HERAPDF2.0 (prel.)

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On behalf of H1 and ZEUS

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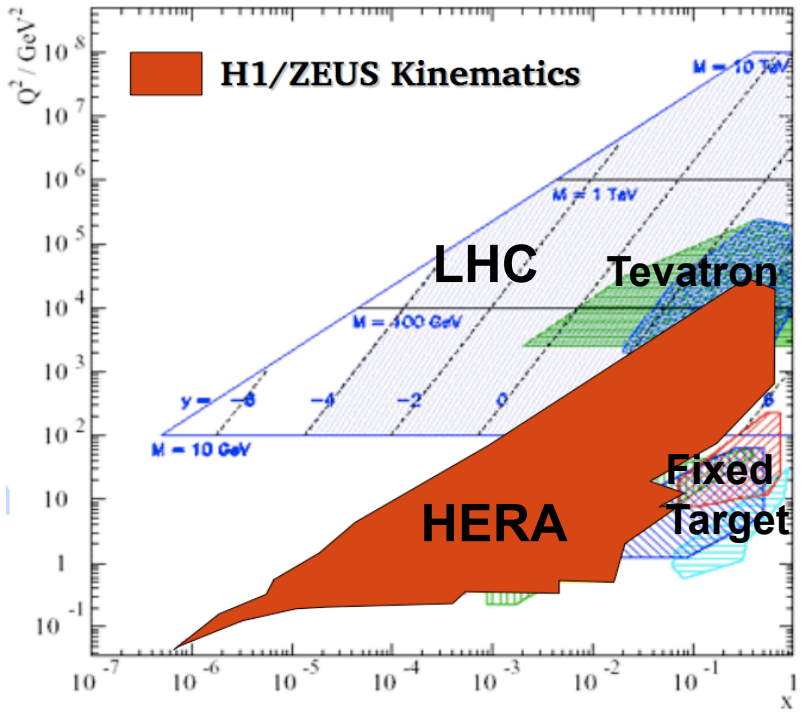
XXII. International Workshop on Deep-Inelastic Scattering and Related Subjects

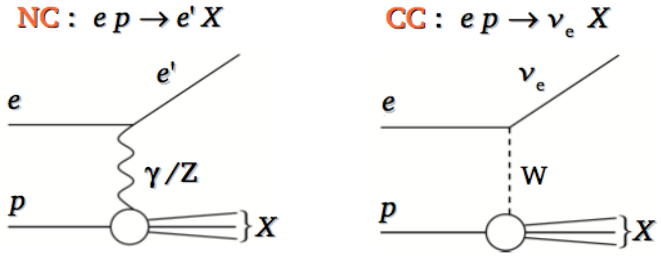
Outline:

- HERAPDF analysis framework
  - QCD settings
  - PDF uncertainties
- Results and Comparison
- Summary



HERA at DESY

- HERA was world's only $e^{\pm}p$ collider
  - located at DESY, Hamburg - Germany
    - In operation for 15 years (1992-2007)
  - H1 and ZEUS collider experiments
    - ~1fb^{-1} of integrated luminosity of physics data.
- HERA provides unique opportunity to study the structure of the proton via DIS processes:



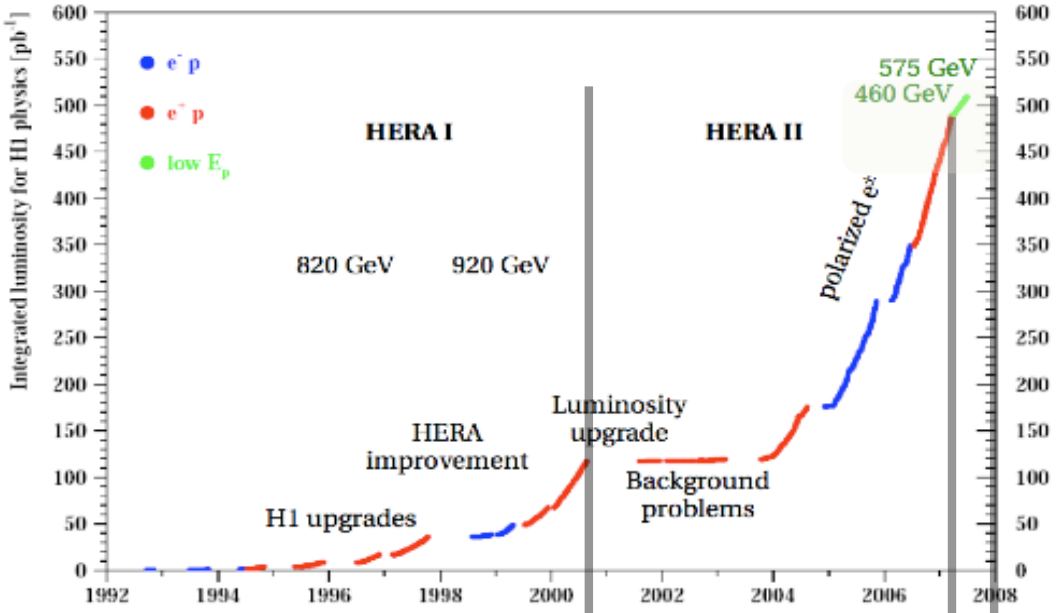
o Kinematic variables:

oVirtuality of exchanged boson: $Q^2 = -q^2 = -(k-k')^2$

oBjorken scaling variable: $x = \frac{Q^2}{2p \cdot q}$

oInelasticity: $y = \frac{p \cdot q}{p \cdot k}$

oInvariant centre of masss: $s = (k+p)^2 = \frac{Q^2}{xy}$



HERA-I	1992-2000	Ep=820,920 GeV	L~0.1/fb per exp.
HERA-II	2003-2007	Ep=920, 460,575 GeV	L~0.4/fb per exp.

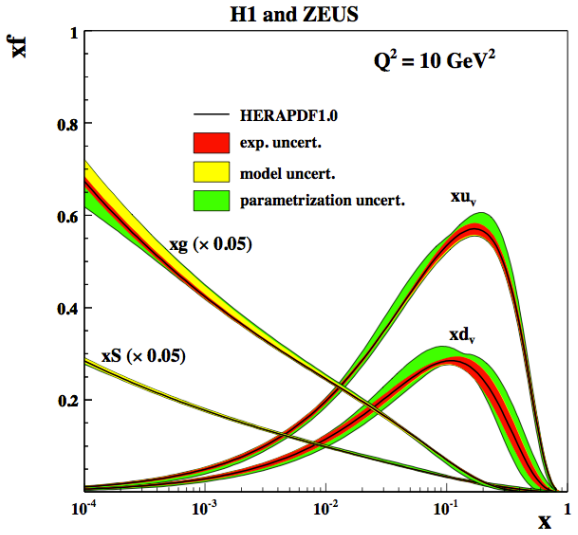
HERAPDF1.0

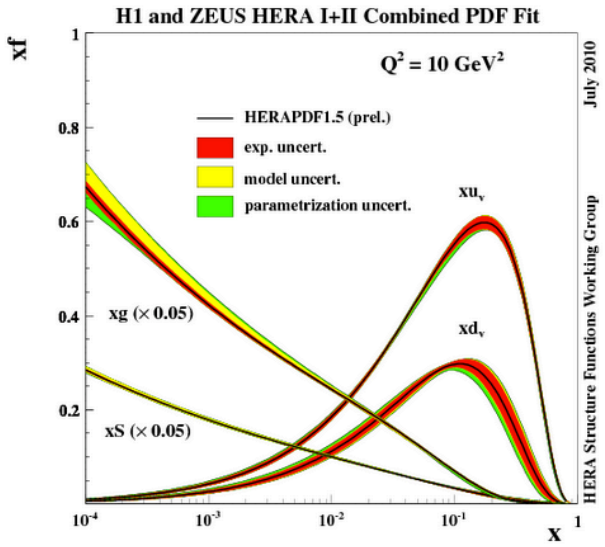
HERAPDF1.5prel [see Mandy's talk]

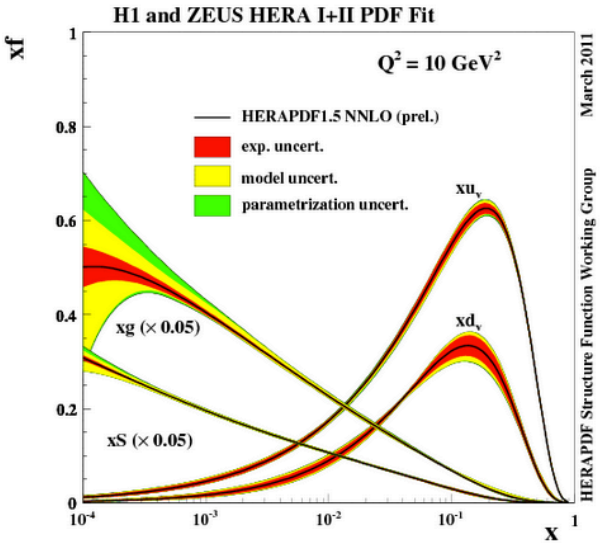
HERAPDF2.0prel → THIS TALK

Reminder of PDF sets from HERA

- **Released to LHAPDF:**
  - HERAPDF1.0 NLO: based on published HERA I data (with All Uncertainties) [JHEP01 (2010) 109]
  - HERAPDF1.5 NLO: based on preliminary HERA I+II data (with All Uncertainties) RECOMMENDED
  - HERAPDF1.5 NNLO: based on preliminary HERA I+II data (with All Uncertainties) RECOMMENDED
  - HERAPDF1.5 LO → see Mandy's talk







- **Not released to LHAPDF:**
  - HERAPDF1.0 NNLO: based on published HERA I data (2 central lines with different alphas)
  - HERAPDF1.6 NLO: based on preliminary HERA I+II and inclusive jets
  - HERAPDF1.7 NLO: : based on preliminary HERA I+II, inclusive jets, charm, low energy runs

New Data Combination from HERA

- New combination of HERA data using full set of inclusive measurements

[see O. Turkot's talk]

H1-prelim-14-042
ZEUS-prel-14-007

7 data sets with 165 sources of uncertainties

HERAPDF1.0

HERAPDF1.5

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
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
H1 low Q^2	96-00	0.0002	0.1	12	150	22	e^+p	301, 319
H1 NC	94-97	0.0032	0.65	150	30000	35.6	e^+p	301
H1 CC	94-97	0.013	0.40	300	15000	35.6	e^+p	301
H1 NC	98-99	0.0032	0.65	150	30000	16.4	e^-p	319
H1 CC	98-99	0.013	0.40	300	15000	16.4	e^-p	319
H1 NC HY	98-99	0.0013	0.01	100	800	16.4	e^-p	319
H1 NC	99-00	0.0013	0.65	100	30000	65.2	e^+p	319
H1 CC	99-00	0.013	0.40	300	15000	65.2	e^+p	319
ZEUS BPC	95	0.000002	0.00006	0.11	0.65	1.65	e^+p	300
ZEUS BPT	97	0.0000006	0.001	0.045	0.65	3.9	e^+p	300
ZEUS SVX	95	0.000012	0.0019	0.6	17	0.2	e^+p	300
ZEUS NC	96-97	0.00006	0.65	2.7	30000	30.0	e^+p	300
ZEUS CC	94-97	0.015	0.42	280	17000	47.7	e^+p	300
ZEUS NC	98-99	0.005	0.65	200	30000	15.9	e^-p	318
ZEUS CC	98-99	0.015	0.42	280	30000	16.4	e^-p	318
ZEUS NC	99-00	0.005	0.65	200	30000	63.2	e^+p	318
ZEUS CC	99-00	0.008	0.42	280	17000	60.9	e^+p	318
HERA II E_p = 920 GeV data sets								
H1 NC	03-07	0.0008	0.65	60	30000	182	e^+p	319
H1 CC	03-07	0.008	0.40	300	15000	182	e^+p	319
H1 NC	03-07	0.0008	0.65	60	50000	151.7	e^-p	319
H1 CC	03-07	0.008	0.40	300	30000	151.7	e^-p	319
H1 NC med Q^2 *y.5	03-07	0.0000986	0.005	8.5	90	182	e^+p	319
H1 NC low Q^2 *y.5	03-07	0.000029	0.00032	2.5	12	182	e^+p	319
ZEUS NC	06-07	0.005	0.65	200	30000	135.5	e^+p	318
ZEUS CC	06-07	0.0078	0.42	280	30000	132	e^+p	318
ZEUS NC	05-06	0.005	0.65	200	30000	169.9	e^-p	318
ZEUS CC	04-06	0.015	0.65	280	30000	175	e^-p	318
ZEUS NC nominal *y	06-07	0.000092	0.008343	7	110	44.5	e^+p	318
ZEUS NC satellite *y	06-07	0.000071	0.008343	5	110	44.5	e^+p	318
HERA II E_p = 575 GeV data sets								
H1 NC high Q^2	07	0.00065	0.65	35	800	17.2	e^+p	252
H1 NC low Q^2	07	0.0000279	0.0148	1.5	90	5.9	e^+p	252
ZEUS NC nominal	07	0.000147	0.013349	7	110	7.1	e^+p	251
ZEUS NC satellite	07	0.000125	0.013349	5	110	7.1	e^+p	251
HERA II E_p = 460 GeV data sets								
H1 NC high Q^2	07	0.00081	0.65	35	800	17.2	e^+p	225
H1 NC low Q^2	07	0.0000348	0.0148	1.5	90	12.2	e^+p	225
ZEUS NC nominal	07	0.000184	0.016686	7	110	13.9	e^+p	225
ZEUS NC satellite	07	0.000143	0.016686	5	110	13.9	e^+p	225

41 input files

```
HERA CC e+p 101 (920)
HERA CC e-p 102 (920)
HERA NC e-p 103 (920)
HERA NC e+p 104 (820)
HERA NC e+p 105 (920)
HERA NC e+p 106 (460)
HERA NC e+p 107 (575)
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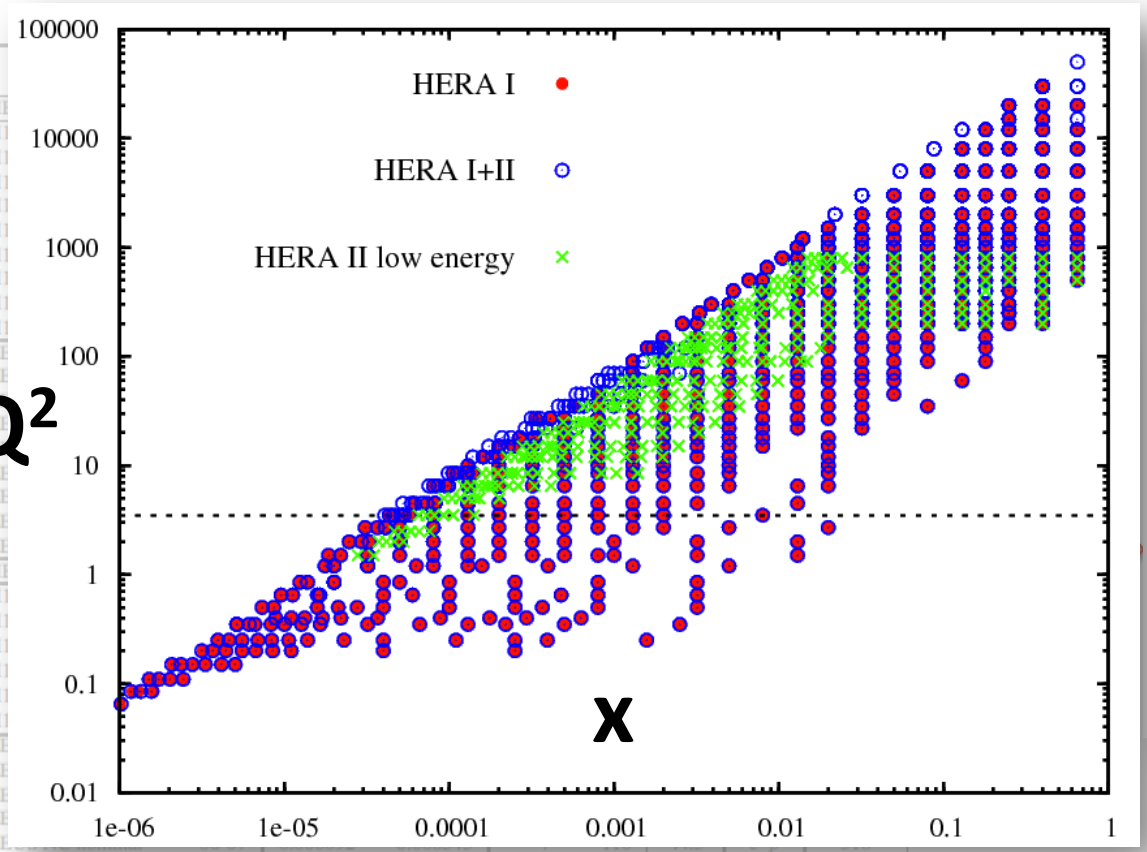
The preliminary HERA I+II combination is used as sole input in QCD fit platform to determine HERAPDF2.0

New Data Combination from HERA

- New combination of HERA data using the full set of inclusive measurements



sets with 165 sources of uncertainties

```
HERA CC e+p 101 (920)
HERA CC e-p 102 (920)
HERA NC e-p 103 (920)
HERA NC e+p 104 (820)
HERA NC e+p 105 (920)
HERA NC e+p 106 (460)
HERA NC e+p 107 (575)
```

The preliminary HERA I+II combination is used as a sole input in QCD fit platform to determine HERAPDF2.0 (prel)

High Q^2 NC Cross Sections

Neutral Current:

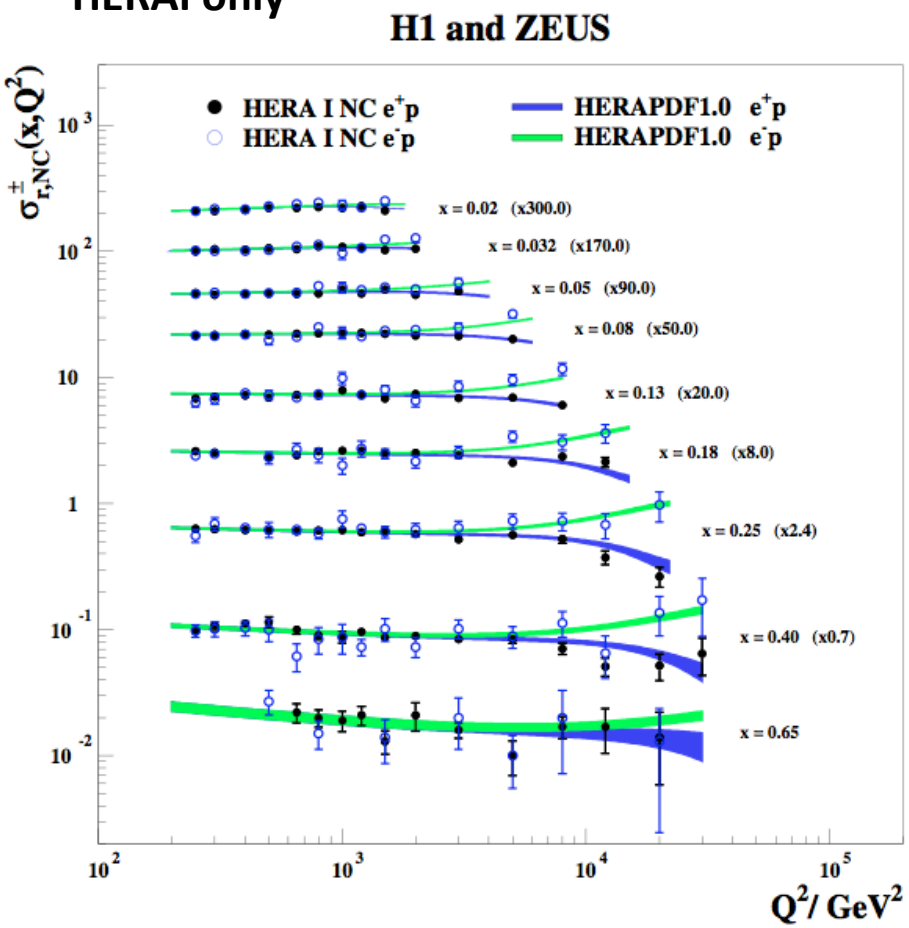
$$\sigma_r(x,Q^2) = \frac{d^2\sigma(e^{\pm}p)}{dxdQ^2}\frac{Q^4x}{2\pi\alpha^2 Y_+} = F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3(x,Q^2)$$

At High Q^2 ⇒interference term Zγ → xF3

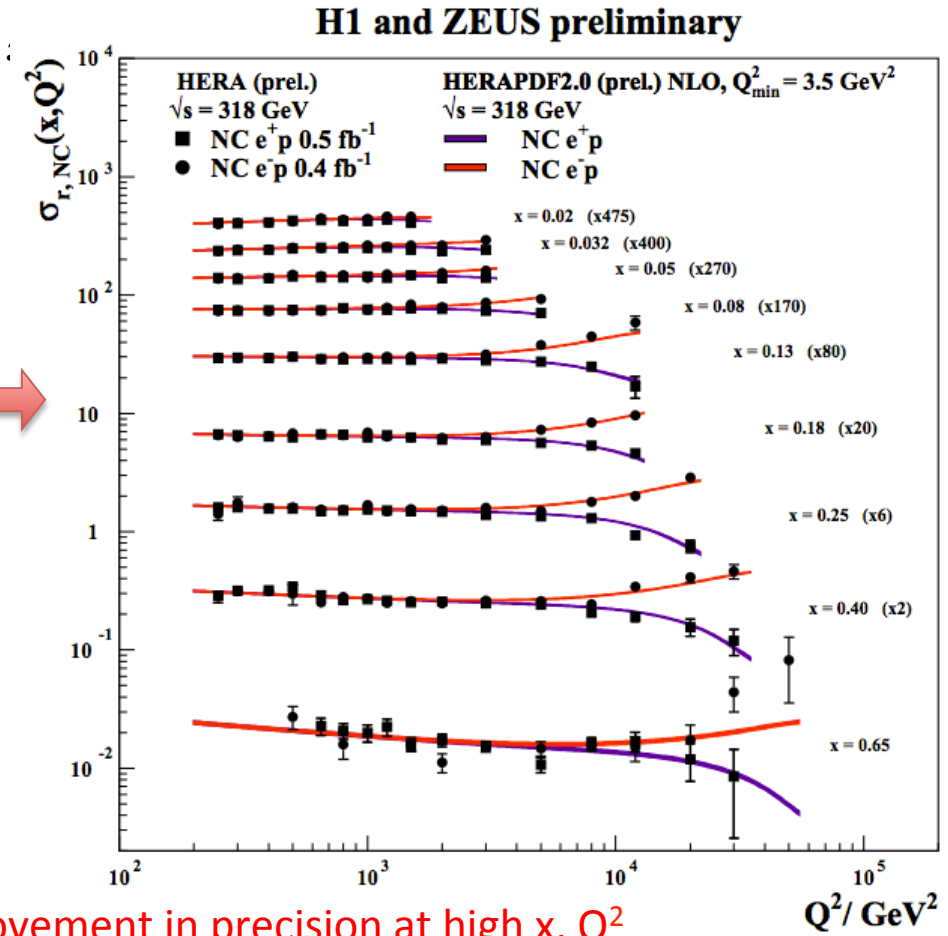
$$Y_{\pm} = 1 \pm (1-y^2)$$

$$NC: \; e\,p \rightarrow e'\,X$$

HERAI only



New HERAI+II



Larger HERA II luminosity yields in significant improvement in precision at high x, Q^2

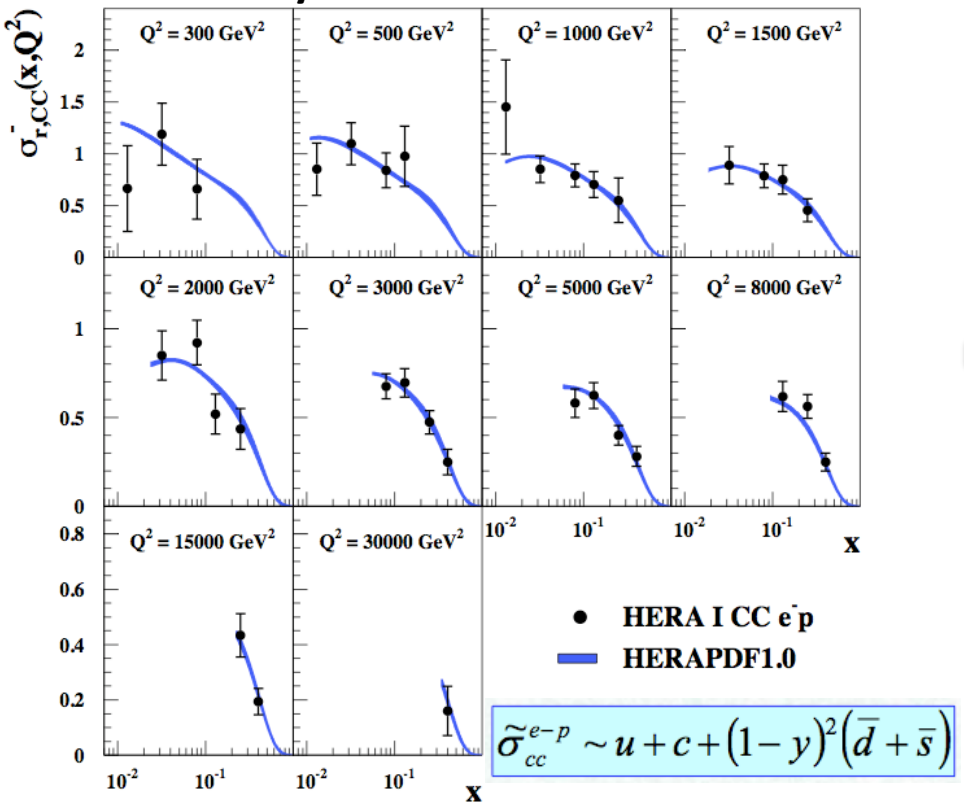
High Q^2 CC cross sections

Charged Current: provides important flavour decomposition

e-p: $$\frac{d^2\sigma^-_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[u + c + (1-y)^2(\bar{d}+\bar{s})\right]$$

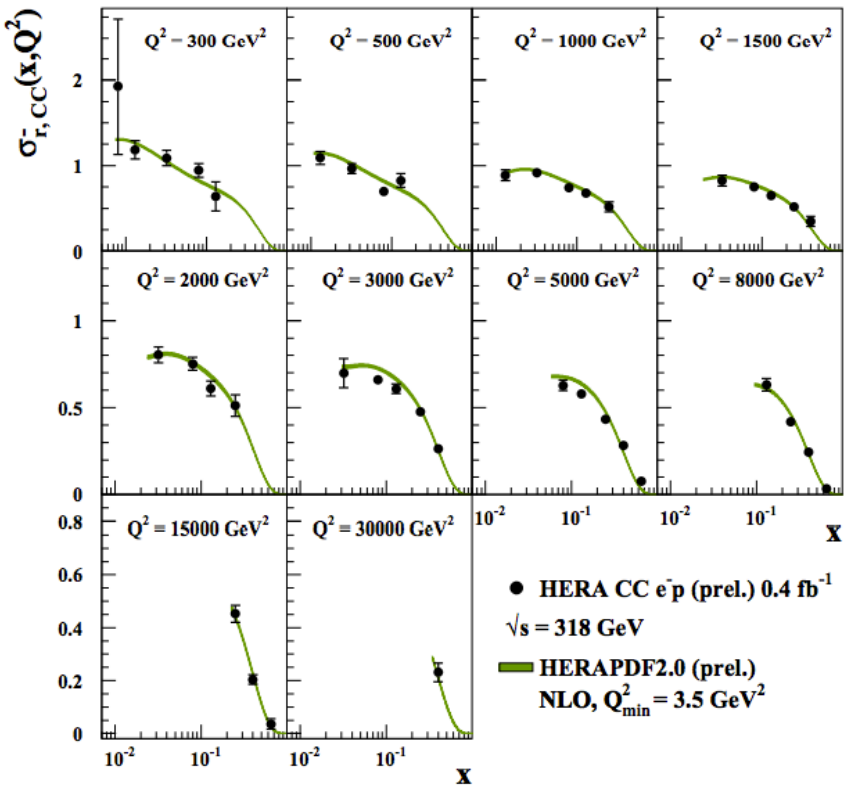
e+p: $$\frac{d^2\sigma^+_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[\bar{u} + \bar{c} + (1-y)^2(d+s)\right]$$

HERAI only H1 and ZEUS



$$\tilde{\sigma}^{e-p}_{cc} \sim u + c + (1-y)^2(\bar{d}+\bar{s})$$

New HERAI+II H1 and ZEUS preliminary



Much more precise CC measurements after including new high Q^2 HERA II set!

QCD Settings for HERAPDF2.0

- The QCD settings are optimised for HERA measurements of proton structure functions (dominated by gamma exchange)

$$F_2(x,Q^2) = \tfrac{4}{9}(xU + x\overline{U}) + \tfrac{1}{9}(xD + x\overline{D})$$

- PDFs are parametrised at the starting scale Q_0^2=1.9 GeV^2 as follows:

$$\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g},\\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + D_{u_v}x + E_{u_v}x^2\right),\\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},\\
x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}}(1-x)^{C_{\overline{U}}}\left(1 + D_{\overline{U}}x\right),\\
x\overline{D}(x) &= A_{\overline{D}} x^{B_{\overline{D}}}(1-x)^{C_{\overline{D}}}.
\end{aligned}$$

QCD Sum rules constrain Normalisation parameters: A_g, A_{u_v}, A_{d_v}
And the condition that:

$$x\overline{u} \to x\overline{d} \text{ as } x \to 0.$$

relate $A_{\overline{U}}$ to $A_{\overline{D}}$, and with $x\overline{s} = f_s x\overline{D}$

  - **Due to increased precision of data, more flexibility in functional form is allowed → 15 free parameters**
- PDFs are evolved via evolution equations (DGLAP) to NLO and NNLO (alphas(MZ)=0.118)[QCDNUM]
- Thorne-Roberts GM-VFNS for heavy quark coefficient functions – as used in MSTW
- Chi2 definition used in the minimisation [MINUIT] accounts for correlated uncertainties:

$$\chi^2 = \sum_i \frac{\left[\mu_i - m_i\left(1 - \sum_j \gamma_j^i b_j\right)\right]^2}{\delta_{i,\mathrm{unc}}^2 m_i^2 + \delta_{i,\mathrm{stat}}^2 \mu_i m_i \left(1 - \sum_j \gamma_j^i b_j\right)} + \sum_j b_j^2 + \sum_i \ln \frac{\delta_{i,\mathrm{unc}}^2 m_i^2 + \delta_{i,\mathrm{stat}}^2 \mu_i m_i}{\delta_{i,\mathrm{unc}}^2 \mu_i^2 + \delta_{i,\mathrm{stat}}^2 \mu_i^2}$$

m_i is the theoretical prediction
μ_i is the measured cross section

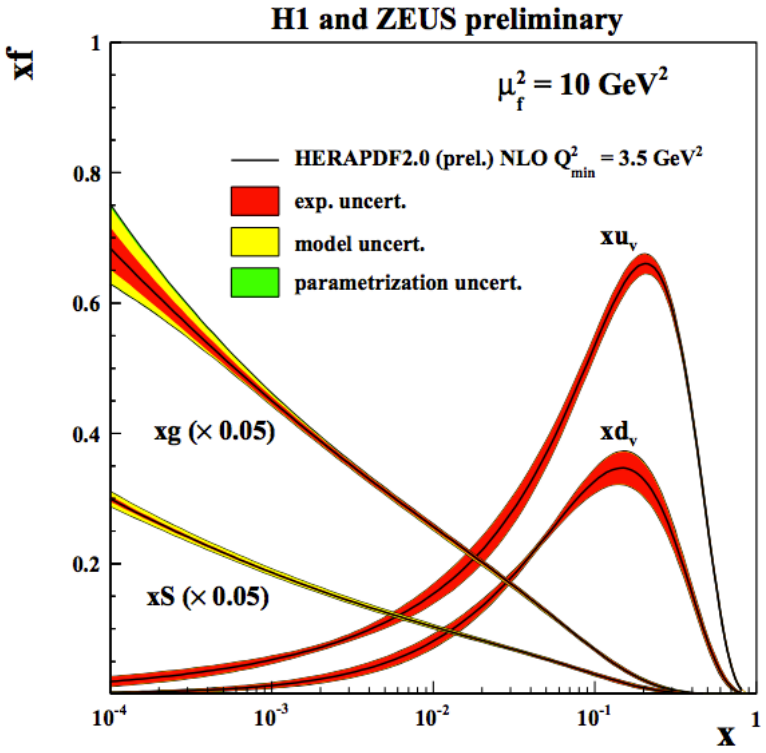
$\delta_{i,\mathrm{stat}}$, $\delta_{i,\mathrm{unc}}$ statistical and uncorrelated systematic uncertainty
γ_j^i correlated systematic uncertainties
b_j shifts

Sources of HERAPDF uncertainties

- **Experimental:**
  - Hessian method is used to evaluate experimental uncertainties
  - Consistent data sets → use $\Delta\chi^2=1$

- **Model:**
  - Following variations have been considered

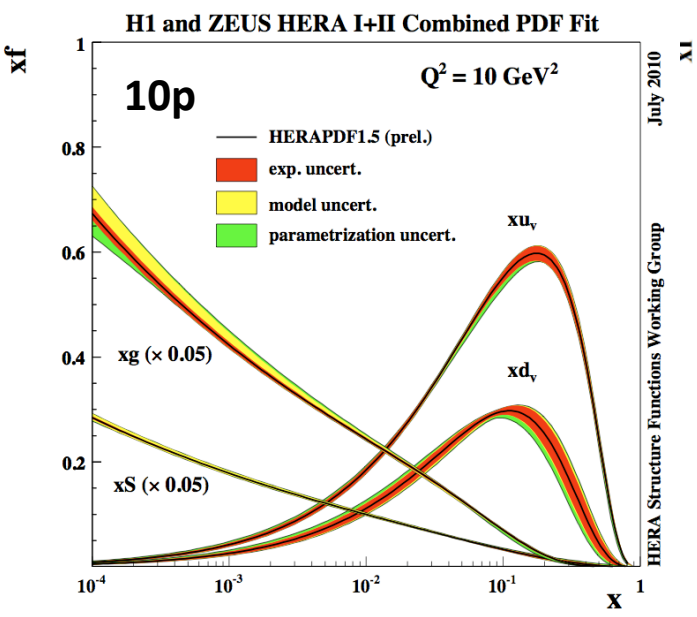
Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.4	0.3	0.5
M_c^{opt}(NLO) [GeV]	1.47	1.41	1.53
M_c^{opt} (NNLO) [GeV]	1.44	1.38	1.50
M_b [GeV]	4.75	4.5	5.0
Q^2_{min} [GeV^2]	10.0	7.5	12.5
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_0 [GeV^2]	1.9	1.6	2.2



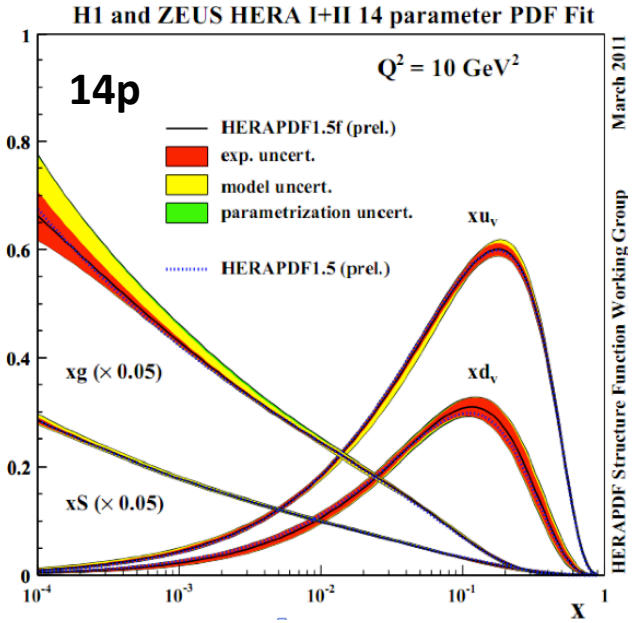
- **Parametrisation:**
  - An envelope is formed from PDF fits using variants of parametrisation form
    - Scanning of 16 parameter space with D or E as extra parameters of $(1 + Dx + Ex^2)$
    - Q_0^2 variation → dominant parametrisation uncertainty

HERAPDF1.5 vs HERAPDF2.0 with Q^2_{min}= 3.5 GeV^2

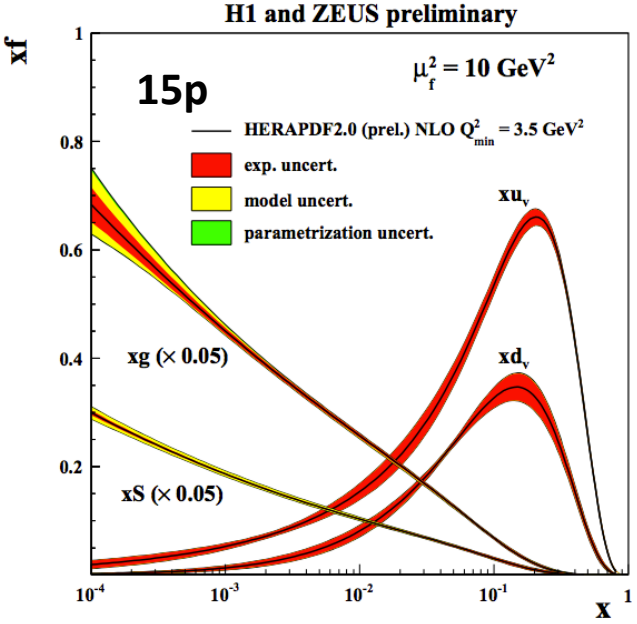
HERAPDF1.5-NLO(10p) → HERAPDF1.5-NLOf(14p) → HERAPDF2.0-NLO (15p)



We started with similar settings as used for HERAPDF1.0 (10 free parameters)



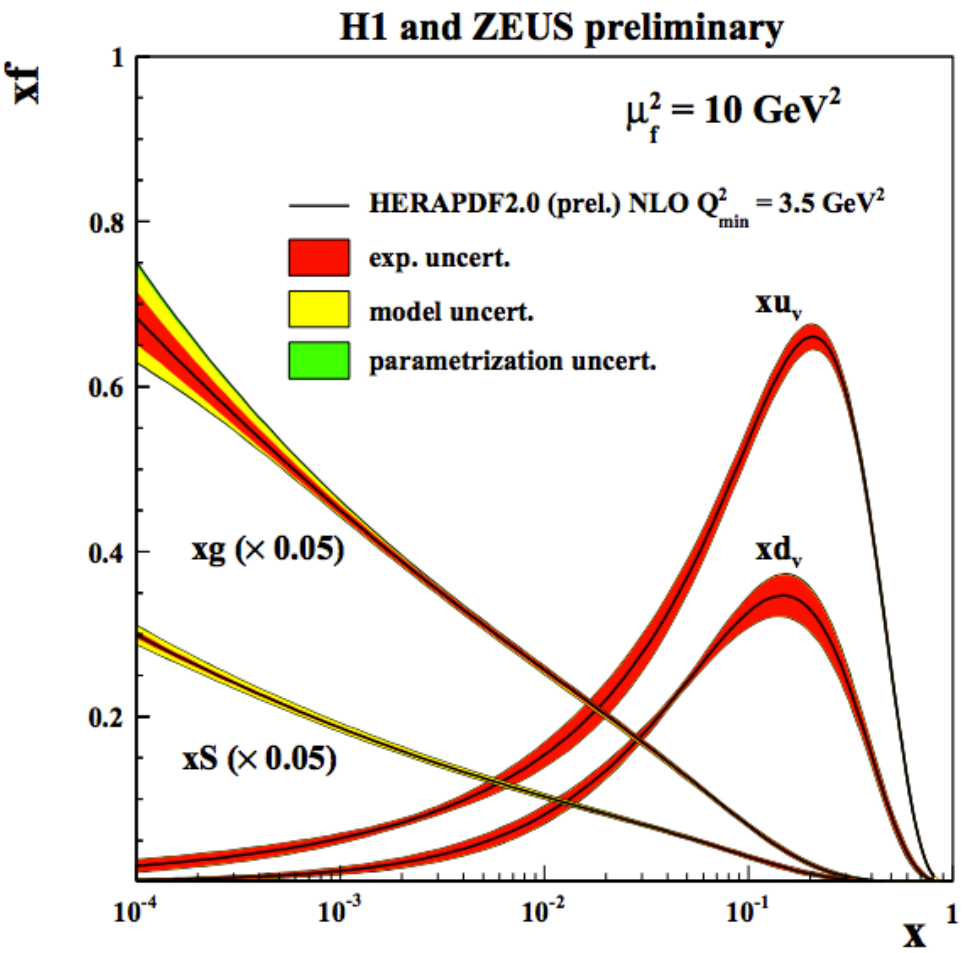
preliminary HERA II data
Required additional flexibility (14 free parameters)



New HERAI+II combiation (15 free parameters)

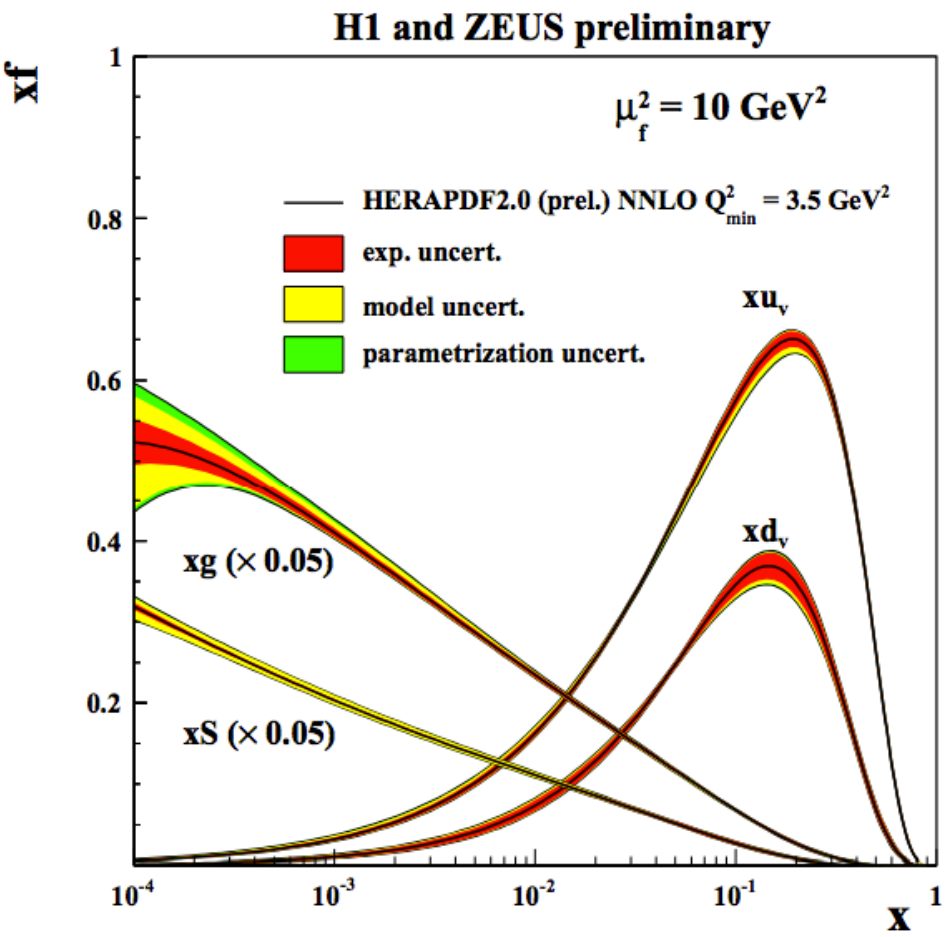
HERAPDF2.0 with Q^2_{min}= 3.5 GeV^2 NLO vs NNLO

At NLO



Chi2/dof = 1386/1130

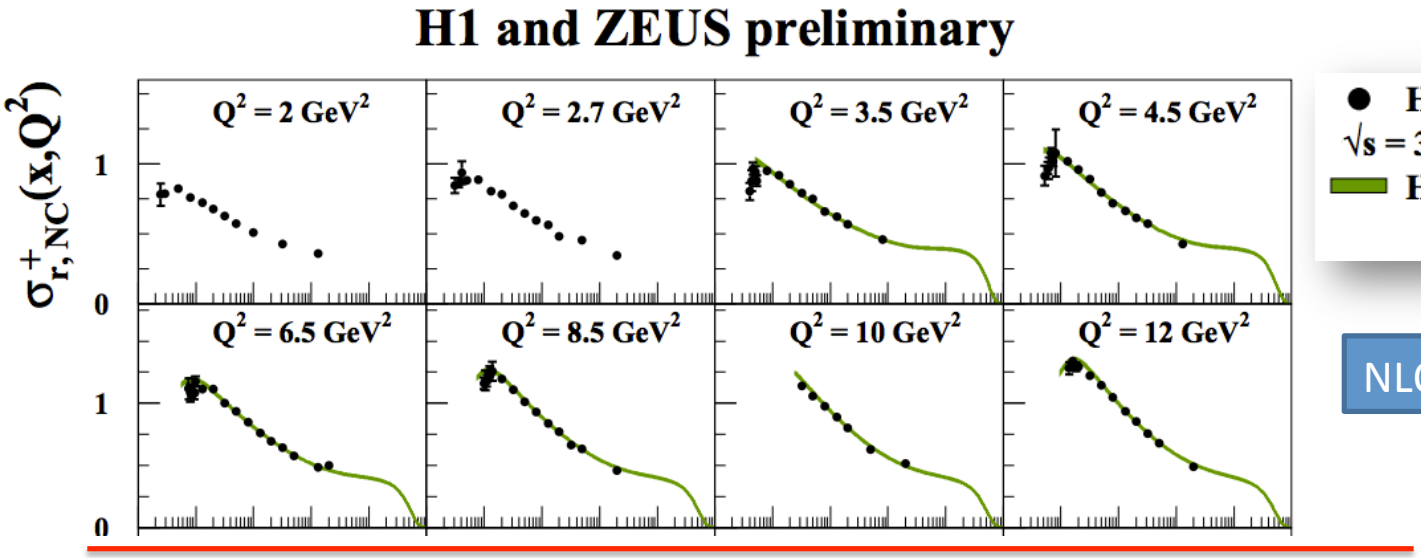
At NNLO



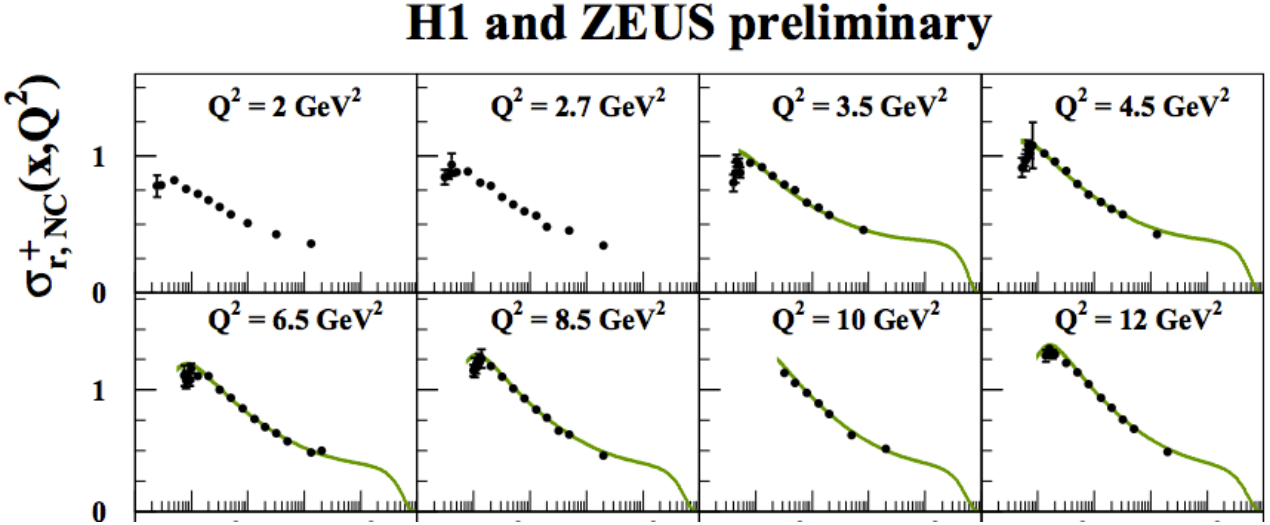
Chi2/dof = 1414/1130

Low Q^2 Data vs HERAPDF2.0 (Q^2_{min}=3.5 GeV^2)

- How does fit at NLO and NNLO describe the low Q^2 data?



NLO Fit

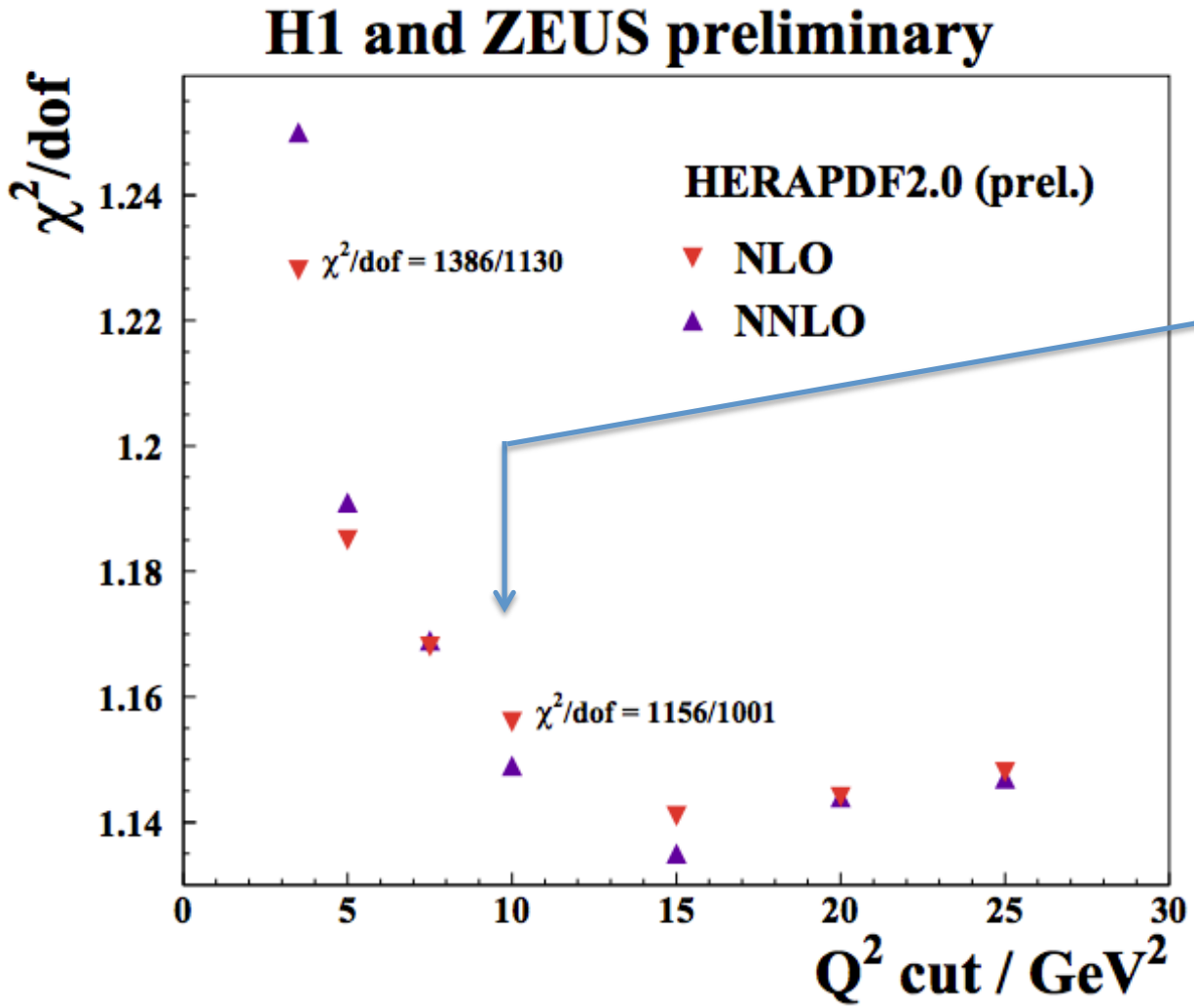


NNLO Fit

Going to higher orders does not improve data description at low-Q^2, low-x

Q^2 cut dependence on fit results

- The Q^2 cut dependence on the fit is already included in the model variation for the HERAPDF sets, however usually we look at small range in cuts when assessing an uncertainty to Q^2_{min} choice.



At Q^2_{min}= 10 is when the fit stabilises with respect of chi2/dof vs Q^2cut

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

Chi2/dof (NLO) = 1386/1130

Chi2/dof(NNLO)= 1414/1130

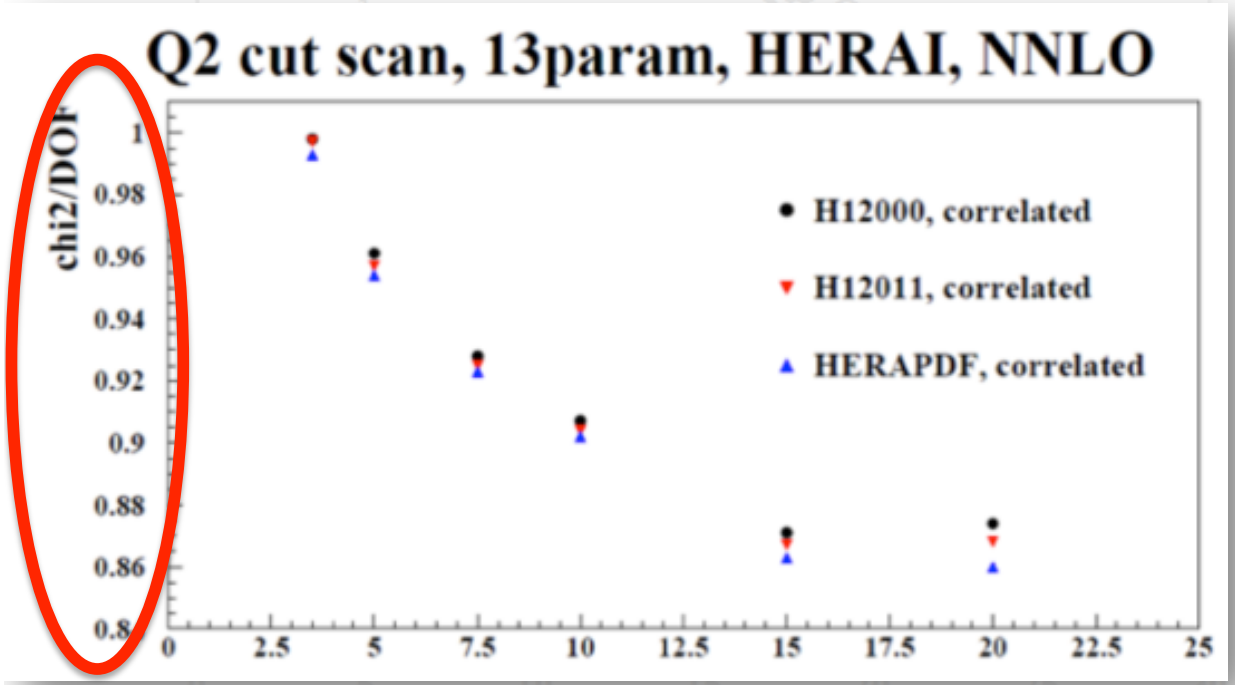
For Q^2_{min}= 10 GeV^2

Chi2/dof (NLO) = 1156/1001

Chi2/dof(NNLO)= 1150/1001

Q^2 cut dependence on fit results

- The Q^2 cut dependence on the fit is already included in the model variation for the HERAPDF sets, however usually we look at small range in cuts.



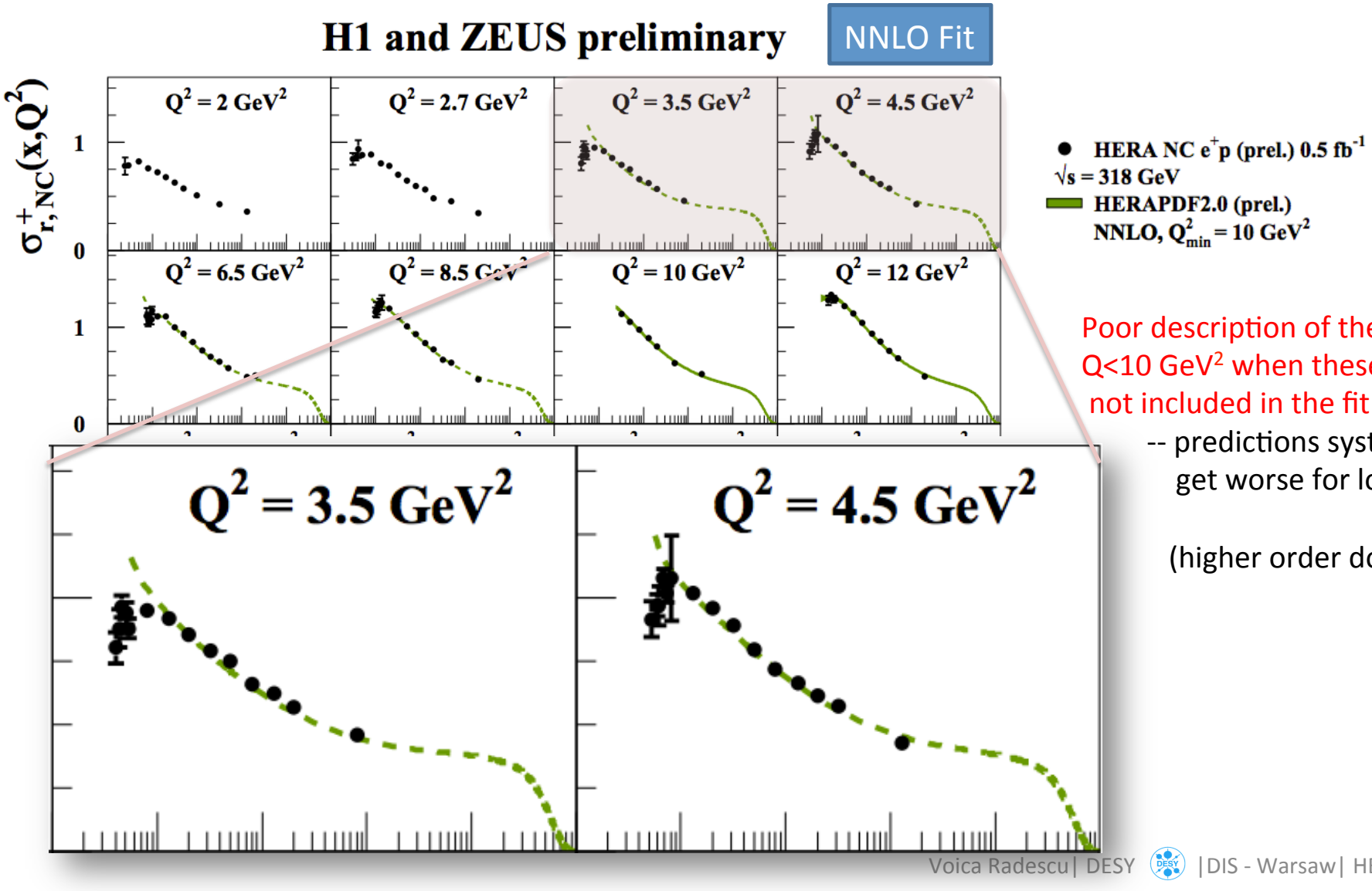
At Q^2_{min}= 10 GeV^2 is when the fit stabilises with respect of chi2/dof vs Q^2cut

This was the case also for HERA I, but due to less precise high Q2 data, was hidden in terms on Chi2/dof

(different symbols represent different forms for Chi2 definitions)

Low Q^2 Data vs HERAPDF2.0 (Q^2_{min}=10 GeV^2)

- How does fit performed with Q2min=10 GeV2 describe the low Q2 data?



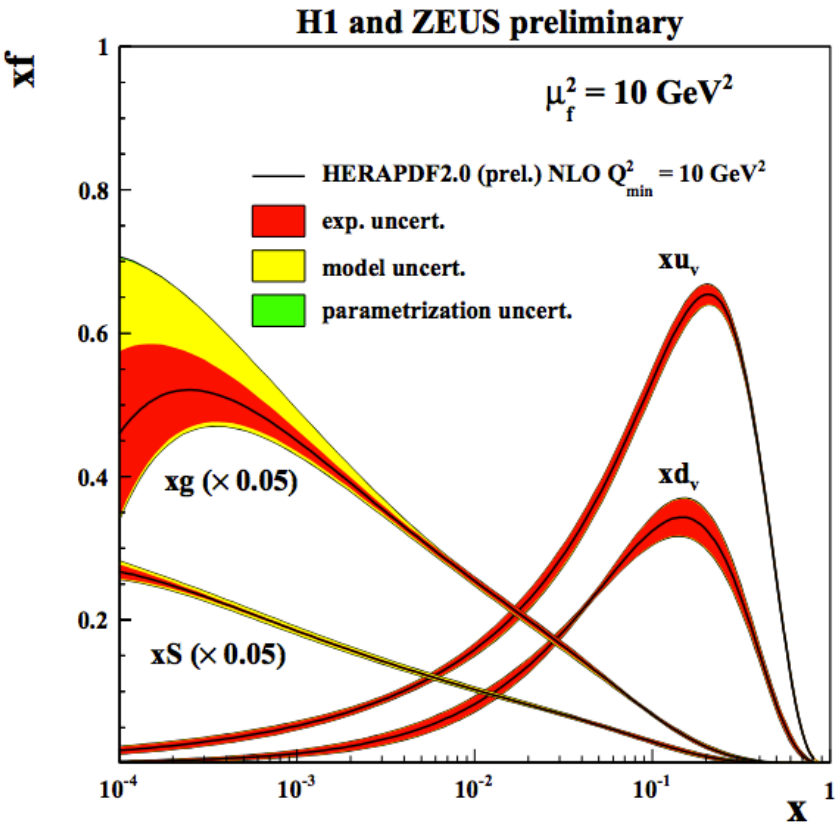
Poor description of the data for $Q<10$ GeV^2 when these data are not included in the fit:

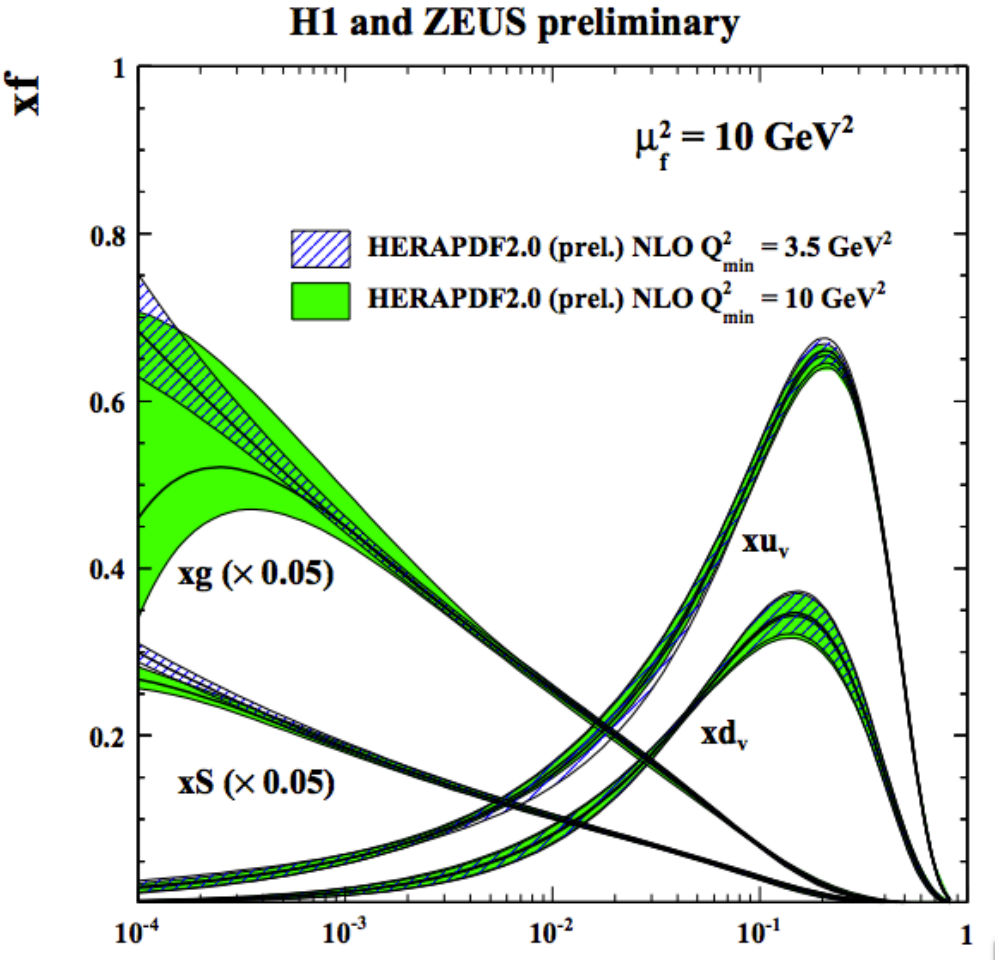
-- predictions systematically get worse for low x, Q^2

(higher order do not help)

HERAPDF2.0 with Q^2_{min}= 3.5 GeV^2 vs Q^2_{min}= 10 GeV^2 @ NLO

- How do PDFs compare between these 2 scenarios of Q^2_{min} choices?



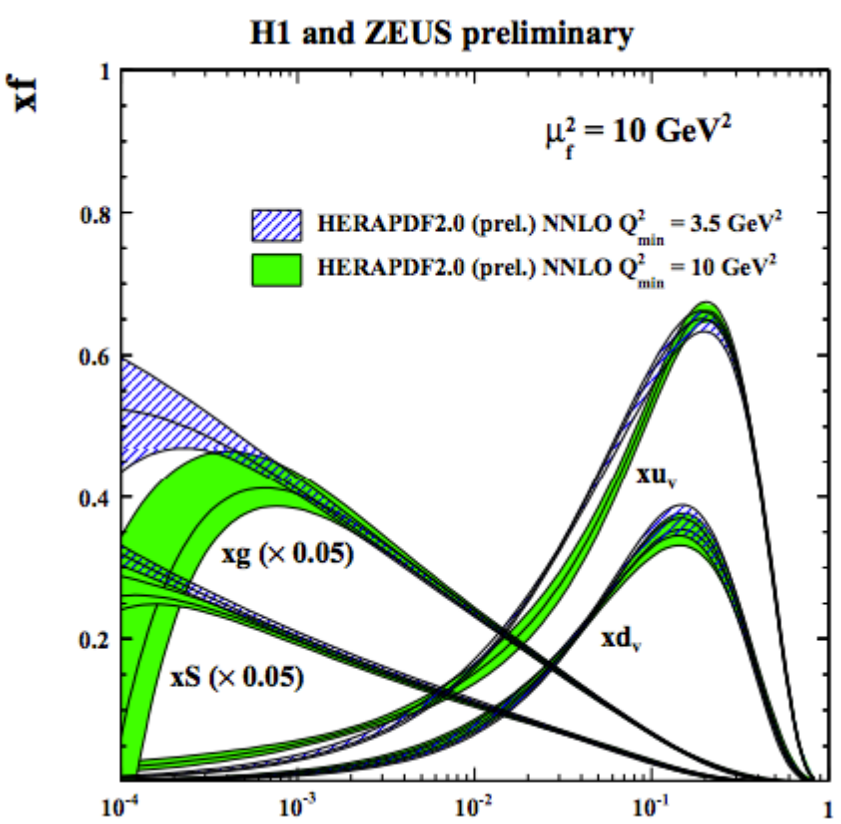


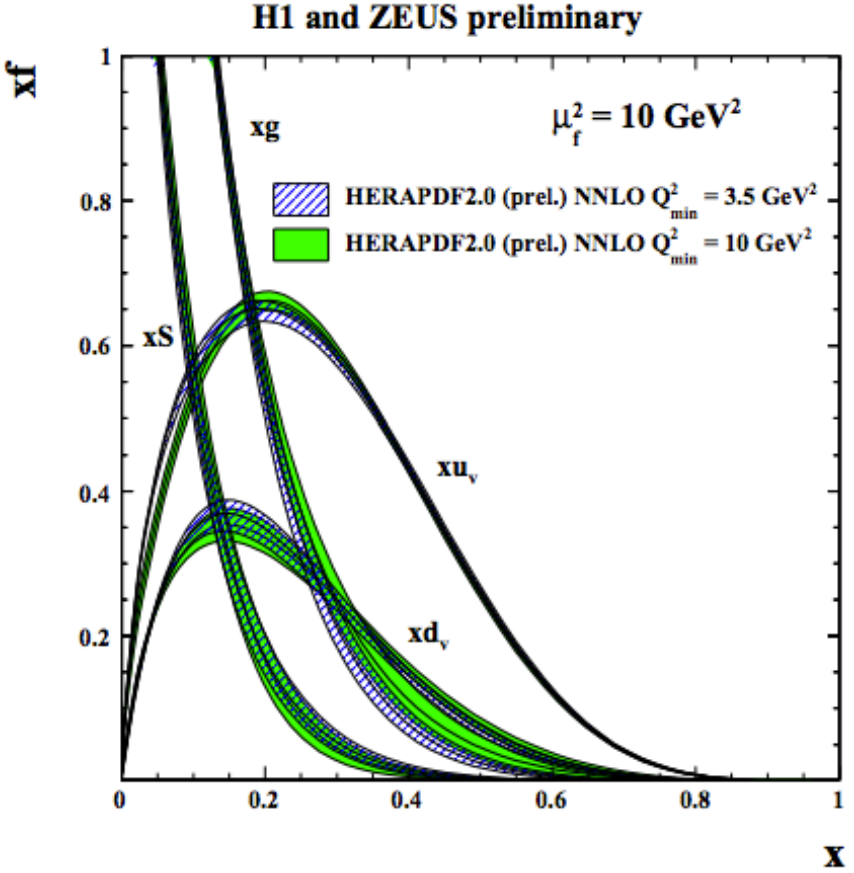
Q^2 cut variation is dominant model uncertainty and it gets enhanced for the fit with Q^2_{min}=10 GeV^2:

→ there is an interplay of the data cut at low Q^2 and impact on gluon at low x.

HERAPDF2.0 with Q^2_{min}= 3.5 GeV^2 vs Q^2_{min}= 10 GeV^2 @ NNLO

- How do PDFs compare between these 2 scenarios for Q^2_{min} choices?





HERAPDF2.0 sets are compatible at high x, but at low x the Q^2 cut on data affects the shape of the gluon (more pronounced at NNLO)

- low q2 ←→ low x

Comparison with HERAPDF1.0 @ NLO

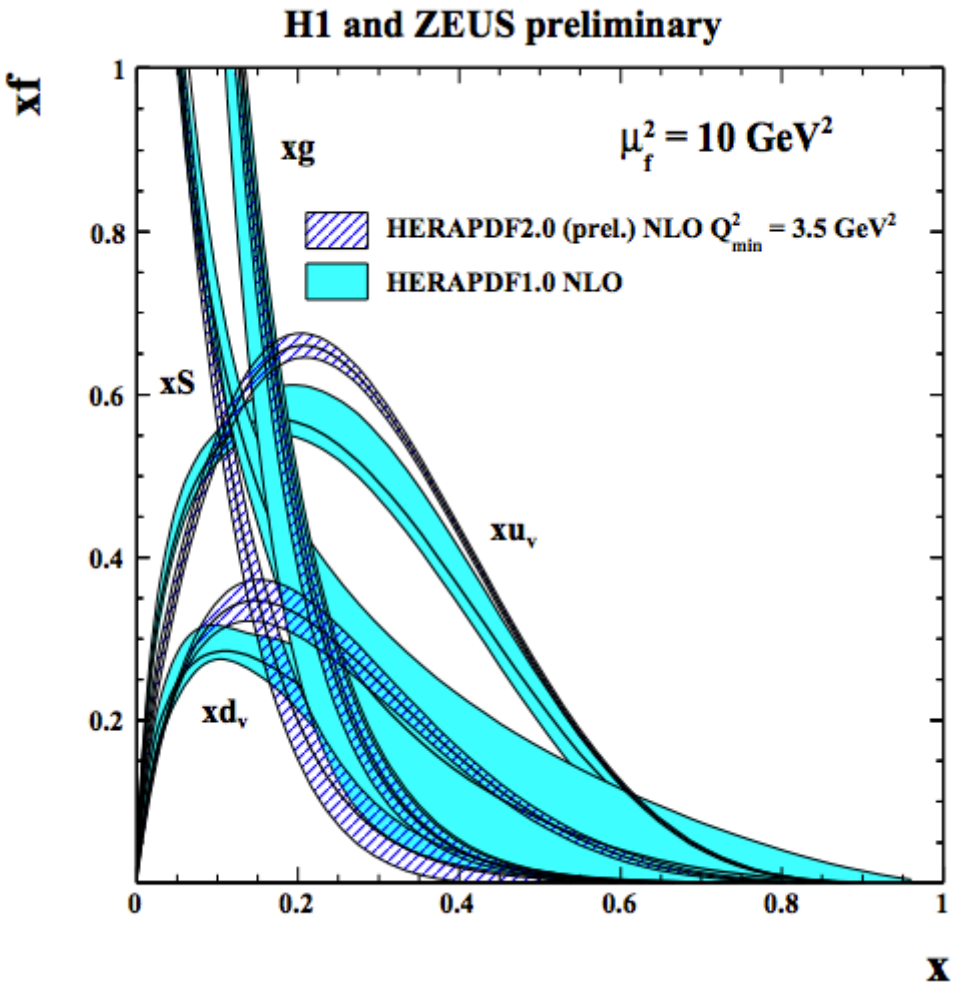
- HERAPDF1.0 is based on HERA I only data

  [JHEP01 (2010) 109]

  - It used a rigid parametrisation form (10p)

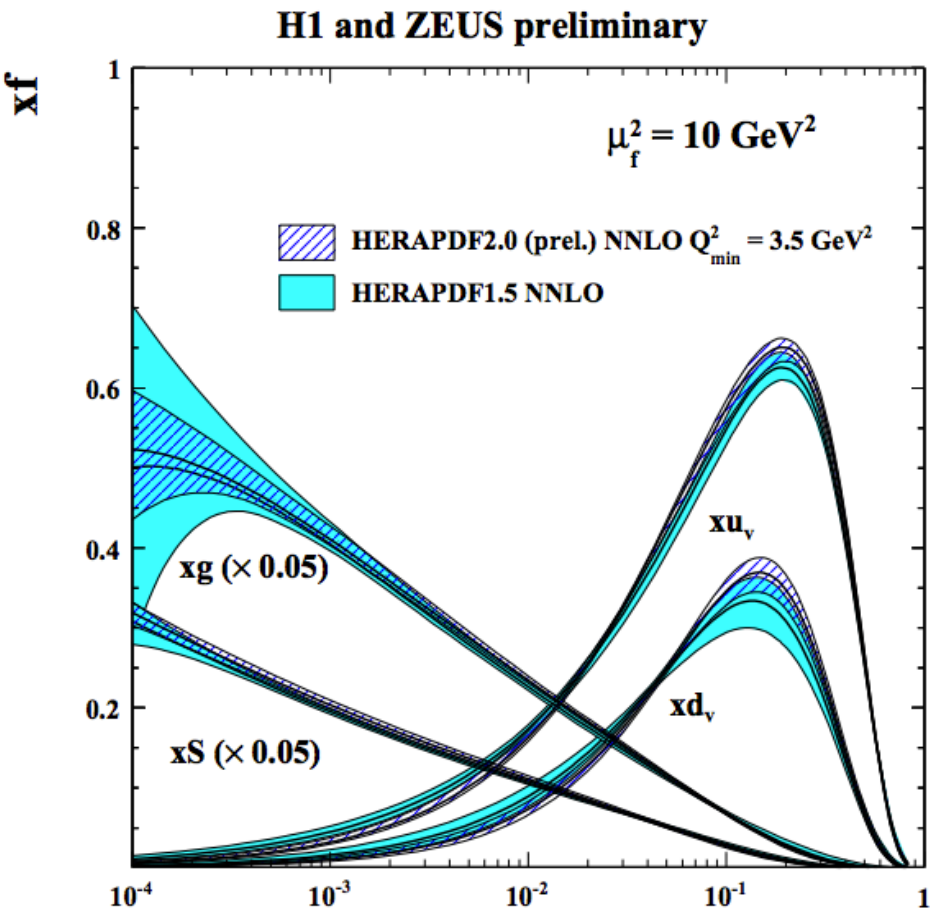
- Comparison with HERAPDF2.0:

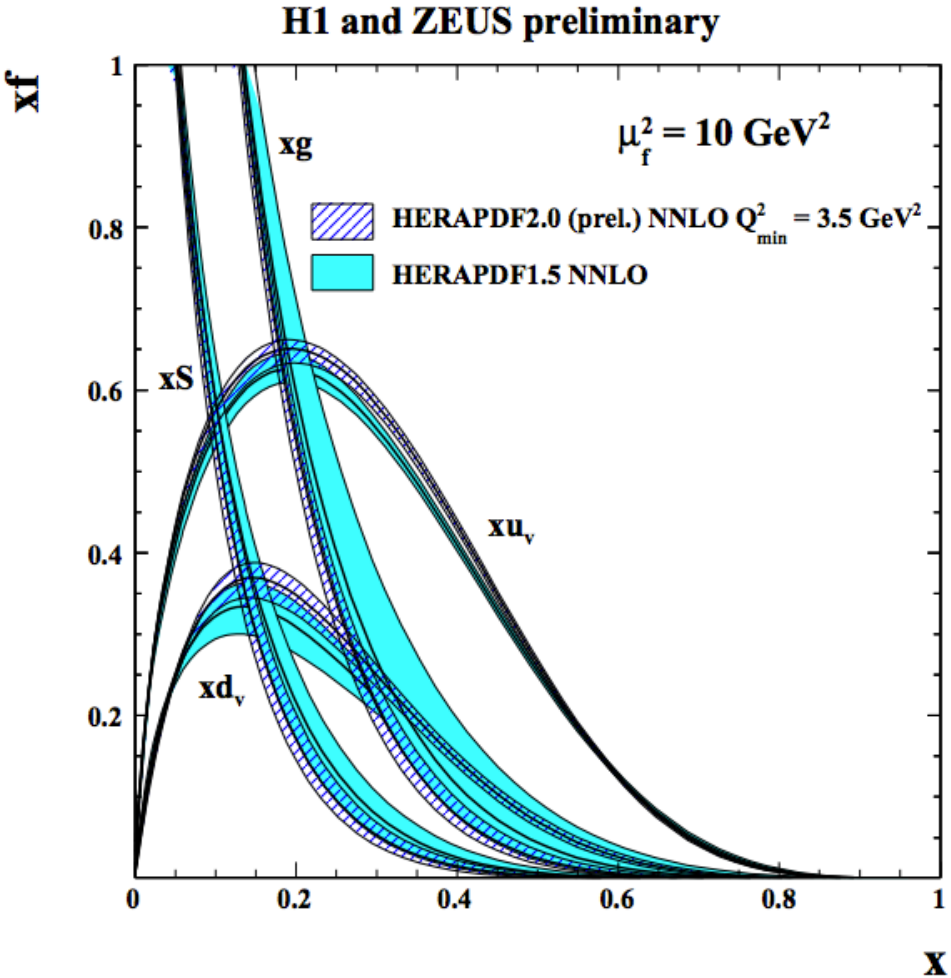
  - Improved distributions at high x
  - Sea is softer at high x
  - Gluon is harder at high x



Comparison with HERAPDF1.5 @ NNLO

- Most used HERAPDF set is HERAPDF1.5NNLO, how does it compare to it?





Shapes are similar:

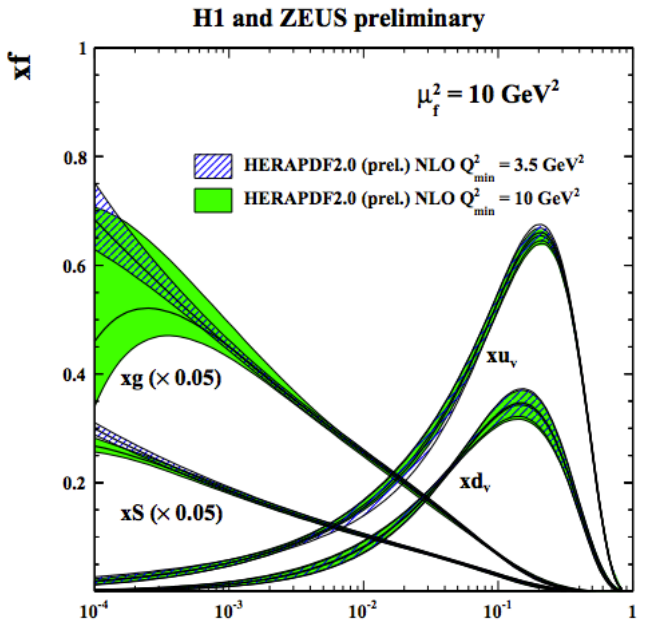
- Gluon and sea at low and high x has improved and they become slightly softer
- Valence at high x has also improved

Summary

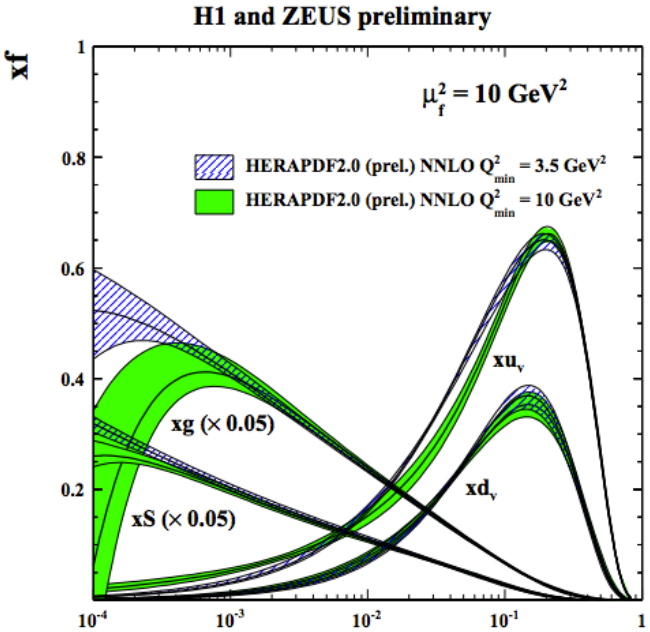
- HERA provides a clean determination of the proton's PDFs based solely on ep collider data
- New preliminary combined HERA I+II+low energy measurements improves precision of PDFs

- Q^2 dependence of fit observed and two sets, Q^2>3.5 GeV^2 and Q^2>10 GeV , provided

HERAPDF2.0(prel) at NLO and NNLO with full uncertainties



NLO

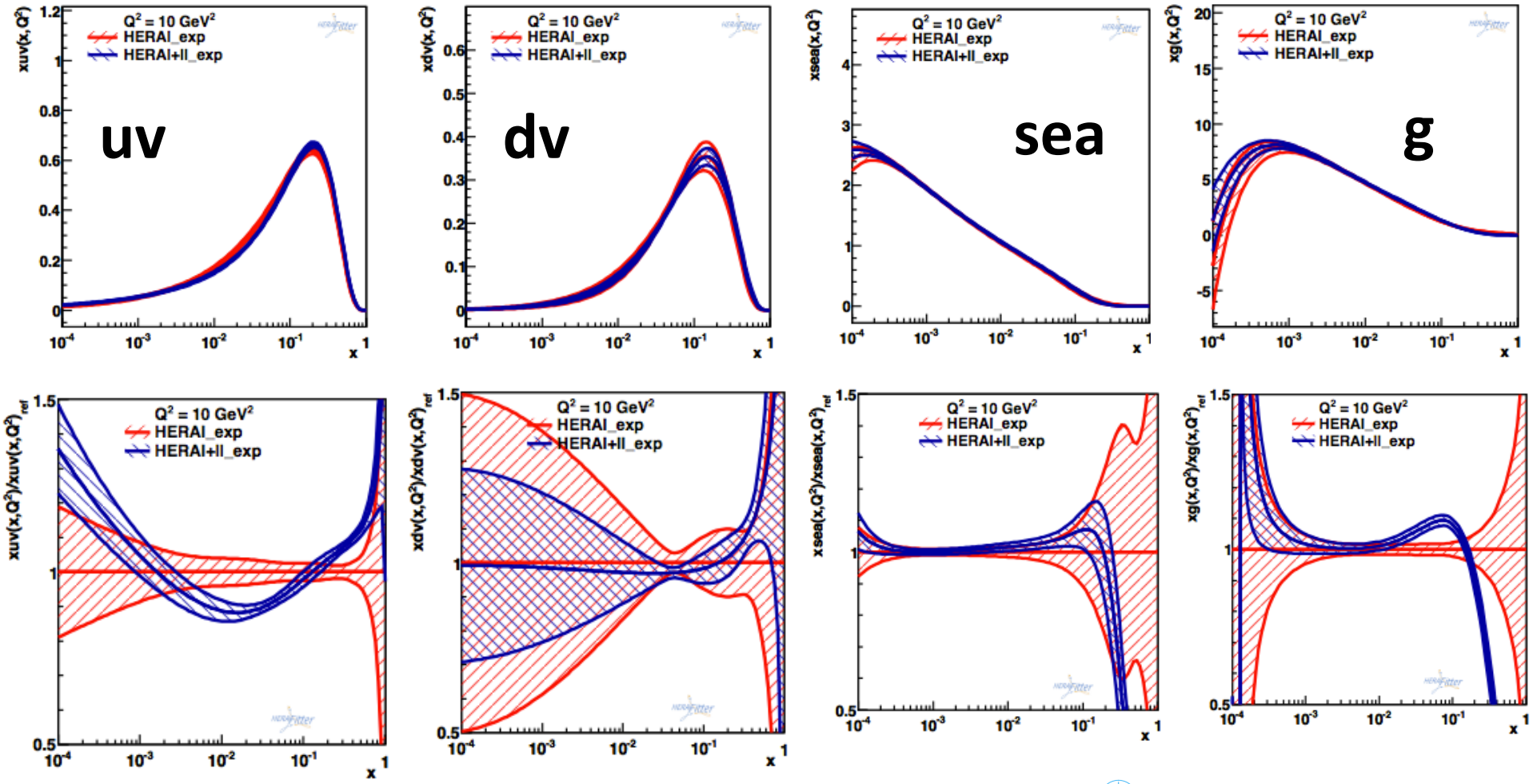


NNLO

EXTRA

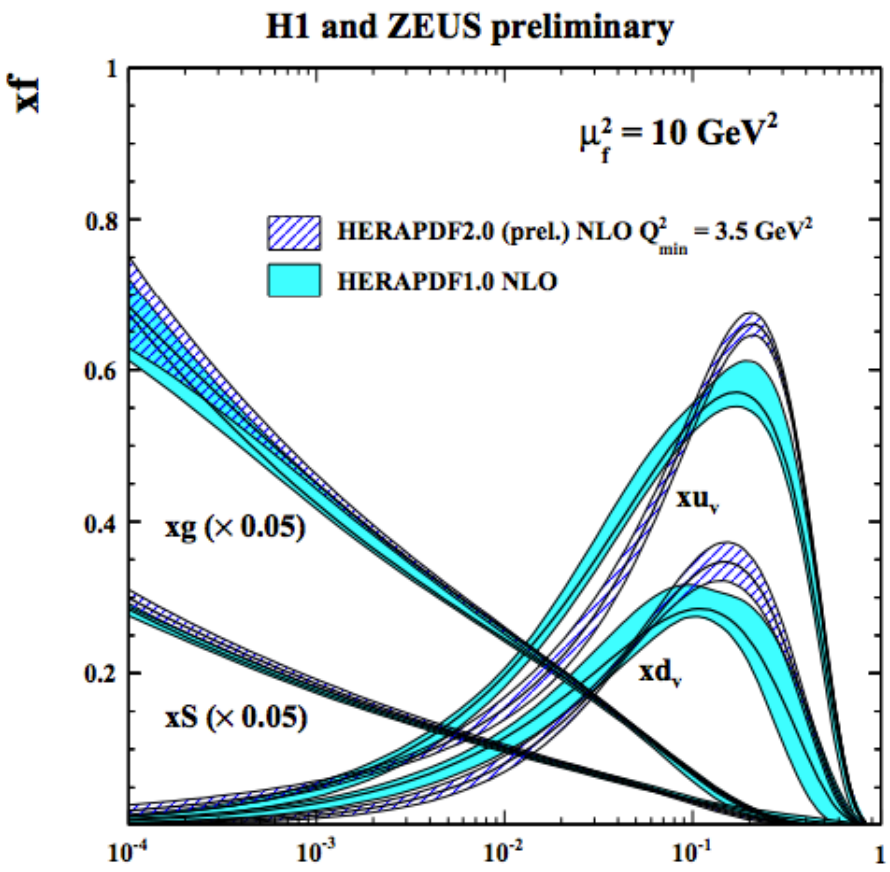
Impact of the experimental precision on PDFs

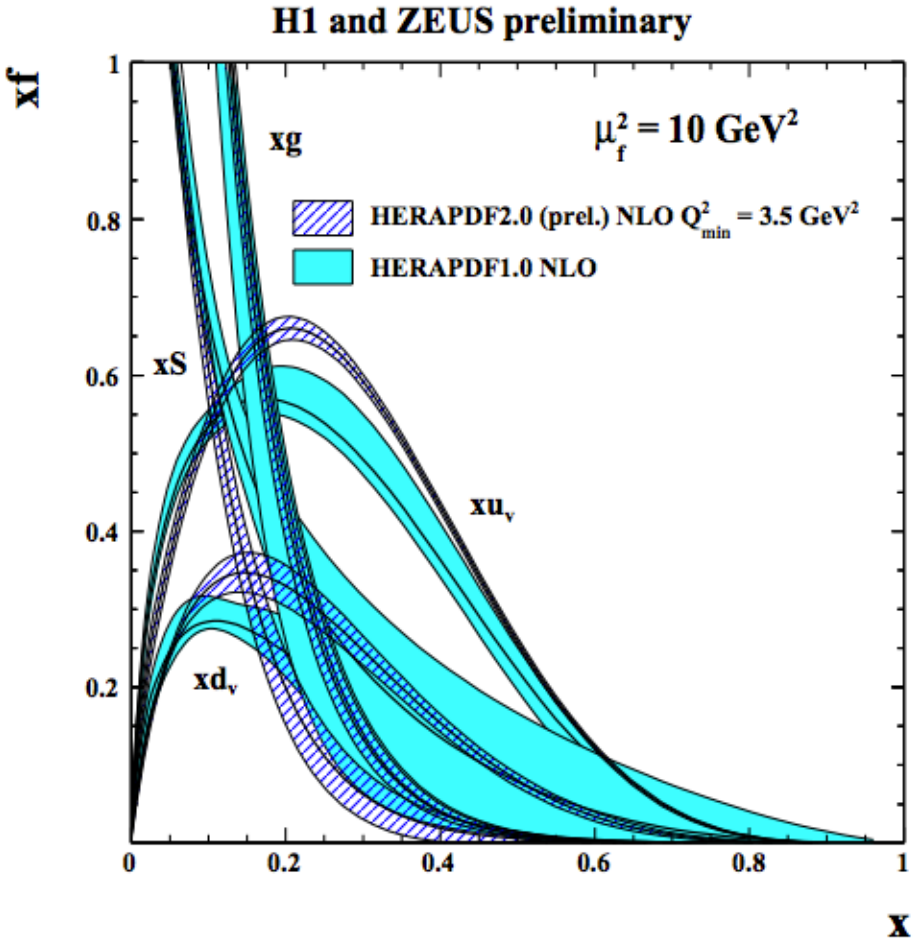
- HERA I+II preliminary data has an increased experimental precision with respect to HERA I which will also reflect on PDFs:
  - refitting HERA I data under same conditions as new HERA I+II data and using only exp uncertainties:



HERAPDF1.0 vs HERAPDF2.0

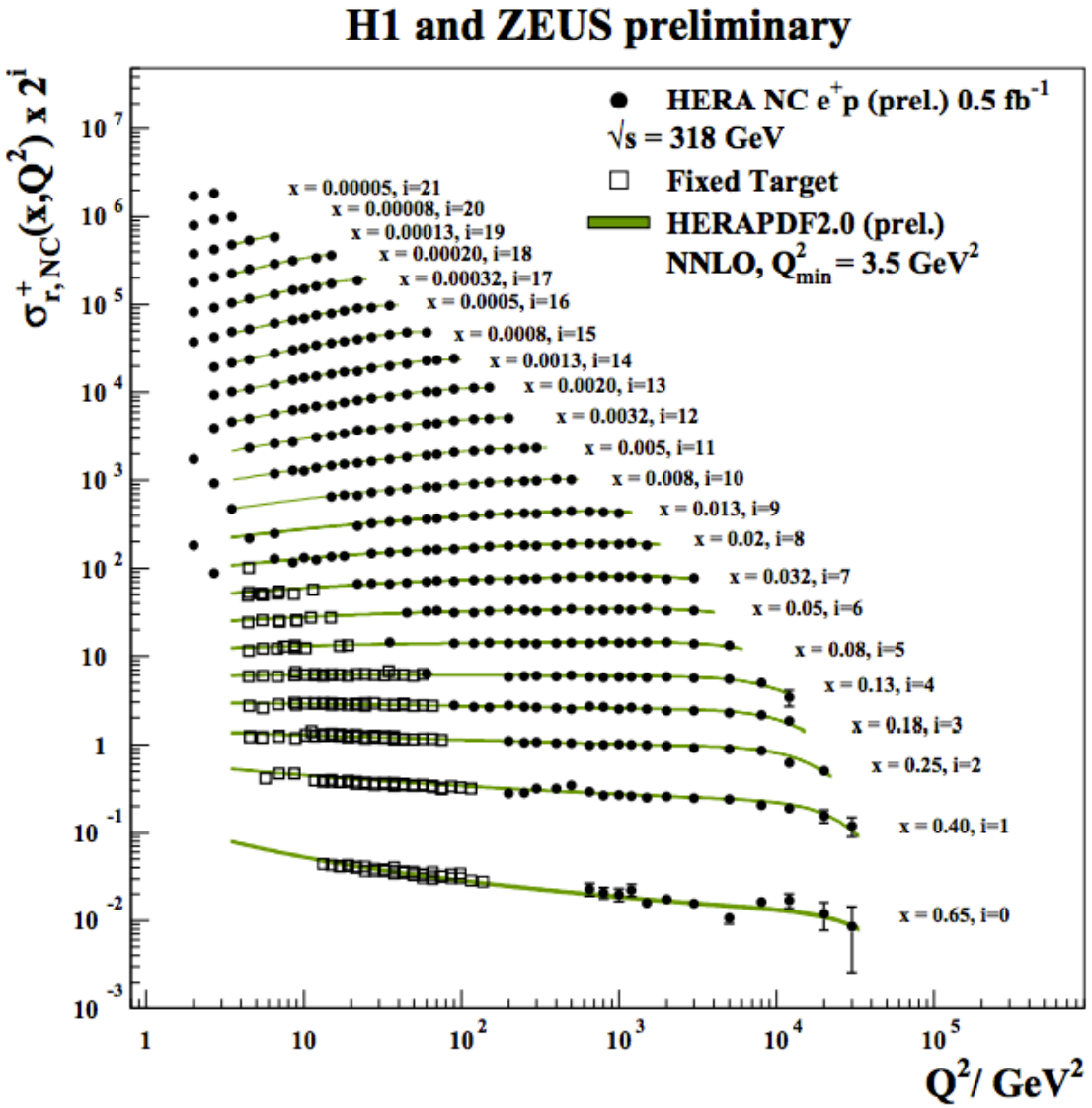
- HERAPDF1.0 used a rigid parametrisation form (10p)





Data vs Predictions

- Text book plot:



Low Energy data vs Fits

- 460 GeV p

575 GeV p