First two sided limit on $\text{BR}(B_s \rightarrow \mu^+\mu^-)$

Matthew Herndon, University of Wisconsin Madison

SUSY 2011
Indirect searches for new physics

Look at processes that are suppressed in the SM

Excellent place to spot non SM contributions

\[ B_{s(d)} \rightarrow \mu^+\mu^- \]

SM:
- No tree level decay
- GIM, CKM and helicity suppressed
- \( BF(B_s \rightarrow \mu^+\mu^-) = 3.2 \pm 0.2 \times 10^{-9} \)

New Physics:
- Loop: MSSM: mSugra, Higgs Doublet
- Rate \( \propto \tan^6 \beta / (M_A)^4 \)
- Large enhancement possible
Measure decay rate of $B_s(d) \rightarrow \mu^+\mu^-$ relative to $B^+ \rightarrow J/\psi K^+$, $J/\psi \rightarrow \mu^+\mu^-$

Apply minimal selection, ensures sample of well measured dimuon events

Final discrimination with NN

Improvements vs. previous publication:
- 20% additional signal acceptance. New triggered regions understood with additional data.
- Expanded NN. 2x background rejection for same efficiency

$$BF(B_s \rightarrow \mu^+\mu^-) = \frac{(N_{\text{cand}} - N_{bg}) \cdot \alpha_B \cdot \epsilon_{B^+} \cdot f_u \cdot \alpha_{B_s} \cdot \epsilon_{B_s}}{N_B \cdot f_s}$$

$$BR(B^+ \rightarrow J/\psi K^+) \cdot BR(J/\psi \rightarrow \mu^+\mu^-)$$

5 X 10^8 $B_s$ events
Signal vs. Background

- Need to discriminate signal from background
  - Reduce background by a factor of ~ 10000

- Signal characteristics
  - Final state fully reconstructed
  - $B_s$ is long lived ($c\tau \sim 450 \, \mu m$)
  - B fragmentation is hard: few additional tracks

- Background contributions and characteristics
  - Sequential semi-leptonic decay: $b \rightarrow c \mu^- X \rightarrow \mu^+ \mu^- X$
  - Double semileptonic decay: $bb \rightarrow \mu^+ \mu^- X$
  - Continuum $\mu^+ \mu^-$
  - $\mu$ + fake, fake+fake
  - Partially reconstructed, lower $p_T$, short lived, doesn’t point to the primary vertex, and has additional tracks

Cut on mass, lifetime, $p_T$, how well $\vec{p}$ points to the vertex and isolation
Discriminating Variables

- 14 discriminating variables +
- Mass $m_{\mu\mu}$ 2.5$\sigma$ window: $\sigma = 24$MeV/c$^2$
  - First 5 variables at left are the most powerful
- Combine in NN

Unbiased optimization based on simulated signal and data sidebands. Validate with $B^+$

Determine background by extrapolating mass sidebands: Extensively tested for mass bias

Perform search in two detector regions (CC and CF), 8 NN bins (0.7-1.0) and 5 mass bins
Combinatoric background estimated by extrapolating mass sidebands

- Shape (slope) with mass determined using all events NN>0.7
- Excludes masses below 5 GeV, B →μ⁺μ⁻X
- Systematic uncertainties from statistical power of sidebands samples and variation of the fit functions
Peaking background dominated by $B \rightarrow hh$, $h = \pi K$

- Rates of hadron misidentification as muons estimated from $D^{*+} \rightarrow D^{0}\pi^+$ $\rightarrow K^{-}\pi^+\pi^+$ decays
- Large sample allows determination of misidentification rate vs. pT and luminosity and study of run conditions dependence

For $B_s$ search $B \rightarrow hh$ background

1/10 the combinatoric

$B_s$ backgrounds vs NN: order 1% X 1%

all but $B_s \rightarrow \pi\pi$ shifted down in mass
Use independent data samples enriched in expected backgrounds to test estimates:

- **OS-**: opposite sign muons, **negative lifetime** (signal sample is OS+)
- **SS+** and **SS-**: same sign muons, positive and negative lifetime. No trigger matching
- **OS-, SS**: Opposite side B hadrons
- **FM**: fake μ enhanced, one μ fails the muon Id cuts. Has a significant B→hh contribution
- **FM**: False muon backgrounds

Compare predicted vs. observed # of bg. events:
For multiple NN cuts
Control Regions

Background predictions and observed background in control regions

- 64 Independent checks of the background estimation method
- $B \rightarrow hh$ seen with expected mass shape and is well estimated
### Expected Sensitivity

#### Efficiencies and acceptances

<table>
<thead>
<tr>
<th></th>
<th>CC</th>
<th>CF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{B^+} / \alpha_{B_s}$</td>
<td>$0.307 \pm 0.018$ (±6%)</td>
<td>$0.197 \pm 0.014$ (±7%)</td>
</tr>
<tr>
<td>$\epsilon_{\text{trig}}$ / $\epsilon_{B^+_s}$</td>
<td>$0.99935 \pm 0.00012$ (±1%)</td>
<td>$0.97974 \pm 0.00016$ (±1%)</td>
</tr>
<tr>
<td>$\epsilon_{\text{reco}}$ / $\epsilon_{B^+_s}$</td>
<td>$0.85 \pm 0.06$ (±8%)</td>
<td>$0.84 \pm 0.06$ (±9%)</td>
</tr>
<tr>
<td>$\epsilon_{B_s}^{NN}$ ($NN &gt; 0.70$)</td>
<td>$0.915 \pm 0.042$ (±4%)</td>
<td>$0.864 \pm 0.040$ (±4%)</td>
</tr>
<tr>
<td>$\epsilon_{B_s}^{NN}$ ($NN &gt; 0.995$)</td>
<td>$0.461 \pm 0.021$ (±5%)</td>
<td>$0.468 \pm 0.022$ (±5%)</td>
</tr>
<tr>
<td>$N_{B^+}$</td>
<td>$22388 \pm 196$ (±1%)</td>
<td>$9943 \pm 138$ (±1%)</td>
</tr>
<tr>
<td>$f_u / f_s$</td>
<td>$3.59 \pm 0.37$ (±13%)</td>
<td>$3.59 \pm 0.37$ (±13%)</td>
</tr>
<tr>
<td>$BR(B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+)$</td>
<td>$(6.01 \pm 0.21) \times 10^{-5}$ (±4%)</td>
<td>$(6.01 \pm 0.21) \times 10^{-5}$ (±4%)</td>
</tr>
<tr>
<td>SES (All bins)</td>
<td>$(2.9 \pm 0.5) \times 10^{-9}$ (±18%)</td>
<td>$(4.0 \pm 0.7) \times 10^{-9}$ (±18%)</td>
</tr>
</tbody>
</table>

Have reached single event sensitivity to the SM rate of $B_s \rightarrow \mu^+ \mu^-$
## Expected Sensitivity

### $B_s \rightarrow \mu^+ \mu^-$ (CC)

<table>
<thead>
<tr>
<th>NN Bin</th>
<th>$\epsilon_{NN}$</th>
<th>$B \rightarrow hh$ Bkg</th>
<th>Total Bkg</th>
<th>Exp SM Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.700 &lt; NN &lt; 0.970$</td>
<td>20%</td>
<td>0.03</td>
<td>129.24 ± 6.50</td>
<td>0.26 ± 0.05</td>
</tr>
<tr>
<td>$0.970 &lt; NN &lt; 0.987$</td>
<td>8%</td>
<td>&lt; 0.01</td>
<td>7.91 ± 1.27</td>
<td>0.11 ± 0.02</td>
</tr>
<tr>
<td>$0.987 &lt; NN &lt; 0.995$</td>
<td>12%</td>
<td>0.02</td>
<td>3.95 ± 0.89</td>
<td>0.16 ± 0.03</td>
</tr>
<tr>
<td>$0.995 &lt; NN &lt; 1.000$</td>
<td>46%</td>
<td>0.08</td>
<td>0.79 ± 0.40</td>
<td>0.59 ± 0.11</td>
</tr>
</tbody>
</table>

### $B_s \rightarrow \mu^+ \mu^-$ (CF)

<table>
<thead>
<tr>
<th>NN Bin</th>
<th>$\epsilon_{NN}$</th>
<th>$B \rightarrow hh$ Bkg</th>
<th>Total Bkg</th>
<th>Exp SM Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.700 &lt; NN &lt; 0.970$</td>
<td>21%</td>
<td>0.01</td>
<td>146.29 ± 7.00</td>
<td>0.19 ± 0.04</td>
</tr>
<tr>
<td>$0.970 &lt; NN &lt; 0.987$</td>
<td>10%</td>
<td>0.01</td>
<td>11.57 ± 1.57</td>
<td>0.09 ± 0.02</td>
</tr>
<tr>
<td>$0.987 &lt; NN &lt; 0.995$</td>
<td>8%</td>
<td>0.01</td>
<td>3.25 ± 0.82</td>
<td>0.08 ± 0.01</td>
</tr>
<tr>
<td>$0.995 &lt; NN &lt; 1.000$</td>
<td>46%</td>
<td>0.03</td>
<td>2.64 ± 0.74</td>
<td>0.43 ± 0.08</td>
</tr>
</tbody>
</table>

**Expected $B_s$ Limit:** $1.5 \times 10^{-8}$ at 95% CL  
**Expected $B_d$ Limit:** $4.6 \times 10^{-9}$ at 95% CL
No significant excess seen in B0 mass window

Limits using the CLs technique, incorporating systematic uncertainties

\[ BF(B_d \rightarrow \mu^+\mu^-) < 6.0 \times 10^{-9} \text{ at 95% CL} \]
BS Results

Excesses over expected backgrounds observed in Bs CC channel

- Limit set in the assumption that the observed events are from background processes

$BF(B_s \rightarrow \mu^+\mu^-) < 4.0 \times 10^{-8}$ at 95% CL
**Bs P Values**

- P values in the background only and background + SM signal hypothesis
- Found by comparing an ensemble of pseudo experiments for each hypothesis to the observed data
- Systematic uncertainties are included in the pseudo experiments

\[ P \text{ Value } B^0: 23.3\% \]
\[ P \text{ Value } B_s: 0.27\% \]
\[ P \text{ Value } B_s (\text{with SM signal}): 1.92\% \]
BF($B_s \rightarrow \mu^+\mu^-$) in the hypothesis that the observed events have a significant contribution from either a SM or a new physics source of $B_s \rightarrow \mu^+\mu^-$.

90% C.L. interval $BF(B_s \rightarrow \mu^+\mu^-)$ using a simple likelihood fit

$4.6 \times 10^{-9} < BF(B_s \rightarrow \mu^+\mu^-) < 3.9 \times 10^{-8}$ at 90% C.L.

$BF(B_s \rightarrow \mu^+\mu^-) = 1.8^{+1.1}_{-0.9} \times 10^{-8}$
First significant excess observed in a $B_s \rightarrow \mu^+\mu^-$ search

Bounds set at 90C.L.

$$4.6 \times 10^{-9} < BF(B_s \rightarrow \mu^+\mu^-) < 3.9 \times 10^{-8}$$

Example of physics reach

Green area of $m_0$ vs. $m_{1/2}$ CMSSM plane favoured by $B_s \rightarrow \mu^+\mu^-$ result

Would indicate reasonably detectable super partner masses and high $\tan(\beta)$

Could be exciting times ahead!

hep-ph 1107.3020, Dutta, Mimura, Santoso
Tevatron and CDF

- Tevatron: 2TeV pp collider
- CDF properties
  - Silicon Tracker
    - $|\eta|<2$, 90cm long, $r_{L00}=1.3 - 1.6\text{cm}$
  - Drift Chamber (COT)
    - 96 layers between 44 and 132cm
  - Muon coverage
    - Triggered to $|\eta|<1.0$
- $B_s(d) \rightarrow \mu^+\mu^-$ benefits from the large integrated lumi of the Tevatron and the excellent mass and vertexing resolution of the CDF detector

Results in this talk uses 6.9fb$^{-1}$
Estimate all relative selection acceptances and efficiencies.

Identify variables that discriminate signal and background
  - Design multivariate discriminant, NN, for background rejection
  - Unbiased optimization based on Pythia signal MC and part of mass sidebands.
  - Validate variable modelling and NN performance on B⁺ data

Estimate combinatoric background level from sidebands

Separately estimate $B \rightarrow \mu^+ \mu^-$
  - Validate background prediction method in control regions designed to be enhanced in expected backgrounds
Discriminating Variables

- BSignal simulated with Pythia
  - Reweighed to match observed $B_s$ $p_T$ and isolation distributions
Discriminating Variables

CDF II Preliminary 7 fb⁻¹

- Low $d_{0μ}$ [cm]
- High $d_{0μ}$ [cm]
- $λ$ [cm]
- $L_{30}$ [cm]
- $L_{x}/σ_{L_{x}}$
- $λ/σ_{λ}$
- $d_{0}(B_{svd})$ [cm]
- $ΔΩ_{xy}$ [rad]
- $ΔΩ$ [rad]

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Variables: Validation

- $B^+ \rightarrow J/\psi K^+$, $J/\psi \rightarrow \mu^+ \mu^-$ sample used to validate kinematic, NN variables, and NN performance

- Simulated using Pythia as with signal same
  - Reweighed to match observed $B^+$ $p_T$ and isolation distributions
Variables: Validation
Mass Bias

- Search method requires there be no mass dependence in the NN
  - Combinatoric background estimated by extrapolating
  - Shape (slope) with mass determined using all events NN>0.7
  - Check for NN correlation with mass in sideband and control sample
  - Test if NN training can distinguish mass
Mass Bias

CDF II Preliminary 7 fb⁻¹

CC

- Outer SB events
- Inner SB events

Entries/0.01 vs NN output

CDF II Preliminary 7 fb⁻¹

CF

- Outer SB events
- Inner SB events

Entries/0.01 vs NN output
### Result

<table>
<thead>
<tr>
<th>Mass Bin (GeV/c(^2))</th>
<th>5.31-5.334</th>
<th>5.334-5.358</th>
<th>5.358-5.382</th>
<th>5.382-5.406</th>
<th>5.406-5.43</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC NN bin</td>
<td>Exp Bkg</td>
<td>8.02±0.62</td>
<td>7.94±0.61</td>
<td>7.87±0.61</td>
<td>7.79±0.6</td>
<td>7.71±0.59</td>
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<tr>
<td>0.7-0.76</td>
<td>Obs</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>CC NN bin</td>
<td>Exp Bkg</td>
<td>8.43±0.64</td>
<td>8.34±0.63</td>
<td>8.26±0.62</td>
<td>8.18±0.62</td>
<td>8.1±0.61</td>
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<tr>
<td>0.76-0.85</td>
<td>Obs</td>
<td>8</td>
<td>6</td>
<td>11</td>
<td>11</td>
<td>7</td>
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<tr>
<td>CC NN bin</td>
<td>Exp Bkg</td>
<td>3.55±0.39</td>
<td>3.51±0.39</td>
<td>3.48±0.39</td>
<td>3.44±0.38</td>
<td>3.41±0.38</td>
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<tr>
<td>0.85-0.9</td>
<td>Obs</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>4</td>
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<td>CC NN bin</td>
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<td>3.41±0.38</td>
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<td>0.9-0.94</td>
<td>Obs</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>7</td>
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<tr>
<td>CC NN bin</td>
<td>Exp Bkg</td>
<td>2.87±0.35</td>
<td>2.84±0.35</td>
<td>2.81±0.34</td>
<td>2.78±0.34</td>
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<td>0.94-0.97</td>
<td>Obs</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>CC NN bin</td>
<td>Exp Bkg</td>
<td>1.62±0.49</td>
<td>1.60±0.48</td>
<td>1.58±0.47</td>
<td>1.57±0.47</td>
<td>1.55±0.46</td>
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<tr>
<td>0.97-0.987</td>
<td>Obs</td>
<td>1</td>
<td>4</td>
<td>7</td>
<td>1</td>
<td>3</td>
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<tr>
<td>CC NN bin</td>
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<td>0.80±0.27</td>
<td>0.79±0.26</td>
<td>0.78±0.26</td>
<td>0.78±0.26</td>
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<tr>
<td>0.987-0.995</td>
<td>Obs</td>
<td>1</td>
<td>1</td>
<td>3</td>
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<td>0</td>
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<tr>
<td>CC NN bin</td>
<td>Exp Bkg</td>
<td>0.21±0.14</td>
<td>0.18±0.13</td>
<td>0.16±0.12</td>
<td>0.16±0.12</td>
<td>0.16±0.12</td>
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<td>0.995-1</td>
<td>Obs</td>
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<td>2</td>
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<td>1</td>
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<tr>
<td>CF NN bin</td>
<td>Exp Bkg</td>
<td>8.49±0.65</td>
<td>8.39±0.64</td>
<td>8.28±0.63</td>
<td>8.17±0.62</td>
<td>8.07±0.61</td>
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<tr>
<td>0.7-0.76</td>
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<td>8</td>
<td>13</td>
<td>9</td>
<td>9</td>
<td>9</td>
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<tr>
<td>CF NN bin</td>
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<td>9.45±0.69</td>
<td>9.33±0.68</td>
<td>9.21±0.67</td>
<td>9.1±0.66</td>
<td>8.98±0.65</td>
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<tr>
<td>0.76-0.85</td>
<td>Obs</td>
<td>7</td>
<td>8</td>
<td>7</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>CF NN bin</td>
<td>Exp Bkg</td>
<td>4.91±0.48</td>
<td>4.85±0.47</td>
<td>4.79±0.46</td>
<td>4.73±0.46</td>
<td>4.67±0.45</td>
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<tr>
<td>0.85-0.9</td>
<td>Obs</td>
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<td>5</td>
<td>6</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>CF NN bin</td>
<td>Exp Bkg</td>
<td>3.87±0.42</td>
<td>3.82±0.41</td>
<td>3.77±0.41</td>
<td>3.73±0.4</td>
<td>3.68±0.4</td>
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<tr>
<td>0.9-0.94</td>
<td>Obs</td>
<td>4</td>
<td>1</td>
<td>6</td>
<td>3</td>
<td>3</td>
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<tr>
<td>CF NN bin</td>
<td>Exp Bkg</td>
<td>3.29±0.38</td>
<td>3.25±0.38</td>
<td>3.21±0.37</td>
<td>3.17±0.37</td>
<td>3.12±0.36</td>
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<tr>
<td>0.94-0.97</td>
<td>Obs</td>
<td>0</td>
<td>5</td>
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<td>4</td>
<td>5</td>
</tr>
<tr>
<td>CF NN bin</td>
<td>Exp Bkg</td>
<td>2.38±0.56</td>
<td>2.34±0.55</td>
<td>2.31±0.54</td>
<td>2.28±0.54</td>
<td>2.25±0.53</td>
</tr>
<tr>
<td>0.97-0.987</td>
<td>Obs</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>CF NN bin</td>
<td>Exp Bkg</td>
<td>0.67±0.24</td>
<td>0.66±0.24</td>
<td>0.65±0.24</td>
<td>0.64±0.23</td>
<td>0.63±0.22</td>
</tr>
<tr>
<td>0.987-0.995</td>
<td>Obs</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>CF NN bin</td>
<td>Exp Bkg</td>
<td>0.56±0.39</td>
<td>0.54±0.38</td>
<td>0.53±0.38</td>
<td>0.52±0.37</td>
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</tr>
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<td>0.995-1</td>
<td>Obs</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table:**  
\( B_s \) signal window for CC(top) and CF(bottom): Expected backgrounds, including \( B \rightarrow hh \), and number of observed events.

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Result $B^0$
Results $B_s$
Results $B_s$
Test Statistic and Interpretation

- $-2\ln(Q), \; Q = \frac{L(s+b|\text{data})}{L(b|\text{data})}$

- $L$ is a likelihood obtained by multiplying all 80 Poison probabilities of hypothesis $s+b$ or $b$ given the observed data. The likelihood is minimized with respect to nuisance parameters that model the systematic uncertainties and a freely floating parameter for the signal.

- P values compare the values of $-2\ln(Q)$ observed in data to a ensemble of pseudo experiments in a given hypothesis.

- The most likely value of the signal is fit using the same likelihood and the confidence intervals are determined by using the change in chi2
Significant excess also observed in the third bin of the $B_s$ CC channel. Given current limits there bin has no expectation of signal at the level observed in this bin.

Analysis of possible sources:

- **$B \rightarrow hh$:** This background is estimated using known BF's and high statistics samples to determine fake rates. It is observed in the FM fake region at the expected rate. Also the mass resolution of CDF is well understood and this background should occur primarily at lower masses.

- **Mass bias:** No similar background is seen in the $B^0$ and the control region show no evidence of a similar mass bias.

- **Highest probably source is a fluctuation of known backgrounds:** order 1% chance. Not unlikely with 80 bins.
P Values

- P values in the background only and background + SM signal hypothesis
- Found by comparing an ensemble of pseudo experiments for each hypothesis to the observed data
- Systematic uncertainties are included in the pseudo experiments

- P Value $B^0$: 23.3%
- P Value $B_s$: 0.27%
- P Value $B_s$: 0.66%
- P Value $B_s$(with SM signal): 1.92%
- P Value $B_s$(with SM signal): 4.14%

Only bins with significant signal expectation
Comparison of Experiments

- **LHCb:** $BF(B_s \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-8}$ at 95% CL

- **CMS:** $BF(B_s \rightarrow \mu^+\mu^-) < 4.0 \times 10^{-8}$ at 95% CL

- **LHC combination:** $BF(B_s \rightarrow \mu^+\mu^-) < 1.08 \times 10^{-8}$ at 95% CL

- **CDF:** $4.6 \times 10^{-9} < BF(B_s \rightarrow \mu^+\mu^-) < 3.9 \times 10^{-8}$ at 90% CL

$$BF(B_s \rightarrow \mu^+\mu^-) = 1.8^{+1.1}_{-0.9} \times 10^{-8}$$

- LHC and CDF confidence intervals overlap.
- More data needed to accurately determine $BF(B_s \rightarrow \mu^+\mu^-)$