Charm Physics at the Tevatron

Kai Yi
Johns Hopkins University
(For the CDF and D0 collaborations)
Weak Interactions and Neutrinos Workshop - 2003
Lake Geneva, Wisconsin
October 8, 2003

Outline

- The Tevatron
- The CDF and D0 Detectors
- Triggers for B/Charm
  - Silicon Vertex Tracker (SVT)
  - Triggers at D0 and CDF
- Cross Sections
  - $J/\psi$ Cross Section
  - Direct Charm Cross Section
- CP Violation in D’s
- Rare Decay: Search for FCNC
- Spectroscopy
  - $\chi_c$ Observation
  - Exotic $D_s$ search
  - Confirmation of X(3872)
- Outlook
The Tevatron

- # of bunches increased: 6X6(3500 ns) to 36X36(396ns)

- Peak Luminosity:
  - $0.16 \times 10^{32} cm^{-2} s^{-1}$ (Run I)
  - $0.8 \times 10^{32} cm^{-2} s^{-1}$ (Run II) by 2005
  - (Record: 0.52) (Run II)
  - $2-4 \times 10^{32} cm^{-2} s^{-1}$ (before LHC)

- Int. Luminosity:
  - $\sim 2 fb^{-1}$ by 2005 (Run II)
  - 330 pb$^{-1}$ delivered
  - 220 pb$^{-1}$ to tape
  - 6-9 fb$^{-1}$ before LHC (Run II)
The CDF and D0 Detectors

- Both Detectors
  - silicon vertex detector (New for D0)
  - solenoid (New for D0)
  - central tracking
  - high rate trigger/DAQ system
  - calorimeter & muon systems

- D0 Detector
  - Excellent electron & muon ID
  - Excellent track acceptance

- CDF Detector
  - Silicon vertex trigger
  - Particle ID (TOF and dE/dx)
  - Excellent mass resolution
Triggers: Revolutionary Silicon Vertex Tracker (SVT)

- Never had hadronic B trigger at Hadron collider (challenging background, high rate)
- Seeded by L1 drift chamber trigger tracks, VME boards find & fit in a 15 μs pipeline, with offline accuracy.
- Significantly reduce L2 trigger rate

- Increase physics sensitivity
  - CDF as “Charm Factory”
  - Hadronic B trigger. $B \rightarrow hh, B_s \rightarrow D_s \pi$
  - Higgs/new particles decaying into b/c quarks

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The D0 Silicon Track Trigger

- Fully built
- In the final commissioning states
- Expect to take data shortly after the shutdown

- D0 Track Fit card
Triggers for B/Charm Physics

- D0 Di-muon-Trigger
  - $J/\psi \to \mu\mu$
  - Two $\mu$ ($|\eta| < 2$)
  - $p_T > 2 - 4$ GeV, $\eta$ dependent

- CDF Di-muon-Trigger
  - $J/\psi \to \mu\mu$
  - Two central $\mu$ ($|\eta| < 1.0$)
  - $p_T > 1.5$ GeV
Triggers for B/Charm Physics

- CDF Two-Track-Trigger (TTT)
  - Hadronic Decays
  - two displaced tracks
  - $p_T > 2$ GeV, $d_0 > 100 \mu m$
  - $\Sigma p_T > 5.5$ GeV
- Large sample: $D^0$, $D_s$, $D^*$...
Cross Section: Introduction and D0 $J/\psi$ Cross Section

Introduction:

- **Run I meas.**, Orders of magnitude larger than **Color singlet**
- **New ingredients** from theorists
  - Gluon **fragmentation** important
  - Color **octet** contribution important...
  - Agree better than 50%
- **D0 $J/\psi |\eta|$** reach of 1.8, $\sigma$ vs $J/\psi |\eta|$ 
- **CDF $p_T(J/\psi)$** down to 0, $\sigma$ vs $J/\psi$ $p_T$
- **D0+CDF**: Whole picture!

- **Dimuon triggers**, 4.7 $pb^{-1}$ of data
- **Two $p_T$ ranges**
- $\sim$ Overall 30% systematic uncertainty
- Agree with D0 Run I and CDF Run I
Cross Section: CDF and D0 $J/\psi$ Cross Section

- **di-muon trigger**, $39.7 \, pb^{-1}$ of data
- cover **whole $J/\psi$ $p_T$ range**
- **Total and diff. incl. cross section (nb)**
  \[ \sigma(p\bar{p} \to J/\psi, |y| < 0.6) \times Br(J/\psi \to \mu\mu) = 240 \pm 1 \pm 30 \]

- $\sigma$ includes direct, feed down, B decays
- For $p_T > 5$ GeV, similar to Run I
  \[ \sigma = 20.8 \pm 0.4 \pm 3.1, \text{ Run II} \]
  \[ \sigma = 17.4 \pm 0.1 \pm 2.6, \text{ Run I} \]
- "Lifetime" distribution to extract B fraction (See Petros's talk)

- prospective measurements(D0+CDF):
  - $\psi(2S)$ cleaner(prompt/secondary)
  - high $p_T$, $p_T^2 \gg m^2$ theoretically reliable
  - polarization, high $p_T$–Run I discrepancy
  - $\Upsilon(1S, 2S, 3S)$ Cross section/polarization
  - $\chi_c$ Cross section

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Cross Section: CDF Charm Cross Section

- two track trigger—charm “factory”.
- direct or from b decay

- direct fraction from impact parameter

CDF Run II Preliminary 5.8 pb\(^{-1}\)

- \(D^{*+} \rightarrow D^{0}\pi^+, D^0 \rightarrow K\pi^+\)
  \(p_T \geq 6\text{GeV/c}\)
  \(N(D^{*+}) = 5515 \pm 85\)

CDF Run II Preliminary 5.8 pb\(^{-1}\)

- \(D^0 \rightarrow K\pi^+\)
  \(p_T \geq 5.5\text{GeV/c}\)
  \(f_D = 86.6 \pm 0.4 \pm 3.5\%\)

CDF Run II Preliminary 5.8 pb\(^{-1}\)

- \(D^{*} \rightarrow K\pi^+\pi^+\)
  \(p_T \geq 6\text{GeV/c}\)
  \(N(D^*) = 28361 \pm 294\)

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Cross Section: CDF Charm Cross Section

CDF Run II preliminary
D^+ Data/Theory Cross Section

CDF Run II preliminary
D^0 Data/Theory Cross Section

CTEQ6M PDF
m_c = 1.5 GeV
Fragm. Func:
from ALEPH
Renorm. & fact. scale
m_T = (m_c^2 + p_T^2)^{1/2}
Uncertainty:
vary scale: 0.5 to 2

- \sigma(D^0, p_T > 5.5 GeV) = 13.3 \pm 0.2 \pm 1.5 \mu b
- \sigma(D^{*+}, p_T > 6 GeV) = 5.2 \pm 0.1 \pm 0.8 \mu b
- \sigma(D^+, p_T > 6 GeV) = 4.3 \pm 0.1 \pm 0.7 \mu b
- \sigma(D_s^+, p_T > 8 GeV) = 0.75 \pm 0.05 \pm 0.22 \mu b

- Measurements higher than FONLL prediction
  by M. Cacciari, P. Nason.
  JHEP 0309, 006(2003)
- Agree within uncertainties
CP violation: CDF Cabbibo suppressed D decay

- CPV asy. for $D^0 \rightarrow KK(\pi\pi)$
- Tag–soft $\pi$, $D^{*+} \rightarrow D^0\pi^+$, $D^{*-} \rightarrow \bar{D}^0\pi^-$
- correction–intrinsic detector charge asymmetry

- $\frac{\Gamma(D^0\rightarrow KK)}{\Gamma(D^0\rightarrow K\pi)} = 9.38 \pm 0.18 \pm 0.10\%$
  - FOCUS 2003: $9.93 \pm 0.14 \pm 0.14\%$
- $\frac{\Gamma(D^0\rightarrow \pi\pi)}{\Gamma(D^0\rightarrow K\pi)} = 3.686 \pm 0.076 \pm 0.036\%$
  - FOCUS 2003: $3.53 \pm 0.12 \pm 0.06\%$
- $A(D^0 \rightarrow K K) = 2.0 \pm 1.7 \pm 0.6\%$, $0.5 \pm 1.6\%$(PDG)
- $A(D^0 \rightarrow \pi\pi) = 3.0 \pm 1.9 \pm 0.6\%$, $0.5 \pm 1.6\%$(PDG)
Rare Decay: FCNC $D^0 \to \mu\mu$

- $\text{BR}(D^0 \to \mu^+\mu^-) \simeq 3 \times 10^{-13} (\text{SM})$
- $\text{BR}$ to $3 \sim 4 \times 10^{-6}$, R-parity violating SUSY
- $D^{*+} \to D^0 \pi^+$ to reduce background
- Normalize to $D^0 \to \pi^+\pi^-$, 69 pb$^{-1}$ from TTT

CDF Run II Preliminary

Normalization mode: $1371 \pm 53 \ D^0 \to \pi^+\pi^-$ in the mass search window

$\int L \ dt = 69 \text{pb}^{-1}$
CMU fiducial

- 1.8 ± 0.7 background events expected
- open blind box, 0 signal observed

\[
\frac{B(D^0 \to \mu\mu)}{B(D^0 \to \pi\pi)} = \frac{N_{\text{upper}}^{CL}(D^0 \to \mu\mu)}{N(D^0 \to \pi\pi)} \times \frac{\epsilon(D^0 \to \pi\pi)}{\epsilon(D^0 \to \mu\mu)}
\]

- $\text{BR}(D^0 \to \mu^+\mu^-) \leq 2.4 \times 10^{-6}$ at 90% CL
- PDG: $\text{BR} \ (D^0 \to \mu^+\mu^-) \leq 4.1 \times 10^{-6}$
Spectroscopy: observation of $\chi_c$ states

- **D0 $\chi_c$ states via conversion:**
  - DØ Run II Preliminary
  - $\chi_{cJ} \rightarrow J/\psi \gamma$
  - $N(\chi_{c1}) = 77\pm12$
  - $N(\chi_{c2}) = 33\pm9$
  - $\Delta M_{c1} = 403.1\pm1.6$ MeV
  - $\sigma = 10.2\pm1.3$ MeV

- **Interesting physics:** BR, Cross Section
- **di-muon trigger, 114 $pb^{-1}$**
- **$J/\psi$ mass window 200 MeV**
- **$\gamma$ recon through conversion $e^+e^-$ pairs**
- **$p_T(\gamma) > 1$ GeV**

- **CDF $\chi_c$ states via calorimeter:**
  - CDF Run 2 Preliminary
  - $\chi_c \rightarrow J/\psi \gamma$
  - 46 $pb^{-1}$

- **Interesting physics:** Cross Section
- **di-muon trigger, 46 $pb^{-1}$**
- **$p_T(\mu) > 2$ GeV, $J/\psi$ mass window 80 MeV**
- **$E_T(\gamma) > 1$ GeV, $\gamma$ through calorimeter**
- **$\sigma(B \rightarrow \chi_cX)$ study in progress**
Spectroscopy: Search for Exotics

- $D_{sJ}(2317)^+ \rightarrow D_s^+ \pi^0$ (BaBar, Apr.):
  - Mass not match expectation for normal $D_{s}^{**}$
  - Models wrong or something else?

- $D_{sJ}(2463)^+ \rightarrow D_{s}^{*+} \pi^0$ (CLEO):

- CDF Search through $D_{s}^{+}\pi^-$, $D_{s}^{+}\pi^+\pi^-$:
  - If exotic, may have analog states like $D_{s}^{+}\pi^-$

- No Signal Seen in $D_{s}^{+}\pi^-$, $D_{s}^{+}\pi^+\pi^-$:
  - $D_{s}\pi^+\pi^-$ allowed if $1^+$; forbidden if $0^+$
  - if $D_{sJ}(2317)$ is the lightest $D_{s}^{**}$
Spectroscopy: Confirmation of new 3872 state to $J/\psi\pi^+\pi^-$

- First Confirmation of Belle’s result
- Info. on production mechanisms
- $\sim 2M \ J/\psi(220 \ pb^{-1})$ at CDF
- Challenging combin. background
- Use inclusive $J/\psi\pi^+\pi^-X$

- New narrow state – Belle (Aug. 10 )
- Using exclusive $B^+ \rightarrow J/\psi\pi^+\pi^-K^+$
- A new Charmonium? or something else?

CDF Strategies:
- minimum $p_T$'s
- good silicon tracks
- only tracks in fixed cone
- optimize $\psi(2s) \rightarrow J/\psi\pi^+\pi^-$
Spectroscopy: Confirmation of new 3872 state to $J/\psi \pi^+ \pi^-$

- $\sim 600$ candidates around 3870 MeV
- Width fixed from $\psi(2S')$ extrapolation
- $M(\pi \pi)$ Cut, Motiv. $\rightarrow$ Belle’s $M(\pi \pi)$

- After $M(\pi \pi)$ cut, $\sim 11 \sigma$ Signal
- $M = 3871.4 \pm 0.7 \pm 0.4$ MeV
  
  Belle: $3872.0 \pm 0.6 \pm 0.5$ MeV

- Good agreement, CDF $\leftrightarrow$ Belle
- Studies in Progress:
  - Charmonium/ $D\bar{D}^*$ molecule/ $X$?
  - Large CDF rate $\rightarrow$ Charmonium?
  - $M(\pi \pi)$ Distribution, $J/\psi \rho$ decay?
  - Prompt/Long lived (Stat. limited)?
  - Angular Distribution(Background)?
  - D0 study in progress
Outlook

• Yield estimate in 220 \( pb^{-1} \)
  - D0 \sim 1M \( J/\psi \), CDF \sim 2M \( J/\psi \)
  - CDF \sim 300k \ Tagged \( D^0 \) from \( D^* \)
  - CDF \sim 900k \( D^+ \rightarrow K^-\pi^+\pi^+ \)

• Cross section:
  - D0+CDF: Cross section/
    Polarization–\( J/\psi, \psi', \Upsilon, \chi_c, \ldots \)
  - CDF: \( c\bar{c} \) correlations

• \( D^0 \) mixing(CDF):
  - \( \Delta\Gamma: D^0 \rightarrow \pi^+\pi^- \) vs \( D^0 \rightarrow K^-\pi^+ \)
  - wrong sign \( D^0 \rightarrow K^+\pi^- \)

• Direct CP violation(CDF):
  - Update \( D^0 \rightarrow \pi^+\pi^- \), \( D^0 \rightarrow K^+K^- \)
  - New channel \( D^+ \rightarrow \pi^+\pi^+\pi^- \)

• FCNC(D0+CDF):
  - Update \( D^0 \rightarrow \mu^+\mu^- \)
  - New channel \( D^+ \rightarrow \pi^+\mu^+\mu^- \)

• Spectroscopy:
  - CDF: More Studies on X(3872)
  - D0+CDF: More Searches…
CDF Run II Preliminary

J/ψ Acceptance

Pt(J/ψ) GeV/c

10^{-2}

10^{-1}

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