Elastic $Z^0$ Production @ HERA

K. Wichmann on behalf of the ZEUS Collaboration

- HERA Accelerator & ZEUS Detector
- $Z^0 @ HERA$
- Search Strategy
- Results
HERA Accelerator

- HERA: ep collider, $\sqrt{s} = 320$ GeV
- From 2003 polarised lepton beam
- 2 colliding beams experiments: H1 & ZEUS
  - collected 0.5 pb$^{-1}$/exp of luminosity in 1992-2007

- ZEUS: general purpose detector at HERA
- High resolution uranium compensating calorimeter
  - electron $\sigma (E) / E = 0.18 / \sqrt{E}$
  - hadrons $\sigma (E) / E = 0.35 / \sqrt{E}$
Electroweak Bosons @ HERA

Virtual

W

Charged Current DIS

Z

High-Q² NC DIS

Real

High-\(p_T\) lepton+\(\not{E}_T\)

Missing piece in HERA EW program?
Electroweak Bosons Production @ HERA

- Dominant process at HERA: Deep Inelastic Scattering (DIS)
- Electroweak bosons production
  - Mainly t-channel exchange
  - unlike at hadron colliders: no s-channel Drell-Yan production $qq \rightarrow Z$
- $W/Z$ produced on-shell by radiation from quark/lepton lines $\rightarrow$ small cross section

- $W$ boson cross section is measured to be:

$$\sigma_{(ep \rightarrow WX \rightarrow l\nu X)} = 1.06 \pm 0.16 \text{ (stat.)} \pm 0.07 \text{ (syst.)} \text{ pb.}$$

The H1 and ZEUS collaborations, JHEP 3 1-19(2010)

- $\sigma(Z)$ is expected to be $\sim 0.4$pb
Elastic $Z^0$ Production

- **Hadronic $Z^0$ decays** → highest branching ratio (leptonic too small)
  - very large QCD multi-jet background

- **Elastic $Z^0$ production**: $\sim 0.16$ pb
  - expected better S/B ratio
Event Selection

- Select events with at least 2 jets & calculate invariant mass from all jets with $E_T > 4\,\text{GeV}$ & $|\eta| < 2$
  - at least 2 high $E_T$ jets ($E_T > 25\,\text{GeV}$)

To discriminate signals from low-$Q^2$ NC:
- RCAL veto
- $E-P_z$ peak at 55 GeV, cut 50 < $E-pz$ < 64 GeV
Elastic Selection

- Multijet sample dominated by QCD background: no $Z^0$ signal

- Use $\eta_{\text{max}}$ for elastic selection:
  - pseudorapidity of the energy deposit in the calorimeter closest to the proton beam direction, calculated from CAL cells with $E > 400$ MeV

\[ \eta_{\text{max}} < 3.0 \]

\[ \eta_{\text{max}} = 4.03 \]

- Elastic event: $\eta_{\text{max}} = 1.24$
Z⁰ Mass Peak

- 496 pb⁻¹ data collected in years 1996-2007 used in this analysis
  - shows excellent resolution of ZEUS uranium calorimeter
  
  15 events observed (+6.8, -6.4 events)

- Details of fit and cross section determination described in next slides

![Graph showing Z⁰ Mass Peak](chart.png)
Cross Section Calculation

Fit the data with shape templates of signal(MC) + bg(data, $\eta_{\text{max}} > 3$)

1. Define the reference number, $N_{\text{ref},i}$, for each bin $i$ in $40 < M < 140$ GeV

$$N_{\text{ref},i} = aN_{\text{signal},i}^\text{MC}(e) + bN_{\text{bg},i}^\text{data}$$

(e: energy shift parameter allowed in $\pm 3\%$)

1. $\chi^2$ is defined as:

$$\chi^2 = -2 \sum_i \log \frac{\mathcal{L}(N_{\text{ref},i}, N_{\text{obs},i})}{\mathcal{L}(N_{\text{obs},i}, N_{\text{obs},i})}$$

2. Find (a, b, e) to minimize $\chi^2$

3. The best fit ‘a’ gives the ratio between observed and SM cross section i.e. we can get $\sigma_{\text{obs}} = a\sigma_{\text{SM}}$
**Number of Signal Events from MC**

- **EPVEC Monte Carlo interfaced with Pythia hadronic fragmentation**
  - Total cross section: 0.40 pb

- **This analysis aims to measure the ‘elastic’ cross section**
  - Elastic cross section: 0.16 pb

- **Expected # of elastic events after all selection cuts: 17.9**

- **Acceptance for elastic production: 0.22**

- **Invariant mass distribution with MC used as signal shape template**

<table>
<thead>
<tr>
<th></th>
<th>cross section [pb]</th>
<th>selection acceptance</th>
<th>expected # of events(xsec×acc×lumi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>elastic</td>
<td>0.163 (total ‘elastic’)</td>
<td>0.22</td>
<td>17.9</td>
</tr>
<tr>
<td>inelastic</td>
<td>0.236 (total ‘inelastic’)</td>
<td>0.0035</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Number of Background Events from Data

- Background studied in data (after all selection cuts) for different slices of $\eta_{\text{max}}$
  - No difference in shape observed
  - **Data for $\eta_{\text{max}} > 3$ used for background template**

Fit final data sample with signal (MC) + BG (Data) shape templates
Elastic $Z^0$ Production Cross Section

\[ \sigma_{obs} \left( ep \rightarrow ep^{(*)} Z^0 \right) = 0.133^{+0.060}_{-0.057} \text{ (stat. only) pb} \]

Consistent with SM elastic cross section $\sigma_{SM} \left( ep \rightarrow ep^{(*)} Z^0 \right) = 0.16 \text{ pb}$
Systematic Uncertainty

- Systematic uncertainty estimated in conservative way (preliminary)
- Measurement dominated by statistical errors

<table>
<thead>
<tr>
<th>Source</th>
<th>Errors on xsection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{T,\text{jet}}$ scale ±3%</td>
<td>(+2.1%, -1.7%)</td>
</tr>
<tr>
<td>Elastic selection uncertainty</td>
<td>(+36.5%, -28.6%)</td>
</tr>
<tr>
<td>BG shape uncertainty</td>
<td>±1.5%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>±1.9%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>(+36.6%, -28.8%)</td>
</tr>
</tbody>
</table>
Final Results

- Z⁰ elastic cross section was measured for the first time in ep collisions by ZEUS experiment
  - Smallest cross section measured @ HERA
  - Demonstrates excellent resolution of ZEUS uranium calorimeter
  - Electroweak bosons fully exploited
  - In agreement with SM elastic cross section of 0.16 pb

$$\sigma_{obs} \left( ep \rightarrow ep^{(*)} Z^0 \right) = 0.133^{+0.060}_{-0.057} \text{ (stat.)}^{+0.049}_{-0.038} \text{ (syst.) pb}$$
Backup Slides
How to obtain cross section

Fit the data with shape templates of signal(MC) + bg(data, ηmax>3)

1. Define reference number at each bin i, \( N_{ref,i} \) (i: 40-140GeV)
   \[
   N_{ref,i} = a N_{signal,i}^{MC} + b N_{bg,i}^{data}
   \]
   - \( N_{signal,i}^{MC} \) is signal expectation at bin i in \( η_{max} < 3 \) region.
   - \( e \) is parameter of energy shift, \( e = [-0.03, 0.03] \) and \( M_{jets} = (1 + e) \times M_{jets} \)
   - \( N_{bg,i}^{data} \) is number of background at bin i in \( η_{max} > 3 \) region.

2. Calculate log-likelihood, LLH, by summing over all bins
   \[
   LLH = \sum_i A_i + \left( \frac{e}{\sigma_e} \right)^2 \quad \left( \frac{e}{\sigma_e} \right)^2 \text{ is a penalty term. (} \sigma_e = 0.03 \right)
   \]
   \[
   A_i = \begin{cases} 
   2N_{ref,i} - 2N_{obs,i} + 2N_{obs,i} \log \left( \frac{N_{obs,i}}{N_{ref,i}} \right) & \text{ (if } N_{obs,i} > 0) \\
   2N_{ref,i} - 2N_{obs,i} & \text{ (if } N_{obs,i} = 0) 
   \end{cases}
   \]

3. \( a, b \) and \( e \) are free parameters. Iterate and find the best fit 
   \((a, b, e)\) giving minimumLLH

4. The best fit ‘a’ gives the ratio between observed and SM cross- 
   section i.e. we can get \( \sigma_{obs} = a \sigma_{SM} \)

Courtesy of T. Nobe