Beauty and Charm Production Cross Section Measurements at the Tevatron

Jennifer Pursley

University of Wisconsin, Madison

Rencontres de Moriond QCD and High Energy Interactions

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Outline

- Motivation
- Quarkonia production
- Recent results:
  - Correlated $b\bar{b}$ production
  - Polarization of $\Upsilon(1S)$ and $\Upsilon(2S)$
  - $\psi(2S)$ production cross section
    - Polarization of $J/\psi$ and $\psi(2S)$
- Summary
Motivation

- Heavy quark production probes QCD at perturbative and non-perturbative interface → important test of models
- Tevatron Run I, many cross section measurements higher than original theoretical predictions:

\[ |y(B)| < 1, \ p_T(B) > 6 \text{ GeV/c} \]
Charm and Beauty Production

- Led to improved measurements and better theoretical understanding – nonrelativistic QCD (NRQCD)
- Now much better agreement between data and theory!
- Fixed Order Next to Leading Log calculations available
Quarkonia Production

- **Color Singlet Model**
  - One hard gluon carries away color
  - $p_T$ spectrum does not match data
  - Underestimates cross sections by factors of 10-50

- **From NRQCD, Color Octet Mechanism**
  - Soft gluons
  - Adjustable hadronization parameter $\rightarrow$ match data $p_T$ and cross section
  - Predicts transverse polarization at high $p_T$
Quarkonia Production

- **Pomeron inspired idea:**
  - Fusion of symmetric color octet and a gluon
  - LO pQCD calculation matches data $p_T$ spectrum and cross section
  - Expect increasing longitudinal polarization at high $p_T$


E.L. Berger, J. Qiu, Y. Wang hep-ph/0411026
Correlated $b\bar{b}$ Production

- For correlated $b\bar{b}$ production (both $b$ quarks within central rapidity and above a $p_T$ threshold), expect:
  - Higher order terms to be smaller
  - NLO predictions should be more accurate

- Tevatron Run I results inconclusive/contradictory:

From F. Happacher et al, PRD73, 014026 (2006)
Correlated $b\bar{b}$ and $c\bar{c} \rightarrow \mu\mu$

- In 740 pb$^{-1}$ of data, select $\mu\mu$ pairs produced by:
  - Decays of heavy flavor pairs ($b\bar{b}$, $c\bar{c}$)
  - Prompt Drell-Yan processes
  - Charmonium, bottomonium, K and $\pi$ decays
  - Misidentification of K and $\pi$ mesons

- Fit 2D impact parameter dist. to extract sample composition

1D template (data, tuned Herwig)  2D template  2D data
Fit Projection

- 2D fit of impact parameter can distinguish:
  - $b \rightarrow \mu, \bar{b} \rightarrow \mu$
  - $b \rightarrow \mu, c \rightarrow \mu$
  - $c \rightarrow \mu, \bar{c} \rightarrow \mu$
  - Contributions with one or more prompt $\mu$

- $c \bar{c}$ measurement is a by-product of background studies
Correlated $b\bar{b}$ and $c\bar{c}$: Results

- Cross sections:
  \[ \sigma_{b \to \mu, \bar{b} \to \mu} = 1549 \pm 133 \text{ pb} \quad \sigma_{c \to \mu, \bar{c} \to \mu} = 624 \pm 104 \text{ pb} \]

- Ratios (includes experimental and theory errors):
  - Peterson fragmentation parameter...
  - Using ratio with $\varepsilon = 0.006$:
    \[ \frac{\sigma_{b \to \mu, \bar{b} \to \mu}^{\text{measured}}}{\sigma_{b \to \mu, \bar{b} \to \mu}^{\text{NLO}}} = 1.2 \pm 0.2 \quad \frac{\sigma_{c \to \mu, \bar{c} \to \mu}^{\text{measured}}}{\sigma_{c \to \mu, \bar{c} \to \mu}^{\text{NLO}}} = 2.7 \pm 0.6 \]
  - Using ratio with $\varepsilon = 0.002$:
    \[ \frac{\sigma_{b \to \mu, \bar{b} \to \mu}^{\text{measured}}}{\sigma_{b \to \mu, \bar{b} \to \mu}^{\text{NLO}}} = 1.0 \pm 0.2 \quad \frac{\sigma_{c \to \mu, \bar{c} \to \mu}^{\text{measured}}}{\sigma_{c \to \mu, \bar{c} \to \mu}^{\text{NLO}}} = 1.6 \pm 0.4 \]

Cacciari, Nason, PRL 89, 122003 (2002); NDE calculation for single $b$ x-section uses...

Using ratio with $\varepsilon = 0.006$:

\[ \sigma_{b\bar{b}}(p_T \geq 6 \text{ GeV}/c, |y| \leq 1) = 1618 \pm 148 \text{ nb} \]

(NLO prediction = 1348 ± 209 nb)
Correlated $b\bar{b}$ Production

- High dimuon cross section *not* observed in Run II
Measuring Quarkonium Polarization

- Measure polarization parameter:

- Extract $\alpha$ from angular distribution, where $\theta^* = \text{angle between J/$\psi$(Y) in lab frame and } \mu \text{ in J/$\psi$(Y) rest frame}$

\[
\alpha = \frac{(\sigma_T - 2\sigma_L)}{(\sigma_T + 2\sigma_L)}
\]

\[
\frac{dN}{d(\cos \theta^*)} \propto 1 + \alpha \cos^2 \theta^*
\]
In 1.3 fb\(^{-1}\), find 420,000 \(\Upsilon(nS) \rightarrow \mu^+\mu^-\) candidates

- \(\Upsilon\) mass differences fixed to measured values
- Number of \(\Upsilon(3S)\) insufficient to extract angular distribution
Data divided into different bins of $p_T$ and $|\cos \theta^*|$

Extract angular distribution for each $p_T$ interval

Significant $p_T$ dependent longitudinal polarization

$\Upsilon(1S)$ Polarization

- $D\O$, Run 2 Preliminary, $1.3 \text{ fb}^{-1}$
- $CDF$ Run I result, $|y(\mu^+\mu^-)| < 0.4$
\( \Upsilon(2S) \) Polarization

- Same study for \( \Upsilon(2S) \)
- Within (lower) statistics, compatible with NRQCD predictions

\[ D\O, \text{ Run 2 Preliminary, } 1.3 \text{ fb}^{-1} \]

NRQCD
Braaten, Lee, PRD63 071501 © (2001)

D\O measurement \( |y(\mu^+\mu^-)| < 2 \)
ψ(2S) Production Cross Section

- Reconstruct ψ(2S) → μ⁺μ⁻ in 1.1 fb⁻¹
  - Rapidity |y(μ⁺μ⁻)| < 0.6, p_T range of 2 – 30 GeV/c

- Maximum likelihood fit in ψ(2S) mass and proper decay length ct
  - Mass fit separates signal from background
  - Proper time fit separates prompt ψ(2S) from B decays
J/$\psi$ and $\psi(2S)$ Polarization

- $\psi(2S)$ acceptance depends on $\psi(2S)$ polarization
- CDF Run II measurement of J/$\psi$ and $\psi(2S)$ polarization shows significant longitudinal polarization
- $\psi(2S)$ measurement statistically limited
  - Theory: prompt $\psi(2S)$ polarization very similar to J/$\psi$
  - Use J/$\psi$ polarization value at center of $p_T(\psi(2S))$ bins

PRL 99, 132001 (2007)
ψ(2S) Production Results

Separate prompt and secondary:

\[ \frac{d\sigma}{dp_T \times BR} \text{ (nb/(GeV/c))} \]

- Run II Prompt
- Run II B-decay

Compare to CDF Run I:

\[ \frac{d\sigma}{dp_T \times BR} \text{ (nb/(GeV/c))} \]

- Run II Prompt
- Run I Prompt
- Run II B-decay \times 0.1
- Run I B-decay \times 0.1

March 12, 2008 J. Pursley, Moriond QCD
ψ(2S) Production Results

- First Run II measurement
- Integrated differential cross section:

\[
\sigma(p\bar{p} \to \psi(2S)X, |y(\psi(2S))| < 0.6, \ p_T > 2 \text{ GeV}/c)_{\sqrt{s}=1.96 \text{ TeV}} \cdot Br(\psi(2S) \to \mu^+\mu^-) = 3.141 \pm 0.038(\text{stat})^{+0.225}_{-0.218}(\text{syst}) \text{ nb.}
\]

- Compare to inclusive CDF Run I:
  - Predict \(1.14 \pm 0.08\) increase for \(\sqrt{s} = 1.96\) TeV

<table>
<thead>
<tr>
<th>Run I (\sqrt{s}=1.80) TeV</th>
<th>Run II (\sqrt{s}=1.96) TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>[\sigma(p\bar{p} \to \psi(2S)X,</td>
<td>\eta</td>
</tr>
</tbody>
</table>
Summary

- Lots of activity in heavy flavor physics at the Tevatron
  - Showed several recent production measurements
  - Both experiments have > 3 fb$^{-1}$ recorded, many more results on the way!

- Detailed studies of heavy flavor production test theoretical understanding
  - Cross section measurements reproduced well by theoretical models
  - Polarization measurements indicate need for better understanding

- Continue challenging theory with measurements
  - Important also for understanding heavy quark production at the LHC
Backup Slides
$\Upsilon$ in prompt dimuons

- $\Upsilon(1S)$ decays used to extract impact parameter template for prompt muons

$9899 \pm 142$
## Summary of $b\bar{b}$ Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>BB</th>
<th>CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stat.</td>
<td>1.2%</td>
<td>6.4%</td>
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<tr>
<td>Fit likelihood</td>
<td>2.9%</td>
<td>8%</td>
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<tr>
<td>Fake removal</td>
<td>4.2%</td>
<td>11.6%</td>
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<tr>
<td>Acceptance</td>
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<td>3.9%</td>
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<tr>
<td>Luminosity</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>Total</td>
<td>8.9%</td>
<td>16.7%</td>
</tr>
</tbody>
</table>
Detectors

CDF:
- Excellent mass resolution and particle ID
- Displaced vertex trigger → hadronic decays

DØ:
- Excellent muon coverage (|\eta| < 2) and forward tracking
- Di muon + semileptonic decays
Tevatron Performances

- Collide $p\bar{p}$ at $\sqrt{s} = 1.96$ TeV
- Record peak luminosity $2.85 \times 10^{32} \text{ sec}^{-1} \text{ cm}^{-2}$
- Each experiment has collected ~3 fb$^{-1}$ out of > 3.5 fb$^{-1}$ delivered

- Current analyses use between ~1 - 2 fb$^{-1}$ of data
- Analyses with more data in the works
- Expect 6 - 7 fb$^{-1}$ by 2009