Heavy Flavor Physics at the Tevatron

Centered on $B_s$ physics

Hideki Miyake
University of Tsukuba
on behalf of the CDF and DØ collaborations

XXVI Rencontres de Physique de la Vallée d’Aoste
La Thuile, Aosta Valley, Italy
February 29, 2012
To be covered in my talk

- **$B_s$ related hot topics**

  - $B_s \rightarrow \mu\mu$
    - $10 fb^{-1}$!
  - $B_s \rightarrow D_s^* (+) + D_s^* (-)$
    - $6.8 fb^{-1}$!
  - CPV in $B_s$ mixing ($B_s \rightarrow J/\psi \phi$)
    - $10 fb^{-1}$!

**$B_s$ Mixing/Decay**

---

H. Miyake

La Thuile 2012, Italy, 2/29/2012
pp collisions at $\sqrt{s}=1.96$ TeV

- Typical initial luminosities of $3.5 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$
- >50 pb$^{-1}$ collected per week

Shutdown after 30 years operation

Delivered 12 fb$^{-1}$ and recorded $\sim$10 fb$^{-1}$
Tevatron Experiments

CDF II Detector

- Silicon vertex detector
- Central tracking
- Calorimeter & muon systems (dimuon trigger)
- Silicon vertex trigger (two track trigger)
- Particle ID (TOF and dE/dx)
- Excellent mass resolution

DØ Detector

- Single muon trigger
- Excellent electron & muon ID
- Excellent tracking acceptance
**Highly suppressed in the SM**

\[ B(B_s^0 \rightarrow \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9} \]

\[ B(B_d^0 \rightarrow \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10} \]


**Enhanced in NP (up to 100x)**

- e.g. MSSM: BR(B\(\rightarrow\)\(\mu\mu\)) (tan\(\beta\))^6

**Experimental status**

- **CDF** \(\text{Br}(B_s \rightarrow \mu\mu) = 1.8^{+1.1}_{-0.9} \times 10^{-8}\)
  PRL107, 191801 (2011)

- **DØ** \(\text{Br}(B_s \rightarrow \mu\mu) < 5.1 \times 10^{-8} @ 95\% \text{ C.L.}\)
  PLB693, 539 (2010)

- **LHCb** \(\text{Br}(B_s \rightarrow \mu\mu) < 1.4 \times 10^{-8} @ 95\% \text{ C.L.}\)
  PLB 708, 55 (2012)

- **CMS** \(\text{Br}(B_s \rightarrow \mu\mu) < 1.9 \times 10^{-8} @ 95\% \text{ C.L.}\)
  PRL107, 191802 (2011)
Dimuon trigger

Optimized event selection using NN

Normalized by control sample \((B^+ \rightarrow J/\psi(\rightarrow \mu\mu)K^+))

14 Discriminating variables

H. Miyake  
La Thuile 2012, Italy, 2/29/2012
Dominant BG: combinatorial
- Mostly rejected by NN discriminant

Peaking BG: $B \rightarrow hh$
- Estimated using MC and $D^*$-tagged $D^0 \rightarrow K\pi^+$ data
- Only 10% of combinatorial BG in $B_s$

Well controlled
- Checked by various control samples
  - Negative lifetime
  - Same/opposite sign
  - Reverse muon ID

<table>
<thead>
<tr>
<th>sample</th>
<th>NN cut</th>
<th>pred</th>
<th>obsv</th>
<th>prob(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.700 &lt; NN &lt; 0.760$</td>
<td>268.8±(14.3)</td>
<td>249</td>
<td>82.3</td>
<td></td>
</tr>
<tr>
<td>$0.760 &lt; NN &lt; 0.850$</td>
<td>320.8±(16.1)</td>
<td>282</td>
<td>95.1</td>
<td></td>
</tr>
<tr>
<td>$0.850 &lt; NN &lt; 0.900$</td>
<td>150.3±(9.9)</td>
<td>156</td>
<td>36.5</td>
<td></td>
</tr>
<tr>
<td>$0.900 &lt; NN &lt; 0.940$</td>
<td>146.2±(9.7)</td>
<td>158</td>
<td>23.0</td>
<td></td>
</tr>
<tr>
<td>$0.940 &lt; NN &lt; 0.970$</td>
<td>146.2±(9.7)</td>
<td>137</td>
<td>72.9</td>
<td></td>
</tr>
<tr>
<td>$0.970 &lt; NN &lt; 0.987$</td>
<td>100.4±(7.8)</td>
<td>98</td>
<td>58.3</td>
<td></td>
</tr>
<tr>
<td>$0.987 &lt; NN &lt; 0.995$</td>
<td>78.8±(6.8)</td>
<td>59</td>
<td>97.0</td>
<td></td>
</tr>
<tr>
<td>$0.995 &lt; NN &lt; 1.000$</td>
<td>41.2±(4.8)</td>
<td>42</td>
<td>47.2</td>
<td></td>
</tr>
</tbody>
</table>
Interesting >2.5σ excess of $B_s$ over BG observed by CDF in 7fb$^{-1}$

Compatible with all other results, but could be first indication of a signal

CDF updates the analysis with whole Run II dataset (+30% data) while keeping the analysis unchanged
**B_d → μμ: results with 10fb⁻¹**

**Good consistency with expected limit:**
\[ \text{BR}(B_d \rightarrow \mu^+\mu^-)_{\text{exp}} < 4.2 \times 10^{-9} \text{ at 95\% C.L.} \]

\[ \text{BR}(B_d \rightarrow \mu^+\mu^-) < 4.6 \times 10^{-9} \text{ at 95\% C.L.} \]

**Consistent with SM**

- Divide signal region by NN discriminant
- Estimate BG from each mass sideband

**CC:** both central muon
**CF:** central+forward muon

H. Miyake  
La Thuile 2012, Italy, 2/29/2012
Summer excess not reinforced by new data, but still there

Keep observing a >2σ fluctuation over BG only, which allows us to quote a BR

\[
BR(B_s \rightarrow \mu^+\mu^-) = (1.3^{+0.9}_{-0.7}) \times 10^{-8}
\]

\[
0.8 \times 10^{-9} < BR(B_s \rightarrow \mu^+\mu^-) < 3.4 \times 10^{-8} \quad 95\% \ C.L.
\]
$B_s \rightarrow \mu^+\mu^-$ comparison

Compatible with SM and other experiments

H. Miyake
La Thuile 2012, Italy, 2/29/2012
CP violation in $B_s$ system

No large NP is present in leading $B$ transitions

\[
\begin{align*}
\Delta m_d & & \Delta m_s \\
A_{SL} & & A_{SL}(B_d) & & A_{SL}(B_s)
\end{align*}
\]

New Physics in $B_d - \bar{B}_d$ mixing

\[
|\text{Mag. of NP in mixing}|
\]

SM

\[
\sin 2\beta; \cos 2\beta > 0
\]

\[
\Delta m_d & & \Delta m_s \\
A_{SL} & & A_{SL}(B_d) & & A_{SL}(B_s)
\]

New Physics in $B_s - \bar{B}_s$ mixing

Less Tevatron

(Mostly) Tevatron

\[
\Delta \Gamma_s & & \tau_s^{FS}
\]

The possibility of NP in the $B_s$ transitions

\[
\begin{pmatrix}
\phi_s \\
\Delta m_d & & \Delta m_s \\
A_{SL} & & A_{SL}(B_d) & & A_{SL}(B_s)
\end{pmatrix}
\]

H. Miyake

La Thuile 2012, Italy, 2/29/2012
Joint fit to mass, angles, decay-time and production flavor distributions to extract the mixing phase.

Flavor tagging to determine initial $B_s$ flavor

Decay time measurement to know time evolution

Angular analysis to separate CP-even/odd

$B_s$ invariant mass fit to separate signal from BG
The golden channel to measure $\beta_s$ dominated by $b \to c\bar{c}s$ tree ~theoretically clean

$B \to VV$ decay: three partial waves
- $L=0,2$ (CP even)
- $L=1$ (CP odd)

Need angular analysis

$N(B_s^0) \sim 11000$

$B_s \to J/\psi \phi$ angular distributions (Transversity basis)

+ Non resonant $J/\psi K K$ with $K K$ in S wave

La Thuile 2012, Italy, 2/29/2012
Flavor tagging

- determine initial $B_s$ flavor at the production
  - Employ two different techniques

- SSKT (Same Side Kaon Tagger)
  - Exploit correlation with particles produced in fragmentation
  - Total tagging power: 3.5%

- OST (Opposite Side Tagger)
  - Exploit decay products of other b-hadron
  - Total tagging power: 1.3%

For CDF full data analysis
  - OST: used for whole data
  - SSKT: used for first 5.2fb$^{-1}$
Consistent with SM $\sim 1\sigma$

$\Phi_s = -0.55^{+0.38}_{-0.36}$ (rad)
$\beta_s = 0.28^{+0.18}_{-0.19}$ (rad)

**NEW result using full data!**

Consistent with SM $< 1\sigma$

$\beta_s$ within $[-\pi/2,-1.51] \cup [-0.06,0.30] \cup [1.26,\pi/2]$ at the 68% C.L.
$B_s \rightarrow D_s^+ D_s^-$

- Predominately CP-even (purely CP-even: $D_s^+ D_s^-$)
- May give dominant contribution to $B_s$ width difference in SM
- Possible to infer $\Delta \Gamma_s / \Gamma_s$ by measuring $\text{BR}(B_s \rightarrow D_s^+ D_s^-) \sim \frac{2B(B_s^0 \rightarrow D_s^+ D_s^-)}{\Gamma_s + \Delta \Gamma_s} \sim \frac{\Delta \Gamma_s}{\Gamma_s}$
  
  under some assumptions:

  $2B(B_s^0 \rightarrow D_s^+ D_s^-) \sim \frac{\Delta \Gamma_s}{\Gamma_s}$

  \(\text{Aleksan et. al., PLB 316, 567 (1993)}\)
  \(\text{Dunietz et. al., PRD 63, 114015 (2001)}\)

- $\text{BR}$ not precisely measured so far

CDF result: $\text{BR}(B_s \rightarrow D_s^+ D_s^-) = (0.94 \pm 0.44 \pm 0.42)\%$

DØ result: $\text{BR}(B_s \rightarrow D_s^+ D_s^-) = (3.5 \pm 1.0 \pm 1.1)\%$

Belle result: $\text{BR}(B_s \rightarrow D_s^+ D_s^-) = (4.3 \pm 0.4 \pm 1.0)\%$

need more data to be conclusive

H. Miyake

La Thuile 2012, Italy, 2/29/2012
\[ B_s \rightarrow D_s^+ D_s^- : \text{analysis} \]

- **CDF update from 355\text{pb}^{-1} analysis**
  - Use 6.8\text{fb}^{-1} two track trigger data

- **Event selection:**
  - Partial reconstruction \((B_s \rightarrow D_s^+ D_s^- \chi)\) since neutral from \(D_s^*\) is hard to reconstruct
  - BR normalized by \(B^0 \rightarrow D^+ D_s^-\)

- **Final state: combination of \(D_s\) subdecays**
  - \(D_s \rightarrow K^{*0} K\) or \(\phi \pi \rightarrow KK\pi\)
  - \(D \rightarrow K\pi\pi\) for normalization channel
  - Use \(D_s\) Dalitz structure for accurate acceptance determination and reduce systematic uncertainty

- **Optimized by neural network**
  - Simultaneous fit to the four decays as a way to better constrain all the yields
    - cross feeds calibrated
Simultaneously fit each fraction of the final states from $D_s D_{(s)}$ mass distribution

$$\text{BR}(B_s \rightarrow D_s^+ D_s^-) = (0.49 \pm 0.06 \pm 0.05 \pm 0.08)\%,$$
$$\text{BR}(B_s \rightarrow D_s^{*+} D_s^{*-}) = (1.13 \pm 0.12 \pm 0.09 \pm 0.19)\%,$$
$$\text{BR}(B_s \rightarrow D_s^{*+} D_s^{*-}) = (1.75 \pm 0.19 \pm 0.17 \pm 0.29)\%,$$
$$\text{BR}(B_s \rightarrow D_s^{(*)+} D_s^{(*)-}) = (3.38 \pm 0.25 \pm 0.30 \pm 0.56)\%,$$

$$\Delta \Gamma_s / \Gamma_s = (6.99 \pm 0.54 \pm 0.64 \pm 1.20)\%.$$
**B_s \rightarrow D_s^+ D_s^-**: results

Simultaneously fit each fraction of the final states from $D_s D_{(s)}$ mass distribution

\[
\text{BR}(B_s \rightarrow D_s^+ D_s^-) = (0.49 \pm 0.06 \pm 0.05 \pm 0.08) \%,
\text{BR}(B_s \rightarrow D_s^{*+} D_s^{-}) = (1.13 \pm 0.12 \pm 0.09 \pm 0.19) \%,
\text{BR}(B_s \rightarrow D_s^{*+} D_s^{*-}) = (1.75 \pm 0.19 \pm 0.17 \pm 0.29) \% ,
\text{BR}(B_s \rightarrow D_s^{(*)+} D_s^{(*)-}) = (3.38 \pm 0.25 \pm 0.30 \pm 0.56) \% ,
\]

\[\Delta \Gamma_s / \Gamma_s = (6.99 \pm 0.54 \pm 0.64 \pm 1.20)\% .\]
Conclusion

- B$_s$ sector: exciting frontier to pursue BSM
- Tevatron Run II allowed dramatic breakthrough in the B$_s$ sector

Analysis of full dataset achieved!

- $B_s \rightarrow \mu \mu$ (10fb$^{-1}$)
- CPV in $B_s$ mixing ($B_s \rightarrow J/\psi \phi$) (10fb$^{-1}$)
- $B_s \rightarrow D_s^{*+}D_s^{*-}$ (6.8fb$^{-1}$)

Don't relax yet, a few more aces up our sleeve!
Pros
- Enormous cross-section
- All species of b-hadrons
  - $B_u, B_d, B_s, B_c, \Lambda_b, \Sigma_b, \ldots$

Cons
- QCD background $\times 10^3$ larger than $\sigma(b\bar{b})$
- Collision rate $\sim 2$MHz
- Tape writing limit $\sim 100$Hz
- Sophisticated triggers are very important!
- Difficulty in $\pi^0$ reconstruction
- Analogously to the neutral $B^0$ system, CP violation in $B_s$ system occurs through interference of decays with and without mixing:

\[ B^0 \rightarrow J/\Psi K_s^0 \quad B_s^0 \rightarrow J/\Psi \phi \]

\[ \Rightarrow \sin(2\beta_s) \]

\[ \Rightarrow \sin(2\beta_s') \]

$B_s$ Mass eigenstates: $B_s^L$, $B_s^H$

Mass difference $\Delta m_s = m_H - m_L \sim 2|M_{12}|$

Width difference $\Delta \Gamma_s = \Gamma_L - \Gamma_H \sim 2|\Gamma_{12}| \cos \phi_s$

CP violating phases:

\[ \phi_s = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \quad \phi_s^{SM} \sim 0.004 \]

\[ \beta_s = \beta_s^{SM} = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \sim 0.02 \]

A. Lenz and U. Nierste, JHEP 06, 072(2007)

- $\phi_s^{NP}$ contributes to both $\phi_s$ and $\beta_s$

\[ -2\beta_s = -2\beta_s^{SM} + \phi_s^{NP} \]

If $\phi_s^{NP}$ dominates: $-2\beta_s \sim \phi_s^{NP}$
Same sign dimuon asymmetry

- Same sign di-lepton asymmetry very small in SM $\sim O(10^{-4}) \rightarrow$ sensitive NP probe

$$A_{sl}^b \equiv \frac{N_{b^+} - N_{b^-}}{N_{b^+} + N_{b^-}} = C_d a_{s1}^d + C_s a_{s1}^s$$

$$a_{s1}^q = \frac{\Gamma(B^0_q(t) \rightarrow \mu^+ X) - \Gamma(B^0_q(t) \rightarrow \mu^- X)}{\Gamma(B^0_q(t) \rightarrow \mu^+ X) + \Gamma(B^0_q(t) \rightarrow \mu^- X)} = \frac{\Delta \Gamma_q}{\Delta M_q} \tan \phi_q \phi = \arg \left( - \frac{M_{12}}{\Gamma_{12}} \right)$$

$$a_{s1}^d (SM) = (-4.8^{+1.0}_{-1.2}) \times 10^{-4}$$
$$a_{s1}^s (SM) = (2.1 \pm 0.6) \times 10^{-5}$$

$$C_d = 0.594 \pm 0.022,$$
$$C_s = 0.406 \pm 0.022.$$


- SM prediction $A_{sl}^b = (-0.028^{+0.005}_{-0.006})%$

Lentz, Nierste, JHEP 0760, 072 (2007)

- Initial D0 measurement with 6 fb$^{-1}$

Abazov, PRD 82, 032001 (2010), Abazov, PRL 105, 081801 (2010)

$$A_{sl}^b = -0.00957 \pm 0.00251 \text{ (stat)} \pm 0.00146 \text{ (sys)}$$

was $3.2\sigma$ away from SM expectation
- D0 updates the analysis with 9 fb\(^{-1}\) from previous 6 fb\(^{-1}\)

- Improved muon selection:
  - 13% increase in statistics due to looser muon longitudinal momentum selection
  - 20% reduction in K and π decay in flight backgrounds

- Muon impact parameter studies support hypothesis that muons are indeed from B decays

- New result is 3.9σ away from the SM expectation:

\[ A_{sl}^b = (-0.787 \pm 0.172 \text{ (stat)} \pm 0.093 \text{ (syst)})\% \]

- Good agreement between muon impact parameter distributions in data and MC

Green histogram: Muons from hadron decays and from punch-through