Rare Decays at the Tevatron

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Outline

- Experimental Environment
- $B_S \rightarrow \mu \mu$ (CDF & D0)
- $B_S \rightarrow \mu \mu X$ (CDF & D0)
- $B, \Lambda_b \rightarrow hh$ (CDF)
- FCNC D Decay (D0)
**Tevatron**

Tevatron is gold mine for rare B decay searches:
- Enormous $b$ production cross section, $x1000$ times larger than $e^+e^-$ B factories
- All B species are produced ($\bar{B}^0, B^+, B_s, \Lambda_b...$)

**Dataset:**
- Di-muon sample, easy to trigger on with good purity level in hadronic environment
- Analyses presented today use 0.450 to 2 fb$^{-1}$ of data

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**B Triggers**

- **Trigger is the lifeline of B physics in a hadron environment**
- Rare B “Di-Muon” triggers:
  - Low single muon thresholds
  - Require Sum $p_T$ or outer muon chambers
  - Di-muon trigger is the primary trigger for the CDF $B_s \rightarrow \mu^+\mu^-$ search

- “Hadronic” triggers using silicon vertex detectors:
  - Exploit long lifetime of heavy quarks
  - Two-track trigger
    - Two oppositely charged tracks with large impact parameters
**BRIEF MOTIVATION**

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

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

- SM prediction is below the sensitivity of current experiments.

Any signal at the Tevatron would indicate new physics.

- New limits place boundaries on theoretical models.
**Analysis Overview**

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

Motto: reduce background and keep signal efficiency high

**Step 1:** Pre-selection cuts to reject obvious background

**Step 2:** Optimization (need to know signal efficiency and expected background)

**Step 3:** Reconstruct \( B^+ \to J/\psi K^+ \) normalization mode

**Step 4:** Open the box \( \rightarrow \) compute branching ratio or set limit

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**B \to \mu^+\mu^- SIGNAL VS BKG DISCRIMINATION**

- **\( \mu^+\mu^- \) mass \( \sim \pm 2.5 \sigma \) mass window
- **B vertex displacement:** \( \lambda = \frac{c\Delta L}{\langle T \rangle} \)
- **Isolation (Iso):** \( ISO = \frac{p_{\tau}(B) + \sum p_{\tau}(\Delta R_i < 1)}{p_{\tau}(B)} \)
- **"pointing \( (\Delta \alpha)"\):** \( \Delta \alpha = \angle (\vec{p}_B, \vec{L}_{B_0}) \)
- **\( \lambda/\sigma_\lambda \):** proper decay length significance
- **\( p_T(\mu\mu) \):** transverse momentum of Bs
- **\( p_T(\mu)_{\text{low}} \):** lower \( \mu \) pT
Discriminating Variables

- Combine in Likelihood for D0 or NN (New Element) for CDF which takes into account the correlations between the variables
  - Removes 25% of the background
- Set limit by using 3 NN bins and 5 mass bins (New Element)
  - Improves expected limit by 25%
- Unbiased optimization
  - Based on simulated signal and data sidebands

CDF Control Samples

- Independent background control samples to cross check the combinatoric background estimate procedure

OS - : Opposite-sign dimuon sample with ct<0

SS+ : Same-sign dimuon sample with ct>0

SS- : Same-sign dimuon sample with ct<0

FM : Fake muon sample ct>0
  (require at least one muon leg to fail our muon likelihood and dE/dX requirement)
Checking Control Samples

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<th>NeuralNet cut</th>
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<td>231±8</td>
<td>230</td>
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<td>OS- &gt;0.90</td>
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<tr>
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<td>0.6±0.4</td>
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<td>&gt;0.995</td>
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<td>FM &gt;0.95</td>
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<td>5</td>
</tr>
<tr>
<td>&gt;0.995</td>
<td>3.3±1.0</td>
<td>3</td>
</tr>
</tbody>
</table>

• Using a wider ± 150 MeV signal window for cross-check

Combinatorial BKG (2/fb)

• Likelihood fit (polynomial) to sidebands
• Separate fit for 3 NN slices
Use linear fit for NN>0.995 slice

Also calculate the B->hh contributions which are added in to background estimate
Unblinding the Signal Region

No significant excess observed!

Limit History

New Results are world’s best limits

CDF:
\[ \text{Br}(B_s \rightarrow \mu \mu) < 4.7 \times 10^{-8} @ 90\% \text{CL} \]
\[ < 5.8 \times 10^{-8} @ 95\% \text{CL} \]

D0:
\[ \text{Br}(B_s \rightarrow \mu \mu) < 7.5 \times 10^{-8} @ 90\% \text{CL} \]
\[ < 9.3 \times 10^{-8} @ 95\% \text{CL} \]
SO(10) Grand Unification Model

Pink regions are excluded by either theory or experiments

Green region is the WMAP preferred region

Blue dashed line is the Br(B_s → µ⁺µ⁻) contour

Light blue region excluded by old B_s → µµ analysis

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Light blue region excluded by old B_s → µµ analysis

Our old result

New Limit


R. Dermisek et al., JHEP 0304 (2003) 037

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Light blue region excluded by old B_s → µµ analysis

Br(B_s → µ⁺µ⁻) at tanβ = 50

95% CL Limits on Br(B_s → µ⁺µ⁻)

mSUGRA at tanβ = 50

m_{12}(GeV)

[B_f C_f] (GeV)

B(B_s → µ⁺µ⁻) and Cosmological Connection

Branching Fraction x 10^7

Luminosity (pb⁻1)
$B(B_s \rightarrow \mu \mu)$ and Cosmological Connection

95% CL Limits on $B(B_s \rightarrow \mu \mu)$

Arnowitt, Dutta, et al., PLB 538 (2002) 121

$M_{R'} \sim 1100 \text{ GeV/c}^2$
$\mathcal{B}(B_s \to \mu\mu)$ and Cosmological Connection

CDF's analysis is also sensitive to $B_d^- \to \mu \mu$
- Due to excellent mass resolution
- $\sim 25$ MeV/c$^2$

Expected limit $1.3 \times 10^{-8}$ at 90% confidence level

Gives new world’s best limit of:

$$BR(B_d \to \mu^+ \mu^-) < 1.5 \times 10^{-8} (1.8 \times 10^{-8})$$

at 90% (95%) C.L.
Search for $B \rightarrow \mu \mu h$

- Non-resonant decays $B \rightarrow \mu \mu h$ via box or penguin diagrams
  - new physics may be observable through interference with SM amplitudes

- Already observed (BaBar, Belle):
  - $B_u \rightarrow \mu \mu K$
  - $B_d \rightarrow \mu \mu K^*$

- Missing:
  - $B_s \rightarrow \mu \mu \phi$
  - prediction: $BR(B_s \rightarrow \mu \mu \phi) = 1.6 \times 10^{-6}$

Search Methodology

- Similar method as used for $B_s \rightarrow \mu \mu$
- Unbiased (blinded) selection optimization using
  - signal event sample: MC simulation
  - background sample: data sidebands
- Normalize to analogous resonant $B \rightarrow J/\psi \, h$ decay

$$\frac{BR(B \rightarrow \mu^+ \mu^- h)}{BR(B \rightarrow J/\psi h) \cdot BR(J/\psi \rightarrow \mu^+ \mu^-)} = \frac{N_{h \mu \mu} \epsilon_{J/\psi h}^{\text{total}}}{N_{J/\psi h} \epsilon_{J/\psi h}^{\text{total}}}$$

- Apply cuts on search mode and normalization mode
- Remove resonant $\mu \mu$ by cutting out $J/\psi$ / $\psi(2S)$ mass ranges
- Unblind

Selection Strategy

Optimize selection based on cuts on similar quantities as used for $B_s \rightarrow \mu \mu$ (decay length, isolation, pointing angle)

Optimize on best value for

$$\frac{S}{\sqrt{S+B}}$$
Observations

<table>
<thead>
<tr>
<th>Observation</th>
<th>( B_u \to \mu \mu K )</th>
<th>( B_d \to \mu \mu K^* )</th>
<th>( B_s \to \mu \mu \phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td># events signal range</td>
<td>90</td>
<td>35</td>
<td>11</td>
</tr>
<tr>
<td># estim. BG events</td>
<td>( 45.3 \pm 5.8 )</td>
<td>( 16.5 \pm 3.6 )</td>
<td>( 3.5 \pm 1.5 )</td>
</tr>
<tr>
<td>Significance</td>
<td>( 4.5 \sigma )</td>
<td>( 2.9 \sigma )</td>
<td>( 2.4 \sigma )</td>
</tr>
</tbody>
</table>

Results (World’s Best)

\[
\text{BR}(B^+ \to \mu \mu K^+) = (0.72 \pm 0.15\text{(stat.)} \pm 0.05\text{(syst.)}) \times 10^{-6}
\]

\[
\text{BR}(B^0 \to \mu \mu K^*) = (0.82 \pm 0.31\text{(stat.)} \pm 0.10\text{(syst.)}) \times 10^{-6}
\]

- **D0:** \[
\frac{\text{BR}(B_s \to \mu \mu \phi)}{\text{BR}(B_s \to J/\psi \phi)} < 4.4 \cdot 10^{-3} \text{ at } 95\% \text{ C.L.} \quad 0.45 \text{ fb}^{-1}
\]

- **CDF:** \[
\frac{\text{BR}(B_s \to \mu \mu \phi)}{\text{BR}(B_s \to J/\psi \phi)} < 2.61 \cdot 10^{-3} \text{ at } 95\% \text{ C.L.} \quad 1 \text{ fb}^{-1}
\]

New World’s Best Limit
\[ B, \Lambda_b \rightarrow hh \]

\[ B^0, B_S, \Lambda_b \rightarrow \pi\pi, K\pi, KK \]

- B→hh decays are the most used B decays for study of CPV because only two light bodies → plenty of final states to measure same observables allowing multiple constraints on interesting parameters as CKM angle gamma.
- The fact that penguin diagrams (bottom-right) participate gives sensitivity to new physics.
- CDF already obtained important results such as: first observation of \( B_S \rightarrow KK \), and measurement of direct CPV asymmetries in \( B^0 \rightarrow K^+\pi^- \).
B → hh' Trigger

- Hard to trigger, only two "stable" hadrons in final state
- Exploit long lifetime of the B-hadrons

Confirm trigger cuts offline
Peak already visible

Disentangling modes

- Despite excellent mass resolution (≈ 22MeV/c^2) different decays overlaps
- Event-by-event particle ID not sufficient to separate modes
  ⇒ Combined kinematics and particle ID fit
Fit Yields

Large yields for known modes

Signal events:

\[ B^0 \rightarrow \pi^+ \pi^- \quad 1121 \pm 63 \]
\[ B^0 \rightarrow K^+ \pi^- \quad 4045 \pm 84 \]
\[ B_s \rightarrow K^+ K^- \quad 1307 \pm 64 \]

| \( B(B^0 \rightarrow \pi^+ \pi^-) \) | \( 0.259 \pm 0.017 \pm 0.015 \) |
| \( B(B^0 \rightarrow K^+ \pi^-) \) | \( (5.10 \pm 0.33 \pm 0.36) \cdot 10^{-6} \) |
| \( B(B_s \rightarrow K^+ K^-) \) | \( 0.324 \pm 0.019 \pm 0.041 \) |
| \( B(B_s \rightarrow K^- K^-) \) | \( (24.4 \pm 1.4 \pm 4.6) \cdot 10^{-6} \) |

• Three New Modes

\[ B_s \rightarrow K^- \pi^+ \quad 230 \pm 34 \pm 16 \quad 8\sigma \]
\[ \Lambda_b \rightarrow p \pi^- \quad 110 \pm 18 \pm 16 \quad 6\sigma \]
\[ \Lambda_b \rightarrow p K^- \quad 156 \pm 20 \pm 11 \quad 11\sigma \]

First measurement of direct CP violating asymmetries in \( \Lambda_b \rightarrow p \pi \) decays

\[ A_{CP}(\Lambda_b^0 \rightarrow p \pi^-) = \frac{B(\Lambda_b^0 \rightarrow p \pi^-) - B(\bar{\Lambda}_b^0 \rightarrow \bar{p} \pi^+)}{B(\Lambda_b^0 \rightarrow p \pi^-) + B(\bar{\Lambda}_b^0 \rightarrow p \pi^+)} = 0.03 \pm 0.17 \text{ (stat.)} \pm 0.05 \text{ (syst.)}, \]

\[ A_{CP}(\Lambda_b^0 \rightarrow p K^-) = \frac{B(\Lambda_b^0 \rightarrow p K^-) - B(\bar{\Lambda}_b^0 \rightarrow \bar{p} K^+)}{B(\Lambda_b^0 \rightarrow p K^-) + B(\bar{\Lambda}_b^0 \rightarrow p K^+)} = 0.37 \pm 0.17 \text{ (stat.)} \pm 0.03 \text{ (syst.)}, \]
First measurement of Branching Ratios in $\Lambda_b \to p\phi$ decays

\[
\begin{align*}
\sigma(p\bar{p} \to \Lambda_b^0 X, p_T > 6 \text{ GeV/c}) & \quad B(\Lambda_b^0 \to p\pi^-) = 0.0415 \pm 0.0074 \text{ (stat.)} \pm 0.0058 \text{ (syst.)}, \\
\sigma(p\bar{p} \to B^0 X, p_T > 6 \text{ GeV/c}) & \quad B(B^0 \to K^+\pi^-) = 0.0663 \pm 0.0089 \text{ (stat.)} \pm 0.0084 \text{ (syst.)}.
\end{align*}
\]

Using $\text{Br}(B \to K^+\pi)$ and ratios of fragmentation functions, can extract $\Lambda_b$ branching ratios:

\[
\begin{align*}
B(\Lambda_b^0 \to p\pi^-) & = (3.1 \pm 0.6 \text{ (stat.)} \pm 0.7 \text{ (syst.)}) \times 10^{-6}, \\
B(\Lambda_b^0 \to pK^-) & = (5.0 \pm 0.7 \text{ (stat.)} \pm 1.0 \text{ (syst.)}) \times 10^{-6}.
\end{align*}
\]

All results agree with the Standard Model Predictions

First Observation and BR Measurement of $B_S \to K\pi$

\[
\frac{f_S}{f_d} \frac{B(B_S \to K^-\pi^+)}{B(B^0 \to K^+\pi^-)} = 0.066 \pm 0.010 \pm 0.010
\]

Using input from HFAG

\[
\Rightarrow B(B_S \to K^-\pi^+) = (5.0 \pm 0.75 \pm 1.0) \times 10^{-6}
\]
Direct CP Violation

\[ A_{CP} = \frac{N(\overline{B}^0 \rightarrow K^- \pi^+)}{N(\overline{B}^0 \rightarrow K^- \pi^+)} - \frac{N(B^0 \rightarrow K^+ \pi^-)}{N(B^0 \rightarrow K^+ \pi^-)} \]

\[ = -0.086 \pm 0.023 \pm 0.009 \]

- Only significant difference in \( K^+/K^- \) interaction with material
- Calibrate with \( D^0 \rightarrow h^+h^- \) with assumption \( A_{CP}(D^0 \rightarrow K \pi) = 0 \)
- Dominant systematic uncertainty
  - Particle ID model
  - WA B meson masses

FCNC D Decays at D0

- First indication of CP violation in \( B_d \) system
- Sign and size agree with SM expectation
- No evidence for 'exotic' sources of CP violation
- Will repeat with more data (already 2.5fb^{-1} on tape)
General Description

- Another place where the SM is highly suppressed and a signal would be indication of new physics
- Uses 1.3 fb-1
- Search for $D_S^+$ and $D^+ \rightarrow \varphi \pi^+ \rightarrow \mu \mu \pi^+$
- Also looks at continuum decay $D^+ \rightarrow \mu \mu \pi^+$ away from $\varphi$ resonance
- SM predictions at $10^{-9}$

Methodology for Direct Decay

- Uses Dimuon trigger
- Reconstruct the dimuon spectrum
- Add in track
  - Use long lifetime properties to separate signal from background
  - Also uses kinematic properties of decay
    - Fits of daughters and decay angles
Continuum D $^+ \to \mu \mu \pi^+$

- Exclude $0.96 < \text{Mass}(\mu \mu \pi^+ ) < 1.06$ resonant peak
- Use same cuts as resonant decays, add in isolation
- 19 signal events seen
- Sideband background $\Rightarrow 25.8 \pm 4.6$
- Probability of background fluctuation is 14%
- Set limit on $D^+ \to \phi \pi^+ \to \mu \mu \pi^+$
  - $Br = 3.9 \times 10^{-6}$ at 90% c.l. New World’s best limit

Conclusions

- Rare decays are highly suppressed in the SM allowing for very sensitive probes of new physics at the Tevatron
- A lot of work is being done to improve the analyses, in addition to just adding luminosity, to push closer to the SM predictions
Search for $\Lambda_b$

- No asymmetry previously seen in hadron decays
- Uses unbinned multivariate Likelihood fit
  - Uses PID

![Graphs showing mass distribution and invariant mass distribution for CDF Run II and Monte Carlo simulations.](image)
B->lh is calculated and added to plot before fitting.

- For $B_s$ signal window
- Bkg includes B->lh backgrounds
- Combine all bins in 2d fit

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<tr>
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