Precision QCD Measurements at HERA

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on behalf of the H1 and ZEUS collaborations

New Physics
Diffraction
Jets
Heavy Flavour
Hadronic Final States
ep-scattering at HERA

\[ E_e = 27.6 \text{ GeV} \quad \text{and} \quad E_p = 920-460 \text{ GeV} \]

- **Q^2 \approx 0 \text{ GeV}^2**: Photoproduction \((\gamma p)\)
- **Q^2 > 1 \text{ GeV}^2**: DIS

\[ Q^2 = -q^2 \quad \text{photon virtuality} \]

\[ x = x_{BJ} \quad \text{Bjorken scaling variable} \]

\[ y \quad \text{Inelasticity in proton rest frame} \]
Interaction matrix @ HERA

<table>
<thead>
<tr>
<th>DIS</th>
<th>LO</th>
<th>NLO</th>
<th>NNLO...</th>
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<tbody>
<tr>
<td>e</td>
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<td>q</td>
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<td>p</td>
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<tr>
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<th>charm</th>
<th>beauty</th>
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<th>gluon</th>
<th>quarks</th>
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<tr>
<td>p</td>
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<td>q</td>
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Reduced DIS NC cross section

Neutral current

\[ \sigma_{NC}^{red}(e^\pm p) = \frac{xQ^4}{2\pi\alpha_{em}Y_+} \frac{d^2\sigma_{NC}}{dx dQ^2} = \frac{F_2}{Y_+} \frac{Y_-}{x} \tilde{F}_3 - \frac{y^2}{Y_+} \tilde{F}_L \]

- Valence + sea quarks dominant
- Valence quarks high \( Q^2 \)
- Gluons high \( y \)

\[ Y_\pm = 1 \pm (1 - y^2) \]
Reduced DIS NC cross section

Data well described by NLO QCD over 4 orders of magnitude in $x, Q^2$
Search for new physics

Data well described by NLO QCD at high $Q^2$ $\Rightarrow$ limits on new physics
Contact interactions

H. Pirumov

New physics with scale $\Lambda \gg Q^2$

- Compositeness
- Leptoquarks
- Extra dimension
- Quark radius

Limits on compositeness scale up to 7.2 TeV
LQ-limits in the BRW model:

[GeV]  
H1  ZEUS
Vector ($\lambda = 0.3$)  800  629
Scalar ($\lambda = 0.3$)  530  466

Scalar LQ limit from ATLAS 607 GeV
No vector LQ limits from LHC so far

H1 Search for First Generation Scalar Leptoquarks

$\lambda = 0.3$

ZEUS

$\lambda = 0.3$

excluded
Interaction of lepton flavour violating leptoquarks:

\[ e q \rightarrow LQ \rightarrow \mu (\tau) q \]

Mass limits ($\lambda = 0.3$) ranges up to 712 GeV (2nd generation LQ); 479 GeV (3rd generation LQ)

Limit from Atlas
Single top production

SM (CC) : $e p \rightarrow v t X \rightarrow v(\mu) v b$

FCNC: $e p \rightarrow e t X \rightarrow e(\mu) v b$

Exclusion region extended for small $tuZ$-couplings
A surprise @ HERA start:
\[ \approx 10\% \text{ with no fwd-activity} \]
\( \Rightarrow \) diffraction

- \( x_{IP} \) p-momentum fraction carried by the colourless exchange (IP)
- \( \beta \) IP-momentum fraction carried by the struck quark
- \( t \) momentum transfer at the proton vertex

Techniques: leading proton or large rapidity gap
Contributions: protons or protons + low mass \( \Delta, N^* \)
Diffraction

DGLAP pQCD Approach

Collinear factorisation:
- $Q^2$ evolution à la DGLAP
- diffractive PDFs

Proton vertex factorisation:
$\beta$, $Q^2$ dependence decoupled from $x_{IP}$, $t$ dependence
Pomeron PDF $\otimes$ Pomeron flux
Pomeron flux from Regge theory

Dipol Approach

$\psi(z,r,Q^2)$: $\gamma qq$ wave function
$T_{qq}$: $qq(qqg)$-proton elastic scattering amplitude
$T_{qq}$ parameterized in the saturation model

$+qqg$ dipol diagrams
Combination of FPS/LPS data

V. Sola  H1prelim-11-111, ZEUS-prel-11-011

Combination includes all correlations
profits from different detectors (systematics)
Combination of FPS/LPS data

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Combination includes all correlations

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Combination of FPS/LPS data

Combination includes all correlations.

Profits from different detectors (systematics)

Cross calibration reduces uncertainties significantly.

Scaling violation clearly visible.

Most precise data as test bench for theory.
New data sets combined with previously published data 
35× more data @ medium $Q^2$

\[
\frac{\text{LRG}}{\text{FPS}} = 1.203 \pm 0.019 \pm 0.087 \\
\text{(exp) (norm)}
\]

(agrees with previous meas.)

LRG and FPS data agree well 
NLO QCD (DPDF) does well for $Q^2 > 10$ GeV$^2$
Comparison to recent ZEUS data (corrected to same $Q^2$ and $M_Y<1.6$ GeV)

ZEUS data: ≈10% higher shape agreement

NLO QCD + DPDF:
- problems @ low $Q^2$
- good for $Q^2>10$ GeV$^2$

Dipol model with saturation:
- good @ low $Q^2$
- too low at high $Q^2$ and $\beta$

**Diffraction with LRG**

E. Sauvan

DESY-12-041

Karin Daum

DIS2012 Bonn March, 26th 2012

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$F_L$ in Diffraction

D. Salek

“Rosenbluth plot”

Direct measurement of $F_2^D$ and $F_L^D$ (no assumptions)

Clearly non-zero $F_L^D$

Predictions agree (no distinction possible)
$\sigma_r^D \propto F_2^{D} - \frac{y^2}{1+(1-y)^2} F_L^D$

$\sigma_r^D$ for same $x, Q^2$ at different $E_p (s)$

First measurement of $F_L^D$

$R^D = \frac{F_L^D}{F_2^D - F_L^D}$

$R^D/R = 2.8 \pm 1.1$

Longitudinal photons more important in diffraction than in inclusive DIS
Diffractive Di-jet production (FPS)

2 topologies:
- 2 central jets
- 1 cen. + 1 fwd. jets

Deviation from DGLAP?

DPDF + NLO QCD works well
No sign for deviations from DGLAP
\( t \)-slope consistent with inclusive diff.
\( \Rightarrow \) Proton vertex factorisation holds
Forward jet correlations (DIS)

L. Goerlich

Test of QCD dynamics @ low x:
- DGLAP: strong $k_T$ ordering
- BFKL: weak $k_T$ ordering $\Rightarrow$ more fwd jets
- CCFM: random in $k_T$ $\Rightarrow$ even more fwd jets

Expected de-correlation effects from $O(\alpha_s^n)$

- Cross section described best by BFKL-type model (CDM)
- $\Delta\phi$ shape: initial differences washed out by parton showers
Inclusive jets in photoproduction

NLO QCD underestimates data at low $p_T$ and large $\eta$

Theory may be reconciled with data by
- adding multiple interactions or
- using a different photon PDF
Inclusive jets in photoproduction

Analysis based on different jet algorithms: $k_t$, anti-$k_t$, SIScone

Results are very consistent

Running of $\alpha_s$ clearly visible in a single experiment

$\alpha_s(M_Z) = 0.1206^{+0.0023}_{-0.0022}$ (exp.) $^{+0.0042}_{-0.0035}$ (theo.)

As for many other processes at HERA theory uncertainties are dominating due to missing NNLO calculations
Combined NLO fit to normalised inclusive, dijet and trijet cross sections

\[ \alpha_s(M_Z) = 0.1166 \pm 0.0011 \text{(exp)} \pm 0.0014 \text{(PDF)} \pm 0.0008 \text{(had)} \pm 0.0044 \text{ (theo)} - 0.0035 \]
\( \alpha_s \) from HERAPDF 1.6/1.7

K. Nowak  
H1prelim-11-031, ZEUS-prel-11-001

**HERAPDF 1.6**
- Combined PDF + \( \alpha_s \) fit to:
  - combined incl. HERA-I+II data
  - published DIS jet data

**HERAPDF 1.7**
- Combined PDF + \( \alpha_s \) fit to:
  - combined incl. HERA-I+II data
  - published DIS jet data
  - combined \( F_2^{cc} \) data
  - low proton energy data

\( \Rightarrow \) same results \( \Rightarrow \) all processes "see" the same PDFs

\[ \alpha_s(M_Z) = 0.1202 \pm 0.0013 \text{(exp)} \pm 0.0007 \text{(model)} \pm 0.0012 \text{(had)} \pm 0.0045 \text{(theo)} \]
Summary on $\alpha_s$

$\alpha_s$ determinations at HERA with sizable uncertainties - missing NNLO

World average dominated by $\alpha_s$ from lattice calculations (appropriate for perturbative calculations?)

All extractions do have caveats e.g. non-perturbative physics higher order contributions…

$\alpha_s$ from HERA with small experimental uncertainties

Precision spoiled due to lack of NNLO calculations
Heavy flavour physics @ HERA

Charm contribution to DIS at HERA up to $\sim 30\%$ (Beauty: $1\% - 2\%$)

Perturbative calculations are faced with a "battle of scales*)"$

m_c, p_T, Q^2$

*) O. Behnke

Different approaches:

- "massive" = charm produced perturbatively
- "massless" (ZM-VFNS) = charm constituent of the proton
  - both not valid in the full phase space

GM-VFNS combines both approaches
  - but how to do the transition? Just make a choice!

Can charm data tell and thereby remove ambiguities?

We better understand charm to get reliable PDFs
Massive NLO QCD describes data reasonably.
Massless (ZM-VFNS) fails.
D* production in DIS

A. Gizhko
ZEUS-prel-11-012

Charm tagging: reconstruction of D* mesons

- High precision data well described by NLO QCD in the full analysis phase space

⇒ provide precise input for $F_2^C$
Charmed jets in DIS

V. Libov

Charmed jet production described by theory within uncertainties
Data more precise than NLO QCD predictions also for charm

Heavy flavour predominantly via photon-gluon-fusion

Charm tagging: displaced tracks in jets plus jet mass

Karin Daum

DIS2012 Bonn March, 26th 2012
$F_{2}^C$ from charmed jets in DIS

V. Libov

ZEUS-prel-12-002

$F_{2}^{cc} = \sigma_{red}^{cc} + \frac{y^2}{1+(1-y)^2} F_{LL}^{cc}$

Charm tagging:
displaced tracks in jets
plus jet mass

-$F_{2}^C$: good agreement
among measurements
-valuable input for PDFs
Dijet $D^*$ meson photoproduction

-Z. Staykova

- MC@NLO underestimates resolved contribution
- non-$D^*$ jet has significant from gluons for $\eta > 0$
Production of hadrons

LO MC models discussed:
Lepto (MEPS): matrix element with parton showers
CDM: color dipol model
+ Lund string model

NLO calculations discussed:
\( \sigma(\text{ep} \rightarrow \text{ehX}) \propto \text{PDF} \otimes \sigma \otimes \text{FF} \)

FF with contributions from quark, anti-quark and gluon (as PDFs)
AKK+CYCLOPS: parameterized from fits to e^+e^- data
DSS: parameterized by fitting to e^+e^-, pp and ep data

Understanding fragmentation as important as understanding PDFs
**K_0^S** and **Λ^0** scaled momentum spectra

I. Abt

DESY-11-205

Monte Carlo models (CDM, MEPS) give a fair description

NLO QCD: AKK+CYCLOPS fails – DSS reasonable at larger x_p

Steep rise with Q^2 at small x_p
Population due to gluon splitting

Scaling violations clearly visible

Steep fall with Q^2 at small x_p
Depletion due to gluon radiation
$K_0^S$ and $\Lambda^0$ scaled momentum spectra

I. Abt

CDM, MEPS give a fair description - but 20% too high

NLO QCD: AKK+CYCLOPS much too steep in $x_p$
Production of very forward photons

At large $\eta$ MCs much above data
⇒ fragmentation to $\pi^0$s in p-remnant not well modeled in MCs

$\gamma$-yield independent of $Q^2,x$
⇒ p-remnant does not “feel” the hard interaction
Conclusions

- The Standard Model is healthy
  - no sign for new physics at HERA

- HERA provides precision measurements in many areas of QCD
  - analyses are profiting from all the efforts made to get the best data

- There is a grain of salt:
  - almost everywhere large theory uncertainties due to missing of NNLO QCD calculations

Still some way to go to finalise the rich HERA physics programme