Quarkonia Production with Leptons and Hadrons

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- Introduction
- **FNAL** - past, present, and future
  - Tevatron (Run I/Run II): \((J/\psi, \psi(2S), \chi_c, \Upsilon, \chi_b, \eta_b)\)
  - Fixed Target: \((\Upsilon\text{ polarization})\)
- **HERA** - past, present, and future
  - Inelastic production measurements \((J/\psi, \psi(2S))\)
  - Diffractive production measurements \((J/\psi)\)
  - Fixed Target: \((J/\psi, \psi (2S), \chi_c, \Upsilon)\)
- Conclusions

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Introduction

- **Tevatron (Run I 1992-96, $\int L\ dt = 20\ pb^{-1}\ (IA) + 90\ pb^{-1}\ (IB)$):**
  - $p \rightarrow \bar{p} p$ at $\sqrt{s} = 1.8\ TeV$
  - $\eta, p_T$, polarization
- **HERA ("Run I", $\int L\ dt = 100\ pb^{-1}$):**
  - $e^\pm\ (27.5\ GeV) \rightarrow p\ (820/920\ GeV)$ at $\sqrt{s} = 300/320\ GeV$
  - $Q^2, W, z, p_T, t$, ..., polarization
  - overconstrained kinematics
- **History**
  - Inelastic $J/\psi$ production at HERA: a golden way to extract gluon density
  - Elastic/diffractive $J/\psi$ production to measure luminosity
- **Variety of presumed production mechanisms:**
  - Diffractive/elastic
  - Gluon-gluon-fusion, photon-gluon-fusion
  - Gluon fragmentation
  - "Resolved photon"-gluon/quark-fusion
  - + decays
# Publications (Most Recent Only)

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Luminosity Delivered and Recorded - CDF

Physics quality data began March 2002
\( \sqrt{s} = 1.96 \, \text{TeV} \)
Delivered 225 pb-1
Recorded 180 pb-1
(80%)
83% since February

Summer Conference
140 pb-1 QCD
110-140 pb-1 EWK
100-110 pb-1 Top+
100-140 pb-1 Exotics
110 pb-1 Bottom

Since Feb 10 2003, silicon in 94% of time

Winter top analyses used 57 pb-1

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Direct $\psi(2S)$ Cross Section - CDF

- $\psi(2S) \rightarrow \mu\mu$, Run IA data, 18 pb$^{-1}$
- "Central muons" ($|\eta| < 0.6$)
- Lifetime information from SVX used to extract prompt component
- Prompt $\equiv$ direct for $\psi(2S)$
- Colour singlet fusion: $\alpha_s^3/p_T^8$
- CS fragmentation (Braaten, Yuan, PRL 71(1993) 1673): $\alpha_s^5/p_T^4$
  
  $$g^* \rightarrow 2g + c\bar{c}(3S_1^{(1)}) \rightarrow \psi(2S)$$
- NRQCD expansion
  
  $$d\sigma(H) = \Sigma_n d\sigma[c\bar{c}(n)]\langle O^H(n) \rangle$$
  
- $n$ includes colour singlet and octet states
- Expansion in $\alpha_s$ and $v$ (relative velocity of quark and anti-quark)

- Colour octet fragmentation (Braaten, Fleming, PRL 74(1995) 3327): $\alpha_s^3v^4/p_T^4$
  
  $$g^* \rightarrow c\bar{c}(3S_1^{(8)}) \rightarrow \psi(2S)$$

- Fragmentation dominates at high $p_T$

Braaten, Fleming PRL 74(1995) 3327
CDF Data: PRL 79(1997) 572

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Prompt / Direct J/ψ Cross Section

Prompt J/ψ cross section includes:
- $\chi_c$ decays ($\chi_c \to J/ψγ$ measured)
- $ψ(2S)$ feed-down (measured)
- Direct J/ψ (64±6%)

CDF, PRL 79(1997) 572, 578
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Direct $J/\psi$ Cross Section

- Large uncertainties in the extracted matrix elements
  - low $p_T$: effects of gluon $k_t$
  - parton density functions

LO colour singlet:
$$g + \cdots \sim \alpha_s^3 \frac{(2m_c)^4}{p_t^8}$$

colour-singlet fragmentation: $g + g \rightarrow [c\bar{c}[^3S_1^{(1)}] + gg] + g$

$$+ \cdots \sim \alpha_s^5 \frac{1}{p_t^4}$$

colour-octet fragmentation: $g + g \rightarrow c\bar{c}[^3S_1^{(8)}] + g$

$$+ \cdots \sim \alpha_s^3 \frac{1}{p_t^4} \nu^4$$

colour-octet fusion: $g + g \rightarrow c\bar{c}[^1S_0^{(8)}, ^3F_J^{(8)}] + g$

$$+ \cdots \sim \alpha_s^3 \frac{(2m_c)^2}{p_t^8} \nu^4$$

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J/ψ Cross Section – Run II

CDF Run II Preliminary

- Data with stat. uncertainties
- Systematic uncertainties

Extends to $p_T=0$

$|\eta|<0.6$

\[ \frac{d\sigma}{dp_T} \cdot BR(J/ψ \rightarrow \mu \mu) = \frac{N'(p_T)}{\epsilon_{\text{rec}} \cdot \Delta p_T^{\text{bin}} \cdot \int L dt} \]

\[ \sigma_{pp \rightarrow J/ψ} = 240 \pm 1(\text{stat})^{+35}_{-28}(\text{syst}) \text{nb} \]

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J/ψ Cross Section - Run II

Cross section as a function of rapidity

Dzero Run2 PRELIMINARY
- pT(J/ψ)>5GeV/c
- pT(J/ψ)>8GeV/c

CDF Run1 results
17.4 +/- 2.8 nb
2.7 +/- 0.4 nb

Cross Section per 1.2 unit of rapidity

4.7 pb⁻¹

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**$J/\psi$ Polarization**

- All CDF Run I data, $\int L \, dt = 110 \, \text{pb}^{-1}$
- $p_T > 4 \, \text{GeV}$, $|y| < 0.6$
- Small acceptance at large $|\cos \theta|$
- $\chi^2$ fit using templates for longitudinal and transverse polarization

$$d\Gamma/d \cos \theta \propto 1 + \alpha \cos^2 \theta$$

$\alpha = 1$ **transverse**

$\alpha = -1$ **longitudinal**

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CDF, PRL 85 (2000) 2886

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$J/\psi$ Polarization

$J/\psi$ Production Polarization

**Prompt $\alpha$**
- CDF Preliminary
- $|y^{J/\psi}| < 0.6$

![Graph showing $\alpha$ vs. $P_{t}^{J/\psi}$ for prompt $J/\psi$ production.]

**B-decay $\alpha$**
- CDF Preliminary
- $|y^{J/\psi}| < 0.6$

![Graph showing $\alpha$ vs. $P_{t}^{J/\psi}$ for B-decay $J/\psi$.]

$J/\psi$ from B decays essentially unpolarized

CDF, PRL 85 (2000) 2886

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Prompt $J/\psi$ Polarization

- Need to take into account $\psi(2S)$ and $\chi_c$ contributions
- Data do not show a trend towards transverse polarization at large $p_T$
- Phenomenological models give better description
  - E.g. colour evaporation model: mostly unpolarized $J/\psi$ at large $p_T$

Braaten, Kniehl, Lee
PRD 62 (2000) 094005
ψ(2S) Polarization

- Same procedure, but limited statistics
- Preferable to J/ψ since no contamination from indirect production
- Inconclusive

CDF, PRL 85 (2000) 2886
Polarization in Run II

CDF study:

- Assume factor 50 in effective statistics
  - Integrated luminosity 2 fb\(^{-1}\)
  - Better SVX coverage (separate prompt/B)
- Lower dimuon trigger threshold (1.5 GeV)
  - Able to measure down to \(p_T(J/\psi)\) of \(\approx 0\)
- Systematic uncertainties still small at larger \(p_T\)
γ Cross Section at CDF

Run I:
PRL 88 (2002)161802

- smaller discrepancy with CSM but similar to $c\bar{c}$ result
- NRQCD CS+CO terms able to fit data with $p_T > 8$ GeV/c

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$\chi_b$ Feed-down to $\Upsilon(1S)$ at CDF

Run I:
PRL 84 (2000) 2094

$\chi_b(1P, 2P) \rightarrow \Upsilon(1S)\gamma$

$\pT (\Upsilon) > 8$ GeV/c

$\gamma$ backgrounds: $\pi^0$, $\eta$, $K_S$ decays

Direct $\Upsilon(1S)$: $(50.9 \pm 8.2 \pm 9.0)\%$

From $\chi_b(1P)$: $(27.1 \pm 6.9 \pm 4.4)\%$

From $\chi_b(2P)$: $(10.5 \pm 4.4 \pm 1.4)\%$

From $\Upsilon(2S)$: $(10.7^{+7.7}_{-4.8})\%$

From $\Upsilon(3S)$: $(0.8_{-0.4}^{+0.6})\%$

Input in theoretical calculations of Bottomonium cross sections

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$\Upsilon$ Polarization at CDF

$|y| < 0.4$
$8 < p_T < 20$ GeV/c

$1 + \alpha \cos^2 \theta$
$\alpha = 0.12 \pm 0.22$

- similar to $c\bar{c}$ → as yet inconclusive
- Insufficient data with $p_T > 20$ GeV/c

Run I:
PRL 88 (2002)161802
E866/Nusea, $\sqrt{s}=38.8$ GeV

$p + Cu \rightarrow \mu^+\mu^- X$
(800 GeV proton beam)

$0 < x_F < 0.6$

$p_T < 4$ GeV/c
(transverse to beam axis)

- $\Upsilon(2S)$ and $\Upsilon(3S)$ not distinguished
- Subtract Drell-Yan $\mu\mu$ continuum
  (100% transverse polarization)
- sideband fit: $\alpha=1.008 \pm 0.016 \pm 0.020$

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E866/Nusea, $\Upsilon$ polarization

Cos$\theta$ distributions for $p_T > 1.8$ GeV/c

- **Inclusive $\Upsilon(1S)$:**
  - NRQCD: $\alpha = 0.28$ to $0.31$, avg over $p_T$, $x_F$
  - Observed: $\alpha = 0.07 \pm 0.04$ (stat)$ \pm 0.06$ (sys)

- **Inclusive $\Upsilon(2S) + \Upsilon(3S)$:**
  - No explicit NRQCD prediction
  - Large observed transverse polarization, contrast with charmonium

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Search for $\eta_b$ at CDF

$\eta_b \rightarrow J/\psi J/\psi$ reconstruction

Braaten, Fleming, Leibovich
PRD 63 (2001) 094006

Expected production rate:
$\sigma(\eta_b) \sim (3-6) \times \sigma(\Upsilon(1S))$
$B(\eta_b \rightarrow J/\psi J/\psi) \sim 7 \times 10^{-4} \pm 1$

100 pb$^{-1}$
Possibly seen in Run I?

Small cluster: 7 events, 1.8 events expected from background

CDF mass resolution $\sim 10$ MeV/c$^2$
Search window 9.36 to 9.46 GeV/c$^2$
Simple mass fit: $9445 \pm 6$ (stat) MeV/c$^2$
Probability of background fluctuation: 1.5% ($\sim 2.2 \sigma$)
Search for $\eta_b$ at CDF

$\eta_b \rightarrow J/\psi J/\psi$ reconstruction

Rate Limit:

$$\sigma_{\eta_b}(|y|<0.4) \cdot B(\eta_b \rightarrow J/\psi J/\psi) \cdot [B(J/\psi \rightarrow \mu\mu)]^2 < 18 \text{ pb}$$

Run 1 SVX $J/\psi \rightarrow \mu\mu$ Data

Central value 3.5 pb

Improves apparent significance
Supportive of signal hypothesis
Need more data for confirmation

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Prospects for Run II

- $\int L \, dt \approx 1.4 \text{ fb}^{-1}$ by end of FY05, $\int L \, dt \approx 9 \text{ fb}^{-1}$ by end of FY09
  - Run II is well underway, data samples about 30% bigger than Run I now
- Will get many $J/\psi$'s and $\psi(2S)$ for free, but
  - Is the charm system massive enough?
  - For $J/\psi$, will always have feed-down to $J/\psi$ final states
- For most measurements, there are now two experiments
- Also better muon and silicon coverage, improved trigger capabilities, decays into $e^+e^-$ (?)
- There will be other possible measurements that can shed light on the colour octet issue
  - $h_c, \chi_c, \Upsilon, \chi_b...$ production cross sections
  - Associated jets in direct production
Run II - CDF

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

$J/\psi$: Events: $1.2 \times 10^3$, Width: $22.6 \pm 0.03$ MeV/$c^2$

$\phi(0s)$: Events: $378$, Width: $21.9 \pm 0.5$ MeV/$c^2$

4146 $\Upsilon(1S)$ events
1307 $\Upsilon(2S)$ events
~80 pb$^{-1}$

All four tracks in silicon
3.5 MeV/$c^2$ resolution

CDF Run II Preliminary 80 pb$^{-1}$

$N(\psi') = 2332.0 \pm 73.3$

$\psi(2s) \rightarrow J/\psi \pi^+ \pi^-$

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Run II – (CDF/D0 on $\chi_c$)

CDF Run II

CDF Run 2 Preliminary

$\chi_c \rightarrow J/\psi \gamma$

46 pb$^{-1}$

γ in calorimeter
$E_T(\gamma) > 1$GeV

CDF - Run I

PRL 79 (1997) 578
PRL 86 (2001) 4472

DO Run II Preliminary

$\chi_c \rightarrow J/\psi \gamma$

$N = 84 \pm 12$

$\Delta M_{c1} = 0.403 \pm 0.004$ GeV

$\sigma = 0.018 \pm 0.004$ GeV

γ conversions

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Quarkonia at HERA

- DIS
  - $1 < Q^2 < 100 \text{ GeV}^2$
- Tagged/untagged photoproduction
  - Scattered e not seen in main detector
  - Median $Q^2 \approx 10^{-4} \text{ GeV}^2$
- Decays into $e^+e^-$ and $\mu^+\mu^-$
- Central tracking ($|\eta| < 1.8$)
  - $30 < W < 180 \text{ GeV}$
  - In addition, dedicated analyses with specific statistical and systematic limitations (forward muon spectrometer, backward calorimetry, ...)

$Q^2 := -q^2$

$W^2 := (p_p + q)^2 \approx Q^2 / x$

$Q^2 \approx xys$
\[ z = \frac{P_p \cdot P_\psi}{P_p \cdot P_\gamma} = \frac{E_\psi}{E_\gamma} \text{ in } p \text{ rest frame} \]

- Order of magnitude comparable
  - "Elastic" \( z \approx 1 \) \( (M_X = m_p) \)
  - p diffractive dissociation \( z \approx 1 \) \( (\sigma \propto 1/M_X^2) \)
  - "Inelastic" \( z < 1 \)

- At small \( z \) contributions from
  - Resolved photon
  - B production

- Background increases with decreasing \( z \)
HERA Production Mechanisms

**Inelastic**

- "resolved" (gg-fusion) direct (γg-fusion)
  - (z<0.3)
  - (z>0.3)

**p-dissociation**

- J/ψ from ψ(2S) decays (ψ(2S) → J/ψππ and others)
  - (not subtracted, measured, ~ 15%)

- J/ψ from χ_c decays (not subtracted)
  - (1% of inelastic, up to 7% at lowest z)

- J/ψ from B decays (not subtracted)
  - (5% of inelastic, up to 25% at lowest z)

**Elastic**

- Cut on z, (fwd.) energy, add'l tracks, ...

- "Forward tagging"

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**J/ψ Photoproduction: CSM**

Colour Singlet Model: NLO calculation of direct photon gluon fusion process (M. Krämer)

LO: too steep
NLO: good agreement


Errorbands: $1.3 \leq m_c \leq 1.5$ GeV

$0.1175 \leq \alpha_s(M_Z) \leq 0.1225$

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$J/\psi$ Photoproduction: NRQCD

- $p_T$ spectra similar at low and medium $z$
- NRQCD (including CS and CO): softer than data
  - Contributions from B decays in data?

J/$\psi$ Photoproduction: inelasticity

EJ C25 (2002) 25
EJ C27 (2002) 173

CO long-distance ME taken from fit to CDF data

NLO CSM agrees with data; Theoretical uncertainties do not allow strong conclusions on CO
Left: NRQCD describes shapes (large LDME uncertainties)
Right: Damping at high $z$ for BSW (LO, CS+CO) ⇒ better agreement

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Photoproduction: $\sigma_{\psi(2S)}/\sigma_{\psi(1S)}$

**ZEUS**

\[\sigma_{\psi(2S)}/\sigma_{\psi(1S)} = 0.33 \pm 0.10^{+0.01}_{-0.02}\]

Flat, consistent with 0.24 from KZSZ (LO,CS)

Estimate of $J/\psi$ fraction coming from $\psi(2S)$
Cascade decays consistent with expectations (15%)
Photoproduction: helicity

\[
dN/d\cos\theta* \approx 1 + \alpha \cos^2\theta^* 
\]

BKV – collinear calculations

Baranov – \( k_t \)-factorization

Statistics is not yet sufficient to discriminate between models
H1 - J/ψ Electroproduction

Data: $2 < Q^2 < 100 \text{ GeV}^2$
$0.3 < z < 0.9$
$50 < W < 225 \text{ GeV}$
$p_T^* > 1 \text{ GeV}$
$\int L \, dt = 77 \text{ pb}^{-1}$

Theory: LO Colour Singlet Model
LO NRQCD (CS+CO)

CS alone: normalization low, too steep in $p_T$

NRQCD (CS+CO): too high at low $Q^2$, $p_T$
better at high $Q^2$, $p_T$

Need: NLO calculations
More data at larger $Q^2$, $p_T$
H1 - J/ψ Electroproduction

Q^2 > 2 GeV^2

Note: Theory normalized to data

Large shape discrepancy

EJ C25 (2002) 41

Rapidity in γp

CMS

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Zeus - $J/\psi$ Electroproduction: $Q^2$ and $W$

- $KZ(\text{CS})$ and $LZ(\text{CS})$: lower but consistent with data
- $KZ(\text{CS+CO})$: mostly overshoots data
- $LZ(\text{kt, CS})$: agrees with data

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Zeus - J/ψ Electroproduction: inelasticity

- KZ(CS+CO): too high at large z values (high-z resummation needed?)
- CS predictions are consistent with data
HERA photo/electro production summary

- **Photoproduction**
  - NLO corrections enable one to describe high production of J/ψ within CSM
  - Theoretical uncertainties are large: CO contributions cannot be excluded

- **Electroproduction**
  - LO CS: below but consistent with data, except high $p_T$ range (NLO corrections?)
  - NRQCD (CS+CO): too high at large $z$ and small $p_T^*$ values
  - $k_t$-factorization (CS): agrees with data except at high $p_T^*$ (too low) and in photon direction (too high)
HERA Prospects

- "HERA I" running period ended in September 2000
  - Another > 50 pb\(^{-1}\) per experiment collected in 2000, giving a total of > 100 pb\(^{-1}\)
- Many analyses make use of the full data sets
- After the HERA upgrade:
  - \(\int L \, dt \sim 100 \text{ pb}^{-1}\) per experiment expected by summer 2004
  - Polarized e\(\pm\) beams
- Various detector upgrades
  - ZEUS Silicon
  - New fast track trigger for H1
  - ...
- High Q\(^2\)/p\(_T\) will greatly benefit from increase in luminosity
HERA vs. Tevatron ME

- Only use theoretically safe regime: \( p_T^2, Q^2 > 4 \text{ GeV}^2, M_X > 10 \text{ GeV} \)
  - Statistics limited in 1999
- Consistent description difficult
- Repeat including recent data?
- Common fit?

\[
\langle \frac{1}{50} \rangle + \frac{3}{m_c^2} \langle \frac{3 P}{3} \rangle \quad \text{J.K. Mizukoshi, hep-ph/9911384}
\]
• HERA-B detector & trigger in good shape


♦ 1200-1400 $J/\psi$ per hour, 70% of available beam time used

♦ ~ 300,000 triggered $J/\psi$ ($e^+e^-/\mu^+\mu^-$)
♦ ~ $210 \cdot 10^6$ Minimum bias events

• Analysis of 2002/03 data in progress
J/ψ - Statistics

$J/ψ \rightarrow e^+e^-$: 40% of statistics

- $N(J/ψ) = 52.8 \text{ k}$
- $M(J/ψ) = 3.125 \text{ GeV}$
- $σ(J/ψ) = 63 \text{ MeV}$

No Bremsstrahlung requirement

$J/ψ \rightarrow μ^+μ^-$: full statistics

- $N_{J/ψ} = 166 \text{ k}$
- $M_{J/ψ} = 3.095 \text{ GeV}$
- $σ_{J/ψ} = 45 \text{ MeV}$
- $N_{ψ(2s)} = 2.7 \text{ k}$
- $M_{ψ(2s)} = 3.672 \text{ GeV}$
- $σ_{ψ(2s)} = 53 \text{ MeV}$

$μ^+μ^-$ invariant mass [GeV/c²]

Invariant Mass

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Detached J/ψ Analysis

$J/\psi \rightarrow e^+e^-$

(40 % of statistics)

$\Delta z/\sigma_z > 10$

impact par. cut

No bremsstrahlung
requirement

2000:

$n_B = 8.6^{+3.9}_{-3.2}$

$\# J/\psi = 40 \pm 12$

$J/\psi \rightarrow \mu^+\mu$

(60 % of statistics)

$\Delta z < 0.5 \text{ cm}$

$\Delta z > 0.5 \text{ cm}$

Impact par. cut

2000:

$n_B = 1.9^{+2.2}_{-1.5}$

No upstream J/ψ

$\# J/\psi = 40 \pm 11$

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Charmonium Production: $\chi_c$

Fraction of $J/\psi$ produced via $\chi_c$

$$R_{\chi_c} = \frac{\sum \sigma(\chi_{ci}) Br(\chi_{ci} \rightarrow J/\psi \gamma)}{\sigma(J/\psi)_{tot}}$$

$\Delta M = M(J/\psi \gamma) - M(J/\psi)$

Background subtracted

$N(\chi_c) = 6806 \pm 1058$

$M(\chi_c) = 0.437 \pm 0.004 \text{ GeV}$

$\sigma(\chi_c) = 0.044 \pm 0.008 \text{ GeV}$

Measurement 2000 based on $380 \pm 74 \chi_c$

$R_{\chi_c} = 0.32 \pm 0.06\text{ stat} \pm 0.04\text{ sys}$

First measurement of $\chi_c$ suppression in nuclear matter possible!

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Upsilon Production: $\sigma(pA \rightarrow \Upsilon)$

$\Upsilon \rightarrow \mu^+\mu^-$

$\Upsilon \rightarrow e^+e^-$

**Invariant mass, GeV**

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<th>ID</th>
<th>Entries</th>
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**Invariant mass, GeV**

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**# \Upsilon events**

- $\Upsilon \rightarrow \mu^+\mu^-$: $35 \pm 8$
- $\Upsilon \rightarrow e^+e^-$: $33 \pm 10$

**Width**

- $\mu^+\mu^-$: 157 MeV
- $e^+e^-$: 335 MeV

**Width: in agreement with MC**

**Measurement of the $\Upsilon$ production cross section is feasible may help to distinguish between Fermilab measurements**

Vaia Papadimitriou (Texas Tech University)  
June 28, 2003
Conclusions

- Tevatron Run I analyses done, most HERA-I analyses too
- Lots of results, many surprises
- Very fruitful interaction with theoretical developments
  - Non-relativistic QCD / colour octet contributions / ...
  - Soft Colour Interactions, Two Pomerons, ...
- Tevatron Run II will provide (1.4-9.0) fb$^{-1}$ (14-90x statistics)
- HERA-II will deliver $< 1$ fb$^{-1}$ (10x statistics, measure at larger $Q^2$, $p_T$, polarization)
- A lot of answers and surprises awaiting!!