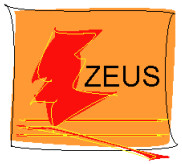
Inclusive DIS and PDFs at HERA

Enrico Tassi
(Universita' della Calabria and INFN)



On behalf of the H1 and ZEUS Collaborations

Diffraction 2014

Primosten - September 10-16, 2014

HERA and the Structure of the Proton

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

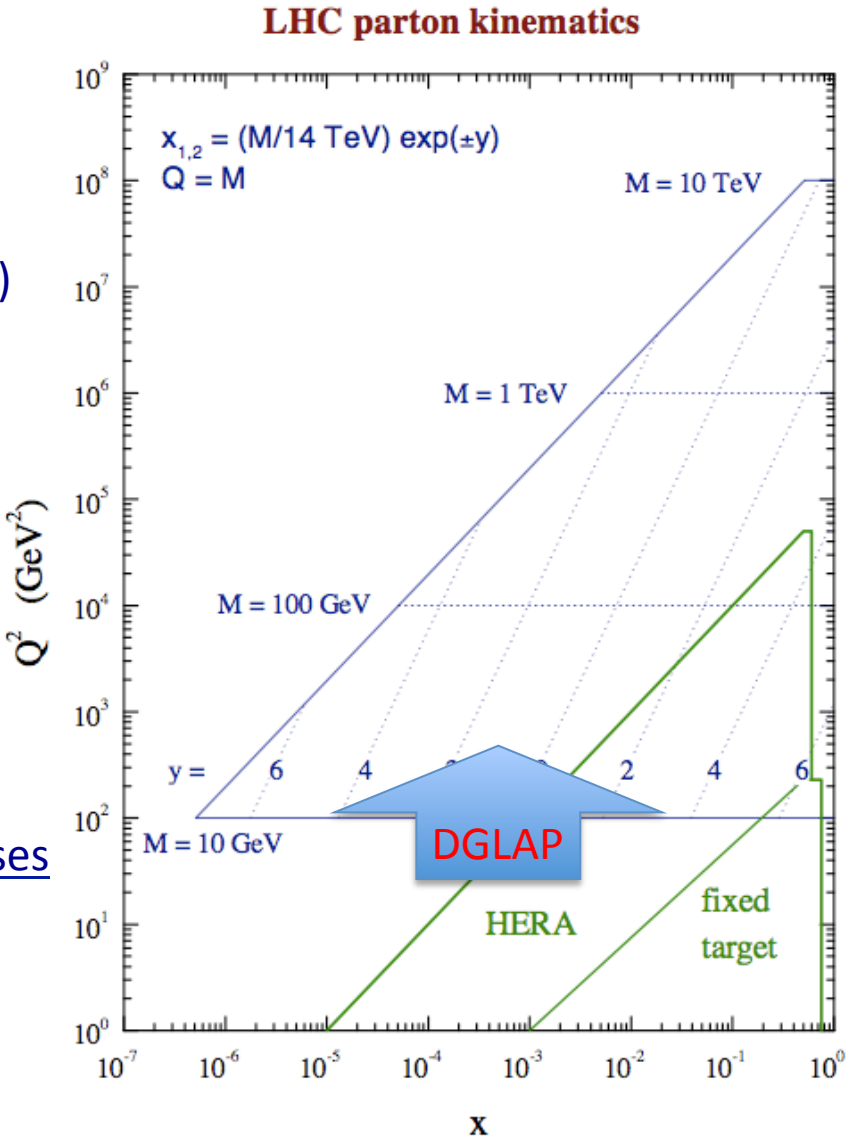
➔ proton's parton distribution functions (PDFs)

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

➔ stringent tests of the Standard Model

➔ searches of Physics Beyond the SM (need to control QCD Background)

<u>Combination of the complete H1 and ZEUS inclusive measurements needed in order to provide the most precise input to DGLAP analyses</u>

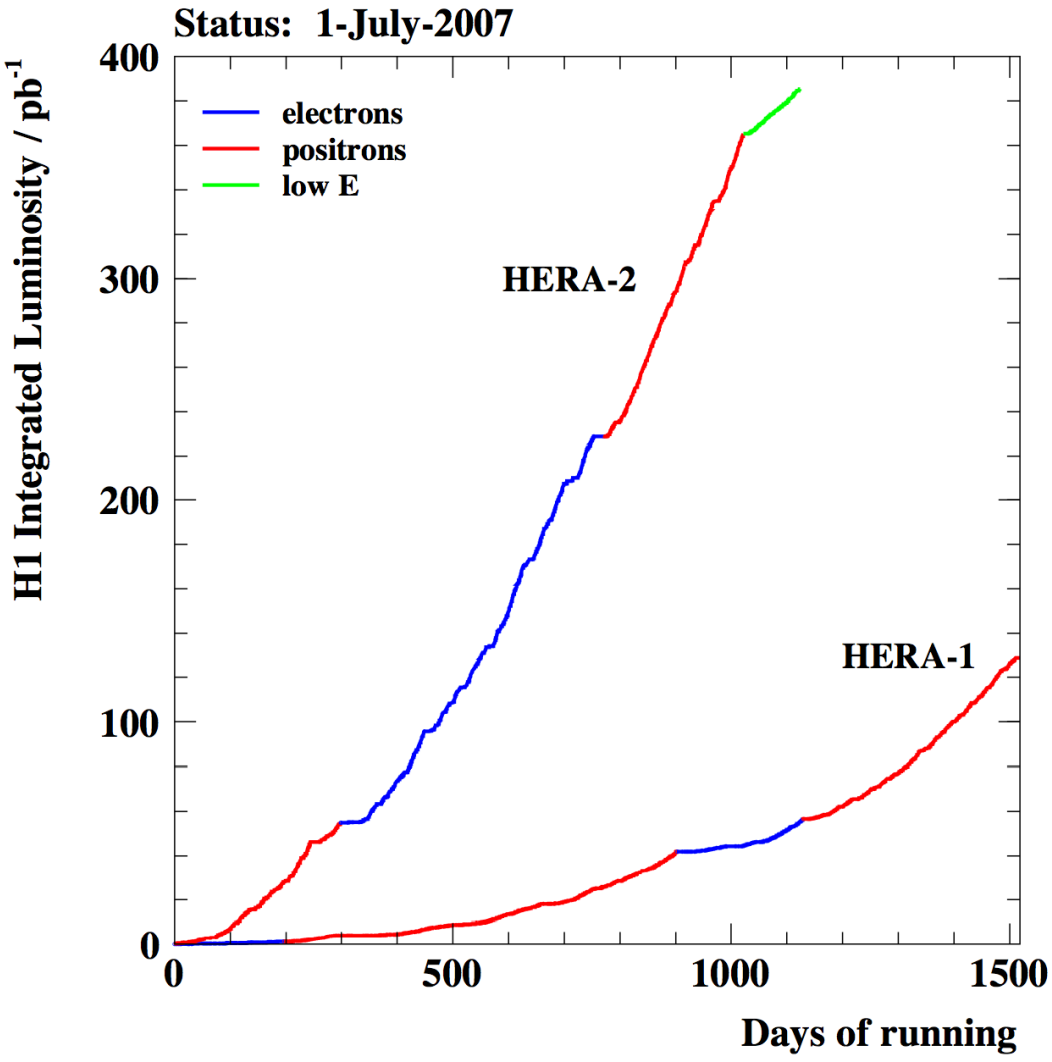


HERA Operation

HERA-I (1992-2000)
Ee=27.6 GeV
Ep=820 & 920 GeV
L_{int} ~ 130 pb^{-1} per experiment
Mostly e^+p

HERA-II (2003-2007)
Ee=27.6 GeV
Ep=920 GeV
L_{int} ~ 360 pb^{-1} per experiment
Longitudinally polarized lepton beams
Similar amounts of e^+p and e^-p

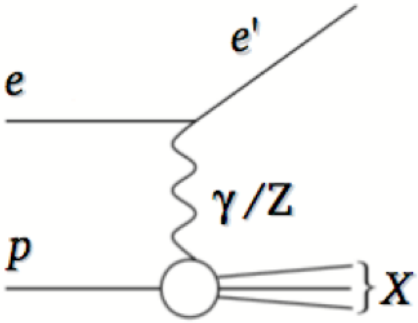
Low Energy Run 2007
Ee=27.6 GeV
Ep=460 & 575 GeV
Runs at reduced √s :
225 GeV (LER), 252 (MER) GeV
Dedicated F_L measurements



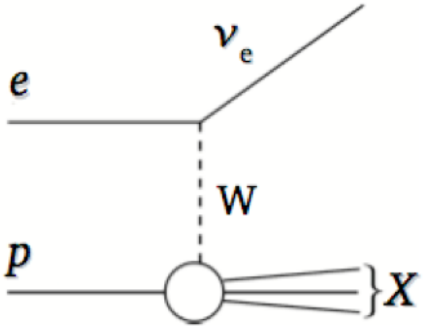
1 fb^{-1} Integrated lumi, H1+ZEUS

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:

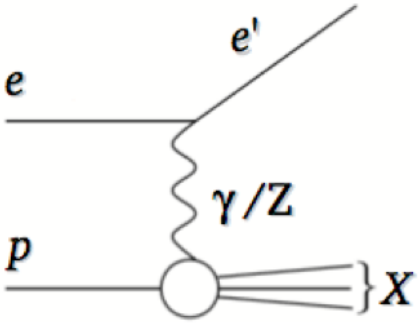
NC: $$\sigma^{\pm}_{r,\mathrm{NC}} = \frac{d^2\sigma^{e^{\pm}p}_{\mathrm{NC}}}{dxdQ^2} \cdot \frac{Q^4 x}{2\pi\alpha^2 Y_+} = F_2 \mp \frac{Y_-}{Y_+} xF_3 - \frac{y^2}{Y_+} F_L$$

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

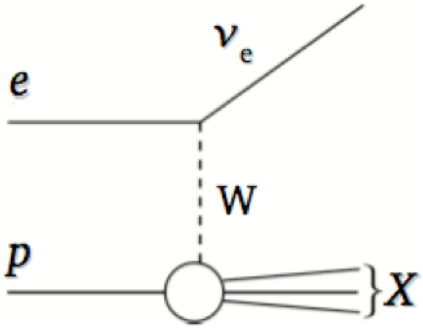
with $$Y_{\pm} = 1 \pm (1 - y)^2$$

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 (NLO & NNLO):

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

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

Results I will cover

- Final HERA combination of the H1 and ZEUS incl. cross sections

Preliminary

- DGLAP analyses based on the HERA combined inclusive cross sections and HERAPDF2.0 PDFs

- NC measurements at E_p= 460, 575 GeV and model independent F_L measurements

H1: EPJ C 74 (2014) 2814

ZEUS: DESY-14-053

- $e^{\pm}p$ NC cross sections at high-x

PRD 89(2014) 072007

Final HERA combination of the H1 and ZEUS inclusive cross sections

For additional details see: H1prelim-14-041 and ZEUS-prel-14-005

H1 & ZEUS Data Combination: Data sets

Data Set		x Grid from	x Grid to	Q^2/GeV^2 Grid from	Q^2/GeV^2 Grid to	$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV	x,Q^2 from equations	Ref.
HERA I E_p = 820 GeV and E_p = 920 GeV data sets										
H1 svx-mb	95-00	0.000005	0.02	0.2	12	2.1	e^+p	301, 319	11,15,16	[2]
H1 low Q^2	96-00	0.0002	0.1	12	150	22	e^+p	301, 319	11,15,16	[3]
H1 NC	94-97	0.0032	0.65	150	30000	35.6	e^+p	301	17	[4]
H1 CC	94-97	0.013	0.40	300	15000	35.6	e^+p	301	12	[4]
H1 NC	98-99	0.0032	0.65	150	30000	16.4	e^-p	319	17	[5]
H1 CC	98-99	0.013	0.40	300	15000	16.4	e^-p	319	12	[5]
H1 NC HY	98-99	0.0013	0.01	100	800	16.4	e^-p	319	11	[6]
H1 NC	99-00	0.0013	0.65	100	30000	65.2	e^+p	319	17	[6]
H1 CC	99-00	0.013	0.40	300	15000	65.2	e^+p	319	12	[6]
ZEUS BPC	95	0.000002	0.00006	0.11	0.65	1.65	e^+p	300	11	[10]
ZEUS BPT	97	0.0000006	0.001	0.045	0.65	3.9	e^+p	300	11, 17	[11]
ZEUS SVX	95	0.000012	0.0019	0.6	17	0.2	e^+p	300	11	[12]
ZEUS NC	96-97	0.00006	0.65	2.7	30000	30.0	e^+p	300	19	[13]
ZEUS CC	94-97	0.015	0.42	280	17000	47.7	e^+p	300	12	[14]
ZEUS NC	98-99	0.005	0.65	200	30000	15.9	e^-p	318	18	[15]
ZEUS CC	98-99	0.015	0.42	280	30000	16.4	e^-p	318	12	[16]
ZEUS NC	99-00	0.005	0.65	200	30000	63.2	e^+p	318	18	[17]
ZEUS CC	99-00	0.008	0.42	280	17000	60.9	e^+p	318	12	[18]
HERA II E_p = 920 GeV data sets										
H1 NC	03-07	0.0008	0.65	60	30000	182	e^+p	319	11, 17	[7][1]
H1 CC	03-07	0.008	0.40	300	15000	182	e^+p	319	12	[7][1]
H1 NC	03-07	0.0008	0.65	60	50000	151.7	e^-p	319	11, 17	[7][1]
H1 CC	03-07	0.008	0.40	300	30000	151.7	e^-p	319	12	[7][1]
H1 NC med Q^2 *y.5	03-07	0.0000986	0.005	8.5	90	97.6	e^+p	319	11	[9]
H1 NC low Q^2 *y.5	03-07	0.000029	0.00032	2.5	12	5.9	e^+p	319	11	[9]
ZEUS NC	06-07	0.005	0.65	200	30000	135.5	e^+p	318	11,12,18	[21]
ZEUS CC	06-07	0.0078	0.42	280	30000	132	e^+p	318	12	[22]
ZEUS NC	05-06	0.005	0.65	200	30000	169.9	e^-p	318	18	[19]
ZEUS CC	04-06	0.015	0.65	280	30000	175	e^-p	318	12	[20]
ZEUS NC nominal *y	06-07	0.000092	0.008343	7	110	44.5	e^+p	318	11	[23]
ZEUS NC satellite *y	06-07	0.000071	0.008343	5	110	44.5	e^+p	318	11	[23]
HERA II E_p = 575 GeV data sets										
H1 NC high Q^2	07	0.00065	0.65	35	800	5.4	e^+p	252	11, 17	[8]
H1 NC low Q^2	07	0.0000279	0.0148	1.5	90	5.9	e^+p	252	11	[9]
ZEUS NC nominal	07	0.000147	0.013349	7	110	7.1	e^+p	251	11	[23]
ZEUS NC satellite	07	0.000125	0.013349	5	110	7.1	e^+p	251	11	[23]
HERA II E_p = 460 GeV data sets										
H1 NC high Q^2	07	0.00081	0.65	35	800	11.8	e^+p	225	11, 17	[8]
H1 NC low Q^2	07	0.0000348	0.0148	1.5	90	12.2	e^+p	225	11	[9]
ZEUS NC nominal	07	0.000184	0.016686	7	110	13.9	e^+p	225	11	[23]
ZEUS NC satellite	07	0.000143	0.016686	5	110	13.9	e^+p	225	11	[23]

H1 & ZEUS have now published all their inclusive measurements
- HERA-II measurements at high-Q^2
- reduced √s

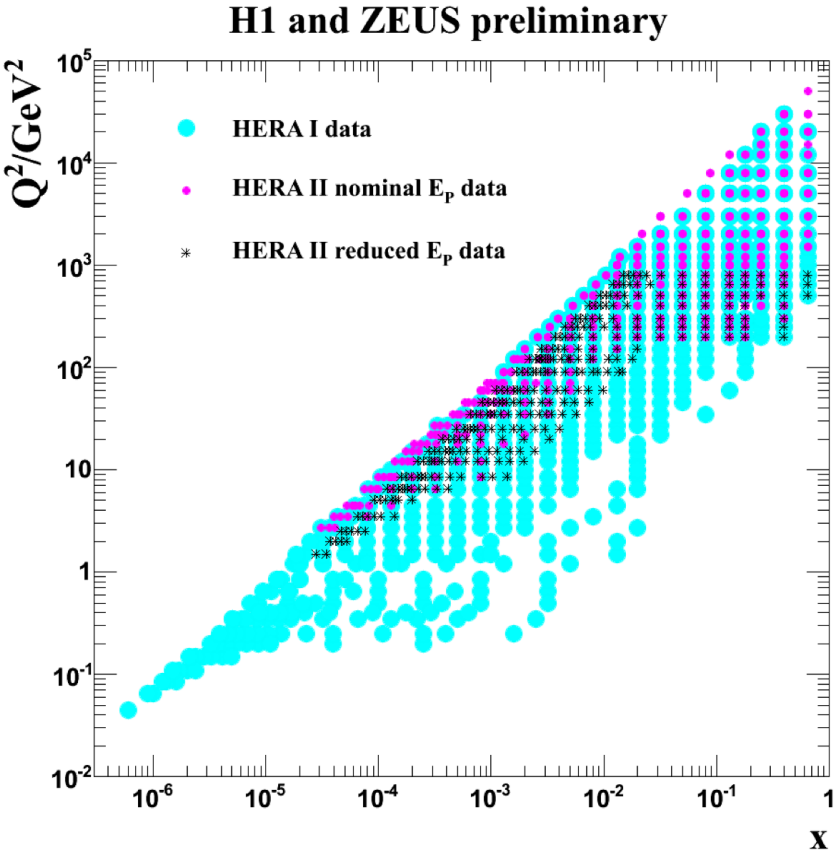
41 data sets to be combined:
- NC & CC cross sections
- e^+p and e^-p scattering
- 4 different √s values (318, 301, 252 and 225 GeV)

2927 data points

1307 combined points

In some cases up to 6 measurements contribute to a combined result

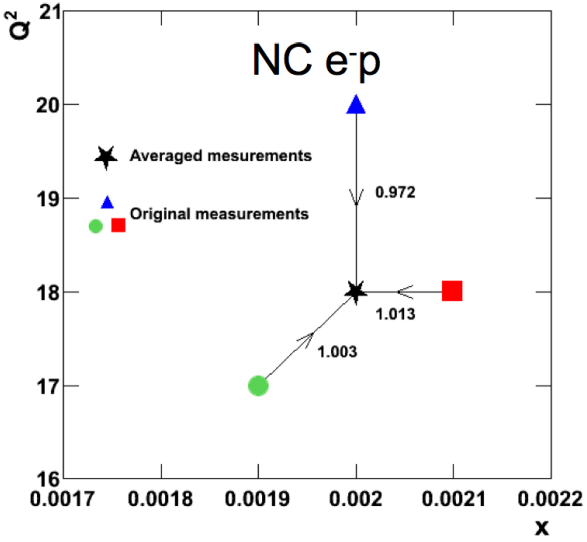
H1 & ZEUS Data Combination: Grid



Data are combined onto a common x,Q^2 grid
Two grids are used:

- Inclusive cross sections at √s = 301, 318 GeV
- Finer x grid for lower √s measurements

Original measurements swum to the nearest grid point, via linear interpolation



$$\sigma(x_{grid}, Q^2_{grid}) = \frac{\sigma_{model}(x_{grid}, Q^2_{grid})}{\sigma_{model}(x_{meas}, Q^2_{meas})} \cdot \sigma_{meas}(x_{meas}, Q^2_{meas})$$

H1 & ZEUS Data Combination: Combination method

Combination performed using the **HERAverager** package

Averaging procedure take correlations of systematic unc. into account

Multiplicative treatment of the systematic uncertainties (as a default choice)

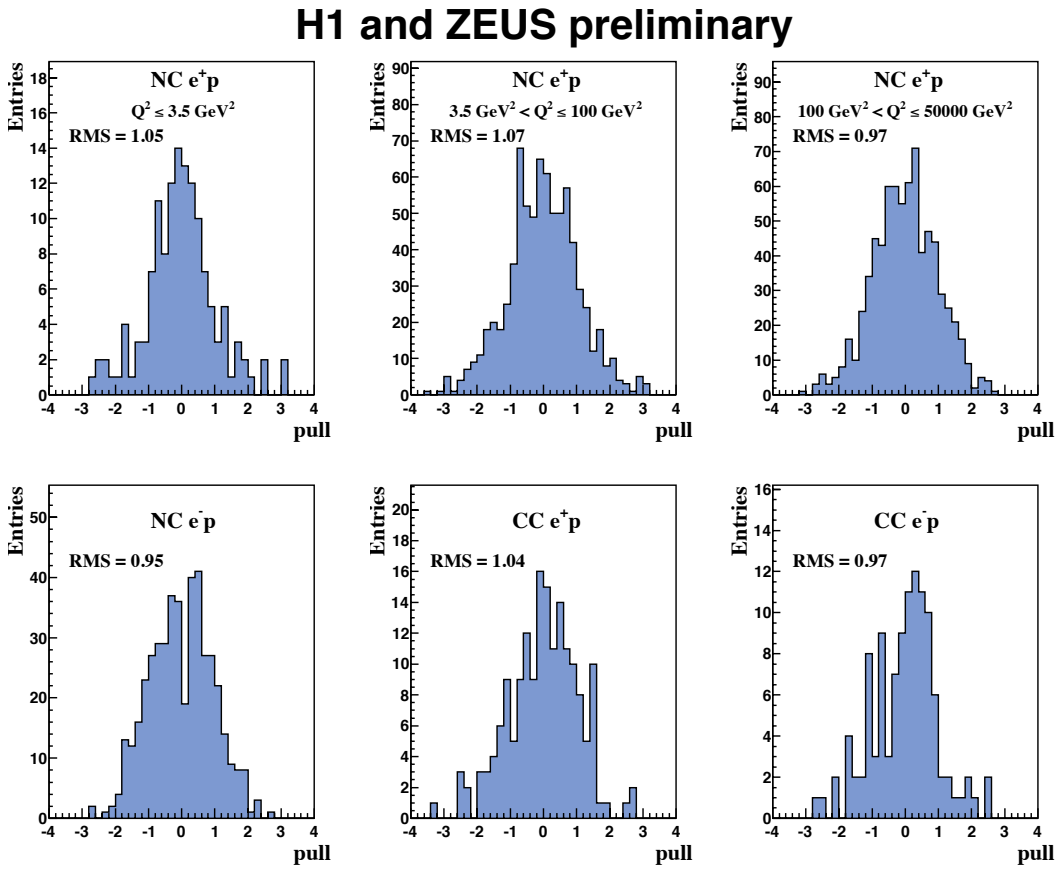
χ^2 minimization:

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

Procedural uncertainties:

- Multiplicative vs additive
- Correlations in photoproduction background and hadronic energy scale

H1 & ZEUS Data Combination: Pulls



χ^2 of the combination:

$$\frac{\chi^2}{ndf} = \frac{1685}{1620}$$

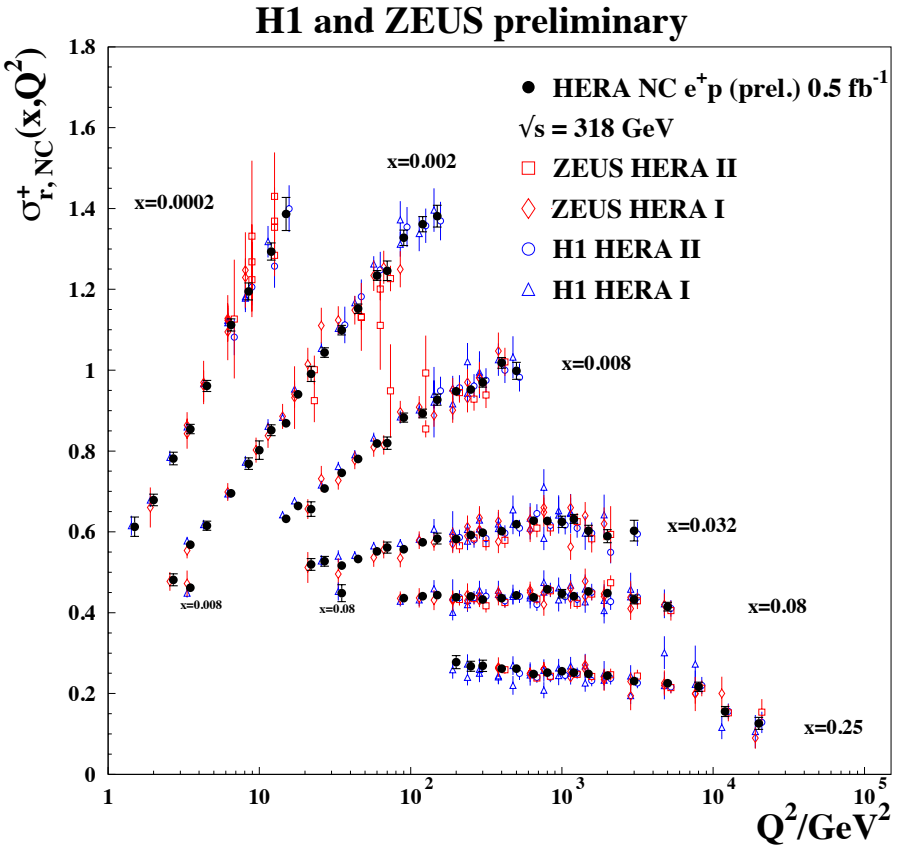
Pull definition:

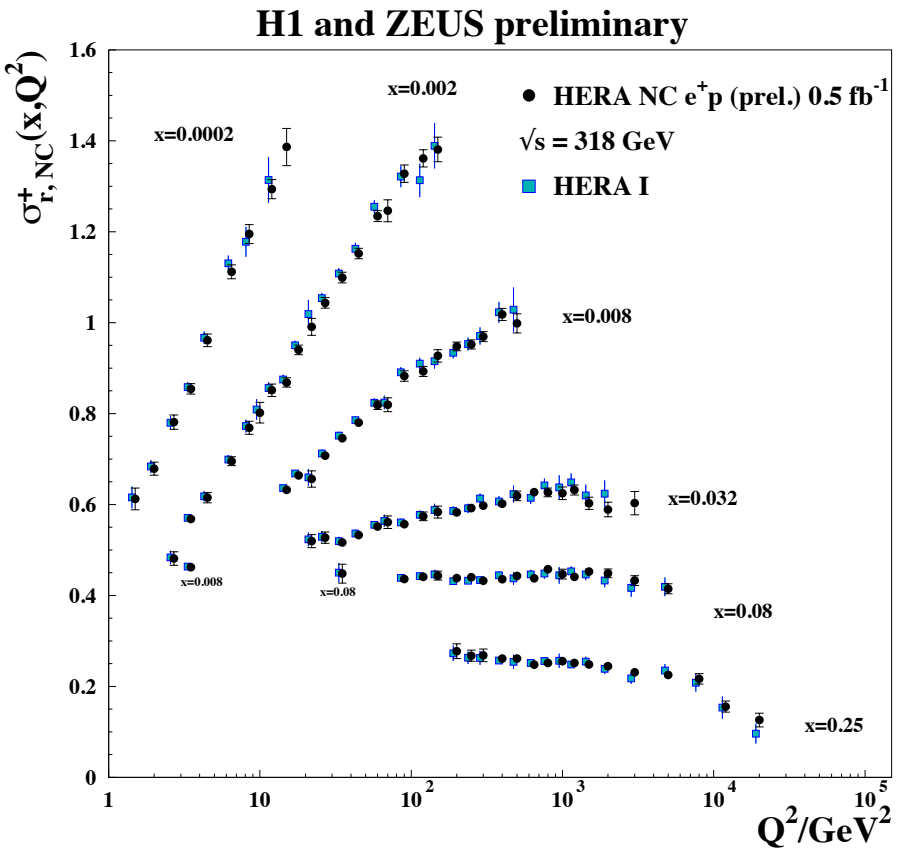
$$p^{i,k} = \frac{\mu^{i,k} - \mu^{i,ave}\left(1 - \sum_j \gamma_j^{i,k} b_{j,ave}\right)}{\sqrt{\Delta_{i,k}^2 - \Delta_{i,ave}^2}}$$

For each process pulls centred at zero with unit width

H1 & ZEUS Data Combination

NC e^+p reduced cross sections - $\sqrt{s}$ = 318 GeV

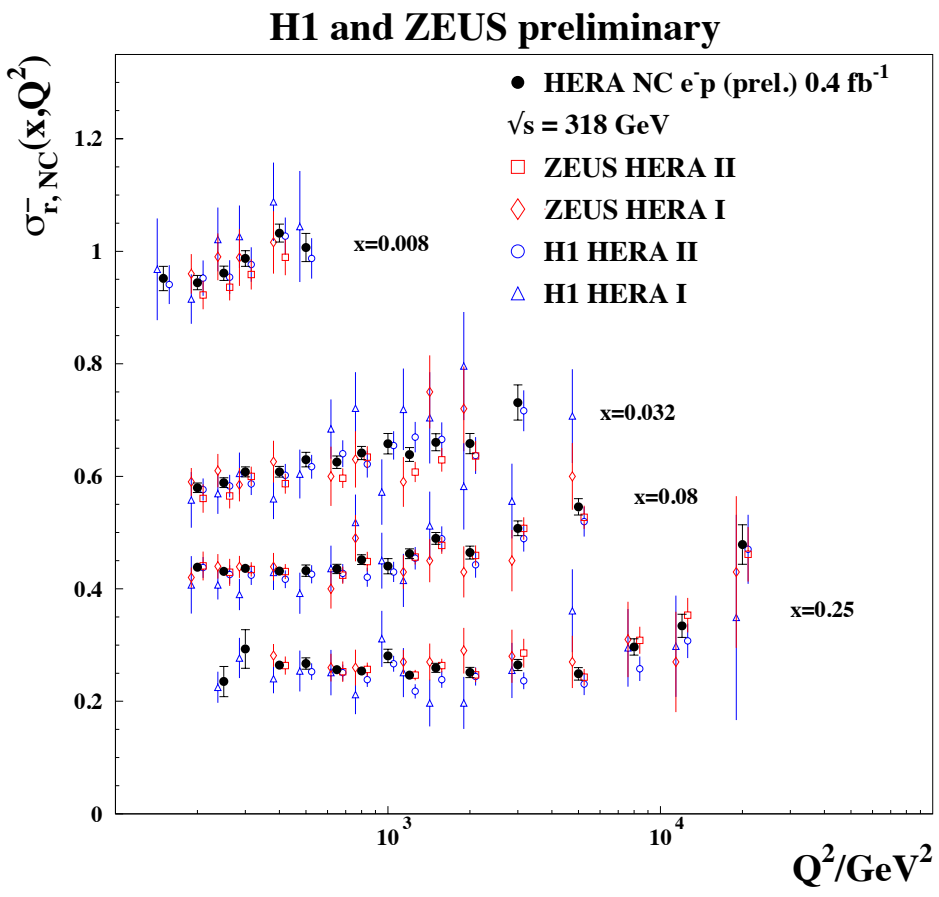


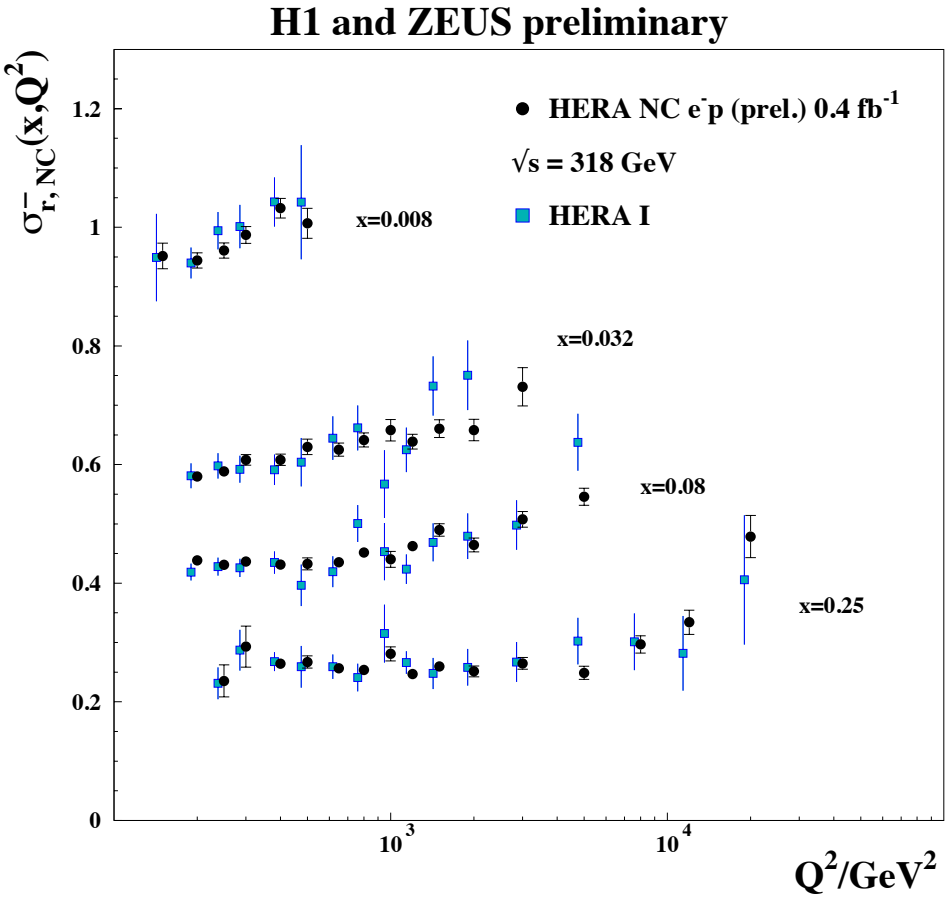


Significant reduction of the uncertainties at high-Q^2

H1 & ZEUS Data Combination

NC e^-p reduced cross sections - $\sqrt{s}$ = 318 GeV

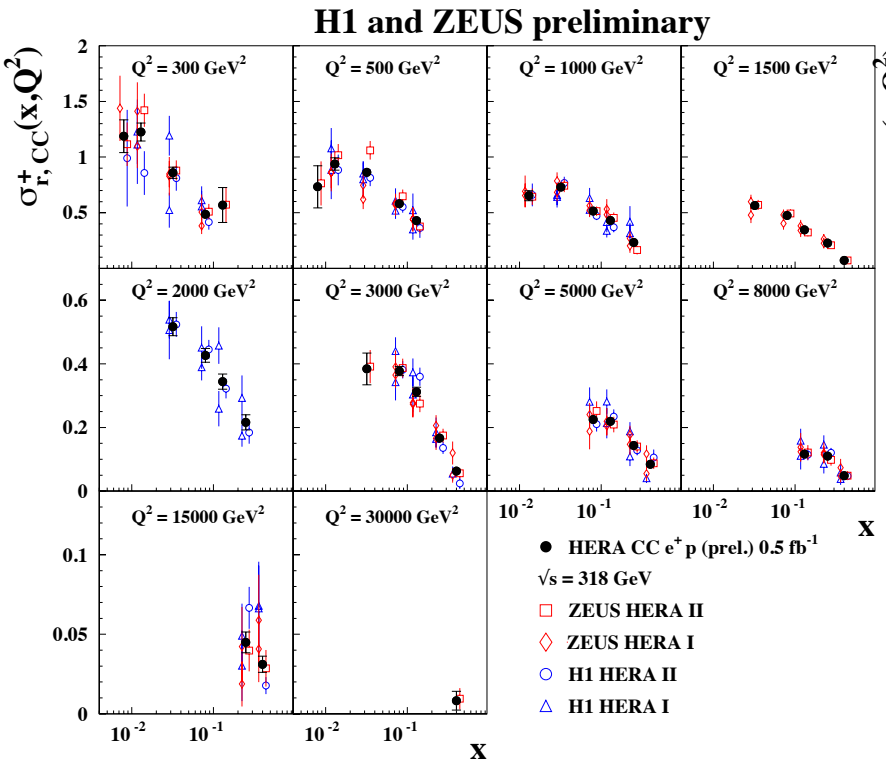


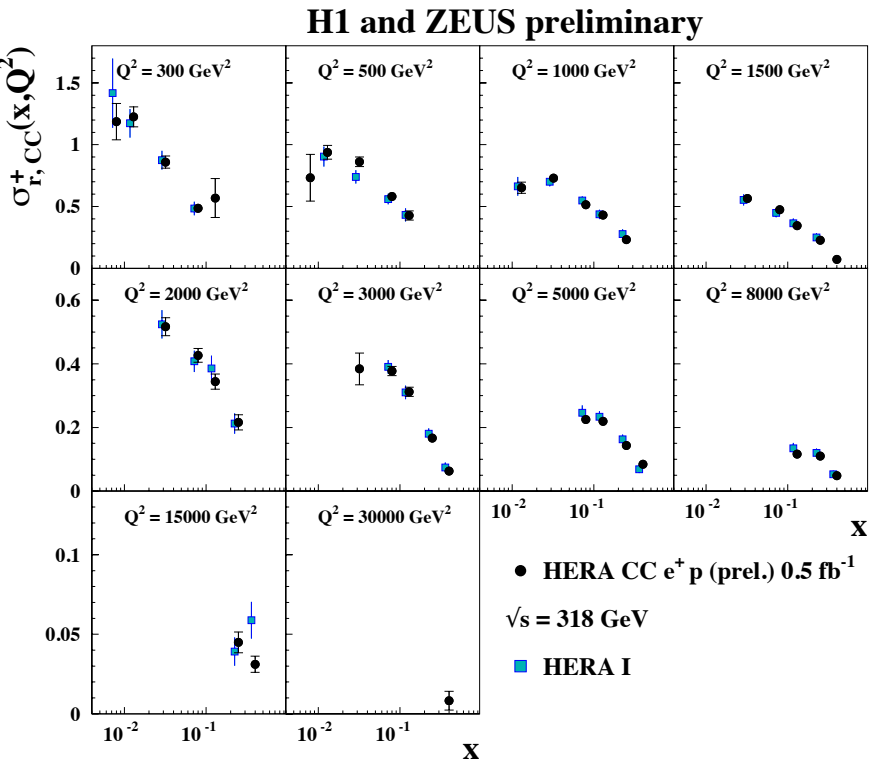


The benefit of averaging is enormous especially for e^-p scattering

H1 & ZEUS Data Combination

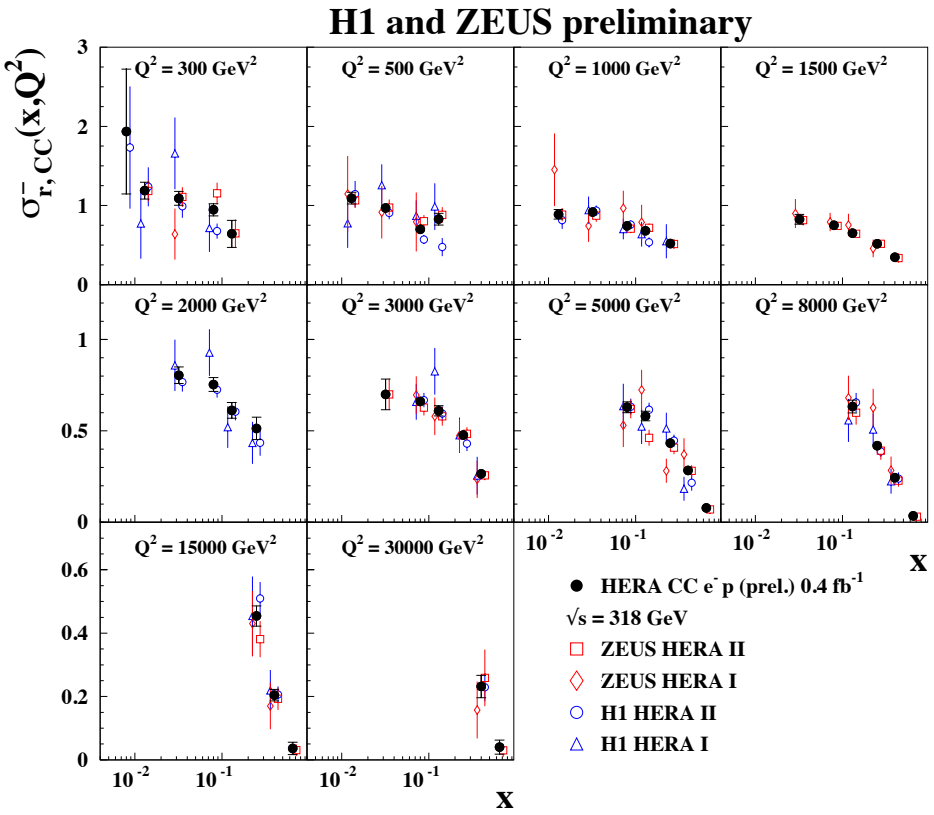
CC e^+p reduced cross sections- $\sqrt{s}$ = 318 GeV

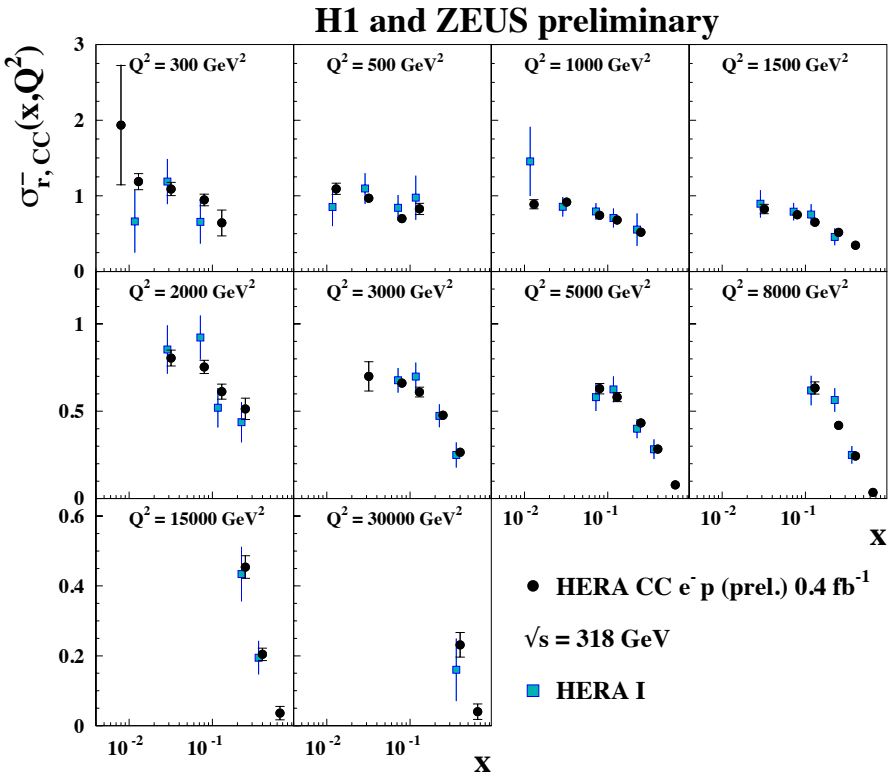




H1 & ZEUS Data Combination

CC e^-p reduced cross sections - $\sqrt{s}$ = 318 GeV





Significant reduction of the uncertainties for CC e^-p

DGLAP Analyses and HERAPDF2.0 PDFs

For additional details see: H1prelim-14-042 and ZEUS-prel-14-007

HERAPDFs: Reminder

HERAPDFs:

DGLAP analyses based only on the final combination of the HERA incl. cross sections
- no need for heavy target/deuterium correction or strong isospin assumptions

Overview of HERAPDF sets:

Data	PDF Set
H1+ZEUS NC,CC - HERA I	HERAPDF1.0 (NLO)
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) + jets + charm	HERAPDF1.7 (NLO)
Complete HERA inclusive data	HERAPDF2.0 (NLO, NNLO)

HERAFitter

Open source QCD fitting tool to determine PDFs
(See R. Placakyte talk)

HERAPDF2.0: Settings for DGLAP analysis

- QCD fit performed using HERAFitter package
- PDFs parameterized at Q_0^2=1.9 GeV^2:

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

$$\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+D_{u_v}x+E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
xU(x) &= A_U x^{B_U}(1-x)^{C_U}(1+D_U x), \\
xD(x) &= A_D x^{B_D}(1-x)^{C_D}.
\end{aligned}$$

- 15 parameters fits (after χ^2 saturation, momentum/counting sum rules etc)
- Massive treatment for heavy flavours (RT-GM-VFNS)
- Detailed study of uncertainties: experimental, model and parameterization
- Fits performed at NLO and NNLO and for two Q^2_{min} cuts (3.5 GeV^2 and 10 GeV^2)

HERAPDF 2.0: χ^2 and Q^2_{min} dependence

Q^2_{min} = 3.5 GeV^2

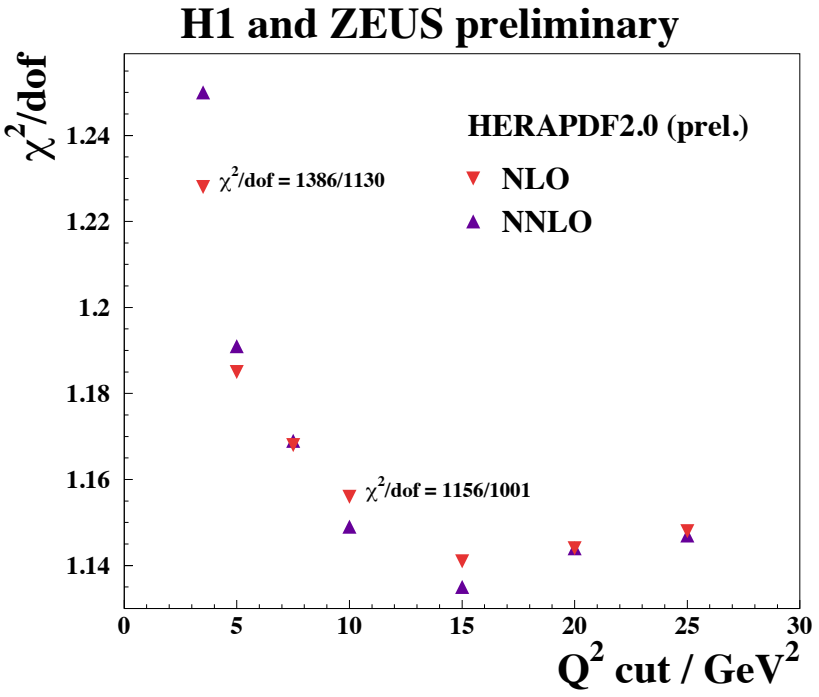
NLO $\quad \frac{\chi^2}{ndf} = \frac{1386}{1130}$

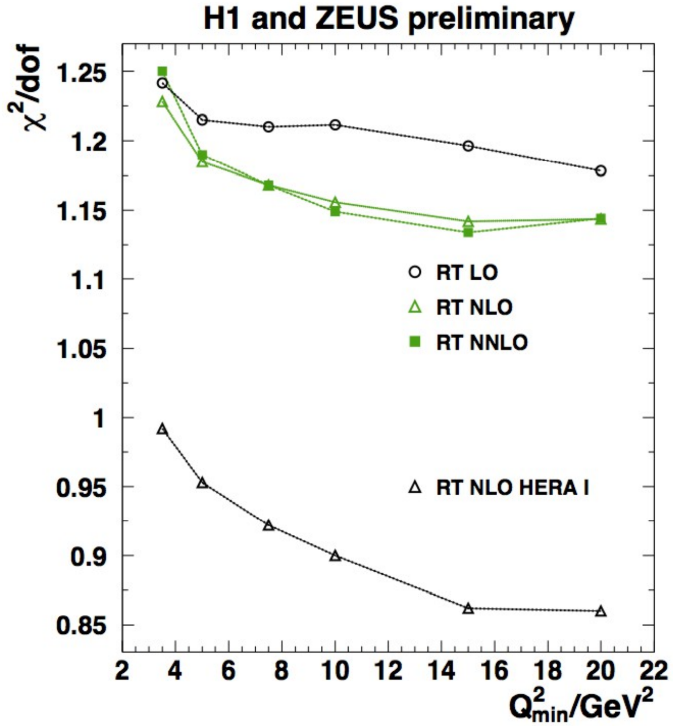
NNLO $\quad \frac{\chi^2}{ndf} = \frac{1414}{1130}$

Q^2_{min} = 10 GeV^2

NLO $\quad \frac{\chi^2}{ndf} = \frac{1156}{1001}$

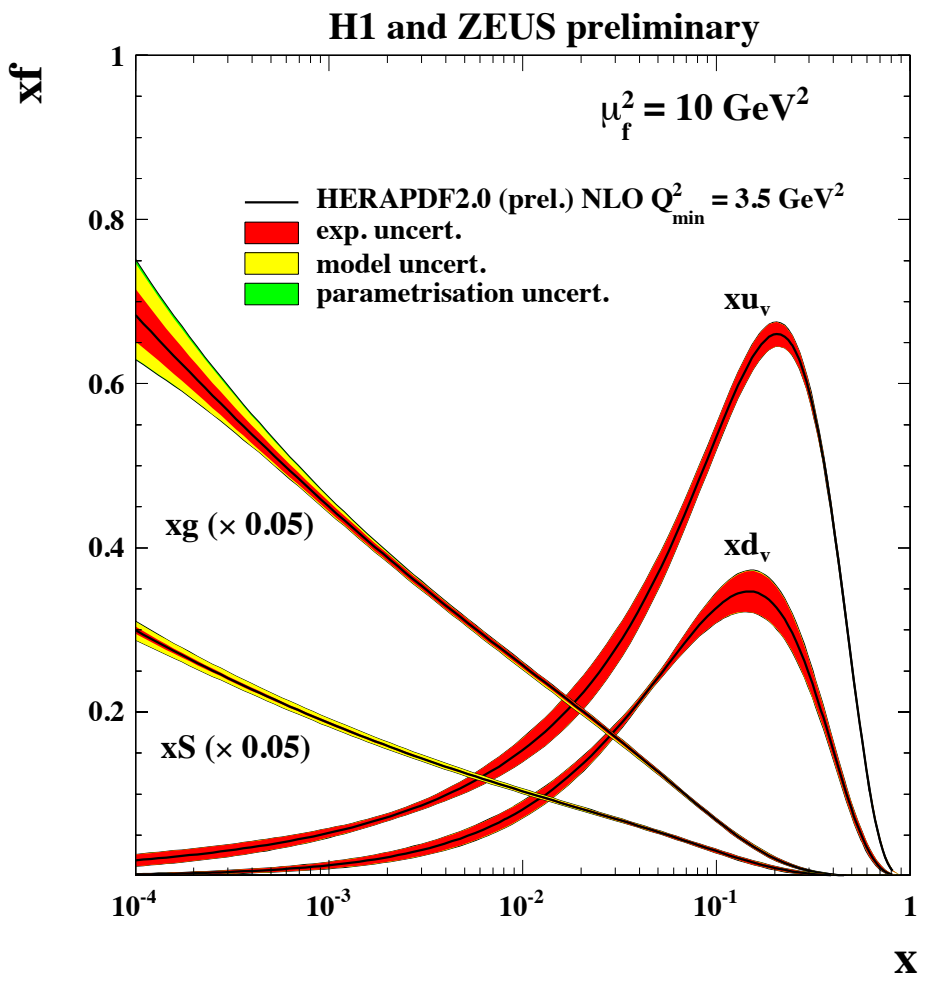
NNLO $\quad \frac{\chi^2}{ndf} = \frac{1150}{1001}$





For HERAPDF1.0 (Q^2_{min}=3.5 GeV^2) $\frac{\chi^2}{ndf} = \frac{637}{656}$ at NLO

HERAPDF2.0: Uncertainties



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	0.4	0.3	0.5
M_c^{opt}(NLO) [GeV]	1.47	1.41	1.53
M_c^{opt} (NNLO) [GeV]	1.44	1.38	1.50
M_b [GeV]	4.75	4.5	5.0
Q^2_{min} [GeV^2]	10.0	7.5	12.5
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q_0^2 [GeV^2]	1.9	1.6	2.2

Parametrization uncertainty:

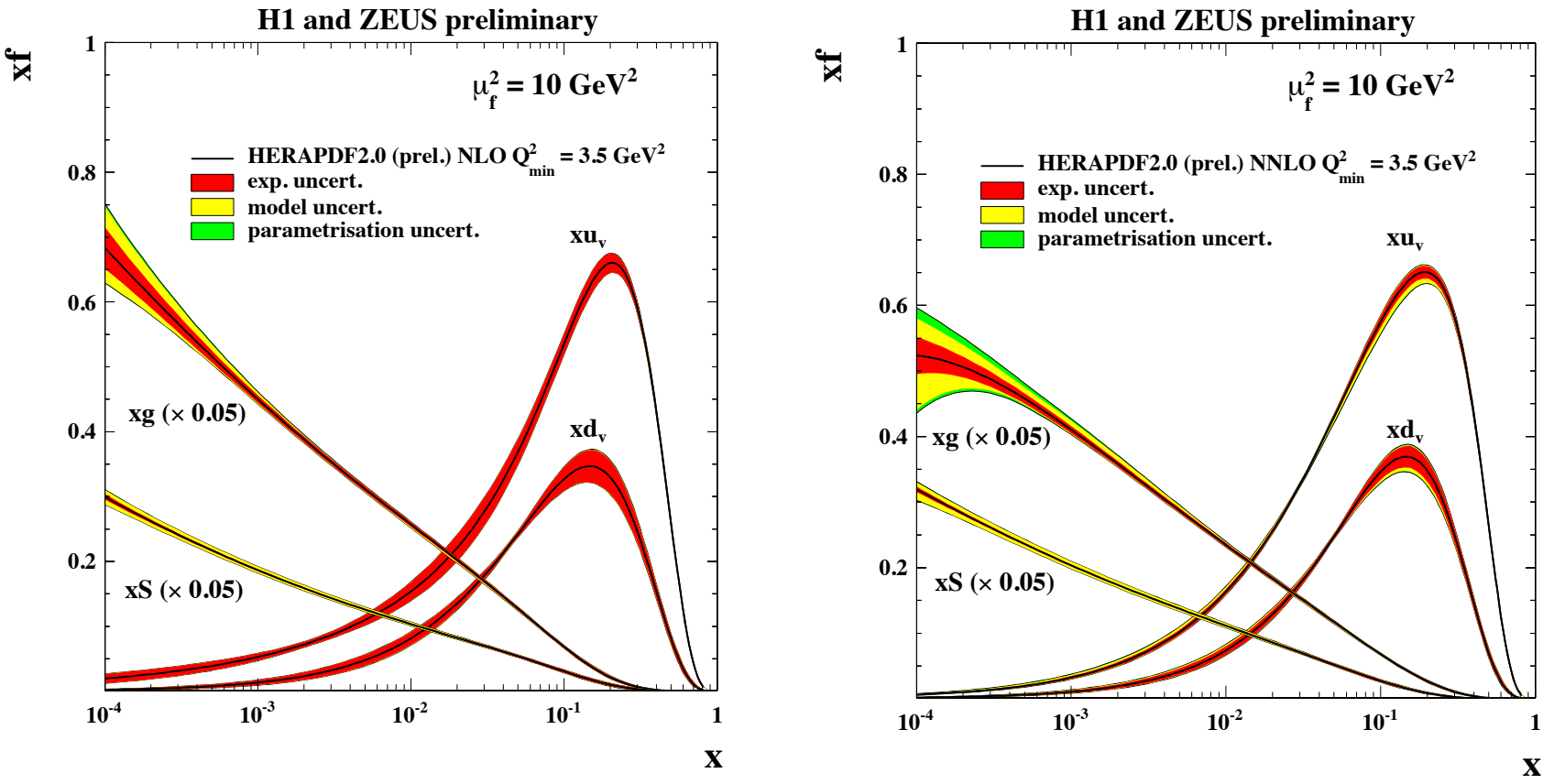
1. Envelope from DGLAP fits using variants of the parametrization form at Q_0^2

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

2. Variation of the starting scale Q_0^2

HERAPDF2.0: NLO and NNLO

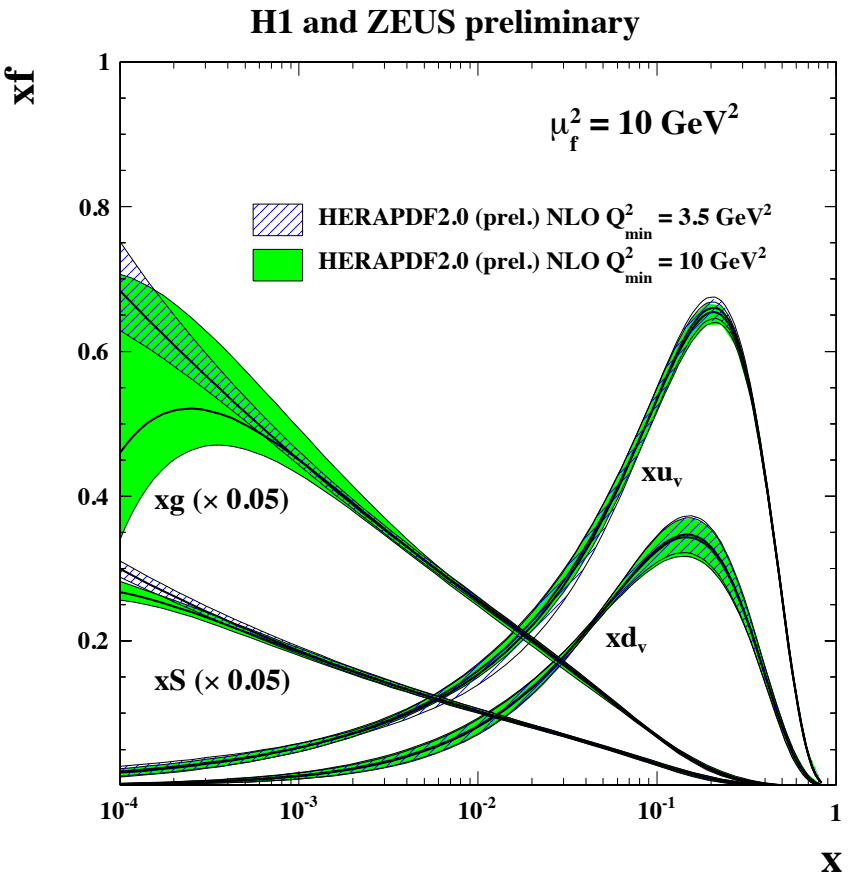
NLO Q^2_{min}=3.5 GeV^2 NNLO



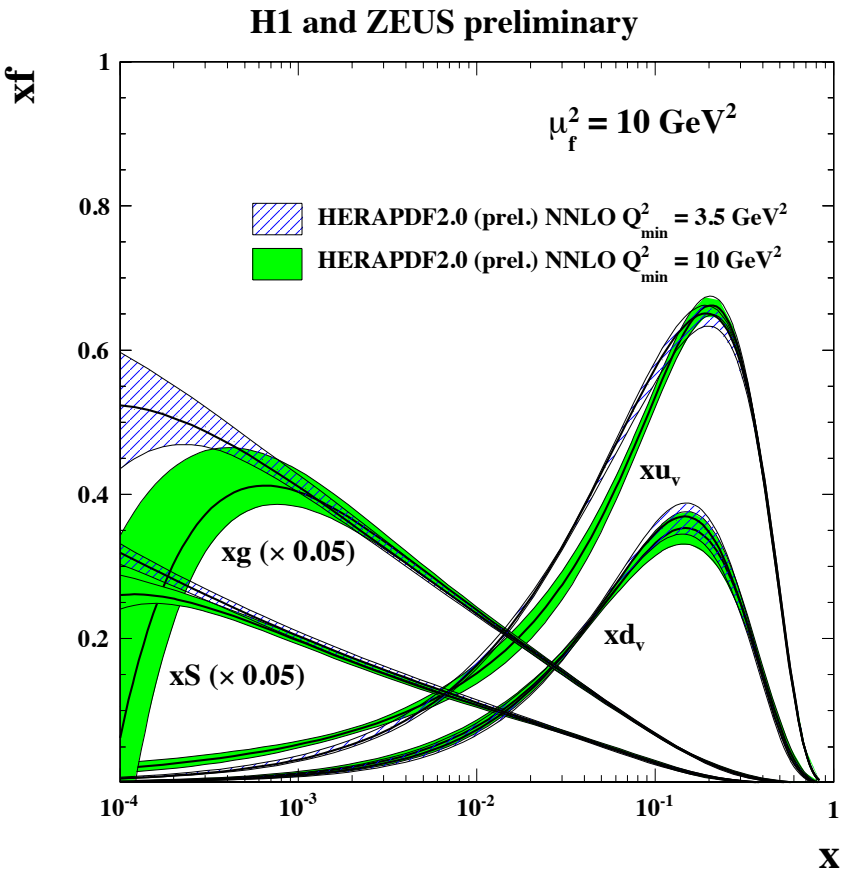
NNLO: Less steeper gluon at low-x / Steeper Sea at low-x

HERAPDF2.0: Q^2_{min}=3.5 vs Q^2_{min}=10 GeV^2

NLO



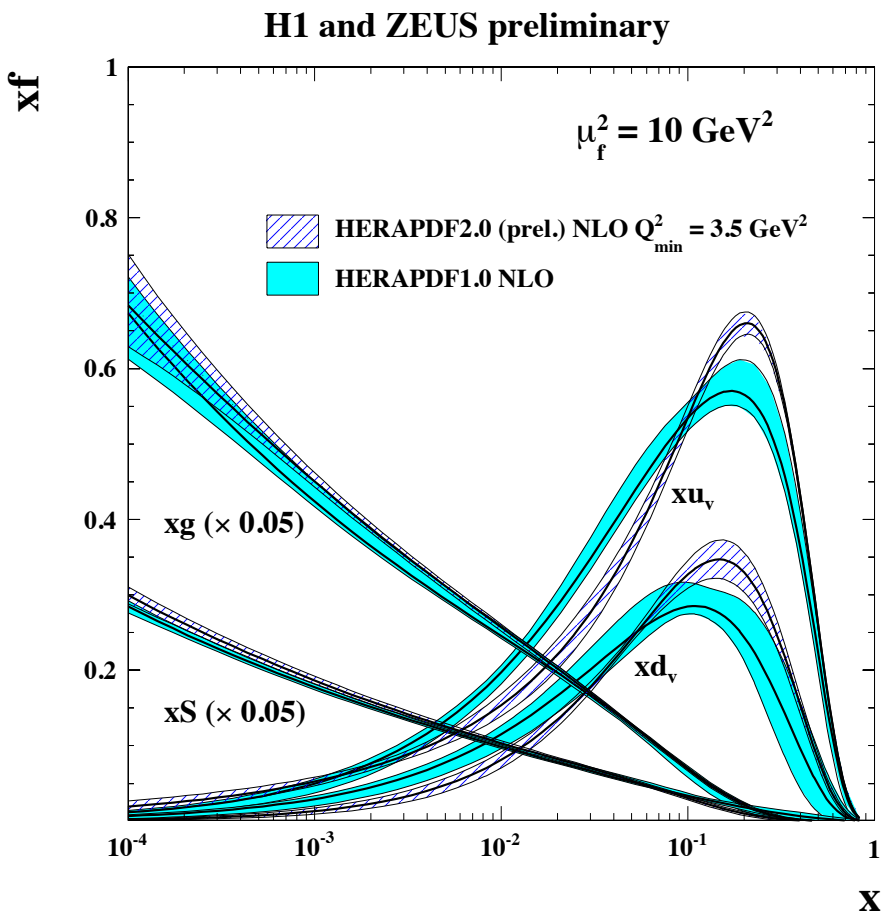
NNLO



Going from Q^2_{min}=3.5 to 10 GeV^2 affects gluon shape and uncertainty at low-x

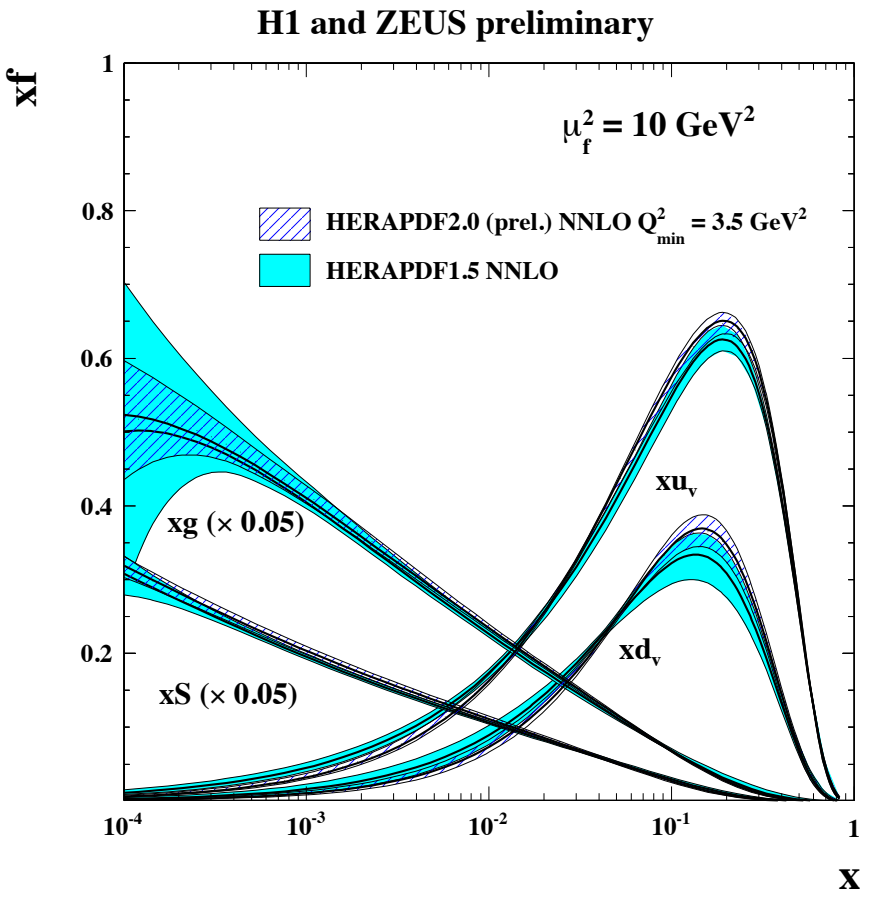
HERAPDF2.0 vs HERAPDF1.0 and 1.5

vs HERAPDF1.0 (NLO)



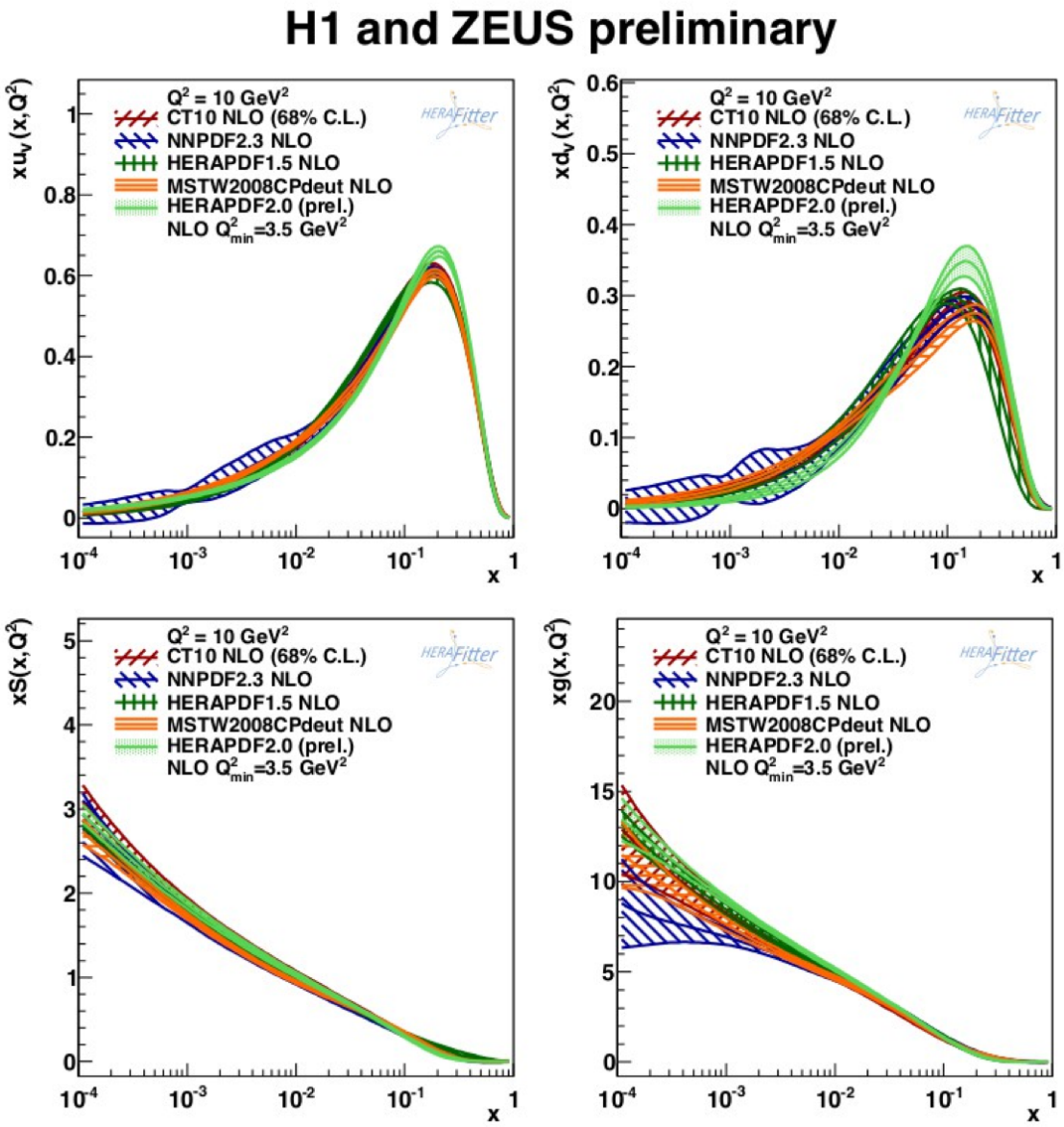
Valence PDFs most affected

vs HERAPDF1.5 (NNLO)



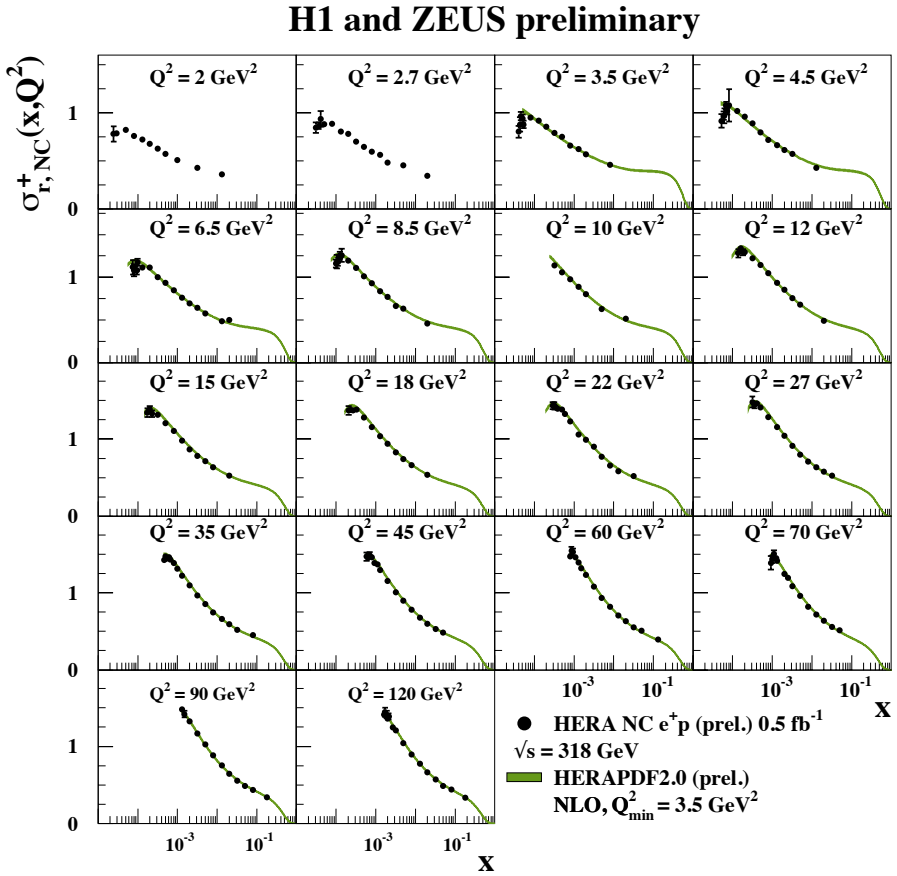
Reduced gluon uncertainty

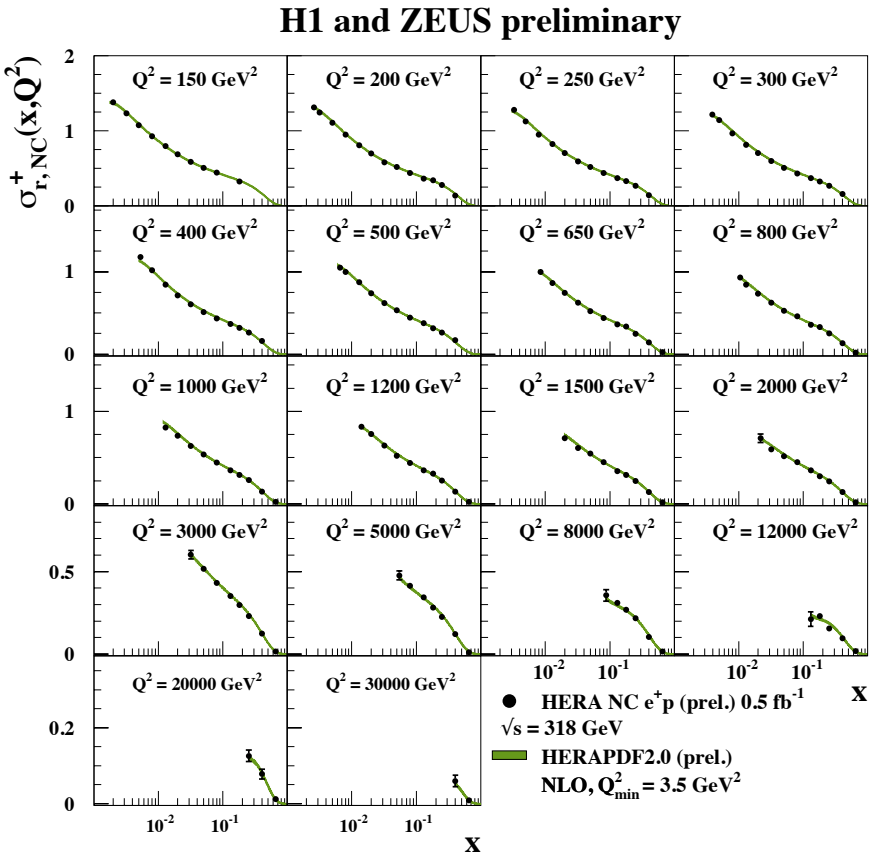
HERAPDF2.0 vs other PDF Sets



HERAPDF2.0

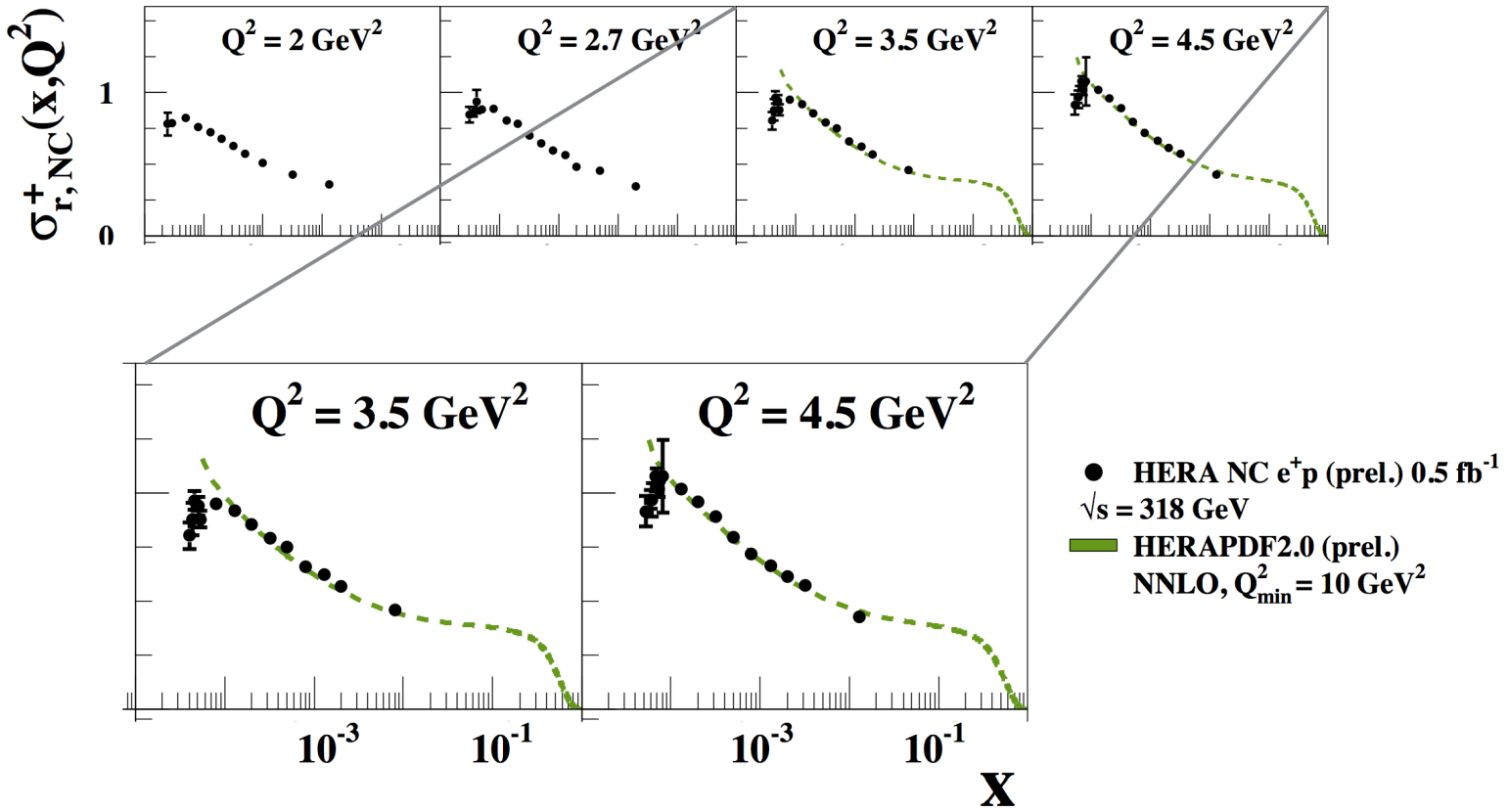
NC e^+p reduced cross sections





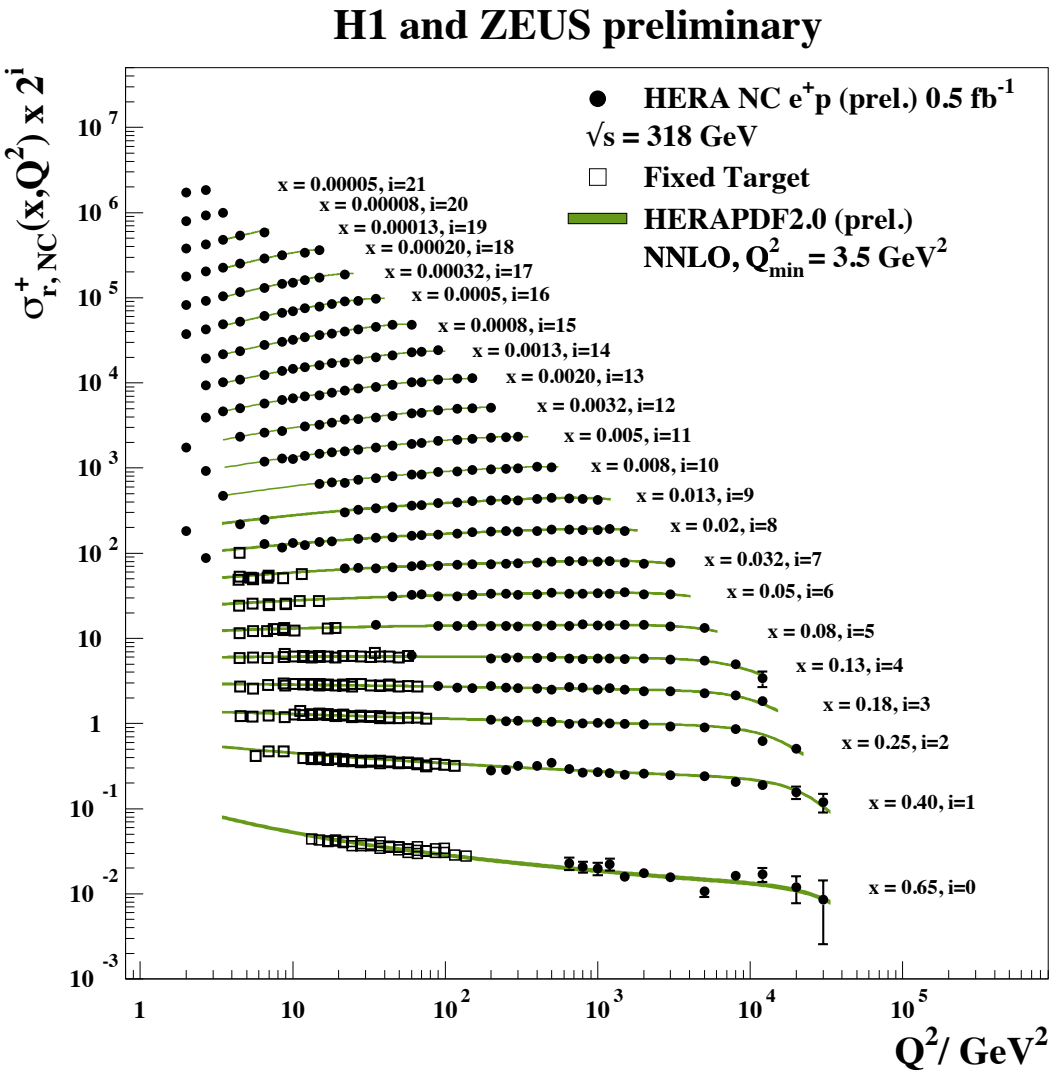
HERAPDF2.0

Closer look at low Q^2 – NC e^+p



Poor description at low Q^2 and $x < 10^{-4}$

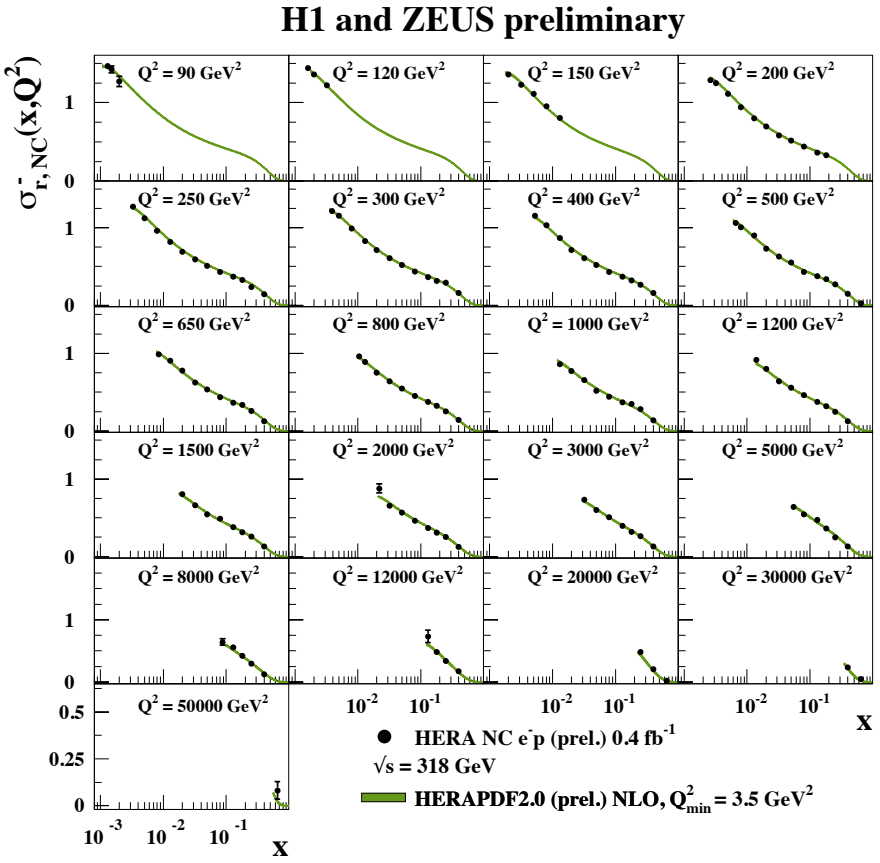
HERAPDF2.0



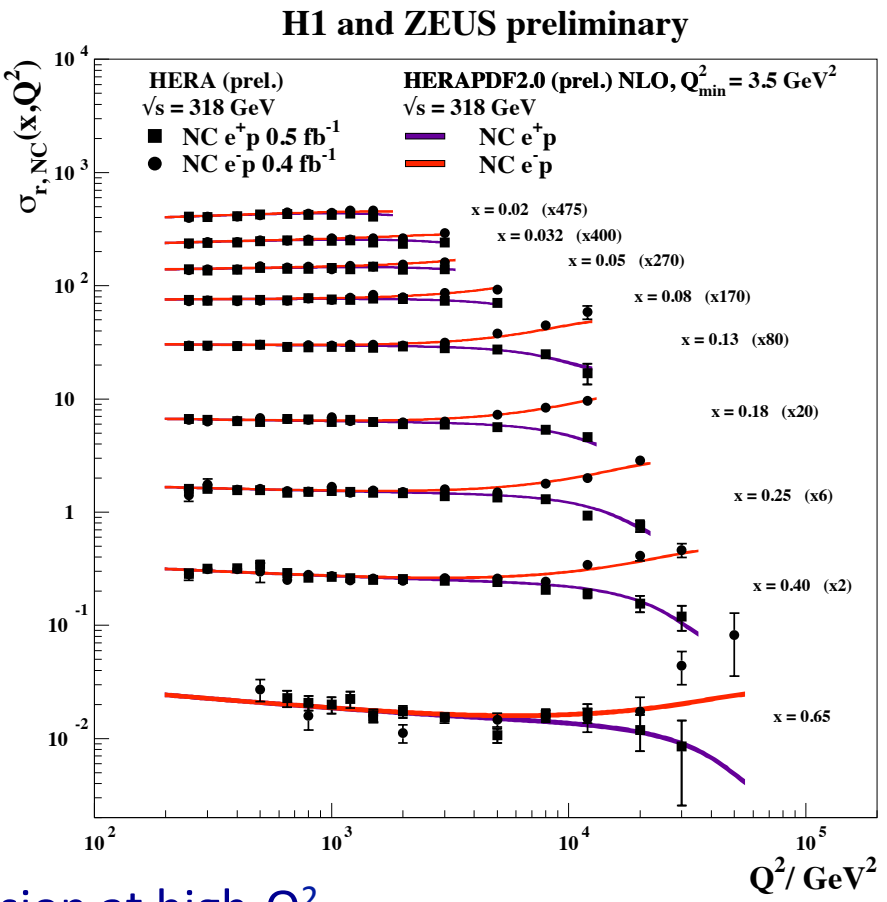
NC e^+p

HERAPDF2.0

NC e^-p reduced cross sections



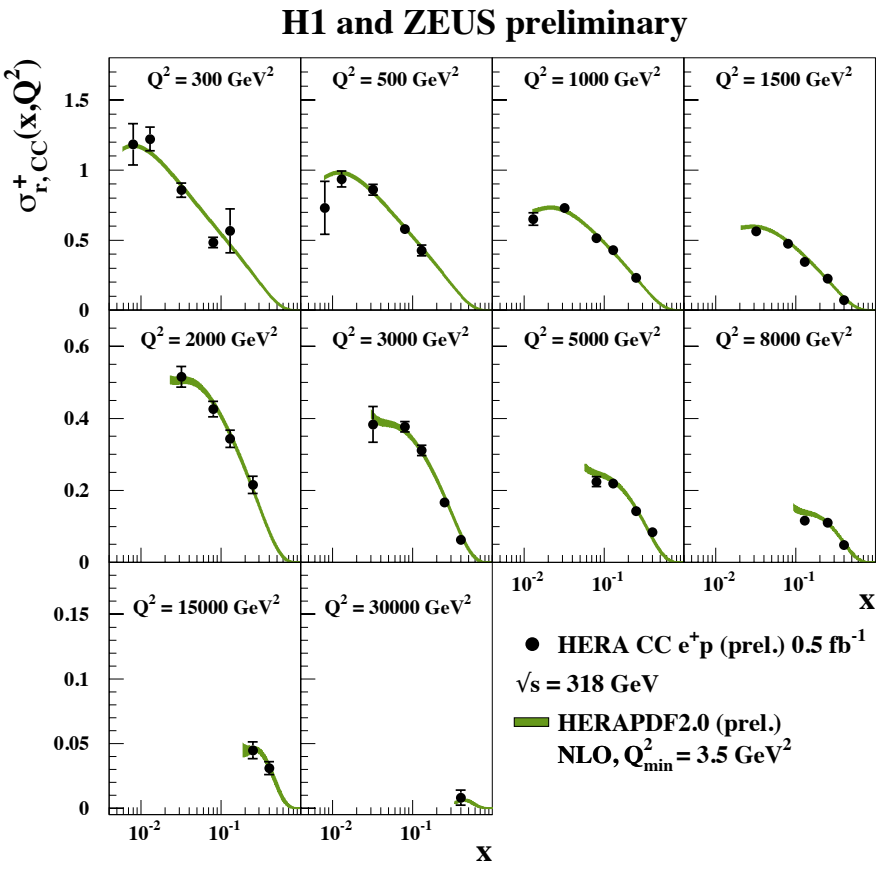
NC e^+p, e^-p comparison at High-Q^2

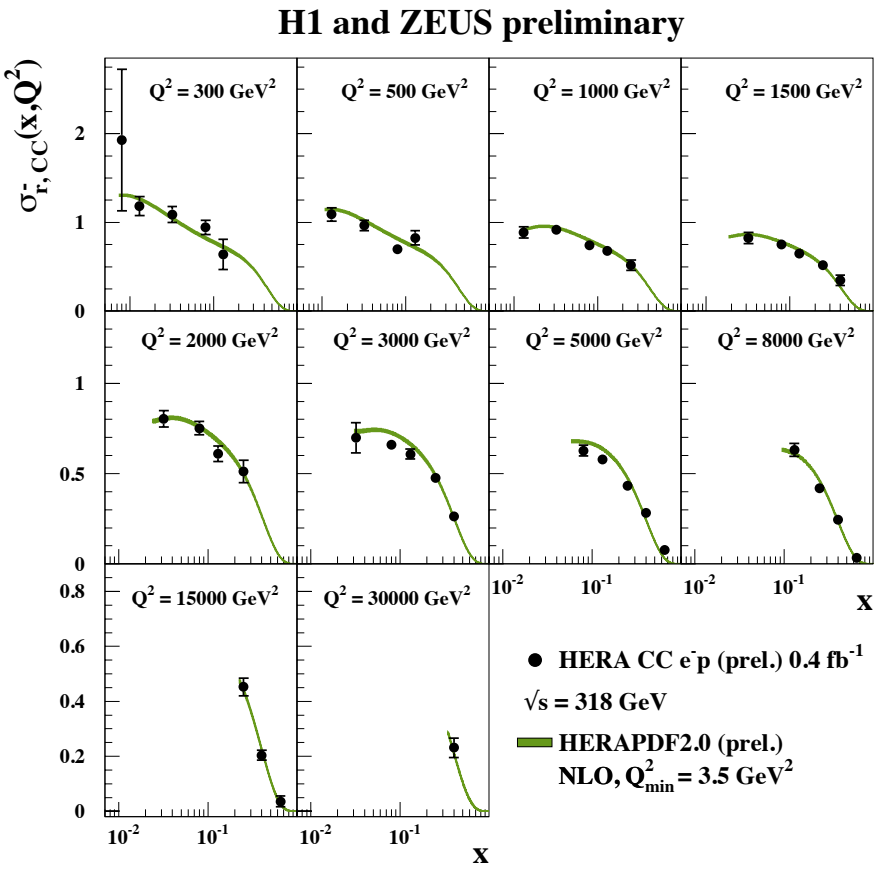


Increased precision at high-Q^2

HERAPDF2.0

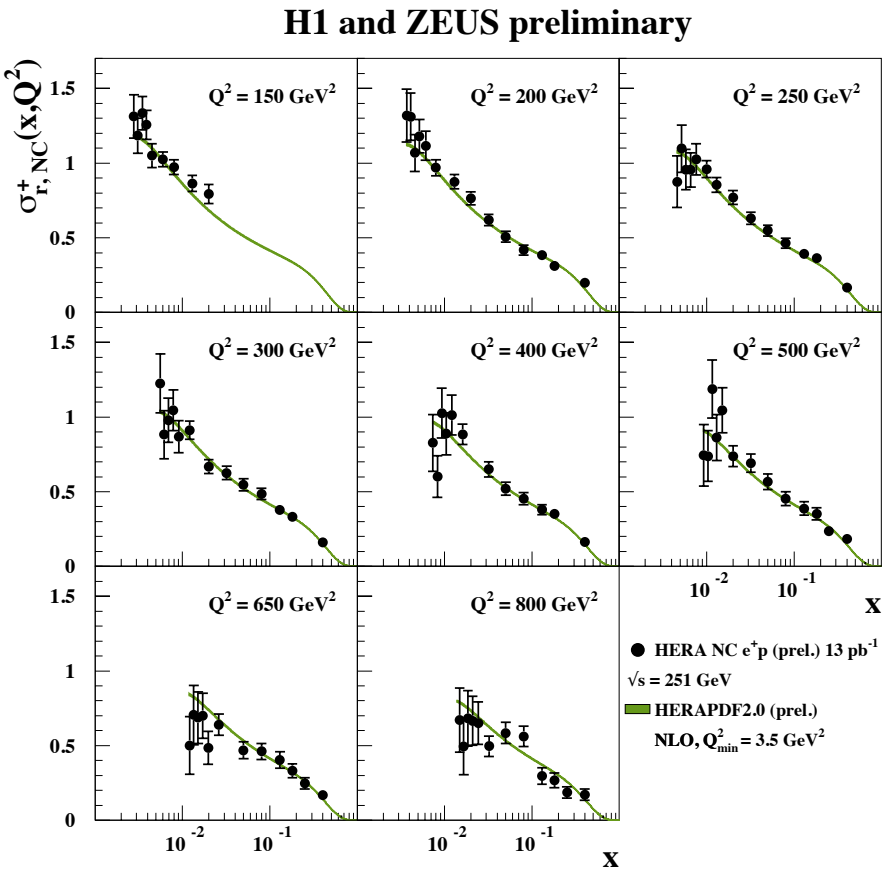
CC $e^{\pm}p$ reduced cross sections

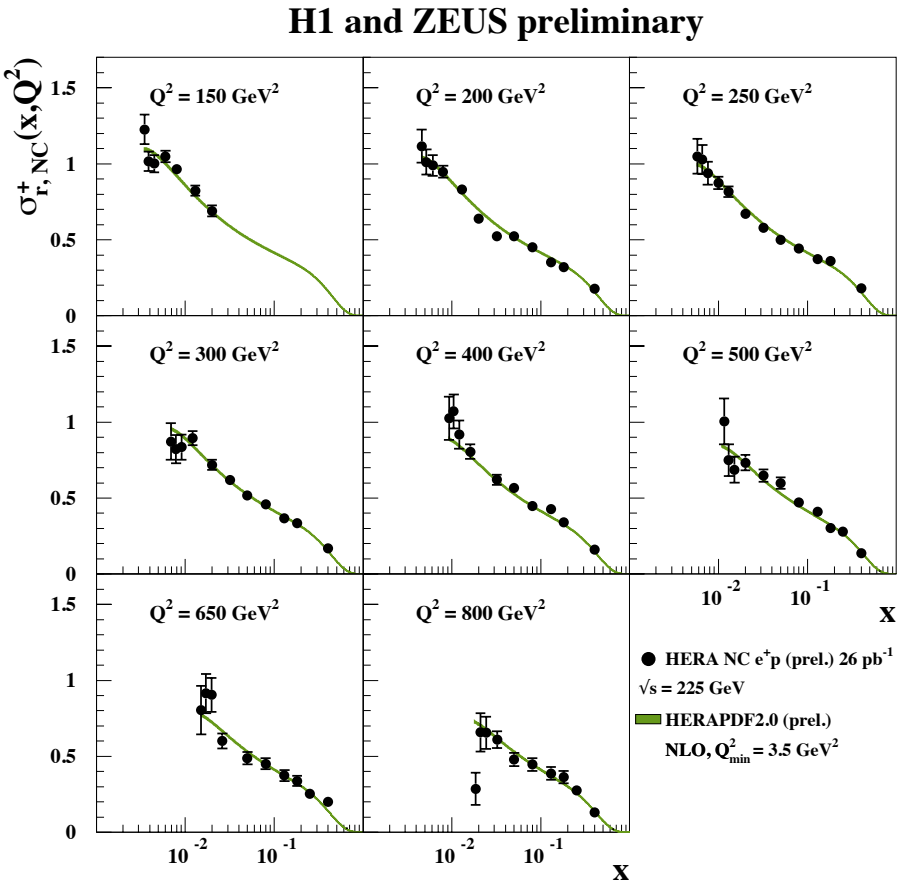




HERAPDF2.0

Low Ep reduced cross sections





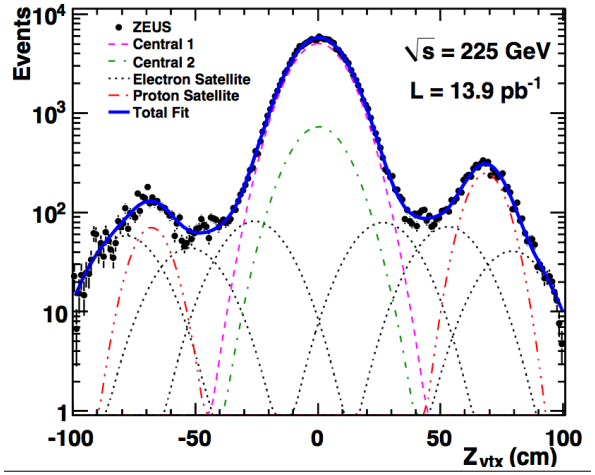
NC Cross sections at high-y (Ep=460,575 GeV)

Data Set		x Grid from	x Grid to	Q^2/GeV^2 Grid from	Q^2/GeV^2 Grid to	$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV	x,Q^2 from equations	Ref.
H1 NC high Q^2	07	0.00065	0.65	35	800	5.4	e^+p	252	11, 17	[8]
H1 NC low Q^2	07	0.0000279	0.0148	1.5	90	5.9	e^+p	252	11	[9]
ZEUS NC nominal	07	0.000147	0.013349	7	110	7.1	e^+p	251	11	[23]
ZEUS NC satellite	07	0.000125	0.013349	5	110	7.1	e^+p	251	11	[23]
HERA II E_p = 460 GeV data sets										
H1 NC high Q^2	07	0.00081	0.65	35	800	11.8	e^+p	225	11, 17	[8]
H1 NC low Q^2	07	0.0000348	0.0148	1.5	90	12.2	e^+p	225	11	[9]
ZEUS NC nominal	07	0.000184	0.016686	7	110	13.9	e^+p	225	11	[23]
ZEUS NC satellite	07	0.000143	0.016686	5	110	13.9	e^+p	225	11	[23]

Recent results:

H1: NC high-Q2: EPJ C74 (2014) 2814
(previously published NC low-Q2: EPJ C71(2011) 1579)

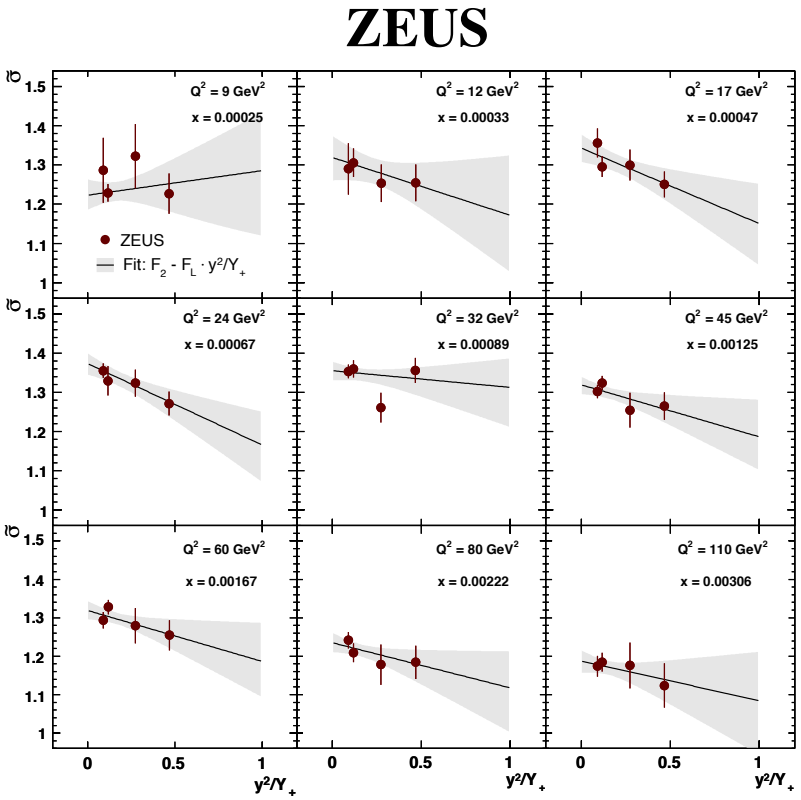
ZEUS: NC "nominal" and "satellite" DESY-14-053
(supersede results of PLB 682 (2009) 8)

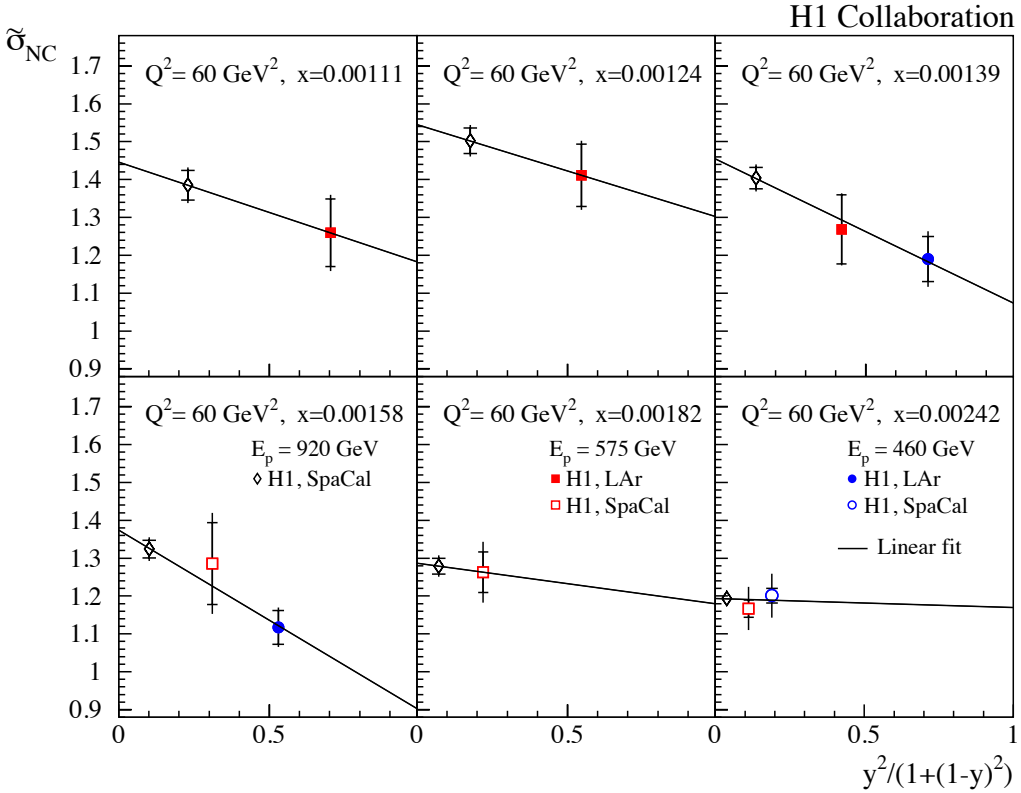


F_2 & F_L model independent extraction

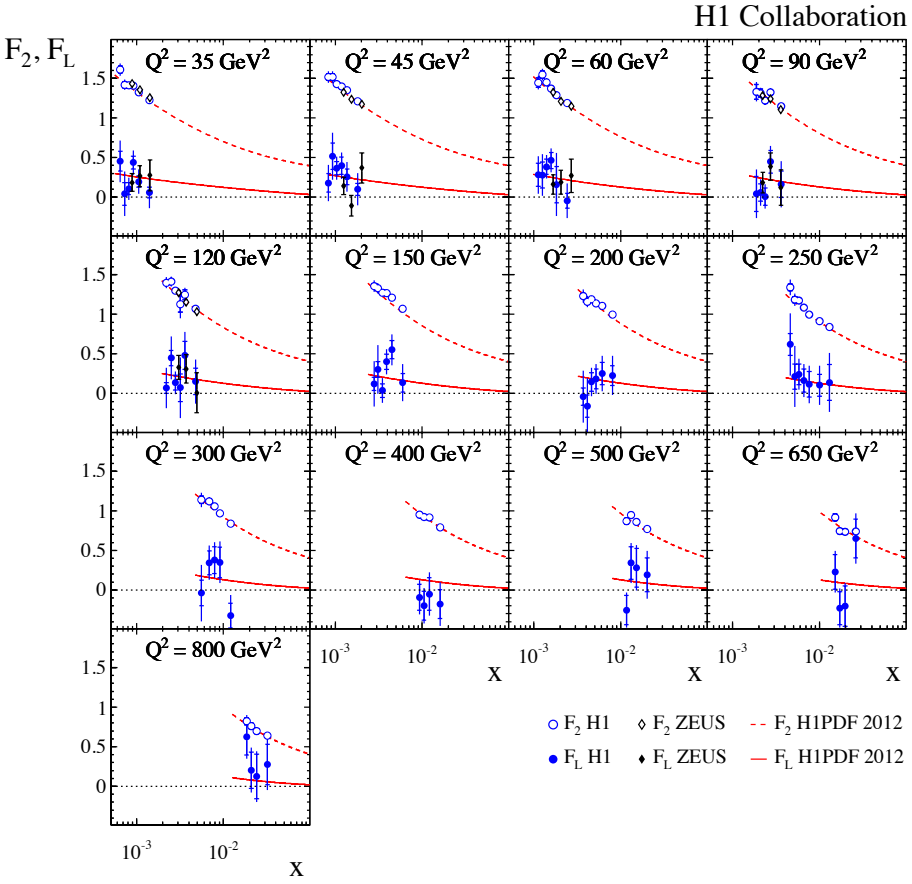
F_L and F_2 are simultaneously determined via a linear fit of $\sigma_{NC}(x,Q^2,y)$:

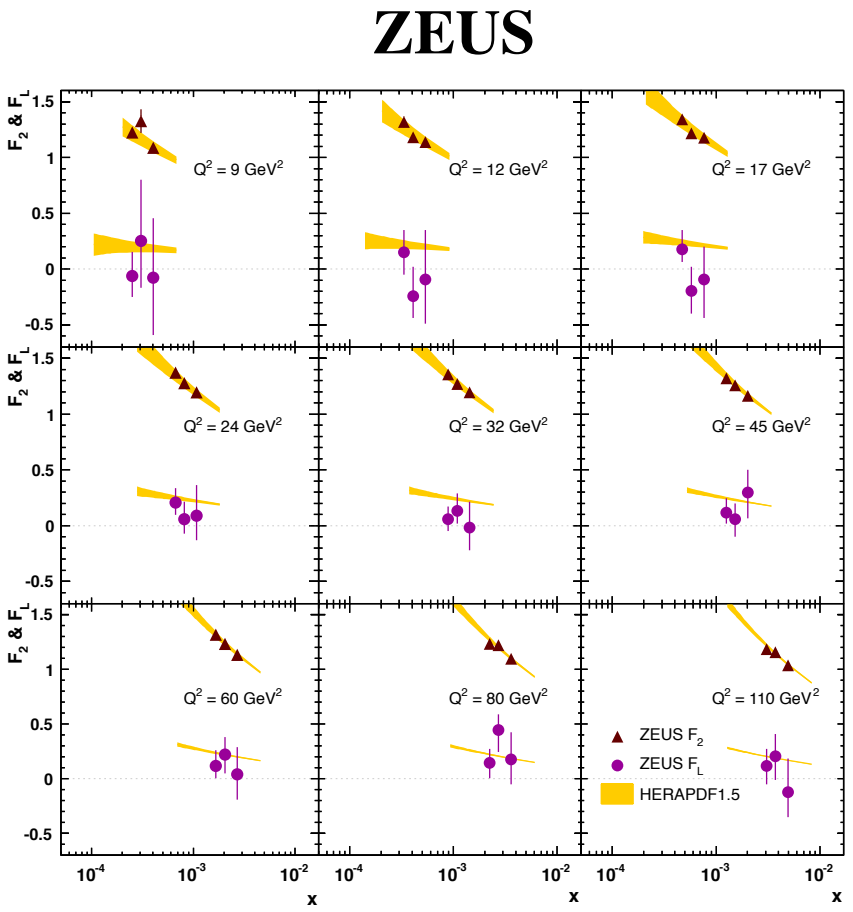
$$\sigma_{NC}(x,Q^2,y) = F_2(x,Q^2) - f(y)F_L(x,Q^2) \qquad \text{with} \qquad f(y) = \frac{y^2}{1+(1-y)^2}$$





Longitudinal Structure Function F_L

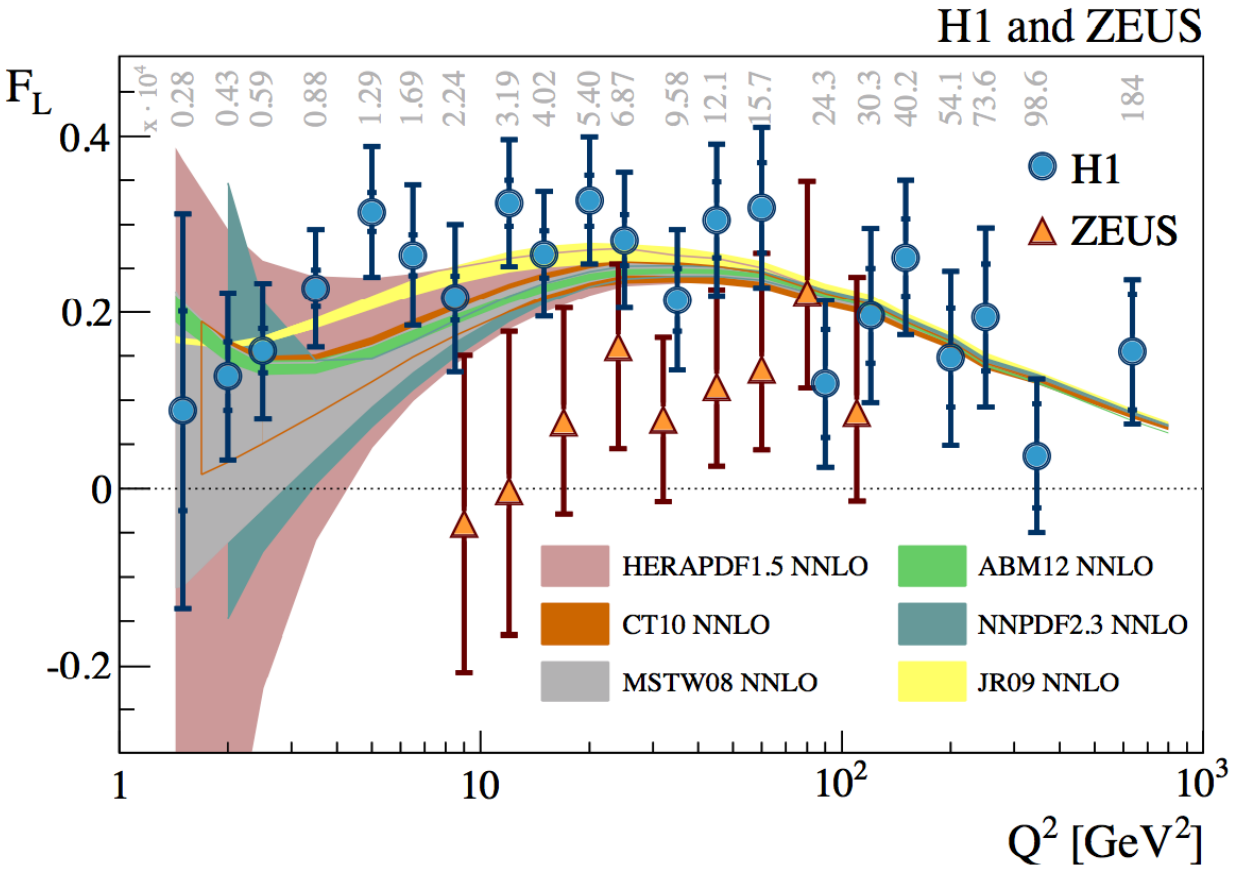




$35 < Q^2 < 800\ GeV^2$

$9 < Q^2 < 110\ GeV^2$

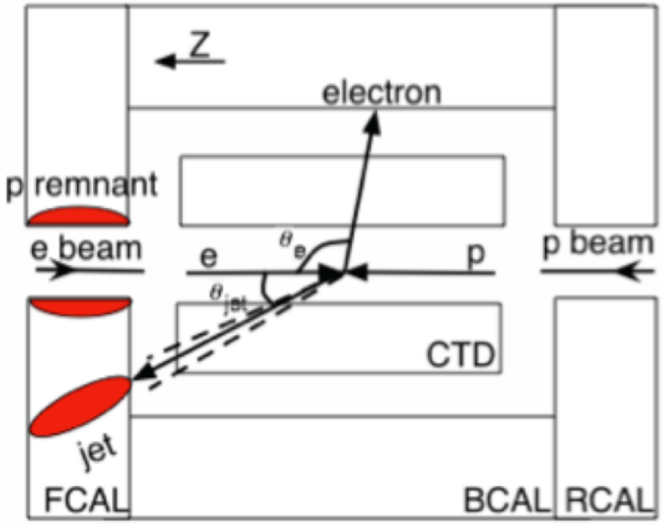
Longitudinal Structure Function F_L



- ZEUS measures smaller F_L in the mid-Q^2 region
- Consistency of H1 and ZEUS F_L results was checked accounting for corr. unc: χ^2/ndf = 11/8 (p-value = 20%)

NC $e^{\pm}p$ cross sections at high-x

NC events at high Q^2 have about 100% acceptance and efficiency for the scattered electron but at the highest x the hadronic final state disappears in the beam pipe and there are no means to measure x

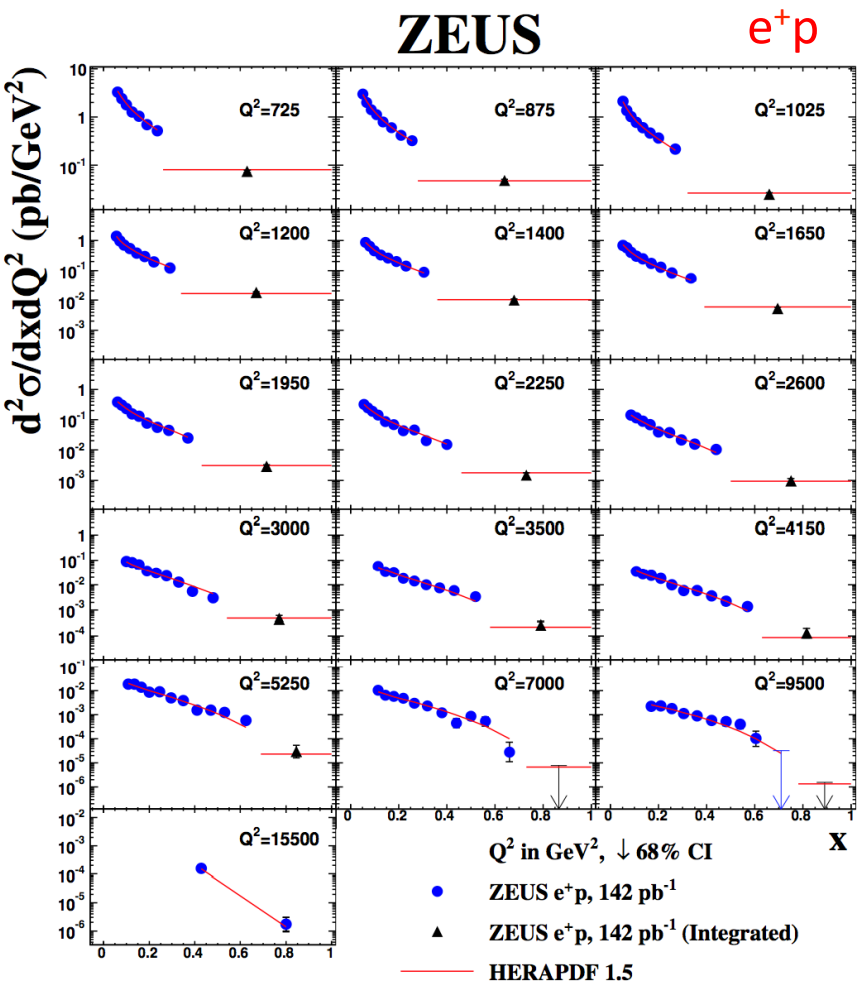


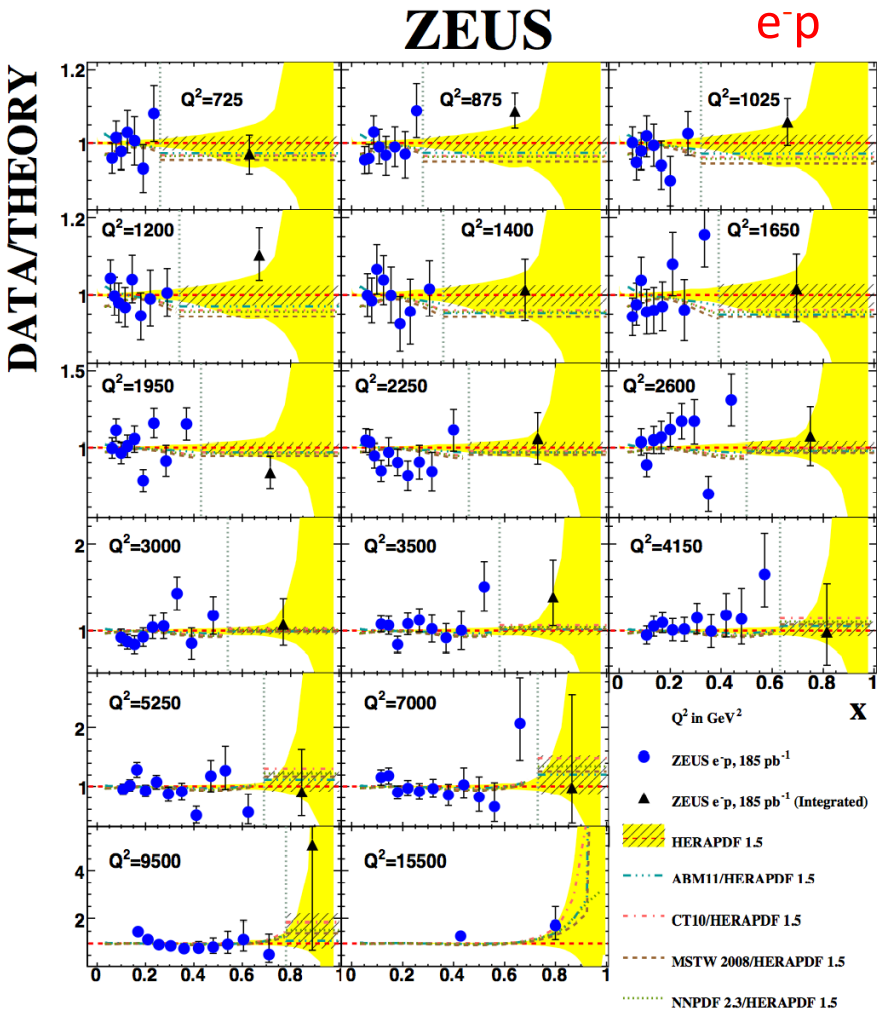
ZEUS exploited the jet originated by the struck-quark to measure the integrated $e^{\pm}p$ NC cross sections up to x=1 using events without jets for x above x_{edge}.

$$\frac{1}{1-x_{\mathrm{edge}}}\int_{x_{\mathrm{edge}}}^{1}\frac{d^2\sigma(x,Q^2)}{dxdQ^2}dx$$

PRD 89(2014) 072007

NC $e^{\pm}p$ cross sections at high-x





Expected increased sensitivity at high-x. Interesting to test impact in future fits.
(Note: this measurement is not included in the HERA combination)

Summary

HERA is our main source of information on proton structure.

The use of the final combination of the complete H1 and ZEUS inclusive measurements will allow to determine proton's PDFs 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 results to be published soon.

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