Recent Results from HERA

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DESY

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Deep Inelastic $ep$ scattering

Neutral scattering cross section:

\[
\frac{d^2\sigma^\pm}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4x} \sigma^\pm =
\]

\[
= \frac{2\pi\alpha^2 Y_+}{Q^4x} \left[ F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) \mp \frac{Y_2}{Y_+} x F_3 \right]
\]

where factors $Y_\pm = 1 \pm (1 - y)^2$ and $y^2$ define polarization of the exchanged boson and $y = Q^2/(S x)$.

Kinematics of inclusive scattering is determined by $Q^2$ and Bjorken $x$.

At leading order:

\[
F_2 = x \sum e_q^2 (q(x) + \bar{q}(x))
\]
\[
xF_3 = x \sum 2e_q a_q (q(x) - \bar{q}(x))
\]
\[
\sigma^{CC}_{e^+p} \sim x(u + \bar{c}) + x(1 - y)^2 (d + s)
\]
\[
\sigma^{CC}_{e^-p} \sim x(u + c) + x(1 - y)^2 (\bar{d} + \bar{s})
\]

$xG(x)$ — from $F_2$ scaling violation, jets and $F_L$

HERA with $\sqrt{S} = 318$ GeV is a unique tool to measure the proton structure.
$x_1, x_2$ are momentum fractions. Factorization theorem states that cross section can be calculated using universal partons $\times$ short distance calculable partonic reaction.

$$x_{1,2} = \frac{M}{\sqrt{S}} \exp(\pm y)$$

Notation clash: $y$ – rapidity (LHC) vs $y$ – inelasticity (HERA, $Q^2 = S x y$).

For $M \sim 100$ GeV and central rapidity proton structure information is provided by HERA.
HERA, H1 and ZEUS. 1992-2007.

Thank You HERA R.I.P.
HERA-II upgrade provides better instantaneous luminosity and longitudinal beam polarization.

Nominal $E_p = 920$ GeV, $E_e = 27.5$ GeV. Special low proton beam energy runs $E_p = 460, 575$ GeV to measure $F_L$
Both the scattered electron and hadronic final state can be used to reconstruct event kinematics.
Structure Function $F_2$ at low $x$

Recent measurement performed by the H1 collaboration. Final H1 result based on HERA-I data. Precision reaches $\sim 1.5\%$.

$F_2(x, Q^2)$ shows strong rise as $x \to 0$, the rise increases with increasing $Q^2$. 

arXiv:0904.3513, submitted to EPJ
arXiv:0904.0929, submitted to EPJ
Large scaling violation at low $x$ — large gluon density. Good agreement between the data and theory.
Data precision allows for local determination of $\frac{\partial F_2}{\partial \ln Q^2} \sim \alpha_s G$. Note that there is a strong anti-correlation between the data points. Good consistency between data and QCD fit (even for extrapolation to low $Q^2$).
• For $x < 0.01$ $x_S$ and $x_G$ dominate.
• Very rapid evolution for $x_S$ and $x_G$.
• Analysis based using the H1 data only.
Average H1 and ZEUS data before applying QCD analysis.
Achieved by fitting $\sigma_r$ values, global normalizations and the correlated systematic uncertainties.

$$\sigma_r^\pm = F_2 - \frac{y^2}{Y_+} \mp \frac{Y_-}{Y_+} x F_3$$

Experiments cross calibrate each other: total uncertainties reduced, sometimes better than $\sqrt{2}$. 
Combined HERA data

H1 and ZEUS Combined PDF Fit

Combination of published H1/ZEUS data for CC, NC, $e^\pm p$ data.

$\chi^2/dof = 637/656$

HERA data approaches precision of fixed target experiments. Combined data vs theory: stringent test of DGLAP evolution.
Sea $S$ and gluon $g$ are far more important at low $x$. Mind the $\times 0.05$ scale factor for them.

Fit to combined H1/ZEUS data returns much more precise $xG(x)$ compared to global fits of CTEQ and MRST: improved data precision and also different data errors treatment.
Determination of $F_L$ requires measurement at high $y \approx 1 - \frac{E_e'}{E_e}$

H1 estimates background directly from data using the measured charge of the electron candidate.
Both H1 and ZEUS collaborations published their first measurements of $F_L$. ZEUS also extracts $F_2$ without any assumption on $F_L$. 

Phys. Lett. **B665** 139, 2008.

DESY-09-046, to be published in Phys. Lett. B
Using the backward silicon tracker, H1 extended the measurement to low $Q^2$. 
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$Q^2 = 5.0 \text{ GeV}^2$
H1 measurements cover $2.5 \leq Q^2 \leq 800 \text{ GeV}^2$ and $0.00005 \leq x \leq 0.04$ range. For $Q^2 \geq 10 \text{ GeV}^2$, agree well with H1PDF 2009 prediction.
$F_L$ measured at $Q^2 < 100 \text{ GeV}^2$

MSTW and H1PDF 2009 predictions use the same scheme to calculate $F_L$. Data agree better with calculation of CTEQ.
Recently ZEUS published analysis of the complete $e^- p$ sample. CC data allows to measure $D, \bar{U}$ and $U, \bar{D}$ separately. (DESY-08-177, accepted by EPJ C)
CC cross section is linearly proportional to the degree of the longitudinal beam polarization:

\[
\frac{d^2\sigma_{e^\pm p}^{CC}}{dx dQ^2} = [1 \pm P_e] \frac{G_F^2}{2\pi x} \left[ \frac{M_W^2}{Q^2 + M_W^2} \right]^2 \phi_{CC}^\pm
\]

Consistent with no right-handed weak currents
Neglecting pure $Z$ exchange term, generalized $F_2$:

$$\tilde{F}_2^\pm \approx F_2 + k(-v_e \mp P_a e)F_2^{\gamma Z}$$

where

$$k = \frac{1}{4 \sin^2 \theta_W \cos^2 \theta_W} \frac{Q^2}{Q^2 + M_Z^2}$$

At leading order

$$F_2^{\gamma Z} = x \sum 2e_q v_{q\bar{q}}(q + \bar{q})$$

(DESY-08-202, accepted by EPJ C, Complete HERA-II sample).
NC Cross Section Polarization Dependence

Polarization asymmetry

\[ A^\pm = \frac{2}{P_R - P_L} \frac{\sigma^\pm(P_R) - \sigma^\pm(P_L)}{\sigma^\pm(P_R) + \sigma^\pm(P_L)} \approx \]

\[ \pm k a_e \frac{F_{\gamma Z}^2}{F_2} \]

measures directly NC parity violation.
We want to have predictions for $W^+$, $W^-$, $Z$ with the main experimental input from $F_{2}^{em}$:

- For LHC, more important $d, s$ quarks
- For $Z$, significant contribution from $b$. 
Measurement of $xS(x)$ by HERMES

Measure $K^\pm$ production on deuteron target compared to inclusive DIS.

$$S(x) \int D^K_S(z)dz \approx Q(x) \left[ 5 \frac{d^2N^K(x)}{d^2N^DIS(x)} - \int D^K_Q(z)dz \right]$$

Based on flatness of $dN^K(x)/dN^DIS(x)$ for high $x$, assume $S(x) = 0$ for $x > 0.15$, measure the fragmentation function $\int D^K_Q(x)dz$.

Subtracting the contribution of $\int D^K_Q(x)dz$, evolving to $Q^2=2.5$ GeV$^2$ and using an external value of the fragmentation function $\int D^K_S(x)dz$, $xS(x)$ distribution is obtained:
Different methods to measure $F_{2}^{c\bar{c}}$

- Displaced secondary vertex (lifetime tag).
- Tagging by measuring $D^*$ meson production.

Methods have different experimental/theoretical uncertainties: combine taking into account correlations, significant reduction of the uncertainty.
Measurements of $c, b$ using displaced vertex.

Larger contribution to $\sigma_r$ allows to determine $\sigma_{r\bar{c}c}$ more precisely than $\sigma_{r\bar{b}b}$. Data agree well with H1PDF2009/MSTW08 predictions.
High $P_t$ jets provide information on $\alpha_S$ and $xG(x)$.

H1 Analysis based on complete HERA sample ($395 \text{ pb}^{-1}$).

$$\alpha_S(M_Z) = 0.1168 \pm 0.0007 \text{ (exp)} \quad +0.0046 \quad -0.0030 \text{ (th.)} \pm 0.0016 \text{ (PDF)}.$$ 

arXiv:0904.3870, Submitted to EPJC.
Summary

- HERA enables precise determination of PDFs for the LHC kinematic range.
- DGLAP evolution works very well so far.
- More information will come with finalization of HERA analyzes, combination of H1/ZEUS data, from the measurements of heavy flavors and of $F_L$. 