Recent Results from HERA

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\[ \sqrt{s} = 320 \text{ GeV} \]
180 bunches
crossing 96 ns \((v \sim \text{LHC}/4)\)

- HERA 1: 1992-2000 \sim 120 \text{ pb}^{-1}/\text{expt}
  - Luminosity upgrade (x3)
  - Polarised electrons/positrons
The harvest H1+ZEUS 2*0.5 fb⁻¹

Status: 1-July-2007

End of collisions: June 30, 2007

Low E p Runs

~200 pb⁻¹ e⁺p
~300 pb⁻¹ e⁻p

HERA-2

HERA-1

√s = 319 GeV

√s = 300 GeV
Deep-Inelastic Scattering

Kinematics reconstructed using measurements \((E;\theta)\)

lepton\((\text{NC})\)+hadrons\((\text{NC/CC})\)

- \[ Q^2 = -q^2 = -(k - k')^2 \]
  - virtuality/resolving power
- \[ x = \frac{Q^2}{2P \cdot q} \]
  - Bjorken scaling variable, momentum fraction of the scattered parton
- \[ y = \frac{q \cdot P}{k \cdot P} \]
  - inelasticity

Related by \( Q^2 = xys \)

Resolved dimension [fm]

\[ \delta \sim \frac{200 \text{ MeV}}{Q} \]

- Rutherford
- Hofstadter
- SLAC \( ep \)
- CERN \( \mu,\nu N \)
- HERA

Year
The proton map in the kinematic plane

Non-perturbative QCD, transition

Highest collision energy
EW+searches

Use the final state processes (exclusive)
for more on QCD, for finer phase space
QCD evolution, but also beyond
HERA is a clean QCD laboratory: heavy flavours, low x, diffraction etc.
The menu

Structured around the three main directions of the HERA program:

- **Proton Structure**
  - Structure Functions and PDF’s
  - Heavy flavours

- **QCD studies**
  - jets and $\alpha_s$
  - inclusive diffraction

- **High Energy Frontier**
  - signatures and searches

Many other exciting subjects not covered:
  exclusive processes, particles production, low $x$ etc.
Cross sections, structure functions, partons

\[ \tilde{\sigma}_{NC}^{\pm} = \frac{d^2 \sigma_{NC}^{e \pm p}}{dx dQ^2} \frac{x Q^4}{2\pi \alpha^2 Y_+} = \tilde{F}_2 - \frac{y^2}{Y_+} \tilde{F}_L + \frac{Y_-}{Y_+} x \tilde{F}_3, \quad Y_\pm = 1 \pm (1 - y)^2 \]

**Leading order picture of the proton**

\[ F_2 \begin{bmatrix} F_2, F_2^{\gamma Z}, F_2^Z \end{bmatrix} = x \sum_q \left[ e_q^2, 2 e_q v_q, v_q^2 + a_q^2 \right] (q + \bar{q}) \quad \text{quarks} \]

\[ F_3 \begin{bmatrix} xF_3^{\gamma Z}, xF_3^Z \end{bmatrix} = 2x \sum_q \left[ e_q a_q, v_q a_q \right] (q - \bar{q}) \quad \text{(valence) quarks} \]

\[ F_L \sim x\alpha_s g \quad \text{gluons} \]

**CC: similar decomposition, but different quarks combinatons accessed**

flavour sensitive (separate in e+p/e-p)

**CC+NC Double Differential cross sections: inputs for PDF's fits**
Cross section combination

Coherent treatment of experimental effects in the average procedure

\[ \chi^2(\{F_2^{true}\}, \{\alpha\}) = \sum_i \left[ \frac{F_2^{true} - \left( F_2^i + \sum_j \frac{\sigma_{F_2}^i}{\sigma_{\alpha_j}^2} \alpha_j \right)}{\sigma_{F_2}^2} \right]^2 + \sum_j \frac{\alpha_j^2}{\sigma_{\alpha_j}^2}. \]

- 1153 individual NC and CC measurements are “averaged” to 554 unique points
  -- $\chi^2$/dof = 510 / 599

Improvements beyond the naively-expected $\sqrt{2}$: the cross calibration
The reduced cross section with novel precision

H1 and ZEUS Combined PDF Fit

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

Coherent data sets combined: vast coverage of the proton “map”
dramatic increase in precision
The common fit of the combined data

Partons parametrized at $Q_0^2 = 4\text{ GeV}^2$ (Data $Q^2>3.5\text{ GeV}^2$)

Experimental+Model uncertainties taken into account

Errors of the fit estimated using $\Delta\chi^2=1$

Improvement in precision is visible
The common fit of the combined data

Improvement in precision most notably at low x remain also at high $Q^2$ (LHC domain)

HERAPDF 0.1: pdf’s predictions using a coherent and precise data set => LHC predictions
Predictions for W/Z boson production at LHC

**Without HERA Data**

**HERA I data (one experiment)**

**HERA I combined**

**HERAPDF 0.1**

Impressive progress: from 5-6% to ~3%

Much more data to be included
(low Q2, bulk, HERA II data high x/Q^2)

A.Cooper-Sarkar and E.Perez in parallel session
Longitudinal structure function $F_L$

$$R = \frac{\sigma_L}{\sigma_T} = \frac{(F_2 - 2x F_1)}{2x F_1} = \frac{F_L}{2x F_1}$$

$= 0$ for spin ½ partons
(Callan-Gross)

Fundamental form factor of the proton

Test QCD

Proportional to the gluon, important for PDF's

Discriminate between theoretical approaches

C. White, R. Thorne, 0706.2609 [hep-ph]
Indirect Determination

\[ \sigma_r = F_2(x, Q^2) - \frac{y^2}{Y_+} \cdot F_L(x, Q^2) \]

see bending at high y
assume F2 -> extract FL

\( Q^2 = 200 \text{ GeV}^2 \)

\[ F_2 \sim F_L \]

data

\( y = 0.75 \)

\( Q^2 \text{ / GeV}^2 \)

\( F_L \text{ published by H1 making assumptions on } F_2 \)

H1 Collaboration

H1 Low y fit

H1 PDF 2000
Direct $F_L$ measurement

Method:

$$\sigma \sim F_2(x, Q^2) + f(y) \ F_L(x, Q^2)$$

keep $x, Q^2$ constant, vary $y$: $y_s = y's' = Q^2/x$

Vary $s$: Special Runs $E_p = 460, 575$ GeV

$$F_L \sim C(y) \ast \left( \sigma(E_p^1) - \sigma(E_p^2) \right)$$

NB: At low $E_p$, same $(x, Q^2)$ and high $y$ means lower energy of the detected electron

Have to fight the background from the hadronic final state (mostly from the photoproduction)

$$y \sim \frac{E_e - E_e^0}{E_e}$$

high $y = low E_e$
The low energy runs

New optics, few days switching time:
Impressive achievement of HERA crew!

\[ \mathcal{L}_s(E) \sim \gamma(E)^2 \]

\[ \mathcal{L}_s(460) = \frac{1}{4} \mathcal{L}_s(920) ! \]
The present measurements

<table>
<thead>
<tr>
<th>H1:</th>
<th>ZEUS:</th>
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</thead>
<tbody>
<tr>
<td>$E_p=920,575,460$ GeV</td>
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</tr>
<tr>
<td>$E_e&gt;3.4$ GeV</td>
<td>$E_e&gt;6$ GeV</td>
</tr>
<tr>
<td>$y&lt;0.9$</td>
<td>$y&lt;0.8$</td>
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</tbody>
</table>

- Medium $Q^2$: 12 – 90 GeV$^2$ submitted to PLB
- High $Q^2$: 90-800 GeV$^2$ preliminary measurements combined
- Low $Q^2$: 5-12 GeV$^2$ (analysis in progress)

More details in the parallel session
Here only $F_L$ results
The $F_L$ measurement

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

- $E_p = 920 \text{ GeV}$
- $E_p = 575 \text{ GeV}$
- $E_p = 460 \text{ GeV}$

- $\sigma_r^{920} \text{ H1 PDF 2000}$
- $\sigma_r^{575} \text{ H1 PDF 2000}$
- $\sigma_r^{460} \text{ H1 PDF 2000}$

- $F_2 \text{ H1 PDF 2000}$
Comparison with target data and indirect determinations

$Q^2$ range of the first publication "medium $Q^2$"
Proton's charm

A lot of analysis improvements still ahead
Experimental program in development

Precision to 5% (or less) possible
Test QCD, cross-check the gluon

HERA $F_2^{cc}$

$\gamma^* p \rightarrow e^+ D^* + X$

$N(D^*)$: 2181 $\pm$ 83
2D $S_{DC} > 3$

HERA II

$e p \rightarrow e + D^* + X$

$Gauss^{med} + p1$

$Gauss^{med} + p1$

H1 HERA I (D^*)
H1 (prel.) HERA I+II (VTX)
ZEUS HERA I (D^*)
ZEUS HERA I (D^*, D^0, D_s^0)
ZEUS (prel.) HERA II:
$D^0 \cdot D^*$

NLO QCD:
CTEQ5F3
MRST2004FF3

$Q^2 (GeV^2)$

$F_2$: $x = 0.00003 \times 4^{20}$
$x = 0.00005 \times 4^{15}$
$x = 0.00007 \times 4^{18}$
$x = 0.00013 \times 4^{17}$
$x = 0.00018 \times 4^{16}$
$x = 0.0003 \times 4^{15}$

$x = 0.00035 \times 4^{14}$
$x = 0.0005 \times 4^{13}$
$x = 0.0006 \times 4^{12}$
$x = 0.0008 \times 4^{11}$
$x = 0.0012 \times 4^{10}$

$x = 0.0015 \times 4^{9}$
$x = 0.002 \times 4^{7}$

$x = 0.003 \times 4^{6}$
$x = 0.004 \times 4^{5}$

$x = 0.006 \times 4^{4}$
$x = 0.008 \times 4^{4}$

$x = 0.012 \times 4^{3}$

$x = 0.02 \times 4^{3}$

$x = 0.03 \times 4^3$
More charm with HERA II data

**DIS**

- **D* in DIS**
  - H1 Preliminary HERA II
  - H1 data (prel.)
  - HVQDIS (MRST2004FF3nlo)
  - HVQDIS (CTEQ5f3)

- **p_T(D*) [GeV]**
  - $5 < Q^2 < 100$ GeV$^2$
  - $0.02 < y < 0.7$
  - $\ln |D^*| < 1.5$

**Photoproduction**

- **D* in Photoproduction**
  - H1 Preliminary HERA II
  - H1 data (prel.)
  - FMNR (CTEQ5f3)

- **p_T(D*) [GeV]**
  - $Q^2 < 2$ GeV$^2$
  - $100 < W_{pT} < 265$ GeV
  - $p_T(D^*) > 1.8$ GeV
  - $|\eta(D^*)| < 1.5$

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**NLO**

**LO**

- **sensitive to PDFs!**

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**best description by massless Pythia**
Proton's beauty

- HERA II data now investigated
- Precision is comparable with theory spread
- A significant improvement (more than a factor of 2) expected after final analyses
Recent precise measurements (HERA II) in agreement with theory

Precision to be improved with HERA II data
150 < Q^2 < 15000 GeV^2,
0.2 < y < 0.7,

Jets in DIS

Clear improvement in precision, bright future for QCDs studies, gluon and $\alpha_s$
**Strong coupling: a sub-percent perspective?**

\( \alpha_s \) from Jet Cross Sections

**H1 Preliminary**
- \( \alpha_s(\mu = Q) \) for \( Q^2 < 100 \text{ GeV}^2 \) (HERA I)
- \( \alpha_s(\mu = Q) \) for \( Q^2 > 150 \text{ GeV}^2 \) (HERA I+II)
- Combined \( \langle \alpha_s(\mu) \rangle \) (incl. 2-, 3-jet) from \( Q^2 > 150 \text{ GeV}^2 \)

\( \alpha_s \) (NLO uncertainty)

**H1 high \( Q^2 \) jet multiplicities**
- H1prelim-08-031

**H1 low \( Q^2 \) incl. jets**
- H1prelim-08-032

**H1 norm. incl. jets**

**ZEUS incl. jets**

**HERA comb. 2007 incl. jets**
- H1prelim-07-032/ZEUS-prel-07-025

**ALEPH 4-jet rate**

**Bethke**

**H1/ZEUS combination (2007):**
\[ \alpha_s = 0.1198 \pm 0.0019\text{(exp.)} \pm 0.0026\text{(theory)} \]

**NEW H1: high \( Q^2 \):**
\[ \alpha_s = 0.1182 \pm 0.0008\text{(exp.)}^{+0.0041}_{-0.0031}\text{(scale)} \pm 0.0018\text{(pdf)} \]

**NNLO theory is an absolute necessity now**

**Scales variation arbitrariness? Theory errors?**
Hard Diffraction at HERA

\[ \sim 10\% \text{ of NC DIS events have gap between } p \text{ and central tracks. Measure gap or detect } p \text{ with LPS/VFPS} \]

\[
\frac{d\sigma_{NC}}{dx_{IP}dtd\beta dQ^2} \propto \frac{1}{Q^4} F_2^{D(4)}(x_{IP}, t, \beta, Q^2)
\]
H1 and ZEUS $M_N<1.6$ GeV

H1 and ZEUS corrected to the same phase space
Ready for combination, more data to come

M. Ruspa in parallel session
The searches for new physics

**Neutral Current (ep → eX)**

- $s^{3/2} = 319$ GeV
- $d/dQ^2 (pb/GeV^2)$
- $Q^2 (GeV^2)$
- $d^2/dQ^2 (pb/GeV^2)$

**H1 Quark Radius Limit HERA I+II (435 pb$^{-1}$)**

- $Q^2 (GeV^2)$
- $d^2/dQ^2 (pb/GeV^2)$

- Quark radius: $< 0.74 \times 10^{-18} m$

**Leptoquark Search, HERA I+II**

- $H1 e^p (449 pb^{-1})$
- $H1 e^p (428 pb^{-1})$

- Mass peaks?

**R**

- $R_{quark} < 0.62 \times 10^{-18} m$ (ZEUS)
- $R_{electron} < 0.28 \times 10^{-18} m$ (LEP)
Multileptons in photon-photon collisions

Measure elastic and inelastic di-leptons in photon-photon collisions

Search for high mass di-leptons

H1: 0.46 fb⁻¹
Isolated leptons+$P_T^{miss}$

Isolated electron

Hadronic system ($X$)

$P_T^X > 25$ GeV

<table>
<thead>
<tr>
<th>Source</th>
<th>Data/SM</th>
<th>$N_{Data}$</th>
<th>$N_{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>0.29 fb$^{-1}$</td>
<td>17/7.1±0.9</td>
<td>(2.9σ)</td>
</tr>
<tr>
<td>ZEUS</td>
<td>0.29 fb$^{-1}$</td>
<td>6/7.5±1.1</td>
<td></td>
</tr>
<tr>
<td>H1+ZEUS</td>
<td>0.58 fb$^{-1}$</td>
<td>23/14.6±1.9 (1.8σ)</td>
<td></td>
</tr>
</tbody>
</table>

Anomaly at large $P_T^X$ (H1) unsolved
Large statistics to measure and investigate
$W$ production in $ep$ collisions
General Searches

- Search for isolated particles at high $P_T$
- Electrons, Photons, Muons, Hadronic Jets, Neutrinos

- Unique phase space:
  - $P_T > 20$ GeV
  - $10^\circ < \theta < 140^\circ$

- Investigate Mass and $\Sigma P_T$

- Statistical Analysis (search for deviations)

New result
Full HERA II
Outlook

60% of the data sample in the last 18 (running) months

+ brand new physics capabilities: polarisation, trigger, tracking

Analytical progress

- HERA I
- HERA II
- upgrade
- analysis in progress

Proposal approval

Startup

Time / Years

Integrated Luminosity

900
800
700
600
500
400
300
200
100

1981 1984
Conclusions

HERA data is a (full) gold mine:
proton map, QCD laboratory, energy frontier searches

• Beginning of the precision era: final analyses in progress
  – Improvement in experimental precision: alignements, calibrations
  – significant progress in all HERA physics subjects expected in the next years.

• H1/ZEUS combinations => one step further in the precision
  – new inclusive combined data/fit display significant improvement in W/Z predictions for LHC
  – other subjects/data in the “combination pipeline”

• Results from HERA will stay for long
  – proton structure, QCD ...

• Input to LHC is essential and perspectives look brilliant!
Backup
Form of the PDF parametrization at $Q_0^2$

$$xf(x) = A x^B (1 - x)^C (1 + D x + E x^2 + F x^3 ... )$$

### The number of parameters for each parton has been optimized

<table>
<thead>
<tr>
<th>PDFs fitted: gluon, $u_v$, $d_v$, $U_{\bar{d}} = u_{\bar{d}} + c_{\bar{d}}$, $D_{\bar{d}} = d_{\bar{d}} + s_{\bar{d}} + b_{\bar{d}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimization means starting without D,E,F parameters and adding parameters until there is no further $\chi^2$ advantage</td>
</tr>
</tbody>
</table>

Sea flavour break-up at $Q_0$: $s = fs*D$, $c = fc*U$, $AU_{\bar{d}} = (1-fs)/(1-fc)AD_{\bar{d}}$

$fs = 0.33D$ ($s=0.5d$), $fc = 0.15U$ consistent with dynamical generation

- $mc=1.4$ GeV mass of charm quark
- $mb=4.75$ GeV mass of beauty quark

Zero-mass variable flavour number heavy quark scheme (for now)

- $Q_0^2 = 4$ GeV$^2$ input scale
- $Q_{\text{min}}^2 = 3.5$ GeV$^2$ minimum $Q^2$ of input data

- $\alpha_s(Mz) = 0.1176$ PDG2006 value

Renormalization and factorization scales = $Q^2$
Model uncertainties: to be added into the total PDF uncertainty

- \( m_c \) 1.3 \( \rightarrow \) 1.55 GeV variation of mass of c quark
- \( m_b \) 4.3 \( \rightarrow \) 5.0 GeV variation of mass of b quark
- \( f_s \) 0.25 \( \rightarrow \) 0.40 variation of strange sea fraction at \( Q_0^2 \)
- \( f_c \) 0.10 \( \rightarrow \) 0.20 variation of charm sea fraction at \( Q_0^2 \)
- \( Q_0^2 \) 2.0 \( \rightarrow \) 6.0 \( GeV^2 \) variation of starting scale

Model variations: to be compared with our results

Variation of \( \alpha_s(M_z) \) 0.1156 \( \rightarrow \) 0.1196

Variation of form of parametrization

Slide from A. Cooper-Sarkar (DIS2008)