Rare Decays at the Tevatron

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Outline

• Overall motivations

• $B_{d,s}^0 \rightarrow \mu^+\mu^-$
  • Motivation
  • CDF and D0 methods
  • CDF and D0 results

• $B_{d,s}^0 \rightarrow \mu^+\mu^- K^+/K^*/\phi$
  • Motivation
  • D0 sensitivity analysis

For discussion of Charmless B decays see following talk by Simone Donati
Searching for New Physics

- Two ways to search for new physics:
  - direct searches – seek e.g. Supersymmetric particles
  - indirect searches – test for deviations from Standard Model predictions e.g. branching ratios
- In the absence of evidence for new physics
  - set limits on model parameters

\[ \text{BR}(B \to \mu\mu) < 1 \times 10^{-7} \]

Trileptons: 2 fb\(^{-1}\)
$B_{d,s}^0 \rightarrow \mu^+\mu^-$
B $\rightarrow \mu\mu$ in the Standard Model

• In Standard Model FCNC decay B $\rightarrow \mu\mu$ heavily suppressed

  $\bar{b} \rightarrow \mu^+ \mu^-$

  $s \rightarrow W^- \nu_l \mu^-$

  $t \rightarrow W^+ \mu^+$

• Standard Model predicts $BR(B_s \rightarrow \mu^+ \mu^-) = (3.4 \pm 0.5) \times 10^{-9}$


• $B_d \rightarrow \mu\mu$ further suppressed by CKM coupling $(V_{td}/V_{ts})^2$

  $BR(B_d \rightarrow \mu^+ \mu^-) = (1.00 \pm 0.14) \times 10^{-10}$

• Both below sensitivity of Tevatron experiments

Observe no events $\Rightarrow$ set limits on new physics
Observe events $\Rightarrow$ clear evidence for new physics
B $\rightarrow \mu\mu$ in New Physics Models

- SUSY could enhance BR by orders of magnitude
  - MSSM: $\text{BR}(B \rightarrow \mu\mu) \propto \tan^6\beta$
  - may be 100x Standard Model

- R-parity violating SUSY: tree level diagram via sneutrino
  - observe decay for low $\tan\beta$

- mSUGRA: $B \rightarrow \mu\mu$ search complements direct SUSY searches
  - Low $\tan\beta \Rightarrow$ observation of trilepton events
  - High $\tan\beta \Rightarrow$ observation of $B \rightarrow \mu\mu$

- Or something else!

A. Dedes et al, hep-ph/0207026
The Challenge

- Large combinatorial background
- Key elements are
  - determine efficiencies
  - select discriminating variables
  - estimate background
Methodology

- Search for muon pairs in $B_d/B_s$ mass windows
- D0 search for only $B_s$ and correct for $B_d$ decays
- Approximately $360\text{pb}^{-1}$ (CDF) / $300\text{pb}^{-1}$ (D0) integrated luminosity
- Unbiased optimisation, signal region blind
- Aim to measure BR or set limit

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

- Reconstruct normalisation mode ($B^+ \rightarrow J/\psi K^+$)
- Construct discriminant to select B signal and suppress dimuon background (CDF)
- Use cuts analysis to suppress dimuon background (D0)
- Measure background
- Measure the acceptance and efficiency ratios
Catched rare B triggers using all chambers to $|\eta| \leq 1.1$
- excellent tracking

Use two types of muon pairs:
- central-central
- central-extension

D0
- four dedicated rare B triggers using all chambers to $|\eta| \leq 2.0$
- excellent muon coverage
Normalisation Mode (CDF)

- Reconstruct normalisation mode \( \text{B}^+ \rightarrow \text{J}/\psi \, \text{K}^+ \)
B → \( \mu \mu \) Optimisation (CDF)

- Chosen three primary discriminating variables:
  - proper decay length (\( \lambda \))
    \[
    \lambda = \frac{cL_{3D}M_{\text{vtx}}}{|\vec{p}(B)|}
    \]
  - Pointing (\( \Delta \alpha \)) \( |\phi_B - \phi_{\text{vtx}}| \)
  - Isolation (Iso)
    \[
    \text{Iso} = \frac{p_T(B)}{p_T(B) + \sum_i p_T(\Delta R_i < 1.0)}
    \]
B → \( \mu\mu \) Optimisation (D0)

- Similar three primary discriminating variables

  - D0 use 2d lifetime variables instead of 3d
  - Optimise using MC for signal, data sidebands for background
  - Random grid search, optimising for 95% C.L.
Likelihood Ratio Discriminant (CDF)

- First iteration of analysis used standard cuts optimisation
- Second iteration uses the more powerful likelihood discriminant

\[ L = \frac{\prod_{i} P_{\text{sig}}(x_i)}{\prod_{i} P_{\text{sig}}(x_i) + \prod_{i} P_{\text{bkg}}(x_i)} \]

- \( i \): index over all discriminating variables
- \( P_{\text{sig/bkg}}(x_i) \): probability for event to be signal / background for a given measured \( x_i \)

- Obtain probably density functions of variables using
  - background: Data sidebands
  - signal: Pythia Monte Carlo sample
Optimisation (CDF)

Likelihood ratio discriminant:

Optimise likelihood and $p_t(B)$ for best 90% C.L. limit
- Bayesian approach
- consider statistical and systematic errors
- Assume 1fb$^{-1}$ integrated luminosity

CDF Preliminary
$B_{s(d)} \rightarrow \mu^+ \mu^-$
364 pb$^{-1}$

Signal
(Pythia MC)

Background
(data sidebands)
**Expected Background (CDF/D0)**

- Extrapolate from data sidebands to obtain expected events
- **CDF:**
  - Scale by the expected rejection from the likelihood ratio cut
  - Expected background: $0.81 \pm 0.12$ (central-central dimuon)
    $0.66 \pm 0.13$ (central-extended dimuon)
  - Tested background prediction in several control regions and find good agreement
- **D0:**
  - Expected background: $4.3 \pm 1.2$
Unblinded Results (D0)

- Apply optimised cuts
- Unblinded results for $B_s \rightarrow \mu \mu$:

  - Expected background: $4.3 \pm 1.2$
  - Observed: 4

  \[
  \text{BR}(B_s \rightarrow \mu \mu) < 3.0 \times 10^{-7} \text{ @ 90\% CL} \\
  < 3.7 \times 10^{-7} \text{ @ 95\% CL}
  \]
Unblinded Results (CDF)

Results with $p_t(B)>4\text{GeV}$ cut applied, Likelihood cut at 0.99:

No events found in $B_s$ or $B_d$ search windows in either muon pair type
Limits on $\text{BR}(B_{d,s} \to \mu\mu)$ (CDF)

$\text{BR}(B_s \to \mu\mu) < 1.6 \times 10^{-7}$ @ 90% CL
< $2.1 \times 10^{-7}$ @ 95% CL

$\text{BR}(B_d \to \mu\mu) < 3.9 \times 10^{-8}$ @ 90% CL
< $5.1 \times 10^{-8}$ @ 95% CL

These are currently world best limits

The future for CDF:

- use optimisation for 1fb$^{-1}$
- need to reoptimise at 1fb-1 for best results
- assume linear background scaling
$B_{d,s}^{0} \rightarrow \mu \mu K^{+}/K^{*}/\phi$
$B_{d,s} \rightarrow \mu\mu K^+/K^*/\phi$

- **B Rare Decays**
  - $B^+ \rightarrow \mu\mu K^+$
  - $B^0 \rightarrow \mu\mu K^*$
  - $B_s \rightarrow \mu\mu \phi$
  - $\Lambda_b \rightarrow \mu\mu \Lambda$

- **FCNC $b \rightarrow s\gamma^*$**

- **Penguin or box processes in the Standard Model:**
  \[
  \begin{array}{c}
  \text{\begin{tabular}{c}
  s \hline
  b \hline
  u,c,t \hline
  W \hline
  \end{tabular}}
  \end{array}
  \]
  \[\begin{array}{c}
  \gamma Z \\
  \mu \\
  \mu \\
  \end{array}\]

- **Rare processes: Latest Belle measurement**
  \[
  B(B \rightarrow K\ell^+\ell^-) = (5.50^{+0.75}_{-0.70} \pm 0.27 \pm 0.02) \times 10^{-7}
  \]
Motivations

1) Would be first observations in $B_s$ and $\Lambda_b$ channels

2) Tests of Standard Model
   • branching ratios
   • kinematic distributions (with enough statistics)

• Effective field theory for $b \to s$ (Operator Product Expansion)

$$\mathcal{H}_{\text{eff}} = -4 \frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) O_i(\mu)$$

• Rare decay channels are sensitive to Wilson coefficients which are calculable for many models (several new physics scenarios e.g. SUSY, technicolor)
• Decay amplitude: $C_9$
• Dilepton mass distribution: $C_7, C_9$
• Forward-backward asymmetry: $C_{10}$
• Use $B \to J/\psi X$ channels as control channels
  • exactly the same signature ($J/\psi \to \mu\mu$)
  • use MC to obtain relative efficiency

• Most likely confirm observation $B^+ \to \mu\mu K^+$ and measure BR
• Then either
  • make first observations in $B_s$ and $\Lambda_b$ or
  • set strong branching ratio limits
Sensitivity Analysis (D0)

- Cuts analysis using same variables as $B_s \rightarrow \mu\mu$ analysis

  ![Graph 1](image1)
  ![Graph 2](image2)
  ![Graph 3](image3)

- Remove the dimuon mass regions corresponding to $J/\psi$, $\psi'$, $\phi$
- Contribution from rare decays not well understood under resonances
Box is unopened
• Expected background: $5.1 \pm 1.0$ events
• Sensitivity for 90% C.L. limit calculated: $\text{BR}(B_s \rightarrow \mu\mu\phi)<1.2 \times 10^{-5}$
Summary

- $B_{d,s} \rightarrow \mu^+ \mu^-$ are a powerful probe of new physics
- Could give first hint of new physics at the Tevatron
- World best limits coming from Tevatron experiments
- Combinations of D0 and CDF results by Lepton Photon 05

- $B_{d,s} \rightarrow \mu^+ \mu^- K/K^*/\phi$ should be observable in Run II
- Also a test of the Standard Model
- Sensitivity analysis performed, awaiting results
Backup
Samples (CDF)

- Dedicated rare B triggers
  - in total six Level 3 paths
  - Two muons + other cuts
  - using all chambers to $|\eta| \leq 1.1$

- Use two types of dimuons:
  - CMU-CMU
  - CMU-CMX

- Additional cuts in some triggers:
  - $\Sigma p_t(\mu) > 5$ GeV
  - $L_{xy} > 100 \mu m$
  - $\text{mass}(\mu \mu) < 6$ GeV
  - $\text{mass}(\mu \mu) > 2.7$ GeV
# Background estimate (CDF)

<table>
<thead>
<tr>
<th>LH cut</th>
<th>CMU-CMU</th>
<th>CMU-CMX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pred</td>
<td>obsv</td>
</tr>
<tr>
<td>&gt;0.50</td>
<td>236+/-4</td>
<td>235</td>
</tr>
<tr>
<td>OS-</td>
<td>&gt;0.90</td>
<td>37+/-1</td>
</tr>
<tr>
<td></td>
<td>&gt;0.99</td>
<td>2.8+/-0.2</td>
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<tr>
<td>&gt;0.50</td>
<td>2.3+/-0.2</td>
<td>0</td>
</tr>
<tr>
<td>SS+</td>
<td>&gt;0.90</td>
<td>0.25+/-0.03</td>
</tr>
<tr>
<td></td>
<td>&gt;0.99</td>
<td>&lt;0.10</td>
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<tr>
<td>&gt;0.50</td>
<td>2.7+/-0.2</td>
<td>1</td>
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<tr>
<td>SS-</td>
<td>&gt;0.90</td>
<td>0.35+/-0.03</td>
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<td></td>
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<td>&lt;0.10</td>
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<tr>
<td>&gt;0.50</td>
<td>84+/-2</td>
<td>84</td>
</tr>
<tr>
<td>FM+</td>
<td>&gt;0.90</td>
<td>14.2+/-0.4</td>
</tr>
<tr>
<td></td>
<td>&gt;0.99</td>
<td>1.0+/-0.1</td>
</tr>
</tbody>
</table>

1.) OS- : opposite-charge dimuon, $\lambda < 0$
2.) SS+ : same-charge dimuon, $\lambda > 0$
3.) SS- : same-charge dimuon, $\lambda < 0$
4.) FM : fake muon sample (at least one leg failed muon stub chi2 cut)
Likelihood p.d.f.s (CDF)

Input p.d.f.s:

- CMU-CMU
  364 pb$^{-1}$

Likelihood ratio discriminant:

- CDF Preliminary
- $B_{s(d)} \rightarrow \mu^+ \mu^-$
- 364 pb$^{-1}$

Signal
(Pythia MC)

Background
(data sidebands)
Methodology (CDF)

- Search for muon pairs in $B_d/B_s$ mass windows
- D0 search for only Bs and correct for Bd decays
- Approximately 360pb$^{-1}$ integrated luminosity
- Blind analysis
- Aim to measure BR or set limit

$$BR(B_s \rightarrow \mu^+ \mu^-) = \frac{N_{B_s}}{N_{B+}} \frac{\alpha_{B+} \cdot \varepsilon_{B+}^{\text{total}}}{\alpha_{B_s} \cdot \varepsilon_{B_s}^{\text{total}}} \frac{f_u}{f_s} BR(B^+ \rightarrow J/\psi K^+) BR(J/\psi \rightarrow \mu^+ \mu^-)$$

- Reconstruct normalization mode ($B^+ \rightarrow J/\psi \ K^+$)
- Construct discriminant to select B signal and suppress dimuon background
- Measure background
- Measure the acceptance and efficiency ratios
Signal and Side-band Regions

- Use events from same triggers for $B^+$ and $B_s(d) \rightarrow \mu \mu$ reconstruction.

- Search region:
  - $-5.169 < M_{\mu \mu} < 5.469$ GeV
  - Signal region not used in optimization procedure

- Sideband regions:
  - 500 MeV on either side of search region
  - For background estimate and analysis optimization.
MC Samples

Pythia MC

- Tune A
- default cdfSim tcl
- realistic silicon and beamline
- \(p_T(B)\) from Mary Bishai
- \(p_T(b) > 3\) GeV \&\& \(|y(b)| < 1.5\)
  - \(B_s \rightarrow \mu^+\mu^-\)  
    (signal efficiencies)
  - \(B^+ \rightarrow J\pi^+ \rightarrow \mu^+\mu^-K^+\)  
    (nrmlztn efncy and xchks)
  - \(B^+ \rightarrow J\pi^+ \rightarrow \mu^+\mu^-\pi^+\)  
    (nrmlztn correction)
• tan(β)~50 constrained by unification of Yukawa coupling

• All previously allowed regions (white) are excluded by this new measurement

• Unification valid for small M_{1/2} (~500 GeV)

• New Br(B_s → µµ) limit strongly disfavors this solution for m_A = 500 GeV

Red regions are excluded by either theory or experiments
Green region is the WMAP preferred region
Blue dashed line is the Br(B_s → µµ) contour
Light blue region excluded by old B_s → µµ analysis
Method: Likelihood Variable Choice

\[ \text{Prob}(\lambda) = \text{probability of } B_s \rightarrow \mu^+ \mu^- \text{ yields } \lambda > \lambda_{\text{obs}} \]

\( \lambda_{\text{obs}} \) (ie. the integral of the cumulative distribution)

\[ \text{Prob}(\lambda) = \exp\left(-\frac{\lambda}{438 \, \mu m}\right) \]

- yields flat distribution
- reduces sensitivity to MC modeling inaccuracies (e.g. L00, SVX-z)
Method: Checking MC Modeling of Signal LH

For CMU-CMX:

- MC reproduces Data efficiency vs LHood cut to 5% or better
- Assign 5% (relative) systematic for CMU-CMX
Step 4: Compute Acceptance and Efficiencies

\[
\left( \frac{\alpha_{B^+}}{\alpha_{B_s}} \right) \cdot \left( \frac{\varepsilon_{B^+}^{\text{trig}}}{\varepsilon_{B_s}^{\text{trig}}} \right) \cdot \left( \frac{\varepsilon_{B^+}^{\text{reco}-\mu\mu}}{\varepsilon_{B_s}^{\text{reco}-\mu\mu}} \right) \cdot \left( \frac{\varepsilon_{B^+}^{\text{vtx}}}{\varepsilon_{B_s}^{\text{vtx}}} \right) \cdot \varepsilon_{B^+}^{\text{reco}-K} \cdot \frac{1}{\varepsilon_{B_s}^{LH}}
\]

- Most efficiencies are determined directly from data using inclusive J/ψ → μμ events. The rest are taken from Pythia MC.
- \( \alpha(B^+/B_s) = 0.297 +/- 0.008 \) (CMU-CMU)
  \[= 0.191 +/- 0.006 \) (CMU-CMX)
- \( \varepsilon^{LH}(B_s) \): ranges from 70% for LH>0.9 to 40% for LH>0.99
- \( \varepsilon^{\text{trig}}(B^+/B_s) = 0.9997 +/- 0.0016 \) (CMU-CMU)
  \[= 0.9986 +/- 0.0014 \) (CMU-CMX)
- \( \varepsilon^{\text{reco}-\mu\mu}(B^+/B_s) = 1.00 +/- 0.03 \) (CMU-CMU/X)
- \( \varepsilon^{\text{vtx}}(B^+/B_s) = 0.986 +/- 0.013 \) (CMU-CMU/X)
- \( \varepsilon^{\text{reco}-K}(B^+) = 0.938 +/- 0.016 \) (CMU-CMU/X)

Red = From MC
Green = From Data
Blue = combination of MC and Data