Heavy Flavor Physics at CDF

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Lake Louise Winter Institute
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Introduction

- Great Tevatron performance → close to 5 fb\(^{-1}\) on tape

- Recent Heavy Flavor Physics results from CDF (up to 2.8 fb\(^{-1}\))
  - Lifetimes: \(\Lambda_b, B_c, B_s\)
  - CP violation in \(B_s \rightarrow J/\Psi\Phi\) decays
  - Rare decays
- 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_{c} Mass and Lifetime**

- B_{c} meson contains two heavy quarks: bottom and anti-charm
- Produced only at the Tevatron → unique testing ground for QCD

- Best mass measurement from CDF in B_{c} → J/Ψ π decays (2.4 fb-1):
  \[ 6275.6 ± 2.8(\text{stat}) ± 2.5(\text{syst}) \text{ MeV/c}^2 \text{ Phys.Rev.Lett.100:182002,2008} \]

- Lifetime measurement in semileptonic decays B_{c} → J/Ψ e/µ (1.0 fb-1)
  http://www-cdf.fnal.gov/physics/new/bottom/080327.blessed-BC_LT_SemiLeptonic

\[ c\tau = 142.5^{+15.8}_{-14.8} \text{ (stat.)} ± 5.5 \text{ (syst.)} \text{ µm.} \]

- Speaker’s lifetime average 0.459 ± 0.037 ps
  - theoretical predictions 0.47 – 0.59 ps
**Λ_b Lifetime in Λ_b→Λ_cπ**

- Important test of models that describe interactions between heavy and light quarks within bound states
- In simple spectator model all b-hadrons have same lifetime
- Precise theoretical predictions difficult due to QCD effects
- OPE/HQET predicts lifetime hierarchy of b-hadrons:
  \[ \tau(B_c) < \tau(Λ_b) < \tau(B_s) \approx \tau(B^0) < \tau(B^+) \]
- CDF analysis with large sample of ~3000 signal events in ~1.1 fb⁻¹
- Displaced track trigger requirements: 120 μm < IP < 1 mm
  → observed lifetime distribution is not an exponential
- Trigger bias corrected using simulation

<table>
<thead>
<tr>
<th>τ(Λ_b)</th>
<th>τ(B^0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory</td>
<td>0.88±0.05</td>
</tr>
<tr>
<td>Exp.</td>
<td>0.92±0.036</td>
</tr>
</tbody>
</table>

CDF II Preliminary, L = 1.1 fb⁻¹

![Graph showing decay time distribution](image-url)
Λ\(_b\) Lifetime Results

- Most precise Λ\(_b\) lifetime measurement:

\[
ct(Λ_b) = 422.8 \pm 13.8 \text{ \(\mu\)m (stat.)} \pm 8.8 \text{ \(\mu\)m (syst.)}
\]

- Main systematic from trigger bias
- Good agreement with theory prediction (0.88 ± 0.05)

\[
\frac{\tau(Λ_b) [\text{this}]}{\tau(B^0) [\text{PDG}]} = 0.922 \pm 0.039
\]

... and with previous world average

CDF II Preliminary, L=1.1 fb\(^{-1}\)

Λ\(_b\) Lifetime Measurements

<table>
<thead>
<tr>
<th>Source</th>
<th>Lifetime (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH Λ(_c) I + Λ(^0) II</td>
<td>1.21 ± 0.11</td>
</tr>
<tr>
<td>OPAL Λ(_c) I</td>
<td>1.29 ± 0.24 ± 0.06</td>
</tr>
<tr>
<td>DELPHI Λ(_c) I</td>
<td>1.11 ± 0.19 ± 0.05</td>
</tr>
<tr>
<td>CDF RunII Λ(_c) I</td>
<td>1.32 ± 0.15 ± 0.07</td>
</tr>
<tr>
<td>D0 RunII Λ(_c) I</td>
<td>1.29 ± 0.20 ± 0.07</td>
</tr>
<tr>
<td>D0 RunII J/ψ Λ</td>
<td>1.21 ± 0.13 ± 0.042</td>
</tr>
<tr>
<td>CDF RunII J/ψ Λ</td>
<td>1.59 ± 0.063 ± 0.033</td>
</tr>
<tr>
<td>CDF RunII Λ(_c) π (PRELIMINARY)</td>
<td>1.410 ± 0.046 ± 0.029</td>
</tr>
</tbody>
</table>

PDG 2008
Bs Lifetime in Flavor Specific Decays $B_s \rightarrow D_s \pi X$

- Decay modes:
  - fully reconstructed $B_s \rightarrow D_s \pi$ (~1100 events)
  - partially reconstructed (2200 events)

- Treatment of lifetime trigger bias similar to $\Lambda_b \rightarrow \Lambda_c \pi$

- Procedure tested and on control samples and found good agreement with world average

- 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 $B_s \rightarrow J/\Psi\Phi$

- Higher value will bring average closer to HQET prediction
  $$\frac{\tau_s}{\tau_d} = 1.0 \pm 0.02$$

- Compared to HFAG 2007: $\frac{\tau_s}{\tau_d} = 0.94 \pm 0.02$
CP Violation in $B_s \to J/\Psi \Phi$ Decays

- CP violation phase $\beta_s$ in SM is predicted to be very small, $O(\lambda^2)$
  \[
  \beta_s^{SM} = \arg(-V_{ts} V_{tb}^*/V_{cs} V_{cb}^*) \approx 0.02
  \]
  → New Physics CPV can compete or even dominate over small Standard Model CPV
- Ideal place to search for New Physics
- Signal yield $\sim 3200$ events in $2.8$ fb$^{-1}$

- Average $B_s$ lifetime:
  $\tau(B_s) = 1.53 \pm 0.04$ (stat) $\pm 0.01$ (syst) ps

- Decay width difference $\Delta \Gamma$:
  $\Delta \Gamma = 0.02 \pm 0.05$ (stat.) $\pm 0.01$ (syst.) ps$^{-1}$
CP Violation Phase $\beta_s$ in Tagged $B_s \rightarrow J/\Psi \Phi$ Decays

- Standard Model probability: 7%, $\sim 1.8\sigma$


- HFAG combines old CDF (1.4 fb$^{-1}$, 1.5 $\sigma$ from SM) and DØ (2.8 fb$^{-1}$, 1.7 $\sigma$ from SM) results yield a 2.2 $\sigma$ deviation from SM (similar results found by UTFit and CKM collaborations).

- The latest CDF analysis (2.8 fb$^{-1}$, 1.8 $\sigma$ from SM) not yet included

- Interesting to see $\beta_s$ with 6/8 fb$^{-1}$ by the end of 2009/2010
Search for $B_{s,d} \rightarrow e^+ \mu^-$ Decays

- Neutrino oscillations: the only process observed in nature which violates lepton flavor
  → lepton flavor violation should occur in charge lepton sector
- Can search for $B_{s,d} \rightarrow e^+ \mu^-$ decays
  - within SM expected to occur at extremely low rates
- Physics beyond SM may enhance rates of such decays
- Pati-Salam GUT theory predicts existence of spin 1
gauge bosons with both lepton and color quantum
numbers (leptoquarks)  
  \textit{PRD 10,275 (1974)}
- Upper limits on leptoquark masses inferred from
upper limits of lepton flavor violation processes
like $B_{s,d} \rightarrow e^+ \mu^-$ decays
- Use $B^0 \rightarrow K\pi$  $B_s \rightarrow K K$ decays selected by
displaced track trigger as normalization modes

\[ B(B_s^0 \rightarrow e\mu) < 2.0(2.6) \times 10^{-7} \text{ @ 90(95)\% C.L.} \]
\[ M_{LQ}(B_s^0 \rightarrow e\mu) > 47.7(44.6) \text{ TeV/c}^2 \text{ @ 90(95)\% C.L.} \]
\[ B(B_d^0 \rightarrow e\mu) < 6.4(7.9) \times 10^{-8} \text{ @ 90(95)\% C.L.} \]
\[ M_{LQ}(B_d^0 \rightarrow e\mu) > 58.6(55.7) \text{ TeV/c}^2 \text{ @ 90(95)\% C.L.} \]

http://www-cdf.fnal.gov/physics/new/bottom/080612.blessed-Bs_emu_limit/
FCNC 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 (will approach SM prediction by the end of Run 2):
  \[ \text{Br}(B^0 \rightarrow \mu^+\mu^-) < 1.8(1.5) \times 10^{-8} \text{ at } 95(90)\% \text{ CL} \] (SM: ~10⁻⁹)
  \[ \text{Br}(B_s \rightarrow \mu^+\mu^-) < 5.8(4.7) \times 10^{-8} \text{ at } 95(90)\% \text{ CL} \] (SM: ~10⁻⁹)

- 2 fb⁻¹:
  \[ \text{Br}(B_s \rightarrow e^+e^-) < 2.8(3.7) \times 10^{-7} \text{ at } 95(90)\% \text{ CL} \] (SM ~10⁻¹⁵)
  \[ \text{Br}(B_d \rightarrow e^+e^-) < 8.3(10.6) \times 10^{-8} \text{ at } 95(90)\% \text{ CL} \] (SM ~10⁻¹⁵)

- 0.9 fb⁻¹
  \[ \text{B}(B^+ \rightarrow \mu^+\mu^-K^+) = (0.60 \pm 0.15 \pm 0.04) \times 10^{-6} \] consistent with world average and
  \[ \text{B}(B^0 \rightarrow \mu^+\mu^-K^0) = (0.82 \pm 0.31 \pm 0.10) \times 10^{-6} \] competitive with best measurements

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

- 0.36 fb⁻¹
  \[ \text{Br}(D^0 \rightarrow \mu\mu) < 5.3(4.3) \times 10^{-7} \text{ at } 95(90)\%\text{CL} \] (SM ~4×10⁻¹³)
- Many other recent results not covered in this talk:
  - Mass Measurement of the $X(3872)$ State
  - Search for Narrow Resonances below the Mesons
  - $b$ baryons: $\Sigma_b, \Xi_b$
  - 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
  - $b$-$\bar{b}$ correlation
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
B Physics at the Tevatron

- Mechanisms for b production in pp 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: Bs, Bc, Λb, Ξb, Σb…
  → complement the B factories physics program

- Total inelastic cross section at Tevatron is ~1000 larger than b cross section
  → large backgrounds suppressed by triggers that target specific decays
CDF B Physics Triggers

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

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

  - di-muon (B → J/Ψ X, B → µµ)

  - two displaced tracks (hadronic decays)
Trigger Efficiency Checks and Systematic Uncertainty

- Use lifetime un-biased $J/\Psi \rightarrow \mu\mu$ sample to determine trigger efficiency as function of $J/\Psi$ vertex displacement in both data and simulation
- Data/simulation efficiency ratio is flat well within statistical uncertainty
- Use slope of linear fit to evaluate systematic uncertainty
- Leads to largest systematic: $\sim 6 \, \mu m$ out of $9 \, \mu m$ total systematic
Simulation Free Lifetime Method in $B^+ \rightarrow D^0 \pi^+$ (1fb$^{-1}$)

- CDF has large sample of fully reconstructed decays of $b$ hadrons collected by trigger which requires two displaced tracks with $120 \text{ mm} < d_0 < 1\text{ mm}$
  → 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
\( B_s \rightarrow J/\Psi \Phi \) Phenomenology

- \( B_s \rightarrow J/\Psi \Phi \) decay rate as function of time, decay angles and initial \( B_s \) flavor:

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

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

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

- Tagging \( \rightarrow \) better sensitivity to \( \beta_s \)

\['strong' phases:
\( \delta_{\parallel} \equiv \arg(A^*_\parallel A_0) \)
\( \delta_{\perp} \equiv \arg(A^*_\perp A_0) \]
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 ($\varepsilon D^2 \sim 4.5\%$ compared to B factories $\sim 30\%$)

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

\[
2\Delta \log(L) = 2.3 \approx 68\% \text{ CL} \\
2\Delta \log(L) = 6.0 \approx 95\% \text{ CL}
\]
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\[
2\Delta \log(L) = 2.3 \approx 68\% \text{ CL} \\
2\Delta \log(L) = 6.0 \approx 95\% \text{ CL}
\]

un-tagged

un-tagged

tagged
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:

<table>
<thead>
<tr>
<th>'short range' processes (negligible in SM)</th>
<th>'long range' processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>d, s, b</td>
</tr>
<tr>
<td>[\Delta \Gamma/\Gamma]</td>
<td>B⁰</td>
</tr>
<tr>
<td>Bₛ</td>
<td>27</td>
</tr>
<tr>
<td>D⁰</td>
<td>&lt; few%</td>
</tr>
</tbody>
</table>

- Recent D⁰ mixing evidence ← different D⁰ decay time distributions in

**Belle**
D⁰ → ππ, KK (CP eigenstates) compared to D⁰ → Kπ

**BaBar**
doubly Cabibbo suppressed (DCS) D⁰ → K⁺π⁻ compared to Cabibbo favored (CF) D⁰ → K⁻π⁺ (Belle does not see evidence in this mode)
Evidence for D⁰ Mixing at CDF (1.5 fb⁻¹)

- CDF sees evidence for D⁰ mixing at 3.8σ significance by comparing DCS D⁰ → K⁺π⁻ decay time distribution to CF D⁰ → K⁻π⁺ (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 \(x = \Delta M/\Gamma\) \(y = \Delta \Gamma/2\Gamma\) 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 / \text{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</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>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>(\text{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 +0.14 -0.13</td>
<td>0.18 +0.21 -0.23</td>
<td>2.0</td>
</tr>
</tbody>
</table>