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Rare decays at the LHCb experiment

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Summary. — Rare flavour-changing neutral-current (FCNC) decays of beauty and charm quarks, lepton flavour- and lepton-number–violating decays can provide a powerful probe for as yet unobserved virtual particles. Recent results on these topics from the LHCb experiment are reviewed. Particular attention is paid to the angular distribution of the $B^0 \to K^{*0}\mu^+\mu^-$ decay, where a measurement performed by LHCb shows a local discrepancy of 3.7 standard deviations with respect to the SM prediction. Using the decay $B^+ \to K^+\pi^+\pi^-\gamma$, LHCb have also been able to demonstrate the polarisation of photons produced in $b \to s$ transitions. An update for the studies dedicated to decays $\tau^+ \to \mu^+\mu^-\mu^+$ and $B^0_{(s)} \to \mu^\pm e^\mp$ and to the on-shell Majorana neutrinos coupling to muons in the $B^+ \to \pi^-\mu^+\mu^+$ decay channel are also presented.

PACS `13.20.He` – Decays of bottom mesons.
PACS `13.35.Dx` – Decays of taus.
PACS `13.35.Hb` – Decays of heavy neutrinos.
PACS `13.30.Ce` – Leptonic, semileptonic, and radiative decays.

1. – Introduction

The Standard Model (SM) of particle physics cannot be the ultimate theory, as it is incomplete and contains too many free parameters, such as the fermion masses and the quark mixing angles. The pattern of these parameters should be governed by a hidden mechanism yet to be discovered, and so the SM is believed to be a low-energy effective theory of a more fundamental theory that will be superseded by a higher-energy scale. This would imply new symmetries, particles, dynamics, and flavor structure (New Physics, NP) that would led to quantum corrections in the decay of known particles especially in flavor-changing neutral-current (FCNC) transitions.

These processes are theoretically calculated using the Operator Product Expansion (OPE) in terms of short-distance Wilson coefficients and long-distance operators describing effective vertices such as tree diagrams, or gluon, photon, electroweak, scalar and pseudo-scalar penguin loops. NP may both enhance some of the Wilson coefficients or introduce new operators, in particular in the right-handed sector that is suppressed in the SM.

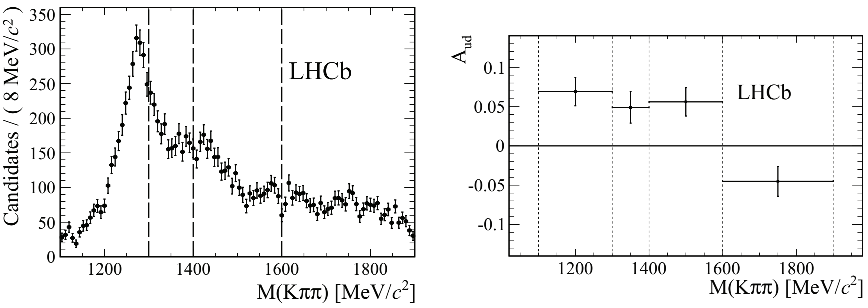

Fig. 1. – Invariant $K^+\pi^+\pi^-$ mass distribution of selected $B^+ \to K^+\pi^+\pi^-$ candidates (left) and the updown asymmetry of the photon with respect to the $K^+\pi^+\pi^-$ system in four bins of $K^+\pi^+\pi^-$ mass (right).

The presence of these new particles can show up either as an increase or, due to interference, decrease in the rate of particular decays or as a change of the helicity structure (and hence the angular distributions) of the particles in the detector.

In the following recent results obtained by the LHCb experiment on rare decays of mesons containing b quarks and lepton-flavor–violating (LFV) decays of the τ leptons are presented.

2. – Photon polarization in $B^+ \to K^+\pi^+\pi^-\gamma$ decays

In the SM, photons produced in $b \to s\gamma$ transitions are expected to be almost purely left-hand polarised due to the coupling of the b- and s-quark to a virtual W boson. Neglecting QCD contributions, the right-handed component ($b_L \to \gamma_R s_R$) is suppressed by the ratio of the s- to the b-quark mass, making it vanishingly small. In many extensions of the SM, the photon is produced unpolarised because there is no preferred left or right-handed coupling. One way to test the photon polarisation is using the photon direction with respect to the $K^+\pi^+\pi^-$ system in $B^+ \to K^+\mu^+\mu^-$ decays [1]. The decay distribution can be written as

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta} = \sum_{n=0,2,4} a_n \cos^2\theta + \lambda \sum_{n=1,3} a_n \cos^n\theta, \tag{1}$$

where θ is the angle between the direction of the photon and the plane defined by the π^+ and $\pi^-$and a_n depends on the mass of the $K^+\pi^+\pi^-$, $K^+\pi^-$ and $\pi^+\pi^-$. The up-down asymmetry A_{ud} of the photon with respect to this plane is proportional to the photon-polarisation, λ. The measurement is conceptually similar to the landmark experiment that discovered the parity violation [2]. The LHCb experiment has performed a first measurement of this up-down asymmetry using a dataset corresponding to $3\,\mathrm{fb}^{-1}$ of integrated luminosity [3]. The complete dataset contains 13876 ± 153 candidates. It is split into four regions of $K^+\pi^+\pi^-$ invariant mass, shown in fig. 1 (left), designed to separate different resonant contributions. The measured up-down asymmetry in the four regions is also shown in fig. 1 (right). Combining the four regions, evidence for non-zero photon polarisation is observed at the level of 5.2 σ. This is the first observation for photon polarisation in radiative b-hadron decays. Whilst clear evidence for polarisation is seen, an understanding of the hadronic system is needed to compare the measured asymmetry to the left-hand polarisation prediction of the SM. Work is needed on the

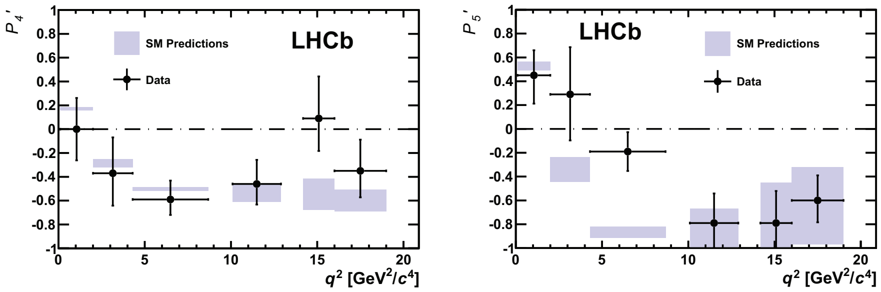

Fig. 2. – Form-factor–free observables P_4', P_5' measured by the LHCb collaboration [8] in $B^0 \to K^{*0}\mu^+\mu^-$ decays in bins of dimuon invariant mass squared, q^2. The data are overlaid with a SM prediction described in ref. [9].

experimental side to understand the different resonant contributions to the $K^+\pi^-\pi^+$ system and on the theoretical side to convert the measured $K^+\pi^-\pi^+$ spectrum and the up-down asymmetry into a measurement of the photon polarisation.

3. – Angular distribution of $B^0 \to K^{*0}\mu^+\mu^-$ decays

The polarisation of virtual photons can also be probed using the angular distribution of $B^0 \to K^{*0}\mu^+\mu^-$, where $K^{*0} \to K^+\pi^-$, decays at low dimuon invariant mass squared, q^2. The angular distribution of this decay can be defined be three angles, θ_l, θ_K and ϕ, as (see for example ref. [4])

$$\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_l \mathrm{d}\cos K \mathrm{d}\phi \mathrm{d}q^2} = \frac{9}{32}\sum_i J_i(q^2) f_i(\cos\theta_l, \cos\theta_K, \phi). \tag{2}$$

Here, θ_l is defined by the direction of the $\mu^+(\mu^-)$ with respect to the B^0 $(\overline{B}^0)$ in the dimuon rest frame and θ_K by the direction of the kaon with respect to the $B^0(\overline{B}^0)$. The angle ϕ is the angle between the plane containing the μ^+ and μ^- and the plane containing the kaon and pion. The angular distribution can be particularly sensitive to the contribution of new virtual particles through their interference with the SM contributions. Different angular terms, $J_i(q^2)$, are sensitive to different K^{*0} polarisation states and provide complementary information.

The ATLAS, CMS and LHCb experiments have all performed measurements of the $B^0 \to K^{*0}\mu^+\mu^-$ angular distribution using the data they collected in 2011 [5, 7]. Due to the rarity of the decay and the small number of candidates that are reconstructed, the experiments do not simultaneously fit for all of the angular terms. ATLAS and CMS measure only the longitudinal polarisation fraction of the K^{*0} and the forward-backward asymmetry of the dimuon system, A_{FB}. The LHCb experiment also measures the asymmetry between the two transverse K^{*0} polarisations, which is particularly sensitive to the handedness of the photon polarisation. All of these measurements are consistent with SM expectations.

The LHCb experiment has also made first measurements of two new observables [8], $P_{4,5}'$ which are free from form factor uncertainties at leading order [9]. The result of these measurements is shown in fig. 2. Interestingly, a large local discrepancy of 3.7 σ is seen between the measurement and the SM prediction in the q^2 range $4.3 < q^2 <$

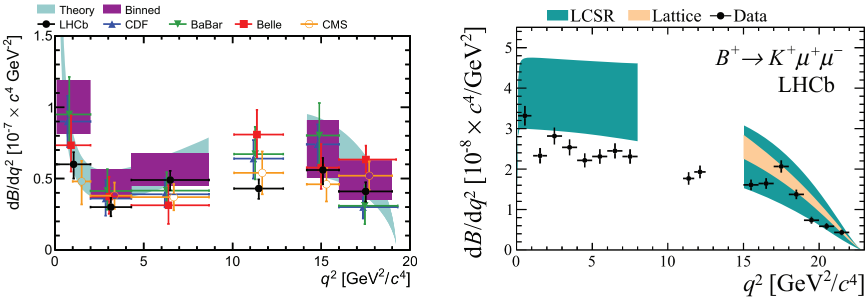

Fig. 3. – Differential branching fraction of the decay $B^0 \to K^{*0}\mu^+\mu^-$ measured by the CMS, CDF, Babar, Belle and LHCb experiments (left) and of the decay $B^+ \to K^+\mu^+\mu^-$ measured by the LHCb experiment (right) as a function of the dimuon invariant mass squared, q^2. The data are overlaid with SM predictions described in refs. [17,18]. A prediction for the differential branching fraction of the $B^+ \to K^+\mu^+\mu^-$ decay using form-factors from lattice [19] is also included.

$8.68\,\mathrm{GeV}^2/c^4$ for P_5'. Several recent attempts have been made to understand this anomaly by performing global fits to the measurements of the angular distribution made by the LHC experiments, CDF and the B factories. The data are best described by a model in which a new vector current is introduced that destructively interferes with the SM contributions [10-12]. This is most visible at low q^2 due to additional interference with the virtual photon contribution in the SM. A new vector current is best explained in models that introduce a Z' boson with flavour-violating couplings [13]. It is less easy to explain this type of deviation in supersymmetric models. It is also possible that part of this discrepancy can be explained by an underestimate of the uncertainty on the SM prediction, coming from the treatment of the form factors [14] or from our understanding of $c\bar{c}$ contributions to the decay [15]. The datasets collected by the experiments in 2012 may help to shed light on the situation.

4. – Branching fraction of semileptonic $b \to s\mu^+\mu^-$ decays

If there is a new vector current that explains the anomaly in the $B^0 \to K^{*0}\mu^+\mu^-$ angular distribution, then its infuence should also show up in other decays involving $b \to s\mu^+\mu^-$ quark level transitions. In particular, the destructive interference will result in branching fractions that are below their SM expectation. In refs. [7, 16] the LHCb collaboration performed measurements of the differential branching fraction of the decays $B^0 \to K^{*0}\mu^+\mu^-$, $B^+ \to K^{*+}\mu^+\mu^-$, $B^0 \to K^0\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^-$. The measurements for $B^0 \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^-$ are shown in fig. 3. All of these measurements are below their SM expectation. However, they are consistent with the SM when accounting for the large uncertainties on the SM predictions coming from the $B \to K^{(*)}$ form factors.

5. – Lepton-flavor and lepton-number–violating decays

The experimental observation of neutrino oscillations has been the first evidence of lepton flavour violation (LFV). The consequent introduction of mass terms for the neutrinos in the Standard Model already implies lepton family number violation also in the charged sector, but with vanishing decay rates smaller than 10^{-40}. New Physics could significantly enhance the rates, but charged-lepton-flavour–violating (cLFV) decays like $\mu \to e\gamma$, $\mu^+ \to e^+e^-e^+$, $\tau^+ \to l^+\gamma$, and $\tau^+ \to l^+l^-l^+$ with $l = e, \mu$, have not been observed so far even with steadily improving experimental sensitivity.

A multiplicity of theories beyond the Standard Model predict enhanced LFV in τ decays over μ decays with branching fractions within experimental reach. An observation of cLFV would thus be a clear sign for New Physics, while lowering the experimental upper limit will help to further constrain exotic theories.

LHCb already with a few fb^{-1} of data has made significant contributions in the search for lepton flavour-violating τ decays. The neutrinoless decay $\tau^+ \to \mu^+\mu^-\mu^+$ is of particular interest for LHCb because the inclusive τ production cross section at the LHC is large ($\sim 80\,\mu\mathrm{b}$) and muon final states provide clean signatures in the detector. It is favoured with respect to the radiative decay $\tau^+ \to \mu^+\gamma$ and $\tau^+ \to e^+e^-e^+$ due to considerably better particle identification of the muons and better possibilities for background discrimination.

With $1\,\mathrm{fb}^{-1}$ collected in 2011 with $\sqrt{s} = 7\,\mathrm{TeV}$, LHCb has put an upper limit [20] on the branching fraction of the $\tau^+ \to \mu^+\mu^-\mu^+$ of $\mathcal{B}(\tau^+ \to \mu^+\mu^-\mu^+) < 6.3(7.8) \times 10^{-8}$ at 90% (95%) CL and demonstrated an experimental sensitivity comparable, even if not yet better, with the current best experimental upper limit from Belle [21], $\mathcal{B}(\tau^+ \to \mu^+\mu^-\mu^+) < 2.1 \times 10^{-8}$ at 90% CL. The large integrated luminosity ($\sim 50\,\mathrm{fb}^{-1}$) that will be collected by the upgraded LHCb experiment will allow to improve the upper limit to the level of 10^{-9}.

The decays $B^0_{(s)} \to e^{\pm}\mu^{\mp}$ are forbidden within the SM. One of the scenarios beyond the SM that allows these decays is the Pati-Salam model of leptoquarks [22]. This model predicts a new interaction to mediate transitions between leptons and quarks via exchange of spin-1 gauge bosons, that carry both color and lepton quantum numbers.

Current limits from ATLAS [23-25] and CMS [26-28] on the masses of first, second- or third-generation leptoquarks are in the range $[0.4, 0.9]\,\mathrm{TeV}/c^2$, depending on the value of the couplings and the decay channel. These leptoquarks arise from a coupling between a quark and lepton of the same generation. The decays $B^0_s \to e^{\pm}\mu^{\pm}$ and $B^0 \to e^{\pm}\mu^{\pm}$ can be mediated by other leptoquarks which couple leptons and quarks that are not necessarily from the same generation [29,30], such as when the τ lepton couples to a first or second quark generation.

The previous best upper limits on the branching fraction of these decays come from the CDF Collaboration [31], $BR(B^0_s \to e^{\pm}\mu^{\pm}) < 2.0\ (2.6) \times 10^{-7}$ and $BR(B^0 \to e^{\pm}\mu^{\pm}) < 6.4\ (7.9) \times 10^{-8}$ at 90% (95%) confidence level (CL). These limits correspond to bounds on the masses of the corresponding Pati-Salam leptoquarks of $M_{\mathrm{LQ}}(B^0_s \to e^{\pm}\mu^{\pm}) > 47.8\,(44.9)\,\mathrm{TeV}/c^2$ and $M_{\mathrm{LQ}}(B^0 \to e^{\pm}\mu^{\pm}) > 59.3\,(56.3)\,\mathrm{TeV}/c^2$ at 90 (95)% CL [31].

The search for the decays $B^0_{(s)} \to e^{\pm}\mu^{\mp}$ at LHCb has been performed with a data sample corresponding to an integrated luminosity of $1.0\,\mathrm{fb}^{-1}$ [32]. The observed number of candidates is consistent with the background expectation and upper limits on the branching ratios of both decays have been determined: $BR(B^0_s \to e^{\pm}\mu^{\pm}) < 1.1\,(1.4) \cdot 10^{-8}$ at 90% (95%) CL, $BR(B^0 \to e^{\pm}\mu^{\mp} < 2.8\,(3.7) \cdot 10^{-9}$ at 90% (95%) CL. These limits are the most restrictive to date and are a factor of 20 lower than those set by the CDF experiment [31]. Using these limits LHCb finds the following lower bounds for the leptoquark masses if the leptoquark links the τ lepton to the first and second quark generation, $M_{\mathrm{LQ}}(B^0_s \to e^{\pm}\mu^{\pm}) > 107\,(101)\,\mathrm{TeV}/c^2$ and $M_{\mathrm{LQ}}(B^0 \to e^{\pm}\mu^{\pm}) > 135\,(126)\,\mathrm{TeV}/c^2$ at 90 (95)% CL, respectively (see fig. 4) which are a factor of two better than the previous ones.

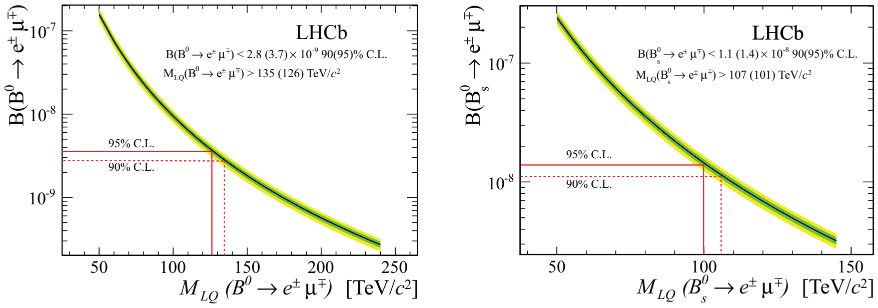

Fig. 4. – Branching fraction as a function of the leptoquark mass for (left) $B^0 \to e^{\pm}\mu^{\pm}$ and (right) $B_s^0 \to e^{\pm}\mu^{\pm}$ for leptoquarks linking the τ lepton (left) to the second and first quark (right) generation, respectively.

The existence of Majorana neutrinos [33] would imply that lepton number, L, is no longer conserved and it would be possible to have decays which violate lepton number by two units ($\Delta L = 2$). The most well known experimental signature for such processes is neutrinoless double-beta decay [34]. However, $\Delta L = 2$ processes could also be observed through meson decays of the form $B^- \to \pi^+ N$ with $N \to \mu^-\mu^-$, fig. 5 (left). No signal has been found by LHCb in the above channel [35] in the full dataset collected in Run I. The decay $B^- \to \pi^+\mu^-\mu^-$ has been used to establish neutrino mass dependent upper limits on the coupling $|V_{\mu 4}|$ of a heavy Majorana neutrino to a muon and a virtual W that is shown in fig. 5 (right).

6. – Conclusions

Thanks to the performances of the LHC and the excellent run of the detector, the LHCb experiment has collected about $3\,\text{fb}^{-1}$ in 2011 and 2012. This has allowed to produce several important measurements in the rare decays of B mesons and τ leptons. No unambiguous signal of deviations from SM predictions has been observed so far. This fact, together with the compatibility of the Higgs properties with the SM predictions raise some doubts about the relevance of the naturalness argument as an organizing principle at higher energies: the Standard Model, in fact, could be a self-consistent stable or meta-stable weakly coupled effective field theory up to very high scales (possibly up to the Planck scale) without adding new particles. The coming Run II at 13 TeV of centre-of-mass energy will help to shed light on the situation.

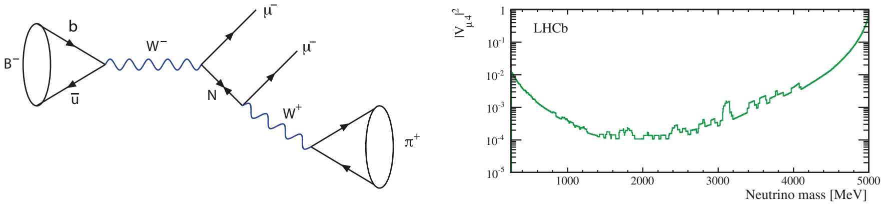

Fig. 5. – Left: Feynman diagram for $B^+ \to \pi^-\mu^+\mu^+$ decay via a Majorana neutrino labeled N. Right: Upper limits at 95% CL on $|V_{\mu 4}|$ are shown as a function of m_N.

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