LHCb Prospects for Rare Decays

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Flavor-changing neutral currents decays

Indirect search for New Physics through FCNC $b \to s$ transitions because:
- suppressed within SM
- precise theoretical predictions for SM values
- NP predictions significantly differ from SM ones

Room to uncover possible NP effects.

Effective Hamiltonian, Operator Product Expansion

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{CKM}} V_{\text{CKM}}^* \left\{ \sum_{i=1}^{10} C_i \mathcal{O}_i + C_P \mathcal{O}_P + C_S \mathcal{O}_S \right\}$$

$C_i(\mu)$ Wilson coefficients: short-range information such as mass of particles in loops. Computed perturbatively for various models, SM and NP.

$\mathcal{O}_i(\mu)$ local operators: long-range contributions

New Physics possibly modifies the Wilson coefficients, affecting observable quantities as branching fractions, polarizations, and angular distributions.
Rare Decays at LHCb

**Outline**

- B^0 \rightarrow K^0 \mu\mu
  - \( B(B^0 \rightarrow K^0 \mu^+\mu^-) = (9.8 \pm 0.21) \times 10^{-7} \)
  - \( C_7 \)
  - AFB of the Muons
  - Angular Distribution
  - LHCb-roadmap-2
  - LHCb-2007-039
  - LHCb-2009-003

- B^0_s \rightarrow \phi \gamma
  - \( B(B_s^0 \rightarrow \phi \gamma) = (5.7^{+2.2}_{-1.9}) \times 10^{-5} \)
  - \( C_7 = C_{7R} + C_{7L} \)
  - \( C_{7R} \)
  - \( C_{7L} \)
  - Photon Polarization
  - LHCb-roadmap-4
  - LHCb-2007-030
  - LHCb-2007-147

- B^0_s \rightarrow \mu\mu
  - \( B(B_s^0 \rightarrow \mu^+\mu^-)|_{SM} = (3.35 \pm 0.32) \times 10^{-9} \)
  - \( C_S, C_P \) and \( C_{10} \)
  - Branching Fraction
  - LHCb-roadmap-1
  - LHCb-2007-033
  - LHCb-2008-018

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**B-Factory**

$L = 2 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}$ single interaction  

$\sigma_{bb} = 500 \mu b$

per year: $2 \text{ fb}^{-1}, 10^{12} \text{ bb}$ produced

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**Trigger**

From 30MHz to 2kHz on tape

- $B^0 \rightarrow K^0 \mu \mu \sim 80\%$
- $B^+ \rightarrow \phi \gamma \sim 40\%$
- $B^+ \rightarrow \mu \mu \sim 90\%$

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**Vertexing**

$\sigma(\text{IP}) \approx 14 \mu m + 35 \mu m/p_T [\text{GeV/c}]$

$\sigma(\tau) \approx 40-100 \text{ fs} \quad B^0 \rightarrow \phi \gamma$

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**MC simulation** in this talk

Full detector simulation, pile-up and spill-over at 14 TeV

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**Tracking**

$\varepsilon \approx 95\%, \text{ ghost} \approx 5\%, \text{ for } p > 5 \text{ GeV}$

$\sigma(p)/p \approx 0.4\%$

$\sigma(m) \approx 20 \text{ MeV/c}^2 \quad B^+ \rightarrow \mu \mu$

$\sigma(m) \approx 15 \text{ MeV/c}^2 \quad B^0 \rightarrow K^0 \mu \mu$

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**Calorimeters**

$\sigma(m) \approx 90 \text{ MeV/c}^2 \quad B^+ \rightarrow \phi \gamma$

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**RICH, Muon**

- $K\text{-id} \sim 97\% \ (\sim 6\% \pi \text{ mis-id})$
- $\mu\text{-id} \sim 93\% \ (\sim 1\% \pi \text{ mis-id})$

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for further LHCb physics talks see

- S. Blusk on NP in CPV
- F. Dettori on first measurements
Flavor-changing neutral current $b \rightarrow s$ transition

First observed at Belle, compatible with SM

\[ \mathcal{B}(B^0 \rightarrow K^{*0} \mu^+\mu^-) = 9.8 \times 10^{-7} \] 

New Physics particles can enter in the loop and modify Wilson coefficients, particularly $C_{7L}$, $C_{7R}$, $C_9$ and $C_{10}$.

The decay kinematics is defined by three angles $\phi$, $\theta_K$ and $\theta_\ell$ and by $q^2$ the invariant mass squared of the muon pair.

Two-step strategy:

- From start, $A_{FB}$ of the $\theta_\ell$ distribution, and particularly its zero-crossing point is particularly well predicted (FF cancel out) and experimentally accessible (acceptance distortion disappears)

- With more data (>2 fb$^{-1}$) a full angular ($\phi$, $\theta_K$ and $\theta_\ell$) analysis becomes possible, giving sensitivity to $C_7$, $C_9$ and $C_{10}$ Wilson coefficients.
$B^0 \rightarrow K^* \mu \mu$  \hspace{1cm} $\theta_1$ \hspace{1cm} A_{FB}

- $A_{FB}$ and $q^2_0$ theoretically well predicted and differ with models. $q^2_0 = 4.36^{+0.33}_{-0.31}$ GeV$^2$/c$^4$ in SM.

- Belle and Babar results shows hint of discrepancy w.r.t SM. note: opposite $A_{FB}$ sign convention between LHCb and B-factories!

- With a few hundreds pb$^{-1}$ LHCb can compete with B-factories.

**binned $A_{FB}$ analysis 2 fb$^{-1}$**

**unbinned $A_{FB}$ analysis 2 fb$^{-1}$**

Yield (2 fb$^{-1}$) and expected resolution
7000 signal events
1700 $b \rightarrow \mu b \rightarrow \mu$ events
\(\sigma(q^2_0) \approx 0.5\) GeV$^2$/c$^4$ with 2 fb$^{-1}$
\(\sigma(q^2_0) \approx 0.3\) GeV$^2$/c$^4$ with 10 fb$^{-1}$
• requires at least 2 fb\(^{-1}\) together and full acceptance correction understanding.

• uses further observable quantities \(F_L, A_T^{(2)}, A_T^{(3)}, A_T^{(4)}\)

• some of which have NP predictions very different from the SM ones.

LHCb sensitivity for the full angular analysis with 10 fb\(^{-1}\), the case of \(A_T^{(3)}\) and \(A_T^{(4)}\). 

**SM predictions (theoretical errors)  
SUSY (MSSM with large-gluino and positive mass insertion (with right-handed current); bands are 1σ and 2σ at LHCb**

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In the SM, right-handed photons (for $B_s^0$) are suppressed by $\tan \psi \equiv \frac{A_R}{A_L} \propto \frac{m_s}{m_b}$.

In New Physics models (Left-Right symmetry, uMSSM) the photon polarization is free.

One indirectly access the photon polarization ratio through the time-dependent decay rate. Contrarily from the $B^0$ case, it is particularly simple in the $B_s^0$ case, thanks to $\Delta \Gamma_s \neq 0$ and $\sin \varphi_s \approx 0$, no tagging needed:

$$\Gamma_{B^0_s(B^0_s) \to \phi \gamma}(t) = |A^2| \ e^{-\Gamma_s t} \left\{ \cosh \frac{\Delta \Gamma_s t}{2} - A^\Delta \sinh \frac{\Delta \Gamma_s t}{2} \right\}$$

$$A_{B^0_s}^\Delta \approx \sin 2\psi$$

Experimental issue:
trigger and offline selection uses IP cut for $\phi$, which directly affects the $B_s^0$ proper time resolution.
Control channel: $B^0 \to K^{*0} \gamma$

Other possible channels to probe photon polarization.
$\Lambda_b \to \Lambda^0 \gamma, \quad \Lambda_b \to (\Lambda^* \to pK^-) \gamma, \quad B^+ \to \phi K^+ \gamma$
Very rare decay, further helicity suppressed, proceed through loops diagrams.
Clean theoretical framework, precise SM prediction:
\[ B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.35 \pm 0.32) \times 10^{-9} \]

Current experimental limit, by CDF and DØ:
\[ B(B_s^0 \rightarrow \mu^+ \mu^-) < 4.7 \times 10^{-8} \text{ at } 90\% \text{ C.L.} \]

Branching fraction sensitive to \( C_S \) and \( C_P \) Wilson coefficients, is strongly enhanced by NP by a factor \((\tan \beta)^6\)

in cMSSM generalization (NUHM realization), best fit using WMAP Dark Matter, (g-2)\( \mu \) constraints gives:
\[ B(B_s^0 \rightarrow \mu^+ \mu^-) \sim 10^{-8} \]

\[ \Delta \chi^2 < 2.39 \]
\[ \Delta \chi^2 < 4.61 \]

\( \mu = 800, \ m_0 = 300 \)
Strategy for finding needles in one haystack

- loose selection
- Categorization of candidate events along **three criteria:**
  
1. **Geometrical information**
   - $B_s$ impact parameter with respect to the PV
   - $B_s$ proper time
   - Smallest impact parameter significance of the muons candidates wrt any PVs
   - The distance of closest approach of the two muons
   - The isolation of the two muons tracks

   \[ B_s^0 \rightarrow \mu^+ \mu^- \] for signal
   \[ B_s^0 \rightarrow K^+ K^- \] mass sidebands for bkgd

2. **Muon identification**
   - $J/\psi \rightarrow \mu^+ \mu^-$ for signal
   - $\Lambda \rightarrow p\pi^-$ for bkgd

3. **Invariant mass** of the di-muon
   - $B_s^0 \rightarrow K^+ K^-$ for signal
   - mass sidebands for bkgd

A 3D space is populated with the candidates, composing a distribution that can be tested against various branching fraction hypotheses.
**$B^0_s \rightarrow \mu^+ \mu^-$ Analysis Strategy II**

- **Normalization** necessary to access absolute branching fraction.

\[
B(B^0_s \rightarrow \mu^+ \mu^-) = B_{\text{norm}} \times \frac{f_{\text{norm}}}{f_s} \times \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{sig}}} \times \frac{N_{\text{sig}}}{N_{\text{norm}}}
\]

Requires channels with well measured branching fraction and close to $B^0_s \rightarrow \mu^+ \mu^-$ to control the efficiency ratio. The channels considered are $B^0 \rightarrow K^+ \pi^-$ and $B^+ \rightarrow J/\psi(\mu^+ \mu^-)K^+$.

$f_s$ represents the main systematic error $\sim 13\%$.

- The 3D distribution obtained experimentally is tested against branching ratio hypotheses using the three likelihoods calibrated on data for signal and background with the CL method. One **Exclude/Observed** a branching fraction.

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Since a result is possible with very little data already, an alternate analysis suitable for a not perfectly understood detector has been developed. This robust analysis is based on variables which do not involve error estimates. The overall strategy being identical to the standard analysis.
LHCb expected **exclusion** sensitivity to $B^0_s \rightarrow \mu \mu$ (in case no signal is observed) as a function of the integrated luminosity with **plain black curves for the standard analysis** and **red dashed curves for the robust analysis**.

LHCb competes with the current Tevatron limit ($4.7 \times 10^{-8}$) with less than 0.1 fb$^{-1}$, and overtake Tevatron expected final limit with about 0.2 fb$^{-1}$.

NP models with high tan$\beta$ value are strongly constrained in the process.
LHCb expected observation sensitivity to $B^0_s \to \mu^+ \mu^-$ as a function of the integrated luminosity.

About 3 fb$^{-1}$ are enough for a 3σ observation if the branching fraction is the SM prediction. Any enhancement driven by NP will be observed sooner. If the branching fraction is $\sim 2 \cdot 10^{-8}$ as in NUHM scenario, a 5σ discovery is possible with very little luminosity ($< 0.5$ fb$^{-1}$).

With 10 fb$^{-1}$, a 5σ discovery occurs if the branching fraction is close to the SM one.

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LHCb is ready to collect the largest B meson sample ever.

Interesting new results will follow:

Possible NP discovery very early with the $\mathcal{B}_s^0 \rightarrow \mu\mu$ decay, or at least strong constraints on NP models with high $\tan\beta$ value within the first run of data-taking.

With 2 $\text{fb}^{-1}$, i.e. one year of data taking in nominal conditions:

- $\mathcal{B}^0 \rightarrow K^*\mu\mu$ The zero crossing point of $\theta_{lA_{FB}}$ is measure with $\sigma(q^2_0) \approx 0.5$ GeV$^2$/c$^4$
- $\mathcal{B}_s^0 \rightarrow \phi\gamma$ The Time-dependent analysis leads to $\sigma(A^\Lambda) \approx 0.22$, which gives $\sigma(\psi) \approx 0.1$
- $\mathcal{B}_s^0 \rightarrow \mu\mu$ Limit on the branching fraction down to the SM prediction if no signal is observed, possible NP observation if the branching fraction is enhanced.

On the long term:

- $\mathcal{B}^0 \rightarrow K^*\mu\mu$ Full angular analysis, sensitive to $C_7, C_9$ and $C_{10}$
- $\mathcal{B}_s^0 \rightarrow \mu\mu$ $5\sigma$ discovery if branching fraction at SM level with about 10 $\text{fb}^{-1}$.

You will hear from Rare Decays at LHCb soon, and for a long time!