Production of $Z^0$ bosons in elastic and quasi-elastic $ep$ collisions at HERA

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- HERA and ZEUS
- EW bosons@HERA
- $Z^0$ Search strategy
- Background estimation
- Results
**HERA and ZEUS**

- **HERA:** World’s only $ep$ collider at DESY
- Collected $\sim 0.5 \text{ fb}^{-1}$ per experiment
- Center-of-mass energy: 318 GeV
  - proton: 920 GeV
  - electron (positron): 27.5 GeV

- **ZEUS:** General-purpose $4\pi$ detector
- High resolution calorimeter using Uranium absorber
  - electron: $\sigma_E/E = 18\% / \sqrt{E} \text{ (GeV)}$
  - hadron: $\sigma_E/E = 35\% / \sqrt{E} \text{ (GeV)}$

key point in this analysis
Electroweak Bosons at HERA

- $e^+e^-$ and hadron colliders
  - abundant $Z/W$ productions via $e^+e^-$ or $qq$ annihilation

- In $ep$ collisions at HERA
  - not the case due to $L,B$ conservation
  - small cross section via radiation from quark/lepton lines
    - $W$ cross section measured using lepton+$E_T^{\text{miss}}$ events ($\sim 1$ pb)
    - $Z$ production even smaller ($\sim 0.4$ pb), not yet measured.

- $Z/W$ bosons play important roles in t-channel (off-shell) exchange
  - NC/CC DIS processes at high-$Q^2$
# Electroweak Bosons at HERA

<table>
<thead>
<tr>
<th></th>
<th>W</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtual</td>
<td>Charged Current DIS</td>
<td>High-$Q^2$ NC DIS</td>
</tr>
<tr>
<td>Real</td>
<td>High-$p_T$ lepton + $E_T$</td>
<td>Missing piece in HERA EW program?</td>
</tr>
</tbody>
</table>

Smallest cross section measured at HERA!
• Use hadronic decay (large branching ratio of ~70%)

• Use elastic (+quasi-elastic) events ($\sigma \sim 0.16$ pb)
  • $ep \rightarrow ep(p^*)Z^0$ ($p^*$: nucleon resonances)
  • require $\eta_{max} < 3$ (maximum pseudo-rapidity of CAL energy deposits)
  • suppress QCD background

$Z^0$ Search strategy

2 (or more) high-$E_T$ jets

beam electron back-scattered to forward (proton) direction
(in forward CAL or beam-pipe)

p or $p^*$: no proton remnant in detector
Search strategy - event selection

- $\eta_{\text{max}} < 3$
to select elastic events
  (this event will be rejected)
- $\eta > 0$, $\eta < 0$

- $\geq 2$ high $E_T$ jets
  ($E_T > 25$ GeV, $|\eta| < 2$)

- E-P$_Z$ peaks at $2E_e=55$ GeV
to suppress low-$Q^2$ NC and photo-production

At most 1 electron in $\theta_e < 80$ deg
  (proton direction)

Rear CAL veto
MC simulation

• **EPVEC** used for signal
  - Baur, Vermaseren, and Zeppenfeld (1992)
  - Interfaced to PYTHIA+JETSET

• **Elastic and quasi-elastic** $ep \rightarrow ep(p^*)Z^0$: $0.16 \text{ pb}$
  - Selection acceptance $\sim 22\%$, expect 17.9 events

• **Inelastic processes**: $0.24 \text{ pb}$
  - DIS ($\gamma*p \rightarrow Z^0X$) and resolved photoproduction ($\gamma p \rightarrow (q\bar{q} \rightarrow Z^0)X$)
  - Selection acceptance $< 1\%$, expect 0.4 events

• **Do not use background MC**
  - Tail of high-$E_T$ diffractive DIS, hard to model
  - Use data-driven estimation for background shape (next page)
Data driven background shape estimation

- Invariant mass shape has little $\eta_{\text{max}}$ dependence

- Use invariant mass distribution:
  - Background template from data in $\eta_{\text{max}} > 3$ region
  - Signal template from EPVEC MC

- Fit signal region ($\eta_{\text{max}} < 3$) with templates
Result after all selections

- invariant mass after $\eta_{\text{max}} < 3$ cut

- **maximum likelihood fit** with signal and background templates

- mass peak shift due to **energy scale** fitted as a nuisance parameter ($\sigma_\varepsilon = 3\%$, the fit gave $\varepsilon = 3 \pm 2\%$)

- $15.0^{+7.0}_{-6.4}$ events observed
  - signal obtained with $2.3\sigma$ significance
Cross section extraction

• **Systematic uncertainties:** total \((+7.2, -6.2)\)%
  - acceptance change by \(\pm 3\)% energy scale: \((+2.1, -1.7)\)%
  - \(\eta_{\text{max}}\) cut varied by \(\pm 0.2\): \((+6.4, -5.4)\)%
  - using different \(\eta_{\text{max}}\) slices for background template: \(\pm 1.5\)%
  - signal template peak width (6 GeV) smeared: negligible
  - luminosity: \(\pm 2\)%

• **Resulting cross section**
  - \(\sigma(\text{ep} \rightarrow eZ^0 p^{(*)}) = 0.13 \pm 0.06 \text{ (stat.)} \pm 0.01 \text{ (syst.)} \text{ pb}\)
  - consistent with SM prediction 0.16 pb
  - first measurement of on-shell \(Z^0\) cross section in \(ep\) collisions!
Summary

• A search for on-shell $Z^0$ production in $\sim 0.5$ fb$^{-1}$ $ep$ collisions at HERA using ZEUS detector

• Hadronic decay was used: (quasi-)elastic process was aimed to suppress inelastic backgrounds.
  • Demonstrates excellent resolution of ZEUS uranium calorimeter

• First measurement of $Z^0$ production in $ep$ collisions

$$\sigma (ep \rightarrow eZ^0p^{(*)}) = 0.13 \pm 0.06 \text{ (stat.)} \pm 0.01 \text{ (syst.)} \text{ pb}$$

• In agreement with SM elastic cross section of 0.16 pb
• Electroweak bosons at HERA fully exploited
backup slides
# Used data period and luminosity

- Data collected between 1996 and 2007
- Total integrated luminosity: 496 pb\(^{-1}\)

## Proton Beam Energy vs. Luminosity

<table>
<thead>
<tr>
<th></th>
<th>Proton Beam Energy (GeV)</th>
<th>Luminosity (pb(^{-1}))</th>
<th>HERA-I total</th>
<th>HERA-II total</th>
</tr>
</thead>
<tbody>
<tr>
<td>96/97 e(^+)</td>
<td>820</td>
<td>38.6</td>
<td></td>
<td>121</td>
</tr>
<tr>
<td>98/99 e(^-)</td>
<td></td>
<td>16.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>99/00 e(^+)</td>
<td></td>
<td>65.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>03/04 e(^+)</td>
<td>920</td>
<td>41.0</td>
<td></td>
<td>375</td>
</tr>
<tr>
<td>04/05 e(^-)</td>
<td></td>
<td>135.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>06 e(^-)</td>
<td></td>
<td>55.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>06/07 e(^+)</td>
<td></td>
<td>143.8</td>
<td></td>
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- Average polarisation is less than 1%
  - the effect is neglected in this analysis
Event selection

• Trigger mainly based on CAL $E_\text{T}$

• Cleaning cuts for cosmic-rays and beamgas (next page)

• **Jets** defined by $k_T$ algorithm
  • At least 2 jets with $E_\text{T} > 25$ GeV, $|\eta| < 2$, $\Delta\Phi_{12} > 2$ rad
  • Use all jets ($E_\text{T} > 4$ GeV, $|\eta| < 2$) for invariant mass
  • Remove jet if it overlaps with $e/\gamma$ within $R<1$

• **At most 1 electron in detector**
  • $E_e > 5$ GeV, isolation, track match if in tracking coverage
  • $\theta_e < 80$ deg required (reject low-$Q^2$ NC background)

• **No particles in rear** (electron beam) direction
  • $E_{\text{RCAL}} < 2$ GeV
  • $50 < \Sigma(E-P_z) < 64$ GeV (sum over all CAL deposits)
Cuts for cosmic-rays & beamgas rejection

• Reject if any of following conditions are met:
  • $|Z_{vtx}| > 50$ cm
  • $175 < \theta_1 + \theta_2 < 185$ deg and $\Delta \Phi_{12} > 175$ deg for jets
  • $|t_u - t_d| > 6$ ns (up-down timing difference in BCAL)
  • $E_T^{\text{miss}} > 25$ GeV
  • $N_{\text{trk}}^{\text{vtx}} < 0.25(N_{\text{trk}}^{\text{all}} - 20)$ (vertex tracks and all tracks)
Fit procedure

• For each bin $i$ on invariant mass $M_{jets}$

$$N_{ref} = a N_{sg,i}^{MC}(\epsilon) + b N_{bg,i}^{data} \quad M_{jets} = (1 + \epsilon) M_{jets}^{MC}$$

• Poisson likelihood and nuisance parameter

$$\mathcal{L} = \mathcal{L}_1(N_{obs}, N_{ref}) \times \mathcal{L}_2(\epsilon, \sigma_{\epsilon}) \quad \mathcal{L}_1 = \prod_i \frac{\exp(-N_{ref,i})(N_{ref,i})^{N_{obs,i}}}{N_{obs,i}!} \quad \text{and} \quad \mathcal{L}_2 = \exp \left( -\frac{\epsilon^2}{2\sigma_{\epsilon}^2} \right)$$

• $\chi^2$-like log-likelihood function

$$\tilde{\chi}^2 = -2 \ln \frac{\mathcal{L}_1(N_{obs}, N_{ref})}{\mathcal{L}_1(N_{obs}, N_{obs})} - 2 \ln \mathcal{L}_2 = 2 \sum f_i + \left( \frac{\epsilon}{\sigma_{\epsilon}} \right)^2$$

$$f_i = \begin{cases} 
N_{ref,i} - N_{obs,i} + N_{obs,i} \ln(N_{obs,i}/N_{ref,i}) & \text{if } N_{obs,i} > 0 \\
N_{ref,i} & \text{if } N_{obs,i} = 0
\end{cases}$$

• Minimize $\chi^2$ to find best set of $(a, b, \epsilon)$

$$\rightarrow \sigma_{obs} = a \cdot \sigma_{MC}, \text{ error of } a \text{ given by } \Delta \chi^2 < 1$$
\[ \eta_{\text{max}} = 4.03 \]

\[ \eta_{\text{max}} = 1.24 \]
Systematics on $\eta_{\text{max}} < 3$

- From PhD thesis by V. Sola

Inclusive Diffractive Cross Sections in Deep Inelastic $ep$ Scattering at HERA

(DESY-THESIS-2012-008)

- MC/data agreement of $\eta_{\text{max}}$ within $\pm 0.2$ for NC-DIS events

- The uncertainty on the cross section measurement was:
  \[
  \{+6.4\% \quad -5.4\%\}
  \]

Figure 5.10: The $\eta_{\text{MAX}}$ distributions for the DIS HER (up) and LER (down) inclusive data samples. The histograms represent the sum of the Monte Carlo contribution: non-diffractive DIS ($\text{Djangoh}$) is the blue histogram, photoproduction ($\text{Pythia}$) is the red one and diffractive events ($\text{Satrap}$) are shown in green.