High Q² cross sections, EW and BSM at HERA

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on behalf of H1 and ZEUS collaborations

→ DIS at HERA
→ High Q² cross sections and electroweak physics
→ Physics beyond Standard Model
→ Summary
e^(±)(27.5 GeV), p(810/920 GeV), \(\sqrt{s} = 300/318\) GeV

- Two large multipurpose detectors: H1 and ZEUS (asymmetric design)

1994-2000: HERA I data
2003-07 HERA II data with longitudinal e^(±) polarisation:

\[ P_e = \frac{N_R - N_L}{N_R + N_L} \approx 30-40\% \text{ at HERA} \]

\(~1\ \text{fb}^{-1} \text{ (H1+ZEUS) of luminosity delivered by HERA}\)
Neutral current DIS cross section

neutral current DIS cross section:

\[ \frac{d^2 \sigma_{NC}^{\pm p}}{dx dQ^2} = \frac{2\pi \alpha^2}{x Q^4} \left[ Y_+ \tilde{F}_2^\pm + Y_- x \tilde{F}_3^\pm - y^2 \tilde{F}_L^\pm \right] \]

- \( Q^2 \) - virtuality of exchange boson
- \( x \) – Bjorken scaling variable
- \( y \) - inelasticity

\( \gamma'Z(q) \)

→ polarisation dependence due to \( \gamma Z \) interference and \( Z \) terms:

\[ \tilde{F}_2^\pm = F_2 + k(-v_e \mp P_e a_e)F_2^{\gamma Z} + k^2(v_e^2 + a_e^2 \pm 2 P_e v_e a_e)F_2^Z \]

\[ x \tilde{F}_3^\pm = k(-a_e \mp P_e v_e)x F_3^{\gamma Z} + k^2(2v_e a_e \pm P_e (v_e^2 + a_e^2))xF_3^Z \]
Charged current DIS cross section:

\[ \frac{d^2\sigma^{e^\pm p}_{CC}}{dx dQ^2} = (1 \pm P_e) \frac{G_F^2}{2\pi x} \left( \frac{M_W^2}{Q^2 + M_W^2} \right)^2 \tilde{\sigma}^{e^\pm p}_{CC} \]

→ linear polarisation dependence

e^+/e^- sensitive to different quark densities:

\[ \tilde{\sigma}^{e^+ p}_{CC} = x[u + c] + (1 - y)^2 x[d + s] \]
\[ \tilde{\sigma}^{e^- p}_{CC} = x[u + c] + (1 - y)^2 x[\bar{d} + \bar{s}] \]

In SM weak interaction acts only on left-handed particles (right-handed anti-particles)
charged and neutral currents at HERA

Charged and neutral currents at HERA

EW unification

good agreement with SM (HERAPDF 0.1)
Neutral currents at HERA

- the charge dependent polarisation asymmetries in neutral currents
  – direct measure of EW effects

neglecting Z term generalised structure function $F_2$ is expressed:

$$\tilde{F}_2^{\pm} \approx F_2 + k(-v_e \mp P_e a_e)F_2^{\gamma Z}$$

at LO: $F_2^{\gamma Z} = x \sum 2e_q v_q (q + \bar{q})$

polarisation asymmetry $A$ is proportional to $a_e v_q$ combination:

$$A^\pm = \frac{2}{P_R - P_L} \frac{\sigma^\pm (P_R) - \sigma^\pm (P_L)}{\sigma^\pm (P_R) + \sigma^\pm (P_L)} \simeq \pm k a_e \frac{F_2^{\gamma Z}}{F_2}$$

and directly measures the parity violation

→ to be updated with all HERA II data

latest ZEUS results: DESY-08-202
Charged currents at HERA

SM weak interactions: only left-handed particles interact (right-handed currents forbidden)

HERA Charged Current $e^+p$ Scattering

HERA results are consistent with SM
Combined QCD & EW fit

- weak couplings $a_u, a_d, v_u, v_d$ of light quarks to Z boson can be extracted from DIS data with combined QCD-EW fit
  - $\gamma Z$ interference and Z exchange in neutral currents
  - charged currents for $u$, $d$-quark separation

- preliminary results with part of polarised HERA II data bring additional sensitivity, especially on $v_q$

HERA results are competitive to LEP and Tevatron
Searches in inclusive DIS

Model-based searches:
- quark radius
- leptoquarks
- squarks in R-parity violating SUSY
- single top
- excited fermions
- magnetic monopoles

Search for new physics in rare excl. processes

Model-independent searches:
- isolated leptons with large missing $P_T$
- multi leptons at high $P_T$
- general search
Possible new interactions between e and q can modify DIS cross section at high $Q^2$ via virtual effects

**Fermion substructure** can be detected measuring the spatial distribution of charge radius:

\[
\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} f_e^2(Q^2) f_q^2(Q^2)
\]

where \( f(Q^2) = 1 - \frac{\langle r^2 \rangle}{6} Q^2 \)

\( R \) is the root-mean-square radius of the electroweak charge of the e/q

reduces SM cross section at high momentum transfer

assuming:

\( f_e = 1, R_q \) can be constrained

\( f_q = f_q', \) common limit on fermion sizes

**ZEUS** (combined 94-06):

\( R_q < 0.62 \cdot 10^{-18} \text{ m} \)

**H1** (94-07, all HERA data):

\( R_q < 0.74 \cdot 10^{-18} \text{ m} \)
Models with composite quarks and leptons can explain the three-family structure and mass hierarchy of fermions. These models predict existence of excited states of leptons and quarks.

- decay channels with hadronic and leptonic decays considered

$\mathcal{L}_{GM} = \frac{1}{2\Lambda} \tilde{F}^*_{\mu \nu} \left[ g f \frac{\tau^\alpha}{2} W^\alpha_{\mu \nu} + g' f' \frac{Y}{2} B_{\mu \nu} + g_s f_s \frac{\lambda^\alpha}{2} G^\alpha_{\mu \nu} \right] F_L + h.c.$

- excited $e^*$
- excited $v^*$
- excited $q^*$

$e^* \rightarrow e \gamma, e^* \rightarrow e Z, e^* \rightarrow \nu W$
$v^* \rightarrow v \gamma, v^* \rightarrow v Z, v^* \rightarrow e W$
$q^* \rightarrow q \gamma, q^* \rightarrow q Z, q^* \rightarrow q W$

→ H1: full HERA $e^\pm p$ data (~0.5 fb$^{-1}$) used for searches
→ no indication of signal found, mass exclusion limits on \(f/\Lambda\) derived
- shown for \(f=+f'\) (\(f=-f'\) also derived for \(\nu^*\))

**Excited states of first generation fermions**

- **Excited e**
  - For \(f=+f'\) and \(f/\Lambda = 1/M_{e^*}\)
  - \(M_{e^*} < 272\) GeV excluded

- **Excited \(\nu^*\)**
  - For \(f=+f'\) and \(f/\Lambda = 1/M_{\nu^*}\)
  - \(M_{\nu^*} < 196\) GeV excluded

- **Excited q**
  - For \(f=+f', f_s = 0\), \(f/\Lambda = 1/M_{q^*}\)
  - \(M_{q^*} < 259\) GeV excluded

→ \(e^*, \nu^*\) results are complementary to LEP and Tevatron, \(q^*\) results has better sensibility (at low \(M_{q^*}\))
Events with multi leptons and high $P_T$

- in Standard Model events with multi leptons are produced in photon-photon interactions ($\gamma\gamma \rightarrow l^+l^-$)
  - at large invariant masses deviations from SM may indicate new physics

- considered final state topologies: $ee$, $eee$, $e\mu$, $\mu\mu$, $e\mu\mu$

- full HERA data ($\sim 1 \text{ fb}^{-1}$) considered by H1 and ZEUS

- the combination of H1 and ZEUS multi-electron analyses is ongoing (next slide)
$\rightarrow$ H1 and ZEUS combined results in the common phase space ($\sim 0.94$ fb$^{-1}$)
sensitivity to new physics – 'hardness' scale ($\Sigma P_T$)

in agreement with SM expectations

for $\Sigma P_T > 100$ GeV:

<table>
<thead>
<tr>
<th>Process</th>
<th># Data</th>
<th># SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+p$ 0.56 fb$^{-1}$</td>
<td>5</td>
<td>1.82 ± 0.21</td>
</tr>
<tr>
<td>$e^-p$ 0.38 fb$^{-1}$</td>
<td>1</td>
<td>1.19 ± 0.14</td>
</tr>
<tr>
<td>$e^\mp$ 0.94 fb$^{-1}$</td>
<td>6</td>
<td>3.00 ± 0.34</td>
</tr>
</tbody>
</table>

more events observed in $e^+p$
General Search

→ Model independent search for deviations from Standard Model predictions
→ full HERA $e^\pm p$ data ($\sim 0.5$ fb$^{-1}$): final result by H1

27 different final states

final state configurations considered

e, $\mu$, jets (j), $\gamma$, $\nu$

– at least 2 particles with $P_T > 20$ GeV

→ deviations searched in $\sum P_T$, $M_{\text{all}}$

with dedicated algorithm

good agreement with SM

high $P_T$ phenomena well understood at HERA
→ a result of successful HERA operation
~1 fb\(^{-1}\) of collected data by H1 and ZEUS experiments together

shown latest results of:
→ high precision measurements:
  high Q\(^2\) NC/CC cross sections, QCD+EW fits
→ physics beyond SM:
  - quark charge radius, excited fermions, multi-leptons at high \(P_T\)
    and general search
  - no large deviations from SM observed

→ not all HERA results covered in this presentation
→ combinations of H1 and ZEUS results are ongoing
HERA data alone can be used for PDF fit

HERAPDF 0.1

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HERA data alone can be used for PDF fit

HERAPDF 0.1

→ impressive precision achieved

→ important input for LHC
General contact interactions (CI)

- Possible new interactions between e and q can modify DIS cross section at high $Q^2$ via virtual effects

- Four fermion $eeqq$ contact interactions → convenient method to investigate these interferences

- Effective Lagrangian for neutral current vector like contact interactions:

$$\mathcal{L}_{CI} = \sum_{i,j=L,R}^{q=u,d,s,c,b} \eta_{ij}^{eq}(\bar{e}_i \gamma^\mu e_i)(\bar{q}_j \gamma_\mu q_j)$$

  couplings: $\eta_{ij}^{eq} = \epsilon_{ij}^{eq} \frac{4\pi}{\Lambda^2}$

  $\Lambda$ – compositeness scale

Limits comparable with those derived at LEP and TEVATRON
Rare topology events with high energy isolated lepton and missing transverse momentum may be a sign for new physics

- in SM: real $W$ production $e p \rightarrow e W^\pm X$ with leptonic decay $W^\pm \rightarrow l \nu_l$

example of $W$ production:

$\rightarrow$ previously an excess in $e$ and $\mu$ has been reported by H1 collaboration (not observed by ZEUS)

$P_T^X$ (hadronic transverse momentum)$>25$ GeV

$\rightarrow$ now full HERA statistics are exploited by both experiments ($2 \times 0.5$ fb$^{-1}$)

consistent with SM

$\rightarrow$ the production cross section of $W$ boson measured

**SM:** $1.27 \pm 0.19$ pb

**H1:** $1.14 \pm 0.25_{\text{stat}}^{\pm 0.14_{\text{syst}}}$ pb

**ZEUS:** $0.89 \pm 0.25_{\text{stat}}^{0.22_{\text{syst}}} \pm 0.10_{\text{syst}}$ pb
Events with isolated leptons and missing $P_T$

**e channel**

- ZEUS 504 pb$^{-1}$
- SM MC
- non-W MC

**μ channel**

- ZEUS 504 pb$^{-1}$
- SM MC
- non-W MC

**H1 $e, \mu + P_T^{\text{miss}}$ events at HERA ($e^\pm p$, 474 pb$^{-1}$)**

**τ channel**

DESY-08-170
ZEUS pub-08-005

H1 $e, \mu + P_T^{\text{miss}}$: 2.4σ excess of events in $e^\pm p$
not confirmed by ZEUS

combinations of H1 and ZEUS results are ongoing
Events with multi leptons and high $P_T$

sensitivity to new physics – 'hardness' scale ($\Sigma P_T$)

in agreement with SM expectations

for $\Sigma P_T > 100$ GeV (0.94 fb$^{-1}$):
data = 6  (5 in $e^+p$)
SM = 3.00 ± 0.34 (1.82 in $e^+p$)

$$\Sigma P_T \geq 100 \text{ GeV (0.94 fb}^{-1})$$

$\text{data} = 6$  (5 in $e^+p$)
$\text{SM} = 3.00 \pm 0.34$ (1.82 in $e^+p$)