Physics at HERA

Summer Student Lectures
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Overview Part 2

- Reminder
- Parton Density Fits
- High $Q^2$ and Electroweak Physics
  - Neutral Current
  - Charged Current
- Exotics
  - Model Dependent Searches
  - Model Independent Searches
Reminder: Deep Inelastic Scattering

- $Q^2 = -q^2 = -(k - k')^2$ four-momentum transfer
- $y = \frac{q \cdot P}{k \cdot P}$ inelasticity
- $x = \frac{Q^2}{2 q \cdot P} = \frac{Q^2}{y \cdot s}$ parton momentum fraction

\[
\frac{d^2 \sigma}{dx \, dQ^2} = \frac{4 \pi \alpha^2}{Q^4} \frac{1}{x} \left[ (1 - y + \frac{y^2}{2}) \, F_2(x, Q^2) \right]
\]

\[
F_2(x, Q^2) = x \sum e_q^2 \left| q(x) + \bar{q}(x) \right|
\]
DGLAP Evolution Equations

\[
\frac{\partial}{\partial \log Q^2} \begin{bmatrix} q(x, Q^2) \\ g(x, Q^2) \end{bmatrix} = \frac{\alpha_s}{2\pi} \begin{bmatrix} P_{q/g} & P_{q/g} \\ P_{q/g} & P_{q/g} \end{bmatrix} \otimes \begin{bmatrix} q(x, Q^2) \\ g(x, Q^2) \end{bmatrix}
\]

\[
P \otimes f(x, Q^2) = \int_x^1 \frac{dy}{y} P(x/y) f(y, Q^2)
\]

- $Q^2$ dependence of quark densities $q(x, Q^2)$ and gluon density $g(x, Q^2)$ is predicted
Parton Density Fits

DGLAP predicts only $Q^2$ dependence

➔ assume parametrisation of the parton density functions (PDFs) as a function of $x$ at a starting scale $Q_0^2$ (typically around 4-7 GeV$^2$):

$$ x \ q(x, Q_0^2) = a x^b (1 - x)^c [1 + d x] $$

➔ evolve the PDFs to all measured $Q^2$, calculate $F_2$, and fit the parameters to match the data

❗ some freedom in the procedure!

- how many parameters, which $Q_0^2$?
- how to combine quark and antiquark densities?
Parton Density Fits

quark and antiquark densities:

- most general: $u, \bar{u}, d, \bar{d}, s, \bar{s}, c, \bar{c}, (b, \bar{b})$

- distinguish valence and sea quarks: $u_v, d_v, sea$
  (some assumptions on decomposition of sea needed)

- distinguish up-type and down-type quarks:
  $U = u + c, \quad D = d + s (+b)$
  $\bar{U} = \bar{u} + \bar{c}, \quad \bar{D} = \bar{d} + \bar{s} (+\bar{b})$
  $\rightarrow u_v = U - \bar{U}, \quad d_v = D - \bar{D}$
H1 & ZEUS Parton Densities

differences:

- **H1**:
  - $U, \overline{U}, D, \overline{D}, g$
  - $xU = ax^b(1-x)^c [1 + dx + fx^3]$
  - 10 free parameters

- **ZEUS**:
  - $u, d, sea, g$
  - $xu = ax^b(1-x)^c[1 + dx]$
  - 11 free parameters
High $Q^2$ & Electroweak Physics
More Structure Functions

\[ \frac{d^2 \sigma_{NC}^\pm}{dx \, dQ^2} = \frac{2 \pi \alpha^2}{Q^4} \frac{1}{x} Y_+ \left[ F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) \mp \frac{Y}{Y_+} x F_3(x, Q^2) \right] \]

\[ F_L = F_2 - 2x F_1 = 0 \quad \text{in the QPM} \]

\[ F_3 : y - Z^0 - \text{interference} \]

\[ Y_\pm = 1 \pm (1 - y)^2 \]

- $F_L$ relevant only at large $y$
- $F_3$ relevant only at large $Q^2$, different sign for $e^+$ and $e^-$
High $Q^2$ Neutral Current

- difference between $e^+p$ and $e^-p$ only at large $Q^2 \approx M_Z^2$

$\rightarrow y - Z^0 -$ interference
High $Q^2$ Neutral Current

\[
\tilde{\sigma} = \frac{x Q^4}{2 \pi \alpha^2} \frac{1}{Y_+} \frac{d^2 \sigma_{NC}^\pm}{dx \, dQ^2}
\]

e$ positive interference

e$ negative interference

$xF_3 \propto x \sum e_q^2(q-\bar{q})$

direct handle on valence quark distribution!
Charged Current Interactions

CC: $Q^2 = 83656$ GeV$^2$; $y=0.83$; $P_T=118$

- Neutrino not visible in detector
- Imbalance in transverse plane
Charged Current Cross Section

\[ \frac{d^2 \sigma_{CC}^\pm}{dx \, dQ^2} = \frac{G_F^2}{4 \pi x} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 Y^+ \left[ W_2^\pm - \frac{y^2}{Y^+} W_L^\pm + \frac{Y^-}{Y^+} x W_3^\pm \right] \]

- \( W \) bosons couple differently to \textit{up}- and \textit{down}-type quarks
- in the QPM:
  \( W_2^- = x(U + D), \quad xW_3^- = x(U - D) \)
  \( W_2^+ = x(U + D), \quad xW_3^+ = x(D - U) \)
  \( W_L^\pm = 0 \)

\[ \Rightarrow \sigma_{CC}^- \propto x \left[ U + (1 - y)^2 D \right] \]
\[ \sigma_{CC}^+ \propto x \left[ U + (1 - y)^2 D \right] \]
Comparison NC vs. CC

- at low $Q^2$: different dependences because of photon in NC
- at high $Q^2$: „electroweak unification“

but:

\[
\frac{d^2 \sigma_{\text{CC}}^{\pm}}{dx \, dQ^2} \approx \frac{G_F^2}{4 \pi x} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \cdot Y + W^2_{\pm}
\]

\[
\frac{d^2 \sigma_{\text{NC}}^{\pm}}{dx \, dQ^2} \approx \frac{2 \pi \alpha^2}{x} \cdot \frac{1}{Q^4} \cdot Y + F_2
\]

similar because \( G_F \approx \frac{4 \pi \alpha}{\sqrt{2} M_W^2} \)
Electroweak Parameters: $W$ Mass

- $G = G_F$ determined by normalization of the CC cross section
- $M_{\text{prop}} = M_W$ determined by the $Q^2$ dependence of the CC cross section

$82.87 \pm 1.82 \, \text{GeV}$
CC & Polarization

- CC cross section depends on longitudinal electron/positron polarization $P_e$

\[
\frac{d^2 \sigma_{cc}^\pm}{dx \, dQ^2}(P_e) \approx (1 \pm P_e) \frac{G_F^2}{4 \pi x} \cdot \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \cdot Y + W_{2}^\pm
\]

- reason: $W$ boson couples only to left-handed (LH) particles and right-handed (RH) antiparticles:
\[ P_e = \frac{N_{RH} - N_{LH}}{N_{RH} + N_{LH}} \]

- transverse polarization builds up in ~40 minutes through synchrotron radiation (Sokolov-Ternov effect)
- spin rotators flip transverse ⟷ longitudinal before experiments and back after
Polarization @ HERA

spin rotator
CC: Polarization Dependence

- Standard Modell expectation:
  \[ \sigma_{CC}^-(P_e=+1) = 0 \]
  \[ \sigma_{CC}^+(P_e=-1) = 0 \]

- Experimental result: (H1)
  \[ \sigma_{CC}^-(+1) = -0.9 \pm 2.9_{\text{stat}} \pm 1.9_{\text{syst}} \pm 1.9_{\text{pol}} \text{ pb} \]
  \[ \sigma_{CC}^+(+1) = -3.9 \pm 2.3_{\text{stat}} \pm 0.7_{\text{syst}} \pm 0.8_{\text{pol}} \text{ pb} \]
Electroweak Parameters: $Z^0$ Couplings

polarization also allows better sensitivity to vector and axial-vector couplings of $u$- and $d$-type quarks to the $Z^0$
Exotics or
Beyond the Standard Modell
New Particles

many theories predict more particles than the SM:

• SUSY:
  – every Standard Model particles has a supersymmetric partner
  – fermion partners are bosons, boson partners fermions

• leptoquarks
  – particle with lepton and quark properties
  – can be produced resonantly in $ep$ collisions

• ... exited fermions, contact interactions, large extradimensions ...

but experimentally search also model-independent!
Leptoquarks

- $M_{LQ}^2 = (xP + k)^2 = xs$
- compare measured cross section with SM expectation
- derive limits on coupling $\lambda$

\[ \begin{align*}
  &\hspace{-1cm}
  \text{Events / 20 GeV} \\
  &\hspace{-1cm}
  \begin{array}{c}
    10^4 \\
    10^3 \\
    10^2 \\
    10 \\
    1
  \end{array}
  \begin{array}{c}
    50 \\
    100 \\
    150 \\
    200 \\
    250 \\
    300
  \end{array}
  \begin{array}{c}
    \text{NC, P=-27%} \\
    \text{H1 data (prelim.)} \\
    \text{SM} \\
    \text{SM uncertainty}
  \end{array}
  \end{align*} \]

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  &\hspace{-1cm}
  \begin{array}{c}
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    \text{SM uncertainty}
  \end{array}
  \end{align*} \]
Limits on Leptoquarks

$\lambda$ vs $M_{LQ}$/GeV

$S_{0,L}$ (e u, v d)
$S_{0,R}$ (e u)
$S_{0,R}$ (e d)
$S_{1,L}$ (e d, e u, v d)

Excluded at 95% C.L.

H1 preliminary
• R parity violation: single SUSY particle can be produced
• limits depend on many parameters (masses, couplings)
• example: stop

ZEUS

Excluded at 95% CL

\[ \lambda'_{131} (\text{APV}) \]

\[ \text{ZEUS (prel.) 99-00 e^+p} \]

\[ 100 \text{ GeV} \leq M_{\tilde{t}_2} \leq 300 \text{ GeV} \]

\[ -300 \text{ GeV} \leq M_{\tilde{\mu}} \leq 300 \text{ GeV} \]

\[ \tan \beta = 6 \]

\[ \text{Excluded in part of SUSY parameters} \]
General Searches

- idea: new particles have typically large mass

→ final state should contain particles with large transverse momentum from the decay
  - jets
  - electrons
  - muons
  - photons
  - neutrinos (missing transverse momentum)
General Searches

H1 General Search, HERA II $e^+p$ (159 pb$^{-1}$)  

H1 General Search, HERA II $e^-p$ (178 pb$^{-1}$)

every channel in reasonable agreement with the standard model
Multi-Leptons

in HERA1 a small excess of di- and tri-electron events at high transverse momenta observed by H1

HERA2 data show no significant excess
Isolated Leptons and Missing $P_T$

- spectacular events
- excess in HERA1 data at large transverse momenta of the hadronic system ($P_T^X$) seen by H1
Isolated Leptons and Missing $P_T$

- no excess in $e^-$ data
- what about $e^+$?
## Isolated Leptons and Missing $P_T$

<table>
<thead>
<tr>
<th>H1+ZEUS Preliminary</th>
<th>Electron obs./exp. (Signal contribution)</th>
<th>Muon obs./exp. (Signal contribution)</th>
<th>Combined obs./exp. (Signal contribution)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l+P_T^{miss}$ events at HERA I+II</td>
<td>(Signal contribution)</td>
<td>(Signal contribution)</td>
<td>(Signal contribution)</td>
</tr>
<tr>
<td>1994-2007 $e^+p$</td>
<td>Full Sample</td>
<td>39 / 41.3 ± 5.0 (70%)</td>
<td>18 / 11.8 ± 1.6 (85%)</td>
</tr>
<tr>
<td>0.58 fb$^{-1}$</td>
<td>$P_T^X &gt; 25$ GeV</td>
<td>12 / 7.4 ± 1.0 (78%)</td>
<td>11 / 7.2 ± 1.0 (85%)</td>
</tr>
<tr>
<td>1998-2006 $e^-p$</td>
<td>Full Sample</td>
<td>25 / 31.6 ± 4.1 (63%)</td>
<td>5 / 8.0 ± 1.1 (86%)</td>
</tr>
<tr>
<td>0.39 fb$^{-1}$</td>
<td>$P_T^X &gt; 25$ GeV</td>
<td>4 / 6.0 ± 0.8 (67%)</td>
<td>2 / 4.8 ± 0.7 (87%)</td>
</tr>
<tr>
<td>1994-2007 $e^\pm p$</td>
<td>Full Sample</td>
<td>64 / 72.9 ± 8.9 (67%)</td>
<td>23 / 19.9 ± 2.6 (85%)</td>
</tr>
<tr>
<td>0.97 fb$^{-1}$</td>
<td>$P_T^X &gt; 25$ GeV</td>
<td>16 / 13.3 ± 1.7 (73%)</td>
<td>13 / 12.0 ± 1.6 (86%)</td>
</tr>
</tbody>
</table>

- H1+ZEUS combined: 1.8 $\sigma$ excess
- H1 alone: 2.9 $\sigma$ excess