HERA proton structure measurements

International Workshop on Physics with Positrons at Jefferson Lab

JPos17

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Outline

- Discussion of the HERA collider and detectors
- Measurements of inclusive DIS
- A few other selected HERA measurements

(Attempts are made to connect with JLEIC on some slides)
The HERA collider

- So far the only ep collider, operated 1992-2007
- 920 x 27.5 GeV (√s=318 GeV)
- Two collider experiments, H1 and ZEUS
- Integrated Luminosity: 
  \(~2\times0.5 \text{ fb}^{-1}\)
- e^+p and e^-p data

Two collider experiments: H1 and ZEUS

Angular coverage with EM+had calorimeters to |\eta_{lab}|<4
Tracking in the central region |\eta_{lab}|<2
HERA compared to other machines

- At construction time: a machine at the energy frontier ($E_p \approx$Tevatron, $E_e \approx \frac{1}{2}$ LEP)
- Detectors designed for discoveries (e.g. leptoquarks or excited e), less so for low $P_T$ physics
- Luminosity $1.5 \times 10^{31}$ cm$^{-2}$s$^{-1}$ (Upgrade in 2001-2002: factor 5 improvement)
- Lepton beam polarisation by Sokolov-Ternov effect
The HERA detectors H1 and ZEUS

Uranium-scintillator calorimeter
\[ \sigma_{\text{had}} = 0.35/\sqrt{E}, \sigma_{\text{EM}} = 0.18/\sqrt{E}, -3.5<\eta<4 \]

Liquid Argon calorimeter
\[ \sigma_{\text{had}} = 0.5/\sqrt{E}, \sigma_{\text{EM}} = 0.11/\sqrt{E}, -1.5<\eta<3.4 \]

Lead+fiber in backward (electron) direction [SpaCal] \[ \sigma_{\text{EM}} = 0.07/\sqrt{E}, -4<\eta<1.4 \]

Drift-chambers as main tracking devices + silicon vertex detectors

Muon chambers

tail catcher / muon chambers

solencid

Liquid argon calorimeter

SpaCal

backward silicon tracker

Central tracker
HERA inclusive measurements

- Select events with electron (neutral current) or with missing transverse momentum (charged current)
- Kinematic variables $Q^2$ and $x$-Bjorken
- Double-differential measurement of the reduced cross section $\sigma_r$
- Corrected for QED radiative effects
- Reduced cross sections: related to structure functions
- Case of lepton polarisation → not discussed in this talk

Neutral Current (NC)

\[
\frac{d^2 \sigma_{\text{NC}}}{dx \, dQ^2} \frac{Q^4 x}{2 \pi \alpha_+^{2Y}} = \sigma_{r, \text{NC}} = \tilde{F}_2 \mp \frac{Y}{Y_+} x \tilde{F}_3 - \frac{y^2}{Y_+} \tilde{F}_L
\]

Charged Current (CC)

\[
\frac{d^2 \sigma_{\text{CC}}}{dx \, dQ^2} \frac{G_F^2}{M_W^2} \left[ \frac{M_W^2 + Q^2}{M_W^2} \right] = \sigma_{r, \text{WC}} = Y_+ W_2^\pm + Y_- W_3^\pm - y^2 W_L^\pm
\]

helicity factors: $Y_\pm = 1 \pm (1 - y)^2$
HERA and Proton PDFs

- Inclusive cross sections probe proton parton density functions (PDFs) $f_i(x,\mu=Q)$
- HERA: $0.05<Q^2<10^5$ GeV$^2$ and $10^{-6}<x<0.6$
- Inclusive cross sections from HERA are the backbone of all modern PDF determinations, using DGLAP for NLO or NNLO QCD fits
  \[\text{→ large impact on LHC physics}\]
- JLEIC: overlap with HERA, expect substantial improvements at high $x$
  \[\text{→ inclusive measurements are an important part of the JLEIC physics program}\]

Original plot taken from PhD thesis J.Kretzschmar
HERA kinematics for neutral current

- Kinematic variables: $Q^2$, $x$, $y$, $Q^2 = s y$
- Determined using scattered electron and hadronic final state

\[ y_e = 1 - \frac{\langle e' p \rangle}{\langle e p \rangle}, \quad y_h = \frac{X p}{(e p)} \]
\[ Q^2 = \frac{p_T^2}{1 - y}, \quad x = \frac{Q^2}{s y} \]

- "Electron" method: $y = y_e$ and $p_T = p_{T,e}$
- At low $y$, use $y = y_h$ (sigma method)
- Other methods: double-angle, etc

- Hadrons lost in proton direction, Electron method is poor (energy resolution, ISR)
- Statistically limited at high $Q^2$
Charged current kinematics

- CC kinematics is reconstructed from hadrons alone: moderate resolution

\[ y_h = \frac{(X_p)}{(ep)} \]

\[ Q_h^2 = \frac{p_{T,\text{miss}}^2}{1 - y_h}, \quad x = \frac{Q^2}{s} \]

- HERA CC analysis is limited to large \( p_{T,\text{miss}} \geq 15 \text{ GeV} \), or \( Q^2 \geq 200 \text{ GeV}^2 \)

- Data-driven analysis of systematic effects: use neutral current events and remove the electron (at H1 called “pseudo-CC events”)
Reminder: the HERA discovery

- Discovery in the early HERA data: structure function $F_2$ rises strongly at low $x$
- At the time: a surprise
- Impressive improvement in precision – it took >20 years to achieve this

Shown here: $F_2$ (1993), reduced cross section (2015), as a function of $x$, in bins of $Q^2$
HERA data analysed over two decades

- Measurements of inclusive NC and CC processes are published in a total of 41 H1 and ZEUS papers
- Data are combined to a uniform HERA dataset: EPJ C75 (2015) 12, 85
- Seven combined datasets:
  - Measurements of NC and CC for both $e^+p$ and $e^-p$ scattering at $\sqrt{s}=318$ GeV
  - Measurements of NC $e^+p$ scattering at reduced $\sqrt{s}=${225,252,300} GeV
The power of combining data

- A total of 2927 H1 and ZEUS measurements are averaged to about 1307 combined reduced cross sections
- Up to six measurements contribute to a single point
- Systematic uncertainties and their cross-correlations are handled consistently
- Better than 1.5% precision is reached over a wide kinematic range
- Excellent data consistency: $\chi^2/N_{\text{D.F.}} = 1687/1620$
The HERA combined NC data

- Shown here: reduced cross section at $\sqrt{s}=318$ GeV for $e^+p$ and $e^-p$ as a function of $Q^2$. Dominating contribution is from structure function $F_2$.

- Scaling violations of are clearly visible: cross section rises with $Q^2$ at low-$x$ but drops with $Q^2$ at high-$x$.

- Gaps between fixed-target data and HERA measurements → JLEIC

- High $Q^2$ data precision is statistically limited

- Difference between $e^+p$ and $e^-p$ at high $Q^2$: extract $x_{F_3}$

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EPJ C75 (2015) 12, 85
Measurement of $x F_3^{\gamma Z}$

- Measurement of $x F_3$ at high $Q^2$
- Structure function is nonzero due to the $\gamma/Z$ interference
- Data are extracted point-by-point by subtracting $e^+p$ from $e^-p$ cross sections
- Extrapolate to $Q^2=1000$ GeV$^2$ and average for each $x$
- Integrate over $x$: expect $5/3$ from naive quark counting

\[
\left[ \int_{0.016}^{0.725} \frac{x F_3^{\gamma Z}(x)}{x} \, dx \right]_{\text{data}} = 1.314 \pm 0.057 \, \text{(stat)} \pm 0.057 \, \text{(syst)}
\]

\[
\left[ \int_{0}^{1} \frac{x F_3^{\gamma Z}(x)}{x} \, dx \right]_{\text{data+extrapol}} = 1.790 \pm 0.078 \, \text{(stat)} \pm 0.078 \, \text{(syst)}
\]

S. Schmitt, HERA proton structure
HERA measurements at high x

- Detector limitations: events at high $x$ are difficult to reconstruct
- High $x$ can be measured only at high $Q^2 \rightarrow$ statistically limited
- H1: largest $x=0.65$ is measured only for $Q^2 \geq 1500$ GeV$^2$ ($x=0.4$ for $Q^2 \geq 650$ GeV$^2$)
- ZEUS: dedicated analysis to measure high $x$ up to $x=1$ (bin-integrated cross section is quoted for last bin)
- Possibility to use these data in future PDF fits
High-y: Measurement of $F_L$

- Structure function $F_L$ can be measured by combining datasets taken at different $\sqrt{s}$ (Rosenbluth)
  \[ \sigma_{r,NC} = F_2 - \frac{y^2}{Y} F_L, \quad y = \frac{Q^2}{sx} \quad F_L \sim xg(x) \] [gluon density]

- Use HERA runs with reduced proton beam energy $E_p = 460$ or 575 GeV, $\sqrt{s} = 225$ or 252 GeV

- $F_L$ is extracted from high $y$ data: only a small area of the kinematic plane is accessible

- Using HERA+JLEIC data, $F_L$ could be turned into a truly double-differential measurement covering a much wider $x$-range → gluon at high $x$ & high $Q^2$
Measurement of $F_L$ at HERA

- Most precise HERA $F_L$ data: H1
- Main ingredients: backward silicon tracker and dedicated trigger for low-energy electrons
- Double-differential extraction of $F_L$
- Average over the [small] accessible x-range in each $Q^2$ bin → one-dimensional projection with $Q^2$ and $x$ varying simultaneously
- H1 and ZEUS data are consistent within 2 sigma (errors are dominated by normalisation uncertainties)

$$\sigma_{r,NC} \approx F_2 - \frac{y^2}{Y} F_L, \quad y = \frac{Q^2}{sx}$$

Gluon density determined from $H1 F_L$ measurement

$$xg(x, Q^2) \approx 1.77 \frac{3\pi}{2\alpha_S(Q^2)} F_L(ax, Q^2)$$

- Consistent with determination from scaling violations (HERAPDF fit)
- Available data at high $x$ is limited → could be changed by JLEIC [+HERA]

The combined Charged Current data

- As compared to NC: reduced number of points and limited to high $Q^2 \geq 300$ GeV²
- Cross section for $e^+p$ is lower than $e^-p$
  - u-valence quark available for $e^-p$ and d-valence for $e^+p$ [~factor 1/2]
  - Helicity factor: extra suppression of valence quark in $e^+p$ [at low $y$]
- Although statistically limited, the CC data are essential in the HERAPDF fit to separate u-type and d-type quarks and to constrain the valence quarks at high $x$
Single differential high $Q^2$ cross sections

- Single-differential cross sections $d\sigma/dQ^2$
- Neutral Current (NC) and Charged Current (CC) measurements, each for $e^+p$ and $e^-p$
- At low $Q^2 \leq 3000$ GeV$^2$ NC is much larger than CC [photon compared to W propagator]
- At high $Q^2$ all cross sections are similar, “electroweak unification”
- A text-book plot from HERA

$$\sigma_{\text{NC}} \sim \frac{1}{Q^4}$$
$$\sigma_{\text{CC}} \sim \frac{1}{(Q^2 + M_W^2)^2}$$

EPJ C75 (2015) 12, 85

H1 and ZEUS
QCD fit of HERA data

- PDFs traditionally are extracted from simultaneous fits of many datasets
- The HERAPDF is extracted from HERA data alone: proton PDFs are determined at NLO and NNLO
- Fit ansatz: at a low scale $\mu_f < m_c$ parameterize the $(u,d,s,g)$ PDFs
- Evolve PDFs to higher scales and fit cross section predictions to DIS data

\[
\begin{align*}
\text{gluon} & \quad xg(x) = A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g}, \\
\text{valence} & \quad xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + E_{u_v} x^2), \\
\text{sea} & \quad xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}}, \\
x\bar{U}(x) & \quad = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}} (1 + D_{\bar{U}} x), \\
x\bar{D}(x) & \quad = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}}. \\
\end{align*}
\]

Strange quark is described by a fraction $f_s$:

\[
x \bar{D} = (1 - f_s) x \bar{d} + f_s x \bar{s}
\]

[f$_s$ is not constrained by HERA data]

Charm and beauty is created above thresholds in the PDF evolution (Variable Flavor-Number Scheme, VFNS) or is present only in the hard matrix elements (Fixed Flavor Number Scheme, FFNS)
The HERAPDF2.0 QCD fit

- Proton PDFs at a scale $\mu^2=10$ GeV$^2$, determined in an NNLO QCD fit of HERA data
- The experimental uncertainties are small
- For low $x<10^{-3}$, model and parameterisation uncertainties are dominant
- The high-$x$ region is not measured well but is constrained mainly by the choice of parameterisation
- With additional data (JLEIC), the assumptions on the parameterisation at high $x$ possibly could be relaxed
Comparisons of data and QCD fit

- The consistency between data and QCD fit is investigated by excluding data below a certain $Q^2$ from the fit and looking at $\chi^2/N_{\text{DF}}$.
- Data at lowest $Q^2$ are least compatible with the QCD fit, the $\chi^2/N_{\text{DF}}$ curve flattens out for $Q^2 \geq 10$ GeV$^2$.
- At low $Q^2$/low-x there are discrepancies in the turn-over region, where the $F_L$ contribution is relevant:

$$\sigma_{r,\text{NC}} \approx F_2 - \frac{Y^2}{Y} F_L$$

$$\sigma_{r,\text{NC}} \approx F_2 - \frac{y^2}{Y} F_L$$
Examples of other HERA measurements

- Charm and beauty production and determination of the respective quark masses
- Jet production and the determination of $\alpha_s$
Charm and beauty production at HERA

Heavy flavour production at HERA in leading order

Experimental methods:
- High pt lepton
- Reconstructed D,D* mesons
- Impact parameter, secondary vertex

Measured quantity: reduced cross section $\sigma_{\text{red}}$ with charm or beauty in final state as a function of $Q^2$ and $x$

NLO calculations: fixed-flavour number scheme (FFNS) where PDF only contains light flavours $u,d,s$ and the gluon. Massive heavy quarks are in the matrix elements.
HERA charm and beauty data

- New combined data (preliminary 2017)
- Rise to low x: typical for sea and gluon
- Cross section evolves with $Q^2$
- NLO predictions describe data reasonably well
- Rather limited data at high x

H1prelim-17-071, ZEUS-prel-17-01

https://www.desy.de/h1zeus/combined_results/index.php?do=heavy_flavours
Charm and beauty: ratio to NLO QCD

- Overall satisfactory description of the HERA c and b data by NLO QCD, not much dependent on PDF choice
- Slope difference data/theory as a function of $x$ is visible for charm data at $Q^2 \sim 12 \text{ GeV}^2$
- Data at higher $x$ will be very interesting to test theories

H1prelim-17-071, ZEUS-prel-17-01

https://www.desy.de/h1zeus/combined_results/index.php?do=heavy_flavours
Charm and beauty quark masses

- Charm and beauty data together with HERA inclusive DIS data are taken as input to a NLO QCD fit (dashed line)
- Simultaneously extract PDFs and c,b masses
  
  \[
  m_c \left( m_c \right) = 1209^{+46}_{-41} \text{ (fit)}^{+62}_{-14} \text{ (model)}^{+7}_{-31} \text{ (param)} \text{ MeV}
  \]
  
  \[
  m_b \left( m_b \right) = 4049^{+104}_{-109} \text{ (fit)}^{+90}_{-32} \text{ (model)}^{+1}_{-31} \text{ (param)} \text{ MeV}
  \]
- Compatible with previous HERA analyses and with world data
  
  PDG: \( m_c \left( m_c \right) = 1270 \pm 30 \text{ MeV} \)
  
  and \( m_b \left( m_b \right) = 4180 \pm 30 \text{ MeV} \)

H1prelim-17-071, ZEUS-prel-17-01  https://www.desy.de/h1zeus/combined_results/index.php?do=heavy_flavours
Jet production in the Breit frame

- New data on jet production in the Breit frame published recently by H1
- NNLO theory calculation became available recently

→ unique change to improve both on the experimental and the theoretical precision

Diagram for jet production at leading order in the Breit-frame (boson-gluon fusion)

Data at high jet $p_T$ and high $Q^2$ are statistically limited but theoretically most precise → JLEIC

New measurements by H1 with new NNLO theory predictions

\( \alpha_s \) determination at NNLO from jet data

- First determination of \( \alpha_s \) from jets in DIS at NNLO accuracy
- Close cooperation with theorists
- DIS jets can compete with LEP results
- Paper in editorial process

H1prelim-17-031, close to publication
HERA analysis and data preservation

- HERA data are preserved at DESY and MPI Munich
- The HERA collaborations are still active in producing papers
- A chance for JLEIC students or post-docs to do analysis on real data
- Both H1 and ZEUS welcome new members
- No financial commitment involved

Contact M.Wing or S.Schmitt to join ZEUS or H1
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DPHEP storage system at DESY

1.2 PB on tape

Online: on disk
- Set of data for direct access + Full file lists of archive content
- 700 TB on disk (data and MC)
- analysis on DESY batch farm
Summary

- World's only ep collider HERA was operated 1992-2007
- Hera kinematic domain: low-x [awaiting high-x from JLEIC]
- Results shown in this talk: inclusive cross sections and PDFs, charm and beauty production, jets and $\alpha_s$
- Another big area of analyses at HERA: diffractive and exclusive processes (not shown in this talk → backup)
- HERA collaborations are still doing analysis, data is preserved for long-term usage

→ join us now to analyze HERA data in view of JLEIC
Backup slides
Diffraction at HERA

Proton taggers
- no proton dissociation
- Direct reconstruction of system Y
- Low acceptance and/or low statistics

Large rapidity gap event selection
- Include dissociation
- Poor reconstruction of system Y
- High statistics

Hard diffraction: DPDF
Soft diffraction: IP trajectory, ...
Select events with large rapidity gap method → momentum transfer \( t \) at proton vertex is not measured

- Measure diffractive cross section \( \sigma_r^{D3}(Q^2, \beta, x_{IP}) \)
- Extract diffractive PDFs
- Status: full (H1) dataset analyzed, but no recent DPDF fit (shown H12006 DPDF Fit-B uses only part of the data)
Measurement of $F_L^D$

- Rosenbluth separation in diffraction: measure longitudinal structure function
- HERA measurements are statistically limited and do not reach to the regions where the model predictions are divergent of each other
- Interesting for JLEIC or JLEIC+HERA?

Forward proton data

- Forward proton was detected at HERA using “Roman pot” detectors
- Measurement of $F_2^{D4}(Q^2, \beta, x_{IP}, t)$
- H1: FPS (HERA-I), FPS and VFPS (HERA-II)
- ZEUS: LPS (HERA-I)
- Data of ZEUS LPS and H1 FPS are combined in a limited t-range
- H1 VFPS data not yet published, preliminary $F_2^{D3}$ measurement


H1prelim 10-014
Exclusive measurements

- Many measurements were performed with HERA-I data but not yet with HERA-II data

- Typical measurements: diffractive vector meson production $\rho,\phi,J/\psi,\psi',\Upsilon$ and DVCS

- HERA-II data sample is interesting because of large available luminosity and dedicated (track) triggers for low-multiplicity states – but not all channels have been analyzed yet

Example: $J/\psi$ photoproduction: 83 citations in only 4 years