Precision QCD measurements at HERA

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on behalf of the H1 and ZEUS Collaborations

OUTLINE:

- NC *ep* cross sections at high Bjorken x — *Phys.Rev.D89(2014)072007*
- NC *ep* cross sections at large y — *Phys.Rev.D90(2014)072002*
- NC *ep* cross sections at high Q^2 and $\sqrt{s}$ = 225 and 252 GeV and extraction of F_L — *E.P.J.C 74(2014)2814*
- Combination of inclusive *ep* cross sections — *ArXiv:1506.06042, submitted to EPJC*
- QCD analysis of combined *ep* cross sections — *ArXiv:1506.06042, submitted to EPJC*

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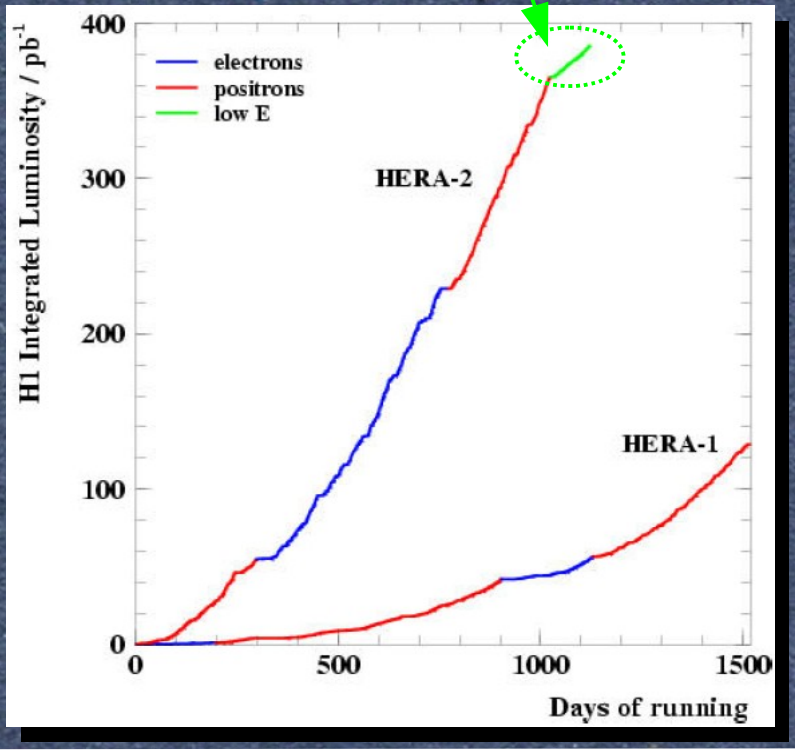
Introduction

HERA, worlds only *ep* collider, located at DESY, Hamburg

- HERA I: 1992 – 2000
- HERA II: 2003 – 2007
  - Low proton energy runs in the end of HERA operation

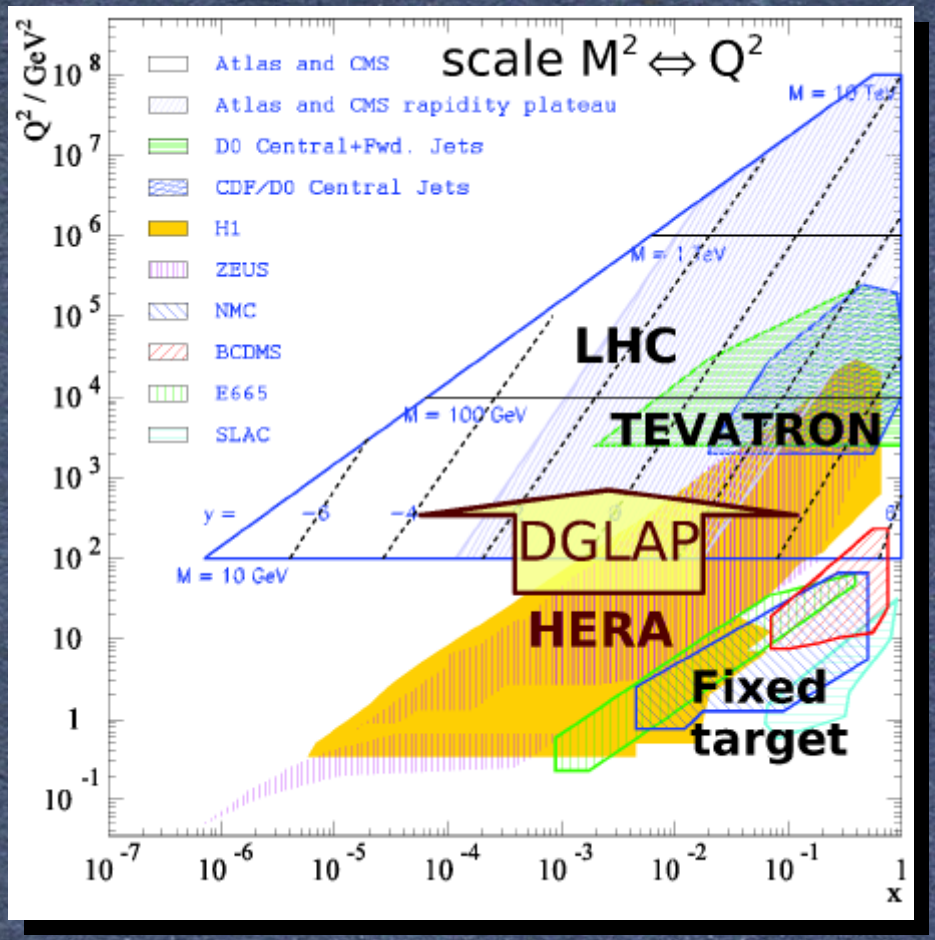


Two collider experiments H1 and ZEUS

- Collected ~*0.5* fb^{-1} of data per experiment

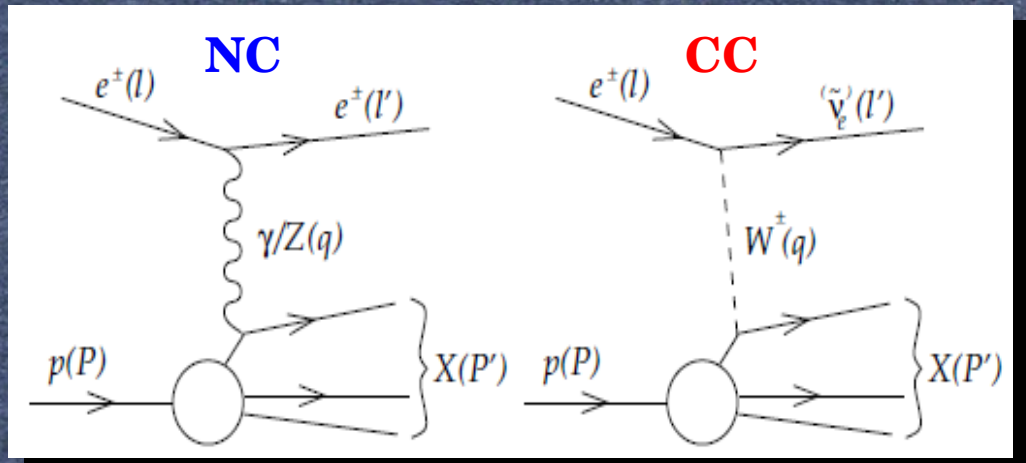
Inclusive deep inelastic *ep* scattering (DIS)

- HERA data covers a wide range in x



- DGLAP allows to evaluate PDFs from HERA to the LHC region

- Neutral and charged current processes



Virtuality of exchanged boson:

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

Bjorken scaling variable:

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

Inelasticity:

$$y = (P \cdot q) / (P \cdot l)$$

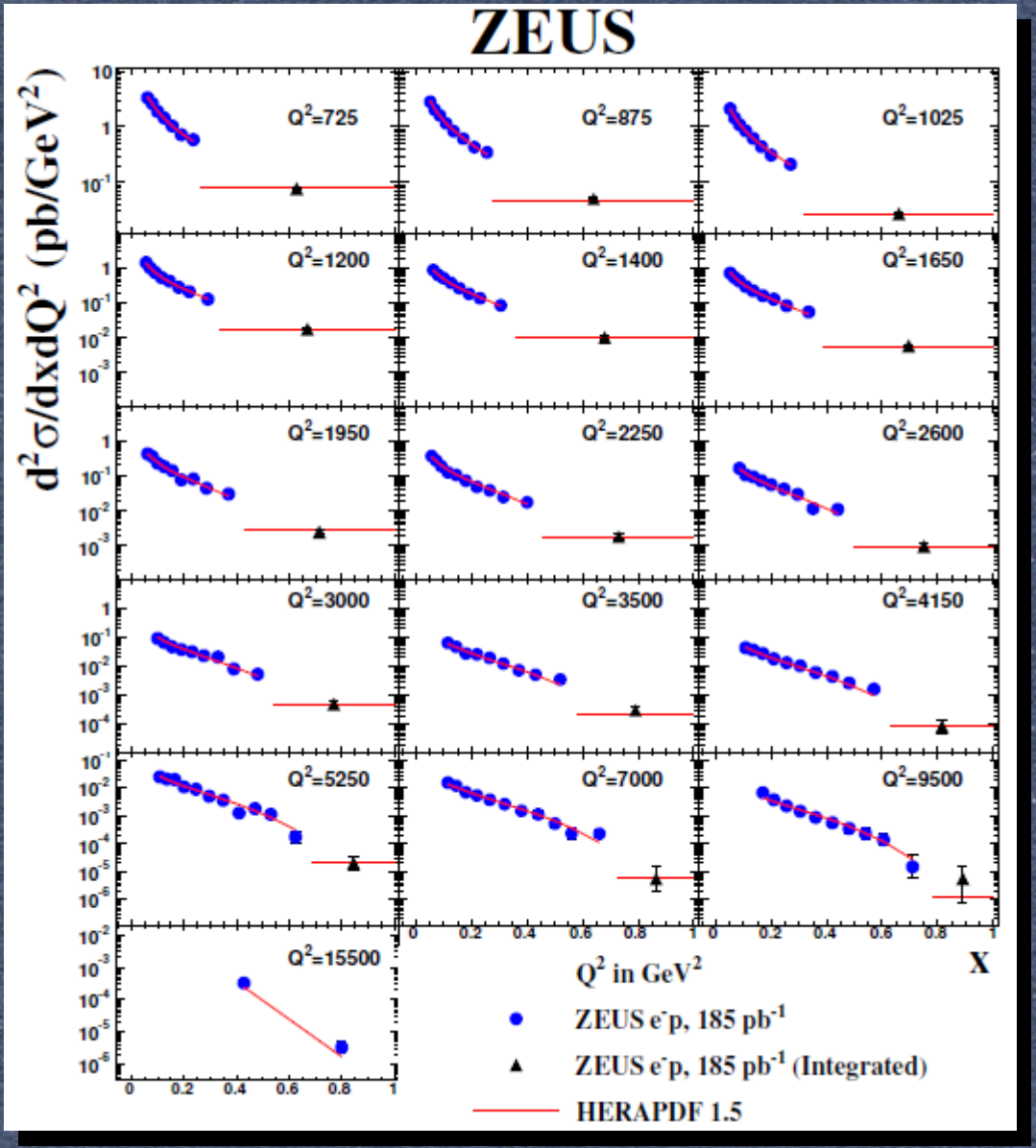
Centre of mass energy squared:

$$s = (l + P)^2 = Q^2 / (x \cdot y)$$

- NC and CC processes provide a unique opportunity to study proton's structure

NC *ep* cross section measurement at high x

Phys.Rev.D89(2014)072007



- High x available from fixed target experiments is only at low Q^2.
- Measuring high x high Q^2 data allows to have additional constrains on PDFs in that region.
- NC ep DIS cross sections at $Q^2 > 725$ GeV^2 up to $x \cong 1$ measured by ZEUS experiment.
- The measurement shows a good agreement with the Standard Model predictions.

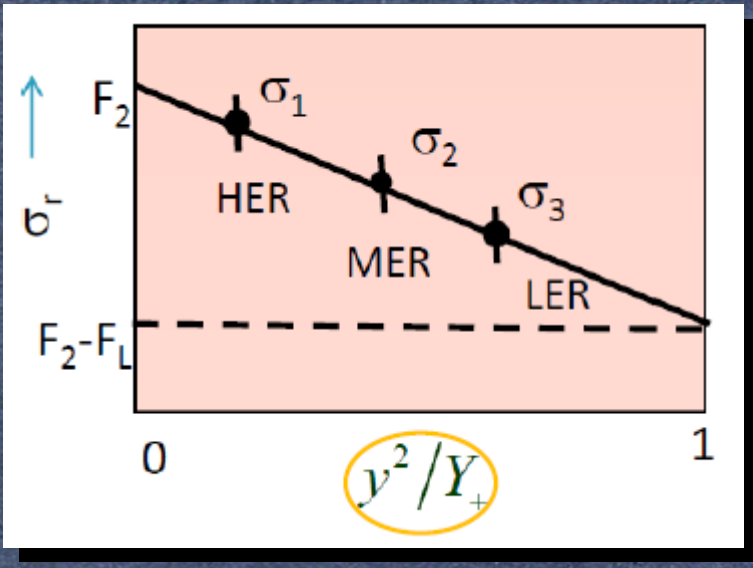
NC cross section and F_L structure function

E.P.J.C 74(2014)2814, Phys.Rev.D90(2014)072002

At moderate values of Q^2:

$$\tilde{\sigma}_{NC}(x,Q^2,y) = \frac{d^2\sigma^{ep}_{NC}}{dxdQ^2} \cdot \frac{xQ^4}{2\pi\alpha Y_+} = F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)$$

where $Y_+ = 1+(1-y)^2$



- Bulk of HERA data: $\sqrt{s}$ = *318* GeV (HER)
- By the end of HERA run: $\sqrt{s}$ = *225* GeV (LER) and $\sqrt{s}$ = *251* GeV (MER) data
- This allows to measure NC cross sections at fixed x and Q^2 for different values of y → disentangle F_L and F_2 structure functions

- **F_L is a QCD effect, direct measurement of which allows to test pQCD**
- **F_L is directly sensitive to the gluon**

NC *ep* cross section at $\sqrt{s}$ = *225, 251* and *318* GeV

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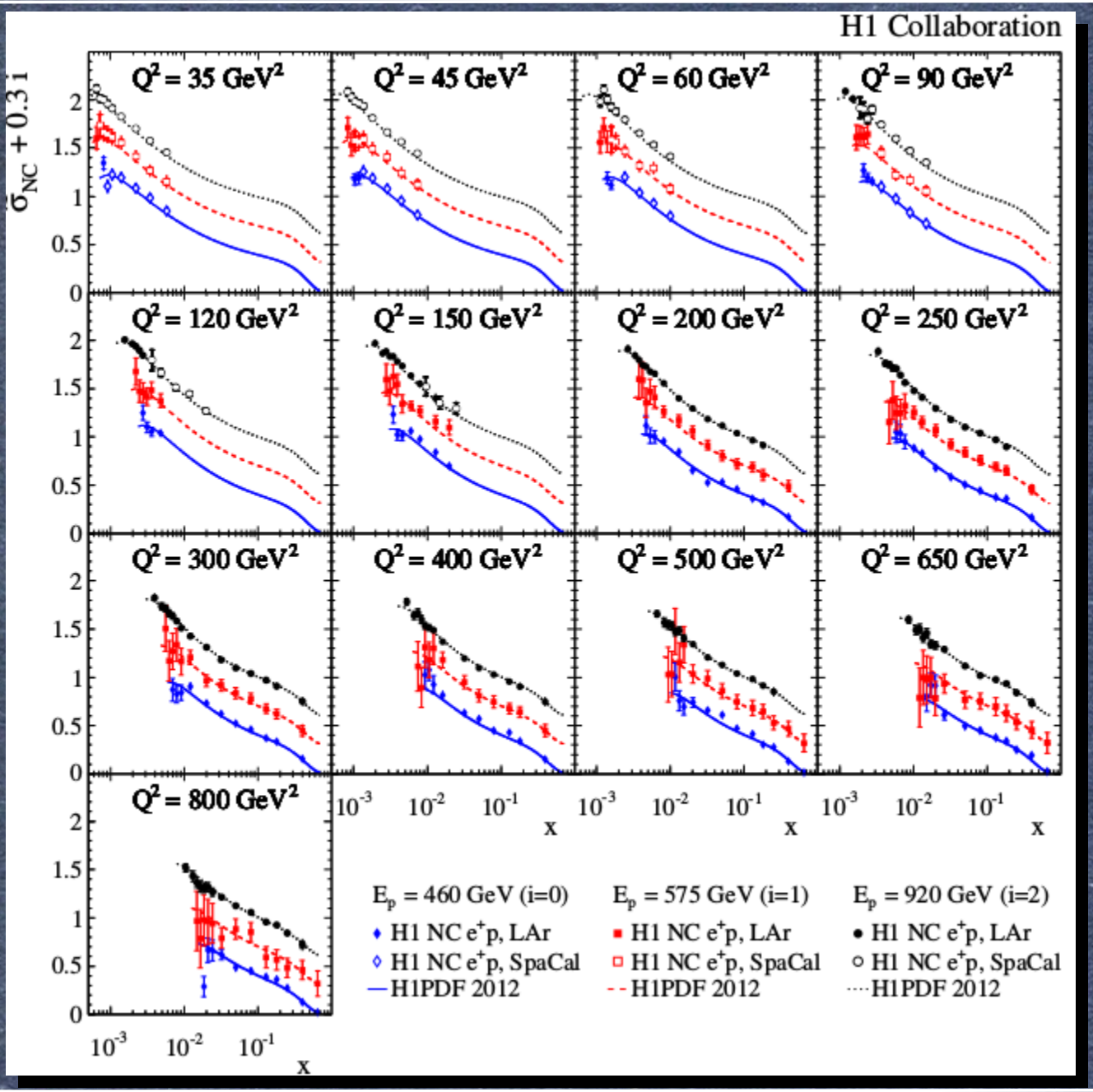


NC cross sections measured by the H1 at different center of mass energies.

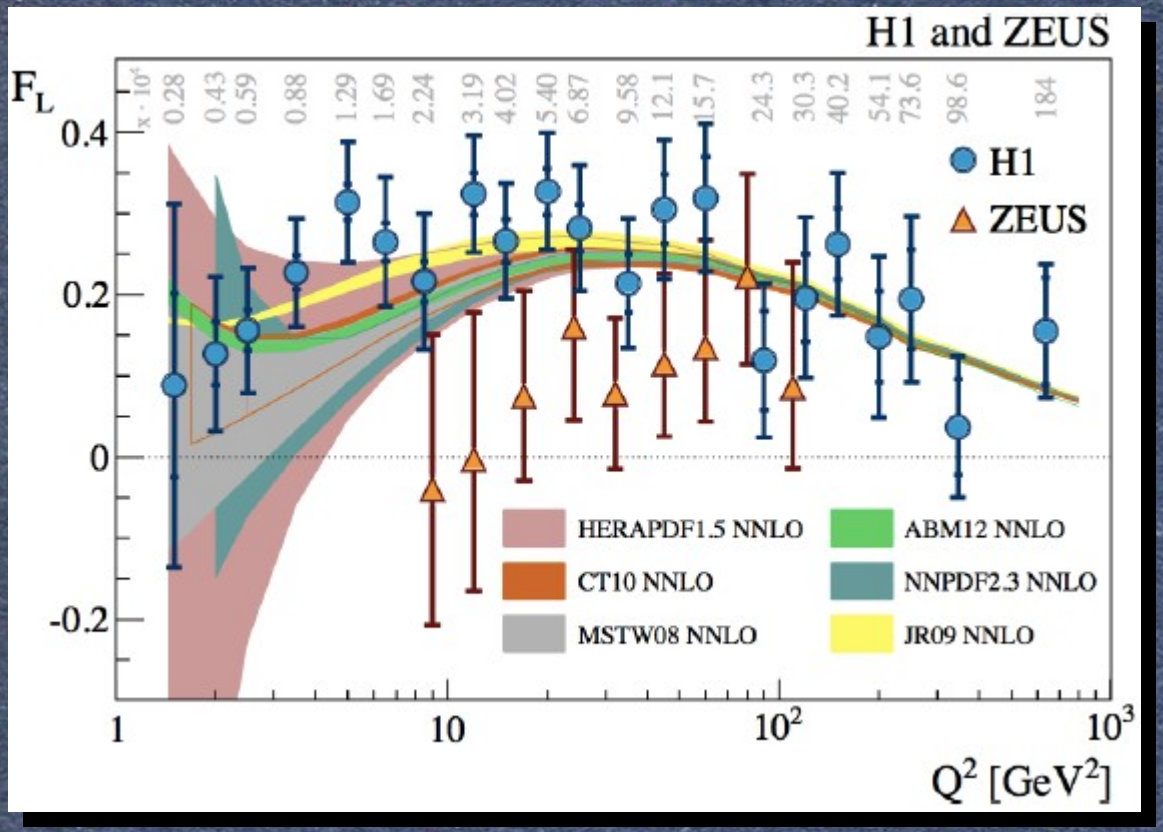
Predictions (H1PDF2012) provide a good description of the data.

Similar measurement performed by ZEUS experiment

Extraction of longitudinal structure function F_L

E.P.J.C 74(2014)2814, Phys.Rev.D90(2014)072002

- F_2 and F_L are simultaneously determined by the H1 from a χ^2 fit, taking correlated systematics into account using HER, MER and LER cross sections.



- Similar technique is used by ZEUS.
- A good agreement between NNLO predictions and the measurements.
- Overall consistency between the H1 and ZEUS about 1 – 2σ.

Extraction of longitudinal structure function F_L

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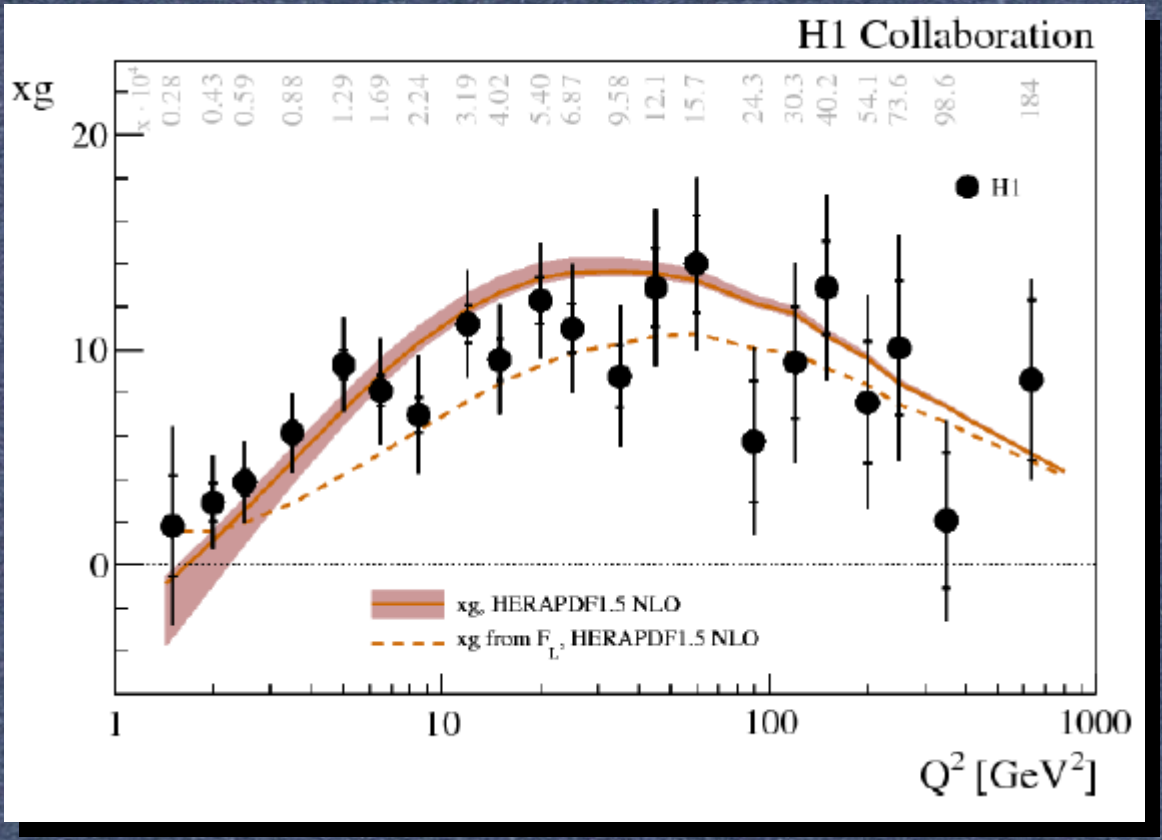
F_L allows to directly measure gluon density:

$$xg(x,Q^2) \approx 1.77 \frac{3\pi}{2\alpha_S(Q^2)} F_L(ax,Q^2)$$



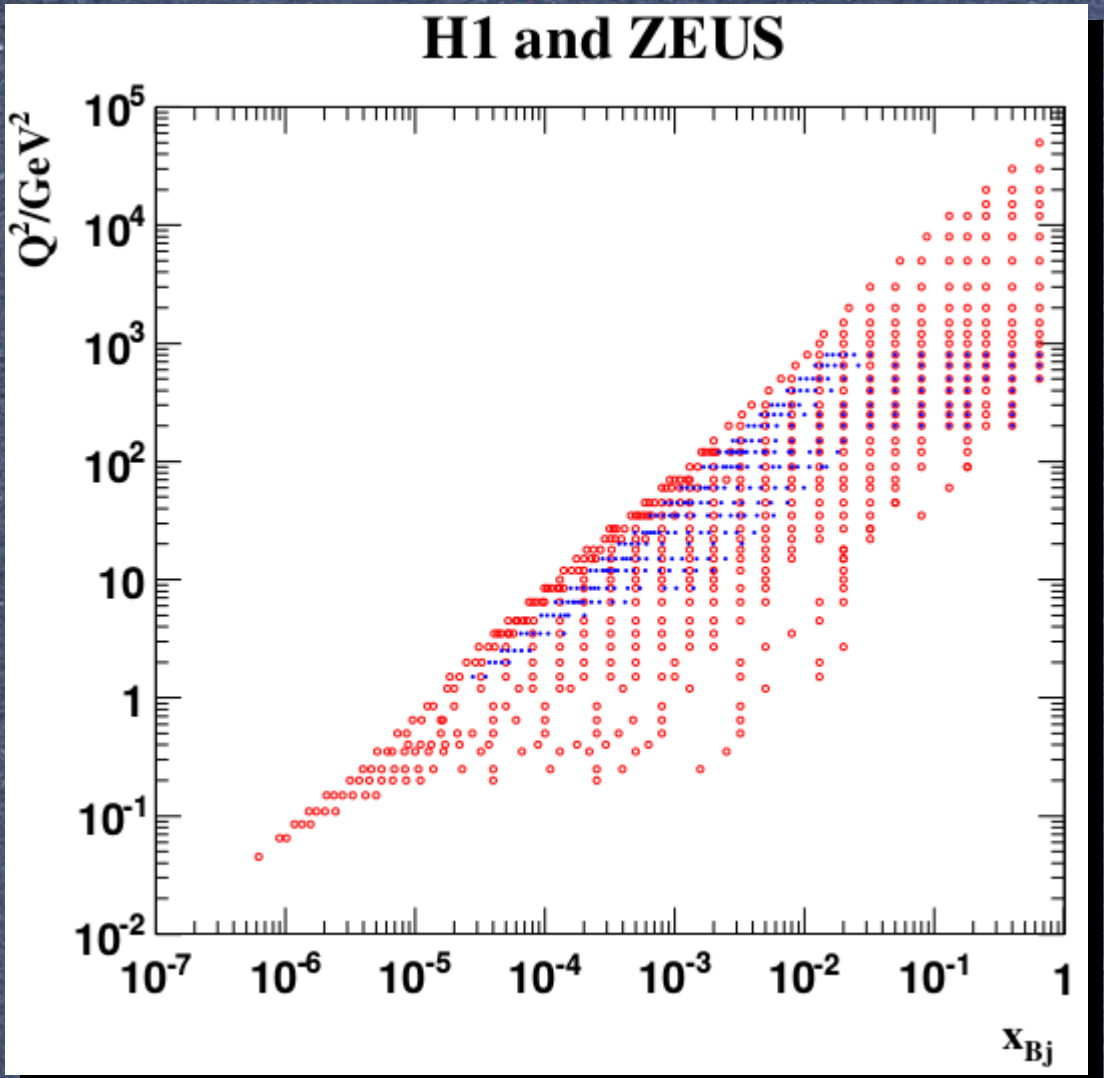
- Gluon density extracted from F_L (solid points) is compared to the gluon density from set of PDFs HERAPDF1.5 (shadowed area) as well as to the result of applying the equation above to the F_L prediction based on HERAPDF1.5 (dashed line).

- Gluon density extracted directly from F_L reasonably well agrees with the gluon density from HERAPDF1.5.

Inclusive DIS combination

ArXiv:1506.06042, submitted to EPJC

- HERA II data provides a great statistical improvement compare to the HERA I data.
- In total 41 final data sets of HERA (21 → HERA I and 20 → HERA II) inclusive measurements.



- Combination is performed with HERAverager tool based on χ^2 minimisation method.
- Grid points shown in red are used for data with $\sqrt{s} = 318$ GeV.
- Blue grid points correspond to data with $\sqrt{s} = 225$ and 251 GeV

Inclusive DIS combination

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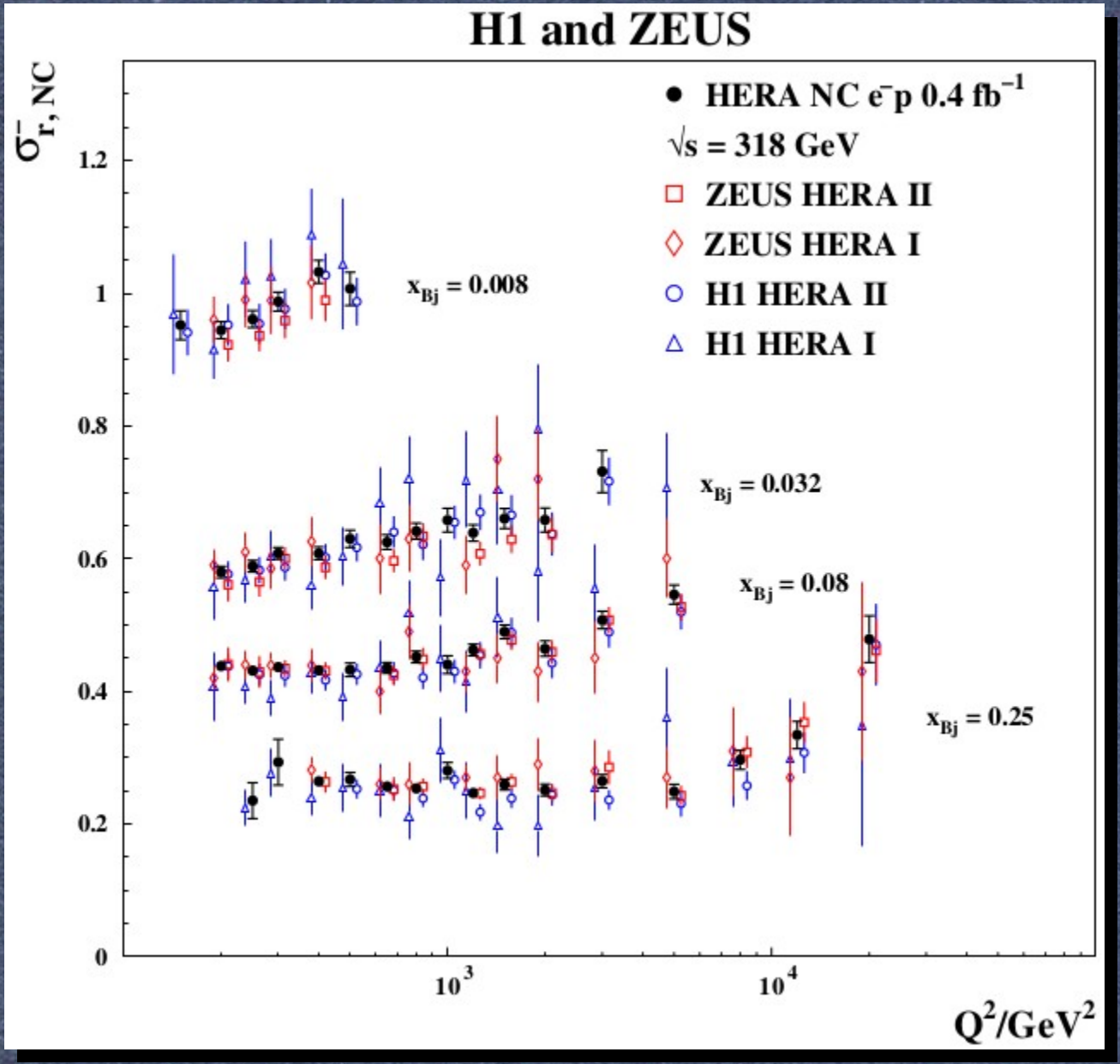

- Data is consistent between HERA I and HERA II as well as between two experiments
- Large uncertainty reduction, especially in e^-p due to 10x increase in luminosity.
- Large HERA II luminosity yields in significant improvement in precision at high x and Q^2.

QCD analysis of combined DIS cross sections

ArXiv:1506.06042, submitted to EPJC

- Final HERA I + II combined inclusive DIS data used as an input to a QCD analysis.

QCD fit is performed using HERAFitter open source QCD fit framework, available at www.herafitter.org

- The PDFs are parametrised at the starting scale $Q^2 = 1.9$ GeV^2 as follows:

$$xg(x) = A_g \cdot x^{B_g} \cdot (1-x)^{C_g} - A_g' \cdot x^{B_g'} \cdot (1-x)^{C_g'}$$
$$xu_v(x) = A_{u_v} \cdot x^{B_{u_v}} \cdot (1-x)^{C_{u_v}} \cdot (1 + E_{u_v} x^2)$$
$$xd_v(x) = A_{d_v} \cdot x^{B_{d_v}} \cdot (1-x)^{C_{d_v}}$$
$$x\bar{U}(x) = A_{\bar{U}} \cdot x^{B_{\bar{U}}} \cdot (1-x)^{C_{\bar{U}}} \cdot (1 + D_{\bar{U}} x)$$
$$x\bar{D}(x) = A_{\bar{D}} \cdot x^{B_{\bar{D}}} \cdot (1-x)^{C_{\bar{D}}}$$

* $x\bar{U} = x\bar{u}$, $x\bar{D} = x\bar{d} + x\bar{s}$, $xs = x\bar{s}$, $x\bar{s} = r_s x\bar{d}$
  normalisation parameters: A_{u_v}, A_{d_v}, A_g
* Condition that $x\bar{u} \to x\bar{d}$ as $x \to 0$ constrains $B_{\bar{U}} = B_{\bar{D}}$ and $A_{\bar{U}} = A_{\bar{D}}/(1 + r_s)$
* 14 free parameters

- PDFs are then evolved via DGLAP evolution equations to LO, NLO and NNLO using QCDNUM package.
- Heavy quarks are treated using Thorne-Roberts General Mass Variable Flavor Number Scheme

HERAPDF 2.0

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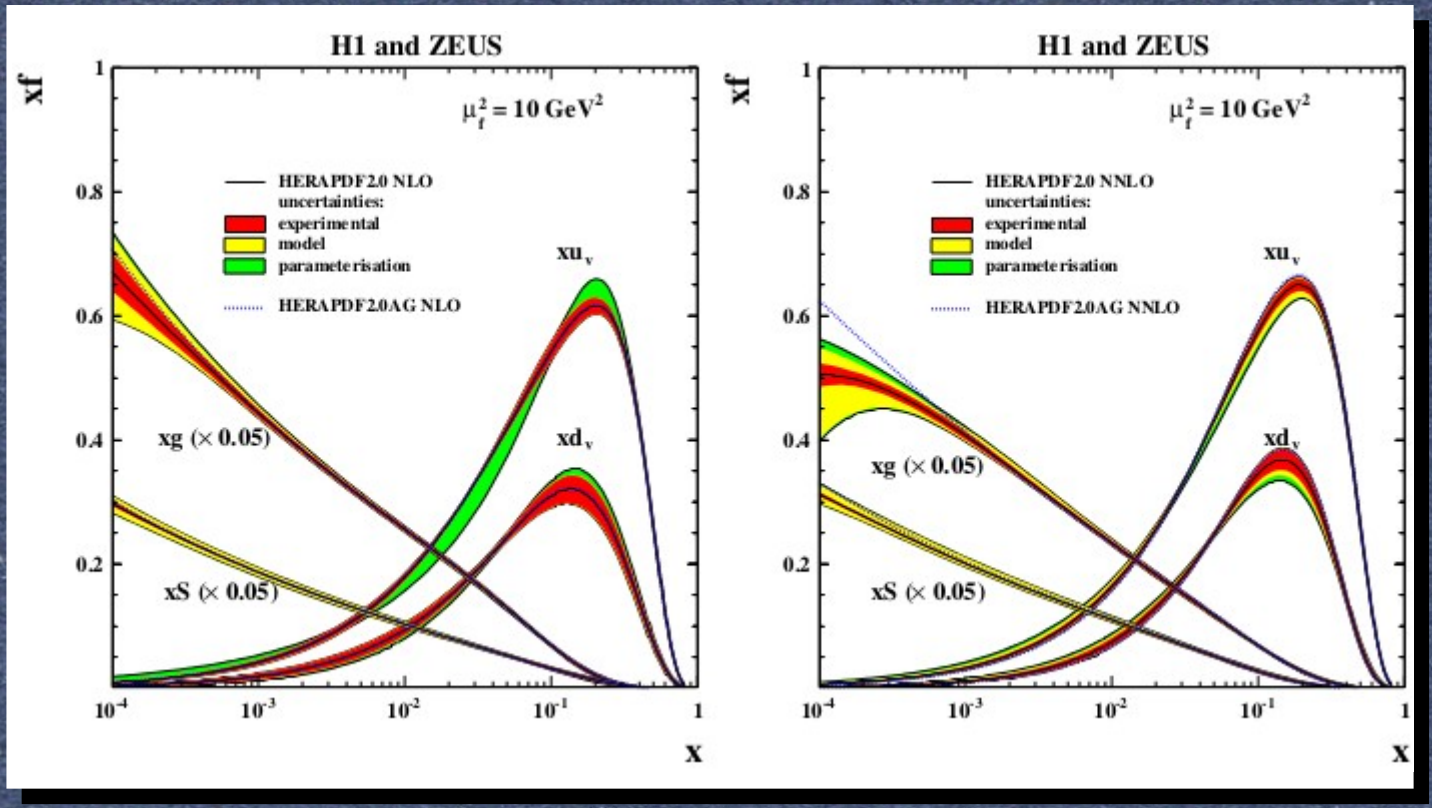
- PDFs are determined by minimizing χ^2 function with the respect to PDF parameters.
- The χ^2 function used has a similar form to the one used in F_L extraction and inclusive data combination.



- Red → experimental uncertainty, estimated using Hessian method.
- Yellow → model uncertainty, from variation of quark masses, α_s etc..
- Green → an envelope from PDF fits using variants of parametrisation form (extra D or E parameters in polynomial) as well as starting scale variations.

Data and fit comparison

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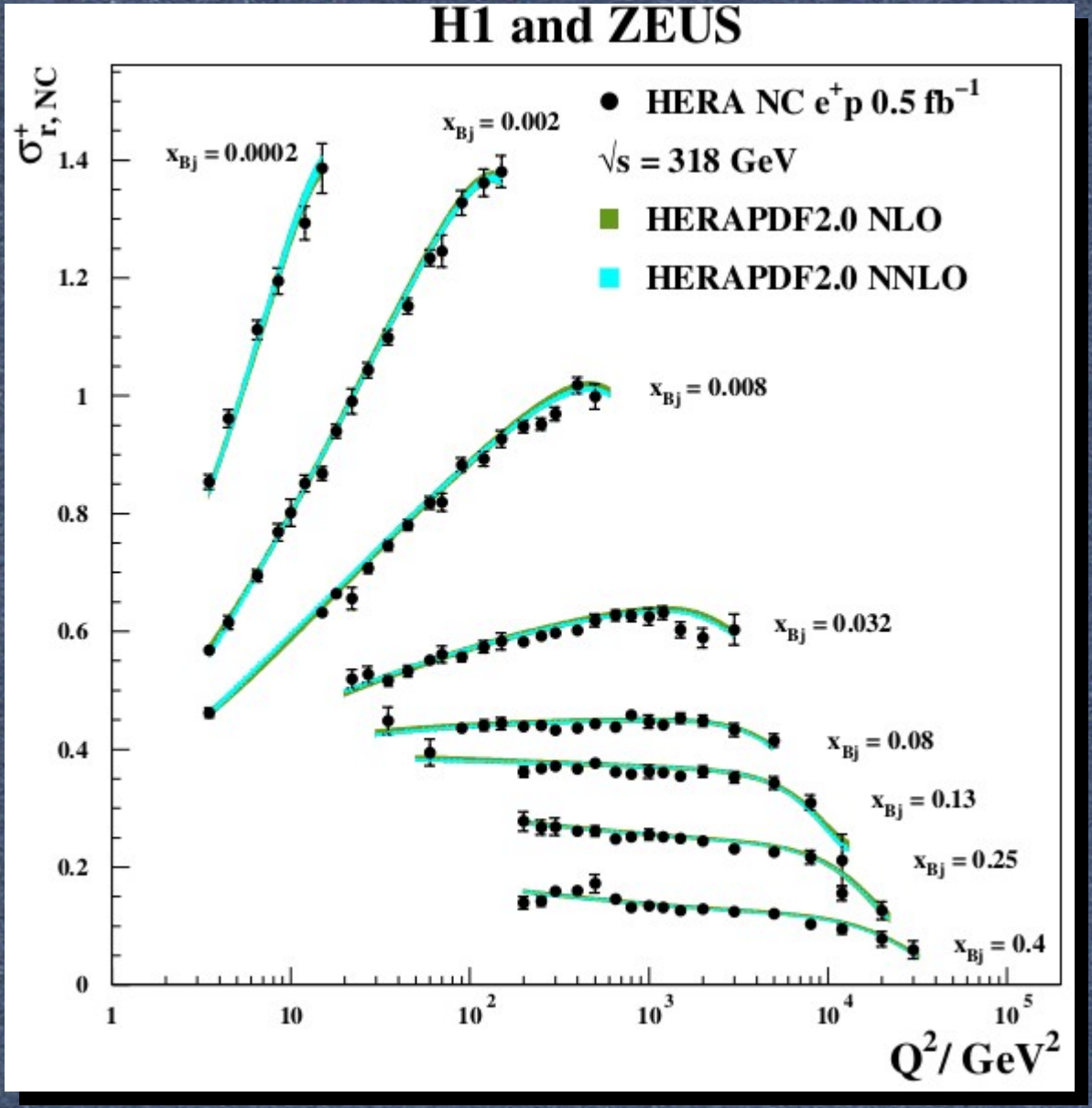

- Predictions based on HERAPDF2.0 give a good description of data in both NLO and NNLO.
- Scaling violations clearly visible over a large kinematic range

HERAPDF 2.0 at high Q^2

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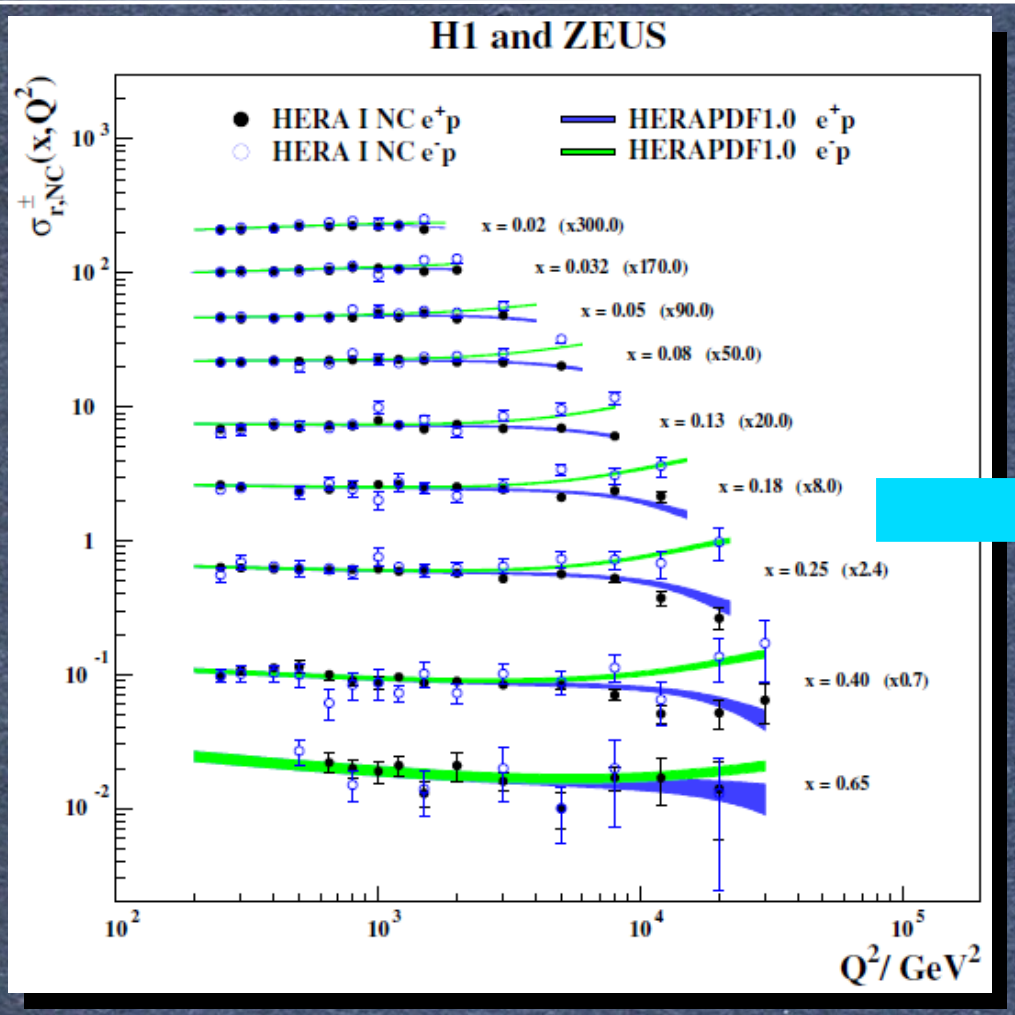
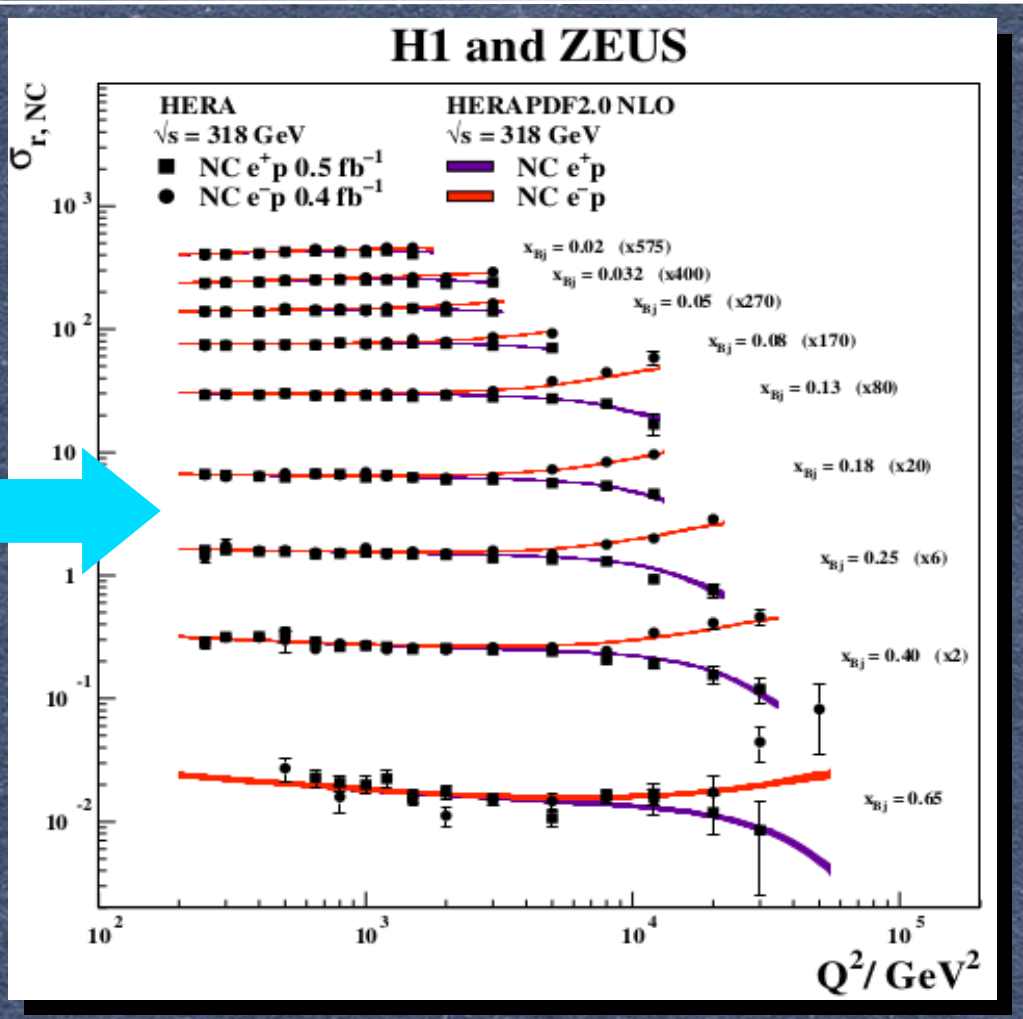




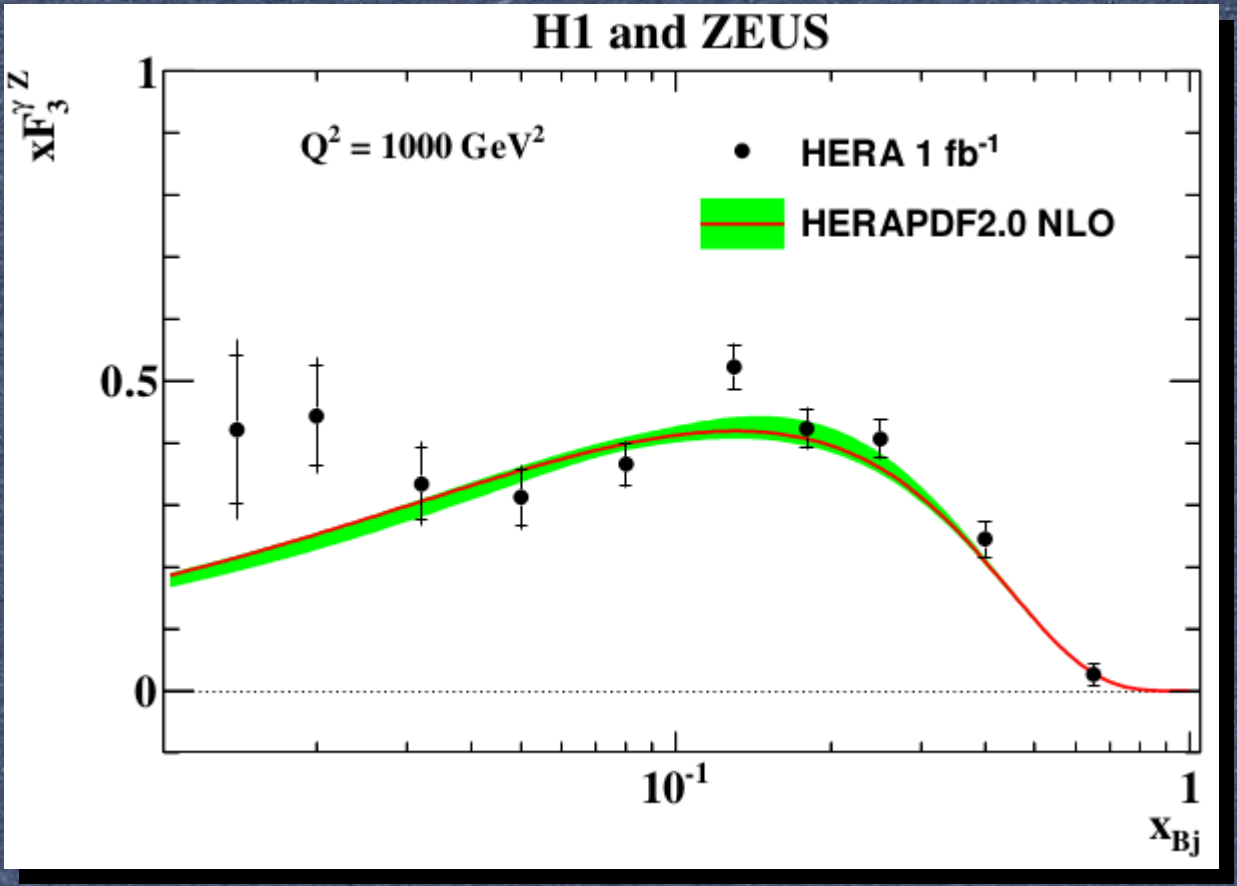
- Combined HERA I inclusive NC cross sections compared to predictions from HERAPDF1.0.
- Great precision achieved both in data and in HERAPDF2.0, by combining HERA I and HERA II measurements.

Structure function $xF_3^{\gamma Z}$

ArXiv:1506.06042, submitted to EPJC

$xF_3^{\gamma Z}$ structure function is extracted by taking the difference between NC e^+p and e^-p cross sections.

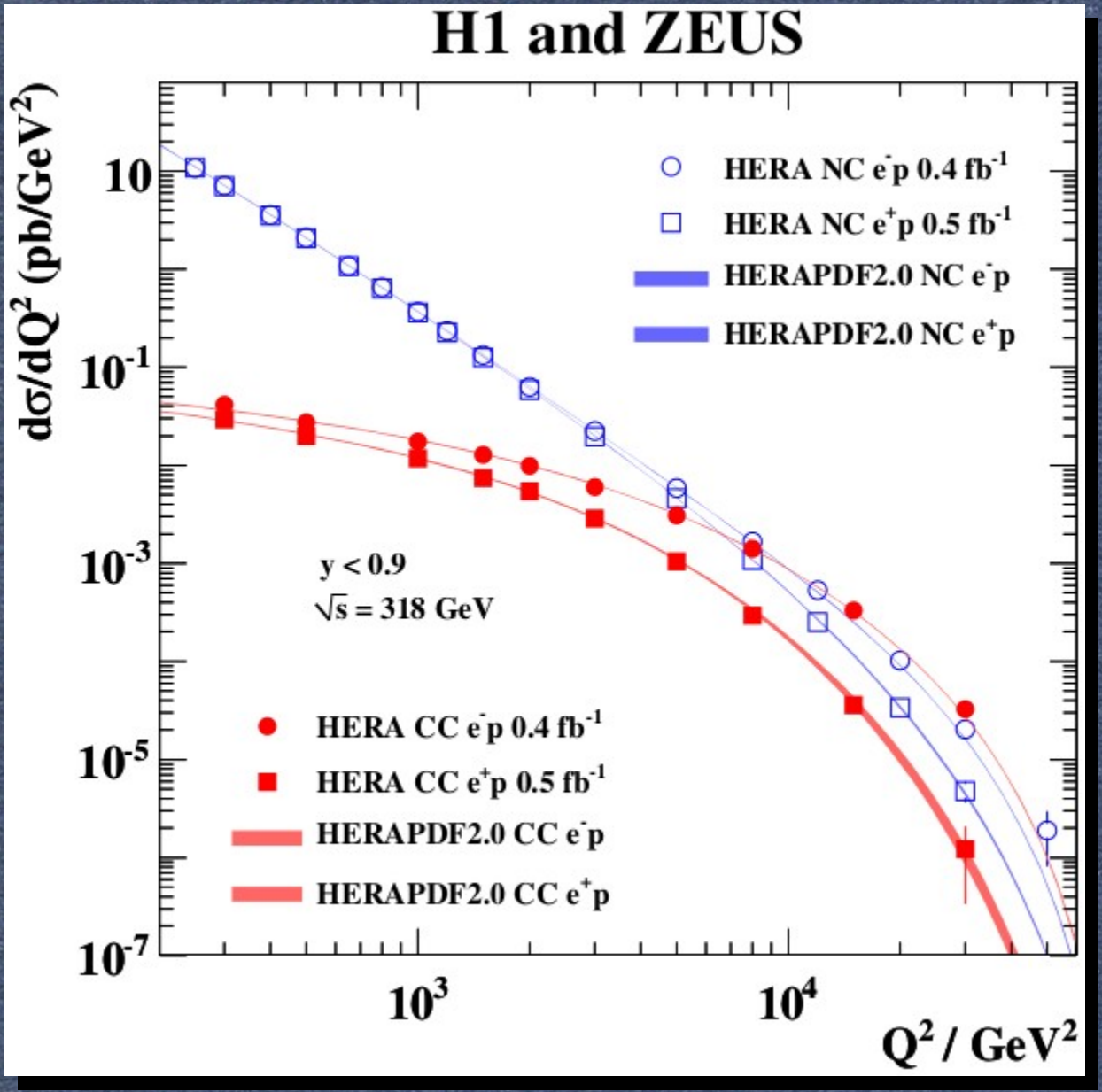
$$\tilde{\sigma}^{+-}_{NC} \sim F_2 \mp \frac{Y_-}{Y_+} xF_3 - \frac{y^2}{Y_+} F_L$$



- $xF_3^{\gamma Z}$ is obtained for $Q^2 \geq 1000$ GeV^2
- This directly probes the valence structure of the proton: $xF_3^{\gamma Z} \sim xu_v + xd_v$

Electroweak unification

ArXiv:1506.06042, submitted to EPJC



- NC e^-p and e^+p are the same in the $\gamma-$exchange dominating region and start to differ in the high Q^2 region where $\gamma-Z$ interference becomes important.
- NC and CC cross sections become similar in magnitude at around the mass-scale squared of the electroweak bosons.

Summary

- The H1 and ZEUS have finalised inclusive DIS measurements and combined the individual results.
- Latest measurements of DIS cross section at very high x by ZEUS are expected to provide constrains on the PDFs at high x region, where the contribution of valence quarks is important.
- Measurements in the high y region by both H1 and ZEUS allow to decouple F_2 and F_L structure functions thus providing direct sensitivity to the gluon.
- The total luminosity of about *1* fb^{-1} collected by the experiments provides cross sections of very high precision, which improve precision of PDFs.