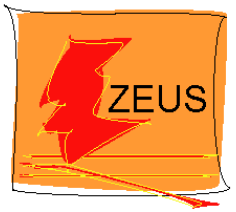
Proton Structure at high Q^2

Enrico Tassi
(Universita' della Calabria and INFN)



On Behalf of the H1 and ZEUS Collaborations

Low-x 2013

May 30 - June 4, 2013, Israel

HERA and the Structure of the Proton

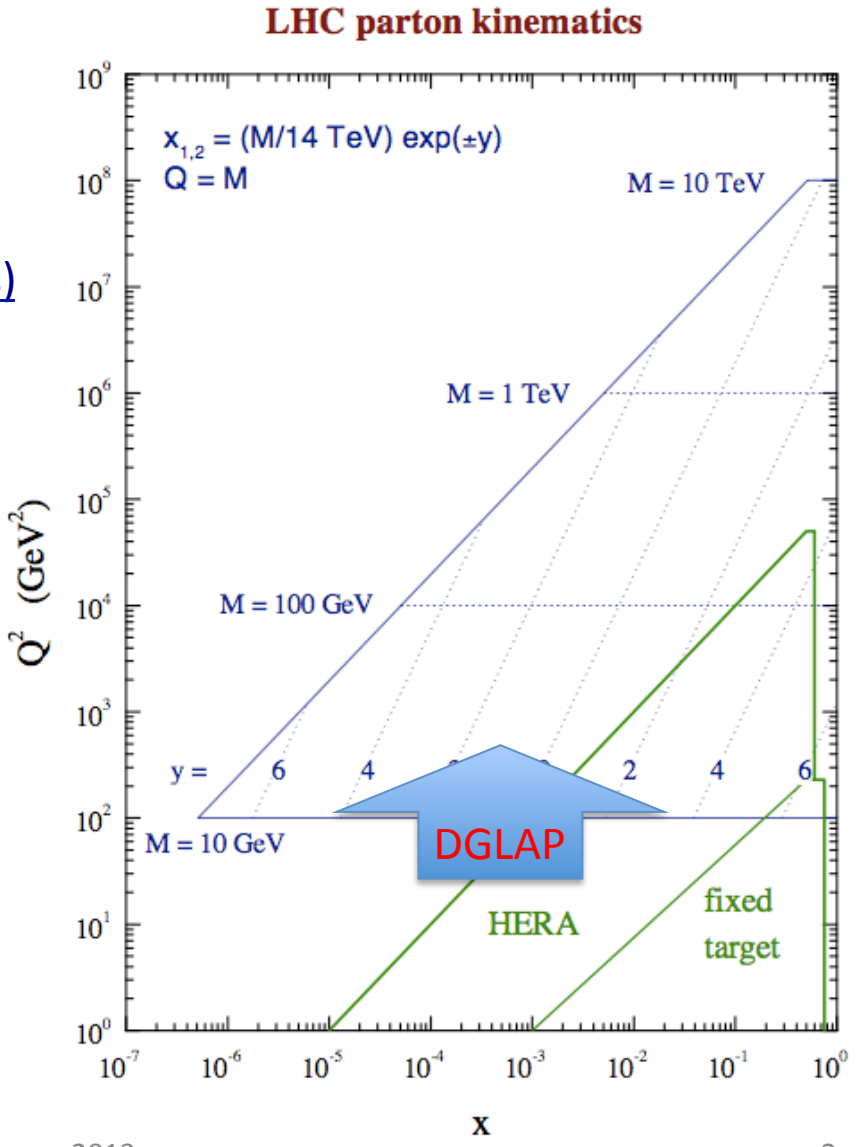
HERA data are our main source of knowledge on proton structure:

➔ proton's parton distribution functions (PDFs)

Combine the H1 and ZEUS data in order to provide the most precise input to DGLAP analyses

Precise knowledge of PDFs crucial to carry out LHC Physics Programme:

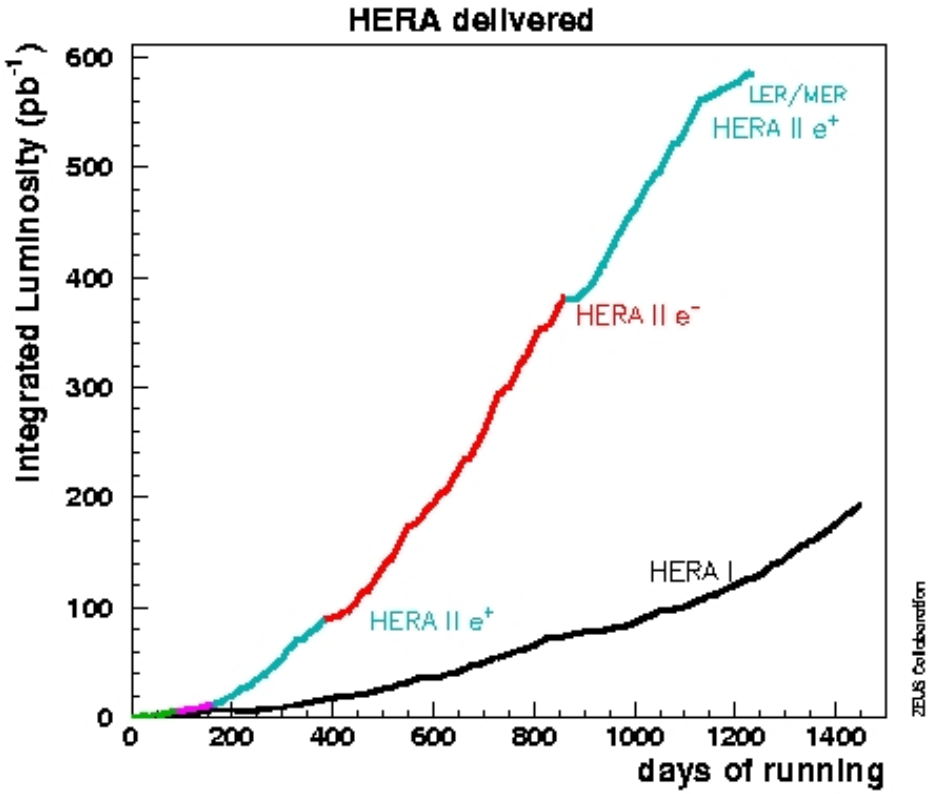
- Very stringent tests of the Standard Model
- Searches of Physics Beyond the SM (need to control QCD Background)



The HERA Collider

World's only ep collider (Desy-Hamburg)
Data taking: Fall 1992 - June 2007

$e^{\pm}$ (27.5 GeV) → ← p (820/920 GeV)

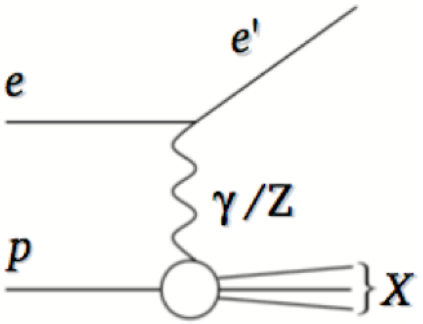


HERA-I (1992-2000)
L ~ 130 pb^{-1}/experiment
Mostly e^+p

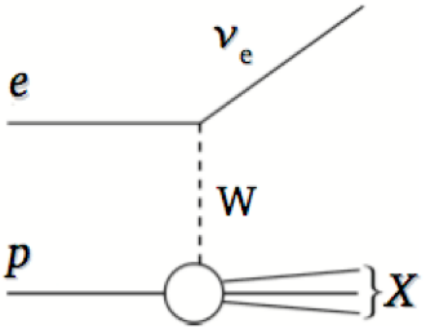
HERA-II (2003-2007)
L~360 pb^{-1}/experiment
Similar amounts of e^+p and e^-p
Long. polarized lepton beams (P~0.35)
Last months: Runs at reduced √s for F_L

DIS processes and cross sections

NC : $e\,p \to e'\,X$



CC : $e\,p \to \nu_e\,X$



Kinematic variables:

- Virtuality exchanged boson

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

- Bjorken scaling variable

$$x = \frac{Q^2}{2p \cdot q}$$

Double differential and "reduced" cross sections:

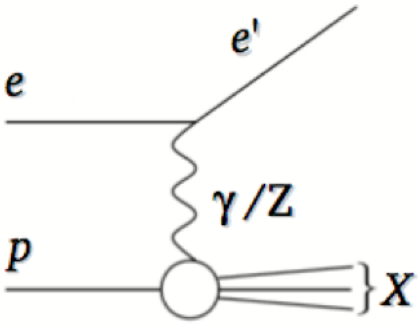
NC: $$\sigma^{\pm}_{r,\mathrm{NC}} = \frac{d^2\sigma^{e^{\pm}p}_{\mathrm{NC}}}{dxdQ^2} \cdot \frac{Q^4 x}{2\pi\alpha^2 Y_+} = F_2 \mp \frac{Y_-}{Y_+} xF_3 - \frac{y^2}{Y_+} F_L$$

CC: $$\sigma^{\pm}_{r,\mathrm{CC}} = \frac{d^2\sigma^{e^{\pm}p}_{\mathrm{CC}}}{dxdQ^2} \cdot \frac{2\pi x}{G_F^2} \left[\frac{M_W^2 + Q^2}{M_W^2}\right]^2 = \frac{1}{2}\left(Y_+ W_2^{\pm} \mp Y_- x W_3^{\pm} - y^2 W_L^{\pm}\right)$$

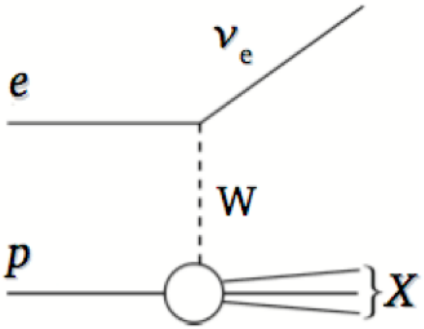
with $\quad Y_{\pm} = 1 \pm (1-y)^2$

DIS processes and cross sections

NC : $e\,p \to e'\,X$



CC : $e\,p \to \nu_e\,X$



Kinematic variables:

- Virtuality exchanged boson

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

- Bjorken scaling variable

$$x = \frac{Q^2}{2p \cdot q}$$

Structure Functions, PDFs and DGLAP evolution equations:

$$x^{-1} F_2(x, Q^2) = \sum_{i=q,g} \int_x^1 \frac{d\xi}{\xi} C_{2,i}\left(\frac{x}{\xi}, \alpha_s(\mu^2), \frac{\mu^2}{Q^2}\right) f_i(\xi, \mu^2)$$

$$\frac{d}{d\ln\mu^2} f_i(\xi, \mu^2) = \sum_k \left[P_{ik}(\alpha_s(\mu^2) \otimes f_k(\mu^2))\right](\xi)$$

Results I will Cover

- Combination of the H1 and ZEUS data and DGLAP fits:

  - HERA-I inclusive cross sections: JHEP 1001:109(2010)
    ➔ Precise determination of the sea quarks and gluons at mid- and low-x

  - HERA-I+HERA-II Inclusive cross sections (high-Q^2):
    ➔ Better determination of the valence quarks at high-x

  - HERA-I + jet data:
    ➔ Strong coupling and gluon density

  Preliminary

- Final results of the H1 an ZEUS collaborations with HERA-II data

  - H1 NC and CC $e^{\pm}p$ high Q^2 Cross Sections and new QCD analysis
    arXiv:1206.7007 ➔ JHEP 09 (2012) 061

  - ZEUS NC $e^{+}p$ high Q^2 cross sections
    arXiv:1208.6138 ➔ PRD 87 (2013) 052014

New results including H1-ZEUS combined charm data (see **O. Behnke presentation**)

HERAPDFs

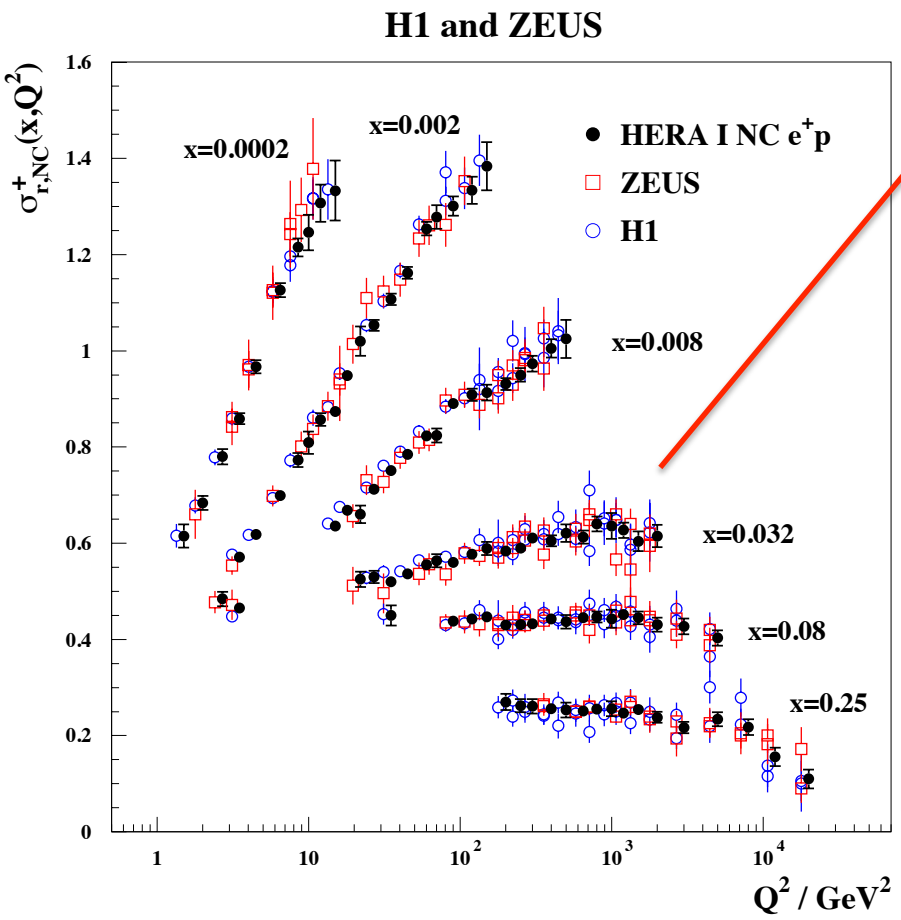
HERAPDF: only HERA data
- uses consistent data with very well understood correlations
- no need for nuclear corrections etc

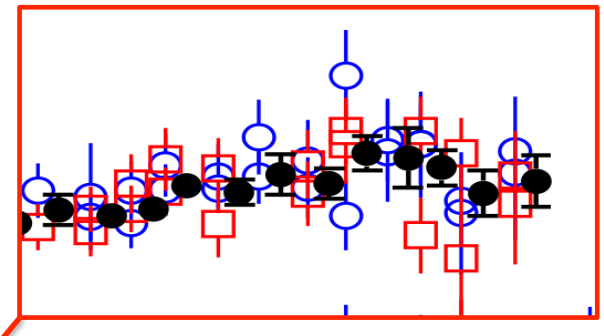
Overview of HERAPDF sets:

Data	PDF Set
H1+ZEUS NC,CC - HERA I	HERAPDF1.0 (NLO,NNLO)
H1+ZEUS NC,CC - HERA I +II (part)	HERAPDF1.5 (NLO,NNLO)
NC,CC HERA I + II (part) + jets	HERAPDF1.6 (NLO)
NC,CC HERA I + II (part) + charm	HERAPDF1.0 + charm
All data above	HERAPDF1.7
Planned: Full HERA data set	HERAPDF2.0 (NLO, NNLO)

HERAFitter Project:
- Open source QCD fitting tool to determine PDFs
  (see https://www.herafitter.org and **V. Radescu presentation**)

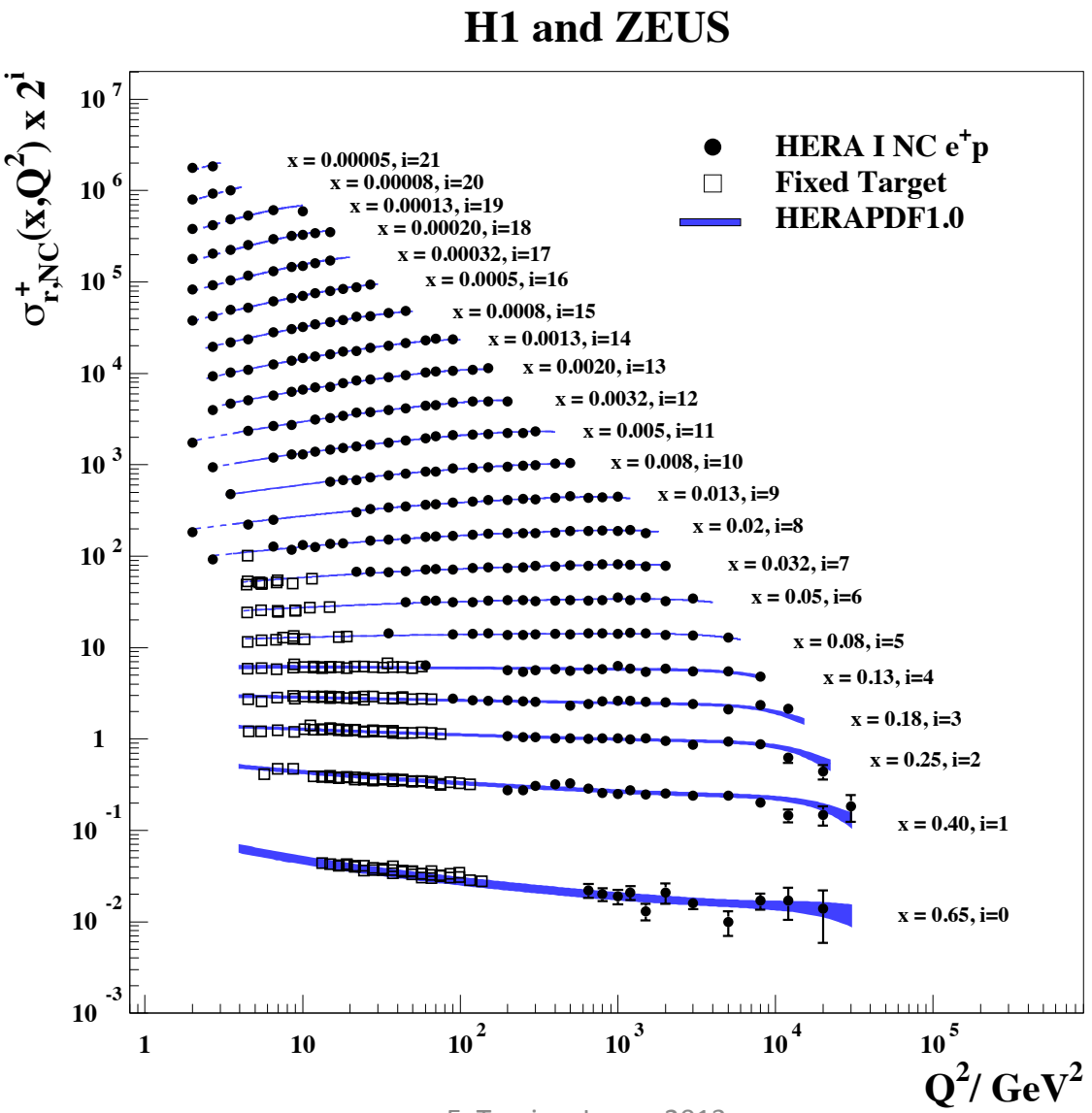
Combination of HERA I data



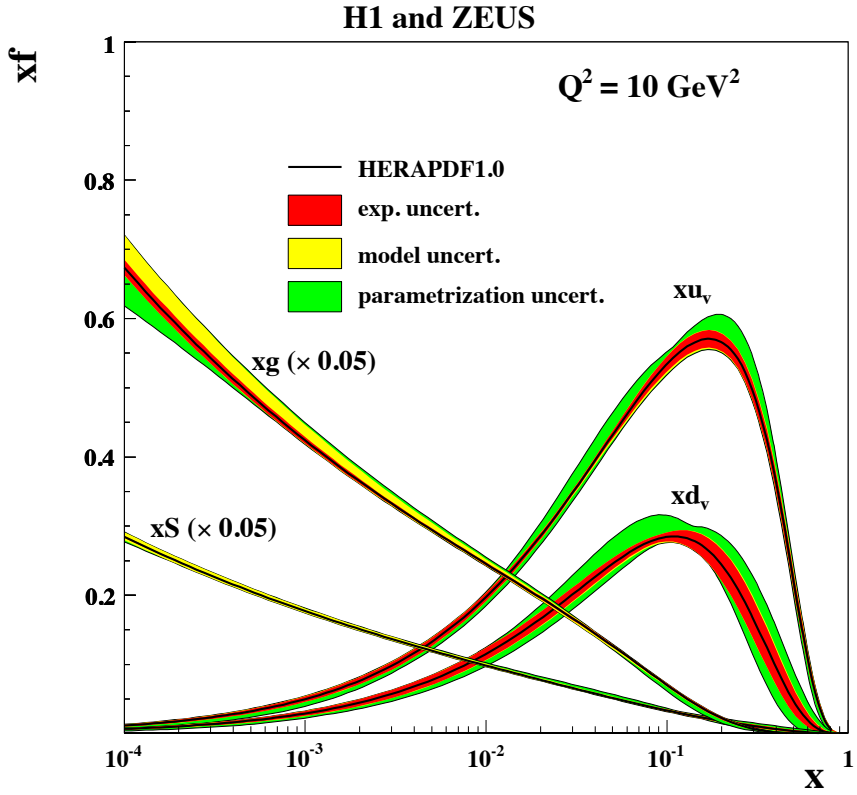


- Combined are all published HERA-I NC,CC $e^{\pm}p$ cross section measurements
  - 1402 data points
  - 110 syst. error sources (and correlations)
  - details on the χ^2 combination method:
    - ➔ see JHEP 1001:109(2010) [arXiv:0904.0929]
- Data show good consistency:
  - χ^2/ndof =637/656
  - small shift of global norms
  - distribution of pulls
- Experiments "cross calibrate" each other
  - 1-2% total uncert. in the low- mid-Q^2 region

Combination of HERA I data



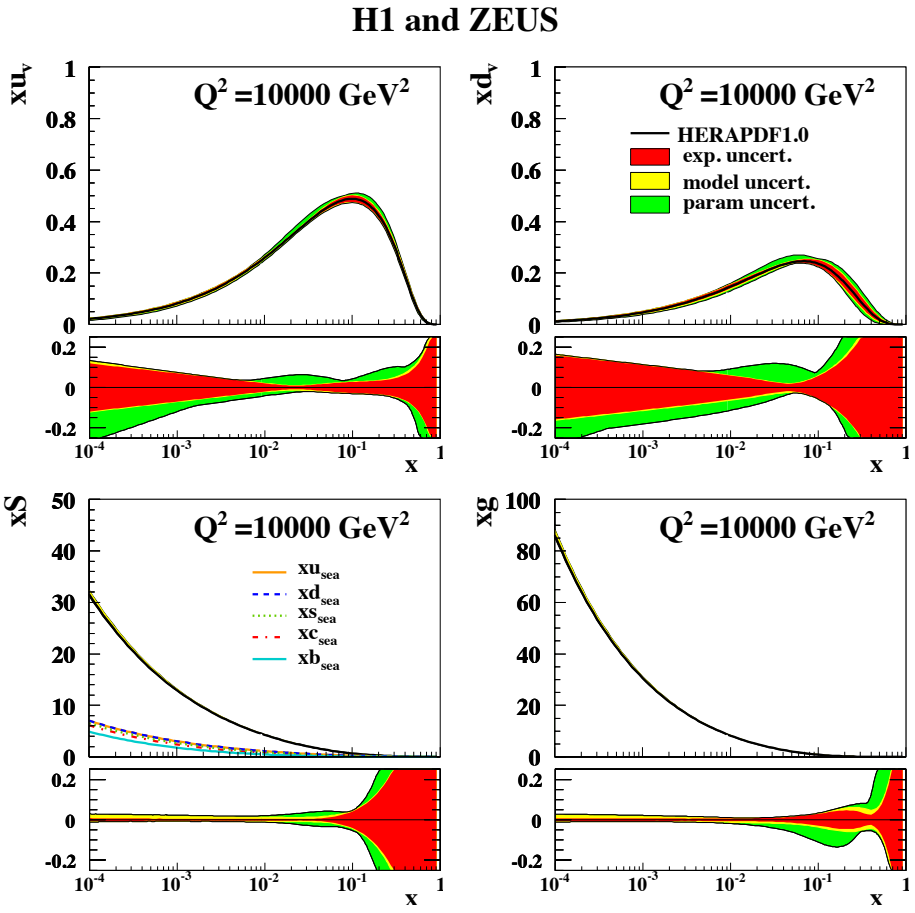
DGLAP Analysis of HERA-I data: HERAPDF 1.0



- NLO DGLAP analysis based only on the HERA-I, fully consistent, combined dataset:
  - no need for heavy target/deuterium corrections or strong isospin assumptions
  - χ^2/ndof = 574/582
- Massive treatment for heavy flavours (RT-VFNS)
- Detailed study of uncertainties:
  - experimental, model and parametrisation

The very precise HERAPDF1.0 set is available in LHAPDF since v5.8.1

DGLAP Analysis of HERA-I data: HERAPDF 1.0



Experimental uncertainty:

Consistent data set → use $\Delta\chi^2 = 1$

Model Uncertainty:

Following variations were considered

Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.31	0.23	0.38
m_c [GeV]	1.4	1.35$^{(a)}$	1.65
m_b [GeV]	4.75	4.3	5.0
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_0 [GeV^2]	1.9	1.5$^{(b)}$	2.5$^{(c,d)}$

Parametrization uncertainty:

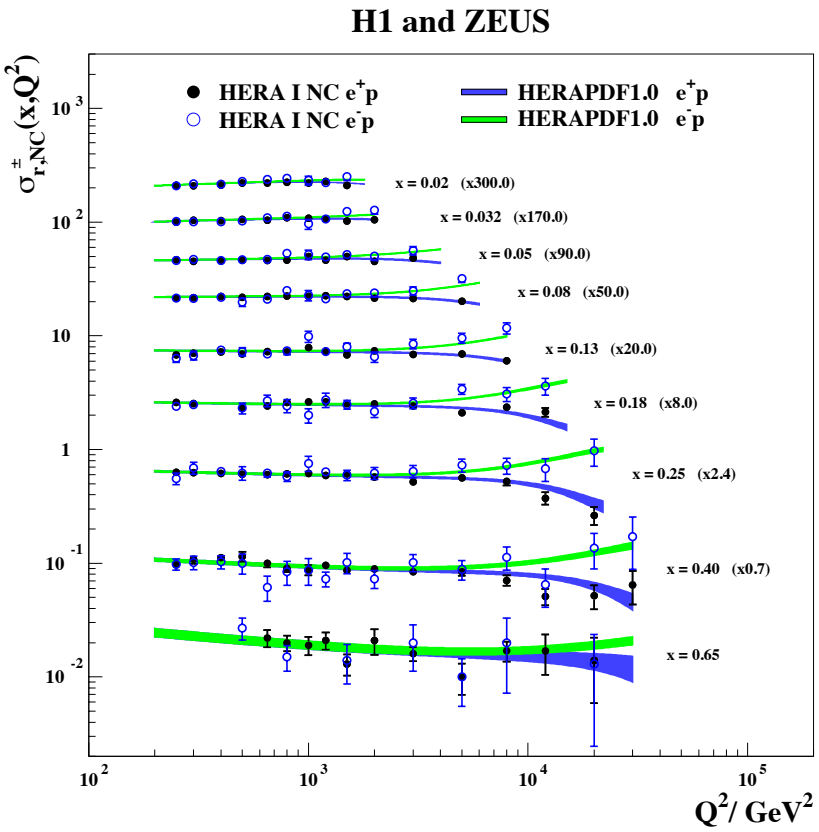
Envelope from DGLAP Fits using variants of the parametrisation form at Q_0^2

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

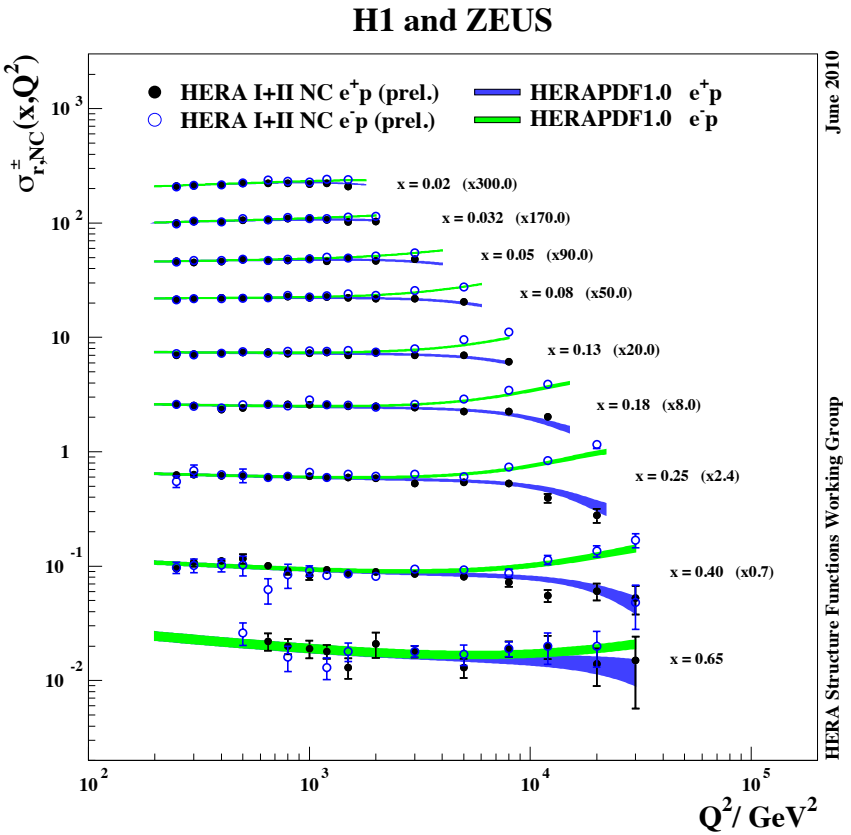
At the scale Q^2=10 000 GeV^2 (relevant to LHC)
the sea and gluon densities are known at the % level for $x \leq 10^{-1}$

HERA-I+II(prel.) High-Q^2 Data: NC $e^{\pm}p$

HERA-I combined results



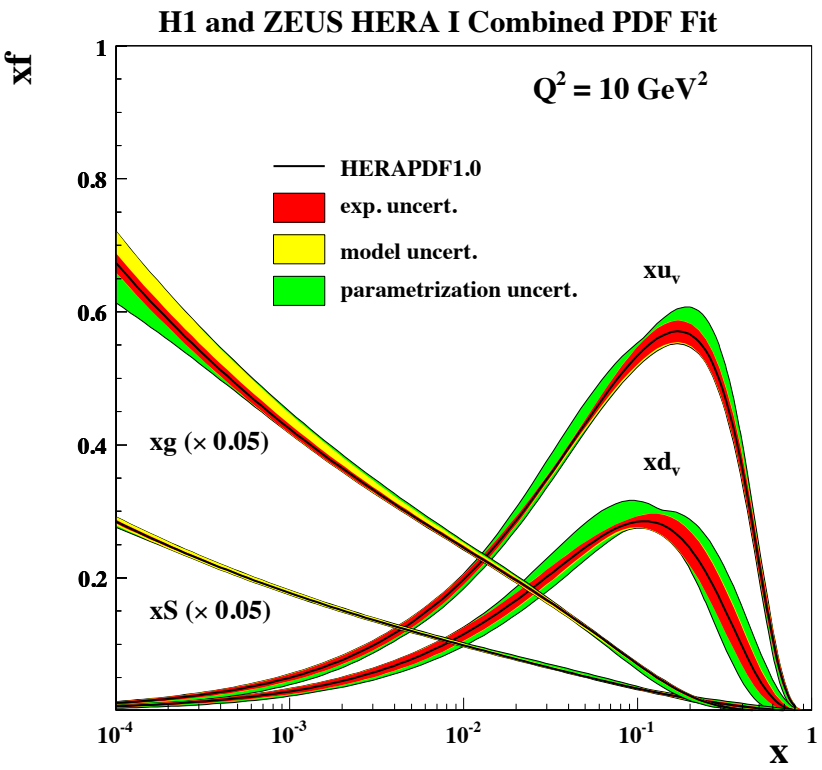
HERA-I + HERA-II combined results



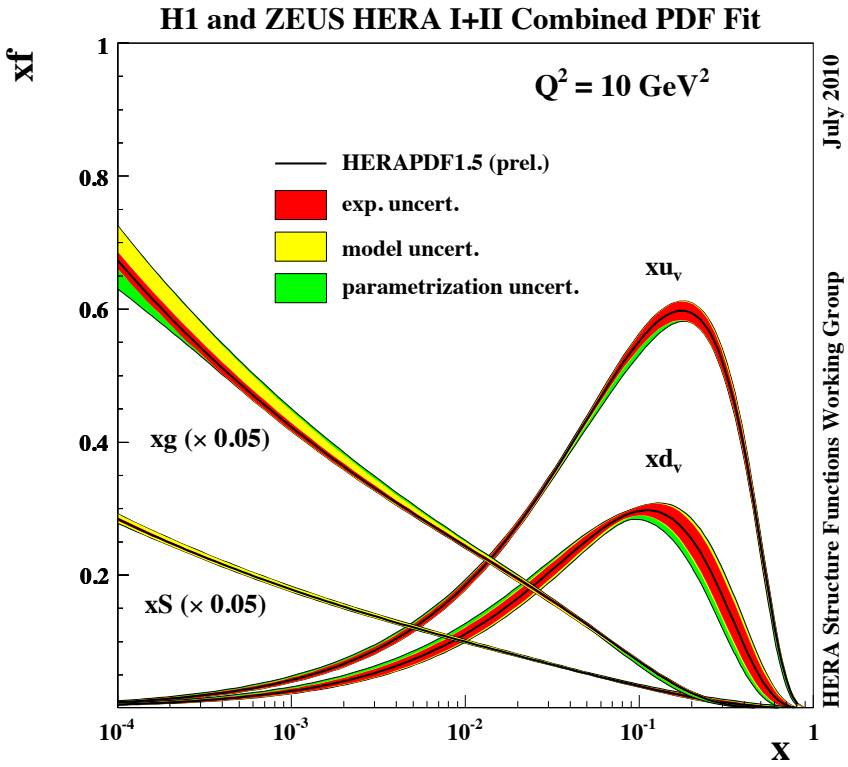
New HERA-II measurements: increased precision at high-Q^2

HERAPDF1.0 vs HERAPDF1.5

HERA-I / HERAPDF1.0



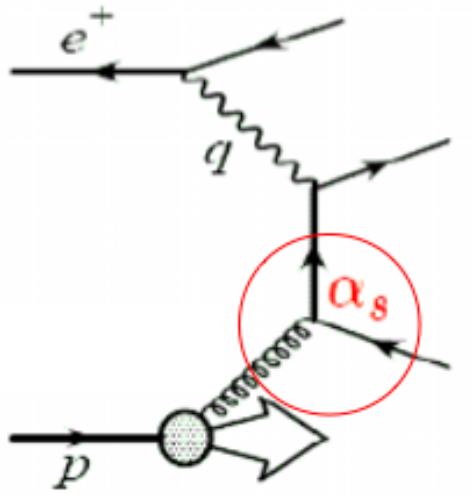
HERA-I+II / HERAPDF1.5



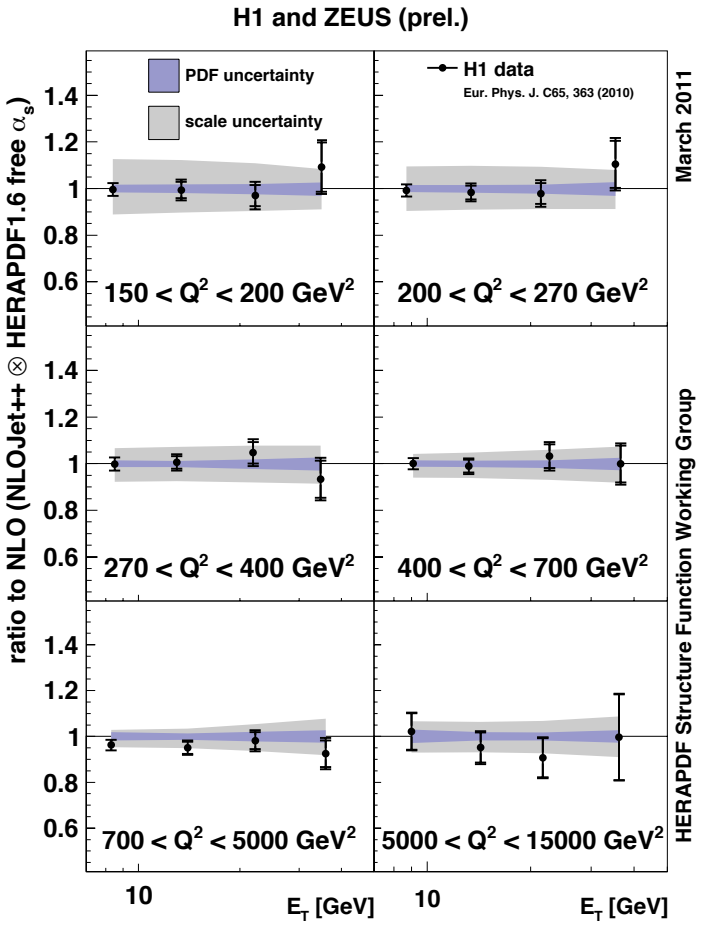
Impact on valence quarks: much better constrained at mid and high-x

Inclusion of jets: HERAPDF1.6

HERAPDF1.6: CC,NC HERA I + II(part) +
4 inclusive jet measurements from H1 and ZEUS

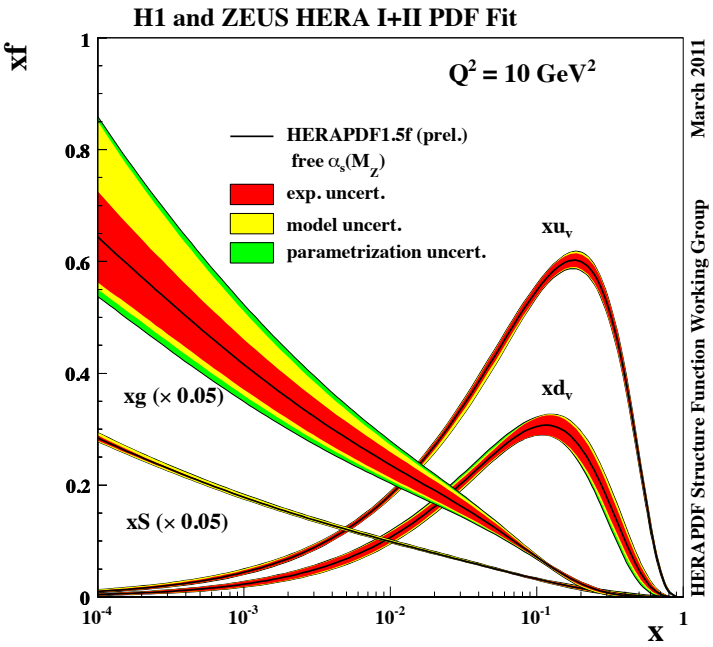


Direct sensitivity to gluon and strong coupling constant

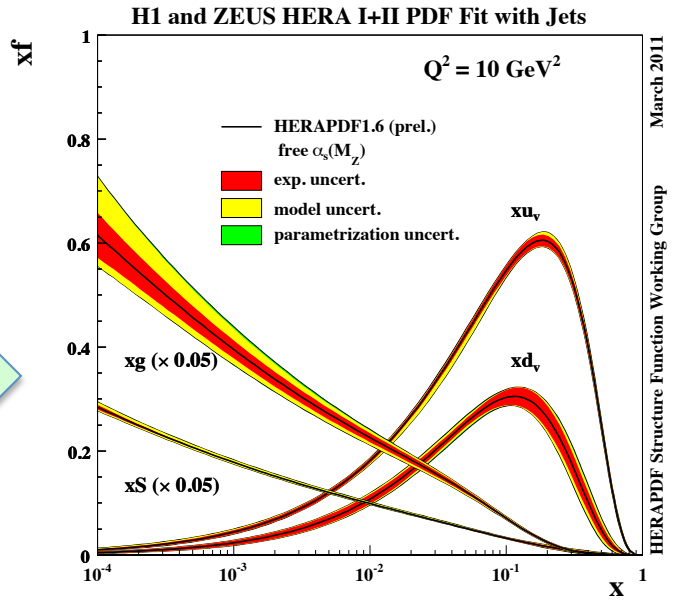


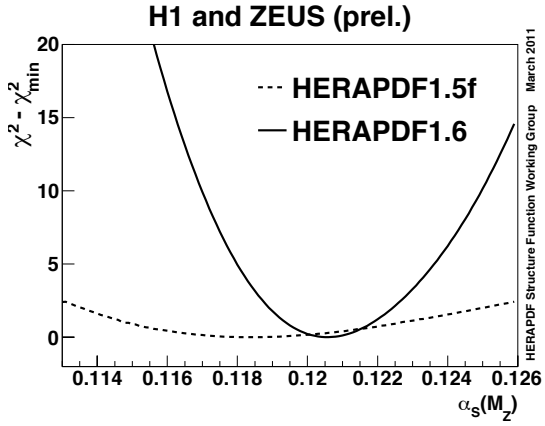
Inclusion of jets: HERAPDF1.6

Free $\alpha_s(M_Z)$



+ jets



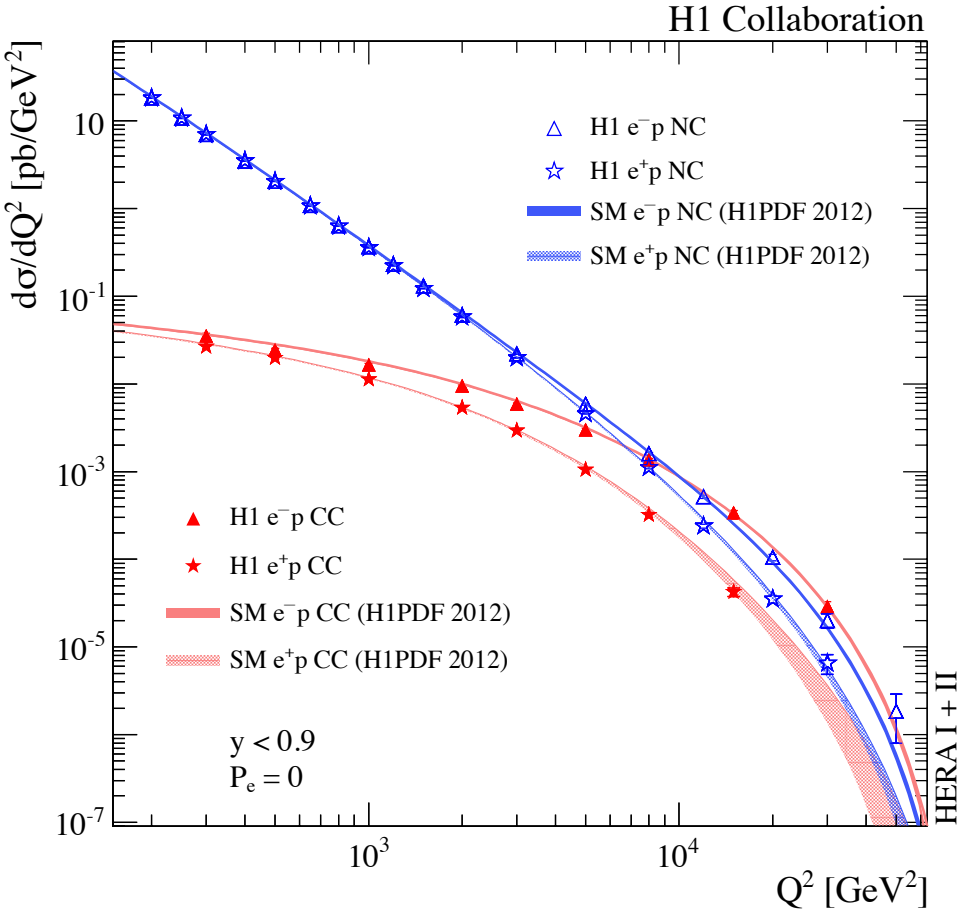


HERA Jet data allow to constrain simultaneously αs and gluon

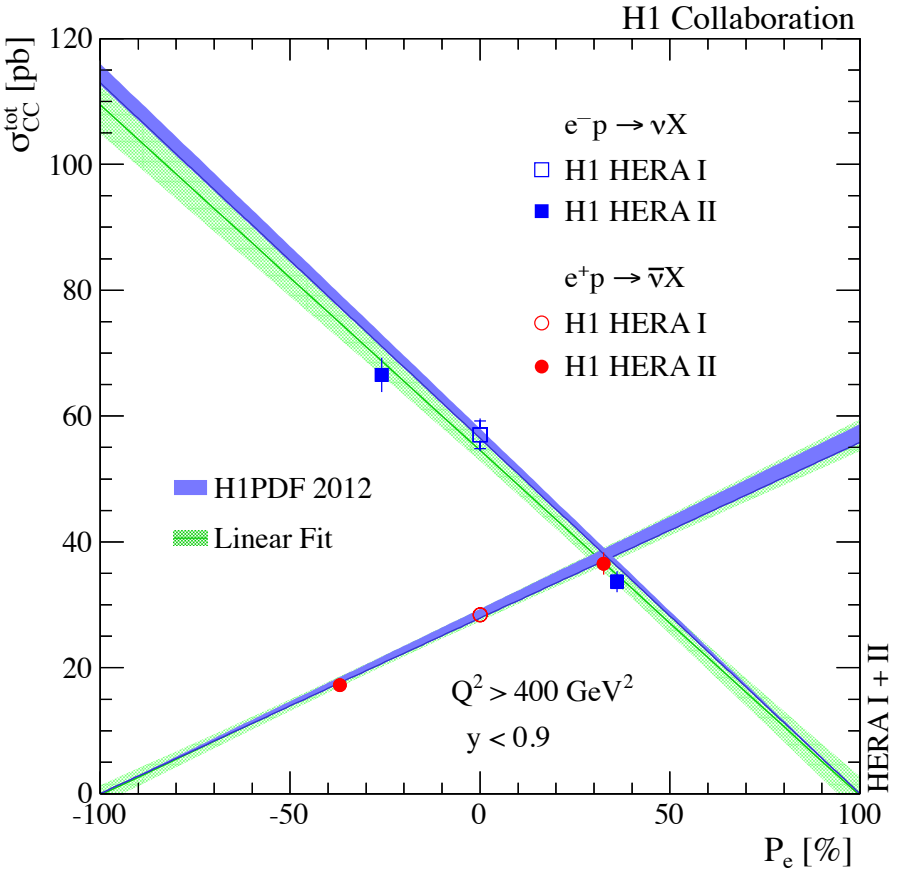
$$\alpha_s(M_Z) = 0.1202 \pm 0.0013(\mathrm{exp}) \pm 0.0007(\mathrm{mod}) \pm 0.0012(\mathrm{had})^{+0.0045}_{-0.0036}(\mathrm{th})$$

Final H1 HERA-I-II NC & CC cross sections

NC



CC

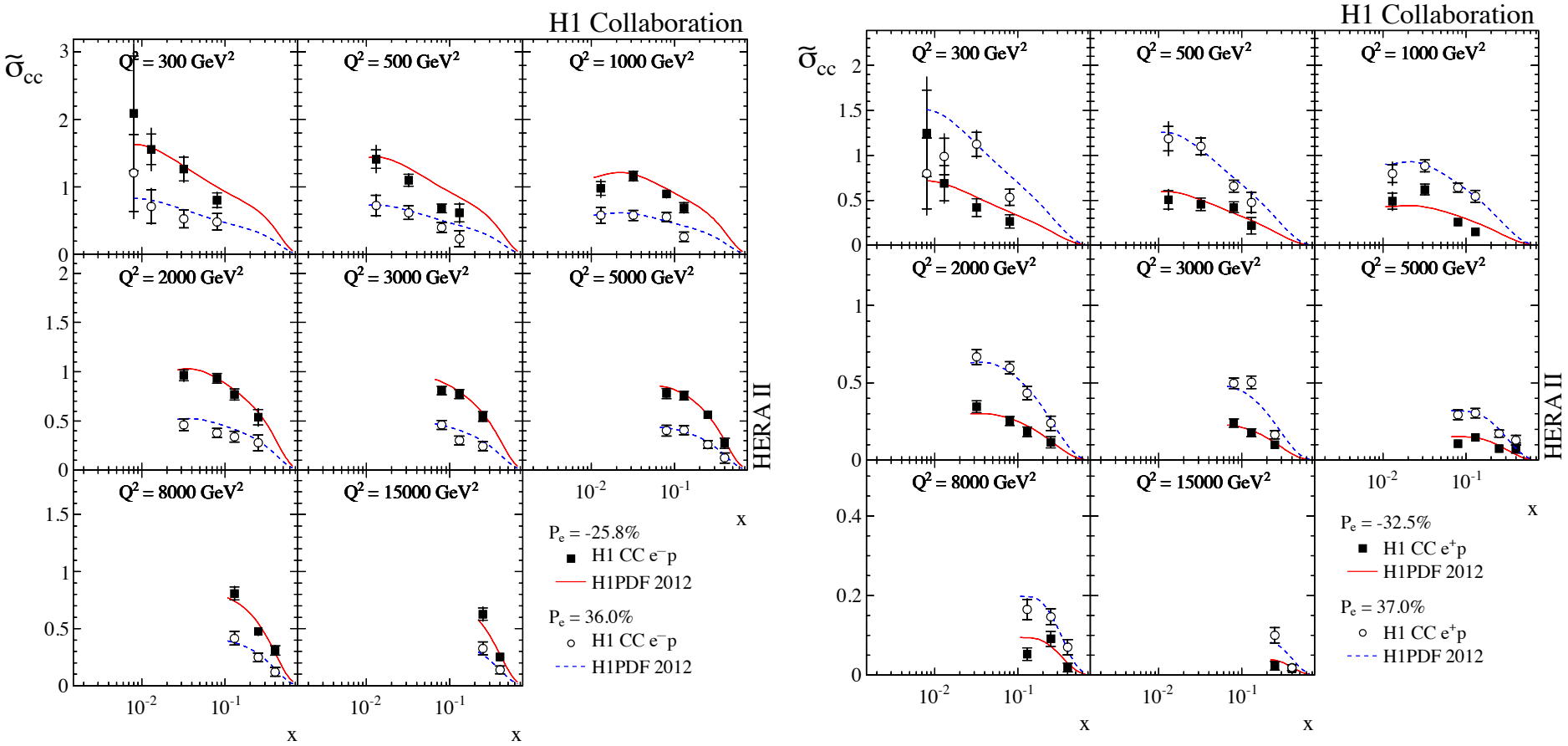


- Neutral Current: Unification at the EW scale
- Charged Current: Chiral structure of the SM confirmed

JHEP 09 (2012) 061

Final H1 HERA-II CC High-Q^2 cross sections

e^- e^+



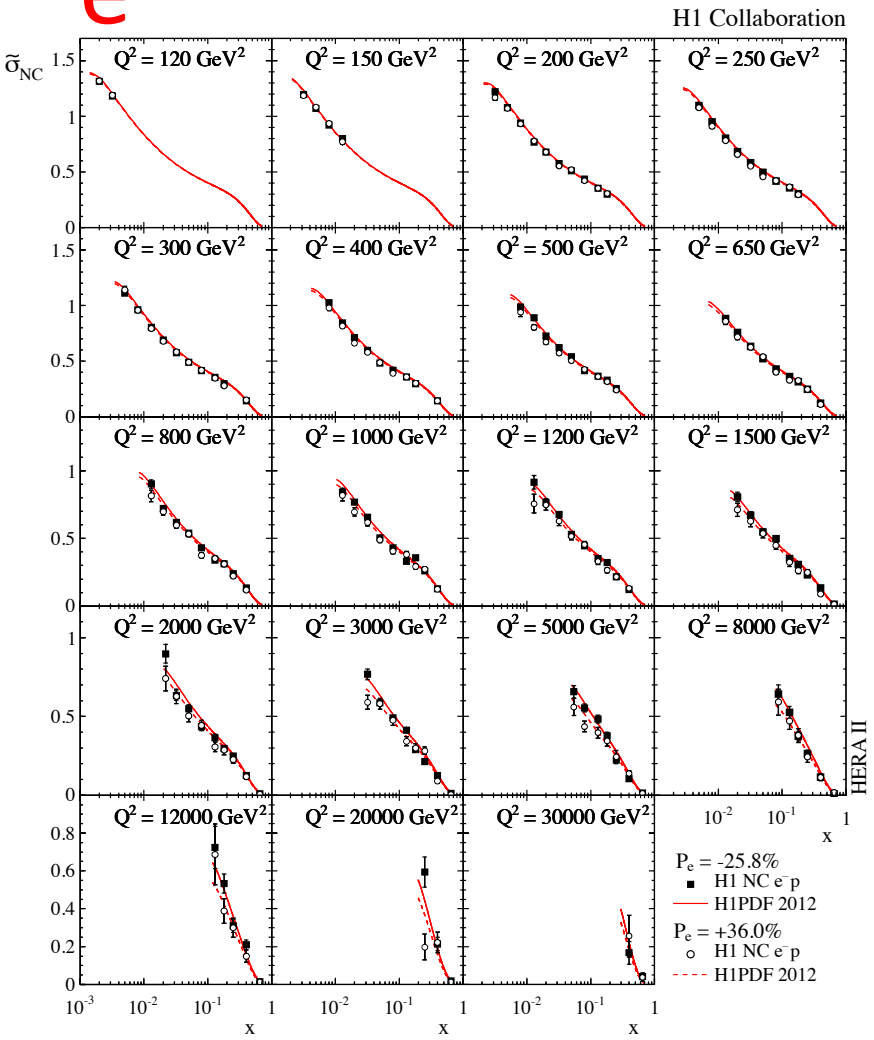
JHEP 09 (2012) 061

Show here CC $e^{\pm}p$ Reduced Cross Sections

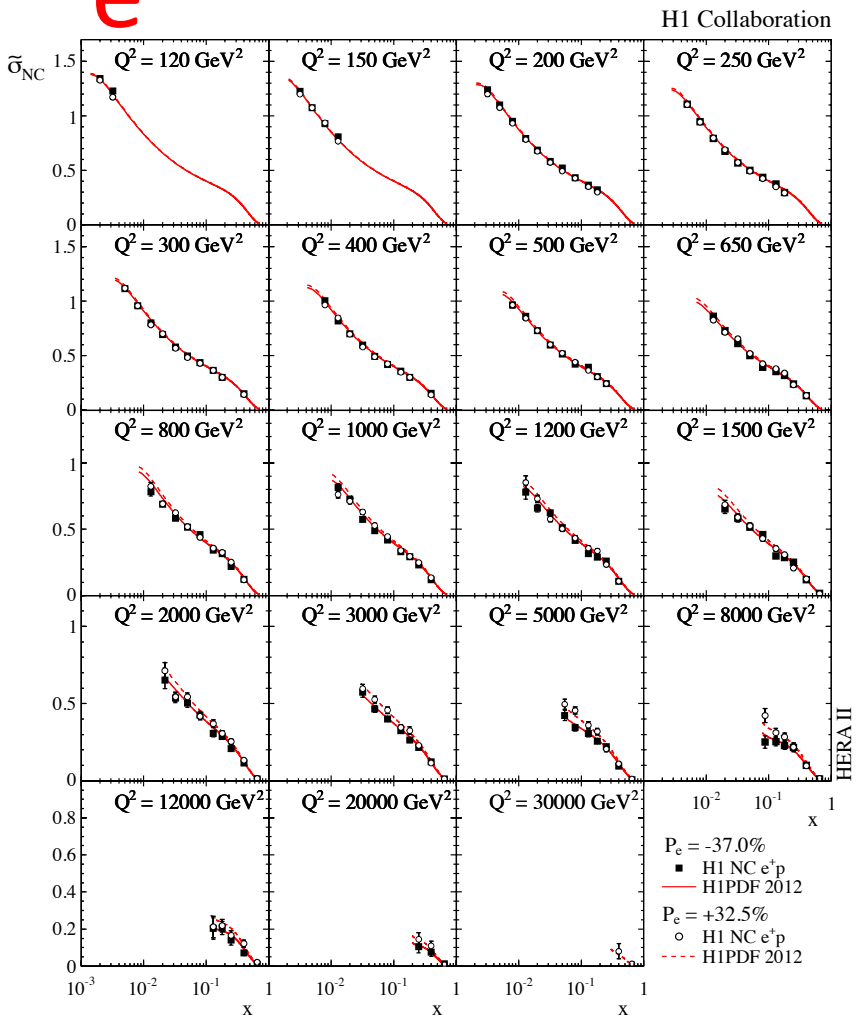
- Polarized CC Cross sections well described by SM predictions (H1PDF 2012)

Final H1 HERA-II NC High-Q^2 cross sections

e^-



e^+



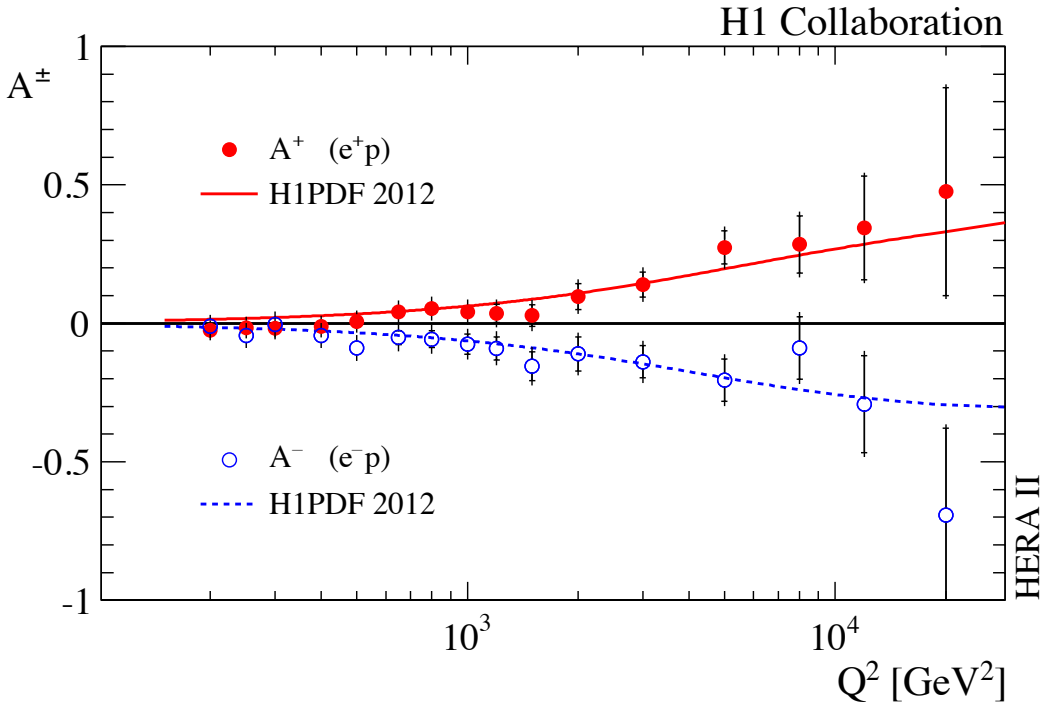
JHEP 09 (2012) 061

Shown here NC $e^{\pm}p$ Reduced Cross Sections

- Polarized Cross sections well described by SM predictions (H1PDF 2012)

NC Polarization Asymmetry

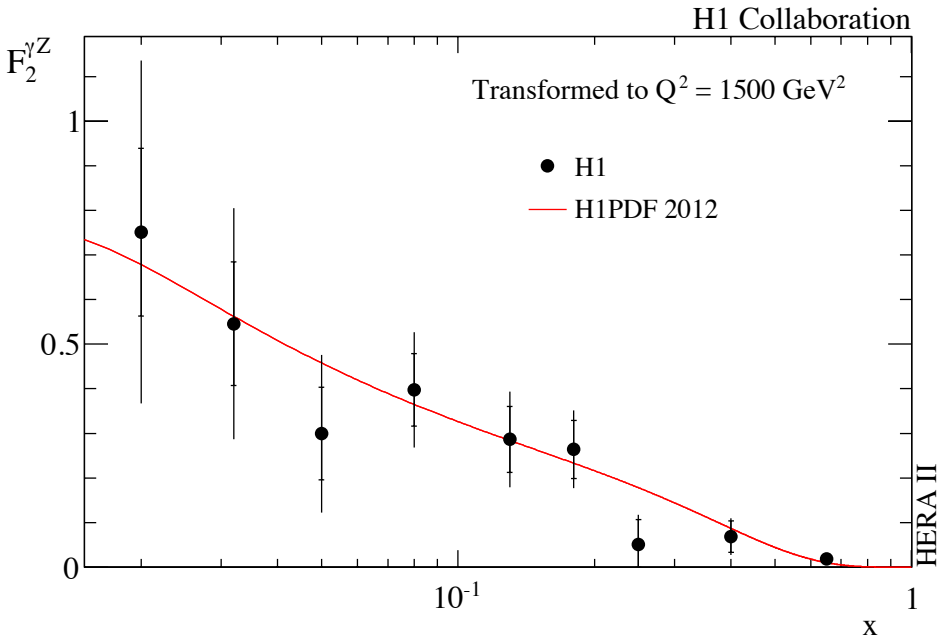
$$A^{\pm} = \frac{2}{P_L^{\pm} - P_R^{\pm}} \cdot \frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{\sigma^{\pm}(P_L^{\pm}) + \sigma^{\pm}(P_R^{\pm})}$$



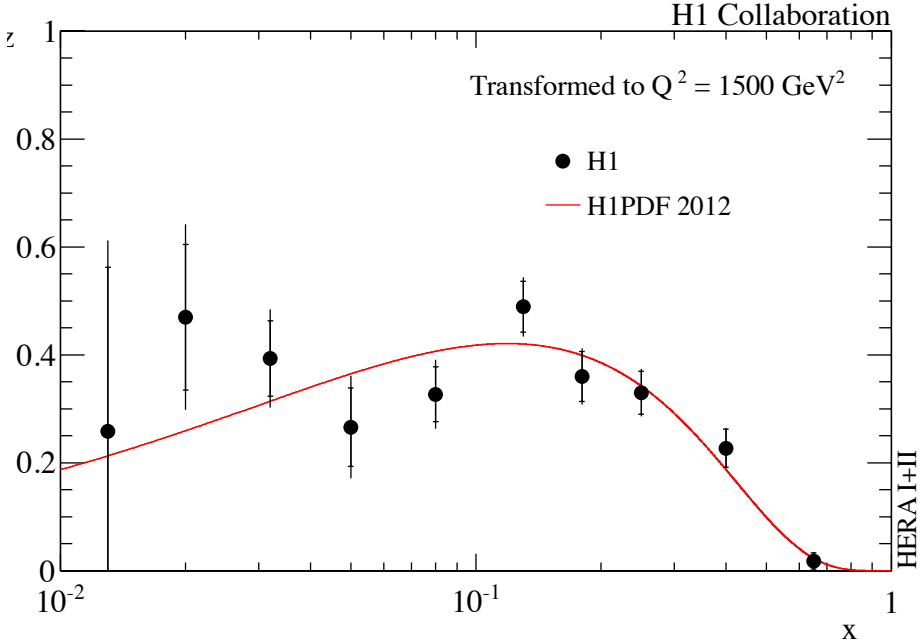
Direct measure of Parity violation effects in NC DIS

Structure Functions $F_2^{\gamma Z}$, $F_3^{\gamma Z}$

First measurement of $F_2^{\gamma Z}$



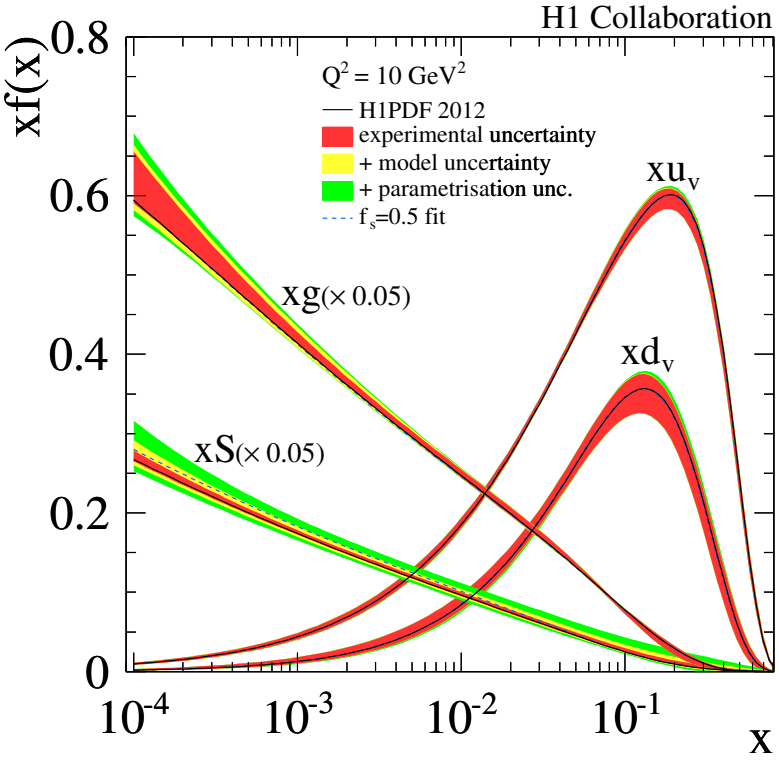
Improved measurement of $F_3^{\gamma Z}$

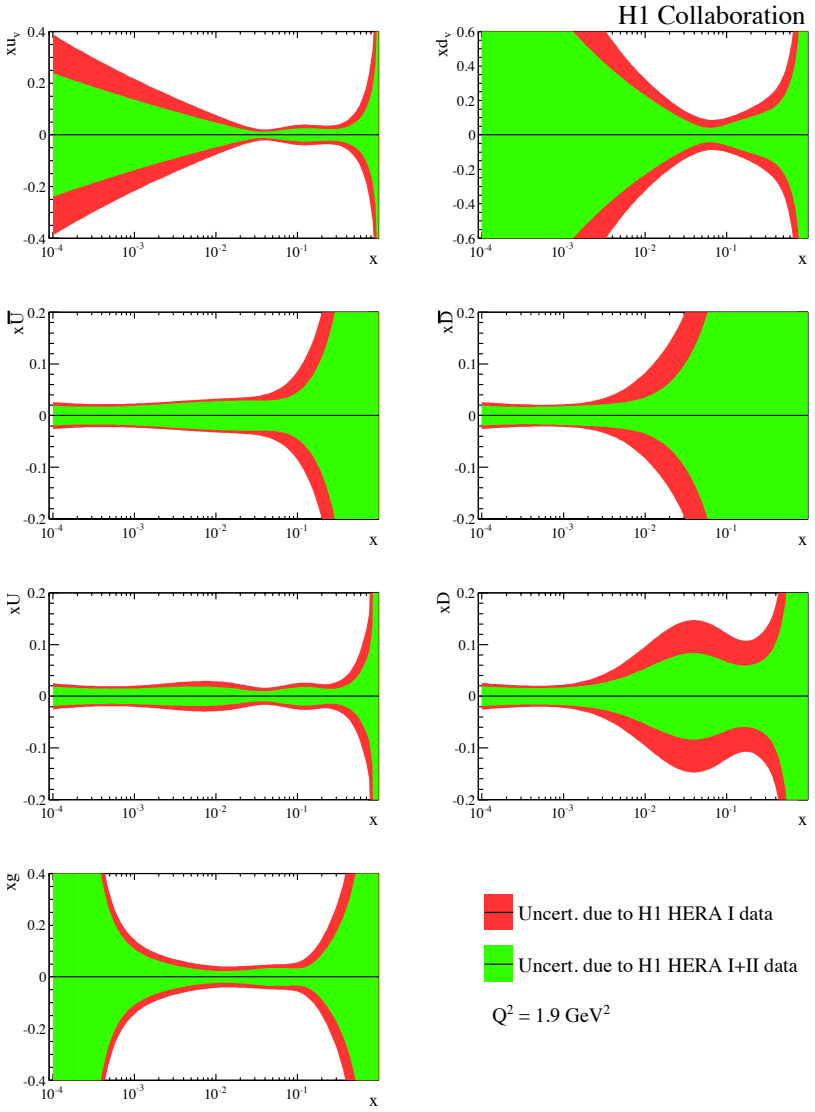


$$F_2^{\gamma Z} \sim q + \bar{q}$$

$$xF_3^{\gamma Z} \sim xq_v$$

H1PDF 2012

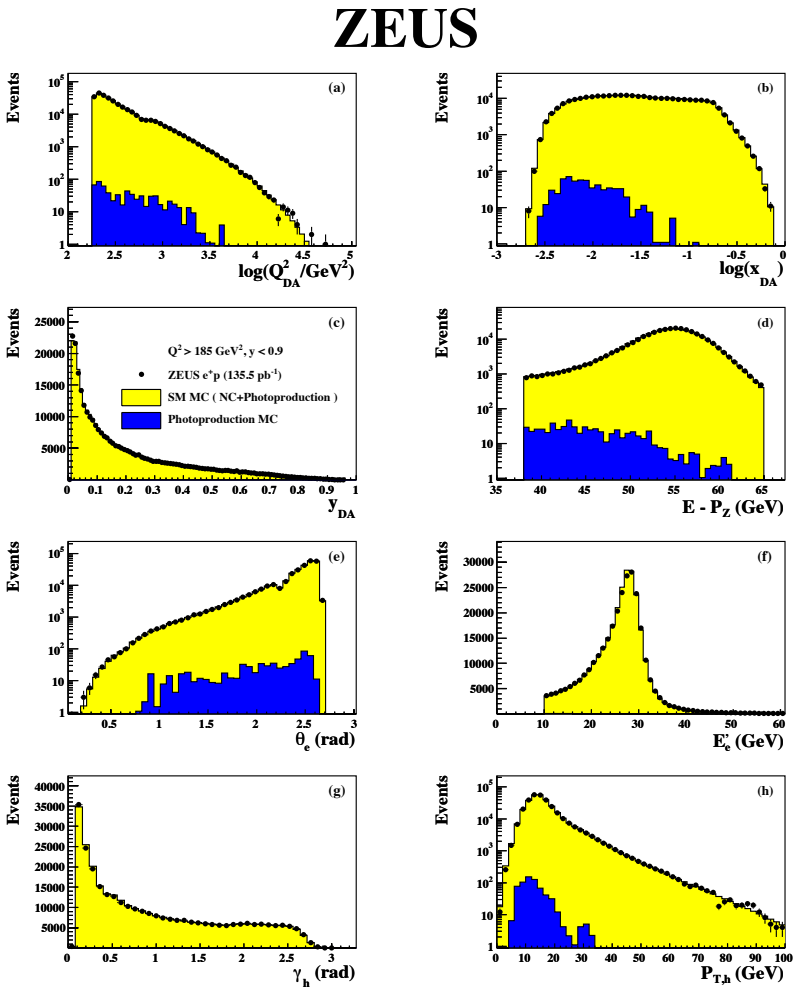


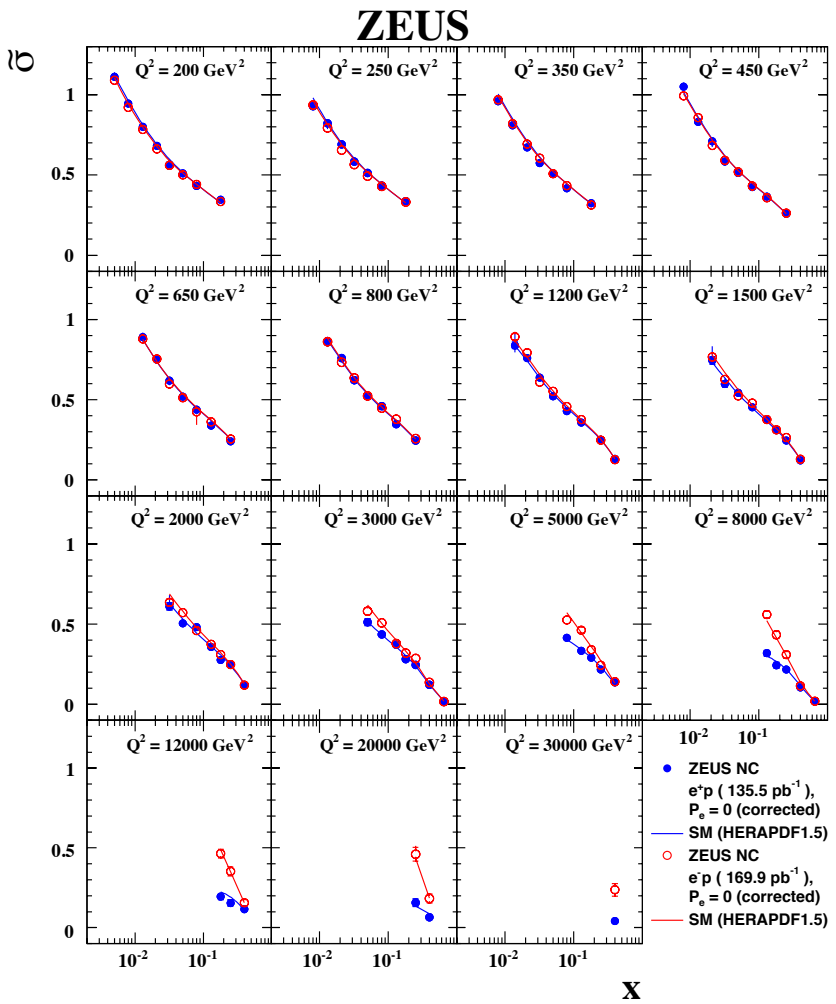


- HERAFitter
- 5 sets of PDFs (with 13 free parameters)

Reduced uncertainties in particular for down-type quarks (xD)

Final ZEUS HERA-II NC e^+p cross sections

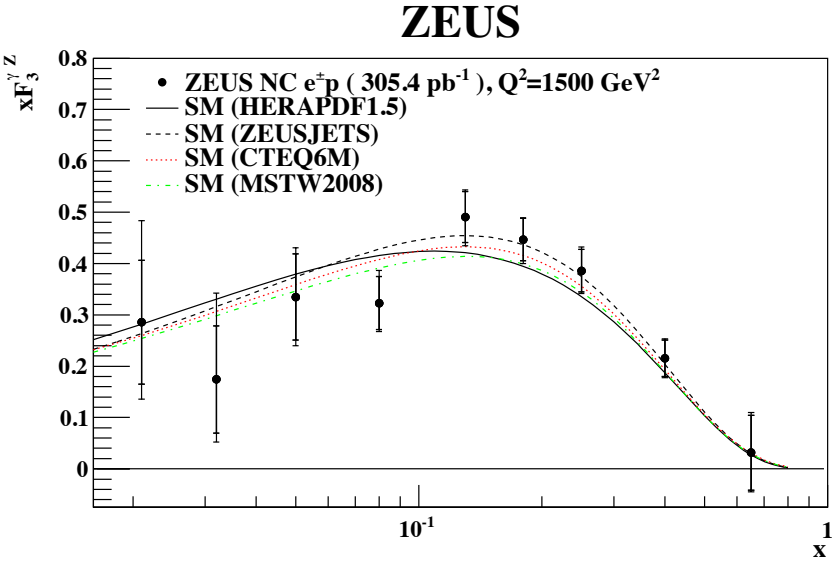


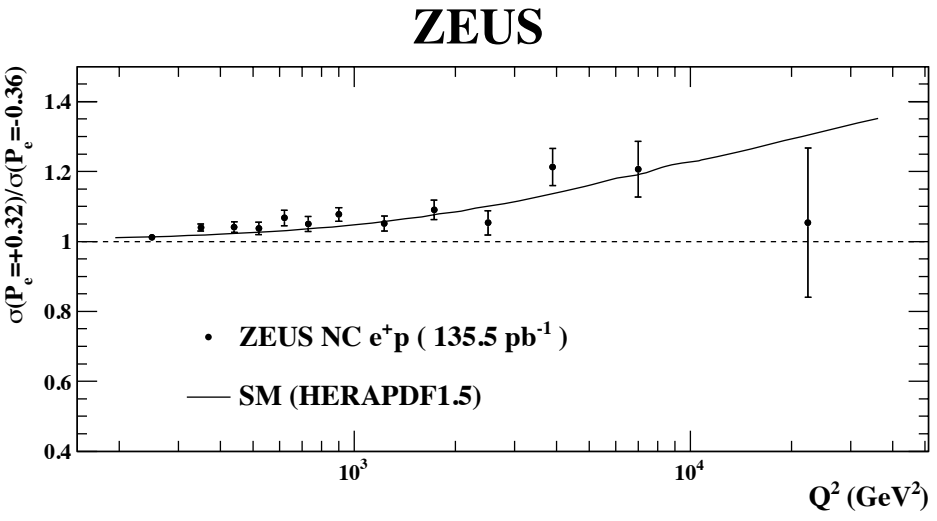


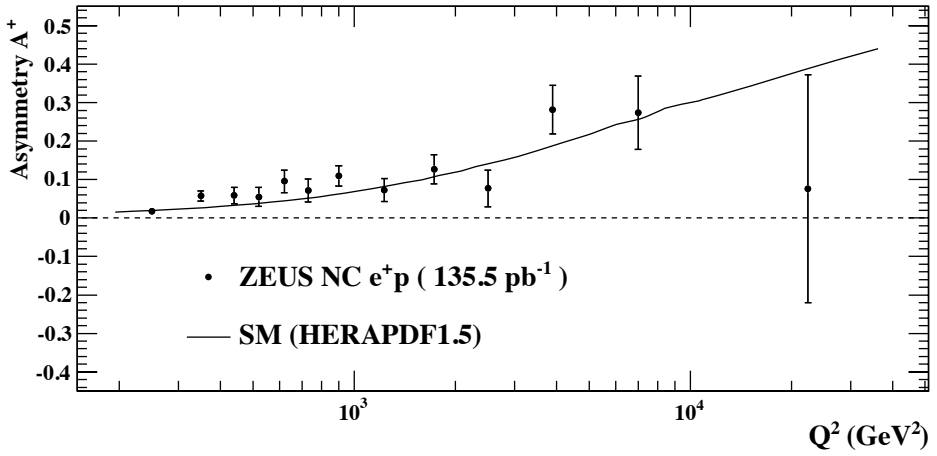
- Very pure signal, good agreement with MC expectations
- Reduced Cross sections (corrected to P=0) well described by SM predictions (HERAPDF1.5)

PRD 87 (2013) 052014

Final ZEUS HERA-II NC e^+p cross sections







- Improved determination of $F_3^{\gamma Z}$

- Parity violation demonstrated down to scale 10^{-18} m

Summary

HERA remains our main source of information on proton structure

Recent combined results of the H1 and ZEUS Collaborations have allowed the proton PDFs to be determined with an unprecedented precision

Most of the improvements in the understanding of the PDFs, described here, are very relevant for the physics programme of the LHC

Final High Q^2 NC and CC HERA II Cross sections now published.
Final HERA combinations and QCD Analysis being worked on.

For additional information and results please refer to:
https://www.desy.de/h1zeus/combined_results/

Measurement of $F_2^{\gamma Z}$, $F_3^{\gamma Z}$

$F_2^{\gamma Z}$:

$$\frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{P_L^{\pm} - P_R^{\pm}} = \frac{\kappa Q^2}{Q^2 + M_Z^2}\left[\mp a_e F_2^{\gamma Z} + \frac{Y_-}{Y_+} v_e x F_3^{\gamma Z} - \frac{Y_-}{Y_+}\frac{\kappa Q^2}{Q^2 + M_Z^2}(v_e^2 + a_e^2) x F_3^Z\right]$$

$F_3^{\gamma Z}$:

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}(\tilde{\sigma}^{e^- p} - \tilde{\sigma}^{e^+ p}). \qquad x\tilde{F}_3 \simeq -a_e \chi_Z x F_3^{\gamma Z}.$$