Recent Results from HERA

Measurements of Proton Structure at Low $Q^2$

The High $Q^2$ regime Neutral and Charged Current Processes

QCD: Partons in the Proton, Jets and $\alpha_s$

First Polarised Measurements from HERA

Heavy Quark Structure Functions and Jets

Searches for new physics

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Introduction

- HERA is world's first and only ep collider
- Collision energy $\sqrt{s}=320$ GeV
- Can collide $e^+$ or $e^-$ with longitudinal polarisation
- Enormous impact on world parton distribution functions
- Tests EW sector of Standard Model
- Charm factory
- Many possible SM extensions show up at HERA

Will only show a personal selection of a few of the hundreds of results. Many important topics skipped altogether
• 5 fold lumi increase achieved by focusing magnets and higher beam currents
• Slow start up 2002-03
• Problems with high beam related backgrounds
• Now solved. Best ever HERA performance
• Looking forward to 2006-07 run
Deep Inelastic Scattering

HERA collides e and p

Study strong, electromagnetic & weak forces through Deep Inelastic Scattering

At fixed $\sqrt{s}$: two kinematic variables:

\[ x \text{ & } Q^2 \]

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

\[ Q^2 = \text{“resolving power” of probe} \]

High $Q^2$: resolve $1/1000^{th}$ size of proton

$x = \text{momentum fraction of proton carried by quark}$

HERA: $\sim 10^{-6} - 1$
Neutral and Charged Current Processes

\[
\frac{d\sigma_{NC}^{\pm}}{dx dQ^2} \approx \frac{e^4}{8\pi x} \left[ \frac{1}{Q^2} \right]^2 \left[ Y_+ \tilde{F}_2^+ + Y_- x \tilde{F}_3^+ - y^2 \tilde{F}_L^+ \right]
\]

\[
\frac{d\sigma_{CC}^{\pm}}{dx dQ^2} \approx \frac{g^4}{64\pi x} \left[ \frac{1}{M_w^2 + Q^2} \right]^2 \left[ Y_+ \tilde{W}_2^\pm + Y_- x \tilde{W}_3^\pm - y^2 \tilde{W}_L^\pm \right]
\]

\[
\tilde{F}_2 \propto \sum (xq_i + x\overline{q}_i)
\]

**Dominant Contribution**

\[
x\tilde{F}_3 \propto \sum (xq_i - x\overline{q}_i)
\]

**Contributes when \( Q^2 \approx M_Z^2 \)**

\[
\tilde{F}_L \propto \alpha_s \cdot xg(x, Q^2)
\]

**Contributes only at high \( y \)**

Similarly for \( W_2^\pm, xW_3^\pm \) and \( W_L^\pm \):

\[
\tilde{\sigma}_{NC} = \frac{Q^2 x}{2\alpha\pi^2} \frac{1}{Y_+} \frac{d^2\sigma}{dx dQ^2}
\]

\[
\tilde{\sigma} = \tilde{F}_2 \quad \text{when} \quad \tilde{F}_L \equiv x\tilde{F}_3 \equiv 0
\]

\[\text{Modified at high } Q^2 \text{ by } Z \text{ propagator} \]

\[Y_\pm = 1 \pm (1 - y)^2\]
Conventional QCD evolution only tells us $Q^2$ dependence

$x$ dependence must come from data

Method:

Measure cross sections

Fit data - extract $x$ dep. of partons

HERA PDFs extrapolate into LHC region

LHC probes proton structure where gluon dominates (gluon collider)

HERA data crucial in calculations of new physics & measurements at LHC
F$_2$ dominates cross-section

Range in $x$: 0.00001 - 1

Range in $Q^2$ ~1 - 30000 GeV$^2$

Measured with ~2-3% precision

Directly sensitive to sum of all quarks and anti-quarks

Indirectly sensitive to gluons via QCD radiation - scaling violations
At high Q2 NC cross sections for $\epsilon^+$ and $\epsilon^-$ deviate

\[ \bar{\sigma}_{NC}^\pm \sim \widetilde{F}_2 \pm \frac{Y}{Y_+} x\widetilde{F}_3 \]

Subtract NC positron from electron cross section

HERA confirm valence quark structure

Errors dominated by stat. error of e- sample

HERA II e- run 2005-06 x10 in stats

Much better precision
Charged current process provides sensitivity to quark flavour

Cross sections small due to large $W$ mass in propagator

At high $x$ (low $y$) lepton charge separates $u$ from $d$

\[ \sigma_{cc}^+ \approx x \left[ \bar{u} + \bar{c} + (1 - y)^2 (d + s) \right] \]

\[ \sigma_{cc}^- \approx x \left[ u + c + (1 - y)^2 (\bar{d} + \bar{s}) \right] \]
• Cross sections measured over 3 orders of magnitude in $Q^2$

• CC cross section suppressed at low $Q^2$ by $W$ propagator

• At high $Q^2$ NC+CC cross sections comparable - electroweak unification
Extraction of light quark couplings to Z

- Take NC+CC cross sections and fit with extra parameters
- H1 data competitive with world's best
- Standard Model looks in good shape so far
Jet Cross Sections

- Many different measurements in DIS+photoproduction
- Precision of few % achieved over much of phase space
- Good agreement with NLO QCD
- Used to measure $\alpha_s$ from jets alone or in a QCD fit
NLO QCD Fits

PDFs parameterised at starting scale $Q_0^2$ and use DGLAP to evolve to higher $Q^2$

$$xPDF(x, Q_0^2) = Ax^b (1-x)^c (1 + dx + e\sqrt{x} + fx^2 + gx^3)$$

parameters $A,b,c,d,e,f$ optimised in fit for each PDF

some parameters constrained by sum rules e.g. momentum sum = 1

$$\int u_v \, dx = 2 \quad \int d_v \, dx = 1$$
- ZEUS also uses jets to extract PDFs without external input.
- H1/ZEUS broadly agree but some differences at medium $x$.
- Reasonable agreement with MRST global fit.
- Errors still large on $d$ and $g$ at high $x$.
\( \alpha_s \) from NLO QCD fits to DIS inclusive and jet data

**H1:** 0.1150 ±0.0017(exp) ±0.0008(model)
\[ ±0.005 \text{ (scale)} \]

**ZEUS:** 0.1166 ±0.0008(unc) ±0.0032(corr)
\[ ±0.0036(\text{norm}) ±0.0018(\text{model}) \]
\[ ±0.004 \text{ (scale)} \]

- Experimental errors competitive with world average

- Largest error from renormalisation scale uncertainty (changed by factor 4 H1, 2 ZEUS)

- NNLO analysis should reduce the scale uncertainty by factor 2-4
- Electron beam naturally transversely polarised
- Spin Rotators at IP give longitudinal polarisation
- Polarimeters provide independent polarisation measurements
No RH charged currents in SM. Expect a linear dependence

- **First Measurement of helicity dependence of** $e^p \rightarrow \nu X$

- **Expect a linear dependence from SM**

- **ZEUS+H1 measurements in agreement + with SM**

  Deviation from straight line means new physics independent of all SM parameters!
Measurement of $F_{2}^{c\bar{c}}$ and $F_{2}^{b\bar{b}}$

Method 1: $D^{*}$

- Access charm by $c \rightarrow D^{* \pm} \rightarrow K^{\pm} \pi^{\pm} \pi^{\mp}$
- Correct for branching fractions and unseen phase space (low $P_T$ of $D^{*}$)
- Only used for $F_{2}^{c\bar{c}}$

- Use $S=DCA/\sigma(DCA)$ of track to vertex
- Make use of silicon tracker
- Minimal extrapolation needed to extract $F_{2}^{c\bar{c}}$ and $F_{2}^{b\bar{b}}$
Semi-inclusive measurements

$F_{2}^{c \bar{c}}$ from $D^*$ and displaced track methods

Measured over wide kinematic range

Good agreement H1/ZEUS

Good agreement both methods

Good agreement with SM
Semi-inclusive measurements

\[ F_2^{b\bar{b}} \] from displaced tracks only

- First measurement of \( F_2^{b\bar{b}} \)

- Good agreement with SM
  - no evidence for excess

- Agreement also good with different QCD models (massive/massless/VFNS) + PDFs

Large difference CTEQ+MRST at low \( Q^2 \)
c+b jets in photoproduction +DIS

- Charm jets good agreement with SM
- Many measurements of b production in DIS + photoproduction
- In DIS data ok within differences in QCD parameterisations
- Excess seen in $\gamma p$. 

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Pentaquarks?

Observations by one experiment not confirmed by other
Many searches performed for SUSY R parity violating models
HERA has world's best limits in large areas of phase space
H1 Events with Isolated e or $\mu$ and missing $P_T$

Excess of events seen in $e^+p$
HERA I and HERA II data for H1

Events at high hadronic $P_T$
No excess seen in ZEUS HERA I
or H1 $e^-p$

Await ZEUS HERA II and 2006-2007 data to see if new physics
Summary

Inclusive measurements from HERA greatly add to our understanding of proton structure. Essential for LHC physics.
- Parton distribution functions have errors of a few % over most of the $x$ range.
- HERA measurements have achieved a very competitive measurement of $\alpha_s$.
- First measurements of polarised CC cross section consistent with a linear dependence as in SM.
- Semi-inclusive charm and bottom show we have a good understanding of QCD and the PDFs.
- Many searches underway looking for physics beyond the Standard Model.