Quarkonium Production at HERA

Andreas B. Meyer
DESY
Experiments H1 and ZEUS

Total integrated Luminosity: ~500pb\(^{-1}\) per experiment
HERA Physics $\sqrt{s_{ep}} \sim 320$ GeV

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

\[ F_2(x,Q^2) \]

\[ \alpha_s \]

 searches using Generic Final States

SCALAR LEPTOQUARKS WITH $F=0$

Leptoquark search

Events

H1 General Search

H1 CI

$S_{1/2, L}$

H1 single prod.

OPAL indir. limit

D0 pair prod.
Charmonium at HERA

- Measure $J/\psi$ and $\psi(2S)$ in decays into $\mu^+\mu^-$ (and $e^+e^-$)
- Trigger and reconstruction down to $p_t \sim 0$
- Moderate backgrounds to inelastic sample (not subtracted):
  - $J/\psi$ from $B$ decays (5% of inelastic, up to 25% at lowest $z$)
  - $J/\psi$ from $\chi$ decays (1% of inelastic, up to 7% at lowest $z$)

38 pb$^{-1}$

low-z region

mid-z region

high-z (diffractive) region

Inelastic sample (not subtracted):

- Trigger and reconstruction down to $p_t \sim 0$
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  - $J/\psi$ from $B$ decays (5% of inelastic, up to 25% at lowest $z$)
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Event Kinematics

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

Electroproduction (DIS): $Q^2 > 2 \text{ GeV}$

$z$ measures softness of final state gluons emitted from $c\bar{c}$ pair

- Photoproduction (yp): $Q^2 \sim 0$
  beam electron scattered under low angles, (not detected in main detector)
- Electroproduction (DIS): $Q^2 > 2 \text{ GeV}$

kinematic variables

$$Q^2 = -q^2$$
$$s = (P + k)^2$$
$$W_{\gamma p} = \sqrt{(P + q)^2}$$
$$z = \frac{p_\psi \cdot P}{q \cdot P} = \frac{E_\psi^*}{E_{\gamma^*}} \text{ in } p \text{ rest frame}$$
**J/ψ Production**

- **Colour Singlet Model**
  - $c\bar{c} \left[ 1,^3S_1 \right]$
  - **CS**: one parameter fixed from $\Gamma(J/ψ \rightarrow ℓ^+ ℓ^-)$
  - NLO (direct): Kraemer et al, 1995

- **Colour Octet Contributions**
  - $c\bar{c} \left[ 8,^{2S+1}L_J \right]$
  - (soft gluon radiation)
  - **NRQCD-factorization**:
    \[
    \sigma_{J/ψX} = \sum \hat{σ}(p\bar{p} \rightarrow c\bar{c}[n]X) \times LDME[n]
    \]
  - Bodwin, Braaten, Lepage 1995
J/$\psi$ Production in $\gamma p$

HERA

NLO (direct): Kraemer et al, 1995

CS (DGLAP, NLO) calculation available for $\gamma p$ since 1995

CS alone is able to describe cross sections at HERA
**J/ψ Production in yp and p̅p**

**HERA**

- ZEUS (38 pb⁻¹)
- H1 (80 pb⁻¹) (scaled)

\( \text{KZSZ (NLO, CS)} \)

\( 0.117 < \alpha_s(M_Z) < 0.121 \)

\( 1.3 < m_c < 1.6 \text{ GeV} \)

\( \text{KZSZ (LO, CS)} \)

**Tevatron**

- NLO (direct): Kraemer et al, 1995
- Artoisenet, Maltoni et al, 2007

**CS (DGLAP, NLO) calculation available for yp since 1995**

**CS alone is able to describe cross sections at HERA**

**CS alone not able to describe the data alone but situation much less dramatic (γ ok)**

Andreas B. Meyer, DESY
Charmonium Production at HERA

QWG08, Nara, Japan, 3/12/08
J/$\psi$ Production in $k_t$-Factorization

HERA-I data comparison with CASCADE MC

H. Jung, 2001

- **CCFM evol. eq.** M. Ciafaloni et al., 1988
- $k_t$ - unintegrated gluon density
- Part of NLO corrections

**CS model using $k_t$-factorization (CCFM) describes data equally well as NLO**

**CCFM implemented in Monte Carlo event generator CASCADE**
HERA-II Data

- Data presented at QWG07
- Significantly improved precision (stat and syst)
- CS (DGLAP, NLO and CCFM) describe data
- NLO: very large normalization uncertainty
- New CCFM: absolute prediction is correct

\[ \frac{d\sigma}{dQ^2} = \frac{dJ'/dP_{T,J'/Y}}{dQ^2} \]

\[ \gamma p \]

\[ H1 \]

\[ P_{T,J'/Y}^2 \text{[GeV}^2] \]

\[ W_{\gamma p} \text{[GeV]} \]

\[ Q^2 \text{[GeV}^2] \]

\[ \text{DIS} \]

\[ \text{H1 preliminary} \]

\[ \text{CASCADE v2.0} \]

\[ \text{H1 data 04-06} \]

\[ \text{H1 (HERA I)} \]

\[ \text{CSM NLO} \]

\[ \text{CSM LO} \]

\[ \text{CASCADE (x1.05)} \]

\[ \text{EPJPSI (x1.25)} \]

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**DIS**

\[ \frac{d^2 \sigma}{dz \, dz'} \] [pb]

\( z \)

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**H1 preliminary**

\[ \frac{d^2 \sigma}{d\gamma_p J/\psi X} \] [nb]

\( \gamma_p \)

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\( \gamma_p \to J/\psi X \) [nb]

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Elasticity $z$

**inelastic boson-gluon fusion**

$\sigma \propto /dt$

$|xg\rangle \propto (\gamma (\gamma \rightarrow t | - 2 c \bar{c})) \rightarrow \otimes$

Fast rise with dipole 2 gluons)

$\hat{\sigma}$

Inelastic boson-gluon fusion

$M_X \gg m_p$

Invariant mass (GeV)

$0.1 < z < 0.55$

0.55 < $z$ < 0.9

$0.9 < z < 1$

0.55

Events

Events

Events

Events

$Elasticity z$

$z \sim 0.9$

$z \sim 1$

Low-z region

Mid-z region

High-z (diffractive) region

ZEUS 96-97

Charmonium Production at HERA

QWG08, Nara, Japan, 3/12/08
Elasticity $z$

**Inelastic boson-gluon fusion**

$z > 0.05$

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

$\sigma \propto |xg(x)|$ moderate rise with $W_{yp}$

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

**Diffractive exchange of colourless state**

$z \sim 0.9$

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

$\sigma \propto |xg(x)|^2$ faster rise with $W_{yp}$

\[
d\sigma/dt \propto -t^{-3}
\]

Transition between inelastic and diffractive production regimes?

$z \sim 1$
Transv. Momentum Distributions

0.3 < z < 0.9

H1

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

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

Behaviour is significantly, but not drastically different:

Cut in \( p_t \) does not provide clean experimental handle

Andreas B. Meyer, DESY

Charmonium Production at HERA

QWG08, Nara, Japan, 3/12/08
Energy Dependence

$0.3 < z < 0.9$

- $2 < Q^2 < 100 \text{ GeV}^2$
- $Q^2 < 1 \text{ GeV}^2$

$W [\text{ GeV}]$

$10^2$

$10$

Fit $W^6$: $\delta \sim 0.49 \pm 0.16$

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

- $2 < |t| < 5 \text{ GeV}^2$
- $5 < |t| < 10 \text{ GeV}^2$
- $10 < |t| < 30 \text{ GeV}^2$

$W_{\gamma p} [\text{GeV}]$

$10^2$

$10$

$\sigma(\gamma^* p \rightarrow J/\psi X) [\text{nb}]$

$\sigma(\gamma p \rightarrow J/\psi Y) [\text{nb}]$

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

Large $z$: steeper energy dependence
Elasticity Distribution

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

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

- H1
- ZEUS (scaled)
- \( p_{t,\psi} > 2 \text{ GeV} \)

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 for data at \( z < 0.9 \) !!!

Elasticity Distribution

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

- H1
- ZEUS (scaled)
- \( p_{t,\psi} > 2 \text{ GeV} \)
- CO
- CS

Description of CO endpoint behaviour (B-factories ↔ HERA)
Elasticity Distribution

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

\[ d\sigma/dz \] averaged over \( 0.95 < z < 1 \), although event distribution in \( z \) is steep

At HERA, cross section does actually rise steeply due to diffractive process

**My extrapolation of H1 published result**

Total cross section for \( z > 0.95 \):

\[ |t| > 4 \text{ GeV}^2 \text{ and } 60 < W_{\gamma p} < 240 \text{ GeV} \]

\[ \sigma = 6.04 \pm 0.35 \pm 0.95 \text{ nb} \]
Elastic VM Production

Elastic VM production has been measured for $\rho^0$, $\omega$, $\phi$, $J/\psi$, $\psi(2S)$ and $\Upsilon(1S)$

ZEUS: New measurement of elastic production of Upsilon
\[
\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta^*} \propto 1 + \lambda \cos^2 \theta^* \\
\frac{1}{\sigma} \frac{d\sigma}{d \Phi^*} \propto 1 + \frac{\lambda}{3} + \frac{\nu}{3} \cos 2\Phi^*
\]

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

- CS (DGLAP, LO): λ ok, ν too high
- CS+CO (DGLAP, LO): ok
- New CS (CCFM): ok
- New CS (DGLAP, NLO): ok

Beneke, Krämer, Väntinnen, 1998
Baranov, 2008
Artoisenet, Lansberg et al, 2008

new calculations available
Similar behaviour for CS (DGLAP, NLO) and CS (CCFM)

ZEUS data show opposite trend, CS (DGLAP, LO) describing data best

Contributions from diffractive backgrounds at low $p_T$ and high $z$ being evaluated
Conclusions

- New HERA data-to-theory comparisons:
  - Several new calculations have become available recently (CCFM and DGLAP, NLO)
  - Both CS (DGLAP, NLO) and CS (CCFM) describe the data rather well
  - Higher order calculations remove need for colour octet contributions

- Inelasticity distributions
  - Diffractive VM production is the dominant production process for $\psi(nS)$ and also for $\Upsilon(nS)$
  - Can not distinguish production processes at large $z$ experimentally
  - Transition between inelastic and diffractive VM production regimes to be understood

- Upcoming final publications from HERA:
  - H1: cross sections and polarization (DIS and $\gamma p$)
  - ZEUS: polarization ($\gamma p$) (cross section measurements planned for later)
  - Looking out for theoretical and experimental input and suggestions