The Dynamics of Proton Structure: *Recent Results from HERA*

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This Talk

- Introduction to HERA
- Standard model physics
 - NC/CC electrons/positrons, +/- helicities
 - Very high x cross sections
 - Heavy quarks
 - F_2, F_3, F_2^c, F_2^b
 - Parton densities
 - $\alpha_s(M_Z)$
 - EW parameters
- Beyond the standard model
 - Quark compositeness
 - Contact interactions
 - Leptoquarks
 - High p_T leptons
- Summary and conclusions

HERA: The Greatest Electron Microscope

Luminosity, $e^\pm$ and polarization = HERA II

- > 200 pb⁻¹/expt delivered
- Both lepton species
- Expect ~ 700 pb⁻¹/expt by the end of HERA (2007)

- Polarization:
 - 50% reached routinely now

Polarization (%)

DIS @ HERA

$$E_e = 27.6 \text{ GeV}, E_p = 920 \text{ GeV}$$

$$\sqrt{s} = 2\sqrt{E_e E_p} = 319 \text{ GeV}$$

$$\Leftrightarrow E_e^{ft} = 54.1 \text{ TeV}$$

$$Q^2 = sxy - \text{high}$$

$$x = Q^2 / sy - \text{low}$$

Standard Model

Charged and Neutral Currents

Neutral current $e^+p \rightarrow e^+X$

Charged current $e^+p \rightarrow \bar{\nu}X$

$$\sigma_{NC}^{\pm} \approx \sigma_{CC}^{\pm} \leftrightarrow Q^2 \approx M_Z^2 \approx 10^4 \text{ GeV}^2$$

Charged Currents

- SM expectation:

- $\sigma^\pm(P_e) = (1 \pm P_e) \sigma^\pm(P_e=0)$

$$\sigma_{e^+p \rightarrow \bar{\nu}X}(P_{e^+} = -1) = 0.2 \pm 1.8(sta) \pm 1.6(sys) pb$$

- Right-handed currents are absent

Neutral Currents: The Expectation

Neutral Current Cross Section

-- Polarisation dependence appears through the interference between γ and Z boson exchanges

$$\frac{d^2\sigma^{NC}(e^\pm p)}{dx dQ^2} = \frac{2\pi\alpha}{xQ^2} [H_0^\pm + P \cdot H_P^\pm]$$

H_0 : unpolarised structure function

H_P : polarised structure function

-- Polarisation effect can be visible only at high Q^2 region

Neutral Currents: First Results

What do we learn?

Structure Functions

High- Q^2 NC DIS $e^\pm p$

$xF_2(x)$

High- Q^2 CC DIS $e^\pm p$

NC cross section @ very high x

$x F_3(x)$

$$\tilde{\sigma}_{NC}^{\pm} = \tilde{F}_2 - \frac{y^2}{Y_+} \tilde{F}_L \mp \frac{Y_-}{Y_+} x \tilde{F}_3$$

$$x \tilde{F}_3 \sim 2u_v + d_v$$

$x F_3$

Charm and beauty in the proton?

$xF_2^b(x)$ and $xF_2^c(x)$

$\tilde{\sigma}^{b\bar{b}}$ (not corrected for F_L)

Parton Densities

Parton Densities

Error on the $xg(x)$

HERA Parton Densities @ LHC

Ref: HERA-LHC WS

$\alpha_s(M_Z)$

- Simultaneous determination of $\alpha_s(M_Z)$ and PDFs
- Due to inclusion of jet cross sections $\alpha_s(M_Z)$ and PDFs are *NOT* strongly correlated

$$\alpha_s(M_Z) = 0.1183 \pm 0.0007 \text{ (uncorr.)} \pm 0.0022 \text{ (corr.)} \\ \pm 0.0016 \text{ (norm.)} \pm 0.0008 \text{ (model)}$$

Precision of $\alpha_s(M_Z)$ @ HERA

$$HERA(prel.) - \alpha_s(M_Z^2) = 0.1186 \pm 0.0011(\text{exp}) \pm 0.005(\text{thy})$$

Light quark couplings

From H1 PDF fits including additional EW parameters

W Propagator Mass & Coupling G_F

- HERA space-like ($q^2 < 0$) mass vs. Tevatron/LEP time-like ($q^2 > 0$) one
- SM relationship between M_W and G_F not used

$$M_W = 82.87 \pm 1.83 (\text{exp}) {}^{+0.30}_{-0.16} (\text{mod}) \text{ GeV}$$

M_W and M_t in the SM

- W mass value:**

$$M_W = 80.786 \pm 0.205_{\text{exp}} \text{ GeV}$$

+ the world average M_Z
 → indirect determination of

$$\sin^2 \theta_W = 1 - M_W^2 / M_Z^2 = 0.2151 \pm 0.0040_{\text{exp}}$$

- Top quark mass:**

$$m_t = 104 \pm 44_{\text{exp}} \text{ GeV}$$

→ First determination in DIS at EW scale

Beyond the SM

Are quarks “elementary”?

- Form factor measurement at $Q^2 \sim 40000 \text{ GeV}^2$
 - Resolution $1/Q \sim 10^{-16} \text{ cm} = 0.001 \text{ proton radius}$
- Compare measured to expected cross section
- Limits on quark size

- H1:

$$R_q < 1.0 \times 10^{-16} \text{ cm}$$

- ZEUS:

$$R_q < 0.85 \times 10^{-16} \text{ cm}$$

Is there TeV scale physics?

(Contact Interactions)

Are there leptoquarks?

- HERA:

- s-channel eq fusion
- resonance in eq (νq) invariant mass in NC (CC) events
- no excess observed

- TEVATRON:

- LQ pair production

- LEP2:

- virtual in $e^+e^- \rightarrow \text{hadrons}$

Puzzle: High p_T lepton events

- Signature:
 - lepton + missing p_T + large $p_T(\text{had})$
- Dominant SM process:
 - on-shell W production ($\sigma \sim 1\text{pb}$)
- Excess seen in HERA I in H1 for e/μ and in ZEUS for τ

High p_T leptons: Latest numbers

- H1 update with HERA II data ($74 \text{ pb}^{-1} e^\pm P$)
 - 6 new electron events with $p_T(\text{had}) > 25 \text{ GeV}$
 - no new muon event
 - overall excess in $e+\mu$ channel
- τ search at H1
 - no excess seen (HERA I only)

$e^\pm p$ data (1994-2005) 192 pb^{-1}
Electron obs./exp. (W)	Muon obs./exp. (W)	Tau ^① obs./exp. (W)
All P_T^X	25/ 18.3 ± 2.5 (70%)	9/ 4.8 ± 0.8 (85%)	5/ 5.8 ± 1.4 (15%)
$P_T^X > 25 \text{ GeV}$	11/ 3.0 ± 0.6 (81%)	6/ 3.0 ± 0.6 (86%)	0/ 0.5 ± 0.1 (49%)

^① $e^\pm p$ (1996-2000) 108 pb^{-1}

Summary and Conclusions

- HERA QCD results on structure functions, pdfs and α_s are becoming more precise ...
- ... but HERA is not only a QCD machine:
 - expect important complementary precision measurements
 - excellent search potential
- ... the really good stuff