Recent QCD results from HERA

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(for the H1 and ZEUS collaborations)

- Proton Structure Functions and Scaling Violations
- $F_2$ (including reference to possible manifestation of non-pert. physics)
- $F_2$ charm
- Diffractive deep inelastic scattering (very briefly)
- $\alpha_s$ measurement from jet rates and from scaling violations
- NC and CC cross sections and structure functions up to very high $Q^2$
Two general purpose collider beam experiments: H1, ZEUS

HERA: e+ colliding with 1.5 TeV (920 GeV) protons from fixed target experiments using polarized proton beam (HERA-B).

HERA: Electron-proton collider beam experiment using electron beam (Hermes).
Hard (GeV)\(\geq 1\) \(\approx\) QED 

- Photoproduction: if hard scale present \((q^2, m^2)\) pert. QCD 
- Hadronic final state: governed by hard (jets) and soft QCD (hadronization)

Structure Functions \(F_1(x, Q^2)\): QCD evolution described by pert. QCD 

\[
\frac{x}{x - 1} \frac{d^2}{Q^2} = z(b + d) = z W \\
\frac{b_p z}{Q^2} = \frac{x}{Q^2} \\
\begin{aligned}
\frac{x}{x - 1} \frac{d^2}{Q^2} &= z(b + d) = z W \\
\frac{b_p z}{Q^2} &= \frac{x}{Q^2} \\
\end{aligned}
\]
\[(\mathcal{G} + 1)(\mathcal{G} - \mathcal{G} - 1)(\mathcal{G} + 1)_{u_\omega} \mathcal{J} \mathcal{O}_{x} = \mathcal{J}_{\mathcal{O} p x p} {\text{O}}_{z} \mathcal{P} \]

\[(\mathcal{G} + 1)_{u_\omega} \mathcal{J} = \mathcal{J}_{x} \mathcal{O}_{\mathcal{W} + \mathcal{O}}_{z} + \mathcal{J}_{x} \mathcal{O}_{\mathcal{W} + \mathcal{O}}_{z} + _{u_\omega} \mathcal{J} = \mathcal{J} \]

\[\mathcal{O}_{z} (\mathcal{O} - 1) + 1 = \mathcal{O}_{\lambda} \]

\[((\mathcal{O} \mathcal{O} + 1)[(\mathcal{O} \mathcal{O} + 1)_{x} \mathcal{J} x^{-1} \lambda - (\mathcal{O} \mathcal{O} + 1)_{x} \mathcal{J} \lambda - (\mathcal{O} \mathcal{O} + 1)_{x} \mathcal{J} x^{-1} \lambda]]_{x} = \mathcal{J}_{\mathcal{O} p x p} {\text{O}}_{z} \mathcal{P} \]

Neutral current selection:
ZEUS Preliminary 1996-97
\[
\left( \frac{\mathcal{K}}{x} \right) \mathcal{D}(\mathcal{K}) \mathcal{K}^{x} \int = \mathcal{D} \ast d
\]

\[
\left( i^b + i^b \right) \sum = s \mathcal{D} \quad ; \quad i^b - i^b =_{SN} \mathcal{D}
\]

\[
\left( \begin{array}{c}
\mathcal{E} \\
s \mathcal{D}
\end{array} \right) \ast \left( \begin{array}{cc}
sy d & \bar{b} \bar{d} \\
\bar{b} \bar{d} & \bar{b} \bar{d}
\end{array} \right) \frac{\mathcal{W}}{(1 \bar{D})^{S} \mathcal{N}} = \left( \begin{array}{c}
\mathcal{E} \\
s \mathcal{D}
\end{array} \right) \frac{\bar{D} \mathcal{E}}{\mathcal{E}} \bar{D}
\]

\[
_{SN} \mathcal{D} \ast \bar{b} \bar{d} \frac{\mathcal{W}}{(1 \bar{D})^{S} \mathcal{N}} = \frac{\bar{D} \mathcal{E}}{_{SN} \mathcal{D} \mathcal{E}} \bar{D}
\]

**The DGLAP equations govern the evolution of the structure functions:**
ZEUS Preliminary 96/97
ZEUS PRELIMINARY 1996-97
to scaling violations at low $x$ - how low can one go?

Beautiful description of data - extraction of gluon density: delicate fit, very sensitive

($Q_0$) (need to be corrected for higher twist contributions etc.)

Need high $x$ (i.e. fixed target - McL, SLAC, BCDMS) data for properly constraining

16 free parameters after imposing sum rules

\[(x + 1) x (x - 1)x = (0) \rho x bx\]

19 parameters to parametrise the parton densities as a function of $x$.

P? This in the framework of DGLAP evolution
Remarks:

- \( F_2 \) measured all the way up to \( Q^2 \sim 30 \text{ GeV}^2 \)
- Extraction of gluon density and \( Q^2 \) at fixed \( x \) (H1, ZEUS very soon)
- Scaling violations in agreement with QCD (DGLAP)
- Systemsatics dominated
- Some overlap with fixed target data
- \( F_2 \) determined at (better than) 5\% up to \( Q^2 \sim 800 \text{ GeV}^2 \)

Conclusions on \( F_2 \)
\[ \epsilon^2 \phi - I = (\epsilon \delta) \delta : \frac{\langle x \rangle^{0 \mathcal{P}} \mathcal{Z}}{\lambda} = \lambda \]

\[ (\epsilon \delta) \delta^0 \mathcal{O} = (\epsilon \delta \chi) \mathcal{O} : \left( \frac{\langle x \rangle^{0 \mathcal{P}} \mathcal{O}}{\lambda} \right) = \langle x \rangle^{0 \mathcal{P}} \mathcal{R} \]

\[ \text{x-dependent radius:} \]

\[ \text{Modelling of dipole cross section, adopting an} \]

\[ (\epsilon \delta \chi)^{T \perp} \mathcal{O} \frac{m_{\gamma}^2 \gamma}{\epsilon \delta} = (\epsilon \delta \chi)^{T \perp} \mathcal{P} \]

\[ (\epsilon \delta \chi) \mathcal{O} \left[ (\epsilon \delta \chi)^{T \perp} \mathcal{P} \right] \int_{\epsilon \delta} \int_{\epsilon \delta} = (\epsilon \delta \chi)^{T \perp} \mathcal{O} \]

Agreement with a saturation model (Golec-Biernat, Wustefalt) to non-perturbative effects: these slopes show a behaviour in qualitative agreement with the scaling violations and may be sensitive to negative gluon distribution (or negative gluon distribution). DGLAP this can be made to work down to GeV? vanishing at which \( \epsilon \delta \mathcal{O} \).

The transition into the non-perturbative regime: not a priori clear.
in a color singlet state
for di-rhicat probability of hitting 2 gluons
Model can also be made to work naturally

\( \gamma_x \sim \frac{1}{R} \) 

\( \frac{0}{\Omega_D} \sim (\Omega D) \frac{d}{dR} \log p^2 \Delta \frac{0}{R} \ll \frac{1}{\Omega D} \) 

\( \gamma_x \sim (\Omega D) \frac{d}{dR} \log p^2 \Delta \frac{0}{R} \gg \frac{1}{\Omega D} \)

**Saturation**

**Scaling**

The cartoon is somewhat misleading; what we draw as an
amplitude is supposed to represent the wavelength
Proton F\textsubscript{2} scaling behaviour changes at low x, $Q^2 \approx 2-6$ GeV$^2$
\[
\left( \frac{d^2 \sigma}{dz d\epsilon} \right)_s = \frac{x_v \sigma}{\epsilon} \left( \frac{d^2 \sigma}{dz d\epsilon} \right)_v
\]
in the lower $p_T$ region

Good (better) description of charm production in DIS, in particular

CCFM: evolution in both $Q$ and $1/x$

Jung, C. J., Calaif, A., Fornal, J., Marcheshini

Framework of CCFM evolution, as implemented in the CASCAD
programme

HI has performed an analysis of charm production in DIS in the
Conclusions on \( R^2 \) charm
Ryskin; Ryskin, Soliano

RIDI - IIA; \( \sigma \sim Q^3 \)

plus saturation

Barnes, Ellis, Kovchegov, Wiese

saturation of parton densities in proton

\( \Sigma \text{ISRAP} \sim \text{dis} + \text{coupl}\) to proton via 2-g exchange

Ingleman, Schlein; Jung

scatterings + Pomeron structure functions (HI)

Three approaches:

• States.

extracted ("quarkic"); now trying to get insights in DIS by studying final

diffractive DIS has been discovered at HERA; Pomeron, parton, have been
Extensive studies have been made, but definitive conclusions in favor of or against one of the models cannot be drawn yet.
9.4. QCD in decays of the $\tau$ lepton

The semi-leptonic branching ratio of the tau ($\tau \rightarrow \ell \nu_\ell + hadrons$, $\ell = e, \mu$) is an intensive quantity. It is related to the contribution of hadrons to the momentum part of the $\tau$-lepton.

The semi-leptonic branching ratio is shown in Fig. 9.1. The error shown is the total error including the relative uncertainties. The values shown indicate the process and the measured value of $\frac{N_{\text{theory}}}{N_{\text{data}}}$ from various processes.

**Figure 9.1:** Summary of the values of $(Z\tau)^{0.8}$ and $(Z\tau)^{0.9}$ from various processes.

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Refer to Ref. [9] for further details on the significance of the QCD in decays of the $\tau$ lepton.
Jet search via Kt cluster algorithm

Analysis of DIS final states in Breit frame
From scaling violations (low x): 2 \frac{W}{\nu} \propto (\frac{\nu}{W})^s \propto 0.0017 \times 1.150 \equiv 2.100.0 \equiv 1.100.0

\text{DISENT (NLO QCD); Caliani, Seymour}

DIS in NC DIS

\begin{align*}
\text{PDG: } \xi^s & \equiv 0.020 + 0.185 \equiv 0.1185 = (\frac{W}{\nu})^s \\
\text{HERA measurement at } & \end{align*}
Using HERA (i.e. H1) data only

H1 preliminary

Correlation: $q^s - g(x)$ and density in a simultaneous NLO QCD fit
ZEUS 96-97 PRELIMINARY
Conclusions on $q_S$

Main sources of uncertainty: choice of scale, need higher order

Calculations and the correlation of $q_S$ and the gluon density

A combined analysis:

$Z^0$-jet production and from $F^Z$ scaling violations and from

Precision measurements possible and achieved, both from

(to be measured independently)
NLO QCD calculations

ZEUS Preliminary

hep-ph/9907348
Klasen, Vossen
reviewed by Hnatiuk

35 > E_T > 90 GeV
25 > E_T > 35 GeV
17 > E_T > 25 GeV
14 > E_T > 17 GeV

NLO QCD, AFG-HO
DATA 96+97
0.2 > y > 0.85
1800 1200 600 0
0 50 100 150 200
0 50 100 150 200
0 50 100 150 200
\[ R = \frac{\sigma \left( x_\gamma^{\text{OBS}} < 0.75 \right)}{\sigma \left( x_\gamma^{\text{OBS}} > 0.75 \right)} \]
The observed difference between experiment and theory observed smaller than the precisely be the effect of updated pdfs on calculations will on b production, but most likely should be done first before drawing conclusions that photon pdfs need updating (↑). However: ZEUS finds (di-jet photoproduction) that colliders than predicted. 

UA1, CDF, D0 find larger b cross section at 1 TeV.

ZEUS: inclusive electrons in di-jets

as compared to NLO QCD predictions 104 ± 17 pb

in limited kinematic range, v (7 GeV, pbar X) = 170 ± 25 pb

H1: inclusive muons in di-jets; impact parameter distribution

Frisono, Mabileau, Naso, Kaidohl

(in lowest order: photon-gluon fusion; NLO calculations available)

Beauty photoproduction
Then theoretical predictions indicate that cross section for photoproduction of beauty is larger than theoretical predictions. Resolved virtual photon component decreases with $Q^2$ $> 0.1$ GeV$^2$ not well described. Resolved virtual photon component up to $Q^2 \sim 49$ GeV$^2$ SAG photon pdf's Schuler, Sjostrand.

$D$-jet production in $p$ interactions reveals virtual photon structure need improved photon pdf's (i.e. include these data in future fits) (need angular distributions corrected, normalization not —

$\rightarrow$ Arenhuis, Fontannaz, Culler

$\rightarrow$ AFQG(HO) and GRV(HO) photon pdf's

$\rightarrow$ NLO QCD predictions below the data for resolved photon (ZEUS)

$\rightarrow$ NLO QCD predictions agree with data for pointlike photon (ZEUS) Pomer.

$\rightarrow$ JETPY calculations (HO) PyTHIA 5.7 event generator (LO)

$\rightarrow$ GRV pdf's for proton and photon (at high $p_T$, no contradiction with (H1) jet $p_T$ spectra well described).

Conclusions on Photoproduction
\[
\frac{\mathcal{W} + \mathcal{D}}{\mathcal{D}} \frac{\mathcal{M}_{\mathcal{D}} \mathcal{S}_{\mathcal{D}} \mathcal{M}_{\mathcal{D}} \mathcal{S}_{\mathcal{D}} \mathcal{D}}{1} = z d
\]

\[
\mathcal{D}f \mathcal{V}^f \mathcal{V}^f \mathcal{V}^f \mathcal{V}^f + \mathcal{D}f \mathcal{V}^f \mathcal{V}^f \mathcal{V}^f \mathcal{V}^f - z = (z \mathcal{D})^f \mathcal{B}
\]

\[
\mathcal{D}f (\mathcal{V}^f + \mathcal{V}^f \mathcal{V}^f \mathcal{V}^f \mathcal{V}^f) + \mathcal{D}f \mathcal{V}^f \mathcal{V}^f \mathcal{V}^f \mathcal{V}^f - \mathcal{D}f = (z \mathcal{D})^f \mathcal{V}
\]

\[
[(z \mathcal{D}^f x)^f \mathcal{B} - (z \mathcal{D}^f x)^f \mathcal{B}] (z \mathcal{D})^f \mathcal{B} \mathcal{X}^f x = (z \mathcal{D}^f x)^f \mathcal{B}
\]

\[
[(z \mathcal{D}^f x)^f \mathcal{B} + (z \mathcal{D}^f x)^f \mathcal{B}] (z \mathcal{D})^f \mathcal{V} \mathcal{X}^f x = (z \mathcal{D}^f x)^f \mathcal{V}
\]

\[
[(z \mathcal{D}^f x)^f \mathcal{B} - (z \mathcal{D}^f x)^f \mathcal{B}] (z \mathcal{D})^f \mathcal{X}^f x = (z \mathcal{D}^f x)^f \mathcal{X}
\]

\[
\frac{\mathcal{V}^f x}{z^f} \mathcal{X}^f x \mathcal{X}^f x = \frac{\mathcal{D}^f x}{z^f} \mathcal{B}^f x \mathcal{B}^f x
\]

Neural current of scattering:
\[([(s + p)_{\ell}(\lambda - 1) + c + n]x = \lambda^{\alpha}_{\delta d_{e}}q_{\ell}p \quad \text{Reduced double differential cross-sections:}\]

For e+ p CC scattering replace (u,c) by anti-(u,c) and anti-(d,s) by (d,s)

\[([(s x + p x)_{\ell}(\lambda - 1) + cx + nx] \left(\frac{\partial p x p}{\partial W} \right) \frac{x_{z W}}{z_{z D}} = \lambda^{\alpha}_{\delta d_{e}}q_{\ell}p \quad \text{Charged Current Scattering:}\]
Outlook

Progress in modeling of transition into low x, low Q^2 region: CFM evolution.

- Photoproduction in DIS and measurement of Q^2
- Jet production in DIS and measurement of Q^2
- Diffractive DIS
- Charm production in DIS
- Measurement of gluon density function
- Quantitative study of scaling violations
  \( x \downarrow 0.05 \) and \( \frac{1}{Q^2} \geq 1 \text{GeV}^2 \)

Measurements of structure functions over large range in

**Conclusions**

HERA offers excellent possibilities for studying \( (p)GCD (p)\)