Rare Decays and Angular Analyses of $B \rightarrow X \mu^+ \mu^-$ at CMS

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CMS is marvelous for HF studies

- Flexible triggers
- Large silicon tracker
- Strong magnetic field
- Broad acceptance
- Superb muon systems
  - Three different devices, coverage up to $|\eta|<2.4$
  - Dimuon mass resolution $\sim$0.6-1.5% (depending on $|y|$).
  - Fake rate $\leq$0.1% for pi,K; $\leq$0.05% for proton.
  - MVA-based ID for $B \rightarrow \mu^+\mu^-$ analysis.
**FCNC processes b → (X)μ⁺μ⁻: golden indirect probes of NP**

Clean exp signature; robust theory calc; high sensitivity

**Effective theory: model independent descriptions**

\[
\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{tq}^* \sum_i C_i O_i + C_i' O_i' + \sum \frac{c}{\Lambda_{\text{NP}}^2} O_{\text{NP}}
\]

<table>
<thead>
<tr>
<th>Operator</th>
<th>Left handed</th>
<th>Right handed, (\frac{m_s}{m_b}) suppressed</th>
<th>Tree</th>
<th>Gluon penguin</th>
<th>Photon penguin</th>
<th>EW penguin</th>
<th>(Pseudo)scalar penguin</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mathcal{O}_7) \sim m_b (\bar{s}<em>L \sigma^{\mu\nu} b_R) F</em>{\mu\nu}</td>
<td>✔</td>
<td>✔</td>
<td>☑</td>
<td>☑</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\mathcal{O}_9) \sim (\bar{s}<em>L \gamma^\mu b_L)(\bar{\ell} \gamma</em>{\mu\nu} \ell)</td>
<td>✔</td>
<td>✔</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>(\mathcal{O}_{10}) \sim (\bar{s}<em>L \gamma^\mu b_L)(\bar{\ell} \gamma_5 \gamma</em>{\mu\nu} \ell)</td>
<td>✔</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\mathcal{O}<em>{S,P}) \sim (\bar{s} b)</em>{S,P}(\bar{\ell} \ell)_{S,P}</td>
<td>(✔)</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Different processes have sensitivities to different operators.
**Rare decay search: \( B_{(s)}^0 \rightarrow \mu^+ \mu^- \)**

\[
\mathcal{B}(B_{s}^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.23) \times 10^{-9}
\]
\[
\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}
\]

**Physical Review Letters** 112 (2014) 101801

**SM diagrams and prediction**

\[
\mathcal{B}(B_{s}^0 \rightarrow \mu^+ \mu^-) = 3.0 \pm 1.0 \times 10^{-9}
\]
\[
\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = 3.5 \pm 2.1 \times 10^{-10}
\]

**CMS: Physical Review Letters** 111 (2013) 101804

**CMS made it with full Run-I data**

\[
\mathcal{B}(B_{s}^0 \rightarrow \mu^+ \mu^-) = 2.9 \pm 1.1 + 0.3 \times 10^{-9}
\]
\[
\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = 3.7 \pm 2.4 + 0.6 \times 10^{-10}
\]


Simultaneous publication with LHCb

Each with > 4σ for \( B_{s} \rightarrow \mu^+ \mu^- \)
CMS&LHCb “deep” combination: First observation of $B_s \rightarrow \mu^+\mu^-$

$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = \left(2.8^{+0.7}_{-0.6}\right) \times 10^{-9}$ (6.2$\sigma$ significance)

$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = \left(3.9^{+1.6}_{-1.4}\right) \times 10^{-10}$ (3.0$\sigma$ significance)

$\mathcal{R} = 0.14^{+0.08}_{-0.06}$, Also consistent with prediction

$\mathcal{R} \equiv \mathcal{B}(B^0 \rightarrow \mu^+\mu^-)_{SM}/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)_{SM} = 0.0295^{+0.0028}_{-0.0025}$. 

History: 30 years of search

Limit (90% CL) or BF measurement

10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}

Year

CMS+LHCb
ATLAS
LHCb
Belle
UA1
CDF
L3
D0

SM: $B^0 \rightarrow \mu^+\mu^-$
SM: $B_s^0 \rightarrow \mu^+\mu^-$


ATLAS2016 arxiv: 1604.04263
Future projection

- Extrapolations using Phase I/II detector setups and L1 triggers
- Invariant mass resolution from full GEANT4 simulation
- Restrict analysis to barrel region

<table>
<thead>
<tr>
<th>( \mathcal{L} ) ( fb(^{-1}) )</th>
<th>( N(B^0_s) )</th>
<th>( N(B^0) )</th>
<th>( \delta B(B^0_s \rightarrow \mu^+\mu^-) )</th>
<th>( \delta B(B^0 \rightarrow \mu^+\mu^-) )</th>
<th>( B^0 ) sign.</th>
<th>( \frac{\delta B(B^0 \rightarrow \mu^+\nu^-)}{\delta B(B^0 \rightarrow \mu^+\mu^-)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>18.2</td>
<td>2.2</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>159</td>
<td>19</td>
<td>14%</td>
<td>63%</td>
<td>0.6 – 2.5 ( \sigma )</td>
<td>66%</td>
</tr>
<tr>
<td>300</td>
<td>478</td>
<td>57</td>
<td>12%</td>
<td>41%</td>
<td>1.5 – 3.5 ( \sigma )</td>
<td>43%</td>
</tr>
<tr>
<td>300 (barrel)</td>
<td>346</td>
<td>42</td>
<td>13%</td>
<td>48%</td>
<td>1.2 – 3.3 ( \sigma )</td>
<td>50%</td>
</tr>
<tr>
<td>3000 (barrel)</td>
<td>2250</td>
<td>271</td>
<td>11%</td>
<td>18%</td>
<td>5.6 – 8.0 ( \sigma )</td>
<td>21%</td>
</tr>
</tbody>
</table>

CMS Simulation
Scaled to \( L = 300 \) fb\(^{-1}\)

Data
- full PDF
- B\(_s\)\( \rightarrow \mu^+\mu^-\)
- B\(_s\)\( \rightarrow \mu^+\nu^-\)
- combinatorial bkg
- semileptonic bkg
- peaking bkg

Extra details:
- Restricted analysis to barrel region
- Invariant mass resolution from full GEANT4 simulation
$B \rightarrow K(\ast)\mu^+\mu^-$ angular analyses

- $B \rightarrow K\mu^+\mu^-$ and $B \rightarrow K^*\mu^+\mu^-$ proceed dominantly through penguin and box diagrams.

Integrating out the short distance dynamics $\rightarrow$ Wilson Coefficients:

- $C_7$ electromagnetic
- $C_9$ semi-leptonic vector
- $C_{10}$ semi-leptonic axial vector

Observables depend on four-momentum transferred to dimuon, $q^2$.
Decay Parameters

\[
\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_K d\phi} = \frac{9}{32\pi} \left[ S_1^8 \sin^2\theta_K + S_1^6 \cos^2\theta_K + S_2^8 \sin^2\theta_K \cos 2\theta_\ell + S_2^6 \cos^2\theta_K \cos 2\theta_\ell + S_3^8 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + S_3^6 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5^8 \sin 2\theta_K \sin \theta_\ell \cos \phi + S_5^6 \sin^2\theta_K \cos \theta_\ell + S_7^8 \sin 2\theta_K \sin \theta_\ell \sin \phi + S_7^6 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9^8 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \right],
\]

Complete description of the decay rate: 11 variables!
Simplified decay rates and parameters

\[
\frac{1}{\Gamma} \frac{d^3 \Gamma}{d \cos \theta_K d \cos \theta_1 d q^2} = \frac{9}{16} \left\{ \frac{2}{3} F_S + A_S \cos \theta_K \right\} (1 - \cos^2 \theta_1) \\
+ (1 - F_S) \left[ 2 F_L \cos^2 \theta_K (1 - \cos^2 \theta_1) \\
+ \frac{1}{2} (1 - F_L) (1 - \cos^2 \theta_K) (1 + \cos^2 \theta_1) \\
+ \frac{4}{3} A_{FB} (1 - \cos^2 \theta_K) \cos \theta_1 \right\}
\]

- **\(F_S\):** fraction of S-wave (~few %)
- **\(A_S\):** interference amplitude

\(A_{FB}\) and \(F_L\) do not depend on \(\phi\), efficiency nearly constant.

**\(F_L\):** Fraction of longitudinal polarization of the \(K^*\)

**\(A_{FB}\):** Forward-backward asymmetry of the dilepton system
Reconstruct the events in 7 $q^2$ bins, excluding $J/\psi$ & $\psi'$ regions, total ~1426 signal events seen.

Signal CP-tagged by the best $K\pi$ invariant mass.

The CMS results are in good agreement with the SM predictions, indicating no strong contribution from physics beyond the standard model.
The results are consistent with the SM predictions and previous

The vertical shaded regions correspond to the J

give the total uncertainty. The vertical shaded regions correspond to the J

Acknowledgements

• CMS precisions are better than CDF, Belle, BaBar but not as good as LHCb (1 fb⁻¹)
• More competitive in high q² region

Combined results 7/8 TeV


The CMS measurements are consistent with the other results, with comparable or higher precision.

• BaBar: Phys. Rev. D 86 (2012) 032012,
• LHCb (3 fb⁻¹): JHEP 08 (2013) 131
Summary

- Rare FCNC decays are good probes of physics beyond standard model
- CMS has established $B_s \rightarrow \mu^+ \mu^-$ from Run-I data and big potential in Run-II with upgrade scenarios
- Angular analysis of $B^0 \rightarrow K^* \mu^+ \mu^-$ provides precise test of SM predictions and no deviation is seen
- More are coming ... Stay tuned!
  - $P_5'$ of $B^0 \rightarrow K^* \mu^+ \mu^-$ based on Run-I data
  - Sister analyses of $B^+ \rightarrow K(\ast) \mu^+ \mu^-$ with Run-I data
  - More results based on Run-II data

Thank You

extra slides...
Analysis Strategy

- Reject candidate events having the di-muon mass compatible with $J/\psi$ or $\psi'$; these events are used for the normalization and cross-check purpose.

- Fit in bins of $q^2$ to the $K\pi\mu\mu$ mass and two angular variables ($\theta_{\ell}$, $\theta_K$) to:
  - estimate $F_S$ and $A_S$ in the $B^0 \to K^{*0}J/\psi$ channel
  - measure $F_L$ and $A_{FB}$ in the signal sample

- Determine the differential branching fraction, normalized w.r.t. $B^0 \to K^{*0}J/\psi$

\[
\frac{\Delta B(B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-)}{\Delta q_i^2} = \left( \frac{Y_{S_i}^{R}}{E_{S_i}^{R}} + \frac{Y_{S_i}^{M}}{E_{S_i}^{M}} \right) \left( \frac{Y_{N_i}^{R}}{E_{N_i}^{R}} + \frac{Y_{N_i}^{M}}{E_{N_i}^{M}} \right) \frac{B(B^0 \to K^{*0}(K^+\pi^-)J/\psi(\mu^+\mu^-))}{\Delta q_i^2}
\]

\[
PDF(m, \theta_K, \theta_{\ell}) = Y_S^C \left[ S_C^C(m) S_a^C(\theta_K, \theta_{\ell}) \epsilon^C(\theta_K, \theta_{\ell}) 
+ \frac{f^M}{1 - f^M} S^M(m) S^a(-\theta_K, -\theta_{\ell}) \epsilon^M(\theta_K, \theta_{\ell}) 
+ Y_B B^m(m) B^{\theta_K}(\theta_K) B^{\theta_{\ell}}(\theta_{\ell}) \right]

Unbinned likelihood fit performed in each $q^2$ bin

- Fit $m(K\pi\mu\mu)$, $\cos \theta_K$, $\cos \theta_{\ell}$
- Background shapes from fit to $m(B^0)$ sidebands
- Signal $m(B^0)$ shapes and fraction of mistagged events from MC
# Systematic uncertainties (8TeV)

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>$F_L (10^{-3})$</th>
<th>$A_{FB} (10^{-3})$</th>
<th>$d\mathcal{B}/dq^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation mismodeling</td>
<td>1–17</td>
<td>0–37</td>
<td>1.0–5.5</td>
</tr>
<tr>
<td>Fit bias</td>
<td>0–34</td>
<td>2–42</td>
<td>–</td>
</tr>
<tr>
<td>MC statistical uncertainty</td>
<td>3–10</td>
<td>5–18</td>
<td>0.5–2.0</td>
</tr>
<tr>
<td>Efficiency</td>
<td>34</td>
<td>5</td>
<td>–</td>
</tr>
<tr>
<td>Kπ mistagging</td>
<td>1–4</td>
<td>0–7</td>
<td>0.1–4.1</td>
</tr>
<tr>
<td>Background distribution</td>
<td>20–36</td>
<td>12–31</td>
<td>0.0–1.2</td>
</tr>
<tr>
<td>Mass distribution</td>
<td>3</td>
<td>1</td>
<td>3.2</td>
</tr>
<tr>
<td>Feed-through background</td>
<td>0–27</td>
<td>0–5</td>
<td>0.0–4.0</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>6–24</td>
<td>0–5</td>
<td>0.2–2.1</td>
</tr>
<tr>
<td>Normalization to $B^0 \rightarrow J/\psi K^*$</td>
<td>–</td>
<td>–</td>
<td>4.6</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>41–65</td>
<td>18–74</td>
<td>6.4–8.6</td>
</tr>
</tbody>
</table>