Proton Structure

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Introduction

recent inclusive data from HERA in relation to pQCD, pdf-fits

Conclusion
emphasis is on recent results from H1 and ZEUS at HERA
Inclusive DIS NC, CC

\[ Q^2 = -q^2 \quad \text{4-momentum transfer} \]
\[ x = Q^2 / (P \cdot q) \quad \text{p momentum fraction of parton inelasticity} \]
\[ y = (P \cdot q) / (P \cdot k) \]

\[ N C \quad d^2\sigma_{NC}^\pm / dx dQ^2 = \frac{2\pi\alpha^2}{xQ^4} [Y_+ \cdot \tilde{F}_2 \mp Y_- \cdot x \tilde{F}_3 - y^2 \cdot \tilde{F}_L] \equiv \frac{2\pi\alpha^2}{xQ^4} Y_+ \tilde{\sigma}_{NC}^\pm \]
\[ Y_\pm = 1 \pm (1 - y)^2 \]

\[ \tilde{F}_2, \quad \text{dominating contribution, in leading order QCD} \quad \sim x \sum_q e_q^2 (q + \bar{q}) \]
\[ x \tilde{F}_3, \quad \text{in particular } \gamma Z \text{ interference, significant at large } Q^2 \gtrsim M_Z^2 \quad \sim x \sum_q A_q (q - \bar{q}) \]
\[ \tilde{F}_L, \quad \text{longitudinal contribution, sensitivity at large } y, \quad \text{zero in LO QCD} \]

\[ C C \quad d^2\sigma_{CC}^\pm / dx dQ^2 = \frac{G_F^2}{2\pi x} \left( \frac{M_W^2}{Q^2 + M_W^2} \right)^2 \cdot \tilde{\sigma}_{CC}^\pm \]

\[ \text{LO} \quad \tilde{\sigma}_{CC}^+ = x[(\bar{u} + \bar{c}) + (1 - y)^2 (d + s)] \quad \tilde{\sigma}_{CC}^- = x[(u + c) + (1 - y)^2 (\bar{d} + \bar{s})] \]
large phase space covered by HERA \( e^+ p \quad e^- p \) data

illustrating electro-weak unification
new data from HERA II

dependence on electron polarisation in CC

linear fit to H1 and ZEUS data

\[ \sigma(e^+p) \rightarrow \bar{\nu}X \quad (P_{e^+} = -1) \]

= 0.2 ± 1.8 ± 1.6 pb

consistent with zero (SM expectation)

no sign of right handed currents

see talk of Yongdok Ri
Proton pdfs from NC and CC data

Inclusive eN DIS data are the most important source for pdf determinations

- **Fixed target**: Large $x$ valence and sea distributions
- **HERA**: Low $x$ gluon and sea distributions (gluon indirectly from scaling violations)
- **Tevatron ($p\bar{p}$)**: Gluon at medium and large $x$ from jets (previously mostly from prompt photons)

HERA experiments aim to determine the gluon at medium $x$ as well as $u$ and $d$ valence (free of nuclear effects of $ed$ scattering)
NC input

HERA provides data over

4 orders of magnitude
in x and $Q^2$

cross sections at largest x

Here large uncertainties
New technique in high $x$ region

$Q^2$ is well measured by electron, but $x$ needs jet information

sketch of ZEUS detector

consider jets with $E_T > 10 \text{ GeV}$, $\Theta > 0.12 \text{ rad}$

reconstruct 1 jet $\rightarrow$ some $x - \text{bin}$

reconstruct 0 jets $\rightarrow$ $x_{\text{edge}}(Q^2) < x < 1$

discard $\geq 2$ jets

e.g. jet multiplicities well described by correcting MC (LEPTO/MEPS)
Results

analyzed $e^+ p$ 65 pb$^{-1}$ $e^- p$ 17 pb$^{-1}$

average cross sections of bins

consistent with expectation over wide range of $Q^2$
NC e+p, ratio to NLO expectation

$Q^2 = 576$

Data close to expectation, but tend to be above at highest $x$ to include in pdf fits
u - d separation at high x

\begin{align*}
\sigma(e^- p) &\sim x(u + c) + (1 - y)^2x (\bar{d} + \bar{s}) \\
\sigma(e^+ p) &\sim x(\bar{u} + \bar{c}) + (1 - y)^2x (\bar{d} + s)
\end{align*}

using CC (and NC)
HERA disentangles flavours free of nuclear effects

When enough data, consistency check also with

\[ xF_3 \sim 2u_v + d_v \]

(mainly \( \gamma Z^0 \) interference)
input from HERA at low $x, Q^2$

rise of $F_2$

\[ F_2 = c \, x^{-\lambda(Q^2)}, \quad x < 0.01 \]

main behaviour for $x < 0.01$

\[ F_2 = c(Q^2) \cdot x^{-\lambda(Q^2)} \]

$Q^2 > 3 \text{ GeV}^2$

$\lambda \sim \ln(Q^2/\Lambda^2)$ \quad $c \approx \text{const}$

$Q^2 \approx 1 \text{ GeV}^2$

$\lambda$ deviates from log dependence

expect $\lambda \to 0.08$ for $Q^2 \to 0$

from soft hadronic interactions

rise of the parton densities vs low $x$ increasing with $Q^2$
Impact of $F_L$

sensitive to gluon density

\[ F_L \sim \alpha_s(Q^2)g(x, Q^2) \]

\[ \frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4x} \gamma + \left( t_2(x, Q^2) - y^2 t_L(x, Q^2) \right), \]

\[ \gamma_+ = 1 + (1 - y)^2 \]

measure reduced $\sigma$

\[ \sigma_r = F_2 - y^2 F_L / \gamma_+ \]

\[ \sigma_r = c \cdot x^{-\lambda} \]

effect of $F_L$

\[ Q^2 = 4.2 \text{ GeV}^2 \]

large spread of predictions

assumption free measurement needed
increased sensitivity to gluons using inclusive ep and jets in QCD analysis

jets sensitive to gluon distribution in LO

in BGF full correlation with $\alpha_s$, different in QCD-Compton graphs
Recent fits by H1 and ZEUS

**Procedure:**
- Parametrisation of PDFs at starting scale $Q^2_0$
- $Q^2$ dependence by DGLAP pQCD evolution in NLO
- PDF parameters at $Q^2_0$ determined by fits to $\sigma_{red}$ at $Q^2 > Q^2_{min}$

**Main differences in:**
- Used data
- Parametrisations at $Q^2_0$
- Treatment of heavy quarks
- Treatment of systematics

<table>
<thead>
<tr>
<th>H1 PDF 1997</th>
<th>H1 PDF 2000</th>
<th>ZEUS-S</th>
<th>ZEUS-JET</th>
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Other experiments used
- BCDMS ($\mu p$)
- (but jets)
- BCDMS, NMC, E665, CCFR ($\mu p, \mu d$) ($\nu F e$)

Fitted distributions
- $ep$ valence and sea terms
- $u + c, \bar{u} + \bar{c}$
- $d + s, \bar{d} + \bar{s}, g$
- $u_v, d_v$
- $S, \bar{d} - \bar{u}, g$
- $u_v, d_v$
- $S, \bar{d} - \bar{u}, g$

$Q^2_0$ $Q^2_{min}$
- 4 3.5
- 4 3.5
- 7 2.5
- 7 2.5

Main aim
- $\alpha_s$ $g(x)$
- PDFs
- PDFs
- PDFs $\alpha_s$
Impact of jet data on gluon determination in ZEUS-JETS fit

fractional error of $g(x)$

- $Q^2 = 1\,\text{GeV}^2$
- $Q^2 = 2.5\,\text{GeV}^2$
- $Q^2 = 7\,\text{GeV}^2$
- $Q^2 = 20\,\text{GeV}^2$
- $Q^2 = 200\,\text{GeV}^2$
- $Q^2 = 2000\,\text{GeV}^2$

**ZEUS**

- NC, CC only
- Jets included

jet data constrain $g(x)$ at medium and high $x$ (0.01 to 0.4)
Impact of jet data on gluon determination in ZEUS-JETS fit

fractional error of $g(x)$

lively progress

NC, CC only

jets included

jet data constrain $g(x)$ at medium and high $x$ (0.01 to 0.4)
Comparison

**ZEUS-JET fit**

H1 pdf 2000

\[
\begin{align*}
U &= u + c \\
\bar{U} &= \bar{u} + \bar{c} \\
D &= d + s \\
\bar{D} &= \bar{d} + \bar{s}
\end{align*}
\]

- results consistent
- differences in gluon visible
Comparison of ZEUS-JETS with H1 pdf 2000 and global fitters

- Results consistent within uncertainties
- $g(x)$ at $x \approx 0.01$ lower in ZEUS-JETS
- Valence $u,d$ higher
HERA results

- Inclusive jet cross sections in NC DIS
  ZEUS prel. (contributed paper to EPS05)
- Inclusive jet cross sections in NC DIS
  H1 prel. (contributed paper to EPS05)
- Multi-jets in NC DIS
  H1 prel. (contributed paper to EPS05)
- Multi-jets in NC DIS
  ZEUS (DESY 05-050 - hep-ex/0503274)
- Jet shapes in NC DIS
- Inclusive jet cross sections in γp
- Subjet multiplicity in CC DIS
  ZEUS (Eur Phys Jour C 31 (2003) 149)
- Subjet multiplicity in NC DIS
  ZEUS (Phys Lett B 558 (2003) 41)
- NLO QCD fit
  H1 (Eur Phys J C 21 (2001) 33)
- NLO QCD fit
  ZEUS (DESY 05-050 - hep-ex/0503274)
- NLO QCD fit
- Inclusive jet cross sections in NC DIS
  H1 (Eur Phys J C 19 (2001) 289)
- Inclusive jet cross sections in NC DIS
  ZEUS (Phys Lett B 547 (2002) 164)
- Dijet cross sections in NC DIS
  ZEUS (Phys Lett B 507 (2001) 70)
- World average
  (S. Bethke, hep-ex/0407021)

α_s

results of
inclusive DIS pdf fits
(with α_s(M_Z) as free parameter)
consistent with
final state analyses
and world average

- exp. precision calls
  for NNLO analysis
- calculations exist
  (Moch, Vermaseren, Vogt)
treatment of charm and beauty

H1 PDF 1997  H1 PDF 2000  ZEUS-S, -JET
massive  massless  VFNS
weight on low Q^2  on high Q^2  variable flavour number
scheme

LO  NLO

BGF

Boson Gluon Fusion

H1 Data (High Q^2)

substantial measured
charm and beauty fractions
(see talk of Mark Bell)

\[ f_{cc} \sim 20\% \text{ to } 30\% \]
\[ f_{bb} \sim 0.3\% \text{ to } 3\% \]
beyond collinear pdfs

collinear pdfs contain no information on parton transverse momenta, parton correlations, proton spin...

GPDs (generalised parton densities, non-integrated pdfs) are deduced from final state data (and the collinear pdfs)

many final states discussed with non-integrated pdfs

jets, in particular forward jets prompt photons (most recently by Lipatov, Zotov)

vector mesons $\rho$ ... $J/\psi$ ...$Y$ DVCS

open charm, beauty

Diffractive processes $\rightarrow$ “diffractive pdfs”

see talks of

Didar Dobur, Mark Sutton

Niklaus Berger

Mark Bell

Vitaly Dodonov
Conclusion and Outlook

• Beautiful inclusive HERA I data available over 4 orders of magnitude in $x$ and $Q^2$

• pdf determinations are improving
  + controlled systematics
  + inclusion of ep jet data improves gluon determination
  + still more HERA I NC data will be finalised

• $\alpha_s$ and pdf precision will improve with NNLO analyses

• HERA II will strongly improve precision at high $Q^2$ and provides polarised cross sections
more stuff
$Q^2$ (GeV$^2$)

1 jet sample
0 jet sample
ZEUS published
HERA e⁻p Charged Current

- H1 e⁻p
- ZEUS e⁻p 98-99
- SM e⁻p (CTEQ6D)
- x (u+c)
- (1-y)^2 x (d+s)

Q^2 = 280 GeV^2
Q^2 = 530 GeV^2
Q^2 = 950 GeV^2
Q^2 = 1700 GeV^2
Q^2 = 3000 GeV^2
Q^2 = 5300 GeV^2
Q^2 = 9500 GeV^2
Q^2 = 17000 GeV^2
Q^2 = 30000 GeV^2

x
heavy quark piece in $F_2$

- strong scaling violations (charm and beauty)
- substantial spread of theoretical predictions
charm and beauty fractions of cross section

\[ f^{c\bar{c}} \sim 20\% \text{ to } 30\% \]
\[ f^{b\bar{b}} \sim 0.3\% \text{ to } 3\% \]

in covered range

fractions well described by MRST04