Deep–Inelastic ep Scattering at Very High $Q^2$

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Minerva–G.I.F. Gentner Symposium
From Elementary Particles to Complex Systems

- Introduction
- DIS in the Standard Model
- Cross–Section Measurements
- Scenarios Beyond the Standard Model
- Conclusion and Outlook

Focus on cross–section measurements
Mainly new results (1994–1997 data)

*Temporarily with the University of Hamburg
**Introduction**

HERA = first electron–proton collider

\[ \text{ep centre-of-mass energy} = 300 \text{ GeV} \]

\[ \text{electron–quark invariant mass up to } \sim 200 \text{ GeV} \]

\[ \text{spatial resolution } 2 \cdot 10^{-16} \text{ cm} \]

\[ \text{at } Q^2 = 10^4 \text{ GeV}^2 \]

ZEUS 1994–1997 integrated \( \mathcal{L} = 46.6 \text{ pb}^{-1} \)

H1 1994–1997 integrated \( \mathcal{L} = 37.0 \text{ pb}^{-1} \)

\[ \rightarrow \text{sensitive to } \sigma \sim 50 \text{ fb} \]
**DIS Signatures and Kinematics**

**Neutral Current (NC)**
Scattered $e$ in main detector
$e$ balances hadronic $p_t$

**Charged Current (CC)**
Scattered $\nu$ invisible
Only hadronic system available for measurements

**Kinematic Variables:**

Four–momentum transfer:
$$Q^2 = -q^2 = -(k - k')^2 = 2E_eE'(1 + \cos \theta_e)$$

Bjorken scaling variable:
$$x = Q^2/(2q \cdot P) = \text{momentum fraction of quark}$$

Inelasticity:
$$y = (q \cdot P)/(k \cdot P)$$
$$y = (1 - \cos \theta^*_e)/2; \quad \theta^*_e = eq \text{ c.m.s. scattering angle}$$

$ep$ centre-of-mass energy:
$$s = (k + P)^2 = 4E_eE_p$$

$eq$ invariant mass:
$$M = \sqrt{xs}$$
DIS at $Q^2 \gtrsim 5000 \text{ GeV}^2$ became accessible with the high-statistics 1996+1997 $e^+p$ data.
**High-$Q^2$ Event Topologies**

Final state topologies for elastic $eq \rightarrow eq$ scattering

- Positrons enter from left, protons from right
- Arrows = scattering angles of $e$ and $q$
- Numbers = energies of scattered $e$ and $q$ (in GeV)
A NC Event in the ZEUS Detector

Uranium-Scintillator Calorimeter

6000 Cells, each read out by 2 PMTs

\[ \sigma_{\theta_e} = 5 \text{ mrad} \]
\[ \frac{\sigma}{\sqrt{E}} \text{ (e)} = 18 \% \]
\[ \frac{\sigma}{\sqrt{E}} \text{ (had)} = 35 \% \]
\[ \frac{\Delta E}{E} \text{ (syst)} = 3 \% \]
in situ calibration good to 1–2\% (e)
A CC Event in the H1 Detector

Liquid Argon Calorimeter

44000 Cells

\[ \sigma_{\theta_e} = 2-5 \text{ mrad} \]
\[ \sigma / \sqrt{E} \ (e) = 12 \% \]
\[ \sigma / \sqrt{E} \ (\text{had}) = 50 \% \]
\[ \Delta E / E \ (\text{syst}) = 3 - 4 \% \]

in situ calibration good to 1 – 3\% (e)
**DIS in the Standard Model**

Deep-inelastic $ep$ scattering =

incoherent sum of elastic $eq$ scatterings

$$\sigma(ep) = \sum_{q,\bar{q}} f_{q|p} \cdot \sigma(eq)$$

$f_{q|p} \equiv q = \text{Parton distribution function (PDF)}$

Probability density to find quark $q$ in the proton carrying a fraction $x$ of the proton momentum

Not predicted by theory

$\sigma(eq) = \text{electron–quark cross–section}$

**Leading Order:**

$\sigma(eq \rightarrow eq) \propto$

\[\begin{array}{c}
\begin{array}{c}
\text{e} \\
\text{q}
\end{array}
\xrightarrow{\gamma}
\begin{array}{c}
\text{Q}_e \\
\text{Q}_q
\end{array}
\xrightarrow{e}
\begin{array}{c}
\text{e} \\
\text{q}
\end{array}
\end{array}
\]

$+\quad 2$

\[\begin{array}{c}
\begin{array}{c}
\text{e} \\
\text{q}
\end{array}
\xrightarrow{Z}
\begin{array}{c}
\text{e} \\
\text{q}
\end{array}
\end{array}
\]

$\sigma(eq \rightarrow \nu q') \propto$

\[\begin{array}{c}
\begin{array}{c}
\text{e} \\
\text{q}
\end{array}
\xrightarrow{W}
\begin{array}{c}
\nu_e \\
\text{q'}
\end{array}
\end{array}
\]

$2$

Given by electroweak sector of Standard Model as functions of $\alpha, G_F, \sin^2 \theta_W, (m_t, m_H)$
\[ \frac{d^2 \sigma^{e^\pm p \rightarrow e^\pm X}}{dx \, dQ^2} = \frac{2\pi \alpha^2}{Q^4} \left[ Y_+ \cdot \mathcal{F}^{NC}_2 \mp Y_- \cdot \mathcal{F}^{NC}_3 \right] \]

- \( Y_\pm = (1 \pm (1 - y)^2) \)
- \( \mathcal{F}^{NC}_2 = \sum_{q=d,u,s,c,b} A_q \cdot [q + \bar{q}] \)
- \( \mathcal{F}^{NC}_3 = \sum_{q=d,u,s,c,b} B_q \cdot [q - \bar{q}] \)
- \( A_q = Q_q^2 - 2Q_q v_e v_{\bar{q}} \cdot P_Z + (v_e^2 + a_e^2)(v_{\bar{q}}^2 + a_{\bar{q}}^2) \cdot P_Z^2 \)
- \( B_q = -2Q_q a_e a_{\bar{q}} \cdot P_Z + 4v_e a_e v_{\bar{q}} a_{\bar{q}} \cdot P_Z^2 \)
- \( P_Z = \frac{Q^2}{Q^2 + M_Z^2} \)

- Photon–exchange dominates at low \( Q^2 \)
- For \( Q^2 \gtrsim M_Z^2 \), \( \gamma \) and \( Z \) contributions are similar
- Radiative corrections are substantial.
\[
\frac{d^2\sigma^{e^+p\rightarrow\nu X}}{dx\,dQ^2} = \frac{G_F^2}{2\pi} P_W^2 \left[ (\bar{u} + c) + (1 - y)^2 (d + s) \right]
\]
\[
\frac{d^2\sigma^{e^-p\rightarrow\bar{\nu}X}}{dx\,dQ^2} = \frac{G_F^2}{2\pi} P_W^2 \left[ (u + c) + (1 - y)^2 (\bar{d} + \bar{s}) \right]
\]
\[
P_W = \frac{M_W^2}{Q^2 + M_W^2}
\]

→ $e^+$ and $e^-$ couple to different quark flavors
→ $e^+p$ cross-section dominated by $d$ and $\bar{q}$
→ $y$–dependence useful to disentangle $q$ and $\bar{q}$
→ $b, t$ contributions compressed by $m_t$ and CKMM
→ At low $Q^2$: weak $Q^2$ dependence
→ At high $Q^2$: some sensitivity to $W$ mass
→ Similar formulae for $\bar{\nu}p, \bar{\nu}N$ scattering
→ Radiative corrections are substantial
Comparison of NC and CC Cross-Sections

ZEUS 93-95
0.8 pb\(^{-1}\) (e\(^-\)p)
9.3 pb\(^{-1}\) (e\(^+\)p)

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

\[ Q^2 \text{ (GeV}^2\text{)} \]

→ At low \( Q^2 \), \( \sigma(\text{CC}) \ll \sigma(\text{NC}) \)
→ At \( Q^2 \gtrsim \frac{M_Z^2}{2} \), \( \sigma(\text{CC}) \sim \sigma(\text{NC}) \)

1995 data are of very limited precision
Leading–order QCD contributions to DIS diagrams:

→ Leading modifications are of $\mathcal{O}(\alpha_s \ln Q^2)$
→ Absorbed into effective PDF’s

DGLAP evolution:
(Dokshizer, Gribov, Lipatov, Altarelli, Parisi)

simplified form:

$$\frac{df_{q/p}(x, Q^2)}{d \ln Q^2} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{d\xi}{\xi} f_{q/p}(\xi, Q^2) P\left(\frac{x}{\xi}\right) + \mathcal{O}(\alpha_s^2)$$

$P(x/\xi) = $ splitting function (given by QCD)

→ DGLAP evolution fixes $Q^2$ dependence of PDF’s
→ PDF’s are evolved towards higher $Q^2$ and lower $x$
→ Effectively all terms of $\mathcal{O}(\alpha_s^n (\ln Q^2)^n)$ are summed
→ Usually employed in next–to–leading order
PDF Determination

PDF fitting technique:

→ Parametrise PDF’s as function of $x$ for $Q^2 = Q_0^2$
→ Perform QCD evolution
→ Calculate cross-sections, structure functions, etc.
→ Determine parameters by fit to experimental data

● Experimental input data:
  → $eN$ and $\mu N$ data (HERA, fixed-target)
  → $\bar{v}N$ data (fixed-target)
  → $W$ production in $p\bar{p}$ experiments
  → Drell–Yan lepton–pair production

● Problems:
  → Low $Q^2$: edge of perturbative QCD regime
  → Higher–twist terms at low $Q^2$, high $x$
  → Theoretical treatment of heavy quark PDF’s
  → Higher–order QCD terms (small effect for high $Q^2$)
  → Nuclear effects in deuteron (may affect $d$ at high $x$)

● Further uncertainties:
  → Experimental errors on input data (dominant)
  → Uncertainty of $\alpha_s$
  → Analytical form of PDF parametrisation
  → Choice of renormalisation/factorisation scales
→ Data span several decades in $x$ and $Q^2$
→ QCD fit gives good description
→ Fit at high $x$ driven by fixed-target data
PDF Uncertainties

\[ \tilde{\sigma} = \frac{xQ^4}{2\pi \alpha^2 Y + dx \, dQ^2} \]

\[ \Delta \tilde{\sigma} / \tilde{\sigma} \lesssim 6.5\% \]

\[ \tilde{\sigma} = \frac{2\pi}{G_F^2 P_W^2} \frac{d^2\sigma}{dx \, dQ^2} \]

\[ \Delta \tilde{\sigma} / \tilde{\sigma} \gtrsim 20\% \]

for \( x \gtrsim 0.5 \) or \( Q^2 \gtrsim 2 \cdot 10^4 \text{ GeV}^2 \)

→ \( \tilde{\sigma} \) = reduced cross-section (\( \sim \)PDF’s)
→ Experimental errors on input data and on \( \alpha_s \)
were propagated in QCD fit (M. Botje, ZEUS)

Minerva/G.I.F. Symposium 26.05.98 U. Katz 14
PDF’s in the High–$Q^2$ Regime

$Q^2 = 100$ GeV$^2$

$Q^2 = 30000$ GeV$^2$

$u_v = u - \bar{u}$

$\bar{d} = d - \bar{d}$

$\text{sea}$

$\text{gluon}$

$-\rightarrow$ For $x \gtrsim 0.2$ valence $\gg$ sea

$-\rightarrow$ $d/u \ll 0.5$ for $x \rightarrow 1$

$-\rightarrow$ $\sigma^{e\pm p}(NC)$ is dominated by $u$

$-\rightarrow$ $\sigma^{e^+p}(CC)$ is dominated by $d$

QCD evolution and spatial resolution:

$-\rightarrow$ Spatial resolution improves with $Q^2$

$-\rightarrow$ $e$ “sees” more partons having lower momentum

$-\rightarrow$ Valence distributions are reduced
Non–Standard PDF Scenarios

- **Modified gluon density (CDF jets):**
  - DIS dominated by $eq$ processes
  - Gluon modification has small effect in DIS

- **Intrinsic charm:**
  - Model: $\mathcal{O}(1\%)$ of the proton momentum is carried by valence–like $c/\bar{c}$ quarks
  - Modifies cross–section at high $x$
  - Effect larger in CC than in NC

- **The $d/u$ ratio::**
  - All current PDF’s use $d/u \to 0$ at $x \to 1$
  - Consistent relativistic treatment of deuteron data indicates that this may be wrong
  - Melnitchouk, Thomas, Phys.Lett.B377(96)11
  - Possible increase of $d$ at large $x$
  - Mainly affects $e^+p$ CC cross–section

- All modifications at large $x$ ($\gtrsim 0.4$)
- Larger effects in CC than in NC
- No explanation for large high–$Q^2$ excess
Cross–Section Measurements

→ 1994–1996 data:
   Excess at high $x$, $Q^2$
→ LP97: Updated results
   What we have now:
→ Increased data samples
→ Improved analysis methods
→ Differential cross–sections

• NC analyses:
  → Event distributions in $(x, y)$ (ZEUS,H1)
  → $d\sigma/dQ^2$ (ZEUS,H1), $d\sigma/dx$ (H1)
  → $d^2\sigma/(dx\,dQ^2)$ and QCD fit (H1)

• CC analyses:
  → $d\sigma/dQ^2$ (ZEUS,H1)
  → reduced cross–section (H1)

Focus on results
Only few analysis details
NC Analyses

- **Kinematic Reconstruction**
  - 4 independent measurements per event:
    \[ \theta_e, E'_e (e) \quad \gamma_h, E_{\text{had}} \text{ (hadrons)} \]
  - Only two independent variables \( Q^2 = xys \)
  - Different reconstruction methods
  - ZEUS: “double-angle”; H1: \( e\Sigma \) (\( e \) based)

  **Initial State Radiation (ISR):**
  - Photon radiation in \( e \) beam direction
  - Photon can escape undetected
  - Effectively reduces \( s \)
  - \( \langle |\Delta_{\text{ISR}}x/x|, |\Delta_{\text{ISR}}Q^2/Q^2| \rangle = O(1 - 3\%) \)
  - Shift in opposite directions for ZEUS, H1

- **Event Selection:**
  - Require identified scattered electron
  - Vertex reconstructed and in fiducial region
  - \( E - p_z > 40 \text{ GeV (ZEUS)}; 35 \text{ GeV (H1)} \)

  **The \( E - p_z \) cut:**
  - \( (E - p_z)_{\text{final}} = (E - p_z)_{\text{initial}} = 2E_e \)
  - Cut removes photoproduction and hard ISR
Resolution $\Delta Q^2/Q^2$ stable in entire $Q^2$ range

Typically $\Delta Q^2/Q^2 = 2 - 3\%$ (Gaussian width)
Basic method: Use redundancy of NC DIS kinematics to calibrate $E'$

Double–angle method yields $E'$ independent of calorimeter energy scale

Accuracy still statistics–limited

$E'$ energy scale reliable to 1 – 3%

Similar methods are used by ZEUS
NC Data Samples and Systematics

Event Samples:

<table>
<thead>
<tr>
<th>ZEUS</th>
<th>H1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^2 &gt; 400 \text{ GeV}^2$</td>
<td>$Q^2 &gt; 200 \text{ GeV}^2$</td>
</tr>
<tr>
<td>$y_e &lt; 0.95$</td>
<td>$y_e &lt; 0.9$</td>
</tr>
<tr>
<td>$\sim 38000$ events</td>
<td>$\sim 75000$ events</td>
</tr>
</tbody>
</table>

Main Systematic Effects:

- Electron energy scale (affects mainly H1)
- Electron finding efficiency
- Accuracy of detector simulation
- Vertex reconstruction
- Trigger efficiency (small effect for ZEUS)
- Luminosity uncertainty ($\sim 2.5\%$)
- Photoproduction background ($< 1\%$)

→ No dominating source
→ Typical systematic errors $= a$ few %
→ Analyses are statistics–limited for $Q^2$ above a few 1000 GeV$^2$
**ZEUS Kinematic Plane (NC)**

**Changes w.r.t. the 1996/LP97 analyses:**
- Improved analysis algorithms
- Slightly modified event selection

![Graph showing $y_{DA}$ vs $x_{DA}$ for different $Q^2$ values with 1994-97 data.]

### Table

<table>
<thead>
<tr>
<th>$Q^2_{\text{min}}$ (GeV$^2$)</th>
<th>$N_{\text{obs}}$</th>
<th>$N_{\text{exp}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500</td>
<td>1817</td>
<td>1792 ± 93</td>
</tr>
<tr>
<td>5000</td>
<td>440</td>
<td>396 ± 24</td>
</tr>
<tr>
<td>10000</td>
<td>66</td>
<td>60 ± 4</td>
</tr>
<tr>
<td>15000</td>
<td>20</td>
<td>17 ± 2</td>
</tr>
<tr>
<td>35000</td>
<td>2</td>
<td>0.29 ± 0.02</td>
</tr>
</tbody>
</table>

**ZEUS 94-97 (preliminary)**

- $Q^2 = 40000$ GeV$^2$
- $Q^2 = 30000$ GeV$^2$
- $Q^2 = 20000$ GeV$^2$
- $Q^2 = 10000$ GeV$^2$
- $Q^2 = 5000$ GeV$^2$
- $Q^2 = 2500$ GeV$^2$
H1 Kinematic Plane (NC)

Changes w.r.t. the 1996/LP97 analyses:
New $E'$ calibration
Slightly modified event selection

<table>
<thead>
<tr>
<th>kinematic region</th>
<th>$N_{obs}$</th>
<th>$N_{exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^2 &gt; 15000$ GeV$^2$</td>
<td>22</td>
<td>14.7 $\pm$ 2.1</td>
</tr>
<tr>
<td>$M_e = (200 \pm 12.5)$ GeV (94–96)</td>
<td>8</td>
<td>3.01 $\pm$ 0.54</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.95 $\pm$ 0.18</td>
</tr>
</tbody>
</table>
NC Cross–Section Status at LP97

ZEUS and H1 NC 1994–1997, LP97
(based on about 70% of the current data samples)

1994-97 Preliminary NC Cross Sections

$\sigma (p\bar{p}) \propto Q^2$

Data points correlated
Shaded area gives $1\sigma$ Error

$Q^2_{\text{min}}$ (GeV$^2$)

$\sim 10^2$

→ Indication of cross–section excess
→ Deviation data – SM increases with $Q^2$
→ Let’s look at $d\sigma/dQ^2$ first
Error band = PDF uncertainty
Very good agreement with SM prediction
Slight excess at highest $Q^2$
NC Cross–Section $d\sigma/dQ^2$ (H1)

<table>
<thead>
<tr>
<th>$Q^2$ / GeV$^2$</th>
<th>Data / SM (QCD Fit)</th>
<th>NLO QCD Fit ($Q^2 \leq 120$ GeV$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^4$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

→ Error band = luminosity uncertainty
→ Very good agreement with SM prediction
→ Slight excess at highest $Q^2$
No indication of excess at highest $x$
Some sensitivity to electroweak effects
Good agreement with SM prediction
→ Measurements cover region $x < 0.65$ and $Q^2 < 30000$ GeV$^2$
→ QCD fit to lower-$Q^2$ data describes $\bar{\sigma}$ in complete $(x, Q^2)$ range
→ Highest-$Q^2$ bins suffer from low statistics
Reduced NC Cross–Section (H1) contd.

→ Gap to fixed–target experiments almost filled
→ No discrepancies HERA/fixed–target obvious
→ Statistical precision still limited
→ Excess at $x \approx 0.45$ remains visible
CC Analyses

• **Kinematic Reconstruction**
  → Scattered neutrino invisible
  → Use $\gamma_h$ and $E_{\text{had}}$ for reconstruction

• **Event Selection:**
  → Main signature: missing $p_t$
    $p_t > 10$ GeV (ZEUS); $p_t > 12$ GeV (H1)
  → Vertex reconstructed and in fiducial region
  → Anti-background event topology cuts

• **Event Samples:**

<table>
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<tr>
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<th>H1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^2 &gt; 400$ GeV$^2$</td>
<td></td>
<td>$x &gt; 0.01$</td>
</tr>
<tr>
<td>$y &lt; 0.9$</td>
<td>$0.03 &lt; y &lt; 0.9$</td>
<td></td>
</tr>
<tr>
<td>869 events</td>
<td>656 events</td>
<td></td>
</tr>
</tbody>
</table>

• **Systematic Effects:**
  → Dominated by hadronic energy scale
$Q^2$ Resolution for CC Events (ZEUS)

- $400 < Q^2 < 708$ with RMS = 27%
- $708 < Q^2 < 1259$ with RMS = 28%
- $1259 < Q^2 < 2239$ with RMS = 26%
- $2239 < Q^2 < 3981$ with RMS = 25%
- $3981 < Q^2 < 7079$ with RMS = 25%
- $7079 < Q^2 < 12589$ with RMS = 25%
- $12589 < Q^2 < 22387$ with RMS = 23%
- $22387 < Q^2 < 39810$ with RMS = 24%

$\rightarrow$ Resolution $\Delta Q^2/Q^2$ stable in entire $Q^2$ range

$\rightarrow$ Typically $\Delta Q^2/Q^2 \approx 25\%$ (R.M.S.)
ZEUS Kinematic Plane (CC)

Changes w.r.t. the 1996/LP97 analyses:
Improved analysis algorithms
Modified event selection

<table>
<thead>
<tr>
<th>$Q^2_{\text{min}}$ (GeV$^2$)</th>
<th>$N_{\text{obs}}$</th>
<th>$N_{\text{exp}}$ and errors</th>
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</thead>
<tbody>
<tr>
<td>1000</td>
<td>586</td>
<td>600 (+52, -52)</td>
</tr>
<tr>
<td>10000</td>
<td>22</td>
<td>17 (+5.7, -5.2)</td>
</tr>
<tr>
<td>15000</td>
<td>8</td>
<td>3.9 (+1.9, -1.6)</td>
</tr>
<tr>
<td>20000</td>
<td>3</td>
<td>0.97 (+0.65, -0.47)</td>
</tr>
<tr>
<td>30000</td>
<td>1</td>
<td>0.06 (+0.08, -0.04)</td>
</tr>
</tbody>
</table>
CC Cross–Section $d\sigma/dQ^2$ (ZEUS)

ZEUS Preliminary 1994-97

- Error band = PDF uncertainty
- Good agreement with SM prediction
- Slight excess at highest $Q^2$?
CC Cross–Section $d\sigma/dQ^2$ (H1)

$\rightarrow$ Error band = luminosity uncertainty
$\rightarrow$ Good agreement with SM prediction
$\rightarrow$ Slight excess at highest $Q^2$ ?
→ Good agreement with SM prediction
→ Data do not yet allow precise study of high–x region ($x \gtrsim 0.3$)
Reduced CC Cross–Section (contd.)

\[ Q^2 = 400 \text{ GeV}^2 \quad Q^2 = 800 \text{ GeV}^2 \]

\[ Q^2 = 2000 \text{ GeV}^2 \quad Q^2 = 4000 \text{ GeV}^2 \]

\[ Q^2 = 8000 \text{ GeV}^2 \quad Q^2 = 16000 \text{ GeV}^2 \]

\[ (1-y)^2(d+s) \]

\[ (\bar{u}+\bar{c}) \text{ MRSH} \]

\[
\rightarrow \quad \text{Sensitivity to different flavours and } q/\bar{q}
\]
Determine $M_W$ from $\chi^2$--fit of theoretical prediction (with variable $M_W$) to data

$$M_W = 78.6^{+2.5}_{-2.4} \text{ (stat.)} +^{3.3}_{-3.0} \text{ (syst.) GeV}$$

→ Statistical error reduced by factor 3
→ Agreement with world average indicates good understanding of $E_{\text{had}}$ scale
→ Confirmation of electroweak prediction in spacelike regime
Cross–Section Summary

• The 1994–1997 HERA data have been used for precision NC and CC cross–section measurements for $Q^2$ up to several 10000 GeV$^2$ and for $x$ as high as 0.65.

• The gap to the lower–$Q^2$ fixed–target data at high $x$ is being closed.

• All data for $Q^2 \lesssim 10000$ GeV$^2$ show very good agreement with the SM prediction and are well described by QCD fits extending over several orders of magnitude in $Q^2$ and $x$.

• The combination of NC and CC $ep$ data in the “electroweak regime” ($Q^2 = \mathcal{O}(M_Z^2)$) promises access to PDF’s of different flavours and of quarks and antiquarks.

• The high–$Q^2$ excess of NC events observed in the 1994–1996 data has not been confirmed by the 1997 data. However, both ZEUS and H1 observe a NC cross–section above the SM prediction for $Q^2 \gtrsim 20000$ GeV$^2$. An excess in the CC data cannot be excluded.
Scenarios Beyond the Standard Model

What if the high–$Q^2$ excess is not a statistical fluctuation?

→ Which phenomenological scenarios explain the excess?
→ Are they compatible with other measurements?
→ How can we test them?

Two scenarios are discussed:

• Contact Interactions
  → “Low–energy” manifestations of processes at mass scales far beyond the HERA regime
  → Cover wide class of different processes
  → Related to $e^+e^-$ and $p\bar{p}$ scattering and to low–energy phenomena

• Positron–quark resonances
  → New particles coupling to $e$ and $q$ can be directly produced in $ep$ collisions
  → Signature: resonance in $M = \sqrt{xs}$
  → Such particles can be pair–produced in $p\bar{p}$ ⇒ detection at Fermilab possible
Contact Interactions (CI)

Can represent:

- Heavy boson exchange
- Leptoquark (s or t channel)
- Interaction of composite electron and quark
- ...

Historical equivalent: 4-fermion interaction

Effective Lagrangian:

\[ \mathcal{L} = \sum_{a,b=L,R; q=u,d} \eta^q_{ab} (\bar{e}_a \gamma^\mu e_a)(\bar{q}_b \gamma_\mu q_b) \]

- Only chiral vector couplings considered
  (avoids e.g. severe constraints from \( \pi \) decays)
- Interference with SM can be constructive or destructive

Example for cross-section modification:
Contact Interaction Scenarios

- CI scenario = linear combination of $\eta_{ab}^q$
  - CI strength given by common factor $4\pi/\Lambda^2$
  - Coefficients are taken to be $\epsilon_{ab} \pm 1$ or 0
  - Marginal effect if including $s, c, b, t$

<table>
<thead>
<tr>
<th>CI</th>
<th>$\epsilon_{LL}^u$</th>
<th>$\epsilon_{LR}^u$</th>
<th>$\epsilon_{RL}^u$</th>
<th>$\epsilon_{RR}^u$</th>
<th>$\epsilon_{LL}^d$</th>
<th>$\epsilon_{LR}^d$</th>
<th>$\epsilon_{RL}^d$</th>
<th>$\epsilon_{RR}^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VV</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>AA</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>VA</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>X1</td>
<td>+</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>-</td>
<td>0</td>
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</tr>
<tr>
<td>X2</td>
<td>+</td>
<td>0</td>
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<td>0</td>
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</tr>
<tr>
<td>X3</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
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<td>0</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>X4</td>
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<td>+</td>
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</tr>
<tr>
<td>X5</td>
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<td>0</td>
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<td>+</td>
</tr>
<tr>
<td>X6</td>
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<td>-</td>
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<td>0</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>U1</td>
<td>+</td>
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<td>+</td>
<td>0</td>
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<td>0</td>
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</tr>
<tr>
<td>U4</td>
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<td>+</td>
<td>0</td>
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</tr>
<tr>
<td>U5</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- Several restrictions:
  - Severe limits from Atomic Parity Violation
    ⇒ all scenarios have $\epsilon_{LL} + \epsilon_{LR} - \epsilon_{RL} - \epsilon_{RR} = 0$
  - $SU(2)_L \times U(1)_R \Rightarrow \epsilon_{ab}^u = \epsilon_{ab}^d$ (not U1–U5)

All CI’s also modify $\sigma(e^+e^-)$ and $\sigma(p\bar{p})$

- Interference sign is different
- LEP/Tevatron and HERA have different sensitivity
**Contact Interaction Analysis (ZEUS)**

- **Analysis method:**
  - Input: raw distributions without acceptance or migration corrections
  - Simulate CI’s by reweighting MC events

  \[
  \text{weight} = \frac{\sigma(\text{SM} + \text{CI})}{\sigma(\text{SM})} \text{ true propagator } (x, Q^2)
  \]

  - Determine log–likelihood ($\pm 1/\Lambda^2$) (LL)

  - **Two approaches:**
    - Binned LL in $Q^2$
    - Unbinned LL in $(x, y)$
    - Very similar results

- **Limit setting:**
  - Log–likelihood $\Rightarrow$ best fit, 95% C.L. limits
  - One–sided limits, probability normalised to unity for positive/negative $\eta$
  - Cross–check with Monte–Carlo experiments
Points with error bars = ratio (data/MC)

Histograms show best fit (red) and upper/lower 1σ limits (green)
CI Limits (ZEUS)

ZEUS Preliminary 94–97

η Fits and 95% CL Limits
$Q^2 > 400 \text{ GeV}^2$

<table>
<thead>
<tr>
<th>$\Lambda^-$ Limit (TeV)</th>
<th>$\Lambda^+$ Limit (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(%) SM Probability</td>
<td>(%) SM Probability</td>
</tr>
<tr>
<td>VV</td>
<td>AA</td>
</tr>
<tr>
<td>4.6 (34.2)</td>
<td>4.0 (37.7)</td>
</tr>
<tr>
<td>2.8 (30.2)</td>
<td>2.8 (32.5)</td>
</tr>
<tr>
<td>3.0 (40.0)</td>
<td>1.8 (26.0)</td>
</tr>
<tr>
<td>1.9 (4.5)</td>
<td>3.9</td>
</tr>
<tr>
<td>X3</td>
<td>X4</td>
</tr>
<tr>
<td>1.5 (24.3)</td>
<td>4.1 (40.0)</td>
</tr>
<tr>
<td>X5</td>
<td>3.0 (40.0)</td>
</tr>
<tr>
<td>X6</td>
<td>1.9 (24.7)</td>
</tr>
<tr>
<td>U5</td>
<td>3.6 (36.0)</td>
</tr>
<tr>
<td>U1</td>
<td>2.9 (39.0)</td>
</tr>
<tr>
<td>U4</td>
<td>4.4 (37.5)</td>
</tr>
</tbody>
</table>

→ Dots = best fit values
→ Double bars = 1σ–intervals
→ Single bars = 95% C.L. limits
→ Numbers = $\Lambda$ values from 95% C.L. limits

All CI fits compatible with SM within 2σ
Comparison to Other CI Results

<table>
<thead>
<tr>
<th>Type</th>
<th>Limit from ZEUS Λ (TeV)</th>
<th>Limit from CDF Λ (TeV)</th>
<th>Limit from OPAL Λ (TeV)</th>
<th>Limit from ALEPH Λ (TeV)</th>
<th>Limit from L3 Λ (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V V^+)</td>
<td>4.9</td>
<td>3.5</td>
<td>3.3</td>
<td>4.0</td>
<td>3.2</td>
</tr>
<tr>
<td>(V V^-)</td>
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<td>5.2</td>
<td>4.3</td>
<td>5.2</td>
<td>3.9</td>
</tr>
<tr>
<td>(A A^+)</td>
<td>2.0</td>
<td>3.8</td>
<td>4.9</td>
<td>5.6</td>
<td>4.3</td>
</tr>
<tr>
<td>(A A^-)</td>
<td>4.0</td>
<td>4.8</td>
<td>3.1</td>
<td>3.7</td>
<td>2.9</td>
</tr>
<tr>
<td>(X 3^+)</td>
<td>2.8</td>
<td>-</td>
<td>3.5</td>
<td>4.1</td>
<td>3.2</td>
</tr>
<tr>
<td>(X 3^-)</td>
<td>1.5</td>
<td>-</td>
<td>2.9</td>
<td>3.6</td>
<td>2.8</td>
</tr>
<tr>
<td>(X 4^+)</td>
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<td>(X 4^-)</td>
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<td>(U 4^+)</td>
<td>4.6</td>
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<td>4.4</td>
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<td>2.3</td>
<td>2.6</td>
<td>2.2</td>
</tr>
</tbody>
</table>

ALEPH Coll., ALEPH 98-021(1998)

→ HERA, LEP and Tevatron limits are of similar magnitude
→ Some ZEUS limits are the most stringent ones
→ No obvious indication for the existence of a CI
→ CI scenarios \(V V\) and \(V A\) with \(\Lambda = 3 - 4\) TeV are excluded
**Positron–Quark Resonances**

- **Leptoquarks (LQ’s), “classical” scheme**
  - LQ’s only couple to $e$, $q$, $\gamma$, $Z$, $W$, $g$
  - LQ’s conserve $SU(2)_L \times U(1)_R$
  - LQ’s are identified by $S$, $F$, $I_w$, $Q$
  - $\text{BR}(\text{LQ} \rightarrow eq) = 1 - \text{BR}(\text{LQ} \rightarrow \nu q')$
  - $= 0, \frac{1}{2}$ or 1

  Only few possibilities are left by low–energy and HERA $e^-p$ data:
  All have $\text{BR}(\text{LQ} \rightarrow eq) = 1$

- **$R_p$–violating squarks ($\tilde{q}$)**
  - $R_p$–violation: SUSY particles can be singly produced
  - Squarks can have LQ–like couplings
  - Alternative, $R_p$–conserving decay modes
    - $\Rightarrow \text{BR}(\tilde{q} \rightarrow eq)$ can be $\ll 1$
  - No CC–type decay modes
LQ’s can be pair–produced in \( p\bar{p} \) collisions

→ Cross–section does not depend on LQ coupling
→ Sensitivity decreases with \( \text{BR}(\text{LQ} \rightarrow eq) \)
→ Stringent restriction for LQ at HERA

### Tevatron Leptoquark Limits

<table>
<thead>
<tr>
<th>LQ type</th>
<th>( \text{BR}(LQ \rightarrow eq) = 1 )</th>
<th>( \text{BR}(LQ \rightarrow eq) = 0.5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S = 0 ) (scalar)</td>
<td>225</td>
<td>204</td>
</tr>
<tr>
<td>( S = 1 ) (vector)</td>
<td>298</td>
<td>270</td>
</tr>
</tbody>
</table>

\( \beta = \text{B}(LQ \rightarrow eq) \)
$e^{-}p$ LQ Coupling Limits from ZEUS (1993–1994)

$\lesssim 1\text{ pb}^{-1} e^{-}p$ data suffices to restrict $F = 2$ LQ species significantly

→ These limits severely restrict $F = 2$ LQ’s as explanation for HERA high–$Q^2$ excess

→ Similar limits available from H1
New LQ Limits from H1

\[ \sigma(ep \rightarrow \text{LQ} + X) \text{ depends on } M_{\text{LQ}}, \text{ coupling } \lambda, \text{ and } \text{BR}(\text{LQ} \rightarrow(eq)) \]

\[ \rightarrow \text{ Fixed } \lambda, M_{\text{LQ}} \text{ limit as function of } \text{BR}(\text{LQ} \rightarrow(eq)) \]

\[ \rightarrow \text{ Use Poissonian statistics in “sliding mass window”} \]

**H1 Preliminary**

\[ M_{\text{LQ}} > \sqrt{s} \] by \( \sim 4 \text{ GeV} \) due to QCD effects

\[ \rightarrow \text{ Bump at } M_{\text{LQ}} \approx 210 \text{ GeV} \]

\[ \rightarrow \text{ Open window at small BR(LQ} \rightarrow(eq)) \]
Conclusions and Outlook

Conclusions

- Precision NC and CC cross-section measurements for $Q^2$ up to several 10000 GeV$^2$ and for $x$ as high as 0.65 have been presented.

- Up to $Q^2 \approx 10000$ GeV$^2$, the data are in perfect agreement with the Standard Model. QCD fits describe the data over several orders of magnitude in $Q^2$ and $x$.

- The excess at $Q^2 \gtrsim 20000$ GeV$^2$ is not confirmed in the 1997 data but is still present.

- New limits on Contact Interactions and $e\gamma$ resonance production have been presented. No significant evidence for deviations from the SM is found. Some discovery windows for HERA.

Outlook

- **1998–1999**: $e^-p$ data at $E_p = 920$ GeV.

- **After 2000**: HERA upgrade: $\sim 100$ pb$^{-1}$ / year
  Longitudinal $e$ polarisation

We envisage an exciting future for high–$Q^2$ physics at HERA