Charmonium Production at HERA

Andreas B. Meyer
DESY
Electron-Proton Collider HERA

The HERA ep-Collider
@ DESY/Hamburg

- Scattering: $L \sim 100 - 1 e^-$
- Polarisation $\sim 50\%$
- In. Luminosity: $320 \text{GeV}$

Meson 2006, Krakow, 13/6/06
Experiments H1 and ZEUS

\[ \sqrt{s} = 320 \text{ GeV} \]

[27.6 GeV]

\[ [920 \text{ GeV}] \]

\[ p \]

\[ e \]

\[ e \]

\[ ZEUS \]

\[ [ZEUS \text{ Collaboration}] \]

Integrated Luminosity:

- HERA-I: 92-00: recorded 120 pb\(^{-1}\)
- HERA-II: 03-05: recorded 180 pb\(^{-1}\)
- Expected total by mid 2007: \( \sim 650 \text{ pb}^{-1} \)

[Central Tracking]

Silicon Detectors

Forw. Tracking

Central Muon System

LAr-Calorimeter

Solenoid

Forw. Muon System

Tof

Central Tracker Resolution

\( \frac{\Delta p_T}{p_T} = 0.006 \frac{p_T}{\text{GeV}} \leq 0.02 \)

\[ \text{ZEUS H1} \]

\[ \text{Summary DIS06 M.Klein} \]

\[ \text{HERA} \]

\[ \text{Status 23.4.06} \]

\[ \text{HERA delivered} \]

\[ \text{HERA I} e^+ \]

\[ \text{HERA II} e^- \]

\[ \text{Status 23.4.06} \]

\[ \text{days of running} \]

\[ \text{Integrated Luminosity (pb}^{-1}\text{)} \]

\[ 0 \]

\[ 50 \]

\[ 100 \]

\[ 150 \]

\[ 200 \]

\[ 250 \]

\[ 300 \]

\[ 350 \]
HERA Physics

- Multipurpose experiments at the high energy frontier
- QCD measurements
- Electroweak physics
- Searches for new physics

\[ \sqrt{s_{ep}} \sim 320 \text{ GeV} \]

\[ e^+ e^- \rightarrow \gamma, Z^0, W^\pm \]

\[ q(xp) \]

Proton Remnant

Struck Quark

\[ \frac{F_2(x, Q^2)}{x} \]

\[ \alpha_s \]

Zeus \( (a) \)

H1

\[ \text{H1 General Search} \]

SCALAR LEPTOQUARKS WITH F=0

Leptoquark search

Excluded

H1 CI

\[ \tilde{S}_{1/2, L} \]

OPAL indir. limit

D0 pair prod.

\[ \lambda \]

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Charmonium Production at HERA
Charmonium at HERA

Have measured J/ψ and ψ(2S) in decays into e⁺e⁻ and μ⁺μ⁻

e⁻ 27.6
p → 920

38 pb⁻¹

low-z region

mid-z region

high-z (diffractive) region

Elasticity z

Events

0.1 < z < 0.55

0.55 < z < 0.9

0.9 < z < 1

ZEUS 96-97

ep - Interactions at HERA

µ
µ
e′
X

−→e
27.6
←−p
920

Invariant mass (GeV)

0
50
100
150
200
250
300

0.05 < z < 0.45

ep → eJ/ψX √

s = 320 GeV ∫

Ldt ∼ 80 pb⁻¹
**Event Kinematics**

- **Photoproduction ($\gamma p$):** $Q^2 \sim 0$
  - beam electron scattered under low angles, (not detected in main detector)

- **Electroproduction (DIS):** $Q^2 > 2$ GeV

- **Kinematic variables**
  \[
  Q^2 = -q^2 \\
  s = (P + k)^2 \\
  W_{\gamma p} = \sqrt{(P + q)^2} \\
  z = \frac{p_\psi \cdot P}{q \cdot P} = \frac{E_{\psi}^*}{E_{\gamma}^*} \text{ in } p \text{ rest frame}
  \]
Production Mechanisms

in elastic
boson-gluon fusion

resolved (hadron-like)

direct

M_x >> m_p

M_x ~ m_p

M_x = m_p

diffra knife exchange of colourless state

p-dissociation

elastic

z>0.05

z~0.9

z~1

Elasticity

low-z region

mid-z region

high-z (diffractive) region

38 pb^{-1}

Events

Invariant mass (GeV)

0 50 100 150 200 250 300 350

0 200 400 600 800 1000

0 2 3 4 5

Events

Invariant mass (GeV)

0 50 100 150 200 250 300 350

0 200 400 600 800 1000

0 2 3 4 5

Events

Invariant mass (GeV)

0 50 100 150 200 250 300 350

0 200 400 600 800 1000

0 2 3 4 5

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0.1 < z < 0.55

0.55 < z < 0.9

0.9 < z < 1

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Production Mechanisms

- **inelastic boson-gluon fusion**
  - Resolved (hadron-like)
  - Direct
  - $M_X \gg m_p$

- **diffractive exchange of colourless state**
  - $p$-dissociation
  - $M_X \sim m_p$

- **elastic**
  - $M_X = m_p$

### Backgrounds to inelastic sample (not subtracted):
- $J/\psi$ from B decays (5% of inelastic, up to 25% at lowest $z$, resolved)
- $J/\psi$ from $\chi_c$ decays (1% of inelastic, up to 7% at lowest $z$, resolved)
- $J/\psi$ from $\psi(2S)$ decays (~15%, see later)

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Elastic VM Production at HERA

Wealth of Measurements of elastic VM Production from HERA

Not covered in this talk
Inelastic J/ψ Production

- **Colour Singlet Model**

  direct: \( \gamma g \rightarrow c\bar{c} \)

  resolved: \( gg \rightarrow c\bar{c} \)

  \[ c\bar{c} [1, ^3 S_1] \]

  **CS:** one parameter

  fixed from \( \Gamma(J/\psi \rightarrow \ell^+ \ell^-) \)

  \( \chi_c \) states are suppressed in (direct) ep and γp


  NLO (direct): Kraemer et al, 1995
Inelastic J/ψ Production

- Colour Octet Contributions (soft gluon radiation)

  direct: $\gamma g \rightarrow c\bar{c}$

  resolved: $gg \rightarrow c\bar{c}$

  $c\bar{c} \left[ 8, 2S+1 L_J \right]$

NRQCD-factorization:

$$\sigma_{J/\psi X} = \sum \hat{\sigma}(p\bar{p} \rightarrow c\bar{c}\,[n]\,X) \times LDME[n]$$

Long distance matrix elements (LDME) - from NRQCD fits to Tevatron data

Bodwin, Braaten, Lepage 1995
Tevatron

\[ \frac{\text{BR}(J/\psi \rightarrow \mu^+ \mu^-) \, \text{d} \sigma(p \bar{p} \rightarrow J/\psi + X) / \text{d}p_T \text{ (nb/GeV)}}{1 \, \eta \, 1 < 0.6} \]

NRQCD

CS(LO)

NRQCD calculations:
LO only
NLO still underway

NRQCD-factorization:

\[ \sigma_{J/\psi X} = \sum \hat{\sigma}(p \bar{p} \rightarrow c \bar{c}[n]X) \times \text{LDME}[n] \]

Test universality of LDME at other experiments (e.g. HERA, LEP, b-facts.)
\( J/\psi \) Photoproduction at HERA

\[ J/\psi \text{ in } \gamma p \text{ at HERA} \]

- ZEUS (38 pb\(^{-1}\))
- H1 (80 pb\(^{-1}\)) (scaled)

- KZSZ (NLO, CS)
- \( 0.117 < \alpha_s(M_Z) < 0.121 \)
- \( 1.3 < m_c < 1.6 \text{ GeV} \)
- KZSZ (LO, CS)

\[ \text{CS(LO)} \]
\[ \text{CS(NLO)} \]

\( \frac{d\sigma}{dp_T^2} \text{ (nb/GeV}\(^2\)) \)

Color singlet model:
NLO calculation is available for \( \gamma p \)

NLO (direct): Kraemer et al, 1995

CS (LO) too steep, too low (like in \( p\bar{p} \))
CS (NLO) alone describes data
**J/ψ Photoproduction at HERA**

CS model using kt-factorization (CASCADE) also describes shape of data  
H. Jung, 2001

CCFM evolution of unint. gluon density contains part of NLO corrections  
M. Ciafaloni et al, 1988
**J/ψ Photoproduction at HERA**

![Graph showing the differential cross section for J/ψ photoproduction with ZEUS and H1 data.]

- **ZEUS (38 pb⁻¹)**
- **H1 (80 pb⁻¹) (scaled)**
- **H1 (80 pb⁻¹) high W**

**KZSZ (LO, CS+CO)**

- 0.117 < α_s(M Z) < 0.121
- 1.3 < m_c < 1.6 GeV

**KZSZ (NLO, CS)**

- 50 < W < 180 GeV
- p_T > 1 GeV

**CASCADE**: too low at large z

\[ z = \frac{E_{\psi}}{E_{\gamma}} \text{ in p rest frame} \]

**CS (NLO):** z distribution reasonably well described

**CS+CO (LO):** also ok
z-Distribution

$Q^2 < 1 \text{ GeV}^2$, $60 < W_{\gamma p} < 240 \text{ GeV}$

$\frac{d\sigma}{dz}[\text{nb}]$

- H1
- ZEUS (scaled)

$p_{t,\psi} > 2 \text{ GeV}$

- CO
- CS

LO Color-Octet Contribution
→ no hard gluon
→ rises to large $z$

Color Singlet contribution:
→ hard gluon
→ falling off at large $z$
z-Distribution

$Q^2 < 1 \text{ GeV}^2$, $60 < W_{\gamma p} < 240 \text{ GeV}$

LO Color-Octet Contribution
→ no hard gluon
→ rises to large $z$

Color Singlet contribution:
→ hard gluon
→ falling off at large $z$

soft Color Octet gluons resummed:
→ reasonable description of shape

M. Beneke, G.A. Schuler, S. Wolf

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Compare with $J/\psi$ at b-factories

Singularity at large $z$, (as for NRQCD at HERA)

Gluon resummation to describe data at endpoint

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

Data falling towards $p^*$ endpoint

S. Fleming, A.K. Leibovich and T. Mehen 2003
\textbf{\(\psi(2S)\) Contribution}

**ZEUS**

\begin{itemize}
  \item \textbf{a)} \(\sigma_{\psi(2S)} / \sigma_{\psi(1S)}\) for \(p_T\) (GeV)
  \item \textbf{b)} \(\sigma_{\psi(2S)} / \sigma_{\psi(1S)}\) for \(W\) (GeV)
  \item \textbf{c)} \(\sigma_{\psi(2S)} / \sigma_{\psi(1S)}\) for \(z\)
\end{itemize}

**ZEUS 96-97**

\[38 \text{ pb}^{-1}\]

\[
\frac{\sigma(\psi(2S))}{\sigma(J/\psi)} = 0.33 \pm 0.1\text{(stat.)}^{+0.01}_{-0.02}\text{(syst.)}
\]

Estimate \(~15\%\) of measured \(J/\psi\) to come from \(\psi(2S)\) feed down (corrected in predictions)
**Elastic Vector Meson Production**

### Inelastic

**Boson Gluon Fusion**

\[ \sum \tilde{\sigma}(\gamma p \rightarrow c\bar{c}[n]X) \times \text{LDME}[n] \]

\[ \sigma \propto |xg(x)| \quad \text{moderate rise with } W_{\gamma p} \]

\[ \frac{d\sigma}{dp_{t,\psi}^2} \propto (p_{t,\psi}^2 + M_{\psi}^2)^{-4...5} \]

### Diffractive

**Colourless exchange: 2 gluons (LO)**

\[ \psi(\gamma \rightarrow c\bar{c}) \otimes \sigma_{\text{dipole}}^2 \otimes \Phi(J/\psi) \]

\[ \sigma \propto |xg(x)|^2 \quad \text{fast rise with } W_{\gamma p} \]

\[ \frac{d\sigma}{dt} \propto -t^{-3} \]
**Energy-Dependence**

- **0.3 < z < 0.9**
  - $2 < Q^2 < 100 \text{ GeV}^2$
  - $Q^2 < 1 \text{ GeV}^2$

- **z > 0.95, |t| > 2 \text{ GeV}^2**

**Fit $W^\delta$:**

$\delta \sim 0.49 \pm 0.16$

$\delta \sim 0.77 \pm 0.14 \pm 0.10$ (lowest t-bin)

Data confirm expected trend
Transv. Momentum Distributions

0.3 < z < 0.9

\[ \left( p^{2}_{t,\psi} + M_{\psi}^{2} \right)^{-n}: n = 4.49 \pm 0.15 \]

\[ z > 0.95, \ |t| > 2 \text{ GeV}^2 \]

\[ n = 6.63 \pm 0.13 \pm 0.08 \]

Data at large z somewhat steeper
**J/ψ Helicity Distributions**

- **Firm NRQCD Prediction:**
  - Transverse polarization at high transverse momentum (from gluon splitting)

\[
\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta^*} \propto 1 + \lambda \cos^2 \theta^* \\
\frac{1}{\sigma} \frac{d\sigma}{d \Phi^*} \propto 1 + \frac{\lambda}{3} + \frac{\nu}{3} \cos 2\Phi^*
\]

\[\lambda = +1: \text{transverse polarisation}\]
J/ψ Polarisation at HERA

Figure 5.18: Polarisation parameters (left panels) and (right panels) in the target rest frame as functions of (top panels) and (bottom panels). The error bars on the data points correspond to the total experimental error. The theoretical calculations shown are from the NRQCD approach [167] (shaded bands) with color-octet and color-singlet contributions, while the curves show the result from the color-singlet contribution separately.

pt-range at HERA: too low for gluon splitting

Results not conclusive yet: → more stats. underway
J/ψ Polarisation at the Tevatron

Prompt J/ψ Polarization

CDF 2 Preliminary, 188 ± 11 pb⁻¹

Both Run-I and Run-II data in contradiction to NRQCD expectation
Additional cut on $p_t^* > 1$GeV:
remove regions of largest theor. uncertainty

- Agreement between ZEUS and H1 data
- CS underestimates normalization but describes shape
- CS+CO too high at high $z$
- CS with kt-factorization ok
Conclusions

- Published Measurements: HERA-I
  - ZEUS and H1 measurements of cross sections and helicity in agreement
  - Wealth of measurements of elastic vector meson production (not covered in this talk)

- Color singlet model @ NLO or using kt-factorization describes $\gamma p$ data well
- NRQCD (LO) predictions not satisfactory at HERA (or other experiments)

  Description of Charmonium Production still causing trouble

  Expect improved measurements and theory calculations

- Upcoming Measurements: HERA-II
  - Increased Luminosity, improved Statistics
  - Larger $Q^2$, $p_t$, Polarization
  - Measure contributions from B-decays
  - Look for CO contributions in $X_c$ production at medium $z$, (where CS is suppressed)
Outlook

Delivered and expected luminosity in HERA in 1992-2007, pb⁻¹

30-40% of Integrated Luminosity still ahead