Studies of Rare Beauty and Charm Decays with the CMS Experiment

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Outline

- The CMS detector
- Tracking and Muon reconstruction
- B-Physics triggers
- Rare decays
  - Search for the $D^0 \rightarrow \mu^+\mu^-$
  - Search for the $B_{s(d)} \rightarrow \mu^+\mu^-$

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August 13, 2012
The CMS Detector

- General details
  - Weight ~ 12500 tons
  - Length of 21.6 meters
  - Diameter of 15 meters
  - 3.8T Magnetic Field

- Sub-detectors used for this analysis
  - Silicon tracker
    - Si pixels and Si strips
  - Muon system

<table>
<thead>
<tr>
<th>Component</th>
<th>Details</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel B(F)</td>
<td>3(2) Si Layers (Disks)</td>
<td>$\delta_z \approx 20 \mu m$, $\delta_\Phi \approx 10 \mu m$</td>
</tr>
<tr>
<td>Tracker B(F)</td>
<td>10(12) Si Strips</td>
<td>$\delta(p_T)/p_T \approx 1%$</td>
</tr>
<tr>
<td>ECal</td>
<td>PbWO$_4$</td>
<td>$\delta E/E \approx 3%/\sqrt{E} \oplus 0.5%$</td>
</tr>
<tr>
<td>HCal (B)</td>
<td>Bras/Sc, &gt; 7.2$\lambda$</td>
<td>$\delta E/E \approx 100 \sqrt{E}%$</td>
</tr>
<tr>
<td>HCal (F)</td>
<td>Fe/Quartz</td>
<td>$\delta(ME_T) \approx 0.98\sqrt{\Sigma E_T}$</td>
</tr>
<tr>
<td>Magnet</td>
<td>3.8T Solenoid</td>
<td></td>
</tr>
<tr>
<td>Muon</td>
<td>DT/SCS and RPC</td>
<td>$\delta(p_T)/p_T \approx 10%$ (sta)</td>
</tr>
</tbody>
</table>

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Tracking and Muon Reconstruction

- Large Acceptance $|\eta| < 2.4$
  - Drift tubes (DT), cathode drift chambers (CDC), resistive plate chambers (RPC)

- Muon reconstruction algorithms
  - Standalone muon: reconstructed in muon system only
  - Global muon (GM): reconstructed outside-in,
    - Standalone muon $\rightarrow$ inner track
  - Tracker muon (TM): reconstructed inside-out
    - Inner track $\rightarrow$ muon detector

Muon misidentification

$\varepsilon(\mu | \pi) \leq 0.1\%$
$\varepsilon(\mu | K) \leq 0.1\%$
$\varepsilon(\mu | p) \leq 0.05\%$
B-Physics Triggers

- Total CMS rate of ~ 300 Hz
- B-Physics rate of a few Hz
  - Used mostly for muon triggers
  - Trigger requirements changed with increasing luminosity

- Trigger selections:
  - $|\eta|$ and $p$ requirements for muons
  - Di-muon invariant mass
  - Impact parameter
  - Secondary vertex probability
  - Pointing angle
  - Flight length significance

![Histogram of dimuon mass](image.png)

**2011 Run, L = 1.1 fb^{-1}**

CMS $\sqrt{s} = 7$ TeV

- Trigger paths
  - $\psi'$
  - $J/\psi$
  - $B_s \rightarrow \mu^+\mu^-$
  - $Y$
  - low $p_T$, double muon
  - high $p_T$, double muon

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Search for the $D^0 \rightarrow \mu^+\mu^-$ decays

Motivation:
- Decay highly suppressed in SM
  - $\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) \sim 10^{-13}$
- This is because:
  - FCNC are forbidden at tree level
  - Decay is helicity suppressed by a factor of $(m_\mu/m_D)^2$
- Decay is enhanced by some New Physics (NP) models
  - Any detection with current sensitivity would be clear evidence of NP

Current best limit from LHCb (LHCb-CONF-2012-005)
- $\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) < 1.3 \times 10^{-8}$ @ 95% C.L.

Best limit from $B$ factories
- Belle: $\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) < 1.4 \times 10^{-7}$ @ 90% C.L.
Strategy

- Calculate the branching fraction by means of the ratio:
  - $D^{*+} \rightarrow D^0(\mu^+\mu^-)\pi^+/D^{*+} \rightarrow D^0(K^-\mu^+\nu)\pi^+$
  - Where $D^{*+} \rightarrow D^0\pi^+$ is the control channel
  - $D^0 \rightarrow K^-\mu^+\nu$ is the normalization channel
- The strategy was to measure the ratio in such a way that most of the systematic uncertainties cancel out
  - Normalization channel chosen for this purpose
  - First time a semi-leptonic channel is being used
- Limitation:
  - Single muon trigger is need for the normalization channel
Event Selection

- Muons: Tight quality → $|\eta| < 2.1$, $p_T > 3$ GeV including the trigger setting muon
- Kaons: Tight quality → $|\eta| < 2.1$, $p_T > 0.8$ GeV reconstructed with kinematic considerations
- Primary and secondary vertex (PV and SV): Vertex probability > 1%, 3D distance significance > 3
- Signal only requirement: $\cos \alpha > 0.99$, where $\alpha$ is the angle between the $D^0$ momentum and the PV-SV direction (pointing angle)
- Pion: Track $p_T > 0.6$ measured from the PV
- Normalization sample is fitted to extract $N(K_{\mu\nu})$
- Signal: two gaussians
- Background: modeled by the same sign $K-\pi$ sample

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Porpoise

Events/(0.5 MeV/c$^2$)

$\Delta M = M(K_{\mu\nu}\pi) - M(K_{\mu\nu})$ (MeV/c$^2$)

CMS preliminary
$\sqrt{s} = 7$ TeV
$L = 54.53$ pb$^{-1}$

December

Events/(0.5 MeV/c$^2$)

$\Delta M = M(\mu\mu\pi) - M(\mu\mu)$ (MeV/c$^2$)

CMS preliminary
$\sqrt{s} = 7$ TeV
$L = 90$ pb$^{-1}$

- Signal: No evidence of $D^0 \rightarrow \mu^+\mu^-$ from $D^{*-}$
- Background is fitted to empirical function:
  $$f(\Delta M) = p_1 \times [(\Delta M - M_\pi)^{1/2} + p_2 \times (\Delta M - M_\pi)^{3/2}]$$
  - $p_1$ and $p_2$ are fit parameters and $M_\pi$ is pion mass

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\( D^0 \rightarrow \mu^+\mu^- \) Upper Limit

- The upper limit on the branching fraction is determined by

\[
B(D^0 \rightarrow \mu^+\mu^-) \leq B(D^0 \rightarrow K^-\mu^+\nu) \times \frac{N(\mu\mu)}{N(K\mu\nu)} \times \frac{a(K\mu\nu)}{a(\mu\mu)} \times \frac{\epsilon_{\text{trig}}(K\mu\nu)}{\epsilon_{\text{trig}}(\mu\mu)} \times \frac{\epsilon_{\text{rec}}(K\mu\nu)}{\epsilon_{\text{rec}}(\mu\mu)}
\]

- Where:
  - \( \mathcal{B}(D^0 \rightarrow K^-\mu^+\nu) = (3.30 \pm 0.13) \times 10^{-2} \) is the normalization branching fraction (PDG)
  - \( N(\mu\mu) \) is the 90\% CL upper limit on the \( D^0 \rightarrow \mu^+\mu^- \) yield
  - \( N(K\mu\nu) \) is the number of \( D^0 \rightarrow K^-\mu^+\nu \) candidates
  - \( a \) and \( \epsilon \) are the acceptance and efficiency of the two modes
$D^0 \rightarrow \mu^+\mu^-$ Results

- Acceptance and efficiency ratios are determined with MC.
- Systematic uncertainties
  - Acceptance and efficiency
    - MC and data driven methods
  - Underestimated trigger efficiencies
  - Contamination from $D^0 \rightarrow K^{*-}(K^-\pi^0)\mu^+\nu$
  - PDG uncertainty for $D^0 \rightarrow K\mu\nu$

$\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) \leq 5.4 \times 10^{-7}$ (90% CL)
Motivation:

Decays are heavily suppressed in the SM

- SM expectation is:
  - \( B(B_s^0 \rightarrow \mu^+\mu^-) = (3.23 \pm 0.27) \times 10^{-9} \)
  - \( B(B^0 \rightarrow \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10} \)

This is because:

- It requires a flavor-changing neutral current (FCNC) transition
- Decay is helicity suppressed by a factor of \((m_\mu/m_B)^2\)
- Internal quark annihilation within \(B\) meson
  - Reduces decay rate by additional factor of \((f_B/m_B)^2\)

These processes are excellent probes for new physics

- 2HDM enhancement: \(B \propto (\tan \beta)^4\)
- MSSM enhancement: \(B \propto (\tan \beta)^6\)
  - Constrains parameter regions
Analysis Overview

• **Signal signature**
  - Two muons from one decay vertex and nothing else
  - Long lived $B$
  - Well reconstructed secondary vertex
  - Momentum aligned with flight direction
  - Mass around the $m_{B_s}$

• **Backgrounds**
  - Two independent semileptonic $B$ decays,
  - One semileptonic ($B$) decay and one misidentified hadron
  - Rare single $B$ decays
    - Peaking, e.g. $B_s \rightarrow K^+K^-$
    - Non-peaking, e.g. $B_s \rightarrow K\mu+\nu$
    - Events with not well-reconstructed secondary vertices

⇒ High signal efficiency and high background reduction
Methodology

• **Measurement of the branching fraction relative to** normalization channel
  • Similar trigger and selection to reduce systematic uncertainties

\[
B(B_s^0 \to \mu^+ \mu^-; 95\%C.L.) = \frac{N(n_{obs}, n_B, n_S; 95\%C.L.)}{\varepsilon_{B_s^0} N_{B_s^0}} = \frac{N(n_{obs}, n_B, n_S)}{\varepsilon_{B_s^0} L \sigma(pp \to B_s^0)}
\]

\[
= \frac{N(n_{obs}, n_B, n_S)}{N(B^\pm \to J/\psi K^\pm)} \cdot \frac{A_{B_s^0} \varepsilon^{ana}_{B_s^0} \varepsilon^{\mu}_{B_s^0} \varepsilon^{trig}_{B_s^0}}{A_{B_s^0} \varepsilon^{ana}_{B_s^0} \varepsilon^{\mu}_{B_s^0} \varepsilon^{trig}_{B_s^0}} \cdot \frac{f_u}{f_s} B(B^+ \to J/\psi [\mu^+ \mu^-] K)
\]

• **Calibration/validation of MC:**
  • \(B^\pm \to J/\Psi K^\pm\) normalization with high statistics
  • \(B_s \to J/\Psi \Phi\) signal MC (p_T, isolation,...)

• **Analysis is done in two channels**
  • Barrel - both muons \(|\eta| < 1.4\)
    • Better signal/background ratio
    • Good mass resolution (36 MeV)
  • Endcap - at least one muon with \(|\eta| > 1.4\)
    • Add more statistics (\(\sigma(m) \approx 70\) MeV)
Event Selection: Vertex

- Discriminating variables
  - Pointing angle $\alpha_{3d}$
  - $B$ vertex fit quality $\chi^2/dof$
  - Flight length significance $l_{3d}/\sigma(l_{3d})$
  - 3D impact parameter ($\delta_{3D}$) and significance ($\delta_{3D}/\sigma(\delta_{3D})$)

- Selections optimized for best upper limit
- Frozen before unblinding
Event Selection: Isolation

- Primary vertex isolation, used to minimize MC/data discrepancies and maximize background rejection
  - For tracks in cone with $\Delta R < 0.7$ with $p_T > 0.9$ GeV
  - Associated to same PV or with $d_{ca} > 500$ $\mu$m if not associated with PV

$$I = \frac{p_\perp (B)}{p_\perp (B) + \sum_{trk} |p_\perp|}$$
Pileup Independence

- Determine selection efficiency vs $N_{PV}$ in data
- 2011 dataset:
  - $\langle N_{PV} \rangle \approx 8$
  - $\text{RMS}(z) \approx 5.6 \text{ cm}$

$B^\pm \to J/\Psi K^\pm$

$B_s \to J/\Psi \Phi$

- In MC:
  - checked $\varepsilon$ for
    - $N_{PV} < 6$
    - $N_{PV} > 10$

- No pileup dependance

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Measurement of $B^\pm \rightarrow J/\Psi K^\pm$

- Needed for the extraction of the branching fraction
- Same selection as for signal, plus
  - $3.0 < m(\mu\mu) < 3.2$ GeV
  - $p_T(\mu\mu) > 7$ GeV
  - $p_T(K) > 0.5$ GeV
- Fit pdf:
  - Signal: double Gaussian
  - Bkg: exponential + error function at 5.145 GeV for $B^0 \rightarrow J/\Psi K^* \rightarrow \mu^+\mu^-K^-\pi^+$ decays

<table>
<thead>
<tr>
<th></th>
<th>Barrel</th>
<th>Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td>0.162 ± 0.006</td>
<td>0.111 ± 0.006</td>
</tr>
<tr>
<td>$\varepsilon_{\text{tot}}$</td>
<td>0.00110 ± 0.00009</td>
<td>0.00032 ± 0.00004</td>
</tr>
<tr>
<td>$N_{\text{obs}}$</td>
<td>82712 ± 4146</td>
<td>23809 ± 1203</td>
</tr>
</tbody>
</table>
### Summary

The signal windows for $B^0 \rightarrow \mu^+ \mu^-$ and $B^0_s \rightarrow \mu^+ \mu^-$ have been used. This result supersedes our previous measurement [1]. Stricter selection criteria have been applied, resulting in a better sensitivity and a higher expected signal.

### Table: The event selection efficiency for signal events

<table>
<thead>
<tr>
<th>Variable</th>
<th>$B^0 \rightarrow \mu^+ \mu^-$ Barrel</th>
<th>$B^0_s \rightarrow \mu^+ \mu^-$ Barrel</th>
<th>$B^0 \rightarrow \mu^+ \mu^-$ Endcap</th>
<th>$B^0_s \rightarrow \mu^+ \mu^-$ Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{tot}}$</td>
<td>$0.0029 \pm 0.0002$</td>
<td>$0.0029 \pm 0.0002$</td>
<td>$0.0016 \pm 0.0002$</td>
<td>$0.0016 \pm 0.0002$</td>
</tr>
<tr>
<td>$N_{\text{signal}}^{\exp}$</td>
<td>$0.24 \pm 0.02$</td>
<td>$2.70 \pm 0.41$</td>
<td>$0.10 \pm 0.01$</td>
<td>$1.23 \pm 0.18$</td>
</tr>
<tr>
<td>$N_{\text{peak}}^{\exp}$</td>
<td>$0.33 \pm 0.07$</td>
<td>$0.18 \pm 0.06$</td>
<td>$0.15 \pm 0.03$</td>
<td>$0.08 \pm 0.02$</td>
</tr>
<tr>
<td>$N_{\text{comb}}^{\exp}$</td>
<td>$0.40 \pm 0.34$</td>
<td>$0.59 \pm 0.50$</td>
<td>$0.76 \pm 0.35$</td>
<td>$1.14 \pm 0.53$</td>
</tr>
<tr>
<td>$N_{\text{total}}^{\exp}$</td>
<td>$0.97 \pm 0.35$</td>
<td>$3.47 \pm 0.65$</td>
<td>$1.01 \pm 0.35$</td>
<td>$2.45 \pm 0.56$</td>
</tr>
<tr>
<td>$N_{\text{obs}}$</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>4</td>
</tr>
</tbody>
</table>

The quoted errors include both statistical and systematic uncertainties. The median expected upper limits at 95% CL are $4 \times 10^3$ events.

Including cross-feed between the $B^0$ and $B^0_s$ decays.

### Figures

- **Barrel**: Dimuon invariant mass distributions in the barrel (left) and endcap (right) channels.
- **Endcap**: Similar to the barrel, but for the endcap channel.

The event selection efficiency for signal events is 0.208\%.
Upper Limit Results

### Upper limit (95%CL)

<table>
<thead>
<tr>
<th>$\mathcal{B}(B_{s}^{0} \rightarrow \mu^{+}\mu^{-})$</th>
<th>observed</th>
<th>expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(B^{0} \rightarrow \mu^{+}\mu^{-})$</td>
<td>$7.7 \times 10^{-9}$</td>
<td>$8.4 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>$1.8 \times 10^{-9}$</td>
<td>$1.6 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

### Conclusions

- **Upper limit now approaching factor 2 of SM expectation**
- **Looking forward to 2012 dataset.**
- **Significant improvement**
  - EPS 2011: $\mathcal{B}(B_{s}^{0} \rightarrow \mu^{+}\mu^{-}) < 1.9 \times 10^{-8}$
  - More/changed variables, e.g., better $B$ vertex isolation
  - Improved sensitivity
  - Higher signal/background ratio
- **Well prepared for**
  - High instantaneous lumi (trigger)
  - High pileup (tracking and vertexing)
LHC Combined Results

- **LHC combination**
  - \( \mathcal{B}(B_s^0 \to \mu^+ \mu^-) \leq 4.2(3.7) \times 10^{-9} \) at 95(90)% CL
  - Combined results from ATLAS, CMS and LHCb
  - Getting close to the SM expectation
  - \( \mathcal{B}(B^0 \to \mu^+ \mu^-) \leq 0.81(0.67) \times 10^{-9} \) at 95(90)% CL
  - Combined results from CMS and LHCb

**Graphs:**
- **ATLAS+CMS+LHCb**
- **CMS+LHCb**

**References:**
- CMS PAS BPH-12-009
- LHCb-CONF-2012-017
- ATLAS-COM-CONF-2012-090
Interpretation Examples

- Empty region due to previous upper limits and other published data

- Strongest impact at large $\tan \beta$

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Conclusion

- Shown here are the results of FCNC decays
  - $D^0 \to \mu^+\mu^-$ and $B_{s(d)} \to \mu^+\mu^-$
    - $\mathcal{B}(D^0 \to \mu^+\mu^-) \leq 5.4 \times 10^{-7} (90\% \text{ CL})$
    - $\mathcal{B}(B_{s(d)} \to \mu^+\mu^-) \leq 7.7 \times 10^{-9} (95\% \text{ CL})$
    - $\mathcal{B}(B^0 \to \mu^+\mu^-) \leq 1.8 \times 10^{-9} (95\% \text{ CL})$
  - LHC combination
    - $\mathcal{B}(B_{s}^0 \to \mu^+\mu^-) \leq 4.2 \times 10^{-9} (95\% \text{ CL})$
    - $\mathcal{B}(B^0 \to \mu^+\mu^-) \leq 0.81 \times 10^{-9} (95\% \text{ CL})$
- CMS is producing high quality results
  - More results to come from 2011 data
  - Analysis of 2012 data ongoing
$B_s$ candidate event
Kinematics: Simulation vs Data

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Vertexing

CMS, 5 fb$^{-1}$ \( \sqrt{s} = 7 \) TeV

- **B$^0 \to J/\psi K^+$**
  - Data
  - MC simulation

- **B$^+ \to \pi^- K^+$**
  - Data
  - MC simulation

- **B$^0 \to J/\psi \phi$**
  - Data
  - MC simulation

- **B$^+ \to \pi^- K^+$**
  - Data
  - MC simulation

---

**flight length sign.**

**B vertex \( \chi^2 \)/dof**

**3D pointing angle**

**3d impact param.**

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Isolation

Candidates

CMS, 5 fb⁻¹  \( \sqrt{s} = 7 \text{ TeV} \)

B⁺ → J/ψ K⁺
- Data
- MC simulation

\( \eta \) close trk

N_{\text{close}}

Candidates

CMS, 5 fb⁻¹  \( \sqrt{s} = 7 \text{ TeV} \)

B⁺ → J/ψ K⁺
- Data
- MC simulation

3D impact param. sign.

Candidates

CMS, 5 fb⁻¹  \( \sqrt{s} = 7 \text{ TeV} \)

B⁺ → J/ψ K⁺
- Data
- MC simulation

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Blinded Results

- **Background** = combinatorial + rare (MC shape)
  - Constant shape assumed for combinatorial
- **Combinatorial events in signal windows:**
  - Subtract rate events from sidebands
  - Scale remaining events to the difference widths of the regions