LHCb: Rare B-decays

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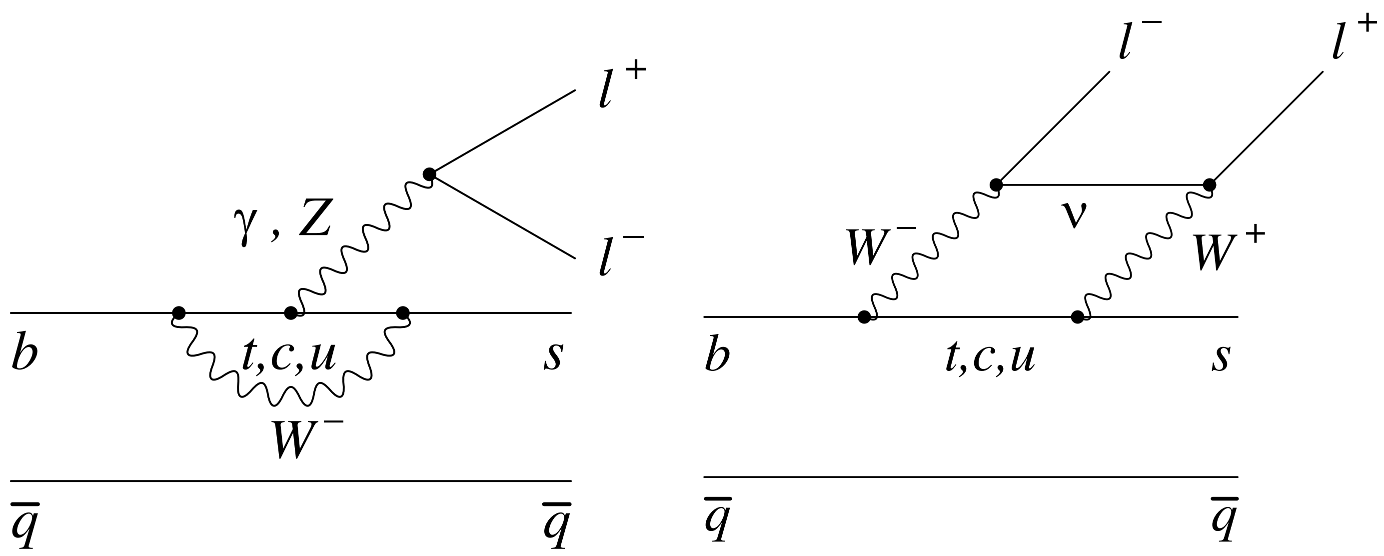
Introduction
Foreword

Rare radiative $\bar{B} \to \bar{V}\,\gamma$, rare semileptonic $\bar{B} \to (\bar{P}, \bar{V})\,\ell^+\ell^-$ and rare leptonic $\bar{B} \to \ell^+\ell^-$ decays are induced by $b \to d,\, s$ transitions (so-called Flavor Changing Neutral Currents). Such currents are forbidden at the tree level in the framework of the Standard Model (SM) and occur starting from the lowest order only through the one-loop "penguin" and "box" diagrams.

The branching ratios of these decays are very small: from $\sim 4 \times 10^{-5}$ for rare radiative decay $B_d^0 \to K^*\gamma$ (discovered by CLEO at 1993) to $\sim 10^{-15}$ for rare Cabibbo suppressed leptonic decay $B_d^0 \to e^+e^-$, that cannot be discovered even with LHC and SuperB.

Introduction
Some examples for one-loop diagrams

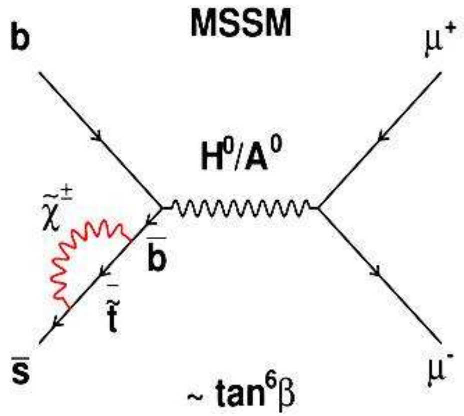
Lowest order Standard Model contributions to the $\bar{B}_q \to (\bar{K}, \bar{K}^*)\ell^+\ell^-$ **decays.**

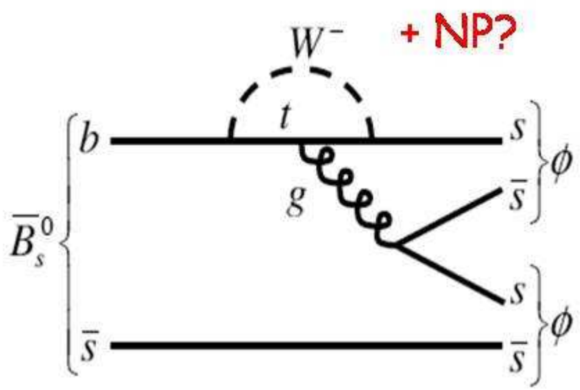


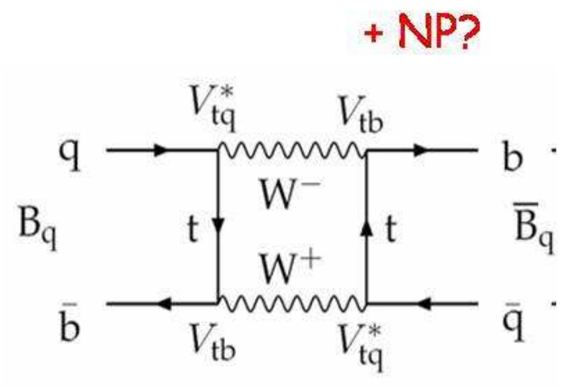
Introduction
Scientific motivation

Main motivation: INDIRECT search of "New Physics" (NP) on LHC and (Super)B-factories.

Heavy virtual non-standard particles may provide a contribution into the amplitudes of rare decays. Absolute value of such a contribution may be measured by studying the invariant dimuon mass distribution and A_{FB}. Phase – by the studies of some CP-violation effects corresponding to an interference between weak and strong phases in a matrix element.







Effective Hamiltonian for rare decays
Common theoretical framework

From the theoretical point of view the $b(\bar{b}) \to q(\bar{q})$ transitions $q = \{d, s\}$ are considered using the effective Hamiltonian

$$H^{eff}(b \to q) = \frac{G_F}{\sqrt{2}} V_{tb} V_{tq}^* \sum_i C_i(\mu) O_i(\mu) + h.c.$$

in the form of Wilson expansion, where G_F is Fermi constant, V_{tq} and V_{tb} are the CKM matrix elements. The set of Wilson coefficients $C_i(\mu)$ depends on the current model. The scale parameter μ separates the perturbative and nonperturbative contributions of the strong interactions. The value of the μ is approximately equal to the mass of b-quark that is $\mu \sim 5$ GeV.

SM NLO: A.Buras, M.Munz, PRD52, p.182, 1995;

SM NNLO: C.Bobeth et al., JHEP0404, 071, 2004.

Effective Hamiltonian for rare decays
The Matrix Elements

$O_i(\mu)$ **is the set of the basic operators (specific for each model like the set of the Wilson coefficients). The nonperturbative contributions of the strong interactions are contained in the matrix elements of these operators**

$$\langle \text{final states} \, |O_i(\mu)| \, \text{initial states} \rangle \, .$$

These matrix elements can be described in terms of Lorentz-invariant form factors and structures constructed using 4-momenta of initial and final particles, tensors $g^{\mu\nu}$ **and** $\varepsilon_{abcd} \equiv \varepsilon_{\alpha\beta\mu\nu} a^{\alpha} b^{\beta} c^{\mu} d^{\nu}$**.**
Accuracy of the nonperturbative calculations depends on a method, but it's not less, than 15% .

The accuracy of the Wilson coefficients in the NLO approach is of the same order.

Theoretical predictions for the branching ratios of rare semileptonic decays in SM

Decay channel	Branching ratio in SM	Reference
$B_d^0 \to \mu^+\mu^-$ $B_s^0 \to \mu^+\mu^-$	0.9×10^{-10} 3.5×10^{-9}	A.Ali, C.Greub, T.Mannel, Preprint DESY-93-016, 1993
$B \to K^*\mu^+\mu^-$ $B \to K\mu^+\mu^-$ $B_s^0 \to \phi\mu^+\mu^-$ $B \to \rho\mu^+\mu^-$ $B \to \pi\mu^+\mu^-$	1.3×10^{-6} 5.3×10^{-7} 1.0×10^{-6} 3.2×10^{-7} 2.0×10^{-8}	D.Melikhov, N.Nikitin, S.Simula, PRD 57, 6814, 1998 D.Melikhov, B.Stech, PRD 62, 014006, 2000
$B_d^0 \to \gamma\mu^+\mu^-$ $B_s^0 \to \gamma\mu^+\mu^-$	4.0×10^{-10} 1.9×10^{-8}	D.Melikhov, N.Nikitin, PRD 70, 114028, 2004 F.Kruger, D.Melikhov, PRD 67,034002, 2003
$\Lambda_b \to \Lambda\mu^+\mu^-$	2.0×10^{-6}	T.Aliev et al., NPB 649, 168, 2003
$B \to K^* \sum \nu\bar{\nu}$ $B \to K \sum \nu\bar{\nu}$	1.7×10^{-5} 6.4×10^{-6}	D.Melikhov, N.Nikitin, S.Simula, PRD 57, 6814, 1998

Here the branching ratios for rare $B^0_{d,s}$ and $B^\pm$-mesons decays are recalculated using $|V^*_{ts}V_{tb}|^2 = 2.2 \times 10^{-3}$ and $|V^*_{td}V_{tb}|^2 = 6.9 \times 10^{-5}$.

Experimental results for BR from Belle, BaBar and Tevatron Collaborations

Decay channel	Experimental BR	Ref.
$B_d^0 \to \mu^+\mu^-$	$< 7.6 \times 10^{-9}$ at 95% CL	CDF Public Note 9892, August 2009
$B_s^0 \to \mu^+\mu^-$	$< 4.3 \times 10^{-8}$ at 95% CL	CDF Public Note 9892, August 2009
$B \to K^*\mu^+\mu^-$	$(8.2 \pm 3.1 \pm 1.0) \times 10^{-7}$ $(10.7^{+1.1}_{-1.0} \pm 0.9) \times 10^{-7}$ $(11.1^{+1.9}_{-1.8} \pm 0.7) \times 10^{-7}$	CDF, PRD 79, 011104(R), 2009 Belle, **arXiv:0904.0770** [hep-ex], 2009 BaBar, **arXiv:0906.1306** [hep-ex], 2009
$B^+ \to K^+\mu^+\mu^-$	$(3.9 \pm 0.07 \pm 0.2) \times 10^{-7}$ $(4.8^{+0.5}_{-0.4} \pm 0.3) \times 10^{-7}$ $(5.9 \pm 1.5 \pm 0.4) \times 10^{-7}$	BaBar, **arXiv:0906.1306** [hep-ex], 2009 Belle, **arXiv:0904.0770** [hep-ex], 2009 CDF, PRD 79, 011104(R), 2009
$B_s^0 \to \phi\mu^+\mu^-$	$< 3.2 \times 10^{-6}$ at 90% CL $< Br(B_s^0 \to J/\psi\phi)\times$ $\times 2.3 \times 10^{-3}$ at 90% CL	D0, PRD 74, 031107, 2006 CDF, PRD 79, 011104(R), 2009
$B^+ \to K^{*+}\sum \nu\bar{\nu}$	$< 9 \times 10^{-5}$ at 90% CL	BaBar, **arXiv:0906.1306** [hep-ex], 2009
$B^+ \to K^+\sum \nu\bar{\nu}$	$< 1.4 \times 10^{-5}$ at 90% CL	Belle, PRL 99, 221802, 2007

Rare leptonic decays at LHCb
Analysis Strategy

The search for the decay $B_s \to \mu^+\mu^-$ is based on counting in bins based on 3 independent variables:

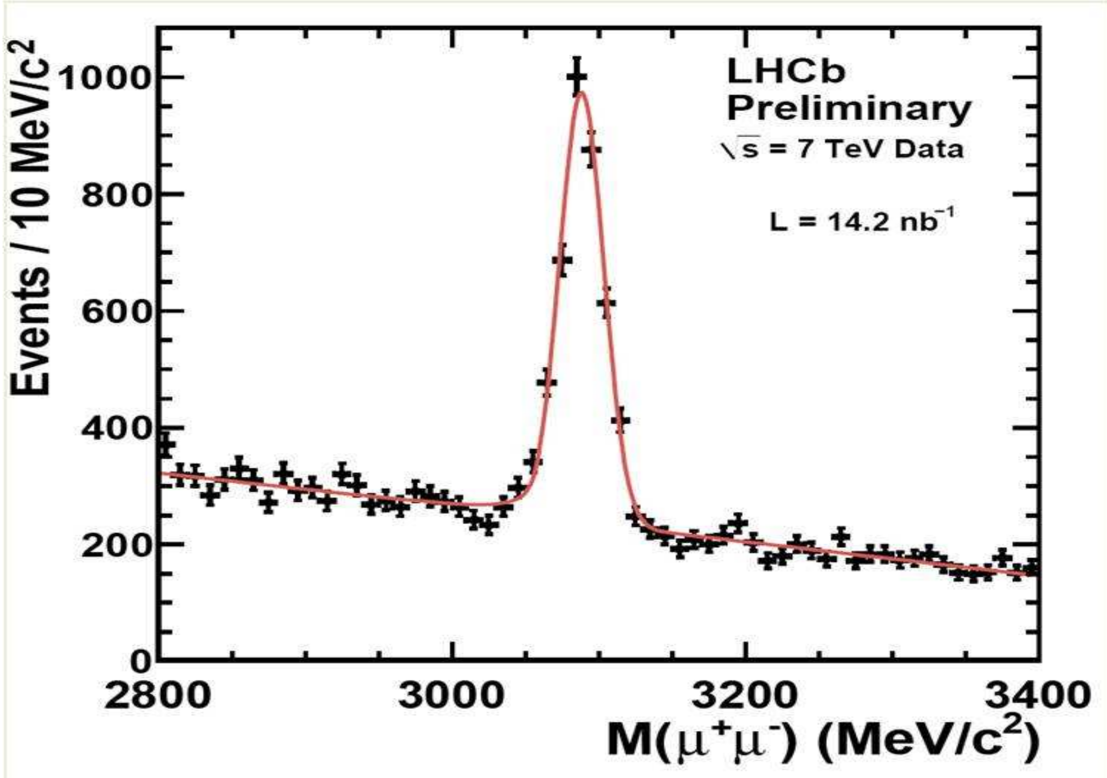
Invariant mass of the muon pair Its resolution is determined by the tracking system resolution and alignment;

Muon identification likelihood Dominated by muon system but also use information from calorimeters and RICH detectors;

Geometrical likelihood (GL) Quantities where the vertex detector provides the main discrimination: impact parameters, isolation, lifetime;

and measure **trigger efficiency**.

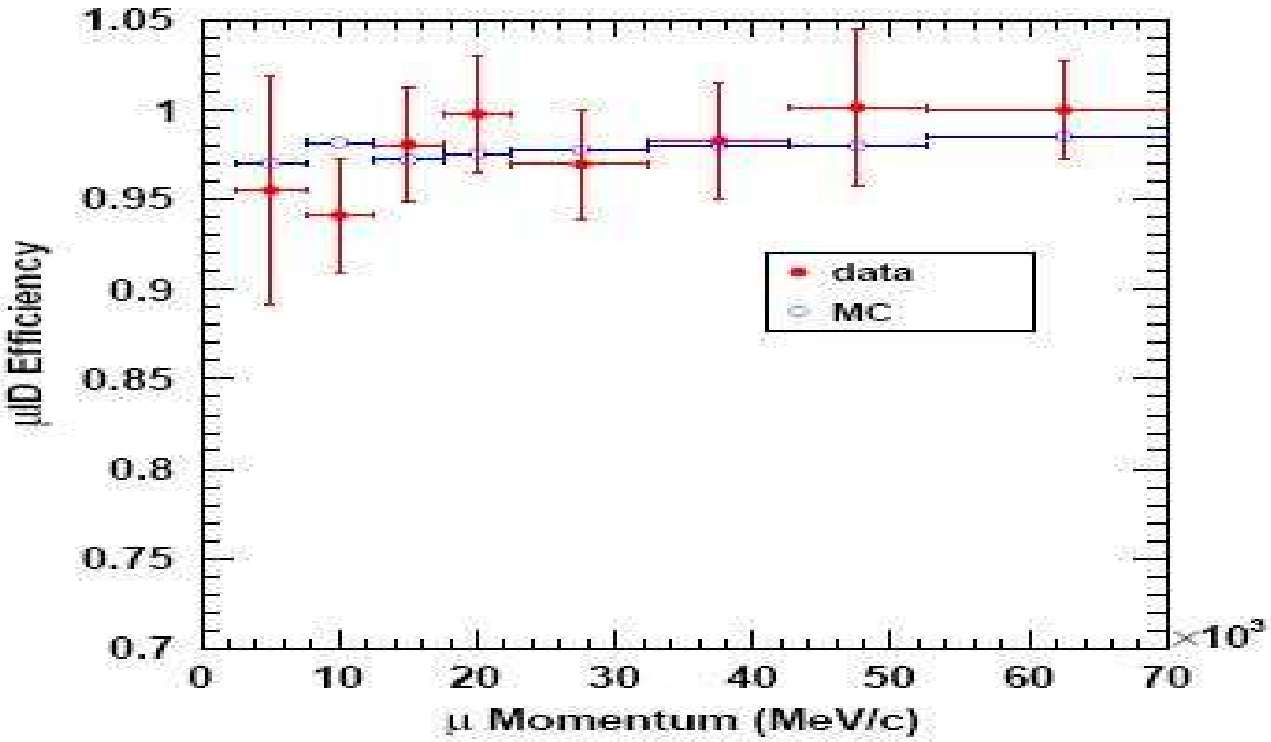
Rare leptonic decays at LHCb
Dimuon invariant mass resolution



For the study of this resolution we use the channel $J/\psi \to \mu^+\mu^-$.

$$\sigma(J/\psi \to \mu^+\mu^-) = 15.0 \pm 0.4\, MeV/c^2 \quad \textbf{with} \quad L \approx 14.2\, nb^{-1}.$$

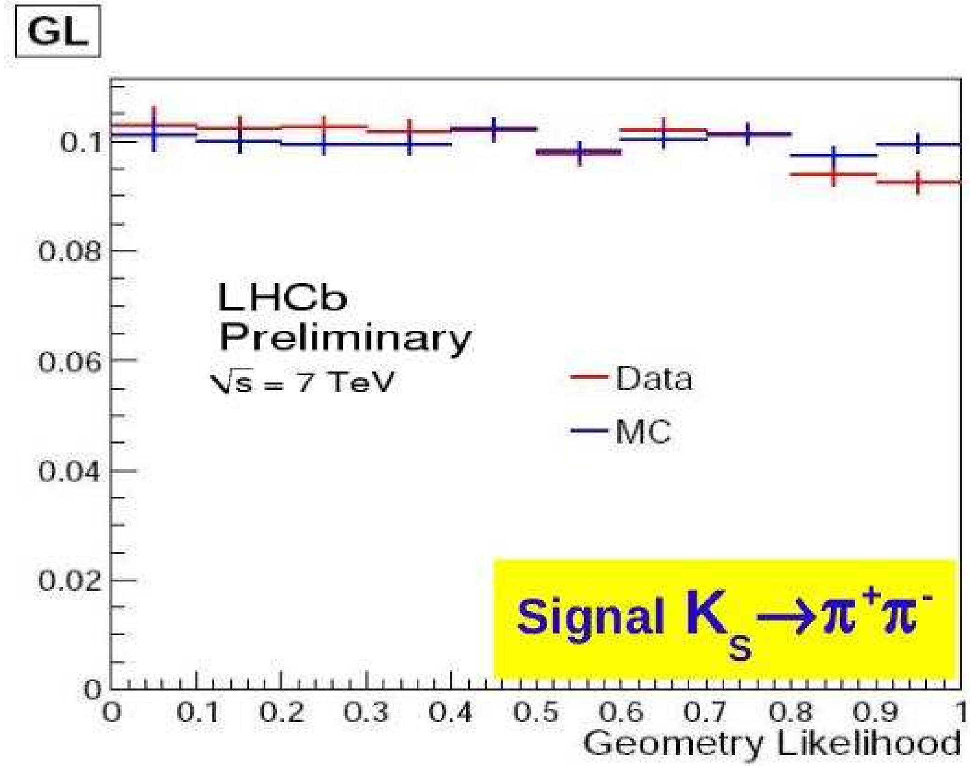
Rare leptonic decays at LHCb Muon Identification (μID)



Tag-and-probe method: $p > 3$ **GeV using** $J/\psi \to \mu^+\mu^-$ **data.**

$$\varepsilon_{MC} = 97.7 \pm 0.1\%, \qquad \varepsilon_{Data} = 98.0 \pm 1.2\%.$$

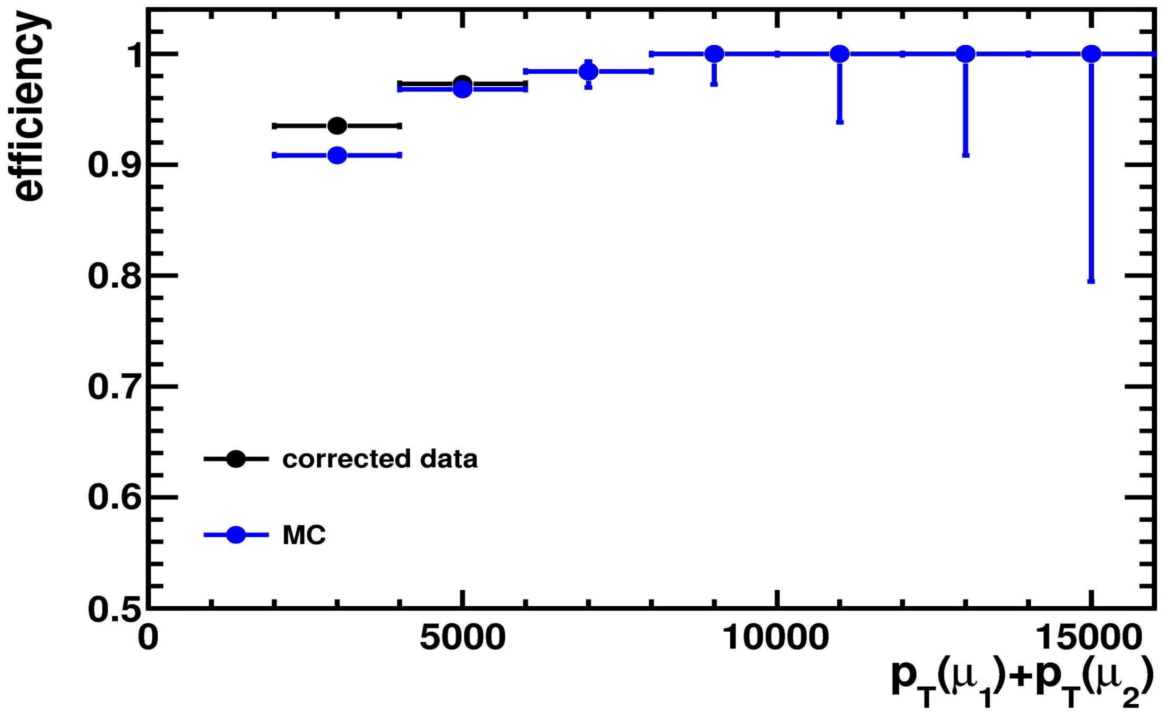
Rare leptonic decays at LHCb Geometrical Likelihood



Signal response is calibrated with data from $K_S^0 \to \pi^+\pi^-$.

Ingredients: IP, isolation, meson lifetime, vertex chi2.

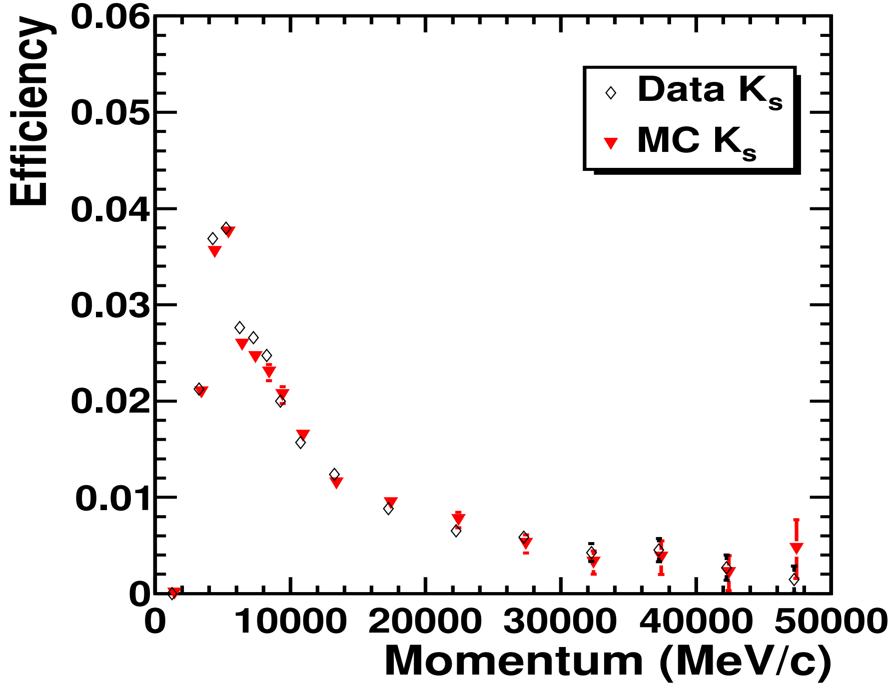
Rare leptonic decays at LHCb
Muon Trigger efficiency

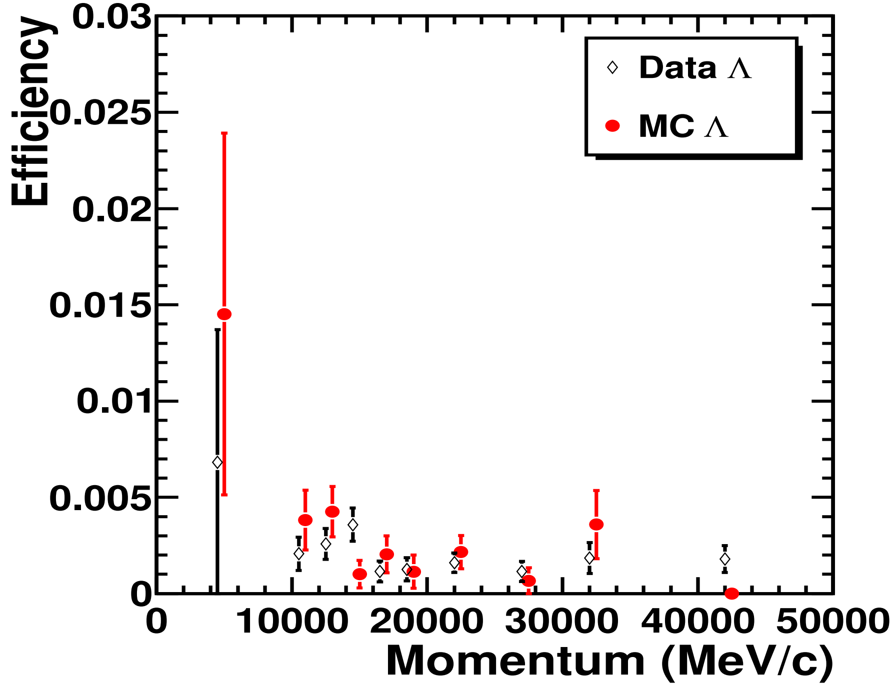


$$\varepsilon_{\text{trig from data}}(B_s \to \mu^+\mu^-) = (98.8 \pm 0.2(\text{stat}) \pm 1.3(\text{syst}))\%.$$

Extracted from trigger unbiased $J/\psi \to \mu^+\mu^-$ data and extrapolated using MC via J/ψ for $B_s \to \mu^+\mu^-$ spectrum.

Rare leptonic decays at LHCb. Muon mis-ID



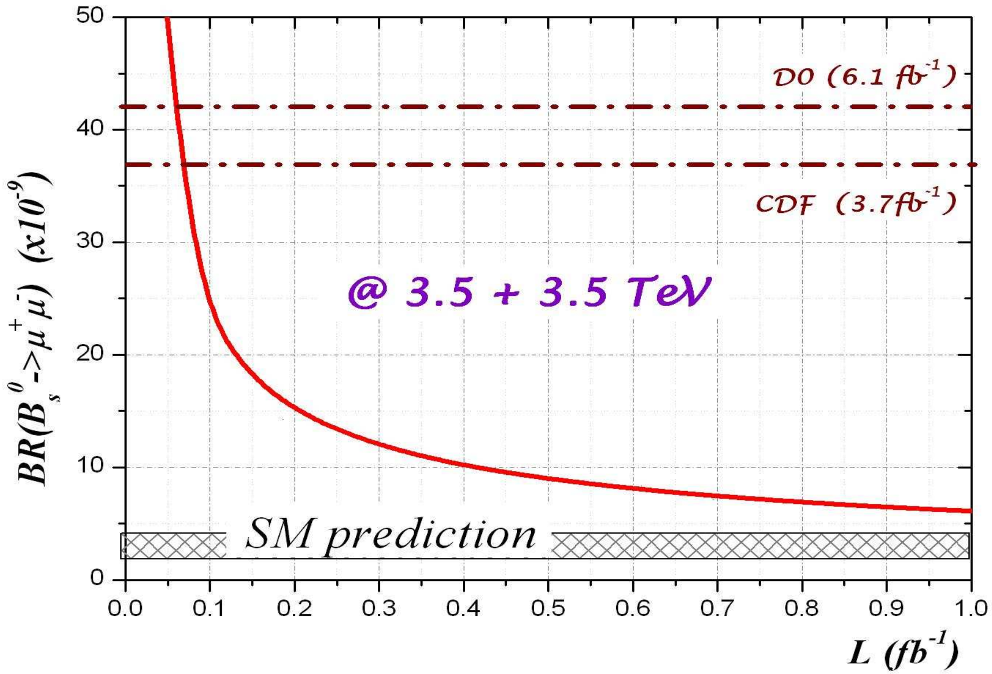


Identification studies are useless without corresponding muon mis-ID studies. Pion sample from $K_S^0 \to \pi^+\pi^-$, proton sample from $\Lambda \to p\pi^-$ at $\sqrt{s} = 7$ TeV.

$$P(\pi \to \mu)_{\rm Data} = (2.38 \pm 0.02)\,\%, \qquad P(\pi \to \mu)_{\rm MC} = (2.34 \pm 0.02)\,\%;$$

$$P(p \to \mu)_{\rm Data} = (0.18 \pm 0.02)\,\%, \qquad P(p \to \mu)_{\rm MC} = (0.21 \pm 0.04)\,\%.$$

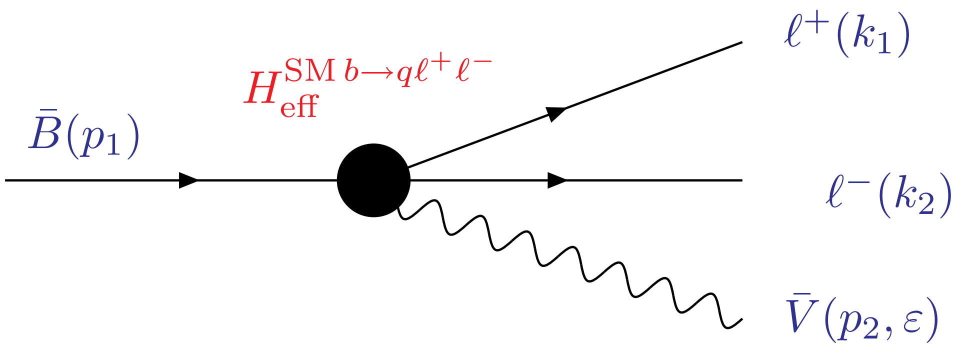
Rare leptonic decays at LHCb. Exclusion limit at 90% CL at $\sqrt{s} = 7$ TeV



Current limit improved with $L < 100pb^{-1}$ **(expected by the end of 2010).**

NP discovery potential already at BR $17 - 21 \times 10^{-9}$ **with** $L \sim 1fb^{-1}$ **at 7 TeV (expected by the end of 2011).**

Rare semileptonic decays
Kinematics



$$p_1 = k_1 + k_2 + p_2, = q + p_2, \quad p_1^2 = M_1^2, \quad p_2^2 = M_2^2, \quad k_1^2 = k_2^2 = m^2.$$

The kinematics of three-body decays can be described in terms of two independent variables. The first independent variable:

$$4\,m^2 \le (s \equiv q^2) \le (M_1 - M_2)^2.$$

In the rest frame of the leptonic pair we define a second independent variable: the angle θ_- between ℓ^- and final $\bar{V}$ meson (initial $\bar{B}$) directions.

Alternatively, we can define the angle θ_+ between ℓ^+ and $\bar{V}$ meson (initial $\bar{B}$).

Rare semileptonic decays
Forward-Backward Asymmetry definition

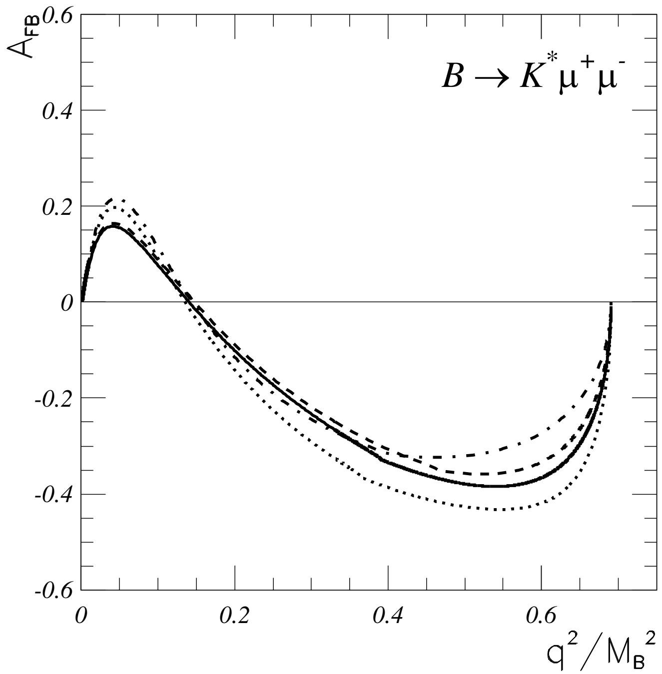
There are many ways to define the Forward-Backward Asymmetry A_{FB}. Therefore we present here the most explicit definition in this talk.

$$A_{FB}(s) = \frac{\displaystyle\int_0^1 d\cos\theta_- \frac{d^2\Gamma(\bar{B}\to\bar{V}\ell^+\ell^-)}{ds\,d\cos\theta_-} - \int_{-1}^0 d\cos\theta_- \frac{d^2\Gamma(\bar{B}\to\bar{V}\ell^+\ell^-)}{ds\,d\cos\theta_-}}{\displaystyle\frac{d\Gamma(\bar{B}\to\bar{V}\ell^+\ell^-)}{d\,s}}.$$

The equivalent definition for A_{FB} is

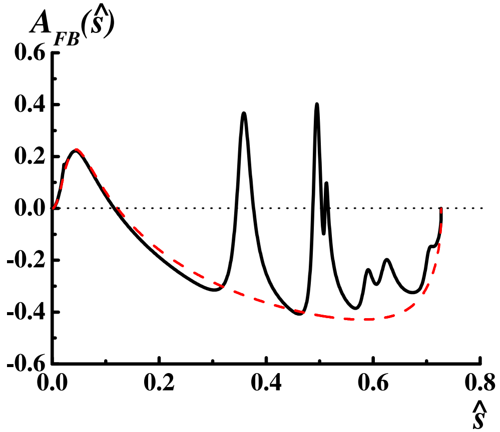
$$A_{FB}(s) = \frac{\displaystyle\int_0^1 d\cos\theta_+ \frac{d^2\Gamma(B\to V\ell^+\ell^-)}{ds\,d\cos\theta_+} - \int_{-1}^0 d\cos\theta_+ \frac{d^2\Gamma(B\to V\ell^+\ell^-)}{ds\,d\cos\theta_+}}{\displaystyle\frac{d\Gamma(B\to V\ell^+\ell^-)}{d\,s}}.$$

Rare semileptonic decays
Zero point Example

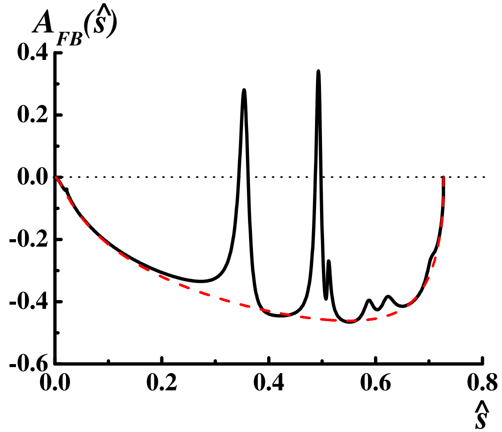


Here we present the $A_{FB}(s/M_1^2)$ for the decay $B_d^0 \to K^{*0}\mu^+\mu^-$ with four form factors sets without resonant contribution. From this picture it's quite obvious, that zero point $s_0/M_1^2 \approx 0.15$ position has a weak dependence on the form factors sets (see G.Burdman, PRD 57, p.4254, 1998).

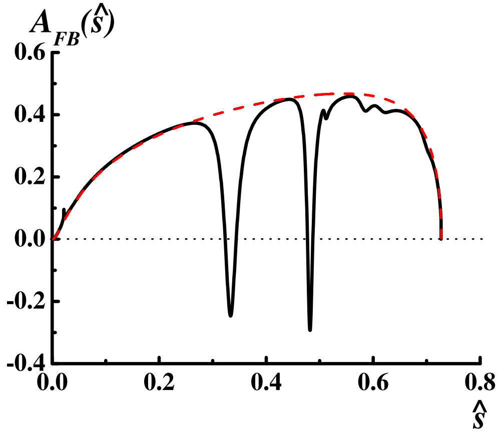
Example for the Forward-Backward Asymmetry



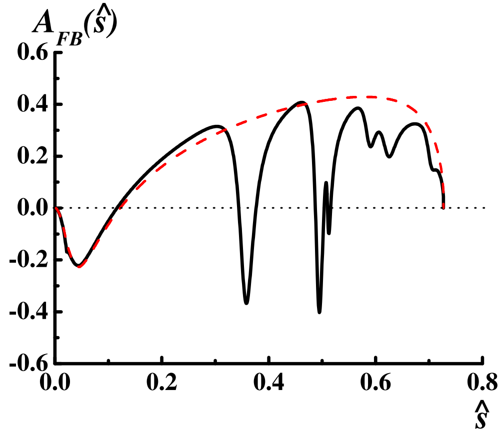
(a)



(b)

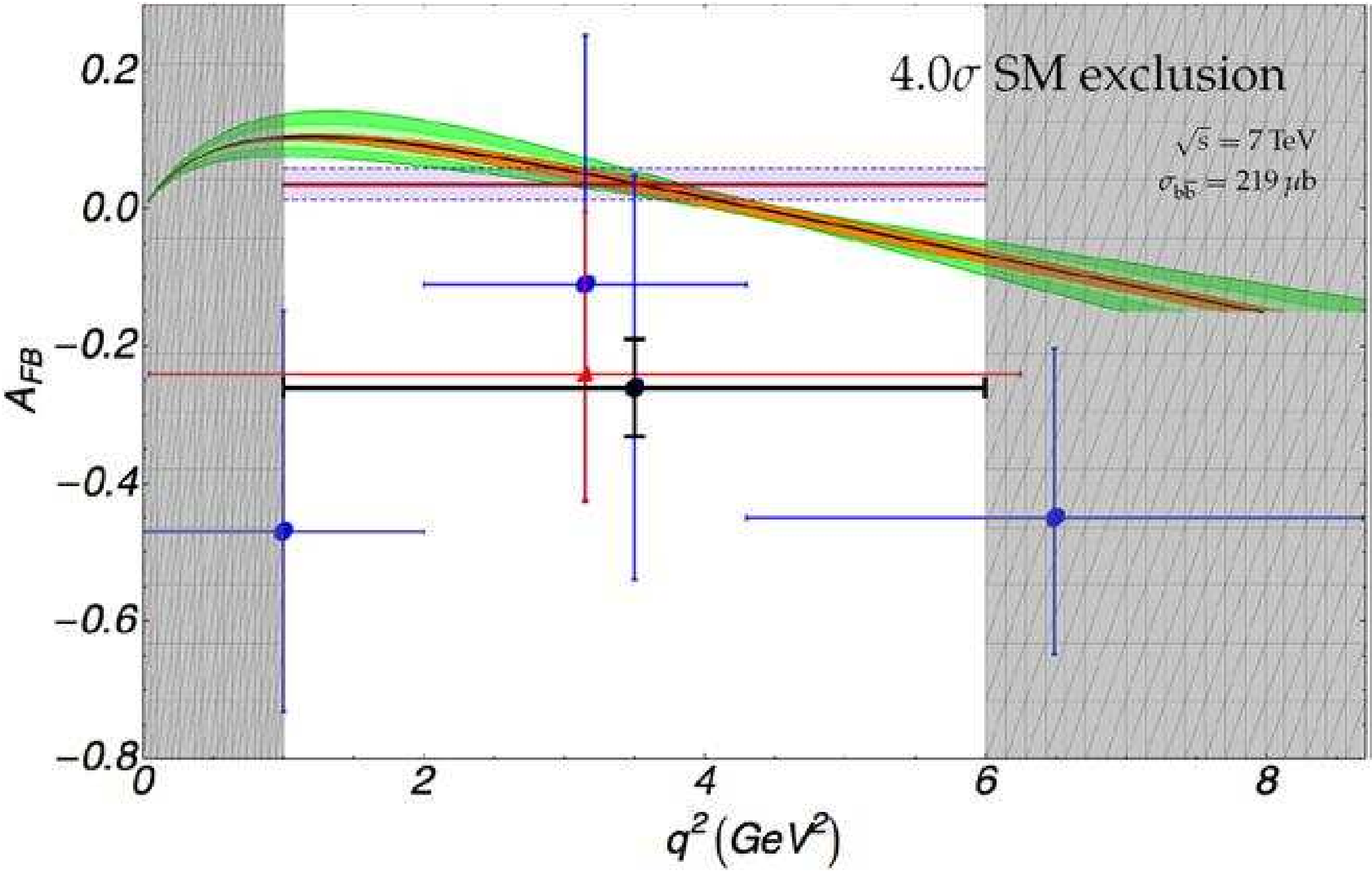


(c)



(d)

A_{FB} **decays** $\bar{B}_d^0 \to \rho^0 \mu^+ \mu^-$**: (a) in the SM; (b) For** $C_{7\gamma} = -C_{7\gamma}^{\rm SM}$**; (c) For** $C_{9V} = -C_{9V}^{\rm SM}$**; (d) For** $C_{10A} = -C_{10A}^{\rm SM}$**. Solid line (black): the full asymmetry which takes into account the** J/ψ, ψ', **etc contributions. Dashed line (red): the non-resonant asymmetry.**



The theoretical prediction for $A_{FB}(s = q^2)$ in SM (form factors calculated in SCET approach U.Egede et al., JHEP 0811:032, 2008) in the s-region $[1, 6]$ GeV^2 and inversed sign Belle (blue crosses) and BaBar (red cross) and expected (end of 2011) LHCb at 1 fb^{-1} $\approx$ 1400 events (black cross) results.

Rare radiative decay $B_s \to \phi\gamma$

In the SM the $b \to s\gamma$ process produces mostly left-polarized photons:

$$\frac{M(\bar{B}_s \to \phi\gamma_R)}{M(\bar{B}_s \to \phi\gamma_L)} \sim \frac{m_s}{m_b}.$$

LHCb expects: 4.8k events for $B_s \to \phi\gamma$ by the end of 2011.

Energy calibration is very promising. Calibration now based on low mass resonances.

High energy calibration will first come when $B_d \to K^*\gamma$ available.

Conclusion

1. **The LHCb detector is fully functional:**
   (a) **Validation of many aspects of detector is now done with control channels;**
   (b) **Performance is very promising for Rare Decays.**
2. **With the data collected in the 2010-2011 run the LHCb experiment will have competitive results in the measurement of $B_s \to \phi\gamma$, $B_d^0 \to K^*\mu^+\mu^-$ and $B_s \to \mu^+\mu^-$ channels which will allow to clarify better the already observed anomalies in the Standard Model picture.**