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

Frank Fiedler, Munich University on behalf of the DØ collaboration
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:
  - $\text{BF}(B_s^0 \rightarrow \mu^+\mu^-) = (3.42 \pm 0.54) \times 10^{-9}$
  - $\text{BF}(B_d^0 \rightarrow \mu^+\mu^-) = (1.00 \pm 0.14) \times 10^{-10}$

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
- => hope to find something...!
Motivation: $B_s \rightarrow \phi \mu^+ \mu^-$

In the Standard Model:

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

- $BF(B_d^0 \rightarrow X_s \mu^+ \mu^-)$ 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...!
Production of $B_s$ Mesons

- 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 $b\bar{b}b\bar{b}$ events
  hadronization: $f(b\to B_s) \sim 10\%$

Run IIa Integrated Luminosity

data samples:
- $B_s\to\mu^+\mu^-$: 300 pb$^{-1}$ analyzed
- $B_s\to\mu^+\mu^-$: 750 pb$^{-1}$ sensitivity estimate
- $B_s\to\phi\mu^+\mu^-$: 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
Event preselection:

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

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

- cut optimization based on MC signal

background from data sidebands

PRL 94, 071802 (2005)
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PRL 94, 071802 (2005)
Normalization

- Analysis based on the ratio

\[ \frac{B_s \rightarrow \mu^+ \mu^-}{B^+ \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) K^+} : \]

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

\[ \text{BF} \left( B^+ \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) K^+ \right) \]

\[ \frac{\int_{b \rightarrow B_s} B_s^0}{\int_{b \rightarrow B_{u,d}} B_{u,d}^0} + R \cdot \frac{\varepsilon_{\mu \mu}}{\varepsilon_{\mu \mu}} \]

- 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 $B_s \rightarrow \mu^+\mu^- / B^+ \rightarrow J/\Psi(\rightarrow \mu^+\mu^-) K^+$:

$$BF(B^0_s \rightarrow \mu^+\mu^-) \leq \frac{N_{ul}}{N_{B^+}} \left( \frac{\mathcal{E}_{\mu\mu K}^{B^+}}{\mathcal{E}_{\mu\mu}^{B^0_s}} \right) BF(B^\pm \rightarrow J/\psi(\mu^+ \mu^-) K^\pm)$$

  \[
  \left( \frac{\int f_{b \rightarrow B_s}}{\int f_{b \rightarrow B_{u,d}}} + R \cdot \frac{\mathcal{E}_{\mu\mu}^{B^0_d}}{\mathcal{E}_{\mu\mu}^{B^0_s}} \right)
  \]

- 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
  \[ \text{BF}(B_s^0 \rightarrow \mu^+\mu^-) \leq \frac{N_{ul}}{N_{B^\pm}} \cdot \frac{\mathcal{E}_{\mu\mu K}^{B^\pm}}{\mathcal{E}_{\mu\mu}^{B_s^0}} \]

- 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 \( B_d \rightarrow \mu^+\mu^- \) contributions (but \( R \) expected to be small)
Results

- **Observed** $B^+ \rightarrow J/\Psi(\rightarrow \mu^+\mu^-)K^+$ signal:
  - **DØ note 4733 (2005)**
  - 300 pb$^{-1}$
  - DØ Run II Preliminary
  - $B^\pm \rightarrow J/\psi K^\pm$
  - $N_{B^\pm} = 906 \pm 35 \pm 22$

- **Selected** $B_S \rightarrow \mu^+\mu^-$ candidates:
  - **DØ note 4733 (2005)**
  - 300 pb$^{-1}$
  - DØ Run II Preliminary
  - **DØ note 5009 (2006)**
  - additional 400 pb$^{-1}$
  - $B^\pm \rightarrow J/\psi K^\pm$
  - $N_{B^\pm} = 899 \pm 37$

- $\text{BF}(B_S \rightarrow \mu^+\mu^-) < 3.7 \times 10^{-7}$ (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:
  $\chi^2$/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
Search for $B_s \rightarrow \phi \mu^+ \mu^-$

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

- 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
Normalization

- Analysis based on the ratio
  \[ \frac{\mathcal{B}(B_s^0 \rightarrow \phi \mu^+ \mu^-)}{\mathcal{B}(B_s^0 \rightarrow J/\Psi \phi)} = \frac{N_{ul}}{N_{B_s^0}} \left( \frac{\epsilon_{J/\Psi \phi}}{\epsilon_{\phi \mu^+ \mu^-}} \right) \mathcal{B}(J/\Psi \rightarrow \mu^+ \mu^-) \]

- 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
- **Efficiency ratio**: signal / reference process
- Branching fraction \( J/\Psi \rightarrow \mu^+ \mu^- \) in reference process
Result

- **Observed** $B_s \rightarrow J/\Psi(-\mu^+\mu^-)\phi(-\rightarrow K^+K^-)$ signal:
  
  ![Graph showing observed signal](image)

  $450 \text{ pb}^{-1}$

  $B_s^0 \rightarrow J/\psi \phi$

  $N_{B_s} = 73 \pm 10 \pm 4$

- **branching fraction (PDG):**

  $\text{BF}( B_s \rightarrow J/\Psi(-\mu^+\mu^-)\phi(-\rightarrow K^+K^-))$

  $= (9.3 \pm 3.3) \times 10^{-4}$

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

  ![Graph showing selected candidates](image)

  $450 \text{ pb}^{-1}$

- **results: limits @ 95% CL**

  ![Graph showing results](image)

  - expect $1.6 \pm 0.4$ background events
  - observe 0 events

  $\text{BF}(B_s^0 \rightarrow \phi\mu^+\mu^-) < 4.4 \times 10^{-3}$

  $\text{BF}(B_s^0 \rightarrow J/\psi \phi)$

  $\text{BF}(B_s^0 \rightarrow \phi\mu^+\mu^-) < 4.1 \times 10^{-6}$

10 times better than previous limit

(CDF I, PRD 65, 111101 (2002))
Conclusions

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

BF( Bs -> μ+μ-):
- SM expectation: = (3.42 ± 0.54) x 10^{-9}
- limit: < 3.7 x 10^{-7} (95% CL) (300 pb^{-1}) DØ note 4733 (2005)
- sensitivity: < 2.3 x 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( Bs -> μ+μ- φ(-→K+K-) ):
- SM expectation: = 1.6 x 10^{-6} (±30%)
- limit: < 4.1 x 10^{-6} (95% CL) (450 pb^{-1}) PRD 74, 031107 (2006)
- SM expectation accessible at Tevatron Run II!
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

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

- \(\varepsilon\): selection efficiency (MC)
- \(N_{bkg}\): expected number of background events
- \(a\): number of standard deviations at which the signal hypothesis is tested (\(a=2 \rightarrow \sim 95\% \text{ CL}\))
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)
BS→μ+μ−: Compare with CDF

- **references:**
  - DØ note 5009
  - CDF note 8176

- **integrated luminosity:**
  - DØ: 700 pb⁻¹
  - CDF: 780 pb⁻¹

- **μμ mass resolution:**
  - DØ: 90 MeV
  - CDF: 24 MeV

- **selection:**
  - DØ: cut-based
  - CDF: likelihood-based

- **resulting limit (95%CL):**
  - DØ: 2.3×10⁻⁷ (sensitivity)
  - CDF: 1.0×10⁻⁷