Search for new physics in $b \to q\ell\ell$ decays

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Recent results obtained in experiments at the LHC in the field of rare b-hadron decays are reviewed in this contribution, with a focus on $b \to q\ell\ell$ processes. A general status is presented as well as recently completed measurements.

1 Introduction

The study of flavour-changing neutral-current processes (FCNC) is a sensitive tool to explore possible interactions beyond those predicted by the Standard Model (SM). In particular, rare hadron decays having tiny probabilities in the SM, can receive possible New Physics (NP) contributions at the same level or even larger than the SM. Probing NP using these techniques is especially sensitive when the SM predictions are very precise; in these cases, we can often probe energy scales orders of magnitude higher than those available for the direct production of new states at colliders. In addition, rare decays offer the possibility of model-independent tests of physics beyond the SM. Finally, historically rare decays have been the laboratory of many particle physics discoveries.

The description of heavy-quark hadrons rare decays is usually made in terms of effective field theories where SM and NP contributions are computed in terms of local operators and their Wilson coefficients. This allows to put model-independent constraints on possible NP couplings. As an example possible new (pseudo)-scalar contributions in $b \to q\ell^+\ell^-$ processes can be defined as a term in the effective hamiltonian proportional to $C_{S(P)}\bar{q}_L b_L \bar{\ell}(\gamma_5)\ell$ where $C_{S(P)}$ are the Wilson coefficients, and the overall normalisation is not reported. Similarly in what follows it is useful to define (axial-)vector contributions as $C_{9(10)}\bar{q}_L\gamma^\mu b_L \bar{\ell}\gamma_\mu(\gamma_5)\ell$. We do not list them, but additional operators also possibly contribute to $b \to q\ell^+\ell^-$ transitions as well as the chirally-flipped versions of the ones defined.

In this contribution we review recent results in rare b-hadron decays based on quark-level $b \to s\ell^+\ell^-$ and $b \to d\ell^+\ell^-$ transitions with a focus on measurements from experiments at the Large Hadron Collider (LHC).

2 Scalar, pseudoscalar and axial-vector couplings

NP contributions in the form of scalar, pseudoscalar and axial-vector couplings are best tested with $B^0_{(s)} \to \ell^+\ell^-$ decays. The branching fractions of these decays are very well predicted in the SM [1,2] and thus allow for extremely sensitive tests of NP. Due to helicity suppression the $B^0_{(s)} \to e^+e^-$ decays are too rare to be currently probed at branching fractions close to the SM contribution. The $B^0_{(s)} \to \tau^+\tau^-$ decays are the less rare but, due to the difficulty of

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[a] On behalf of the LHCb collaboration

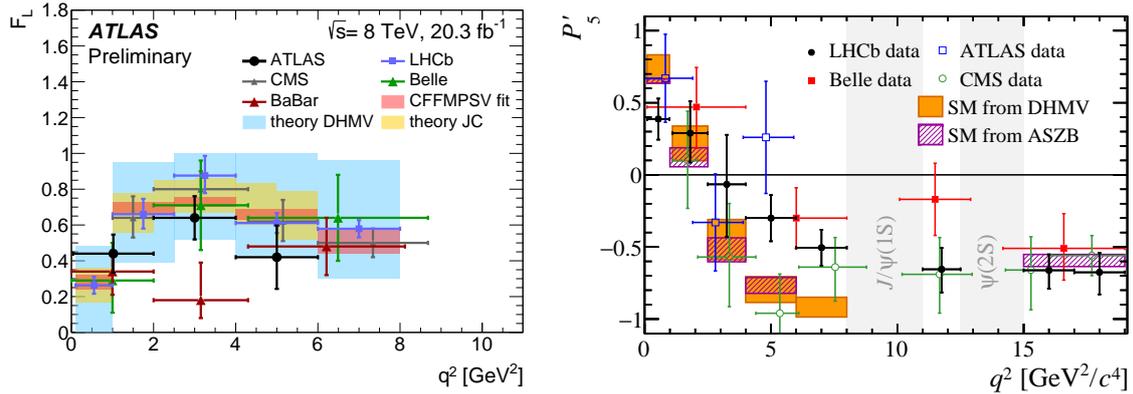Figure 1 – Measurements of the F_L and P_5' observables in $B_d^0 \to \bar{K}^{*0}\mu^+\mu^-$ decays, in bins of q^2, for different experiments and compared with SM predictions.

reconstructing τ leptons, especially at hadron colliders, the SM branching fraction is still out of reach. The current world best limits on these decays have been recently set by LHCb [3]. Nevertheless it is important to probe these decays, especially in light of possible hints of lepton non universality (see C. Langenbruch contribution at this same conference [4]). The $B_{d,s}^0 \to \mu^+\mu^-$ decays instead, being cleaner from an experimental point of view, are being probed by several experiments. The first evidence for the $B_s^0 \to \mu^+\mu^-$ decay, came from the LHCb experiment [5], while the definitive observation resulted from the combined analysis of the LHCb and CMS Run 1 measurements [6]. The current world best measurement comes from the last LHCb measurement [7], where the full Run 1 as well as 1.4 fb^{-1} of integrated luminosity collected in Run 2 was exploited leading to the first observation of the $B_s^0 \to \mu^+\mu^-$ decay from a single experiment. The branching fraction measurement yields $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.0 \pm 0.6^{+0.3}_{-0.2}\right) \times 10^{-9}$, in good agreement with recent SM predictions [1,2] as well as with the previous measurements. The Run 1 ATLAS search for the same decay is instead in slight tension with these results [8], reporting only a 1.4σ excess over background expectations and thus putting an upper limit on the branching fraction at $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 3.0 \times 10^{-9}$ at 90% CL, lower than the SM prediction. For more details on these and other very rare decays measurements see M. van Veghel contribution at this same conference [9].

3 Vector couplings and a possible anomaly

While scalar and pseudo-scalar couplings seem to be in good agreement with the SM, the same is not true for other couplings, especially vector ones (C_9). Several small discrepancies, which we review briefly, are accumulating giving an overall tension with the SM.

We start from the $B_d^0 \to \bar{K}^{*0}\mu^+\mu^-$ decay; its rich phenomenology allows to test several couplings simultaneously through the study of its angular distributions. Recent measurements have been done by four experiments, often exploiting the so-called optimised observables [10], which have the advantage of reduced theoretical uncertainty. Within the Run 1 LHCb measurement [11] the full fit to CP-averaged observables shows a tension with the SM with a significance of 3.4 standard deviations. Considering single variables, the most striking feature is a discrepancy in the P_5' parameter. This behaviour seems to be confirmed by ATLAS [12] and Belle [13] measurements; while the CMS [14] measurement is more in agreement with SM. This is shown in Figure 1, where the different measurements are presented as a function of q^2, the dimuon invariant mass squared, and compared with SM predictions [15,16,17].

Similarly, discrepancies are present in the branching fractions of several $b \to s\mu^+\mu^-$ processes, recently measured by LHCb, which tend to show a mild tension with the SM. In particular the differential and integrated branching fractions of $B^+ \to K^+\mu^+\mu^-$, $B^+ \to K^{*+}\mu^+\mu^-$,
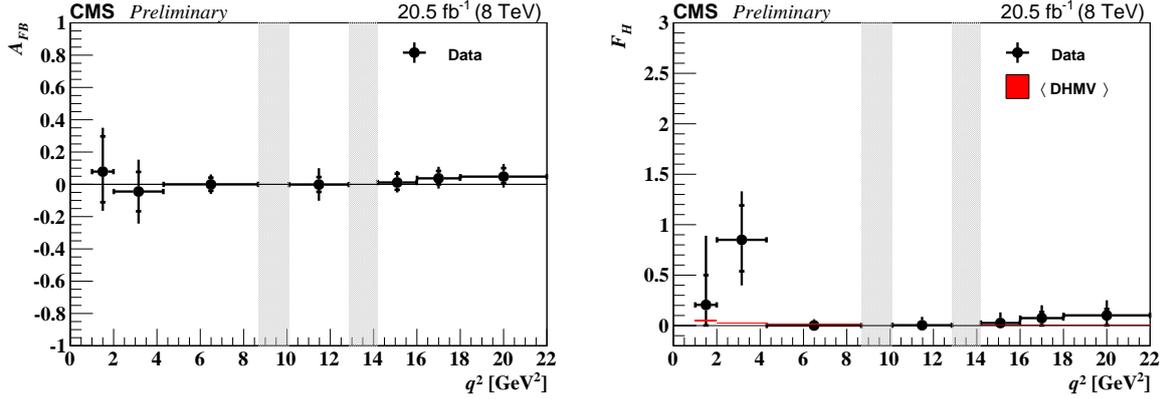
Figure 2 – Measurement of (left) the A_{FB} parameter and (right) the F_H parameter as a function of q^2 in the angular analysis of $B^+ \to K^+\mu^+\mu^-$ decays in CMS.

$B^0 \to K^0\mu^+\mu^-$ [18] as well as $B^0_d \to \bar{K}^{*0}\mu^+\mu^-$ [19] and $B^0_s \to \phi\mu^-\mu^+$ [20] lie all below the SM prediction, albeit not with great significance.

These discrepancies summed with the hints of lepton flavour universality violation in $B^+ \to K^+\ell^+\ell^-$, $B^0_d \to \bar{K}^{*0}\ell^+\ell^-$ and $B \to D^{(*)}\ell\nu$ decays [4] lead to possible global discrepancies with respect to the SM even above the 5σ level. In particular, global fits [21,22,23,24] could indicate possible NP contributions on the C_9 Wilson coefficient, or to the C_9 and C_{10} simultaneously. The significance of these discrepancies is almost completely dominated by the statistical uncertainties, hence they will need to be confirmed with additional statistics by the same experiments, and cross-checked by other experiments (such as Belle-II), but give encouraging hints on the direction to follow.

3.1 Angular analysis of $B^+ \to K^+\mu^+\mu^-$ at CMS

Presented for the first time at this conference, the CMS collaboration has performed an angular analysis of the $B^+ \to K^+\mu^+\mu^-$ decays, exploiting $20.5 fb^{-1}$ of integrated luminosity collected in Run 1 at $\sqrt{s} = 8$ TeV [25]. The differential decay rate of this decay can be written as:

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

where θ_ℓ is the angle between the direction of the μ^- and the one of the K^+ meson for the B^+ decay. The two parameters on which the differential decay rate depends (A_{FB} and F_H) are a function of q^2 and sensitive probes to scalar and tensor new physics contributions. The $B^+ \to K^+\mu^+\mu^-$ angular analysis was previously performed also by the LHCb [26], BaBar [27], Belle [28] and CDF [29] experiments. The CMS results as a function of q^2 are shown in Figure 2, as extracted from about 2300 signal candidates. The largest systematic uncertainties are due to modelling of the background components and dominate the total uncertainty in some bins. The results are compatible with previous measurements and with SM predictions. While this measurement is not yet the world most precise, it is important to have measurements from different experiments, especially when anomalies such as the ones described are surfacing. A measurement of the $B^+ \to K^+\mu^+\mu^-$ differential branching fraction by CMS is therefore important and awaited.

3.2 $b \to d\ell\ell$

Processes involving $b \to d\ell^+\ell^-$ transitions are even more rare than those with an s quark due to the additional CKM suppression. The observation of these processes was established by LHCb in $B^+ \to \pi^+\mu^+\mu^-$ and $\Lambda^0_b \to p\pi^-\mu^+\mu^-$ decays [30,31]. The $B^0_s \to \bar{K}^{*0}\mu^+\mu^-$ decay is
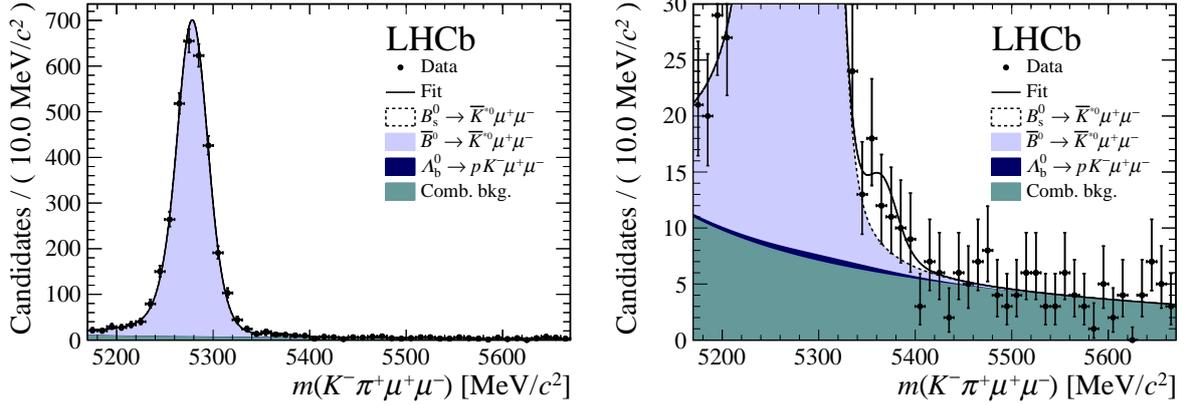
Figure 3 – Invariant mass distribution for (left) $K^-\pi^+\mu^+\mu^-$ candidates for the three most sensitive neural network bins of the LHCb analysis and (right) a zoom on the same plot to highlight the $B_s^0 \to \bar{K}^{*0}\mu^+\mu^-$ signal.

instead yet to be observed. This decay can be sensitive to NP contributions, but is also an important probe of the $|V_{td}|/|V_{ts}|$ ratio. A search for this decay has been performed by LHCb exploiting $4.6fb^{-1}$ collected at different energies in Run 1 and 2 [32]. A common selection for the $B_s^0 \to \bar{K}^{*0}\mu^+\mu^-$ and the control and normalisation channels $B_d^0 \to \bar{K}^{*0}\mu^+\mu^-$, $B_d^0 \to \bar{K}^{*0}J/\psi$ and $B_s^0 \to \bar{K}^{*0}J/\psi$ is devised. The search for the rare non-resonant channel is restricted to dimuon invariant masses squared of $0.1 < q^2 < 19.0$ GeV^2/c^4 excluding the region $12.5 < q^2 < 15.0$ GeV^2/c^4, which is dominated by charmonium resonances. After a loose pre-selection, candidates are classified in bins of a neural network based on geometric and kinematic variables. The background is predominantly composed of combinatorial background and of the upper tail of the $B_d^0 \to \bar{K}^{*0}\mu^+\mu^-$ distribution. The distribution of the $K^-\pi^+\mu^+\mu^-$ candidates summed over the three most sensitive bins of neural network is shown in Figure 3. The presence of an excess on top of the background at the B_s^0 mass can be seen. From a simultaneous fit a combined significance of 3.4 standard deviations is derived, including systematic uncertainties, which represents the first evidence of the $B_s^0 \to \bar{K}^{*0}\mu^+\mu^-$ decay. Normalising the signal to the $B_d^0 \to \bar{K}^{*0}\mu^+\mu^-$ decay a branching fraction of $\mathcal{B}(B_s^0 \to \bar{K}^{*0}\mu^+\mu^-) = (2.9\pm1.0\pm0.2\pm0.3)\times10^{-8}$ is obtained, where the first uncertainty is statistical, the second systematic and the third is due to limited knowledge of parameters used in the normalisation. This result is in agreement with SM expectations.

3.3 b-baryons

A different look to $b \to s\ell^+\ell^-$ transitions can be taken by studying b-baryon decays, the rare decays of which start to be probed only recently. In addition to the already mentioned $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$, the LHCb collaboration has studied the $\Lambda_b^0 \to pK^-\mu^+\mu^-$ decay exploiting $3fb^{-1}$ of Run 1 data [33]. The $\Lambda_b^0 \to pK^-\mu^+\mu^-$ decay is observed for the first time, with large significance. Exploiting a signal yield of 600 ± 44 candidates, a search for CP violation is performed in this channel which can be a sensitive probe of NP [34]. A measurement of CP violation is built from raw yields as:

$$\mathcal{A}_{\rm CP} \propto \mathcal{A}_{\rm raw} = \frac{N(\Lambda_b^0 \to pK^-\mu^+\mu^-) - N(\bar{\Lambda}_b^0 \to \bar{p}K^+\mu^+\mu^-)}{N(\Lambda_b^0 \to pK^-\mu^+\mu^-) + N(\bar{\Lambda}_b^0 \to \bar{p}K^+\mu^+\mu^-)} \quad , \tag{2}$$

where the proper conversion to $\mathcal{A}_{\rm CP}$ is obtained correcting for production and reconstruction asymmetries. For additional robustness, CP violation is searched in the difference of this observable between the $\Lambda_b^0 \to pK^-\mu^+\mu^-$ and the control channel $\Lambda_b^0 \to pK^-J/\psi$, on which no significant CP violation is expected. This measurement results in: $\Delta\mathcal{A}_{CP} = (-3.5 \pm 5.0(stat) \pm 0.2(syst))\times10^{-2}$, showing no sign of CP violation. A second CP violating variable is constructed

from the positive-negative asymmetry of the triple products $C_{\widehat{T}} = \vec{p}_{\mu^\pm} \cdot \vec{p}_p \times \vec{p}_{K^+}$; comparing the positive and negative muon CP-odd and P-odd observables are obtained. The results for the CP-odd observable are $a_{CP}^{\widehat{T}-odd} = (1.2 \pm 5.0(stat) \pm 0.7(syst)) \times 10^{-2}$, showing again no sign of CP violation, in agreement with SM predictions [35,36].

4 Conclusions

A very brief account of recent rare decays searches and measurements, in the field of $b \rightarrow q\ell^+\ell^-$ transitions was given in this contribution. The topic is among the most exiting in current particle physics as small discrepancies that point towards possible NP contributions beyond the SM are accumulating. The results based on the analysis of Run 1 LHC data by the LHCb, ATLAS and CMS experiments show tantalising hints of possible deviations from the SM, especially in the muonic vector coupling. These discrepancies will be possibly confirmed or disproved by Run 2 data and through different observables. Finally, the LHC experiments will face soon the healthy competition of the Belle II experiment in the run for new physics.

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