Beauty and charm decay physics at CDF

S. Donati
University and INFN Pisa

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Why B physics at $\bar{p}p$ collider

Open wide spectrum of B hadrons:
- $B^\pm$, $B^0$, $B_s$, $B_c$, $\Lambda_b$, $\Xi_b$

$b\bar{b}$ cross section is 50–100 $\mu$b
$\sim O(10^5)$ larger than @\(\Upsilon(4S)/Z^0\)

$c\bar{c}$ cross section even larger
($\times 10$ $b\bar{b}$ cross section)

See Peter J. Bussey’s talk on Charm and Beauty production at CDF

BUT:
B hadrons are hidden in a $10^3$ larger background ($\sigma_{\text{inelastic}(p\bar{p})} \approx 50$ mb)

Events more complicated than at $\Upsilon(4S)$

Crucial detector components:
- Tracking system
  Excellent pt res./Vertexing
- Trigger
  Large bandwidth
  Strong background reduction
- Particle identification
CDF Detector in Run II

Inherited from Run I:
- Central Calorimeter (|\eta|<1)
- Solenoid (1.4T)

Partially New:
- Muon system (extended to |\eta|\sim 1.5)

Completely New:
- Tracking System
  - 3D Silicon Tracker (up to |\eta|\sim 2)
  - Faster Drift Chamber (dE/dx)
- Time-of-Flight (particle ID)
- Plug and Forward Calorimeters
- DAQ & Trigger system (Online Silicon Vertex Tracker: trigger on displaced vertices, first time at hadron collider)
Tevatron $p\bar{p}$ collider

Center of mass energy: 1.96 TeV
Collision rate: 396 ns crossing time
(36x36 bunches) $\rightarrow$ ~2M collisions/sec

Goal was 8E31 w/o Recycler

Peak Luminosity: ~7E31

Data for physics (Data taking eff. 80% - 90%)

Detector commissioning
First data for analysis

CDF analyses reported in this talk use ~65 to ~190 pb$^{-1}$
**Triggers and data samples**

**Conventional**

- **Di-Muon** $(J/\psi)$
  
  $Pt(\mu) > 1.5 \text{ GeV}$
  
  $J/\psi$ modes down to low $Pt(J/\psi)$ (~ 0 GeV)

  - Masses, lifetimes
    
    (fully rec. $B \rightarrow J/\psi X$)
  
  - Quarkonia, rare decays ($B_{s(d)} \rightarrow \mu\mu$)

**Unconventional**

- **Displaced trk** + lepton ($e$, $\mu$)
  
  $IP(\text{trk}) > 120 \mu m$
  
  $Pt(\text{lepton}) > 4 \text{ GeV}$

  - High statistics lifetime
  
  - Sample for tagging studies, mixing

- **2-Track Trig.**
  
  $Pt(\text{trk}) > 2 \text{ GeV}$
  
  $IP(\text{trk}) > 100 \mu m$

  - $CP$ asymmetry in 2-body/multibody charmless decays

- **Fully hadronic modes**
  
  - $B_s$ mixing
  
  - Charm physics

- **Semileptonic modes**

  - High statistics lifetime

- **Fully hadronic modes**

  - $B_s$ mixing

- Charm physics

**Primary Vertex**

**Secondary Vertex**

$B$

$PT(B) \geq 5 \text{ GeV}$

$L_{xy} \geq 450 \mu m$

$d = \text{impact parameter}$
B hadron masses measurements

Competitive measurements for \( B_d \) and \( B^+ \):
\[
M(B_d) = 5280.30 \pm 0.92 \pm 0.96 \text{ MeV}/c^2 \\
M(B^+) = 5279.32 \pm 0.68 \pm 0.94 \text{ MeV}/c^2
\]

World's best measurements for \( B_s \) and \( \Lambda_b \):
\[
M(B_s) = 5365.50 \pm 1.29 \pm 0.94 \text{ MeV}/c^2 \\
M(\Lambda_b) = 5620.4 \pm 1.6 \pm 1.2 \text{ MeV}/c^2
\]
B Lifetimes

**Heavy Quark Expansion predictions for B lifetimes:**

\[ \tau(B_c) \ll \tau(\Xi_b^0) \sim \tau(\Lambda_b) < \tau(B^0) \sim \tau(B_s) < \tau(B^-) < \tau(\Xi_b^-) < \tau(\Omega_b) \]

HQE gives precise predictions for lifetime ratios - good testing ground:

\[ \tau(B^+)/\tau(B^0) = 1.067 \pm 0.027 \]

\[ \tau(B_s)/\tau(B^0) = 0.998 \pm 0.015 \]

\[ \tau(\Lambda_b)/\tau(B^0) = 0.90 \pm 0.05 \]

CDF is now approaching Run I precision and is currently limited only by statistics. Run II will provide real test of HQE
Exclusive $B \rightarrow J/\psi K$ lifetime

$B^+ \rightarrow J/\psi K^+$: 2160 events
$B^+ \rightarrow J/\psi K^{*+} (K^{*+} \rightarrow K_s \pi)$: 200 events
$B^0 \rightarrow J/\psi K^{*0} (K^{*0} \rightarrow K \pi)$: 950 events
$B^0 \rightarrow J/\psi K_s$: 600 events

$\tau(B^+) = 1.66 \pm 0.04(\text{stat}) \pm 0.02(\text{sys})$ ps
$\tau(B^0) = 1.49 \pm 0.05(\text{stat}) \pm 0.03(\text{sys})$ ps
$\tau(B^+)/\tau(B^0) = 1.119 \pm 0.046(\text{stat}) \pm 0.014(\text{sys})$

Unbinned simultaneous fit of $M_B$: extract signal fraction
$ct$: extract the lifetime

Largest systematic error from background model
Exclusive $B_s \rightarrow J/\psi \phi$ lifetime
($B_s$ Unique to Tevatron)

$\tau(B_s) = 1.33 \pm 0.14\text{(stat)} \pm 0.02\text{(sys)} \text{ ps}$

$\tau(B_s)/\tau(B^0) = 0.88 \pm 0.11\text{(stat)}$

With more statistics
Angular analysis measures $\Delta \Gamma_s = B_s^H - B_s^L$

Large $CP$ asymmetry (measures phase of $V_{ts}$) is a signal of new physics (requires $\Delta m_s$)
**Rare decays: $B_d(s) \rightarrow \mu^+\mu^-$**

*Standard Model* predicts $\text{BR}(B_s \rightarrow \mu^+\mu^-) = (3.8 \pm 1.0) \times 10^{-9}$

Several *SM* extensions predict an enhancement by 1 to 3 orders of magnitude: no excess already constrains several *SUSY* models

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**CDF II**

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<tr>
<th>M($\mu^+\mu^-$) [GeV/c]</th>
<th>entries</th>
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<tbody>
<tr>
<td>4.8</td>
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<td>5</td>
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<td>5.8</td>
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<table>
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<th>entries</th>
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<tr>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>0.3</td>
<td>0.1</td>
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</tbody>
</table>

**CDF Run II Preliminary**

- $B^0_{s(d)} \rightarrow \mu^+\mu^-$
- 171 pb$^{-1}$

**1 event in the overlap region**

"Blind" analysis: cuts were optimized before looking at the signal mass region
Rare decays: $B_d(s) \rightarrow \mu^+\mu^-$

<table>
<thead>
<tr>
<th></th>
<th>$B_s \rightarrow \mu^+\mu^-$</th>
<th>$B_d \rightarrow \mu^+\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Background</strong></td>
<td>$1.05\pm0.30$</td>
<td>$1.07\pm0.31$</td>
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<tr>
<td><strong>Data</strong></td>
<td>1</td>
<td>1</td>
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<tr>
<td><strong>BR limit @95% C.L.</strong></td>
<td>$7.5 \times 10^{-7}$</td>
<td>$1.9 \times 10^{-7}$</td>
</tr>
<tr>
<td><strong>BR limit @90% C.L.</strong></td>
<td>$5.8 \times 10^{-7}$</td>
<td>$1.5 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

Best world result for $B_s$ (improves CDF Run I)

Slightly better results than Belle and BaBar for $B_d$

Measured/Expected BR limits vs. luminosity

Best published limit (CDF)

Extrapolations based on 110 pb$^{-1}$ using $|\eta(\mu)|<0.6$, $P_t(B_s)>6$ GeV/c

this result with 171 pb$^{-1}$
B+/B0 from lepton+displaced track

CDF: high statistics semileptonic B samples
Excellent calibration samples for B+/B0 lifetime, tagging and B0 mixing

B+ → l+ D0X (D0 → Kπ): ~41,800 events
B+ → l+ D*X (D*X → D0π): ~8,400 events
B+ → l+ D+X (D+ → Kππ): ~18,700 events

Run II yields significantly larger, lower lepton pt threshold possible thanks to i.p trigger
**B_S from lepton + displaced track**

\[ B_S \rightarrow D_s \nu \rightarrow [\phi \pi] \nu \rightarrow [[KK] \pi] \nu \]

**ONLY @ Tevatron**

**HIGH STATISTICS SAMPLE:**

- Inclusive lifetime: \( \frac{\tau(B_s)}{\tau(B_d)} \)
- Mixing (moderate \( x_s \)): good S/N, limited time resolution: back-up sample

\[ B_s \rightarrow D_s \nu \rightarrow [\phi \pi] \nu \rightarrow [[KK] \pi] \nu \]

CDF RunII Preliminary

L = 185 pb\(^{-1}\)

**300 \( D_s \rightarrow \pi \pi \pi \)**

**1400 \( D_s \rightarrow \phi \pi \)**

**S/N ~ Run I x 2**

Several \( D_s \) channels reconstructed

\( D_s \rightarrow \phi \pi, D_s \rightarrow \pi \pi \pi, D_s \rightarrow KsK, D_s \rightarrow K*K \)
CDF has unique access to Bs fully hadronic decays
(crucial for CP violation and Bs mixing)
Also huge samples of hadronic charm signals
(CDF results are competitive with charm dedicated experiments)
B→h⁺h⁻⁻: towards \( \gamma \) and direct \( A_{CP} \)

Measure relative fractions of

\( B_{d}^{0} \to \pi^{+}\pi^{-} \) and charge conjugate

\( B_{d}^{0} \to K^{+}\pi^{-} \) and c.c.

\( B_{s}^{0} \to K^{+}K^{-} \) and c.c.

\( B_{s}^{0} \to K^{-}\pi^{+} \) and c.c.

Combine kinematics with dE/dx to achieve statistical separation

(ToF doesn’t help @p_T >2 GeV/c)

Expect ~ 6500 evts / fb^{-1}
Disentangling signals in $B \rightarrow h^+h'^-$

**Specific ionization**

dE/dx calibrated on 78K $D^*$ decays.

$\pi/K \Rightarrow 1.16\sigma$ (improved to $1.4\sigma$)

**Kinematics**

Exploit correlation between mass, charge and momentum imbalance

$M_{\pi\pi}$ vs $(1- p_{\text{min}}/p_{\text{max}})q_{\text{min}}$

CDF RunII Preliminary

$D' \rightarrow D^0 \pi$

$D^0 \rightarrow K\pi$

$(p_t > 2 \text{ GeV/c})$

$\pi/\pi$ separation $= 1.16\sigma$

$B_d \rightarrow \pi\pi$

$B_d \rightarrow K^-\pi^+$

$B_d \rightarrow K^+\pi^-$

$B_s \rightarrow KK$

$B_s \rightarrow K^+\pi^-$

$B_s \rightarrow K^-\pi^+$
B → h⁺h'⁻ results (only 65 pb⁻¹)

Measurement of relative fractions not sensitive to B⁰_s → K⁻ π⁺ yet.

Dominant systematic from dE/dx calibration

\[ f_s \cdot BR(B_s \rightarrow KK) / f_d \cdot BR(B_d \rightarrow K\pi) = 0.74 \pm 0.20\text{(stat)} \pm 0.22\text{(syst)} \]

**First evidence of Bs → K⁺K⁻ decay**

Direct ACP(B_d → K\pi) = 0.02 ± 0.15(stat) ± 0.02(syst)

15% statistical error, systematics comparable to B-factories

\[ BR(B_d \rightarrow \pi\pi) / BR(B_d \rightarrow K\pi) = 0.26 \pm 0.11\text{(stat)} \pm 0.06\text{(syst)} \]

Consistent with B-factories results
**Angle $\gamma$ from $B^0 \rightarrow h^+h^-$**

$B^0 \rightarrow \pi^+\pi^-$ has two (comparable) decay amplitudes:

- **Tree**
  - $B^0 \left\{ \bar{b}, \bar{d}, \bar{u} \right\} \pi^+$
  - $\{ d, u \} \pi^-$

- **Penguin**
  - $B^0 \left\{ \bar{d}, \bar{u} \right\} \pi^+$
  - $\{ d, u \} \pi^-$

$\mathcal{A}_{CP}(t) = \mathcal{A}_{CP}^{\text{dir}} \cos(\Delta m_d t) + \mathcal{A}_{CP}^{\text{mix}} \sin(\Delta m_d t)$

$\mathcal{A}_{CP}^{\text{dir}}, \mathcal{A}_{CP}^{\text{mix}}$ functions of $\gamma, \beta, d, \theta$  

($d e^{i\theta} \approx P/T$ decay amplitude)

**R. Fleischer (PLB 459 (1999) 306):**

Assume U-spin symmetry ($d \leftrightarrow s$)

Similar relation holds for $B_s \rightarrow K^+K^-$ ($\Delta m_d$ replaced by $\Delta m_s$)

The 4 asymmetries can be expressed as function of $\gamma, \beta$ and $P/T$.

Parameters can be extracted from fit of $\mathcal{A}_{CP}(t)$ for $B_d \rightarrow \pi\pi$ and $B_s \rightarrow KK$
**CPV in other B → PV and B → V V**

Measure direct $A_{CP}$ in $B^+ \to \phi K^+ \to [K^+ K^-] K^+$ and c.c.

$$\frac{BR(B^\pm \to \phi K^\pm)}{BR(B^\pm \to J/\psi K^\pm)} = [6.8 \pm 2.1 (stat) \pm 0.7 (syst)] \cdot 10^{-3}$$

**Searching for B → VV**

$B^0_s \to \phi \phi$ and c.c. ($\Delta \Gamma_s$ too)

$B^0_d \to \phi K^*$ and c.c.

$B^0_d \to \phi K^0_s$ and c.c.

..and for baryons (SM expects ~10% CPV)

$\Lambda^0_b \to \phi \Lambda$ and c.c.

$\Lambda^0_b \to pK^-/p\pi^-$ and c.c.
Evidence for $B_s \rightarrow \phi\phi$

Angular distributions in $B \rightarrow VV$ allow measurement of $\gamma$ (theoretically clean)

$$BR = (1.4 \pm 0.6 \text{ (stat)} \pm 0.2 \text{ (syst.)} \pm 0.5 \text{ (BRs}) \times 10^{-5}$$

BR measured relative to $B_s \rightarrow J/\psi\phi$

**CDF RunII Preliminary**  
$L = 179 \pm 10 \text{ pb}^{-1}$

8 events in search window  
Expected BG events = $0.75 \pm 0.41$

~4σ significance

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>XFT efficiency by particle species</td>
<td>7.0%</td>
</tr>
<tr>
<td>XFT efficiency due to COT ageing</td>
<td>0.3%</td>
</tr>
<tr>
<td>other time dependent efficiency</td>
<td>2.4%</td>
</tr>
<tr>
<td>Polarization of decay</td>
<td>7.0%</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ theory uncertainty</td>
<td>3.5%</td>
</tr>
<tr>
<td>$\psi\phi$ yield determination</td>
<td>6.1%</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>3.2%</td>
</tr>
<tr>
<td>track-muon stub matching efficiency</td>
<td>5.8%</td>
</tr>
<tr>
<td>sub-total</td>
<td>14.2%</td>
</tr>
<tr>
<td>BR($\psi\phi$) and daughter BR</td>
<td>36%</td>
</tr>
<tr>
<td>Total</td>
<td>38.7%</td>
</tr>
</tbody>
</table>
Ingredients for $B^0_s$ mixing

$$A_{\text{mix}}(t) = \frac{N_{\text{unmix}}(t) - N_{\text{mix}}(t)}{N_{\text{unmix}}(t) + N_{\text{mix}}(t)} = D \cdot \cos(\Delta m_s t)$$

1. **Reconstruct the final state** (use fully rec. $B^0_s \rightarrow D^-_s \pi^+(3\pi)$) with good S/B (thanks to precise tracking, vertexing, PID)

2. **Measure proper decay time:**

   \[ c\tau = \frac{L_{xy}}{\gamma \beta} \; ; \; \gamma \beta = P_T(B) / M(B) \]

   \[ \sigma_{c\tau} = \left( \frac{\sigma_{L}}{\gamma \beta} \right) \oplus \left( \frac{\sigma_{\gamma \beta}}{\gamma \beta} \right) \cdot c\tau \]

   **Current limit:** $\Delta m_s \geq 14.4 \text{ ps}^{-1}$

   **67 fs** (SVX II detector)

   **50 fs** (also Layer 00 is used)

   Error on B momentum, $\sim 15\%$ (semileptonic) negligible ($\sim 0.5\%$) for fully reconstructed final states

3. **Identify the flavor of $B_s$ at production:** B-flavor tagging algorithms
First steps towards $B^0_s$ mixing

“Golden channel”: $B^0_s \rightarrow D^-_s \pi^+ \rightarrow [\phi \pi^-] \pi^+ \rightarrow [[K^+K^-]\pi^-] \pi^+$

maximum proper time resolution resolves fast oscillations.

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

$N(B^0_s) = 84 \pm 11$

$N(B^0) = 1135 \pm 43$

$S/B \sim 2$

Yield/Lum=$0.7 \text{ pb}$

$D^-_s \pi^+$ Mass [$\text{GeV}/c^2$]

$f_s \cdot BR(B^0_s \rightarrow D^-_s \pi^+) / f_d \cdot BR(B^0_d \rightarrow D^- \pi^+) = 0.35 \pm 0.05(stat) \pm 0.04(syst) \pm 0.09(BR)$

Low statistics: plan to add $B_s \rightarrow D_s 3\pi$ and $D_s \rightarrow K^*K/K_sK/3\pi$
B Flavor Tagging

**OST** (opposite side tagging): B’s produced in pairs → tag flavor of opposite B

**JETQ**: sign of the weighted average charge of opposite B-Jet

**SLT**: identify the soft lepton from semileptonic decay of opposite B

**SST** (same side tagging): \( \overline{B^0} (B^0) \) is likely to be accompanied by a \( \pi^+ (\pi^-) \)

Search for the track with minimum \( P_T^{REL} \)

**Kaon taggers** (new in CDF):

<table>
<thead>
<tr>
<th>CDF tagger</th>
<th>( \varepsilon D^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft muon</td>
<td>( 0.7 \pm 0.1 % )</td>
</tr>
<tr>
<td>Soft electron</td>
<td>in progress</td>
</tr>
<tr>
<td>Jet charge</td>
<td>in progress</td>
</tr>
<tr>
<td>Same side</td>
<td>( 2.4 \pm 1.2 % )</td>
</tr>
<tr>
<td>Kaon</td>
<td>in progress</td>
</tr>
</tbody>
</table>
Hadronic $\Lambda_b \to \Lambda_c \pi$ signal

$\Lambda_b \to \Lambda_c \pi \to [pK\pi] \pi$

Largest fully rec. hadronic channel

- Measure mass, lifetime, polarization
- Precise Lifetime $\to \frac{\tau(\Lambda_b)}{\tau(B^0)}$

Discrepancy with theory:
Is it valid for baryons?

$f_{\Lambda_b} \cdot BR(\Lambda_b \to \Lambda_c \pi)/f_d \cdot BR(B_d \to D\pi) = 0.66 \pm 0.11\text{(stat)} \pm 0.09\text{(syst)} \pm 0.18\text{(BR)}$
Cabibbo-suppressed decays of $D^0$

Cabibbo suppressed $D^0$ decays seen in mass plot.

$\Gamma(D^0 \rightarrow KK)/\Gamma(D^0 \rightarrow K\pi) = 9.96 \pm 0.11 \pm 0.12\%$

$\Gamma(D^0 \rightarrow \pi\pi)/\Gamma(D^0 \rightarrow K\pi) = 3.608 \pm 0.054 \pm 0.040\%$

compare with FOCUS (2003)

$\Gamma(D^0 \rightarrow KK)/\Gamma(D^0 \rightarrow K\pi) = 9.93 \pm 0.14 \pm 0.14\%$

$\Gamma(D^0 \rightarrow \pi\pi)/\Gamma(D^0 \rightarrow K\pi) = 3.53 \pm 0.12 \pm 0.06\%$

CP asymmetry: tagging the soft $\pi$ with $D^*$ decays.

$A(D^0 \rightarrow KK) = 2.0 \pm 1.2 \text{(stat)} \pm 0.6 \text{(syst)} \%$

$A(D^0 \rightarrow \pi\pi) = 3.0 \pm 1.3 \text{(stat)} \pm 0.6 \text{(syst)} \%$
FCNC with $D^0 \rightarrow \mu \mu$ decays

SM BR is $3 \times 10^{-13}$, can grow by $10^7$ in R-violating SUSY

$D^0 \rightarrow \pi \pi$ used as reference sample

0 events observed, $1.6 \pm 0.7$ estimated from BG

$BR(D^0 \rightarrow \mu \mu) < 2.5 (3.3) \times 10^{-6}$ at 90% (95%) CL

(improves PDG by a factor 2)
Conclusions

The upgraded CDF detector is taking new data

Great B physics potential, we have results on:
- Masses, lifetimes in the $B \to J/\psi K$ exclusive channels and production cross sections
- New impact parameter trigger: huge and clean semileptonic/all hadronic B signals (also Charm):
  - Large and clean $B \to \pi X$ signals reconstructed (excellent for lifetime, tagging and $\Delta m_d$ meas.)
  - $B^0 \to h^+h^-$: important results on our way to $\gamma$
    ($B^0_s \to KK$, CP in $B^0_d \to K\pi$)
  - $B^0_s \to D^-\pi^+$: first ingredients towards $\Delta m_s$

Lots of Beauty (and Charm) at the Tevatron