Overview of recent LHCb results

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Abstract. A selection of the most recent and relevant measurements by the LHC*b* experiment is presented. It includes the determination of the CKM angle γ, obtained from a combination of a number of measurements of B meson decays, the measurement of the $D^0 - \overline{D}^0$ mixing parameters and the results of several tests of the lepton-flavour universality of the electroweak couplings.

1 Introduction

The LHC*b* detector is a forward spectrometer designed for precision studies of b- and c-hadron decays [1]. Of particular relevance for the measurements discussed in this proceeding is its excellent precision in reconstructing vertices associated to primary pp interactions and to the decays of long-lived particles such as B and D mesons and τ leptons. The momenta of charged particles are reconstructed with high precision by a system of tracking detectors. Different types of charged hadrons, such as protons, kaons and pions, are distinguished using information from two ring-imaging Cherenkov detectors, while electromagnetic particles are identified by means of a calorimeter system and a muon detector.

Unless specified, the measurements presented in the following rely on a data sample of pp collisions at centre-of-mass energies of 7 and 8 TeV collected by the LHC*b* detector during Run1 and corresponding to an integrated luminosity of 3 fb^{-1}.

2 Measurement of the CKM angle γ

The angle $\gamma \equiv \arg(-(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*))$ of the CKM unitarity triangle can be measured in tree level b-hadron decays exploiting the interference of $b \to c$ and $b \to u$ transitions. Among the different angles, γ is the least well measured: the current world average value is $\gamma = (65.3^{+1.0}_{-2.5})^\circ$ and $(72.1^{+5.4}_{-5.8})^\circ$ based on indirect and direct measurements, respectively [2].

The measurement of γ is considered as a Standard Model (SM) benchmark: from a theoretical point of view it is very clean as it is dominated by tree level processes, where higher contributions from loops are very suppressed ($O(10^{-4})$). Unfortunately, the experimental determination of γ is quite challenging since the visible branching fractions of the concerned B decays and the typical size of these interferences are quite small ($\mathcal{B}_{\text{vis}} \sim O(10^{-7})$, $\mathcal{I} \sim O(10\%)$). The best precision on the angle γ results from a combination of all the possible measurements that exploit different analysis methods (namely GLW [3], ADS [4], GGSZ [5], from the name of the authors that proposed them, and Dalitz and time-dependent, TD) and external inputs, such as amplitude ratios and strong phases of the involved particle decays.

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Table 1. Measurements contributing to the latest determination of the angle γ by the LHC*b* collaboration. New and updated results with respect to the previous combination are marked with the (*) and (†) symbols, respectively. References to each measurement can be found in Ref. [6].

B decay	D decay	Method	Dataset
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	Run1&Run2 (†)
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	Run1
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	Run1
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	Run1
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	Run1
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	Run2 (*)
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	Run1
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	Run1&Run2 (†)
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	Run1&Run2
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	Run1&Run2 (*)
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	Run1
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	Run1
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	Run1
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	Run1
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD	Run1 (†)
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^+\pi^-\pi^+$	TD	Run1 (*)

The LHC*b* collaboration performed several measurements of different 2 and 3 or 4-body B or D decays corresponding to different analysis methods listed in Table 2 and a new, improved combination of the results, using a frequentist approach, was recently released [6]. Figure 2 shows the result of the new combination, where the partial contributions from the measurements using B^+, B^0 and B^0_s are also shown individually. The best value corresponds to $\gamma = (74.0^{+5.0}_{-5.8})^\circ$ and represents the most precise determination of γ from a single experiment.

Improving further the precision of γ with additional and more accurate measurements is particularly important to possibly reveal new physics phenomena beyond the SM that could affect its value at a level just below current experimental accuracy. For instance, a precision of 4° is expected for the combination of γ measurements based on the full Run1 and Run2 statistics.

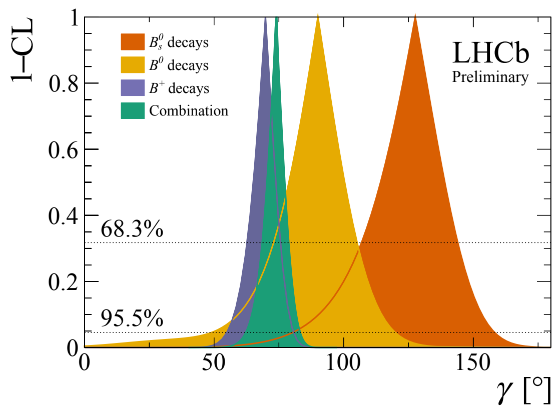

Figure 1. Confidence level plots for combinations of the CKM angle γ measurements split by the initial B meson flavour. Figure is taken from Ref. [6].

3 Measurement of the $D^0 - \overline{D^0}$ mixing parameters

The study of D mesons offers a unique opportunity to access *up*-type quarks in neutral current processes. It offers complementary constraints on possible NP contributions to those arising from the measurements of corresponding processes of *down*-type quarks (B or K mesons). In this context a precise measurement of $D^0 - \overline{D^0}$ mixing and searches for evidences of CP-violating processes play a key role. The $D^0 - \overline{D^0}$ mixing was established by previous measurements [7–10]. The mixing rate is consistent with, but at the upper end of the range of SM expectations [11] and constrains many NP models [12]. At present, no evidence of CP violation, either direct, indirect or in the mixing, has been found.

The parameters describing the $D^0 - \overline{D^0}$ mixing, x' and y',[1] can be determined from a fit of the decay-time-dependent ratio of D^0 decay rates to a wrong sign (WS) sample of $K^+\pi^-$ and to a right sign (RS) sample of $K^-\pi^+$. In particular, the WS decays receive both the contributions of the double Cabibbo-suppressed decay, $D^0 \to K^+\pi^-$, and of the Cabibbo-favored one following the $D^0 - \overline{D^0}$ oscillation, $D^0 \to \overline{D^0} \to K^+\pi^-$. The ratio of yields of WS to RS signal events expressed as a function of the D^0 decay time depends on the parameters x' and y'. Large statistics samples of D^0 mesons from prompt $D^*(2010)^+ \to D^0\pi^+$ decays [2] collected by LHCb during Run1 and part of Run2, corresponding to an integrated luminosity of 5 fb^{-1}, were recently analysed [13]. Depending on the charge of the pion, separate ratios for the D^0 and $\overline{D^0}$ decay rates were determined, their difference being sensitive to possible CP violation effects in the mixing or in the decay. The resulting distributions are consistent with the hypothesis of CP conservation setting the most stringent bounds on the parameters that describe it. Under the assumption of CP conservation, the best determination of the mixing parameters from a single measurement $x'^2 = (3.9 \pm 2.7) \times 10^{-5}$, $y' = (5.28 \pm 0.52) \times 10^{-3}$, was obtained.

4 Tests of lepton flavour universality

In the SM the gauge boson couplings to the different charged lepton species are assumed to be the same. Differences among the semileptonic decays to electron, muon or tau leptons can only arise due to their different masses. Several tests on this fundamental property have been performed by different experiments using charged- and neutral-current processes and have revealed hints of deviations from the expectations of the SM that could potentially be due to NP. In the following, the LHCb results concerning tests of LFU in b-hadron decays are presented.

4.1 Charged current transitions

Semileptonic decays of b-hadrons are an optimal laboratory to test LFU given their relatively large branching fractions and due to the availability of precise SM predictions. Such tests are performed by comparing branching fractions of semileptonic b-hadron (H_b) decays to a common c-hadron (H_c) with different lepton species in the final state:

$$\mathcal{R}(H_c) \equiv \frac{\mathcal{B}(H_b \to H_c \tau \nu_\tau)}{\mathcal{B}(H_b \to H_c \ell \nu_\ell)}, \quad (1)$$

where ℓ represents a light lepton, which is a muon in the case of the LHCb measurements.

[1] $x \equiv \Delta m/\Gamma$, $y \equiv \Delta\Gamma/2\Gamma$, $x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$, where δ is the strong phase difference between CS and CF amplitudes. For further details see Ref. [13].

[2] Charge conjugated states and decays are also implied.

The LHC*b* collaboration performed two independent measurements of $\mathcal{R}(D^{*+})$, using either the muonic or the three-prong τ decays, and a measurement of $\mathcal{R}(J/\psi)$, exploiting the non negligible production of B_c^+ mesons at the LHC.

In the first measurement of $\mathcal{R}(D^{*+})$ [14], the tau leptons are reconstructed in the muonic decay channel $\tau^- \to \mu^- \overline{\nu_\mu} \nu_\tau$, so that both the decays involved in the ratio are reconstructed in the same visible final state given by a muon and a charged $D^*(2010)^+$ meson decaying to $D^0(\to K^-\pi^+)\pi_s^+$. The yields of the signal and normalisation channels are extracted from a simultaneous maximum-likelihood fit to three kinematic observables that show a discrimination power among the different contributions. These are: the muon energy in the B rest frame, E_μ^*, the missing mass squared, $m_{miss}^2 = (p_B - p_{D^*} - p_\mu)^2$, and the momentum transferred to the lepton pairs, $q^2 = (p_B - p_{D^*})^2$, where p_i stands for the four-momenta of the i-th particle. Since the kinematics of the B decay is not well defined both for the signal and the normalisation channels, such quantities are approximated. In particular, the B momentum is computed using the B direction and the visible momentum $p_{\text{vis}} = p_{D^*} + p_\mu$. In the fit, the distributions of signal, normalisation and background channels are derived from simulation and control data samples. The resulting ratio is $\mathcal{R}(D^{*+}) = 0.336 \pm 0.027(\text{stat.}) \pm 0.030(\text{syst.})$, in agreement with previous results by BaBar [16] and Belle [17] collaborations but 2.1σ above the SM prediction, $\mathcal{R}^{\text{SM}}(D^*) = 0.252 \pm 0.003$ [18].

In the second measurement of $\mathcal{R}(D^{*+})$ [15], the tau lepton is reconstructed in the three-prong decay channel $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$. The $\overline{B^0} \to D^{*+}\pi^+\pi^-\pi^-$ decay channel is chosen as normalisation, being its topology similar to the one of the signal. As a consequence the determination of $\mathcal{R}(D^{*+})$ relies on external branching fraction measurements of the $\overline{B^0} \to D^{*+}\pi^+\pi^-\pi^-$ and $\overline{B^0} \to D^{*+}\mu^-\overline{\nu_\mu}$ decays. For the signal selection the three-pion vertex from the τ lepton candidate is required to be downstream with respect to the B-candidate decay vertex. In this way the large background from $B \to D^*3\pi$ is highly suppressed. Furthermore a Boosted Decision Tree (BDT) is optimised to discriminate between the signal and the $B \to D^*D_{(s)}$ decays which have similar topologies. Similarly to the previous measurement, the yield of the signal is determined from a multidimensional fit to three observables using templates to model the contributions of the signal and of different backgrounds. The templates are taken from simulations and validated with control samples whenever possible. In this case the observables are the τ lepton decay time, the four-momentum transferred to the lepton pairs, q^2, and the output of the BDT mentioned above. The normalisation channel is reconstructed exclusively and its yield extracted from a fit to the invariant mass distribution. The result is $\mathcal{R}(D^{*+}) = 0.291 \pm 0.019(\text{stat.}) \pm 0.026(\text{syst.}) \pm 0.013(\mathcal{B})$, which is in agreement with previous experimental results and compatible with the SM at 1.1σ level.

An overview of the current experimental situation for $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ ratios is represented in Fig. 2, where the measurements from different experiments are shown, combined and compared to the SM predictions. Both $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ combinations exceed the SM expectations. The global compatibility with the SM is of 3.8σ, of which 3.0σ is due to the $\mathcal{R}(D^*)$ measurement [19]. Though still not statistically significative to claim LFU violation, a common pattern of anomalies seems to be present in all these measurements. More precise and additional measurements are needed to clarify the picture.

For this purpose LHC*b* performed for the first time the measurement of the $\mathcal{R}(J/\psi)$ ratio [20], exploiting the non negligible production of B_c^+ mesons at the LHC and the high efficiency of LHC*b* in triggering events with a J/ψ meson decaying to $\mu^+\mu^-$ pairs. The analysis follows the same strategy of the first $\mathcal{R}(D^{*+})$ measurement described above. After the event selection, the yields of signal and normalisation are determined from the same final state $J/\psi(\to \mu^+\mu^-)\mu^+$ by means of a multidimensional fit to the distributions of the B_c^+ decay time, the missing mass and of a variable Z that defines different ranges

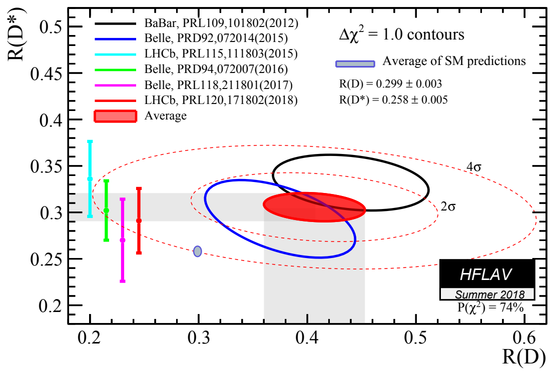

Figure 2. Measurements of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ ratios from different experiments, average values and SM predictions. The plot corresponds to the summer 2018 update of Ref. [19] available on the HFLAV webpage.

of dilepton momentum transfer, q^2, and muon energy, E^*_μ. For these semileptonic decays the form factors are not well determined, so they are extracted from data and used to determine both the signal and the normalisation templates. The resulting value of the ratio is $\mathcal{R}(J/\psi) = 0.71 \pm 0.17(\text{stat.}) \pm 0.18(\text{syst.})$ which is above but compatible at 2σ level with the range of predicted SM values, $\mathcal{R}^{\text{SM}}(J/\psi) = 0.25 - 0.28$ [21].

More analyses are ongoing within the LHC*b* collaboration aiming to extend the tests of LFU to other *b*-hadron decays, such as Λ_b and B^0_s mesons.

4.2 Neutral current transitions

Tests of LFU can be performed by exploiting $b \to s\ell^+\ell^-$ neutral current transitions, which are mediated by loops in the SM and are highly suppressed. By measuring the ratio of branching fractions of $B \to H_s\mu^+\mu^-$ and $B \to H_s e^+e^-$ decays, where H_s represents a strange hadron,

$$\mathcal{R}(H_s) = \frac{\mathcal{B}(B \to H_s\mu^+\mu^-)}{\mathcal{B}(B \to H_s e^+e^-)}, \tag{2}$$

the universality of the couplings to the second and first generation of leptons can be tested. The ratio is predicted with a very high precision in the SM and expected to be close to unity.

The LHC*b* collaboration performed the measurement of the $\mathcal{R}(K^{*0})$ [22] and $\mathcal{R}(K^+)$ [23] ratios using exclusively reconstructed decays of B^0 and B^+ mesons. To minimise the experimental uncertainties, both the analyses measured the double ratio

$$\mathcal{R}(H_s) = \frac{\mathcal{B}(B \to H_s\mu^+\mu^-)}{\mathcal{B}(B \to H_s e^+e^-)} \times \frac{\mathcal{B}(B \to H_s J/\psi(\to e^+e^-))}{\mathcal{B}(B \to H_s J/\psi(\to \mu^+\mu^-))}, \tag{3}$$

where the additional normalisation term, corresponding to the two leptonic decays of the J/ψ meson, allows to cancel some systematic uncertainties and to perform stringent checks of the reconstruction efficiency of the signal channels.

The ratio is determined in different regions of dilepton momentum transferred, q^2, using the yields of signal events obtained from a fit to the invariant mass distributions of the selected candidates. The reconstruction of the dilepton final states exhibits different challenges for the

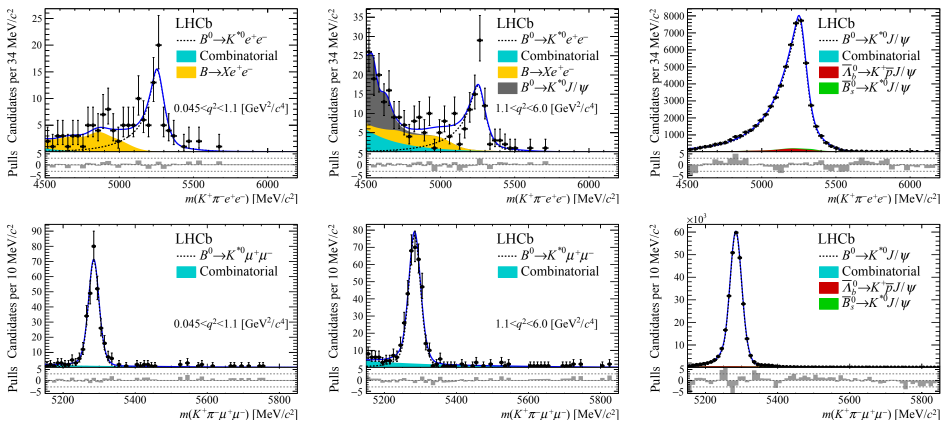

Figure 3. Fit to the invariant mass distributions of $B^0 \to K^{*0}\ell^+\ell^-$ ($\ell = e, \mu$ for top and bottom) candidate decays in different intervals of momentum transferred to the dilepton pairs. Figure is taken from Ref. [22].

electron and muon modes. In particular, for the final states containing e^+e^- pairs, it accounts for the energy loss due to Bremsstrahlung that affects the B mass and momentum resolutions as well as the reconstruction efficiency and the background contamination of these channels. Figure 3 shows the invariant mass distributions of the selected candidates in the measurement of $\mathcal{R}(K^{*0})$ as an example; similar plots are available for the measurement of $\mathcal{R}(K^+)$.

The measured ratios are

$$
\begin{aligned}
\mathcal{R}(K^{*0}) &= 0.66\,^{+0.11}_{-0.07} \pm 0.03 \quad (0.045 < q^2 < 1.1\ \mathrm{GeV}^2/c^4)\,,\\
\mathcal{R}(K^{*0}) &= 0.69\,^{+0.11}_{-0.07} \pm 0.05 \quad (1.1 < q^2 < 6\ \mathrm{GeV}^2/c^4)\,,\\
\mathcal{R}(K^{+}) &= 0.745^{+0.090}_{-0.074} \pm 0.036 \quad (1.0 < q^2 < 6\ \mathrm{GeV}^2/c^4)\,,
\end{aligned}
$$

which are compatible with the SM predictions [24] within 2.1-2.6σ, depending on the q^2 range and the model prediction, but consistently smaller. The LHCb results are considerably more precise than the previous measurements at the "B factories".

The experimental picture that emerges from these measurements become even more intriguing considering that additional anomalies arose in other observables concerning $b \to s\ell^+\ell^-$ transitions. Among them it is worth to recall the smaller differential branching fraction compared to SM predictions observed by LHCb in $B^+ \to K^+\mu^+\mu^-$ [25], $B^0 \to K^{*0}\mu^+\mu^-$ [26] and $B^0_s \to \phi(1020)\mu^+\mu^-$ [27] decays. Furthermore, the most relevant deviation was observed in two bins of q^2 for the coefficient P'_5 describing the angular distributions of $B^0 \to K^{*0}\mu^+\mu^-$ decays [28].

If such anomalies are confirmed with more precise measurements, it would be a clear sign of new physics contributions. Several global fits have been performed trying to obtain a consistent interpretation of the different anomalies observed introducing new physics contributions by means of the effective Hamiltonian expansion and modification of the Wilson coefficients. The outcome of these studies are promising, but further efforts are still required, both from the experimental and theoretical side, to clarify the present scenario.

5 Conclusions and outlook

The LHC*b* experiment is approaching the end of Run2 data taking, aiming at collecting a total integrated luminosity of 9 fb^{-1}. In 2019 the detector will be upgraded in many parts in order to improve the data taking capabilities, such as the instantaneous luminosity and the trigger efficiency. In the next running periods LHC*b* is expected to collect a total integrated luminosity of around 23 fb^{-1} (end of Run3, 2023) and 50 fb^{-1} (end of Run4, 2029) [29, 30].

The results presented at this workshop clearly indicate that LHC*b* is contributing to precision tests of the SM. The measurement of the CKM angle γ has now approached the precision of 5° using a multitude of decay channels and analysis methods and represents the best determination from a single experiment. The current precision is expected to improve to 4° once the full Run2 data sample will have been analysed and to 1° after the upgrade.

The mixing of neutral D mesons is established and the result presented at the workshop constitutes the best single measurement. Currently the results are compatible with CP conservation. The improvements foreseen with the detector upgrade are expected to have a strong impact on the precision of the CP measurements in the charm sector.

Intriguing discrepancies from the SM are observed in measurements of semileptonic B decays to leptons in the context of tests of the lepton flavour universality. Several analyses by the LHC*b* collaboration are ongoing exploiting larger data sets currently available and different decay channels. If the experimental picture will be confirmed with more data, there are good prospects to test the consistency of the anomalies and to perform test of NP models.

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