LHC semileptonic and radiative rare B decays program

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Rare loop-induced decays are sensitive to New Physics in many Standard Model extensions. In this paper we discuss the reconstruction of the radiative penguin decays b→sγ and the electroweak penguin decay b→$\ell\ell$s at the LHC. The expected annual yields and B/S estimates are presented.

Studies of the rare radiative penguin decays b→sγ, the electroweak penguin decay b→$\ell\ell$s, and the decay $\mathrm{B_s}$→$\mu\mu$ [1] allow to extract valuable information about penguin and box loop-diagrams. The complex couplings of new particles may result in enhancement of decay rates or in the appearance of non-trivial $\mathcal{CP}$-violating phases. For example for the decay $\mathrm{B_d}$→$\mathrm{K}^*\gamma$ because of the one-diagram dominance (the strong phase appears only at order α_S and $1/\mathrm{m_b}$) the direct $\mathcal{CP}$-asymmetry is reliably predicted in the SM to be $\leq 1\%$ [2], but for some SUSY scenarios it could be as large as 10–40% [2,3].

Due to the $V-A$ structure of the weak current the photon polarisation in $\mathrm{b} \rightarrow \mathrm{s}\,(\mathrm{d})\,\gamma$ transitions is almost 100%. In the SM this causes mixing-induced $\mathcal{CP}$-asymmetries to vanish [4], while in extensions of the SM these asymmetries could be as large as 50% [5]. This effect can be used as a probe for the spin structure of new particles.

The test of QCD models in radiative penguin decays still plays an important rôle [6]. The ratio $|\mathrm{V_{td}}|\ /|\mathrm{V_{ts}}|$ could be extracted from $\Gamma\,(\mathrm{B_d}\rightarrow\omega\gamma)/\Gamma\,(\mathrm{B_d}\rightarrow\mathrm{K}^*\gamma)$ with moderate theoretical uncertainty [7].

The forward-backward asymmetry A_FB for the decay b→$\ell\ell$s, is defined through the angle θ_FB between the ℓ^+ and the b hadron flight directions in the di-lepton rest frame. The shape of the asymmetry $A_\mathrm{FB}\left(m^2_{\ell\ell}\right)$ and especially the position of the zero crossing in the SM are almost unaffected by hadronic form factor uncertainties, thus providing a good basis for searching for deviations [8].

The ratio of b→$\mu\mu$s and b→ees decays in any exclusive mode is also a clean probe of the SM. Lepton-universality predicts this ratio to be 1 with theoretical errors below 1% [9].

The LHC will produce copious amounts of b-hadrons, with a total $\mathrm{b\bar{b}}$ cross-section of 500 μb. This potential will be exploited by the ATLAS, CMS and LHCb experiments.

ATLAS and CMS are general-purpose central spectrometers designed for new physics searches at high luminosity [10]. Yet they will have a small trigger bandwidth dedicated to B-physics for decays involving muons during the initial running at lower luminosity. We assume for the following that this programme covers 3 years of running at $\mathcal{L} = 10^{33}\ \mathrm{cm^{-2}s^{-1}}$, i.e. $30\,\mathrm{fb^{-1}}$.

LHCb is a forward spectrometer [11] optimised for b physics. Its main features are the precise vertex detector, the two RICH detectors and the versatile trigger with a 2 kHz output rate dominated by $\mathrm{pp} \rightarrow \mathrm{b\bar{b}X}$ events. LHCb will operate at a lower luminosity of $\mathcal{L} = 2 \cdot 10^{32}\ \mathrm{cm^{-2}s^{-1}}$, corresponding to $2\,\mathrm{fb^{-1}}$ per year.

The reconstruction of rare b decays at LHC is a challenge due to the small rates and large backgrounds from various sources. The most critical is the combinatorial background from $\mathrm{pp} \rightarrow \mathrm{b\bar{b}X}$ events, containing secondary vertices and characterised by high charged and neutral multiplicities.

1. Radiative B meson decays at LHCb

Radiative b→sγ decays can be reconstructed in the modes $\mathrm{B_d}$→$\mathrm{K}^*\gamma$[1] and $\mathrm{B_s}$→$\phi\gamma$ [12]. K^*

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[1] The charge conjugate mode is always implied unless explicitly stated otherwise

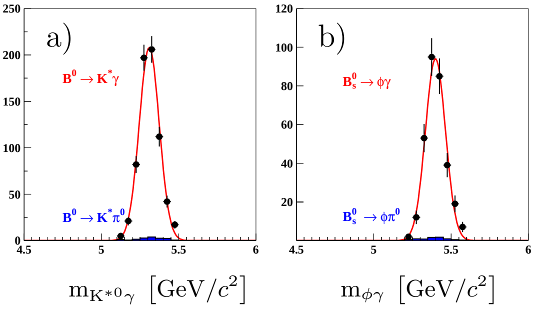

Figure 1. Reconstructed $B_d \to K^* \gamma$ and $B_s \to \phi\gamma$ mass distributions for signal events after trigger and selection cuts. The specific background from $B \to K^* \pi^0$ and $B \to \phi\pi^0$ decays is shown with proper normalisation. The dominant combinatorial background is not shown.

and ϕ candidates are reconstructed in the $K^+\pi^-$ and K^+K^- modes respectively. Charged tracks have to be inconsistent with any reconstructed primary vertex. Selected K^{*0} (ϕ) candidates are combined with photon candidates of transverse energy greater than 2.8 GeV. The reconstructed B candidate is required to be compatible with coming from a primary vertex. This requirement is one of the most powerful cuts against combinatorial background. Background from the decays $B_d \to K^* \pi^0$ and $B_d \to \phi\pi^0$ with an energetic π^0 reconstructed as a single photon is suppressed by cutting on the K^* and ϕ helicity angle. The mass resolution of the selected and triggered B candidates is expected to be 65 MeV/c^2 as shown in Figure 1.

The selection of the Cabibbo suppressed decay $B_d \to \omega\gamma$ followed by $\omega \to \pi^+\pi^-\pi^0$ follows a similar approach, but it is complicated by the π^0 reconstruction [13].[2]

The expected annual (2 fb^{-1}) yields and B/S ratios in a ±200 MeV/c^2 mass window are given in the table below:

	Yield	B/S
$B_d \to K^* \gamma$	35 000	< 0.7
$B_s \to \phi\gamma$	9 000	< 2.4
$B_d \to \omega\gamma$	40	< 3.5

The background is estimated from a fully simulated $pp \to b\bar{b}X$ MC sample. The limits are given at 90% C.L.

These yields will for instance allow $\mathcal{CP}$ asymmetry measurements at the per-cent level in the $B_d \to K^* \gamma$ channel.

2. $\Lambda_b \to \Lambda\gamma$ at LHCb

Radiative b baryon decays like $\Lambda_b \to \Lambda\gamma$ can be used to probe the chirality of the effective Hamiltonian by measuring the photon polarisation [14]. The angular asymmetry between the Λ_b spin and the photon momentum combined with the $\Lambda \to p\pi$ decay polarisation probes the predicted $V - A$ structure of this decay.

The Λ reconstruction is delicate at the LHC since it may traverse a large fraction of the tracking system before decaying. Therefore one also uses decays to heavier Λ resonances decaying strongly to pK, losing the handle from the Λ decay polarisation [15].

The event selection is similar to the one presented above for B mesons. In a preliminary study LHCb expects the following annual yields and B/S ratios for one year (2 fb^{-1}):

	Yield	B/S
$\Lambda_b \to \Lambda\gamma$	750	< 42
$\Lambda_b \to \Lambda(1520)\gamma$	4 200	< 10
$\Lambda_b \to \Lambda(1670)\gamma$	2 500	< 18
$\Lambda_b \to \Lambda(1690)\gamma$	2 500	< 18

The same comment as in Section 1 applies about the background estimates.

The Λ_b is expected to be polarised in pp collisions at LHC, especially in the forward region. This polarisation is assumed to be 20%, a fraction that will be measured to a 1% precision with $\Lambda_b \to J/\psi\Lambda$ decays [16].

With these yields LHCb will be able to measure the right-handed polarisation component to an accuracy of 5% after 5 years of data taking (10 fb^{-1}), which is smaller than the expected SM contribution [17]. This accuracy only depends weakly on the actual value of the Λ_b polarisation.

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[2] The $B_d \to \rho\gamma$ mode has not yet been studied, but is expected to be cleaner than the ω counterpart.

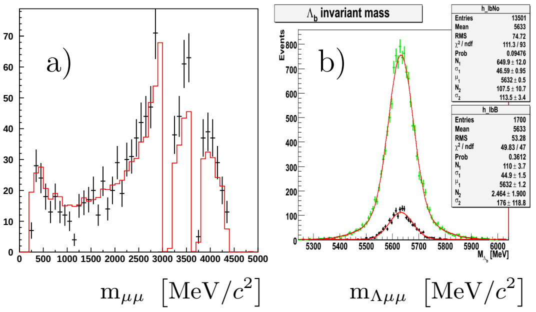

Figure 2. a) The $\mu\mu$ mass in $B_d \to \mu\mu K^*$ at LHCb. Selected events (crosses) are compared with generated events (solid). b) The $\Lambda\mu\mu$ mass at ATLAS (all signal and selected event compared).

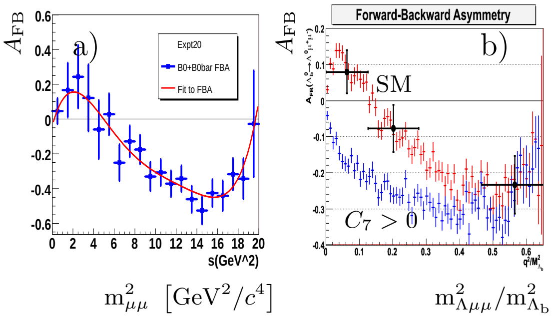

Figure 3. Typical A_{FB} versus di-lepton mass plots for a) $B_d \to \mu\mu K^*$ with 2 fb^{-1} at LHCb and b) $\Lambda_b \to \mu\mu\Lambda$ with 30 fb^{-1} at ATLAS compared to two theoretical expectations.

3. A_{FB} at the LHC

Thanks to its very clean experimental signature the decay $b \to \mu\mu s$ can be accessed by ATLAS, CMS and LHCb in the exclusive decays $B_u \to \mu\mu K$, $B_s \to \mu\mu\phi$, $B_d \to \mu\mu K^*$ and $\Lambda_b \to \mu\mu\Lambda$. The latter two can be used to extract A_{FB}.[3]

The selections combine two tracks positively identified as opposite-charged muons with the relevant hadronic final state. Similar selection criteria as in Section 1 are applied. Very strict requirements on the vertex quality are applied to reduce the backgrounds from cascade semileptonic $b \to \mu\nu c$, $c \to \mu\nu s$ decays and from two semileptonic $b \to \mu\nu c$ decays. The former background needs to be well under control because it induces an A_{FB} bias. The background from $c\bar{c}$ resonances is removed by vetoing the J/ψ and $\psi(2S)$ mass windows.

LHCb expects a 15 MeV/c^2 resolution for the B mass and 10 MeV/c^2 for the $\mu\mu$ mass. The resolution for θ_{FB} is 4 mrad. The distributions for the di-muon invariant mass and the angle θ_{FB} are not distorted by acceptance or selection cuts, as illustrated in Fig. 2a for $m_{\mu\mu}$ [18].

ATLAS has also studied these channels and obtains a typical mass resolution of 60 MeV/c^2 for the final candidates as shown in Fig. 2b for the decay $\Lambda_b \to \mu\mu\Lambda$.

The expected yields for these channels are listed below for one nominal year of running at LHCb and three years of running at ATLAS.

	$\int \mathcal{L}dt$		Yield	B/S
LHCb	2 fb^{-1}	$B_d \to \mu\mu K^*$	4 400	< 3
LHCb	2 fb^{-1}	$B_u \to \mu\mu K$	1 600	~ 3
ATLAS	30 fb^{-1}	$B_d \to \mu\mu K^*$	2 500	< 20
ATLAS	30 fb^{-1}	$B_u \to \mu\mu K$	1 500	< 6
ATLAS	30 fb^{-1}	$B_s \to \mu\mu\phi$	900	< 11
ATLAS	30 fb^{-1}	$\Lambda_b \to \mu\mu\Lambda$	800	< 5

LHCb estimates its sensitivity to A_{FB} in $B_d \to \mu\mu K^*$ in a toy MC study using these yields, B/S and the relevant distributions. A typical year of running could provide the A_{FB} versus $m^2_{\mu\mu}$ plot shown in Fig. 3a, already allowing to exhibit non-SM features. LHCb expects to extract the C_9/C_7 Wilson-coefficients ratio from the crossing point with the $A_{FB} = 0$ axis to a precision of 13% after 5 years of running (10 fb^{-1}).

ATLAS will also be able to disentangle the SM expectation from extensions with $C_7 > 0$ after three years (30 fb^{-1}), as shown in Fig. 3b for $\Lambda_b \to \mu\mu\Lambda$.

4. R_K at LHCb

Reconstructing $B_u \to eeK$ as well as $B_u \to \mu\mu K$ allows us to extract the ratio R_K of the two branching fractions, integrated over a given di-

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[3] The A_{FB} in $B_u \to \mu\mu K$ is expected to be null in the SM and most extensions. $B_s \to \mu\mu\phi$ is not self tagging which greatly reduces the sensitivity.

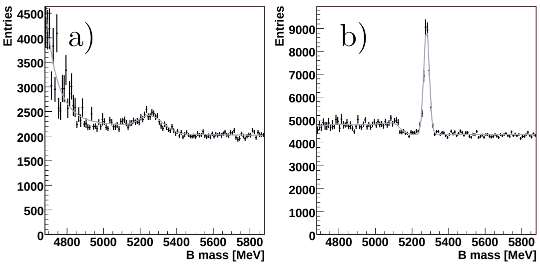

Figure 4. Expected B candidate mass distributions in a) $B_u \to eeK$ and b) $B_u \to \mu\mu K$ modes for $10\,fb^{-1}$ at LHCb.

lepton mass range.[4] $B_u \to \mu\mu K$ decays are reconstructed as explained above and the same requirements are applied for the $B_u \to eeK$ decay. A proper bremsstrahlung correction is essential in this channel. The correction for the lower reconstruction and trigger efficiency in the electron mode is extracted from $B_u \to J/\psi K$ decays. The di-lepton mass range is chosen to be $1 < m^2_{\ell\ell} < 6\ \mathrm{GeV}^2/\mathrm{c}^4$ in order to avoid $c\bar{c}$ resonances (especially in the ee mode) and thresholds effect due to the higher μ mass. The event yields are extracted from a two-dimensional fit to the $\ell\ell K$ and $\ell\ell$ masses in order to take into account the backgrounds from $b \to J/\psi s$ and $B \to \ell\ell K^*$.

The expected B candidate mass distributions are shown in Fig. 4 for five years ($10\,fb^{-1}$) of data taking. The yields are:

	Yield	B/S	$\sigma(m_B)$
$B_u \to \mu\mu K$	$8\,000 \pm 50$	~ 3	$15\ \mathrm{MeV/c^2}$
$B_u \to eeK$	1800 ± 35	~ 5	$75\ \mathrm{MeV/c^2}$

The errors on the yields are the statistical error in the estimate. Using these errors one gets an error on R_K of 4% after five years of running ($10\,fb^{-1}$).

5. Conclusion

The LHC experiments have a promising physics potential for the study of numerous loop-induced rare decays such as the radiative penguin decays $b \to s\gamma$ and the electroweak penguin decay $b \to \ell\ell s$. The expected annual signal event yields and preliminary estimates on background-to-signal ratios have been presented.

The precision and reliability of background-to-signal estimates are expected to improve with a significant increase of Monte Carlo samples. Studies of high level trigger efficiencies, systematic uncertainties, and the sensitivity to new physics are in progress.

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[4] $B_d \to \ell\ell K^*$ is also a good candidate (measuring R_{K^*}) but has not yet been studied.