Final combined deep inelastic scattering cross sections at HERA

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On behalf of the H1 and ZEUS Collaborations

- Introduction: motivation, HERA and DIS
- Data combination
- Physics highlights
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- Summary

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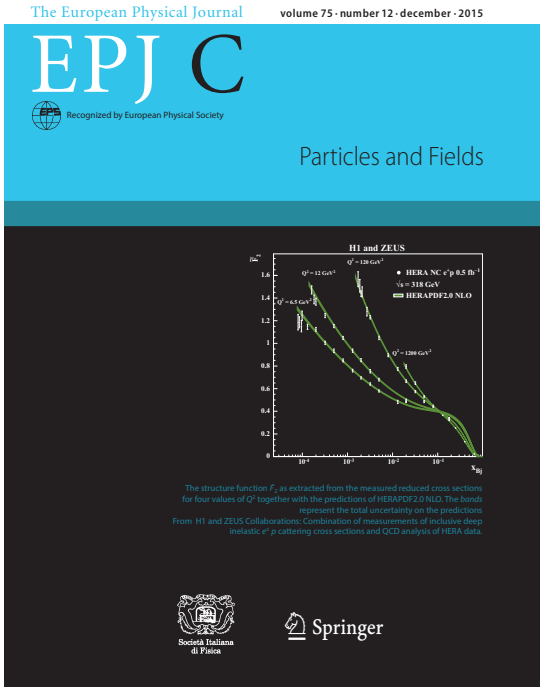


Alexander von Humboldt Stiftung/Foundation

Introduction

Motivation—DIS at HERA

Probe the electroweak structure of the Standard Model :

- Unification of electromagnetism and weak force.
- Chiral nature of electroweak force.

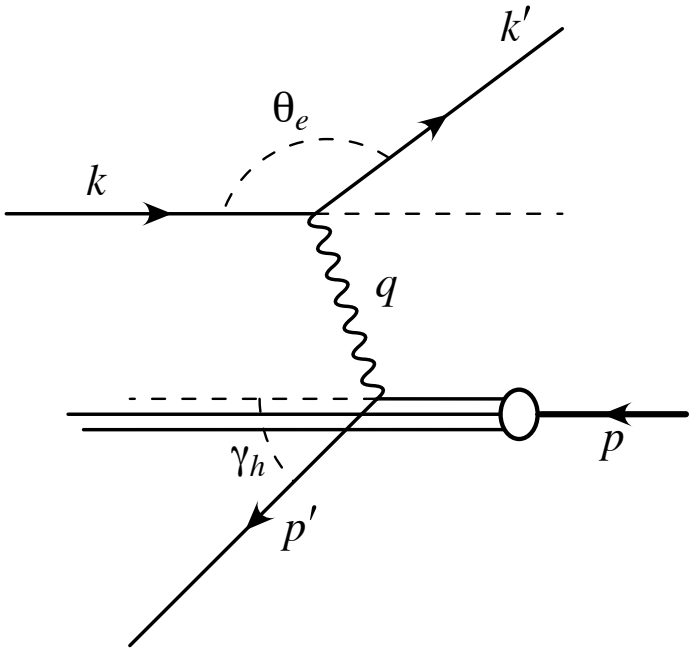
Want to understand the structure of the proton :

- As protons are bound by the strong force, can learn much on the (strong) interaction through study of the structure.
- Provide precise determination of the partonic density functions (PDFs) of the proton to be used at other proton colliders.

Comparison with theory:

- Allows extraction of fundamental QCD parameters, e.g. quark masses and α_s.
- Allows extraction of fundamental EW parameters, e.g. qZ couplings, $sin^2\theta_W$, etc.
- May elucidate new physics, e.g. quark substructure, or will constrain it.

Deep inelastic scattering : definitions



Momentum transfer :

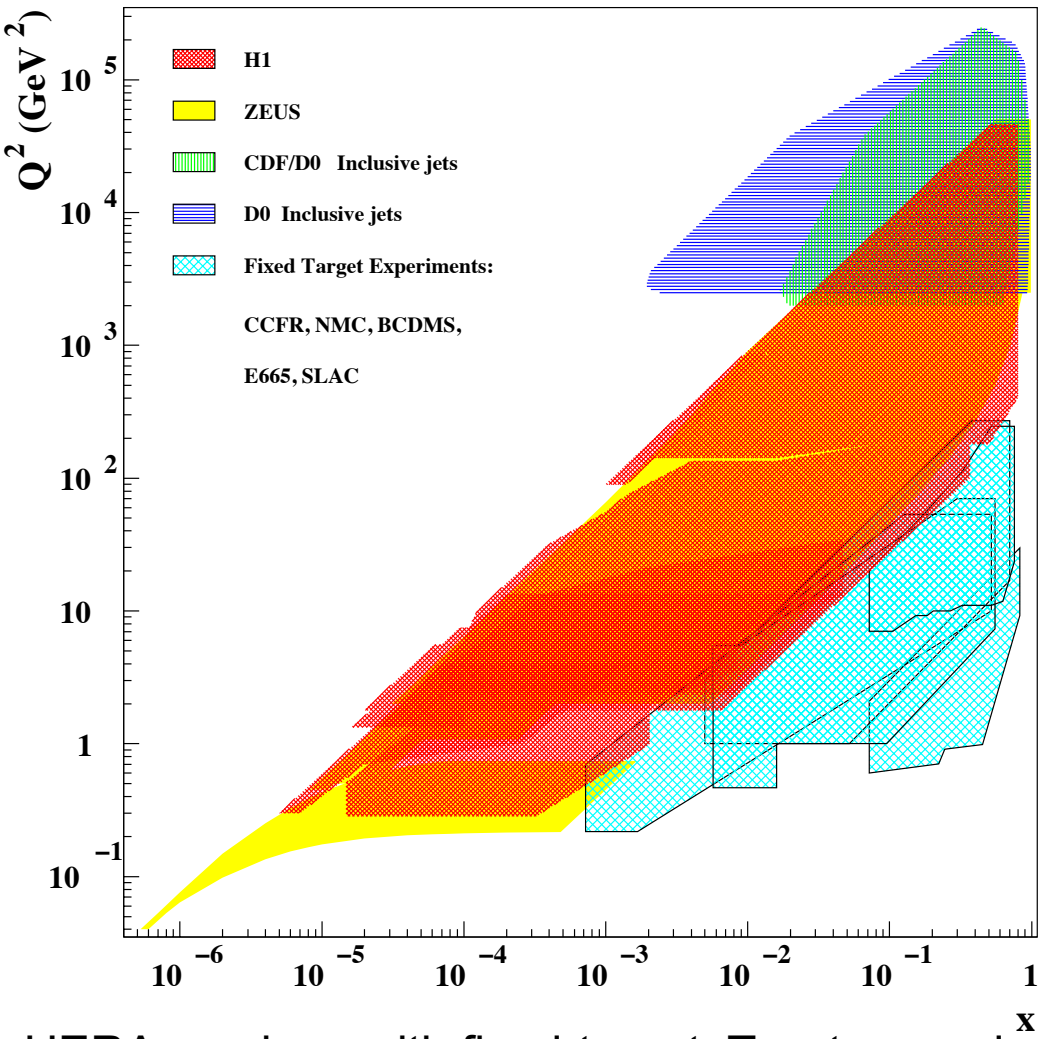
$$Q^2 = -q^2 = -(k-k')^2$$

Momentum fraction carried by struck parton :

$$x = Q^2/(2p\cdot q)$$

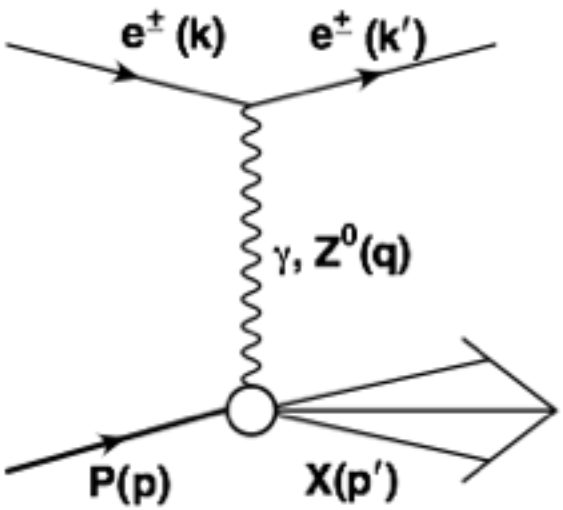
Inelasticity :

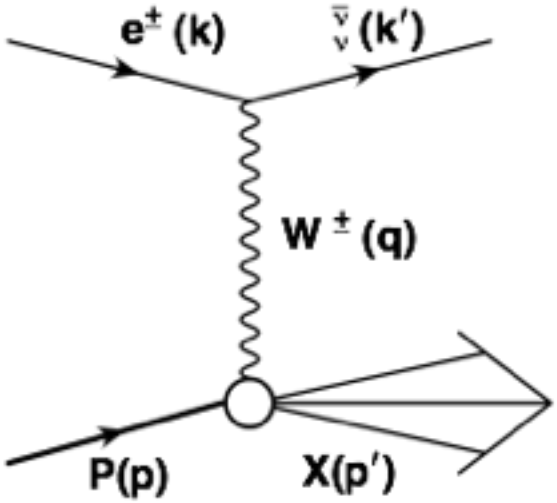
$$y = (q\cdot p)/(k\cdot p)$$



HERA overlaps with fixed-target, Tevatron and LHC experiments

Neutral and charged current DIS processes





$$\frac{d^2\sigma^{e^\pm P}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2 \mp Y_- xF_3 - y^2 F_L\right]$$

$$\frac{d^2\sigma^{e^\pm P}}{dxdQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^2}{Q^2+M_W^2}\tilde{\sigma}^{e^\pm P}$$

$F_2 \sim$ **sum of q and $\bar{q}$ densities**

$xF_3 \sim$ **density of valence quarks; from Z exchange**

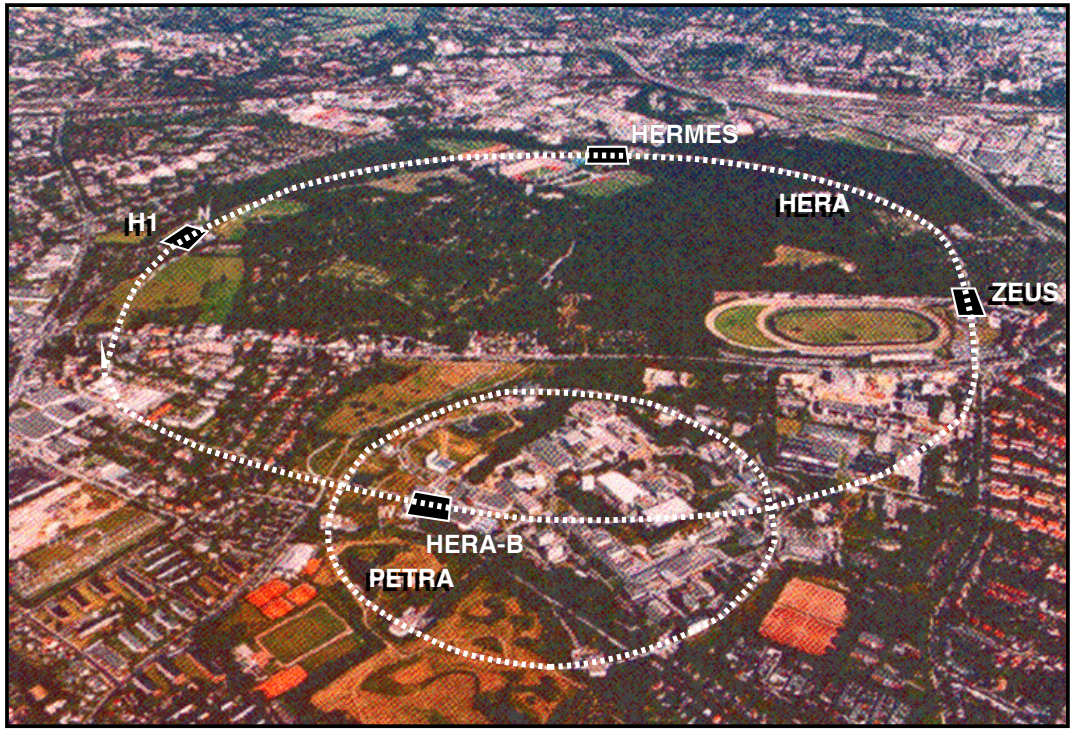
$F_L \sim$ **gluon density**

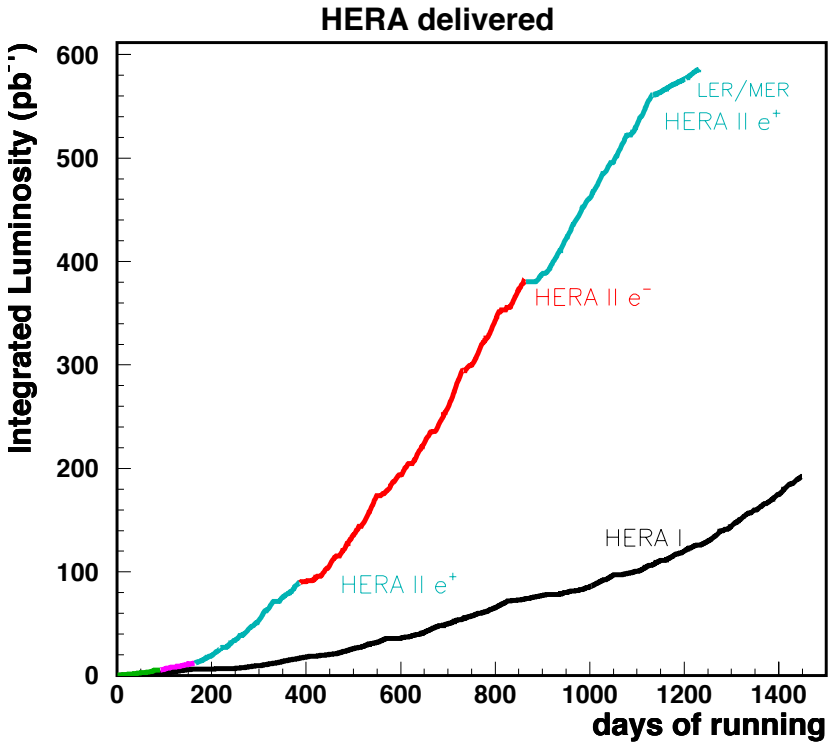
$$\tilde{\sigma}^{e^+P} \sim \left(\bar{u} + \bar{c} + (1-y)^2(d+s)\right)$$

$$\tilde{\sigma}^{e^-P} \sim \left(u + c + (1-y)^2(\bar{d}+\bar{s})\right)$$

Sensitive to individual quark flavours

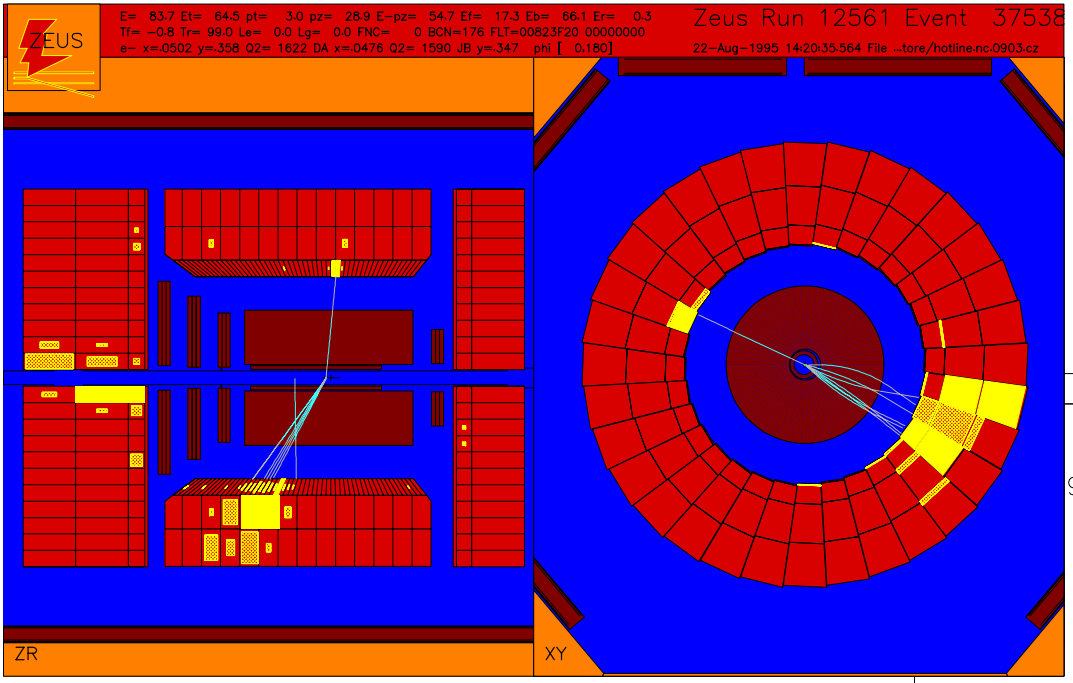
The HERA collider





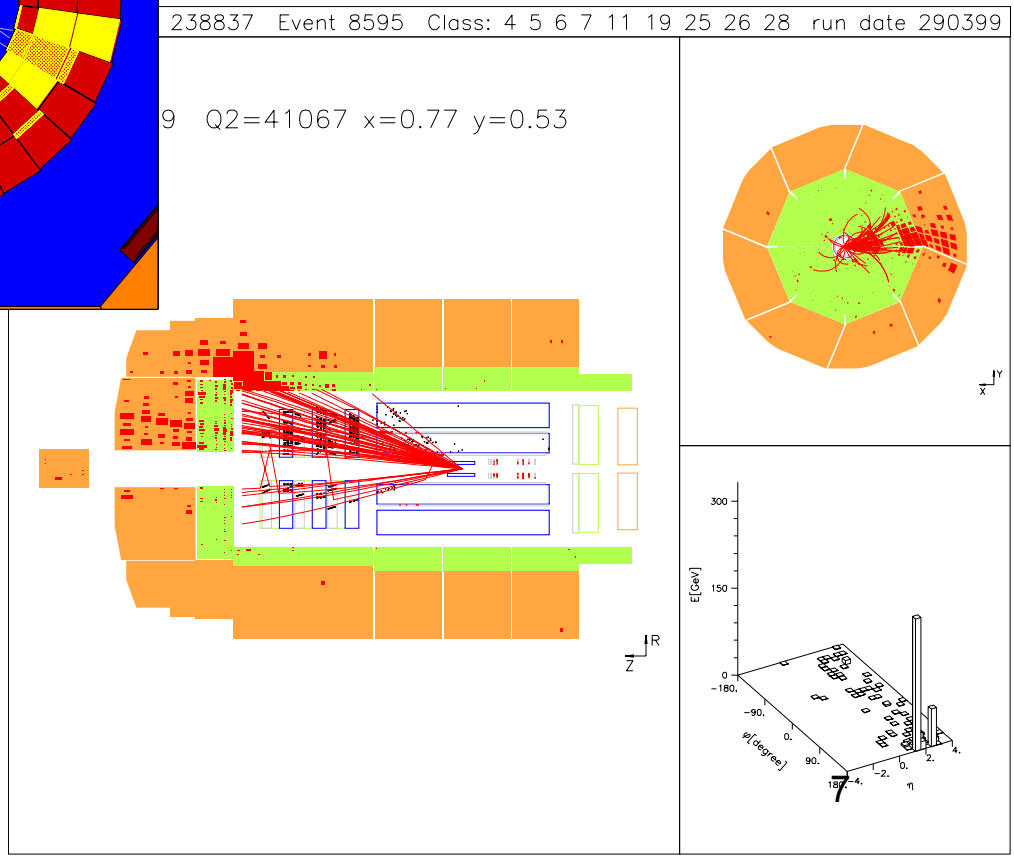
- During 1992–2007, mainly E_e = *27.5 GeV*, E_p = *920 GeV* giving $\sqrt{s}$ ~ *320 GeV;* and dedicated data at different proton energies.
- Colliding-beam experiments collected combined sample ~ *1 fb*$^{-1}$.
- About 75% data taken with polarised (~ 30%) lepton beams, with equal amounts of e^- and e^+ and positive and negative polarisation.

DIS events in H1 and ZEUS



Charge current :

- Missing p_T from escaped neutrino
- Hadronic jet
- Reconstruction not as precise, larger backgrounds

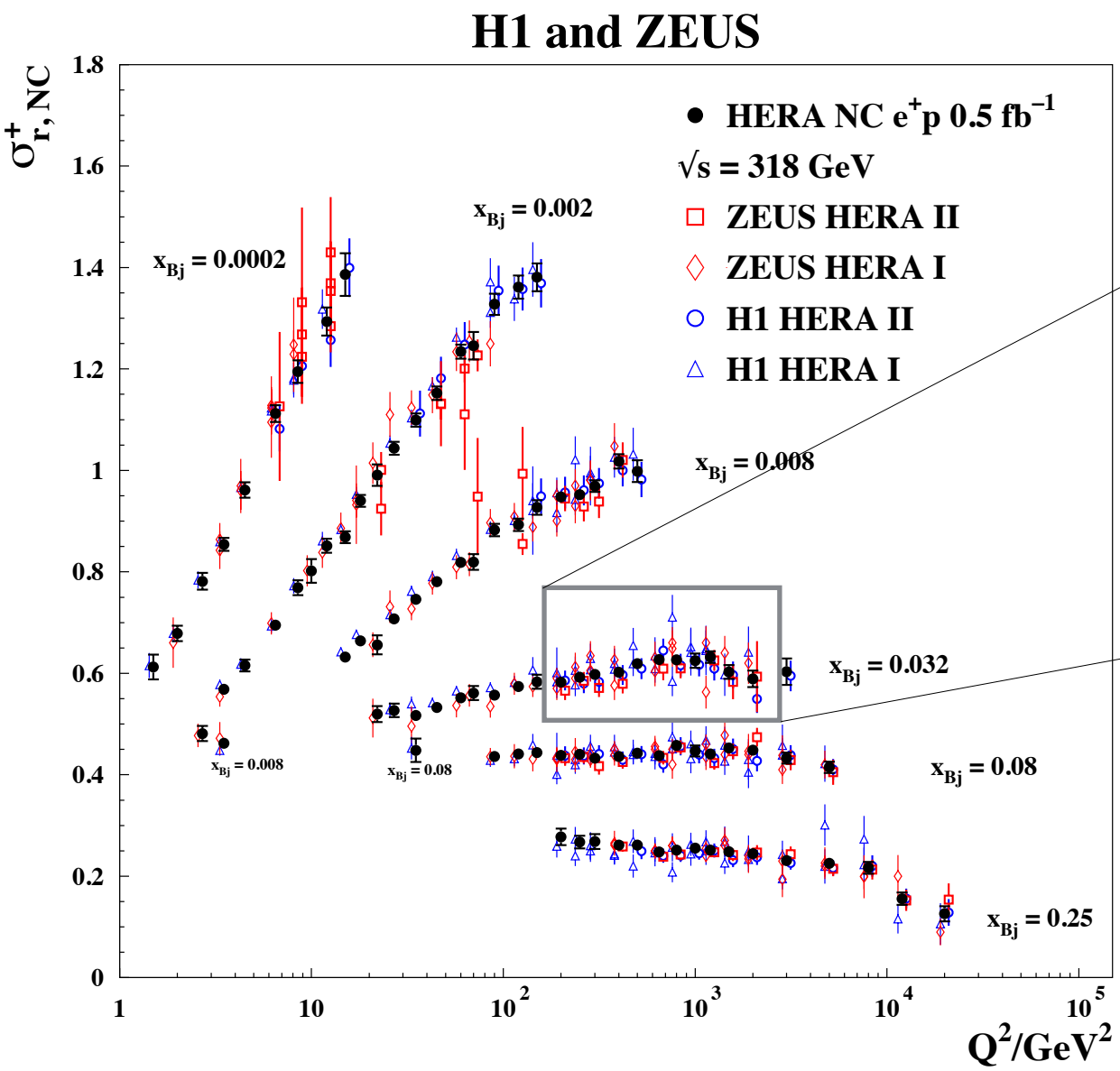


Neutral current :

- High energy isolated electron
- Back-to-back with hadronic jet
- Kinematics can be reconstructed in several ways, clean samples

Data combination

Combined NC data

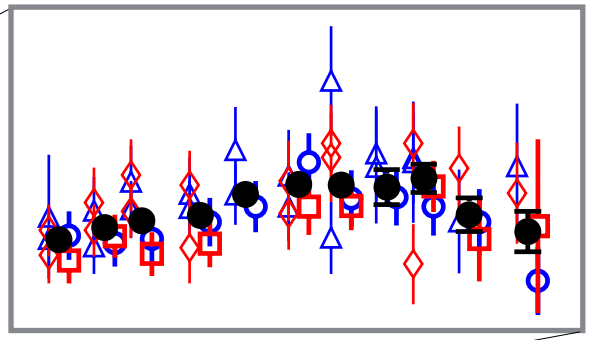


Combined 41 data sets

2927 → 1307 points

$0.045 < Q^2 < 50000\ GeV^2$

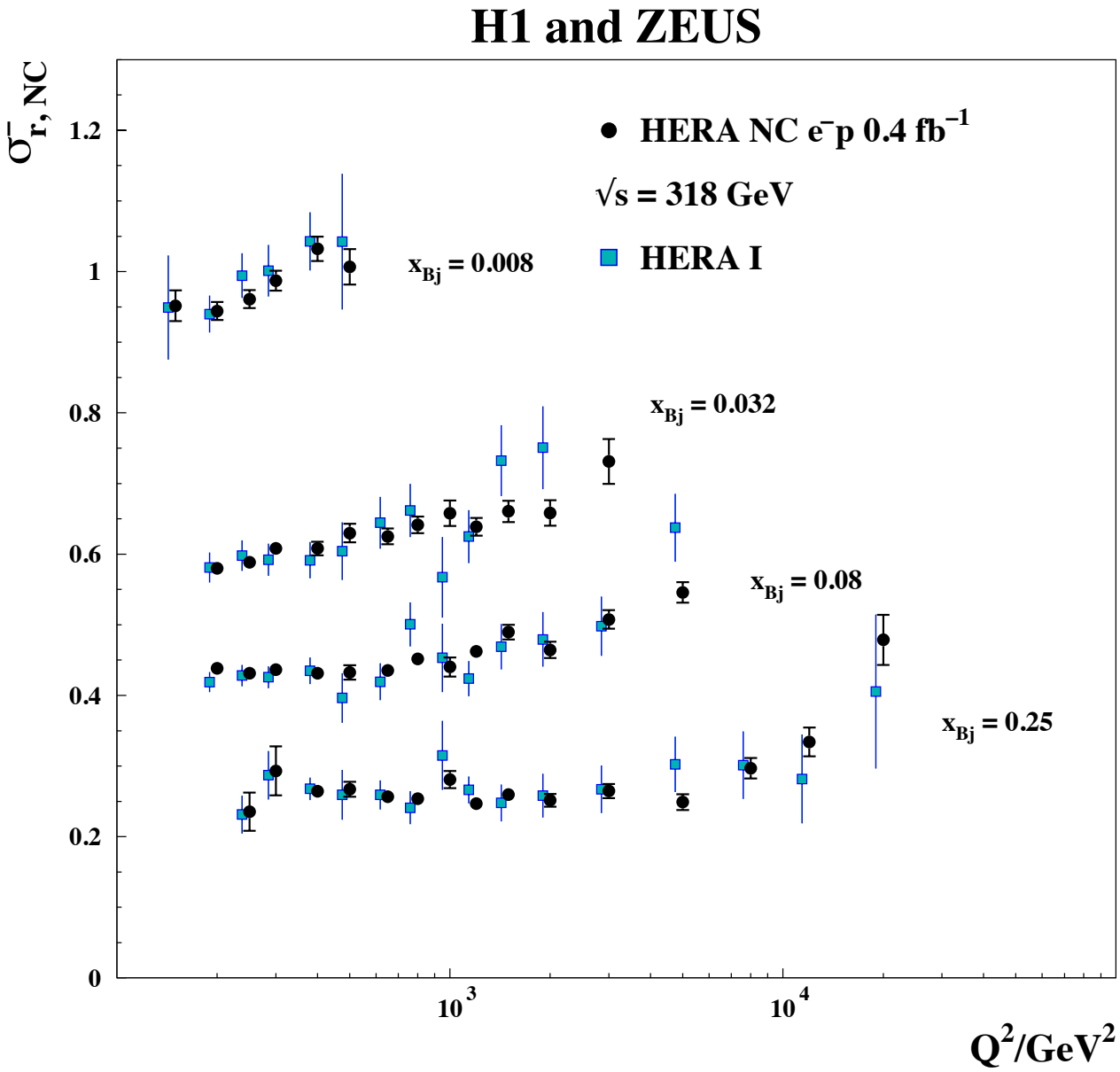
~160 systematic uncertainties



Up to eight cross sections at a given point

$\chi^2/ndf = 1.04$; consistent data sets

Comparison with HERA I combination



Overall improvement compared to HERA I

- 4 × lumi

Particularly at high Q^2

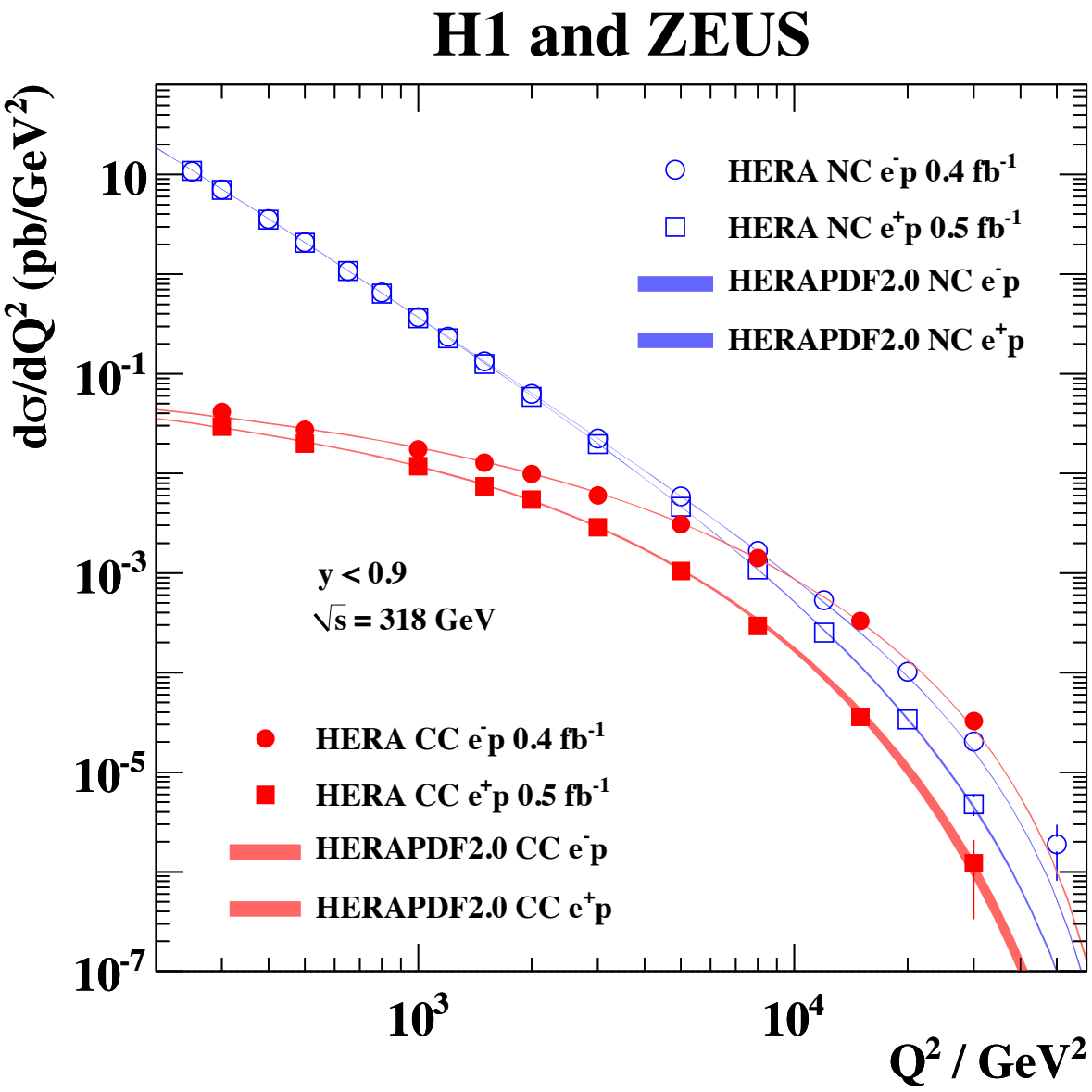
And particularly for e^-p data

- 15 × lumi

Consistent combination and high-precision data set.

Physics highlights

Electroweak unification



Cross section for both neutral and charged current interactions

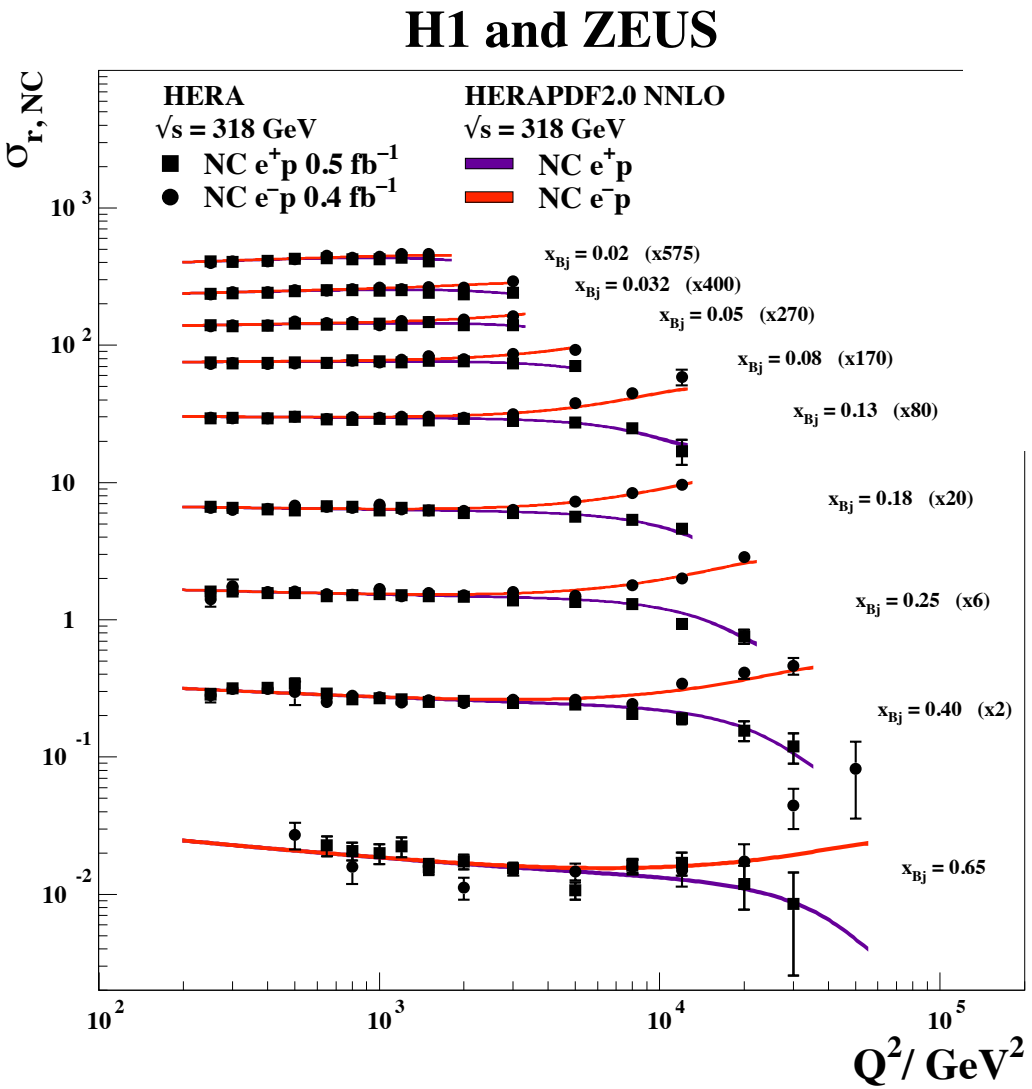
Photon exchange dominates at low Q^2

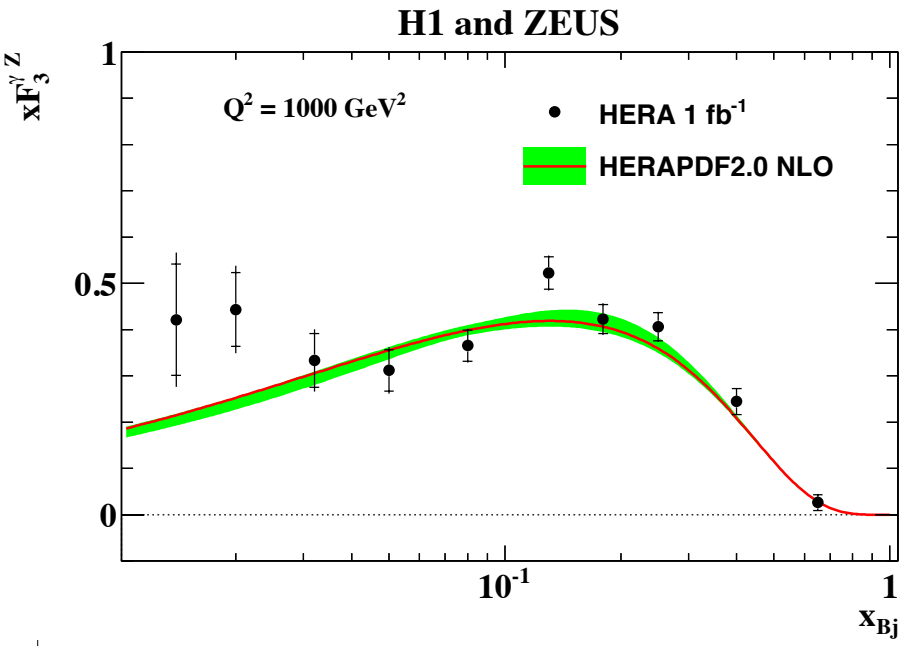
NC and CC become similar at $Q^2 \sim 10{,}000\ GeV^2$

Difference in e^+p and e^-p due to γ–Z interference

Beautiful demonstration of electroweak unification

Photon–Z interference





Clear γ–Z interference effects

Allows extraction of $xF_3^{\gamma Z}$

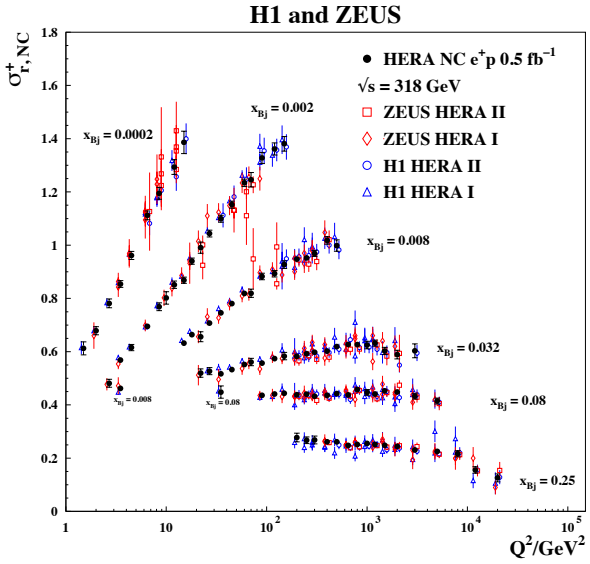
Probes the valence structure of the proton

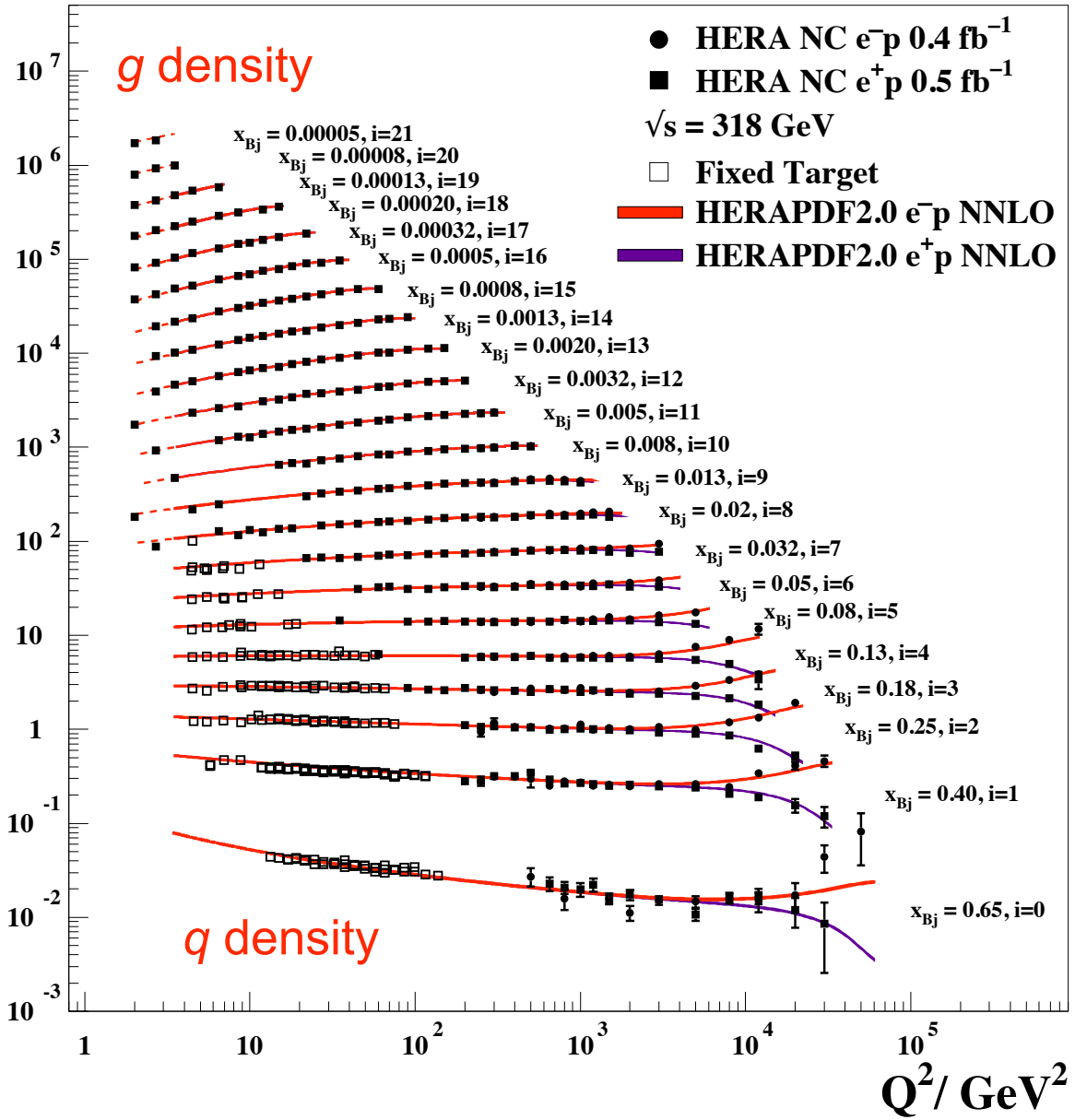
Scaling violations

Scaling violations over a huge kinematic range.

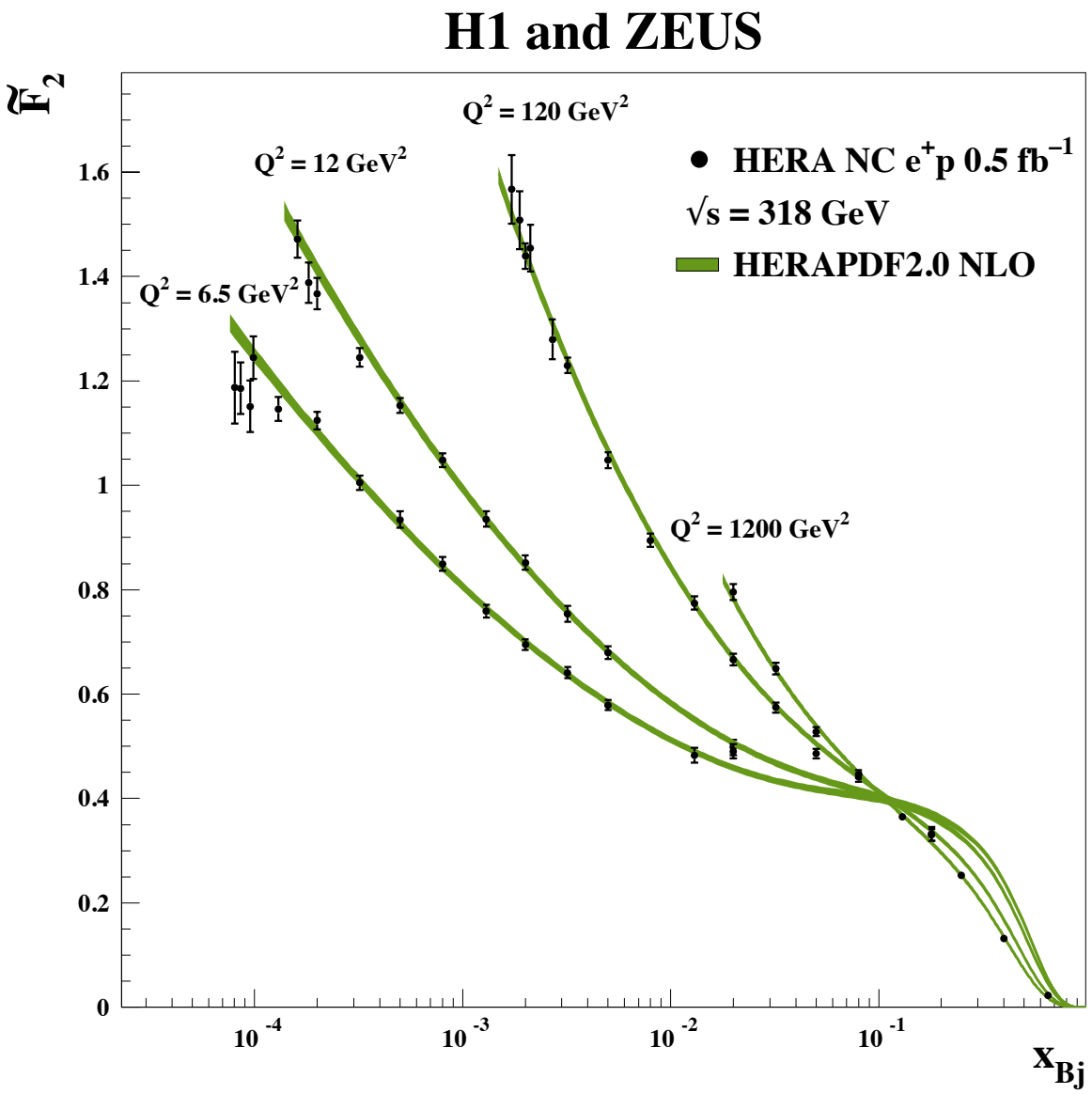
Remember data-only plot, below.

Indicative of a large gluon density in proton.





Rise of the gluon density



Rise of gluon density can also be seen in F_2.

Rise is steeper with increasing Q^2

- as in previous page.

High precision demonstration.

Detailed understanding or structure of the proton crucial.

QCD analysis, HERAPDF2.0

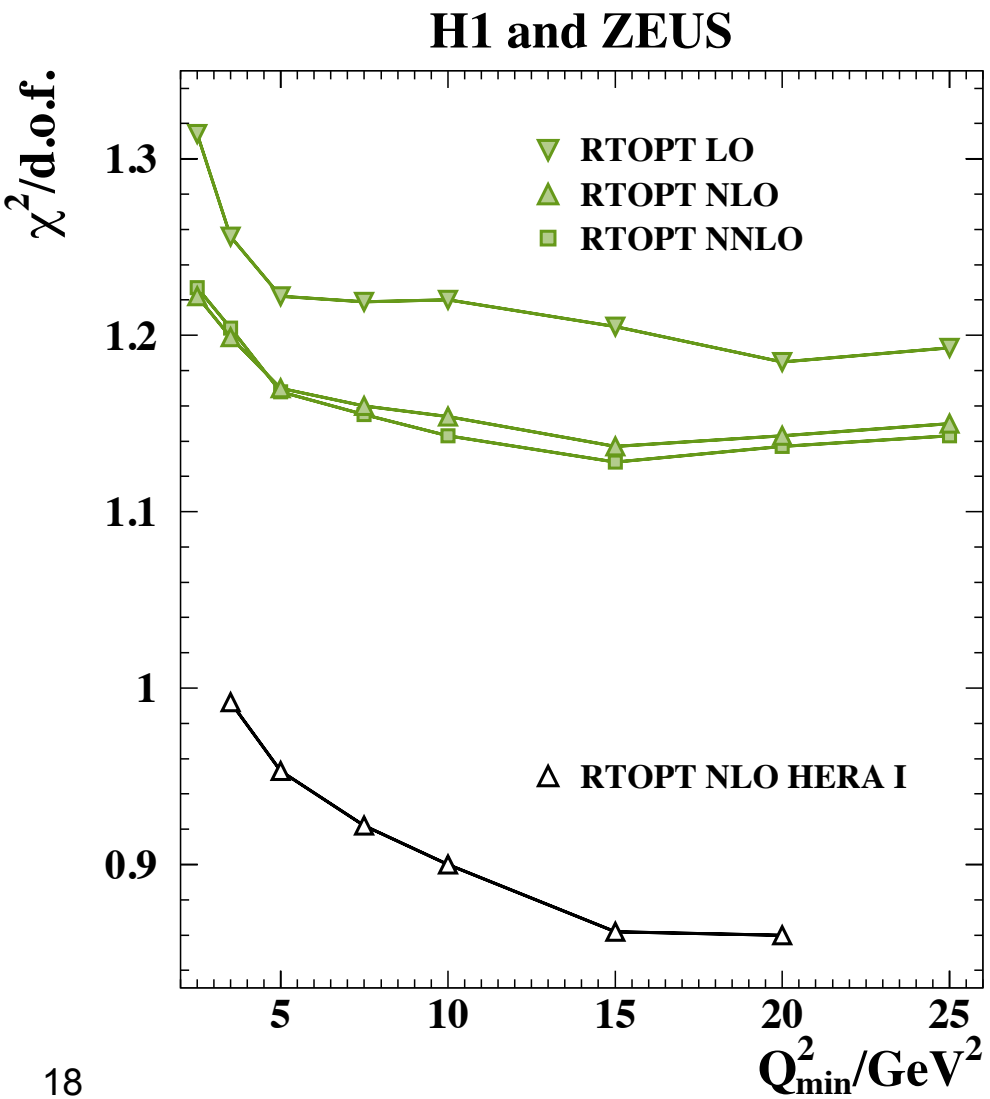
QCD analysis, HERAPDF2.0

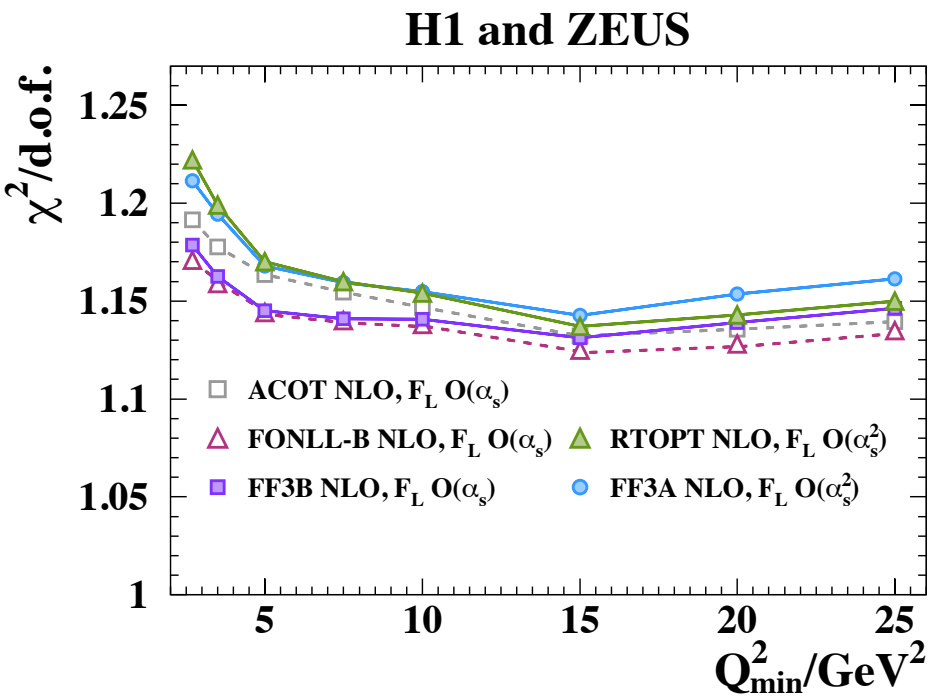
- These data used as sole input to QCD analysis.
- QCD fit in ranges $3.5 < Q^2 < 50{,}000\ \text{GeV}^2$, $0.651 \times 10^{-4} < x_{Bj} < 0.65$
- DGLAP equations solved at LO, NLO and NNLO.
- $\alpha_s\,(M_Z) = 0.118$
- PDFs parametrised as:

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1 + D_{\bar{U}}x\right), \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

- χ^2 fit accounting for correlations of uncertainties, with model and parametrisation uncertainties.

HERAPDF2.0 Q^2 dependence





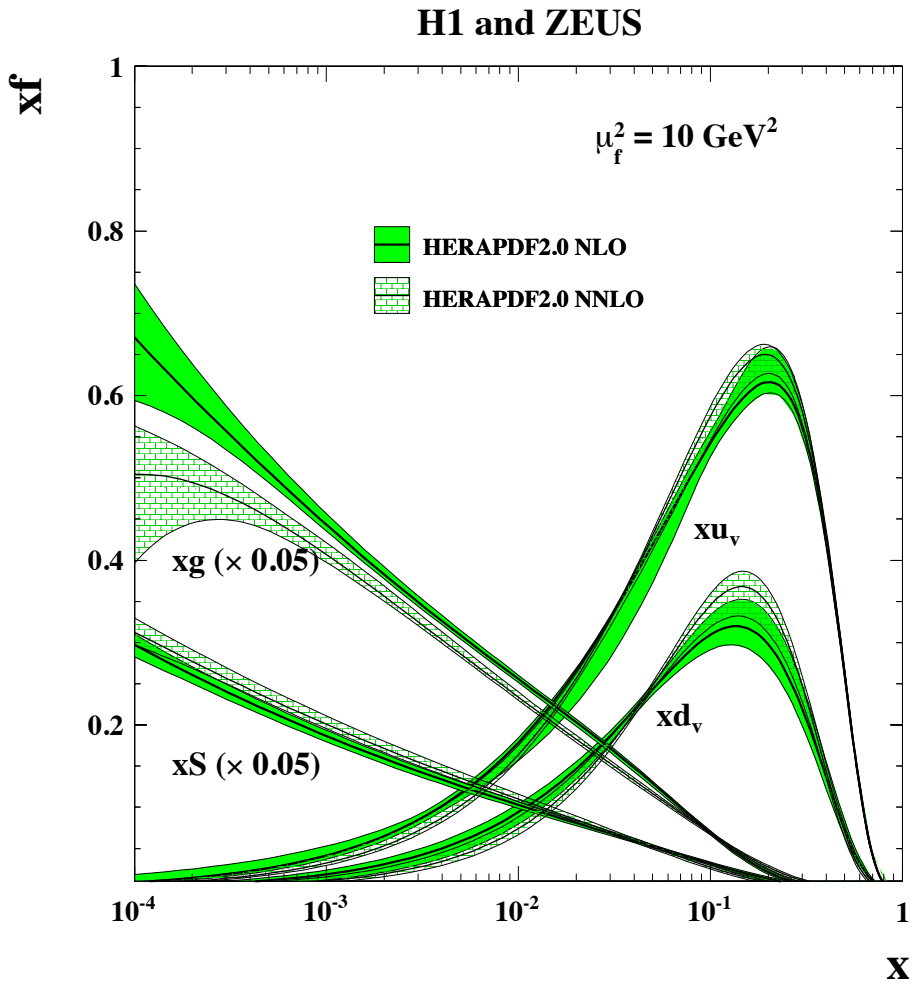
Overall χ^2 about ~*1.2* and significant Q^2 dependence.

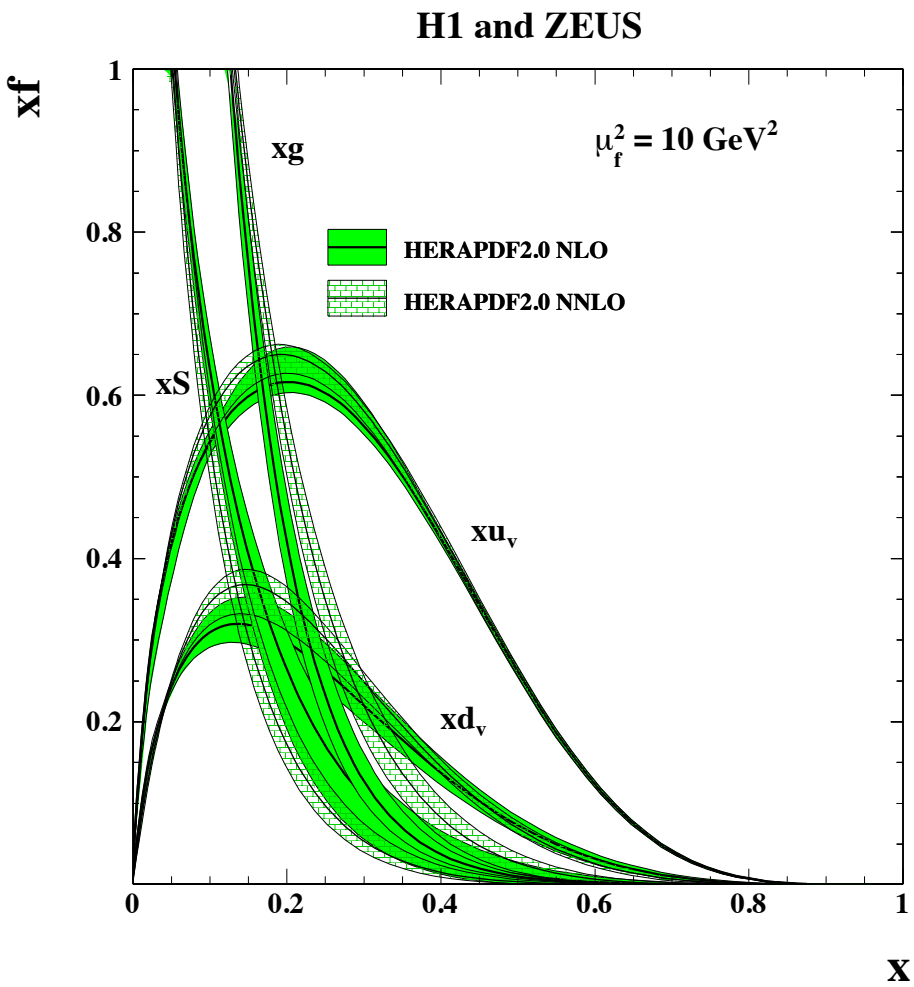
NNLO not better than NLO.

Dependent on schemes.

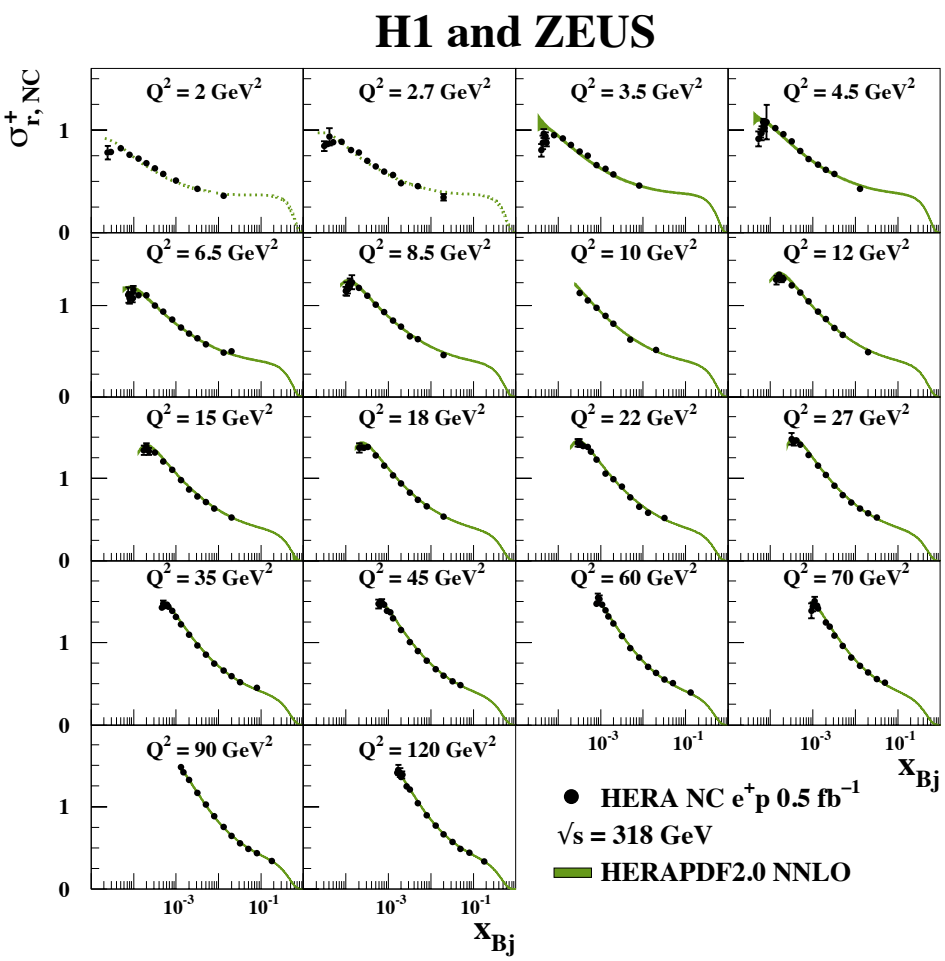
Indication of breakdown of DGLAP ?

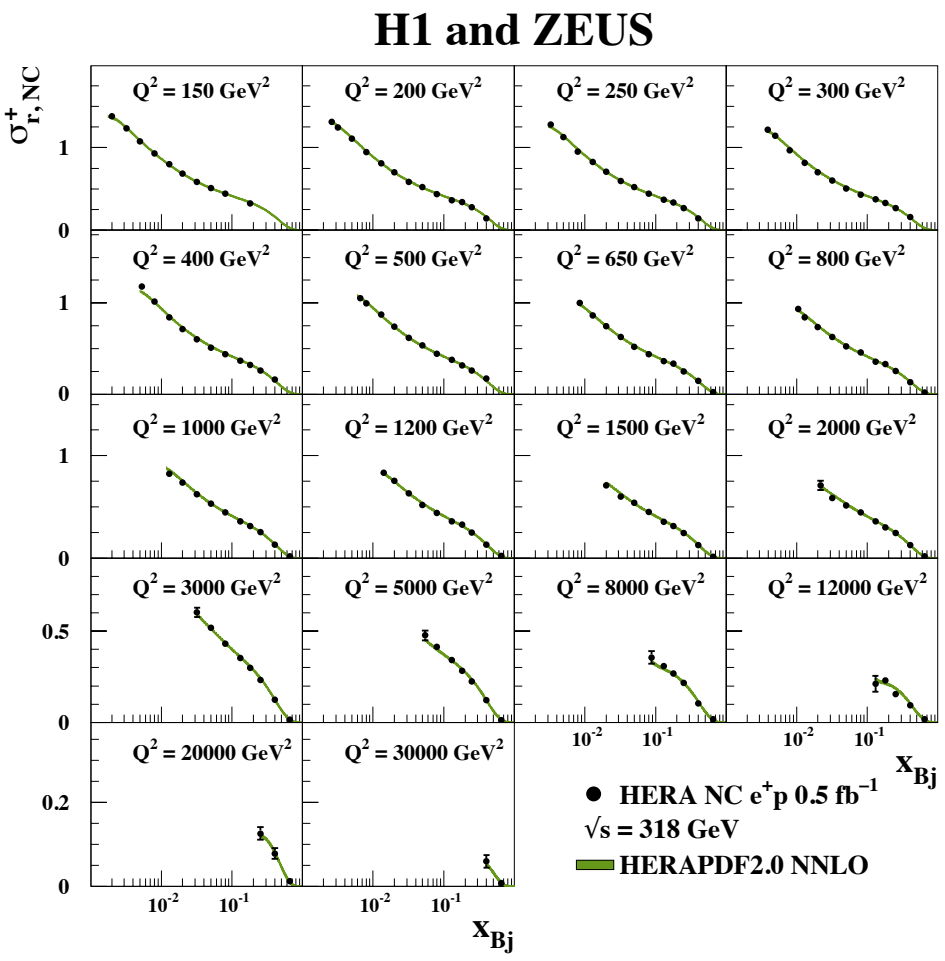
HERAPDF2.0 at NLO and NNLO





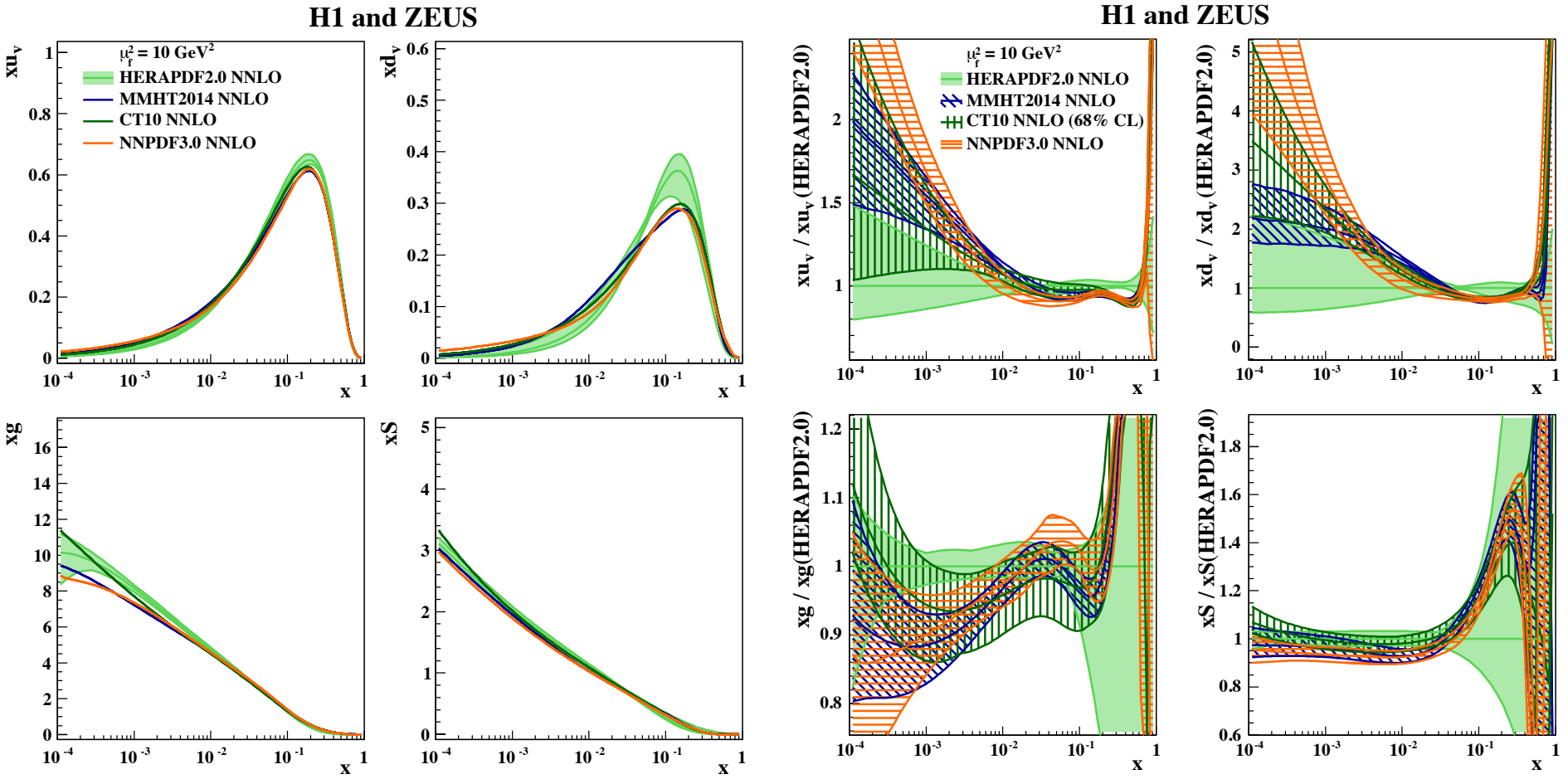
HERAPDF2.0 compared to data





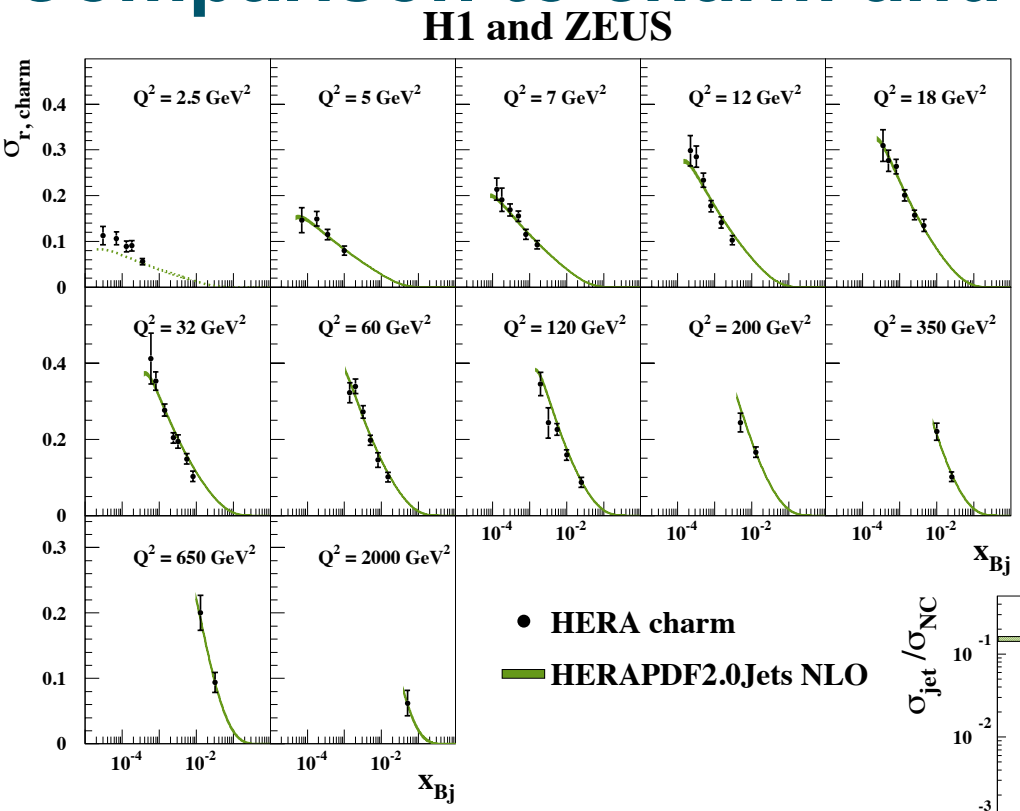
Good description of the data (just examples shown here).

Comparison to other PDFs



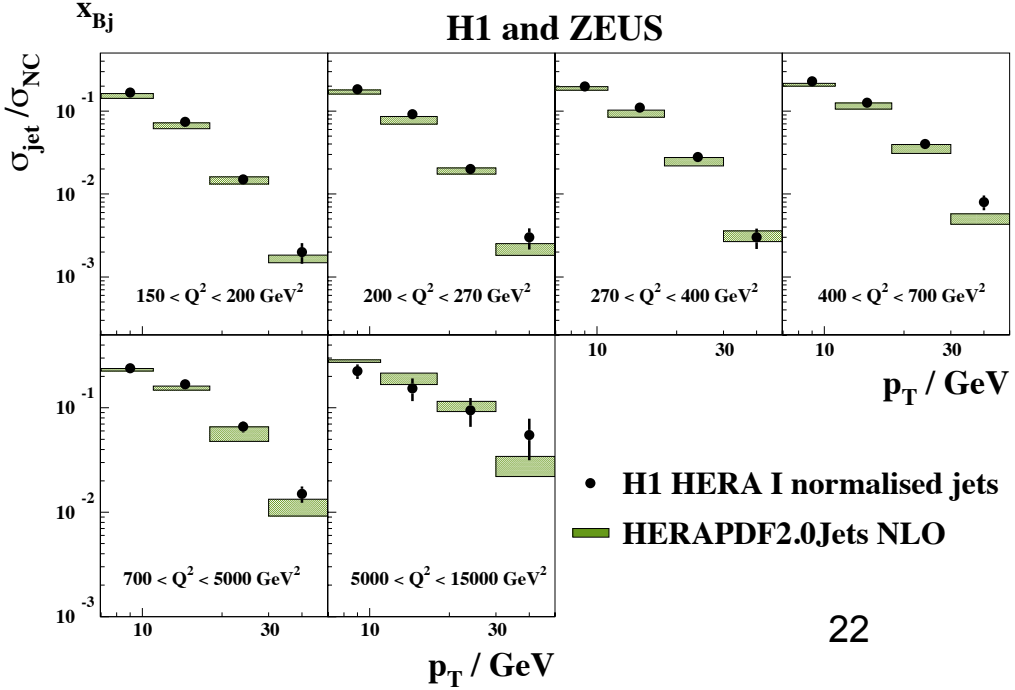
Overall PDFs are compatible (other comparisons with different schemes).

Comparison to charm and jet data



Very good description of charm data

Very good description of jet data

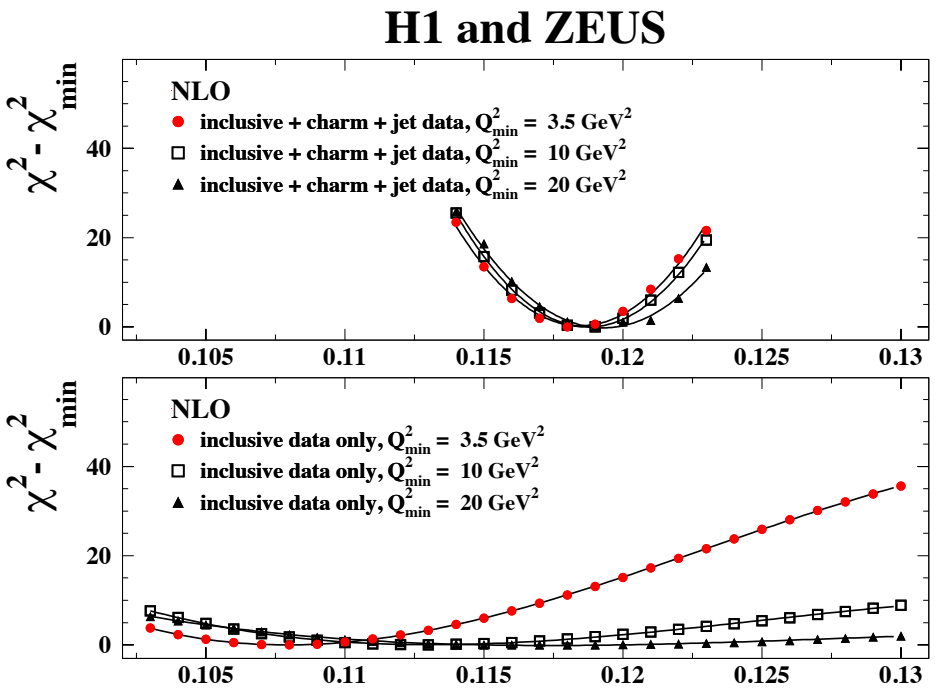


Extraction of α_s

Inclusive DIS data alone is weakly dependent of α_s.

Inclusion of jet data allows a precise extraction to be made.

Similar PDFs are found compared to nominal fit with α_s fixed to 0.118.



$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0009(\text{exp}) \pm 0.0005(\text{model/parameterisation})$$
$$\pm 0.0012(\text{hadronisation}) \; {}^{+0.0037}_{-0.0030}(\text{scale}) \; .$$

Uncertainties dominated by scale variation in theory.

Extracted at NLO as jet calculations not available at NNLO.

Excellent agreement with the world average.

Summary

Summary

- H1 and ZEUS have combined inclusive *ep* scattering cross sections for all *1 fb*$^{-1}$ of data taken.
- The data span six orders of magnitude in Q^2 and x_{Bj}.
- Beautiful demonstrations of electroweak unification, scaling violations, etc.
- Used as sole input to QCD analysis of PDFs in the proton, HERAPDF2.0 up to NNLO.
- Comparison with jet data also led to a precise extraction of the strong coupling constant.
- Deeper understanding of the structure of matter and crucial input to the LHC programme.
- A veritable milestone of the HERA programme.