Total and Diffractive Cross Sections in Photon-Proton Collisions at HERA

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Pomeron and Odderon in Theory and Experiment

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Outline of the talk

- Introductory remarks
- Real Photon case
- Virtual Photon case
- Summary and Outlook
**Motivation**

- **Soft DD and Unitarity**
  - $\sigma_{tot} \propto s^\epsilon \rightarrow$ Froissart boundary?
  - $\sigma_{el/diff} \propto s^{2\epsilon} \rightarrow \sigma_D/\sigma_{tot} \propto s^\epsilon$ (Pumplin limit?)
  - Do we see this at present energies?
  - How to restore unitarity? (RFT, eikonalisation, ...)

- **Hard DD (high $Q^2$ DIS ?)**
  - do we see ‘hard’ (pQCD) Pomeron?

- **Transition regime**
  - how to combine in a common picture
    soft and hard interactions, RFT and pQCD?

- **HERA specifics**
  - $\gamma^*(Q^2)$ provides additional resolving power ($10^{-8} < Q^2 < 10^5$ GeV$^2$)
  - $x/Q^2 \geq 10^{-5}$ GeV$^{-2}$ $\rightarrow$ low $x$ regime
    $\rightarrow$ high parton densities
  - large energy range ($40 \leq W_{\gamma p} \leq 300$ GeV)
  - asymmetric beam configuration $\rightarrow$
    excellent acceptance for $\gamma^*$ DD system

$\Rightarrow$ a unique facility to probe partonic content of
diffractive exchange ($IP$) and to study the transition
from soft to hard regime
S-channel Unitarity

\[ \sigma_{\text{tot}} \leq \sigma^{\text{FR}} = \frac{\pi}{m_{\pi}^2} \ln^2 \left( \frac{s}{s_0} \right) \]

Problematic area – beyond the GUT scale → no practical importance

T-channel Unitarity and Screening Corrections

DL Romeou violates unitarity at small values of impact parameter \( b \) already at few TeV!

Unitarity can be restored e.g. by cirkualisation of scattering amplitude:

\[ a(s, b) = i(1 - e^{-\Omega(s, b)}) \]
The Pomeron

Soft scale (long distances)
RFT

Hard scale (short distances)
PQCD

Underlying dynamics

$\alpha, t, M, p_t, ...$

"large"

$\sigma_{tot}, \, uu, dd, ...$

D.I.S. DD

$G_L, \, J/\psi$

light quark

Diffraction
Tagged electrons at HERA

$ZEUS (\geq 1995)$

$Q^2 \approx 0.15 \text{ GeV}^2$

$\gamma LQ$ calorimeter

$0.02 \leq Q^2 \leq 1 \text{ GeV}^2$
Important remarks

- Direct comparisons of data are often difficult
  - different treatment of non-diffractive background
  - $M_x/\sqrt{s} \ll 1$; cuts vary in $0.01 \div 0.1$ range

- Multi-dimensional measurements are important
  - e.g. at HERA essential variables are: $M_X, t, W^2, Q^2$
    $\rightarrow$ statistics limitations

- Limited detection capabilities in rapidity space
  - model dependencies in data corrections
  - losses of interesting and eventually novel physics

1. HERA Luminosity Upgrage is important! (Y-2000)
2. New improved experiments are desirable! (FELIX ?)
Real Photons: $\sigma_{tot}$

\[
\frac{d^2\sigma^{ep}(s)}{dy\,dQ^2} = \frac{\sigma^{ep}(y,s)}{\sigma^{tot}(y,s)} \cdot (1+\delta_{K}) \cdot F(y, Q^2) \cdot \sigma_{WWA} \cdot \sigma_{\text{flex}}
\]

Ensure low $Q^2 \leq 10^{-2}$ GeV$^2$ by tagging photons with ET of $Z$-split.

Then:

\[
\frac{dN}{dy\,dQ^2} = \mathcal{E} \cdot A(y, Q^2) \cdot \frac{d^2\sigma^{ep}}{dy\,dQ^2}
\]

- Efficiency of the lumin detector
- Acceptance of the Electron Tagger
- to pp final states

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<table>
<thead>
<tr>
<th>Experiment</th>
<th>ZEUS</th>
<th>H1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data sample</td>
<td>1992</td>
<td>1994</td>
</tr>
<tr>
<td>$L$/nb$^{-1}$</td>
<td>13.</td>
<td>25 +25</td>
</tr>
<tr>
<td>Trigger</td>
<td>$e^+\bar{e}^-$ +CMO</td>
<td>$e^+$ (track)</td>
</tr>
<tr>
<td>Kin. range</td>
<td>$\omega &lt; 0.02; \bar{\omega}=180$</td>
<td>$\omega &lt; 0.01; \bar{\omega}=200$</td>
</tr>
</tbody>
</table>
Diffractive event classes:

**EL:**
\[ m_p \]
Better seen from IP = +70 cm

**PD:**
\[ M_x \]
Better seen from nominal IP = 0 cm

**GD:**
\[ m_p \]
\[ M_x \]

**DD:**
\[ M_x \]
\[ p\text{-tagger} \]
\[ \text{PLUG} \]
\[ \{ \text{"Forward detectors"} \} \]
Real Photons: $\sigma_{\text{tot}}$

- Electron Target acceptance: very sensitive to the beam conditions (optics)

- Changes in the $A_{E_T}(y)$ originating from the ±1mm horizontal offset of the beam trajectory in IP

- Solution: controlled using real data (except beam)

**Important practical consequence:**

Use preferentially short dedicated runs with stable beam conditions!

$\Rightarrow$ New round:

**ZEVUS:** 1995 (-1 week) $\Rightarrow$ results expected soon

**H1:** 1997 (≈ 2 weeks) $\Rightarrow$ analysis started...
Real Photons: $\sigma_{tot}$

- Main detector response:

Energy distributions in various parts of ZEUS calorimeter compared to min. bias pp MC simulation using PYTHIA and HERWIG models.

Description of the H1 tracking system response by the PYTHIA and PHOJET MC models.
Real Photons: $\sigma_{\text{tot}}$

- Most sensitive distributions are used to fix the event class composition into $\sigma_{\text{tot}}$:
  - **EL**: $p\bar{p}\rightarrow Vp$
  - **GD**: $p\bar{p}\rightarrow Xp$
  - **PD**: $p\bar{p}\rightarrow VY$
  - **DD**: $p\bar{p}\rightarrow XY$
  - **ND**: $p\bar{p}\rightarrow X$ (the rest)

ZEUS energy weighted Radii of the cluster in REAR calorimeter

H1 shifted IP sample

- All component can be fixed except DD (very similar to ND)

<table>
<thead>
<tr>
<th>Event category</th>
<th>ZEUS</th>
<th>H1</th>
</tr>
</thead>
<tbody>
<tr>
<td>EL</td>
<td>$31 \pm 4$</td>
<td>$53 \pm 3$</td>
</tr>
<tr>
<td>GD</td>
<td>$30 \pm 5$</td>
<td>$75 \pm 2$</td>
</tr>
<tr>
<td>PD</td>
<td>$37 \pm 4$</td>
<td>$69 \pm 2$</td>
</tr>
<tr>
<td>DD+ND</td>
<td>$88 \pm 8$</td>
<td>$70 \pm 3$</td>
</tr>
</tbody>
</table>
Real Photons: $\sigma_{tot}$

$$\sigma_{tot}^{(ZEUS)} = 143 \pm 4 \text{ (stat)} \pm 17 \text{ (syst)} \ \mu b$$

$$\sigma_{tot}^{(H1)} = 165.3 \pm 2.3 \text{ (stat)} \pm 10.9 \text{ (syst)} \ \mu b$$

<table>
<thead>
<tr>
<th>Main uncertainties (%)</th>
<th>ZEUS</th>
<th>H1</th>
<th>Aim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tagging acceptance</td>
<td>9</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Main det. eff. (KEL models)</td>
<td>7</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Luminosity error</td>
<td>4.3</td>
<td>1.6</td>
<td>1</td>
</tr>
<tr>
<td>Stat. error (80% mbrs)</td>
<td>2.5</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Total error</td>
<td>~12%</td>
<td>~4%</td>
<td>&lt;4%</td>
</tr>
</tbody>
</table>
\[ \gamma p \rightarrow M_x p \]

Analysis of the diffractive mass spectra in triple Regge approach by H1 and ZEUS collaborations:

\[
\frac{d^2\sigma}{dt dM_x^2} = \left( \frac{1}{W^2} \right)^2 \sum_{ijk} G_{ijk}(t) \left( \frac{W^2}{M_x^2} \right)^{\alpha_i(t)+\alpha_j(t)} M_x^{2\alpha_k(0)}
\]

\[\sum_{i,X} \gamma X p \]

\[\sum_{i,j,p} \gamma \gamma X p p \]

\[\sum_{i,j,k} \gamma \gamma \gamma p p p \]

- This is an additional measurement compared to \( \sigma_{tot} \) analyses (mass of the dissociative system is measured)

**Q1:** Do we see the same \( \Lambda_c(0) \) here, as in \( \sigma_{tot} \) (w) behaviour?

**Q2:** Can we see a bigger absorptive (screening) corrections as compared to \( \sigma_{tot} \) case (like in \( pp \) at Tevatron)?
DEFINITION OF TERMS

THE GENERIC DIAGRAM ABOVE DESCRIBES ALL PROCESSES CONSIDERED

EL - QUASI ELASTIC VM PRODUCTION
\[ M_X = m_p / m_\omega / m_\phi \quad M_Y = m_p \]

GD - SINGLE PHOTON DISSOCIATION
\[ M_X \text{ continuum} \quad M_Y = m_p \]

PD - SINGLE PROTON DISSOCIATION
\[ M_X = m_p / m_\omega / m_\phi \quad M_Y \text{ continuum} \]

DD - DOUBLE DISSOCIATION
\[ M_X \quad M_Y \text{ continuua} \]
$\gamma p \rightarrow M_x p$

\[
\alpha_{IP}(0) = 1.068 \pm 0.016 \pm 0.022 \pm 0.041 \quad \text{(H1)}
\]
\[
\alpha_{IP}(0) = 1.12 \pm 0.04 \pm 0.08 \quad \text{(ZEUS)}
\]

Subleading trajectory is needed in the fit

No evidence for enhanced screening w.r.t. $\sigma_{tot}(\gamma p)$

(although $\sigma_D/\sigma_{tot} \simeq 40\%$ in photoproduction at HERA)

→ close to Pumplin limit (?)
\[ \gamma p \rightarrow Mxp \]

<table>
<thead>
<tr>
<th>Value</th>
<th>ZEUS</th>
<th>H1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \langle W_{sp} \rangle )</td>
<td>200</td>
<td>187; 231</td>
</tr>
<tr>
<td>( M_x / \text{GeV} )</td>
<td>3.24</td>
<td>0.4 ( \div 30 )</td>
</tr>
<tr>
<td>Analysis method</td>
<td>TR (DD)</td>
<td>TR(DD+DD+D1+ref.)</td>
</tr>
<tr>
<td>( L_p (0) )</td>
<td>4.12 ( \pm 0.09 )</td>
<td>1.07 ( \pm 0.05 )</td>
</tr>
<tr>
<td>( \sigma_{GD,6_{tot}} )</td>
<td>( (13.3 \pm 3.6) % )</td>
<td>( (22.2 \pm 3.1) % )</td>
</tr>
</tbody>
</table>

**Both:** \( \sigma_{GD} > \sigma_{PP} \) prediction

**ZEUS:** 26% contribution from \( \gamma p \) R

**H1:** both subleading trajectories and interference terms \( \sigma_{DD} \) are necessary to describe the data
Virtual Photon: $\sigma_{\gamma^* p}^{\text{tot}}$

\[
\begin{align*}
Q^2 &= -q^2 = -(k-k')^2 \\
x &= \frac{Q^2}{(2p_p)} \\
y &= \frac{p \cdot q}{(p \cdot k)} \\
W^2 &= (p+q)^2 \approx \frac{Q^2}{x}
\end{align*}
\]

\[
\sigma_{\gamma^* p}^{\text{tot}} = 6 \sigma_T + 6 \sigma_L \approx \frac{4\pi \alpha^2}{Q^2} F_2(x, Q^2)
\]

$F_2(x, Q^2)$ or equivalently $\sigma_{\gamma^* p}^{\text{tot}}(w_0, \Theta^2)$ is well described by pQCD down to $Q^2 = 1.5 GeV^2$

Then theoretical prediction starts to deviate from the data trend.
Virtual Photon: $\sigma_{\gamma^*p}^{tot}$

Very good description by pQCD
For fixed $Q^2$, $W^2 \sim \frac{1}{x} \Rightarrow \sigma_{\gamma^* p} \sim W^2 \lambda$

$$\lambda_{\text{eff}} = \frac{\partial \ln F_2}{\partial \ln (\frac{1}{x})}$$

Find the data and plot $\lambda_{\text{eff}} (Q^2)$
Transition regime $\sigma_{\gamma^* p}^{\text{tot}}$

(H. Abramowitz and A. Levy, hep-ph/9712415)

[Another more recent, but similar empirical approach interpolating between soft Regge and hard pQCD regimes: P. Desgroux et al., hep-ph/9803286]

\[ \text{Graph showing data points and curves for different experiments.} \]

- Good description of data, but 23 (8) parameters!
- Transition is smooth, but what is the dynamics behind that?
- $\Delta p (Q^2)$ dependence is very similar to CKM model picture
  \[ \Delta p (Q^2) = \Delta p \text{ basis } f(Q^2) = \Delta p (\mu, Q^2) \frac{1}{1 + \frac{2Q^2}{m^2}} \]

\[ \text{Graph showing the behavior of } \Delta p (Q^2) \text{ with quark mass corrections.} \]
Transition regime

**ZEUS BPC Data**

- $W=104$ GeV
- $W=134$ GeV
- $W=153$ GeV
- $W=172$ GeV
- $W=190$ GeV
- $W=202$ GeV
- $W=232$ GeV
- $W=251$ GeV

**Graph:**

- This fit
- This fit, BPC data only
- Donnachie Landshoff

**Figure:**

- ZEUS
- Fixed target data
- BPC 1995

**Axes:**

- $Q^2$ (GeV$^2$)
- $\sigma_W^p$ (mb)

**Legend:**

- $W^{105}$
The data clearly show the departure from 'soft' Pomeron towards larger values of $\alpha_{IP}(0)$ whenever a hard scale is present.
SUMMARY

Total photoproduction cross section at HERA as well as inclusive $\gamma p$ diffractive dissociation properties are in a perfect agreement with Regge model and universal DL Powerlaw

The behaviour of virtual photon-proton cross sections (or $R^2$) is very well described by perturbative QCD based on DGLAP dynamics ($Q^2 > 16\,\text{GeV}^2$)

The transition region between these two extremes can be quite precisely described by several empirical fits using significant number of free parameters ($8 \div 23$)

The major task: to reveal underlying dynamics (non-perturbative QCD) still with us: join the effort!