Beauty and Charm Production
at the Fermilab Tevatron

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$b$ quark discovered - 1977

"It now appears .... that there may be a fifth quark"
20 years later.....

In 1997, $b$ production cross-sections were still $\geq 2\times$ larger than QCD predictions. At that time only a small portion of the $b$ hadron inclusive cross-section, $p_T > 6.0$ GeV/c, had been measured.

$$\sigma(p\bar{p} \rightarrow bx) \text{ for } (p_T > p_T^{min})$$

Is this a shape or normalization problem? What about charm?
Outline

- Recent advances in the theory of heavy quark production cross-sections in $p\bar{p}$ collisions.
- Description of the Run II CDF and D0 detectors at the Tevatron.
- Run II results on beauty and charm hadron production cross-sections.
- Quarkonia production (including diffractive!)
- Exotic baryon spectroscopy:
  - confirmation of Belle’s $X(3870) \rightarrow J/\psi\pi\pi$.
  - New: Pentaquark searches at the Tevatron
THE THEORY
Heavy Quark Production in $pp\bar{p}$

Factorization theorem: factorize physical observable into a calculable part and a non-calculable but universal piece:

$$\frac{d\sigma(qq/gg/qg \rightarrow bX)}{dp_T(b)} \times f_{p,p} \times D_{b \rightarrow B} = \frac{d\sigma(p\bar{p} \rightarrow BX)}{dp_T(B)}$$

Proton structure

fragmentation

NLO/NNLO QCD

NLO: Gluon splitting

NLO: Flavour excitation
Parton Density Functions (PDF)

New PDFs with uncertainties extracted from fits to the data

The uncertainties from one PDF fit do not always cover differences with other fits:

Uncertainties on gluonic function
Evolution of PDFs

By 2004, recalculating the cross-section with updated PDFs increases theoretical value by almost 2X!
2001: $k_T$ Factorization Scheme

Standard PDFs are functions of $x$, the fraction of the momentum carried by the parton longitudinal to the hadron direction. Partons also have a small transverse momentum component:

$k_T$ factorization: $f(x) \rightarrow f(x, k_T)$, $\sigma(x, s) \rightarrow \sigma(k_T, x, s)$

$p\bar{p} \rightarrow bX$, $\sqrt{s}=1.8$ TeV, $|y|<1$

DØ Data

Errors have correlations.

Dimuons

Muons+Jets

(This Analysis)

Inclusive Muons

NLO QCD, MRSR2, $m_b=4.75$ GeV/c$^2$, $\mu=\mu_0$

Theoretical Uncertainty

H.Jung, hep-ph/0110034
Fragmentation Functions $D^{b \rightarrow B}$

$$D^{\text{meas}}(x) = \int \frac{D^{\text{pert}}(x')}{pQCD/MC} \otimes \frac{D^{\text{non-pert}}(x')}{\text{Parameterized/MC}} \, dx'$$

Peterson parameterization

$$z = \frac{(E+p_{||})_{\text{hadron}}}{(E+p)_{\text{quark}}}$$

$x_L = E_{\text{lead}, B}/E_{\text{beam}}$
Recent Theory Advances

- Next-to-Leading-log resummations (2001): In pQCD calculations powers of $\alpha_s \log p_T/m_Q$ modify shape of fragmentation function:
  
  \[ p_T \gg m_Q = \text{Large corrections} \]

- Moment analysis (2002): Mellin transformation into moment space
  \[ \tilde{D}(N) = \int x^{N-1} D(x) \, dx \]

  \[ \tilde{D}^{\text{meas}}(N) = \tilde{D}^{\text{pert}}(N) \times \tilde{D}^{\text{non-pert}}(N) \]

  A product

Non-perturbative functions used must match perturbative assumptions
Fixed order (FO) QCD NLO calculation + Resummation of next-to-leading logs (NLL). Method of moments instead of a fragmentation model \( \Rightarrow \) Better agreement with CDF and D0 Run I data

\[
d\sigma(p\bar{p} \rightarrow B^+ X)/dp_T \text{ vs } p_T(B^+) \text{ (CDF)}
\]

- \( p\bar{p} \rightarrow B^+X, \sqrt{s}=1.8 \text{ TeV}, |y|<1 \)
- Dashed: \( \mu_R=\mu_F=\mu_0=\sqrt{(m_b^2+p_T^2)} \)
- Solid: \( \mu_0/2<\mu_R,\mu_F<2\mu_0 \)
- CTEQ5M1
- \( m_b = 4.75 \text{ GeV} \)
- \( f(b\rightarrow B)=0.375 \)
- Dotted: Peterson, \( \epsilon = 0.006 \)

O: CDF data
Theory: FONLL with N=2 fit

Cacciari, Nason hep-ph/0204025 (Run I)
Theory Summary

Agreement with the Run I $b$ cross-section data for $p_T > 5.0$ GeV/c has greatly improved without the need to invoke exotic sources of excess $b$ quarks. Most of the improvement is due to improved treatment of experimental inputs.

BUT: Different theoretical approaches: different factorization schemes, FONLL calculations, new methods to extract the non-perturbative part of fragmentation function. Which is the correct approach?

Total cross-sections do not depend on the fragmentation model!

= powerful experimental test of QCD calculations.

Charm quark mass and production cross-sections are close to $b$-quark but fragmentation is very different - test theory predictions.
THE EXPERIMENTS
The Tevatron Today

- In 1985, Tevatron collider begins operating @ $\sqrt{s} = 1.6$ TeV
- Run I of the Tevatron collected collider data at $\sqrt{s} = 1.8$ TeV from 1992-1995. $\sim 109 \text{ pb}^{-1}$ of data was collected by the 2 collider detectors with $\mathcal{L}^{\text{typical}} = 1.6 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$

Run II: Summer 2001 - present. 4X more data already!
CDF Run II - Overview

Signals: \( J/\psi \rightarrow \mu \mu, \ D \rightarrow K\pi, \) displaced \( b \) vertices

Central Muon (CMU)

Central Hadron Calorimeter (CHA)

EM Calorimeter (CEM)

Solenoid Coil

R=150 cm

TOF

R=1.4 cm

SVX-II

End-Plug Hadron Calorimeter (PHA)

End-Wall Hadron Calorimeter (WHA)

Central Muon detector: Prop. chambers outside central calor. \( \sim 5\pi \) interaction lengths.

96 layer COT:

\[ \sigma(p_t)/p_t = 0.002p_t \]

Silicon vertex detector: 8 Layers of 3-D Silicon up to \( |\eta| = 2 \), 700,000 readout channels, \( \sigma(d_0) \sim 30 \mu m \)

\[ \eta = -1/2 \ln \tan \theta/2 \]
D0 Run II - Overview

- New forward muon system with $|\eta| < 2$ and good shielding
- 16 layer Fiber Trackers in 2T
- 4 layer Silicon, $\sigma(d_0) = 54\mu m$ at 1 GeV/c
RUN II MEASUREMENTS OF THE $J/\psi$ AND $b$-HADRON INCLUSIVE CROSS-SECTIONS
$J/\psi \rightarrow \mu\mu$ signals

CDF Run II Preliminary, 120 inv. pb, June 2003

$\Psi(2s)$: Events: 38k, Width: 22.1 ± 0.5 MeV/c$^2$

$J/\psi$: Events: 1.2M, Width: 22.6 ± 0.03 MeV/c$^2$

Dfl Run II Preliminary

$\sim 707k J/\psi$

Mean = 3.0751 ± 0.0002 GeV

$\sigma_{inner} = 58.1 \pm 0.5$ MeV

Mary Bishai, Fermi National Accelerator lab 19 – p.19/54
L1 Muon triggers (CDF)

Tracks are reconstructed in the COT by the Level 1 Trigger eXtra Fast Tracker (XFT). A match is made to hits in the Muon Chambers. (Offline $\epsilon = 0.986 \pm 0.010$)

L1 muon trigger efficiency vs. $1/p_T$

Can now reach $p_T(J/\psi) = 0$ GeV/c.
Counting $J/\psi$s ($p_T = 0$ to 20 GeV/c)

$0 < p_T(J/\psi) < 0.25\text{GeV/c}$

CDF Run II Preliminary 0<$p_T(\mu\mu)$<0.25 GeV/c

358$\pm$26 Events
Luminosity = 14.8 pb$^{-1}$

$5 < p_T(J/\psi) < 5.5\text{GeV/c}$

CDF Run II Preliminary 5.0<$p_T(\mu\mu)$<5.5 GeV/c

18,200$\pm$200 Events
Luminosity = 39.7 pb$^{-1}$

$12 < p_T(J/\psi) < 14\text{GeV/c}$

CDF Run II Preliminary 12.0<$p_T(\mu\mu)$<14.0 GeV/c

1551$\pm$60 Events
Luminosity = 39.7 pb$^{-1}$

- Transverse momentum resolution:
  \[ \delta(p_T)/p_T = 0.003p_T \]
- A detector simulation is used to model the expected shape of the $J/\psi$ signal.
Muon triggers (D0)

- Large rapidity coverage up to $|\eta| < 2.0$

- Offline reco eff:
  - loose $\epsilon = 0.905 \pm 0.0033$
  - medium $\epsilon = 0.8 \pm 0.0045$
$\frac{d\sigma(p\bar{p}\rightarrow J/\psi X)}{dp_T(J/\psi)} = \frac{\text{Number of } J/\psi}{\text{luminosity} \times \text{acceptance} \times \text{efficiency} \times \Delta p_T}$

$\sigma(p\bar{p} \rightarrow J/\psi X, |y| < 0.6) \text{ vs } p_T(J/\psi)$

CDF Run II Preliminary

$\sigma(p\bar{p} \rightarrow J/\psi X, p_T > 5, 8\text{GeV}/c) \text{ vs } y(J/\psi)$

$\sigma(p\bar{p} \rightarrow J/\psi X, |y| < 0.6) = 4.08 \pm 0.02(\text{stat})^{+0.60}_{-0.48}(\text{syst}) \mu b$
Separate $H_b \rightarrow J/\psi X$ from Total

- The $J/\psi$ inclusive cross-section includes contributions from:
  - Direct production of $J/\psi$
  - Indirect production from decays of excited charmonium states such as $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$
  - Decays of $b$-hadrons such as $B \rightarrow J/\psi X$

- $b$-hadrons have long lifetimes, $J/\psi$ from $H_b \rightarrow J/\psi X$ will be displaced.
Extracting the $b$-fraction

A maximum likelihood fit to the flight path of the $J/\psi$ in the $r - \phi$ plane, $L_{xy}$ is used to extract the $b$-fraction.

**Prompt $J/\psi$** is a double Gaussian = resolution function

**$b \rightarrow J/\psi X$** shape from MC template

**Parameterized background**
$b$-Production cross-section

$\sigma(p\bar{p} \rightarrow B^+ X) \, vs \, (p_T(B^+))$

$\sigma(p\bar{p} \rightarrow bX) \, versus \, (p_T(H_b))$

CDF Run II Preliminary

**1997**

Data: $\sigma = 29 \pm 6 \mu b$, FONLL: $\sigma = 27.5 \mu b$ (CTEQ6M, $m_b = 4.75$, $\mu = \mu_0$)

**2003**

$\sigma = 29 \pm 6 \mu b$, FONLL: $\sigma = 27.5 \mu b$ (CTEQ6M, $m_b = 4.75$, $\mu = \mu_0$)
High $p_T$ $b$-Jet Production (D0)

- $b$-jets include much of the quark fragmentation remnants $\Rightarrow$ jet cross-sections have small dependence on fragmentation.
CHARM MESON CROSS-SECTIONS
L2 Silicon Vertex Trigger (CDF)

Eff. vs track $p_t$

SVT Eff. vs track $d_0$
Charm Production in Run II

- Analysis uses $5.8\text{pb}^{-1}$ of early 2002 data.
- Challenges: SVT not fully efficient at the time. Efficiency is a complex function of $p_T$, $z$, $\cot(\theta)$ and time.
Direct Charm Production Run II

Use impact parameter of reconstructed charm mesons $F_D(d_0)$ to distinguish directly produced charm from $B \rightarrow DX$, $F_B(d_0)$

From $K_S \rightarrow \pi\pi$ data we find $F_D(d_0) = \text{Gaussian} + \exp$ tails. From $B \rightarrow DX$ MC: $F_B(d_0) = \text{a double exponential}$.
Charm cross-sections

$D^0$ Meson Differential Cross-section

$\frac{d\sigma}{dp_T} (\text{nb}/\text{GeV})$

$|y| < 1$

$\times$ CDF preliminary data

$0 \leq p_T \leq 30$ GeV

$D$ Meson Cross-sections Data/Theory

$\sigma(p\bar{p} \rightarrow D^0 X, |y| < 1.0, p_T > 5.5 \text{ GeV/c}) = 13.3 \pm 0.2(\text{stat}) \pm 1.5(\text{syst}) \mu b$

$\sigma(p\bar{p} \rightarrow D^+ X, |y| < 1.0, p_T > 6.0 \text{ GeV/c}) = 4.3 \pm 0.1(\text{stat}) \pm 0.7(\text{syst}) \mu b$

$\sigma(p\bar{p} \rightarrow D^{*+} X, |y| < 1.0, p_T > 6.0 \text{ GeV/c}) = 5.2 \pm 0.1(\text{stat}) \pm 0.8(\text{syst}) \mu b$

$\sigma(p\bar{p} \rightarrow D_s X, |y| < 1.0, p_T > 8.0 \text{ GeV/c}) = 0.75 \pm 0.05(\text{stat}) \pm 0.22(\text{syst}) \mu b$

Charm and Beauty meson cross-section predictions are consistent
QUARKONIA PRODUCTION

Quarkonia = discovery. $J/\psi$ signal at Brookhaven in 1974
Prompt Quarkonia Production

Quarkonia bound states are non-relativistic. NRQCD LO perturbative expansion is \( \mathcal{O}(\alpha_s^3 v^0) \) as in the color singlet model (CSM) + higher order \( \mathcal{O}(\alpha_s^3 v^4) \).

Fragmentation processes \( \propto \) color octet matrix element dominate. CO matrix elements extracted from fits to data - agree well with Run I data at high \( p_t \).

CDF Preliminary

CDF Run II Preliminary

Prompt \( J/\psi \) production (Run I)  Prompt \( J/\psi \) production (Run II)
Bottomonium production

At lower $p_t$, NRQCD non-fragmentation diagrams from other octet matrix elements are important, soft gluon effects cause rates to diverge.

\begin{align*}
\gamma(1S) \text{ production (CDF Run I)} \quad \gamma(1S) \text{ production (D0 Run II)}
\end{align*}

No new theoretical predictions for low $p_T$ quarkonium at $p\bar{p}$ yet.

BUT: resummation of color octet matrix elements by summer 2004?.
BUT Inclusion of color octet in NRQCD leads to a prediction of increasing transverse polarization of charmonium at high $p_t$.

Method: Fit the production angle, $\cos \theta^*$, distribution to MC distribution which is a mixture of transverse and longitudinal polarizations. Use lifetime fit method to separate prompt and $b \rightarrow J/\psi X$

$$\frac{dN}{d \cos \theta^*} \propto (1 + \alpha \cos^2 \theta^*)$$

Run II : Need more precise measurements

N.B. Accurate measurements needed to reduce systematic uncertainty on detector acceptance
Diffractive production of $\chi_c$

- At LHC SM Higgs boson could be produced by exclusive production with NOTHING else in the interaction ($\sigma \sim 40$ fb $\sim$):

  \[ p + p \rightarrow p + H + p \]

- To test prediction, search for a similar process at the Tevatron:

  \[ p + \bar{p} \rightarrow p + \chi^0_c + \bar{p} \rightarrow p + J/\psi\gamma + \bar{p} \]

\[ \text{c–loop: } \chi_c \]

\[ \text{b–loop: } \chi_b \]

\[ \text{t–loop: } H \]
Exclusive $\chi_c$ candidate 1
Exclusive $\chi_c$ candidate 2

Event: 149270  Run: 156365  EventType: DATA

Missing $E_t$
$E_t = 1.1 \phi = 1.0$

List of Tracks

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<th>$p_t$</th>
<th>$\phi$</th>
<th>$\eta_C$</th>
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<tr>
<td>8</td>
<td>-1.5</td>
<td>-0.4</td>
<td>-0.5</td>
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</table>

To select track type

SelectCdfTrack(Id)
Analysis of exclusive events

Need to understand backgrounds!

IF all 10 events are signal then:

$$\sigma(p\bar{p} \rightarrow p\bar{p}\mu\mu\gamma, |y| < 0.6) = 49 \pm 18 \text{(stat)} \pm 39 \text{(syst)} \text{ pb}$$

Prediction: $$\sigma = \sim 200 \text{ pb}$$ hep-ph/0011393
EXOTIC SPECTROSCOPY
Belle observes $X(3870) \rightarrow J/\psi \pi \pi$

- At LP 2003, the Belle collaboration announced the observation of a new state decaying into $J/\psi \pi \pi$ from analysis of $B$ decays.

- Belle signal favors large $\pi \pi$ mass

$M = 3872.0 \pm 0.6 \pm 0.5$ MeV
\( X(3870) \rightarrow J/\psi \pi \pi \) observed in \( p\bar{p} \)

\[ M(\text{CDF}) = 3871.3 \pm 0.7 \pm 0.4 \text{ MeV} \]

Yield : \( 730 \pm 90 \) (CDF) \( 522 \pm 100 \) (D0).
What is it?

**PDG Quark Model:**

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<tr>
<th>$N^2S+1L_J$</th>
<th>$J^{PC}$</th>
<th>$ud, ud, s\bar{s}$</th>
<th>$uu, ud, ss$</th>
<th>$cc$</th>
<th>$\bar{c}c$</th>
<th>$\bar{b}b$</th>
<th>$\bar{u}u, \bar{d}d$</th>
<th>$\bar{s}s$</th>
<th>$\bar{c}s$</th>
<th>$\bar{b}u, \bar{d}d$</th>
<th>$\bar{b}s$</th>
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<td>$\eta, \eta'$</td>
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<td>$\eta_b(1S)$</td>
<td>$K$</td>
<td>$D$</td>
<td>$D_s$</td>
<td>$B$</td>
<td>$B_s$</td>
<td>$B_c$</td>
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<td>1$^{-+}$</td>
<td>$\rho$</td>
<td>$\omega, \phi$</td>
<td>$J/\psi(1S)$</td>
<td>$\Upsilon(1S)$</td>
<td>$K^*(892)$</td>
<td>$D^*(2010)$</td>
<td>$D_s^*$</td>
<td>$B^*$</td>
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<td>$B_c^*$</td>
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<td>$f_0(1370)^*, f_0(1710)$</td>
<td>$\chi_0(1P)$</td>
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<td>$K_1(1430)$</td>
<td>$D_1(2420)$</td>
<td>$D_{s1}(2536)$</td>
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<td>$\chi_{21}(1P)$</td>
<td>$K_{1A}^*$</td>
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**BUT:** $^3D_2$ expected around 3810 MeV/c$^2$

**Is this a $DD^*$ molecule?** Can CDF/D0 determine production mechanism? If mostly prompt, looks like a quarkonium rate. **Is the $\pi\pi$ a $\rho$?**
Pentaquarks at the Tevatron?

Evidence for $\Theta^{+}(1530)$ (CLAS)
$\Xi^{-}(1860)$ (NA49) $M(D^{*}\bar{p}) = 3099$ (H1).

No evidence for “pentaquark” states at CDF with larger statistics.
**Summary**

Studies of heavy quark production are precision tests of NLO pQCD.

- **NEW:** Run II measurements of heavy flavor production at the Tevatron:
  - Quarkonia: New measurements of the inclusive $J/\psi$ cross-sections down to $p_T = 0$ GeV/c (CDF) and $|y| < 2.0$ (D0). New $\Upsilon$ cross-sections (D0). Diffractive production of exclusive $\mu\mu\gamma$ candidates observed (CDF).
  - Measurement of the central $b$-hadron cross-sections over all $p_T$ (CDF) and $b$-jet cross-sections at $\sqrt{s} = 1960$ GeV (D0)
  - $D^{+,0,*}, D_s$ cross-sections published (CDF).
  - Exotic Spectroscopy: $X(3870)$ confirmed at $p\bar{p}$ (CDF/D0). CDF observes no pentaquark candidates.
Lots of theory advances:
- New PDF fits to proton structure data and better understanding of uncertainties.
- New factorization schemes: $k_T$
- Resummation of NLL for factorization schemes where quarks are massive - now valid for all $p_T$
- New and improved treatments of heavy quark fragmentation

Total inclusive $b$-hadron cross-sections are in agreement with theoretical predictions within uncertainties.

Charm cross-sections in reasonable agreement with theory and consistent with beauty meson results.

Mysteries: Quarkonia production/polarization, $X(3870)$, $Θ$
CDF Data Flow

L1 latency: Pipeline depth = L1 processing time $\sim 5\mu$secs.

The SVXII detector is readout on L1 Accept.

L2 processing time: The Silicon Vertex Trigger is in L2 $\Rightarrow$ readout of the Silicon takes place in $\sim 15\mu$secs $+$ $\sim 15\mu$secs SVT processing time

Data logging rate: sustained rate of 18MB/s (150-200 KB/event)

250 pb $^{-1} \Rightarrow 480$TB on tape
A detector simulation is used to estimate acceptance:

**Transverse momentum**

![Graph showing J/ψ Acceptance vs. Pt(J/ψ) GeV/c](image)

**Rapidity**

![Graph showing J/ψ Acceptance vs. J/ψ Rapidity](image)
\[ d\sigma(p\bar{p} \rightarrow H_bX)/dp_T(J/\psi) \]

Fraction of \( J/\psi \)s from \( H_b \)

CDF Run II Preliminary

- Red circles: Run II (stat. uncertainties only)
- Blue squares: Run I (stat. uncertainties only)

\begin{align*}
\text{Fraction of } J/\psi \text{ from } b & \quad \text{CDF Run II Preliminary} \\
\text{p}_T(J/\psi) \text{ GeV/c} & \quad 0 \quad 5 \quad 10 \quad 15 \quad 20
\end{align*}

\[ \sigma(p_T(J/\psi)>1.25 \text{ GeV}): \]

Points: CDF, 19.9_{-3.2}^{+3.8} \text{ nb}

Solid: FONLL, 19.9_{-6.0}^{+8.4} \text{ nb}

Dashes: MC@NLO, 17.2 \text{ nb}

Algorithm to extract $d\sigma/dp_T(H_b)$

- Count the observed number of $b$-hadrons in a given $p_T(H_b)$ bin

$$N_i^b = \sum_{j=1}^{N} w_{ij} N_j^{J/\psi}$$

$w_{ij}$ is the fraction of $b$ events in the $i^{th}$ $p_T(H_b)$ from the $j^{th}$ $p_T(J/\psi)$ bin obtained from MC.

- Correct the observed number of $b$-hadrons for the kinematic acceptance
After a $d\sigma/dp_T(H_b)$ spectrum is obtained, the MC weights $w_{ij}$ are recomputed using the new spectrum and the algorithm repeated.

A $\chi^2$ test is performed on the input and output spectra until no difference is seen.