New Charm(onium) Results from CDF

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DIS 2003, St. Petersburg
23 April 2003

- The Fermilab accelerator complex
- The CDF II detector
- Production
  - $J/\psi$ cross section
  - Charm cross section
- Cabibbo suppressed D decays
- $D_s, D^+$ Mass Difference
- Search for $D^0 \rightarrow \mu^+\mu^-$
- Summary
Fermilab Accelerator Complex

**p\bar{p} collisions at \( \sqrt{s} = 1.96 \text{ TeV} \) (up from 1.8TeV)**

Increased # of bunches:
- 6 (3500 ns)
- \( \rightarrow \) 36 (396 ns)

**Main Injector**
- (p storage ring up to 150GeV)
- replaces Main Ring

- **Peak luminosity**
  - \( 0.16 \cdot 10^{32}\text{cm}^{-2}\text{s}^{-1} \) (Run I)
  - \( \rightarrow \) \( 0.8 \cdot 10^{32}\text{cm}^{-2}\text{s}^{-1} \) (Run IIa)
  - \( \rightarrow \) \( 2-4 \cdot 10^{32}\text{cm}^{-2}\text{s}^{-1} \) (Run IIb)

- **Run IIa:** \( \int L \, dt \approx 2 \text{ fb}^{-1} \) by 2005
  (factor 20 compared to Run I)

- **Run IIb** \( \int L \, dt \approx 10 - 15 \text{ fb}^{-1} \)
  (before “LHC physics”)

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Trigger Overview

- **Level 1 (5.5\(\mu\)s latency):**
  - Every front-end system stores data in 42 clock cycles deep pipeline
  - 18kHz accept rate (\(\rightarrow\) 40–50 kHz)
  - On L1 accept, data is stored in one of four L2 buffers. Si readout starts.

- **Level 2 (asynchronous):**
  - Nominal 20\(\mu\)s decision time
  - Trigger algorithms run on custom Alpha boards (up to 4)
  - 300Hz accept rate (\(\rightarrow\) 1kHz)
  - Event readout starts on L2A

- **Level 3:**
  - \(\approx\) 250 dual-CPU Linux boxes

- **“Deadtimeless”:** DT only incurred when all L2 or DAQ buffers are full

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L2: Silicon Vertex Tracker

- Major rate reduction at L2 from revolutionary **displaced vertex trigger (SVT)**
- Seeded by L1 (drift chamber) tracks (XFT=eXtremely Fast Tracker), $\approx 150$ VME boards find and fit Silicon tracks, with offline accuracy, in a $15\mu s$ pipeline
- Increases physics sensitivity of CDF
  - CDF as “Charm Factory”
  - Purely hadronic B trigger, e.g. $B^0 \rightarrow \pi^+\pi^-$, $B_s \rightarrow D_s \pi$
  - Higgs/new particles decaying into b/c quarks

Online fit and subtraction of beamline

Online track impact parameter

$\sigma = 47 \mu m$ (incl. $\approx 35\mu m$ beamspot)
Triggers for B/Charm

- CDF has three dedicated triggers for B/Charm physics

**Di-muon**
\[ J/\psi \rightarrow \mu^+\mu^- \]
2 central \( \mu \) (|\( \eta \)| < 1.0) with \( p_T > 1.5 \) GeV
(Run I: > 2.2 GeV)
0.5 Million \( J/\psi \rightarrow \mu^+\mu^- \)
in datasets of \( \approx 70 \) pb\(^{-1}\) each

**Lepton + Track**
Semileptonic Decays
1 \( \mu/e \) with \( p_T > 4 \) GeV
1 addl. track with \( p_T > 2 \) GeV and
SVT \( d_0 > 120\mu m \)
0.5 Million \( B \rightarrow \ell^+ X \)

**Two-Track**
Hadronic Decays
2 tracks with \( p_T > 2 \) GeV,
SVT \( d_0 > 120\mu m \) and
\( \Sigma p_T > 5.5 \) GeV
0.5 Million \( D^0 \rightarrow K\pi \)

**CDF Run II Preliminary, L=70pb\(^{-1}\)**

More than one million fully reconstructed charm decays per 100 pb\(^{-1}\)

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Data Taking

- Run II total: \( \int L \, dt \approx 200 \, \text{pb}^{-1} \) delivered, CDF wrote 150 \( \text{pb}^{-1} \) to tape
- Present analyses make use of up to \( \approx 70 \, \text{pb}^{-1} \) (Run I \( \approx 110 \, \text{pb}^{-1} \))
- 1\( \text{fb}^{-1} \) at BaBar corresponds to about 1\( \text{pb}^{-1} \) at CDF (# of reconstructed \( \text{c} \) mesons)
J/ψ: Following up on Run I

- **Pre-Tevatron:** Colour singlet fusion
  - Low by orders of magnitude

- **Two new ingredients:**
  - Gluon fragmentation important (e.g. CS fragmentation)
  - Colour octet states important - e.g. NRQCD expansion:
    - \( d \sigma (H) = \sum_n d \sigma [c \bar{c} (n)] \langle O^H (n) \rangle \)
    - \( n \) includes colour singlet and octet states
    - Expansion in \( \alpha_s \) and \( v \) (relative velocity of quark and anti-quark)

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CDF Data: PRL 79(1997) 572 (Run 1A data, 18 pb⁻¹)

**Colour octet fragmentation dominates at high \( p_T \)**

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**J/ψ Cross Section**

- Increased cms energy $1.8\text{TeV} \rightarrow 1.96\text{TeV}$
- Dimuon trigger threshold lowered to $1.5\text{GeV}$
  - Acceptance down to $J/ψ$ at rest ($P_T(J/ψ) > 5\text{GeV}$ in Run I)
  - $J/ψ \rightarrow μ^+μ^-$ yield: 3nb (Run I) $\rightarrow$ 9nb (Run II)
- Cross section measurement based on data taken in February to October 2002, $\int L \, dt = 40\text{pb}^{-1}$

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Fit mass spectra using templates from signal MC (including radiative tail from internal bremsstrahlung)

- Chebyshev polynomial for background

**Systematic uncertainties**

- $J/\psi$ polarization: $4 - 10\%$ ($p_T$ dep.)
- $J/\psi$ $p_T$ spectrum: $3 - 30\%$ ($p_T$ dep.)
- L1 trigger efficiency: $-7\%$ to $+13\%$ ($p_T$ dep.)
- Mass fits: $-1\%$ to $+13\%$ ($p_T$ dep.)
- SVXII material description: $-3\%$ to $+6\%$ ($p_T$ dep.)
- Momentum scale: $-0.1\%$ to $+0.7\%$ ($p_T$ dep.)

**Luminosity**

- 6%

**Total**

$7\% \oplus \sigma(p_T(J/\psi))$
Inclusive $J/\psi$ Cross Section

CDF Run II Preliminary

- Data with stat. uncertainties
- Systematic uncertainties

New for Run II

- Soon: separate prompt from $B \to J/\psi X$

Run II vs. Run I:

\[
\sigma(p \bar{p} \to J/\psi X, |y| < 0.6) \cdot BR = 240 \pm 1 \text{ (stat)} + 35–28 \text{ (syst)} \text{ nb}
\]

\[
\sigma(p \bar{p} \to J/\psi X, |\eta| < 0.6, p_T(J/\psi) > 5\text{GeV}) \cdot BR = 17.4 \pm 0.1 \text{ (stat)} + 2.6–2.8 \text{ (syst)} \text{ nb}
\]

Prompt $J/\psi$ cross section includes

- $\chi_c$ decays ($\chi_c \to J/\psi \gamma$)
- $\psi(2S)$ feed-down
- Direct $J/\psi$ (64±6% Run 1)

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Future Onia Measurements

- $\psi(2S) \to$ cleaner (prompt $\equiv$ direct)
- High $p_T$ ($p_T^2 \gg m^2$ theoretically reliable)
- Polarization
- $\gamma(1S,2S,3S)$ cross section/polarization

CDF, PRL 85 (2000) 2886

Braaten, Kniehl, Lee
hep-ph/9911436
Open Charm Production

- Accumulating large amounts of fully reconstructed charm final states through hadronic “B” trigger
  - Small amount of integrated luminosity is sufficient
- There is no published charm cross section measurement from the Tevatron
  - Unpublished CDF measurement using muons with $p_T > 8$ GeV ($D^* \rightarrow D^0 \pi_s$, $D^0 \rightarrow \mu \nu KX$)

- Of particular interest due to the somewhat large $b$ cross section - what about Charm?
  - Larger discrepancy? (Stronger nonperturbative effects)
  - Smaller discrepancy? (Charm produced further from threshold; softer fragmentation is better understood)
Charm Cross Section Recipe

1. Reconstruct and count charm mesons
2. Measure direct charm meson fraction
   (Direct vs. secondary from B mesons)
3. Trigger and reconstruction efficiency
4. Luminosity
5. Calculate cross section

\[
\sigma_i = \frac{N_i}{2 \cdot f_{D,i}} \cdot \int L \, dt \cdot \varepsilon_i \cdot BR
\]

- Data sample: 5.7pb\(^{-1}\) (Feb-Mar 2002)
- Two-Track Trigger-like selection
- In addition, minimum p\(_T\), L\(_{xy}\)
- Pure 2D-Reconstruction

\[D^0 \to K^-\pi^+\]
\[D^{*+} \to D^0\pi^+_S \text{ with } D^0 \to K^-\pi^+\]
\[D^+ \to K^-\pi^+\pi^+\]
\[D_S^+ \to \phi\pi^+ \text{ with } \phi \to K^+K^-\]
Charm Cross Section: Direct Charm

Use $D^0$ impact parameter distribution to determine direct component

Secondary $D$ has finite impact parameter

Direct charm meson fraction:

- $D^0 \rightarrow K^- \pi^+ \quad 86.5 \pm 0.4 \pm 3.5 \%$
- $D^{*+} \rightarrow D^0 \pi^+_s \quad 88.1 \pm 1.1 \pm 3.9 \%$
- $D^+ \rightarrow K^- \pi^+ \pi^+ \quad 89.1 \pm 0.4 \pm 2.8 \%$
- $D_s^+ \rightarrow \phi \pi^+ \quad 77.3 \pm 4.0 \pm 3.4 \%$

Most reconstructed charm mesons are direct
Charm Cross Section: Efficiencies

- Most efficiencies (XFT, SVT, SVX) and resolutions (XFT, SVT, SVX) determined from data
- Example: XFT efficiency
- COT track efficiency determined from MC track embedding in real data
- Reweight Monte Carlo simulation with measured $p_T$ spectra

CDF Run II preliminary

Decay angle of $\pi$ in $D^*$ rest frame

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Total cross sections (PDG2002 BR's), \(|y|<1:\)

\[\sigma(D^0, p_T>5.5\text{GeV}) = 13.3 \pm 0.2 \pm 1.5 \ \mu b\]

\[\sigma(D^{*+}, p_T>6\text{GeV}) = 5.2 \pm 0.1 \pm 0.8 \ \mu b\]

\[\sigma(D^+, p_T>6\text{GeV}) = 4.3 \pm 0.1 \pm 0.7 \ \mu b\]

\[\sigma(D_s^+, p_T>8\text{GeV}) = 0.75 \pm 0.05 \pm 0.22 \ \mu b\]
Charm Cross Section cont.

Calculation from M. Cacciari and P. Nason: Resummed pQCD (FONLL)

**Ratio of measured to predicted cross section:**

- Measured cross section higher
- Not incompatible with uncertainties
- $p_T$ shape consistent for D mesons

CTEQ6M PDF
$m_c = 1.5$ GeV

Fragm. function:
from Aleph meas.

Renorm and fact. scale:
$m_T = (m_c^2 + p_T^2)^{1/2}$

Uncertainty:
vary scale from .5 to 2

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\( D^0 \rightarrow K\pi, \; KK, \; \pi\pi \)

- Relative branching fraction for Cabibbo suppressed \( D^0 \) decays
  - Ratio of branching ratios \( \rightarrow \) many systematics cancel (normalize to dominant \( D^0 \rightarrow K\pi \))
  - Relative acceptance of the KK and \( \pi\pi \) modes is within 10% of \( D^0 \rightarrow K\pi \)
- Measure CP-violating decay asymmetries for \( D^0 \rightarrow KK \) and \( \pi\pi \) with respect to \( K\pi \)
  - Need to control intrinsic detector charge asymmetry
  - Tag \( D^0 \) through soft pion charge correlation in the \( D^* \) sample: \( D^{*+} \rightarrow D^0\pi^+ \) vs. \( D^{*-} \rightarrow \bar{D}^0\pi^- \)

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$D^0 \rightarrow K\pi, \ KK, \ \pi\pi$

\[
\frac{\Gamma(D \rightarrow KK)}{\Gamma(D \rightarrow K\pi)} = 9.41 \pm 0.18 \ (\text{stat}) \pm 0.13 \ (\text{syst}) \% \\
\frac{\Gamma(D \rightarrow \pi\pi)}{\Gamma(D \rightarrow K\pi)} = 3.686 \pm 0.076 \ (\text{stat}) \pm 0.084 \ (\text{syst}) \% 
\]

FOCUS 2003:

\[ 9.93 \pm 0.20 \% \ (\text{KK/K}\pi) \]
\[ 3.53 \pm 0.13 \% \ (\pi\pi/K\pi) \]

Uncertainties for CP-asymmetry limit are also comparable to best measurement
D_s, D^+ Mass Difference

- \( m(D_s) - m(D^+) \) enters the global PDG fit for all charmed meson masses
- Reconstruct both mesons in the decay channel \( D \rightarrow \phi \pi \)
  - kinematically very similar
  - many systematics cancel
- Spring 2002 data, \( \int L \, dt \approx 11.6 \, \text{pb}^{-1} \), Two-Track Trigger
- Exploit polarization of \( \phi \) coming from \( D \) decay: \( |\cos \alpha| > 0.4 \), where \( \alpha \) is the helicity angle (angle between K and D direction in the \( \phi \) rest frame)

CDF Run II Preliminary

![Graph 1](party pleater)

![Graph 2](party pleater)
For mass measurements, need excellent understanding of energy loss and magnetic field

Calibrate with $J/\psi$

Reconstructed $J/\psi$ mass as function of $p_T (J/\psi)$

Verify with other decays

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**Unbinned maximum likelihood fit on all candidates that pass the selection criteria within 1.80 < m < 2.05 GeV**

- **Fitting method** tested against toy Monte Carlo to check for fitting biases and other problems

- **Main systematic uncertainties**
  - Selection: 0.11 MeV
  - "false curvature", momentum scale, ...: 0.12 MeV
  - Fitting procedure: 0.14 MeV

  **Total syst. uncertainty**: 0.21 MeV

\[
\text{m}(D_s) - \text{m}(D^+) = 99.41 \pm 0.38 \text{ (stat)} \pm 0.21 \text{ (syst)} \text{ MeV}
\]

(PDG: 99.2 ± 0.5 MeV)
Search for FCNC Decay $D^0 \rightarrow \mu^+\mu^-$

- **Standard Model expectation** $\text{BR}(D^0 \rightarrow \mu^+\mu^-) \approx 3 \cdot 10^{-13}$
- Clean territory for new physics search
- R-parity violating SUSY models: **BR up to** $3-4 \cdot 10^{-6}$
- Use $D^{*+} \rightarrow D^0 \pi^+$ to reduce background
- Normalize to $D^0 \rightarrow \pi^+\pi^-$
- Background:  
  a) Combinatorics (from high mass sideband)  
  b) Muon fake rates (from $D^0 \rightarrow K^-\pi^+$)
Search for Rare Decay $D^0 \rightarrow \mu^+\mu^-$

CDF Run II Preliminary

Normalization mode:
$1371 \pm 53 \ D^0 \rightarrow \pi^+\pi^-$
in the mass search window
$\int L \, dt = 69 \text{pb}^{-1}$
CMU fiducial

In $\int L \, dt \approx 69 \text{pb}^{-1}$ of data collected with Two-Track Trigger: no signal events observed, $1.8 \pm 0.7$ expected background events

$$\frac{\mathcal{B}(D^0 \rightarrow \mu^+\mu^-)}{\mathcal{B}(D^0 \rightarrow \pi^+\pi^-)} = \frac{N_{\text{upper}}^{CL}(D^0 \rightarrow \mu^+\mu^-)}{N(D^0 \rightarrow \pi^+\pi^-)} \times \frac{\epsilon(D^0 \rightarrow \pi^+\pi^-)}{\epsilon(D^0 \rightarrow \mu^+\mu^-)}$$

$$\text{BR}(D^0 \rightarrow \mu^+\mu^-) \leq 2.4 \cdot 10^{-6} \text{ at } 90\% \text{ CL} \quad (\text{PDG: BR}(D^0 \rightarrow \mu^+\mu^-) \leq 4.1 \cdot 10^{-6})$$
The Silicon Vertex Trigger turned CDF into a Charm factory

- $O(10^7)$ $D^0 \rightarrow K\pi$ expected in 2 fb$^{-1}$

- $J/\psi$ cross section in new kinematic region

- First measurement of charm cross section at the Tevatron

- Several competitive measurements
  - $\text{BR}(D^0 \rightarrow \mu^+\mu^-)$, $\text{BR}(D^0 \rightarrow K\pi/KK/\pi\pi)$ ratios, $m(D_s^-) - m(D^+)$

- The first Run II CDF paper is out
  - “Measurement of the Mass Difference $m(D_s^+) - m(D^+)$ at CDF II”