Physics at HERA

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- HERA and ZEUS
- Electroweak results
- Structure of the proton

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HERA: (27.5GeV e vs 920GeV p) the world largest electron microscope
A view of the HERA ring tunnel

Proton ring

Electron ring
The corner stone (定礎)
In 1984
Experiments started in 1992
Progress in accelerator enables us to investigate the smaller structure.

**HERA:**
(27.5GeV electron vs 920GeV proton)

\[ Q^2 \equiv -\left(q_i - q_f \right)^2 \]

In order to obtain the same CMS energy as HERA in a fixed target experiment, it requires 54TeV electron beam.
HERA probes the quarks in the proton

- Proton
  - @ KEKPH2005
  - 920 GeV
- Electron
  - 27.5 GeV
- Scattered quark
  - $\bar{q}$
  - Jet
- Parton distribution in the proton
  - Good sensitivity to the interaction type
  - High Energy
  - High Resolution
  - Polarized experiment

- New interactions and new particles

- Neutral Current
  - Charged Current

- HERA

3/March/2005
Introduction: Deep Inelastic Scattering

Described by 2 kinematic variables

\[ Q^2 = -q^2 \]

\[ x = \frac{Q^2}{2p.q} \]

\[
\frac{d\sigma_{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} (Y_+ F_2 - y^2 F_L \mp Y_- x F_3)
\]

\[ y = \frac{Q^2}{xs}, \] the inelasticity parameter, \( Y_\pm = (1 \pm (1 - y)^2) \)

\( F_2, F_L, \) and \( x F_3 \) are structure functions of the proton.

- \( F_L \): longitudinal component, damped by \( y^2 \).
- \( x F_3 \): Small at \( Q^2 \ll M_Z^2 \),

\[
F_2 = \sum_f e^2 x q_f(x, Q^2)
\]

\( q_f(x, Q^2) \): quark distribution function
Kinematical region for HERA structure function measurements

\[ s = Q^2 xy \]

- 2 order higher region in \( Q^2 \),
- 2 order lower region in \( x \)
- Wide (\( O(10^6) \)) span in \( Q^2 \): Precise measurements for \( Q^2 \) evolution
High Q² measurements: still limited by statistics

→ HERA II
At high $Q^2$ ($Q^2 \sim M_{WZ}^2$),

\[ \frac{d\sigma}{dQ^2} \propto \frac{\alpha'^2}{\left(Q^2 + M_{\text{Exchange}}^2\right)^2} \]

\[ \sigma_{\text{NC}} \sim \sigma_{\text{CC}} \]

\[ \rightarrow \text{Electroweak unification} \]

Good agreement with the SM

\[ M_W = 80.3 \pm 2.1(\text{stat}) \pm 1.2(\text{syst}) \pm 1.0(\text{PDF}) \text{ GeV} \]

(from ZEUS $e^+p$ data)

- $\sigma_{e^+p} < \sigma_{e^-p}$
  \[ \leftrightarrow Z \text{ interference} \]
- $\sigma_{e^+p} < \sigma_{e^-p}$
  \[ \leftrightarrow u,d\text{-quark distribution in the proton} \]

Measurements of NC/CC Cross sections

HerA-I Final Results

\[ \sigma_{\text{NC}} \sim \sigma_{\text{CC}} \]
"softer" scattering
If the quark is not point-like

Good agreement with the SM

Quark Radius < \(0.85 \times 10^{-16}\) cm

No signal for Leptoquarks

Excess in 1994-1997 data (e+p)
NC Cross section including Z

\[
d\sigma_{e^+p}^{x}{dx\partial Q^2} = \frac{2\pi\alpha^2}{xQ^4} \left[ \left\{ 1 + (1-y)^2 \right\} F_2 + \left\{ 1 - (1-y)^2 \right\} xF_3 \right]
\]

\[
F_2(x, Q^2) = \sum_q \left\{ e^2_f - 2e_f v_f v_e P_Z + (v_f^2 + a_f^2)(v_e^2 + a_e^2) P_Z^2 \right\} \left[ xq(x, Q^2) + xq(x, Q^2) \right]
\]

\[
xF_3(x, Q^2) = \sum_q \left\{ -2e_f a_f a_e P_Z + 4v_f a_f v_e a_e P_Z^2 \right\} \left[ xq(x, Q^2) - xq(x, Q^2) \right]
\]

\[
P_z = \frac{1}{\sin^2 2\theta_w} \left( \frac{Q^2}{Q^2 + M_Z^2} \right)
\]

ZEUS

\[
Q^2 > 10,000 \text{ GeV}^2
\]

\[
\frac{d\sigma}{dx} (\text{pb})
\]

\[
x,
\]

\[
\gamma Z \text{ interference effect}
\]

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Longitudinal polarization of lepton beam: → Direct EW sensitivity

- Sokolov-Ternov effect
  → Lepton beam has transverse polarization
  +
- Spin rotator before/after the H1/ZEUS/HERMES detectors.

Luminosity Upgrade:
← High-$Q^2$ requires large luminosity

- Final focusing magnets in the detector
CC Expectations

With ~ 200 pb\(^{-1}\) for each polarized beam.

$M_{WL} \sim 80\text{MeV}$

$M_{WR} > 400\text{GeV}$
HERA delivered

Physics Luminosity 2002 - 2005

Even better performance with e⁻ p

04/05 e⁻

04 e⁺

03 e⁺

02/03 e⁺

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Integrated Luminosity (pb⁻¹)

Days of running

Average HERA polarisation

Average longitudinal Polarization

P=+32%

P=-40%

(~50% in Feb 2005)

04 2003 Nov 2003 Dec 2003 Jan 2004

Oct 2003

Polarisation [%]

Day in month

Mar 2004

Jun 2004

Jul 2004

Aug 2004

~50% in Feb 2005

Polarisation [%]

Day in month

Avg. HERA Polarisation

P organisat

Mar 2004

Jun 2004

Jul 2004

Aug 2004

Polarisation [%]

Day in month

Avg. HERA Polarisation

P organisat
The first measurement of Left/Right asymmetry in CC in this energy region.

Consistent with the Standard Model.
Polarization effects observed in overall, i.e. no phase space bias.

→ Agrees with the SM prediction of: overall normalization change by (1+P) factor.
CC Cross-Sections [H1/ZEUS]

H1 preliminary result on $\perp_R$

$\sigma_{cc}(P=-1) = -3.7 \pm 2.4_{\text{stat}} \pm 2.7_{\text{syst}} \text{ pb}$

H1 cross sections are slightly lower but the two results are consistent.

$\rightarrow \perp_{cc} (RH) = 0$

$Q^2 > 400 \text{ GeV}^2$

$y < 0.9$
Polarized Neutral Current Cross section

- Very subtle effect from $\gamma$-Z interference
- Larger effect in e-p
  (The experiment has started in Nov 2004)

$\chi^2 = 1.69$
(w/ Pol.)

$\chi^2 = 2.29$
(w/o Pol.)
at $Q^2 > 1000$ GeV$^2$

Pol.=70%

$\sigma^2 = 1.69$
(w/ Pol.)

$\sigma^2 = 2.29$
(w/o Pol.)

at $Q^2 > 1000$ GeV$^2$

- ZEUS
- $P=\pm 32\% / P=0$
- $P=\pm 40\% / P=0$

- Polarized Neutral Current Cross section
- Very subtle effect from $\gamma$-Z interference
- Larger effect in e-p
  (The experiment has started in Nov 2004)

Pol.=70%
**Kinematical region for HERA structure function measurements**

\[ s = Q^2 x y \]

- 2 order higher region in \( Q^2 \),
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Early ZEUS data showed rapid increase of $F_2$ at low $x$.

Donnachie & Landshoff

“Hadronic”: Regge theory behavior of $\bar{p}p$ total cross section

“pQCD”: parton evolution

Gluck, Reya and Vogt

Predictions of $F_2$
Scaling violation

DGLAP evolution (Dokshitzer, Gribov, Lipatov, Altarelli, Parisi)

\[ \frac{dF_2}{d \ln Q^2} = \alpha \sum_q e_q^2 \frac{\alpha_s(Q^2)}{2\pi} \int_1^\infty \frac{dy}{y} \left[ P_{qq}(x/y) \cdot q(y, Q^2) + P_{qg}(x/y) \cdot g(y, Q^2) \right] \]

Q2 larger:
high-x q and g are split into low x q and g.
• Strong rise of $F_2$ as $x$ decreases
  – Soft ‘sea’ of quarks in the proton
• Slope of rise gets steeper as $Q^2 \uparrow$
  softer part
  smaller resol.
  dynamics of quarks and gluons
• Good agreement with fixed-target experiments at middle - high $x$
  – Sea + valence quarks
F₂ for fixed x, as a function of Q²

- At low x, strong scaling violation is seen.
  Large gluon density + $g \rightarrow q\bar{q}$ splitting → F₂ increases
- At $x \sim 0.1$, approximate scaling.
- At higher x, F₂ decreases as $Q^2 \uparrow$.
  Quark radiates off gluon: $q \rightarrow qg$

- Line = result of QCD fit
  - All data points well described.
PDF parameterization

- \( xf(x) = p_1 x^{p_2} (1-x)^{p_3} (1+p_5 x) \) at \( Q_0^2 = 7 \text{GeV}^2 \)
  - \( p_1 \): normalization
  - \( p_2(p_3) \): \( x \to 0 \) (\( x \to 1 \)) bahavior
  - \( p_5 \): high-\( x \) shape

- Some assumptions
  - For \( xu_v \) and \( xd_v \), fix \( p_2=0 \) (not sensitive to low-\( x \) valence)
  - For \( xg \), fix \( p_5=0 \) (not sensitive to high-\( x \) gluon shape)
  - \( x\text{Sea}=(x\text{ubar}+x\text{dbar}+x\text{Strange}+x\text{Charm}) \), \( x\text{Strange}=0.2*x\text{Sea} \) (CCFR)
  - Use MRST form for \( x(u\text{bar}-d\text{bar}) \) shape (only fit \( p_1 \))

- Sum-rule constraints (number and momentum)
  - \( \int u_v(x)dx=2 \), \( \int d_v(x)dx=1 \), \( \int x\Sigma f(x)dx=1 \)

- Total: 11 free parameters, 1263 data points
As seen in the $F_2$ rise at low-$x$, many sea quarks.

Gluons are dominant at low-$x$.

Similar conclusion from ZEUS and the PDF fitters (Durham, CTEQ).

How about H1 results?

PDFs obtained from the fits

Note the scale factor. Gluon dominant at low-$x$.

H1/ZEUS comparison:
The main difference comes from

- Initial Parameter
- Selection of low energy experiments
Simultaneous extraction of $\alpha_s$ and PDF

- Scaling violation:
  \[ \frac{\partial F_2}{\partial \ln Q^2} \sim \alpha_s \cdot x g(x, Q^2) \]

Data at low $x$ allow disentangling correlation of $\alpha_s$ and $x g$

- $\alpha_s$-free fit gives:
  \[
  \begin{align*}
  \text{H1:} & \quad \alpha_s = 0.1150 \pm 0.0017 \text{(exp)} \pm 0.0009 \text{(model)} \\
  & \quad \text{(additionally } \pm 0.0005 \text{ from renormalization scale)} \\
  \text{ZEUS:} & \quad \alpha_s = 0.1166 \pm 0.0049 \text{(exp)} \pm 0.0018 \text{(model)} \\
  & \quad \text{(additionally } \pm 0.0004 \text{ from renormalization scale)}
  \end{align*}
  \]

Difference in exp. error mainly from the treatment of systematic error and normalization of data points in the fitting procedure and error propagation.
What if there were no HERA data?

- HERA data determine the low-x gluon and sea-quark PDF.
- HERA revealed: $F_2$ is very steep.
Low-$Q^2$ sea and gluon distributions

- At $Q^2 \sim 1\text{GeV}^2$, gluon becomes valence-like (and even tends to be negative)
- Sea quark is still rising
S.F. measurements with 1 fb$^{-1}$

- Expected precision in $F_2$ and gluon determination
Flavor-specific measurements

- Complete ‘mapping’ of the proton...
  - $d/u$ at high $x$: charged current
  - **Strange**: charm in CC and/or leading $\phi$ particle
  - **Charm and bottom**: improved tagging with micro-vertex

Charm 500 pb$^{-1}$

Bottom/charm 500 pb$^{-1}$
Summary

• HERA and ZEUS/H1 experiments
  – Collider = x100 extended region in \( Q^2 \) and \( x \).

• High- \( Q^2 \) NC and CC: electroweak effects
  – NC: effect of Z exchange (different coupling of quark-antiquark)
  – CC: flavor-specific (sees positive and negative quarks differently)

• HERA-II with longitudinal polarization just started.
  – \( W \) should couple with only right-handed \( e^+ \) (and left-handed \( e^- \)).

• \( F_2 \) measurement and PDF determination
  – Very steep rise of sea and gluon at low \( x \).