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LHCb results on flavour physics and implications to BSM

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Summary. — LHCb is a dedicated flavour physics experiment at the LHC. Precision measurements of CP violation and the study of rare decays of hadrons containing beauty and charm quarks constitute powerful searches for New Physics. A selection of recent LHCb results and their implications to physics beyond the Standard Model are discussed.

PACS `13.25.Hw` – Decays of bottom mesons.
PACS `11.30.Er` – Charge conjugation, parity, time reversal, and other discrete symmetries.

1. – Introduction

In the study of heavy flavour decays the LHCb experiment profits from the large $b\bar{b}$ production cross section of the LHC of around $300\,\mu$b at a center of mass energy of $\sqrt{s} = 7\,$TeV. The LHCb detector [1] is a single arm forward spectrometer in the pseudo-rapidity range $2 < \eta < 5$. The detector includes a high precision tracking system which provides excellent momentum and impact parameter resolution. In addition, two ring-imaging Cherenkov detectors provide excellent particle identification capabilities for charged hadrons [2]. Together with the highly efficient trigger system [3], the LHCb experiment is therefore ideally suited for the study of heavy flavour decays.

This article focuses on recent LHCb results relevant to searches for New Physics (NP). Section **2** covers selected precision measurements of CP violation. In sect. **3** results from rare decay measurements are discussed. Conclusions are given in sect. **4**.

2. – CP violation

2·1. *Determination of the CKM angle* γ. – CP violation in the Standard Model (SM) is caused by a single phase in the CKM matrix [4, 5]. The unitarity condition of the CKM matrix results in three unitarity conditions that can be expressed as triangles in the complex plane. The least well determined angle in the β_d triangle, given in fig. 1, is the angle γ defined as $\gamma = \arg\left(-\frac{V_{\mathrm{ud}}V^*_{\mathrm{ub}}}{V_{\mathrm{cd}}V^*_{\mathrm{cb}}}\right)$. Combinations of the current direct measurements

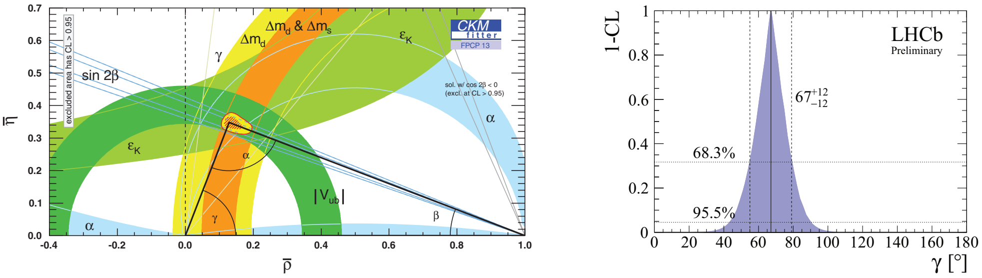

Fig. 1. – Current experimental status of the unitarity triangle [6] (left). Determination of the CKM angle γ combining the GLW/ADS methods [9,10] using $1\,\text{fb}^{-1}$ and the GGSZ method [11] using $3\,\text{fb}^{-1}$ of data [15] (right).

give $\gamma = (68.0^{+8.0}_{-8.5})^\circ$ [6] or $\gamma = (70.8 \pm 7.8)^\circ$ [7], depending on the statistical approach. The determination of γ using $B^- \to D^0(\bar{D}^0)K^-$ tree level decays is free from possible NP effects. As such it is of major importance since the result can be compared to γ measurements that could potentially be affected by new particles [8]. The angle γ can be determined in interference if the D^0 and $\bar{D}^0$ decay into a common final state. The determination of γ using the CP eigenstates $\pi^+\pi^-$ or K^+K^- as common final state is called GLW method, named after the proponents in ref. [9]. A second option is to use flavour eigenstates $K^+\pi^-$ and $K^+\pi^-\pi^+\pi^-$ as final state, the ADS method [10]. Finally, it is possible to determine γ by performing a Dalitz analysis of the three-body final states $K^0_S\pi^+\pi^-$ and $K^0_S K^+K^-$, which is the GGSZ method [11].

LHCb has published measurements of γ using both the GLW and ADS methods [12, 13]. Using the GGSZ method a measurement using $1\,\text{fb}^{-1}$ of data was performed [14]. A preliminary update of the GGSZ method using the full data sample of $3\,\text{fb}^{-1}$ combined with the GLW and ADS methods using $1\,\text{fb}^{-1}$ results in $\gamma = (67 \pm 11)^\circ$ [15], the most precise measurement of γ from a single experiment today, is shown in fig. 1.

2˙2. *The flavour specific CP-violating asymmetry* a^s_{sl}. – The flavour specific CP-violating asymmetry a_{sl} is defined as

$$a_{\text{sl}} = \frac{\Gamma(\bar{B}(t) \to f) - \Gamma(B(t) \to f)}{\Gamma(\bar{B}(t) \to f) + \Gamma(B(t) \to f)}\,. \tag{1}$$

In the SM, a_{sl} is predicted to be tiny [16], but it could be enhanced by NP. The LHCb experiment uses $D^-_s\mu^+X$ as final state f, thus determining the flavour specific asymmetry in the B^0_s system, a^s_{sl}. Production asymmetries can be neglected due to the fast B^0_s mixing frequency. Using a data sample corresponding to $1\,\text{fb}^{-1}$, a^s_{sl} is determined to be $a^s_{\text{sl}} = (-0.06 \pm 0.50_{\text{stat.}} \pm 0.36_{\text{syst.}})\%$ [17]. This result is in excellent agreement with the SM prediction and the most precise measurement of this quantity to date. Figure 2 shows the result in comparison with measurements by the D0 collaboration [18-20].

2˙3. *The CP-violating phase* ϕ_s. – $B^0_s - \bar{B}^0_s$ mixing is a flavour changing neutral current (FCNC) process. Since FCNCs in the SM are forbidden at tree level, B^0_s mixing can only occur via loop-diagrams. New particles beyond the SM can enter the loop and affect the mixing phase. The mixing phase is experimentally accessible in the interference between the direct decay of the B^0_s to the final state $J/\psi\phi$ and the decay after mixing into a $\bar{B}^0_s$.

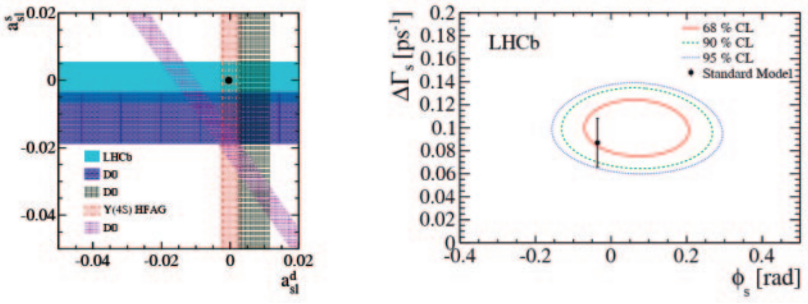

Fig. 2. – Measurements of $a_{\text{sl}}^{(s,d)}$ by the LHCb [17] and D0 [18-20] Collaborations (left). Determination of ϕ_s and $\Delta\Gamma_s$ from $B_s^0 \to J/\psi\phi$ decays [21] (right).

The resulting time-dependent CP asymmetry depends on the phase ϕ_s which, in the SM, is well known to be $\phi_s = (-0.0367 \pm 0.0014)\,\text{rad}$ [6]. Since the decay $B_s^0 \to J/\psi\phi$ is a $P \to VV$ transition, the final state is not a CP eigenstate. An angular- and decay time dependent fit is needed to statistically separate the CP-even from the CP-odd contribution to the final state. Using the decay $B_s^0 \to J/\psi\phi$, the phase ϕ_s and the decay width difference in the B_s^0 system, $\Delta\Gamma_s$, are determined to $\phi_s = (0.07 \pm 0.09_{\text{stat.}} \pm 0.01_{\text{syst.}})\,\text{rad}$ and $\Delta\Gamma_s = (0.100 \pm 0.016_{\text{stat.}} \pm 0.003_{\text{syst.}})\,\text{ps}^{-1}$ as shown in fig. 2. Combined with the decay mode $B_s^0 \to J/\psi\pi^+\pi^-$ the sensitivity to ϕ_s increases, resulting in $\phi_s = (0.01 \pm 0.07_{\text{stat.}} \pm 0.01_{\text{syst.}})\,\text{rad}$ and $\Delta\Gamma_s = (0.106 \pm 0.011_{\text{stat.}} \pm 0.007_{\text{syst.}})\,\text{ps}^{-1}$ [21]. This result is in excellent agreement with the SM prediction.

3. – Rare decays

Rare decays are decays that are mediated by FCNCs. Contributions from new particles beyond the SM can affect both the branching fractions of rare decays as well as the angular distributions of the final state particles. Rare $b \to s$ transitions can be described with the effective Hamiltonian:

$$\mathcal{H}_{\text{eff.}} = -\frac{4G_F}{\sqrt{2}} V_{\text{td}} V_{\text{ts}}^* \sum_i \left[\mathcal{C}_i \mathcal{O}_i + \mathcal{C}_i' \mathcal{O}_i'\right]. \tag{2}$$

The quantities $\mathcal{C}_i$ and $\mathcal{C}_i'$ denote generalized couplings, the Wilson coefficients; $\mathcal{O}_i$ and $\mathcal{O}_i'$ are the corresponding local operators. Any observed significant deviation of the Wilson coefficients from their SM predictions would not only be a sign of physics beyond the SM, but also give important information on the operator structure of the NP contribution.

3·1. *The very rare decay $B_s^0 \to \mu^+\mu^-$.* – The decay $B_s^0 \to \mu^+\mu^-$ is a $b \to s$ FCNC transition which is not only loop- but, in addition, helicity-suppressed. Since the final state of the decay is purely leptonic, the decay is both theoretically and experimentally extremely clean. The branching fraction of the decay is particularly sensitive to scalar and pseudoscalar NP contributions. The SM prediction for this decay mode is extremely small, $\mathcal{B}(B_s^0 \to \mu^+\mu^-)^{\text{SM}} = (3.23 \pm 0.27) \times 10^{-9}$ [22]. The time integrated branching fraction, which corresponds to the experimentally measured branching fraction in the B_s^0 system, needs to account for the sizeable $\Delta\Gamma_s$, resulting in $\mathcal{B}(B_s^0 \to \mu^+\mu^-)^{\text{SM}}_{\Delta\Gamma_s} = (3.56 \pm 0.18) \times 10^{-9}$ [23]. In the SM, the decay $B^0 \to \mu^+\mu^-$ is further suppressed by $|V_{\text{td}}/V_{\text{ts}}|^2$

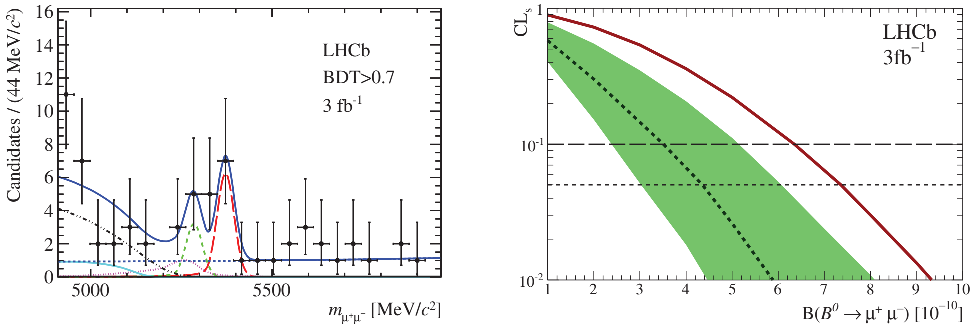

Fig. 3. – Signal-like $B_q^0 \to \mu^+\mu^-$ candidates (left) and limit of the $B^0 \to \mu^+\mu^-$ branching fraction (right).

with respect to the decay $B_s^0 \to \mu^+\mu^-$. The LHCb experiment has performed an analysis of the full data sample taken in 2011 and 2012 corresponding to an integrated luminosity of $3\,\mathrm{fb}^{-1}$. Figure 3 shows signal candidates that are classified to be signal-like by a multivariate classifier. The significance of the $B_s^0 \to \mu^+\mu^-$ signal corresponds to 4σ. For the decay $B^0 \to \mu^+\mu^-$ an upper limit of $\mathcal{B}(B^0 \to \mu^+\mu^-) < 7.4\times10^{-10}$ is set at 95% CL. A fit of the branching fractions results in $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9\,^{+1.1}_{-1.0}(\mathrm{stat})\,^{+0.3}_{-0.1}(\mathrm{syst}))\times10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7\,^{+2.4}_{-2.1}(\mathrm{stat})\,^{+0.6}_{-0.4}(\mathrm{syst}))\times10^{-10}$ [24]. Combination with the CMS experiment, which sees the decay with a significance of 4.3σ [25], results in the first observation of the decay $B_s \to \mu^+\mu^-$ [26]. The result is in agreement with the SM prediction. No large contributions from NP are observed.

3·2. *The rare decay* $B^+ \to K^+\mu^+\mu^-$. – The final state of the decay $B^+ \to K^+\mu^+\mu^-$ is fully described by one angle θ_ℓ and the invariant mass of the dimuon system squared, $q^2 = m(\mu^+\mu^-)^2$. The angular distribution of this decay is given by

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_\ell} = \frac{3}{4}(1-F_H)(1-\cos^2\theta_\ell) + \frac{1}{2}F_H + A_{\mathrm{FB}}\cos\theta_\ell, \tag{3}$$

where F_H denotes the flat parameter and A_{FB} the forward-backward asymmetry. In ref. [27] these angular observables are determined together with the differential branching fraction $\mathrm{d}\Gamma/\mathrm{d}q^2$ in bins of q^2. Good agreement with the SM prediction is observed. In addition, the CP asymmetry of the decay, $\mathcal{A}_{\mathrm{CP}} = \frac{\Gamma(B^-\to K^-\mu^+\mu^-)-\Gamma(B^+\to K^+\mu^+\mu^-)}{\Gamma(B^-\to K^-\mu^+\mu^-)+\Gamma(B^+\to K^+\mu^+\mu^-)}$, is determined, using the decay $B^+ \to J/\psi K^+$ to control production and detection asymmetries. The resulting CP asymmetry is measured in bins of q^2 and is in good agreement with the SM prediction [28]. Furthermore, an interesting resonance structure is found at high q^2 in the $K^+\mu^+\mu^-$ final state [29]. The mass of the state is determined to 4191^{+9}_{-8} MeV, its width to 65^{+22}_{-16} MeV, compatible with the known $\Psi(4160)$.

3·3. *The rare decay* $B^0 \to K^{*0}\mu^+\mu^-$. – The decay $B^0 \to K^{*0}\mu^+\mu^-$ has a particularly rich phenomenology due to the many observables that are accessible in this mode. The final state is fully described by the three decay angles θ_ℓ, θ_K and Φ and q^2. The

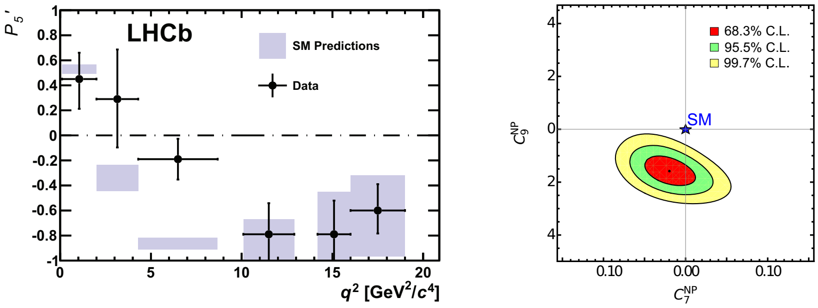

Fig. 4. – The angular observable P_5' determined in the decay $B^0 \to K^{*0}\mu^+\mu^-$ [31], together with the SM predictions from [32] (left), and the result of a fit of the Wilson coefficients $\mathcal{C}_7$ and $\mathcal{C}_9$ [33] (right).

differential decay rate is given by

$$\begin{aligned}(4)\quad \frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_K \mathrm{d}\Phi} = \frac{9}{32\pi}\Bigg[&\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K \\ &+\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell \\ &-F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\Phi \\ &+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\Phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\Phi \\ &+\frac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\Phi \\ &+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\Phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\Phi\Bigg],\end{aligned}$$

where F_L denotes the longitudinal polarisation fraction of the K^{*0}, A_FB the forward-backward asymmetry and S_i the remaining CP-averaged angular observables. Due to the limited size of the analyzed data sample corresponding to only 1 fb^{-1}, angular foldings are employed to reduce the number of observables to be determined in a fit of the angular distributions. Good agreement with the SM predictions is seen for the angular observables F_L, A_FB and $S_{3,9}$ [30]. Applying different angular foldings, the less form-factor dependent angular observables $P'_{4,5,6,8} = S_{4,5,7,8}/\sqrt{F_L(1-F_L)}$ are determined [31]. Good agreement with the SM predictions is seen for all angular observables except for P_5', given in fig. 4. Here, a local deviation corresponding to 3.7σ is observed in one q^2 bin. Assuming that all observables are statistically independent, and taking into account that four observables in six bins of q^2 are determined in ref. [31], this deviation corresponds to a p-value of 0.5%. Several theory groups have performed global fits to determine the Wilson coefficients from the angular observables in $B^0 \to K^{*0}\mu^+\mu^-$ and other $b \to s$ transitions. The authors of ref. [33] have found improved agreement of the prediction with the data for a negative shift of the coefficient $\mathcal{C}_9$ as shown in fig. 4. An updated analysis of the full LHCb data sample corresponding to 3 fb^{-1} is currently ongoing to clarify wether the observed deviation is a hint of NP or just a statistical fluctuation.

3˙4. *The radiative decay* $B^+ \to K^+\pi^+\pi^-\gamma$. – The radiative decay $B^+ \to K^+\pi^+\pi^-\gamma$ is sensitive to NP contributions to the photonic penguin. In the SM the photon emitted in the decay is predominantly left-handed. NP can however cause significant right-handed contributions.

Using the three final state hadrons a plane is defined in the $K^+\pi^+\pi^-$ system. The asymmetry in the number of events with the photon going upwards and downwards with respect to this plane carries information on the photon polarisation [34]. A preliminary measurement of the up-down asymmetry $\mathcal{A}_{\rm ud}$ results in $\mathcal{A}_{\rm ud} = -0.085 \pm 0.019_{\rm stat.} \pm 0.003_{\rm syst.}$ [35], which corresponds to a 4.6σ evidence for photon polarization. In addition, the first measurement of CP violation in this mode is performed resulting in $\mathcal{A}_{\rm CP} = -0.007 \pm 0.015_{\rm stat.} \pm 0.008_{\rm syst.}$.

4. – Conclusions

The LHCb experiment has performed many studies of CP violation and rare decays with excellent sensitivity to physics beyond the SM, yet clear signs of NP are still absent. There are however some interesting hints, for example a deviation in the angular observable P_5' in the decay $B^0 \to K^{*0}\mu^+\mu^-$. An update of the analysis of this decay using the full LHCb data sample is currently ongoing.

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