HERA Collider Physics

Summer Student Lectures
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Hans-Christian Schultz-Coulon
Universität Dortmund
[H1 Collaboration]

[e-mail: coulon@mail.desy.de]
Overview
on topics covered (or touched) in this lecture

A. Introduction
• Elastic eN-Scattering
• Inelastic Scattering
• Quark-Parton-Model
• Structure Functions

B. HERA Experiments
• The HERA Collider
• H1 & ZEUS

C. Proton Structure
• $F_2$ measurement
• Parton densities
• $\alpha_s$ and the Gluon

D. (Di)-Jet Production

E. Photon Structure
• Scale Problem
• DGLAP & BFKL
• Concept of Photon Structure

F. Diffraction
{ • Introduction
  • Inclusive Diffraction
  • Exclusive Final States
}

G. Heavy Flavour Physics
{ • Quarkonia Production
  • Open Charm & Bottom
}

H. Electroweak Aspects
• ep Cross Section
• EW Unification
• PDFs at High x, $Q^2$

I. Searches
{ • Direct Searches
  • Indirect Searches
}

J. HERA II Upgrade
• Experimental Setup
• Physics Prospects
Elastic Scattering
Cross Section

\[ e + N \underset{i}{\rightarrow} e' + N' \]

\[ \frac{d\sigma}{d\Omega} \sim |M_{if}|^2 \rho_f \]

Fermi's Golden Rule

\[ M_{if} = \int \psi_f^* V(\hat{r}) \psi_i d\tau \]

Rutherford pointlike scattering (no spin)

\[ F(\hat{q}) = \int \rho(\hat{r}) e^{-i \hat{q} \cdot \hat{r}} d^3 \hat{r} \]

Form Factor
[describes structure of target]
Form Factor Properties

A. Describes the difference between scattering on extended objects with respect to pointlike target

B. For \( q \to 0 \) also \( e^{-iqr} \to 1 \) and

\[
\lim_{\hat{q} \to 0} F(\hat{q}) = \int \rho(\hat{r}) d^3\hat{r} = 1
\]

C. If \( 1/q \sim r \), small changes of \( q \) imply large changes of \( e^{-iqr} \).

D. For \( 1/q \ll r \), i.e. \( qr \gg 1 \) the expression \( e^{-iqr} \) oscillates fast. Hence

\[
\lim_{\hat{q} \to \infty} F(\hat{q}) \approx 0
\]

E. For a spherical charge distribution one gets

\[
F(\hat{q}) = F(\hat{q}^2) = 1 - \frac{1}{6} \hat{q}^2 \langle r^2 \rangle
\]

---

Proton: \( \sqrt{\langle r_{Proton}^2 \rangle} \approx 10^{-15} \) m

To resolve proton structure one needs \( Q^2 \gg 0.04 \text{ GeV}^2 \)

HERA: max. \( Q^2 \approx 10^5 \text{ GeV}^2 \)

\( \to \) probing down to \( 10^{-18} \) m
### Relation of $\rho(r)$ and $F(q^2)$

| $\rho(r)$ | $|F(q^2)|$ | Example | $\rho(r)$ | $F(q^2)$ |
|---|---|---|---|---|
| pointlike | constant | Electron | $\frac{\delta(r)}{4\pi}$ | 1 |
| exponential | dipole | Proton | $\frac{a^3}{8\pi} e^{-ar} \left( 1 + \frac{q^2}{a^2 \hbar^2} \right)^{-2}$ | |
| gauss | gauss | $^6\text{Li}$ | $\left( \frac{a^2}{2\pi} \right)^{3/2} e^{-\frac{a^2 r^2}{2}} \exp \left( -\frac{q^2}{2 a^2 \hbar^2} \right)$ | |
| homogeneous sphere | oscillating | $^4\text{He}$ | $\frac{3}{4\pi} R^3 \theta(R - r) \frac{3(\sin \alpha - \alpha \cos \alpha)}{\alpha^3}$ with $\alpha = f(R)$ | |
| sphere with a diffuse surface | oscillating | $^{40}\text{Ca}$ | $\frac{1}{1 + e^{\left( \frac{r - 8}{a} \right)}}$ | |
Nuclear Form Factors
Experimental Results

From difference of position of minima

\[ R_{^48\text{Ca}} > R_{^40\text{Ca}} \]

Charge distribution of atomic nuclei
Elastic eN-Scattering

Fixed target experiment [Lab frame]

\[ q = k - k' = (\nu, \hat{q}) \]
with \( \nu = E - E' \)

\[ Q^2 = -q^2 \propto \left( \frac{\hat{h}}{\lambda} \right)^2 \]
Resolving power of the photon

Target stays intact (elastic scattering):

\[ p_f^2 = M_N^2 = (M_N + \nu)^2 - \hat{q}^2 \]
\[ M_N^2 = M_N^2 + 2M_N\nu + \nu^2 - \hat{q}^2 \]

\[ \nu = \frac{Q^2}{2M_N} \]

Expect: narrow peak at \( x=1 \)

\[ x = \frac{Q^2}{2M_N\nu} \]
Fixed Target Experiments

[Example: DESY — Strahl 22]

T: Target
Qx: Quadrupoles
H: Collimator
V: Collimator
Mx: Dipoles
C: Cherenkov Counter
Sx: Scintillators

Electrons from DESY

Spectrometer

VIEWER SEM
FARADAY CUP

S1 S2 Č
Č S3 S4 S5 S6

///// CONCRETE
///// LEAD
First DIS Result [DESY 1968]

\[
\frac{d^2\sigma}{dE'd\Omega} \quad [nb \text{ GeV}^{-1} \text{ sr}^{-1}]
\]

\[E' = \frac{M_p E}{[E(1-\cos\theta)+M_p]}\]

\[E' \approx 4.5 \text{ GeV}\]

using:
\[Q^2 = 2EE'(1-\cos\theta)\]
\[Q^2 = 2M_p^2\]

\[\text{and } M_p = 1 \text{ GeV}\]

\( E = 4.9 \text{ GeV} \)
\( \theta = 10^\circ \)
Observed Cross Section dependence at lower $x$.

[schematic diagram]

Quark-antiquark pairs

$Q^2 \sim 100 \text{ GeV}^2$

Valence quark peak (Fermi-smeared)

Expected if proton consists out of quarks with effective mass $m_q = \frac{1}{3} M_p$

$Q^2 \sim 1 \text{ GeV}^2$

Nucleon-pion resonances

Elastic

Position of $e-p$ peak

1956 (e-He Scattering)

Hofstatter experiment

$x = \frac{Q^2}{2M_N\nu}$
Naive QPM Model
[Feynman 1969]

Proton consists out of **partons**
Interaction due to interaction of partons
Hadronic structure defined by distribution
of partons at any given time
→ changes in number and momenta of partons
should be small during time they are probed

Partons “frozen” during interaction time
Can be treated as “free”
during short time of interaction
Photon-Proton interactions can be expressed as sum of incoherent scattering from point-like partons

Partons identified with Quarks

Infinite momentum frame:
Proton is moving with infinite momentum; proton mass can be neglected.

\[ \sum x_i = 1 \]
\[ 0 < x_i < 1 \]
DIS Kinematics

Electron

\[ k = (E, \hat{k}) \]

\[ k' = (E', \hat{k}') \]

\[ Q^2 = -(k - k')^2 \]

Deep-Inelastic Scattering:

- Extra degree of freedom
- Relation between \( Q^2 \) and \( \nu \) no longer valid

Proton

\[ W^2 = (P + q)^2 = P^2 + q^2 + 2Pq = M_p^2 - Q^2 + 2Pq \]

\[ P'^2_q = (q + xP)^2 = 2xPq - Q^2 = 0 \]

\[ x = \frac{Q^2}{2Pq} \]

[Bjorken-x]

Elastic:

\[ Q^2 = 2Pq \]

Inelastic:

\[ Q^2 = 2Pq + M_p^2 - W^2 \]
DIS Kinematics
Summary of Relevant Kinematic Variables

\[
s = (k+p)^2 = 4E_E E_p
\]
\[
Q^2 = -q^2 = (k-k')^2 = 2E_E E'_e (1-\cos \theta'_e)
\]
\[
\nu = q.p/M_p
\]
\[
\nu_{\text{max}} = s/(2M_p)
\]
\[
\gamma = (q.p)/(k.p) = \nu/\nu_{\text{max}}
\]
\[
x = Q^2/(2q.p)
\]
\[
W^2 = (p+q)^2 = M_p - Q^2 + 2M_p \nu
\]

Centre-of-mass energy squared
Negative squared four momentum transfer
Energy transfer in proton rest frame
Maximum energy transfer
Fraction of energy transfer
Bjorken scaling variable
Invariant mass of total hadronic system

\[Q^2 = s \times x \times y\]

At fixed \(s\) only two independent variables

\[p = (E_p,0,0,E_p)\]
\[k = (E_E,0,0,-E_E)\]
\[k' = (E'_e,0,E'_e \sin \theta'_e,-E'_e \cos \theta'_e)\]
**Structure Function $F_2$**

Electron-Quark scattering (spinless case)

\[
\frac{d\sigma(eq)}{dq^2} = \frac{4\pi\alpha^2}{q^4} e_q^2
\]

Rutherford scattering on pointlike target

\[
\frac{d\sigma(ep)}{dq^2} = \frac{4\pi\alpha^2}{q^4} [2e_u^2 + e_d^2] = \frac{4\pi\alpha^2}{q^4}
\]

With quark-quark interactions

\[
\frac{d\sigma(ep)}{dq^2} = \frac{4\pi\alpha^2}{q^4} [e_u^2 u(x) + e_d^2 d(x) + ...]
\]

\[
= \frac{4\pi\alpha^2}{q^4} \frac{F_2(x)}{x}
\]

**QPM:** Structure Function $F_2$ independent of $Q^2$
Scaling [SLAC 1972]

$F_2$ vs $Q^2 \,[\text{GeV}^2]$ for $x = 0.25$.
Scaling Violations [1990++]

Deuteron
- NMC
- SLAC
- BCDMS

F_2(x, Q^2) vs. Q^2 (GeV/c)^2

SLAC 1972

x = 0.008 (x 4.0)

x = 0.0125 (x 3.2)

x = 0.0175 (x 2.5)

x = 0.025 (x 2.0)

x = 0.035 (x 1.5)

x = 0.050 (x 1.2)

x = 0.070 (x 1.0)

x = 0.009 (x 7.5)

x = 0.11 (x 5.2)

x = 0.14 (x 3.7)

x = 0.18 (x 2.5)

x = 0.225 (x 1.7)

x = 0.275 (x 1.2)

x = 0.35 (x 1.0)

x = 0.50 (x 1.0)
DGLAP Evolution

\[ \frac{\partial}{\partial \log Q^2} \frac{q(x, Q^2)}{\bar{q}(x, Q^2)} = \frac{\alpha_s}{2\pi} \left( \begin{array}{c} p_{q/q} \left[ x, \gamma \right] p_{q/q} \left[ x, \gamma \right] \\ p_{q/q} \left[ x, \gamma \right] p_{q/q} \left[ x, \gamma \right] \end{array} \right) \times \left( \begin{array}{c} q(x, Q^2) \\ \bar{q}(x, Q^2) \end{array} \right) \]

\[ P \otimes f(x, Q^2) = \int_{y_{min}}^{y_{max}} P(y, Q^2) f(y, Q^2) \]
**F₂ at Low Bjorken-x**

[Pre-HERA Knowledge]

\[ \frac{2}{\log q^2} \left( \frac{q}{2} \right) = \frac{\alpha_s}{2\pi} \left[ \begin{array}{cc} p_{qg} & p_{gq} \\ p_{qg} & p_{gq} \end{array} \right] \otimes \left( \frac{q}{2} \right) \]

DGLAP: No prediction for the \(x\)-dependence of \(F₂\)

[except asymptotic behaviour]

A. De Rujula et.al. 1974

**Remark:** Accessing low \(x\) offers possibility to determine \(g(x,Q^2)\)

[see later]

**Measure!!**
### List of Fixed Target Experiments

[Mostly Pre-HERA]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Year</th>
<th>Reaction</th>
<th>Beam Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC - MIT</td>
<td>1968</td>
<td>ep, ed</td>
<td>4.5-20 GeV</td>
</tr>
<tr>
<td>CDHS, CHARM</td>
<td>&lt;1984</td>
<td>νµFe</td>
<td>&lt;260 GeV</td>
</tr>
<tr>
<td>FMMF</td>
<td>&lt;1988</td>
<td>νµ</td>
<td>&lt;500 GeV</td>
</tr>
<tr>
<td>CCFR</td>
<td>1979-1988</td>
<td>νµFe</td>
<td>&lt;600 GeV</td>
</tr>
<tr>
<td>BCDMS</td>
<td>1981-1985</td>
<td>μp, μd</td>
<td>100-280 GeV</td>
</tr>
<tr>
<td>EMC</td>
<td>&lt;1983</td>
<td>μp, μd</td>
<td>&lt;325 GeV</td>
</tr>
<tr>
<td>NMC</td>
<td>1986-1989</td>
<td>μp, μd</td>
<td>90-280 GeV</td>
</tr>
<tr>
<td>E665</td>
<td>1987-1992</td>
<td>μp, μd</td>
<td>90-470 GeV</td>
</tr>
<tr>
<td>NuTeV</td>
<td>1996-1997</td>
<td>νµFe</td>
<td>&lt;600 GeV</td>
</tr>
</tbody>
</table>

Electron energy limited by synchrotron radiation → Muon beam experiments
Different processes → Universality of parton density functions
Accessing Lower Bjorken-x

\[ Q^2 = s \times y \times y \]

**HERA Experiments**

\[ s \approx 10^5 \text{ GeV}^2 \]

**Fixed Target Experiments**

\[ s < 10^3 \text{ GeV}^2 \]

Accessing lower x at fixed \( Q^2 \) needs higher s

Fixed Target:

\[ s = 2M_p E_e \]

\[ s = 10^5 \text{ GeV} \]

\[ \Rightarrow E_e = 50 \text{ TeV} \]

ep-Collider:

\[ s = 4E_p E_e \]

\[ E_e = 30 \text{ GeV} \]

\[ E_p = 900 \text{ GeV} \]

\[ \Rightarrow s = 10^5 \text{ GeV} \]
The HERA Accelerator Complex

**Proton ring:**
- Energy*: 920 GeV
- Mag. Field: 4.682 T
- Current: ~ 100 mA

* before 1998: 820 GeV

**Electron ring:**
- Energy: 27.5 GeV
- Mag. Field: 0.164 T
- Current: ~ 40 mA

**General:**
- Energy in cms: 318 GeV
- Circumference: 6.3 km
- BX rate: 10.4 MHz
- Lumi: $1.5 \cdot 10^{31}$ cm$^{-2}$s$^{-1}$
View into the Tunnel
Luminosity

\[ N \equiv \mathcal{L} \cdot \sigma \]

\[ N = \sigma \int \mathcal{L} dt \]

\[ \sigma = N/L \]

Collider experiments:

\[ \Phi_a = \frac{\dot{N}_a}{A} = \frac{N_a \cdot n \cdot v}{U} = \frac{N_a \cdot n \cdot f}{A} \]

\[ \mathcal{L} = f \frac{n N_a N_b}{A} = f \frac{n N_a N_b}{4 \pi \sigma_x \sigma_y} \]

**HERA:**
- \( N_x \approx 10^{10} \)
- \( A \approx 0.01 \text{ mm}^2 \)
- \( n \approx 200 \)
- \( f \approx 50 \text{ kHz} \)
- \( \mathcal{L} \approx 10^{31} \text{ cm}^{-2}\text{s}^{-1} \)

\( N_a \): number of particles per bunch (beam A)
\( N_b \): number of particles per bunch (beam B)
\( U \): circumference of ring
\( n \): number of bunches per beam
\( v \): velocity of beam particles
\( f \): revolution frequency
\( A \): beam cross-section
\( \sigma_x \): standard deviation of beam profile in x
\( \sigma_y \): standard deviation of beam profile in y
The **H1 Detector**

1. Beam pipe & magnets
2. Central tracking chambers
3. Forward tracking
4. Electromagn. calorimeter
5. Hadronic calorimeter
6. Superconducting coil
7. Compensating magnet (PreUpgr.)
8. Helium cryogenics
9. Muon chambers
10. Instrumented iron
11. Muon toroid magnet
12. Backward calorimeter (SpaCal)
13. Plug calorimeter
14. Concrete shielding
15. Liquid argon cryostat
H1 detector in parking position
H1 Collaboration
Large $Q^2$ range

- Precision QCD
- Test of DGLAP evolution

Small $x$ range

- High parton densities
- Novel quantum system

Small $Q^2$ regime

- Non-perturbative QCD
- Confinement

Large CMS energy

- Electroweak Physics
- Search for new phenomena

HERA Kinematic Coverage

- H1
- ZEUS
- CDF/D0 Inclusive jets $\eta<0.7$
- D0 Inclusive jets $\eta<3$
- Fixed Target Experiments:
  - CCFR, NMC, BCDMS,
  - E665, SLAC