Precision $B$ Lifetimes and $B$ Mixing in CDF

- **Precision $B$ Lifetimes**
  - $B^+ \to J/\psi K^+$
  - $B_d \to J/\psi K^*$
  - $B_s \to J/\psi \phi$
  - $\Lambda_B \to J/\psi \Lambda$

- **Measurement of Polarization Amplitudes**
  - $B_d \to J/\psi K^*$
  - $B_s \to J/\psi \phi$

- **$B$ Mixing**
  - $B$ Flavor Tagging using Opposite Side $SMT$ and $JQT$
  - $\Delta m_d$ using $SST$ in Fully Reconstructed $B$ Decays
  - $\Delta m_d$ using $SST$ in Semileptonic $B$ Decays
  - $\Delta m_s$ Measurement Prospects

Jónatan Piedra, June 28 2004
6th International Conference on Hyperons, Charm and Beauty Hadrons
Tevatron & CDF

- 980 + 980 GeV pp collisions
- Record peak luminosity $9 \times 10^{31}$ sec$^{-1}$ cm$^{-2}$
- ~450 pb$^{-1}$ on tape (Run I $\approx$ 100 pb$^{-1}$)
- Interaction region
  - 30 cm $z \Rightarrow$ need a long Si detector
  - 30 µm xy $\ll c\tau(B) \sim 450$ µm

- Improved Silicon coverage
  - $|\eta| < 2$
- Central Drift Chamber (COT)
  - 96 layers
- Time of Flight
- Expanded muon coverage
- Trigger on displaced tracks at L2
Acquired luminosity in 2004 already surpassed 2003 total

But with high luminosity
- Less trigger bandwidth for B Physics
- Overlapping events degrade performance

Record peak luminosity
$9.23 \times 10^{31} \text{ sec}^{-1} \text{ cm}^{-2}$

June 22, 2004
Huge production rates
- $\sigma(p\bar{p} \to bX, |y| < 0.6) = 17.6 \pm 0.4$ (stat.) $\pm 2.5$ (syst.) $\mu$b

3 orders of magnitude higher than at $e^+e^- \to \Upsilon(4S)$

Heavy states produced
- $B^0, B^+, B_s, B_c, \Lambda_b, \Xi_b$

Backgrounds are also 3 orders of magnitude higher
- Inelastic cross section $\sim 100$ mb
- Challenge is to pick one $B$ decay from $\sim 10^3$ QCD events

Di-muon trigger
- $p_T(\mu) > 1.5$ GeV/c
- $B$ yields 2x Run I (lowered $p_T$ threshold, increased acceptance)

Lepton + displaced-track trigger
- $p_T(\mu, e) > 4$ GeV/c, $120$ $\mu$m $< d_0 < 1$ mm, $p_T > 2$ GeV/c
- $B$ yields 3x Run I

Two displaced-tracks trigger
- $p_T > 2$ GeV/c, $120$ $\mu$m $< d_0 < 1$ mm, $\Sigma p_T > 5.5$ GeV/c
Precision $B$ Lifetimes
Test HQET measuring \( \frac{\tau_{B^+}}{\tau_{B^0}}, \frac{\tau_{B_s}}{\tau_{B^0}} \).

Extract \( \frac{\Delta \Gamma_{B_s}}{\Gamma_{B_s}} \) with Polarization Amplitudes.

\[
\frac{\Delta \Gamma_{B_s}^{\text{SM}}}{\Delta m_s^{\text{SM}}} \approx \frac{5\pi}{6} \frac{m_b^2}{M_W^2} \eta_{B_s B B} S(m_t^2/M_W^2) \left| F_S(z) \right| \frac{B_{B_s}^{S^I}}{B_{B_s}} \left[ 1 + \mathcal{O} \left( \frac{\Lambda_{QCD}}{m_b} \right) \right] = (3.7^{+0.8}_{-1.5}) \times 10^{-3}
\]

indirect \( \Delta m_s \) measurement
# Precision B Lifetimes

## Selection and Fit Method

<table>
<thead>
<tr>
<th>Decay</th>
<th>$p_T(B)$ GeV/c²</th>
<th>$p_T(K/\phi)$ GeV/c²</th>
<th>$Pr(\chi^2)$</th>
<th>$K/\phi$ mass MeV/c²</th>
<th>$B$ mass MeV/c²</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow J/\psi K^+$</td>
<td>$&gt; 5.5$</td>
<td>$&gt; 1.6$</td>
<td>$&gt; 10^{-3}$</td>
<td>–</td>
<td>5170 – 5390</td>
</tr>
<tr>
<td>$B_d \rightarrow J/\psi K^{*0}$</td>
<td>$&gt; 6.0$</td>
<td>$&gt; 2.6$</td>
<td>$&gt; 10^{-4}$</td>
<td>$M_{PDG}(K^{*0}) \pm 50.0$</td>
<td>5170 – 5390</td>
</tr>
<tr>
<td>$B_s \rightarrow J/\psi \phi$</td>
<td>$&gt; 5.0$</td>
<td>$&gt; 1.5$</td>
<td>$&gt; 10^{-5}$</td>
<td>$M_{PDG}(\phi) \pm 6.5$</td>
<td>5220 – 5520</td>
</tr>
</tbody>
</table>

- **Fraction of signal events in the sample**: 1 parameter
- **Mass**: 3 parameters
  
  $Gaus(m) + Pol_1(m)$

- **Proper decay length**: 8 parameters
  
  $\delta \otimes Gaus(ct) + \sum_{n} \text{Exp}_n \otimes Gaus(ct)$

- **Unbinned maximum likelihood**: 1+3+8 = 12 parameters
  
  $L = -2 \log \prod_i f(m_i, \sigma m_i, ct_i, \sigma ct_i | \text{parameters})$
Precision B Lifetimes $B_s$ Projections

**long lived**
- Displaced $J/\psi$ (~15%) paired with (random) track
- $b \to c \to s$
- Remaining reflections and partially reconstructed $B$

**short lived**
- Combinations with mis-measured tracks ($\pm$ lived)
- Prompt $J/\psi$ (~85%) paired with (slightly) displaced track ($+$ lived)
Precision B Lifetimes $B^+$ and $B^0$ Projections

CDF Run II Preliminary

$B^+ \rightarrow J/\psi K^+$
3386±68 sig. candidates
Fit prob: 86.9%

CDF Run II Preliminary

$B^0 \rightarrow J/\psi K^0$
1156±39 sig. candidates
Fit prob: 31.6%

CDF Run II Preliminary

$B^+ \rightarrow J/\psi K^+$
Fit prob: 44.2%

CDF Run II Preliminary

$B^0 \rightarrow J/\psi K^0$
Fit prob: 64.2%
Precision B Lifetimes

**Results**

\[ c\tau_{B^+} = 498.1 \pm 9.9\ (\text{stat.}) \pm 2.4\ (\text{syst.})\ \mu m \]
\[ c\tau_{B^0} = 461.3 \pm 15.4\ (\text{stat.}) \pm 2.4\ (\text{syst.})\ \mu m \]
\[ c\tau_{B_s} = 410.4 \pm 30.0\ (\text{stat.})^{+2.4}_{-2.9}\ (\text{syst.})\ \mu m \]

<table>
<thead>
<tr>
<th></th>
<th><strong>This</strong></th>
<th><strong>PDG'03</strong></th>
<th><strong>Single best</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^+)</td>
<td>1.662 ± 0.033 ± 0.008</td>
<td>1.671 ± 0.018</td>
<td>1.695 ± 0.026 ± 0.015</td>
</tr>
<tr>
<td>(B^0)</td>
<td>1.539 ± 0.051 ± 0.008</td>
<td>1.537 ± 0.015</td>
<td>1.529 ± 0.012 ± 0.029</td>
</tr>
<tr>
<td>(B_s)</td>
<td>1.369 ± 0.100^{+0.008}_{-0.010}</td>
<td>1.461 ± 0.057</td>
<td>1.36 ± 0.09^{+0.06}_{-0.05}</td>
</tr>
</tbody>
</table>

\[ \tau_{B^+}/\tau_{B^0} = 1.080 \pm 0.042\ (\text{tot.}) \]
\[ \tau_{B_s}/\tau_{B^0} = 0.890 \pm 0.072\ (\text{tot.}) \]
First measurement of $\tau(\Lambda_B)$ in a fully reconstructed mode

$$\Lambda_B \rightarrow \Lambda J/\psi$$

$\Lambda_c \rightarrow pK\pi$ $\tau = 1.33 \pm 0.15 \pm 0.07 \text{ ps}$

CDF Run I

World average$^{2002}$ for $\tau(\Lambda_B)/\tau(B^0)$ is $0.798 \pm 0.052$

Theory predicts $0.9 – 1.0$

Nowadays only Tevatron produces $\Lambda_B$

$$c\tau(\Lambda_B) = 374 \pm 78 \text{ (stat.)} \pm 29 \text{ (syst.) } \mu m$$

$$\tau(\Lambda_B) = 1.25 \pm 0.26 \text{ (stat.)} \pm 0.10 \text{ (syst.) } \text{ps}$$

$\tau(\Lambda_B \text{ PDG 2002}) = 1.23 \pm 0.08 \text{ ps}$
Polarization Amplitudes
**Polarization Amplitudes**

**Motivation**

- $B_{d(s)} \rightarrow J/\psi K^{*0}(\phi)$ Pseudoscalar $\rightarrow$ Vector – Vector

Decay amplitude decomposed into 3 linear polarization states

- $|A_0|^2 + |A_{||}|^2 + |A_{\perp}|^2 = 1$
- $A_0 = S + D$ wave $\Rightarrow$ P even
- $A_{||} = S + D$ wave $\Rightarrow$ P even
- $A_{\perp} = P$ wave $\Rightarrow$ P odd

- The mass eigenstates $B_{s,H}$ and $B_{s,L}$ have
  \[
  \frac{\Delta \Gamma_s}{\Gamma_s} = 0.07^{+0.09}_{-0.07} \left( < 0.29 \ 95\% \ CL \right)
  \]

- If CP violation neglected
  - $B_{s,\text{Light}} \approx$ CP even
  - $B_{s,\text{Heavy}} \approx$ CP odd
  - Angular distributions are different

Together with lifetime measurement, angular analysis can separate both states and determine $\Delta \Gamma_s$
$\mathbf{B_d \rightarrow J/\psi K^0}$

- 1000 candidates
- $\sigma = 13.2 \pm 1.0 \text{ MeV/c}^2$

$\mathbf{B_s \rightarrow J/\psi \phi}$

- 180 candidates
- $\sigma = 11.2 \pm 1.0 \text{ MeV/c}^2$

- $|M_{J/\psi} - 3096.87_{(\text{PDG})}| < 80 \text{ MeV}$
- $|M_\phi - 1019.46_{(\text{PDG})}| < 15 \text{ MeV}$
- $|M_{K^0} - 896_{(\text{PDG})}| < 80 \text{ MeV}$
- $c\tau(B) > 0$
\[ g = \frac{9}{32\pi} \left\{ 2 \cos^2 \Theta_K \cdot (1 - \sin^2 \Theta_T \cos^2 \Phi_T) |A_0|^2 \\
+ \sin^2 \Theta_K \cdot (1 - \sin^2 \Theta_T \sin^2 \Phi_T) |A_\parallel|^2 \\
+ \sin^2 \Theta_K \cdot \sin^2 \Theta_T |A_\perp|^2 \\
- \sin^2 \Theta_K \cdot \sin 2\Theta_T \sin \Phi_T Im(A_\parallel^* A_\perp) \zeta \\
+ \frac{1}{\sqrt{2}} \sin 2\Theta_K \cdot \sin^2 \Theta_T \sin 2\Phi_T Re(A_0^* A_\parallel) \\
+ \frac{1}{\sqrt{2}} \sin 2\Theta_K \cdot \sin 2\Theta_T \cos \Phi_T Im(A_0^* A_\perp) \zeta \right\} \]

\[ \zeta = +1 \Rightarrow \text{particle} \]
\[ \zeta = -1 \Rightarrow \text{antiparticle} \]
\[ \zeta = 0 \Rightarrow \text{untagged } B_s \]

**B_{d00} \rightarrow J/\psi \ K^0(\phi)**

Transversity basis = J/\psi rest frame

**K^0 (\phi)** flight direction = positive x
**K\pi (KK) plane** = xy plane
Polarization Amplitudes Angular Projections

\[ \mathcal{B}_d \rightarrow J/\psi K^0 \]

\[ \mathcal{B}_s \rightarrow J/\psi \phi \]

\[ \cos \Theta_T \]

\[ \Phi_T \]

\[ \cos \Theta_K \]

**sideband subtracted distributions**

CDF Run II Preliminary

\[ \chi^2 \text{ Prob.: } 21.5\% \]

\[ \chi^2 \text{ Prob.: } 23.9\% \]

\[ \chi^2 \text{ Prob.: } 66.7\% \]

\[ \chi^2 \text{ Prob.: } 7.0\% \]

\[ \chi^2 \text{ Prob.: } 47.5\% \]

\[ \chi^2 \text{ Prob.: } 48.9\% \]
**Polarization Amplitudes**

**Results**

\[
A_0 = 0.767 \pm 0.045 \pm 0.017
\]

\[
A_{||} = (0.424 \pm 0.118 \pm 0.013) e^{(2.11 \pm 0.55 \pm 0.29)i}
\]

\[
|A_{\perp}| = 0.482 \pm 0.104 \pm 0.014
\]

\[
A_0 = 0.792 \pm 0.024 \pm 0.016
\]

\[
A_{||} = (0.436 \pm 0.057 \pm 0.045) e^{(3.07 \pm 0.40 \pm 0.07)i}
\]

\[
A_{\perp} = (0.428 \pm 0.059 \pm 0.063) e^{(0.11 \pm 0.23 \pm 0.06)i}
\]
$B$ Mixing
**Motivation**

- $B_d$ oscillations are sensitive to $|V_{td}|$
- Compromised by hadronic uncertainties
- Most cancel in $B_d/B_s$ oscillation ratio

\[
\frac{|V_{td}|}{|V_{ts}|} = 1.01 \frac{\Delta m_d}{\Delta m_s}
\]

from LATTICE

- New Physics may affect $\Delta m_s/\Delta m_d$
- $\Delta m_s$ prerequisite for time-dependent $B_s$ CP violation measurement
**B Mixing** $B_s$ Mixing Current Status

- **Heavy Flavor Averaging Group**
  *LEP, SLD and CDF I combined*

- **Most analyses used partially reconstructed decays**
  *Poor sensitivity at high $\Delta m_s$*

\[
\sigma(A) \propto e^{\frac{(\sigma_{ct}\Delta m_s)^2}{2}}
\]

\[
ct = \frac{L_{xy}}{\beta\gamma} = \frac{L_{xy}m_B^B}{p_T^B} \Rightarrow \sigma_{ct} = \frac{m_B^B}{p_T^B} \sigma_{L_{xy}} \oplus ct \left( \frac{\sigma_{p_T^B}}{p_T^B} \right)
\]

Semileptonic decays
\[
\left( \frac{\sigma_{p_T^B}}{p_T^B} \right)_{CDF} \approx 15\%
\]

Hadronic decays
\[
\left( \frac{\sigma_{p_T^B}}{p_T^B} \right)_{CDF} \approx 0.5\%
\]

$\Delta m_s > 14.5$ ps\(^{-1}\) 95% CL (more than 3 full oscillations per lifetime)

From CKM fit $\Delta m_s < 30$ ps\(^{-1}\) 95% CL
Efficiency $\varepsilon \equiv \text{fraction of tagged events}$

Dilution $D \equiv 2P - 1$ with $P$ the correct answer probability

Tagging effectiveness $\varepsilon D^2$ shows statistical power of the tagger

Flavor taggers can be topologically separated
  - Same-Side is sample dependent
  - Opposite-Side is based on properties of the non-reconstructed $b$
Find events with Opposite Side $B \rightarrow \mu X$

Opposite Side $\mu$ charge gives Soft Muon Tagger (SMT) decision

Qualities
- High purity (OS $\mu$ almost always from $B \rightarrow \mu X$)
- Low efficiency, BR($B \rightarrow \mu X$) $\sim$ 10%
- OS $B$ mixing reduces performance

Combined $\sum \varepsilon D^2$ for all subsamples

Find jet of the Opposite Side $b$

Calculate weighted average $Q$ of jet tracks

$Q_{jet}$ sign gives Jet Charge Tagger (JQT) decision

Qualities
- Moderate purity ($Q_{jet}$ not 100% correlated with $b$ flavor)
- High efficiency ($b$ in acceptance almost always gives a jet)
- Non-$b$ jets in the event complicate $b$-jet finding

Combined $\sum \varepsilon D^2$ for all subsamples

Run I JQT algorithm

Not optimized

$\varepsilon D^2 = 0.660 \pm 0.193$ (stat. %)

$\varepsilon D^2 = 0.415 \pm 0.017$ (stat. %)
Look for the fragmentation track that is charge correlated with the produced $B$

Divide data into 3 subsamples depending on tagger decision
- Right-Sign events (unmixed), Wrong-Sign events (mixed) and Not-Tagged events

Consider tracks close to the $B$ meson

$$\Delta R(\text{track}, B) = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.7$$

Originating from primary vertex

If multiple track candidates, select the one with minimum $p_T^{\text{rel}}$
B Mixing Fully Reconstructed Decays

\[ B^0 \rightarrow J/\psi K^0, \ J/\psi \rightarrow \mu^+\mu^-, \ K^*^0 \rightarrow K^+\pi^- \]

CDF Run II Preliminary \[L \approx 245 \text{ pb}^{-1}\]

- \( |M(J/\psi) - M_{\text{PDG}}| < 80 \text{ MeV/c}^2 \)
- \( |m(K^*) - m_{\text{PDG}}| < 50 \text{ MeV/c}^2 \)
- Reject events with >1 \( K^*^0 \) candidate

\[ J/\psi \]

\[ K^*^0 \]

- \( L_{xy} > 100 \mu\text{m} \)

\[ B \]

- Vertex probability > 0.1%
- \( L_{xy} > 100 \mu\text{m} \)

\[ B^0 \rightarrow D^- \pi^+_B, \ D^- \rightarrow K^+\pi^-\pi^- \]

CDF Run II Preliminary \[L \approx 245 \text{ pb}^{-1}\]

- \( \chi^2_{\rho\phi} < 14 \)
- \( \Delta R(D,\pi_B) < 1.5 \)
- \( p_T > 1.6 \text{ GeV/c} \)

\[ D \]

\[ \pi_B \]

\[ B \]

- \( \chi^2_{r\phi} < 15 \)
- \( L_{xy} > 300 \mu\text{m} \)
\[ \Delta m_d \] using SST in \( B_d \rightarrow J/\psi \ K^{*0} (D^- \pi^+) \)

**CDF Run II Preliminary**

L = 245 pb\(^{-1}\)

**Asymmetry**

- **Exact proper time**
  \[ A^{\text{meas}}(t) = D \cos \Delta m_d t \]

- **Detector finite resolution**
  \[ A^{\text{meas}}(t) = \frac{G(ct;ct', \sigma_{ct}) \otimes \left[ e^{-t/\tau} \cos(\Delta m_d t) \right]}{G(ct;ct', \sigma_{ct}) \otimes e^{-t/\tau}} \]

**Combined \( \chi^2 \) fit**

- \( \Delta m_d = 0.55 \pm 0.10 \) (stat.) \( \pm 0.01 \) (syst.) ps\(^{-1}\)
- \( D = 12.4 \pm 3.3 \) (stat.) \( \pm 1.2 \) (syst.) %
- \( \varepsilon D^2 = 1.0 \pm 0.5 \) (stat.) \( \pm 0.2 \) (syst.) %

More decays soon
Increased statistics
SST not optimized
$\Delta m_d$ using SST in $B_d \rightarrow ID^{(*)}$ Decays

$\Delta m_d = 0.443 \pm 0.052 \text{ (stat.)} \pm 0.030 \text{ (s.c.)} \pm 0.012 \text{ (syst.)} \text{ ps}^{-1}$

$D_0 = 12.8 \pm 1.6 \text{ (stat.)} \pm 1.0 \text{ (s.c.)} \pm 0.6 \text{ (syst.)} \%$

$D_+ = 28.3 \pm 1.3 \text{ (stat.)} \pm 1.1 \text{ (s.c.)} \pm 1.0 \text{ (syst.)} \%$

$\varepsilon D^2(B^0) = 1.1 \pm 0.3 \text{ (stat.)} \pm 0.2 \text{ (s.c.)} \pm 0.1 \text{ (syst.)} \%$
**Requirements**
- Clean signals (S/B)
- Vertexing resolution
- Tagging effectiveness

**Modest improvements**
- Adding $D_s \rightarrow K^+ K$, $D_s \rightarrow K_s K$ and $B_s \rightarrow D_s 3\pi$
- L00 innermost silicon layer
  - $\sigma_t = 67 \text{ fs} \rightarrow \sigma_t = 50 \text{ fs}$

**Short term 500 pb$^{-1}$** no improvement up to 2005
- $2\sigma$ (for $\Delta m_s = 15 \text{ ps}^{-1}$)
- Reach the current limit
- Cover the Standard Model favored range

**Beyond the SM favored range** conservative improvements up to 2008
- $5\sigma$ if $\Delta m_s = 18 \text{ ps}^{-1}$ with 1.8 fb$^{-1}$
- $5\sigma$ if $\Delta m_s = 24 \text{ ps}^{-1}$ with 3.2 fb$^{-1}$
Conclusions

**Precision B Lifetimes**
- $B^0$, $B^+$, $B_s$ competitive with PDG
- First time $\Lambda_B$ lifetime is measured in a fully reconstructed decay

**Polarization Amplitudes**
- $B_d$ amplitudes consistent with $B$ factories
- Best $B_s$ amplitude measurement
- $B_s \rightarrow J/\psi \phi$ mostly CP-even $\Delta \Gamma_s$ measurement imminent

**B Mixing**
- First time $\Delta m_d$ is measured based on the displaced-track trigger
- We are able to reproduce the $B_d$ oscillation frequency
- $B_s$ mixing
  - Reach current limit with 500 pb$^{-1}$ near future
Wow, it really snowed last night! Isn't it wonderful?

Everything familiar has disappeared! The world looks brand-new!

A new year... a fresh, clean start!

It's like having a big white sheet of paper to draw on!

A day full of possibilities!

It's a magical world, Hobbes, ol' buddy...

Let's go exploring!
Back Up Slides
B Mixing  Semileptonic Sample

- Test arena for Soft Muon and Jet Charge
- Based on lepton + displaced-track trigger
  - High statistics ~1 million semileptonic $b$ events
  - lepton charge $\Rightarrow$ signal $B$ flavor at decay

- Background suppression $\Rightarrow$ pure $bb$ sample
  - QCD background $pp \rightarrow uu, dd, ss$
    - Remove with signed impact parameter
  - Charm background $pp \rightarrow cc$
    - Remove by $2 < M_{\text{lepton-track}} < 4 \text{ GeV}/c^2$