RECENT HOT RESULTS (INCLUDING SEMILEPTONIC B DECAYS)

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The LHCb experiment has collected large samples of heavy flavoured hadrons during Run 1 of the LHC. The conjectured tetraquark state $X(5568)$, observed by D0 in the $B_s^0\pi^\pm$ final state, is not confirmed in the LHCb data. Other interesting results have been published using semileptonic B decays. Amongst which are a novel measurement of $|V_{ub}|$, and the most precise measurements of the $B^0-\overline{B}^0$ mixing frequency and of CP violation in $B^0-\overline{B}^0$ and $B_s^0-\overline{B}_s^0$ mixing. A new measurement of CPT violation in $B^0-\overline{B}^0$ and $B_s^0-\overline{B}_s^0$ mixing (using hadronic B decays) is also presented.

1 Introduction

The LHCb detector is a single-arm forward spectrometer designed for the study of heavy flavour hadrons. The detector is described in detail elsewhere[1,2]. The data collected during Run 1 of the LHC corresponds to an integrated luminosity of $3\,\text{fb}^{-1}$ at pp centre-of-mass energies of 7 and 8 TeV. Most analyses that have been published so far use the full Run 1 data set, or are in the process of updating to the full data set. Many interesting results have been been published by the LHCb collaboration on, amongst others, CP violation in decays of b and c hadrons, studies of rare decays of b and c hadrons, spectroscopy of excited states, the production of exotic hadrons, and W and Z production. Three new results are highlighted in these proceedings: a search for new states in the $B_s^0\pi^\pm$ spectrum[3], the most precise measurement of the $B^0-\overline{B}^0$ oscillation frequency[4], and a measurement of CPT violation in $B^0-\overline{B}^0$ and $B_s^0-\overline{B}_s^0$ mixing[5]. Furthermore, an overview of LHCb's results in semileptonic B decays is given.

2 Search for $X(5568)$ in the $B_s^0\pi^\pm$ spectrum

On February 25, 2016, the D0 collaboration announced the observation of a new state in the $B_s^0\pi^\mp$ invariant mass spectrum[6] (charge conjugate modes are implied throughout these proceedings). This state, which is called $X(5568)$ hereafter, received a considerable amount of attention in literature as it would be the first tetraquark consisting of four different quark flavours. The experimental observation of exotic hadrons has boosted the interest in this field[7]. The tetraquark

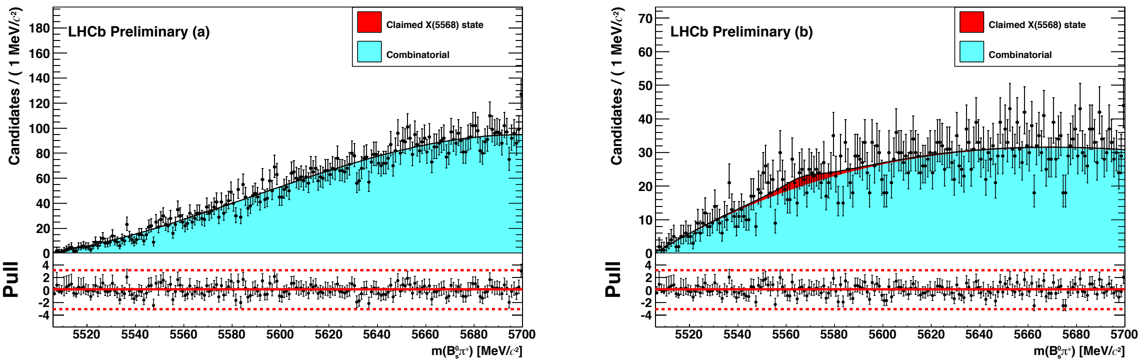

Figure 1 – Distribution of the $B_s^0\pi^\pm$ invariant mass where the B_s^0 candidate has (left) $p_{\rm T} > 5\,{\rm GeV}/c$ and (right) $p_{\rm T} > 10\,{\rm GeV}/c$. The pull distributions, underneath the figures, show good agreement between the fit functions and the data.

candidate states $X(3872)$, $Z(4430)$ and $Z(3900)$ are now well established as they have been confirmed by two or more experiments. Moreover, the pentaquark $P_c(4450)$ state has only been observed by LHCb, but with very high significance[8]. The $X(5568)$ state must consist of four different flavours (b, s, u, d) and can provide new insights in the binding nature of these exotic hadrons.

The $B_s^0\pi^\mp$ spectrum at D0 is obtained from a sample of 5.5 thousand $B_s^0 \to J/\psi\,\phi$ decays, combined with charged pions. The significance of the observed peak in is found to be 5.1 standard deviations. The measured mass and decay width are $m = 5567.8 \pm 2.9\,({\rm stat})^{+0.9}_{-1.9}\,({\rm syst})\,{\rm MeV}/c^2$ and $\Gamma = 21.9 \pm 6.4\,({\rm stat})^{+5.0}_{-2.5}\,({\rm syst})\,{\rm MeV}/c^2$. A relatively large fraction of the B_s^0 mesons is found to originate from this state,

$$\rho_X^{\rm D0} = \frac{\sigma(pp \to X(5568) + \text{anything}) \times \mathcal{B}(X(5568) \to B_s^0\pi)}{\sigma(pp \to B_s^0 + \text{anything})} = (8.6 \pm 1.9\,({\rm stat})1.4\,({\rm syst}))\%\ .$$

A new search, with preliminary results[3], for the $X(5568)$ state has been carried out using the full LHCb data sample of Run 1. To reduce background, B_s^0 mesons are required to have transverse momentum, $p_{\rm T}$, larger than $5\,{\rm GeV}/c$. The final result is also given for $p_{\rm T} > 10\,{\rm GeV}/c$, corresponding to the D0 selection. The data sample consists of about 50 thousand $B_s^0 \to J/\psi\,(\mu^+\mu^-)\phi(K^+K^-)$ candidates and 70 thousand $B_s^0 \to D_s^-(K^+K^-\pi^-)\pi^+$ candidates, both with low background contamination. This B_s^0 sample is approximately 20 times larger compared to the one from D0.

When combining the B_s^0 mesons with charged pions, no requirement is made on the opening angle between the two particles. This is done to avoid any broad peaking structures in the $B_s^0\pi^\pm$ spectrum that a cut on this variable introduces. Figure 1 shows the $B_s^0\pi^\pm$ mass spectra for B_s^0 candidates with $p_{\rm T} > 5\,{\rm GeV}/c$ and $p_{\rm T} > 10\,{\rm GeV}/c$. The background is modelled with a polynomial function, while the signal shape is modelled with an S-wave Breit-Wigner function. The mass and width are taken from the D0 result. No significant signal is observed and therefore upper limits are given at 90% and 95% confidence level (CL) on the relative production rate of the $X(5568)$ state in the acceptance of the LHCb detector,

$$\begin{aligned} \rho_X^{\rm LHCb}(B_s^0\ p_{\rm T} > 5\,{\rm GeV}/c) &< 0.009(0.010) \quad @\ 90(95)\%\ {\rm CL}\ , \\ \rho_X^{\rm LHCb}(B_s^0\ p_{\rm T} > 10\,{\rm GeV}/c) &< 0.016(0.018) \quad @\ 90(95)\%\ {\rm CL}\ . \end{aligned}$$

3 Semileptonic B decays

At the LHC, b hadrons are produced copiously. The largest b-hadron samples are coming from semileptonic decays, due to their large branching fraction of around 10%. In semileptonic B

decays, a hadron is produced together with a lepton and neutrino. From the leptons, the muon provides a powerful signal because of the high trigger and reconstruction efficiency at LHCb. There are millions of semileptonic B decays recorded in the current data set, which opens up the opportunity for precision measurements. On the other hand, the partial reconstruction due to the missing neutrino makes these studies experimentally challenging.

In these proceedings, the measurement of the $b \to u$ coupling strength, $|V_{ub}|$, the new and precise determination of the $B^0-\overline{B}^0$ oscillation frequency, and the measurements of *CP* violation in the $B^0 - \overline{B}^0$ and $B^0_s - \overline{B}^0_s$ mixing processes are highlighted.

3.1 Measurement of $|V_{ub}|/|V_{cb}|$

In the SM, the mixing of quarks due to the weak interaction is described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Due to unitarity, this 3×3 complex matrix has three real parameters and one complex phase. The latter is responsible for all *CP* violation in the SM. The unitarity of this matrix can be tested by measuring all sides and angles of the unitarity triangle[9]. A precise test can be made by comparing the well-measured angle β obtained from decays like $B^0 \to J/\psi K^0_{\mathrm{S}}$, with the opposite side, given by the ratio $|V_{ud}V^*_{ub}/(V_{cd}V^*_{cb})|$. The smallest CKM element and the one with the largest experimental uncertainty in this ratio is V_{ub}. The value of $|V_{ub}|$ is obtained from semileptonic B decays. There is a long standing disagreement between the two methods to determine this quantity. One method uses inclusive decays by measuring the total semileptonic decay rate. Experimentally, the lepton and its energy spectrum are reconstructed in a region of phase space where background from $b \to c$ is relatively small. The average result[9] is found to be $|V_{ub}| = (4.41 \pm 0.22) \times 10^{-3}$. The other method uses exclusive decays of the type $B \to \pi\ell\nu$, where the form factor is determined from lattice calculations. Using the most recent lattice calculations[10], the average is found to be $|V_{ub}| = (3.72 \pm 0.16) \times 10^{-3}$. The disagreement between the inclusive and exclusive determinations is 2.5 standard deviations. Until this is resolved, this disagreement limits a precise test of the CKM unitarity.

A new measurement of $|V_{ub}|$ from LHCb sheds some light on this problem[11]. This measurement makes use of the exclusive decay $\Lambda^0_b \to p\mu\nu$, instead of the traditional decay modes as, e.g., $B \to \pi\ell\nu$. The traditional modes face a much larges background from random pions that are produced at the LHC. The presence of the (anti-)proton in $\Lambda^0_b \to p\mu\nu$ leads to a much reduced combinatorial background. Additionally, a rather large fraction, about 20%, of the b quarks hadronizes into a Λ^0_b baryon, which makes the use of $\Lambda^0_b \to p\mu\nu$ decays a natural first step to measure $|V_{ub}|$ at LHCb. The $\Lambda^0_b \to p$ form factors have recently been calculated on the lattice[12], with an accuracy of about 5%. The invariant mass of the Λ^0_b candidates cannot be fully reconstructed due to the missing neutrino. The invariant mass of the visible $p\mu$ system is corrected using the flight direction of the Λ^0_b, which is reconstructed from the origin vertex and decay vertex. Events which have a large uncertainty on this corrected mass quantity are removed in order to have a better separation between signal and background. The main background comes from $\Lambda^0_b \to \Lambda^+_c\mu\nu$ decays. At the same time this background is also used as a normalization channel, by reconstructing the Λ^+_c in the $pK^-\pi^+$ final state. The branching fraction of the Λ^+_c decay is measured[13] to an precision of 5%. Due to the normalisation, the actual measurement is a ratio of CKM elements, which is found to be[11]

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004\,(\mathrm{stat}) \pm 0.004\,(\mathrm{syst}) \ .$$

This result can be compared with indirect measurements of this side of the unitarity triangle, as obtained using the measurements[14] of $\sin(2\beta)$ and the averages[9] of $|V_{ud}|$ and $|V_{cd}|$. The indirect measurements give $|V_{ub}|/|V_{cb}| = 0.0861 \pm 0.0025$, which agrees well with the measurement above. These numbers show a preference for the exclusive determination of $|V_{ub}|$.

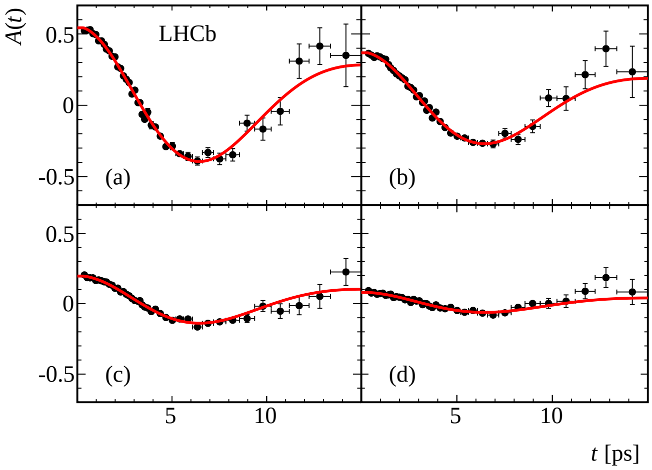

Figure 2 – Mixing asymmetry measured in the $B^0 \to D^-\mu^+\nu_\mu X$ decay for 2012 data. The average mistag probability increases when going from (a) to (d).

3.2 Measurement of Δm_d (new)

When B^0 mesons evolve in time, they mix between the B^0 and $\overline{B}^0$ states. The oscillation frequency, Δm_d, of the mixing process can be measured when the flavour (B^0 or $\overline{B}^0$) is measured both at production and at decay. The world average[9] is $\Delta m_d = (510 \pm 3)\,\mathrm{ns}^{-1}$. The mixing asymmetry as function of decay time is determined from the numbers of B^0 mesons that changed flavour (mixed) or not (unmixed) as

$$A(t) = \frac{N^{\mathrm{unmix}}(t) - N^{\mathrm{mix}}(t)}{N^{\mathrm{unmix}}(t) + N^{\mathrm{mix}}(t)} = \cos(\Delta m_d t)\ . \tag{1}$$

The flavour of the B^0 meson at production is determined using flavour tagging methods[15]. Wrong flavour tags dilute the amplitude in Eq. 1 by a factor $1 - 2\omega$, where ω is the probability of a wrong tag.

LHCb has measured Δm_d already with a time-dependent analysis of hadronic $B^0 \to D^-\pi^+$ decays[16]. A new measurement was recently published using semileptonic $B^0 \to D^{(*)-}\mu^+\nu_\mu X$ decays, where X is any additional particle in the decay that is not reconstructed[4]. This supersedes a preliminary result that used the same decay modes[17]. The semileptonic decay modes give larger event yields, resulting in reduced statistical uncertainty. On the other hand, due to the missing particles in the reconstructed decay, the momentum of the B^0 meson is not well known, affecting the reconstruction of the B^0 decay time. This problem is overcome by correcting the time with a multiplicative k-factor, based on the visible $D^{(*)-}\mu^+$ mass. The k-factor is calibrated using simulated decays. Backgrounds from B^+ decays are suppressed by a boosted decision tree exploiting kinematic and isolation criteria. Figure 2 displays the mixing asymmetry for one of the decay modes using the data taken in 2012. The B^0 oscillation frequency is measured to be

$$\Delta m_d = (505.0 \pm 2.1\,(\mathrm{stat}) \pm 1.0\,(\mathrm{syst}))\,\mathrm{ns}^{-1}\ .$$

This is the most precise single measurement of this quantity, consistent with the world average. Recent improvements in lattice calculations[18] allow to place stronger constraints on the CKM unitarity triangle, although the theoretical uncertainties are still dominating.

3.3 Semileptonic asymmetries

In the mixing process of neutral B mesons, the probabilities for the $B \to \overline{B}$ and $\overline{B} \to B$ processes can be different. This effect is called *CP* violation in mixing, and has, so far, only been observed in the neutral kaon system ($\varepsilon_K \approx 0.2\%$). In the neutral B systems, B^0 and B^0_s, it is best measured with semileptonic (sl) decays due to the large branching fraction and because their final states determine the flavour of B at decay. The semileptonic asymmetry is defined in terms of numbers of B and $\overline{B}$ decays to final states f and $\bar{f}$, as

$$a_{\rm sl} = \frac{N(\overline{B} \to f) - N(B \to \bar{f})}{N(\overline{B} \to f) + N(B \to \bar{f})} \; . \tag{2}$$

Compared to the experimental precisions, the SM predictions for B systems[19] are effectively zero with $a^d_{\rm sl} = (-4.7 \pm 0.6) \times 10^{-4}$ in the B^0 system and $a^s_{\rm sl} = (2.22 \pm 0.27) \times 10^{-5}$ in the B^0_s system.

Due to the low efficiency of the flavour tagging in the hadronic pp environment of the LHC, it is more favourable to consider the untagged asymmetry, which is, as function of B decay time, given by

$$A(t) = \frac{N(f,t) - N(\bar{f},t)}{N(f,t) - N(\bar{f},t)} = A_{\rm D} + \frac{a_{\rm sl}}{2} - \left(\frac{a_{\rm sl}}{2} + A_{\rm P}\right) \cos(\Delta m\, t) \; . \tag{3}$$

The observed asymmetry is affected by differences in detection efficiency between f and $\bar{f}$ states, $A_{\rm D}$. The detection asymmetry is measured by means of large calibration samples, mainly consisting of prompt charm decays. The observed asymmetry is further affected by (possible) different production cross sections for B and $\overline{B}$ states, $A_{\rm P}$. Different strategies are applied for the analyses in the B^0 and B^0_s systems. For the measurement of $a^d_{\rm sl}$, a time-dependent analysis is performed such that both $A_{\rm P}$ and $a^d_{\rm sl}$ can be measured simultaneously. For the measurement of $a^s_{\rm sl}$, a time-integrated measurement is made as the cosine term in Eq. 3 is heavily diluted by the fast $B^0_s - \overline{B}^0_s$ oscillations. The results of the two measurements[20,21] are found to be

$$\begin{aligned} a^d_{\rm sl} =& (-0.02 \pm 0.19\,({\rm stat}) \pm 0.30\,({\rm syst}))\% \; , \\ a^s_{\rm sl} =& (-0.06 \pm 0.50\,({\rm stat}) \pm 0.36\,({\rm syst}))\% \; . \end{aligned}$$

The systematic uncertainties are dominated by detection asymmetries, which are of statistical nature, and therefore reduce with more data. The measurement of $a^s_{\rm sl}$ uses only part of the Run 1 data set. An update of this number is expected to reduce the total uncertainty by roughly a factor two due to the larger data set and improved selection.

4 Search for *CPT* and Lorentz violations

In addition to *CP* violation in the mixing of neutral B mesons, it is also possible to search for *CPT* violation in the mixing process, as published recently by LHCb[5]. The mixing between B and $\overline{B}$ states creates an interferometric system that enhances the sensitivity to *CPT* violation enormously. Conservation of *CPT* symmetry implies equal mass and lifetime of B and $\overline{B}$ mesons. The observable in the B mixing process is given by

$$z = \frac{\delta m - i\delta\Gamma/2}{\Delta m + i\Delta\Gamma/2} \; , \tag{4}$$

where δm and $\delta\Gamma$ are the mass and decay width differences between the particle (B) and antiparticle ($\overline{B}$) states. The high sensitivity to z comes through the small values of the eigenvalue differences, Δm and $\Delta\Gamma$, in the denominator. In any local, interacting quantum field theory, *CPT* symmetry is conserved and deeply connected with Lorentz invariance[22]. The Standard Model Extension (SME) is an effective field theory, where *CPT*- and Lorentz-violating terms are added to the SM Lagrangian[23,24]. This framework opens up an experimental opportunity as the parameters (couplings) in these terms can be measured. The z observable becomes[25,26]

$$z = \frac{\beta^\mu \Delta a_\mu}{\Delta m + i\Delta\Gamma/2} \; , \tag{5}$$

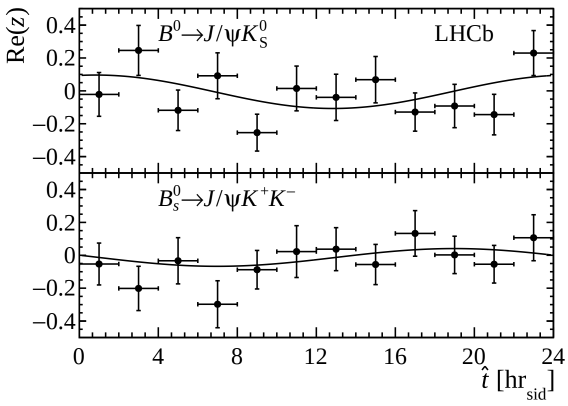

Figure 3 – Values of $\mathcal{R}e(z)$ obtained from fits in bins of sidereal phase for (top) the B^0 sample and (bottom) the B^0_s sample. The solid line shows the variation of $\mathcal{R}e(z)$ from the Δa_μ fits, using the average B momentum.

Table 1: Results from unbinned likelihood fits to the observables (decay time, decay angles) in the decay channels $B^0 \to J/\psi K^0_S$ and $B^0_s \to J/\psi K^+K^-$. The results are given in terms of the SME parameters (Δa_μ), and for the B^0_s system also independent of any assumption of Lorentz violation (the complex z parameter).

B^0 system	B^0_s system
$\Delta a_\parallel = (-0.10 \pm 0.82 \pm 0.54) \times 10^{-15}$ GeV	$\Delta a_\parallel = (-0.89 \pm 1.41 \pm 0.36) \times 10^{-14}$ GeV
$\Delta a_\perp = (-0.20 \pm 0.22 \pm 0.04) \times 10^{-13}$ GeV	$\Delta a_\perp = (-0.47 \pm 0.39 \pm 0.08) \times 10^{-12}$ GeV
$\Delta a_X = (+1.97 \pm 1.30 \pm 0.29) \times 10^{-15}$ GeV	$\Delta a_X = (+1.01 \pm 2.08 \pm 0.71) \times 10^{-14}$ GeV
$\Delta a_Y = (+0.44 \pm 1.26 \pm 0.29) \times 10^{-15}$ GeV	$\Delta a_Y = (-3.83 \pm 2.09 \pm 0.71) \times 10^{-14}$ GeV
	$\mathcal{R}e(z) = -0.022 \pm 0.033 \pm 0.003$
	$\mathcal{I}m(z) = 0.004 \pm 0.011 \pm 0.002$

where $\beta^\mu = (\gamma, \gamma\vec{\beta})$ is the four velocity of the B meson and Δa_μ is a real four-vector vacuum expectation value that describes the coupling with the B mesons. Since Δa_μ must be real[27], and Δm is the dominant contribution in the denominator, it follows that z is mostly real. Due to the dependence on β^μ, z now depends on the on the momentum and on the direction of the B meson in an absolute coordinate frame, such as the Sun-centred frame[27]. In this frame, Eq. 5 can be written as

$$\mathcal{R}e(z) = \frac{\gamma}{\Delta m}\Big[\Delta a_0 + \cos(\chi)\Delta a_Z + \sin(\chi)\big[\Delta a_Y \sin(\Omega\hat{t}) + \Delta a_X \cos(\Omega\hat{t})\big]\Big] , \qquad (6)$$

where $\hat{t}$ is the sidereal phase, Ω the sidereal frequency, and $|\vec{\beta}| \approx 1$. Due to the high boost of the B mesons at LHCb, $\langle\gamma\beta\rangle \approx 20$, the parameter $\mathcal{R}e(z)$ is very sensitive to Δa_μ. The angle χ is the angle of the B mesons with the Earth's rotational axis, given by $\cos\chi = -0.38$. Since the B mesons fly almost parallel to the beam axis, LHCb is mostly sensitive to the linear combination $\Delta a_\parallel \equiv \Delta a_0 - 0.38\Delta a_Z$, and less to the orthogonal combination $\Delta a_\perp \equiv 0.38\Delta a_0 + \Delta a_Z$.

The value of $\mathcal{R}e(z)$ can be best measured[28] with the decay channels $B^0 \to J/\psi K^0_S$ and $B^0_s \to J/\psi K^+K^-$, rather than with semileptonic decay modes. In Fig. 3, $\mathcal{R}e(z)$ is shown as function of the sidereal phase[5]. The numerical results[5] from unbinned likelihood fits to the data samples are shown in Table 1. No significant sidereal variation and no violation of *CPT* symmetry are observed. As a cross check, a search for periodic variations of $\mathcal{R}e(z)$ is performed in a wide range of frequencies around the sidereal frequency. Again no periodic signal is observed. The results on the SME parameters given in Table 1 constitute one to three orders of magnitude improvement in precision compared to the previous best results[29,30].

5 Summary

In summary, LHCb has found no confirmation[3] of a new exotic resonance, $X(5568)$, in the $B_s^0\pi^\pm$ spectrum, as recently claimed by D0[6]. Using semileptonic B decays, LHCb has published interesting results, amongst others, a new measurement on B^0 oscillations[4], on CP violation in B mixing[20,21], and on $|V_{ub}/V_{cb}|$ [11]. Finally, strongly improved limits on CPT violation and Lorentz symmetry breaking in B mixing have been published as well[5]. In the current Run 2, an integrated luminosity of $0.32\,\text{fb}^{-1}$ has been recorded in 2015. In this run, heavy flavour yields are higher due to the larger cross sections at the new centre-of-mass energy of 13 TeV. Updated results and new analyses are expected towards the end of 2016 when a total of $2\,\text{fb}^{-1}$ is expected to be added, and thereby almost doubling the current heavy flavour yields.

Acknowledgments

This work is supported by the Netherlands Organisation for Scientific Research (NWO Vidi grant 680-47-523) and the Foundation for Fundamental Research on Matter (FOM).

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