Heavy-Quark Physics at the Tevatron: Charm, Bottom and Top

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For the CDF and D0 Collaborations
Tevatron upgrades/status

• Run 2 upgrades → new physics opportunities:
  – Peak luminosity (goal):
    \(2 \times 10^{31} \rightarrow 2-4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}\)
    → more events
  – Energy: 1.8 → 1.96 TeV
    → larger cross sections
• Tevatron has delivered
  \(~220 \text{ pb}^{-1}\), experiments analyzing \(~<100 \text{ pb}^{-1}\).
• “Run 2a” goal: 2 fb\(^{-1}\),
  20x Run-1 integrated luminosity
D0 and CDF experiments

**D0**

- New tracking: silicon and fibers in magnetic field
- Upgraded muon system
- Upgraded DAQ/trigger (displaced track soon)

**CDF**

- New bigger silicon, new drift chamber
- Upgraded calorimeter, $\mu$, new TOF
- Upgraded DAQ/trigger, esp. displaced-track trigger

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Resonance reconstruction

Both experiments have quality charged-particle tracking!

CDF Run II Preliminary, L=70 pb$^{-1}$

$J/\psi \rightarrow \mu^+\mu^-$

510K signal candidates

D0 Run II Preliminary

$\Omega^+ \rightarrow \Lambda K^+$

$\Sigma^+ \rightarrow \Lambda\pi^+$

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Why care about charm?

• Study CKM angles, CP asymmetries, production mechanisms
• Huge cross sections: large yields in CKM-suppressed modes, access to rare decays
• Control samples for B physics: testbed for analyses, particle ID

FOCUS has charm!

BaBar has charm!

Belle has charm!

CLEO-c has charm!

CDF/D0 have charm?!?
CDF: Charm masses, production

First CDF paper submission!

CDF Run II Preliminary
\( D^+, D_s \rightarrow \phi \pi, \phi \rightarrow KK \)
Unbinned likelihood fit projected

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CDF $D^0 \rightarrow \mu \mu$ search

- SM expectation $\sim 10^{-13}$, RPV SUSY $\sim 10^{-6}$
- Best limit: $< 4.1 \times 10^{-6}$ (90% CL)

- Events from all-hadronic trigger
- Normalize to $D^0 \rightarrow \pi \pi$
- Use $D^*$-tagged $D^0$
- Backgrounds: $0.22 \pm 0.02$ fakes, $1.5 \pm 0.7$ combinatoric
- No events in signal region

- CDF limit: $< 2.4 \times 10^{-6}$ (90% CL)

- Can extend to $D^0 \rightarrow e e, e \mu$ and $D^+ \rightarrow \pi \mu \mu$
- Experience for $B_s \rightarrow \mu \mu$

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CDF D⁰ CP asymmetries – new!

- Large cross section, trigger yield large number of D⁰→ππ, D⁰→KK → measure ratio of BR’s.
- Requiring D*±→D⁰π± identifies flavor → measure CP asymmetry!

\[ A_{CP}(D^0\rightarrow\pi\pi) = (2.0\pm1.7\text{(stat)}\pm0.6\text{(sys)})\% \]
\[ A_{CP}(D^0\rightarrow\text{KK}) = (3.0\pm1.9\text{(stat)}\pm0.6\text{(sys)})\% \]

- Current PDG:

\[ A_{CP}(D^0\rightarrow\pi\pi) = (0.5\pm1.6)\% \]
\[ A_{CP}(D^0\rightarrow\text{KK}) = (2.1\pm2.6)\% \]

- Competitive, statistics-limited!
Why care about bottom?

- $B_d$, $B_u$ provide proof of principle, calibration:
  - Measure CKM angles
  - Rare decay
- $B_s$, $B_c$, $\Lambda_b$ are unique to hadron colliders:
  - Explore properties
  - Test SU(3) flavor symmetry
  - Rare decays
  - Access to $|V_{ts}|$ via $B_s$ mixing – short-term goal!

- Reconstruct final states
- Measure decay time
- Identify flavor

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BOTTOM, STRANGE MESONS
($B = \pm 1$, $S = \mp 1$)

- $B_s^0 = s \bar{b}$, $B_s^{*0} = s \bar{b}$, similarly for $B_s^{*+}$s

- $i(J^{P}) = 0(0^-)$

- Mass $m_{B_s^0} = 5369.6 \pm 2.4$ MeV
- Mean life $\tau = (1.461 \pm 0.057) \times 10^{-12}$ s
  - $\sigma_r = 438 \mu$m
D0/CDF $B_u,B_d$ decays with $J/\psi$
CDF other $B_u, B_d$ decays

Find $B$ decays in all-hadronic trigger samples – PID for $B \to hh$ soon.

Also have signals for semileptonic decay modes.
D0/CDF $B_s$, $\Lambda_b$ decays to $J/\psi$

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CDF other $B_s$, $\Lambda_b$ decays

$D_s\pi$ is a golden mode for $B_s$ mixing!

$65 \pm 4 \, pb^{-1}$ April 3rd 2003  CDF Run 2 PRELIMINARY

$B_s \rightarrow D_s^{(*)}\pi$
$D_s \rightarrow \phi \pi$
$\phi \rightarrow KK$

$\Lambda_b \rightarrow \Lambda_c^+ \pi$
$\Lambda_c \rightarrow p^+ K^- \pi^+$

Normalized $t^0$ reflection based on MC study

$\frac{f_s}{f_d} \frac{Br(B_s \rightarrow D_s \pi)}{Br(B_d \rightarrow D^\pm \pi)} = 0.42 \pm 0.11^{\text{(stat)}} \pm 0.11^{\text{(BR)}} \pm 0.06^{\text{(sys)}}$

Also have signals for semileptonic decay modes for $B_s$, $\Lambda_b$

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D0/CDF lifetimes with J/ψ

Average lifetime of b hadrons, use J/ψ decay length as approximation, correct with MC.

Lifetime of B+, using complete reconstruction of the meson decay length.
### D0/CDF lifetimes with J/ψ

#### PDG

<table>
<thead>
<tr>
<th></th>
<th>PDG</th>
<th>CDF</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_b$ (ps)</td>
<td>1.564 ± 0.014</td>
<td>1.53 ± 0.03 ± 0.04</td>
<td>1.56 ± 0.02 ± 0.07</td>
</tr>
<tr>
<td>$\tau_{Bu}$ (ps)</td>
<td>1.674 ± 0.018</td>
<td>1.57 ± 0.07 ± 0.02</td>
<td>1.76 ± 0.24 (stat)</td>
</tr>
<tr>
<td>$\tau_{Bd}$ (ps)</td>
<td>1.542 ± 0.016</td>
<td>1.42 ± 0.07 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>$\tau_{Bs}$ (ps)</td>
<td>1.461 ± 0.057</td>
<td>1.26 ± 0.20 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>$\tau_{Bu}/\tau_{Bd}$</td>
<td>1.083 ± 0.017</td>
<td>1.11 ± 0.09</td>
<td></td>
</tr>
<tr>
<td>$\tau_{Bs}/\tau_{Bd}$</td>
<td>0.947 ± 0.038</td>
<td>0.89 ± 0.15</td>
<td></td>
</tr>
</tbody>
</table>

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D0 flavor tagging

Identify flavor of B with:
- Muon charge
- Jet charge

Significance of mixing measurement goes as tagging power $\varepsilon D^2$

<table>
<thead>
<tr>
<th></th>
<th>Muon</th>
<th>Jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon$ (%)</td>
<td>8.2±1.9</td>
<td>55.1±4.1</td>
</tr>
<tr>
<td>D (%)</td>
<td>63.9±30.1</td>
<td>21.0±10.6</td>
</tr>
<tr>
<td>$\varepsilon D^2$ (%)</td>
<td>3.3±1.8</td>
<td>2.4±1.7</td>
</tr>
</tbody>
</table>
Why care about top?

Quantum numbers?  
Production properties?  
Decay properties?  
Relation to other particles?  
Is it special?  
Clues to new physics?
SM top-physics overview

Top-antitop pair production via strong interaction:

EW single-top production x2 smaller rate, not seen.

$B(t \rightarrow Wb) = 100\%$, label decays by $W$ modes

$\bar{t} t \rightarrow \ell \nu b \ell \nu b \Rightarrow \text{dilepton (5\%)}$

$\bar{t} t \rightarrow \ell \nu b q q b \Rightarrow \text{lepton + jets (44\%)}$

Theory prediction: $\sigma_{tt} = 6.7^{+0.8}_{-0.9} \text{ pb}$

@ 1.96 TeV (Cacciati et al.)
Dilepton mode

- Clean, low background
- Small rate, two neutrinos

- Two isolated high-$p_T$ leptons ($\ell, \mu$)
- Large missing $E_T$
- At least two jets
- Large total energy
- Backgrounds from $Z/\gamma \rightarrow \ell\ell, WW/WZ, \ell$ fakes, QCD

- CDF: Veto $Z$-mass window for $ee, \mu\mu$; $E_T$ separated from $\ell, \text{jets}$
- D0: Raise $E_T$ cut in $Z$ window

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D0/CDF Run II dilepton results

D0 Run II preliminary:
4 ee, 2 $\mu\mu$, 1 $e\mu$ observed
1.7$\pm$0.5 background, 33-48 pb$^{-1}$

CDF Run II preliminary:
1 ee, 1 $\mu\mu$, 3 $e\mu$ observed
0.3$\pm$0.1 background, 79 pb$^{-1}$

$\sigma(t\bar{t}) = 29.9^{+21.0}_{-15.7}$ (stat) +14.1$^{-6.1}_{-6.1}$ (sys) $\pm$ 3.0(lum) pb

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Lepton plus jets mode

Larger rate than dileptons, straightforward kinematics, substantial backgrounds:
- W+jets production
- QCD multijets
- Detector fakes, dibosons

- One isolated high-\(p_T\) lepton (e,\(\mu\))
- Large missing \(E_T\)
- At least three jets
- Not a dilepton event

D0: Require four jets and kinematics, or soft-lepton b tag
CDF: Require displaced-vertex b tag
D0 Run II lepton plus jets results

• Select $W$ sample (lepton+$E_T$), no soft-lepton $b$ tags.

• Evaluate QCD backgrounds from data in each $N_{jet}$ bin

• Evaluate $W$+jets backgrounds in four-jet events via Berends scaling

• Apply topological cuts: $H_T$, aplanarity

• Count four-jet events

<table>
<thead>
<tr>
<th></th>
<th>$N_W$</th>
<th>$N_{QCD}$</th>
<th>All BG</th>
<th>$N_{obs}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>e+jets</td>
<td>1.3±0.5</td>
<td>1.4±0.4</td>
<td>2.7±0.6</td>
<td>4</td>
</tr>
<tr>
<td>$\mu$+jets</td>
<td>2.1±0.9</td>
<td>0.6±0.4</td>
<td>2.7±1.1</td>
<td>4</td>
</tr>
</tbody>
</table>
D0 Run II lepton plus jets results

- Enhance S/B with soft-lepton tagging, include three-jet events.
- Similar preselection, looser $H_T$, aplanarity requirements

<table>
<thead>
<tr>
<th></th>
<th>All BG</th>
<th>$N_{\text{obs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>e+jets</td>
<td>0.2±0.1</td>
<td>2</td>
</tr>
<tr>
<td>$\mu$+jets</td>
<td>0.7±0.4</td>
<td>0</td>
</tr>
</tbody>
</table>

Lepton plus jets analyses (40-49.5 pb$^{-1}$):

$$\sigma(t\bar{t}) = 5.8^{+4.3}_{-3.4} (\text{stat})^{+4.1}_{-2.6} (\text{sys}) \pm 0.6 (\text{lum}) \text{ pb}$$

(preliminary)

Combined D0 top cross section

$$\sigma(t\bar{t}) = 8.5^{+4.5}_{-3.6} (\text{stat})^{+6.3}_{-3.5} (\text{sys}) \pm 0.8 (\text{lumi}) \text{ pb}$$

(preliminary)
CDF Run II lepton plus jets results

Require at least one jet w/displaced-vertex tag, $\varepsilon_{\text{tag}} = (45 \pm 5)\%$ for $t\bar{t}$.

Account for all non-top SM processes:

- Mistags from “negative” tag rate in data
- Non-$W$ from data
- Dibosons, single-top from MC.
- $W$+heavy flavor from MC fractions, b-tag efficiency, normalized to # of $W$ in data.

Any excess in $\geq 3$ jets attributed to top!
CDF Run II lepton plus jets results

<table>
<thead>
<tr>
<th></th>
<th>W+1jet</th>
<th>W+2jets</th>
<th>W+3jets</th>
<th>W+≥4jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events before tagging</td>
<td>4913</td>
<td>768</td>
<td>99</td>
<td>26</td>
</tr>
<tr>
<td>Events after tagging</td>
<td>31</td>
<td>26</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Background</td>
<td>33.8±5.0</td>
<td>16.4±2.4</td>
<td>2.88±0.05</td>
<td>0.87±0.2</td>
</tr>
<tr>
<td>SM Bkgnd + tt</td>
<td>34.0±5.0</td>
<td>18.65±2.4</td>
<td>7.35±1.4</td>
<td>7.62±2.0</td>
</tr>
</tbody>
</table>

$$\sigma(\bar{t}t) = 5.3 \pm 1.9\text{(stat)} \pm 0.8\text{(sys)} \pm 0.3\text{(lum)}\text{ pb} \ (57.5\text{ pb}^{-1})$$

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CDF Run II top mass

- 33 lepton plus 4 jets candidates
- No b tags required → 24 jet combinations per event, choose one with minimum $\chi^2$
- Fit to signal, background shapes

- Target jet-energy resolution is 3 GeV for Run 2a.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (GeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Energy Measurement</td>
<td>9.3</td>
</tr>
<tr>
<td>Initial and Final State Radiation</td>
<td>2.4</td>
</tr>
<tr>
<td>Background Shape</td>
<td>0.3</td>
</tr>
<tr>
<td>Parton Distribution Functions</td>
<td>1.8</td>
</tr>
<tr>
<td>Monte-Carlo Generators</td>
<td>1.8</td>
</tr>
<tr>
<td>Total</td>
<td>9.9</td>
</tr>
</tbody>
</table>
CDF Run II top mass – b tags

*Require at least one tagged jet:*
  - 12 combinations
  - Better S/B
*Allow lower-energy 4th jet
  - 11 candidates

*Work in progress*
Summary: charm and bottom

• Charm:
  – Detector upgrades give new physics program!
  – Results already competitive with world’s best.
  – Excellent calibration for B physics.

• Bottom:
  – Studies of $B_u$ and $B_d$ give proof of principle.
  – Run 2 already reaching Run 1 precision.
  – Beginning studies of $B_s$ and $\Lambda_b$.
  – Work underway for mixing measurements.
Summary: top and beyond

• Top quark is “rediscovered”:
  – Benchmark measurements performed, consistent with expectations.
  – Starting precision studies of top properties, searches for new physics.

• Experiments are performing to expected capabilities, systematics will still be improved, most measurements are statistics-limited.

• Eagerly awaiting additional data!