Rare B Decays at ATLAS and CMS

Pavel Řezníček (Charles University) for the ATLAS & CMS Collaborations
23rd November 2021
• $B \to ll$ and $B \to s(d)ll$ suppressed at tree level in the SM
  • Further suppression by CKM and helicity
• For pure leptonic decays BR is predicted within SM with small uncertainties

Bobeth et al., PRL 112 (2014) 101801

\[
\begin{align*}
B(B_s^0 \to ee) &= (8.54 \pm 0.55) \times 10^{-14} \\
B(B_s^0 \to \mu\mu) &= (3.65 \pm 0.23) \times 10^{-9} \\
B(B_0 \to \tau\tau) &= (7.73 \pm 0.49) \times 10^{-7}
\end{align*}
\]

Beneke et al., JHEP 10 (2019) 232

\[
\begin{align*}
B(B_s^0 \to \mu\mu) &= (3.66 \pm 0.14) \times 10^{-9} \\
B(B_0 \to \mu\mu) &= (1.03 \pm 0.05) \times 10^{-10}
\end{align*}
\]

New physics contributions
• ... could suppress or enhance BR

\[
\begin{align*}
\bar{b} &\rightarrow W^+ \tilde{\chi}^0, c, u \\
W^- &\rightarrow l^+ \\
s &\rightarrow W^-, \tilde{\chi}^0, \bar{t} \rightarrow l^- \\
\end{align*}
\]

• ... could affect angular distributions in $b \to sll$

\[
\begin{align*}
\bar{b} &\rightarrow W^+ H^+, \tilde{\chi}^0, \mu^+ \\
W^- &\rightarrow \mu^- \\
s &\rightarrow \mu^+, \bar{t} \rightarrow \mu^- \\
\bar{b} &\rightarrow LQ, \bar{t} \rightarrow l^- \\
\end{align*}
\]

• Direct probing of potential LFU effects in progress too (not discussed)
B-Physics at ATLAS & CMS

- Data: Run 2 ~140 fb\(^{-1}\) pp collisions at \(\sqrt{s} = 13\) TeV (2015-18), Run 1 ~25 fb\(^{-1}\) at 7/8 TeV (2011-12)
- Producing 2.5 M \(b\bar{b}\) pairs/second, \(B_s, B_c, \Lambda_b\), etc. available
- Program focused mostly on muonic final states, fully reconstructable; exceptions exist:
  - CMS B-parking Run 2 data collecting huge unbiased (~ 10\(^{10}\)) \(b\)-hadron events
  - Di-electron triggers in Run 2 at ATLAS

![ATLAS Preliminary Data 2018](image)

- CMS Preliminary
  - Online Reconstructed Dimuon Events
    - \(\eta, \phi, \Psi, \Psi', \Omega, \Upsilon(nS)\)
    - \(L1\)-Trigger Selection Requirements

![CMS Preliminary Data 2018](image)
Rare B decays results from ATLAS & CMS

Purely leptonic decays

- Branching ratio of $B_{(s)}^0 \rightarrow \mu \mu$ and $B_s^0 \rightarrow \mu \mu$ effective lifetime in $pp$ collisions with 2011-2016 data (CMS)
- Branching ratio of $B_{(s)}^0 \rightarrow \mu \mu$ in $pp$ collisions during LHC Run 1 and 2015 and 2016 data (ATLAS)
  JHEP 04 (2019) 098, EPJC 76 (2016) 513

Semileptonic decays (all using $pp$ collisions data at $\sqrt{s} = 8$ TeV)

- Angular analysis of $B^\pm \rightarrow K^\pm \mu \mu$ (CMS) PRD 98 (2018) 112011
- Angular analysis of $B^\pm \rightarrow K^{*\pm} \mu \mu$ (CMS) JHEP 04 (2021) 124
- Angular analysis of $B^0 \rightarrow K^{*0} \mu \mu$ (CMS) PLB 781 (2018) 517 ($P_1$, $P'_5$), PLB 753 (2016) 424 ($A_{FB}$, $F_L$)
- Angular analysis of $B^0 \rightarrow K^{*0} \mu \mu$ (ATLAS) JHEP 10 (2018) 047

$B_{(s)}^0 \rightarrow \mu\mu$: Analyses

Datasets

- ATLAS data: 2015+2016 data analysis, combined with Run 1 result
- CMS data: Run 1 + 2016 data analysis

$\mathcal{B}(B_{(s)}^0 \rightarrow \mu\mu)$ measurement relative to $\mathcal{B}(B^\pm \rightarrow J/\psi K^\pm)$, $B_s^0 \rightarrow J/\psi \phi$ as control channel

\[
\mathcal{B}(B_{(s)}^0 \rightarrow \mu^+\mu^-) = N_{d(s)} \cdot \frac{\mathcal{B}(B^\pm \rightarrow J/\psi K^\pm) \cdot \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)}{N_{J/\psi K^\pm} \cdot \frac{\epsilon_{\mu^+\mu^-}}{\epsilon_{J/\psi K^\pm}}} \cdot \frac{f_u}{f_{d(s)}}
\]

- Blinded signal di-muon invariant mass region
- Backgrounds
  - Combinatorial background suppressed by BDT, trained on data sidebands
    - ATLAS: 4 BDT bins with equal signal efficiency, 15 variables on kinematics, isolation and $B$-vertex separation from PV
    - CMS: 14 BDT categories (barrel/endcap, year datasets), 10-15 pile-up independent variables
  - Peaking backgrounds (mostly mis-id) and partially reconstructed $B$-decays from simulations
- Yields $N_{d(s)}$ and $N_{J/\psi K^\pm}$ obtained from UML fits to the mass spectra
- Relative reconstruction efficiencies and acceptances from simulation (corrected for data-MC differences)
- Known branching ratios from PDG, $f_u/f_{d(s)}$ from HFLAV
In Run 1 ATLAS measurement lower in both $B_s^0 \rightarrow \mu\mu$ and $B^0 \rightarrow \mu\mu$ BR compared to combined CMS+LHCb; tension in $B_d^0$ reduced with the Run 2 LHCb measurement (PRL 118 (2017) 191801)

**ATLAS 2015 + 2016 data**

$B(B_s^0 \rightarrow \mu\mu) = (3.2^{+1.1}_{-1.0}) \times 10^{-9}$

$B(B^0 \rightarrow \mu\mu) < 4.3 \times 10^{-10}$ at 95% CL

**ATLAS Run 1 + 2015 + 2016 data**

$B(B_s^0 \rightarrow \mu\mu) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$

$B(B^0 \rightarrow \mu\mu) < 2.1 \times 10^{-10}$ at 95% CL

- Contours obtained using Neyman construction
- Compatible with SM at 2.4 $\sigma$
- Statistic uncertainties dominate
$B^{0}_{(s)} \rightarrow \mu\mu$: CMS results

CMS 2011 + 2012 + 2016 data

Multi-bin BDT fit

$\mathcal{B}(B^{0}_s \rightarrow \mu\mu) = (2.9 \pm 0.7\,_\text{exp} \pm 0.2\,_{\text{frag}}) \times 10^{-9}$

- $5.6\sigma$ observed, $6.5\sigma$ expected

$\mathcal{B}(B^{0} \rightarrow \mu\mu) < 3.6 \times 10^{-10}$ at 95% CL

- resp. $\mathcal{B}(B^{0}_s \rightarrow \mu\mu) = 0.8^{+1.4}_{-1.3} \times 10^{-10}$ ($0.6\sigma$)

Lifetime measurement

Single BDT category; fit range $[1, 11] \text{ps}$

$\tau_{\mu^+\mu^-} = (1.70^{+0.64}_{-0.44}) \text{ ps}$
Combining binned 2D profile likelihoods, systematics treated as independent, except for $f_s/f_d$ which is the only source of correlation between experiments.

<table>
<thead>
<tr>
<th>LHC</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(B^0_s \to \mu^+\mu^-) \times 10^{-9}$</td>
<td>$2.69^{+0.37}_{-0.35}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B^0 \to \mu^+\mu^-) \times 10^{-10}$</td>
<td>$&lt; 1.9 \text{ at 95% CL}$</td>
</tr>
<tr>
<td>Ratio of above</td>
<td>$&lt; 0.052 \text{ at 95% CL}$</td>
</tr>
<tr>
<td>$\tau_{B^0_s \to \mu\mu} \text{ [ps] (LHCb+CMS)}$</td>
<td>$1.91^{+0.37}_{-0.35}$</td>
</tr>
</tbody>
</table>
$B_{(s)}^0 \rightarrow \mu\mu: \text{HL-LHC projections}$

- Theory prediction limited by $|V_{cb}|$
- Experimental uncertainty on $B_s^0$ dominated by $f_s/f_d$
- Mass resolution improvements will help distinguishing the $B_s^0$ and $B_d^0$ peaks
- Additional information from effective lifetime and $CP$ asymmetry
  - Distinguish RH and LH contributions
  - Inclusion of $B_s^0 \rightarrow \mu\mu\gamma$ studies to probe vector coupling
- Computations in SUSY unified models (PRD 91 (2015) no.9, 095011)
- Subset consistent with other measurements
Semimuonic rare B decays

Analyses of decay angles distributions, based on unbinned maximum likelihood fit to the data in rough $q = m(\mu\mu)^2$ bins (due to low yields)

- Inclusive backgrounds data driven, few peaking background contributions (simulated)
- 8 TeV collision data ($\sim 20\text{fb}^{-1}$)

$B^\pm \rightarrow K^\pm \mu\mu$ at CMS

- Muon-kaon angle in the $\mu\mu$ rest frame: $\theta_l$
- Forward-backward asymmetry $A_{FB}$
- Pseudo-scalar/tensor contribution $F_H$
- Measured also differential BR
- $\sim 2300$ signal events

$$\frac{1}{\Gamma_f} \frac{d\Gamma}{d \cos \theta_l} = \frac{3}{4} (1 - f_H)(1 - \cos^2 \theta_l) + \frac{1}{2} f_H + A_{FB} \cos \theta_l$$

$B^0 \rightarrow K^{*0} \mu\mu$ at CMS and ATLAS

- Richer angular structure
- Folding in $\phi$ and $\theta_l$ to reduce number of fit-parameters
- CMS: $\sim 1400$ signal events across $q^2 = (0 - 20) \text{GeV}^2$
- ATLAS: $\sim 350$ signal events across $q^2 = (0 - 6) \text{GeV}^2$
- No $K/\pi$ identification; $\min|m_{K^\mp} - m_{K^{*}}|$ to tag B-flavor; $(12 - 14)\%$ mis-ID

$B^0 \rightarrow K^{*\pm} \mu\mu$ at CMS

- Similar fit structure to $B^0 \rightarrow K^{*0} \mu\mu$
- $\sim 90$ signal events across full $q^2$ range

$$\frac{1}{\Gamma f d \cos \theta_K d \cos \theta_f d q^2} \frac{d^3 \Gamma}{d \cos \theta_f d \cos \theta_K d d q^2} = \frac{9}{8\pi} \frac{3(1 - f_L)}{4} \sin^2 \theta_K + f_L \cos^2 \theta_K + \frac{1 - f_L}{4} \sin^2 \theta_K \cos 2\theta_f - f_L \cos^2 \theta_K \cos 2\theta_f + S_3 \sin^2 \theta_K \sin^2 \theta_f \cos 2\phi + S_2 \sin \theta_K \sin \theta_f \cos \phi$$
Semimuonic rare $B$ decays

Analyses of decay angles distributions, based on unbinned maximum likelihood fit to the data in rough $q = m(\mu\mu)^2$ bins (due to low yields)

- Inclusive backgrounds data driven, few peaking background contributions (simulated)
- 8 TeV collision data ($\sim 20 fb^{-1}$)

$B^\pm \rightarrow K^{\pm} \mu\mu$ at CMS

<table>
<thead>
<tr>
<th>CMS</th>
<th>20.5 fb$^{-1}$ (8 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 &lt; q^2 &lt; 6$ GeV$^2$</td>
<td></td>
</tr>
</tbody>
</table>

$B^0 \rightarrow K^{*0} \mu\mu$ at CMS and ATLAS

$B^\pm \rightarrow K^{*\pm} \mu\mu$ at CMS

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Rare B Decays at ATLAS and CMS

23 Nov 2021
$B^\pm \to K^\pm \mu\mu$, $B^\pm \to K^{*\pm} \mu\mu$: Results (CMS)

**$B^\pm \to K^\pm \mu\mu$**

- Consistent with SM predictions (and previous results)

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>$A_{FB}$ ($\times 10^{-2}$)</th>
<th>$F_{H}$ ($\times 10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finite size of MC samples</td>
<td>0.4–1.8</td>
<td>0.9–5.0</td>
</tr>
<tr>
<td>Efficiency description</td>
<td>0.1–1.5</td>
<td>0.1–7.8</td>
</tr>
<tr>
<td>Simulation mismodeling</td>
<td>0.1–2.8</td>
<td>0.1–1.4</td>
</tr>
<tr>
<td>Background parametrization model</td>
<td>0.1–1.0</td>
<td>0.1–5.1</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>0.1–1.7</td>
<td>0.1–3.3</td>
</tr>
<tr>
<td>Dimuon mass resolution</td>
<td>0.1–1.0</td>
<td>0.1–1.5</td>
</tr>
<tr>
<td>Fitting procedure</td>
<td>0.1–3.2</td>
<td>0.4–25</td>
</tr>
<tr>
<td>Background distribution</td>
<td>0.1–7.2</td>
<td>0.1–29</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>1.6–7.5</td>
<td>4.4–39</td>
</tr>
</tbody>
</table>

**$B^\pm \to K^{*\pm} \mu\mu$**

- Consistent with SM predictions

<table>
<thead>
<tr>
<th>Source</th>
<th>$A_{FB}$ ($10^{-3}$)</th>
<th>$F_{L}$ ($10^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC statistical uncertainty</td>
<td>12–29</td>
<td>18–38</td>
</tr>
<tr>
<td>Efficiency model</td>
<td>3–25</td>
<td>4–12</td>
</tr>
<tr>
<td>Background shape functional form</td>
<td>0–9</td>
<td>0–33</td>
</tr>
<tr>
<td>Background shape statistical uncertainty</td>
<td>16–73</td>
<td>20–87</td>
</tr>
<tr>
<td>Background shape sideband region</td>
<td>28–153</td>
<td>38–78</td>
</tr>
<tr>
<td>S-wave contamination</td>
<td>4–22</td>
<td>5–12</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>42–174</td>
<td>55–127</td>
</tr>
</tbody>
</table>

P. Řezníček

Rare B Decays at ATLAS and CMS

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$B^0 \rightarrow K^{*0} \mu\mu$: Results (CMS, ATLAS)

**CMS: $P_1, P'_5, A_{FB}, F_L$; full $q^2$ range**

- Consistent with SM predictions

<table>
<thead>
<tr>
<th>Source</th>
<th>$P_1 \times 10^{-3}$</th>
<th>$P'_1 \times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation mismodeling</td>
<td>1–33</td>
<td>10–23</td>
</tr>
<tr>
<td>Fit bias</td>
<td>5–78</td>
<td>10–120</td>
</tr>
<tr>
<td>Finite size of simulated samples</td>
<td>29–73</td>
<td>31–110</td>
</tr>
<tr>
<td>Efficiency</td>
<td>17–100</td>
<td>5–65</td>
</tr>
<tr>
<td>$K\pi$ mistagging</td>
<td>8–110</td>
<td>6–66</td>
</tr>
<tr>
<td>Background distribution</td>
<td>12–70</td>
<td>10–51</td>
</tr>
<tr>
<td>Mass distribution</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>Feed-through background</td>
<td>4–12</td>
<td>3–24</td>
</tr>
<tr>
<td>$F_L, F'_L, A_3$ uncertainty propagation</td>
<td>0–210</td>
<td>0–210</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>2–68</td>
<td>0.1–12</td>
</tr>
<tr>
<td>Total</td>
<td>100–230</td>
<td>70–250</td>
</tr>
</tbody>
</table>

**ATLAS: $P_1, P'_4, P'_5, P'_6, P'_8, F_L$; low $q^2$ range only**

- Consistent with SM predictions

<table>
<thead>
<tr>
<th>Source</th>
<th>$P_1$</th>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
<th>$S_4$</th>
<th>$S_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combinatoric $K\pi$ (fake $K^*$) background</td>
<td>0.03</td>
<td>0.03</td>
<td>0.05</td>
<td>0.04</td>
<td>0.06</td>
<td>0.16</td>
</tr>
<tr>
<td>$D$ and $B^+$ veto</td>
<td>0.11</td>
<td>0.04</td>
<td>0.05</td>
<td>0.04</td>
<td>0.01</td>
<td>0.06</td>
</tr>
<tr>
<td>Background pdf shape</td>
<td>0.04</td>
<td>0.04</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Acceptance function</td>
<td>0.01</td>
<td>0.01</td>
<td>0.07</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Partially reconstructed decay background</td>
<td>0.03</td>
<td>0.05</td>
<td>0.02</td>
<td>0.08</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>Alignment and B field calibration</td>
<td>0.02</td>
<td>0.04</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Fit bias</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>Data/MC differences for $p_T$</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$S$-wave</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>Nuisance parameters</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$A_\psi, B^*$ and $B_L$ background</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Misreconstructed signal</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Dilution</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&lt; 0.01</td>
<td>-</td>
<td>-</td>
</tr>
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$B^0 \to K^{*0} \mu\mu$: Results (CMS, ATLAS)

### CMS: $P_1, P'_5, A_{FB}, F_L$; full $q^2$ range

- **Consistent with SM predictions**

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- $P'_5$ and $P'_4$ deviation of 2.7σ in $q^2 = (4 - 6)$ GeV$^2$ following direction of the LHCb deviation
- But still compatible with SM prediction

### ATLAS: $P_1, P'_4, P'_5, P'_6, P'_8, F_L$; low $q^2$ range only

- $P'_5$ and $P'_4$ deviation of 2.7σ in $q^2 = (4 - 6)$ GeV$^2$ following direction of the LHCb deviation
- But still compatible with SM prediction
• The transitions $b \rightarrow sll$ provide access to number of operators
• Statistics would allow improvement in the precision by one order
  • $\sim (5 - 9) \times$ for ATLAS
  • $\sim 15 \times$ for CMS
ATLAS and CMS produced results mostly based on Run 1 and few based on Run 2 data

- ATLAS+CMS+LHCb results on $B_{(s)}^0 \rightarrow \mu\mu$ decays using Run 1 and (2015+)2016 datasets combined; most precise measurement of effective lifetime $\tau_{\mu^+\mu^-}$ to date
- Angular analyses of $B^0 \rightarrow K^{*0}\mu\mu$, $B^\pm \rightarrow K^{\pm}\mu\mu$ and $B^\pm \rightarrow K^{*\pm}\mu\mu$ performed
- Results are consistent with SM prediction (within the limited experimental precision)

- More results to come with full Run 2 data
  - 4× more integrated luminosity
  - Improved tracking precision (Insertable B-Layer for ATLAS in 2014, new pixel detector for CMS since 2017)

- Stay tuned for more in Run 3 and with High-Luminosity LHC