Search for $B_{s(d)}^0 \rightarrow \mu^+\mu^-$ at CMS

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Motivation: sensitivity to new physics

- The rare flavor changing neutral current decays are highly suppressed in the SM:
  \[ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.2 \pm 0.2) \times 10^{-9} \]
  \[ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.0 \pm 0.1) \times 10^{-10} \]

- New physics scenarios can significantly enhance the BR's:
  - In MSSM BR \( \propto (\tan \beta)^6 \)
  - Especially sensitive to models with extended Higgs sectors
  - Small theoretical uncertainties and high sensitivity to NP make this a Golden Channel
The CMS detector

- All silicon inner tracker with $p_T$ resolution $\sim 1\%$ and $d_0$ resolution $\sim 20 \, \mu m$ for tracks in this analysis

- Tracking efficiency $> 99\%$ for central muons

- Redundant muon system triggers and records muons with $p_T > 3 \, GeV$ and $|\eta| < 2.4$
Muon reconstruction

- Muons reconstructed with three detector technologies
  - Drift tubes
  - Cathode strip chambers
  - Resistive plate chambers
- Muons required to be found by each of two reconstruction algorithms
  - Outside-in: stand alone track in muon system matched to a compatible track in silicon tracker
  - Inside-out: silicon track matched to compatible hits in muon system
- Low muon mis-ID rates
  - < 0.3% for pions and kaons
  - < 0.05% for protons
Analysis overview

- **Signal**
  - Clean B decay with only 2 muons
  - Long-lived B produces well separated vertex

- **Background**
  - 2 semi-muonic B decays
  - A semi-muonic B decay plus a misidentified charged hadron
  - Rare single B decays, such as
    - $B_s^0 \rightarrow K^- K^+$ (peaking)
    - $B_s^0 \rightarrow K^- \mu^+ \nu$ (non-peaking)

- **Main handles:** good dimuon vertex; correct B mass; momentum pointing to interaction point
Signal selection

- Mass windows: 5.2-5.3 GeV for $B^0$ and 5.3-5.45 GeV for $B_s^0$
- Split into barrel (both $|\eta_{\mu}| < 1.4$) and endcap channels
- $l_{3D} > 15$ or $20 \sigma$, $\alpha_{3D} < 0.050$ or 0.025
- $p_{T\mu} > 4.5$ or 4.0 GeV, $p_{TB} > 6.5$ GeV,
- $B$ fit $\chi^2$/dof $< 1.6$, dca min $> 0.15$ mm (endcap only), isolation (next slide)

- Select best primary vertex based on consistency with $B$ candidate momentum direction
- Average of 5.5 primary vertices per event
Signal selection: isolation

- Require relative isolation of muon pair

\[ I = \frac{p_\perp(\mu^+\mu^-)}{p_\perp(\mu^+\mu^-) + \sum_{\Delta R < 1} p_\perp} \]

- Cone of \( \Delta R = 1 \) around the dimuon momentum

- Include all tracks with \( p_T > 900 \) MeV from same primary vertex or within 500 \( \mu \)m of B vertex

- Require isolation > 0.75

- All selection criteria have been optimized for limit sensitivity with a grid search before unblinding signal region
Background estimation

- Non-peaking background measured in data
  - Count events in B mass sidebands 4.80-5.20 GeV and 5.45-6.00 GeV
  - Interpolate to signal region with assumption of flat shape

- Peaking background obtained from MC with inputs from data
  - $B \rightarrow hh$ backgrounds with two muons from misidentified charged hadrons peak in B mass
  - Measure muon mis-ID rates in data from identified $K_S \rightarrow \pi\pi$, $\phi \rightarrow KK$ and $\Lambda \rightarrow p\pi$ samples
  - Use MC without muon selection cuts to simulate backgrounds and apply fake rate measurements from data
  - Affects $B^0$ more than $B^0_S$ because backgrounds peak low
BR calculation: normalized to $B^+$

- Measure $B_s^0 \rightarrow \mu^- \mu^+$ branching fraction relative to normalization channel $B^+ \rightarrow J/\Psi(\mu^- \mu^+)K^+$
- Reduce many systematic effects with similar reconstruction and triggering techniques

$$B(B_s^0 \rightarrow \mu \mu) = \frac{N(B_s^0 \rightarrow \mu \mu)}{N(B^+ \rightarrow J/\Psi K)} \times \frac{\epsilon_{B^+}}{\epsilon_{B_s}} \times \frac{f_u}{f_s} \times B(B^+ \rightarrow J/\Psi K)$$

- $B(B^+ \rightarrow J/\Psi K)$ is well known and relatively large
- Take $f_u/f_s$ from PDG
- Only need relative efficiency terms
- No need for absolute luminosity measurement
- Same reconstruction cuts for $B^+$, plus require two muons bend away from each other to aid trigger efficiency calculation
Selection efficiency

- Signal and normalization efficiencies calculated in MC
  - Overall signal efficiency 0.4% in the barrel and 0.2% in the endcap
  - Overall normalization efficiency 0.08% (0.03%) in the barrel (endcap)
- Validate MC performance with control samples:
  \[ B_s^0 \rightarrow J/\Psi(\mu^-\mu^+)\phi \quad B^+ \rightarrow J/\Psi(\mu^-\mu^+)K^+ \]
- Good agreement observed
- Residual differences used as systematics
Trigger efficiency

- **Signal trigger**
  - Opposite charge muons with mass 4.8-6.0 GeV
  - $p_T^\mu > 2$ GeV, $p_T^{\mu\mu} > 4$ GeV

- **Normalization trigger**
  - Opposite charge muons with mass 2.9-3.3 GeV
  - $p_T^\mu > 3$ GeV, $p_T^{\mu\mu} > 6.9$ GeV
  - $\cos \alpha > 0.9$, $\mu\mu$ vertex fit probability $> 0.5\%$

- Trigger efficiency measured after selection cuts $\approx 80\%$
  - Stable with time
  - Measured in MC
  - Cross checked with measurement in data
Systematic uncertainties

- **Fragmentation functions from PDG**: 13%
- **Background**: 4%
  - Loosened selection cuts; inverted isolation studies
- **Signal**
  - Acceptance: variation from different bb production processes: 4%
  - Selection efficiency: comparison of data and MC cut by cut: 8%
  - Track momentum scale: from J/ψ resonance reconstructed mass: 3%
- **Normalization**
  - Selection efficiency: comparison of data and MC cut by cut: 5%
  - Hadron track efficiency: from data with D* decay studies: 4%
  - Yield fits: variation of fitting functions: 5%
- **Muon identification and trigger**
  - Evaluated from data/MC differences
  - Muon identification efficiency ratio: 5%
  - Trigger efficiency ratio: 3%
- **Total**: 19%
Observation consistent with expectation from background + SM signal in all 4 channels
Branching fraction upper limits

- Upper limits for $B_s^0 \rightarrow \mu^- \mu^+$ and $B^0 \rightarrow \mu^- \mu^+$ computed with CLs

<table>
<thead>
<tr>
<th>Process</th>
<th>Upper Limit</th>
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<tbody>
<tr>
<td>$B(B_s^0 \rightarrow \mu^+ \mu^-)$</td>
<td>$&lt; 1.9 \times 10^{-8}$ (95% C.L.)</td>
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<tr>
<td>$B(B_s^0 \rightarrow \mu^+ \mu^-)$</td>
<td>$&lt; 1.6 \times 10^{-8}$ (90% C.L.)</td>
</tr>
<tr>
<td>$B(B^0 \rightarrow \mu^+ \mu^-)$</td>
<td>$&lt; 4.6 \times 10^{-9}$ (95% C.L.)</td>
</tr>
<tr>
<td>$B(B^0 \rightarrow \mu^+ \mu^-)$</td>
<td>$&lt; 3.7 \times 10^{-9}$ (90% C.L.)</td>
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</tbody>
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- Expected 95% upper limits: 1.8×10^{-8} for $B_s^0$
  4.8×10^{-9} for $B^0$

- Background-only p values: 0.11 for $B_s^0$ (1.2 σ)
  0.40 for $B^0$ (0.3 σ)

- p value for CDF $B_s^0$ result (5.6×SM) = 0.05
Combination with LHCb

- The two LHC results for $B_s^0 \rightarrow \mu^- \mu^+$ have been combined to produce an upper limit of $1.1 \times 10^{-8}$ at 95% confidence.

- All uncertainties treated as uncorrelated, except for $f_s/f_d$, which is taken to be 100% correlated between the measurements.

- Same CL$_s$ upper limit procedure as used for CMS and LHCb results independently.

- Background-only p value = 8%, background plus SM signal p value = 55%, CDF central value p value = 0.3%.

- Public as CMS PAS BPH-11-019.
Prospects and interpretation

- New limit constrains CMSSM parameter space beyond direct searches for many large $\tan \beta$ scenarios
  - Dependent on $A_0$ (see talk by C. Beskidt)
- Standard model branching fraction projected to be within reach in the next few years

arXiv:1108.3018 Akeroyd et al.
Conclusion

- First results from CMS presented for the search for the rare decays $B_s^0 \rightarrow \mu^- \mu^+$ and $B^0 \rightarrow \mu^- \mu^+$
- No significant excess observed above expected background plus standard model signal
- Prospects for future updates are bright
  - LHC luminosity increasing very rapidly
  - Multivariate analysis will replace cut-n-count
  - Current combined LHC limit at 95% confidence is just 3.4 times the SM branching fraction—still room left for new physics, but it’s closing fast
Candidate event

CMS Experiment at the LHC, CERN

Data recorded: 2011-Apr-30 05:02:54 899533 GMT (00:02:54 CDT)
Run / Event: 103739 / 61490047
Candidate event

CMS Experiment at the LHC, CERN

Run / Event: 167998 / 1773082763
Non-universal Higgs masses fits

- 2011 direct searches only on left
- 2011 direct + $B_s \rightarrow \mu\mu$ on right

Frederic Ronga, Mastercode collaboration, Implications of LHC results
Comparison to direct searches

- 2010 $\tan \beta = 50$
- exclusion from direct CMS hadronic SUSY search

CMS preliminary
- $\tan \beta = 50$, $\mu > 0$, $A_0 = 0$
- $L_{int} = 36/pb, \sqrt{s} = 7$ TeV

CMS hadronic SUSY search
- $B_s \rightarrow \mu \mu$

CMSSM - $\tan \beta = 50$, $A_0 = 0$
- Excluded by $B_s \rightarrow \mu \mu$

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Pileup independence

- Check influence of multiple primary vertices on selection cuts: isolation and flight length significance
- No significant dependence found in signal MC or control sample data