Search for Rare Flavor-Changing and Electroweak Penguin Decays of the $B_s$ Meson at the DØ Experiment

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Motivation: $B_s \rightarrow \mu^+\mu^-$

In the Standard Model:
- $B_s \rightarrow \mu^+\mu^-$: FCNC process, $BF=0$ at tree level
- Standard Model expectations:
  
  $BF(B_s^{0} \rightarrow \mu^+\mu^-) = (3.42 \pm 0.54) \times 10^{-9}$
  
  $BF(B_d^{0} \rightarrow \mu^+\mu^-) = (1.00 \pm 0.14) \times 10^{-10}$

Physics beyond the Standard Model:
- additional particles can contribute to loops
- MSSM: $BF$ enhanced by up to 3 orders of magnitude
- enhancements in many models
- $\Rightarrow$ hope to find something...!
Motivation: $B_s \rightarrow \phi \mu^+ \mu^-$

In the Standard Model:

- $B_s \rightarrow \phi \mu^+ \mu^- :$ larger expected BF
  
  \[ BF(B_s^0 \rightarrow \phi \mu^+ \mu^-) = 1.6 \times 10^{-6} \ (\sim 30\% \ theory \ uncertainty) \]

- $BF(B_d^0 \rightarrow X_s \mu^+ \mu^-)$ measured at BaBar/Belle

- Sensitivity close to prediction $\Rightarrow$ test the Standard Model!

Physics beyond the Standard Model:

- Additional particles can contribute to loops

- $\Rightarrow$ hope to find something...!
No production of $B_s$ mesons in $\Upsilon(4s)$ decays

Tevatron: abundant source of $b\bar{b}b\bar{b}$ events
hadronization: $f(b\to B_s) \sim 10\%$

The Tevatron:

DØ muon detector:
Production of $B_s$ Mesons

- No production of $B_s$ mesons in $\Upsilon(4s)$ decays
- Tevatron: abundant source of bbbar events
  hadronization: $f(b\rightarrow B_s) \sim 10\%$

![Graph showing production of $B_s$ mesons](image)

Run IIa Integrated Luminosity

Data samples:
- $B_s\rightarrow \mu^+\mu^-$: 300 pb$^{-1}$ analyzed
- $B_s\rightarrow \mu^+\mu^-$: 750 pb$^{-1}$ sensitivity estimate
- $B_s\rightarrow \phi\mu^+\mu^-$: 450 pb$^{-1}$ analyzed
Search for $B_s \rightarrow \mu^+\mu^-$

Concepts:

- Preselection of dimuon events
- Optimized selection of $B_s \rightarrow \mu^+\mu^-$ decay candidates
- Reconstruct resonant decay $B^+ \rightarrow J/\Psi K^+$ => efficiency normalization
- Side band technique => background subtraction
- Blind analysis => avoid bias
Search for $B_s \rightarrow \mu^+\mu^-$

Event preselection:

- **dimuon trigger**
- **two muons:** $p_T(\mu) > 2.5 \text{ GeV}$
  - $|\eta(\mu)| < 2.0$
  - opposite charges
- **muons form common secondary vertex** (reconstructed in 3d):
  - $\chi^2$/dof < 10
  - $4.5 \text{ GeV} < m(\mu^+\mu^-) < 7.0 \text{ GeV}$
  - minimum number of hits in vertex (3) and tracking detectors (4)
  - $\delta L_{xy} < 0.15 \text{ mm}$ ($L_{xy}$: secondary vertex decay length in xy)
  - $p_T(\mu^+\mu^-) > 5 \text{ GeV}$
Search for $B_s \rightarrow \mu^+\mu^-$

Final event selection:
- $\rightarrow$ pointing angle
- $\rightarrow$ isolation
- $\rightarrow$ decay length significance

- cut optimization based on MC signal
- background from data sidebands

PRL 94, 071802 (2005)
Search for $B_s \rightarrow \mu^+\mu^-$

Final event selection:
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Final event selection:
- pointing angle
- isolation
- decay length significance

- cut optimization based on MC signal
- background from data sidebands

PRL 94, 071802 (2005)
Normalization

- Analysis based on the ratio
  \( B_s \rightarrow \mu^+\mu^- \ / \ B^+ \rightarrow J/\psi(\rightarrow \mu^+\mu^-) K^+ \):

\[
\text{BF}\left( B_s^0 \rightarrow \mu^+ \mu^- \right) \leq \frac{N_{ul}}{N_{B_s^0}} \cdot \frac{B_s^0}{\varepsilon_{\mu\mu}} \cdot \text{BF}\left( B^\pm \rightarrow J/\psi(\mu^+ \mu^-) K^\pm \right)
\]

\[
= \frac{\int_{b \rightarrow B_s} + R \cdot \int_{b \rightarrow B_{u,d}}}{\text{BF}_{b \rightarrow B_{u,d}}} + \text{BF}_{b \rightarrow B_s}
\]

- Branching fraction we want to calculate
  and number of observed events (for example: upper limit)

- Branching fraction for reference process
  and number of observed events
Normalization

- Analysis based on the ratio
  \[ B_s \rightarrow \mu^+\mu^- \ / \ B^+ \rightarrow J/\Psi(-\rightarrow\mu^+\mu^-) K^+ : \]

\[ \text{BF}(B^0_s \rightarrow \mu^+\mu^-) \leq \frac{N_{ul}}{N_{B^\pm}} \frac{E_{B^\pm}}{E_{B^0_s}} \text{BF}(B^\pm \rightarrow J/\psi(\mu^+\mu^-) K^+) \left( \frac{f_{b \rightarrow B_s}}{f_{b \rightarrow B_{u,d}}} + R \cdot \frac{E_{B^0_d}}{E_{B^0_s}} \right) \]

- Branching fraction we want to calculate and number of observed events (for example: upper limit)
- Branching fraction for reference process and number of observed events
- Efficiency ratio: signal / reference process
- Production ratio: \( B_s \) (signal) / \( B^+ \) (reference)
Normalization

- Analysis based on the ratio
  \( \mathcal{B}_s \to \mu^+\mu^- / \mathcal{B}^+ \to J/\psi(\to \mu^+\mu^-) K^+ \):

  \[
  \mathcal{B}_s \to \mu^+\mu^- \leq \frac{N_{ul}}{N_{B^\pm}} \cdot \frac{\mathcal{B}^\pm}{\mathcal{E}_{\mu\mu K}} \ \mathcal{B}^\pm \to J/\psi(\mu^+\mu^-) K^+ \]

  - Branching fraction we want to calculate and number of observed events (for example: upper limit)
  - Branching fraction for reference process and number of observed events
  - Efficiency ratio: signal / reference process
  - Production ratio: \( B_s \) (signal) / \( B^+ \) (reference)
  - Account for \( B_d \to \mu^+\mu^- \) contributions (but \( R \) expected to be small)
Results

- **Observed** $B^+ \rightarrow J/\Psi(\rightarrow \mu^+\mu^-) K^+$ signal:
  - $N_{B^+} = 906 \pm 35 \pm 22$
  - Additional $400 \text{ pb}^{-1}$

- **Selected** $B_s \rightarrow \mu^+\mu^-$ candidates:
  - $N_{B_s} = 899 \pm 37$
  - Additional $400 \text{ pb}^{-1}$

$BF(B_s \rightarrow \mu^+\mu^-) < 3.7 \times 10^{-7}$ (95% CL)

Comb. sensitivity: $2.3 \times 10^{-7}$
Search for $B_s \rightarrow \phi \mu^+ \mu^-$

Event preselection:
- similar to $B_s \rightarrow \mu^+ \mu^-$ preselection
- dimuon trigger
- two muons (as before)
- dimuon system: as before, but
  \[ 0.5 \text{ GeV} < m(\mu^+ \mu^-) < 4.4 \text{ GeV} \]
  exclude \[ 2.72 \text{ GeV} < m(\mu^+ \mu^-) < 4.06 \text{ GeV} \] (5\sigma around $J/\Psi$, $\Psi'$)
- two additional tracks: $\phi \rightarrow KK$ decay
  \[ p_T > 0.7 \text{ GeV} \]
  \[ 1.008 \text{ GeV} < m_{KK} < 1.032 \text{ GeV} \]
- tracks form common secondary vertex:
  \[ \chi^2/\text{dof} < 36 \]
  \[ 4.4 \text{ GeV} < m(\mu^+ \mu^-KK) < 6.2 \text{ GeV} \]
  \[ p_T(\mu^+ \mu^-KK) > 5 \text{ GeV} \]

Efficiency and thus result depends on decay model
Final event selection:

- similar to $B_s \rightarrow \mu^+\mu^-$ selection
  - pointing angle
  - isolation
  - decay length significance
- cut optimization based on MC signal
  background from data sidebands
Normalization

- Analysis based on the ratio

\[
\frac{\mathcal{B}(B_s^0 \rightarrow \phi \mu^+ \mu^-)}{\mathcal{B}(B_s^0 \rightarrow J/\psi \phi)} = \frac{N_{ul}}{N_{B_s^0}} \cdot \frac{\epsilon_{J/\psi \phi}}{\epsilon_{\phi \mu^+ \mu^-}} \cdot \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)
\]

- Branching fraction we want to calculate
- and number of observed events (for example: upper limit)
- Branching fraction for reference process
- and number of observed events
Normalization

- Analysis based on the ratio
  \[ \frac{B(S \rightarrow \mu^+\mu^- \phi(\rightarrow K^+K^-))}{B(S \rightarrow J/\Psi(\rightarrow \mu^+\mu^-) \phi(\rightarrow K^+K^-))} = \frac{N_{ul}}{N_{B_S}} \left( \frac{\epsilon_{J/\Psi \phi}}{\epsilon_{\phi \mu^+\mu^-}} \right) \cdot B(J/\Psi \rightarrow \mu^+\mu^-) \]

- Branching fraction we want to calculate and number of observed events (for example: upper limit)
- Branching fraction for reference process and number of observed events
- **Efficiency ratio**: signal / reference process
- Branching fraction \(J/\Psi \rightarrow \mu^+\mu^-\) in reference process
Result

- Observed $B_s \rightarrow J/\Psi(\rightarrow \mu^+\mu^-) \phi(\rightarrow K^+K^-)$ signal:
  - Branching fraction (PDG):
    $$BF(B_s \rightarrow J/\Psi(\rightarrow \mu^+\mu^-) \phi(\rightarrow K^+K^-)) = (9.3 \pm 3.3) \times 10^{-4}$$

- Selected $B_s \rightarrow \mu^+\mu^- \phi(\rightarrow K^+K^-)$ candidates:

- **results: limits @ 95% CL**
  - $BF(B^0_s \rightarrow \phi\mu^+\mu^-) < 4.4 \times 10^{-3}$
  - $BF(B^0_s \rightarrow J/\psi \phi) < 4.1 \times 10^{-6}$

PRD 74, 031107 (2006)
Conclusions

- Searches for FCNC processes may yield information on physics beyond the Standard Model.
- Hadron colliders (→Tevatron): “natural $B_s$ laboratory”

**$BF( B_s \rightarrow \mu^+\mu^-)$:**
- **SM expectation:** $= (3.42 \pm 0.54) \times 10^{-9}$
  - **limit:** $< 3.7 \times 10^{-7}$ (95% CL) (300 $pb^{-1}$)  DØ note 4733 (2005)
  - **sensitivity:** $< 2.3 \times 10^{-7}$ (95% CL) (700 $pb^{-1}$)  DØ note 5009 (2006)

- Probing new physics models
- Further improvements soon (likelihood selection, full Run IIa dataset)

**$BF( B_s \rightarrow \mu^+\mu^- \phi(\rightarrow K^+K^-) )$:**
- **SM expectation:** $= 1.6 \times 10^{-6}$ (±30%)
  - **limit:** $< 4.1 \times 10^{-6}$ (95% CL) (450 $pb^{-1}$)  PRD 74, 031107 (2006)
- **SM expectation accessible at Tevatron Run II!**
Backup Slides
Optimization of the Selection

- Optimization based on
  - signal MC events
  - background data events from mass sidebands (>3σ away from Bs mass)
- Procedure to find the optimum cut values:
  - random grid search (N. Amos et al., proceedings of CHEP95, p. 215)
  - optimization (G. Punzi, proceedings of Phystat03, p. 79):
    maximize the variable

\[ P = \frac{\varepsilon(B_s\to\mu^+\mu^-)}{a/2 + \sqrt{N_{\text{bkg}}}} \]

\( \varepsilon \): selection efficiency (MC)
\( N_{\text{bkg}} \): expected number of background events
\( a \): number of standard deviations at which the signal hypothesis is tested (\( a=2 \) -> ~95% CL)
Limit Calculation

- Limits take into account
  - statistical uncertainty on the background expectation
  - systematic uncertainties, e.g. for $B_s \rightarrow \mu^+\mu^-$:
    - ratio of $B_s/B_{u/d}$ hadronization fractions
    - $B^+ \rightarrow \mu^+\mu^-K^+ / B_s \rightarrow \mu^+\mu^-$ efficiency ratio
    - number of reconstructed $B^+ \rightarrow \mu^+\mu^-K^+$ decays
    - $B^+ \rightarrow J/\Psi K^+$ branching fraction
    - $J/\Psi \rightarrow \mu^+\mu^-$ branching fraction


- Alternative:
  Bayesian approach (flat prior, Gaussian uncertainties)
**B_s -> \mu^+\mu^-**: Compare with CDF

<table>
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<th>references:</th>
<th>DØ note 5009</th>
<th>CDF note 8176</th>
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<td>integrated luminosity:</td>
<td>700 pb(^{-1})</td>
<td>780 pb(^{-1})</td>
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<tr>
<td>\muon p_T &gt;:</td>
<td>2.5 GeV</td>
<td>2.0 GeV, 2.2 GeV (CMX)</td>
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<td>\mu\mu mass resolution:</td>
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<td>resulting limit (95%CL):</td>
<td>2.3x10(^{-7}) (sensitivity)</td>
<td>1.0x10(^{-7})</td>
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