ violation in $D^+$ and $D^+_s$ decays have yielded null results \cite{121,125}, so that currently there is no evidence for $CP$ violation in the charm system.

7. Rare decays

A powerful way to search for new physics is to study decays which are either forbidden or suppressed due to features of the Standard Model that may not be present in a more general theory. The flavour sector of the Standard Model presents several such features: there are no flavour changing neutral currents at tree-level, vertices involving quarks of different families are suppressed by CKM quark mixing matrix elements, and the $V - A$ structure of the weak interaction leads to distinctive effects. Rare decays of $B$ mesons to final states containing
leptons or photons are particularly useful for Standard Model tests since observables can be calculated with reduced theoretical uncertainty compared to fully hadronic final states.

Perhaps the most powerful of all Standard Model tests with rare $B$ decays is the search for $B^0_s \to \mu^+\mu^-$ decays. The decay rate is suppressed by all three of the features mentioned above, and in particular the helicity suppression due to the $V-A$ structure of the weak interaction is expected to be alleviated in models with extended Higgs sectors, such as supersymmetry. Prior to LHC data taking, experimental limits [126, 127] still allowed the $B^0_s \to \mu^+\mu^-$ rate to be enhanced by more than a factor of ten compared to its Standard Model prediction of $(3.35\pm0.28)\times10^{-9}$. However, a series of results from LHCb [128–130], CMS [131] and ATLAS [132] progressively reduced the phase space for new physics signals. In late 2012, LHCb announced the first evidence for the $B^0_s \to \mu^+\mu^-$ decay [133], and this was subsequently confirmed by both LHCb [134] and CMS [135] with their full Run I data sets. The signals, shown in Fig. 8 when combined now reach the $5\sigma$ threshold for observation [136]. The combined result for the branching fraction

$$B(B^0_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

is consistent with the Standard Model prediction. Future updates with more statistics are nonetheless of great interest to reduce the uncertainty, to search for the $B^0 \to \mu^+\mu^-$ decay and to test the Standard Model prediction for the effective lifetime of the $B^0_s \to \mu^+\mu^-$ decay.

New physics can also be searched for using $B^0 \to K^{*0}\mu^+\mu^-$ decays, or similar $b \to s\mu^+\mu^-$ transitions. Such decays offer a wealth of asymmetries and angular observables that can be studied as functions of the dimuon invariant mass squared, $q^2$, several of which have been shown to have reduced theoretical uncertainty. For example, although the absolute values of the branching fraction...
fractions are hard to predict precisely, isospin and CP asymmetries, between $B^+$ and $B^0$ or $B$ and $\bar{B}$ decays respectively, provide powerful null tests of the Standard Model. Evidence of isospin asymmetry in $B \rightarrow K\mu^+\mu^-$ decays [137] has not been confirmed in an update with larger statistics [138], and all CP asymmetry measurements in $B \rightarrow K^{(*)}\mu^+\mu^-$ decays are also consistent with zero [139, 140].

Among other angular observables, the forward-backward asymmetry in $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decays, i.e. the difference in the average directions of the $\mu^+$ and $\mu^-$ particles in the rest frame of the decay, has received considerable interest. In the Standard Model such an asymmetry arises, and varies with $q^2$ in a predictable way, due to interference between diagrams where the dimuon system is produced by virtual $\gamma$ and $Z^0$ bosons. While previous measurements had shown evidence for a net forward-backward asymmetry when integrated over $q^2$ [141–143], a measurement from LHCb [144], shown in Fig. 9, was the first to pin down the shape of the variation and measure the $q^2$ at which the asymmetry crosses zero. LHCb has additionally extended the analysis to study further angular observables that have reduced theoretical uncertainty [145]. In one of them, labelled $P'_5$, an interesting discrepancy with the Standard Model prediction is seen. This result is based on the 2011 data sample, and an update with the full Run I statistics together with improved theoretical predictions will help to determine whether the discrepancy is robust. Further results on this topic are also anticipated from CMS [146] and ATLAS [147]. As more data is collected similar observables can also be studied in $B^0_s \rightarrow \phi\mu^+\mu^-$ [66] and $A^0_s \rightarrow A\mu^+\mu^-$ [148] decays as well as in $b \rightarrow d\mu^+\mu^-$ transitions such as $B^+ \rightarrow \pi^+\mu^+\mu^-$ [149].

The study of the lowest region of the $q^2$ spectrum is of particular interest since the strong polarisation of the emitted photon in $b \rightarrow s\gamma^{(*)}$ transitions that is predicted in the Standard Model can be probed. The non-negligible muon mass implies that it is preferable to carry out such studies with either $b \rightarrow s\gamma$ or $b \rightarrow se^+e^-$ decays. The trigger capability of LHCb has allowed it to measure branching fractions and CP asymmetries of $B^0 \rightarrow K^{*0}\gamma$ and $B^0_s \rightarrow \phi\gamma$ decays [150, 151]. The latter channel is particularly interesting because with
more data the $CP$ violating parameters of its decay time distribution can be used to probe the photon polarisation with low theoretical uncertainty. Angular distributions in $B^0 \to K^{*0}e^+e^-$ and $B^+ \to K^+\pi^+\pi^−\gamma$ decays provide complementary ways to test this Standard Model prediction, with the latter mode giving the first observation of non-zero photon polarisation.

8. Summary and outlook

The large data samples collected from high-energy $pp$ collisions during Run I of the Large Hadron Collider have enabled dramatic progress in heavy flavour physics. Significant advances have been achieved in understanding spectroscopy, $CP$ violation and rare decays. The results are consistent with Standard Model predictions, although several puzzles and hints of discrepancies demand further investigation with larger data samples. Since many of the results to date are based on data collected in 2011 only, further progress can be anticipated in the near future as the analyses are updated to the full Run 1 samples.

Substantial further improvement in precision will be possible with the data from the LHC Run II. The increased centre-of-mass energy of the collisions is expected to result in higher production cross-sections for heavy-flavoured particles, and therefore more useful events can in principle be recorded per fb$^{-1}$ of data collected. The actual gain will be determined by the trigger algorithms used for online event selection.

Beyond Run II, the LHCb detector will be upgraded [10] to allow improved trigger efficiencies with higher luminosity operation. With the LHCb upgrade, and the ongoing capability of ATLAS and CMS in the field of heavy flavour physics, this topic will remain a priority throughout the high luminosity LHC era.

References

[1] G. Aad, et al., The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003. doi:10.1088/1748-0221/3/08/S08003.

[2] S. Chatrchyan, et al., The CMS experiment at the CERN LHC, JINST 3 (2008) S08004. doi:10.1088/1748-0221/3/08/S08004.

[3] A. A. Alves Jr., et al., The LHCb detector at the LHC, JINST 3 (2008) S08005. doi:10.1088/1748-0221/3/08/S08005.

[4] G. Aad, et al., Measurement of Upsilon production in 7 TeV $pp$ collisions at ATLAS, Phys. Rev. D87 (2013) 052004. arXiv:1211.7255 doi:10.1103/PhysRevD.87.052004.

[5] S. Chatrchyan, et al., Measurement of the $\Upsilon(1S), \Upsilon(2S),$ and $\Upsilon(3S)$ cross sections in $pp$ collisions at $\sqrt{s} = 7$ TeV, Phys. Lett. B727 (2013) 101. arXiv:1303.5900 doi:10.1016/j.physletb.2013.10.033.
[6] R. Aaij, et al., Production of $J/\psi$ and $Y$ mesons in $pp$ collisions at $\sqrt{s} = 8$ TeV, JHEP 06 (2013) 064. arXiv:1304.6977, doi:10.1007/JHEP06(2013)064

[7] R. Aaij, et al., The LHCb trigger and its performance in 2011, JINST 8 (2013) P04022. arXiv:1211.3055, doi:10.1088/1748-0221/8/04/P04022

[8] R. Aaij, et al., Performance of the LHCb Vertex Locator, to appear in JINST. arXiv:1405.7808

[9] M. Adinolfi, et al., Performance of the LHCb RICH detector at the LHC, Eur. Phys. J. C73 (2013) 2431. arXiv:1211.6759, doi:10.1140/epjc/s10052-013-2431-9

[10] LHCb collaboration, Framework TDR for the LHCb Upgrade: Technical Design Report, LHCB-TDR-012 (2012).

[11] S.-K. Choi, et al., Observation of a narrow charmonium-like state in exclusive $B^\pm \to K^\pm \pi^+\pi^- J/\psi$ decays, Phys. Rev. Lett. 91 (2003) 262001. arXiv:hep-ex/0309032, doi:10.1103/PhysRevLett.91.262001

[12] S.-K. Choi, et al., Bounds on the width, mass difference and other properties of $X(3872) \to \pi^+\pi^- J/\psi$ decays, Phys. Rev. D84 (2011) 052004. arXiv:1107.0163, doi:10.1103/PhysRevD.84.052004

[13] B. Aubert, et al., Study of the $B^- \to J/\psi K^- \pi^+\pi^-$ decay and measurement of the $B^- \to X(3872) K^-$ branching fraction, Phys. Rev. D71 (2005) 071103. arXiv:hep-ex/0406022, doi:10.1103/PhysRevD.71.071103

[14] V. M. Abazov, et al., Observation and properties of the $X(3872)$ decaying to $J/\psi\pi^+\pi^-$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. Lett. 93 (2004) 162002. arXiv:hep-ex/0405004, doi:10.1103/PhysRevLett.93.162002

[15] D. Acosta, et al., Observation of the narrow state $X(3872) \to J/\psi\pi^+\pi^-$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. Lett. 93 (2004) 072001. arXiv:hep-ex/0312021, doi:10.1103/PhysRevLett.93.072001

[16] E. S. Swanson, The new heavy mesons: a status report, Phys. Rept. 429 (2006) 243. arXiv:hep-ph/0601110, doi:10.1016/j.physrep.2006.04.003

[17] S. Godfrey, S. L. Olsen, The exotic XYZ charmonium-like mesons, Ann. Rev. Nucl. Part. Sci. 58 (2008) 51. arXiv:0801.3867, doi:10.1146/annurev.nucl.58.110707.171145

[18] R. Aaij, et al., Observation of $X(3872)$ production in $pp$ collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C72 (2012) 1972. arXiv:1112.5310, doi:10.1140/epjc/s10052-012-1972-7
[19] S. Chatrchyan, et al., Measurement of the X(3872) production cross section via decays to $J/\psi \pi^+\pi^-$ in pp collisions at $\sqrt{s} = 7$ TeV, JHEP 1304 (2013) 154. \texttt{arXiv:1302.3968} doi:10.1007/JHEP04(2013)154

[20] P. Artoisenet, E. Braaten, Production of the X(3872) at the Tevatron and the LHC, Phys. Rev. D81 (2010) 114018. \texttt{arXiv:0911.2016} doi:10.1103/PhysRevD.81.114018

[21] R. Aaij, et al., Determination of the X(3872) meson quantum numbers, Phys. Rev. Lett. 110 (2013) 222001. \texttt{arXiv:1302.6269} doi:10.1103/PhysRevLett.110.222001

[22] R. Aaij, et al., Evidence for the decay $X(3872) \rightarrow \psi(2S)\gamma$, Nucl. Phys. B886 (2014) 665. \texttt{arXiv:1404.0275} doi:10.1016/j.nuclphysb.2014.06.011

[23] R. Aaij, et al., Observation of the resonant character of the $Z(4430)^-$ state, Phys. Rev. Lett. 112 (2014) 222002. \texttt{arXiv:1404.1903} doi:10.1103/PhysRevLett.112.222002

[24] S. Choi, et al., Observation of a resonance-like structure in the $\pi^\pm\psi'$ mass distribution in exclusive $B \rightarrow K\pi^\pm\psi'$ decays, Phys. Rev. Lett. 100 (2008) 142001. \texttt{arXiv:0708.1790} doi:10.1103/PhysRevLett.100.142001

[25] R. Mizuk, et al., Dalitz analysis of $B \rightarrow K\pi^\pm\psi'$ decays and the $Z(4430)^+$, Phys. Rev. D80 (2009) 031104. \texttt{arXiv:0905.2869} doi:10.1103/PhysRevD.80.031104

[26] K. Chilikin, et al., Experimental constraints on the spin and parity of the $Z(4430)^+$, Phys. Rev. D88 (2013) 074026. \texttt{arXiv:1306.4894} doi:10.1103/PhysRevD.88.074026

[27] T. Aaltonen, et al., Evidence for a narrow near-threshold structure in the $J/\psi\phi$ mass spectrum in $B^+ \rightarrow J/\psi\phi K^+$ decays, Phys. Rev. Lett. 102 (2009) 242002. \texttt{arXiv:0903.2229} doi:10.1103/PhysRevLett.102.242002

[28] R. Aaij, et al., Search for the X(4140) state in $B \rightarrow J/\psi\phi K^+$ decays, Phys. Rev. D85 (2012) 091103(R). \texttt{arXiv:1202.5087} doi:10.1103/PhysRevD.85.091103

[29] S. Chatrchyan, et al., Observation of a peaking structure in the $J/\psi\phi$ mass spectrum from $B^\pm \rightarrow J/\psi\phi K^\pm$ decays, Phys. Lett. B734 (2014) 261. \texttt{arXiv:1309.6920} doi:10.1016/j.physletb.2014.05.055

[30] F. Abe, et al., Observation of the $B^+_s$ meson in $pp$ collisions at $\sqrt{s} = 1.8$ TeV, Phys. Rev. Lett. 81 (1998) 2432. \texttt{arXiv:hep-ex/9805034} doi:10.1103/PhysRevLett.81.2432
A. Abulencia, et al., Evidence for the exclusive decay $B^+_c \rightarrow J/\psi \pi^\pm$ and measurement of the mass of the $B^+_c$ meson, Phys. Rev. Lett. 96 (2006) 082002.  arXiv:hep-ex/0505076, doi:10.1103/PhysRevLett.96.082002.

R. Aaij, et al., First observation of the decay $B^+_c \rightarrow J/\psi \pi^+ \pi^- \pi^+$, Phys. Rev. Lett. 108 (2012) 251802.  arXiv:1204.0079, doi:10.1103/PhysRevLett.108.251802.

R. Aaij, et al., Observation of the decay $B^+_c \rightarrow \psi(2S) \pi^+$, Phys. Rev. D87 (2013) 071103(R).  arXiv:1303.1737, doi:10.1103/PhysRevD.87.071103.

R. Aaij, et al., Observation of $B^+_c \rightarrow J/\psi D^+_s$ and $B^+_c \rightarrow J/\psi D^*_s$ decays, Phys. Rev. D87 (2013) 112012.  arXiv:1304.4530, doi:10.1103/PhysRevD.87.112012.

R. Aaij, et al., First observation of the decay $B^+_c \rightarrow J/\psi K^+$, JHEP 09 (2013) 148.  arXiv:1404.0287, doi:10.1007/JHEP09(2013)148.

R. Aaij, et al., Measurement of $\sigma(B^+_c) \times Br(B^+_c \rightarrow J/\psi \pi^\pm)$ and \(\frac{Br(B^+_c \rightarrow J/\psi \pi^0 \pi^+ \pi^-)}{Br(B^+_c \rightarrow J/\psi \pi^+)}\) at $\sqrt{s} = 7$ TeV, CMS-PAS-BPH-12-011 (2013).

R. Aaij, et al., Observation of the decay $B^+_c \rightarrow B^0_s \pi^+$, Phys. Rev. Lett. 111 (2013) 181801.  arXiv:1308.4544, doi:10.1103/PhysRevLett.111.181801.

R. Aaij, et al., Measurement of the $B^+_c$ meson lifetime using $B^+_c \rightarrow J/\psi \mu^+ \nu_\mu X$ decays, Eur. Phys. J. C74 (2014) 2839.  arXiv:1401.6932, doi:10.1140/epjc/s10052-014-2839-x.

G. Aad, et al., Observation of an excited $B^+_c$ meson state with the ATLAS detector, submitted to Phys. Rev. Lett.  arXiv:1407.1032.

H.-Y. Cheng, A phenomenological analysis of heavy hadron lifetimes, Phys. Rev. D56 (1997) 2783.  arXiv:hep-ph/9704260, doi:10.1103/PhysRevD.56.2783.
[44] M. Neubert, C. T. Sachrajda, Spectator effects in inclusive decays of beauty hadrons, Nucl. Phys. B483 (1997) 339. arXiv:hep-ph/9603202 doi:10.1016/S0550-3213(96)00559-7

[45] N. Uraltsev, On the problem of boosting nonleptonic b baryon decays, Phys. Lett. B376 (1996) 303. arXiv:hep-ph/9602324 doi:10.1016/0370-2693(96)00305-X

[46] G. Aad, et al., Measurement of the $\Lambda^0_b$ lifetime and mass in the ATLAS experiment, Phys. Rev. D87 (2013) 032002. arXiv:1207.2284 doi:10.1103/PhysRevD.87.032002

[47] S. Chatrchyan, et al., Measurement of the $\Lambda^0_b$ lifetime in $pp$ collisions at $\sqrt{s} = 7$ TeV, JHEP 07 (2013) 163. arXiv:1304.7495 doi:10.1007/JHEP07(2013)163

[48] R. Aaij, et al., Precision measurement of the $\Lambda^0_b$ baryon lifetime, Phys. Rev. Lett. 111 (2013) 102003. arXiv:1307.2476 doi:10.1103/PhysRevLett.111.102003

[49] R. Aaij, et al., Measurements of the $B^+$, $B^0$, $B^0_s$ meson and $\Lambda^0_b$ baryon lifetimes, JHEP 04 (2014) 114. arXiv:1402.2554 doi:10.1007/JHEP04(2014)114

[50] R. Aaij, et al., Precision measurement of the ratio of the $\Lambda^0_b$ to $\bar{B}^0$ lifetimes, Phys. Lett. B734 (2014) 122. arXiv:1405.7223 doi:10.1016/j.physletb.2014.05.021

[51] J. Beringer, et al., Review of particle physics, Phys. Rev. D86 (2012) 010001, and 2013 partial update for the 2014 edition. doi:10.1103/PhysRevD.86.010001

[52] R. Aaij, et al., Measurement of the $\Xi^-_b$ and $\Omega^-_b$ baryon lifetimes, Phys.Lett. B736 (2014) 154. arXiv:1405.1543 doi:10.1016/j.physletb.2014.06.064

[53] R. Aaij, et al., Precision measurement of the mass and lifetime of the $\Xi^0_b$ baryon, Phys.Rev.Lett. 113 (2014) 032001. arXiv:1405.7223 doi:10.1103/PhysRevLett.113.032001

[54] S. Chatrchyan, et al., Observation of a new $\Xi_b$ baryon, Phys. Rev. Lett. 108 (2012) 252002. arXiv:1204.5955 doi:10.1103/PhysRevLett.108.252002

[55] R. Aaij, et al., Observation of excited $\Lambda^0_b$ baryons, Phys. Rev. Lett. 109 (2012) 172003. arXiv:1205.3452 doi:10.1103/PhysRevLett.109.172003

[56] A. Abulencia, et al., Observation of $B^0_s - B^0_s$ oscillations, Phys. Rev. Lett. 97 (2006) 242003. arXiv:hep-ex/0609040 doi:10.1103/PhysRevLett.97.242003
[57] R. Aaij, et al., Opposite-side flavour tagging of B mesons at the LHCb experiment, Eur. Phys. J. C72 (2012) 2022. arXiv:1202.4979 doi:10.1140/epjc/s10052-012-2022-1

[58] LHCb collaboration, Optimization and calibration of the same-side kaon tagging algorithm using hadronic B^0_s decays in 2011 data, LHCb-CONF-2012-033 (2012).

[59] R. Aaij, et al., Measurement of the B^0_s → B^0_s oscillation frequency \Delta m_s in B^0_s → D_s^- (3)\pi decays, Phys. Lett. B709 (2012) 177. arXiv:1112.4311 doi:10.1016/j.physletb.2012.02.031

[60] R. Aaij, et al., Precision measurement of the B^0_s → B^0_s oscillation frequency in the decay B^0_s → K^+ K^-, New J. Phys. 15 (2013) 053021. arXiv:1304.4741 doi:10.1088/1367-2630/15/5/053021

[61] R. Aaij, et al., Observation of B^0_s-B^0_s mixing and measurement of mixing frequencies using semileptonic B decays, Eur. Phys. J. C73 (2013) 2655. arXiv:1308.1302 doi:10.1140/epjc/s10052-013-2655-8

[62] R. Aaij, et al., Measurement of the effective B^0_s → K^+ K^- lifetime, Phys. Lett. B707 (2012) 349. arXiv:1111.0521 doi:10.1016/j.physletb.2011.12.058

[63] R. Aaij, et al., Measurement of the effective B^0_s → K^+ K^- lifetime, Phys. Lett. B716 (2012) 393. arXiv:1207.5993 doi:10.1016/j.physletb.2012.08.033

[64] R. Aaij, et al., Effective lifetime measurements of the B^0_s → K^+ K^-, B^0 → K^+ \pi^-, and B^0_s → \pi^+ K^- decays, to appear in Phys. Lett. B. arXiv:1406.7204

[65] R. Aaij, et al., Measurement of the B_s^0 → D_s^- D^+_s and \bar{B}_s^0 → D^- D^+_s effective lifetimes, Phys. Rev. Lett. 112 (2014) 111802. arXiv:1312.1217 doi:10.1103/PhysRevLett.112.111802

[66] R. Aaij, et al., Measurement of the \bar{B}_s^0 effective lifetime in the J/ψ f_0(980) final state, Phys. Rev. Lett. 109 (2012) 152002. arXiv:1207.0878 doi:10.1103/PhysRevLett.109.152002

[67] R. Aaij, et al., Measurement of the effective B^0_s → J/ψ K^0_S lifetime, Nucl. Phys. B873 (2013) 275. arXiv:1304.4500 doi:10.1016/j.nuclphysb.2013.04.021

[68] G. Aad, et al., Time-dependent angular analysis of the decay B^0_s → J/ψ φ and extraction of ΔΓ_s and the CP-violating weak phase φ_s by ATLAS, JHEP 12 (2012) 072. arXiv:1208.0572 doi:10.1007/JHEP12(2012)072
[69] G. Aad, et al., Flavour tagged time dependent angular analysis of the \( B_s^0 \to J/\psi \phi \) decay and extraction of \( \Delta \Gamma_s \) and the weak phase \( \phi_s \) in ATLAS, submitted to Phys. Rev. D. arXiv:1407.1796

[70] CMS collaboration, Measurement of the decay width \( \Delta \Gamma_s \) and the CP-violating phase \( \phi_s \) in the \( B_s^0 \to J/\psi \phi \) decays at CMS, CMS-BPH-13-012 (2014).

[71] R. Aaij, et al., Measurement of the CP-violating phase \( \phi_s \) in the decay \( B_s^0 \to J/\psi \phi \), Phys. Rev. Lett. 108 (2012) 101803. arXiv:1112.3183 doi:10.1103/PhysRevLett.108.101803

[72] R. Aaij, et al., Measurement of \( \Delta \Gamma_s \) and the \( \phi_s \) in the \( B_s^0 \to J/\psi \phi \) decays, Phys. Rev. D87 (2013) 112010. arXiv:1304.2600 doi:10.1103/PhysRevD.87.112010

[73] R. Aaij, et al., Determination of the sign of the decay width difference in the \( B_s^0 \) system, Phys. Rev. Lett. 108 (2012) 241801. arXiv:1202.4717 doi:10.1103/PhysRevLett.108.241801

[74] B. Aubert, et al., Evidence for \( D^0 - \bar{D}^0 \) mixing, Phys. Rev. Lett. 98 (2007) 211802. arXiv:hep-ex/0703020 doi:10.1103/PhysRevLett.98.211802

[75] M. Staric, et al., Evidence for \( D^0 - \bar{D}^0 \) mixing, Phys. Rev. Lett. 98 (2007) 211803. arXiv:hep-ex/0703036 doi:10.1103/PhysRevLett.98.211803

[76] T. Aaltonen, et al., Evidence for \( D^0 - \bar{D}^0 \) mixing using the CDF II detector, Phys. Rev. Lett. 100 (2008) 121802. arXiv:0712.1567 doi:10.1103/PhysRevLett.100.121802

[77] R. Aaij, et al., Observation of \( D^0 - \bar{D}^0 \) oscillations, Phys. Rev. Lett. 110 (2013) 101802. arXiv:1211.1230 doi:10.1103/PhysRevLett.110.101802

[78] R. Aaij, et al., Measurement of \( D^0 - \bar{D}^0 \) mixing parameters and search for \( CP \) violation using \( D^0 \to K^+ K^- \) and \( D^0 \to J/\psi \pi^+ \pi^- \) decays, Phys. Rev. Lett. 111 (2013) 251801. arXiv:1309.6534 doi:10.1103/PhysRevLett.111.251801

[79] Y. Amhis, et al., Averages of \( b \)-hadron, \( c \)-hadron, and \( \tau \)-lepton properties as of early 2012, updated results and plots available at http://www.slac.stanford.edu/xorg/hfag/ arXiv:1207.1158

[80] R. Aaij, et al., Measurements of indirect \( CP \) asymmetries in \( D^0 \to K^- K^+ \) and \( D^0 \to \pi^- \pi^+ \) decays, Phys. Rev. Lett. 112 (2014) 041801. arXiv:1310.7201 doi:10.1103/PhysRevLett.112.041801
[81] B. Aubert, et al., Measurement of time-dependent $CP$ asymmetry in $B^0 \rightarrow c\bar{c}K^{(*)0}$ decays, Phys. Rev. D79 (2009) 072009. arXiv:0902.1708 doi:10.1103/PhysRevD.79.072009

[82] I. Adachi, et al., Precise measurement of the $CP$ violation parameter $\sin 2\phi_1$ in $B^0 \rightarrow (c\bar{c})K^0$ decays, Phys. Rev. Lett. 108 (2012) 171802. arXiv:1201.4643 doi:10.1103/PhysRevLett.108.171802

[83] N. Cabibbo, Unitary symmetry and leptonic decays, Phys. Rev. Lett. 10 (1963) 531. doi:10.1103/PhysRevLett.10.531

[84] M. Kobayashi, T. Maskawa, $CP$ violation in the renormalizable theory of weak interaction, Prog.Theor.Phys. 49 (1973) 652. doi:10.1143/PTP.49.652

[85] R. Aaij, et al., Measurement of the time-dependent $CP$ asymmetry in $B^0 \rightarrow J/\psi K_S$ decays, Phys. Lett. B721 (2013) 24. arXiv:1211.6093 doi:10.1016/j.physletb.2013.02.054

[86] T. Aaltonen, et al., First flavor-tagged determination of bounds on mixing-induced $CP$ violation in $B^0_s \rightarrow J/\psi f_0(980)$ decays, Phys. Rev. Lett. 100 (2008) 161802. arXiv:0712.2397 doi:10.1103/PhysRevLett.100.161802

[87] V. Abazov, et al., Measurement of $B^0_s$ mixing parameters from the flavor-tagged decay $B^0_s \rightarrow J/\psi f_0(980)$, Phys. Rev. Lett. 101 (2008) 241801. arXiv:0802.2255 doi:10.1103/PhysRevLett.101.241801.

[88] R. Aaij, et al., Measurement of the $CP$ violating phase $\phi_s$ in $B^0_s \rightarrow J/\psi \pi^+\pi^-$ decays, Phys. Lett. B736 (2014) 186. arXiv:1405.4140 doi:10.1016/j.physletb.2014.06.079

[89] R. Aaij, et al., Measurement of the $CP$ violating phase $\phi_s$ in $B^0_s \rightarrow J/\psi f_0(980)$, Phys. Lett. B707 (2012) 497. arXiv:1112.3056 doi:10.1016/j.physletb.2012.01.017

[90] R. Aaij, et al., Measurement of the $CP$-violating phase $\phi_s$ in $B^0_s \rightarrow J/\psi \pi^+\pi^-$ decays, Phys. Lett. B713 (2012) 378. arXiv:1204.5675 doi:10.1016/j.physletb.2012.06.032

[91] R. Aaij, et al., Analysis of the resonant components in $B^0 \rightarrow J/\psi \pi^+\pi^-$, Phys. Rev. D86 (2012) 052006. arXiv:1204.5643 doi:10.1103/PhysRevD.86.052006

[92] R. Aaij, et al., Measurement of resonant and $CP$ components in $B^0 \rightarrow J/\psi \pi^+\pi^-$ decays, Phys. Rev. D89 (2014) 092006. arXiv:1402.6248 doi:10.1103/PhysRevD.89.092006

[93] R. Aaij, et al., First measurement of the $CP$-violating phase in $B^0_s \rightarrow \phi \phi$ decays, Phys. Rev. Lett. 110 (2013) 241802. arXiv:1303.7125 doi:10.1103/PhysRevLett.110.241802
[94] R. Aaij, et al., Measurement of CP violation in $B^0_s \rightarrow \phi\phi$ decays, submitted to Phys. Rev. D. arXiv:1407.2222.

[95] V. M. Abazov, et al., Study of CP-violating charge asymmetries of single muons and like-sign dimuons in $p\bar{p}$ collisions, Phys. Rev. D89 (2014) 012002. arXiv:1310.0447 doi:10.1103/PhysRevD.89.012002

[96] R. Aaij, et al., Measurement of the flavour-specific CP-violating asymmetry $a_s$ in $B^0_s$ decays, Phys. Lett. B728 (2014) 607. arXiv:1308.1048 doi:10.1016/j.physletb.2013.12.030

[97] V. Fanti, et al., A new measurement of direct CP violation in two pion decays of the neutral kaon, Phys. Lett. B465 (1999) 335. arXiv:hep-ex/9909022 doi:10.1016/S0370-2693(99)01030-8

[98] A. Alavi-Harati, et al., Observation of direct CP violation in $K^0_{S,L} \rightarrow \pi\pi$ decays, Phys. Rev. Lett. 83 (1999) 22. arXiv:hep-ex/9905060 doi:10.1103/PhysRevLett.83.22

[99] B. Aubert, et al., Observation of direct CP violation in $B^0 \rightarrow K^+\pi^-$ decays, Phys. Rev. Lett. 93 (2004) 131801. arXiv:hep-ex/0407057 doi:10.1103/PhysRevLett.93.131801

[100] Y. Chao, et al., Evidence for direct CP violation in $B^0 \rightarrow K^+\pi^-$ decays, Phys. Rev. Lett. 93 (2004) 191802. arXiv:hep-ex/0408100 doi:10.1103/PhysRevLett.93.191802

[101] R. Aaij, et al., First evidence of direct CP violation in charmless two-body decays of $B^0_s$ mesons, Phys. Rev. Lett. 108 (2012) 201601. arXiv:1202.6251 doi:10.1103/PhysRevLett.108.201601

[102] R. Aaij, et al., First observation of CP violation in the decays of $B^0_s$ mesons, Phys. Rev. Lett. 110 (2013) 221601. arXiv:1304.6173 doi:10.1103/PhysRevLett.110.221601

[103] R. Aaij, et al., Measurement of CP violation in the phase space of $B^\pm \rightarrow K^\pm\pi^+\pi^-$ and $B^\pm \rightarrow K^\pm K^+K^-$ decays, Phys. Rev. Lett. 111 (2013) 101801. arXiv:1306.1246 doi:10.1103/PhysRevLett.111.101801

[104] R. Aaij, et al., Measurement of CP violation in the phase space of $B^\pm \rightarrow K^+K^-\pi^\pm$ and $B^\pm \rightarrow \pi^+\pi^-\pi^\pm$ decays, Phys. Rev. Lett. 112 (2014) 011801. arXiv:1310.4740 doi:10.1103/PhysRevLett.112.011801

[105] R. Aaij, et al., Observation of CP violation in $B^\pm \rightarrow DK^\pm$ decays, Phys. Lett. B712 (2012) 203. arXiv:1203.3662 doi:10.1016/j.physletb.2012.04.080

[106] R. Aaij, et al., Observation of the suppressed ADS modes $B^\pm \rightarrow [\pi^\pm K^+\pi^-\pi^\pm]_D K^\pm$ and $B^\pm \rightarrow [\pi^\pm K^+\pi^-\pi^\pm]_D \pi^\pm$, Phys. Lett. B723 (2013) 44. arXiv:1303.4646 doi:10.1016/j.physletb.2013.05.009
R. Aaij, et al., A model-independent Dalitz plot analysis of $B^\pm \to DK^\pm$ with $D \to K^0_S h^+ h^-$ ($h = \pi, K$) decays and constraints on the CKM angle $\gamma$, Phys. Lett. B718 (2012) 43. arXiv:1209.5869, doi:10.1016/j.physletb.2012.10.020.

LHCb collaboration, Model-independent measurement of $CP$ violation parameters in $B^\pm \to (K^0_S h^+ h^-)_D K^\pm$ decays, LHCb-CONF-2013-004 (2013).

R. Aaij, et al., A study of $CP$ violation in $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ decays with $D \to K^0_SK^\pm\pi^\mp$ final states, Phys. Lett. B733 (2014) 36. arXiv:1402.2962, doi:10.1016/j.physletb.2014.03.051.

LHCb collaboration, A measurement of the CKM angle $\gamma$ from a combination of $B^\pm \to Dh^\pm$ analyses, Phys. Lett. B726 (2013) 151. arXiv:1305.2050, doi:10.1016/j.physletb.2013.08.020.

LHCb collaboration, A measurement of $\gamma$ from a combination of $B^\pm \to DK^\pm$ analyses including first results using $2 fb^{-1}$ of 2012 data, LHCb-CONF-2013-006 (2013).

R. Aaij, et al., Measurement of $CP$ observables in $B^0 \to DK^{*0}$ with $D \to K^+ K^-$, JHEP 03 (2013) 067. arXiv:1212.5205, doi:10.1007/JHEP03(2013)067.

R. Aaij, et al., Measurements of $CP$ violation in $B^0 \to DK^{*0}$ decays, submitted to Phys. Rev. D. arXiv:1407.8136.

LHCb collaboration, First observation of $B^- \to D^0 K^- \pi^+ \pi^-$ decays to $CP$ even final states, LHCb-CONF-2012-021 (2012).

R. Aaij, et al., Measurement of $CP$ asymmetry in $B^0 \to D_s^+ K^\pm$ decays, submitted to JHEP. arXiv:1407.6127.

R. Aaij, et al., Evidence for $CP$ violation in time-integrated $D^0 \to h^- h^+$ decay rates, Phys. Rev. Lett. 108 (2012) 111602. arXiv:1112.0938, doi:10.1103/PhysRevLett.108.111602.

R. Aaij et al., and A. Bharucha, et al., Implications of LHCb measurements and future prospects, Eur. Phys. J. C73 (2013) 2373. arXiv:1208.3355, doi:10.1140/epjc/s10052-013-2373-2.

LHCb collaboration, A search for time-integrated $CP$ violation in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays, LHCb-CONF-2013-003 (2013).

R. Aaij, et al., Search for direct $CP$ violation in $D^0 \to h^- h^+$ modes using semileptonic $B$ decays, Phys. Lett. B723 (2013) 33. arXiv:1303.2614, doi:10.1016/j.physletb.2013.04.061.
[120] R. Aaij, et al., Measurement of $CP$ asymmetry in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays, JHEP 07 (2014) 041. arXiv:1405.2797 doi:10.1007/JHEP07(2014)041.

[121] R. Aaij, et al., Search for $CP$ violation in $D^+ \to K^- K^+ \pi^+$ decays, Phys. Rev. D84 (2011) 112008. arXiv:1110.3970 doi:10.1103/PhysRevD.84.112008.

[122] R. Aaij, et al., Search for $CP$ violation in $D^+ \to K^- K^+ \phi$ and $D^+_s \to K^0_S \pi^+$ decays, JHEP 06 (2013) 112. arXiv:1303.4906 doi:10.1007/JHEP06(2013)112.

[123] R. Aaij, et al., Model-independent search for $CP$ violation in $D^0 \to K^- K^+ \pi^+ \pi^-$ and $D^0 \to \pi^- \pi^+ \pi^- \pi^+$ decays, Phys. Lett. B726 (2013) 623. arXiv:1308.3189 doi:10.1016/j.physletb.2013.09.011.

[124] R. Aaij, et al., Search for $CP$ violation in the decay $D^+_s \to K^0_S K^0_S \mu^+ \mu^-$ and $B_s \to K^0_S K^0_S \mu^+ \mu^-$ decays, submitted to JHEP. arXiv:1406.2624.

[125] V. M. Abazov, et al., Search for the rare decay $B_0 \to \mu^+ \mu^-$, Phys. Lett. B693 (2010) 539. arXiv:1006.3469 doi:10.1016/j.physletb.2010.09.024.

[126] T. Aaltonen, et al., Search for $B_0 \to \mu^+ \mu^-$ and $B_0 \to \mu^+ \mu^-$ decays with CDF II, Phys. Rev. Lett. 107 (2011) 191801. arXiv:1107.2304 doi:10.1103/PhysRevLett.107.191801,10.1103/PhysRevLett.107.239903.

[127] R. Aaij, et al., Search for the rare decay $B^0 \to \mu^+ \mu^-$ and $B^0 \to \mu^+ \mu^-$ decays, Phys. Lett. B699 (2011) 330. arXiv:1103.2465 doi:10.1016/j.physletb.2011.04.031.

[128] S. Chatrchyan, et al., Search for the decay $B^0 \to \mu^+ \mu^-$ with the ATLAS detector, Phys. Lett. B713 (2012) 387. arXiv:1204.0735 doi:10.1016/j.physletb.2012.06.013.
[133] R. Aaij, et al., First evidence for the decay $B^0_s \rightarrow \mu^+\mu^-$, Phys. Rev. Lett. 110 (2013) 021801. arXiv:1211.2674 doi:10.1103/PhysRevLett.110.021801.

[134] R. Aaij, et al., Measurement of the $B^0_s \rightarrow \mu^+\mu^-$ branching fraction and search for $B^0 \rightarrow \mu^+\mu^-$ decays at the LHCb experiment, Phys. Rev. Lett. 111 (2013) 101805. arXiv:1307.5024 doi:10.1103/PhysRevLett.111.101805.

[135] S. Chatrchyan, et al., Measurement of the $B^0_s \rightarrow \mu^+\mu^-$ branching fraction and search for $B^0 \rightarrow \mu^+\mu^-$ with the CMS experiment, Phys. Rev. Lett. 111 (2013) 101804. arXiv:1307.5025 doi:10.1103/PhysRevLett.111.101804.

[136] CMS and LHCb collaborations, Combination of results on the rare decays $B^0 \rightarrow \mu^+\mu^-$ from the CMS and LHCb experiments, CMS-PAS-BPH-13-007, LHCb-CONF-2013-012 (2013).

[137] R. Aaij, et al., Measurement of the isospin asymmetry in $B \rightarrow K^{(*)}\mu^+\mu^-$ decays, JHEP 07 (2012) 133. arXiv:1205.3422 doi:10.1007/JHEP07(2012)133.

[138] R. Aaij, et al., Differential branching fractions and isospin asymmetry of $B \rightarrow K^{(*)}\mu^+\mu^+$ decays, JHEP 06 (2014) 133. arXiv:1403.8044 doi:10.1007/JHEP06(2014)133.

[139] R. Aaij, et al., Measurement of the $CP$ asymmetry in $B^0 \rightarrow K^{(*)}\mu^+\mu^-$ decays, Phys. Rev. Lett. 110 (2013) 031801. arXiv:1210.4492 doi:10.1103/PhysRevLett.110.031801.

[140] R. Aaij, et al., Measurement of the $CP$ asymmetry in $B^+ \rightarrow K^+\mu^+\mu^-$ decays, Phys. Rev. Lett. 111 (2013) 151801. arXiv:1308.1340 doi:10.1103/PhysRevLett.111.151801.

[141] B. Aubert, et al., Measurements of branching fractions, rate asymmetries, and angular distributions in the rare decays $B \rightarrow K\ell^+\ell^-$ and $B \rightarrow K^*\ell^+\ell^-$, Phys. Rev. D73 (2006) 092001. arXiv:hep-ex/0604007 doi:10.1103/PhysRevD.73.092001.

[142] J.-T. Wei, et al., Measurement of the differential branching fraction and forward-backward asymmetry for $B \rightarrow K^{(*)}\ell^+\ell^-$, Phys. Rev. Lett. 103 (2009) 171801. arXiv:0904.0770 doi:10.1103/PhysRevLett.103.171801.

[143] T. Aaltonen, et al., Measurements of the angular distributions in the decays $B \rightarrow K^{(*)}\mu^+\mu^-$ at CDF, Phys. Rev. Lett. 108 (2012) 081807. arXiv:1108.0695 doi:10.1103/PhysRevLett.108.081807.
[144] R. Aaij, et al., Differential branching fraction and angular analysis of the decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$, JHEP 08 (2013) 131. arXiv:1304.6325 doi:10.1007/JHEP08(2013)131

[145] R. Aaij, et al., Measurement of form-factor-independent observables in the decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$, Phys. Rev. Lett. 111 (2013) 191801. arXiv:1308.1707 doi:10.1103/PhysRevLett.111.191801

[146] S. Chatrchyan, et al., Angular analysis and branching fraction measurement of the decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$, Phys. Lett. B727 (2013) 77. arXiv:1308.3409 doi:10.1016/j.physletb.2013.10.017

[147] ATLAS collaboration, Angular analysis of $B_d \rightarrow K^{*0} \mu^+ \mu^-$ with the ATLAS experiment, ATLAS-CONF-2013-038 (2013).

[148] R. Aaij, et al., Measurement of the differential branching fraction of the decay $\Lambda^b_0 \rightarrow \Lambda \mu^+ \mu^-$, Phys. Lett. B725 (2013) 25. arXiv:1306.2577 doi:10.1016/j.physletb.2013.06.060

[149] R. Aaij, et al., First observation of the decay $B^+ \rightarrow \pi^+ \mu^+ \mu^-$, JHEP 12 (2012) 125. arXiv:1210.2645 doi:10.1007/JHEP12(2012)125

[150] R. Aaij, et al., Measurement of the ratio of branching fractions $B(B^0 \rightarrow K^{*0}\gamma)/B(B_s^0 \rightarrow \phi\gamma)$, Phys. Rev. D85 (2012) 112013. arXiv:1202.6267 doi:10.1103/PhysRevD.85.112013

[151] R. Aaij, et al., Measurement of the ratio of branching fractions $B(B^0 \rightarrow K^{*0}\gamma)/B(B_s^0 \rightarrow \phi\gamma)$ and the direct $CP$ asymmetry in $B^0 \rightarrow K^{*0}\gamma$, Nucl. Phys. B867 (2013) 1. arXiv:1209.0313 doi:10.1016/j.nuclphysb.2012.09.013

[152] R. Aaij, et al., Measurement of the $B^0 \rightarrow K^{*0}e^+e^-$ branching fraction at low dilepton mass, JHEP 05 (2013) 159. arXiv:1304.3035 doi:10.1007/JHEP05(2013)159

[153] R. Aaij, et al., Observation of photon polarization in the $b \rightarrow s\gamma$ transition, Phys. Rev. Lett. 112 (2014) 161801. arXiv:1402.6852 doi:10.1103/PhysRevLett.112.161801