Study of $B_s^0 \rightarrow \mu^+ \mu^-$ in CMS

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- Introduction
- The CMS Experiment
- Analysis
Introduction

- **Decays highly suppressed** in Standard Model (Buras, 2003)
  - effective FCNC
  - helicity suppression
  - $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.42 \pm 0.54) \times 10^{-9}
    \mathcal{B}(B_d^0 \rightarrow \mu^+\mu^-) = (1.00 \pm 0.14) \times 10^{-10}$

- **Sensitivity to new physics**
  - 2HDM: $\mathcal{B} \propto (\tan \beta)^4, m_{H^+}$; MSSM: $\mathcal{B} \propto (\tan \beta)^6$
  - ‘Measurement’ of $\tan \beta$ (Kane, et al. ph/0310042)

- $B_s^0 \rightarrow \mu^+\mu^-$ Cabibbo-favored over $B_d^0 \rightarrow \mu^+\mu^-$
  - not true for non-minimal flavor violation
  - mass resolution critical!

- **This decay channel**
  - not $B$ physics, but a search for ‘new physics’
  - well suited for early CMS data (with pixel detector)
State of the art

• All decay channels beyond the reach of experiments:

<table>
<thead>
<tr>
<th>Mode</th>
<th>$B_s^0 \rightarrow \mu^+ \mu^-$</th>
<th>$B_d^0 \rightarrow \mu^+ \mu^-$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM Expect.</td>
<td>$3.5 \times 10^{-9}$</td>
<td>$1.0 \times 10^{-10}$</td>
<td>Buras, 2003</td>
</tr>
<tr>
<td>CLEO</td>
<td>-</td>
<td>$6.1 \times 10^{-7}$</td>
<td>PRD62, 091102</td>
</tr>
<tr>
<td>BELLE</td>
<td>-</td>
<td>$1.6 \times 10^{-7}$</td>
<td>PRD68, 111101</td>
</tr>
<tr>
<td>CDF</td>
<td>$5.8 \times 10^{-7}$</td>
<td>$1.5 \times 10^{-7}$</td>
<td>PRL93, 032001</td>
</tr>
<tr>
<td>D0</td>
<td>$4.1 \times 10^{-7}$</td>
<td>-</td>
<td>PRL94, 071802</td>
</tr>
<tr>
<td>BABAR</td>
<td>-</td>
<td>$0.61 \times 10^{-7}$</td>
<td>PRL94, 221803</td>
</tr>
<tr>
<td>CDF</td>
<td>$1.5 \times 10^{-7}$</td>
<td>$0.39 \times 10^{-7}$</td>
<td>PRL95, 221805 + Err.</td>
</tr>
<tr>
<td>CDF</td>
<td>$0.8 \times 10^{-7}$</td>
<td>$0.23 \times 10^{-7}$</td>
<td>CDF public note 8176</td>
</tr>
</tbody>
</table>

• $B$-factories search also for
  - $B^0 \rightarrow e^+ e^-$
  - $B^0 \rightarrow e^\pm \mu^\mp$

• SM branching ratio is very low:
  - $b\bar{b}$ cross section at LHC $\sim 10 \times$ larger than at Tevatron
  - Events can be triggered at high luminosity
The CMS Experiment

- The Compact Muon Solenoid
  - Length 22 m, diameter 15 m, 14 kton
  - Magnetic field 4 T

- Muon system
  - DT, CSC, RPC
  - $p_{\perp} > 3$ GeV

- All-silicon tracker
  - $|\eta| < 2.5$
  - pixel: 3 layers
  - strip tracker: 10 layers

- Pixel detector startup plans
  - 2007: minimal commissioning system
  - 2008: three layers for first first physics run
The CMS Tracker

- All-silicon tracker configuration
  - Few measurement layers
  - Very precise measurements

- Pixel Detector
  - hit resolution: 10--15 µm

- Silicon Strip Detector
  - 10--14 points

- Resolution:

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Overview

- Search for a very rare decay
  - Clean experimental signature
    - Efficiency and background reduction

- $b$-hadrons produced in
  - gluon splitting
  - flavor excitation
  - gluon-gluon fusion

- Background composition
  - two independent semileptonic $B$ decays
    (mostly from gluon splitting)
  - rare single $B$ decays

- Background reduction in analysis
  - 2 final state muons consistent with one decay vertex
  - large (transverse) flight length
  - isolation of dimuon system
Event Samples

- Full MC simulation study for $\mathcal{L} = 2 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$
  - Including 5 pile-up events

- Signal MC sample
  - 20k signal events
  - Minimum bias QCD events

- Background MC sample
  - 15k background events
  - Minimum bias QCD events
  - 2 muons on generator level, $p_\perp > 3 \text{GeV}, |\eta| < 2.4, 0.3 < \Delta R(\mu\mu) < 1.2$

- Rare decays with PYTHIA (phasespace)
  - $B_d \rightarrow \pi^0 \mu^+ \mu^-$
  - $B^+ \rightarrow \mu^+ \mu^- \mu^+ \nu_\mu$

for first studies (with full simulation)
Trigger Strategy

- CMS has two-level trigger architecture

- Level 1
  - muons and calorimeters
  - Latency: $3.2 \mu s$
  - $40 \text{ MHz} \rightarrow 100 \text{ kHz}$

- High-level trigger (HLT)
  - fast (local) reconstruction
  - $100 \text{ kHz} \rightarrow 100 \text{ Hz}$

- $B$-physics triggers
  - Level 1: single- or di-muon trigger
    - single-muon: $p_\perp > 14 \text{ GeV}$
    - di-muons: $p_\perp > 3 \text{ GeV}$
  - HLT: exclusive and inclusive $b, c$ triggers at $\sim 5 \text{ Hz}$
    - exclusive $B$ decays: partial (local) reconstruction

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High-level trigger selection study

- Primary vertex reconstruction with pixel detector
  - use three most probable vertices

- Regional track reconstruction in cones around L1-muon candidates
  - partial reconstruction using $\leq 6$ hits
  - $p_\perp > 4$ GeV

- Track pairs
  - mass windows for signal (and background)
  - (un)like sign charge

- Vertex fit
  - $\chi^2 < 20$
  - Decay flight length $l_{3d} > 150 \mu$m

$\Rightarrow$ HLT accept rate $< 1.7$ Hz

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Analysis: Variables

- Decay flight length significance \( l_{xy}/\sigma_{xy} \)
  - transverse plane: \( l_{xy}/\sigma_{xy} > 18 \)

- Muon separation in \( \eta\phi \):
  \[
  \Delta R(\mu\mu) = \sqrt{(\eta_{\mu_1} - \eta_{\mu_2})^2 + (\phi_{\mu_1} - \phi_{\mu_2})^2}
  \]
  - \( 0.3 < \Delta R(\mu\mu) < 1.2 \)

- Isolation of muon pair
  \[
  I = \frac{p_\perp(B_s)}{p_\perp(B_s) + \sum_{trk} |p_\perp|}
  \]
  tracks in cone with \( r = \sqrt{\eta^2 + \phi^2} < 1.0 \) and \( p_\perp > 0.9 \text{ GeV} \)
  - \( I > 0.85 \)

- Secondary vertex
  - Pointing angle: \( \cos(\alpha) > 0.995 \)
  - vertex fit \( \chi^2 < 1 \)
Mass Reconstruction

- **Fit with two Gaussians**

<table>
<thead>
<tr>
<th>Gaussian</th>
<th>Narrow</th>
<th>Wide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>$5372.5 \pm 1.3$</td>
<td>$5398.8 \pm 3.3$</td>
</tr>
<tr>
<td>Sigma</td>
<td>$32.1 \pm 1.4$</td>
<td>$60.2 \pm 2.4$</td>
</tr>
<tr>
<td>Normalization</td>
<td>0.08</td>
<td>0.03</td>
</tr>
</tbody>
</table>

(statistical errors only)

- **Good mass resolution**
  - essential against rare $B$ decays
  - $\sim 2\sigma$ separation to $B_d$

- **Impact of tracker misalignment on mass resolution**
  - 2 alignment scenarios
    - short-term $\sim 20\%$
    - long-term $\sim 10\%$

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Results

- **Signal selection efficiency** $\varepsilon = 0.019 \pm 0.002_{stat}$
  where the efficiency $\varepsilon = \varepsilon_{cuts} \varepsilon_I \varepsilon_{\chi^2}$ is factorized
  - In $10 \text{ fb}^{-1}$: $N_S = 6.1 \pm 0.6$ signal events

- **Background rejection** $\eta = 2.6 \times 10^{-7}$
  - In $10 \text{ fb}^{-1}$: $N_B = 13.8^{+22.0}_{-13.8}$ background events
    (one remaining background event in $5 < m_{\mu\mu} < 6 \text{ GeV}$)

- **Extract upper limit with Bayesian procedure (CDF)**

  \[
  \mathcal{B}(B_s^0 \to \mu^+\mu^-) \leq \frac{N(n_{obs}, n_B, n_S)}{\varepsilon_{\text{gen}} \varepsilon_{\text{total}} N_{B_s}} \leq 1.4 \times 10^{-8} \text{ (90\% C.L.)}
  \]

  including statistical and systematic error
Systematics

- Systematics have minor impact compared to statistical error with current background MC sample
- Determination of efficiency with factorizing cuts
  - 15%
- Tracker misalignment (decay flight significance, $\chi^2$, $\cos \alpha$)
  - 10% for signal efficiency, 50% for background
- L1 trigger efficiency
  - 10%
- Particle identification
  - muon ID and hadron mis-ID
- Tracking
  - efficiency: isolation veto
- Normalization
  - 15%, a la CDF and D0

Summary:

$\Delta(\varepsilon) : 24\%$

$\Delta(n_B) : 50\%$

$\Delta(N_{B_s}) : 15\%$
Background from rare $b$-hadron decays

- Study selected rare $b$-hadron decays
  - full simulation
  - average hadron muon fake rate $< 0.5\%$

- Background yields (misidentified dimuons)
  - for $\mathcal{L} = 10 \text{ fb}^{-1}$
  - no mass constraints
  - no analysis efficiency

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$N_{\text{evt}}$</th>
<th>$N_{\mu\mu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d \to K\pi$</td>
<td>$2.5 \times 10^6$</td>
<td>61</td>
</tr>
<tr>
<td>$B_d \to \pi\pi$</td>
<td>$7.3 \times 10^5$</td>
<td>18</td>
</tr>
<tr>
<td>$B_d \to \pi\mu\bar{\nu}$</td>
<td>$4.5 \times 10^6$</td>
<td>22000</td>
</tr>
<tr>
<td>$B_s \to K\pi$</td>
<td>$2.7 \times 10^5$</td>
<td>7</td>
</tr>
<tr>
<td>$B_s \to KK$</td>
<td>$1.1 \times 10^5$</td>
<td>3</td>
</tr>
<tr>
<td>$B_s \to K\mu\bar{\nu}$</td>
<td>$2.0 \times 10^6$</td>
<td>10000</td>
</tr>
<tr>
<td>$\Lambda_b \to p\pi$</td>
<td>$4.2 \times 10^4$</td>
<td>1</td>
</tr>
<tr>
<td>$\Lambda_b \to pK$</td>
<td>$8.4 \times 10^4$</td>
<td>2</td>
</tr>
<tr>
<td>$B^+ \to \mu^+\mu^-\mu^+\bar{\nu}$</td>
<td>$1.4 \times 10^5$</td>
<td>13000</td>
</tr>
</tbody>
</table>
Rare $b$-hadron decays II

- Normalization to $10 \text{ fb}^{-1}$
  - Background: same analysis efficiency as for signal
Conclusions

- First CMS update on search for $B_s^0 \rightarrow \mu^+\mu^-$ since 1999
  - Full reconstruction with pileup for $2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$

- Expected upper limit in $10 \text{ fb}^{-1}$: $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) \leq 1.4 \times 10^{-8}$
  - study limited by size of background MC sample
  - good mass resolution

- Outlook
  - include rare $B$ decays
  - full analysis: likelihood selection and normalization sample

(From hep-ph/0310042)