

Beauty and charm rare decays at the LHC: prospects for Run II

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The main results on the searches for rare decays of B and D mesons from ATLAS, CMS and LHCb experiments are summarised in this report. Particular attention will be given to the measurements performed by at least two of the three experiments, where common aspects and differences are highlighted. Detector improvements and perspectives of the three experiments for Run II ongoing data campaign are also discussed.

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1. Introduction

Rare decays proceeding via flavour changing neutral currents (FCNC) are forbidden at tree level in the Standard Model (SM), and can only occur at loop order. However, in SM extensions new particles can contribute at loop or tree level, resulting in a modification of the amplitude of the process, appearance of new sources of CP violation or change in the angular distribution of final-state particles. Therefore, information about physics beyond the SM can be gathered by searching for possible deviations from the predictions on branching fractions or angular distributions of rare decay processes.

This article reviews some of the studies on rare b and c decays conducted during LHC Run I by the ATLAS [1], CMS [2] and LHCb [3] experiments, and outlines the perspectives for Run II measurements.

The LHCb detector has been specifically designed to access the physics of heavy flavours in the forward region. It is characterized by an excellent particle identification provided by RICH detectors, and good impact parameter and momentum resolutions. LHCb runs at a leveled instantaneous luminosity in order to limit the pile-up effects. Thanks to its forward geometry and highly efficient and flexible trigger, able to efficiently select muons, electrons, hadrons and photons, LHCb can access very low transverse momentum ranges.

The general purpose experiments ATLAS and CMS cover a rapidity range up to $|\eta| < 2.5$. Both experiments fully exploit the tracking devices located closest to the interaction point and the muon-detectors, the farthest out sub-detector. Their capabilities to measure rare decay properties are almost entirely driven by their excellent muon reconstruction and identification performance. In fact, in both experiments heavy flavour analyses are mainly based on multi-muon triggers, which can collect signals down to low muon transverse momenta (few GeV).

All three experiments already explored the two benchmark channels, $B_{s(d)}^0 \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ using Run I data (ATLAS contribution on the latter measurement is still to be published).

The increased amount of events that will be delivered by the LHC during Run II will allow to improve the precision on those measurements, along with offering the opportunity to access to other very rare decay modes. However, due to the high instantaneous luminosity, a significant limitation for the two omni-purpose experiments is represented by the increase in the trigger thresholds, which might reduce the reach of their heavy flavour program.

Both the ATLAS and the CMS experiments have been facing significant detector improvements to deal with the high rate and pileup environment of Run II. In particular, a new pixel layer, called Insertable B-Layer (IBL), has been installed in the ATLAS detector during the long shutdown of the LHC machine. The new detector, inserted at a radius of about 33.25 mm from the beam-pipe, will provide up to a factor of 2 improvement in the impact parameter resolution for low p_T tracks. The ATLAS muon system has also been upgraded with the installation of new chambers and the addition of a new Thin Gap Chamber (TGC) coincidence layer, which minimises fakes in the high pseudorapidity region.

The CMS pixel detector will be renewed during the extended end-of-year shutdown 2016-2017. The so-called Phase1 Pixel foresees one additional barrel layer and one additional endcap disk, which will provide more robust tracking performance. It also includes a new improved readout chip, lower material budget, and the installation of more efficient cooling and powering systems.

The trigger systems of all the three experiments have also been revised for Run II. The two levels of the ATLAS trigger system have been upgraded. The capabilities of the Level-1 trigger were improved in several ways. In particular, additional inputs were added to the Level-1 Muon trigger and both the Level-1 Calorimeter and Muon triggers have been interfaced to a new topological trigger processor, currently under commissioning, which supplies information about the event topology. This additional information will help in suppressing the background rate while maintaining low thresholds on muon transverse momentum, providing significant improvements in the low p_T physics performance. Furthermore, the ATLAS experiment planned the installation of an hardware processor dedicated to tracking: the Fast TracKer (FTK) processor. FTK is designed to perform a fast track reconstruction between the Level-1 and the High Level Trigger step and to provide a fast track reconstruction similar to the offline reconstruction.

The CMS experiment underwent a complete renovation of its hardware trigger (L1) in 2016. Both the L1 Calorimeter and Muon triggers have been upgraded. As far as the Muon trigger is concerned, data from the three muon detection systems (Drift Tubes, Resistive Plate Chambers and Cathode Strip Chambers) have been combined in order to obtain a higher efficiency and a better rate reduction. More sophisticated algorithms and the possibility to use more complex topological requirements and invariant mass selections also contribute maintaining low thresholds on muon momenta and affordable trigger rates.

The LHCb software trigger has been completely revised. The trigger farm has been improved to be able to write to storage 12.5 kHz instead of 5 kHz. The running of the two levels of software trigger has been split in two separate instances: the first one running synchronous with the LHC collisions with the second stage running asynchronously. This split allows to perform a real-time calibration and alignment of the detector before the second software trigger level. The software trigger is thus able to select events based on a reconstruction with a quality identical to the offline processing.

2. Measurements of the $B_{(s)}^0 \rightarrow \mu\mu$ rare decays

The $B_{(s)}^0$ decays into a pair of oppositely charged muons (referred in the following to as $B_{(s)}^0 \rightarrow \mu\mu$) is extremely interesting because it is forbidden at lowest perturbative order in the SM due to FCNC suppression and the additional helicity suppression (by a factor of m_μ^2/m_B^2). Thus the decay can only proceed through loop diagrams. New heavy particles in extensions of the SM can appear in competing Feynman diagrams and significantly affect the decay branching fractions. Therefore these processes are sensitive to a wide range of new physics phenomena which are not predicted by the SM. Furthermore, thanks to the helicity suppression, the $B_{(s)}^0 \rightarrow \mu\mu$ branching fractions are accurately predicted in the SM: $BR(B_s^0 \rightarrow \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$ and $BR(B_d^0 \rightarrow \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$ [4]. Hence any significant deviations from these predictions would be a hint of New Physics (NP).

Recently, all three Collaborations (ATLAS, CMS and LHCb) have reported measurements of these branching fractions using full Run I dataset, corresponding to 25 fb^{-1} for ATLAS and CMS and 3 fb^{-1} for LHCb respectively. CMS and LHCb Collaborations also performed a combined measurement of both branching fractions. The $B_s^0 \rightarrow \mu\mu$ decay was observed with a $BR(B_s^0 \rightarrow \mu\mu) = 2.8_{-0.8}^{+0.7} \times 10^{-9}$ while an evidence of the $B_d^0 \rightarrow \mu\mu$ decay, with a $BR(B_d^0 \rightarrow \mu\mu) = 3.9_{-1.4}^{+1.6} \times$

10^{-10} [5] was found. The ATLAS Collaboration has only recently published the measurements, reporting a value for $\text{BR}(B_s^0) = 0.9_{-0.8}^{+1.1} \times 10^{-9}$ and setting an upper limit at 95% C.L. on $\text{BR}(B_d^0) < 4.2 \times 10^{-10}$. [6]

All these analyses extracted both branching fractions simultaneously from a fit in the di-muon invariant mass. In order to minimise the systematic uncertainties affecting the measurement, the branching fractions were evaluated with respect to the same reference channel $B^\pm \rightarrow J/\psi(\rightarrow \mu\mu)K^\pm$. Despite the better resolution in invariant mass of CMS and especially of LHCb, ATLAS showed a similar single-event-sensitivity due to a better rejection of the combinatorial and the peaking backgrounds. The latter especially was achieved applying a multivariate selector based on calorimetric and tracking variables which significantly reduced the contribution of the hadrons (namely π and K) that are misidentified as muons. On the other hand, LHCb and CMS provided a better treatment of the partially reconstructed and semileptonic decays contributions in the di-muon invariant mass fit. In Figure 1 a summary of the branching fractions measurements performed by the three experiments is shown.

All three experiments consider these measurements crucial in the respective physics programs. All detector improvements described in Section 1 will be highly beneficial for all experiments to fully exploit the larger dataset they will collect during the Run II campaign. Since these measurements are still statistically limited, ATLAS and CMS can be competitive in Run II with respect to LHCb, given the larger integrated luminosity that the LHC machine will deliver to them. Nevertheless, the capability of the two experiments to keep the di-muon trigger p_T thresholds as low as possible will be the main challenge in order to maintain the competitiveness in these measurements. The combination of the results of the three experiments using the full Run II expected integrated luminosity will allow to produce a measurement of the $B_{(s)}^0 \rightarrow \mu\mu$ branching fraction with a precision comparable to the theoretical predictions.

3. Electroweak penguins decays

Similarly to $B_{(s)}^0 \rightarrow \mu\mu$ decays, also $b \rightarrow sl^+l^-$ transitions are suppressed in the SM and thus very sensitive to New Physics processes. These decays are forbidden at the lowest perturbative order and proceed through loops involving electroweak penguin diagrams. Contrary to $B_{(s)}^0 \rightarrow \mu\mu$ decays, the $b \rightarrow sl^+l^-$ transitions do not have any helicity suppression. This means that possible NP contributions can modify not only the branching ratios of the decays, but also the angular distributions of the particles in the final state. Eventual contributions from NP processes can be parameterised into the SM lagrangian using the effective field theory (EFT) approach. This approach allows to describe any NP contribution simply using higher dimension operators O_i and the energy scale Λ_{NP} where NP phenomena should appear. The total lagrangian L , which includes NP contributions, can then be written as:

$$L = L_{SM} + \sum_i c_i \frac{O_i}{\Lambda_{NP}^2} \quad (3.1)$$

where L_{SM} represents the SM lagrangian and c_i are complex coefficients (called Wilson coefficients) related to the strength of the interaction. In the SM, all c_i coefficients are zero. Any significant discrepancy would then be a hint of the presence of NP phenomena.

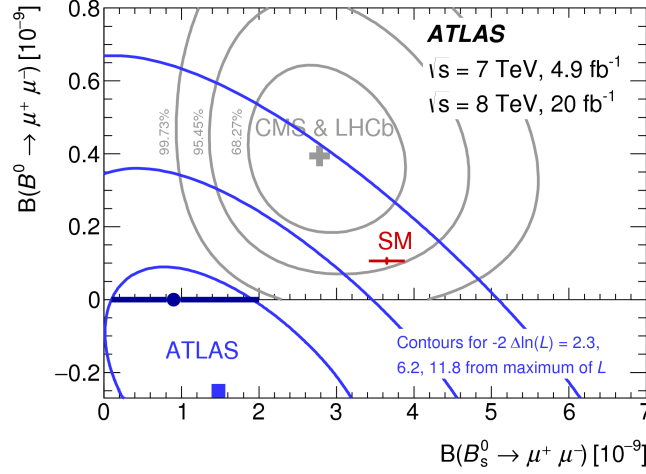


Figure 1: Contours in the plane $\text{BR}(B_s^0 \rightarrow \mu\mu)$, $\text{BR}(B_d^0 \rightarrow \mu\mu)$ for intervals of $-2\Delta\ln(L)$ equal to 2.3, 6.2 and 11.8 relative to the absolute maximum of the likelihood (blue square), without imposing the constraint of non-negative branching fractions. Also shown are the corresponding contours for the combined result of the CMS and LHCb experiments, the SM prediction, and the maximum of the likelihood within the boundary of non-negative branching fractions (blue dot), with the error bars covering the 68.3% confidence range for $\text{BR}(B_s^0 \rightarrow \mu\mu)$.

Several decay topologies involving mesons and baryons that contain b -quark belong to this category. One of the most interesting channels is $B^0 \rightarrow K^{*0}\mu^+\mu^-$, where only the $K^{*0} \rightarrow K^+\pi^-$ decay mode is considered. The SM predicts a branching ratio of about 4.5×10^{-7} , and the full kinematics of the decay can be described by three angles and the invariant mass squared q^2 of the two muons in the final state. The measurement of the three decay angles and of the differential decay rate as a function of q^2 allows to extract specific parameters called P'_i (referred to in the following as optimised observables since they are independent, at the first order, of the form-factors involved in the calculation) which can be directly related to the Wilson coefficients c_i introduced above.

The most complete analysis has been performed by LHCb [7]. The branching ratio and the three angles have been measured simultaneously and the full set of P'_i parameters was extracted. A partial angular analysis has also been performed by the CMS Collaboration [8]. The analysis led to the extraction of the forward-backward asymmetry A_{FB} measured in the di-muon system. A_{FB} is another observable entering in the formula which describes the differential decay rate for this channel. Both ATLAS and CMS Collaborations are preparing the full angular analysis on the full Run I dataset. Figure 2 (left) shows the measurements of the A_{FB} parameter as a function of q^2 performed by CMS experiment (compared with the SM prediction [9]), while Figure 2 (right) shows the measurement of one of the optimised observables (namely P'_5) as a function of q^2 , performed by the LHCb Collaboration (compared with the values obtained by Belle Collaboration [11] and the SM predictions [12]). A discrepancy of the order of $2.8\text{--}3.0\sigma$ with respect to the SM predictions, has been reported by LHCb experiment for q^2 values between 4 and 8 GeV^2 .

Several other decay modes associated with the $b \rightarrow s\mu^+\mu^-$ transition process have been considered by LHCb (such as $B^+ \rightarrow K^+\mu^+\mu^-$, $B_s \rightarrow \phi\mu^+\mu^-$ and $\Lambda_b \rightarrow \Lambda\mu^+\mu^-$). Each of these

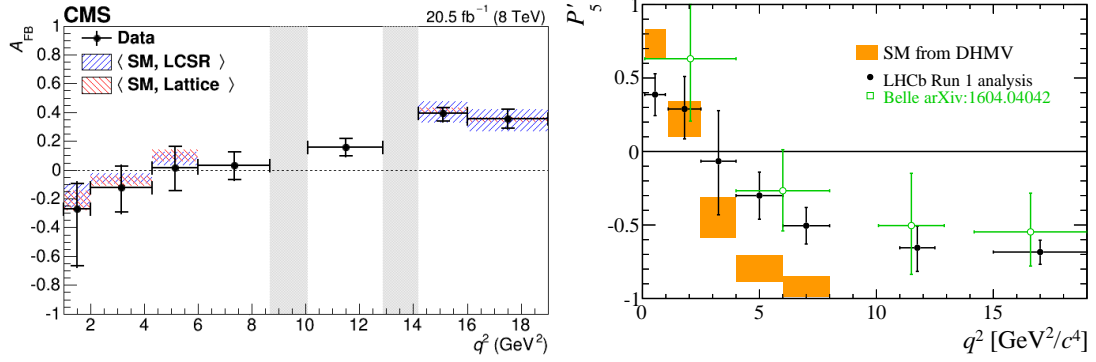


Figure 2: (Left) A_{FB} measurements as a function of q^2 as reported from CMS. The SM predictions are taken from [9, 10]. (Right) P'_5 distribution as a function of q^2 for the measurements performed by LHCb [7] (black dots) and Belle [11] (green) Collaborations. The uncertainties include both statistical and systematic components. The SM predictions (yellow bands) are taken from [12].

processes is sensitive to a different set of Wilson coefficients with respect to $B^0 \rightarrow K^{0*} \mu^+ \mu^-$ channel. The differential branching fractions as a function of q^2 have been measured for each channel and compared with the SM predictions. Some discrepancy with respect to the SM calculations, even if not significant, has been found also in some of these measurements.

The plan for the Run II campaign of the three experiments in this domain is to systematically analyse several decay modes related to $b \rightarrow s \mu^+ \mu^-$ transitions in order to find any significant discrepancy of the optimised observables with respect to the SM predictions. The LHCb experiment is also planning to perform the same set of measurements using electrons rather than muons in the final state.

4. Other rare decays

In this section we describe a set of studies which are important for their NP sensitivity but whose results are almost exclusively from LHCb. We do not go into the detail of the measurements but give only a brief review of them.

4.1 Lepton Flavour Violation

The violation of lepton number (LNV) and lepton flavour conservation (LFV) are strictly prohibited inside the SM, with the notable exception of neutrino oscillations, producing negligibly small effects in the charged sector. The discovery of a LNV or LFV decay of a known particle would be therefore a striking evidence of physics beyond the SM.

A rich program of searches for LNV and LFV decays is undergoing at the LHC experiments. While the LHCb experiment can cover the full spectrum of beauty, charm and τ decays, the ATLAS and CMS experiments, given the low p_T of the physical objects involved, do concentrate on specific decays which are easier to trigger.

LHCb has set world best upper limits on $B_{(s)}^0 \rightarrow e \mu$ [13] and $D^0 \rightarrow e \mu$ [14] decays and has set a competitive limit on $\tau \rightarrow \mu \mu \mu$ decays, contributing to improve the world combined limit

[15]. The ATLAS experiment has contributed recently to the same decay by looking for $\tau \rightarrow \mu\mu\mu$ where the τ comes from a W boson leptonic decay [16]; the sensitivity of this search is not yet competitive with LHCb and B-factories but proves the feasibility of such a delicate analysis in the high p_T environment. Finally among the searches for LNV the most prominent is the LHCb search for prompt or long-living Majorana neutrinos in $B^+ \rightarrow \pi^- \mu^+ \mu^+$ decays [17].

Already exploiting Run I data, many other searches are in progress in the whole family of $B \rightarrow X e \mu$ decays and $B \rightarrow X \mu \tau$ decays where X is a SM hadron.

All the mentioned searches will be continued with Run II data aiming at NP hints or pushing further the limits on LFV and LNV couplings. During this period, the Belle II experiment will start accumulating data and will compete strongly on the same channels. While channels with muons, being easy to trigger, are essentially limited by the collected luminosity, the others will profit of the improved LHCb trigger in Run II and will stay as key measurement also for the Phase I Upgrade.

4.2 Radiative decays

Rare radiative b -hadrons decays, probing the FCNC $b \rightarrow s\gamma$ transition, are complementary to $b \rightarrow s\ell\ell$ processes and are particularly sensitive to the C_7 Wilson coefficient.

The LHCb core physics program includes also radiative b -mesons decays. In particular the LHCb experiment has published the first observation of the photon polarisation in $b \rightarrow s\gamma$ transitions through the study of $B^+ \rightarrow K^+ \pi^+ \pi^- \gamma$ decays [18]. Furthermore the ratio of branching fractions of the $B^0 \rightarrow K^{*0} \gamma$ and $B_s^0 \rightarrow \phi \gamma$ decays has been measured together with a search for direct CP asymmetry of the $B^0 \rightarrow K^{*0} \gamma$ decay [19]. These measurements are only the starting point of a long program of measurements of which a notable example will be the measurement of the effective lifetime of the $B_s^0 \rightarrow \phi \gamma$ decay, which is strongly sensitive to NP.

The study of radiative b -hadron decays at ATLAS and CMS is difficult due to the low efficiency of reconstructing very low p_T photons, either directly or as e^+e^- pairs. Therefore, at present, no contribution from the two experiments is foreseen in this field.

4.3 Rare charm decays

Rare decays involving charm hadrons are fundamental probes of new physics: not only being complementary to b - and s -hadrons by probing the up sector, but also because up-type FCNC transitions undergo a more effective GIM suppression, owing to the much smaller mass of the b -quark with respect to the t -quark.

A rich program of rare charm physics is brought forward by LHCb, ranging from FCNC to the already mentioned LFV decays. In particular the studies of $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ [20], $D^0 \rightarrow K^- \pi^+ \mu^+ \mu^-$ [21], $D_{(s)}^+ \rightarrow \pi^+ \mu^+ \mu^-$ [22] and $D^0 \rightarrow \mu^+ \mu^-$ [23] are putting strong bounds on NP scenarios, e.g. models with Leptoquarks [24]. The $D^0 \rightarrow \mu^+ \mu^-$ decays has been studied also by the CMS experiment [25], however this was based on a loose trigger configuration that could not be maintained.

The LHCb experiment will soon exploit Run II data and the study of rare charm decays will still be part of the core physics program also in the upgrade phase. Although ATLAS and CMS could explore the study of these decays exploiting events triggered independently by other particles, they are not expected to be very competitive in the future on this domain. The Belle II experiment is expected to produce significant results in this field, but we do not discuss further this aspect here.

5. Discussion

The searches for rare and semi-rare decays of B and D -mesons are central in the B -physics programme of the three experiments. As for all B -physics searches, the leading role is taken by the LHCb Collaboration, whose detector was designed specifically for this type of physics. Nevertheless, ATLAS and CMS Collaborations can be competitive in the searches for rare processes, that are basically limited by the size of the datasets to be analysed. In fact, both experiments will take advantage of the larger integrated luminosity they will be able to collect during the Run II LHC campaign. Hence we envisage that, for some specific decays, such as the $B_{(s)}^0 \rightarrow \mu\mu$ or those related to the $b \rightarrow sl^+l^-$ transitions (see Section 2 and Section 3), the three experiments will be able to work together to combine their results to fully profit of the statistical power of the available datasets. A good step in this direction has been already made by CMS and LHCb Collaborations in the combination of the $B_{(s)}^0 \rightarrow \mu\mu$ analyses and also by the creation of the LHCC Heavy-Flavour group. We hope that these steps will be the beginning of a fruitful collaboration among the LHC experiments.

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