B_s \to \mu^+\mu^- At the Tevatron

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Flavour in the Era of LHC

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In the Standard Model, the FCNC decay of $B \rightarrow \mu^+\mu^-$ is heavily suppressed. The SM prediction is below the sensitivity of current experiments (CDF+D0): SM predicts 0 events at the Tevatron (Buchalla & Buras, Misiak & Urban).

$B_d \rightarrow \mu\mu$ is further suppressed by the CKM factor $(v_{td}/v_{ts})^2$.

The SM prediction is below the sensitivity of current experiments (CDF+D0): SM predicts 0 events at the Tevatron. Any signal at the Tevatron would indicate new physics!!

See A. Dedes’ talk next for new physics scenarios (also talks by C. Kao, G. Isidori, Y. Okada, and others).
Tevatron is the highest energy collider in operation

- Collide proton – antiproton at c.m.s. = 1.96 TeV
- Record luminosity \( \approx 1.8 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \)
- Now in the middle of a 3-months shutdown for upgrade
• CDF/D0 have collected $> 1 \text{fb}^{-1}$/experiment.
  x10 more data than Run I
• Doubling dataset every year
Tevatron is expected to deliver $8 \text{ fb}^{-1}/\text{exp}$ for Run II
CDF and D0 Detectors

CDF:
• Excellent silicon vertex detector
• Good particle identification ($K, \pi$)
• Good momentum and track impact parameter resolutions

D0:
• Extended tracking and muon coverage
• Good electron identification
• New innermost-layer silicon detector installed
B Triggers at Tevatron

- **Trigger is the lifeline of B physics in a hadron environment !!!**

- **“Muon” triggers:**
  - Requiring single-muon or di-muons (very clean)
  - working horse for masses, lifetimes, rare decays etc.
  - keys to B physics program at DØ

- **“Hadronic”** triggers using silicon vertex detectors:
  - exploit long lifetime of heavy quarks
  - Two-track trigger (CDF) –
    - Two oppositely charged tracks with large impact parameters
  - Important for Bs mixing
Rare B Dataset

- **CDF:**
  - 780 pb$^{-1}$ di-muon triggered data
  - Two separate search channels
    - Central/central muons (CMU-CMU)
    - Central/forward muons (CMU-CMX)
  - Extract $B_s$ and $B_d$ limit

- **DØ:**
  - First 300 pb$^{-1}$ di-muon triggered data with box opened $\rightarrow$ limit
  - 400 pb$^{-1}$ data still blinded
  - Combined sensitivity for 700 pb$^{-1}$ of recorded data (300 pb$^{-1}$ + 400 pb$^{-1}$)

S/B is expected to be extremely small. Effective bkg rejection is the key to this analysis!!
Analysis Overview

\[ BR(B_s \rightarrow \mu^+ \mu^-) = \frac{N_{B_s}}{N_{B^+}} \frac{\alpha_{B^+} \cdot \epsilon_{B^+}^{\text{total}}}{\alpha_{B_s} \cdot \epsilon_{B_s}^{\text{total}}} \int_{b \rightarrow B^+} f_{b \rightarrow B^+} \frac{BR(B^+ \rightarrow J/\psi K^+)}{BR(J/\psi \rightarrow \mu^+ \mu^-)} \]

Motto: reduce background and keep signal eff high

Step 1: pre-selection cuts to reject obvious bkg

Step 2: optimization (need to know signal efficiency and expected bkg)

Step 3: reconstruct \( B^+ \rightarrow J/\psi K^+ \) normalization mode

Step 4: open the box \( \rightarrow \) compute branching ratio or set limit
\textbf{CDF Pre-selection}

- **Pre-Selection cuts:**
  - $4.669 < m_{\mu\mu} < 5.969$ GeV/c$^2$
  - muon quality cuts
  - $p_T(\mu) > 2.0$ (2.2) GeV/c CMU (CMX)
  - $p_T(B_s \text{ cand.}) > 4.0$ GeV/c
  - $|\eta(B_s)| < 1$
  - good vertex
  - 3D displacement $L_{3D}$ between primary and secondary vertex
  - $\sigma(L_{3D}) < 150$ $\mu$m
  - proper decay length $0 < \lambda < 0.3$ cm

\textbf{Bkg substantially reduced but still sizeable at this stage}
Pre-selection DØ:
- $4.5 < m_{\mu\mu} < 7.0 \text{ GeV}/c^2$
- muon quality cuts
- $p_T(\mu) > 2.5 \text{ GeV}/c$
- $|\eta(\mu)| < 2$
- $p_T(B_s \text{ cand}) > 5.0 \text{ GeV}/c$
- good di-muon vertex

Potential sources of background:
- continuum $\mu\mu$ Drell-Yan
- sequential semi-leptonic $b \rightarrow c \rightarrow s$ decays
- double semi-leptonic $bb \rightarrow \mu\mu X$
- $b/c \rightarrow \mu x + \text{fake}$
- fake + fake
- $\mu^+\mu^-$ mass

- B vertex displacement:
  \[ \lambda = \frac{cL_{3D}M}{|\vec{p}(B)|} \]

- Isolation (Iso):
  \[ ISO = \frac{p_T(B)}{p_T(B) + \sum_i p_T^i(\Delta R_i < 1)} \]
  (fraction of $p_T$ from $B \to \mu\mu$ within $\Delta R = (\Delta \eta^2 + \Delta \phi^2)^{1/2}$ cone of 1)

- "pointing ($\Delta \alpha$)":
  \[ \Delta \alpha = \angle (\vec{p}(B) - \vec{L}_{3D}) \]
  (angle between $B_s$ momentum and decay axis)
D0 Optimization

- Optimize cuts on three discriminating variables
  - Pointing angle
  - 2D decay length significance
  - Isolation
- Random Grid Search
- Maximize S/(1+sqrt(B))
CDF Optimization

- CDF constructs a likelihood ratio using discriminating variables $\lambda, \Delta\alpha, \text{Iso}$

$$L_R = \frac{\prod_i P_s(x_i)}{\prod_i P_s(x_i) + \prod_i P_b(x_i)}$$

$P_{s/b}$ is the probability for a given sig/bkg to have a value of $x$, where $i$ runs over all variables.

- Optimize on expected upper limit
- $L_R(\text{optimized}) > 0.99$
**Background Estimate**

- Extrapolated bkg from side-bands to signal region assume linear shape

- CDF signal region is also contaminated by $B \rightarrow h^+h^-$ (e.g. $B \rightarrow K^+K^-$, $K^+\pi^-$, $\pi^+\pi^-$)
  - $K,\pi \rightarrow$ muon fake rates measured from data
  - Convolute fake rates with expected $\text{Br}(B \rightarrow h^+h^-)$ to estimate #
    - $B_s$ signal window = $0.19 \pm 0.06$
    - $B_d$ signal window = $1.37 \pm 0.16$
- Total bkg = combinatoric + $(B \rightarrow hh)$
• CDF (780 pb$^{-1}$):
  – central/central: observe 1, expect $0.88 ± 0.30$
  – Central/forward: observe 0, expect $0.39 ± 0.21$

• DØ (300 pb$^{-1}$):
  – observe 4, expect $4.3 ± 1.2$
D0 Sensitivity for 700 pb\(^{-1}\)

- Obtain a sensitivity (w/o unblinding) w/o changing the analysis
- Combine “old” Limit with obtained sensitivity

Cut Values changed only slightly!

Expect 2.2 ± 0.7 background events
Setting Limits

\[
BR(B_s \to \mu^+ \mu^-) = \frac{N_{UL}^{B_s}}{N_{B^+}^{Bs}} \cdot \frac{\alpha_{B^+} \cdot \epsilon_{B^+}^{total}}{\alpha_{B^+} \cdot \epsilon_{Bs}^{total}} \cdot \frac{f_{b \to B^+}}{f_{b \to Bs}} \cdot BR(B^+ \to J/\psi K^+) \cdot BR(J/\psi \to \mu^+ \mu^-)
\]

- **B^+** reconstructed using similar selection criteria as Bs
- Acceptance and efficiency ratios are obtained from combination of data and Monte Carlo
- Fragmentation ratio \(\left(\frac{fs}{fu}\right)\) from world average with \(\sim 12\%\) uncertainty
- Branching ratios of norm mode taken from world average
**Branching Ratio Limits**

- Using Bayesian methods (flat prior) and including stat+syst errors
- Time evolution of limits (in 95%CL):

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Data (pb⁻¹)</th>
<th>Branching Ratio (×10⁻⁷)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF (B_s\rightarrow\mu\mu)</td>
<td>176</td>
<td>7.5×10⁻⁷</td>
<td>Published</td>
</tr>
<tr>
<td>DØ (B_s\rightarrow\mu\mu)</td>
<td>240</td>
<td>5.1×10⁻⁷</td>
<td>Published</td>
</tr>
<tr>
<td>DØ (B_s\rightarrow\mu\mu)</td>
<td>300</td>
<td>4.0×10⁻⁷</td>
<td>Prelim.</td>
</tr>
<tr>
<td>DØ (B_s\rightarrow\mu\mu)</td>
<td>700</td>
<td>&lt;2.3×10⁻⁷</td>
<td>Prelim. Sensitivity</td>
</tr>
<tr>
<td>CDF (B_s\rightarrow\mu\mu)</td>
<td>364</td>
<td>2.0×10⁻⁷</td>
<td>Published</td>
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<td>CDF (B_s\rightarrow\mu\mu)</td>
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<td>1.0×10⁻⁷</td>
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<td>4.9×10⁻⁸</td>
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<td>CDF (B_d\rightarrow\mu\mu)</td>
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<td>3.0×10⁻⁸</td>
<td>Prelim.</td>
</tr>
</tbody>
</table>

Combine CDF + D0 (expected limit) improves result by ~20% → \(\text{Br}(B_s\rightarrow\mu\mu) < \sim 0.8\times10^{-7} @ 95\%\text{C.L.}\)
Projection was made about a year ago.

So far we are doing slightly better than the projection.

Based on current projection, Tevatron can push down to low $10^{-8}$ region.
Summary

• CDF and D0 have analyzed first ~800 pb\(^{-1}\). No signal is seen in the CDF data. D0 has not opened the box for the later data.

• A full Tevatron \(B_s \rightarrow \mu \mu\) analysis update for 1 fb\(^{-1}\) is planned for this summer. The expected sensitivity is in the mid 10\(^{-8}\) level

• Based on conservative estimate, Tevatron will be able to reach down to the low 10\(^{-8}\). However, if \(BR(B_s \rightarrow \mu \mu)\) is at the SM value 😞 Then we will need to wait for LHC for observation.