Measurement of the energy dependence of $\sigma_{\text{tot}}(\gamma p)$ with the ZEUS detector at HERA

Amir Stern
Tel Aviv University

On behalf of the ZEUS collaboration
Motivation I

Donnachie and Landshoff (DL) (Phys. Lett. B296, 227 (1992)) showed that all hadron-hadron total cross sections can be described by a simple form:

$$\sigma_{\text{tot}}(h-h) = A s^{\varepsilon} + B s^{-\eta}$$

With $$\varepsilon = \alpha_{\text{IP}}(0) - 1 = 0.0808$$
$$\eta = 1 - \alpha_{\text{IR}}(0) = 0.4525$$

Cudell et al. (Phys. Rev. D61 034019, 1 (2000))
$$\varepsilon = 0.093 \pm 0.003$$

$$\varepsilon$$ is universal!
Motivation II

The $\sigma_{\text{tot}(\gamma p)}$ dependence on $W$ is particularly interesting because of the nature of the photon.  \[ \gamma \rightarrow q\bar{q} \]

The first measurements of $\sigma_{\text{tot}(\gamma p)}$ at HERA showed that it has a similar $W$ dependence to that of hadron-hadron reactions.

Further measurements of $\sigma_{\text{tot}(\gamma p)}$ at HERA have reduced its statistical error but the systematic uncertainty remained too large for a precise determination of the $W$ dependence of the cross section.

\[ \sigma_{\text{tot}(\gamma p)} = 0.283 (W^2-m_p^2)^{0.418} + 65.4(W^2-m_p^2)^{0.0808} + 138(W^2-m_p^2)^{-0.4525} \]

\[ \sigma_{\text{tot}(\gamma p)} = (57\pm5)(W^2)^{0.100\pm0.012} + (121\pm13)(W^2)^{(0.358\pm0.015)} \]
Concept of measurement

Prior to its shut-down on 30\textsuperscript{th} June 2007, HERA was running with constant nominal positron energy and switched to two additional proton energies, lower than the nominal value of 920 GeV.

This opened up the possibility to determine precisely the power of the $W$ dependence of $\sigma_{\text{tot}(\gamma p)}$ from a single experiment.

Assuming $\sigma \sim W^{2\varepsilon}$, $\varepsilon$ can be extracted from the ratio $R$ of cross sections probed at different $W$ values.

\[ R = \frac{\sigma(W_1)}{\sigma(W_2)} = \left( \frac{W_1}{W_2} \right)^{2\varepsilon} \]

Experimentally, $\sigma = \frac{N}{A \cdot L}$ and therefore $R = \frac{N_1 \cdot A_2 \cdot L_2}{N_2 \cdot A_1 \cdot L_1}$.

The acceptance is expected to be the same for the three energy setups as the photon energy is the same and RCAL covers the fragmentation region of the photon → the ratio of acceptances will be canceled.
Kinematics

\[ Q^2 \equiv -q^2 = -(k - k')^2 \]
\[ y = \frac{p \cdot q}{p \cdot k} \]
\[ W^2 = (q + p)^2 \]

Experimentally:
\[ Q^2 = Q_{\text{min}}^2 + 4E_e E'_e \sin^2 \frac{\theta}{2}, \quad Q_{\text{min}}^2 = \frac{m_e^2 y^2}{1 - y} \]
\[ y = 1 - \frac{E'_e}{2E_e} (1 + \cos \theta_e) \approx 1 - \frac{E'_e}{E_e} \]
\[ W \approx 2\sqrt{E_e E_p y} \]
From $e^+p$ cross section to $\gamma p$ cross section

$$\frac{d\sigma^{e^+p}(y)}{dy} = \frac{\alpha}{2\pi} \left[ \frac{1}{y} \ln \frac{Q_{\text{max}}^2}{Q_{\text{min}}^2} - 2 \frac{(1-y)}{y} \left(1 - \frac{Q_{\text{min}}^2}{Q_{\text{max}}^2}\right) \right] \sigma^{\gamma p}_{\text{tot}}(y)$$

$\sigma_{\text{tot}}(\gamma p)$ can be extracted from $\sigma^{e^+p}$

$$\sigma_{\text{tot}}(e^+p) = f \cdot \sigma_{\text{tot}}(\gamma p)$$

$$f = \int_{y_{\text{min}}}^{y_{\text{max}}} \frac{\alpha}{2\pi} \left[ \frac{1}{y} \ln \left(\frac{1-y}{m_e^2 y^2}\right) - 2 \frac{(1-y)}{y} \left(1 - \frac{m_e^2 y^2}{(1-y)Q_{\text{max}}^2}\right) \right] dy$$

$$y_{\text{min/max}} = 1 - \frac{E'_{e_{\text{max/min}}}}{E_e}$$

Flux uncertainty dominated by range of integral.
During few months before HERA shutdown, it was running 27.5 GeV positrons and protons of three different energies:

- **High Energy Run (HER)** - 920 GeV
- **Medium Energy Run (MER)** - 575 GeV
- **Low Energy Run (LER)** - 460 GeV

The detector and trigger

The luminosity collected in the ZEUS detector was determined in two independent ways (photon calorimeter and spectrometer) by measuring the rate of the Bethe-Heitler (BH) process

\[ e^+ p \rightarrow e^+ \gamma p \]

Required a hit in the 6m Tagger (TAG6) and energy deposition in the rear part of the calorimeter. In addition, \( E_{PCAL} < 14 \text{ GeV} \).

The 6m tagger was calibrated with the spectrometer:

\[ E_{6mT} = E_e - E_{\text{spec}} \]

energy dependence of \( \sigma_{\text{tot}(\gamma p)} \) at HERA
Monte Carlo Simulation

The PYTHIA 6.416 generator coupled to the HERACLES 4.6 generator (to include radiative corrections) was used. The mixture of photoproduction processes generated was adjusted to describe the CAL energy distributions in the total cross section data.

The acceptance of the ZEUS detector for photoproduction events is determined by the acceptance of the TAG6 and that of the main detector which are independent, thus:

\[ \sigma^{e^+p} = \frac{N}{A_{TAG6} \cdot A_{RCAL} \cdot L} \quad \Rightarrow \quad \sigma^{\gamma p} = \frac{N}{f \cdot A_{TAG6} \cdot A_{RCAL} \cdot L} \]

At the generated level:

- \( Q^2 < 0.001 \text{ GeV}^2 \)
- \( y \) range slightly different for HER/MER/LER due to different magnet settings:
  - HER: \( 274 \text{ GeV} < W < 296 \text{ GeV} \)
  - MER: \( 216 \text{ GeV} < W < 233 \text{ GeV} \)
  - LER: \( 194 \text{ GeV} < W < 209 \text{ GeV} \)
Event selection

TAG6

- clean hit in TAG6- highest cell not at the edge of the detector, energy sharing between cells around highest energy cell.

- The positron position was reconstructed using a neural network trained on the MC.

- Neural network was also used to correct the energy of positrons for a small number of noisy cells which were excluded.

- The energy (E) and the vertical position (Y) were determined as a function of the horizontal position (X) and cuts were made to reject off-momentum beam positrons and background from beam-gas interactions.
Event selection (Cont’d)

RCAL

• A cut was placed on the fraction of the total RCAL energy in the cell with the highest energy when it was immediately adjacent to the beam-pipe hole, to reject off-momentum beam positrons and debris from beam-gas interactions that satisfied the trigger.

This cut rejects about 2-3% of physics events but most of the background.
Data analysis

The number of selected events was corrected to take into account beam-gas interactions and overlays with bremsstrahlung interactions.

• background from beam-gas interactions was determined using non-colliding positron bunches and subtracted statistically (scaled to the ratio of currents).

• Photoproduction events with hit in TAG6 that occurred in coincidence with a hit in PCAL of bremsstrahlung photon with energy >14 GeV were vetoed- corrected by weighting the number of accepted events by a factor determined from the rate of overlaps at the time the event was accepted.

• Photoproduction events that satisfied the RCAL trigger but had no hit in TAG6 that occurred in coincidence with bremsstrahlung event with a hit in TAG6 that was not vetoed by the PCAL veto (due to limited acceptance and resolution of the PCAL) were subtracted.

• The photon flux in each energy setup was determined (different due to different magnetic fields).
Results

The $\gamma p$ cross sections ratio

$$R = \frac{\sigma_i^{\gamma p}}{\sigma_{\gamma p}^{\text{HER}}} = \frac{N_i}{N_{\text{HER}}} \cdot \frac{A_{\text{HER}}}{A_i} \cdot \frac{\mathcal{L}_{\text{HER}}}{\mathcal{L}_i} \cdot \frac{f_{\text{HER}}}{f_i}$$

ZEUS

- $\mathcal{L}_{\text{LER}} = 912 \text{ nb}^{-1}$
- $\mathcal{L}_{\text{MER}} = 949 \text{ nb}^{-1}$
- $\mathcal{L}_{\text{HER}} = 567 \text{ nb}^{-1}$
- $f_{\text{LER}} = 0.877 \times 10^{-3}$
- $f_{\text{MER}} = 0.895 \times 10^{-3}$
- $f_{\text{HER}} = 0.852 \times 10^{-3}$
- $N_{\text{LER}} = 116740$
- $N_{\text{MER}} = 128954$
- $N_{\text{HER}} = 76310$

$$\mathcal{E} = 0.111 \pm 0.009 \text{ (stat.)} \pm 0.036 \text{ (sys.)}$$

Consistent with previous determinations of $\mathcal{E}$. 

23.9.2010  ISMD 2010  Amir Stern  energy dependence of $\sigma_{\text{tot}}(\gamma p)$ at HERA
Summary

• The energy dependence of the photon-proton total cross section was measured with the ZEUS detector at HERA and the result is consistent with earlier determinations of the energy dependence of total cross sections.

• This is the first determination of the high energy ($W$) dependence of $\sigma_{\text{tot}}(\gamma p)$ from a single experiment.

• This result can be used for estimation of total cross sections at high energies.

Thank you!