Study of Neutral Current Deep Inelastic $ep$ Scattering at High $x$ and $Q^2$

with the ZEUS Detector at HERA

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On behalf of the ZEUS Collaboration

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- Standard Model Deep Inelastic $ep$ Scattering
- Neutral Current DIS Kinematics and Reconstruction
- Data Selection
- Final Data Sample
- Backgrounds
- Systematic Uncertainties from Theory and Experiment
- Significance Analysis
  - Search for an excess in the $x$ spectrum
  - Search for an excess in the $Q^2$ spectrum
  - Likelihood of the $(x, y)$ distribution
- Conclusions

ZEUS 1994–1996 integrated luminosity $= 20.1 \text{ pb}^{-1}$
  → sensitive to $\sigma \sim 50 \text{ fb}$
\[ \sqrt{s} = 300 \text{ GeV}, \ x = 0.5 \rightarrow M = \sqrt{sx} = 212 \text{ GeV} \]
\[ Q^2 = 10000 \text{ GeV}^2 \rightarrow \text{ spatial resolution} = 2 \cdot 10^{-16} \text{ cm} \]
Deep Inelastic $ep$ Scattering

\[ Q^2 = -(k - k')^2 \]
\[ x = \frac{Q^2}{2P \cdot (k - k')} \]
\[ y = \frac{P \cdot (k - k')}{P \cdot k} \]

\[ \frac{d\sigma}{dQ^2} (\text{pb}/\text{GeV}^2) \]

**ZEUS 93-95**

- 0.8 pb$^{-1}$ ($e^- p$)
- 9.3 pb$^{-1}$ ($e^+ p$)
Standard Model Reaction: $t$-channel $\gamma$ or $Z$ Exchange

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left\{ Y_+ \mathcal{F}_2(x, Q^2) - Y_- x\mathcal{F}_3(x, Q^2) \right\}$$

$$Y_+ = 1 \pm (1 - y)^2$$

The structure functions $\mathcal{F}$ are given by

$$\begin{pmatrix} \mathcal{F}_2(x, Q^2) \\ x\mathcal{F}_3(x, Q^2) \end{pmatrix} = x \sum_{q=\text{quarks}} \begin{pmatrix} C_2^q(Q^2) [q(x, Q^2) + \overline{q}(x, Q^2)] \\ C_3^q(Q^2) [q(x, Q^2) - \overline{q}(x, Q^2)] \end{pmatrix}$$

with coefficient functions

$$\begin{pmatrix} C_2^q(Q^2) \\ C_3^q(Q^2) \end{pmatrix} = \begin{pmatrix} e_q^2 & -2e_q v_q v_e \chi_Z + (v_q^2 + a_q^2)(v_e^2 + a_e^2)\chi Z^2 \\ -2e_q a_q a_e \chi_Z + (2v_q a_q)(2v_e a_e)\chi Z^2 \end{pmatrix}$$

$$\chi Z = \frac{1}{4 \sin^2 \theta_w \cos^2 \theta_w} \frac{Q^2}{Q^2 + M_Z^2}$$
Experimental Input to Cross Section Prediction

The NC DIS cross section depends on:

- well measured Electroweak parameters $\alpha$, $\theta_w$, $M_Z$
  $\rightarrow$ uncertainties at the 0.25% level.
- the quark structure in the proton, $q(x, Q^2)$, $\bar{q}(x, Q^2)$.

At high $x$, $Q^2$:
$\rightarrow$ Quark densities are determined from a NLO DGLAP evolution of parton densities at higher $x$ and lower $Q^2$.
$\rightarrow$ The $u$ quark dominates the cross section since $q \gg \bar{q}$ and $u > d$ and $|e_u| = 2|e_d|$.
ZEUS DGLAP Fit to SLAC, BCDMS, and NMC Data

\[ \sigma(e^+p) \equiv \frac{xQ^4}{2\pi\alpha^2} \frac{d^2\sigma_{NC}^{e^+p}}{dx dQ^2} = F_2 - \frac{y^2}{Y_+} F_L - \frac{Y_-}{Y_+} x F_3 \]

Error Bands include:
→ SLAC, BCDMS, NMC statistical and systematic errors
→ the effect of varying \( \alpha_s \) between 0.112 and 0.122

NC DIS cross section predictions at high \( x, Q^2 \)
accurate to \( \approx 6.5\% \)
Kinematic Reconstruction

ZEUS uses the **Double Angle Method**:

\[
\begin{align*}
x_{DA} &= \frac{E_e}{E_p} \frac{\sin \gamma}{(1 - \cos \gamma)} \frac{\sin \theta}{(1 - \cos \theta)} \\
y_{DA} &= \frac{\sin \theta_e(1 - \cos \gamma)}{\sin \gamma + \sin \theta_e - \sin(\gamma + \theta_e)} \\
Q_{DA}^2 &= s \ x_{DA} \ y_{DA}
\end{align*}
\]

The **Electron Method** is used as a cross-check:

\[
\begin{align*}
x_e &= \frac{E_e}{E_p} \frac{E'_e(1 + \cos \theta_e)}{2E_e - E'_e(1 - \cos \theta_e)} \\
y_e &= 1 - \frac{E'_e}{2E_e}(1 - \cos \theta_e) \\
Q_e^2 &= s \ x_e \ y_e
\end{align*}
\]

- Insensitive to energy scale
- Does not use hadronic final state
The ZEUS Detector

- **Calorimeter (CAL):**
  
  - Energy resolution: \( \frac{\sigma(E)}{E} = \begin{cases} 
  18\% / \sqrt{E} & \text{em.} \\
  35\% / \sqrt{E} & \text{hadronic} 
  \end{cases} \)
  
  - Energy scale uncertainty: \( \pm 3\% \)

- **Central tracking detector (CTD):**
  
  - Angular acceptance: \( 15^\circ < \theta < 164^\circ \)
  
  - Resolution: \( \frac{\sigma(p_t^{\text{track}})}{p_t^{\text{track}}} = [0.005 \ p_t^{\text{track}} \ (\text{GeV})] \oplus 0.016 \)
    
    (for full length tracks)
Reconstruction of Event Variables

\[ (E^i, p^i_X, p^i_Y, p^i_Z) = \text{measured 4-momentum in calorimeter cell } i. \]

\[
\begin{align*}
\mathcal{p}_t &= \sqrt{\left(\sum_i p^i_X\right)^2 + \left(\sum_i p^i_Y\right)^2} \\
E - p_Z &= \sum_i (E^i - p^i_Z) \\
E_t &= \sum_i \sqrt{(p^i_X)^2 + (p^i_Y)^2}
\end{align*}
\]

\[
\begin{align*}
(p_t)_{\text{had}} &= \sqrt{\left(\sum'_i p^i_X\right)^2 + \left(\sum'_i p^i_Y\right)^2} \\
(E - p_Z)_{\text{had}} &= \sum'_i (E^i - p^i_Z) \\
\cos \gamma_{\text{raw}} &= \frac{(p_t)_{\text{had}}^2 - (E - p_Z)_{\text{had}}^2}{(p_t)_{\text{had}}^2 + (E - p_Z)_{\text{had}}^2} \\
E_q &= \frac{(p_t)_{\text{had}}}{\sin \gamma}
\end{align*}
\]
Initial State Radiation and Kinematic Reconstruction

\[ e(k) \rightarrow \gamma, e(k') \]

\[ \gamma, Z \rightarrow q \]

\[ p(P) \rightarrow p \text{ Remnant} \]

**Initial State Radiation (ISR):**
- mostly collinear with \( e \) beam
- can escape detection
- effectively reduces \( E_e \)
- events with ISR photons with \( E_\gamma \gtrsim 7.5 \text{ GeV} \) rejected by cuts

\[ f_\gamma = \frac{E_\gamma}{E_e} = \text{fractional energy carried by} \ \gamma \]

\[
\begin{align*}
 x_{DA} &= x \frac{1}{1 - f_\gamma} \\
 Q_{DA}^2 &= Q^2 \frac{1}{(1 - f_\gamma)^2}
\end{align*}
\]

\[
\begin{align*}
 x_e &= x \frac{(1 - f_\gamma/y_e)}{(1 - f_\gamma)} \\
 Q_e^2 &= Q^2 \frac{1}{(1 - f_\gamma)}
\end{align*}
\]

Average shifts of true kinematic variables due to ISR for events passing all cuts and having \( 0.4 < x < 0.6, \ y > 0.25 \)

\[
\begin{align*}
 \langle \delta x_{DA} \rangle &= \frac{x_{DA} - x}{x} = +1.7\% \\
 \langle \delta Q_{DA}^2 \rangle &= \frac{Q_{DA}^2 - Q^2}{Q^2} = +2.5\% \\
 \langle \delta x_e \rangle &= \frac{x_e - x}{x} = -2.5\% \\
 \langle \delta Q_e^2 \rangle &= \frac{Q_e^2 - Q^2}{Q^2} = +1.8\%
\end{align*}
\]
Shifts and Resolution of Uncorrected $x_{DA}$

Problem at low $y \leftrightarrow$ small $\gamma$ :

→ At small $\gamma$, $\gamma_{\text{raw}} > \gamma_{\text{true}}$ on average.
→ the uncorrected $x_{DA}$ yields a biased $x$ measurement.

We correct $\gamma$ event by event.
Resolution of the Corrected $x_{DA}$

\[ \sigma_x = \text{RMS of } \frac{x_{DA} - x}{x} \]

Effects of ISR are included.
## Data Selection

Efficiencies are evaluated using NC MC events with $Q_{\text{true}}^2 > 5000$ GeV

<table>
<thead>
<tr>
<th>Selection</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex found</td>
<td>100.0 %</td>
</tr>
<tr>
<td>$</td>
<td>Z_{\text{vtx}}</td>
</tr>
<tr>
<td>$40 \text{ GeV} &lt; E - p_Z &lt; 70$ GeV (lower cut rejects photoproduction or hard ISR)</td>
<td>92.0 %</td>
</tr>
<tr>
<td>Positron with $E_e' &gt; 20$ GeV identified in CAL</td>
<td>89.4 %</td>
</tr>
<tr>
<td>Positron isolation $E_{\text{cone}}^{R=0.8} &lt; 5$ GeV</td>
<td>87.2 %</td>
</tr>
<tr>
<td>If $\theta_e &gt; 17.2^\circ$:</td>
<td></td>
</tr>
<tr>
<td>track–cluster match (DCA &lt; 10 cm)</td>
<td>85.7 %</td>
</tr>
<tr>
<td>If $\theta_e &lt; 17.2^\circ$:</td>
<td></td>
</tr>
<tr>
<td>$p_{t,e} &gt; 30$ GeV</td>
<td>83.9 %</td>
</tr>
<tr>
<td>$E - p_Z &gt; 44$ GeV (tighter Photoproduction rejection)</td>
<td>83.8 %</td>
</tr>
<tr>
<td>Reject events with 2 isolated e.m. clusters (Compton rejection)</td>
<td>83.4 %</td>
</tr>
<tr>
<td>$Q_{\text{DA}}^2 &gt; 5000$ GeV$^2$</td>
<td>81.5 %</td>
</tr>
</tbody>
</table>
Data/MC Comparison for $E - P_z$ and Vertex $Z$–Position.

Data is plotted only for $|z_{vtx}| < 50$ cm.
Data/MC Comparison for Final-State Positron

Green indicates MC distributions for $x_{DA} > 0.55$ and $y_{DA} > 0.25$. 
Data/MC Comparison for $p_t$ and Energy

Green indicates MC distributions for $x_{DA} > 0.55$ and $y_{DA} > 0.25$. 
Final Data Sample

The final sample consists of 191 events

Zeus 1994-1996

$Q_{DA}^2 =
\begin{align*}
40000 \text{ GeV}^2 \\
20000 \text{ GeV}^2 \\
10000 \text{ GeV}^2 \\
5000 \text{ GeV}^2
\end{align*}$
<table>
<thead>
<tr>
<th>$y_{DA}$ range</th>
<th>0.05 - 0.15</th>
<th>0.15 - 0.25</th>
<th>0.25 - 0.35</th>
<th>0.35 - 0.45</th>
<th>0.45 - 0.55</th>
<th>0.55 - 0.65</th>
<th>0.65 - 0.75</th>
<th>0.75 - 0.85</th>
<th>0.85 - 0.95</th>
<th>0.95 - 1.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.95 - 1.00</td>
<td>0.15</td>
<td>0.015</td>
<td>0.033</td>
<td>0.013</td>
<td>0.0055</td>
<td>0.0015</td>
<td>0.0012</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.85 - 0.95</td>
<td>8.8</td>
<td>1.2</td>
<td>0.32</td>
<td>0.10</td>
<td>0.028</td>
<td>0.01</td>
<td>0.0034</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.75 - 0.85</td>
<td>12</td>
<td>2.5</td>
<td>0.50</td>
<td>0.15</td>
<td>0.050</td>
<td>0.011</td>
<td>0.0039</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.65 - 0.75</td>
<td>13</td>
<td>3.7</td>
<td>0.86</td>
<td>0.26</td>
<td>0.082</td>
<td>0.022</td>
<td>0.0054</td>
<td>1</td>
<td>0.0020</td>
<td></td>
</tr>
<tr>
<td>0.55 - 0.65</td>
<td>15</td>
<td>6.1</td>
<td>1.65</td>
<td>0.46</td>
<td>0.15</td>
<td>0.046</td>
<td>0.0090</td>
<td>0.0024</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.45 - 0.55</td>
<td>12</td>
<td>11</td>
<td>2.5</td>
<td>0.85</td>
<td>0.28</td>
<td>0.084</td>
<td>0.0208</td>
<td>0.0032</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.35 - 0.45</td>
<td>4.6</td>
<td>18</td>
<td>5.5</td>
<td>1.75</td>
<td>0.52</td>
<td>0.16</td>
<td>0.0403</td>
<td>0.0093</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25 - 0.35</td>
<td>18</td>
<td>11</td>
<td>3.74</td>
<td>1.19</td>
<td>0.34</td>
<td>0.1104</td>
<td>0.0175</td>
<td>0.0066</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.15 - 0.25</td>
<td>2.2</td>
<td>14</td>
<td>9.6</td>
<td>3.32</td>
<td>1.2</td>
<td>0.2784</td>
<td>0.0717</td>
<td>0.0077</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05 - 0.15</td>
<td>1.3</td>
<td>2.14</td>
<td>1.6</td>
<td>0.9052</td>
<td>0.3022</td>
<td>0.1216</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## ZEUS 1994–1996 Selected Events

<table>
<thead>
<tr>
<th>Event Date</th>
<th>11-Oct-94</th>
<th>03-Nov-95</th>
<th>12-Sep-96</th>
<th>12-Oct-96</th>
<th>21-Nov-96</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_t$ [GeV]</td>
<td>8.9</td>
<td>8.2</td>
<td>2.9</td>
<td>2.2</td>
<td>10.2</td>
</tr>
<tr>
<td>$E - p_Z$ [GeV]</td>
<td>47.8</td>
<td>53.2</td>
<td>49.7</td>
<td>50.2</td>
<td>49.1</td>
</tr>
<tr>
<td>$\gamma_{raw}$ [degrees]</td>
<td>69.0</td>
<td>28.1</td>
<td>19.9</td>
<td>40.7</td>
<td>19.7</td>
</tr>
<tr>
<td>$\theta_e$ [degrees]</td>
<td>11.9</td>
<td>27.8</td>
<td>39.3</td>
<td>15.4</td>
<td>41.1</td>
</tr>
<tr>
<td>$[x_{DA}]_{raw}$</td>
<td>0.468</td>
<td>0.541</td>
<td>0.535</td>
<td>0.668</td>
<td>0.515</td>
</tr>
<tr>
<td>$[y_{DA}]_{raw}$</td>
<td>0.868</td>
<td>0.503</td>
<td>0.330</td>
<td>0.733</td>
<td>0.316</td>
</tr>
<tr>
<td>$(Q^2_{DA})_{raw} [10^4 \text{GeV}^2]$</td>
<td>3.67</td>
<td>2.45</td>
<td>1.59</td>
<td>4.42</td>
<td>1.47</td>
</tr>
<tr>
<td>$\gamma$ [degrees]</td>
<td>67.6</td>
<td>26.7</td>
<td>17.3</td>
<td>38.6</td>
<td>17.0</td>
</tr>
<tr>
<td>$x_{DA}$</td>
<td>0.480</td>
<td>0.570</td>
<td>0.617</td>
<td>0.709</td>
<td>0.597</td>
</tr>
<tr>
<td>$\delta x_{DA}$</td>
<td>0.035</td>
<td>0.029</td>
<td>0.054</td>
<td>0.034</td>
<td>0.053</td>
</tr>
<tr>
<td>$y_{DA}$</td>
<td>0.865</td>
<td>0.490</td>
<td>0.299</td>
<td>0.721</td>
<td>0.285</td>
</tr>
<tr>
<td>$\delta y_{DA}$</td>
<td>0.008</td>
<td>0.010</td>
<td>0.017</td>
<td>0.008</td>
<td>0.017</td>
</tr>
<tr>
<td>$Q^2_{DA} [10^4 \text{GeV}^2]$</td>
<td>3.75</td>
<td>2.52</td>
<td>1.66</td>
<td>4.61</td>
<td>1.54</td>
</tr>
<tr>
<td>$\delta [Q^2_{DA}] [10^4 \text{GeV}^2]$</td>
<td>0.26</td>
<td>0.07</td>
<td>0.05</td>
<td>0.16</td>
<td>0.04</td>
</tr>
<tr>
<td>$x_e$</td>
<td>0.525</td>
<td>0.536</td>
<td>0.562</td>
<td>0.605</td>
<td>0.443</td>
</tr>
<tr>
<td>$\delta x_e$</td>
<td>0.048</td>
<td>0.048</td>
<td>0.102</td>
<td>0.060</td>
<td>0.063</td>
</tr>
<tr>
<td>$y_e$</td>
<td>0.854</td>
<td>0.505</td>
<td>0.319</td>
<td>0.752</td>
<td>0.350</td>
</tr>
<tr>
<td>$\delta y_e$</td>
<td>0.018</td>
<td>0.024</td>
<td>0.039</td>
<td>0.021</td>
<td>0.032</td>
</tr>
<tr>
<td>$Q^2_e [10^4 \text{GeV}^2]$</td>
<td>4.05</td>
<td>2.44</td>
<td>1.62</td>
<td>4.10</td>
<td>1.40</td>
</tr>
<tr>
<td>$\delta [Q^2_e] [10^4 \text{GeV}^2]$</td>
<td>0.31</td>
<td>0.11</td>
<td>0.09</td>
<td>0.30</td>
<td>0.07</td>
</tr>
</tbody>
</table>
**Backgrounds**

Prompt Photon Production:

\[ e \rightarrow e \quad (\text{goes down beampipe}) \]

\[ p \rightarrow \gamma \rightarrow \text{Jet} \]

\[ \gamma \text{ can have large energy, and } P_T. \text{ Mostly a background for } \theta_e < 17.2^\circ \text{ where no track is required.} \]

Photoproduction of Dijets:

\[ e \rightarrow e \rightarrow \gamma \rightarrow \text{Jet} \]

\[ p \rightarrow \text{Jet} \]

Direct Photoproduction

\[ e \rightarrow \text{Jet} \]

\[ p \rightarrow \text{Jet} \]

Resolved Photoproduction

**Background when jet satisfies electron requirements**

QED Compton:

\[ e \rightarrow e \rightarrow \gamma \rightarrow \text{Jet} \]

\[ p \rightarrow \text{Jet} \]

\[ e, \gamma \text{ can be produced with large transverse momentum} \]
Backgrounds — continued

Dilepton Photoproduction:

\[ p \to e^+ e^- \]
\[ l \quad l \]
\[ l \text{ can have large } P_T. \]
\[ \text{Background if } e \text{ or } l \text{ misidentified} \]

Weak Boson Production:

\[ e \text{ (goes down beampipe)} \]
\[ W \to e \nu \quad Z \to e^+ e^- \]
\[ \text{Jet} \]
\[ \text{Can produce } e \text{ with large transverse momentum} \]

---

**Expected cross sections for backgrounds**  
(< indicates 90% confidence level upper limit)

<table>
<thead>
<tr>
<th>Background Process</th>
<th>Cross-section [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma p \to \gamma X )</td>
<td>( x &gt; 0.45 )</td>
</tr>
<tr>
<td>( \gamma p \to \text{dijets} )</td>
<td>&lt; 1.8</td>
</tr>
<tr>
<td>( ep \to e\gamma X )</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>( \gamma\gamma \to \ell\ell )</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>( W \to e\nu )</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Accepted NC DIS</td>
<td>165</td>
</tr>
</tbody>
</table>
Systematic errors in SM predictions

Luminosity uncertainty 2.3%

Electroweak parameters 0.25%

Radiative corrections 2%

Evaluated with HERACLES and HECTOR
ISR $E_\gamma$ spectrum in LUMI monitor agrees well with MC.

Detector simulation 4.4%

~ 2% for $y_{DA} > 0.2$

4 – 7% for $y_{DA} > 0.5$

Effects included:

- variation of ±3% in the FCAL, BCAL energy scales
- smearing of the electron scattering angle (~ 5 mrad)
- variation in the electron finding efficiency
  - variation of HAC fraction of electron candidate
  - variation of lateral energy profiles of the electron
  - variation of non-electron energy in the cone
  - variation of track–cluster matching angles
  - variation of track momentum resolution
Systematic errors in SM predictions — continued

Structure Functions 6.5%

Uncertainties from structure function fit:
- Fixed-target experimental uncertainties \( \pm 6.2\% \)
- \( 0.112 < \alpha_s < 0.122 \) \( \pm 1.9\% \)

Cross checks on SF uncertainties include:
- 10% < strange fraction < 30% small
- Uncertainties in charm evolution < 0.5%
- GRV94, MRSA, CTEQ3 comparison \( \pm 2.0\% \)
- GRV94 NLO versus LO +1.0%
- High-\( x \) gluon (CDF inspired, CTEQ4 HJ) +1.9%

Summary of systematic errors in SM predictions

for \( x > 0.55 \) and \( y > 0.25 \)

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity measurement</td>
<td>2.3%</td>
</tr>
<tr>
<td>Electroweak parameters</td>
<td>0.25%</td>
</tr>
<tr>
<td>Radiative corrections</td>
<td>2%</td>
</tr>
<tr>
<td>Detector simulation</td>
<td>4.4%</td>
</tr>
<tr>
<td>Structure Functions</td>
<td>6.5%</td>
</tr>
<tr>
<td>Total</td>
<td>8.4%</td>
</tr>
</tbody>
</table>
Comparison between data and MC of the ISR photon energy spectrum

- Data/MC comparison of $E_\gamma$ spectrum in the luminosity monitor photon calorimeter (LUMI-$\gamma$).
- Select NC events with $Q^2_{DA} > 400 \text{ GeV}^2$ and $E_{\text{LUMI}-\gamma} > 1.2 \text{ GeV}$ (460 events out of 5630).
- Subtract rate of random bremsstrahlung coincidences using events in which the positron is tagged in the 44 m ($E_\gamma < 6 \text{ GeV}$) or 35 m ($E_\gamma \approx 7 - 25 \text{ GeV}$) calorimeters.
- The resulting $E_\gamma$ spectrum agrees well with the MC prediction, with $88 \pm 24$ events measured and 105 expected in the range $1.2 \text{ GeV} < E_{\text{LUMI}-\gamma} < 4.8 \text{ GeV}$.
Significance Analysis
Excess in $x$

\[ N_{\text{obs}}(x^*) = \int_{x^*_D}^1 dx_{DA} \frac{dN}{dx_{DA}} \]

\[ P(x^*_D) = \sum_{n=N_{\text{obs}}}^{\infty} e^{-\mu} \frac{\mu^n}{n!} \]
### Minimal Poisson probabilities of the $x_{\text{DA}}$ distributions for different $y_{\text{DA}}$ cuts

<table>
<thead>
<tr>
<th>$y_{\text{DA}}$ range</th>
<th>$\mathcal{P}<em>{\text{min}}(x</em>{\text{DA}}^*)$ [%]</th>
<th>$x_{\text{DA}}^*$</th>
<th>$N_{\text{obs}}$</th>
<th>$\mu$</th>
<th>$P_{\text{SM}}$ [%]</th>
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<tbody>
<tr>
<td>$y_{\text{DA}} &gt; 0.05$</td>
<td>1.61</td>
<td>0.708</td>
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<td>0.95</td>
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<td>$y_{\text{DA}} &gt; 0.15$</td>
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<td>$y_{\text{DA}} &gt; 0.65$</td>
<td>0.50</td>
<td>0.708</td>
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<td>0.005</td>
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- $\mathcal{P}_{\text{min}}(x_{\text{DA}}^*)$ = the minimal probability
- $x_{\text{DA}}^*$ = the value of $x_{\text{DA}}$ where it occurs
- $N_{\text{obs}}$ = number of events observed with $x_{\text{DA}} > x_{\text{DA}}^*$
- $\mu$ = expected number of events with $x_{\text{DA}} > x_{\text{DA}}^*$
- $P_{\text{SM}}$ = prob. that a simulated experiment yields a lower $\mathcal{P}_{\text{min}}(x_{\text{DA}}^*)$ than observed
Excess in $Q^2$

\[ N_{\text{obs}}\left((Q_{\text{DA}}^2)^*\right) = \frac{1}{(Q_{\text{DA}}^2)^*} \int dN_{\text{DA}} \, dN/dx_{\text{DA}} \]

\[ P((Q_{\text{DA}}^2)^*) = \sum_{n=N_{\text{obs}}}^{\infty} e^{-\mu} \frac{\mu^n}{n!} \]

\[ \text{ZEUS 94-96} \]
The probability for a simulated experiment to obtain $P_{min}((Q^2_{DA})^*) < 0.004$ is 6.0%.
2–Dimensional Likelihood Test

• Divide $x$-$y$ plane into $10 \times 10$ grid
• Assign Poisson probability to $i^{th}$ bin

\[
P_i = e^{-\mu_i} \frac{\mu_i^{N_i}}{N_i!} \quad N_i = \text{Number observed} \quad \mu_i = \text{Number expected}
\]

• Form likelihood over a subset of bins $\mathcal{R}$

\[
\mathcal{L}_\mathcal{R} = \prod_{i \in \mathcal{R}} P_i
\]

• Evaluate the significance by performing many Monte Carlo experiments

\[
\mathcal{L}_\mathcal{R} = \prod_{i \in \mathcal{R}} P_i^{(m)} \quad \text{for } m^{th} \text{ experiment}
\]

• Significance $\equiv$ Probability ($\mathcal{L}_\mathcal{R} \leq \mathcal{L}_\mathcal{R}^{\text{obs}}$)
## 2-Dimensional Likelihood Test – continued

### ZEUS 94-96

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**A**

**B**
Likelihood Distributions

A  
0.55 < x < 1.0  
0.25 < y < 1.0  
P = 0.72%

Data

B  
0.05 < x < 1.0  
0.05 < y < 1.0  
excluding A  
P = 50.2%

Data

A + B  
0.05 < x < 1.0  
0.05 < y < 1.0  
P = 7.8%
Conclusions

1. We have searched for deviations from Standard Model expectations in $eP \to eX$ scattering at high $Q^2$ and high $x$.
   - The Neutral Current DIS cross section predictions are known to an accuracy at the level of 6%.
   - The events are experimentally very clean. There are no significant backgrounds.

2. In a sample with integrated luminosity 20.1 pb$^{-1}$, we find:

   - 2 events with $Q^2 > 35\,000$ GeV$^2$ where only $0.145 \pm 0.013$ are expected, corresponding to a Poisson probability of 0.96%.
   - 4 events for $(x > 0.55, y > 0.25)$ where only $0.91 \pm 0.08$ are expected, corresponding to a Poisson probability of 1.4%.

   An analysis using a large ensemble of simulated Standard Model experiments indicates that statistical fluctuations at these levels would occur
   - at some $Q^2$ for $(Q^2 > 5000$ GeV$^2)$ in 6% of all experiments;
   - at some $x$ for $(y > 0.25, Q^2 > 5000$ GeV$^2)$ in 7.6% of all experiments.

3. A likelihood analysis sensitive to the event distribution in $(x, y)$ gives probabilities of

   - 0.72% for the events in the region $(x > 0.55, y > 0.25)$,
   - 50.2% for the events in the region $(x > 0.05, y > 0.05)$, excluding the region $(x > 0.55, y > 0.25)$, indicating that the data are in good agreement with Standard Model expectations at lower $x$ and $Q^2$.

4. The effect is particularly interesting because it occurs in an unexplored kinematic region.