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Rare B decays at LHC

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For the LHCb, ATLAS, and CMS collaborations

This paper gives an overview of the latest performance studies of LHCb, ATLAS, and CMS in rare-B sector. Flavour Changing Neutral Currents involves $b \to d$ or $b \to s$ transitions occurring only from loop-level in the Standard Model. They consequently provide an excellent probe of effects of New Physics. Within the Standard Model, these decays are sensitive to the CKM matrix elements $|V_{ts}|$ and $|V_{td}|$. Some of these channels, like $B \to K^*\gamma$, have already been measured at B-factories. However, due to a very large $b\bar{b}$ production, the LHC will play a leading role in rare B-decays studies. Very promising sectors, like $B \to K^*\mu\mu$ or $B \to \rho\mu\mu$, will be extensively studied at LHC. Other rare channels, like $B \to \mu\mu$ or $B_s \to \phi\gamma$, could be observed for the first time at the LHC.

1. Introduction

Flavor-changing neutral current decays involving $b \to s$ or $b \to d$ transitions occur only from loop-level in the SM. Therefore they come with small branching ratios and thus provide an excellent probe of indirect new physics effects. Within the SM, these decays are sensitive to the CKM matrix elements $|V_{ts}|$ and $|V_{td}|$. A measurement of these parameters would be complementary to their determination from B mixing.

So far the following exclusive decays have been evaluated for LHC experiments:

- **Radiative decays:** $B_d \to K^{*0}\gamma$ (LHCb, ATLAS), $B_s \to \phi\gamma$ (LHCb, ATLAS), $B_d \to \omega\gamma$ (LHCb).
- **Di-muonic decays:** $B_d \to K^{*0}\mu\mu$, $B_s \to \phi\mu\mu$, $B_d \to \rho\mu\mu$.
- **Purely muonic decays:** $B_{d,s} \to \mu\mu$.

Some of these channels, in particular $B_d \to K^{*0}\gamma$, have already been observed at B-factories. Other channels, like $B \to \mu\mu$, might be seen before the LHC start only if their branching is strongly enhanced, i.e. if new physics effects are large. $B_d \to K^{*0}\mu\mu$ precision measurements, or observation of rare B decays in the B_s sector, will also be reserved for the LHC or BTeV with their higher luminosities.

In any case, LHC will provide radically increased statistics in the rare B decays area. However, these decays will be observed only if they are triggered. Exclusive rare B channels cross-sections are of the order of a *picobarn* or a *femtobarn*, to be compared to LHC global inelastic cross-section of 80 *mbarn*. Consequently we will start with a presentation the different trigger strategies proposed for rare B decays study for LHC.

2. Trigger strategies for rare B decays

Rare B selection in ATLAS, CMS, and LHCb is based on different schemes, depending on each experiment. We could still define two large categories: radiative decays selection, based on electromagnetic first-level trigger, and muonic or semi-muonic decays selection, based on di-muon trigger.

2.1. LHCb

LHCb trigger [1] is presented on fig.1. It is divided into three steps. At the lowest order (called L0), single particles with *high* transverse momentum are searched (thresholds of $1-5$ GeV). L0 is passed if the highest E_T calorimeter cluster, or the two highest p_T muon tracks in the muon stations (named M1 to M5 on fig.1) reach these requirements.

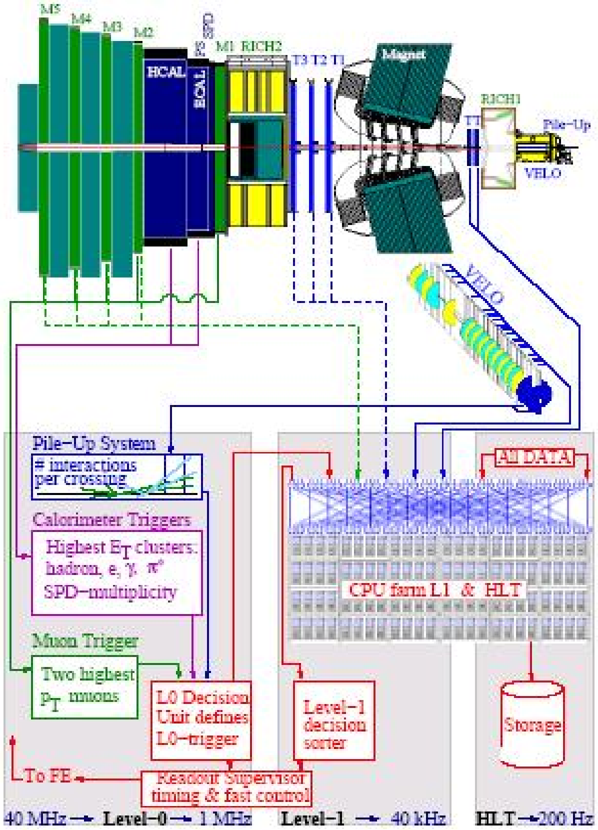

Figure 1. Overview of the LHCb trigger system [1], in parallel with the LHCb detector. Different steps are described with links to the concerned part(s) of the detector.

The B decay vertex is reconstructed at the next level (L1), thus allowing to perform important topological cuts. This vertex trigger is the key in the LHCb selection scheme. Using this feature, LHCb expects very high trigger efficiency for different B physics channels, which are treated separately only at the next step: high-level trigger (HLT).

At the HLT, full event reconstruction is performed and specific cuts are applied. As the efficiencies after HLT are very close to those after L1, the proportion of staged events is very important. For example, 38% of the $B_d \to K^{*0}\gamma$ and 74% of the $B_d \to K^{*0}\mu\mu$ which are within the LHCb acceptance will be selected. This very high trigger efficiency fully compensates LHCb lower luminosity ($2 \times 10^{32} cm^{-2}s^{-1}$, compared to *at least* $2 \times 10^{33} cm^{-2}s^{-1}$ for ATLAS and CMS).

2.2. ATLAS and CMS

In ATLAS and CMS the situation is not equivalent to LHCb. Detector acceptance, instantaneous luminosity, and physics objectives are different. In particular, ATLAS and CMS have more extended physics programs and have to deal with important pile-up effects. These differences lead to additional constraints for the rare B selection.

Muonic and semi-muonic decays are using the classical B-physics dimuon trigger, which is quite similar in ATLAS and CMS than in LHCb, at least at level 1. In this case differences arise only at level 2 (equivalent to LHCb L1). As the vertex trigger is not feasible in ATLAS and CMS, less selective cuts and then higher thresholds are applied, thus lowering the efficiencies. Vertexing and specific cuts are performed at the next level: event filter (EF). As in the LHCb HLT, efficiencies for the signal after EF are equivalent to efficiencies after LVL2. Trigger efficiencies are expected to be smaller in ATLAS and CMS than in LHCb, but di-muon trigger will also work at LHC high luminosity, which will be 50 times larger than LHCb. Thus providing very large and competitive event samples.

Radiative B decays selection is more difficult to handle. Due to pile-up effect (about 5 interactions per crossing at $2 \times 10^{33} cm^{-2}s^{-1}$), “LHCb-like” trigger is not feasible in ATLAS and CMS. In order to reach acceptable rates after level 1, a complementary muon, in addition to the low E_T electromagnetic cluster, is requested. At level 2 interesting tracks coming from K^{*0} or ϕ meson decay are selected in the inner detector, but this step is more difficult to manage in ATLAS and

CMS than in LHCb, and luminosity is at least 10 times larger. However, a recent study has shown that selecting radiative B decays in ATLAS at low luminosity, with about 5% efficiency after HLT and reasonable trigger rates, will be feasible [2].

3. Radiative B decays

Only exclusive radiative B decays, such as $B_d \to K^{*0}\gamma$, $B_s \to \phi\gamma$, or $B_d \to \rho\gamma$, will be observed at the LHC. They are theoretically more difficult to handle than inclusive $B \to X_{(s,d)}\gamma$ channels, but easier to access experimentally. Moreover, theoretical uncertainties affecting branching ratio estimates largerly cancel when doing $\mathcal{CP}$ or isospin violation measurements. These asymmetries are expected to be small within the SM, but they could be largely enhanced by new physics effects [3], [4].

LHC experiments will be able to perform these measurements with a large precision. Table 1 summarize LHCb and ATLAS expectations after one year of running at $2 \times 10^{33} cm^{-2}s^{-1}$, i.e. $2\ fb^{-1}$ for LHCb, and $20\ fb^{-1}$ for ATLAS.

	$B_s \to \phi\gamma$	$B_d \to K^{*0}\gamma$	Ref.
LHCb	9300	35000	[5]
ATLAS	2300	5700	[2]

Table 1: Radiative channels expectations after one year at low luminosity.

LHCb expectations are slightly better than ATLAS. We have see in the previous section that this difference mainly comes from the trigger scheme, which is more efficient in LHCb (no muon needed at first level, vertex trigger, no pile-up).

However, we see that even ATLAS will be very competitive with current experiments (BaBar and BELLE expect to collect about 1000 $B_d \to K^{*0}\gamma$ each).

Signal to background ratio ($\frac{S}{B}$) and signal significance ($\frac{S}{\sqrt{B}}$) have not been precisely evaluated at this point, principally because of the lack of simulated background events. Large event production, Data Challenge 2, is ongoing and will allow reprocess to this point. Nevertheless, it has been shown that $\frac{S}{B}$ will be at least greater than 0.4 for LHCb in the $B_s \to \phi\gamma$ case, and larger than a few percents for ATLAS. Actually, far better results are expected, in particular for $B_s \to \phi\gamma$.

The significance, estimated with those pessimistic limits on $\frac{S}{B}$, is **in any case** larger than 5 after only one year of running. Consequently, a clear observation of radiative B decays, with both LHCb and ATLAS experiments, could be possible after LHC's first year of running.

ATLAS will be able to provide an useful cross-check to LHCb results, in particular for $B_s \to \phi\gamma$, which could be seen for the first time.

$\frac{S}{B}$ and reconstruction efficiencies will be precisely estimated, in order to evaluate LHC potential for asymmetry measurements in the radiative B decays sector.

4. Dimuonic B decays

4.1. Exclusive channels

Because of the di-muon final state, semi-muonic and purely muonic decays will be easier to select than radiative ones (see section 2). This remark is particularly true for ATLAS and CMS, where radiative B decays are difficult to trigger.

$B_d \to K^{*0}\mu\mu$ observation gives access to a large number of observables which, if they are measured with a sufficient precision, could give very interesting information for new physics reach.

Forward-backward asymmetry is one of the most promising parameter of $B_d \to K^{*0}\mu\mu$ planned study. It is defined by [6]:

$$\frac{A_{FB}}{dq^2} = \frac{1}{d\Gamma/dq^2}\left(\int_0^1 \frac{d^2\Gamma}{dq^2 d\cos(\theta)} d\cos(\theta) - \int_{-1}^0 \frac{d^2\Gamma}{dq^2 d\cos(\theta)} d\cos(\theta)\right) \quad (1)$$

where θ is the angle between the B meson and the μ^+ in the di-muon center-of-mass system.

Within the SM, A_{FB} vanishes at a q_0^2 value defined by the relation:

$$-\frac{Re(C^9_{eff})}{C^7_{eff}} = 2\frac{m_b}{q_0^2}\frac{m_B^2 - q_0^2}{m_B^2 + m_{K^*}^2 - q_0^2} \tag{2}$$

It comes out from (2) that A_{FB} has zero value if and only if $C^7_{eff}Re(C^9_{eff})$ is negative. Standard Model predicts a negative sign for this expression, the absence of a q_0 value will thus be a clear evidence for new physics. Another interesting feature of q_0, shown of figure 2, is that theoretical uncertainties on this parameter are small.

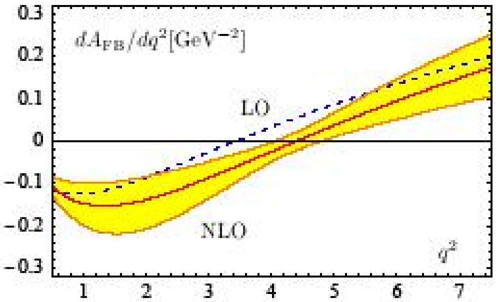

Figure 2. A_{FB} at next-to-leading order (solid center line), and leading order (dashed). The band includes all the theoretical uncertainties [6].

However, the precise measurement of A_{FB} requires a large sample of reconstructed $B_d \rightarrow K^{*0}\mu\mu$ events, which will be available only at LHC.

Statistics expected for one year at low luminosity are summarized in table 2. As for the radiative B decays study, LHCb results presented here have been obtained with the re-optimized detector [10]. ATLAS and CMS results were obtained with older versions of the detector layout [9].

In addition, CMS studies were done only at the particle level, thus explaining the large discrepancies with the other experiments. ATLAS and CMS analysis will be soon reprocessed, smaller number of events are expected.

	$B_d \rightarrow K^{*0}\mu\mu$	Ref.
LHCb	4400	[7]
ATLAS	1400	[8]
CMS	8000	[8]

Table 2: Di-muonic channels expectations after one year at low luminosity.

In order to compare LHCb with ATLAS and CMS, it should be pointed out that semi-muonic decay will be also studied at high luminosity, so that radically increased statistics than those of table 2 will be collected by ATLAS and CMS. However, ATLAS and CMS expectations at high luminosity have not yet been estimated.

Due to a more specific trigger, the significance is radically larger for the semi-muonic decays than for the radiative ones, and a very clean signal should be observed by LHCb, ATLAS, and CMS after only one year of running.

The expected precision on forward-backward asymmetry is presented on figures 3 and 4, for ATLAS and LHCb respectively. LHCb plots are for two years of data taking ($4\ fb^{-1}$), ATLAS for 3 years at $10^{33}\ cm^{-2}s^{-1}$ ($30\ fb^{-1}$). After two years of running, LHCb expects to determine q_0 with a precision of 0.01, thus allowing a determination of $\frac{Re(C^9_{eff})}{C^7_{eff}}$ with a 6% accuracy. We clearly see with figure 3 that precise measurements will also be feasible in ATLAS and CMS.

4.2. Semi-inclusive channels

Very efficient particle identification will allow LHCb to partially reconstruct $B \rightarrow X_d\mu\mu$ and $B \rightarrow X_s\mu\mu$ modes.

It has been shown [11] that using partially integrated branching ratios, defined as follows:

$$\Delta\mathcal{B}_i = \int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B \rightarrow X_i\mu\mu)}{dq^2}dq^2 \tag{3}$$

with $i = s, d$, $q^2_{min} = 1\ GeV^2$, and $q^2_{max} =$

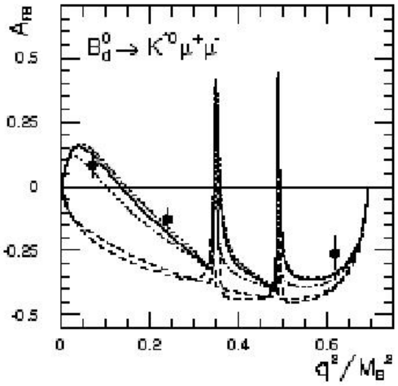

Figure 3. ATLAS sensitivity to A_{FB}. The three points with error bars are the simulated results in the SM case after obtaining 30 fb^{-1}. The solid line shows the SM prediction. The dotted lines show the range predicted by the MSSM if $C^7_{eff} < 0$ and the dashed lines show the range predicted by the MSSM if $C^7_{eff} > 0$ [9].

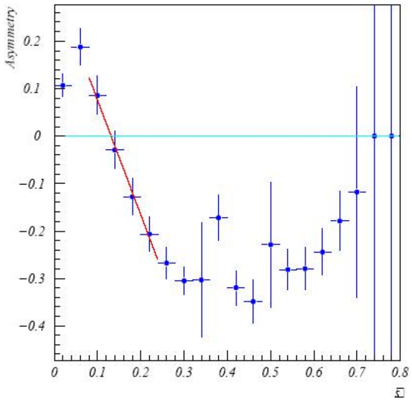

Figure 4. LHCb sensitivity to A_{FB} as a function of s ($s = \frac{q^2}{m_B^2}$). The points with error bars are the simulated results in the SM case after obtaining 4 fb^{-1}. Straight line is a linear fit determining s_0. ψ resonances were vetoed [12].

6 GeV^2, we have the following relation:

$$\Delta\mathcal{R} = \frac{\langle\Delta\mathcal{B}_d\rangle}{\langle\Delta\mathcal{B}_s\rangle} = \frac{|V_{td}|^2}{|V_{ts}|^2}(1 + corrections) \qquad (4)$$

with $\langle\Delta\mathcal{B}_i\rangle = \frac{\Delta\mathcal{B}_i + \Delta\bar{\mathcal{B}}_i}{2}$. Theoretical corrections in (4) are only of the order of one percent. $\Delta\mathcal{R}$ measurement, if feasible, will thus provide a very competitive estimation of $\frac{|V_{td}|}{|V_{ts}|}$ independent from the one given by B_s oscillations measurement.

This study has been done for LHCb [12]. Results show that $\frac{|V_{td}|}{|V_{ts}|}$ ratio could be estimated with a 10% uncertainty after two years of data taking, and 5% after 10 years.

5. Muonic B decays

As purely leptonic B decays are theoretically very clean, they provide an ideal laboratory for seeking indirect hints of new physics effects. However, they are very difficult to observe because of their small branching fractions ($O(10^{-9}, 10^{-10})$). Most probably new physics cannot increase these branchings to level visible before LHC.

Consequently, LHC experiments will play a major role in this sector. In addition, if $B \to \mu\mu$ analysis requires huge luminosity, triggering is not really problematic, even at high luminosity. In this context, ATLAS and CMS have a clear advantage on LHCb. This is confirmed by the estimations obtained for each experiment which are summarized on table 3, where ATLAS and CMS results are given for one year of running at high luminosity (100 fb^{-1}).

	$B_s \to \mu\mu$	*Background*	Ref.
LHCb	17	< 100	[13]
ATLAS	92	660	[9]
CMS	26	< 6	[9]

Table 3: Purely muonic channels expectations after one year at LHC.

ATLAS and CMS background rejection are slightly different. This discrepancy couldn't be explained only by CMS better precision on muon transverse impulsion. It is currently under investigation, and probably comes from analysis differences between the two experiments (calorimeter isolation, for example, is included in CMS but not in ATLAS).

LHCb statistics are smaller than ATLAS and CMS. Nevertheless, it was shown in [13] that a clear signal might be observed by the experiment after five years of running.

In conclusion, purely muonic decays will be extensively observed and studied in ATLAS and CMS during the high luminosity era. However, a first observation after one year at low luminosity is not excluded.

6. Conclusions

The more recent estimations concerning rare B-decays at LHC have been presented. As expected, the high $b\bar{b}$ production cross section leads to a very good performance in the search for flavour changing neutral currents. A large number of exclusive channels will be fully reconstructed by ATLAS, CMS, and LHCb, some of them, like $B_s^0 \to \phi\gamma$, should even be observed for the first time.

Very large reconstructed event sample after only one year of running sould allow to measure precisely very promising parameters for new physics search, particularly forward backward asymmetry of $B_d \to K^*\mu\mu$.

This paper also confirm the large complementarity between ATLAS and CMS and LHCb in the search for exclusive rare B decays. ATLAS and CMS will certainly take the lead role in purely leptonic area, whereas LHCb will be more efficient in the radiative sector. In the meantime, very promising semi-muonic decays should be extensively studied by all three experiments.

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