Heavy Flavor Physics at CDF

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on behalf of CDF collaboration

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Outline

- Introduction
  - Tevatron, CDF detector
  - B Physics at the Tevatron

- Recent results
  - $B_c$ - mass
    - lifetime
  - $B_s$ - lifetime
    - decay width difference
    - CP violation

- Topics not covered

- Conclusions
Tevatron

- $p\bar{p}$ collisions at 1.96 TeV

  $\sim 3.5 \text{ fb}^{-1}$ data on tape

- Initial instantaneous luminosity $3 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$
- Central tracking:
  - silicon vertex detector
  - drift chamber
  → excellent momentum, mass and vertex resolution
  → trigger on long lived particles

- Particle identification: dE/dx and TOF
- Good electron and muon ID by calorimeters and muon chambers
B Physics at the Tevatron

- Mechanisms for $b$ production in $p\bar{p}$ collisions at 1.96 TeV

- At Tevatron, $b$ production cross section is much larger compared to B-factories
  → Tevatron experiments CDF and DØ enjoy rich B Physics program

- Plethora of states accessible only at Tevatron: $B_s$, $B_c$, $\Lambda_b$, $\Xi_b$, $\Sigma_b$...
  → complement the B factories physics program

- Total inelastic cross section at Tevatron is $\sim1000$ larger than $b$ cross section
  → large backgrounds suppressed by triggers that target specific decays
**B_c Mass in B_c → J/ψ π (2.4 fb⁻¹)**

- **B_c** – unique meson as it contains two heavy quarks: bottom and anti-charm (b̅c)

- **Mass predictions:**
  - NR potential models 6247 - 6286 MeV
  - lattice QCD 6304 +/- 12 +18⁻⁰ MeV

- **Best mass measurement:**
  
  \[6275.6 \pm 2.9 \text{ (stat.)} \pm 2.5 \text{ (syst.)} \text{ MeV/}c^2\]

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**Diagram:**

- **Signal yield**
  
  \[108 +/- 15\] significance 8σ

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**Graph:**

- ** Entries per 10 MeV/c²**
  
  ![Graph](image-url)
**B_c Lifetime in** \( B_c \rightarrow J/\Psi \) **lepton (1 fb\(^{-1}\))**

http://www-cdf.fnal.gov/physics/new/bottom/080327.blessed-BC_LT_SemiLeptonic/

- Lepton can be either muon or electron

- Different contributions to total decay width:
  - c quark decays \( B_c^+ \rightarrow B_c^0 \pi^+ \)
  - b quark decays \( B_c^+ \rightarrow J/\Psi \ell^+ \nu \)
  - annihilation \( B_c^+ \rightarrow \ell^+ \nu. \)

- Lifetime expected \( \sim 1/3 \) of other B mesons (0.5ps compared to typical 1.5ps)

- Signal reconstruction from \( \sim 5.5 \) million J/\( \Psi \)

- Third lepton is vertexed with J/\( \Psi \)

- Partially reconstructed mode (missing neutrino)
  - use simulation to correct missing momentum

- Main challenge is understanding multiple backgrounds:
  - real J/\( \Psi \) + fake lepton
  - fake J/\( \Psi \) + real lepton
  - real J/\( \Psi \) + real lepton from bb events
  - prompt J/\( \Psi \) + \( \mu \)
**B_c Lifetime Results**

- Most precise B_c lifetime measurement (same precision as DØ)
  
  muon mode \[ c\tau_\mu = 179.1^{+32.6}_{-27.2} \text{ (stat.) } \mu m, \]
  
  electron mode \[ c\tau_e = 121.7^{+18.0}_{-16.3} \text{ (stat.) } \mu m. \]
  
- Combined:
  \[ c\tau = 142.5^{+15.8}_{-14.8} \text{ (stat.) } \pm 5.5 \text{ (syst.) } \mu m. \]

- Speaker’s average (neglect correlations)
  \[ \tau = 0.459 \pm 0.037 \text{ ps} \]

- Large theoretical uncertainties and model to model variations \[ \tau = 0.47 \div 0.59 \text{ ps} \]

- Expect CDF B_c lifetime measurement in fully reconstructed B_c → J/Ψ π
Neutral $B_s$ System

- Time evolution of $B_s$ flavor eigenstates described by Schrodinger equation:

$$i \frac{d}{dt} \left( \left| B_s^0(t) \right> \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \left| B_s^0(t) \right> \right)$$

- Diagonalize mass ($M$) and decay ($\Gamma$) matrices → mass eigenstates

$$| B_s^H \rangle = p | B_s^0 \rangle - q | \bar{B}_s^0 \rangle \quad | B_s^L \rangle = p | B_s^0 \rangle + q | \bar{B}_s^0 \rangle$$

- Different mass eigenvalues: $\Delta m_s = m_H - m_L \rightarrow B_s$ oscillates with frequency $\sim \Delta m_s$

  CDF $\Delta m_s = 17.77 +/- 0.12$ ps$^{-1}$
  DØ $\Delta m_s = 18.56 +/- 0.87$ ps$^{-1}$

- Mass eigenstates have different decay widths (different lifetimes)

  $\Delta \Gamma = \Gamma_L - \Gamma_H$
CP Violation in $B_s$ System

- Standard Model CP violation occurs through complex phases in the unitary CKM quark mixing matrix:

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

- Expanded in $\lambda = \sin(\theta_{\text{Cabibbo}}) \approx 0.23$:

$$
\begin{pmatrix}
  1 - \frac{1}{2} \lambda^2 - \frac{1}{8} \lambda^4 \\
  -\lambda + \frac{1}{2} A^2 \lambda^5 [1 - 2(\rho + i\eta)] \\
  A\lambda^3 [1 - (1 - \frac{1}{2} \lambda^2)(\rho + i\eta)]
\end{pmatrix}
\begin{pmatrix}
  \lambda \\
  1 - \frac{1}{2} \lambda^2 - \frac{1}{8} \lambda^4 (1 + 4A^2) \\
  -A\lambda^2 + \frac{1}{2} A\lambda^4 [1 - 2(\rho + i\eta)]
\end{pmatrix}
\begin{pmatrix}
  A\lambda^3 (\rho - i\eta)
\end{pmatrix}
$$

- Unitary matrix $\rightarrow V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0$

$$
\begin{vmatrix}
  |V_{ts} V_{tb}^*| \\
  |V_{us} V_{ub}^*| \\
  |V_{cs} V_{cb}^*|
\end{vmatrix} \sim 1
$$

$$
\begin{vmatrix}
  |V_{ts} V_{tb}^*| \\
  |V_{us} V_{ub}^*| \\
  |V_{cs} V_{cb}^*|
\end{vmatrix} \sim \lambda^2 \approx 0.05
$$

very small CPV phase $\beta_s$

accessible in $B_s \rightarrow J/\Psi \Phi$ decays
CP Violation in $B_s \to J/\Psi \Phi$ Decays

- Analogously to the neutral $B^0$ system, CP violation in $B_s$ system occurs through interference of decay with and without mixing:

\[
\begin{align*}
B^0 & \to J/\Psi K^0_s & \bar{B}^0 & \to J/\Psi \Phi \\
\Rightarrow \sin(2\beta) & \Rightarrow \sin(2\beta_s)
\end{align*}
\]

- CP violation phase $\beta_s$ in SM is predicted to be very small:

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

- New Physics affects the CP violation phase as:

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

- If NP phase $\phi_s^{NP}$ dominates $\to 2\beta_s = -\phi_s^{NP}$
**B_s Lifetime in B_s → J/ΨΦ Decays (1.7 fb⁻¹)**

- ~2500 signal events in ~1.7 fb⁻¹
- **B_s lifetime measurements from B_s → J/ΨΦ decays**
- Measures average decay width $\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2}$

$$\tau_s = \frac{1}{\Gamma_s} = 1.52 \pm 0.04 \text{ (stat)} \pm 0.02 \text{ (syst)} \text{ ps}$$
Width Difference $\Delta \Gamma$ in $B_s \rightarrow J/\Psi \Phi$ (1.7 fb$^{-1}$) \cite{Phys.Rev.Lett. 100, 121803 (2008)}

- Can also measure decay width $\Delta \Gamma$

- The decay of $B_s$ (spin 0) to $J/\Psi$(spin 1) $\Phi$(spin 1) leads to three different angular momentum final states:
  - $L = 0$ (s-wave), 2 (d-wave) → CP even
  - $L = 1$ (p-wave) → CP odd

- At good approximation mass eigenstates $|B_s^L\rangle$ and $|B_s^H\rangle$ are CP eigenstates
  - use angular information to separate heavy and light states
  - determine decay width difference
    $\Delta \Gamma = \Gamma_L - \Gamma_H = 0.08 +/- 0.06 \text{ (stat) +/- 0.01 \text{ (syst) ps}^{-1}}$

  → some sensitivity to CP violation phase $\beta_s$

- Determine $B_s$ flavor at production (flavor tagging)
  → improve sensitivity to CP violation phase $\beta_s$

→ $\Delta \Gamma \neq 0$
CP Violation Phase $\beta_s$ in Tagged $B_s \to J/\Psi\Phi$ Decays (1.4 fb$^{-1}$)

- First tagged analysis of $B_s \to J/\Psi\Phi$ (1.4 fb$^{-1}$)
- Signal $B_s$ yield $\sim$2000 events with S/B $\sim$ 1
- Irregular likelihood does not allow quoting point estimate
- Quote Feldman-Cousins confidence regions with frequentist inclusion of systematic uncertainties

- 1D Feldman-Cousins procedure without external constraints:
  $2\beta_s$ in $[0.32, 2.82]$ at the 68% C.L.

- with external constraints (on strong phases, lifetime and $\Delta\Gamma$)
  $2\beta_s$ in $[0.40, 1.20]$ at 68% C.L.

**Figure:**
- SM prediction
- 68% C.L.
- 95% C.L.

Standard Model probability 15% $\sim 1.5\sigma$

**Reference:**
Comparison with DØ  arXiv:0802.2255

- DØ quotes the results in terms of $\phi_s = -2\beta_s$
  See talk by E. Fisk for DØ analysis

- DØ quotes a point-estimate with strong phases constrained from $B^0 \rightarrow J/\psi K^{*0}$
  $\phi_s = -0.57^{+0.24}_{-0.30} \text{(stat)} +0.07 \text{(syst)}$

- Can be compared to CDF constrained result
  $2\beta_s \in [0.40,1.20] \text{ @ 68\% CL}$

- HFAG combined CDF + DØ result to appear very soon!
**B_s Lifetime in Flavor Specific Decay B_s → D_s π X**


- Decay modes:
  - fully reconstructed $B_s → D_s(\Phi\pi) \pi$ (≈1100 events)
  - partially reconstructed (2200 events)

- Partially reconstructed modes ← use simulation to model mass distribution shapes and missing momentum:

$$ct = \frac{L_{xy} \cdot m_B^{rec}}{p_T} \cdot \mathcal{K}$$

![Graph showing decay modes and mass distribution](image-url)
B₅ Lifetime in Bₛ → DₛπX (cont)

- Data collected using displaced track trigger
  - two displaced tracks with 120 μm < d₀ < 1mm
  → lifetime bias corrected using simulation

- Procedure tested and on control samples

  \[ B^0 \rightarrow D^- (K^+ \pi^- \pi^+) \pi^+ \]
  \[ B^0 \rightarrow D^0 (K^+ \pi^- \pi^-) \pi^+ \]
  \[ B^+ \rightarrow D^0 (K^+ \pi^-) \pi^+ \]

- Found good agreement with world average
**B_s → D_s \pi Lifetime Result**

- **Best flavor specific B_s lifetime:**
  \[ \tau(B_s) = 1.518 \pm 0.041 \pm 0.025 \text{ ps} \]

- In good agreement with CDF and DØ results in B_s → J/ΨΦ

- Higher value will bring average closer to HQET prediction \( \tau_s/\tau_d = 1.0 \pm 0.02 \)

- HFAG 2007: \( \tau_s/\tau_d = 0.94 \pm 0.02 \)
- Many other recent results not covered in this talk:

- b baryons: $\Lambda_b$, $\Sigma_b$, $\Xi_b$
- Best limits of rare decays:
  - $B_s \rightarrow \mu\mu$, $B_s \rightarrow \mu\mu\Phi$, $B_s \rightarrow e\mu$, $B_s \rightarrow ee$, $D^0 \rightarrow \mu\mu$
- CP asymmetry in semileptonic $B$ decays
- CP violation in charmless $B$ and $\Lambda_b$ two-body decays
- CP asymmetry in $B^+ \rightarrow D^0 K^+$
- Charm mixing
- Simulation free lifetime measurement
- $\Psi(2S)$ production, $Y(1S)$, $Y(2S)$ polarization
- $B^0 \rightarrow J/\psi K^{*0}$ angular analysis
- orbitally excited $B$ mesons
- $b$-$b$ correlation

http://www-cdf.fnal.gov/physics/new/bottom/bottom.html
Conclusions

- Very rich B physics program at CDF

- Complementary and competitive with *Belle* and *BaBar*

- Great Tevatron performance
  → accumulate data fast
  → expect 6-8 fb\(^{-1}\) by the end of Run 2

- Expect updates of many analyses

- Exciting time for flavor physics at Tevatron!
Backup Slides
CDF B Physics Triggers

- Triggers designed to select events with topologies consistent with B decays:

  - 4 GeV lepton + displaced track (semileptonic B decays)

  ![Diagram of lepton + displaced track](image)

  - di-muon (B → J/Ψ X, B → μμ)

  ![Diagram of di-muon](image)

  - two displaced tracks (hadronic decays)

  ![Diagram of two displaced tracks](image)
Simulation Free Lifetime Method in $B^+ \rightarrow D^0 \pi^+$ (1 fb$^{-1}$)

- CDF has large sample of fully reconstructed decays of b hadrons collected by trigger which requires two displaced tracks with $120 \text{ mm} < d_0 < 1\text{ mm}$
  $\rightarrow$ in general, use simulation to correct for trigger induced lifetime biases

- Already good measurements of $B_s$ ($\Lambda_b$ lifetime measurement expected soon)
- Use alternative lifetime measurement techniques not based on simulation for better control of systematic uncertainties

- First lifetime measurement without use of simulation in trigger biased sample $B^+ \rightarrow D^0 \pi^+$ shows proof of principle
  - use event by event acceptance function:
Simulation Free $B^+$ Lifetime Results

- 24200 +/- 200 signal events with S/B ~4.8

$$\tau(B^+) = 1.662 \pm 0.023 \text{ (stat.)} \pm 0.013 \text{ (syst.)} \text{ ps}$$

- In good agreement with PDG average: 1.638 \pm 0.011 \text{ ps}

- Method to be used in the future for better measurements of $B_s$ and $\Lambda_b$ lifetimes in trigger biased samples
  - with large data samples will also need better control of systematic uncertainties

- Important proof of principle for LHC experiments
**Σ_b Mass Measurement (1.1 fb⁻¹)**

- Σ_b properties predicted by HQET, now tested by exp
- First observation of Σ_b and Σ_b* by CDF in 2007
- Reconstructed decay mode:

  \[ \Sigma_b^{(*)\pm} \rightarrow \Lambda_b^0 \pi^\pm \]

\[ \Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \]

\[ \Lambda_c^+ \rightarrow pK^- \pi^+ \]

\[ m_{\Sigma_b^+} = 5807.8^{+2.0}_{-2.2} \text{ (stat.)} \pm 1.7 \text{ (syst.) \ MeV/c^2} \]

\[ m_{\Sigma_b^-} = 5815.2 \pm 1.0 \text{ (stat.)} \pm 1.7 \text{ (syst.) \ MeV/c^2} \]

\[ m_{\Sigma_b^{*+}} = 5829.0^{+1.6}_{-1.8} \text{ (stat.)}^{+1.7}_{-1.8} \text{ (syst.) \ MeV/c^2} \]

\[ m_{\Sigma_b^{*-}} = 5836.4 \pm 2.0 \text{ (stat.)}^{+1.8}_{-1.7} \text{ (syst.) \ MeV/c^2} \]
\( \Xi_b \) Mass Measurement (1.9 fb\(^{-1}\))

- \( \Xi_b \) (quark content: \( bds \)) → third observed b baryon after \( \Lambda_b \) and CDF’s recent discovery of \( \Sigma_b \)

- Study b baryons → great way to test QCD which predicts \( M(\Lambda_b) < M(\Xi_b) < M(\Sigma_b) \)

- Decay mode

\[
\Xi_b^- \rightarrow J/\psi \Xi^-, \quad \text{with} \quad J/\psi \rightarrow \mu^+ \mu^- \\
\text{and} \quad \Xi^- \rightarrow \Lambda \pi^- \rightarrow p\pi^- \pi^-
\]

- \( \Xi \) tracked in silicon vertex detector for the first time at hadron collider

- Most precise measurement at 7.8\( \sigma \) significance

\[
M(\Xi_b^-) = (5,792.9 \pm 2.4(\text{stat.}) \pm 1.7(\text{syst.})) \text{ MeV}/c^2
\]

- \( \Xi_b \) can be measured in hadronic decays at CDF

- With more data will study other properties of \( \Xi_b \)
Branching Fractions and CP Asymmetry in $B^+ \rightarrow D^0 K^+$ (1 fb$^{-1}$)

- Measures quantities relevant for determination of the CKM angle

$$\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$$

$$A_{CP^+} = \frac{BR(B^- \rightarrow D_{CP^+}^0 K^-) - BR(B^+ \rightarrow D_{CP^+}^0 K^+)}{BR(B^- \rightarrow D_{CP^+}^0 K^-) + BR(B^+ \rightarrow D_{CP^+}^0 K^+) + BR(B^- \rightarrow D_{CP^+}^0 \pi^-) + BR(B^+ \rightarrow D_{CP^+}^0 \pi^+)}$$

$$R_{CP^+} = \frac{R_+}{R}$$

where:

$$R = \frac{BR(B^- \rightarrow D^0 K^-) + BR(B^+ \rightarrow D^0 K^+)}{BR(B^- \rightarrow D^0 \pi^-) + BR(B^+ \rightarrow D^0 \pi^+)}$$

$$R_+ = \frac{BR(B^- \rightarrow D_{CP^+}^0 K^-) + BR(B^+ \rightarrow D_{CP^+}^0 \pi^+)}{BR(B^- \rightarrow D_{CP^+}^0 \pi^-) + BR(B^+ \rightarrow D_{CP^+}^0 \pi^+)}$$

**CP even eigenstate:**

$D_{CP^+}^0 \rightarrow K^+K^-$

$D_{CP^+}^0 \rightarrow \pi^+\pi^-$

**Flavor eigenstate:**

$D^0 \rightarrow K^-\pi^+$

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<tr>
<th>CDF Run II Preliminary</th>
<th>$L_{int} = 1$ fb$^{-1}$</th>
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<tbody>
<tr>
<td>B$^−$ → D$^0$π$^−$</td>
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<td>D$^0$ → K$^−$π$^+$</td>
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<td>signal yield ~8000</td>
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<td>B$^−$ → D$^{0, CP^+}$π$^−$</td>
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<td>yield ~250</td>
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Branching Fractions and CP Asymmetry in $B^+ \to D^0 K^+$ (1 fb$^{-1}$)

- Discriminating variables used to disentangle decay modes:
  - $(D^0, \text{track})$ invariant mass
  - momentum imbalance: $p_{tr} < p_{D^0} \quad \alpha = 1 - p_{tr}/p_{D^0} > 0$
  - total momentum $p_{tr} \geq p_{D^0} \quad \alpha = -(1 - p_{D^0}/p_{tr}) \leq 0$
  - ‘kaonness’ contains $dE/dx$ information

of direct B track $p_{tot} = p_t + p_{D^0}$
Branching Fractions and CP Asymmetry in $B^+ \to D^0 K^+ (1 \, \text{fb}^{-1})$

- **Results:**
  - ratio of branching fractions:
    \[
    R = \frac{BR(B^- \to D^0 K^-) + BR(B^+ \to \bar{D}^0 K^+)}{BR(B^- \to D^0 \pi^-) + BR(B^+ \to \bar{D}^0 \pi^+)} = 0.0745 \pm 0.0043(\text{stat.}) \pm 0.0045(\text{syst.})
    \]
    \[
    R_{CP^+} = \frac{BR(B^- \to D_{CP+}^0 K^-) + BR(B^+ \to D_{CP+}^0 K^+)}{[BR(B^- \to D^0 K^-) + BR(B^+ \to \bar{D}^0 K^+)]/2} = 1.57 \pm 0.24(\text{stat.}) \pm 0.12(\text{syst.})
    \]
  - direct CP asymmetry:
    \[
    A_{CP^+} = \frac{BR(B^- \to D_{CP+}^0 K^-) - BR(B^+ \to D_{CP+}^0 K^+)}{BR(B^- \to D_{CP+}^0 K^-) + BR(B^+ \to D_{CP+}^0 K^+)} = 0.37 \pm 0.14(\text{stat.}) \pm 0.04(\text{syst.})
    \]
  - Quantities measured for the first time at hadron colliders
  - Results in agreement and competitive with B factories

- **Graphs:**
  - BABAR (arXiv:0708.1534)
  - Belle (PRD 73, 051106(2006))
  - CDF II
  - Old AVG (Babar+Belle)
  - New AVG (Babar+Belle+CDF)

- **Values:**
  - BABAR: $A_{CP^+} = 0.35 \pm 0.09 \pm 0.05$
  - Belle: $A_{CP^+} = 0.06 \pm 0.14 \pm 0.05$
  - CDF II: $A_{CP^+} = 0.37 \pm 0.14 \pm 0.04$
  - Old AVG (Babar+Belle): $A_{CP^+} = 0.26 \pm 0.08$
  - New AVG (Babar+Belle+CDF): $A_{CP^+} = 0.28 \pm 0.07$
  - BABAR: $R_{CP^+} = 1.07 \pm 0.10 \pm 0.04$
  - Belle (PRD 73, 051106(2006)): $R_{CP^+} = 1.13 \pm 0.16 \pm 0.08$
  - CDF II: $R_{CP^+} = 1.57 \pm 0.24 \pm 0.12$
  - Old AVG (Babar+Belle): $R_{CP^+} = 1.09 \pm 0.09$
  - New AVG (Babar+Belle+CDF): $R_{CP^+} = 1.14 \pm 0.09$
Branching Fractions and CP Asymmetry in $\Lambda_b \rightarrow p \pi(K)$ (1 fb$^{-1}$)

- Direct CP violation
- First study of CP asymmetry in b baryon decays (SM prediction ~10%)
- Use large sample collected by two displaced track trigger

- Different states that contribute to $\pi^+\pi^-$ invariant mass are not separated in mass
- Use additional kinematic and dE/dx information to achieve better statistical separation

Branching Fractions and CP Asymmetry in $\Lambda_b \rightarrow p \pi (K)$

- Results:

\[
A_{CP}(\Lambda_b^0 \rightarrow p\pi^-) = \frac{B(\Lambda_b^0 \rightarrow p\pi^-) - B(\Lambda_b^0 \rightarrow \bar{p}\pi^+)}{B(\Lambda_b^0 \rightarrow p\pi^-) + B(\Lambda_b^0 \rightarrow \bar{p}\pi^+)} = 0.03 \pm 0.17 \text{ (stat.)} \pm 0.05 \text{ (syst.)}
\]

\[
A_{CP}(\Lambda_b^0 \rightarrow pK^-) = \frac{B(\Lambda_b^0 \rightarrow pK^-) - B(\Lambda_b^0 \rightarrow \bar{p}K^+)}{B(\Lambda_b^0 \rightarrow pK^-) + B(\Lambda_b^0 \rightarrow \bar{p}K^+)} = 0.37 \pm 0.17 \text{ (stat.)} \pm 0.03 \text{ (syst.)}
\]

- First CP asymmetry measurement in b baryon decays

- Additionally, first measurement of branching fraction relative to $B^0 \rightarrow K\pi$ decays:

\[
\frac{\sigma(p\bar{p} \rightarrow \Lambda_b^0 X, p_T > 6 \text{ GeV}/c)}{\sigma(p\bar{p} \rightarrow B^0 X, p_T > 6 \text{ GeV}/c)} \frac{B(\Lambda_b^0 \rightarrow p\pi^-)}{B(B^0 \rightarrow K^+\pi^-)} = 0.0415 \pm 0.0074 \text{ (stat.)} \pm 0.0058 \text{ (syst.)}
\]

\[
\frac{\sigma(p\bar{p} \rightarrow \Lambda_b^0 X, p_T > 6 \text{ GeV}/c)}{\sigma(p\bar{p} \rightarrow B^0 X, p_T > 6 \text{ GeV}/c)} \frac{B(\Lambda_b^0 \rightarrow pK^-)}{B(B^0 \rightarrow K^+\pi^-)} = 0.0663 \pm 0.0089 \text{ (stat.)} \pm 0.0084 \text{ (syst.)}
\]

B_s → J/ΨΦ Phenomenology

- B_s → J/ΨΦ decay rate as function of time, decay angles and initial B_s flavor:

\[
\frac{d^4P(t, \bar{\rho})}{dtd\bar{\rho}} \propto |A_0|^2 T_+ f_1(\bar{\rho}) + |A||^2 T_+ f_2(\bar{\rho}) + |A_\perp|^2 T_+ f_3(\bar{\rho}) + |A||A_\perp| U_+ f_4(\bar{\rho}) + |A_0||A_\perp| \cos(\delta_\parallel) T_+ f_5(\bar{\rho}) + |A_0||A_\perp| V_+ f_6(\bar{\rho}),
\]

\[T_\pm = e^{-\Gamma t} \times \left[ \cosh(\Delta \Gamma t/2) \mp \cos(2\beta_s) \sinh(\Delta \Gamma t/2) \mp \sin(2\beta_s) \sin(\Delta m_s t) \right],\]

\[U_\pm = \pm e^{-\Gamma t} \times \left[ \sin(\delta_\perp - \delta_\parallel) \cos(\Delta m_s t) - \cos(\delta_\perp - \delta_\parallel) \cos(2\beta_s) \sin(\Delta m_s t) \pm \cos(\delta_\perp - \delta_\parallel) \sin(2\beta_s) \sinh(\Delta \Gamma t/2) \right],\]

\[V_\pm = \pm e^{-\Gamma t} \times \left[ \sin(\delta_\parallel) \cos(\Delta m_s t) - \cos(\delta_\parallel) \cos(2\beta_s) \sin(\Delta m_s t) \pm \cos(\delta_\parallel) \sin(2\beta_s) \sinh(\Delta \Gamma t/2) \right].\]

- Tagging → better sensitivity to \( \beta_s \)
CP Violation Phase $\beta_s$ in Tagged $B_s \rightarrow J/\Psi\Phi$ Decays

- Likelihood expression predicts better sensitivity to $\beta_s$ but still double minima due to symmetry:
  \[ 2\beta_s \rightarrow \pi - 2\beta_s \]
  \[ \Delta \Gamma \rightarrow -\Delta \Gamma \]
  \[ \delta_{||} \rightarrow 2\pi - \delta_{||} \]
  \[ \delta_{\perp} \rightarrow \pi - \delta_{\perp} \]

- Study expected effect of tagging using pseudo-experiments

- Improvement of parameter resolution is small due to limited tagging power ($\epsilon D^2 \sim 4.5\%$ compared to B factories $\sim 30\%$)

- However, $\beta_s \rightarrow -\beta_s$ no longer a symmetry
  → 4-fold ambiguity reduced to 2-fold ambiguity
  → allowed region for $\beta_s$ is reduced to half

\[
2\Delta \log(L) = 2.3 \approx 68\% \text{ CL} \quad 2\Delta \log(L) = 6.0 \approx 95\% \text{ CL}
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CDF Impact on $\Phi_s$ World Average

- Overlay CDF result on UT world average which includes DØ combined result

http://www.utfit.org/

- CDF measurement suppresses large fraction of CP violation parameter space!
CP Violation Phase $\beta_s$ in Un-tagged $B_s \rightarrow J/\Psi\Phi$ Decays (1.7 fb$^{-1}$)

- Without identification of the initial $B_s$ flavor still have sensitivity to $\beta_s$

- Due to irregular likelihood and biases in fit, CDF only quotes Feldman-Cousins confidence regions (Standard Model probability 22%)

- Symmetries in the likelihood $\rightarrow$ 4 solutions are possible in $2\beta_s$-$\Delta\Gamma$ plane

![Graph showing $\Delta\Gamma$ vs. $2\beta_s$ with confidence regions and new physics models]
D₀ Mixing

- After recent observation of fastest neutral meson oscillations in Bₛ system by CDF and DØ → time to look at the slowest oscillation of D₀ mesons 😊

- D₀ mixing in SM occurs through either:

**‘short range’ processes** (negligible in SM)

<table>
<thead>
<tr>
<th>Process</th>
<th>AM/Γ</th>
<th>ΔΓ/Γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>K⁰</td>
<td>0.474</td>
<td>0.997</td>
</tr>
<tr>
<td>B⁰</td>
<td>0.77</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Bₛ</td>
<td>27</td>
<td>0.15</td>
</tr>
<tr>
<td>D₀ (&lt; few%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**‘long range’ processes**

Recent D₀ mixing evidence ← different D₀ decay time distributions in

- **Belle**
  \[D₀ \rightarrow ππ, KK \text{ (CP eigenstates)}\]
  compared to \[D₀ \rightarrow Kπ\]

- **BaBar**
  doubly Cabibbo suppressed (DCS) \[D₀ \rightarrow K^+π^−\]
  compared to Cabibbo favored (CF) \[D₀ \rightarrow K^−π^+\]

(Belle does not see evidence in this mode)
Evidence for $D^0$ Mixing at CDF (1.5 fb$^{-1}$)

- CDF sees evidence for $D^0$ mixing at $3.8\sigma$ significance by comparing DCS $D^0 \rightarrow K^+\pi^-$ decay time distribution to CF $D^0 \rightarrow K^-\pi^+$ (confirms BaBar).
- Ratio of decay time distributions:

$$R(t/\tau) = R_D + \sqrt{R_D} y'(t/\tau) + \frac{x'^2 + y'^2}{4} (t/\tau)^2$$

where $x' = x \cos \delta + y \sin \delta$ and $y' = -x \sin \delta + y \cos \delta$

$\delta$ is strong phase between DCS and CF amplitudes.

Mixing parameters $x = \Delta M/\Gamma$ and $y = \Delta\Gamma/2\Gamma$ are 0 in absence of mixing.

<table>
<thead>
<tr>
<th>Fit type</th>
<th>$R_D (10^{-3})$</th>
<th>$y' (10^{-3})$</th>
<th>$x'^2 (10^{-3})$</th>
<th>$\chi^2$ / d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconstrained</td>
<td>3.04 ± 0.55</td>
<td>8.5 ± 7.6</td>
<td>-0.12 ± 0.35</td>
<td>19.2 / 17</td>
</tr>
<tr>
<td>Physically allowed</td>
<td>3.22 ± 0.23</td>
<td>6.0 ± 1.4</td>
<td>0</td>
<td>19.3 / 18</td>
</tr>
<tr>
<td>No mixing</td>
<td>4.15 ± 0.10</td>
<td>0</td>
<td>0</td>
<td>36.8 / 19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$R_D (10^{-3})$</th>
<th>$y' (10^{-3})$</th>
<th>$x'^2 (10^{-3})$</th>
<th>Mixing Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>3.04 ± 0.55</td>
<td>8.5 ± 7.6</td>
<td>-0.12 ± 0.35</td>
<td>3.8</td>
</tr>
<tr>
<td>BABAR</td>
<td>3.03 ± 0.19</td>
<td>9.7 ± 5.4</td>
<td>-0.22 ± 0.37</td>
<td>3.9</td>
</tr>
<tr>
<td>Belle</td>
<td>3.64 ± 0.17</td>
<td>0.6 $^{+4.0}_{-3.9}$</td>
<td>0.18 $^{+0.21}_{-0.23}$</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Rare Decays

- In SM FCNC processes are forbidden at tree level → only occur at higher order
- In many new physics models, decay rates of FCNC decays of b- or c-mesons are enhanced w.r.t. SM expectations
- Best limits are set by CDF in various channels:

- 2.0 fb⁻¹

\[ \mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 1.8 \times 10^{-8} \ (1.5 \times 10^{-8}) \quad \text{at 95(90)\%CL} \]
\[ \mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) < 5.8 \times 10^{-8} \ (4.7 \times 10^{-8}) \quad \text{at 95(90)\%CL} \]

- 0.9 fb⁻¹

\[ \mathcal{B}(B^+ \rightarrow \mu^+\mu^-K^+) = (0.60 \pm 0.15 \pm 0.04) \times 10^{-6} \quad \text{consistent with world average and} \]
\[ \mathcal{B}(B^0 \rightarrow \mu^+\mu^-K^0) = (0.82 \pm 0.31 \pm 0.10) \times 10^{-6} \quad \text{competitive with best measurements} \]

\[ \mathcal{B}(B_s \rightarrow \mu^+\mu^-\phi)/\mathcal{B}(B_s \rightarrow J/\psi\phi) < 2.61(2.30) \times 10^{-3} \quad \text{at 95(90)\%CL} \]

- 0.36 fb⁻¹

\[ \text{Br}(D^0 \rightarrow \mu\mu) < 5.3 \times 10^{-7} \ (95\%) \]

- Search for lepton flavor violation with 2fb⁻¹ leads to best limits in \( B_{s/d} \rightarrow e\mu \) channel:

\[ \text{Br} \ (B_s \rightarrow e\mu) < 2.0(2.6) \times 10^{-7} \]
\[ \text{Br} \ (B_d \rightarrow e\mu) < 6.4(7.9) \times 10^{-8} \]