Rare decays of charm & bottom at Tevatron

- Introduction
- Tevatron
- CDF & DØ Detector
- Rare charm decays
- Rare bottom beauty
- Summary & Conclusions

Frank Lehner
U Zurich
DIF ’06, Frascati
28 Feb - 03 March, 2006
- excellent performance of Tevatron in 2005 and early 2006
- machine delivered more than 1500 pb$^{-1}$ up to now !!
- recorded (DØ/CDF)
  - 1.2/1.4 fb$^{-1}$
  - record luminosity of $1.7 \times 10^{32}$ cm$^{-2}$/s in January 2006
- high data taking efficiency ~85%
- current dataset reconstructed and under analysis
  - ~1000 pb$^{-1}$
  - compare with ~100 pb$^{-1}$ Run I
CDF detector

- Silicon Tracker SVX
  - up to $|\eta|<2.0$
  - SVX fast $r-\phi$ readout for trigger
- Drift Chamber
  - 96 layers in $|\eta|<1$
  - particle ID with $dE/dx$
  - $r-\phi$ readout for trigger
- tracking immersed in Solenoid 1.4T
- Time of Flight
  - $\rightarrow$ particle ID
DØ detector

- 2T Solenoid
- Hermetic forward & central muon detectors
  - Excellent coverage $|\eta|<2$
- Fiber Tracker
  - 8 double layers
- Silicon Detector
  - Up to $|\eta|<2.5$
Charm and bottom production at Tevatron

- bb cross section orders of magnitude larger than at B-factories $\Upsilon(4S)$ or $Z$
- all kinds of b hadrons produced:
  - $B_d, B_s, B_c, B^{**}, \Lambda_b, \Xi_b, ...$
- charm cross section even higher, about 80-90% promptly produced
- However:
  - QCD background overwhelming, b-hadrons hidden in $10^3$ larger background
  - events complicated, efficient trigger and reliable tracking necessary
- crucial for bottom and charm physics program:
  - good vertexing & tracking
  - triggers w/ large bandwidth, strong background rejection
  - muon system w/ good coverage

E.g., integrated cross sections for $|y|<1$:
- $\sigma(D^0, p_T \geq 5.5 \text{ GeV/c}) \sim 13 \mu b$
- $\sigma(B^+, p_T \geq 6 \text{ GeV/c}) \sim 4 \mu b$
Triggers for bottom & charm physics

- “classical” triggers:
  - robust and quiet di-muon and single-muon triggers
  - working horse for masses, lifetimes, rare decays etc.
  - keys to B physics program at DØ

- “advanced” triggers using silicon vertex detectors
  - exploit long lifetime of heavy quarks
  - displaced track + leptons for semileptonic modes
  - two-track trigger (CDF) - all hadronic mode
    - two oppositely charged tracks with impact parameter
    - 2-body charmless B decays etc.
    - charm physics

\[ p_T(B) \geq 5 \text{ GeV} \]
\[ L_{xy} \geq 450 \mu m \]
FCNC & new physics

- flavor-changing neutral current processes
  - in SM forbidden at tree level
  - at higher order occur through box- and penguin diagrams
  - sensitive to virtual particles in loop, thus can discern new physics
- GIM-suppression for down-type quarks relaxed due to large top mass
  - observable SM rates lead to tight constraints of new physics
- corresponding charm decays are less scrutinized and largely unexplored
  - smaller BRs, more suppressed by GIM-mechanism, long-distance effects also dominating
  - nevertheless large window to observe new physics beyond SM exists: $R_p$-violating models, little Higgs models w/ up-like vector quark etc.
Search for $D^0 \rightarrow \mu^+ \mu^-$

- FCNC decay with $c \rightarrow u l^+ l^-$ quark transition as short distance physics
- in SM BR $\sim 3 \times 10^{-13}$, but dominated by long-distance two-photon contribution
- $R_p$-violating SUSY may enhance BR of this mode considerably
- present exp. limit: $1.3 \times 10^{-6}$ @90% C.L. (BaBar)
- CDF analysis:
  - PRD68 (2003) 091101
  - data (65 pb$^{-1}$) collected with two-track trigger to search for $D \rightarrow \mu^+ \mu^-$
  - normalization of search to topological similar $D \rightarrow \pi \pi$, trigger efficiency and acceptance cancel
  - mass resolution for two-body decays $\sigma = 10$ MeV/c$^2$
  - $D \rightarrow \pi \pi$ almost completely overlap with the $\mu^+ \mu^-$ search window, good understanding of $\pi \rightarrow \mu$ fake rate, determined from a sample of $D^* \rightarrow \pi K$ decays.
  - Misidentification: $1.3 \pm 0.1\%$
Search for $D^0 \rightarrow \mu^+ \mu^-$

- Optimization of analysis on discriminating variables keeping the signal box hidden
- Combinatorial background estimated from high mass sideband: $1.6 \pm 0.7$
- Fake background from $#D \rightarrow \pi\pi$ events reconstructed in signal window multiplied with misidentification probability $\pi \rightarrow \mu$: $0.22 \pm 0.02$
- Total expected background: $1.8 \pm 0.7$ events
- Zero events found -> limit
- Updated analysis from CDF with much more data coming soon, will also look into $ee$ and $e\mu$ channel

**CDF:**

$$\text{BR}(D^0 \rightarrow \mu^+ \mu^-) \times 2.5 \times 10^{-6} \text{ @90% C.L.}$$
towards $D^\pm \rightarrow \pi^\pm \mu^+\mu^-$

- non-resonant $D^\pm \rightarrow \pi^\pm \mu^+\mu^-$ is a good place to search for new physics in up-type FCNC - enhanced in $R_p$-violating models or little Higgs models (see talk by S. Fajfer)
- Strategy at DØ: establish first resonant $D_{s}^\pm \rightarrow \phi \pi^\pm \rightarrow \mu^+\mu^-\pi^\pm$ and search then for $D^+$ candidates in the continuum for non-resonant decay
- DØ analysis based on ~500 pb$^{-1}$ of dimuon triggered data, select:
  - $\mu^+\mu^-$ consistent with $m(\phi)$
  - combine $\mu^+\mu^-$ with track $p_t>0.18$ GeV/c in same jet for $D_{(s)}$ candidates with $1.3 < m(\mu^+\mu^-\pi^\pm) < 2.5$ GeV/c$^2$
  - in average 3.3 candidates $\Rightarrow$ apply vertex-$\chi^2$ criterion to select correct one in 90% of cases (MC)
to further minimize background:
- construct likelihood ratio for signal (MC) and background (sideband) events based on
  - isolation of D candidate $I_D$
  - transverse decay length significance $S_D$
  - collinearity angle between D momentum and vector between prim. & sec. Vertex $\theta_D$
  - significance ratio $R_D = \text{impact parameter of } \pi^\pm / S_D$
  - correlations taken into account
- Likelihood cut chosen to maximize $\varepsilon_S / \sqrt{\varepsilon_B}$ with background modeled from sidebands
after cuts a signal of 51 $D_s$ resonant decay candidates with expected background of 18 are observed
- excess with ($>7\sigma$) significance
- first observation of resonant decay $D_s^{\pm} \rightarrow \phi \pi^{\pm} \rightarrow \mu^+\mu^-\pi^\pm$ as benchmark
- the number of (resonant) $D^+ \rightarrow \phi \pi^+ \rightarrow \mu^+\mu^-\pi^\pm$ is determined in fit with parameters fixed in looser selection
- fit yields $13\pm5$ $D^\pm$ events (significance: $2.7\sigma$), set either limit or calculate BR
- accomplished first major step in FCNC three-body charm decay program
- analysis will be updated with more statistics soon ($\sim1$fb$^{-1}$)
- as future goal: search for excess in non-resonant continuum region

$$\text{Br}(D^\pm \rightarrow \phi \pi^\pm \rightarrow \mu^+\mu^-\pi^\pm) = (1.70^{+0.08+0.06}_{-0.73-0.82}) \times 10^{-6}$$

$$\text{Br}(D^\pm \rightarrow \phi \pi^\pm \rightarrow \mu^+\mu^-\pi^\pm) < 3.14 \times 10^{-6} \text{ (90\% C.L.)}$$
**Purely leptonic B decay**

- $B^- \rightarrow l^+ l^-$ decay is helicity suppressed FCNC
- SM: $\text{BR}(B_s \rightarrow \mu^+\mu^-) \sim 3.4 \times 10^{-9}$
- depends only on one SM operator in effective Hamiltonian, hadronic uncertainties small
- $B_d$ relative to $B_s$ suppressed by $|V_{td}/V_{ts}|^2 \sim 0.04$ if no additional sources of flavor violation
- reaching SM sensitivity: present limit for $B_s \rightarrow \mu^+\mu^-$ comes closest to SM value

**SM expectations:**

<table>
<thead>
<tr>
<th>$l$</th>
<th>$\text{Br}(B_d \rightarrow l^+ l^-)$</th>
<th>$\text{Br}(B_s \rightarrow l^+ l^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>$3.4 \times 10^{-15}$</td>
<td>$8.0 \times 10^{-14}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$1.0 \times 10^{-10}$</td>
<td>$3.4 \times 10^{-9}$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$3.1 \times 10^{-8}$</td>
<td>$7.4 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

**Current published limits:**

<table>
<thead>
<tr>
<th>$l$</th>
<th>C.L. 90%</th>
<th>$\text{Br}(B_d \rightarrow l^+ l^-)$</th>
<th>$\text{Br}(B_s \rightarrow l^+ l^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td></td>
<td>$&lt; 6.1 \cdot 10^{-8}$</td>
<td>$&lt; 5.4 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td></td>
<td>$&lt; 8.3 \cdot 10^{-8}$</td>
<td>$&lt; 1.5 \cdot 10^{-7}$</td>
</tr>
<tr>
<td>$\tau$</td>
<td></td>
<td>$&lt; 2.5%$</td>
<td>$&lt; 5.0%$</td>
</tr>
</tbody>
</table>
Purely leptonic B decay

- excellent probe for many new physics models
- particularly sensitive to models w/ extended Higgs sector
  - BR grows \( \sim \tan^6 \beta \) in MSSM
  - 2HDM models \( \sim \tan^4 \beta \)
  - mSUGRA: BR enhancement correlated with shift of \((g-2)\mu\)
- also, testing ground for
  - minimal SO(10) GUT models
  - \(R_p\) violating models, contributions at tree level
  - (neutralino) dark matter ...
Experimental search

- **364 pb⁻¹ di-muon triggered data**
  - CDF: central/central muons
  - DØ: central/forward muons
- **two separate search channels**
- **central/forward muons**
- **extract B_s and B_d limit**
- **240 pb⁻¹ (update 300 pb⁻¹) di-muon triggered data**
- **blind analysis to avoid experimenter's bias**
- **side bands for background determination**
- **use B⁺ -> J/ψ K⁺ as normalization mode**
- **J/ψ -> μ⁺ μ⁻ cancels μ⁺μ⁻ selection efficiencies**

**blinded signal region:**
- **DØ:** $5.160 < m_{μμ} < 5.520$ GeV/c²;
  - $σ = 90$ MeV
- **CDF:** $5.169 < m_{μμ} < 5.469$ GeV/c²;
  - $σ = 25$ MeV
Pre-selection

- **Pre-selection DØ:**
  - $4.5 < m_{\mu\mu} < 7.0$ GeV/c$^2$
  - muon quality cuts
  - $p_T(\mu) > 2.5$ GeV/c
  - $|\eta(\mu)| < 2$
  - $p_T(B_s \text{ cand.}) > 5.0$ GeV/c
  - good vertex

- **Pre-Selection CDF:**
  - $4.669 < m_{\mu\mu} < 5.969$ 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

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

- **DØ:**
  - optimize cuts on three discriminating variables
    - angle between $\mu^+\mu^-$ and decay length vector (pointing consistency)
    - transverse decay length significance ($B_s$ has lifetime): $L_{xy}/\sigma(L_{xy})$
    - isolation in cone around $B_s$ candidate
  - use signal MC and $1/3$ of (sideband) data for optimization
  - random grid search
  - maximize $\varepsilon/(1+\sqrt{B})$
  - total efficiency w.r.t 38k selection criteria: 38.6%
- **CDF**: discriminating variables
  - pointing angle between \( \mu^+\mu^- \) and decay length vector
  - isolation in cone around \( B_s \) candidate
  - proper decay length probability
    \[ p(\lambda) = \exp(-\lambda/\lambda_{B_s}) \]

- construct likelihood ratio to optimize on “expected upper limit”
Unblinding the signal region

**CDF:**
- central/central: observe 0, expect $0.81 \pm 0.12$
- Central/forward: observe 0, expect $0.66 \pm 0.13$

**DØ:**
- observe 4, expect $4.3 \pm 1.2$
Normalization

- relative normalization is done to $B^+ \rightarrow J/\psi K^+$
- advantages:
  - $\mu^+\mu^-$ selection efficiency same
  - high statistics
  - BR well known
- disadvantages:
  - fragmentation $b \rightarrow B_u$ vs. $b \rightarrow B_s$
- $\mathrm{D}\O$: apply same values of discriminating cuts on this mode
- $\mathrm{CDF}$: no likelihood cut on this mode

\[ \chi^2 / \text{ndf} = 67.99 / 57 \]
Prob $= 0.1512$
Norm $= 322.1 \pm 12.2$
Mean $= 5.28 \pm 0.0003826$
Sigma $= 0.0003798 \pm 0.01084$
Intrcpt $= 74.61 \pm 152.6$
Slope $= 14.14 \pm -9.954$

$N(B^-) = 1785 \pm 60$
$\rho_T(B) > 4 \text{ GeV}/c$
$|\eta(\mu)| < 0.6$

$\mathrm{B}^\pm \rightarrow J/\psi K^\pm$
$N_{B^\pm} = 906 \pm 35 \pm 22$
$B(B^0_s \rightarrow \mu^+ \mu^-) \leq \frac{N_{ul}}{N_{B^\pm}} \cdot \frac{\epsilon_{B_\mu^+ \mu^-}^{B^\pm}}{\epsilon_{B_\mu^+ \mu^-}^{B^0_s}} \cdot \frac{\mathcal{B}(B^\pm \rightarrow J/\psi(\mu^+ \mu^-)K^\pm)}{f_{b \rightarrow B_{u,d}} + R \cdot \frac{\epsilon_{B_\mu^+ \mu^-}^{B^0_d}}{\epsilon_{B_\mu^+ \mu^-}^{B^0_s}}},$

(2)

- $R = \text{BR}(B_d)/\text{BR}(B_s)$ is small due to $|V_{td}/V_{ts}|^2$
- $\epsilon_{B^+}/\epsilon_{B_s}$ relative efficiency of normalization to signal channel
- $\epsilon_{B_d}/\epsilon_{B_s}$ relative efficiency for $B_d \rightarrow \mu^+ \mu^-$ versus $B_s \rightarrow \mu^+ \mu^-$ events in $B_s$ search channel (for CDF $\sim 0$, for DØ $\sim 0.95$)
- $f_s/f_u$, fragmentation ratio (in case of $B_s$ limit) - use world average with 15% uncertainty
The present (individual) limits

- DØ mass resolution is not sufficient to separate $B_s$ from $B_d$. Assume no $B_d$ contribution (conservative)
- CDF sets separate limits on $B_s$ & $B_d$ channels
- all limits below are 95% C.L. Bayesian incl. sys. error, DØ also quotes FC limit

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CDF $B_s\rightarrow\mu\mu$</strong></td>
<td>176 pb$^{-1}$</td>
<td>$7.5\times10^{-7}$</td>
<td>Published</td>
</tr>
<tr>
<td><strong>DØ $B_s\rightarrow\mu\mu$</strong></td>
<td>240 pb$^{-1}$</td>
<td>$5.1\times10^{-7}$</td>
<td>Published</td>
</tr>
<tr>
<td><strong>DØ $B_s\rightarrow\mu\mu$</strong></td>
<td>300 pb$^{-1}$</td>
<td>$4.0\times10^{-7}$</td>
<td>Prelim.</td>
</tr>
<tr>
<td><strong>CDF $B_s\rightarrow\mu\mu$</strong></td>
<td>364 pb$^{-1}$</td>
<td>$2.0\times10^{-7}$</td>
<td>Published</td>
</tr>
<tr>
<td><strong>CDF $B_d\rightarrow\mu\mu$</strong></td>
<td>364 pb$^{-1}$</td>
<td>$4.9\times10^{-8}$</td>
<td>Published</td>
</tr>
</tbody>
</table>

$B_d$ limit x2 better than published Babar limit w/ 111 fb$^{-1}$

updates on limits/sensitivities expected soon
### Tevatron limit combination I

- **fragmentation ratio** $b \to B_s/b \to B_{u,d}$
  - standard PDG value as default
  - Tevatron only fragmentation (from CDF) improves limit by 15%
- **uncorrelated uncertainties**:
  - uncertainty on eff. ratio
  - uncertainty on background
- **correlated uncertainties**:
  - BR of $B^\pm \to J/\psi(\to \mu\mu) K^\pm$
  - fragmentation ratio $b \to B_s/b \to B_{u,d}$

---

<table>
<thead>
<tr>
<th></th>
<th>CDF U-U</th>
<th>CDF U-X</th>
<th>DØ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Luminosity</strong></td>
<td>364 pb⁻¹</td>
<td>336 pb⁻¹</td>
<td>300 pb⁻¹</td>
</tr>
<tr>
<td>$(A_{B^+/A_{B_s^0}})$</td>
<td>0.852 ± 0.084</td>
<td>0.485 ± 0.048</td>
<td>0.247 ± 0.019</td>
</tr>
<tr>
<td>$N_{B^+}$</td>
<td>1785 ± 60</td>
<td>696 ± 39</td>
<td>906 ± 41</td>
</tr>
<tr>
<td>$N_b$</td>
<td>0.81 ± 0.12</td>
<td>0.66 ± 0.13</td>
<td>4.3 ± 1.2</td>
</tr>
<tr>
<td>$N_o$</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>$ses \times 10^7$</td>
<td>1.04 ± 0.16</td>
<td>1.52 ± 0.25</td>
<td>0.59 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>(0.62 combined)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>expect. limit 90% C.L.</strong></td>
<td>$3.5 \times 10^{-7}$</td>
<td>$5.6 \times 10^{-7}$</td>
<td>$3.5 \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>(2.0 \times 10^{-7} combined)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>obsvd. limit 90% C.L.</strong></td>
<td>$(1.5 \times 10^{-7} combined)$</td>
<td>$3.2 \times 10^{-7}$</td>
<td></td>
</tr>
</tbody>
</table>

**DØ** has larger acceptance due to better $\eta$ coverage, **CDF** has greater sensitivity due to lower background expectations.

[hep-ex/0508058](http://arxiv.org/abs/0508058)
Combination II

- combined CDF & DØ limit:
  - $\text{BR}(B_s \to \mu^+ \mu^-) < 1.2 (1.5) \times 10^{-7}$ at 90% (95%) C.L.

- world-best limit, only factor 35 away from SM
- important to constrain models of new physics at $\tan\beta$
- e.g. mSO(10) model is severely constraint

Example: SO(10) symmetry breaking model

R. Dermisek et al.
hep-ph/0507233

Contours of constant $\text{Br}(B_s \to \mu^+ \mu^-)$
Future Prospects for $B_s \rightarrow \mu^+\mu^-$

- assuming unchanged analysis techniques and reconstruction and trigger efficiencies are unaffected with increasing luminosity
- for 8 fb$^{-1}$/experiment an exclusion at 90% C.L. down to $2 \times 10^{-8}$ is possible
- both experiments pursue further improvements in their analysis
Search for $B_s \rightarrow \mu^+\mu^-\phi$

- long-term goal: investigate $b \rightarrow s l^+ l^-\text{FCNC}$ transitions in $B_s$ meson
- exclusive decay: $B_s \rightarrow \mu^+\mu^-\phi$
- SM prediction:
  - short distance BR: $\sim 1.6 \times 10^{-6}$
  - about 30% uncertainty due to $B \rightarrow \phi$ form factor
- 2HDM: enhancement possible, depending on parameters for $\tan \beta$ and $M_{H^+}$
- presently only one published limit
  - CDF Run I: $6.7 \times 10^{-5}$ @ 95% C.L.
Search for $B_s \rightarrow \mu^+\mu^-\phi$

- **DØ**: 300 pb$^{-1}$ of dimuon data
- normalize to resonant decay $B_s \rightarrow J/\psi \phi$
- cut on mass region $0.5 < M(\mu\mu) < 4.4$ GeV/c$^2$ excluding $J/\psi$ & $\psi'$
- two good muons, $p_t > 2.5$ GeV/c
- two additional oppositely charged tracks $p_t > 0.5$ GeV/c for $\phi$
- $\phi$ candidate in mass range $1.008 < M(\phi) < 1.032$ GeV/c$^2$
- good vertex
- $p_t(B_s$ cand.$) > 5$ GeV/c
- non-resonant decay: cut out $J/\psi$ and $\psi'$
Search for $B_s \rightarrow \mu^+\mu^-\phi$

- blind analysis: optimization with following variables in random grid search
  - pointing angle
  - decay length significance
  - Isolation
- background modeled from sidebands
- use resonant decay $B_s \rightarrow J/\psi \phi$ with same cuts as normalization
- gaussian fit with quadratic background: $73 \pm 10$ $B_s \rightarrow J/\psi \phi$ resonant decays

![Graph showing $B_s^0 \rightarrow J/\psi \phi$ with $N_{B_s^0} = 73 \pm 10$]
Limit on $B_s \rightarrow \mu^+\mu^-\phi$

- expected background from sidebands: $1.6 \pm 0.4$ events
- observe zero events in signal region

$$BR(B_s \rightarrow \phi \mu^+\mu^-)/BR(B_s \rightarrow J/\psi \phi) < 4.4 \times 10^{-3} @ 95\% \text{ C.L.}$$

Using central value for $BR(B_s \rightarrow J/\psi \phi) = 9.3\times10^{-4}$ PDG2004:

$$BR(B_s \rightarrow \phi \mu^+\mu^-) < 4.1\times10^{-6} @ 95\% \text{ C.L.}$$
Conclusions

- Tevatron is also a charm & bottom production factory for probing new physics in rare charm and bottom decays
- CDF limit on D→ μ⁺ μ⁻ decay already competitive with only 65 pb⁻¹, improved limit will come soon...
- first DØ observation of benchmark channel Dₛ± → φ π± → μ⁺μ⁻ π± as first step towards a charm rare FCNC decay program
- CDF & DØ provide world best limits on purely leptonic decays B_d,s → μ⁺μ⁻, limit important to constrain new physics
- with more statistics to come enhance exclusion power/discovery potential for new physics
- improved DØ limit on exclusive Bₛ → μ⁺μ⁻φ decay shown, about 2x above SM
- Tevatron is doubling statistics every year - stay tuned for many more exciting results on charm & bottom
Systematic uncertainties

- systematics for DØ (CDF very similar)
- efficiency ratio determined from MC with checks in data on trigger/tracking etc.
- large uncertainty due to fragmentation ratio
- background uncertainty from interpolating fit

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{B^\pm}^{B_s^0}\epsilon_{B_s^0}^{B_s^0}$</td>
<td>7.7</td>
</tr>
<tr>
<td>Number of $B^\pm \rightarrow J/\psi K^\pm$ events</td>
<td>5.1</td>
</tr>
<tr>
<td>$\mathcal{B}(B^\pm \rightarrow J/\psi K^\pm)$</td>
<td>4.0</td>
</tr>
<tr>
<td>$\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)$</td>
<td>1.7</td>
</tr>
<tr>
<td>$f_{b \rightarrow B_s^0}/f_{b \rightarrow B_{u,d}^0}$</td>
<td>12.7</td>
</tr>
<tr>
<td>Background uncertainty</td>
<td>29.7</td>
</tr>
</tbody>
</table>
expected limit $B_s \rightarrow \mu^+\mu^-\phi$

- expected limit at 95% C.L. for $B_s \rightarrow \mu^+\mu^-\phi$

![Graph showing expected limit of $BR(B_s \rightarrow \mu\mu\phi)$ vs. Run II integrated Luminosity in units of fb$^{-1}$ with a shaded region indicating the SM prediction.](image)
Constraining dark matter

- mSUGRA model: strong correlation between $BR(B_s \rightarrow \mu^+\mu^-)$ with neutralino dark matter cross section especially for large $\tan \beta$
- constrain neutralino cross section with less than, within and greater than 2σ of WMAP relic density

S. Baek et al., JHEP 0502 (2005) 067