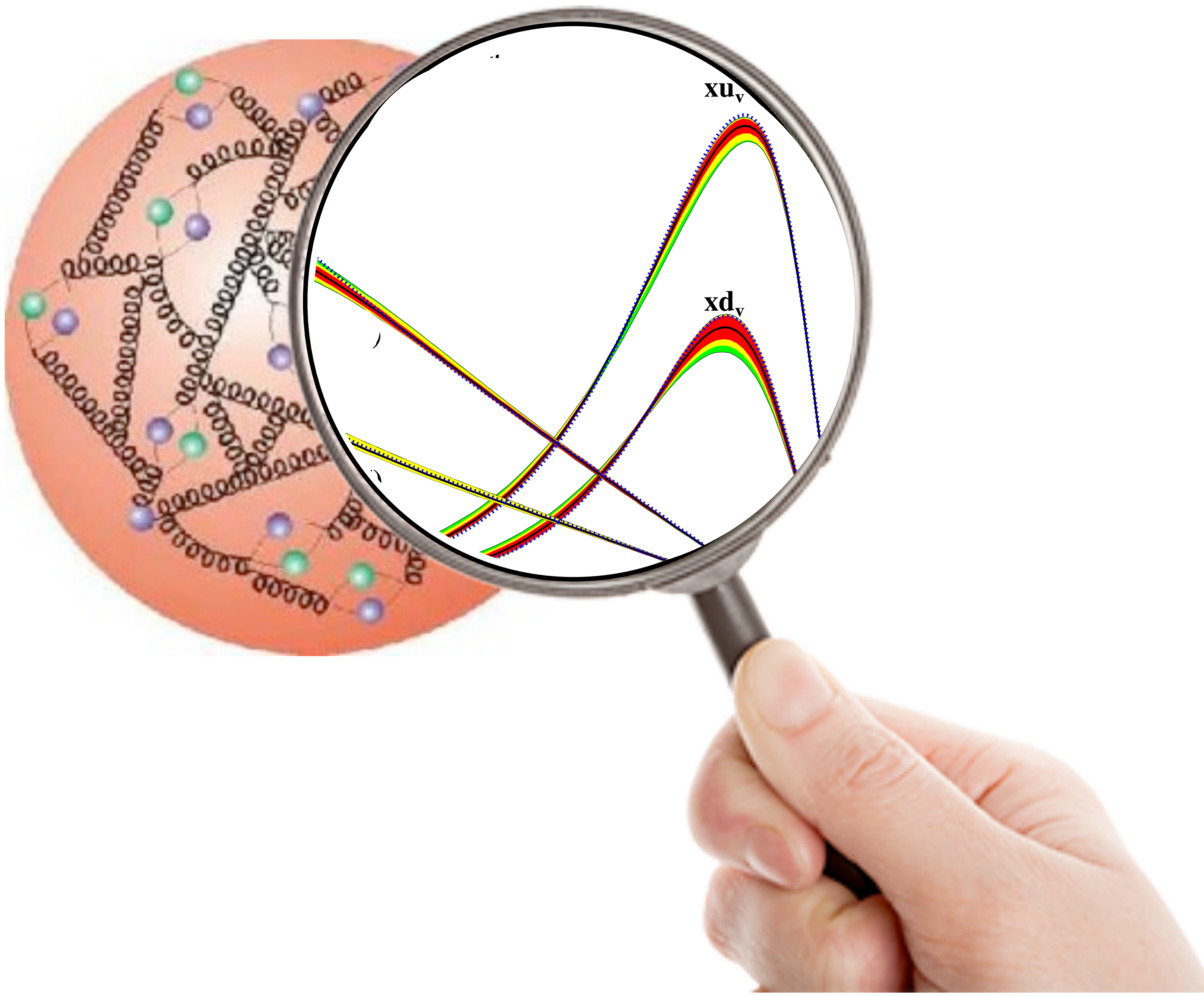
Combination of Measurements of Inclusive Deep Inelastic ep Scattering Cross Sections and QCD Analysis of HERA Data [arxiv: 1506.06042]



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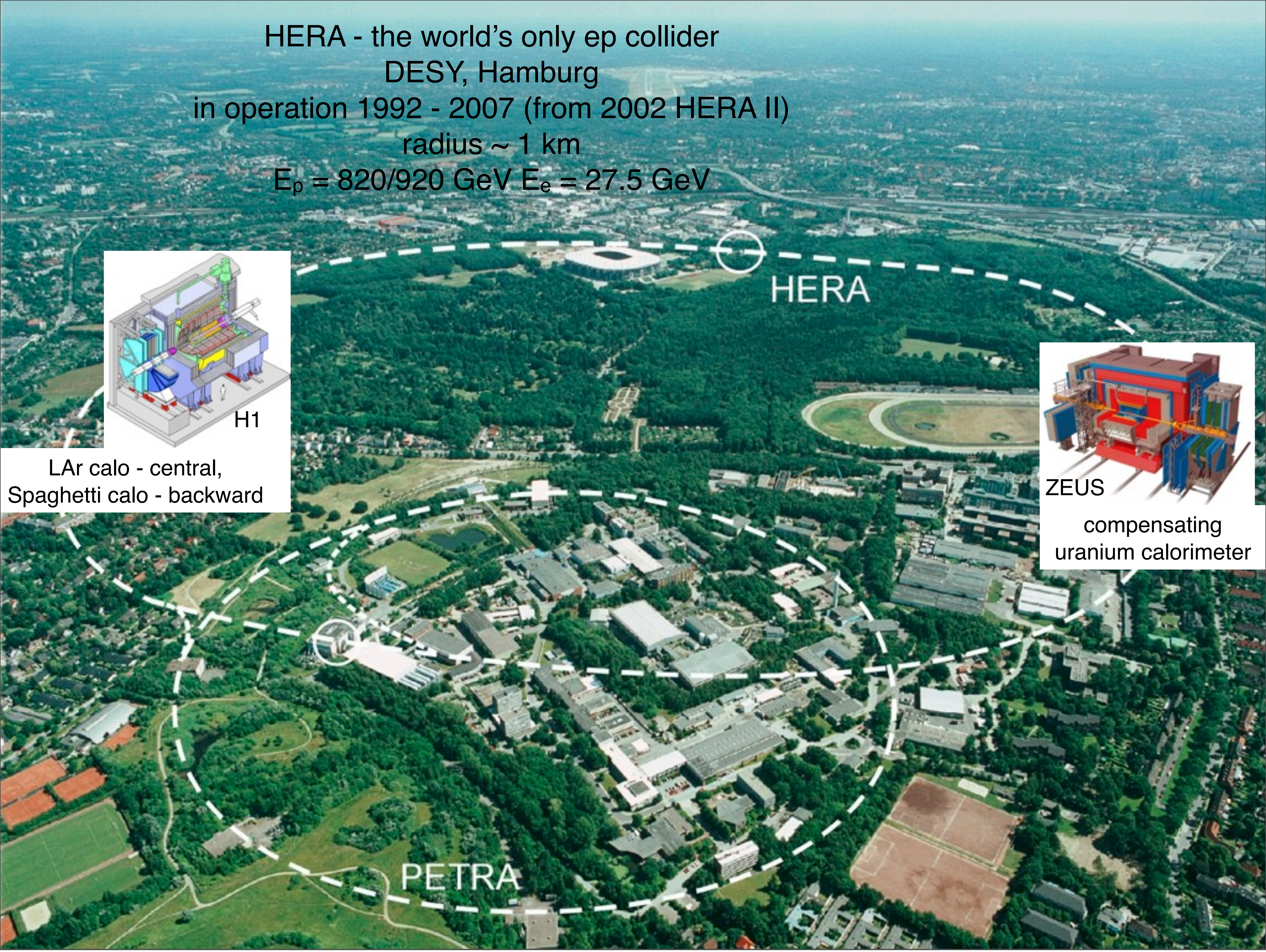
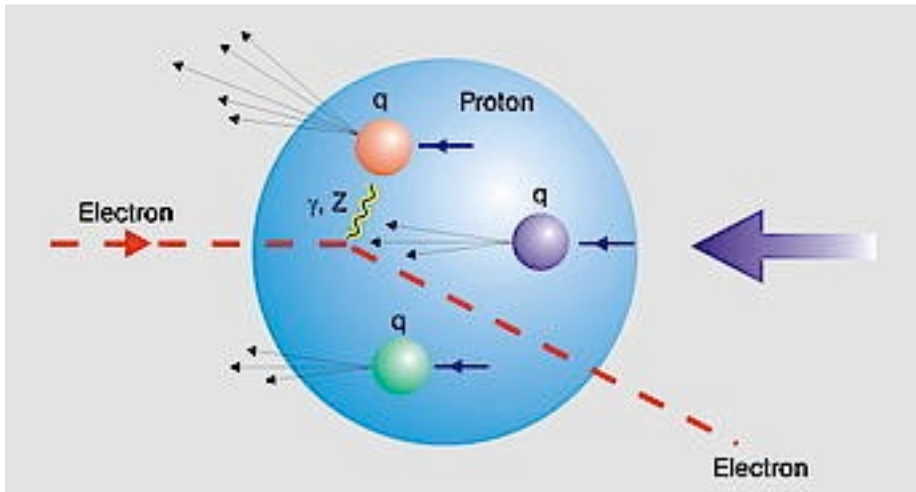
for H1 and ZEUS Collaborations

Low-x Sandomierz
IX 2015

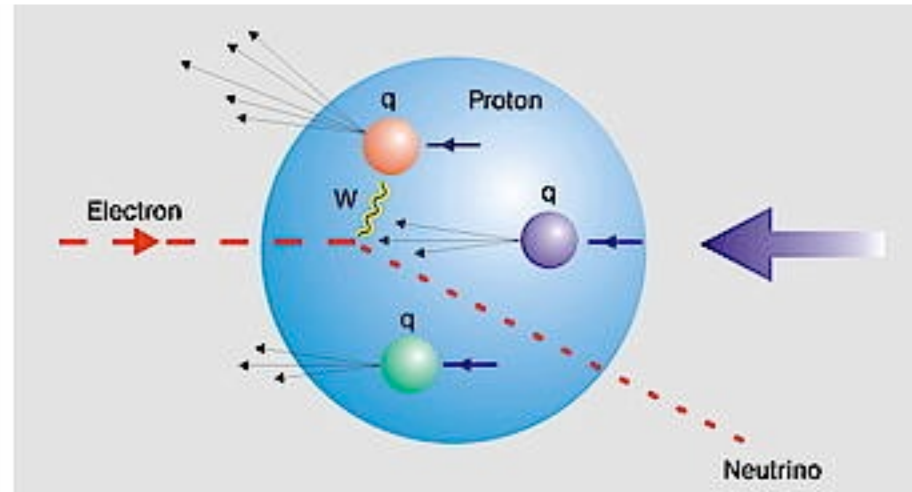
HERA - the world’s only ep collider
DESY, Hamburg
in operation 1992 - 2007 (from 2002 HERA II)
radius ~ 1 km
E_p = 820/920 GeV E_e = 27.5 GeV



Inclusive Deep Inelastic Scattering

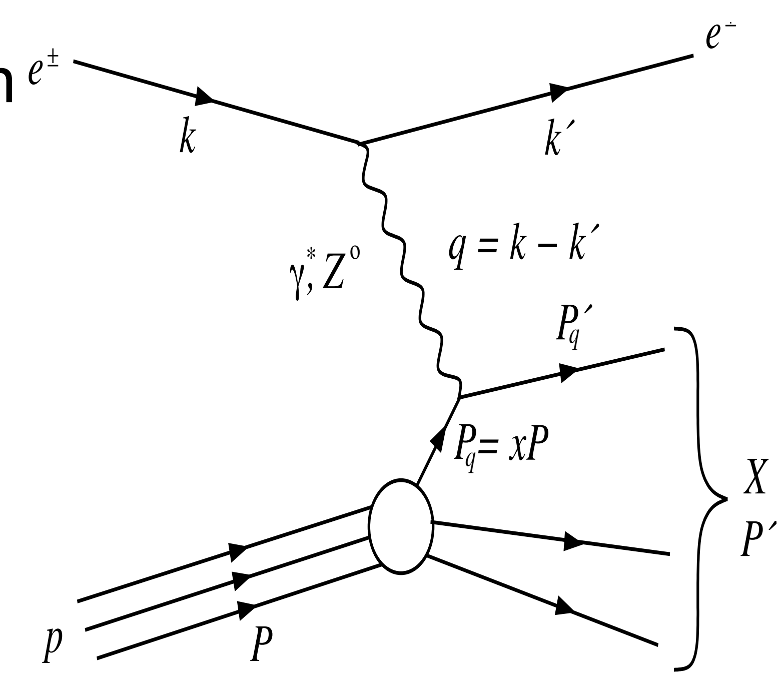


Neutral current

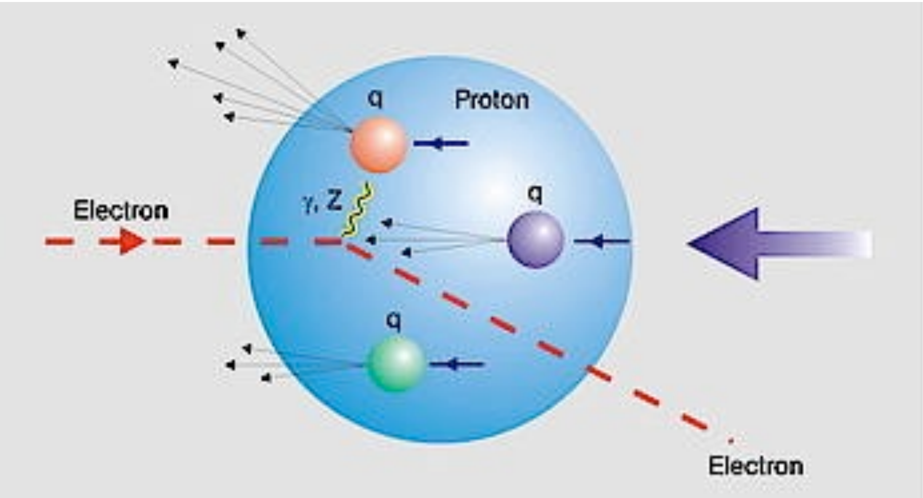


Charged current

- Variables used:
- $q = k - k'$ 4-momentum of exchanged boson
- $Q^2 = -q^2 > 0$ virtuality of the exchanged boson
- $s = (k+p)^2$ central mass energy
- $x = Q^2 / 2\, p \cdot q$ Bjorken x
- $y = p \cdot q / p \cdot k$ inelasticity
- $Q^2 = x\, y\, s$



Cross Sections and Structure Functions



Reduced cross section for ep scattering NC:

$\sigma^{\mp}_{r,NC} = F_2 \pm Y_-/Y_+ \, xF_3 - y^2/Y_+ \, F_L$

$Y_\pm = 1 \pm (1 - y)^2$

At low Q^2 i.e. $Q^2 << M_Z^2$

$\sigma_{r,NC} = F_2 - y^2/Y_+ \, F_L$

At low Q^2 and low y:

$\sigma_{r,NC} = F_2$

$F_2 = x \sum e^2_q [q(x) + \bar{q}(x)]$

F_2 sensitive to quarks

$xF_3 = x \sum 2e_q a_q [q(x) - \bar{q}(x)]$

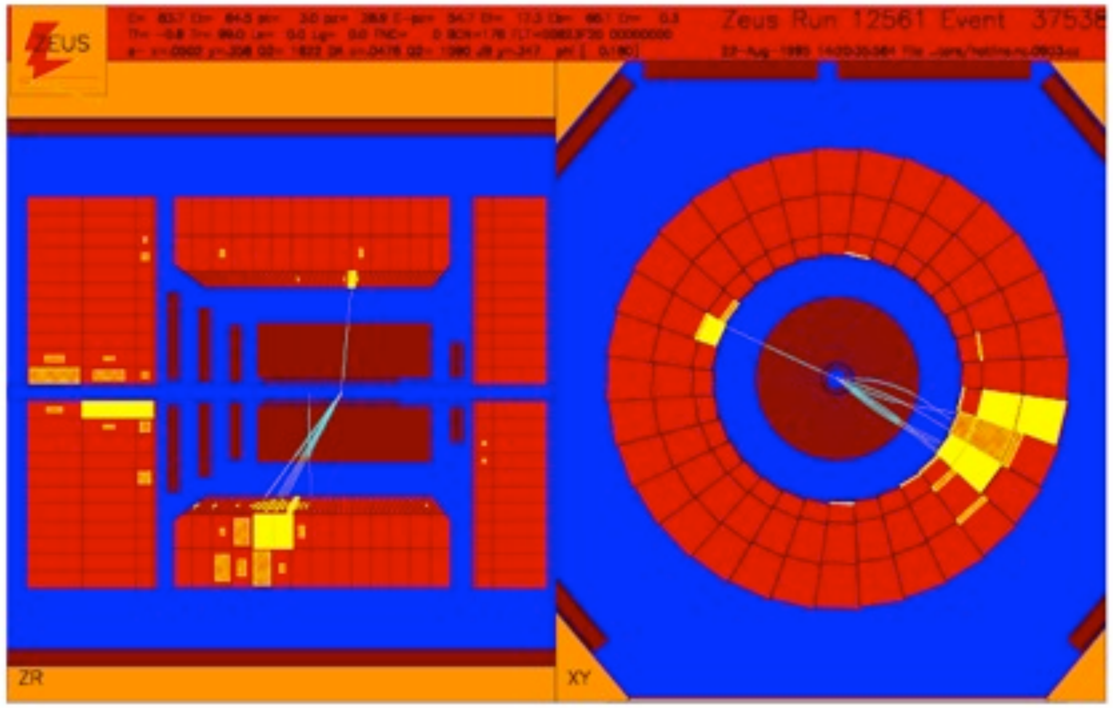
xF_3 sensitive to valence quarks distribution

$F_L \sim \alpha_s \times g$

F_L sensitive to gluons distribution

(gluons also from scaling violation and charm+jet distributions)

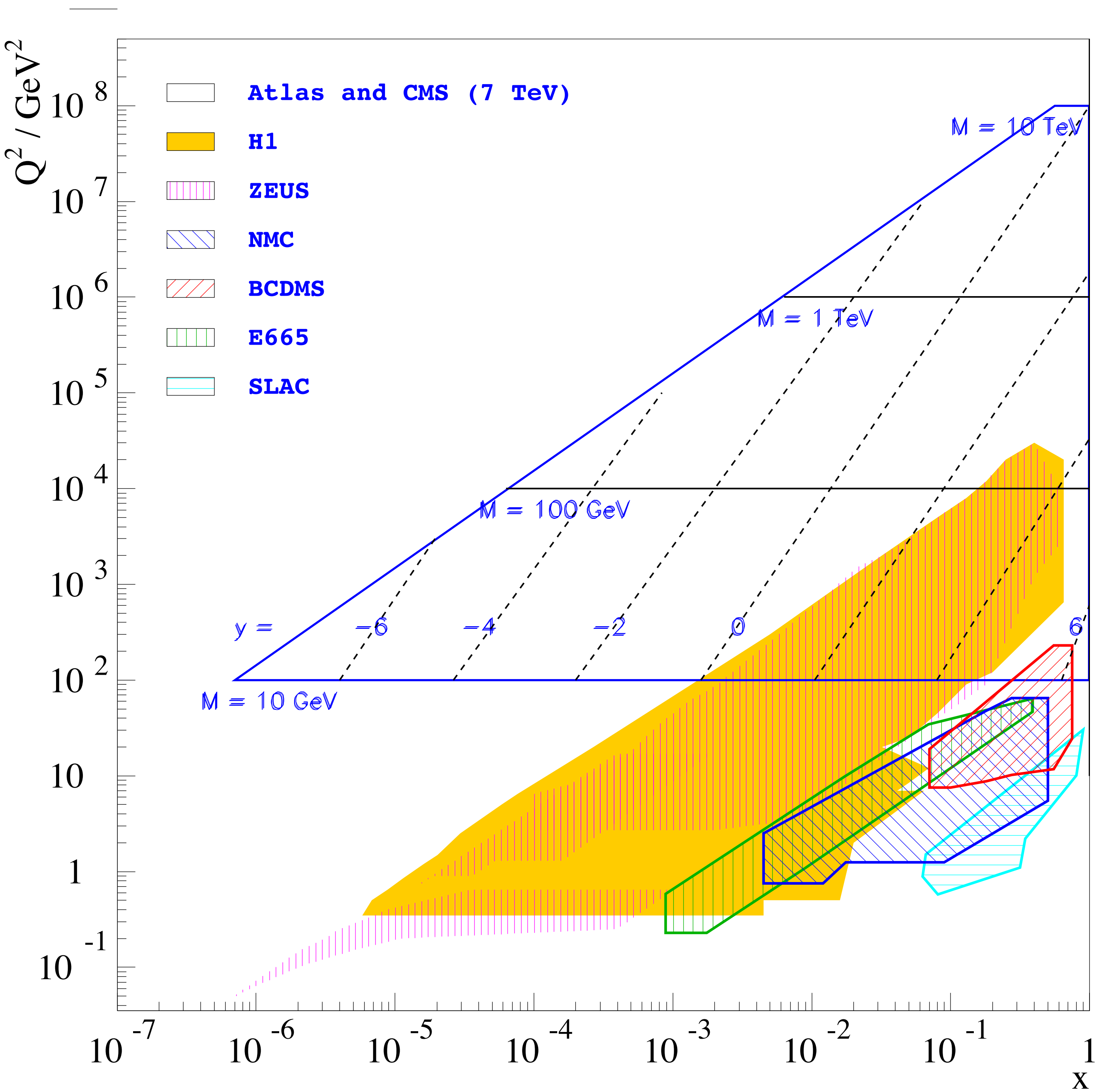
Inclusive DIS data samples



- data collected for E_e = 27.5 GeV and E_p = 920, 820, 575, 460 GeV
- HERA I lumi 100 pb^{-1} e^+p and 15 pb^{-1} e^-p per experiment
- HERA II lumi 150 pb^{-1} e^+p and 235 pb^{-1} e^-p per experiment
- 41 data sets with HERA inclusive measurements
- 21 HERA I data samples
- 20 HERA II data samples
- Data taken 1994-2007 (over 10 years of data taking!)
- 22 papers on inclusive DIS measurements in years 1997-2014 (almost 20 years of data analysis!)

In total 2927 data points combined to 1307

Kinematic plane coverage of the HERA measurements



For NC:

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

$6\ 10^{-7} \leq x \leq 0.65$

$0.005 \leq y \leq 0.95$

For CC:

$200 \leq Q^2 \leq 50000$ GeV^2

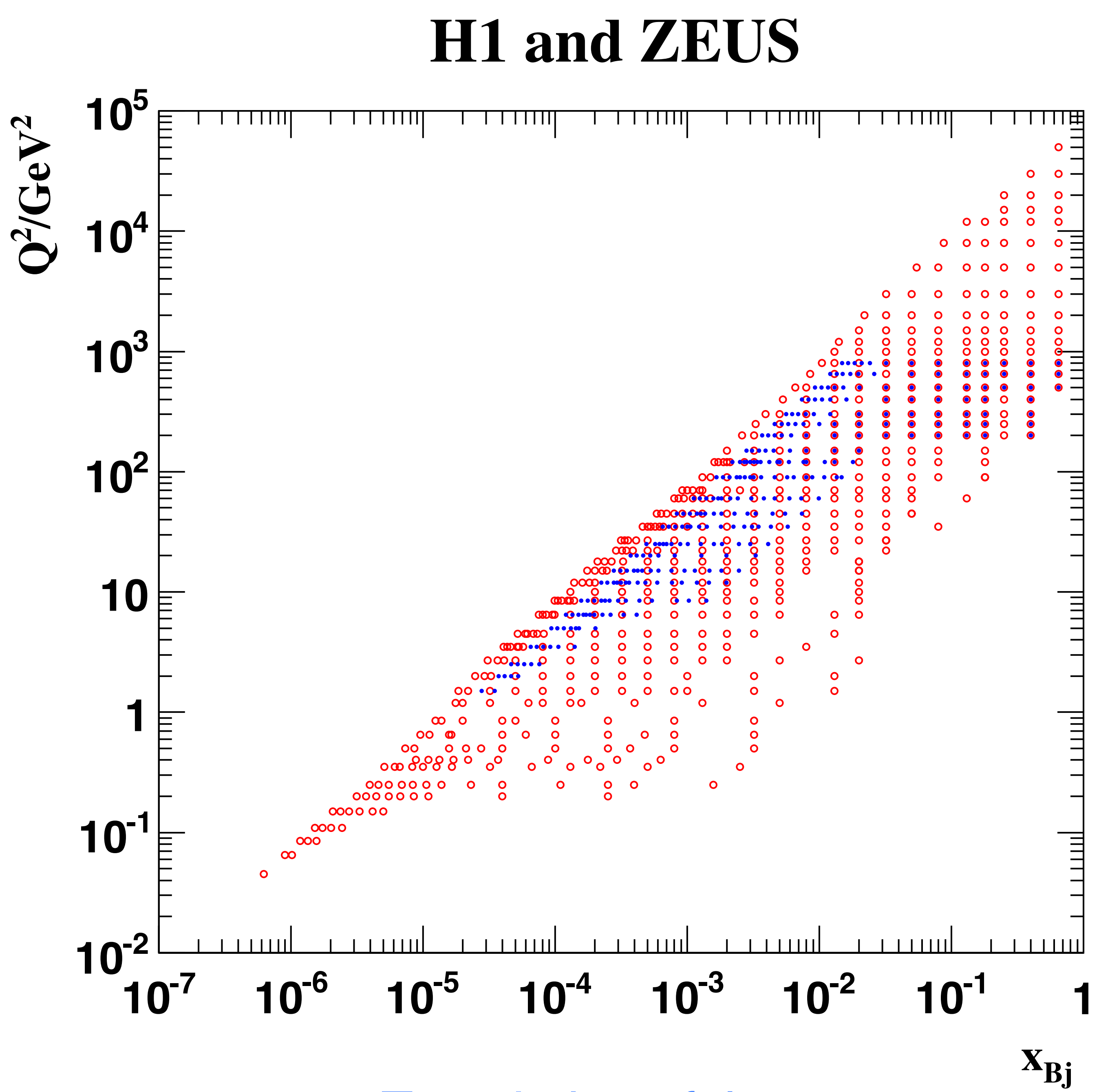
$1.3\ 10^{-2} \leq x \leq 0.4$

$0.037 \leq y \leq 0.76$

HERA data span six orders of magnitude in Q^2 and x

Measurements from HERA core of all PDFs extractions

Common (x , Q^2) grids



Two common grids :

○ ➛ inclusive grid for $\sqrt{s}$ = 318 GeV, E_p=920 GeV and E_p=820 GeV

● ➛ fine grid for $\sqrt{s}$ = 251 GeV and $\sqrt{s}$ = 225 GeV, E_p=575 GeV and Ep=460 GeV

In total 1307 points.
Vast majority of points contains data from both H1 and ZEUS (often several points from independent samples) .

Translation of the measurement points to the grid points

done with help of HERAFitter fits to the data.

For $Q^2 > 3$ GeV^2 DGLAP NLO, below 4.9 GeV^2 fractal fit.

Averaging

Averaging done using HERAverager (https://wiki-zeuthen.desy.de/HERAverager)
based on χ^2 minimisation method

$$\chi^2_{\exp,ds}(\boldsymbol{m},\boldsymbol{b}) = \sum_i \frac{\left[m^i - \sum_j \gamma_j^{i,ds} m^i b_j - \mu^{i,ds}\right]^2}{\delta^2_{i,ds,\mathrm{stat}}\,\mu^{i,ds}\left(m^i - \sum_j \gamma_j^{i,ds} m^i b_j\right) + \left(\delta_{i,ds,\mathrm{uncor}}\, m^i\right)^2} + \sum_j b_j^2$$

correlated shifts

relative statistical uncer.

measured value at point i

relative correlated systematic uncer.

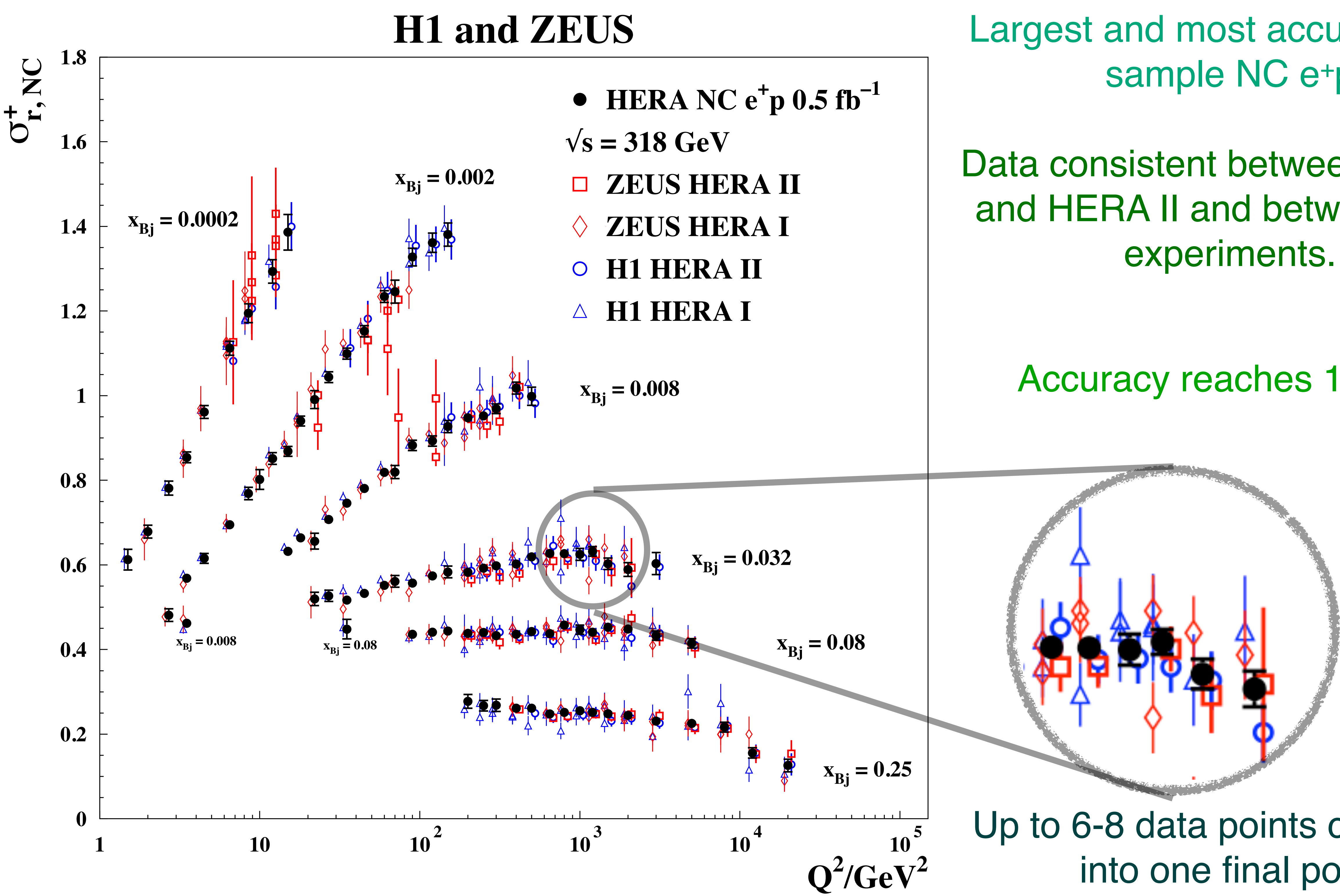
relative uncorrelated uncer.

162 correlated systematic sources taken into account

2927 published cross-sections combined to 1307 final measurements.
For 1620 degrees of freedom, χ^2_{min} = 1687 obtained

Different reconstruction methods used by H1 and ZEUS => similar systematic sources influence the measurement differently => efficient constrain of systematics.

Combined results



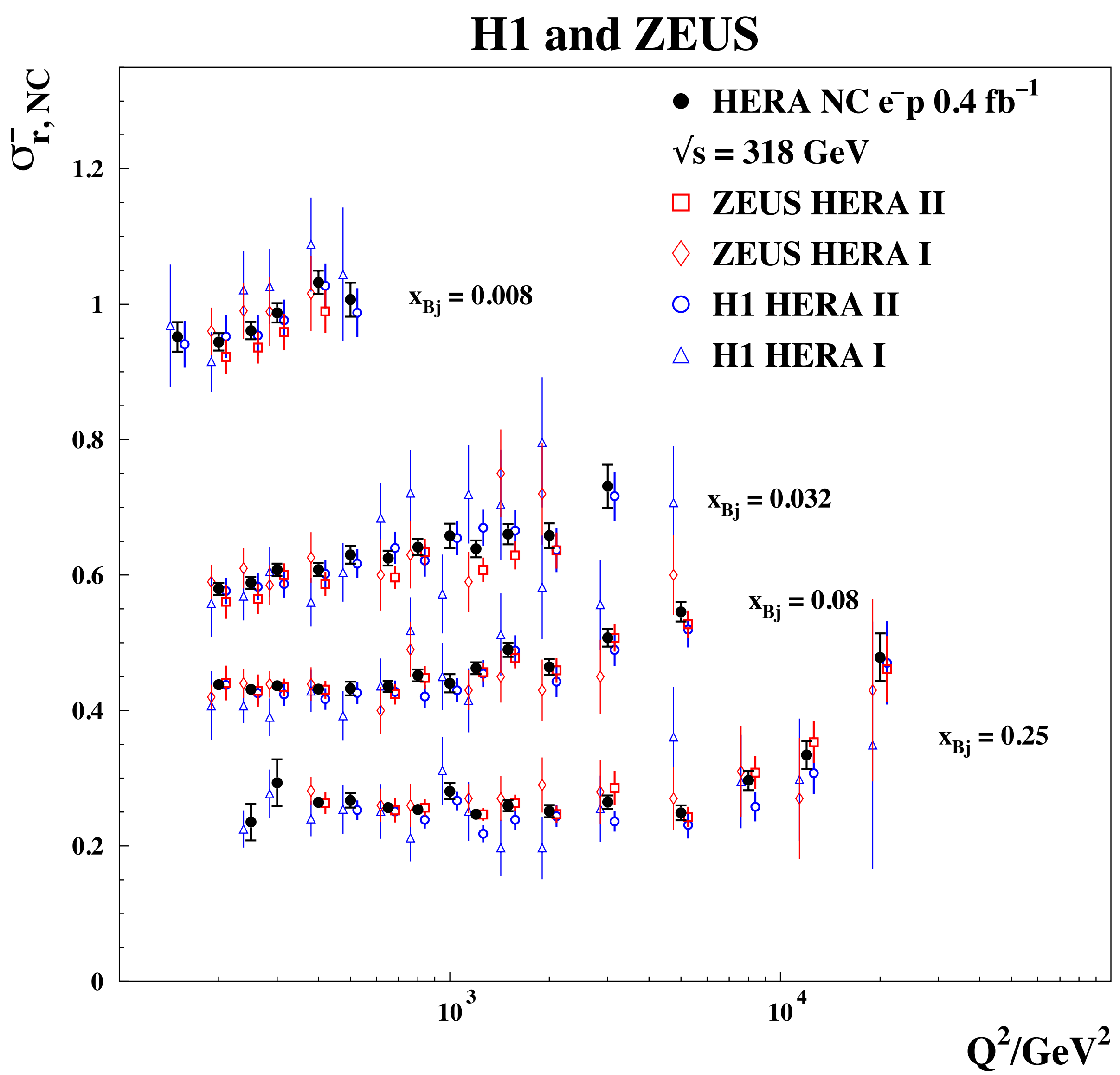
Largest and most accurate data sample NC e^+p

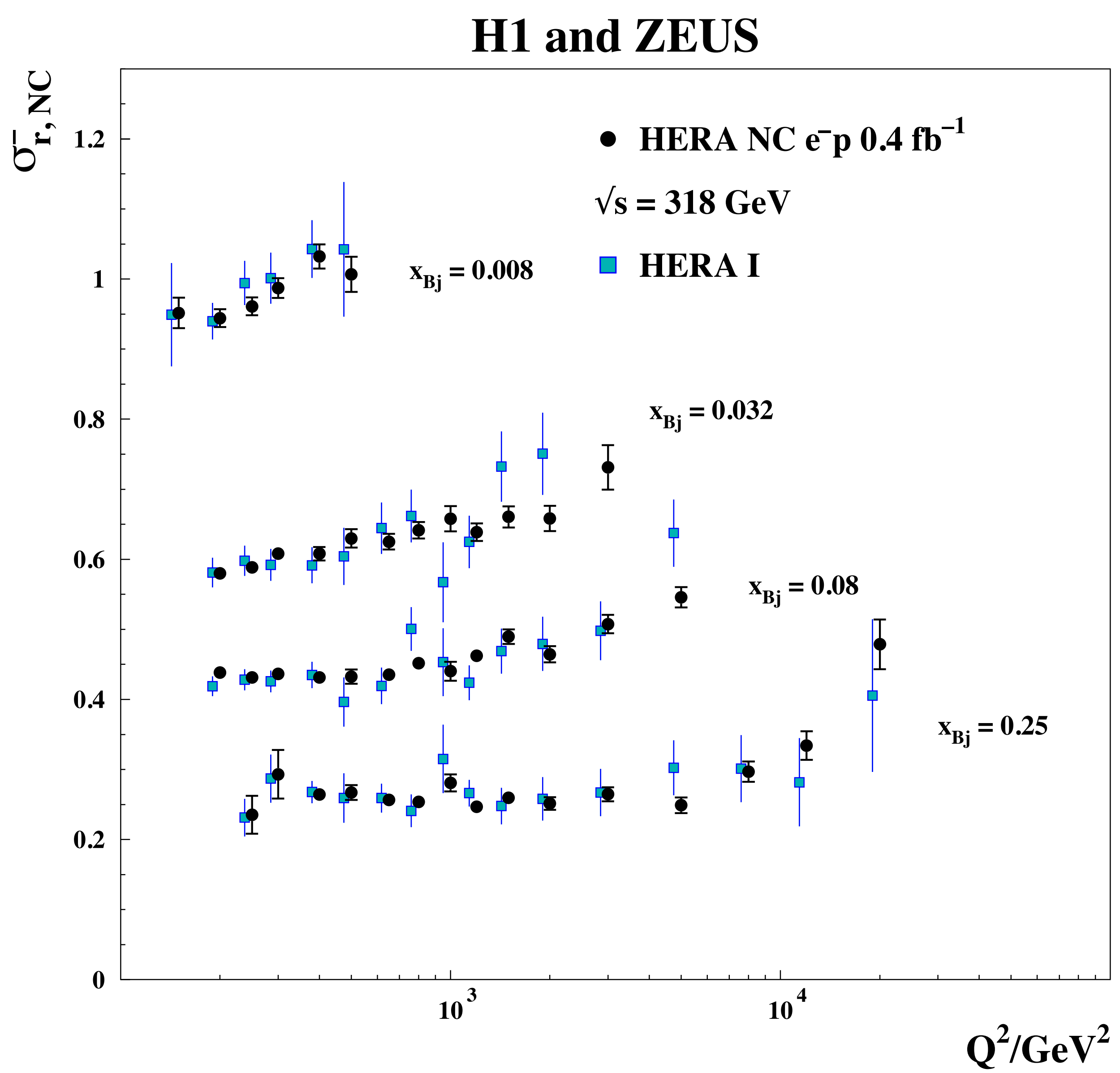
Data consistent between HERA I and HERA II and between both experiments.

Accuracy reaches 1%

Up to 6-8 data points combined into one final point

Combined results





Largest improvement for NC e⁻p - 10 times more luminosity.
Significant improvement in accuracy
Consistent with HERA I, but higher precision

HERA PDF2.0

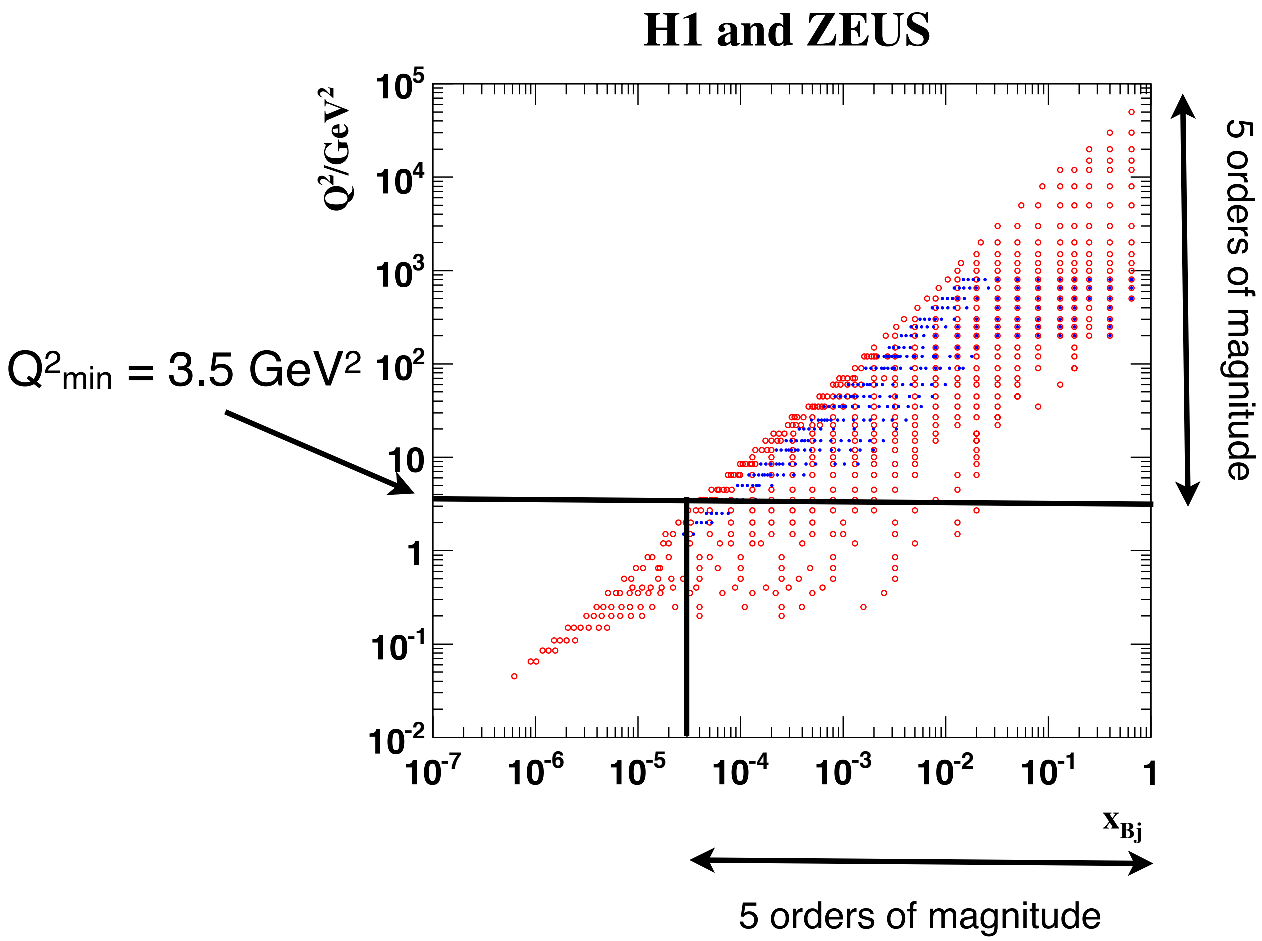
1 fb^{-1} HERA data exclusively used as input !

4 different processes present: NC and CC for e^+p and e^-p

NC e^+p data at different centre-of-mass energy => sensitivity to F_L

Consistent data set with small correlated systematic uncertainties

M_c and M_b constrained using charm and beauty data.



Additional HERAPDF2.0 sets:

HERAPDF2.0HiQ2 at NLO and NNLO - Q^2_{min} = 10 GeV^2

HERAPDF2.0AG at LO, NLO, NNLO - alternative gluon parameters (strictly positive)

HERAPDF2.0Jets at NLO - charm and jets data added => reduced uncertainty on high-x gluon distribution and possibility for simultaneous determination of α_S.

QCD Analysis

Goal: determination of the input distributions of light quarks and gluons

PDFs at starting scale $\mu_{f0} = 1.9$ GeV^2 parametrised:

$$xf(x) = Ax^B(1 - x)^C (1 + Dx + Ex^2)$$

for xg, xu_v, xd_v, $x\bar{U} \overset{\mu_{f0}}{=} x\bar{u}$, $x\bar{D} \overset{\mu_{f0}}{=} x\bar{d} + x\bar{s}$

Evolution using DGLAP equations at LO, NLO and NNLO

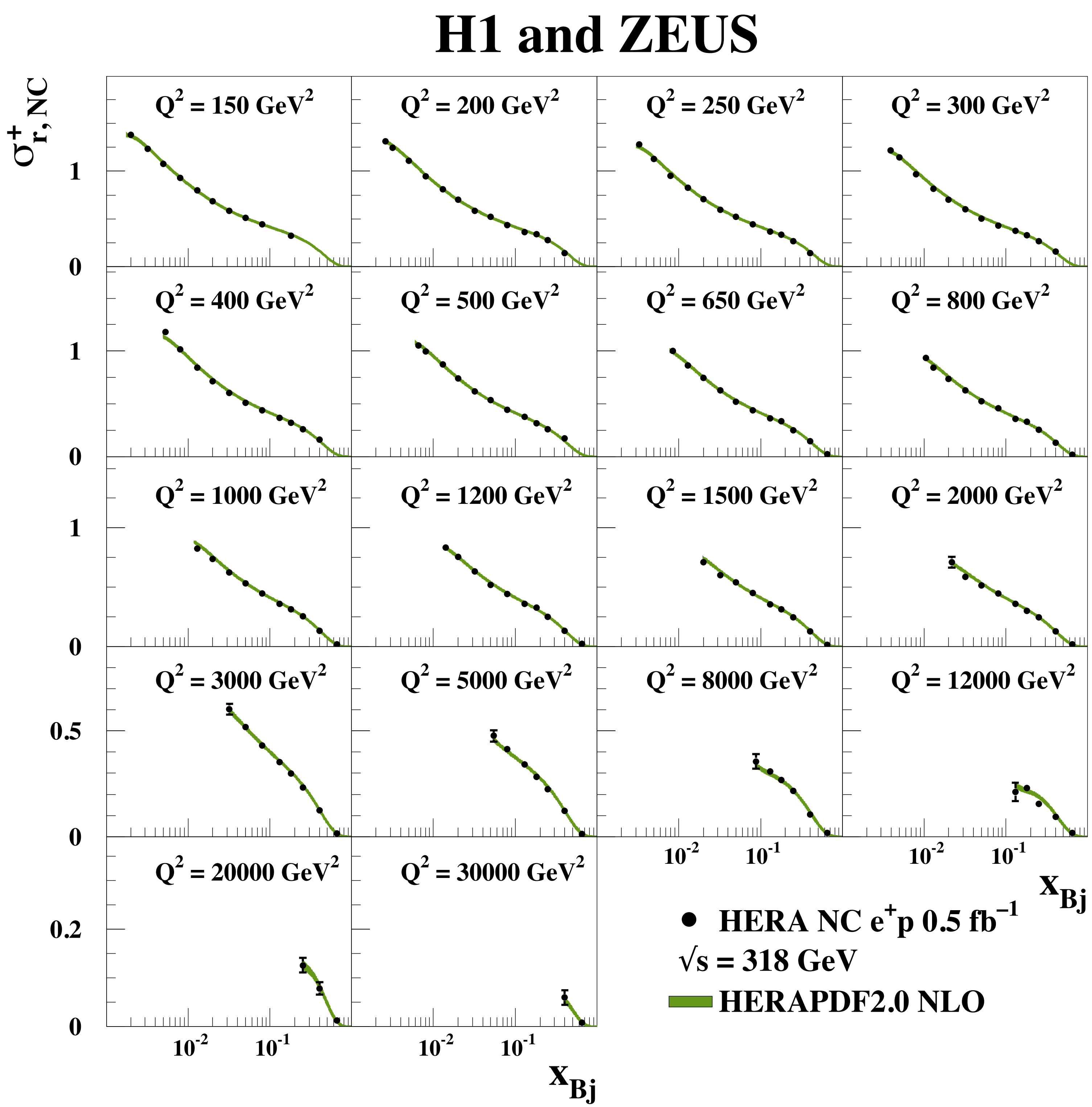
Fits to the data using χ^2 method

14 fit parameters at NNLO

Heavy Quarks from Roberts-Thorne Variable Flavour Number Scheme

HERAFitter framework used (www.herafitter.org)

HERAPDF2.0 - inclusive data comparison



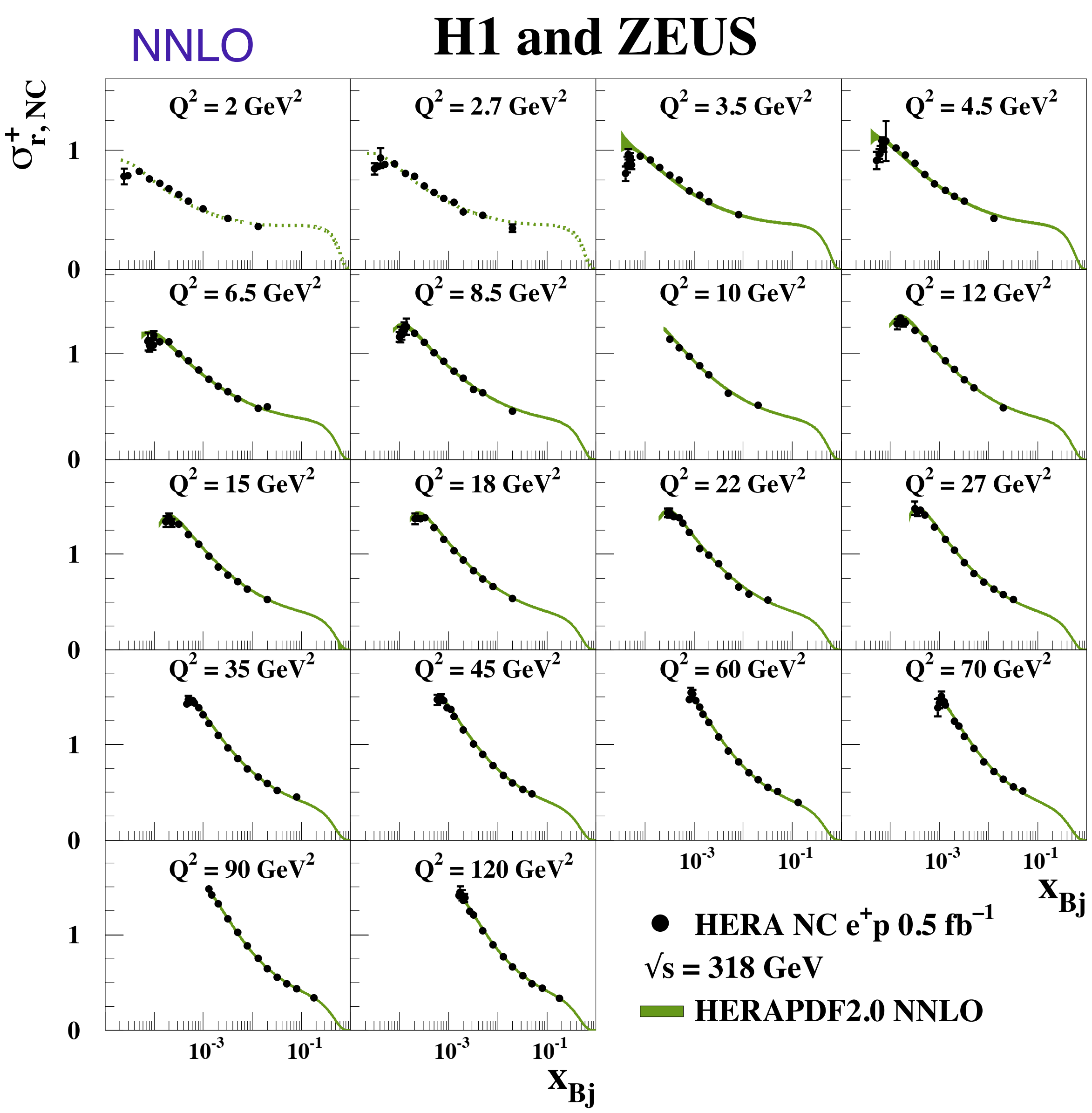
χ^2/dof = 1357/1131
(HERAPDF2.0)
for Q^2_{min} = 3.5 GeV^2

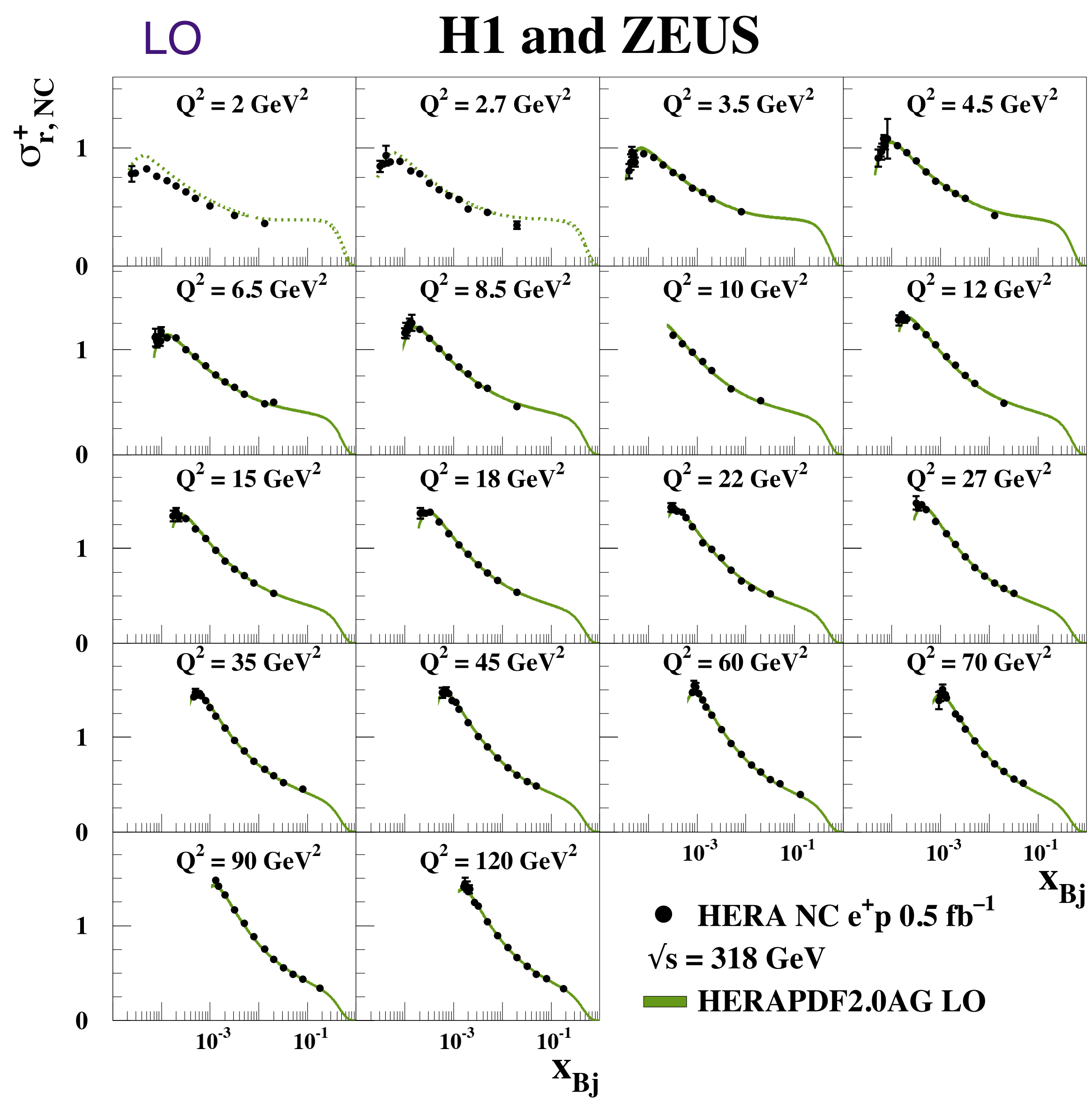
tried also Q^2_{min} = 10 GeV^2
(HERAPDF2.0HiQ2)
χ^2/dof = 1156/1002

including jet data Q^2_{min}= 3.5 GeV^2
(HERAPDF2.0Jets)
χ^2/dof = 1568/1340

Good description of NC, CC data by NLO and NNLO HERAPDF2.0

HERAPDF2.0 - comparison to low Q^2 data

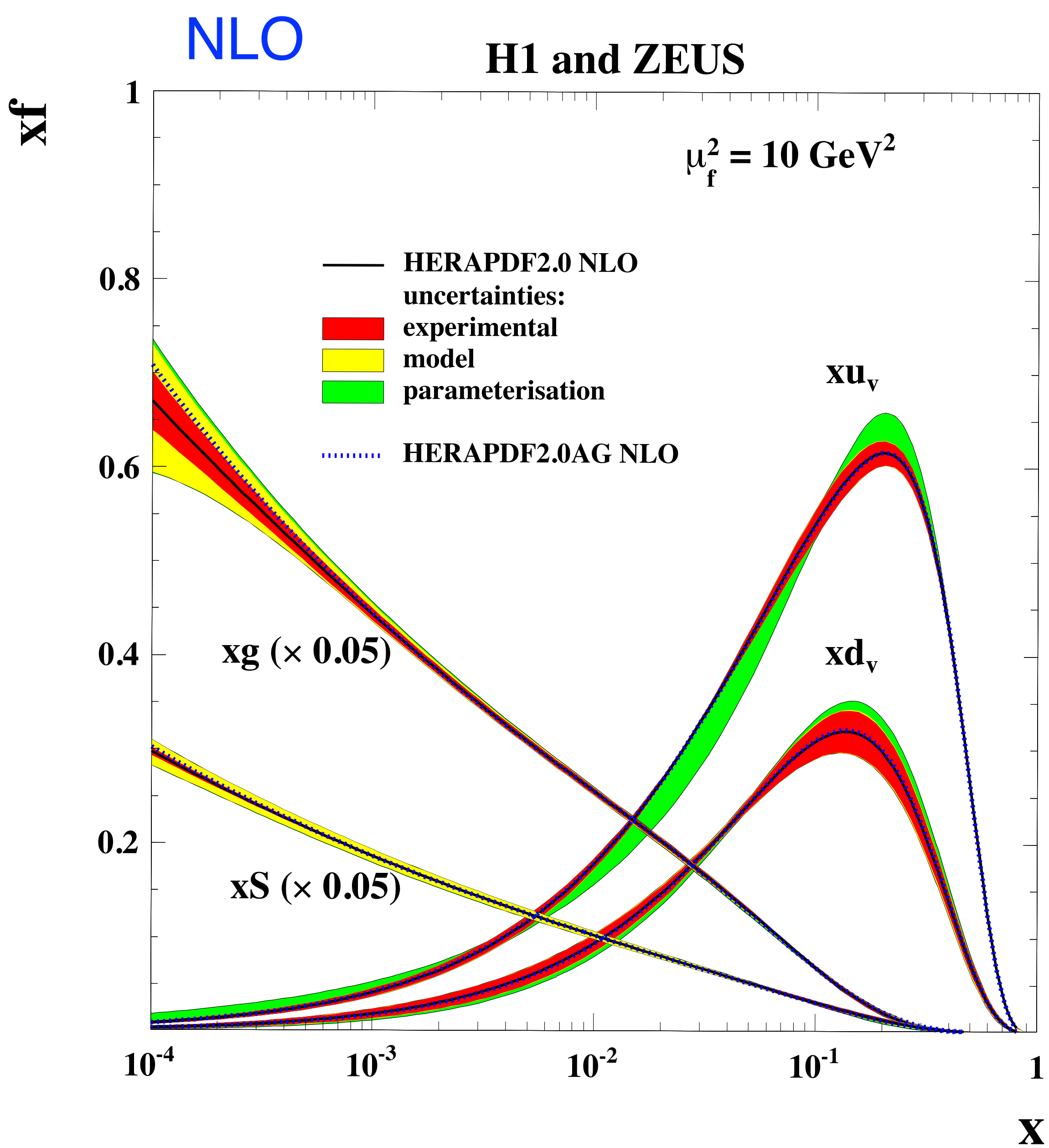


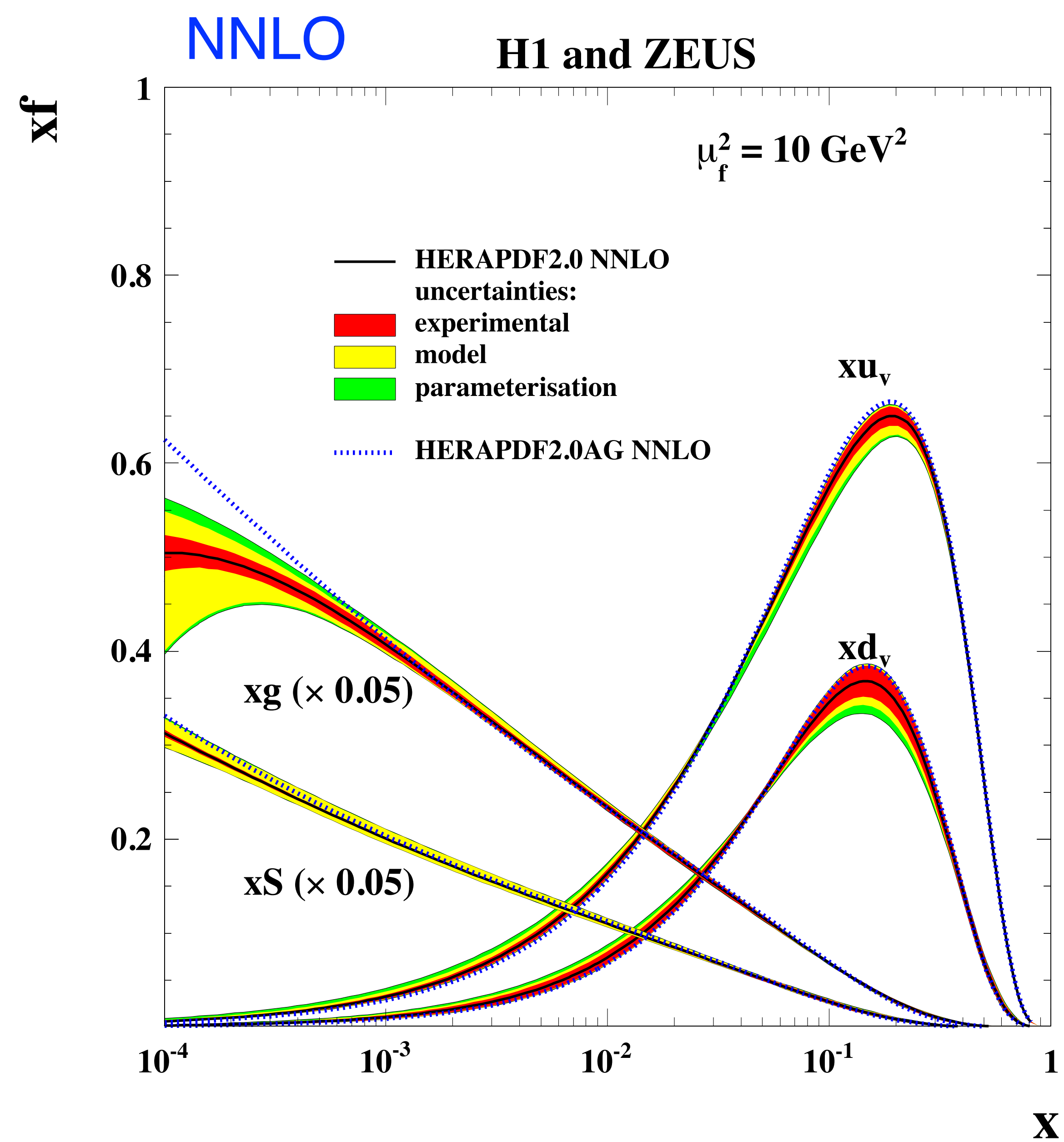


Description generally good, however some problems at low x and Q^2 with the turnover related to F_L.

For the lowest Q^2 prediction too high, however the turnover present as expected at low x and Q^2.

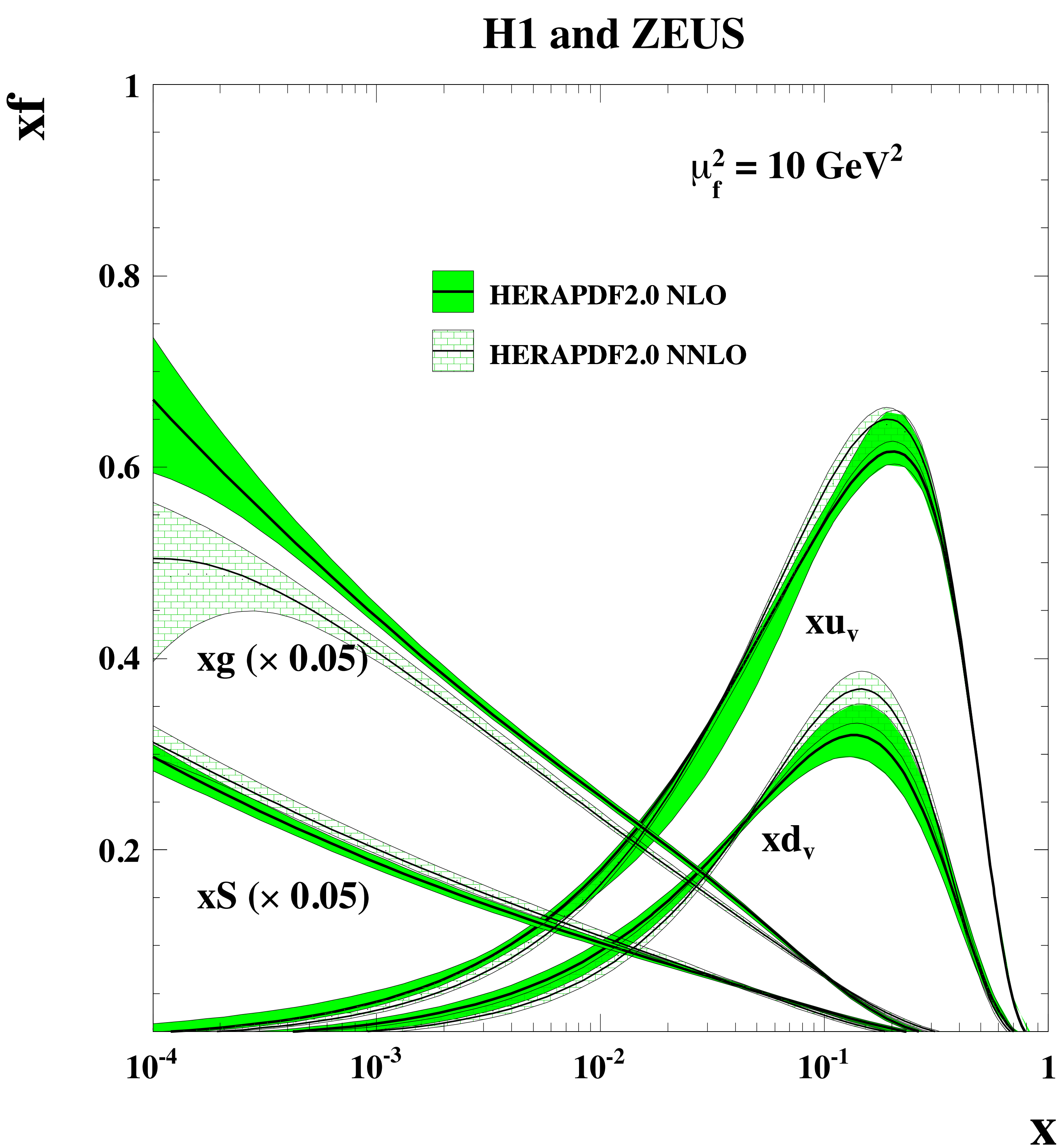
Parton distribution functions extracted with HERAPDF2.0





Experimental, model and parametrisation uncertainties shown separately.

HERAPDF2.0 parton distributions NNLO vs NLO

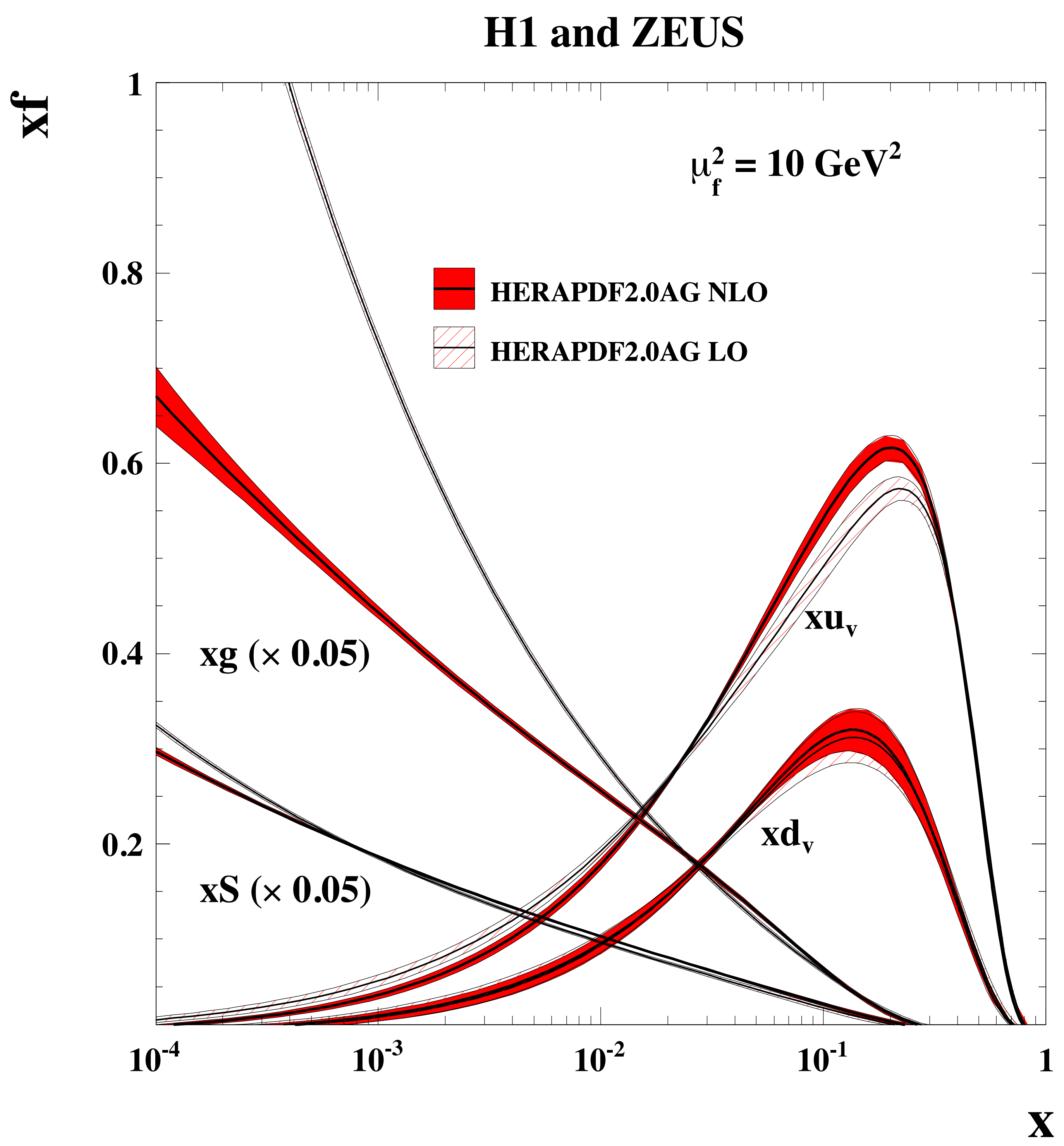


Bands show total PDF uncertainty calculated by adding in quadrature experimental, model and parametrisation uncertainties.

Main difference - different shapes of gluon distributions.

Valence quarks very similar.

HERAPDF2.0 parton distributions NLO vs LO



LO predictions needed for LO Monte Carlo generators.

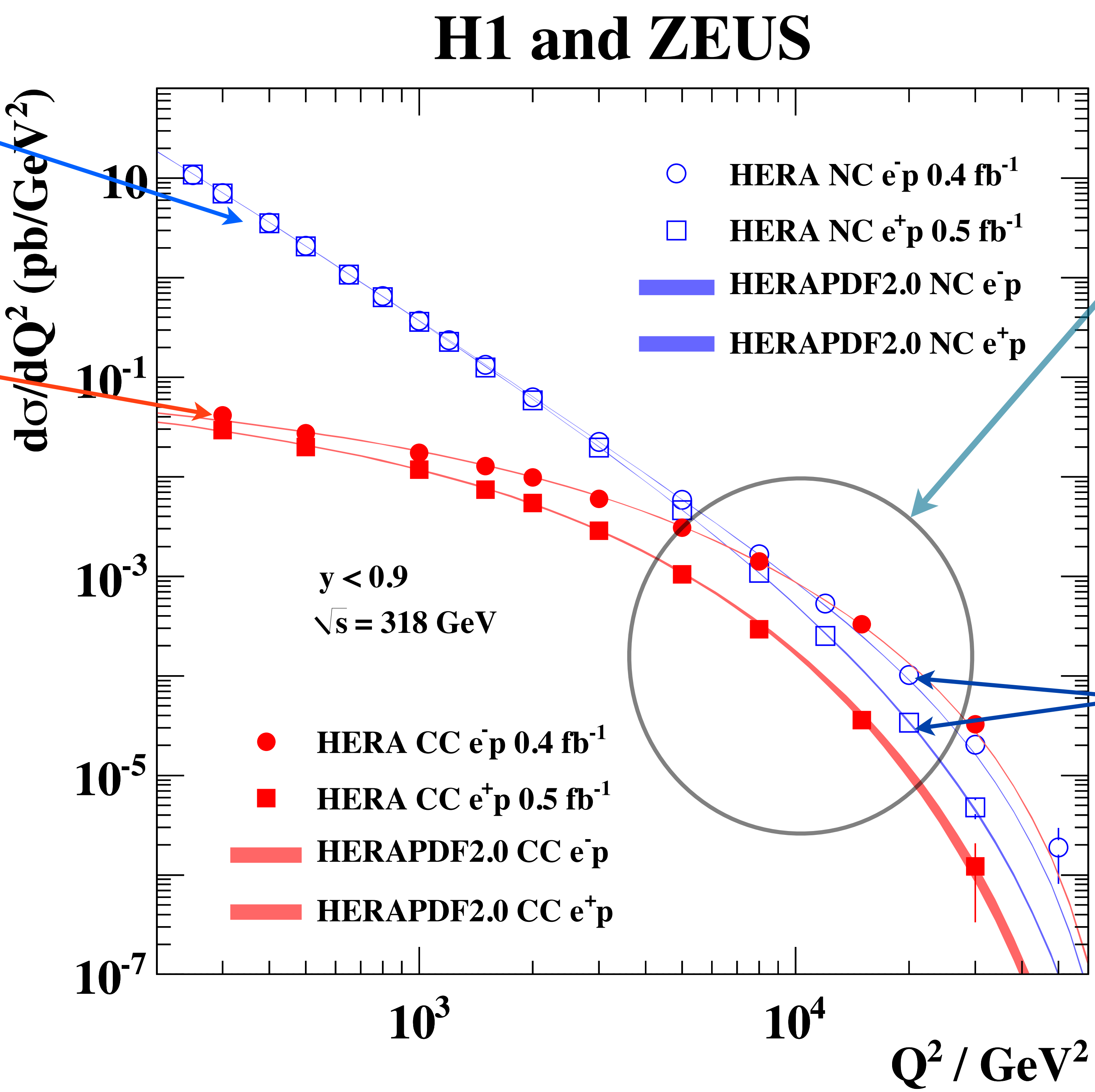
Only experimental uncertainties shown for LO predictions.

Gluon distribution at LO rises much faster than in NLO.

xu_v distribution softer at LO.

Electroweak unification

NC cross section dominated by photon exchange - much bigger than CC cross section.



NC and CC cross sections become similar in magnitude around 10^4 GeV^2 i.e. M^2_Z, M^2_W.

Electroweak unification observed with impressive precision!

NC e^+p and e^-p cross sections start to differ, when γ-Z interference becomes important.

xF_3 structure function

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}(\sigma^-_{r,\mathrm{NC}} - \sigma^+_{r,\mathrm{NC}})$$

xF_3 calculated from the difference of e^-p and e^+p NC cross sections

$$xF_3^{\gamma Z} \approx \frac{x}{3}(2u_v + d_v)$$

gives information about valence quarks

Weak Q^2 dependence => translated to common scale and averaged.

Integrated over x:

$0.016 < x < 0.725$

$$\mathrm{HERAPDF2.0}: 1.165^{+0.042}_{-0.053}$$

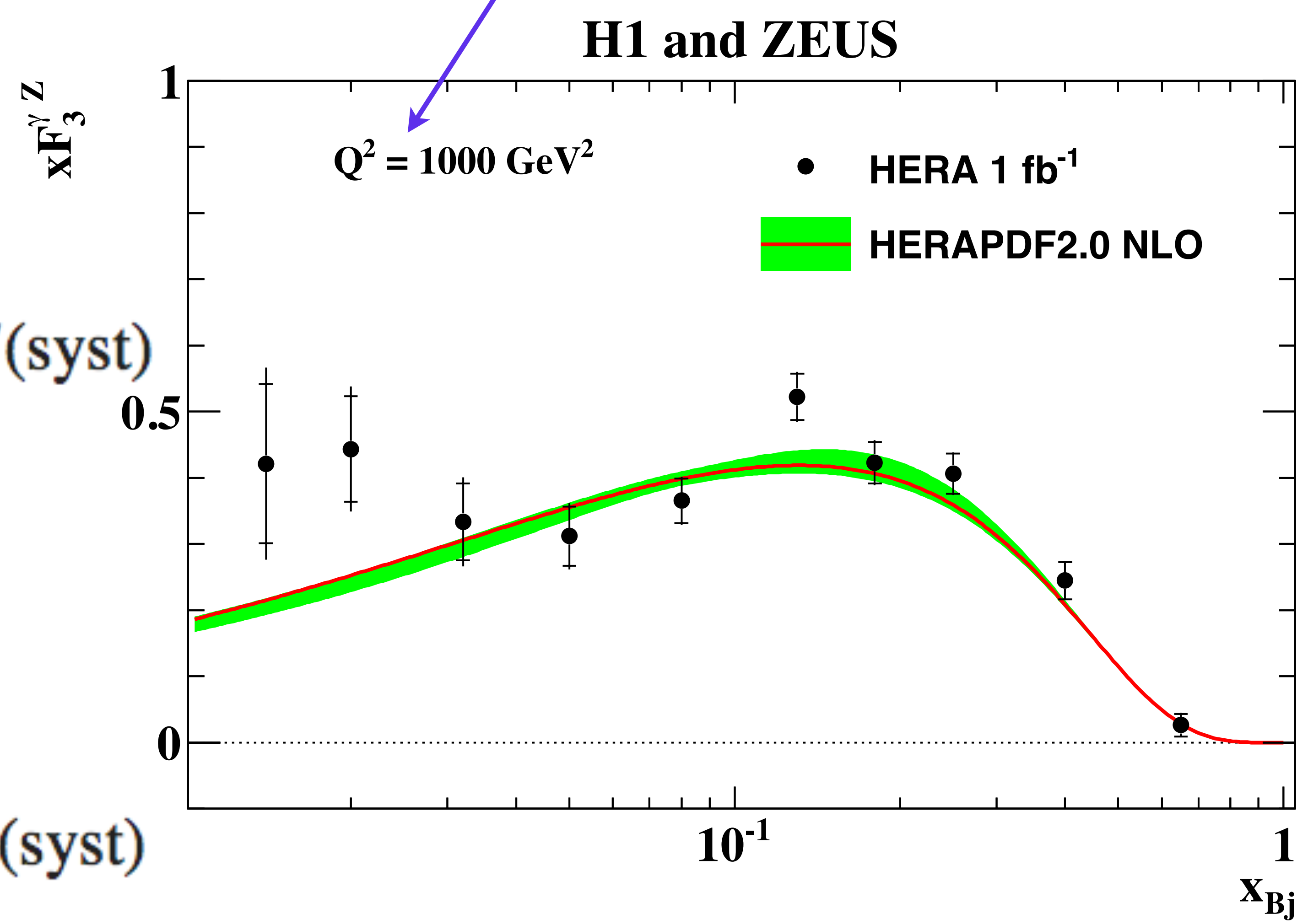
$$\mathrm{Data}: 1.314 \pm 0.057(\mathrm{stat}) \pm 0.057(\mathrm{syst})$$

$0 < x < 1$

$$\mathrm{HERAPDF2.0}: 1.588^{+0.078}_{-0.100}$$

$$\mathrm{QPM}: 5/3$$

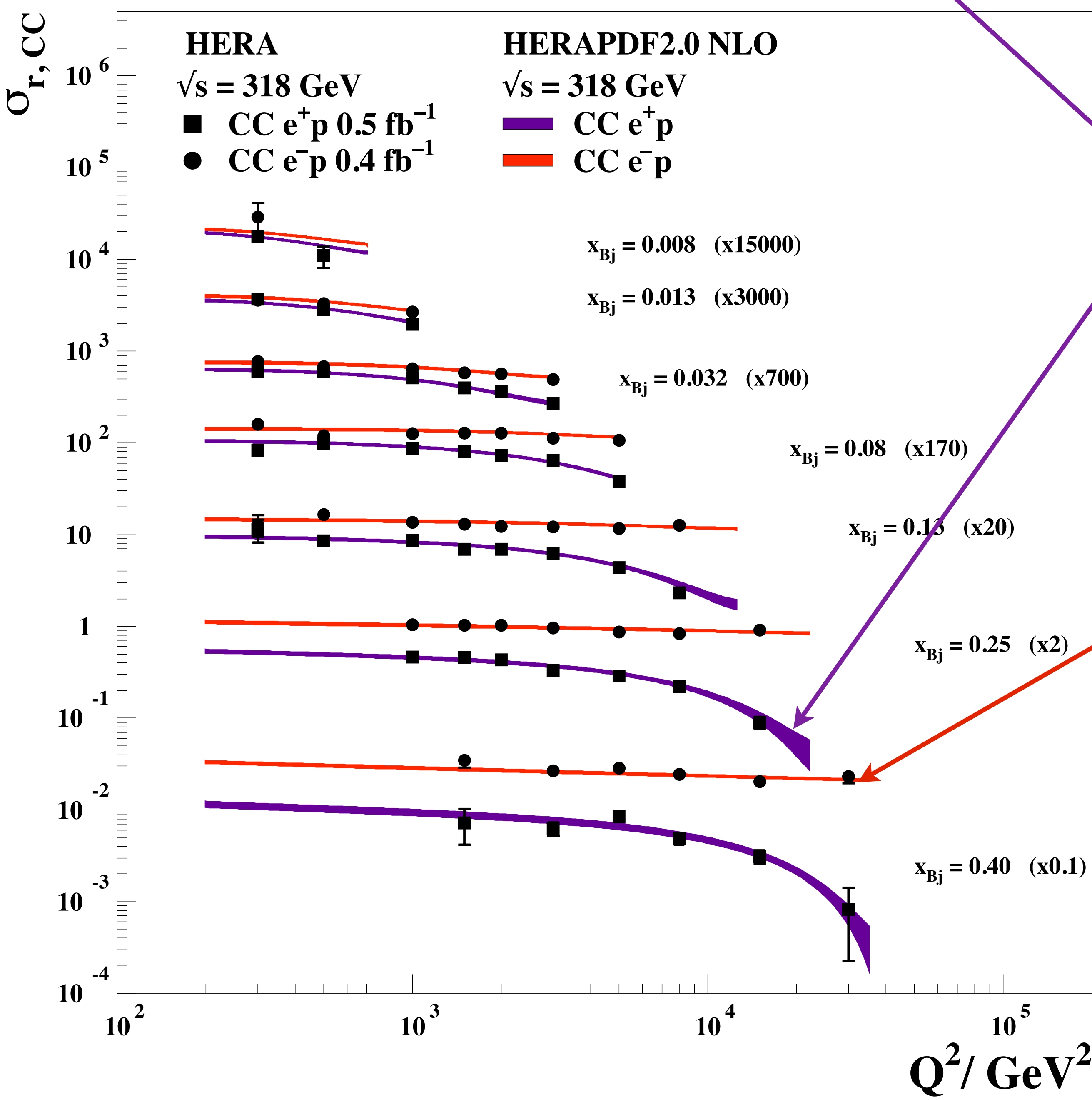
$$\mathrm{Data}: 1.790 \pm 0.078(\mathrm{stat}) \pm 0.078(\mathrm{syst})$$



Good agreement with predictions.

Helicity effects in CC

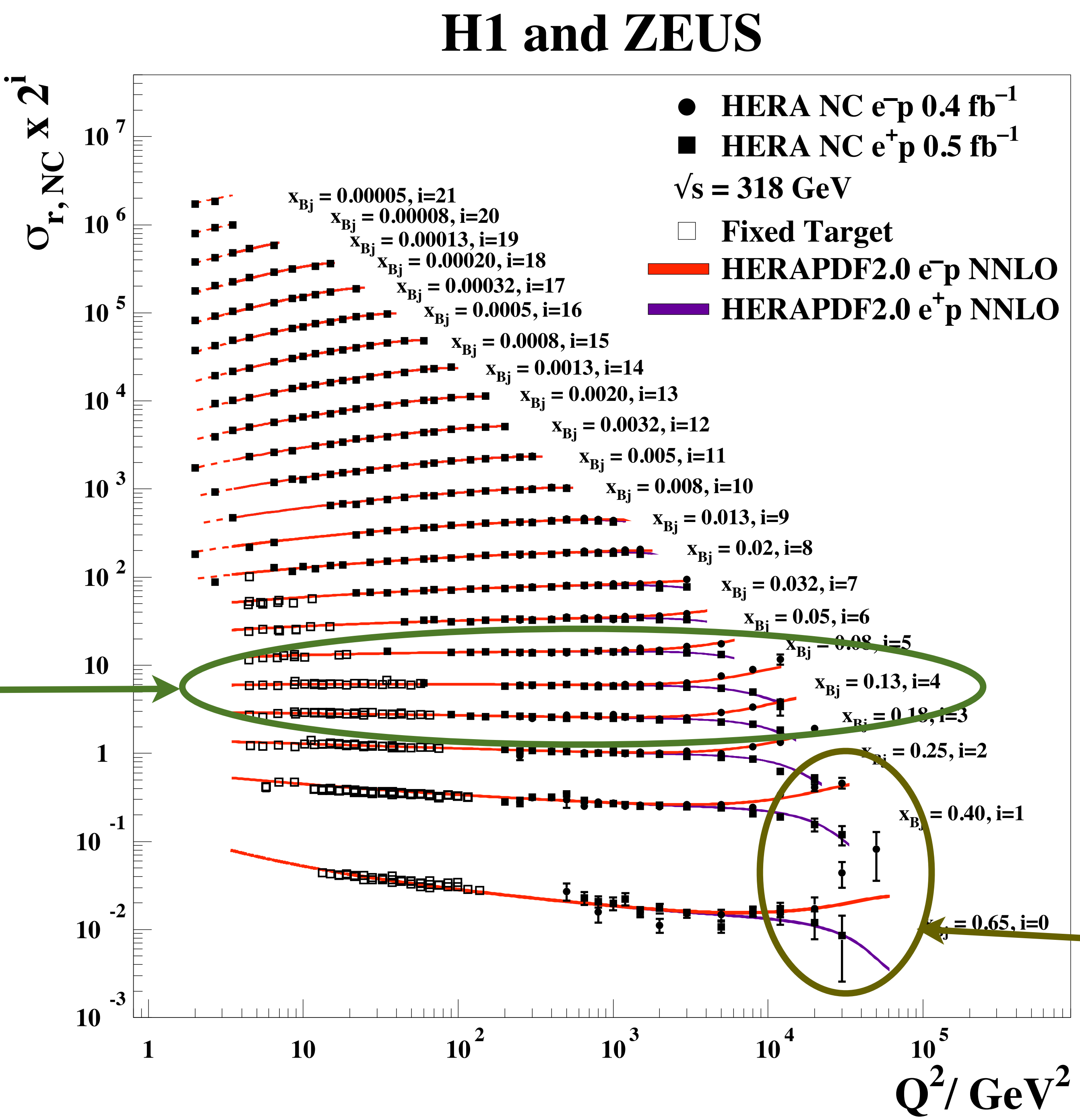
$$\sigma^{+}_{r,CC} \approx (x\bar{U} + (1-y)^2 xD)\,, \qquad \sigma^{-}_{r,CC} \approx (xU + (1-y)^2 x\bar{D})$$



e⁺p: contribution of the valence quarks is suppressed by the helicity factor at high Q^2 (high y)

e⁻p: almost no effect, as helicity factor applies to see quarks only

Scaling violations

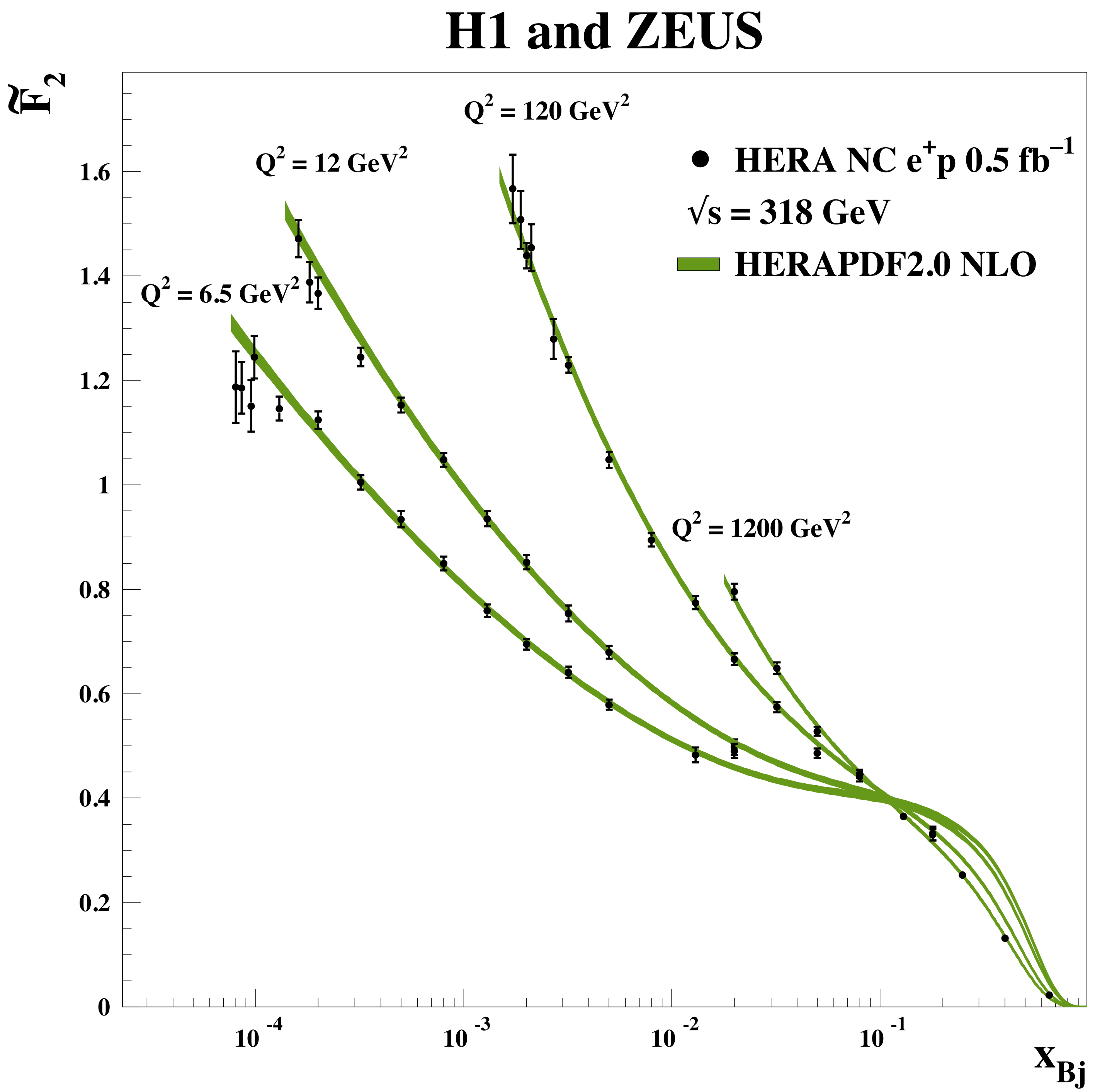


scaling
(independence of Q^2)

Interference between γ and Z

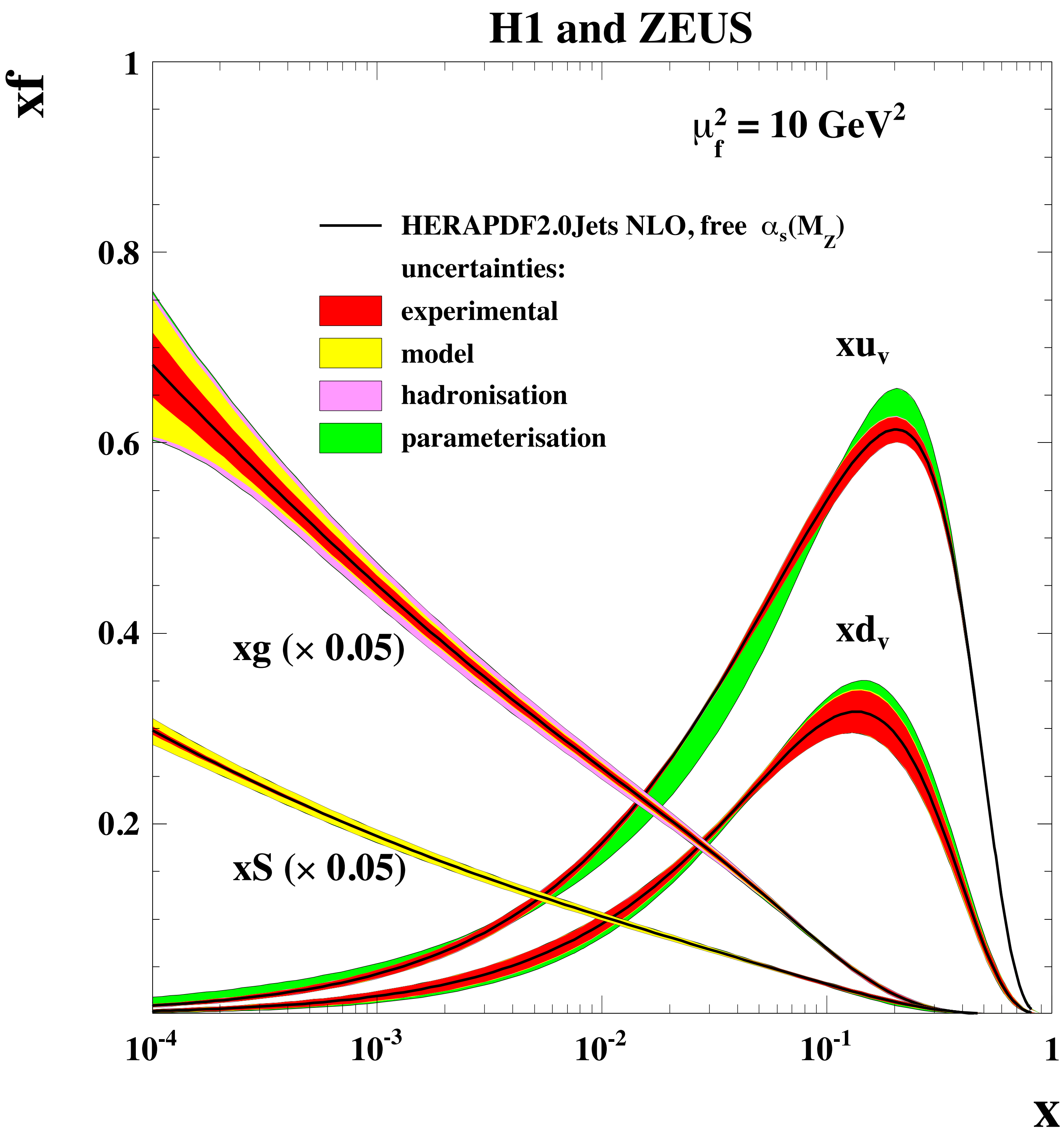
Scaling seen only at moderate x, at high and low x no scaling due to gluon emission and gluon splitting.

Rise of F_2 at low x



The higher Q^2 the steeper rise - another demonstration of scaling violation.

Determination of α_s



α_s determined from QCD fit (to inclusive data + charm + jets) - HERAPDF2.0Jets with α_s as a free parameter

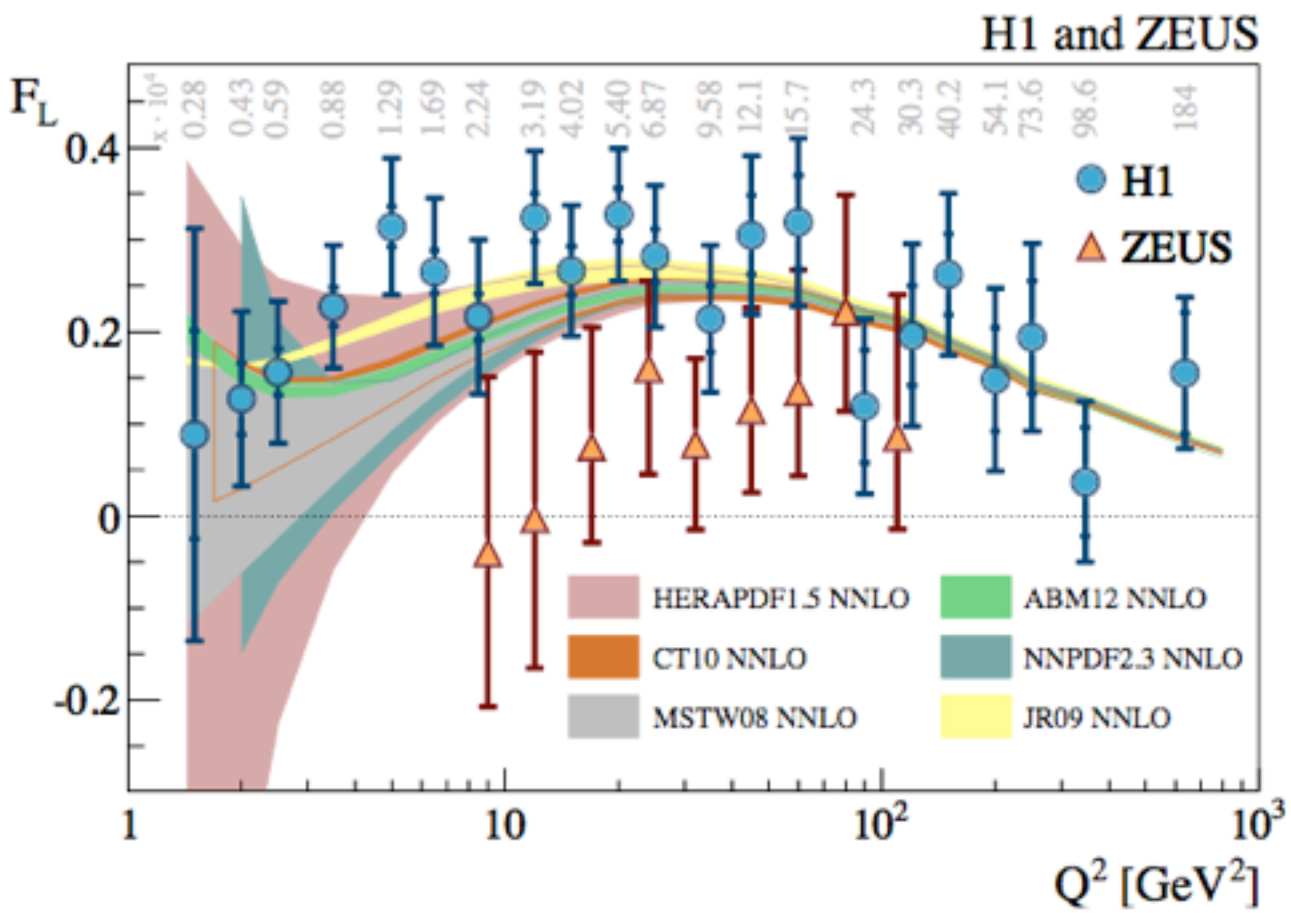
$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0009(\text{exp}) \pm 0.0005(\text{model/parameterisat}$$
$$\pm 0.0012(\text{hadronisation})^{+0.0037}_{-0.0030}(\text{scale})$$

Experimental uncertainty below 1%. Uncertainty dominated by theory - NNLO ep jet calculations needed.

Very good agreement with world average:

$$\alpha_s(M_Z^2) = 0.1185$$

Longitudinal structure function F_L



F_L structure function sensitive to gluons.
Directly measured by H1 and ZEUS using runs with lowered proton beam energy.
F_L measurements not combined yet.

Consistency between H1 and ZEUS:
$\chi^2/\mathrm{ndf} = 11/8$

$R=\sigma_L/\sigma_T = F_L/F_2\text{-}F_L$

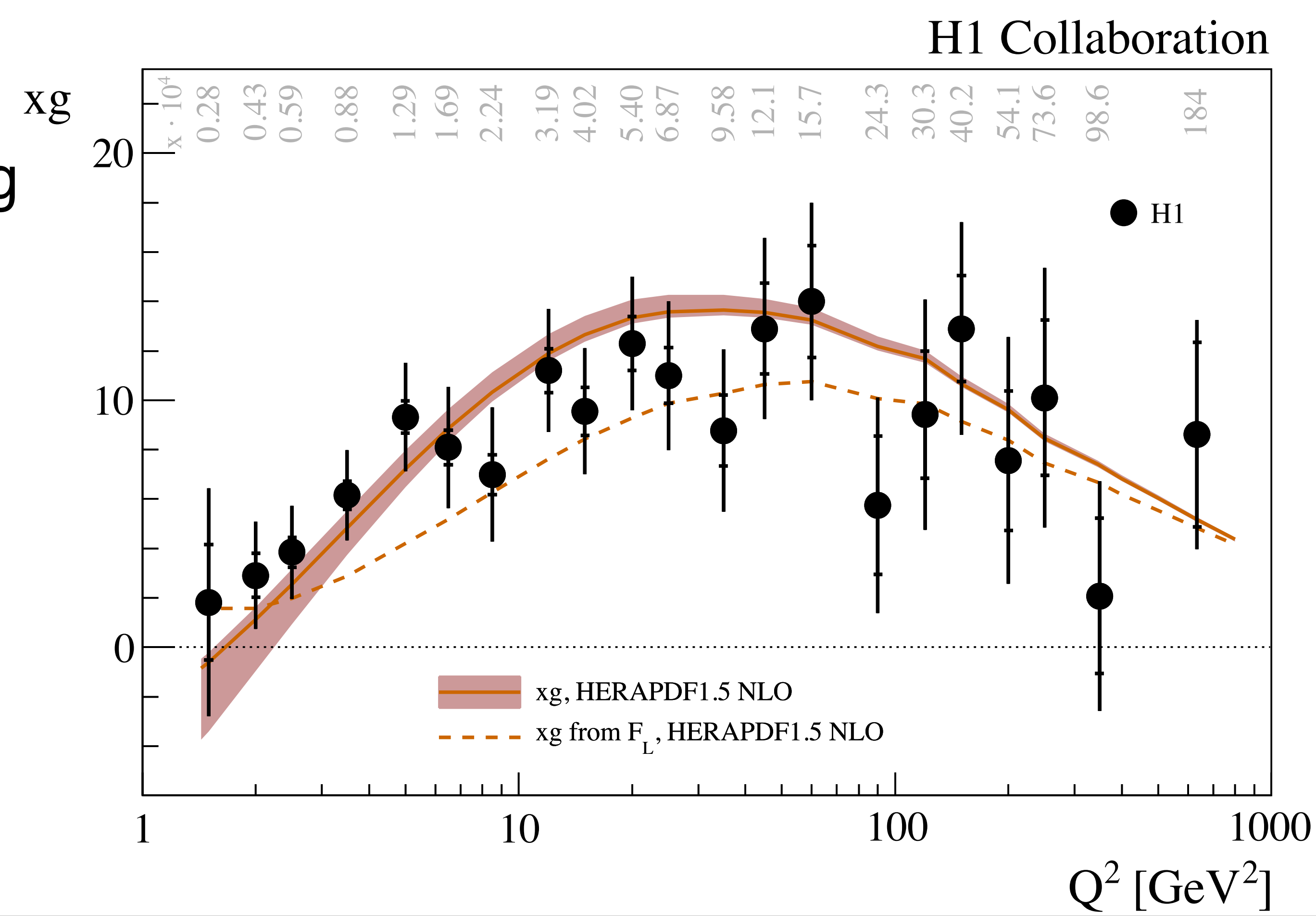
$R_{H1}=0.23\pm0.04 \quad 1.5 \leq Q^2 \leq 800\ \mathrm{GeV}^2$

$R_{ZEUS}=0.105 + 0.055 - 0.037 \quad 9 \leq Q^2 \leq 110\ \mathrm{GeV}^2$

H1 extracted gluon density from F_L using approximation:

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

result consistent with gluon determined from scaling violations.



Summary

- All inclusive HERA data combined in consistent set of NC and CC cross section measurements, spanning 6 orders of magnitude in x and Q^2.

- The inclusive cross sections used as an input to a QCD analysis within the DGLAP formalism. Resulting parton distributions - HERAPDF2.0 - available at LO, NLO, NNLO. Included into LHAPDF.

- All three structure functions (F_2, F_L and xF_3) measured.

- The results constitute the HERA legacy of nearly 25 years of activity.