Structure-function measurements at HERA

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- Introduction
- $F_2$ measurement and PDF fit
- Low-$Q^2$ region
- High-$Q^2$ region
- Current status and prospects
HERA $ep$ Collider at DESY/Hamburg

- $E_p = 920 GeV \otimes E_e = 27.5 GeV (e^+ or e^-) \Rightarrow \sqrt{s} = 318 GeV$
- 2 colliding experiments and 2 fixed-target experiments
- On-tape luminosity: $\sim 110 \text{ pb}^{-1} e^+p$, $\sim 15 \text{ pb}^{-1} e^-p$ (‘98-’99) for H1 or ZEUS
Deep Inelastic Scattering (DIS)

- Probe the proton (our most familiar micro-cosmos) with a point-like lepton probe. ‘giant electron-microscope’
- Bjorken $x$: Fractional momentum of a parton in the nucleon.
- $1/Q$ (momentum transfer) gives the spacial resolution.
- Neutral or Charged current in t-channel propagator

$$Q^2 = s x y$$

$$Q^2 = -(k - k')^2$$

$$x = \frac{Q^2}{2 P \cdot (k - k')}$$

$$y = \frac{P \cdot (k - k')}{P \cdot k}$$
Kinematic region probed

• > 100x larger kinematic reach compared to fixed-target DIS experiments at CERN, DESY, FNAL, SLAC… (if proton is at rest, HERA CM energy means $E_e = 54 TeV$)

• At high $Q^2$, probe the validity of QCD at smallest distance $\rightarrow$ Quark structure? New particles? ($Q^2 = 40,000 \text{ GeV}^2 \rightarrow 1/Q = 0.001 \text{ fm}$)

• At low $Q^2$, probe the low-$x$ region $\rightarrow$ very soft constituents of proton; Saturation? Breakdown of standard DGLAP formalism (BFKL)?
The Detectors

- **ZEUS Detector**
  - Uranium-Scintillator calorimeter
    - $\sigma(E)/E = 18\%/\sqrt{E}$ for electrons
    - $\sigma(E)/E = 35\%/\sqrt{E}$ for hadrons
  - Central tracking detector
    - $\sigma(p_T)/p_T = 0.0058 p_T \pm 0.0065 \pm 0.0014 / p_T$

- **H1 Detector**
  - Liquid-Ar calorimeter
    - $\sigma(E)/E = 12\%/\sqrt{E}$ for electrons
    - $\sigma(E)/E = 50\%/\sqrt{E}$ for hadrons
  - Central tracking detector

2 out of $(E_e, \theta_e, E_h, \theta_h) \rightarrow$ Reconstruction of $(x, Q^2)$
Cross section & Structure functions

- NC differential cross section

\[
\frac{d^2\sigma_{e^+p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[ Y^+ F_2(x, Q^2) + Y^- x F_3(x, Q^2) - y^2 F_L(x, Q^2) \right]
\]

\[
F_2 = \sum x q_f^+(x, Q^2)[e_f^2 - 2e_f v_f v_e P_Z + (v_f^2 + a_f^2)(v_e^2 + a_e^2) P_Z^2]
\]

\[
xF_3 = \sum x q_f^-(x, Q^2)[- 2e_f a_f a_e P_Z + 4v_f a_f v_e a_e P_Z^2]
\]

\[
xq_f^\pm = x q_f(x, Q^2) \pm x \overline{q}_f(x, Q^2) \quad (\text{Parton Distribution Functions})
\]

\[
P_Z = \sin^{-2} 2\theta_W \cdot Q^2/(Q^2 + M_Z^2) \quad (\text{Z-exchange & } \gamma - \text{Z interference})
\]

\[
Y^\pm = 1 \pm (1-y)^2, \quad e_f: \text{quark charge, } v_i/a_i: \text{EW couplings}
\]

\[
F_L = F_2 - 2xF_1 \quad (\text{\(\rightarrow 0\) in LO QCD, longitudinal Str. Function})
\]
Results of $F_2$ Structure Function

- 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 parton
  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 → q̅q splitting → F₂ increases
- At x ~ 0.1, approximate scaling.
- At higher x, F₂ decreases as Q² ↑.

- Line = result of QCD fit (next slide)
  - All data points well described.
Perturbative-QCD fit of $F_2$ data

- Example: ZEUS NLO DGLAP analysis \cite{PRD67} (2003) 012007
  - At $Q^2 = Q^2_0$, input functional form of PDF ($Q^2_0 = 7\text{GeV}^2$)
    - $xf(x) = p_1 x p_2 (1-x) p_3 (1+p_5 x)$ for u-valence, d-valence, sea quarks and gluons
  - ‘$Q^2$ evolution’ is predicted by DGLAP (‘Altarelli-Parisi’) Equations
    - $\frac{\partial f_i}{\partial \ln Q^2} = (\alpha_s/2\pi) \sum f_j \otimes P_{ij}$
  - Use world’s precision DIS data + ZEUS $F_2$
    - BCDMS, NMC, E665, CCFR ($\mu$-p, $\mu$-D, $\nu$-Fe)
  - $\chi^2$ fit to determine $p_1 \ldots p_5$
PDFs obtained from the fits

**ZEUS**

- ZEUS NLO QCD fit
  - $\alpha_s(M_Z^2) = 0.118$
- tot. error
- CTEQ 6M
- MRST2001
- $x_{uv}$
- $x_d$ (× 0.05)
- $x_g$ (× 0.05)

**HERA: PDF determination**

- H1 2002 PDF Fit (prel.)
  - $\alpha_s(M_Z^2) = 0.1185$ fixed
  - data set: H1 (94/00) + BCDMS
- ZEUS NLO QCD fit
  - $\alpha_s(M_Z^2) = 0.1180$ fixed
  - data set: ZEUS (96/97) + BCDMS, NMC, E665, CCFR

- experimental errors only

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17/May/2003 NufactJ03 meeting
Low-x 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
Simultaneous extraction of $\alpha_s$ and PDF

- Scaling violation: $\partial F_2/\partial \ln Q^2 \sim \alpha_s \cdot xg(x, Q^2)$
  Data at low $x$ allow disentangling correlation of $\alpha_s$ and $xg$

- $\alpha_s$-free fit gives:
  
  **H1:**  
  $$\alpha_s = 0.1150 \pm 0.0017(\text{exp})^{+0.0009}_{-0.0005} (\text{model})$$  
  (additionally $\pm 0.0005$ from renormalization scale)

  **ZEUS:**  
  $$\alpha_s = 0.1166 \pm 0.0049(\text{exp}) \pm 0.0018(\text{model})$$  
  (additionally $\pm 0.0004$ from renormalization scale)

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.
Where is the lowest applicability of pQCD?

- Recall gluon becomes negative at low $Q^2$.
- It is not necessarily a problem, since PDF itself is not a physical observable.
- However, $F_L$ (observable) becomes also negative for $Q^2 < \sim 1 \text{ GeV}^2$.
- Is this the lowest end of p-QCD applicability?

Look at the $F_2$ data →
Transition from perturbative to non-p. region

- At very low $Q^2$, $\alpha_s \uparrow$ and non-perturbative effects important.
- ZEUS BPT data at very low $Q^2$ available.
- Data cannot be described by pQCD fit below $Q^2 \sim 1 \text{ GeV}^2$. (rather, it’s a surprise that pQCD works as low as 1 GeV$^2$ !)
- This is evident thanks to HERA data at low $x$. 

![Graph showing transition from perturbative to non-perturbative region]
F₂ slope in low-x region

- For x < 0.01, F₂ can be well parameterised by \( c \cdot x^{-\lambda} \).

- \( \lambda \) fairly independent of x, linearly rises with \( \log Q^2 \) in ‘DIS’ regime.

- Qualitative change happens around \( Q^2 < \sim 1 \text{GeV}^2 \), then \( \lambda \) flattens in non-pert. region.
DIS in the hadronic picture

- At very low $Q^2$, quasi-real photon acts like a hadron (vector-meson dominance).
- Plot shows $F_2$ for fixed $y$, i.e. at fixed $\gamma^*-p$ CM energy $W$ ($W^2 \sim sy = Q^2/x$).
- $\sigma_{\text{tot}}(\gamma^*p) = (4\pi^2\alpha/Q^2)F_2(x=Q^2/W^2, Q^2)$ so $F_2$ must vanish as $F_2 \propto Q^2$ as $Q^2 \to 0$.
- Data show this behaviour ($25 < W < 270$ GeV) and successfully fitted by a Regge-type fit. (consistent with Pomeron and Reggeon trajectories determined from hadron-hadron scattering)

Regge fit:

$$F_2(x, Q^2) = \left( \frac{Q^2}{4\pi^2\alpha} \right) \cdot \left( \frac{M_0^2}{M_0^2 + Q^2} \right) \cdot \left( A_{\text{IR}} \cdot (W^2)^{\alpha_{\text{IR}} - 1} + A_{\text{IP}} \cdot (W^2)^{\alpha_{\text{IP}} - 1} \right)$$

$\alpha_{\text{IP}} \approx 1.1$ and $M_0 \approx 0.7$ GeV.
Attempts to describe both regions

Dipole models: a class of phenomenological models
example: Golec-Biernat & Wuesthoff

- $\gamma$ dissociates into a $q\bar{q}$ pair (dipole) of radius $r=1/Q$ upstream of the proton.
- Its cross section with proton ($\hat{\sigma}_{dipole}$) rises as $r^2$ for small $r$ (pQCD region).
- It saturates at large $r$, for $r \sim R_0$.
- The critical radius $R_0$ is characterised by the parton density: $R_0 \sim 1/$gluon$\sim x^\lambda$ (low $x =$ high-density environment).
- DIS cross section is a convolution of $\hat{\sigma}_{dipole}$ and photon wave function $\Psi$.

\[
\sigma = \int d^2 r \int dz |\Psi(z, r)|^2 \hat{\sigma}_{dipole}(x, r)
\]
Does it describe the data?

- This simple model gives a good description of $x<0.01$ $F_2$ data for both $Q^2$ regions.
- Amazing thing is that the single model describes $F_2$, diffractive cross section and vector-meson production at the same time (not discussed here).

Red: original GB&W
Blue: modified one (includes DGLAP evolution)
Bartels, GB, Kowalski
PRD66(2002)014001
High-$Q^2$ region – Electroweak effects

- $P_z = Q^2/(Q^2 + M_Z^2)$
  At $Q^2 \sim 5000$ GeV$^2$, effect of Z-exchange clearly visible.

- $\sigma(e^-p) > \sigma(e^+p)$ due to $\pm xF_3$
  $xF_3 \propto q(x, Q^2) - q(x, Q^2)$ sensitive to valence quarks

- Statistically limited: more luminosity helps (esp. $e^-p$)

\textbf{Diagram:}

- $Q^2 = 1500$ GeV$^2$
- $Q^2 = 3000$ GeV$^2$
- $Q^2 = 5000$ GeV$^2$
- $Q^2 = 8000$ GeV$^2$
- $Q^2 = 12000$ GeV$^2$
- $Q^2 = 30000$ GeV$^2$

\textbf{Legend:}

- ZEUS
- NLO QCD fit
- tot. error
- ZEUS NC $e^-p$ 98/99
- ZEUS NC $e^+p$ 96/97
- SM
- H1
Charged current – flavour decomposition

- $e^+ p$: only negative-charge quarks take part.

$$\frac{d^2\sigma_{e^+p}}{dx dQ^2} = \frac{G_F}{2\pi} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 [\bar u + \bar c + (1 - y)^2(d + s)]$$

At high $x$, mainly $d(x, Q^2)$ probed.

- $e^- p$: only positive-charge quarks take part.

$$\frac{d^2\sigma_{e^-p}}{dx dQ^2} = \frac{G_F}{2\pi} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 [u + c + (1 - y)^2(\bar d + \bar s)]$$

At high $x$, mainly $u(x, Q^2)$ probed.

- In addition to $u(x, Q^2) > d(x, Q^2)$, $e^+ p$ gets helicity suppression $(1-y)^2$. ($y=Q^2/sx$)

$$\Rightarrow \sigma(e^-p) \gg \sigma(e^+p) \text{ at large } Q^2.$$  

- Data (not used in the fit) well described by QCD prediction.
Can valence be determined by HERA only?

- **ZEUS-only fit** (all HERA-I NC/CC data, prel.) still a bit less precise than global fit, but looks promising with future HERA-II data (e.g. d/u at high $x$).
- **Using only ep data**: no uncertainty from nuclear corrections (D, Fe, …).
Evidence of Electro-Weak Unification

- At low $Q^2$:
  NC $\sim 1/Q^4$ (EM current)
  CC $\sim G_F^2$ (Weak current)
- At high $Q^2 (> M_Z^2, M_W^2)$:
  Both NC and CC mediated by unified EW current.
  $\sigma_{NC} \sim \sigma_{CC}$
- Dumping of $\sigma_{CC}$ at high $Q^2$ comes from $M_W$. Fit gives: $(Z, e^-p)$ $M_W = 80 \pm 2$(stat)$\pm 1$(syst)$\pm 1$(PDF) GeV
- Space-like: $q^2$(boson) $\ll 0$
  Completely different phase-space from time-like bosons at LEP and Tevatron ($q^2 > 0$).
  Complementary evidence/measurement.
Limits on quark radius

- Repeat ‘form-factor measurement’ as we did for protons, but at $Q^2 \sim 40,000\ \text{GeV}^2$ instead of 1 GeV$^2$.
  - Resolution $= 1/Q \sim 10^{-16}\text{cm} = 0.001\ \text{proton radius}$
- If quark has a finite radius, cross section will decrease as the probe ‘penetrates’ into it (sees less EW charge).
  \[ \sigma = \sigma_{\text{SM}}(1-<R_q^2>Q^2/6)^2 \]

- Limits on quark size
  (assuming electron is pointlike)
  ZEUS: $R_q < 0.73 \times 10^{-16}\ \text{cm}$
  H1: $R_q < 0.82 \times 10^{-16}\ \text{cm}$
  (95% CL)

High-$Q^2$ NC data
Large Extra Dimensions?

- **Arkani-Hamed, Dimopoulos and Dvali:** Assume n extra dimensions compactified to scale R, where only gravity propagates. Real GUT scale could be as low as TeV \( R^n M_s^{n+2} \sim M_{\text{Planck}}^2 \)

- **Collider consequence:** exchange of Kaluza-Klein excitations of gravitons would modify SM-particle scattering at high energy.

- **HERA:** eeqq CI formalism with \( \lambda/M_s^4 \) as a parameter
  - \( \lambda=+1: M_s > 0.83 \text{ TeV (H1)}, 0.81 \text{ TeV (ZEUS)} \)
  - \( \lambda=-1: M_s > 0.79 \text{ TeV (H1)}, 0.82 \text{ TeV (ZEUS)} \)

- LEP, Tevatron limits \( \sim 1 \text{ TeV} \)
HERA luminosity upgrade

• 2000-2001: shutdown for lumi upgrade.
  – Final focussing magnets inside detector
    → 5x luminosity than 2000 values
  – Goal: Accumulate \( \sim 1 \) fb\(^{-1} \) in HERA-II run (till 2006)
  – Longitudinal e\(^\pm\) polarization for H1/ZEUS by spin rotators
    (was available only for HERMES)

• Also detector upgrades (ZEUS example)
  – Micro-vertex detector (b,c-tagging)
  – Straw-tube tracker (forward tracking)
  – New luminosity counters (calorimeter + spectrometer)
Current status

• New detector components successfully commissioned.
• New machine optics fine, achieved design specific luminosity (luminosity per beam currents).
• 2002-03 run: with commissioning (modest) beam currents.
• Beam currents limited by backgrounds at detectors (chamber currents).
  – Unexpectedly high double-scattered synchrotron radiation
  – Vacuum conditioning of the new ring slower than expected
  → high proton beam-gas background in the detector
• Remedies will be taken in the shutdown March to June 2003.
• Achieved before shutdown: $L=2.7 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$ (design 7.0)
• Max 50% $e^+$ polarization achieved with H1/HERMES/ZEUS rotators.
Summary

• **Probing the proton with very high-energy probe** showed us:
  – Precise measurement of sea-quark and gluon distributions at low \( x \rightarrow \) Crucial inputs for current and future experiments.
  – Point of transition from perturbative to non-perturbative picture of the proton in QCD: \( Q^2 \sim 1 \text{GeV}^2 \)
  – At high \( Q^2 \), EW effects clearly visible and QCD evolution is valid up to \( \sim 10,000 \text{GeV}^2 \).

• **HERA-2 has started. High-luminosity run expected this fall.**
  – Very precise determination of \( F_2 \) and gluon distribution.
  – Flavour decomposition using various tools.
  – Polarized \( e^\pm p \) to probe EW structure of DIS.

• **Exciting future ahead with 10x more data and polarization.**