Vector Meson Production at HERA

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Aim is understand dynamics of high energy scattering in QCD

- test pQCD in transition regime soft-hard
- measure non-perturbative quantities (generalised) pdfs
Vector meson production in $\gamma^* p$

**HERA regime:** collisions of 27.5 GeV $e$ with 920 GeV $p$

$0 < Q^2 < 100 \text{ GeV}^2$ and $30 < W < 220 \text{ GeV}$

- $Q^2$ - virtuality of exchanged $\gamma^*

\begin{align*}
Q^2 &= -q^2 = -(k - k')^2
\end{align*}$

- $W$ - $\gamma^* p$ centre of mass energy

\begin{align*}
W &= (q + p)^2
\end{align*}$

- 4-momentum transfer squared at the $p$ vertex

\begin{align*}
t &= (P - P')^2
\end{align*}$

- $x$ - Bjorken variable

\begin{align*}
x &= \frac{Q^2}{P \cdot q} = \frac{Q^2}{Q^2 + W^2}
\end{align*}$
QCD factorization - two approaches

QCD - Breit frame

\[ \gamma^*_{T(L)} \text{ wave function} \quad \text{VM wave function} \]

\[ \bar{q} \quad V \quad q \]

\[ x + \xi \quad x + \xi \]

\[ p \quad p \text{ elastic form-factor} \]

NLO calculation available for

\[ J/\psi (\gamma p, \text{DIS}) \text{ and } \rho (\text{DIS}) \]

\[ \sigma_L \simeq \frac{\alpha_s^2}{Q^6} |xG(x, Q^2)|^2 \Rightarrow \]

\[ \sigma_L \propto \frac{\alpha_s^2}{Q^6} |H(x_1, x_2, t, Q^2)|^2 \]

Generalised PDFs build from PDFs with skewing effect and \( t \)-dependence

\[ \gamma^* \text{ fluctuates in } q\bar{q} + q\bar{q}g + .. \]

\[ \text{Lifetime of dipole very long because of large } \gamma \text{ boost} \]

\[ \text{Transverse size } \propto 1/(Q^2 + M^2_{q\bar{q}}) \]

\[ \sigma_{\gamma^* p}(x, Q^2) = \int dr^2 dz \psi^{in}(r, z, Q^2) \sigma_{\text{dipole}}^2(x, Q^2) \]

\[ \sigma_{\text{dipole}} \text{ from model (2-gluons, ..)} \]
Clean experimental signature

- scattered $e$ reconstructed in CAL or beam pipe calorimeter (DIS) or undetected ($\gamma p$)
- scattered $p$ undetected
- i.e. $\rho \rightarrow \pi^+\pi^-$, $J/\psi \rightarrow l^+l^-$ (BR 6%)
- 2 tracks reconstructed in central chamber associated to pions, electrons or muons in CAL electrons can be reconstructed in CAL, outside tracking acceptance
- nothing else in the detector
Clean experimental signature - $J/\psi$

data from 1999/2000 (HERA I): 55 pb$^{-1}$ central, 30 pb$^{-1}$ backward

<table>
<thead>
<tr>
<th>Electroproduction</th>
<th>Photoproduction</th>
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<td><strong>(TT)</strong></td>
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<td><strong>(&quot;track-track&quot;)</strong></td>
<td><strong>$J/\psi \rightarrow \mu^+ \mu^-$</strong></td>
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<td>$40 &lt; W_{\gamma p} &lt; 160$ GeV</td>
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2 tracks
$\geq 1$ muon + scatt. electron

Photoproduction
**(TC)**
**("track-cluster")**
$J/\psi \rightarrow e^+ e^-$

1 cluster
1 track

Photoproduction
**(CC)**
**("cluster-cluster")**

$135 < W_{\gamma p} < 235$ GeV

Electron analysis
2 clusters

Muon analysis
2 tracks
$\geq 1$ muon
Exclusive $J/\psi$ production

**Kinematic range**

- **ZEUS**
  
  \[ Q^2 \approx 10^{-5} \]
  
  \[ 35 < W < 280 \text{ GeV} \]
  
  \[ -t < 1.5 \text{ GeV}^2 \]

  \[ 0.15 < Q^2 < 0.8 \text{ GeV}^2 (69 \text{ pb}^{-1}) \]

  \[ 2 < Q^2 < 100 \text{ GeV}^2 (83 \text{ pb}^{-1}) \]

  \[ 30 < W < 220 \text{ GeV} \]

  \[ -t < 1 \text{ GeV}^2 \]

- **H1**
  
  \[ Q^2 \approx 0.05, 2 < Q^2 < 80 \text{ GeV}^2 \]

  \[ 40 < W < 300 \text{ GeV} \]

  \[ -t < 1.2 \text{ GeV}^2 \]
Exclusive $J/\psi$ production - $W$ dependence

$\sigma$ vs $W$ in bins of $Q^2$

- $\sigma \propto W^\delta$, with $\delta = 0.7$
- no dependence of $\delta$ from $Q^2$
$\sigma$ vs $W$ in bins of $Q^2$

- General transition to hard behaviour at high values of $Q^2 + M^2$
\[ \frac{d\sigma}{dt}(p \rightarrow J/\psi p)/dt \ (nb/GeV^2) \]

- **Fit** 
  
  \[ e^{bt}, \ b = 4.72 \pm 0.15 \pm 0.12 \text{ GeV}^{-2} \]
  
  \[ (1 - t/m^2_g)^4, \ m^2_g = 0.55 \pm 0.02 \text{ GeV}^2 \]

- **t-dependence in bins of** \( Q^2 \)

- **Fit** 
  
  \[ b = 4.5 \pm 0.2 \text{ GeV}^{-2} \]
  
  \[ \langle Q^2 \rangle \text{ [GeV}^2\rangle \]

- **H1 prelim.**
  
  \[ 40 < W_p < 160 \text{ GeV} \]

- **d\sigma/dt \propto e^{bt}, \ for |t| < 1 \text{ GeV}^2**

- **d\sigma/dt \propto e^{bt}**

- **b related to transverse size of the interaction c\bar{c}-p**

- **no dependence of b from** \( Q^2 \), interaction dominated by size of p
$t$ dependence

$$d\sigma/dt \propto e^{bt}$$

**General transition to small configuration at high values of $Q^2 + M^2$**
Exclusive VM production - effective Pomeron trajectory

\[ d\sigma/dt \propto \exp^{b_0 t} W^4(\alpha_{IP}(t) - 2) \]

**Photoproduction:**
\[ \alpha_{IP}(t) = (1.224 \pm 0.010 \pm 0.012) + (0.164 \pm 0.028 \pm 0.030) GeV^{-2}t \]

**DIS:**
\[ \alpha_{IP}(t) = (1.18 \pm 0.05 \pm 0.03) + (0.02 \pm 0.14 \pm 0.07) GeV^{-2}t \]
Exclusive VM production - effective Pomeron trajectory

\[ \frac{d\sigma}{dt} \propto \exp^{b_0 t} W^4(\alpha_{IP}(t)-1) \text{ with } \alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP} t \]
Exclusive $J/\psi$ production

comparison with QCD models

Martin, Ryskin Teubner
Frankfurt, Koepf, Strikman
Gotsman, Levin, Lublisky, Maor, Naftali

models differ for

- assumptions on $c\bar{c}$ wave function
- corrections applied to LO calculations
- assumptions on GPDFs
- large uncertainty in normalisation
- models describe qualitatively data
- rise of $\sigma$ with $W$ related to increase in gluon density at low $x$
Exclusive $\rho$ - comparison with models

- First NLO: Ivanov, Krasnikov and Szymanowski

\[ \sigma_{\gamma p \rightarrow \rho p} \text{ [nb]} \]

- $Q^2$ [GeV$^2$]
- $\delta$ (± stat.)
- 0.0: $0.16±0.06$
- 0.47: $0.12±0.03$
- 0.47: $0.33±0.05$
- 0.56: $0.38±0.05$
- 0.56: $0.38±0.05$
- 0.56: $0.56±0.10$
- 0.52: $0.52±0.09$
- 0.52: $0.52±0.09$
- 0.46: $0.46±0.10$
- 0.46: $0.46±0.10$
- 0.88: $0.88±0.28$

- $M=$MRST2001, $C=$CTEQ6M
- solid line $\mu_R = \mu_F$, dashed line $\mu_R = Q$
Exclusive $J/\psi$ production - comparison to different PDFs

- strong sensitivity to generalised gluon distribution
- could the data be used to constrain gluon density?
VM at large $t$: BFKL dynamics

- BFKL evolution driven by terms $\alpha_s^n \ln^n(W^2/|t|)$
- At high $t$, proton mostly dissociates
- BFKL-based models reproduce the trend of data (but NLO missing)
BFKL dynamics

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

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

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

- BFKL LL (fixed \( \alpha_s \))
- BFKL LL + NL (fixed \( \alpha_s \))
- DGLAP LL

- DGLAP fails to describe evolution at large \( t \)

\[ \frac{d\sigma}{dt} \text{ [nb/GeV}^2 \text{]} \]

- ZEUS 96-97 (prel.), \( <W>=200 \text{ GeV} \)
- ZEUS 96-97, \( <W>=100 \text{ GeV} \)

Alessia Bruni, INFN Bologna

Blois, May 15-20, 2005
VM at large $t$: BFKL dynamics

ZEUS

H1 Preliminary ($\gamma p \rightarrow \rho Y$)

$\gamma p \rightarrow \rho Y$

$\gamma p \rightarrow \phi Y$

$\gamma p \rightarrow J/\Psi Y$

$1/\sigma d\sigma/d|t|$ (GeV$^2$)

$|t|$ (GeV$^2$)

$Q^2 < 0.01$ GeV$^2$

$75 < W < 100$ GeV

$M_{\gamma} < 5$ GeV

$n = 4.41 \pm 0.07^{+0.07}_{-0.06}$
Decay angular distributions

Helicity angles
\( \theta_h, \phi_h \) - angles of decay particle in the meson rest frame
\( \Phi \) - angle between scattering and production plane

Angular distributions are related to the spin of \( \gamma^* \) and meson
Angular distr. \( \rightarrow \) spin density matrix elements \( r_{ij}^{kl} \rightarrow \) helicity amplitudes
\( T_{\lambda_V \lambda_M \lambda_\gamma} \)
DECAY Angular Distributions

Spin Matrix Elements

s-channel helicity conservation (SCHC):

- the VM retains the $\gamma^*$ helicity. $R = \sigma_L / \sigma_T$ is related to the spin density matrix elements $r_{00}^{04}$ (good approximation).

pQCD:

- during the interaction, the orbital angular momentum of the $q\bar{q}$ can be modified through the transfer of transverse momentum carried by gluons;

- the helicity of the outgoing vector meson can be different from that of the incoming photon, helicity flip between photon and meson is possible.
VM at large $t$: BFKL dynamics

- $t$ dependence well described by BFKL models
- but BFKL models unable to describe $\tau_{10}^{04}$
- progress expected
Summary

- Experimentally much progress has been achieved,
  - high precision in wide kinematic region
  - increased statistics at high $Q^2$ will help (700 pb$^{-1}$ expected at HERA II)
- Theoretically chance to investigate the QCD dynamics in the semi-hard regime,
  - the overall picture looks correct
  - large uncertainties
  - full NLO calculations are missing