Rare B-decays @LHC

(Results from CMS, ATLAS and LHCb)

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on behalf of CMS collaboration
In search for New Physics…

Two ways to search for New Physics:

• Produce new heavy particles beyond SM, that may have existed in early universe. The production cross-section of those particles are usually very small.

• Measure the observables/parameters of SM processes (usually rare decay processes). Any significant deviation of these observables from SM prediction will be hint of NP.

Studying both processes are important and are complementary to each other

I will show the results of $B_{(S)} \rightarrow \mu^+\mu^-$, $K^{(*)}\mu^+\mu^-$, $K^{(*)}\gamma$ from CMS, ATLAS and LHCb.
SM & NP contributions to $B_{(S)} \rightarrow \mu^+\mu^-$

- The golden rare decays: $B_{d/s} \rightarrow \mu\mu$
  - Highly suppressed in Standard Model
  - Forbidden at tree level, can only proceed through higher-order loop diagrams
  - Helicity suppressed, by factor of $(m_\mu/m_B)^2$
  - Rate is Cabibbo suppressed $|V_{ts(td)}|^2$

<table>
<thead>
<tr>
<th>decay</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_c \rightarrow \mu^+\mu^-$</td>
<td>$3.65\pm0.23 \times 10^{-9}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \mu^+\mu^-$</td>
<td>$1.1\pm0.1 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

**History of this search**

![Graph showing the history of the search for $B$ meson decays](image)

**SM process**

![Diagram illustrating the Standard Model process](image)

**NP contributions**

![Diagram illustrating new physics contributions](image)
Measurement of $B_{(S)} \rightarrow \mu^+ \mu^-$ from CMS

- **$B_d$ and $B_s$ signals** [blind analysis]
  - Crystal Ball, fixed shape
  - normalization floating
- **combinatorial background**
  - first-degree polynomial
- **rare semi-leptonic background** ($b \rightarrow q \mu \nu$)
  - fixed shape, floated normalization
- **rare peaking background**
  - constrained to expectation

Rare decay backgrounds are normalized, channel by channel, to data size.

PRL 111 (2013) 101804
$BF$ of $B_{(S)} \rightarrow \mu^+ \mu^-$ from CMS

$\text{B}_S \rightarrow \mu\mu$
significance: 4.3 $\sigma$

$$\text{BR}(B_S \rightarrow \mu\mu) = \left(3.0^{+0.9}_{-0.8} \text{ (stat)}^{+0.6}_{-0.4} \text{ (syst)}\right) \times 10^{-9}$$

$\text{B}_d \rightarrow \mu\mu$

significance: 2.0 $\sigma$

$$\text{BR}(B_d \rightarrow \mu\mu) = \left(3.5^{+2.1}_{-1.8} \text{ (stat+syst)}\right) \times 10^{-10}$$

upper limit CLs method, using BDT

$$\text{BR}(B_d \rightarrow \mu\mu) < 1.1 \times 10^{-9} @ 95\% \text{ CL}$$

Results are compatible with SM expectations.
Measurement of $B_{(S)} \rightarrow \mu^+\mu^-$ from LHCb

- Used full dataset of 3fb\(^{-1}\) (1fb\(^{-1}\) @7TeV, 2fb\(^{-1}\) @8TeV)
- Improved BDT, optimized by using $B_{(S)} \rightarrow \mu^+\mu^-$ and $b\bar{b} \rightarrow \mu^+\mu^- X$ (topology & kinematics)
- Observed sensitivity: 4σ
Measurement of $B_{(S)} \to \mu^+\mu^-$ from ATLAS

• Blind analysis: +/- 300MeV around Bs mass is blinded.
  
<table>
<thead>
<tr>
<th>Channel</th>
<th>Blinded/Signal Region</th>
<th>Sideband Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \to \mu^+\mu^-$</td>
<td>[5066, 5666] MeV</td>
<td>[4766, 5066] MeV</td>
</tr>
<tr>
<td>$B_s^0 \to \mu^+\mu^-$</td>
<td>[5666, 5966] MeV</td>
<td>[5666, 5966] MeV</td>
</tr>
<tr>
<td>$B^+ \to J/\psi K^+$</td>
<td>[4930, 5130] MeV</td>
<td>[5180, 5380] MeV</td>
</tr>
<tr>
<td>$B^+ \to J/\psi K^+$</td>
<td>[5430, 5630] MeV</td>
<td>[5430, 5630] MeV</td>
</tr>
</tbody>
</table>

• Signal/Background discrimination: Multivariate analysis
  BDT based on 13 variables

bb$\to$$\mu\mu$X dominant background

$\text{Br}_{\text{obs.}} < 1.5 \times 10^{-8} @ 95\% \text{ CL}$
**Preliminary combination of results**

\[
B(B_s^0 \rightarrow \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}
\]

\[
B(B^0 \rightarrow \mu^+\mu^-) = (3.6 \pm 1.6) \times 10^{-10}
\]

**B_s^0 \rightarrow \mu^+\mu^-** is observed at more than 5σ

**SM (decay-time integrated) expectation:**

\[
B(B_s^0 \rightarrow \mu^+\mu^-) = (3.57 \pm 0.30) \times 10^{-9}
\]

\[
B(B^0 \rightarrow \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}
\]  

(Buras, et al., 2012)
CMS reach for $B_{(S)} \rightarrow \mu^+\mu^-$

<table>
<thead>
<tr>
<th>L (fb$^{-1}$)</th>
<th>No. of $B_{S}^0$</th>
<th>No. of $B^0$</th>
<th>$\delta B/B(B_{S}^0 \rightarrow \mu^+\mu^-)$</th>
<th>$\delta B/B(B^0 \rightarrow \mu^+\mu^-)$</th>
<th>$B^0$ sign.</th>
<th>$\delta \frac{B(B^0 \rightarrow \mu^+\mu^-)}{B(B_{S}^0 \rightarrow \mu^+\mu^-)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>16.5</td>
<td>2.0</td>
<td>35%</td>
<td>&gt;100%</td>
<td>0.0–1.5 $\sigma$</td>
<td>&gt;100%</td>
</tr>
<tr>
<td>100</td>
<td>144</td>
<td>18</td>
<td>15%</td>
<td>66%</td>
<td>0.5–2.4 $\sigma$</td>
<td>71%</td>
</tr>
<tr>
<td>300</td>
<td>433</td>
<td>54</td>
<td>12%</td>
<td>45%</td>
<td>1.3–3.3 $\sigma$</td>
<td>47%</td>
</tr>
<tr>
<td>3000</td>
<td>2096</td>
<td>256</td>
<td>12%</td>
<td>18%</td>
<td>5.4–7.6 $\sigma$</td>
<td>21%</td>
</tr>
</tbody>
</table>

- Expectation assuming SM branching fraction and planned detector upgrade
- Large pileup will affect the detection efficiency, tightening the selection criteria
- Reduce in background, better determination of peaking backgrounds...
Electroweak penguin decays: $B \to X_s l^+l^-$

- Forbidden at tree level, but allowed via loop diagrams in SM
- Sensitive to NP through BSM particles in the loop
- Small branching fraction
- More precise theoretical prediction
- Observables to compare with SM predictions:
  Branching fraction, $A_{CP}$, $A_{FB}$, $P'_5$, Isospin-asymmetry.

All LHC experiments see clear signals of $B^0 \to K^{*0} \mu^+\mu^-$.

Electroweak penguin decay ($b \to s l^+l^-$)
B → Xl⁺l⁻ @LHC, Belle, BaBar, CDF

<table>
<thead>
<tr>
<th># of events</th>
<th>BaBar 433fb⁻¹</th>
<th>Belle 605fb⁻¹</th>
<th>CDF 9.6fb⁻¹</th>
<th>LHCb 1 / 3 fb⁻¹</th>
<th>ATLAS 5fb⁻¹</th>
<th>CMS 5fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>B⁰ → K⁺⁺⁺⁺ l⁺l⁻</td>
<td>137±44*</td>
<td>247±54*</td>
<td>288±20</td>
<td>2361±56</td>
<td>466±34</td>
<td>415±29</td>
</tr>
<tr>
<td>B⁺ → K⁺⁺⁺⁺ l⁺l⁻</td>
<td>24±6</td>
<td></td>
<td></td>
<td></td>
<td>162±16</td>
<td></td>
</tr>
<tr>
<td>B⁺ → K⁺⁺⁺⁺ l⁺l⁻</td>
<td>153±41*</td>
<td>162±38*</td>
<td>319±23</td>
<td></td>
<td>4746±81</td>
<td></td>
</tr>
<tr>
<td>B⁰ → K⁺⁺⁺⁺ l⁺l⁻</td>
<td>32±8</td>
<td></td>
<td></td>
<td></td>
<td>176±17</td>
<td></td>
</tr>
<tr>
<td>B⁺ → K⁺⁺⁺⁺ l⁺l⁻</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B⁺ → K⁺⁺⁺⁺ l⁺l⁻</td>
<td>62±9</td>
<td></td>
<td></td>
<td></td>
<td>174±15</td>
<td></td>
</tr>
<tr>
<td>Λ⁺⁺⁺⁺ → Λ⁺⁺⁺⁺ l⁺l⁻</td>
<td>51±7</td>
<td></td>
<td></td>
<td></td>
<td>78±12</td>
<td></td>
</tr>
<tr>
<td>B⁺ → π⁺⁺⁺⁺ l⁺l⁻</td>
<td>limit</td>
<td></td>
<td></td>
<td></td>
<td>25±7</td>
<td></td>
</tr>
</tbody>
</table>

*B*mixture of B⁰ and B⁺⁺⁺⁺ and l = e⁺,μ⁺ and other experiments: l = μ only

Babar arXiv:1204.3933
Belle arXiv:0904.0770
ATLAS (preliminary) [ATLAS-CONF-2013-038]
CMS (preliminary) [CMS-BPH-11-009]
Decay parameters for $B \to K^{*0} \mu^+ \mu^-$

- Decay is characterized by 3 angular variables

$$
\frac{1}{d\Gamma/dq^2 \cos \theta_\ell \cos \theta_K \ d\phi \ dq^2} \ d^4\Gamma
$$

$$
= \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos \phi \\
- F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi \\
+ S_6 \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \\
+ S_8 \sin 2\theta_K \sin \theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right],
$$

- One of the interesting parameter is muon forward-backward asymmetry ($A_{FB}$) which is sensitive to new physics

$A_{FB} \propto -\text{Re} \left[ \left( 2C_7^{\text{eff}} + \frac{q^2}{m_b^2} C_9^{\text{eff}} \right) C_{10} \right]$

Dimuon invariant mass

Forward event

Backward event
Observables for $B \rightarrow K^{*0} \mu^+ \mu^-$ @LHC
• Some new observables used by LHCb which are free from hadronic uncertainties are

\[ P'_{4,5} = S_{4,5} / F_L (1 - F_L) \]

• There is a local discrepancy of 3.7σ in \(P'_5\) parameter. More data will either establish/reject this discrepancy.

SM predictions from [Decotes-Genon et al. JHEP 05 (2013) 137]
Direct CP violation in $B \rightarrow K^{(*)} \mu^+ \mu^-$ @LHCb

- Direct CP asymmetry is defined to be
  \[ A_{CP} \equiv \frac{\Gamma(B \rightarrow \bar{K}^{(*)} \mu^+ \mu^-) - \Gamma(B \rightarrow K^{(*)} \mu^+ \mu^-)}{\Gamma(B \rightarrow \bar{K}^{(*)} \mu^+ \mu^-) + \Gamma(B \rightarrow K^{(*)} \mu^+ \mu^-)} \]

- Better theoretical prediction due to form-factor cancellation in asymmetry.

- LHCb uses 3$\text{fb}^{-1}$ data

\[ A_{CP}(B^0 \rightarrow K^{*0} \mu^+ \mu^-) = -0.035 \pm 0.024 \pm 0.003, \]
\[ A_{CP}(B^+ \rightarrow K^+ \mu^+ \mu^-) = 0.012 \pm 0.017 \pm 0.001, \]

arXiv: 1408:0978
Test of lepton Universality in $B^+ \rightarrow K^+ \ell^+ \ell^-$

- SM requires the three lepton family to have identical coupling to gauge bosons
- One can test universality by comparing the results from $B^+ \rightarrow K^+ \mu^+ \mu^-$ and $B^+ \rightarrow K^+ e^+ e^-$

$$R_K = \frac{\int_{q^2=1 \text{ GeV}^2/c^4}^{6 \text{ GeV}^2/c^4} (d\mathcal{B}[B^+ \rightarrow K^+ \mu^+ \mu^-]/dq^2) dq^2}{\int_{q^2=1 \text{ GeV}^2/c^4}^{6 \text{ GeV}^2/c^4} (d\mathcal{B}[B^+ \rightarrow K^+ e^+ e^-]/dq^2) dq^2} = 1 \pm \mathcal{O}(10^{-3})$$

SM: JHEP 12 (2007) 040

\begin{align*}
\text{LHCb} & \quad \text{LHCb} \\
\begin{array}{c}
B^+ \rightarrow J/\psi(e^+e^-) K^+ \\
\text{(a)}
\end{array} & \quad \begin{array}{c}
B^+ \rightarrow K^+ e^+ e^- \\
\text{(d)}
\end{array}
\end{align*}

In $3 \text{fb}^{-1}$ LHCb determines

$$R_K = 0.745^{+0.090}_{-0.074} \text{ (stat)}^{+0.036}_{-0.036} \text{ (syst)}$$

(consistent with SM at $2.6\sigma$)

LHCb-PAPER-2014-024 [Preliminary],
Belle [PRL 103 (2009) 171801],
BaBar [PRD 86 (2012) 032012]
Observables for $B \to X \gamma$

Photon polarization measured from up-down asymmetry
- Asymmetry of photon direction in $K\pi\pi$ rest frame
- Analogously to the Wu experiment

Reconstruct $B^+ \to K^+\pi^+\pi^−\gamma$
- $\sim13000$ signal candidates in $3\text{fb}^{-1}$
- Several overlapping resonances in $m(K^+\pi^+\pi^-)$
  $\to$ data divided in 4 bins in $m(K^+\pi^+\pi^-)$

Combining the 4 bins, the photon is observed to be polarized at 5.2$\sigma$

- First observation of photon polarization in $b \to s\gamma$ decays
Summary

• Rare quark decays play an important role in search for New Physics

• So far there is no conclusive hint for New Physics, however few observables show some deviation from SM
  $\rightarrow P'_5$ in $B \rightarrow K^{(*)}\mu^+\mu^-$ in LHCb
  $\rightarrow$ Lepton Universality in $B \rightarrow K^+\mu^+\mu^-$ from LHCb

• Need more work from theory as well as experimental side.

• Many more new results will come soon: $B \rightarrow K^{(*)}\mu^+\mu^-$ (CMS, ATLAS, LHCb), $B \rightarrow \mu^+\mu^-$ (LHCb + CMS)

STAY TUNED!