Quarkonia Production at CDF in Run II

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2nd Quarkonium Workshop
September 20-22, 2003
Fermilab, IL, USA
CDF Detector in Run II

Inherited from Run I:
Central Calorimeter ($|\eta|<1$)
Solenoid (1.4T)

Partially New:
Muon system (extended to $|\eta|\sim1.5$)

Completely New:
Tracking System
- 3D Silicon Tracker (up to $|\eta|\sim2$)
- Faster Drift Chamber
Time-of-Flight (particle ID)
Plug and Forward Calorimeters
DAQ & Trigger system (Online Silicon Vertex Tracker: trigger on displaced vertices, first time at hadron collider)
B physics with Run II CDF

Open wide spectrum of B hadrons
- $B^\pm$, $B^0$, $B_s$, $B_c$, $\Lambda_b$, $\Xi_b$ ... (unique)

- $B^0$ cross section is 50-100 $\mu$b
- $\sim O(10^5)$ larger than $e^+e^-@\Upsilon(4S)/Z^0$
- $\sim O(10^3)$ B's per second at design luminosity
  ($\sim 10$ B's per second at $\Upsilon(4S)$ factories)

BUT:
- B hadrons are hidden in a $10^3$ larger background ($\sigma_{\text{inelastic}}(pp) \approx 50$ mb
- Events more complicated than at $\Upsilon(4S)$
- BRs for interesting processes: $\sim O(10^{-6})$
  - S/B @ production (Tevatron): $\sim 10^{-9}$
  - S/B @ production (B factory): $\sim 10^{-6}$

Mean multiplicity of tracks/event: $\sim 4\Upsilon(4S)$
- Combinatoric background
- Events pile-up within the same beam x-ing
- Typical S/B @ analysis level: $\sim O(0.5\div5)$

Solution:
- Vertex detector
- Trigger
- Particle ID

B physics signatures:

- QCD physics
  - Quarkonium cross section and B fraction down to 0 GeV, polarization
  - B cross section; fragmentation

- CKM studies: CP violation and mixing
  - $B_s$ mixing, $B_s \rightarrow D_s\pi$, $\eta' D_s$
  - $|V_{td}|: B^0 \rightarrow J/\psi K^0_0$, $\eta' D_s$, $|V_{ts}|: B_s \rightarrow J/\psi \phi$
  - $\Delta \Gamma_s$: $B_s \rightarrow J/\psi \phi$, $J/\psi \eta$, $\eta' D_s$, $D_s D_s$
  - CP asymmetry: $B^0(B_s) \rightarrow hh$
  - $\gamma$: $B_s \rightarrow D_s K^+$, $B \rightarrow DK$
  - $\gamma$: $B^0$, $B_s \rightarrow K\pi, \pi\pi, KK$
  - $\beta$: $B^0 \rightarrow J/\psi K^0_0$
  - $\alpha$: $B^0 \rightarrow \pi\pi$

- Properties of $B_s$, $B_c$, $\Lambda_b$, etc
  - Production, mass, lifetime

- Rare decays
  - $B \rightarrow \mu\mu K^*(\rho)$
  - Physics beyond the standard model:
    - $B^0$, $B_s \rightarrow \mu\mu$ and $B_s \rightarrow e\mu$
**J/ψ production cross section**

**Theory:** Non-Relativistic QCD (NRQCD)
- color octet and color singlet mechanism
- J/ψ production is dominated by the color octet mechanism
- reasonable agreement of the shape with Run I data
- normalized by fitting the data
- no prediction at low $p_T$(J/ψ)
- J/ψ is polarized at high $p_T$
  (2σ discrepancy with Run I)

Run II: 1.8 TeV ⇔ 1.96 TeV

CDF Run I J/ψ production 1.8 TeV

**CDF Preliminary**

$\sigma/\sqrt{dE}\ (nb/GeV/c)$

- Forcing J/ψ and ψ'
i.e. amplitudes to have the same ratio

$M(^{3}S_{1}^{0}) = 11.0 \pm 0.8 \times 10^{-3}$ GeV

$M(^{1}S_{0}^{0} \cdot P_{0}^{0}) = 29.9 \times 10^{-3}$ GeV

$J/ψ \rightarrow μ^+μ^−$

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Lepton B triggers

\[ \frac{\sigma(b\bar{b})}{\sigma(pp)} \approx 10^{-3} \]

Need specialized triggers

**CDF Run I**, lepton-based triggers:

- Di-leptons \((\mu\mu, P_T \geq 2 \text{ GeV/c})\): \(B \to J/\psi X, J/\psi \to \mu\mu\)
- Single high \(P_T\) lepton \((\geq 8 \text{ GeV/c})\): \(B \to l \nu D X\)

Suffer of low BR and not fully reconstructed final state

Nevertheless, many important measurements by CDF I:
- \(B^0_d\) mixing, \(\sin(2\beta)\), \(B\) lifetimes, \(B_c\) observation, ...

Now enhanced, thanks to XFT (precise tracking at L1):
- Reduced \((2 \to 1.5 \text{ GeV/c})\) and more effective \(P_T\) thresholds
- Increased muon and electron coverage
- Also \(J/\psi \to ee\)
**Di-μ trigger (J/ψ)**

2 central muons

$$P_T(μ) \geq 1.5 \text{ GeV}, P_T(J/ψ) \geq 0$$

Run I: $$P_T(μ) > 2 \text{ GeV}, 18 \text{ pb}^{-1}$$

Trigger on $$J/ψ \rightarrow μμ$$

Collected ~ 240 pb^{-1}

~ 2.4M $$J/ψ \rightarrow μμ$$ signal

$$J/ψ$$ modes down to low $$P_T(J/ψ) (~ 0 \text{ GeV})$$

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

- **Psi(2s)**: Events: 38k, Width: 22.1 ± 0.5 MeV/c^2
- **J/Ψ**: Events: 1.2M, Width: 22.6 ± 0.03 MeV/c^2

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**CMU-CMU J/ψ Yield (nb)**

- Failed Offline Validation
- $|\text{Yield} - \langle \text{Yield} \rangle| > 4σ$
- Good Runs

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**Run Number**

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Run II dimuon sample: yield 10 nb, $p_T(\mu) > 1.5$ GeV/c
Run I measurement: yield 3 nb, $p_T(J/\psi) > 5.0$ GeV/c, $p_T(\mu) > 2.0$ GeV/c
J/ψ Yield from Invariant Mass Fits

Fitted using signal MC mass template shapes + Chebyshev polynomial for background

CDF Run II Preliminary 0<\(p_T(J/ψ)\)<0.25 GeV/c
356±26 Events
Luminosity = 14.0 pb⁻¹

CDF Run II Preliminary 5.0<\(p_T(J/ψ)\)<5.5 GeV/c
18200±200 Events
Luminosity = 39.7 pb⁻¹

CDF Run II Preliminary 12.0<\(p_T(J/ψ)\)<14.0 GeV/c
1551±60 Events
Luminosity = 39.7 pb⁻¹

0 < \(p_T(J/ψ)\) < 0.25 GeV/c
5.0 < \(p_T(J/ψ)\) < 5.5 GeV/c
10.0 < \(p_T(J/ψ)\) < 12.0 GeV/c
Acceptance $A(p_T(J/\psi), |y|<0.6)$

Full GEANT simulation of the CDF detector, kinematics match well. Parametric simulation also used to study effects of different detector components.
Differential Cross Section

CDF Run II Preliminary

\[ \frac{d\sigma}{dp_T}\left( |y|<0.6 \right) \cdot Br(J/\psi \rightarrow \mu\mu) \text{ nb/(GeV/c)} \]

\[ p_T(J/\psi) \text{ GeV/c} \]

\[ \begin{array}{c}
\text{Data with stat. uncertainties} \\
\text{Systematic uncertainties}
\end{array} \]

Total Integrated Inclusive \( J/\psi \) Cross-Section:

\[ \sigma(p\bar{p} \rightarrow J/\psi X, |y(J/\psi)| < 0.6, \cdot Br(J/\psi \rightarrow \mu\mu) = 240 \pm 1\text{(stat)}^{+35}_{-28}\text{(syst)} \text{ nb} \]

\[ \sigma(p\bar{p} \rightarrow J/\psi X, |\eta(J/\psi)| < 0.6, p_T(J/\psi) > 5.0 \text{ GeV/c}) \cdot Br(J/\psi \rightarrow \mu\mu) = 17.4 \pm 0.1\text{(stat)}^{+2.6}_{-2.8}\text{(syst)} \text{ nb} \]

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## Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi$ Polarization</td>
<td>$\pm 4 - 10%$ ($p_T$ dependent)</td>
</tr>
<tr>
<td>$J/\psi$ Spectrum</td>
<td>$\pm 3 - 30%$ ($p_T$ dependent)</td>
</tr>
<tr>
<td>SVXII material</td>
<td>$-3%$ to $+6%$ ($p_T$ dependent)</td>
</tr>
<tr>
<td>L1 trigger efficiency</td>
<td>$-7.0%$ to $+13%$ ($p_T$ dependent)</td>
</tr>
<tr>
<td>Mass fits</td>
<td>$-0.7%$ to $+13%$ ($p_T$ dependent)</td>
</tr>
<tr>
<td>Momentum scale</td>
<td>$-0.08%$ to $+0.7%$ ($p_T$ dependent)</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$\pm 5.9%$</td>
</tr>
<tr>
<td>CMU Simulation</td>
<td>$\pm 1.4%$</td>
</tr>
<tr>
<td>Data quality</td>
<td>$\pm 1.0%$</td>
</tr>
<tr>
<td>Reconstruction eff.</td>
<td>$+2.1 - 2.7%$</td>
</tr>
<tr>
<td>L1 trigger efficiency</td>
<td>$\pm 0.2%$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$\pm 6.7% \oplus \epsilon(p_T^{J/\psi})$</td>
</tr>
</tbody>
</table>
**Cross Section: \( \frac{d\sigma}{dp_T^2} \)**

\( \frac{d\sigma}{dp_T^2} \) is Lorentz invariant phase space element proportional to the matrix elements.

Measurement of the \( J/\psi \) Meson and \( b \) Quark Production Cross Sections in \( \bar{p}p \) Collisions at \( \sqrt{s} = 1960 \) GeV

**M.Bishai et al.**
Simultaneous fit was used to $J/\psi$ proper decay length, $X = L_{xy}(J/\psi)/p_T(J/\psi) M(J/\psi)$ and invariant mass $M(\mu\mu)$ to extract the fraction of events from b-hadron decays

- **B-hadron signal shape**: MC templates of $X$ distributions are convoluted with resolution function measured in data
- **Prompt signal shape**: A double Gaussian with width of the dominant Gaussian = scale factor $X$ decay length uncertainty. 2nd Gaussian relative width and area fixed. This is also the resolution function shape.
- **Background decay length shape**: A prompt double Gaussian with different scale factor + symmetric exponential + long lived positive exponential
- **Invariant mass signal shape**: Double Gaussian with all parameters floating
- **Invariant mass background shape**: 1st order polynomial

MC templates used for $B \rightarrow J/\psi$ signal with decay table tuned using CLEO results

$L_{xy}/p_T$ convoluted with resolution function

Reliable separation for $J/\psi$ from $B$ and prompt at $p_T(J/\psi) > 1.25$ GeV

- $J/\psi$ has different shapes for $B$ and prompt components

Fitter tested on MC sample

MC templates of the $J/\psi$ proper decay length, $X$ are used to fit the b-hadron contribution to the inclusive $J/\psi$ distribution.

A parametric simulation is used to model the detector geometric and kinematic acceptance
$f_b = 0.097 \pm 0.010^{+0.012}_{-0.010}$

$f_b = 0.143 \pm 0.005^{+0.006}_{-0.006}$

$f_b = 0.279 \pm 0.012^{+0.008}_{-0.007}$
\begin{center}
\textbf{CDF } \textbf{Run II Preliminary}
\end{center}

\begin{table}
\begin{tabular}{|l|l|}
\hline
Source of uncertainty & Value \\
\hline
\multicolumn{2}{|c|}{Uncertainties on \( b \)-fraction} \\
\hline
Resolution function shape (including tails) & \(1 - 8\% \ (p_T \ \text{dependent})\) \\
MC production spectrum & \(2 - 7\% \ (p_T \ \text{dependent})\) \\
MC decay spectrum & \(0.5 - 4\% \ (p_T \ \text{dependent})\) \\
MC \( b \)-hadron lifetime & \(1 - 4\% \ (p_T \ \text{dependent})\) \\
Background fit model & \(< 3\% \ (p_T \ \text{dependent})\) \\
\hline
\end{tabular}
\end{table}

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**b Cross Section**

\[
\frac{d^2\sigma}{dy} (J/\psi \rightarrow \mu \mu) = 19.9 \pm 0.3 \text{(stat)} \pm 3.8 \text{(syst)} \text{ nb}
\]

\[
\sigma(p\bar{p} \rightarrow H_b X, |y| < 0.6) \cdot Br(H_b \rightarrow J/\psi X) \cdot Br(J/\psi \rightarrow \mu \mu) = 24.5 \pm 0.5 \text{(stat)} \pm 4.7 \text{(syst)} \text{ nb}
\]

\[
\sigma(p\bar{p} \rightarrow \bar{b} X, |y| < 1.0) = 29.4 \pm 0.6 \text{(stat)} \pm 6.2 \text{(syst)} \mu\text{b}
\]

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$\chi_c$ contribution

PRL 79, 578 (1997)

65% of prompt $J/\psi$ are direct
35% - from $\chi_c$ and $\psi(2S)$

$p^+ p^- \to \chi_c X; \chi_c \to J/\psi \gamma$

Run I: $1230 \pm 72$ events in $18 \text{ pb}^{-1}$

CDF Run 2 Preliminary

$\chi_c \to J/\psi \gamma$

46 pb$^{-1}$

$\Delta M = M(J/\psi \gamma) - M(J/\psi)$
52% of prompt $\Upsilon(1S)$ are direct.
$\Upsilon(1S)$ unpolarized at 2-20 GeV/c
Run I: $77\text{pb}^{-1}$, $4430\pm95 \Upsilon(1S)$,
$1114\pm65 \Upsilon(2S)$, $584\pm53 \Upsilon(3S)$
$|y(\Upsilon)|<0.4$, $p_T(\Upsilon) = 0-20$ GeV/c
Search for $\eta_b$ in Run I data (80 pb$^{-1}$):

Decay $\eta_b \rightarrow J/\psi \ J/\psi$

Expected mass: 9.36 – 9.46 GeV

7 events in window (background: 1.8 events)
1.5% probability (2.2$\sigma$)

Mass of potential signal 9446 $\pm$ 6(stat) MeV

Soon sufficient data for further $\eta_b$ study
Observation of a narrow state decaying to $J/\psi \pi^+\pi^-$

See talk G. Bauer “Quarkonium production: new results from CDF”
Summary

- Run II CDF collected ~234 pb\(^{-1}\) (in FY 2003) of data for heavy flavor physics (Run I total: 110 pb\(^{-1}\))
- Detector is well calibrated, mass scales and vertexing resolution are understood, Run I physics signals are re-established
- First measurement of inclusive \(J/\psi\) Cross Section down to \(p_T(J/\psi) = 0\)
- Observation of \(X(3870)\)
- CDF as Charm/B factory
- Great heavy flavor physics potential, we have results on: Masses, lifetimes, production Cross Sections competitive with or superseding Run I
- Near future: excellent quarkonia prospects. Measurement of polarization for \(J/\psi, \psi(2S)\) and \(Y\), production Cross Sections for \(B_c\) and \(\eta_b\)

Lots of heavy flavors at CDF, stay tuned for new exiting results