Physics at HERA

Summer Student Lectures
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Katja Krüger
Kirchhoff-Institut für Physik
H1 Collaboration
email: katja.krueger@desy.de
Overview

- Introduction to HERA
- Inclusive DIS & Structure Functions
  - formalism
  - HERA results
- High $Q^2$ & Electroweak Physics
- QCD: Jet Physics, Heavy Flavour Production
- Beyond the Standard Model
- (Diffraction)
Collider Types

$e^+e^-$
- clean initial and final state
- small background
- limited energy
- LEP (200 GeV)
- ILC (1 TeV)

$p^\pm p^\pm$
- high energy
- complicated final state
- large background
- Tevatron (2 TeV)
- LHC (14 TeV)

$ep$
- unique initial state
- electron as probe of proton structure
- two accelerators
- HERA (300 GeV)
HERA

H1

ZEUS

p 920 GeV  e 27.6 GeV
Collected Luminosity

- lumi upgrade in 2001
  - higher luminosity
  - $e$ polarization for H1 & ZEUS
  - detector upgrades
- in total $\sim 500 \text{ pb}^{-1}$ of high energy data collected per experiment
- last months devoted to low $p$ energy (460, 575 GeV)
ZEUS Detector

- tracking detector
- magnet coil
- calorimeter
- muon system
H1 Detector

- tracking detector
- calorimeter
- magnet coil
- muon system
Schematic View of the H1 Detector
Physics Topics at HERA

expected

- proton structure
  - structure functions
  - parton densities
- photon structure
- perturbative QCD
  - jets
  - $\alpha_s$
  - heavy quarks
- electroweak

not (so) expected

- exotics (beyond the standard model)
  - SUSY
  - leptoquarks
  - ...
- diffraction
$ep$ Scattering & Structure Functions
An $ep$ scattering event
The HERA Textbook Plots

H1 and ZEUS

\[ \sigma_{NC}(x,Q^2) x^2 \]

\( x = 0.06, i=21 \)
\( x = 0.00008, i=20 \)
\( x = 0.00013, i=19 \)
\( x = 0.00020, i=18 \)
\( x = 0.00032, i=17 \)
\( x = 0.0005, i=16 \)
\( x = 0.0008, i=15 \)
\( x = 0.0013, i=14 \)
\( x = 0.0020, i=13 \)
\( x = 0.0032, i=12 \)
\( x = 0.005, i=11 \)
\( x = 0.008, i=10 \)
\( x = 0.013, i=9 \)
\( x = 0.02, i=8 \)
\( x = 0.032, i=7 \)
\( x = 0.05, i=6 \)
\( x = 0.08, i=5 \)
\( x = 0.13, i=4 \)
\( x = 0.18, i=3 \)
\( x = 0.25, i=2 \)
\( x = 0.4, i=1 \)
\( x = 0.65, i=0 \)

Q^2 = 10 GeV^2

\[ x_f \]

\[ x_g (\times 0.05) \]

\[ x_S (\times 0.05) \]

\[ x_d \]

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Physics @ HERA
Rutherford Scattering

- first scattering experiment
  → existence of the nucleus

\[ \frac{d\sigma}{d\Omega} = \left( \frac{1}{4\pi\varepsilon_0} \frac{Z_1 Z_2 e^2}{4 E_{\text{kin}}} \right)^2 \frac{1}{\sin^4 \frac{\theta}{2}} \]

assumes
- Coulomb potential
- no spins
- no recoil
Elastic Electron Scattering

variables:
- \( q = k - k' \)
- \( Q^2 = -q^2 = 4 \frac{E}{E'} \sin^2(\Theta/2) \)
- \( E' = \frac{E}{1 + (2E/M)\sin^2(\Theta/2)} \)

\( \Rightarrow \) only one independent!

\[
\frac{d\sigma}{dQ^2} = \frac{4\pi \alpha^2 z^2}{Q^4} \left( \frac{E'}{E} \right)^2 \cos^2 \frac{\Theta}{2}
\]

Coulomb-Potential \( \sim 1/r \)

recoil

particles stays intact

mass \( M \), charge \( z \), spin 0

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Elastic Electron Scattering: Cross Section

- Mott Scattering: electron on a pointlike charged particle with spin 0
  \[ \left( \frac{d \sigma}{d Q^2} \right)_{\text{Mott}} = \frac{4 \pi \alpha^2}{Q^4} \left( \frac{E'}{E} \right)^2 \cos^2 \frac{\Theta}{2} \]

- Dirac Scattering: electron on a pointlike charged particle with spin \( \frac{1}{2} \)
  \[ \left( \frac{d \sigma}{d Q^2} \right)_{\text{Dirac}} = \left( \frac{d \sigma}{d Q^2} \right)_{\text{Mott}} \left[ 1 + 2 \tau \tan^2 \frac{\Theta}{2} \right] \quad \text{with} \quad \tau = \frac{Q^2}{4 M^2} \]

- electron on proton: „form factors“ needed:
  \[ \left( \frac{d \sigma}{d Q^2} \right)_{ep} = \left( \frac{d \sigma}{d Q^2} \right)_{\text{Mott}} \left[ \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1 + \tau} + 2 \tau G_M^2(Q^2) \tan^2 \frac{\Theta}{2} \right] \]
  \[ \rightarrow \text{protons are not pointlike!} \]
Electric Form Factor of the Proton

- describes the charge distribution in the proton (Fourier transform)
- measured:
  - $G_E(0) = 1$
  - $G_M(0) = 2.79$
  - $G_E(Q^2), G_M(Q^2) \propto \left(1 + \frac{Q^2}{0.71 \text{ GeV}^2}\right)^{-2}$
  - elastic scattering only import at low $Q^2$

from J.J. Murphy et al., "Proton form factor from 0.15 to 0.79 fm$^2$"
Inelastic Electron Scattering

variables:

- $q = k - k'$
- $Q^2 = -q^2$
- $s = (P + k)^2$
- $W^2 = (P + q)^2$
  $= M^2 + 2q \cdot P - Q^2$
- $y = q \cdot P / k \cdot P$

$\rightarrow$ two independent!

elastic: $W = M$

inelastic: $W > M$
Inelastic Electron Proton Scattering

- inelastic scattering: \( W > M_p \)
- ratio to Mott cross section nearly flat in \( Q^2 \)
Deep Inelastic Scattering (DIS)

- deep: $Q^2 > (M_p)^2$
- inelastic: $W > M_p$
- for HERA: $m_e, M_p \ll W$
  \[ s = 4 E_p E_e \]
  \[ Q^2 = 2 E_e E'_e (1 + \cos \theta_e) \]
  \[ y = 1 - \frac{E'_e}{E_e} \sin^2 \frac{\theta_e}{2} \]
  \[ W^2 = y s - Q^2 \]
- one more variable: $x = Q^2 / (2 P \cdot q) = Q^2 / ys$

$k' = (E'_e, 0, E'_e \sin \theta_e, E'_e \cos \theta_e)$

$k = (E_e, 0, 0, -E_e)$

$P = (E_p, 0, 0, E_p)$

attention $\theta_e = \pi - \Theta$
DIS: What is $x$?

$x$ can be interpreted as the momentum fraction of the struck parton of the proton:

\[
(q + xP)^2 = -Q^2 + 2x q \cdot P + (xP)^2 \\
(q + xP)^2 = (xP)^2 = (m_q)^2
\]

\[
x = \frac{Q^2}{2q \cdot P} = \frac{Q^2}{ys}
\]

inelastic proton scattering is scattering on a parton of the proton!
Structure Functions $F_1$ & $F_2$

- the DIS cross section can be written as

\[
\frac{d^2 \sigma}{dx \, dQ^2} = \frac{4 \pi \alpha^2}{Q^4} \frac{1}{x} \left[ (1-y) \, F_2(x, Q^2) + \frac{y^2}{2} \, 2 \, x \, F_1(x, Q^2) \right] \\
= \frac{4 \pi \alpha^2}{Q^4} \frac{1}{x} \frac{E'}{E} \left[ F_2(x, Q^2) \cos^2 \frac{\Theta}{2} + \frac{Q^2}{2 \, x^2 \, M_p^2} \, 2 \, x \, F_1(x, Q^2) \sin^2 \frac{\Theta}{2} \right]
\]

- comparison with Dirac formula

\[
\left( \frac{d \sigma}{d \, Q^2} \right)_{\text{Dirac}} = \frac{4 \pi \alpha^2}{Q^4} \left( \frac{E'}{E} \right)^2 \left[ \cos^2 \frac{\Theta}{2} + \frac{Q^2}{2 \, M^2} \sin^2 \frac{\Theta}{2} \right]
\]

$\rightarrow F_2$ corresponds to electric field of the parton
$\rightarrow F_1$ corresponds to spin of the parton
Parton Spin

- parton spin $\frac{1}{2}$: \[ 2 \times F_1 = F_2 \] (Callan Gross)
- parton spin 0: \[ 2 \times F_1 = 0 \]

from P. Schmüser, „Feynman-Graphen und Eichtheorien für Experimentalphysiker“
Scaling: $F_2$ independent of $Q^2$

SLAC 1972

independent of $Q^2$, we always see the same partons (=quarks)
(Naive) Quark Parton Model

- proton consists of 3 partons, identified with the QCD quarks
- during the interaction proton is „frozen“
- electron proton scattering is sum of incoherent electron quark scatterings
- proton structure is defined by parton distributions

\[ F_2(x, Q^2) = x \sum e^2_q q(x) \]
The HERA Textbook Plots

H1 and ZEUS

\[ \sigma_{\text{NC}}(xQ^2\times x^2) \]

- HERA I NC e+p
- Fixed Target
- HERAPDF1.0

quarks ✓
How does $F_2(x)$ look like?
How do we expect $F_2(x)$ to look like?
How does $F_2(x)$ look like?

what happens at low $x$?

from Povh et al., „Teilchen und Kerne“
Scaling Violations

at smaller & larger x, the amount of quarks depends on $Q^2$. 
Parton Evolution

- number of partons changes with $Q^2$
- $Q^2$ can be interpreted as resolving power: $Q^2 \propto (\hbar/\lambda)^2$

small $Q^2$:
- many partons with large $x$
- (nearly) no partons at low $x$

large $Q^2$:
- less partons with large $x$
- more partons at low $x$
Scaling Violations

large $x$: quarks radiate gluons, so the studied $x$ decreases
$\rightarrow F_2$ decreases with increasing $Q^2$

small $x$: gluons split into seaquarks, so more quarks become visible
$\rightarrow F_2$ increases with increasing $Q^2$
DGLAP Evolution Equations

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

- \( Q^2 \) dependence of quark densities \( q(x, Q^2) \) and gluon density \( g(x, Q^2) \) is predicted
- no prediction for the \( x \) dependence \( \rightarrow \) initial condition needed
HERA Kinematic Range

- HERA Standard DIS
- HERA ZEUS BPT
- HERA Shifted Vertex
- Fixed Target Experiments

Before HERA

New

before HERA
**F₂ vs. Q²**

- HERA data cover huge range:
  - 5 orders in Q² and
  - 4 orders in x

- approximate scaling at large x

- clear scaling violations at small x
$F_2$ vs. $Q^2$: example bins

- clear scaling violations at small $x$
- approximate scaling at large $x$
How does $F_2(x)$ look like at low $x$?
strong rise towards low $x$, steepness rising with $Q^2$
DGLAP Evolution Equations

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

- $Q^2$ 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 2 - 7 GeV$^2$):

$$x \ q(x, Q_0^2) = A \ x^B (1 - x)^C \left[ 1 + D \ x + E \ x^2 + F \ x^3 \right]$$

→ 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 (ZEUS): $u_{v}, d_{v}, \text{Sea}, \bar{d} - \bar{u}$
- distinguish $u$-type and $d$-type quarks (H1):
  
  $$U = u + c, \quad D = d + s ( + b)$$  
  $$\bar{U} = \bar{u} + \bar{c}, \quad \bar{D} = \bar{d} + \bar{s} ( + \bar{b})$$  
  $$\rightarrow u_{v} = U - \bar{U}, \quad d_{v} = D - \bar{D}$$
Combined H1 & ZEUS Parton Density

combination of data from H1 and ZEUS gives big improvements!
Longitudinal Structure Function $F_L$

- Callan-Gross relation $2 \times F_1 = F_2$ only true in naive Quark-Parton-Model
- the longitudinal structure function $F_L$ is defined as $F_L = F_2 - 2 \times F_1$
- $F_L$ is directly proportional to the gluon density
- for a measurement of $F_L$ one needs data at the same $x$ and $Q^2$, but different $y$

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

- only possible with different $s$ because $Q^2 = xys$
  - measure at different beam energies!
Longitudinal Structure Function $F_L$

$$Q^2 = 25 \text{ GeV}^2$$

$$\sigma_r = \frac{x Q^4}{2 \pi \alpha^2} \frac{1}{Y_+} \frac{d^2 \sigma}{dx \, dQ^2}$$

$$= F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

with $Y_+ = 1 + (1 - y)^2$

- linear expression in $y^2/Y_+$
- use linear fits in $y^2/Y_+$ and determine $F_L$ from slope
Longitudinal Structure Function $F_L$

- **ZEUS**: simultaneous determination of $F_2$ and $F_L$
- consistent with PDF fit to $F_2$
- most precise information on gluon still from scaling violations
„The“ HERA Textbook Plots

H1 and ZEUS

$\sigma_{NC}(Q^2 \times x)$

$Q^2 / \text{GeV}^2$

$1 \times 10^{-6}$

$1 \times 10^{-3}$

$1 \times 10^{-1}$

$1 \times 10^{1}$

$1 \times 10^{3}$

$1 \times 10^{5}$

$1 \times 10^{7}$

$\times$ 0.0005, $i = 16$

$\times$ 0.001, $i = 14$

$\times$ 0.0015, $i = 13$

$\times$ 0.002, $i = 12$

$\times$ 0.0025, $i = 11$

$\times$ 0.003, $i = 10$

$\times$ 0.0035, $i = 9$

$\times$ 0.004, $i = 8$

$\times$ 0.0045, $i = 7$

$\times$ 0.005, $i = 6$

$\times$ 0.006, $i = 5$

$\times$ 0.007, $i = 4$

$\times$ 0.008, $i = 3$

$\times$ 0.009, $i = 2$

$\times$ 0.01, $i = 1$

$\times$ 0.011, $i = 0$

H1 and ZEUS

$Q^2 = 10 \text{ GeV}^2$

$\times u_x$

$\times d_x$

$\times (0.05)$

exp. uncert.

model uncert.

parametrization uncert.

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