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Rare decays at LHCb

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Rare decays of B and D mesons are sensitive to the presence of physics beyond the Standard Model as they are mediated by loop diagrams. New physics can be probed by measuring unexpectedly high branching ratios, CP, isospin and forward backward asymmetries and other angular observables. Recent results obtained by the LHCb experiment in this field are presented in this document.

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[*] Speaker.

1. Introduction.

Rare decays are good tools to probe New Physics (NP) beyond the Standard Model (SM). Indeed, they proceed via Flavor Changing Neutral Currents (FCNC) like $b \to s$, $b \to d$ for the B-decays and $c \to u$ for the D-decays, which are possible only at loop level in the SM. NP particles might contribute in the loops and become detectable by causing deviations of observables such as branching ratios, CP, isospin or angular asymmetries from the SM prediction.

The LHCb detector [1] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream. The combined tracking system has a momentum resolution $\Delta p/p$ that varies from 0.4% at 5GeV/c to 0.6% at 100GeV/c, and an impact parameter (IP) resolution of 20 μm for tracks with high transverse momentum. Charged hadrons are identified using two ring-imaging Cherenkov detectors. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers. The LHCb trigger system [2] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage which applies a full event reconstruction.

The LHCb results presented here were obtained using a dataset corresponding to an integrated luminosity of 1.0 fb^{-1} collected in 2011 at $\sqrt{s} = 7$ TeV. In the case of the search for $B_{(s)} \to \mu\mu$ decays, half the data collected in 2012 (1.1 fb^{-1}) were also analysed.

2. General analysis strategy.

Rare decays make use of the highly flexible and configurable software trigger that divides the available bandwidth among many specific *lines*. A series of such lines, similar to offline selections, were designed to ensure a high trigger efficiency on the rare decays. This constituted a first step in the analyses presented in this document.

Rare decays suffer of large relative backgrounds. There are two types of background: a combinatorial component and an exclusive or partially-reconstructed component, defined by hadronic decays that peak in the invariant mass region close to the signal mass peak, when the hadrons in the final state are misidentified as leptons. These peaking background can be reduced by using particle identification techniques: in the particular case of hadrons misidentified as muons, cuts on a combined likelihood based on the informations from the muon system, the calorimeter and the RICH detectors are applied. In general, the combinatorial background is addressed by using multivariate techniques such as neural networks or Boosted Decision Trees (BDT) [3]. They are based on the kinematical and topological properties of the signal decays such as: transverse momenta, flight distances, displaced vertexes, etc...

Normalisation modes are used to minimize systematic uncertainties.These are decays that have a similar final state as the signal and are consequently reconstructed and selected with similar efficiency.

The branching fraction (BF) of the studied decays is measured by using the known branching fraction of the normalization mode: $BF_{signal} = BF_{norm} \times \frac{\varepsilon_{norm}}{\varepsilon_{signal}} \times \frac{N_{signal}}{N_{norm}}$, where N_{signal}, N_{norm} are the signal and normalization yields, and where ε_{signal}, ε_{norm} are the efficiencies with which they are reconstructed and selected.

Efficiencies are calculated using Monte Carlo (MC), corrected with the help of control samples selected in real data. For instance, $B \to J/\psi X(J/\psi \to \mu^+\mu^-)$ decays are used to determine the muon identification performance. A large part of the systematic effects cancels in the efficiency ratio, yielding corrections typically of a few per cents at most.

The searches presented in this document are based on blind analyses. Upper limits on branching fractions are derived using the CLs method [4].

3. Searches and Branching fraction measurements.

Searches for very rare decays are an important part of LHCb's physics program. In addition to the golden $B^0_{(s)} \to \mu\mu$ channel, that allows stringent constraints on NP models due to its very small branching ratio in the SM and to the precision of the theoretical predictions, D, K and τ very rare decays are studied. These searches benefit of large production cross sections [5], thanks to which LHCb is a general purpose flavour factory.

3.1 Evidence for $B^0_{(s)} \to \mu^+\mu^-$.

The $B^0_{(s)} \to \mu^+\mu^-$ mode is a FCNC decay which is also helicity suppressed. The SM predictions are: $BF(B^0 \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$ [6] and $BF(B^0_s \to \mu^+\mu^-)_{<t>} = (3.54 \pm 0.30) \times 10^{-9}$ [7]. Previous upper limits are $BF(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-9}$ @ 95% CL and $BF(B^0_s \to \mu^+\mu^-) < 0.9 \times 10^{-9}$ @ 95% CL [8].

In LHCb's analysis [9], two BDTs have been designed to separate the signal and background. The first one reduces the data size to a manageable level by keeping the efficiency on the signal as high as possible. It uses the impact parameter and impact parameter χ^2 of the B candidate, the χ^2 of the secondary vertex, the angle between the direction of the momentum of the B candidate and the direction defined by the difference between the secondary and the primary vertex, the minimum distance between the two daughter tracks, the minimum impact parameter of the muons with respect to any primary vertex. A cut is applied on its score to enhance the signal purity to the point where setting an upper limit or measuring a branching fraction of the order of the SM prediction is possible. Then, instead of seeking a signal peak in the distribution of the B-meson reconstructed mass alone, a two-dimensional search is performed. The second BDT provides the second variable. This BDT is based on the B candidate IP, the minimum IPχ^2 of the two muons with respect to any PV, the sum of the degrees of isolation of the muons (the number of good two-track vertices a muon can make with other tracks in the event), the B candidate decay time, transverse momenta, and isolation, the distance of closest approach between the two muons, the minimum transverse momenta of the muons, and the cosine of the angle between the muon momentum in the dimuon rest frame and the vector perpendicular to both the B candidate momentum and the beam axis. It is necessary to know precisely the shape of the BDT's output variable for the signal. This is obtained by studying $B^0_{(s)} \to hh$ decays selected in real data, rather than by using the less reliable simulated events.

The new result shows the first 3.5σ evidence with respect to the background-only hypothesis in the $B^0_s \to \mu^+\mu^-$ mode. The corresponding branching fraction is $BF(B^0_s \to \mu^+\mu^-) = (3.17 \pm^{+1.5}_{-1.2}) \times 10^{-9}$. The $B^0 \to \mu^+\mu^-$ decay was also searched for, yielding the following upper limit: $BF(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$ @ 95% *CL* [9].

3.2 Search for $\tau^- \to \mu^+\mu^-\mu^-$.

This process goes with charged lepton flavour violation (cLFV), which is extremely suppressed in the SM ($< 10^{-40}$ [10]). It has never been observed, unlike the neutral LFV in the neutrino mixing. Some NP models predicts values within LHCb's reach ($< 10^{-7}$ [11]). The previous upper limit was set by the Belle Collaboration to $BF(\tau^- \to \mu^+\mu^-\mu^-) < 2.1 \times 10^{-8}$ @ 90% *CL* [12].

Searches for $\tau^- \to \mu^+\mu^-\mu^-$ were done by LHCb too. In the analysis the standard LHCb muon identification variables were not used, a dedicated BDT was developed instead. It was based on the response from the muon system, RICH and calorimeters to the muons of this particular decay. Against combinatorial background a BDT with geometrical parameters of the decay was used. Both BDTs were calibrated with real data by using $D_s \to \phi(\mu^+\mu^-)\pi^-$ decay.

The upper limit obtained by LHCb, $BF(\tau^- \to \mu^+\mu^-\mu^-) < 6.3 \times 10^{-8}$ @ 90% *CL* [13] , proves that it is possible to perform such kind of searches at hadron colliders.

3.3 First observation of $B^+ \to \pi^+\mu^+\mu^-$.

For $B^+ \to \pi^+\mu^+\mu^-$ the SM predicts $BF(B^+ \to \pi^+\mu^+\mu^-) = (2.0 \pm 0.2) \times 10^{-8}$ [14]. Previously set upper limit, $BF(B^+ \to \pi^+\mu^+\mu^-) < 6.9 \times 10^{-8}$ @ 90% *CL* [15], is still above this prediction. LHCb obtained the first observation of this decay, and measured $BF(B^+ \to \pi^+\mu^+\mu^-) = (2.3 \pm 0.6(stat.) \pm 0.1(syst.)) \times 10^{-8}$ [16]. This is the first observation of the $b \to dl^+l^-$ neutral current, with 5.2 σ significance.

3.4 Search for $D^0 \to \mu^+\mu^-$.

According to the SM, this mode is extremely suppressed ($BF(D^0 \to \mu^+\mu^-) < 6 \times 10^{-11}$ [17]). It indeed proceeds via a FCNC where no very massive particle such as the top quark can enter the loop to mitigate the GIM suppression, unlike in the case of B decays. Nevertheless some NP models, like MSSM-RPV where FCNC are possible at the tree level, predict that the BF could be as high as $\sim 10^{-10}$ [18]. Previous upper limit has been set up by the Belle Collaboration $BF(D^0 \to \mu^+\mu^-) < 1.4 \times 10^{-7}$ @ 90% *CL* [19].

One of the angular stones in LHCb's analysis [20], is the use of tight muon identification criteria. Indeed, peaking backgrounds in case of charm decays are higher than in case of B decays. This is due to the fact that charm meson decays to two, three or four charged hadrons occur at the percent level. Tight criteria can be used thanks to a precise determination of LHCb's performance in terms of pion to muon misidentification. We used real data with a high statistics control mode $D^0 \to K^-\pi^+$.

The obtained upper limit is $BF(D^0 \to \mu^+\mu^-) < 1.3 \times 10^{-8}$ @ 90% *CL* [20].

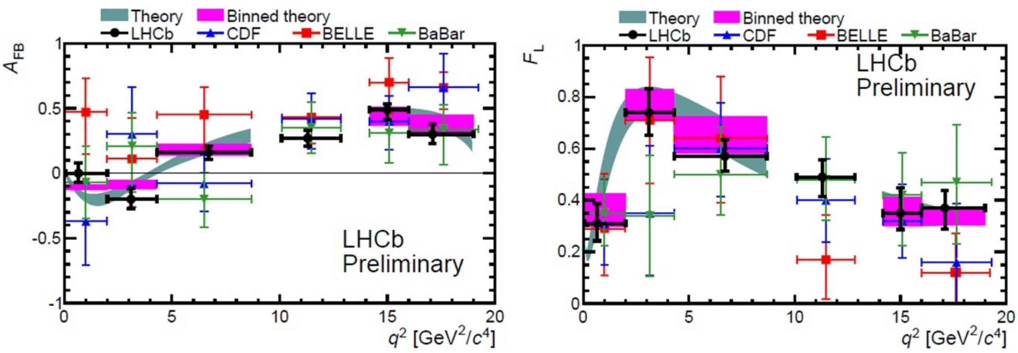

Figure 1: Lepton forward-backward asymmetry, A_{FB}, and fraction of longitudinal polarization of the K^{0*}, F_L, as functions of dimuon mass $q^2 = m^2(\mu\mu)$. The SM expectation, results of previous experiments are included for reference. Figure is taken from [25].

3.5 Search for $K_s \to \mu^+\mu^-$.

Even if the $K_L \to \mu^+\mu^-$ decay is measured, the $K_s \to \mu^+\mu^-$ is highly suppressed due to short-distance domination, while in K_L decay long-distance effects prevail. The SM predicts $BF(K_s \to \mu^+\mu^-) = (5.0 \pm 1.5) \times 10^{-12}$ [21]. The most recent upper limit, $BF(K_s \to \mu^+\mu^-) < 3.2 \times 10^{-7}$ @ 90% CL [22], dates back to 1973.

New upper limit is $BF(K_s \to \mu^+\mu^-) < 9 \times 10^{-9}$ @ 90% CL [23].

4. Analysis of the angular distributions, CP and Isospin asymmetries.

Angular distributions and asymmetries are observables with small hadronic uncertainties. They can provide a very clean probe of physics beyond the SM.

4.1 Angular analysis of $B^0 \to K^{0*}\mu^+\mu^-$.

With four particles in the final states, the full description of the $B^0 \to K^{0*}\mu^+\mu^-$ decay involve the invariant mass squared of the dimuon system, q^2, as well as three angles [24]. The observables that govern the shape of the angular distributions, such as the forward-backward asymmetry A_{FB}, depend strongly on the underlying physics. In particular, the presence of right handed currents could make them deviate from the SM predictions. This, and the fact that they can be predicted with a good control over theoretical uncertainties makes them excellent probes for NP.

The LHCb analysis [25] gives the last measurements of these observables. For that purpose, the angular distributions are fitted in six regions of q^2. The fit accounts for the signal acceptance as a function of the angles. The determination of this acceptance is one of the main ingredients of this measurement. It uses the MC simulation, which has been corrected based on real data to produce a reliable result. Figure 1 shows two of the observables (A_{FB} and F_L), together with the SM predictions and the previous measurement performed by CDF [26], BELLE [27] and Babar [28]. No deviation from the SM predictions is observed.

Of particular interest is q_0^2, the zero crossing point of A_{FB} as a function of q^2 (i.e. $A_{FB}(q_0^2) = 0$). It is very sensitive to NP, and can be predicted with a small theoretical uncertainty. In the

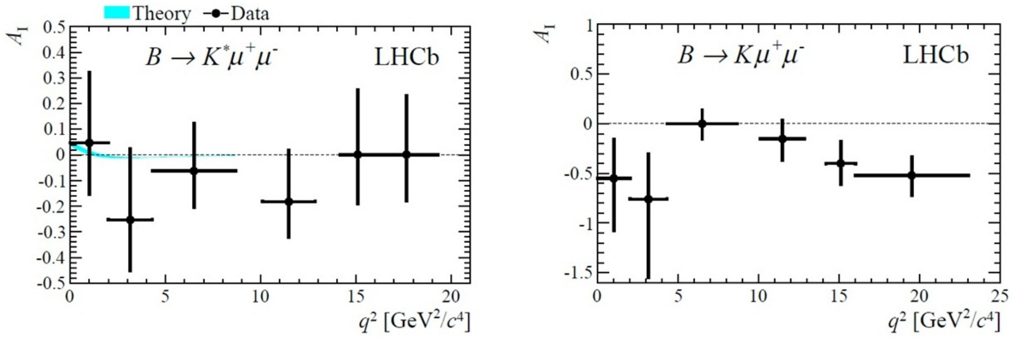

Figure 2: Isospin asymmetries as measured by LHCb [25]. The asymmetry comparing the $B^0 \to K^{0*}\mu^+\mu^-$ and $B^\pm \to K^{*\pm}\mu^+\mu^-$ modes is shown on the left. That comparing the $B^0 \to K^0\mu^+\mu^-$ and $B^\pm \to K^\pm\mu^+\mu^-$ modes is shown on the right.

SM: $4.0 < q_0^2 < 4.3 GeV^2/c^4$ (see for example [29]). LHCb measured it for the first time: $q_0^2 = (4.3^{+1.1}_{-1.3})$ GeV$^2/c^4$[25]. This is which is consistent with the SM predictions.

4.2 Measurement of the CP asymmetry in $B^0 \to K^{0*}\mu^+\mu^-$ decays.

In the SM, CP asymmetry($\mathscr{A}_{CP}$) in the $B^0 \to K^{0*}\mu^+\mu^-$ is expected to be $\sim 10^{-3}$ [24], but in some NP models $\mathscr{A}_{CP}$ could be enhanced up to ± 0.15 [30]. Previous measurements have shown no sizeable CP asymmetry in these decays and are dominated by their statistical uncertainty: $\mathscr{A}_{CP}(B^0 \to K^{0*}l^+l^-) = -0.10 \pm 0.10(stat.) \pm 0.01(syst.)$ [31] and $\mathscr{A}_{CP}(B^0 \to K^{0*}l^+l^-) = 0.03 \pm 0.13(stat.) \pm 0.01(syst.)$ [32].

With almost 100 times more statistics, LHCb improved this measurement, but found no evidence of CP violation: $\mathscr{A}_{CP}(B^0 \to K^{0*}\mu^+\mu^-) = -0.072 \pm 0.040(stat.) \pm 0.005(syst.)$ [33].

4.3 Measurement of the isospin asymmetry in $B \to K^{(*)}\mu^+\mu^-$ decays.

The CP averaged isospin asymmetry is defined as

$$\mathscr{A}_I = \frac{BF(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}BF(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}{BF(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}BF(B^\pm \to K^{(*)\pm}\mu^+\mu^-)},$$

where τ_0/τ_+ is the ratio of the B^0 to B^+ lifetimes.

In the SM the isospin asymmetry in $B \to K^*\mu^+\mu^-$ is predicted to be $\sim 1\%$ at high q^2, while it could reach $\sim \mathscr{O}(10\%)$ when $q^2 \to 0$ [34]. NP models where d/u-quarks are not spectators predict $\mathscr{A}_I \neq 0$. Previous measurements have not shown any deviation from the SM [35].

The most recent measurement by LHCb (Figure 2) is also consistent with the SM. In the case of $B^0 \to K^0\mu^+\mu^-$ - $B^\pm \to K^\pm\mu^+\mu^-$, where no precise theoretical predictions are available, a deviation seems to appear. Integrated over the whole dimuon spectrum, it adds up to a 4.4 σ significance (Figure 2) [36]. New theoretical predictions are needed to interpret this results.

5. Conclusions.

Rare decays are valuable probes of physics beyond the Standard Model. Their searches are an important part of LHCb's physics program. Branching fractions, CP, isospin and forward backward asymmetries and other angular observables were studied in B, D, K and τ very rare decays. The presented results are based on 1.0 fb^{-1} of data collected in 2011. They are consistent with SM expectations, with the possible exception of the isospin asymmetry in the $B \to K\mu^+\mu^-$. Updated results using the data collected in 2012 at $\sqrt{s} = 8$ TeV should be available in the coming months.

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