Measurements of the Masses, Mixing, and Lifetimes, of B Hadrons at the Tevatron

Mike Strauss

The University of Oklahoma
The Oklahoma Center for High Energy Physics
for the CDF and DØ Collaborations
Outline

- $B$ Physics at the Tevatron
- $B$ Resonances
- $B^0$ oscillations
- $B$ Lifetimes
  - Exclusive Decays
  - Lifetime Ratios and Differences
• ~0.5 fb\(^{-1}\) delivered this year
• Detectors collect data at typically 85% efficiency
• These analyses use 150–350 pb\(^{-1}\)
• About 150 pb\(^{-1}\) of data has been recorded and is currently being analyzed
Why \( B \) Physics?

- Understanding the structure of flavour dynamics is crucial
  - 3 families, handedness, mixing angles, masses, …
  - any unified theory will have to account for it
- Weak decays, especially mixing, CP violating and rare decays, provide insight into short-distance physics
- Short distance phenomena are sensitive to beyond-SM effects
- CKM matrix determines the charged weak decays of quarks,
  - tree level diagrams, one-loop transitions…
- Lifetime measurements probe QCD at large distances and give information on form factors and quark models
Large production cross sections
All $B$ Hadrons produced (Best $B_s$ and $\Lambda_b$)
Larger inelastic cross section ($S/B \approx 10^{-3}$)
Specialized Triggers:
- Single lepton triggers
- Dilepton triggers (e.g. $J/\psi \rightarrow \mu^+\mu^-$)
- L1 Track triggers
- L2 displaced track trigger for CDF

$\sigma(p\bar{p} \rightarrow b\bar{b}) \approx 150 \mu b$ at 2 TeV
$\sigma(e^+e^- \rightarrow b\bar{b}) \approx 7$ nb at $Z^0$
$\sigma(e^+e^- \rightarrow b\bar{b}) \approx 1$ nb at $\Upsilon(4S)$
Detectors

Silicon vertex tracker, Axial solenoid, Central tracking, High rate trigger/DAQ, Calorimeter, Muon system

CDF

DØ

L2 trigger on displaced vertexes
Low $p$ particle ID (TOF and dE/dx)
Excellent mass resolution

Excellent muon ID; $|\eta| < 2$
Excellent calorimetry
Tracking acceptance $|\eta| < 2-3$
L3 trigger on impact parameter
DØ Tracker

\[ \eta = - \ln (\tan(\theta/2)) \]

SMT + CFT
\[ \eta_{\text{max}} = 1.65 \]

SMT region
\[ \eta_{\text{max}} = 2.5 \]
Silicon Microstrip Tracker (SMT)

12 F-disks
6 Barrels
4 H-disks

Multi-layer barrel cross-section

<table>
<thead>
<tr>
<th></th>
<th>Barrels</th>
<th>F-disks</th>
<th>H-disks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stereo angle</td>
<td>0°, 2°, 90°</td>
<td>±15°</td>
<td>±7.5°</td>
</tr>
<tr>
<td>Channels</td>
<td>~400K</td>
<td>~250K</td>
<td>~150K</td>
</tr>
<tr>
<td>Inner radius</td>
<td>2.7 cm</td>
<td>2.6 cm</td>
<td>9.5 cm</td>
</tr>
<tr>
<td>Outer radius</td>
<td>9.4 cm</td>
<td>10.5 cm</td>
<td>26 cm</td>
</tr>
</tbody>
</table>

3m² of silicon
Tracking Performance

Muon $\eta$ in $J/\psi$ events

Coverage of Muon system is matched by L3/offline tracking

$p_T$ spectrum of soft pion candidate in $D^* \rightarrow D^0 \pi$

Tracks are reconstructed starting from $p_T = 180$ MeV
SMT Resolution and $dE/dx$

Impact Parameter Resolution

$\sigma(DCA) \approx 53 \, \mu m \, @ \, P_T = 1 \, GeV$
and $\approx 15 \, \mu m \, @ \, higher \, P_T$

Can provide:
$K/\pi$ separation for $P_{tot} < 400 \, MeV$
$p/\pi$ separation for $P_{tot} < 700 \, MeV$

NOT yet used for PID
Belle’s Discovery of $X(3872)$

$X \rightarrow J/\psi \pi^+ \pi^-$

- No signal in $\gamma X_{c1}$ decay
- Mass doesn’t fit easily into charm spectroscopy models
- Near $D^0 D^{*0}$ threshold
- Charmonium? A loosely bound meson state?

$$M_X = 3872.0 \pm 0.6 \text{ (stat)} \pm 0.5 \text{ (sys)}$$
CDF and DØ have confirmed Belle’s discovery of the $X(3872)$

$M_X = 3871.3 \pm 0.7 \text{ (stat)} \pm 0.4 \text{ (sys) MeV/c}^2$

$\Delta M = 774.9 \pm 3.1 \text{ (stat)} \pm 3.0 \text{ (sys) MeV/c}^2$

$\Delta M + M(J/\psi) = 3871.8 \pm 4.3 \text{ MeV/c}^2$
Long Lifetime fraction of $X(3872)$

Is the $X$ charmonium, or something else?

$\psi(2S)$:

$X(3872)$:

$\psi(2S)$: $28.3 \pm 1.0\text{(stat)} \pm 0.7\text{(syst)}\%$

$X(3872)$: $16.1 \pm 4.9\text{(stat)} \pm 2.0\text{(syst)}\%$
**X(3872) – ψ(2S) comparison**

Is the $X$ charmonium, or something else?

**DØ multi-parameter comparison**
First Observation of $B_S \rightarrow \phi \phi$

- Charmless $B \rightarrow VV$ decay not yet observed
- Dominated by penguin contributions
- Cuts optimized on $B_S \rightarrow J/\psi \phi$
  - BR error on this decay is dominant systematic uncertainty

$$\text{BR}(B_S \rightarrow \phi \phi) = 1.4 \pm 0.6(\text{stat}) \pm 0.2(\text{syst}) \pm 0.5(\text{BR}) \times 10^{-5}$$
$B \rightarrow h^\pm h\bar{O}^+$ Fractions

- $h, h' = \pi, K$
- Motivation is to construct many charmless two body decays for CP studies
- Hadronic $B$ trigger using SVT
- $dE/dx$ and $\alpha$ used for PID
- Signal reconstructed with vertex constrained fit
- Fractions measured with unbinned likelihood fit using $M_{\pi\pi}$, $\alpha$, ID1, ID2.

CDF Run 2 Preliminary, $L = 180$ pb$^{-1}$
PID using $\alpha = (1-p_1/p_2)q_1$
$B \rightarrow h^\pm h\bar{O}^+$ Fractions
\[ B \rightarrow h^\pm h\bar{O}^+ \text{ Fractions} \]

\[ \frac{BR(B_d \rightarrow \pi^+\pi^\mp)}{BR(B_d \rightarrow K^\pm\pi^\mp)} = 0.24 \pm 0.06 \text{ (stat)} \pm 0.05 \text{ (syst)} \]

\[ A_{CP} = \frac{N(\overline{B}_d^0 \rightarrow K^-\pi^+) - N(B_d^0 \rightarrow K^+\pi^-)}{N(\overline{B}_d^0 \rightarrow K^-\pi^+) + N(B_d^0 \rightarrow K^+\pi^-)} = -0.04 \pm 0.08 \pm 0.01 \]

Assuming \( B_s \rightarrow K^+K^- \) is 100\% CP even, \( \Delta\Gamma_s/\Gamma_s = 0.12 \pm 0.06 \), \( \Gamma_s = \Gamma_d \),

\[ \frac{f_d \cdot BR(B_d \rightarrow \pi^\pm\pi^\mp)}{f_s \cdot BR(B_s \rightarrow K^\pm K^\mp)} = 0.48 \pm 0.12 \text{ (stat)} \pm 0.07 \text{ (syst)} \]

\[ \frac{f_d \cdot BR(B_s \rightarrow K^\pm K^\mp)}{f_d \cdot BR(B_d \rightarrow K^\pm\pi^\mp)} = 0.50 \pm 0.08 \text{ (stat)} \pm 0.07 \text{ (syst)} \]
Search for $B^0_{(s,d)} \rightarrow \mu^+ \mu^-$

SM BR($B^0_s \rightarrow \mu^+ \mu^-$) ≈ $(3.4 \pm 0.5) \times 10^{-9}$; BR($B^0_d \rightarrow \mu^+ \mu^-$) ≈ $(1.5 \pm 0.9) \times 10^{-10}$

Expected BG: $1.05 \pm 0.30$

BR($B^0_s \rightarrow \mu^+ \mu^-$): < $7.5 \times 10^{-7}$ at 95% CL (CDF)

Expected BG: $3.7 \pm 1.1$ events

BR($B^0_s \rightarrow \mu^+ \mu^-$): < $4.2 \times 10^{-7}$ at 95% CL (DØ)

BR($B^0_d \rightarrow \mu^+ \mu^-$): < $1.9 \times 10^{-7}$ at 95% CL
Observation of $B^{**}$

- $B$ Spectroscopy:
  - $B$ ($J^p = 0^-$)
  - $B^*$ ($J^p = 1^-$) – decays to $B\gamma$ (100%)
    - $\Delta M = M(B^*) - M(B) = 46$ MeV/c$^2$
  - The $B^{**}$ consists of four separate states
    - 2 narrow states $B_1$ ($1^+$) and $B_2^*$ ($2^+$), decay via D-wave;
    - 2 wide states $B_0^*$ ($0^+$) and $B_1$' ($1^+$), decay via S-wave;
    - None of these individual states are well established
  - Decay channels used:
    - $B_{d}^{**} \rightarrow B^{\pm} \pi^\mp$; $B^{*+} \rightarrow B_d \pi^+$; $B^{**} \rightarrow B^* \pi \rightarrow B \pi (\gamma)$
    - $B^\pm \rightarrow J/\psi K^\pm$; $B_d \rightarrow J/\psi K^{*0}$; $B_d \rightarrow J/\psi K^0_s$
Distinct Narrow $B^{**}$ States

• The first direct measurement of masses and splitting between $B_2^*$ and $B_1$
• $M(B^*) = M(B) + 46$ MeV ($\gamma$)

$M(B_1) = 5724 \pm 4 \pm 7$ MeV/$c^2$

$M(B_2^*) - M(B_1) = 23.6 \pm 7.7 \pm 3.9$ MeV/$c^2$
Observation of $B_c \rightarrow J/\psi \mu X$

Combined unbinned likelihood fit made to mass and lifetime

$M(B_c) = 5.95^{+0.14}_{-0.13} \pm 0.34 \text{ GeV/c}^2$

$\tau(B_c) = 0.448^{+0.123}_{-0.096} \pm 0.121 \text{ ps}$

First 5$\sigma$ measurement
\[ B_s \rightarrow D_s^- \pi^+ \]
Fully Reconstructed $B_s$

CDF Run II Preliminary, $L = 119 \text{ pb}^{-1}$

$N(B_s^0) = 84 \pm 11$

Useful for $B_s$ Mixing

CDF “golden channels”:

$B_s \rightarrow D_s \pi$

$D_s \rightarrow \phi \pi, K^*K, \pi\pi\pi$

$B_s \rightarrow D_s \pi \pi \pi$
**$B_d$ Mixing**

- In SM $B_d$ mixing is explained by box diagrams
  - Constrains $V_{td}$ CKM matrix element
  - Mixing frequency $\Delta m_d$ has been measured with high precision at $e^+e^- B$ factories ($0.502 \pm 0.007$ ps$^{-1}$)
- $\Delta m_d$ measurement at Hadron Colliders
  - Confirms initial state flavor tagging for later use in $B_s$ and $\Delta m_s$ measurements
**B Oscillation Variables**

**Opposite side**

$b^{-1/3} \rightarrow Q<0$

$b \rightarrow K^-$

(CDF)

$b \rightarrow \ell^-$

**Same side**

$b \rightarrow \bar{B}^0 \rightarrow \pi^-$

$b \rightarrow B^- \rightarrow \pi^+$

$B_s \rightarrow K^+$

(CDF)
Final State Ambiguities in SS Tag
$B^0$ Mixing with SS Tag

\[ A = \frac{N_{RS} - N_{WS}}{N_{RS} + N_{WS}} \]

\[ N_{RS}:N(B^0 \pi^+) \]

\[ N_{WS}:N(B^0 \pi^-) \]

$\Delta m_d = 0.443 \pm 0.052\text{(stat)} \pm 0.030\text{(sc)} \pm 0.012\text{(syst)} \text{ ps}^{-1}$
$B^0$ Mixing with SS Tag

$B \to \mu D^* X$, $D^* \to D^0 \pi$

Visible Proper Decay Length:

$$x^M = L_{xy} M_B c / p_T^{\mu D}$$

Tagging purity: $55.8 \pm 0.7 \pm 0.8\%$

Preliminary

$$\Delta m_d = 0.488 \pm 0.066(\text{stat}) \pm 0.044(\text{syst}) \text{ ps}^{-1}$$
**B⁰ Mixing with OS μ Tag**

Decay Mode:
- $B \rightarrow \mu D^* X$, $D^* \rightarrow D^0 \pi$

Tagging:
- $\muon p_T > 2.5$ GeV/c
- $\cos \Delta \phi(\mu, B) < 0.5$
- Tagging efficiency: $4.8 \pm 0.2 \%$
- Tagging purity: $73.0 \pm 2.1 \%$

Fit procedure:
- Binned $\chi^2$ fit

Preliminary

$$\Delta m_d = 0.506 \pm 0.055(\text{stat}) \pm 0.049(\text{syst}) \text{ ps}^{-1}$$
$B^0$ Mixing with Combined Tag

- Uses $B \rightarrow l D(*)$
- Lepton plus SVT trigger
- Combines:
  - Same Side Pion Tagging
  - Opposite Side Muon Tagging
  - Opposite Side Jet Charge Tagging
    - With and without vertex tagging
- Ten subsamples
  - Tagged with SST
  - Tagged with OST (3 samples)
  - Tagged with SST and OST that agree (3 samples)
  - Tagged with SST and OST that don’t agree (3 samples)
- Tagging priority is determined
# Efficiency and Dilution

<table>
<thead>
<tr>
<th>Channel</th>
<th>ε(%)</th>
<th>D(%)</th>
<th>εD^2(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only SST</td>
<td>25.89 ± 0.17</td>
<td>12.45 ± 1.46</td>
<td>0.401 ± 0.028</td>
</tr>
<tr>
<td>Only SMT</td>
<td>1.17 ± 0.04</td>
<td>29.13 ± 2.26</td>
<td>0.099 ± 0.016</td>
</tr>
<tr>
<td>SST and SMT (agree)</td>
<td>1.34 ± 0.04</td>
<td>40.12 ± 2.42</td>
<td>0.216 ± 0.027</td>
</tr>
<tr>
<td>SST and SMT (disagree)</td>
<td>1.22 ± 0.04</td>
<td>17.31 ± 2.79</td>
<td>0.037 ± 0.012</td>
</tr>
<tr>
<td>Only JQT-SecVtx</td>
<td>2.73 ± 0.06</td>
<td>20.11 ± 1.57</td>
<td>0.110 ± 0.017</td>
</tr>
<tr>
<td>SST and JQT-SecVtx (agree)</td>
<td>3.38 ± 0.07</td>
<td>31.76 ± 1.99</td>
<td>0.341 ± 0.043</td>
</tr>
<tr>
<td>SST and JQT-SecVtx (disagree)</td>
<td>3.19 ± 0.07</td>
<td>7.86 ± 2.19</td>
<td>0.020 ± 0.010</td>
</tr>
<tr>
<td>Only JQT-High P_t</td>
<td>16.13 ± 0.14</td>
<td>4.85 ± 0.65</td>
<td>0.038 ± 0.010</td>
</tr>
<tr>
<td>SST and JQT-High P_t (agree)</td>
<td>15.70 ± 0.14</td>
<td>17.20 ± 1.57</td>
<td>0.464 ± 0.084</td>
</tr>
<tr>
<td>SST and JQT-High P_t (disagree)</td>
<td>16.08 ± 0.14</td>
<td>7.65 ± 1.61</td>
<td>0.094 ± 0.040</td>
</tr>
<tr>
<td>Total</td>
<td>86.86 ± 0.33</td>
<td></td>
<td>1.820 ± 0.114</td>
</tr>
</tbody>
</table>

Preliminary

\[
\Delta m_d = 0.536 \pm 0.037\text{(stat)} \pm 0.009\text{ (sc)} \pm 0.015\text{(syst)} \text{ ps}^{-1}
\]
**$B^0$ Mixing with Combined Tag**

$B^0 \rightarrow D^{*\pm} \mu^\mp X$

$B \rightarrow \overline{D}^0 \mu^+ X$

\[ K\pi\pi \text{ mass - } K\pi \text{ mass} \]

Dominated by $B^+$ events
**B^0 Mixing with Combined Tag**

- Soft muon tag
- If not tagged by muon:
  - Opposite side jet charge
  - Soft Pion

\[ D^0 \mu \text{“asymmetry”} \]

Preliminary

\[ \Delta m_d = 0.456 \pm 0.034\text{(stat)} \pm 0.025\text{(syst)} \text{ ps}^{-1} \]
B Hadron Lifetimes

- Naive quark spectator model: a $1 \rightarrow 3$ decay process common to all $B$ hadrons.
- (NLO) QCD $\rightarrow$ Heavy Quark Expansion predicts deviations in rough agreement with data.
- Experimental and theoretical uncertainties are comparable.
- Lifetime differences probe the HQE to 3rd order in $\Lambda_{QCD}/m_b$.
- Goal: measure the ratios accurately.
**B Hadron Lifetime Ratios**

- $\tau(B^-)/\tau(B^0)$: $1.085 - 0.017$
- $\tau(B_s)/\tau(B^0)$: $0.951 - 0.038$
- $\tau(\Lambda_b)/\tau(B^0)$: $0.798 - 0.052$
- $\tau(b\text{ baryon})/\tau(B^0)$: $0.786 - 0.034$

From PDG 2003
\( \Lambda_b \) Lifetime

New Measurement from DØ
\[ \Lambda_b \rightarrow J/\psi \Lambda^0 \]

\[ \tau(\Lambda_b) = 1.221^{+0.217}_{-0.179} \pm 0.043 \text{ ps} \]

\[ \frac{\tau(\Lambda_b)}{\tau(B^0_d)} = 0.874^{+0.169}_{-0.142} \pm 0.028 \]

CDF Preliminary from 2003:

\[ \tau(\Lambda_b) = 1.25 \pm 0.26 \pm 0.10 \text{ ps} \]
$B_s$ Lifetime using $B_s \to J/\psi \phi$

**CDF**

CDF Run II Preliminary

$B_s \to J/\psi \phi$

- 256 ± 19 sig. candidates
- Fit prob: 89.6%

**DØ**

Preliminary

$B_s \to J/\psi \phi$

- Events: $337 \pm 25$

**Improvements since 2003:**
- Selection minimizes $\text{stat} \oplus \text{syst}$
- 12 parameter maximum likelihood fit
- 240 pb$^{-1}$

**DØ analysis is similar to this CDF “improved” analysis**
$B_s$ Lifetime using $B_s \rightarrow J/\psi \phi$

CDF

CDF Run II Preliminary

$B_s \rightarrow J/\psi \phi$

- data
- $ct(Sig)$
- $ct(Bkg_{all})$
- $ct(Bkg_{s})$

Fit prob: 26.9%

Preliminary

$\tau(B_s) = 1.369 \pm 0.100^{+0.008}_{-0.010} \text{ ps}$

DØ

250 pb$^{-1}$

$\tau(B_s) = 1.444^{+0.098}_{-0.090} \pm 0.020 \text{ ps}$

Uses one exponential decay in the fit
$B_d$ Lifetimes Using $B_d \rightarrow J/\psi K_s^*$

CDF

DØ

$\tau(B^0) = 1.539 \pm 0.051 \pm 0.008$ ps

$\tau(B_d^0) = 1.473^{+0.052}_{-0.050} \pm 0.023$ ps

$\tau(B_s)/\tau(B^0) = 0.890 \pm 0.072$

$\tau(B_s)/\tau(B^0) = 0.980^{+0.075}_{-0.070} \pm 0.003$
$B^+ \text{ Lifetime Using } B \rightarrow J/\psi K^+$

$\tau(B^+) = 1.662 \pm 0.033 \pm 0.008 \text{ ps}$

$\tau(B^+)/\tau(B^0) = 1.080 \pm 0.042$

Most systematic uncertainties cancel in the ratio
Lifetime Ratio $\tau(B^+)/\tau(B^0)$

Novel Analysis Technique using $B \to \mu D^{c(*)}X$

- Directly measure ratio instead of individual lifetimes
- Split $D^0 \to K\pi$ sample:
  - $D^{*+}$ (with slow $\pi^+$) $\leftarrow$ mainly from $B^0$
  - $D^0$ $\leftarrow$ mainly from $B^+$

![Diagram showing $B$ decays]

- $12\%$ $B^+$
- $2\%$ $B_S$
- $86\%$ $B^0$
- $16\%$ $B^0$
- $2\%$ $B_S$
- $82\%$ $B^+$
$D^0$ and $D^{*+}$ Candidates

109k inclusive $B \rightarrow \mu^- \nu \ D^0$ candidates
25k $B \rightarrow \mu^- \nu \ D^*$ candidates

DØ RunII Preliminary, Luminosity=250 $pb^{-1}$

Dominated by $B^+$ decays

Dominated by $B^0$ decays
Lifetime Ratio $\tau(B^+)/\tau(B^0)$

- Measure $N(\mu D^{*+})/N(\mu D^0)$ in bins of VPDL
- In both cases fit $D^0$ signal to extract $N$
- Use slow pion only to distinguish $B^0$ from $B^+$ (not in vertexing, K-factors etc., to avoid lifetime bias)

$\tau(B^+)/\tau(B^0) = 1.093 \pm 0.021$(stat) $\pm 0.022$(syst)
Lifetime Ratio $\frac{\tau(B^+)}{\tau(B^0)}$

- ALEPH $D^{(93)}$ (91-95)
- ALEPH exclusive (91-94)
- CDF J/$\psi$ K (92-95)
- CDF D (92-95)
- DELPHI $D^{(93)}$ (91-93)
- DELPHI topology (91-93)
- DELPHI topology (94 Prel.)
- L3 Topology (94-95)
- OPAL topology (93-95)
- OPAL $D^{(93)}$ (91-93)
- SLD vert. $+1$ (93-96)
- SLD topology (93-98 Prel.)
- BELLE exclusive (99-01)
- BABAR exclusive (99-01)
- $D^0$ D $+1$ (03-04 Prel.)

World average

$\tau(B^+) / \tau(B^0)$

- 1.085$\pm$0.059$\pm$0.018
- 1.27$^{+0.23}_{-0.19}$ $\pm$0.02
- 1.06$^{+0.07}_{-0.06}$ $\pm$0.02
- 1.110$^{+0.033}_{-0.030}$
- 1.00$^{+0.17}_{-0.15}$ $\pm$0.10
- 1.06$^{+0.13}_{-0.11}$ $\pm$0.10
- 1.065$\pm$0.022 $\pm$0.033
- 1.09$^{+0.07}_{-0.06}$ $\pm$0.03
- 1.079$\pm$0.064 $\pm$0.041
- 0.99$^{+0.14}_{-0.04}$ $\pm$0.05
- 1.03$^{+0.16}_{-0.14}$ $\pm$0.09
- 1.037$^{+0.025}_{-0.024}$ $\pm$0.024
- 1.09$\pm$0.023 $\pm$0.014
- 1.08$\pm$0.026 $\pm$0.012

- $1.093\pm0.021\pm0.022$ (New)
- $1.073\pm0.014$
B Decay Angular Amplitudes

- Uses $B_s \rightarrow J/\psi \phi$; Uses $B_d \rightarrow J/\psi K^{*0}$
- Allows measurement of many parameters including polarization amplitudes and $\Delta \Gamma_s = 1/\tau_L - 1/\tau_H$

\[
\begin{align*}
|B_s^H\rangle &= p|B_s\rangle + q|\overline{B}_s\rangle = \frac{1}{\sqrt{2}}\left(|B_s\rangle + |\overline{B}_s\rangle\right) \quad \text{CP odd} \\
|B_s^L\rangle &= p|B_s\rangle - q|\overline{B}_s\rangle = \frac{1}{\sqrt{2}}\left(|B_s\rangle - |\overline{B}_s\rangle\right) \quad \text{CP even}
\end{align*}
\]

Initial particle or antiparticle

\[
\begin{align*}
|B_s\rangle &= \frac{1}{\sqrt{2}}\left(|B_s^H\rangle + |B_s^L\rangle\right) \\
|\overline{B}_s\rangle &= \frac{1}{\sqrt{2}}\left(|B_s^H\rangle - |B_s^L\rangle\right)
\end{align*}
\]
Decay Modes

\[ B_S \rightarrow J/\psi \phi \]

Compare the two similar topologies

\[ B_d \rightarrow J/\psi K^* \]
Transversity Angles

- The $J/\psi$ rest frame
- $KK$ defines $(x,y)$ plane
  - $K^+(K)$ defines $+y$ direction
- $\Theta$, $\Phi$: polar & azimuthal angles of $\mu^+$
- $\Psi$: helicity angle of $\phi(K^*)$

Extract polarization amplitudes:
- $A_0$: Longitudinal
- $A_\parallel$, $A_\perp$: Transverse
Angular Projections and fit for $B_s$

\[
\frac{d^4 P}{d\vec{\rho} \, dt} = \sum_{i=1}^{6} A_i \cdot g_i(t) \cdot f_i(\vec{\rho})
\]

\[
\vec{\rho} = (\Theta, \Phi, \Psi)
\]
Decay Angular Distributions

\[ \frac{d^4 \mathcal{P}}{d \hat{\rho} \, dt} \propto |A_0|^2 \cdot g_1(t) \cdot f_1(\hat{\rho}) + |A_\parallel|^2 \cdot g_2(t) \cdot f_2(\hat{\rho}) + |A_\perp|^2 \cdot g_3(t) \cdot f_3(\hat{\rho}) \pm \text{Im}(A_0^* A_\perp) \cdot g_4(t) \cdot f_4(\hat{\rho}) \pm \text{Re}(A_0^* A_\parallel) \cdot g_5(t) \cdot f_5(\hat{\rho}) \pm \text{Im}(A_0^* A_\perp) \cdot g_6(t) \cdot f_6(\hat{\rho}) \equiv \sum_{i=1}^{6} A_i \cdot g_i(t) \cdot f_i(\hat{\rho}) \]

\[ f_1(\hat{\rho}) = 2 \cos^2 \theta \psi (1 - \sin^2 \theta \cos^2 \phi) \]
\[ f_2(\hat{\rho}) = \sin^2 \theta \psi (1 - \sin^2 \theta \sin^2 \phi) \]
\[ f_3(\hat{\rho}) = \sin^2 \psi \sin^2 \theta \]
\[ f_4(\hat{\rho}) = -\sin^2 \psi \sin 2\theta \sin \phi \]
\[ f_5(\hat{\rho}) = \frac{1}{\sqrt{2}} \sin 2\psi \sin^2 \theta \sin 2\phi \]
\[ f_6(\hat{\rho}) = \frac{1}{\sqrt{2}} \sin 2\psi \sin 2\theta \cos \phi \]

\[ g_i(t) \text{ different for } B_d \text{ and } B_s \text{ and are rather non-trivial} \]

\[ A_0 = \text{longitudinal pol. amplitude} \]
\[ A_\parallel, A_\perp = \text{transverse pol. amplitudes} \]

$B_d$ Amplitudes vs BaBar/Belle

CDF Run II Preliminary

$B_d \rightarrow J/\psi K^{*0}$

L~260 pb$^{-1}$

$1\sigma$ contour

Real Axis

Imaginary Axis

CDF Run II

Babar

Belle

$A_\parallel$

$A_\perp$

$A_0$
$B_s$ and $B_d$ Amplitudes

For $B_d^0$

$A_0 = 0.750 \pm 0.017 \pm 0.012$

$A_\parallel = (0.473 \pm 0.034 \pm 0.006) \times e^{i(2.86 \pm 0.22 \pm 0.04)}$

$|A_\perp| = (0.482 \pm 0.104 \pm 0.014) \times e^{i(0.15 \pm 0.15 \pm 0.04)}$

For $B_s^0$

$A_0 = 0.784 \pm 0.039 \pm 0.007$

$A_\parallel = (0.510 \pm 0.082 \pm 0.013) \times e^{i(1.94 \pm 0.36 \pm 0.03)}$

$|A_\perp| = 0.354 \pm 0.098 \pm 0.003$

DØ results coming soon
**$B_s$ Mass and Lifetime Projections**

Unconstrained fit

\[ \tau_L = 1.05^{+0.16}_{-0.13} \pm 0.02 \text{ ps} \]
\[ \tau_H = 2.07^{+0.58}_{-0.46} \pm 0.03 \text{ ps} \]
\[ \Delta \Gamma = 0.47^{+0.19}_{-0.24} \pm 0.01 \text{ ps}^{-1} \]

Using SM and constrained fit:

\[ \Delta \Gamma / \Gamma = 0.65^{+0.25}_{-0.33} \pm 0.01 \]

\[ \Delta m_s = 125^{+65}_{-55} \text{ ps}^{-1} \]
Conclusions

• The Tevatron is working great, producing many $B$ hadrons.
• We now have about 500 pb$^{-1}$
• DØ and CDF are measuring many properties of $B$ hadrons that nicely complement those measured at “$B$ factories”
• More exciting results are expected in the future
CDF Sensitivity Estimate

\[ \text{SM BR}(B_s^0 \to \mu^+ \mu^-) \approx (3.4 \pm 0.5) \times 10^{-9}; \]

![Graph showing expected limit BR(B_s \to \mu^+ \mu^-) vs. RunII Integrated Luminosity (pb^{-1}) with CDFII Preliminary 90\% CL Upper Limits and best published limit (CDF). The graph includes extrapolations based on 110 pb^{-1} using |\eta(\mu)| < 0.6, P_{t(B_s)} > 6 \text{ GeV}/c. A star indicates this result with 171 pb^{-1}.]
\[ \Delta m_d = \frac{G_F^2}{6\pi^2} m_B f_{B_d}^2 B_{B_d} \eta_B m_t^2 F\left(\frac{m_t^2}{M_W^2}\right) |V_{td}^* V_{tb}|^2 = 0.502 \pm 0.006 \text{ ps}^{-1} \]

- Determines an annulus centered at (1,0), but large errors
  \[ f_{B_d} \sqrt{B_{B_d}} = 228 \pm 32 \text{ MeV} \]

- B decay constant and Bag parameter are almost common to B_s
  \[ \Rightarrow \text{ Good to measure ratio} \]

\[ \frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d}}{m_{B_s}} \frac{f_{B_d}^2 B_{B_d}}{f_{B_s}^2 B_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2} \]

\[ \frac{f_{B_d}^2 B_{B_d}}{f_{B_s}^2 B_{B_s}} = 1.21 \pm 0.06 \]

\[ \Delta \Gamma_s \text{ also suffers from needing } f_{B_s} \text{ and } B_{B_s} \]
and depends upon \[ V_{cb}, \text{ so } \frac{\Delta m_d}{\Delta \Gamma_s} \text{ good too} \]

From Colin Gay, FNAL Wine and Cheese, July 16, 2004