Searches for very rare decays to purely leptonic final states at LHCb

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Introduction

New physics searches in Heavy Flavour sector:

- **CP violation:** expected extra force

- **LFV:**
  - in the SM leptons do not change flavour
  - possible symmetry between quarks and leptons
  - \( B^0_{(s)} \rightarrow e^+\mu^- \)

- **Rare decays:**
  - small prediction in the SM and NP effects could arise at the same level
  - \( B^0_{(s)} \rightarrow \mu^+\mu^- \)
$B^0(s) \rightarrow \mu^+\mu^-$

Branching fractions well predicted in the SM:

\[
\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-)^{CP} = (3.34 \pm 0.27) \cdot 10^{-9} \\
\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)^{CP} = (1.07 \pm 0.05) \cdot 10^{-10}
\]

Due to the finite width of the $B^0_s$ system, the time-integrated BF is:

\[
\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)^{<t>} = (3.56 \pm 0.30) \cdot 10^{-9}
\]

Probe for models with an extended Higgs sector

Experimental Status

LHCb reported the first evidence of $B_s \rightarrow \mu^+\mu^-$ decay with a 3.5 $\sigma$ significance:

\[
\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.2^{+1.4}_{-1.2} \text{ (stat)}^{+0.5}_{-0.3} \text{ (syst)}) \times 10^{-9} 
\]

[PRL 110, 021801 (2013)]

best upper limit on $B^0 \rightarrow \mu^+\mu^-$ (ATLAS+CMS+LHCb):

\[
\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 8.4 \cdot 10^{-10} \text{ @ 95\% CL}
\]

[LHCb-CONF-2012-017]
Analysis strategy

- Blind analysis based on 3fb$^{-1}$ of data recorded during 2011 and 2012
  - 2fb$^{-1}$ of previous analysis included, re-reconstructed and re-analyzed

- Sig and bkg classification in $m_{\mu\mu}$ vs BDT plane:
- BDT (improved respect 2fb$^{-1}$ analysis):
  - Based on kinematic and geometrical variables
  - trained with MC calibrated on data
- Data driven calibration

- Comparison between expectation and observed events:
  - Branching fraction from unbinned likelihood fit
  - Upper limit from CLs method

[arXiv:1307.5024]
Calibrations

- BDT classifier PDFs are calibrated using:
  - $B \to hh'$ events for signal
  - mass sidebands $B \to \mu\mu$ candidates for bkg

- Invariant mass:
  - signal described by a Crystal Ball function:
    - mean value calibrated with exclusive $B \to hh'$ decays
    - resolution from di-$\mu$ resonance and exclusive $B \to hh'$
  - background PDFs from data sidebands

\[
\sigma_{B^0} = 22.8 \pm 0.4 \text{ MeV}/c^2 \\
\sigma_{B^0_s} = 23.2 \pm 0.4 \text{ MeV}/c^2
\]
Normalization

- Two control channels used for the normalization: $B^+ \rightarrow J/\psi K^+$ and $B^0 \rightarrow K^+ \pi^-$

$$BR = BR_{cal} \times \frac{\epsilon_{cal}}{\epsilon_{sig}} \times \frac{f_{cal}}{f_{d(s)}} \times \frac{N_{B^0(s) \rightarrow \mu^+ \mu^-}}{N_{cal}} = \alpha(s) \times N_{B^0(s) \rightarrow \mu^+ \mu^-}$$

- From MC and x-checked on data
- Trigger efficiency from $J/\psi \rightarrow \mu \mu$ data
- $fs/fd$ from LHCb measurement (next slide)
- Using the SM signal we expect $39.5 \pm 4.3 \text{ } B_s \rightarrow \mu^+ \mu^-$ and $4.5 \pm 0.4 \text{ } B^0 \rightarrow \mu^+ \mu^-$

$\alpha_s = (9.41 \pm 0.65) \cdot 10^{-11}$
$\alpha = (2.40 \pm 0.09) \cdot 10^{-11}$
b fragmentation $f_s/f_d$

- LHCb used semileptonic decays: ratio of $B^0_s \rightarrow D_s \mu X$ to $B \rightarrow D^+ \mu X$
- Combined with hadronic results: ratio of $B^0_s \rightarrow D^- \pi^+$ to $B^0 \rightarrow D^- K^+$
- Recently updated using new $BF(D_s \rightarrow K^+ K^- \pi^+)$ from CLEO, BaBar and Belle
- Updated $B$ lifetime measurements

New

$$\frac{f_s}{f_d} = 0.259 \pm 0.015$$

- PT dependence negligible for $B^0_{(s)} \rightarrow \mu^+ \mu^-$. Checked the variation as a function of $\sqrt{s}$ with $B^+ \rightarrow J/\psi K^+$ and $B^0_s \rightarrow J/\psi \phi$
Time dependent acceptance

- $B_s \rightarrow \mu^+ \mu^-$ time dependent width:

$$\Gamma(B_s^0(t) \rightarrow \mu^+ \mu^-) = (R_H + R_L)e^{-\Gamma_s t} \left[ \cosh \frac{y_{st}}{\tau_{B_s}} + A_{\Delta \Gamma} \sinh \frac{y_{st}}{\tau_{B_s}} \right]$$

where:

$$y_s = \frac{\Gamma_L - \Gamma_H}{\Gamma_L + \Gamma_H} = 0.01615 \pm 0.0085$$

$$A_{\Delta \Gamma} = \frac{\Gamma_{B_{s,H}^0 \rightarrow \mu \mu} - \Gamma_{B_{s,L}^0 \rightarrow \mu \mu}}{\Gamma_{B_{s,H}^0 \rightarrow \mu \mu} + \Gamma_{B_{s,L}^0 \rightarrow \mu \mu}} \overset{SM}{=} 1$$

- So the time integrated efficiency is model dependent:

$$\varepsilon = \frac{\int e(t) \Gamma_{A_s, y_s(t)} dt}{\int \Gamma_{A_s} y_s(t) dt}$$

- Normalization to be corrected to take into account this effect:

$$\delta \varepsilon = \frac{\varepsilon^{A_{\Delta \Gamma}, y_s}}{\varepsilon_{MC}} = \frac{\int_0^\infty \Gamma(B_s^0(t) \rightarrow \mu^+ \mu^-, A_{\Delta \Gamma}, y_s) e(t) dt}{\int_0^\infty \Gamma(B_s^0(t) \rightarrow \mu^+ \mu^-, A_{\Delta \Gamma}, y_s) dt} \cdot \frac{\int_0^\infty e^{-\Gamma_{MC} t} e(t) dt}{\int_0^\infty e^{-\Gamma_{MC} t} dt}$$

Correction for $B_s = 4.50 \pm 0.03\%$
Correction for $B^0 = 1.48 \pm 0.01\%$

- BDT PDF also corrected because time dependent
\[ \mathbf{BF}(B^0_s \rightarrow \mu^+ \mu^-) \]

- A simultaneous unbinned likelihood fit to the mass spectra is performed on 8 BDT bins
- Combinatorial bkg, \( B_s \) and \( B^0 \) yields free
- yield and PDFs of exclusive backgrounds constrained to their expectations.

- For the \( B_s \) we obtain:
  \[ \mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (2.9^{+1.1}_{-1.0} \text{stat})^{+0.3}_{-0.1} \text{syst}) \times 10^{-9} \]
  with a significance of \( 4.0 \sigma \)
- For the \( B^0 \):
  \[ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (3.7^{+2.4}_{-2.1} \text{stat})^{+0.6}_{-0.4} \text{syst}) \times 10^{-10} \]
  with a significance of \( 2.0 \sigma \)
The statistical uncertainty is derived by repeating the result of the fit is overlaid (blue solid line) and the branching fraction. The method provides method [38] is used, to set an upper limit on the is found, a modified frequentist approach, the candidates with BDT from the fit are in agreement with the SM expectations.

As no significant excess of background by including the obtained from the likelihood with all nuisance parameters of the statistical uncertainty from the total uncertainty background, to their expected values. The systematic results in candidates / (44 MeV/c) Candidates / (44 MeV/c) 2/\(\mu\) and by varying the mass shapes of backgrounds from

\[ B(\mu^+\mu^-) \quad [10^{-10}] \]

<table>
<thead>
<tr>
<th></th>
<th>90 % CL</th>
<th>95 % CL</th>
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<tbody>
<tr>
<td>Exp. bkg</td>
<td>3.5 \times 10^{-10}</td>
<td>4.4 \times 10^{-10}</td>
</tr>
<tr>
<td>Exp. bkg+SM</td>
<td>4.5 \times 10^{-10}</td>
<td>5.4 \times 10^{-10}</td>
</tr>
<tr>
<td>Observed</td>
<td>6.3 \times 10^{-10}</td>
<td>7.4 \times 10^{-10}</td>
</tr>
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</table>
\[ B^0(s) \rightarrow e\mu \]

- Charged LFV process are forbidden in the SM \((\sim 10^{-54})\)
- Decays like \(B^0(s)\rightarrow e\mu\) are allowed in model with a local gauge symmetry between leptons and quarks like the Pati-Salam model \([\text{Phys. Rev. D 10 (1974) 275.}]\)
  - new interaction between lepton and quarks mediated by a spin-1 gauge boson (LQ)
  \[
  \mathcal{B}(B_s \rightarrow e^\pm \mu^\mp) < 2.0(2.6) \cdot 10^{-7} \ \text{at} \ 90(95)\% \ \text{CL} \\
  \mathcal{B}(B^0 \rightarrow e^\pm \mu^\mp) < 6.4(7.9) \cdot 10^{-8} \ \text{at} \ 90(95)\% \ \text{CL}
  \]
Analysis strategy

- Blind analysis based on 1fb\(^{-1}\) of data recorded in 2011 (\(\sqrt{s} = 7\)TeV)
- Analysis inherited from \(B^0(s)\to\mu^+\mu^-\)
- Events studied in \(m_{e\mu}\) vs BDT plane
- Normalized to \(B_d\to K\pi\) yield in data
- Upper limit on BF evaluated using the CLs method
Results

CL$_s$ method to set limits on the branching fractions

\[ B^0_s \rightarrow e^+ \mu^- \]

\[ B^0 \rightarrow e^+ \mu^- \]

<table>
<thead>
<tr>
<th></th>
<th>$B^0_s \rightarrow e^+ \mu^-$ at 90% (95%) CL</th>
<th>$B^0 \rightarrow e^+ \mu^-$ at 90% (95%) CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected (LHCb 1fb$^{-1}$)</td>
<td>$1.5 \ (1.8) \ 10^{-8}$</td>
<td>$3.8 \ (4.8) \ 10^{-9}$</td>
</tr>
<tr>
<td>Observed (LHCb 1fb$^{-1}$)</td>
<td>$1.1 \ (1.4) \ 10^{-8}$</td>
<td>$2.8 \ (3.7) \ 10^{-9}$</td>
</tr>
<tr>
<td>Current (CDF 2fb$^{-1}$)</td>
<td>$20.0 \ (20.6) \ 10^{-8}$</td>
<td>$64.0 \ (79.0) \ 10^{-9}$</td>
</tr>
</tbody>
</table>

New world best limits \textbf{~20 times} more stringent than limits previously reported.
lepto-quark mass bounds

UL on branching fractions set lower bounds to the Pati-Salam lepto-quark mass.

CDF measurements:
\[ m_{LQ}(B_s \to e^+ \mu^-) > 47.8(44.9) \text{ TeV}/c^2 @ 90(95)\% \text{CL}, \]
\[ m_{LQ}(B_d \to e^+ \mu^-) > 59.3(56.3) \text{ TeV}/c^2 @ 90(95)\% \text{CL}, \]

LHCb new constraints:
\[ m_{LQ}(B_s \to e^+ \mu^-) > 107(101) \text{ TeV}/c^2 @ 90(95)\% \text{CL}, \]
\[ m_{LQ}(B_d \to e^+ \mu^-) > 135(126) \text{ TeV}/c^2 @ 90(95)\% \text{CL}, \]
Conclusions

- Rare decays powerful probe to search NP beyond the SM
- LHCb is demonstrating its power in search for rare decays in Heavy Flavour sector
- New world’s best limit on $B^0_{(s)} \rightarrow e\mu$ is presented
- Brand new results for $B^0_{(s)} \rightarrow \mu^+\mu^-$ using the full LHCb sample of 3fb$^{-1}$
  - Confirmed evidence for $B_s \rightarrow \mu^+\mu^-$ with a significance of 4.0 $\sigma$
- New world best limit on $B^0 \rightarrow \mu^+\mu^-$ branching fraction
Spares
The BDT PDFs trained on MC are calibrated using:

- $B \rightarrow hh$ for signal:
  - same topology and kinematics
  - correction introduced for the presence of an electron in the final state
- Data Sidebands for the calibration of the background
Mass Calibration $B^0(s)\rightarrow e\mu$

- No proxy channel to calibrate the mass PDF
- J/ψ→ee used for MC validation

<table>
<thead>
<tr>
<th>Mass window</th>
<th>$\epsilon_{\text{mass}}(B_s)$</th>
<th>$\epsilon_{\text{mass}}(B_d)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[5.1 – 5.5] GeV/$c^2$</td>
<td>(85.0 ± 0.1$<em>{\text{stat}}$ ± 4.5$</em>{\text{syst}}$)%</td>
<td>(82.1 ± 0.1$<em>{\text{stat}}$ ± 3.6$</em>{\text{syst}}$)%</td>
</tr>
</tbody>
</table>
Normalization $B^0(s)\to e\mu$

$$BR_{B^0(s)\to e\mu} = BR_{\text{cal}} \times \frac{f_d}{f_q} \times \frac{\epsilon_{\text{cal}}^{\text{SEL|REC}}}{\epsilon_{\text{sig}}^{\text{SEL|REC}}} \frac{\epsilon_{\text{cal}}^{\text{TRIG|SEL}}}{\epsilon_{\text{sig}}^{\text{TRIG|SEL}}} \frac{1}{\epsilon_{\text{PID}}^{\text{SIG}}} \times \frac{N_{B^0(s)\to e\mu}}{N_{\text{cal}}}$$

$$= \alpha \times N_{B^0(s)\to e\mu}$$

<table>
<thead>
<tr>
<th>$BR(B_d \to K^+\pi^-)$</th>
<th>$(1.94 \pm 0.96) \cdot 10^{-5}$ [a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_d/f_s$</td>
<td>$3.91 \pm 0.29$ [b]</td>
</tr>
<tr>
<td>$\epsilon_{\text{cal}}^{\text{SEL</td>
<td>REC}}/\epsilon_{\text{sig}}^{\text{SEL</td>
</tr>
<tr>
<td>$\epsilon_{\text{cal}}^{\text{TRIG</td>
<td>SEL}}/\epsilon_{\text{sig}}^{\text{TRIG</td>
</tr>
<tr>
<td>$\epsilon_{\text{PID}}^{\text{SIG}}$</td>
<td>Data driven</td>
</tr>
<tr>
<td>$N_{\text{cal}}$</td>
<td>$10124 \pm 916$ [c]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\alpha_{B^0_s\to e\mu}$</th>
<th>$(1.1 \pm 0.2) \times 10^{-9}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{B^0\to e\mu}$</td>
<td>$(2.8 \pm 0.5) \times 10^{-10}$</td>
</tr>
</tbody>
</table>
Backgrounds $B^0(s) \rightarrow \mu^+ \mu^-$

- The main background is the combinatorial from $b b \rightarrow \mu^+ \mu^-$ events extrapolated from mass sidebands.

- Decays from partially reconstructed and/or misidentified decays:
  - contributing to the signal region: $B \rightarrow h^+ h^- \rightarrow \mu^+ \mu^-$
  - modifying the sidebands composition:
    - Semileptons: $B^0 \rightarrow \pi^+ \mu^- \nu$, $B^0_s \rightarrow K^+ \mu^- \nu$, $\Lambda_b \rightarrow \pi \mu^- \nu$, $B^+_c \rightarrow J/\psi \mu^+ \nu$
    - Rare decays: $B^+ \rightarrow \pi^+ \mu^- \mu^+$, $B^0 \rightarrow \pi^0 \mu^- \mu^+$
  - Many others considered and found negligible.

<table>
<thead>
<tr>
<th>Decay</th>
<th>Yield in full BDT range</th>
<th>Fraction with BDT $&gt; 0.7%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0(s) \rightarrow h^+ h^-$</td>
<td>15$\pm$1</td>
<td>28</td>
</tr>
<tr>
<td>$B^0 \rightarrow \pi^+ \mu^- \nu$</td>
<td>115$\pm$6</td>
<td>15</td>
</tr>
<tr>
<td>$B^0_s \rightarrow K^- \mu^+ \nu$</td>
<td>10$\pm$4</td>
<td>21</td>
</tr>
<tr>
<td>$B^{0(+)} \rightarrow \pi^{0(+)} \mu^+ \mu^-$</td>
<td>28$\pm$8</td>
<td>15</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow \pi \mu^- \nu$</td>
<td>70$\pm$30</td>
<td>11</td>
</tr>
</tbody>
</table>

Expected background yields from b-hadron decays, with dimuon mass $m_{\mu\mu} \in [4900, 6000]$ MeV/c$^2$. 