Vector Meson production and DVCS at HERA

On behalf of the H1 and ZEUS Collaborations

Janusz Tomasz Malka
University of Łódź
Exclusive diffractive processes

Diffraction - no quantum numbers are exchanged in the interaction btw \( \gamma \) and \( p \) → no colour flux → large rapidity gap

- Vector Meson \((\rho, \omega, \phi, J/\psi, \psi', \gamma)\) photon \((\gamma)\)
- Photon virtuality \(Q^2\) → \(Q^2 = -q^2 = -(k - k')^2\)  
  \((Q^2 \approx 0 \rightarrow \text{photoproduction}, Q^2 > 0 \rightarrow \text{electroproduction})\)
- C.m. energy of \(\gamma p\) system \(W\) → \(W^2 = (q + p)^2\)
- (4-mom. transfer)\(^2\) at \(p\)-vertex \(t\) → \(t = (P - P')^2\)

The proton can stay intact \(p(P')\) or dissociate \(Y(P')\)
Vector Dominance Model (VDM):

- The photon fluctuates into a vector meson, $V$, which carries the same quantum numbers as the photon ($\gamma p \rightarrow V p$)
- The vector meson scatters elastically off the incoming proton ($V p \rightarrow V p$)

Predictions:

Experimental observations:

- $\alpha(t) = \alpha(0) + \alpha' t$, $\alpha(0) = 1.08$, $\alpha' = 0.25$; (Donnachie-Landschof)
- Shrinkage of the diffractive peak $b(W) = b_0 + 4\alpha' \ln \left( \frac{W}{W_0} \right)$
- Weak energy dependence of cross section $\sigma \propto W^\delta$, $\delta \approx 4 \left[ \alpha(0) - \frac{\alpha'}{b_0} - 1 \right]$, $\delta \approx 0.2$;

\[
\frac{d\sigma(\gamma p \rightarrow V p)}{dt} \propto e^{-b_0 t} \left( \frac{W^2}{W_0^2} \right)^{2(\alpha(t)-1)}
\]
**pQCD models (Hard physics)**

- the photon fluctuates into a $q\bar{q}$ state
- the $q\bar{q}$ pair scatters off the proton target
- the scattered $q\bar{q}$ pair turns into a vector meson

**Predictions:**

- $\sigma \propto [xg(x,\mu^2)]^2$ where $\mu^2 = f(Q^2,M^2,v,t)$
- Increasing $W$ corresponds to going to small $x$
- Fast increase of the $\gamma^* p \rightarrow V p$ cross section with energy $W$
- Universal exponential $t$ dependence
  - $b \sim 4 - 5 GeV^{-2} \Rightarrow \alpha' \approx 0$

\[x \approx \frac{Q^2}{W^2} \text{ at low } x\]
Transition from soft to hard physics

\[ \delta \approx 0.2 \]
\[ b \approx 10 \text{GeV}^{-2} \]
\[ \alpha' \approx 0.25 \text{GeV}^{-2} \]

\[ \sigma \propto W^\delta \]
\[ \frac{d\sigma}{d|t|} \propto e^{-b|t|} \]

\[ \delta \leq 0.7 \]
\[ b \approx 4-5 \text{GeV}^{-2} \]
\[ \alpha' \approx 0 \]
Vector mesons mass distributions

- $0.0 \leq |t| < 0.2 \text{ GeV}^2$
- $N_{\text{obs}}$
- $M_{\rho\omega\phi} \text{ [GeV]}$
- $N_{\text{obs}}$
- $M_{\rho\omega\phi} \text{ [GeV]}$

Graphs showing distributions for $\rho$, $\omega$, $\phi$, $\psi'$, and $J/\psi$. Additionally, a graph for $\gamma$ and mass distributions for $\mu^+\mu^-$. 

ZEUS 1996 - 1997

ZEUS 96/07 (468 pb$^{-1}$)
**W dependence of the photoproduction of VM**

The parameterisation of the cross section: \( \sigma \propto W^\delta \)

Process becomes hard (steeper W dependence) as mass of VM becomes larger

Apply pQCD models
$W$ dependence of the photoproduction of VM

The parameterisation of the cross section: $\sigma \propto W^\delta$

Sensitivity to gluon density

$\gamma p \rightarrow J/\psi p$

FMS – L. Frankfurt, M. McDermott and M. Strikman, JHEP 0103 (2001)
W dependence of the photoproduction of VM

The parametrisation of the cross section:

$$\sigma \propto W^\delta$$

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cross section $W$ dependence becomes steeper at high $Q^2$ for $\rho$, $\phi$ from soft to hard regime

fit: $\sigma \sim W^\delta$
Deeply Virtual Compton Scattering (W dependence)

- fit: $\sigma \sim W^\delta$
- No $\delta$ dependence on $Q^2$ is observed
- Hard regime
Summary (W dependence)

- process becomes hard as scale \((Q^2 + M^2)\) becomes larger
|t| dependence ($\rho$)

\( \frac{d\sigma}{d|t|} \sim \exp(-b|t|) \) in bins of \( Q^2 \)

- \( b \) describes the transverse size of the interaction region \( b \propto R^2 \)

Transverse size of dipole decreases with \( Q^2 \)

\( b \) decreases from soft values to pQCD expected values (\( \sim 4-5 \text{ GeV}^{-2} \))
\[ |t| \text{ dependence (DVCS)} \]

**H1:** \[ b = 5.41 \pm 0.14 \pm 0.31 \text{ GeV}^{-2} \]

**ZEUS:** \[ b = 4.5 \pm 1.3 \pm 0.4 \text{ GeV}^{-2} \]

- DVCS point don’t show \( Q^2 \) dependence

Direct \( t \) measurement using Leading Proton Spectrometer
\[ |t| \text{ dependence (Upsilon) photoproduction} \]

2 times far from present results at \( Q^2 + M^2 = 89.5 \text{ GeV}^2 \)

Elastic:

\[ b = 4.3^{+1.7}_{-1.1} \pm 0.5 \text{ [GeV}^{-2}] \]
\[ \frac{d\sigma}{dt} \sim e^{-b|t|} \]

transverse size:
\[ b = b_V + b_p \]

Vector Meson transverse size
\[ b_V \sim \frac{1}{Q^2 + M_V^2} \]

Target size:
\[ b_p \approx 5 \text{GeV}^{-2} \]

\( r_{\text{gluons}} \approx 0.5 \text{ fm} \)
\( r_{\text{em}} \approx 0.8 \text{ fm} \)

b decreases with from \( \sim 10 \text{ GeV}^{-2} \) (soft) to \( \sim 5 \text{ GeV}^{-2} \) (hard)
size of scattered VM getting smaller with scale
**J/ψ photoproduction at high |t|**

Hard scale provided by |t| and mass. |t| dependence no longer exponential.

\[
\frac{d\sigma}{d|t|} \propto t^n
\]

\( n = -1.9 \pm 0.1, \ 2 < |t| < 4 \ \text{GeV}^2 \)
\( n = -3.0 \pm 0.1, \ 4 < |t| < 16 \ \text{GeV}^2 \)

\( \sigma_{\text{W}} \) in |t| ranges: data rise with W for all |t|

EMP (BFKL) below data

GLMN (DGLAP) fails at |t| > 5 GeV^2

FSZ gives good description up |t| = 12 GeV^2

BFKL LL and FSZ are too steep (W dependence)

None of the models describes the data over the full phase space.
effective Pomeron trajectory

\[ \frac{d\sigma}{dt} \propto \left( \frac{W}{W_0} \right)^{4(\alpha(t) - 1)} \]

\[ \alpha(t) = \alpha(0) + \alpha' t \]

\[ \alpha(0) \text{ consistent with } 1.08 \text{ from soft pp scattering} \]

\[ \alpha' \sim \text{twice smaller than } 0.25 \text{ GeV}^{-2} \]
Two pion diffractive electroproduction

Measure two pion mass distribution $0.4 < M_{\pi\pi} < 2.4$ GeV in $2 < Q^2 < 80$ GeV$^2$

\[ \frac{dN(M_{\pi\pi})}{dM_{\pi\pi}} = N \left[ |F_{\pi}(M_{\pi\pi})|^2 + \frac{B}{M_{\pi\pi}^2} \right] \]

$F_{\pi}(M_{\pi\pi}) = \frac{BW(\rho) + \beta BW(\rho') + \gamma BW(\rho'')}{1 + \beta + \gamma}$

11 parameters fit:
N, B, n, $M(\rho)$, $\Gamma(\rho)$, $M(\rho')$, $\Gamma(\rho')$, $M(\rho'')$, $\Gamma(\rho'')$, $\beta$, $\gamma$, where N - total normalization factor, B, n - described background, M, $\Gamma$ - masses and widths of vector mesons and $\beta$, $\gamma$ - relative amplitudes
Measure two pion mass distribution $0.4< M_{\pi\pi} < 2.4$ GeV in $2<Q^2< 80$ GeV$^2$

\[
\frac{dN(M_{\pi\pi})}{dM_{\pi\pi}} = N \left[ |F_\pi(M_{\pi\pi})|^2 + \frac{B}{M_{\pi\pi}^2} \right]
\]

11 parameters fit:
N, B, n, M($\rho$), $\Gamma(\rho)$, M($\rho'$), $\Gamma(\rho')$, M($\rho''$), $\Gamma(\rho'')$, $\beta$, $\gamma$,
where N - total normalization factor, B, n - described background, M, $\Gamma$ - masses and widths of vector mesons and $\beta$, $\gamma$ - relative amplitudes

$F_\pi(M_{\pi\pi}) = \frac{BW(\rho) + \beta BW(\rho') + \gamma BW(\rho'')}{1 + \beta + \gamma}$
$\rho, \rho', \rho''$ electroproduction (cross section ratios)

$\rho'/\rho$ increases with $Q^2$

The anomalous behaviour of $\rho'/\rho$ production ratio with $Q^2$ was predicted in works of J. Nemchik, B. Kopeliovich, N. Nikolaev, B. Zakharov, (see hep-ph/9605208)

$\rho''/\rho$ constant with $Q^2$
Summary

New measurements of $\rho$, $\phi$ and $\Upsilon$ at HERA.

The measurements allow us to study the transition from the soft to hard regime.

Effective Pomeron trajectory has smaller slope than that extracted from soft hadron-hadron scattering.

DVCS asymmetries and $|t|$ slope measurements provide access to GPDs.

Measurement of $\rho, \rho', \rho''$ production shows anomalous behaviour of $\rho'/\rho$ cross section ratio

$pQCD$ expectations are in general compatible with the data, but still a lot to be understood.
Backup
HERA experiments

27.5 GeV electrons/positrons with 920 GeV protons beam
CMS energy = 318 GeV
$\sigma_L, \sigma_T$ \textbf{cross sections}

- Unique opportunity to extract $R = \sigma_L / \sigma_T \quad \sigma = \sigma_T + \varepsilon \sigma_L \quad \varepsilon \approx 0.996$
- $R$ measured from angular distributions $f(\cos \theta_{hr} r_{0400})$, in SCHC approximation

![Graphs showing $\sigma_L$ and $\sigma_T$ vs. $Q^2+M^2$](image)

\textbf{expectation:} $R = \sigma_L / \sigma_T \sim Q^2/M^2$

\textbf{as the scale gets harder} $\sigma_L$ dominates

$\sigma_L$ and $\sigma_T$ have different $Q^2+M^2$ dependence

Models based on pQCD describe well $\sigma_L$, but not $\sigma_T$

\textbf{INS} - I.P. Ivanov, N.N. Nikolaev and A.A. Savin, Phys.Part.Nucl. 37 (2006) 1


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Effective Pomeron trajectory

\[ \frac{d\sigma}{dt} \propto \left( \frac{W}{W_0} \right)^{4(\alpha(t)-1)} \]

\[ \alpha(t) = \alpha(0) + \alpha\' t \]

\[
\begin{align*}
\alpha(0) &= 1.0871 \pm 0.0026 \pm 0.0030 \\
\alpha' &= 0.126 \pm 0.013 \pm 0.012 \text{GeV}^{-2}
\end{align*}
\]

\( \alpha(0) \) consistent with 1.08 from soft pp scattering

\( \alpha' \) ~ twice smaller than 0.25 GeV\(^{-2}\)
DVCS and Bethe-Heitler have the same initial and final states and they are indistinguishable. The QCD-QED interference term is sensitive to the real part of the QCD amplitude. It changes sign with lepton beam charge:

$$\sigma = \sigma_{DVCS} + \sigma_{BH} \pm \sigma_{interf.}$$

where $x_{1,2} = x \pm \xi$ – parton longitudinal momentum fraction, $\xi$ – fraction of the momentum transfer.

$$A_C = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = p_1 \cos(\phi) + \ldots$$

$p_1 = 0.16 \pm 0.04 \pm 0.06$

$\phi$ is the angle between two planes defined by incoming and outgoing electron and $\gamma^*$ and outgoing proton.

DVCS gives access to Generalized Parton Distributions (GPD), which describe the correlations between two partons ($x_1, x_2$) which differ by longitudinal ($x_1 \neq x_2$) and transverse ($t$) momentum at given $Q^2$.

GPD’s based model compatible with data.