Shedding Light on the Structure of the Photon

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ZEUS
Zeus in Numbers

**Calorimeter:** DU / Scintillator\( EMC = 25x_0 \)  \( HAC = 7\delta \rightarrow 150x_0 \)
- 99.7% Coverage \( 2.5 \leq \theta \leq 176 \)
- Resolution: \( 18\% = \frac{\sigma(E)}{E} \) electrons
  - \( 35\% \) hadrons
  - \( < 1\text{ns} \) time

**Tracking:** \( \text{Ar/CO}_2/\text{C}_2\text{H}_6 \) (72 layers, 9 super with 4 stereo)
- Coverage: \( 15^\circ \rightarrow 164^\circ \)
- Resolution: \( 4 \text{ cm in z} \ -- \ 1\text{mm in xy} \)
- Vertex Resolution: \( 0.4 \text{ cm in z} \ -- \ 0.1 \text{ cm in xy} \)
- Momentum: \( \frac{\sigma(P_t)}{P_t} = 0.003P_t \)
- Resolution:
  - \( B = 1.43T \)

**Luminosity:** Pb (electron), Pb (photon)
- \( \sigma(\mathcal{L}) < 1\% \)
Luminosity Monitor
ZEUS Trigger

- **First Level Trigger:**
  - 10⁷ Hz input
  - 600 Hz output
    - Calorimeter First Level Trigger (no Deadtime)
      - Global and regional energy sums
      - Isolated electron/muon finding
    - Track/Muon hits

- **Second Level Trigger:**
  - 600 HZ input
  - 70 HZ output
    - Timing cuts
    - E-p_z cuts
    - Spark rejection

- **Third Level Trigger:**
  - 70 Hz input
  - 14 Hz output (100 KBytes/Event)
    - Physics filters
    - Some timing
Timing of Background vs. Physics

(Forward Cal. Time - Rear Cal. Time) vs. (Rear Cal. Time)
96 ns First Level Trigger Pipeline
Deep Inelastic Scattering

\[ Q^2 = -q^2 = 2EE'(1 - \cos \Theta_e) \]

\[ x = \frac{Q^2}{2(q \cdot k)} \]

\[ y = \frac{q \cdot k}{p \cdot k} \quad y_e = 1 - \frac{E'}{E} \cos^2 \Theta \]

\[ y_{JB} = y_{cal} = \frac{\sum_i (E - p_{zi})}{2E_e} \quad (\text{valid if } e^\pm \text{ down BP}) \]

\[ Q^2 = xys \]

\[ s = (p + k)^2 \]
ZEUS covers previously unmeasured range.
If the photon lives long enough...

Short-lived $\gamma$ (high $Q^2$ $\leftrightarrow$ short life) -- virtual

Longer lived $\gamma$ (low $Q^2$ $\leftrightarrow$ longer life) -- Quasi-real

$e^\pm$ photon

$e^\pm$ photon $q$ $\bar{q}$ hadronic “stuff”

$e^\pm$ photon vector meson
Photoproduction at Electron Proton Collider

**Leading Order**

- $e^\pm$
- $p$
- $e$

**Direct**

- photon
- gluon
- $q$ → jet
- $\bar{q}$ → jet

**Resolved**

- $\gamma - remnant$
- photon
- gluon
- $q$
- jet
- jet

**Next to Leading Order**

- $e$
- $p$

- $W^2 = (p + q)^2 = 4yJB_eE_p$

- $\sum_{jets} (E - p_e)_jets$

- $x_\gamma = \frac{\sum_{jets} (E - p_e)_jets}{2yE_e}$

- Distinction between Direct and Resolved blurs

- $p$ remnant current jet

- scattered electron

- $p$ remnant current jet

- scattered electron

- hard vs. soft
Photoproduction at ZEUS

Signatures

Direct

$e^\pm$ → proton\ Remnant

Resolved

$e^\pm$ → proton\ Remnant

$\eta = -\ln(\tan \frac{\Theta}{2})$
ZEUS Run 13299 Event
7428 (LAZE)
ZEUS Run 6790 Event 24894 (LAZE)
Photon has Hadronic Structure

In proton (DIS) case:

\[
\frac{d\sigma(ep \rightarrow eX)}{dx dy} = \frac{4\pi\alpha^2 s}{Q^4} [(1 - y + \frac{y^2}{2}) F_2^P(x, Q^2) - \frac{y^2}{2} F_L^P(x, Q^2)]
\]

F(x, Q^2) is a structure function and includes the momentum distribution of the partons.

\[
F_2^P(x, Q^2) \approx x \left\{ \frac{4}{9} [u(x) + \bar{u}(x)] + \frac{1}{9} [d(x) + \bar{d}(x) + s(x) + \bar{s}(x)] \right\}
\]

In photon (2γ exchange) case:

\[
\frac{d\sigma(e\gamma \rightarrow eX)}{dx dy} = \frac{4\pi\alpha^2 s}{Q^4} [(1 - y + \frac{y^2}{2}) F_2^\gamma(x, Q^2) - \frac{y^2}{2} F_L^\gamma(x, Q^2)]
\]

y → 0

\[
\frac{d\sigma(e\gamma \rightarrow eX)}{dx dy} \sim F_2^\gamma(x, Q^2)
\]
Why is $F_2^\gamma(x,Q^2)$ Interesting?

- **Test of Quark Parton Model (QPM)**
  - $F_2^\gamma$ should peak toward high $x$
  - Pair Production of Quarks (Direct Photoproduction)

- **Test of Quantum Chromo-Dynamics (QCD)**
  - $F_2^\gamma$ should peak toward low $x$
  - Gluon Bremsstrahlung, Quarks Radiating Gluons (Resolved Photoproduction)
Why is $F_2^\gamma(x,Q^2)$ Interesting?

- $F_2^\gamma$ scaling violation different than $F_2^p$ violation
  - The Quark Parton Model of the proton is expected to fulfill Bjorken scaling.
    - Gluon Bremsstrahlung causes scaling violation in the proton. (QCD)
  - The Quark Parton Model of the photon violates Bjorken scaling.

- No sum rule for photon
  - The momentum of the partons in the proton must sum to the total momentum of the proton.
  - The photon may remain a photon, in which case the partons in the photon carry none of the photon’s momentum.
    - $F_2^\gamma$ is large in the high x region
\[ \sigma(\gamma \ast p)[\mu b] \text{ vs. } W_{\gamma p}^2[GeV^2] \] Plot
Electron Positron Collider as Gamma Gamma Collider

- $e e$
- $\Theta > 0$ (in detector)
- $Q^2 > 0$
- $X$ (in detector)
- $P^2 \approx 0, \ y \approx 0$
- $\Theta \sim 0$ (not in detector)
- $\Theta \gg 0$ (in detector)
Previous Measurements of $F_2^\gamma(x,Q^2)$

Scaling violation seen as well as low and high $x$ peaks.
ZEUS Data Set and Monte Carlo

Accumulated Data
- 1993: 550 nb⁻¹ (~4.5 Million Events on Tape)
- 1994: 3300 nb⁻¹ (~10 Million Events on Tape)
- 1995: 6400 nb⁻¹ (~15 Million Events on Tape)

Monte Carlo
- HERWIG
  - Uses Lowest Order Diagrams
  - Fragmentation done by cluster algorithm
  - Exact matrix elements used for photon-lepton vertex
- PYTHIA
  - Uses Lowest Order Diagrams
  - Fragmentation done by LUND string model
  - Weizsaecker-Williams approximation for photon-lepton vertex
ZEUS Photoproduction Cuts

- **2 Jets as found by cone algorithm**
  - $E_T^{\text{jet}} > 5$ GeV (compensate for energy loss in dead material)
  - $-1.125 < h^{\text{jet}} < 1.875$ (keep edge of jet in detector)

- **Remove beam gas events**
  - At least 2 tracks pointing to vertex
  - Vertex position along beam axis $-48 \text{ cm} < z < 36 \text{ cm}$
  - Fewer than 5 tracks not pointing to vertex
  - $y_{JB} > 0.2$ (if lots of stuff in Forward Cal, $E-p_z$ will be small)

- **Reject charged current events**
  - Missing $p_T / E_T^{0.5} < 2 \text{ GeV}^{0.5}$

- **Reject DIS**
  - Identify Electrons (Energy Distribution in Cal)
    - Reject event if $y_e < 0.7$ (Electrons that are not scattered beam electrons tend to have high $y_e$)
      - Very effective against DIS events with $Q^2 > 4 \text{ GeV}^2$
  - $y_{JB} < 0.7$ (If electron in Rear Cal, $E-p_z$ will be high)
Hard processes observed in both Direct and Resolved photoproduction.
Poor reproduction of Resolved, while Direct is described more accurately.
Decrease of $F_{\text{eff}}$ with increasing $P^2$ seen
Virtual $\gamma$ structure at ZEUS

How does $F_2^\gamma$ change with $P^2$?

- Expect partonic content (i.e. resolved) of photon to decrease with increasing $P^2$.

- Each “fluctuation step” takes time and lifetime of $\gamma$ decreases as $P^2$ increases.
  - expect gluons to be suppressed faster than quarks

- Prediction by Drees and Godbole:
  - Expect Direct/Resolved fraction to increase as $P^2$ increases.
Theoretical Prediction

- Quarks and gluons suppressed in virtual photon
Tag Real and Virtual Photons at ZEUS

Use Beam Pipe Calorimeter and Luminosity monitor. (BPC and LUMI)

Measure $\frac{D}{R}$ in BPC ($0.1 < P^2 < 0.55 \text{ GeV}^2$) and in LUMI ($P^2 < 0.02 \text{ GeV}^2$, median $P^2 = 10^{-5} \text{ GeV}^2$)
The Beam Pipe Calorimeter (BPC)
Beam Pipe Calorimeter Measures Position
BPC Resolution

Tungsten with Scintillator layers

- Total $24X_0 \rightarrow 24$ layers

1994

$$\frac{\Delta E}{E} = \frac{30\%}{\sqrt{E}} \quad \text{(in GeV)}$$

$$\Delta x = 2\text{mm}$$

$$17\text{mrad} \leq \Theta \leq 35\text{mrad}$$

$$0.1\text{GeV}^2 \leq Q^2 \leq 0.55\text{GeV}^2$$

$$\Delta Q^2 = 3 - 6\%$$
$\sigma(\gamma \ast p)[\mu b] \ \text{vs.} \ W_{\gamma p}^2[GeV^2] \ \text{Plot}$

BPC fills in important unexplored territory.
Luminosity Monitor

- **Lead/Scintillator sandwich**
  - 24 $X_0$ total

\[
\frac{\Delta E}{E} = \frac{16 - 18\%}{\sqrt{E}} \quad \text{(in GeV)}
\]

\[0.2E_e \leq E'_e \leq 0.9E_e\]

\[\Delta x = 3\text{mm}\]

\[0 \leq Q^2 \leq 0.02\text{GeV}^2 \quad (\text{median} = 10^{-5}\text{GeV}^2)\]

\[\Delta Q^2 = \sim 10^{-4} \rightarrow 10^{-2}\text{GeV}^2\]
Enhancement of Resolved in LUMI (lower virtuality) observed.
Ratio decreases with $P^2$ but errors too large to constrain theory.
Outlook

• **Increase in Statistics**
  - 1994: ~2pb⁻¹
    - 375 “BPC events” (Virtual)
    - 14 181 “LUMI events” (Quasi-real)
  - 1995: ~6pb⁻¹ **project:**
    - 1125 BPC
    - 42 500 LUMI

• **New BPC**
  - 1994: \( \frac{\Delta E}{E} = \frac{30\%}{\sqrt{E}} \) \( \Delta x = 2\text{mm} \)
  - 1995: \( \frac{\Delta E}{E} = \frac{16\%}{\sqrt{E}} \) \( \Delta x = 1\text{mm} \)

• **Expect to be able to make firm statement about \( P^2 \) evolution of photon structure.**