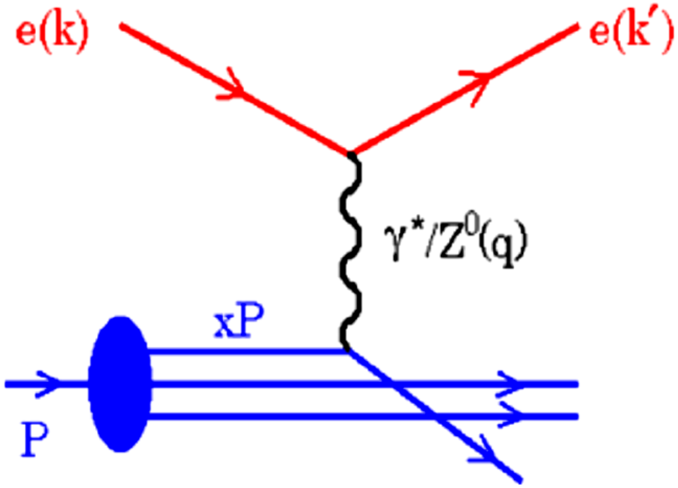
Proton Structure Results from HERA

S. Glazov, DESY,
for H1 and ZEUS collaborations
Gatchina 2014

Proton structure probe



Neutral current Deep Inelastic Scattering (DIS) cross section:

$$\frac{d^2\sigma^\pm}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x}\sigma_r^\pm =$$

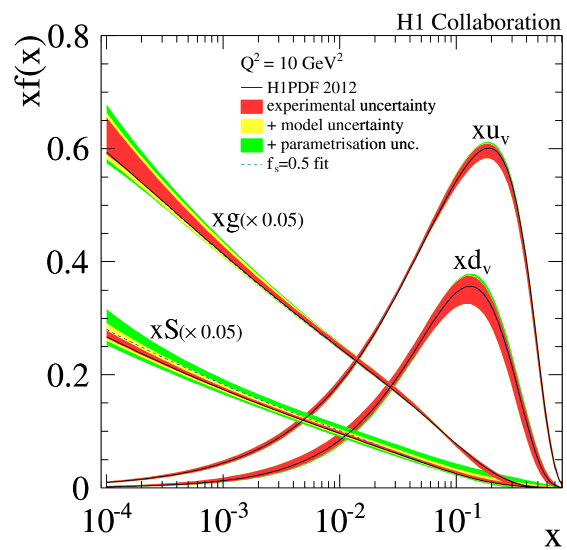
$$= \frac{2\pi\alpha^2 Y_+}{Q^4 x}\left[F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3\right]$$

where factors $Y_\pm = 1 \pm (1-y)^2$ and y^2 define polarisation of the exchanged boson and $y = Q^2/(S\ x)$.

Kinematics is determined by Q^2 and Bjorken x. At leading order:

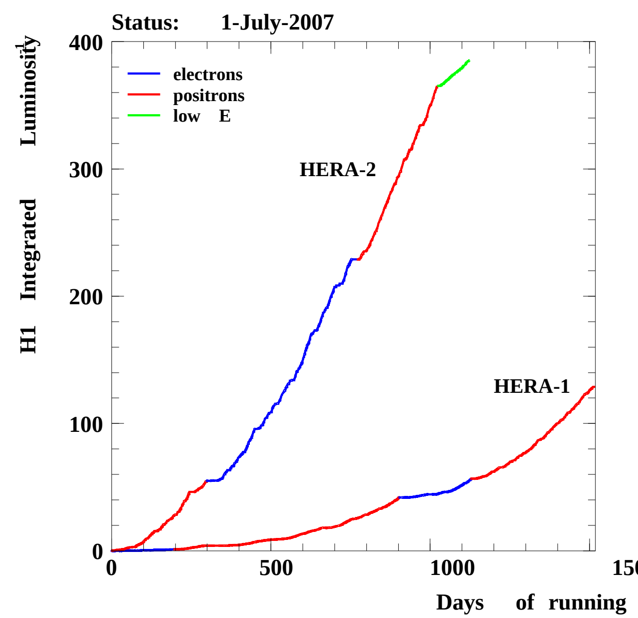
$$\begin{aligned} F_2 &= x\sum e_q^2(q(x)+\bar{q}(x)) \\ xF_3 &= x\sum 2e_q a_q(q(x)-\bar{q}(x)) \\ \sigma^+_{CC} &\sim x(\bar{u}+\bar{c}) + x(1-y)^2(d+s) \\ \sigma^-_{CC} &\sim x(u+c) + x(1-y)^2(\bar{d}+\bar{s}) \end{aligned}$$

$xg(x)$ — from F_2 scaling violation, jets and F_L



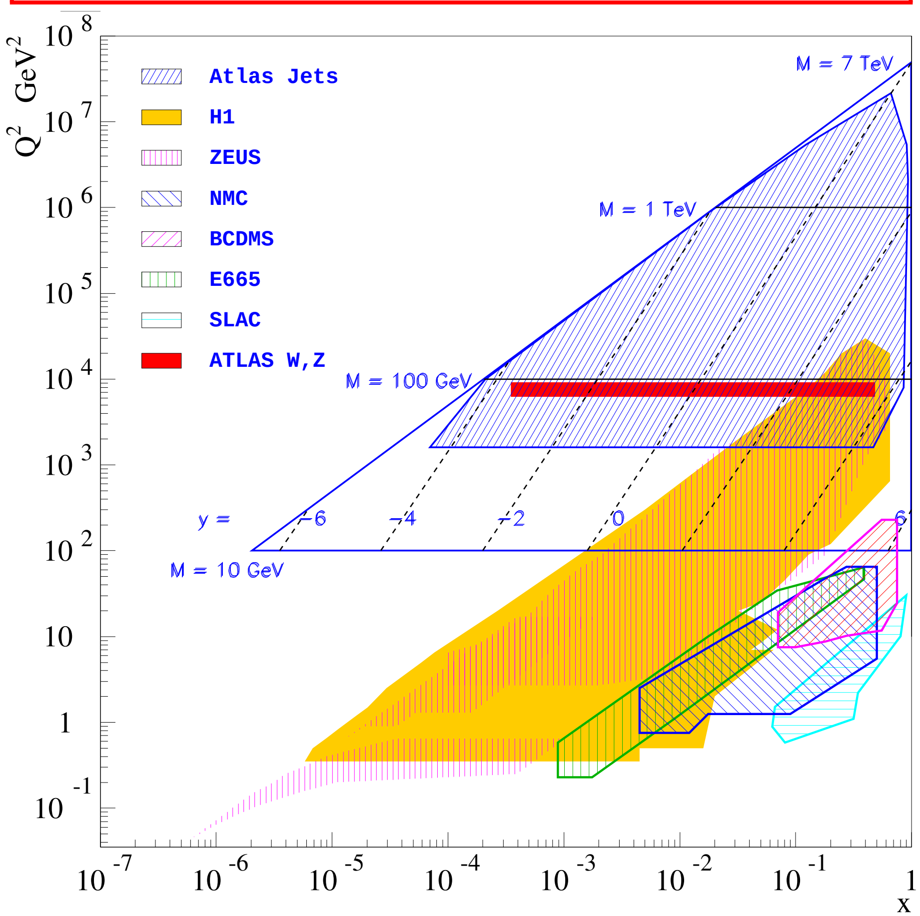
HERA, H1 and ZEUS.

$E_e \times E_p$=27.5×920 GeV^2
$\sqrt{s}$ = 318 GeV
L= 5·10^{31}cm^{-2}s^{-1}
e-beam polarisation.



Integrated luminosity: about 500 pb^{-1} per experiment.

Cross sections at the LHC



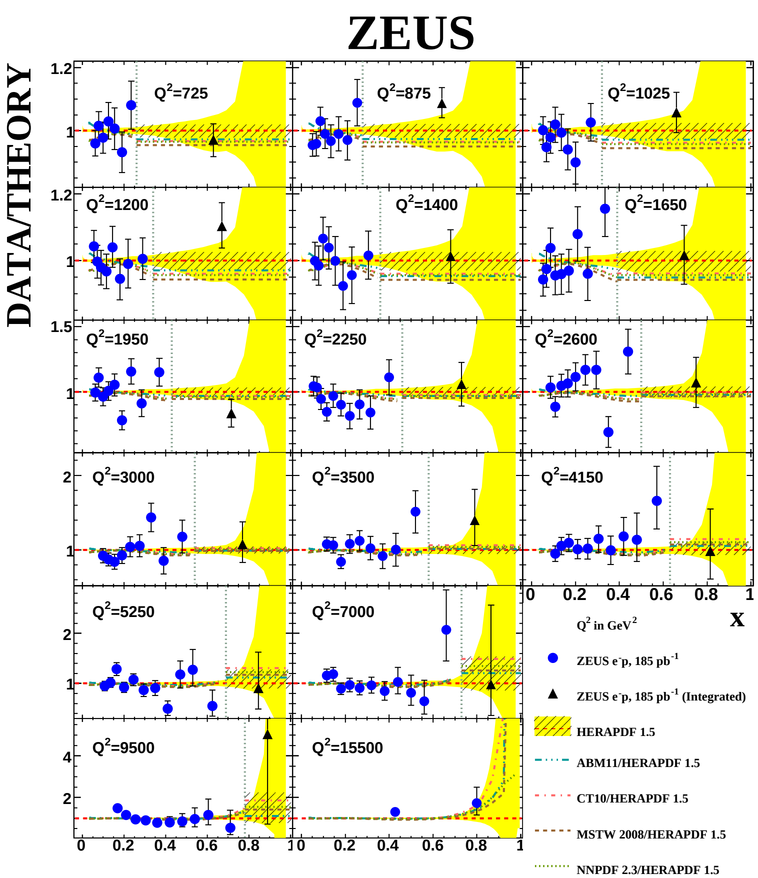
The cross sections are given by a convolution of the parton densities and coefficient functions, $\sim x_1 f_1(x_1, \mu)\, x_2 f_2(x_2, \mu)\, \hat{\sigma}(x_1, x_2, \mu)$. Leading order relation between rapidity y and x_1, x_2: $x_{1,2} = \frac{M_{\ell\ell}}{\sqrt{S}} e^{\pm y_{\ell\ell}}$.

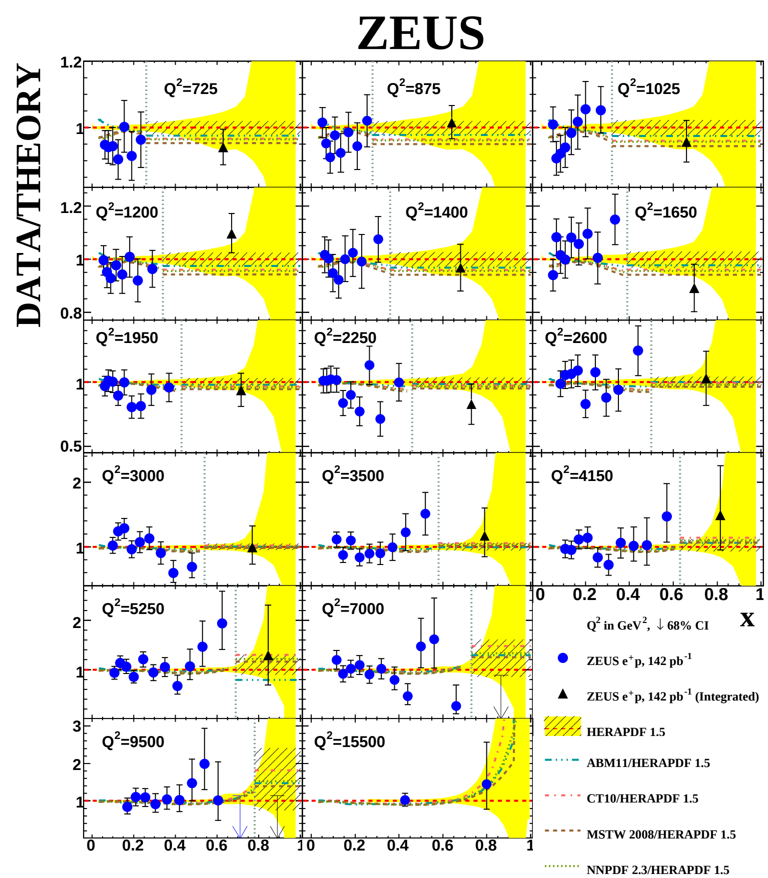
→ HERA data are essential for the LHC predictions.

Overview of the recent H1 and ZEUS results

- ZEUS
  - Measurement of the DIS cross section at high x and high Q^2 Phys. Rev. D 89, 072007 (2014)
  - Measurement of the structure function F_L arXiv:1404.6376
- H1
  - Measurement of the structure function F_L at high Q^2 Eur. Phys. J. C 74 (2014) 2814
- HERA
  - Combination of the H1 and ZEUS cross section measurements H1prelim-14-041, ZEUS-prel-14-005
  - QCD analysis of the combined HERA data. H1prelim-14-042,ZEUS-prel-14-007

ZEUS measurement at high x



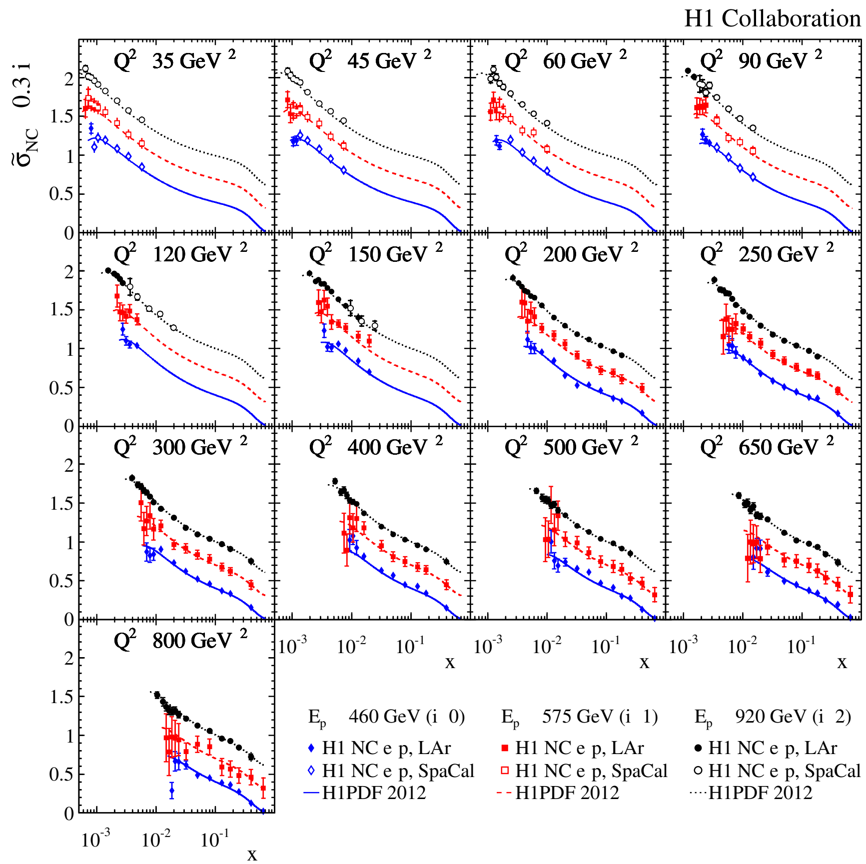


- Not so many accurate constraints on PDFs at largest x.
- Resolution of kinematic reconstruction degrades for low $y < 0.01$

→ Integrated $x_{min} < x \leq 1$ measurement.

Phys. Rev. D 89, 072007 (2014)

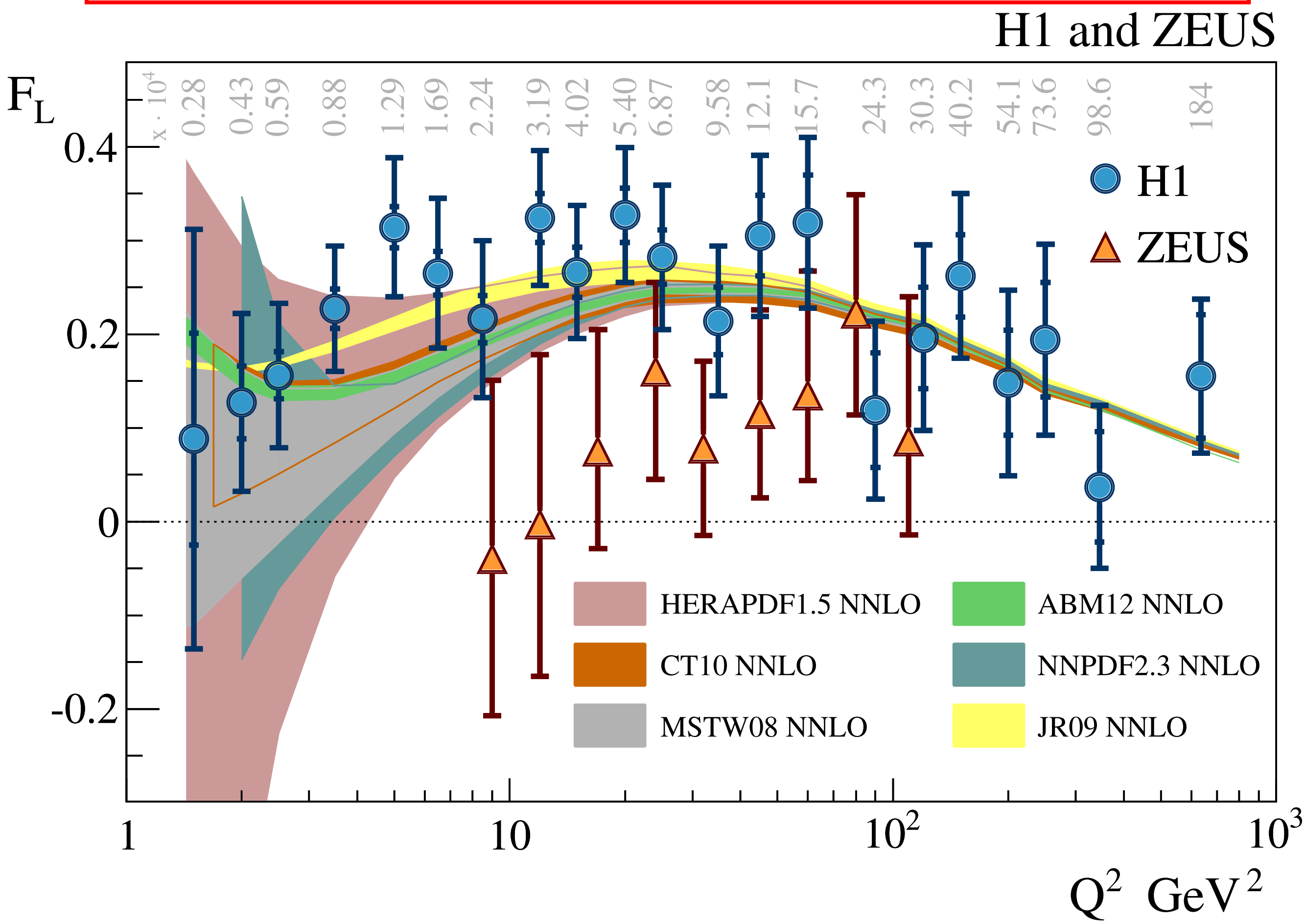
H1 cross section measurements at reduced $\sqrt{S}$



- At low Q^2, $\sigma_r = F_2 + y^2/Y_+ F_L$, varying y at fixed x, Q^2 allows one to separate contributions from s.f. F_2 and F_L. Achieved by changing S: $y = Q^2/(S\,x)$.
- New H1 cross section measurement using central LAr calorimeter

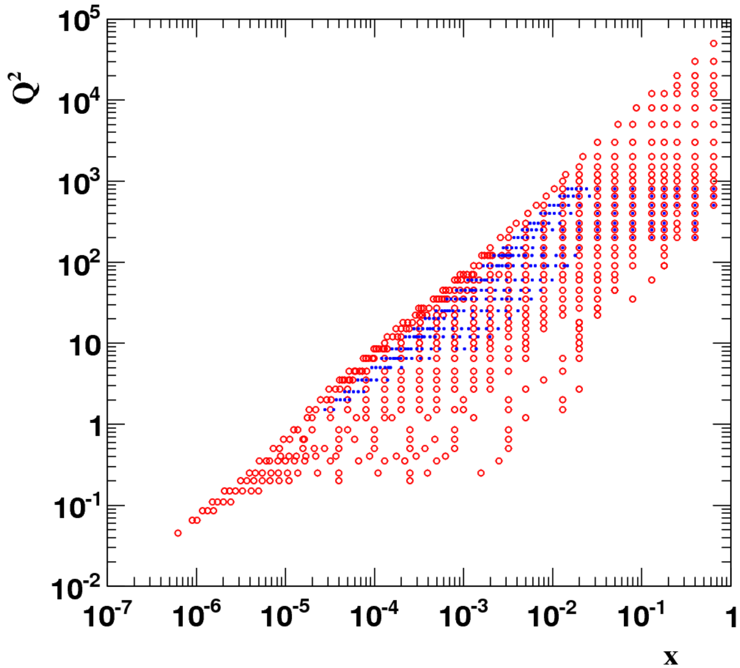
Eur. Phys. J. C 74 (2014) 2814

H1 and ZEUS measurements of F_L



- New measurement of the structure function F_L by ZEUS. arXiv:1404.6376
- H1 result is systematically above ZEUS, however the measurements agree at $\sim 1.5\sigma$ level.

HERA combination: input data samples



- Simultaneous combination of the 2927 data points from 41 data set published by the H1 and ZEUS collaborations corresponding to total integrated luminosity of $1\ \mathrm{fb}^{-1}$
- The measurements cover $0.045 \leq Q^2 \leq 50000\ \mathrm{GeV}^2$ and extends to $6 \times 10^{-6} \leq x$ for the neutral current process.
- Different detector technologies and kinematic reconstruction method lead to cross calibration of the measurements and reduction of the systematic uncertainties.

H1prelim-14-041, ZEUS-prel-14-005

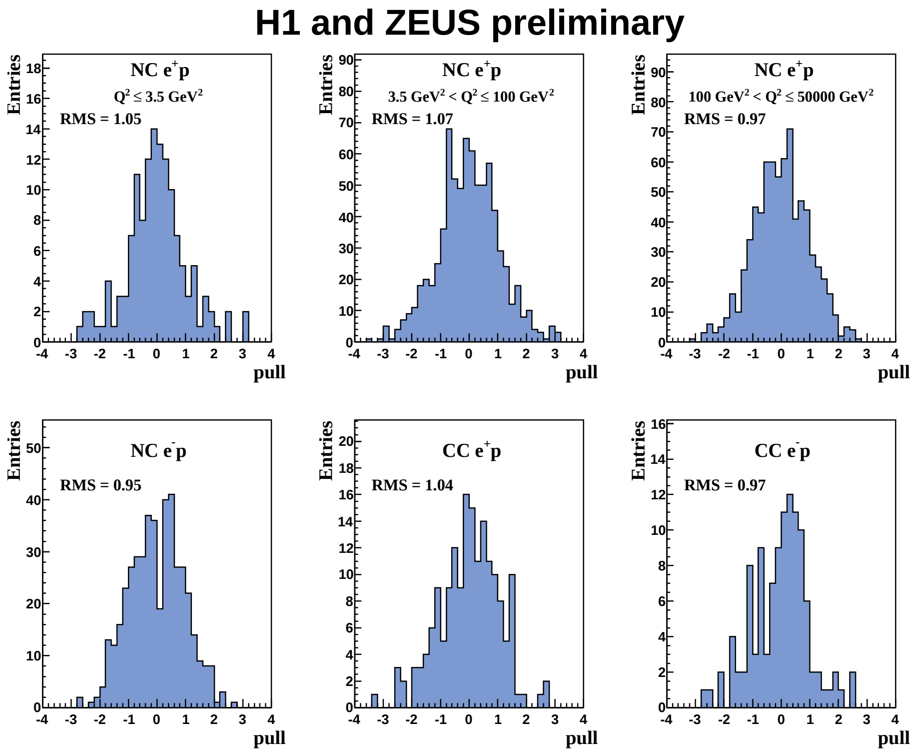
Combination procedure

$$\chi^2(m,b) = \sum_i \frac{\left(\mu_i - m_i\left(1+\sum_j b_j\gamma_i^j\right)\right)^2}{\delta_{i,\mathrm{stat}}^2\mu_i m_i\left(1+\sum_j b_j\gamma_i^j\right)+\delta_{i,\mathrm{uncor}}^2 m_i^2} + \sum_j b_j^2\,.$$

- Define the common x, Q^2 grid for the combined data.
- Repeat iteratively:
  - Parameterise the (combined) data by a smooth function;
  - Correct the data to the common grid using the parameterisation at the data original x, Q^2 and at the nearest grid point;
  - Combine the data, taking into account correlated systematic uncertainties.

The combination of the data is performed using the HERAverager program. The cross section data are parameterised using fractal model for $Q^2 < 3\ \mathrm{GeV}^2$ and using DGLAP NLO fit for higher Q^2, performed with the HERAFitter program.

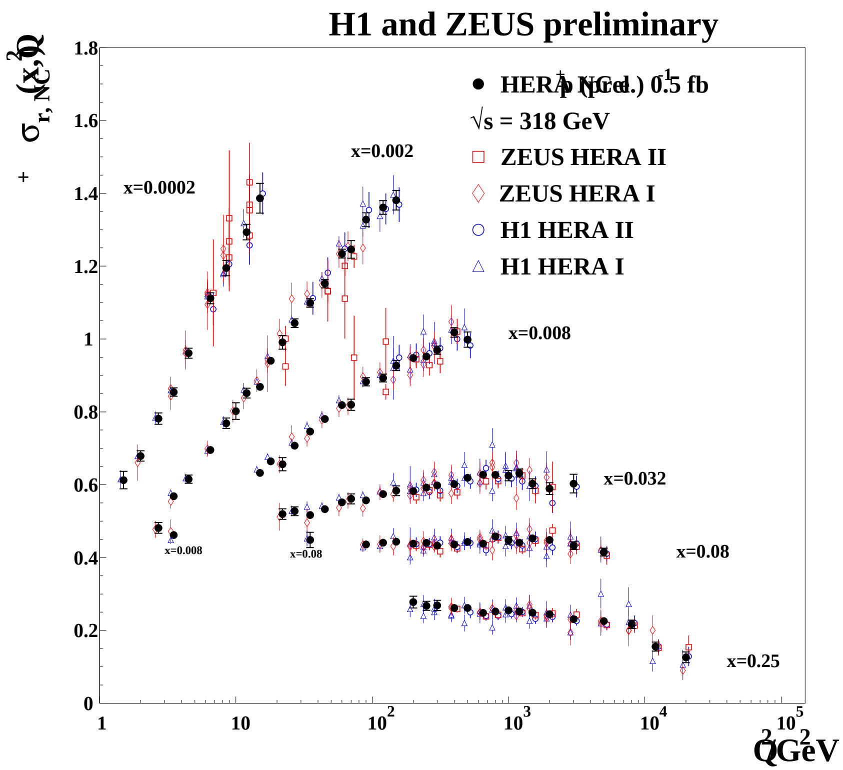
Combination quality

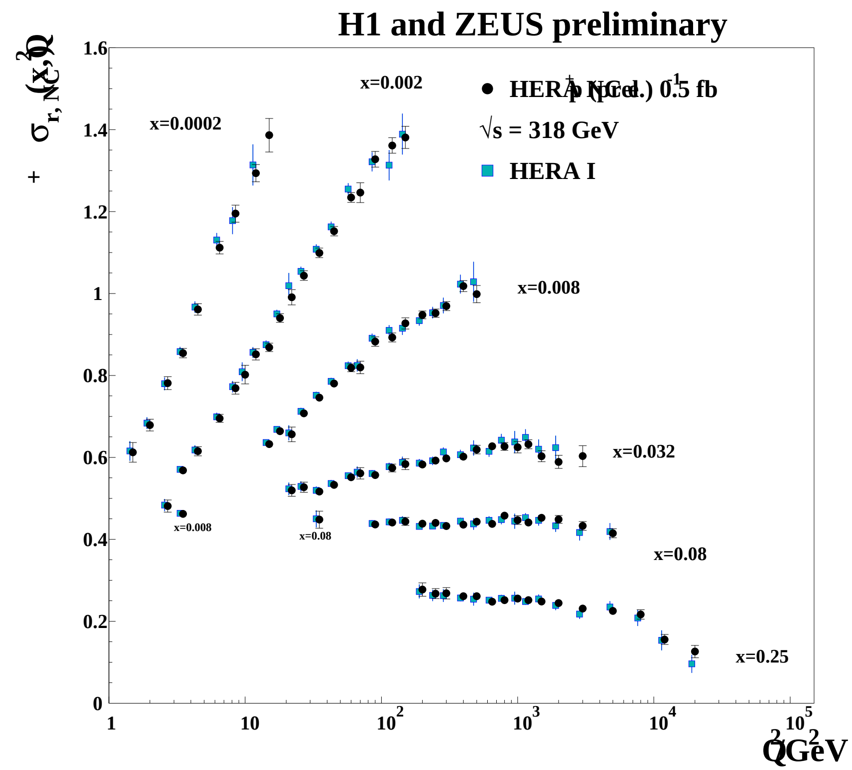


The combination yields a good overall $\chi^2/dof = 1685/1620$ value. The combination quality for different processes and different regions in phase space can be checked using distribution of pulls:

$$p_i = \frac{\mu_i - \mu_i^{\text{ave}}\left(1 - \sum_j \gamma_i^j \beta_{j,\text{ave}}\right)}{\sqrt{\Delta_i^2 - \Delta_{i,\text{ave}}^2}}.$$

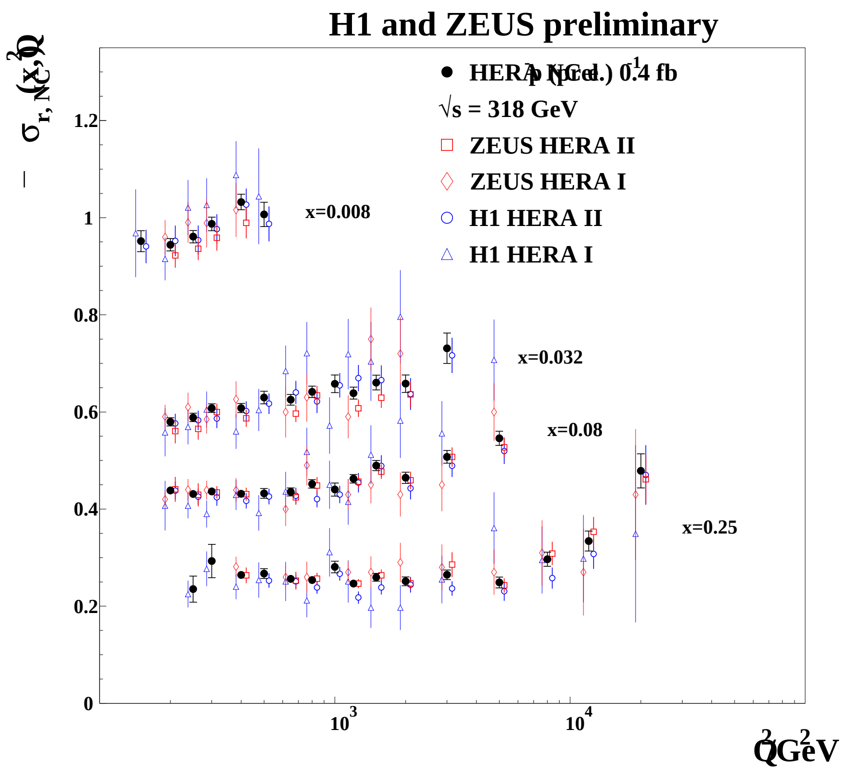
Combination results: NC e^+p

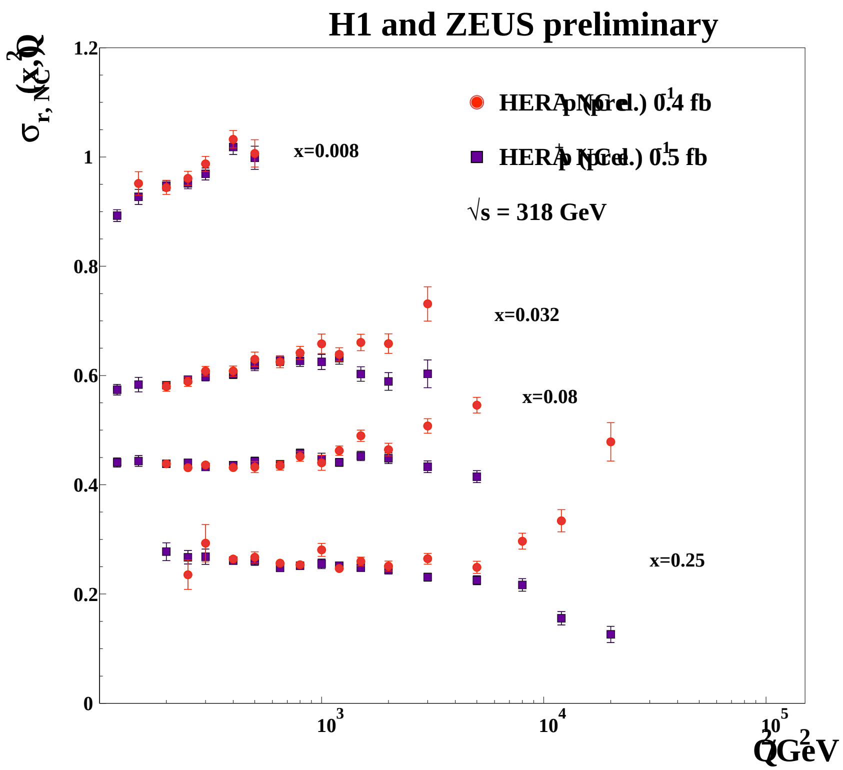




- Largest and most accurate data sample is for the NC e^+p process.
- The combined data accuracy reaches $\sim 1\%$.
- New HERA combination is consistent with HERA-I, with improved uncertainties.

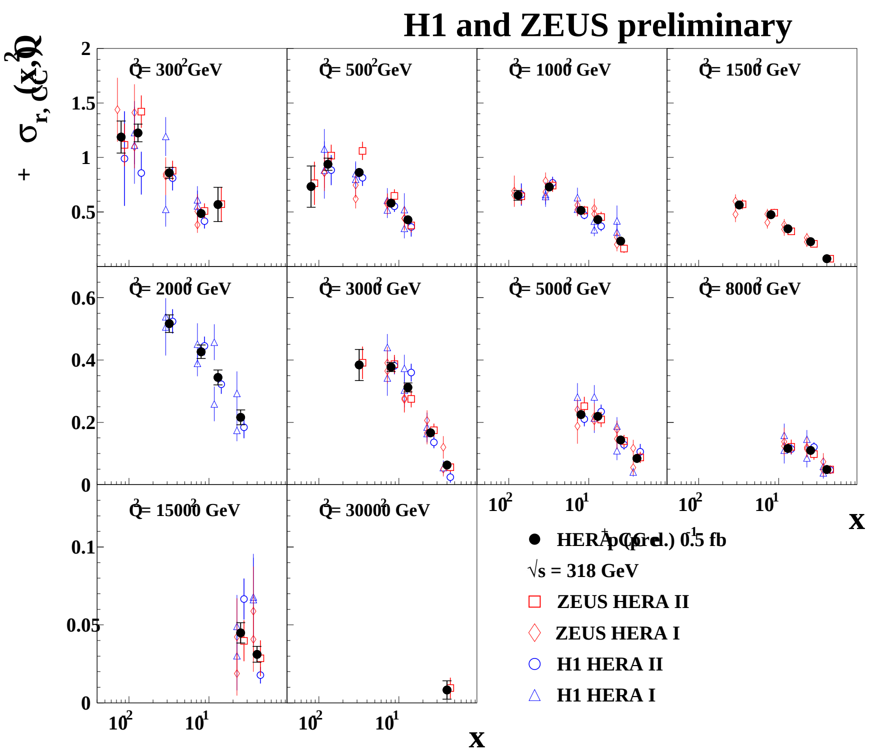
Combination results: NC e^-p

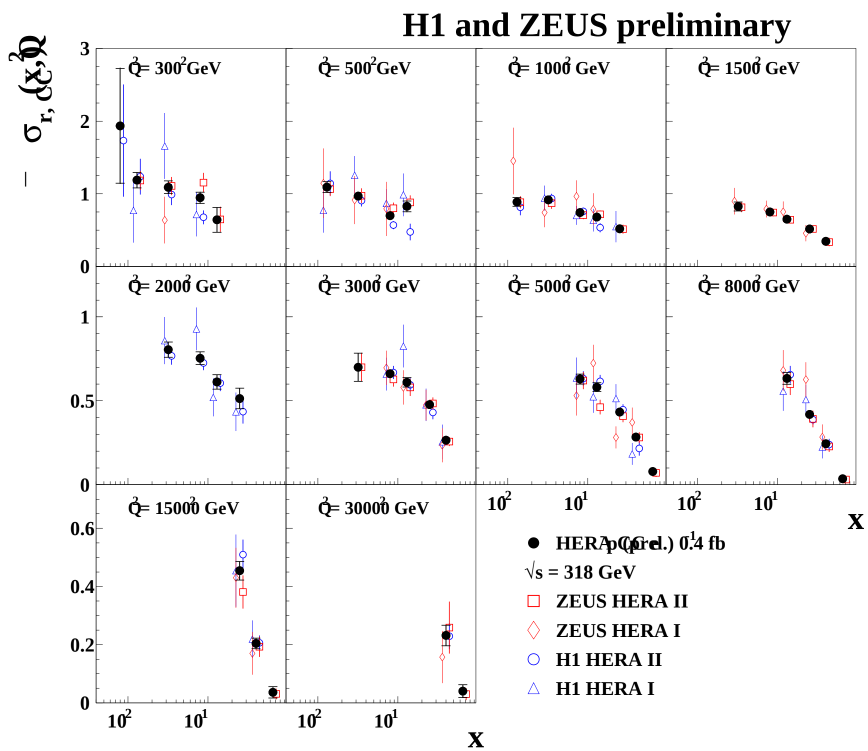




- HERA-II increases the e^-p sample luminosity by order of magnitude compared to HERA-I.
- At high Q^2, clear difference between the e^+p and e^-p cross sections is observed corresponding to the γZ interference and the structure function xF_3.

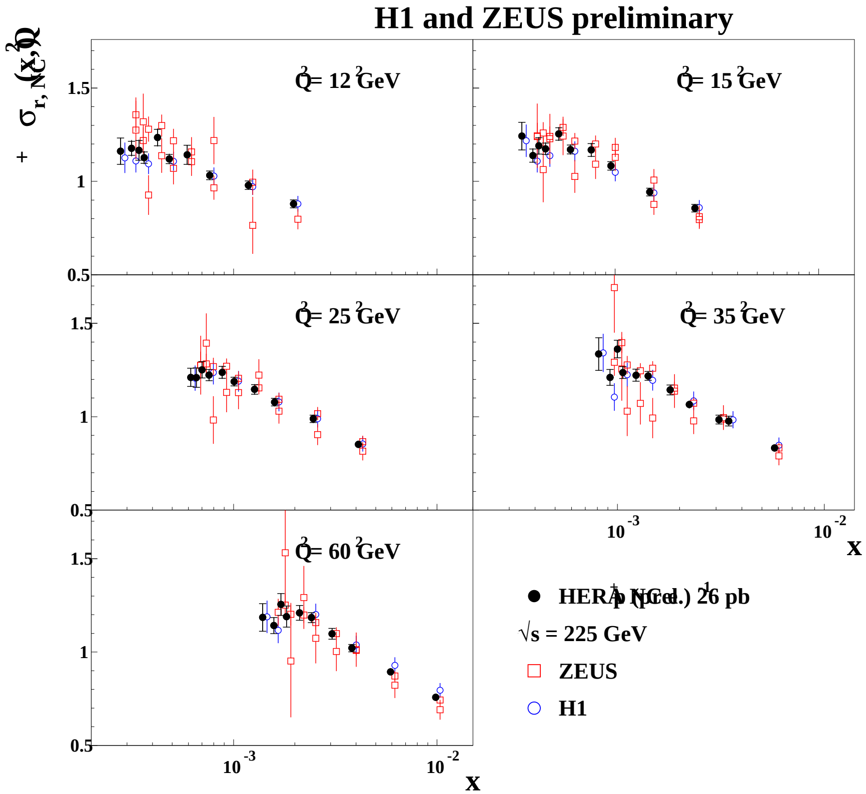
Combination results: CC

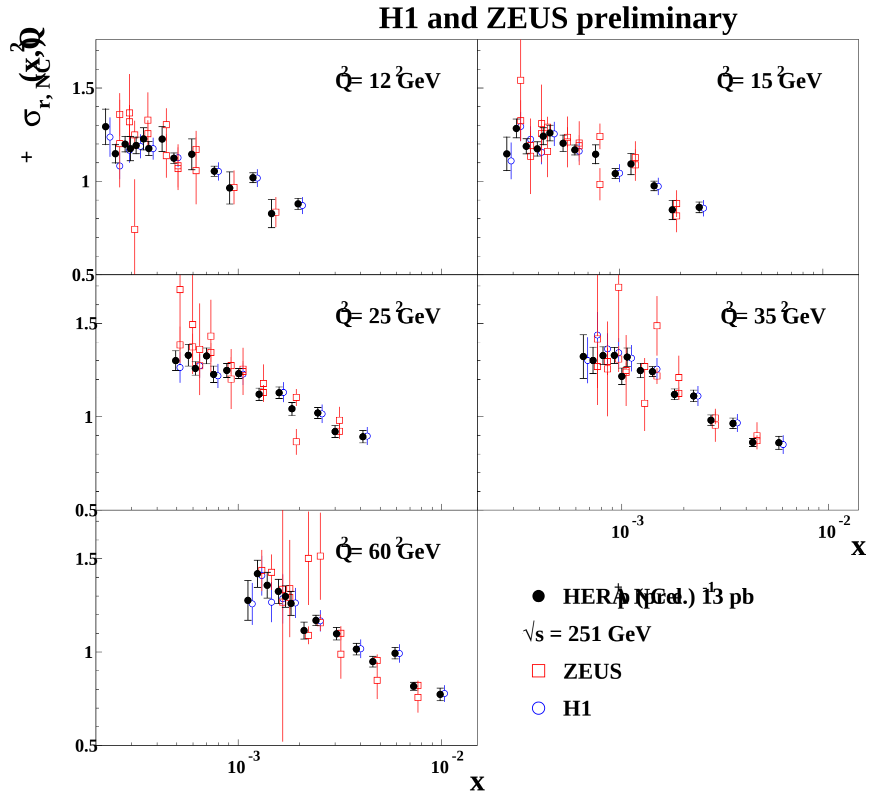




- Charged current data benefit from increased luminosity of the HERA-II data sample, this is in particular true for the $e^- p$ process.
- Increased accuracy of the combined data should reflect in improved determination of the valence quark distributions.

Combination results: reduced $\sqrt{s}$



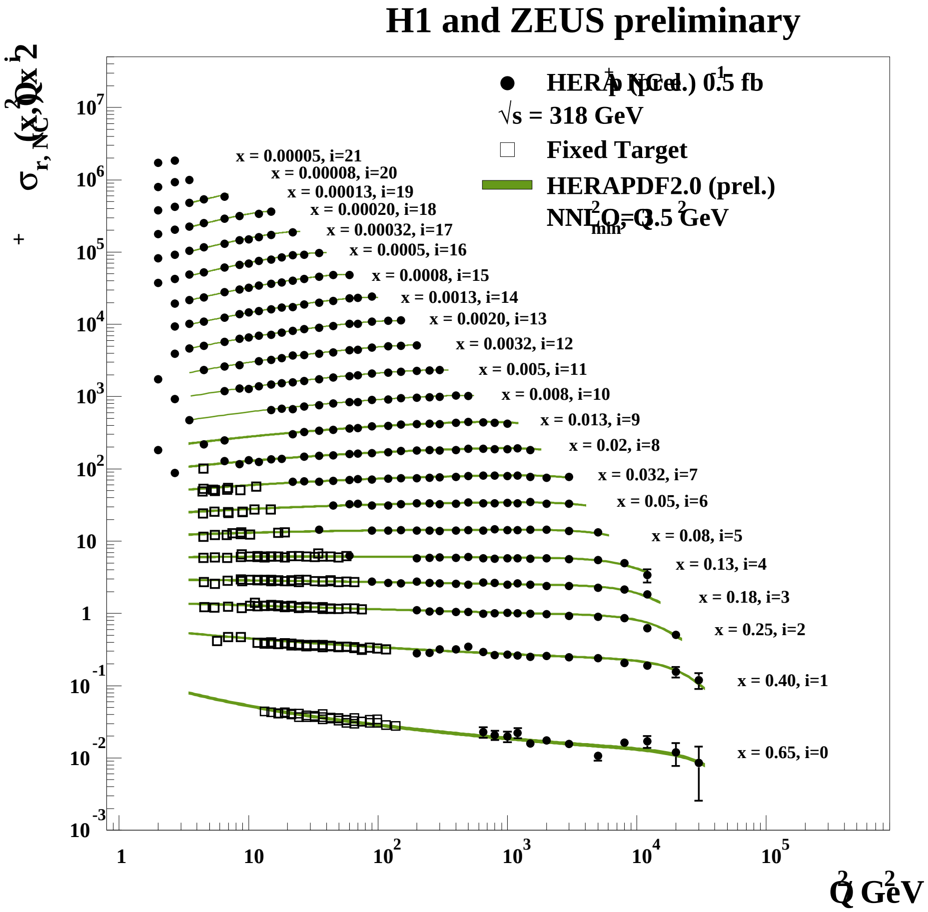


- New combination of the neutral current data at reduced $\sqrt{S}$.
- The data provide additional constraint to the gluon distribution function at low x.

HERAPDF2.0 fit settings

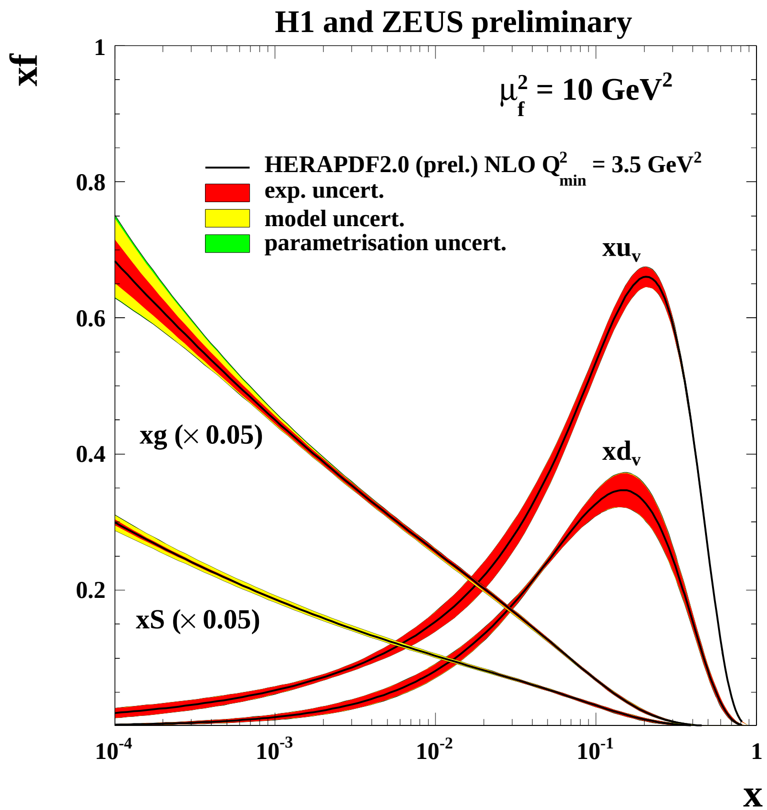
- Use HERAFitter package for the calculations.
- Two types of fits are considered: with the data restricted to $Q^2 \geq 3.5$ GeV^2 and $Q^2 \geq 10$ GeV^2.
- QCD analysis is performed at NLO and NNLO, with evolution using QCDNUM. Evolution starting scale is set to $Q_0^2 = 1.9$ GeV^2
- Light-quark coefficient functions evaluated using QCDNUM convolution engine. Heavy-quarks are treated using variable-flavour-number scheme from RT (nominal fit) and ACOT (variants). Fixed-flavour-number schemes tried too.
- Parameterized PDFs are $xg, xu_v, xd_v, x\bar{U}, x\bar{D}$ where $x\bar{D} = x\bar{d} + x\bar{s}$. The strange-sea distribution is assumed to be a fraction of total sea, $xs = f_s x\bar{D}$ where $f_s = 0.4$ is chosen.
- Model uncertainties are evaluated by varying input parameter values. Parameterisation uncertainties are estimated by changing the parameterisation form.

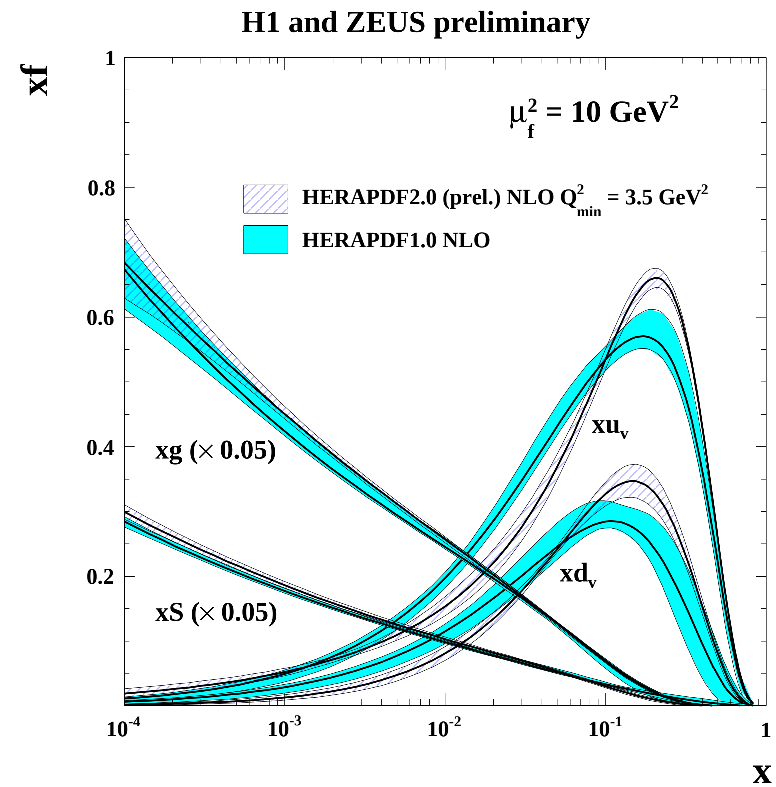
Central PDF fit results



Neutral current e^+p data compared to NNLO QCD fit result with $Q^2_{\text{min}} = 3.5\ \text{GeV}^2$. While visually the fit describes the data well, the overall $\chi^2/dof = 1414/1130$ is rather poor.

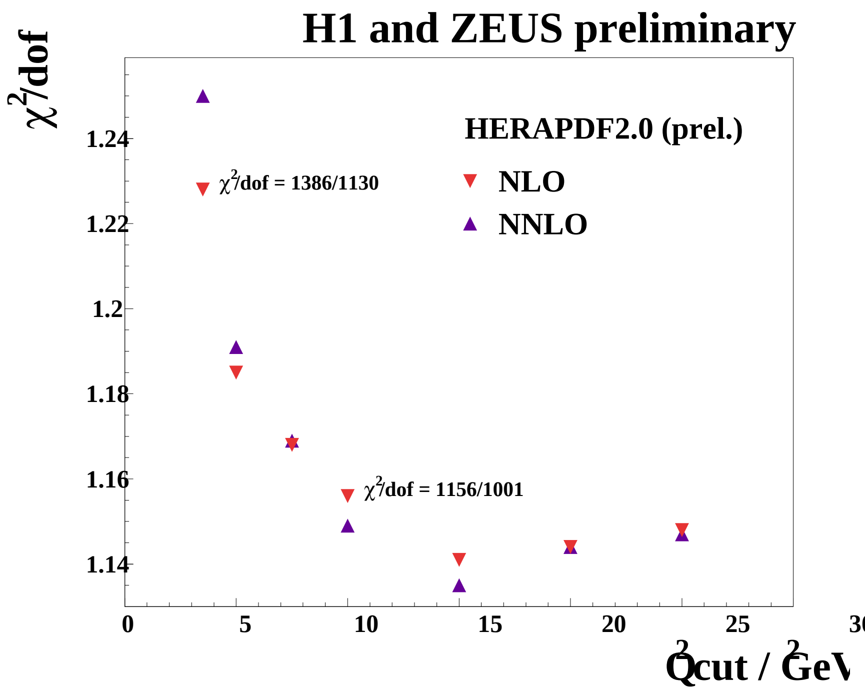
HERAPDF2.0 parton distribution functions

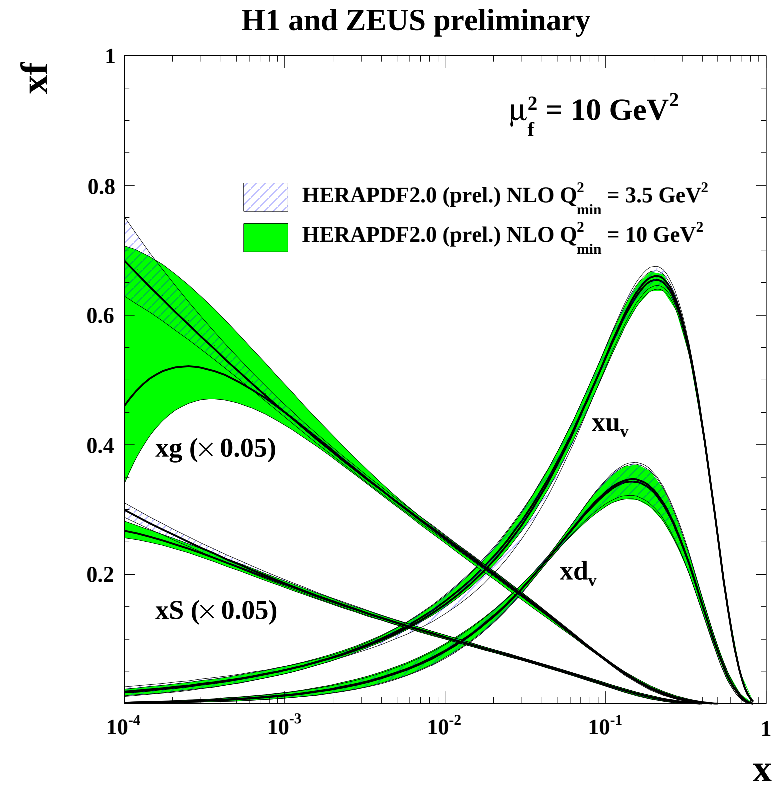




- Experimental uncertainties dominate for the quark distribution functions while model uncertainties are important for the gluon.
- Compared to HERAPDF1.0, the new fit has reduced uncertainties and somewhat different shape for the valence quark distributions.

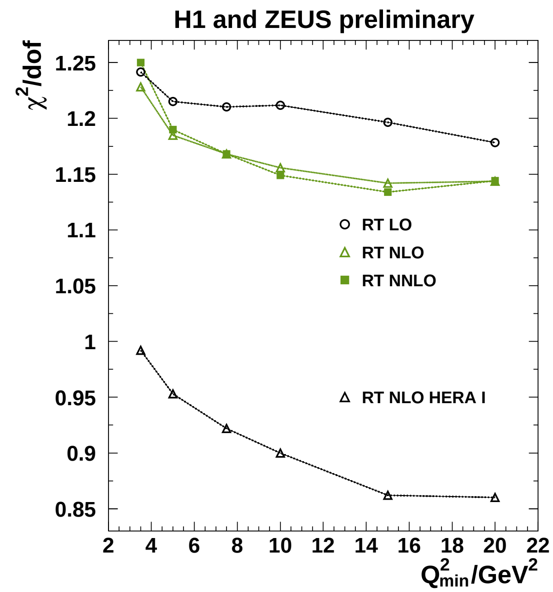
Effect of low Q^2 data

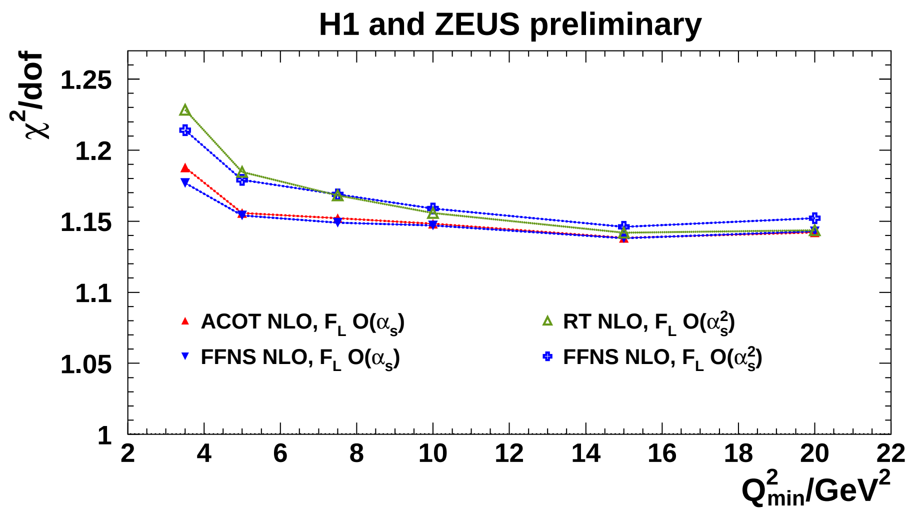




- A dedicated study is performed to investigate fit quality depending on Q^2_{min} cut in the data. For $Q^2_{\text{min}} \geq 10$ GeV^2 a plateau for χ^2/dof is observed with NNLO fit performing better compared to NLO. For smaller Q^2_{min}, fit quality deteriorates with the NNLO fit performing worse vs NLO (RT-scheme study).
- Harder Q^2_{min} cut leads to smaller gluon at low x with larger uncertainties.

Variation of coefficient functions treatment

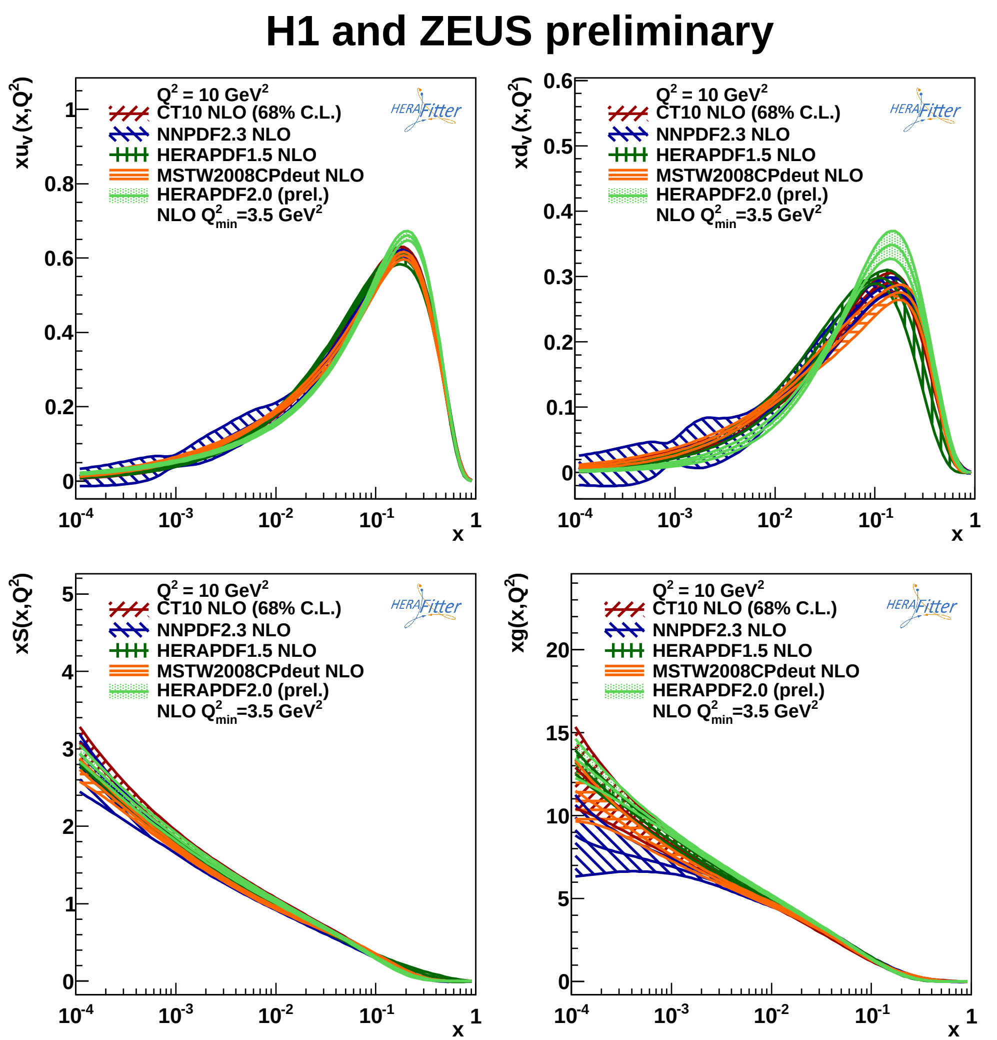




Further studies of the low Q^2 data show that

- HERA-I data showed similar deterioration of the quality for low Q^2 as the HERA-II data.
- Fits using ACOT scheme, which calculates F_2 and F_L using consistent order in α_S, are of better quality compared to the RT scheme, which calculates the s.f. using the same number of loops. Similar effect is observed for the fixed-flavour-number scheme.

HERAPDF2.0 vs other PDFs



HERAPDF2.0 has similar distributions and uncertainties compared to other PDFs with some differences for the valence quarks.

Summary and Outlook

- HERA measurements of the proton structure are close to completion.
- New results from ZEUS and H1 on the cross sections at high x, for reduced $\sqrt{S}$, and on the structure function F_L provide constrains on PDFs close to the kinematic limit and on the gluon density at low x.
- The combined HERA data set provides an ultimate sample for inclusive neutral and charged current cross section studies in a wide kinematic range.
- The new HERAPDF2.0 PDF set at NLO and NNLO has improved uncertainties compared to HERAPDF1.0.
- The low Q^2 data provide additional checks of the QCD calculations.

EXTRAS

PDF Sets

Several groups determine PDFs in fits to various data samples:

	MSTW08	CTEQ6.6/CT10	NNPDF2.1/2.3	HERAPDF1.0/1.5	ABM11	JR09
Evolution	LO	LO	LO	—	—	—
Order	NLO	NLO	NLO	NLO	NLO	NLO
	NNLO	NNLO	NNLO	NNLO	NNLO	NNLO
HF Scheme	RT-GMVF	ACOT-GMVF	FONLL-GMVF	RT-GMVF (*)	BMSN-FFNS	FFNS
α_S NLO	0.120	0.118(f)	0.1191(b)	0.1176(f)	0.118	0.1135
α_S NNLO	0.1171	0.118(f)	0.1174(b)	0.1176(f)	0.1135	0.1124
HERA DIS	not up-to-date	+	+	+/prelim.	partial	+
Fixed target DIS	+	+	+	-	+	+
DY	+	+	+	-	+	+
Tevatron W,Z	some	some	some	-	some	some
Tevatron jets	some	+	+	-	some	some
LHC	-	-	W, Z+jets (NNPDF2.3)	-	-	-

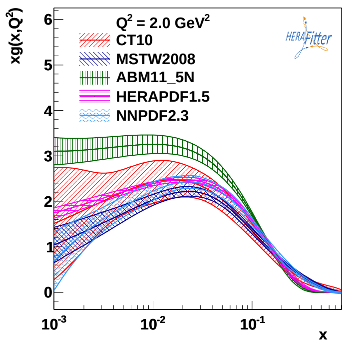
The analyses differ in many areas:

- Higher orders counting (e.g. F_L), heavy flavour corrections, α_S treatment, EW corrections, extra theory assumptions.
- Inclusion of datasets, accounting for data-data-theory tensions.
- PDF parameterisation.

PDF4LHC meetings is a forum to discuss/understand these differences.
HERAFitter, open source PDF fit project, to study them in details.

arXiv:1101.0536, arXiv:1101.0538

HERAFitter in an nutshell



- Open-source program for development of QCD analyses herafitter.org
- Fast LO,NLO and NNLO evolution code using the QCDNUM program.
- Coefficient functions for deep inelastic scattering processes using the fast convolution engine of QCDNUM and codes from ACOT, RT, ABM. Coefficient functions for pp and $p\bar{p}$ processes using APPLGRID and FastNLO programs.
- Alternative evolution: dipole model and TMD gluons.
- Flexible interface to include new data with correlated uncertainties.
- Fast analytic minimization vs nuisance parameters, MINUIT for PDFs.

Time to calculate NNLO predictions and χ^2 for 592 HERA data points with 114 nuisance parameters is 0.06 seconds using i7-3687U CPU at 2.6 GHz.