$B_s$ Mixing and Lifetime Difference Measurements

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For the DØ and CDF Collaborations

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Mixing and CP Violation

- Standard model: mass ≠ weak eigenstates

\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix} =
\begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
\]

- 3 generations provides for CP violation

\[\text{Mag}(\text{CPV}) \approx f(m^2_j - m^2_i) \times f(\theta_{ij}) \times \sin\phi_{CP}\]

- Small value of CP phase expected:
  - Can’t explain \( N_b \) excess

- Mesons are ideal for studying CPV
  - Matter – antimatter bound state
  - Neutral mesons: continuously transforming between matter and antimatter states

\[ V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0 \]

\[ \phi_s = 4.2 \pm 1.4 \times 10^{-3} \]

A. Lenz, U. Nierste hep-ph/0612167
Measurements in $B_s$ System

- $\Delta M_s$
  - Thru box diagrams: sensitive to new physics
  - D0: $B_s \rightarrow D_s l \nu$  
    D0 Collab. PRL 97 021802 (2006)
  - CDF: $B_s \rightarrow D_s l \nu$; $B_s \rightarrow D_s \pi X$

- $\Delta \Gamma$
  - Tree level, not sensitive to new physics
  - Defines how see CPV
  - $B_s \rightarrow D_s D_s (D0)$; $J/\psi \phi$, KK

- $\phi_s$
  - Also loops: sensitive to new CP effects
    $\phi_s = -0.5 - 0.8$ in 4-gen models
    Hou, Nagashima, Soddu; hep-ph/0610385
  - $B_s \rightarrow J/\psi \phi$, combination (D0)
Data Samples
>2.7 fb\(^{-1}\) delivered
>2.3 fb\(^{-1}\) recorded
up to 1.3 fb\(^{-1}\) results

Production  B-Factories  Tevatron  \(\Upsilon(5S)\) (in accept)
Approx B\(_s\) Rate  1 Hz  600 Hz

\[
\text{best } \int L \, dt \text{ (1 wk)} = 44 \text{ pb}\(^{-1}\)
\]
\[
\text{best } L_{\text{initial}} = 2.6 \times 10^{32} \text{ /cm}^2 /\text{s}
\]
Track and Muon Detection

Important at the Tevatron
- Triggering
- Muons
- Tracking/Vertexing • (π/K Separation)

<table>
<thead>
<tr>
<th>Trigger</th>
<th>CDF</th>
<th>DØ</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Track</td>
<td>( P_T^{\text{trk}}&gt;2.0 \text{ GeV} )</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>( 0.12&lt;d_0&lt;1 \text{ mm} )</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>( \Sigma P_T&gt;5.5 \text{ GeV} )</td>
<td>—</td>
</tr>
<tr>
<td>/ + Displ Trk</td>
<td>( p_t&gt;4, p_t^{\text{trk}}&gt;2 \text{ GeV} )</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>( 0.12&lt;d_0&lt;1 \text{ mm} )</td>
<td>—</td>
</tr>
<tr>
<td>1-Muon</td>
<td>—</td>
<td>( P_T&gt;3,4,5 \text{ GeV} ) or ( P_T&gt;5 \text{ GeV} ) &amp; ( d_0/\sigma(d_0)&gt;3 ) (luminosity dependent)</td>
</tr>
<tr>
<td>2-Muon</td>
<td>( P_T^{\mu's}&gt;1.5 \text{ GeV} )</td>
<td>( P_T^{\mu's}&gt;2.0 \text{ GeV} )</td>
</tr>
</tbody>
</table>

Muons Coverage Shielding

|        | \(|\eta|<2.0\) | 12-18 \( \lambda_l \) |
|--------|---------------|------------------|
| DØ     | \(|\eta|<2.0\) | 12-18 \( \lambda_l \) |
| CDF    | \(|\eta|<1.0\) | >5 \( \lambda_l \) |

R. Kehoe - Bs Mixing and CPV
Measuring $\Delta m_s$

- **Channels**
  - **Semileptonic:**
    \[ \bar{B}^0_s \rightarrow D_s^{(*)} l^- \bar{\nu}_e \quad (l = e, \mu) \]
  - **Hadronic:**
    \[ \bar{B}^0_s \rightarrow D_s^{(*)} \pi^-, D_s^+ \pi^- \pi^+ \pi^-, D_s^+ \rho^- \]

- **same-side and opposite-side tagging**
  - **Opposite-side**
    - Lepton, jet, K charge $\rightarrow$ ANN
  - **Same-side**
    - Use K identification likelihood and kinematics $\rightarrow$ ANN

- **Samples**
  - Fully reconstructed hadronic: **5600**
  - Partially reconstructed hadronic: **3100**
  - Partially reconstructed semileptonic: **61500**
Amplitude Scan

- **Semileptonic channel**

- **Hadronic channel**
  - Superior decay time resolution gives excellent sensitivity at values of $\Delta M_s \sim 20 \text{ ps}^{-1}$

- **Combinatorial background**

R. Kehoe - Bs Mixing and CPV
Precision Measurement of $\Delta m_s$

CDF Run II Preliminary

$\Delta m_s = 17.77 \pm 0.10 \pm 0.07$ ps$^{-1}$

CDF Collab. PRL 97 062003 (2006)
Measurement of $\Delta \Gamma$: $B_s \to D_s^{(*)} D_s^{(*)}$

- $\Delta \Gamma = \Gamma_L - \Gamma_H = \Gamma_{CP^+} - \Gamma_{CP^-}$
  - Determine assuming SM level CPV in $B_s$ mixing: $\cos \phi_s \equiv 1$

- Consider $B_s \to D_s^{(*)} D_s^{(*)}$
  - $D_s D_s$ (PP), $D_s^* D_s$ (VP), $D_s D_s^*$ (VV)

$$2BR(B_s \to D_s^{(*)} D_s^{(*)}) \approx \left( \frac{\Delta \Gamma_{CP}^s}{\Gamma_s} \right) \left( 1 + \mathcal{O} \left( \frac{\Delta \Gamma_s}{\Gamma_s} \right) \right)$$

- Heavy quark limit + factorization
  - $B_s^{odd} \to D_s^* D_s$ forbidden

- $D_s^* D_s^*$ in S-wave
  $\Rightarrow D_s^{(*)} D_s^{(*)}$ pure CP even

- Expectations of 5% odd R. Alexan et al., PLB 316, 567 (1993)
  - Others suggest up to 30% odd

R. Kehoe - Bs Mixing and CPV 9
$B_s \rightarrow D_s^{(*)} D_s^{(*)}$\textit{ Decay}

$B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$

$D_{s1} \rightarrow \phi \pi^+; \phi_1 \rightarrow K^+ K^-$

$D_{s2} \rightarrow \phi \mu^- \nu; \phi_2 \rightarrow K^+ K^-$

\text{Normalize to } B_s \rightarrow D_s^{(*)} \mu \nu

- Look for correlated production of $D_s \rightarrow \phi \pi$ and $D_s \rightarrow \phi \mu$
- Trigger on muon from semileptonic $D_s$ decay

$N(D_s^{(*)} D_s^{(*)}) = 13.4^{+6.6}_{-6.0}$
\[ \text{BR}(B_s \rightarrow D_s^{(*)} D_s^{(*)}) \text{ AND } \Delta \Gamma_s \]

\[ R = \frac{\text{BR}(B_s \rightarrow D_s^{(*)} D_s^{(*)}) \text{BR}(D_s \rightarrow \phi \mu \nu)}{\text{BR}(B_s \rightarrow \mu \nu D_s^{(*)})} = 0.015 \pm 0.007 \text{ (stat)} \]

\[ \text{BR}(B_s \rightarrow D_s^{(*)} D_s^{(*)}) = 0.039^{+0.019}_{-0.017} \text{ (stat)}^{+0.016}_{-0.017} \text{ (sys)} \]

\[ \frac{\Delta \Gamma_{CP}}{\Gamma} = 0.079^{+0.038}_{-0.035} \text{ (stat)}^{+0.031}_{-0.030} \text{ (sys)} \]

DO Collab. hep-ex/0702049, subm. to PRL
$B_s \to J/\psi \phi$

- $b \to c \bar{c} s \to$ CP even and CP odd final states
  - Separate with time-dependent angular distributions
  - Measurement of lifetime difference
  - Large lifetime difference: can extract mixing phase

$1039 \pm 45 \, B_s$ signal candidates
Decay Angle Fit

- signal, prompt and non-prompt BG
  - Decay angles: $\theta$, $\varphi$ and $\psi$

$$L = \prod_{i=1}^{N} \left[ f_{\text{sig}}^i F_{\text{sig}}^i + (1 - f_{\text{sig}}^i) F_{\text{bg}}^i \right]$$
**Fit Results**

- $B_s \rightarrow J/\psi \phi$
- $5.26 < M(B_s) < 5.46 \text{ GeV}$
- $ct/\sigma(ct) > 5$

![Graphs showing fit results with data points, total fit, total signal, background, and fit probability of 95.9%](image)

R. Kehoe - Bs Mi
**Direct Measurement of $\phi_s$**

\[ \Delta \Gamma_s = 0.17 \pm 0.09 \pm 0.02 \text{ps}^{-1} \]

\[ \phi_s = -0.79 \pm 0.56^{+0.14}_{-0.01} \]

*D0 Collab. hep-ex/0701012 submitted to PRL*

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Tying It All Together

• Several additional measurements provide information to further constrain the CP phase

• Flavor-specific lifetime of $B_s$ mesons

$$\tau_{f_s} = 1/\Gamma_{f_s} = 1.440 \pm 0.036 \text{ ps (world avg.)}$$

  - Which includes D0 meas.

$$\tau_{f_s} = 1.398 \pm 0.044 \text{ (stat)} ^{+0.028}_{-0.025} \text{ (sys) ps}$$

D0 Collab. PRL 97, 241801 (2006)

• Semileptonic charge asymmetry

  - induced by B mixing

  - same-sign dimuon charge asymmetry

$$A_{SL}^d + \frac{f_sZ_s}{f_dZ_d} A_{SL}^s = -0.0092 \pm 0.0044 \text{ (stat) } \pm 0.0032 \text{ (sys)}$$

D0 Collab. PRD 94, 092001 (2006)

- Using B-factory value of $A_{SL}^d$, get

$$A_{SL}^s = -0.0064 \pm 0.0101$$
Combination Analysis

• Direct asymmetry measurement: $B_s \rightarrow \mu \nu D_s, D_s \rightarrow \phi \pi$

$$A_{SL}^s = +0.0245 \pm 0.0193 \text{(stat)} \pm 0.0035 \text{(sys)}$$

CDF Collab., subm. To PRL, hep-ex/0701007

- nearly independent of dimuon-based measurement

$$A_{SL}^s = 0.0001 \pm 0.0090$$

• Use CDF $\Delta M_s = 17.8 \pm 0.1 \text{ ps}^{-1}$

$$\Delta \Gamma_s \tan \phi_s = A_{SL}^s \Delta M_s = 0.02 \pm 0.16 \text{ ps}^{-1}$$

• Refit $B_s \rightarrow J/\psi \phi$ data using $\Delta \Gamma_s \tan \phi_s$ and $\tau_{fs}$ as constraints

$\phi_s < 0$, $\cos \delta_1 > 0$, $\cos \delta_2 < 0$ choice

$$\Delta \Gamma_s = 0.13 \pm 0.09 \text{ ps}^{-1}$$

$$\phi_s = -0.70^{+0.47}_{-0.39}$$

SM Pred

$$\Delta \Gamma_s \quad 0.088 \pm 0.017 \text{ ps}^{-1}$$

$$\phi_s \quad (4.2 \pm 1.4) \times 10^{-3}$$
Results from Combination

ΔΓ_s \tan \phi_s = A_s^{SL} \Delta m_s

ΔΓ = ΔΓ_s^{SM} \times |\cos(\phi_s)|
Final Notes

- $B_s$ physics at Tevatron has been quite productive
  - New measurements of several key parameters:
    \[
    \Delta M_s = 17.77 \pm 0.10\text{(stat)} \pm 0.07\text{(sys)} \text{ps}^{-1} \\
    \left| V_{td} / V_{ts} \right| = 0.2060 \pm 0.007\text{(exp)}^{+0.0081}_{-0.0060}\text{(theo)} \\
    \Delta \Gamma_s = 0.13 \pm 0.09 \text{ps}^{-1} \\
    \phi_s = -0.70^{+0.47}_{-0.39} \\
    \]

- Tevatron prognosis:
  - Since April ‘06 upgrade, rate of lum. recorded 1.2 fb\(^{-1}\)/yr and growing
  - Records continually being set
  - Expect several fb\(^{-1}\) by the end of the run

- $B_s$ physics prospects
  - Do not see evidence for new physics
  - Many new measurements to be updated by both experiments
    - E.g. $\Delta \Gamma$ from CDF, all-hadronic $\Delta M_s$ from D0
    - Continued effort to constrain $\phi_s$ is ongoing
Backup Slides
The detector consists of:
- 48 modules mounted on carbon fiber support structure at 1.7 cm radius
  - 6 l-segments, 8 z-segments
- Four sensor types provide 98.4% of acceptance
  - Sensors 12 and 7 cm lengths