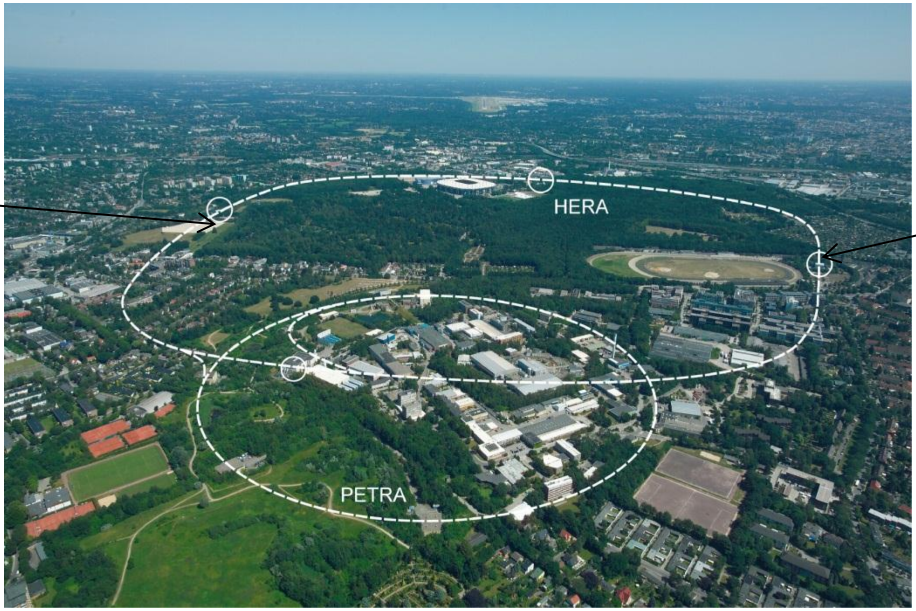
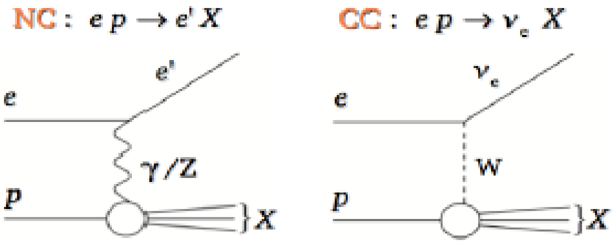


Proton Structure and Hard QCD at HERA

AM Cooper-Sarkar, Oxford
QCD@LHC2015, Queen Mary, London

Deep Inelastic Scattering (DIS) is the best tool to probe proton structure



- Kinematic variables:

$Q^2 = -q^2 = -(k - k')^2$ Virtuality of the exchanged boson

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

$y = \frac{p \cdot q}{p \cdot k}$ Inelasticity parameter

$s = (k + p)^2 = \frac{Q^2}{xy}$ Invariant c.o.m.

Neutral current:

$$\frac{d^2\sigma^{\pm}_{NC}}{dx dQ^2} = \frac{2\alpha\pi^2}{xQ^4}\left(Y_+ F_2 \mp Y_- xF_3 - y^2 F_L\right)$$

$F_2 \propto \sum_i e_i^2 (xq_i + x\bar{q}_i)$

quark distributions

$xF_3 \propto \sum_i (xq_i - x\bar{q}_i)$

valence quarks

$F_L \propto \alpha_s \times g$

gluon at NLO

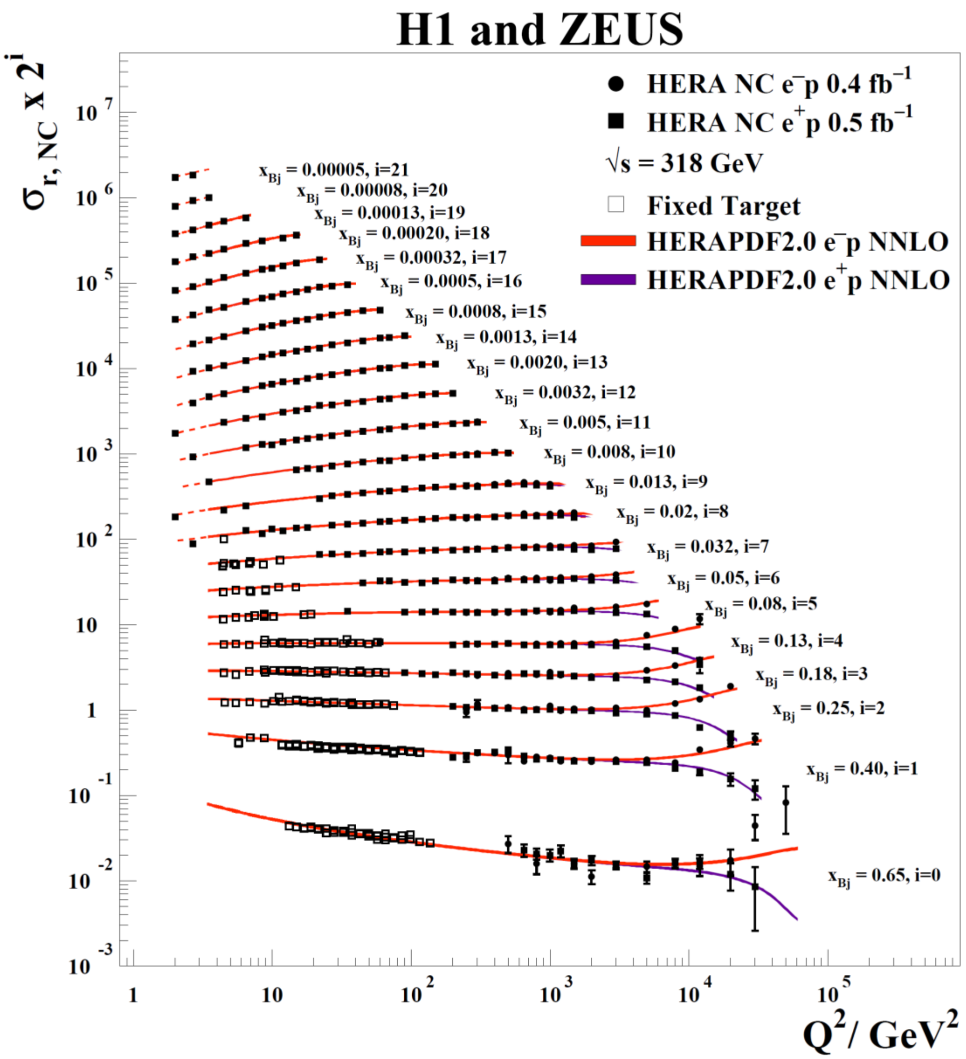
LO expressions

Charged current:

$$\frac{d^2\sigma^{-}_{CC}}{dx dQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^2}{M_W^2 + Q^2}\left(u + c + (1 - y^2)(\bar{d} + \bar{s})\right)$$

$$\frac{d^2\sigma^{-}_{CC}}{dx dQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^2}{M_W^2 + Q^2}\left(\bar{u} + \bar{c} + (1 - y^2)(d + s)\right)$$

flavour decomposition



Gluon from the scaling violations: DGLAP equations tell us how the partons evolve

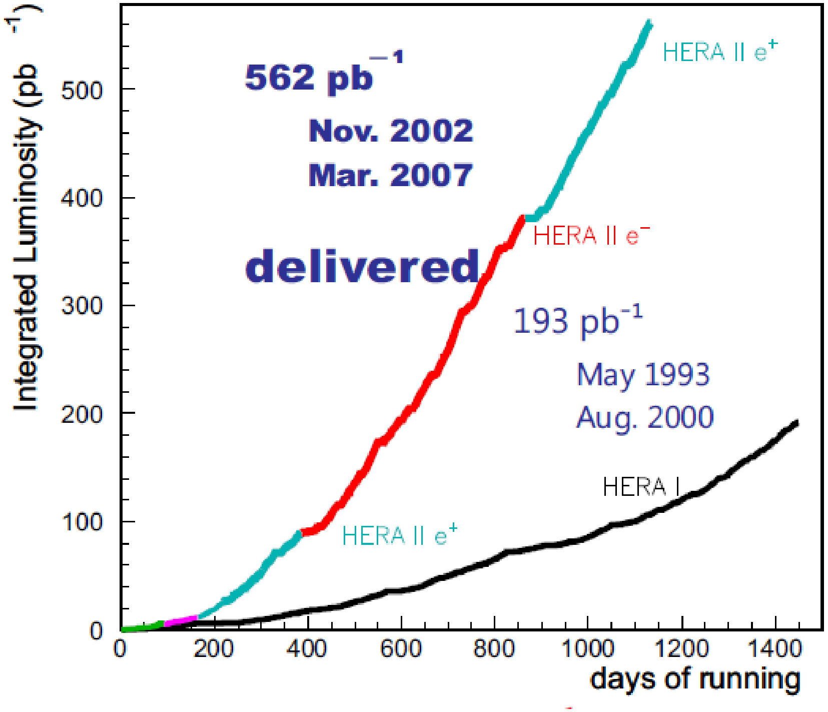
Final inclusive data combination from all HERA running

~500pb^{-1} per experiment split ~equally between e^{+} and e^{-} beams: DESY-15-039

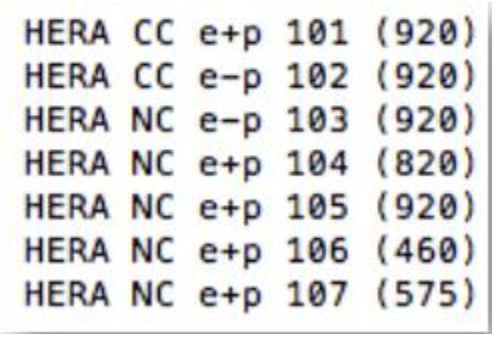
10 fold increase in e^{-} compared to HERA-I

Running at Ep = 920, 820, 575, 460 GeV
$\sqrt{s}$ = 320, 300, 251, 225 GeV

The lower proton beam energies allow a measurement of F_L and thus give more information on the gluon.

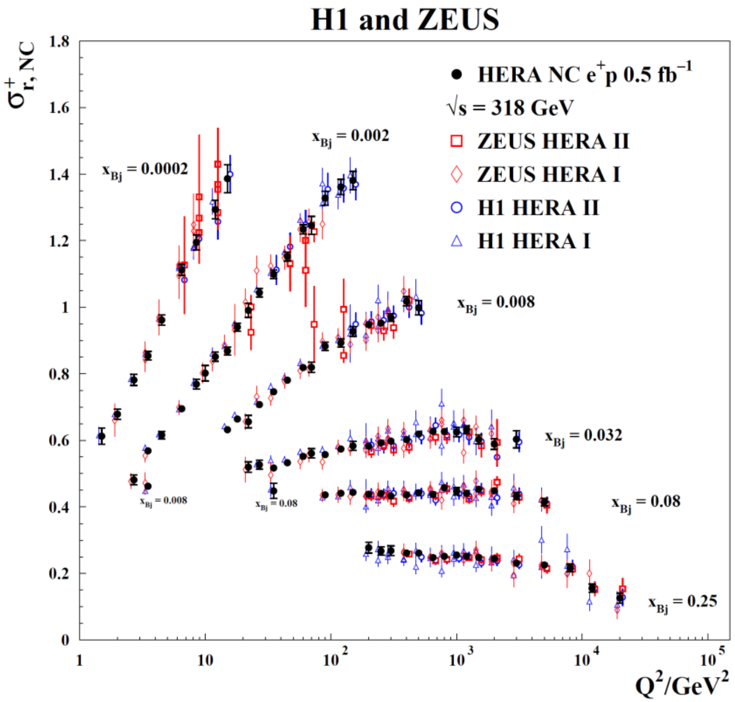


41 input data files to 7 output files with
169 sources of correlated uncertainty

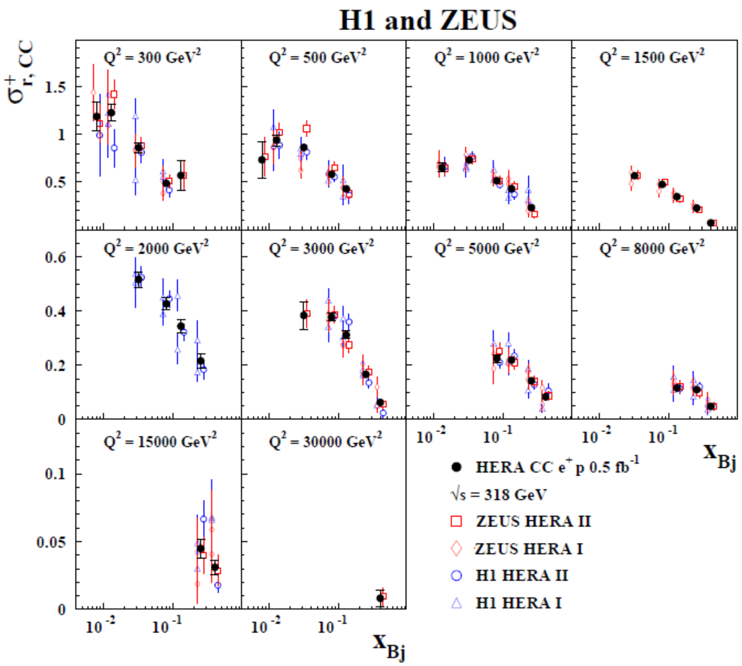


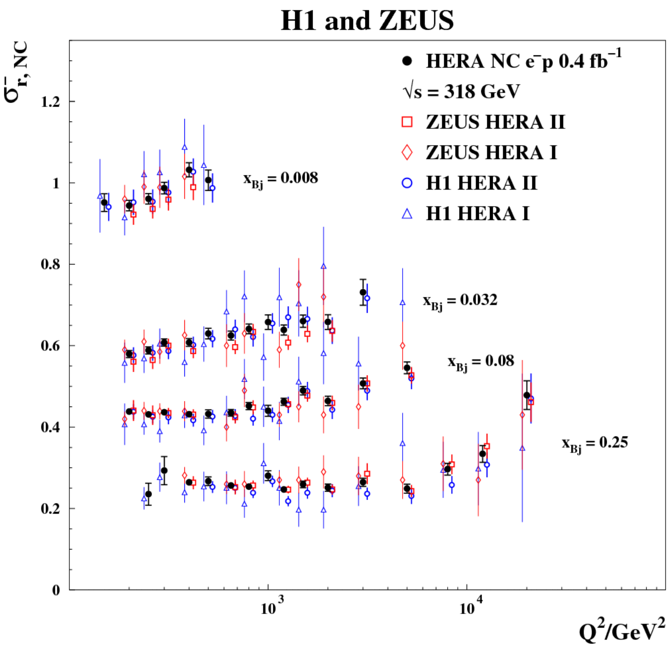
```
HERA CC e+p 101 (920)
HERA CC e-p 102 (920)
HERA NC e-p 103 (920)
HERA NC e+p 104 (820)
HERA NC e+p 105 (920)
HERA NC e+p 106 (460)
HERA NC e+p 107 (575)
```

0.045 < Q^2 < 50000 GeV^2 6. 10^{-7} < x_{Bj} < 0.65

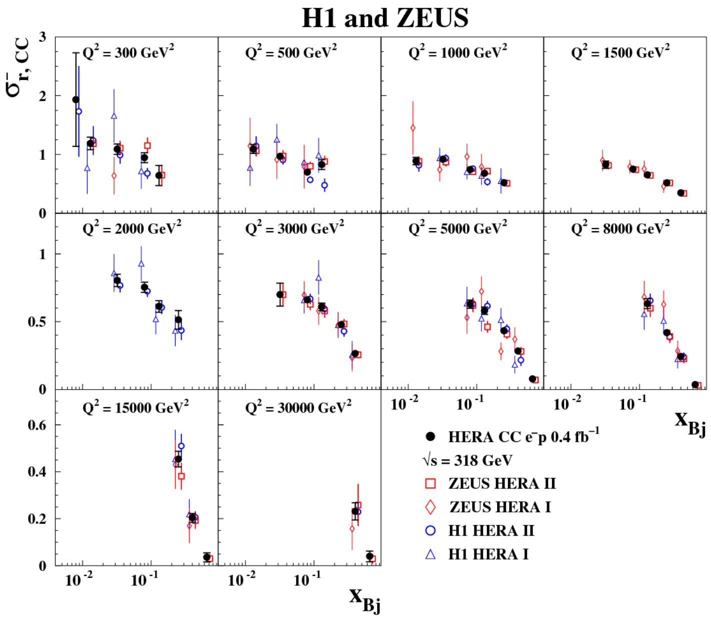


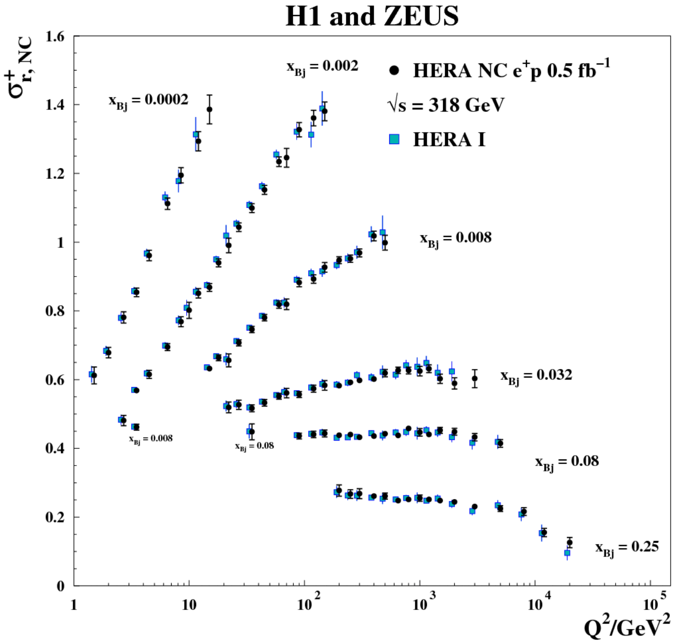
NC and CC e^+ vs H1 and ZEUS inputs



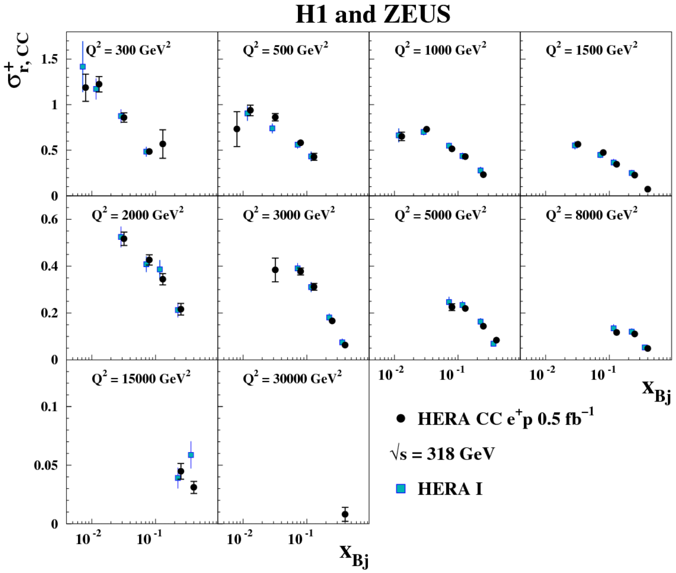


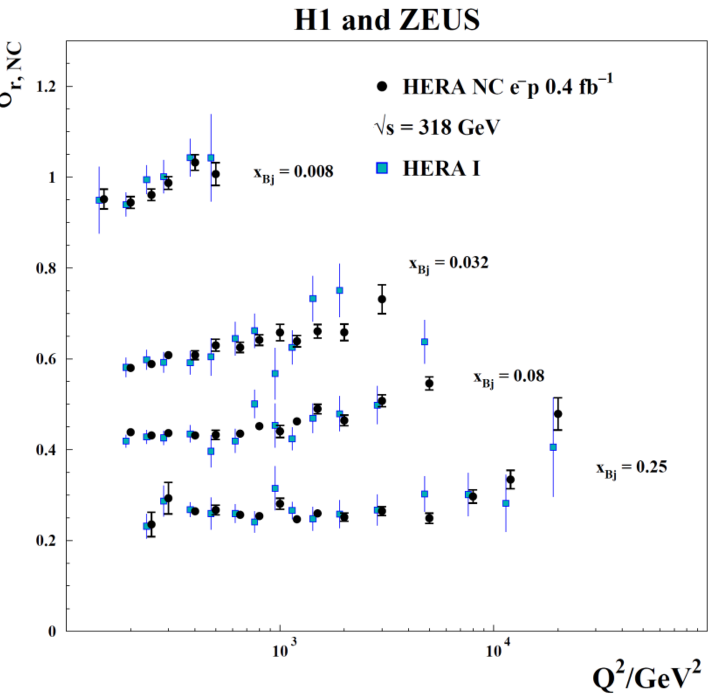
NC and CC e^- vs H1 and ZEUS inputs





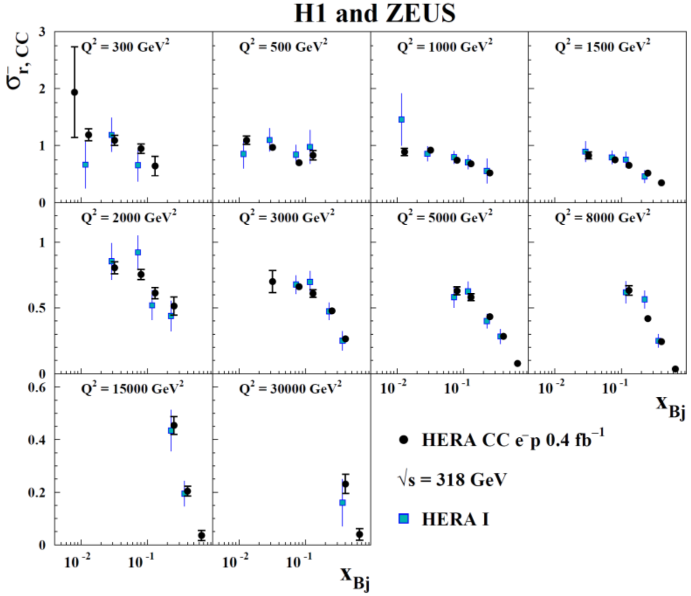
NC and CC e$^+$ vs HERA-1 combination

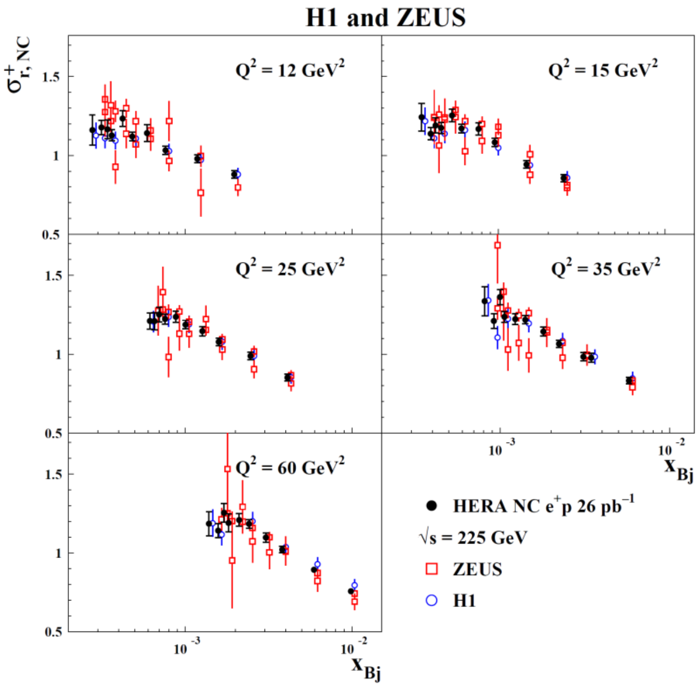




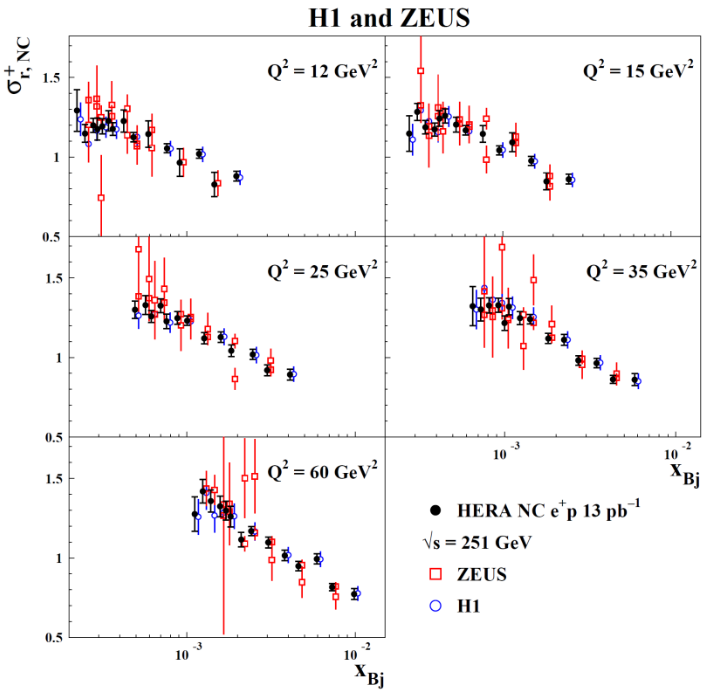
NC and CC e$^-$ vs HERA-1 combination

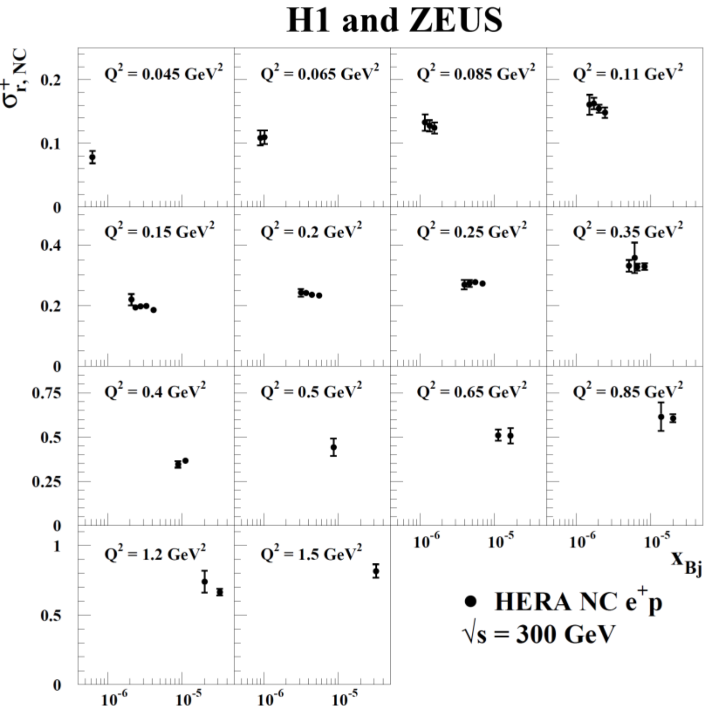
- 10 fold increase in e$^-$ statistics



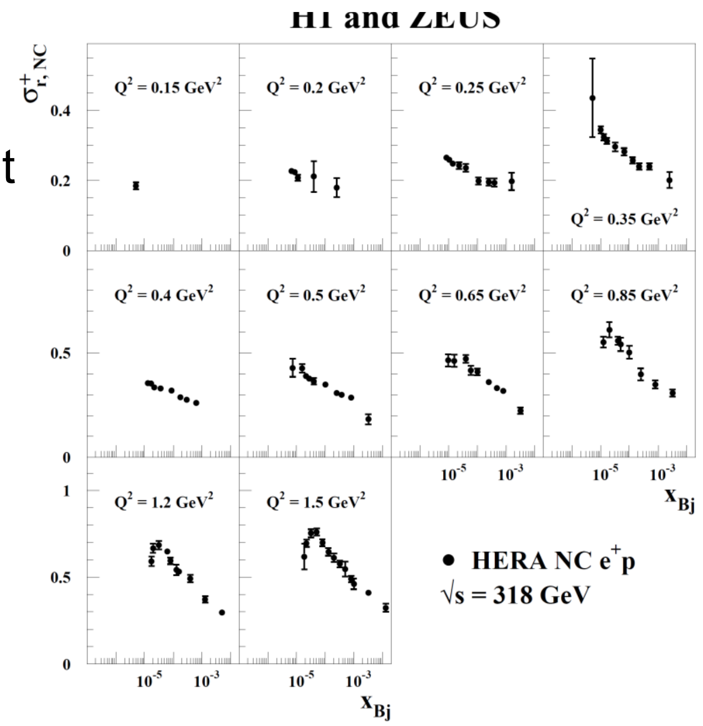


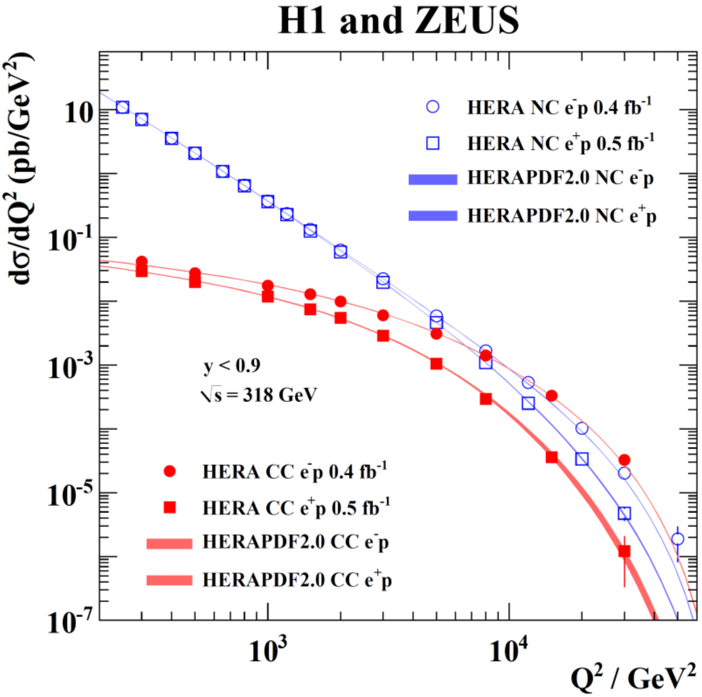
New for this combination is the data at different beam energies





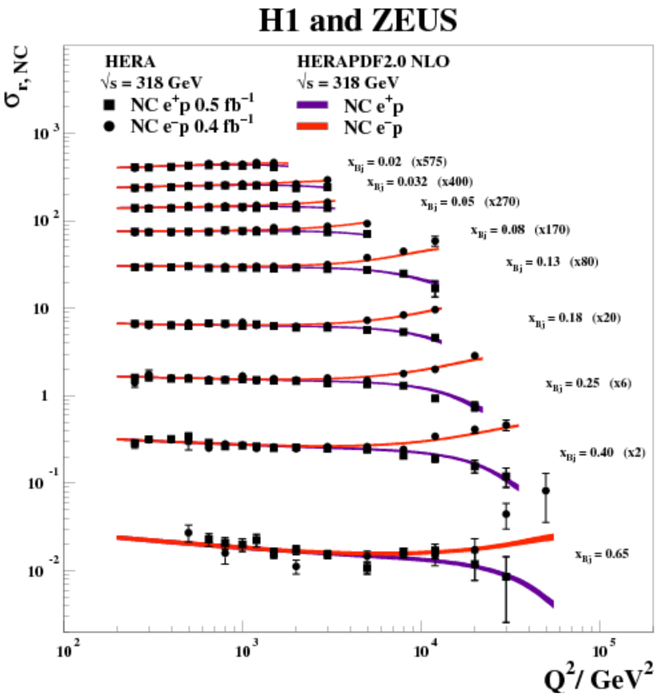
And let's not forget that there is data at very low Q^2



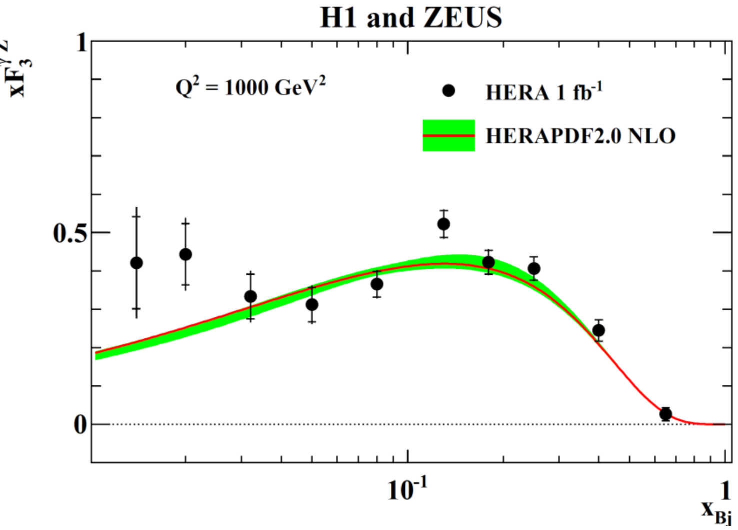


Electroweak unification

NCe^+/NCe^- difference at high Q^2 due to γZ interference

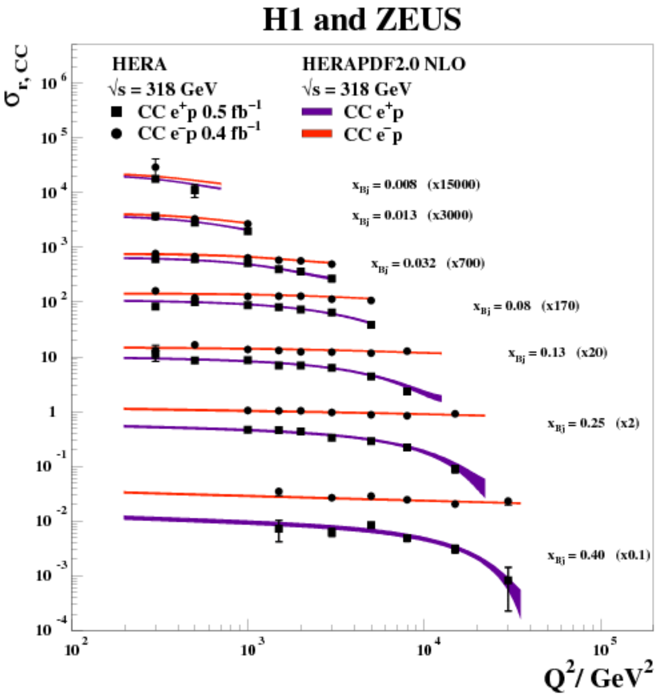


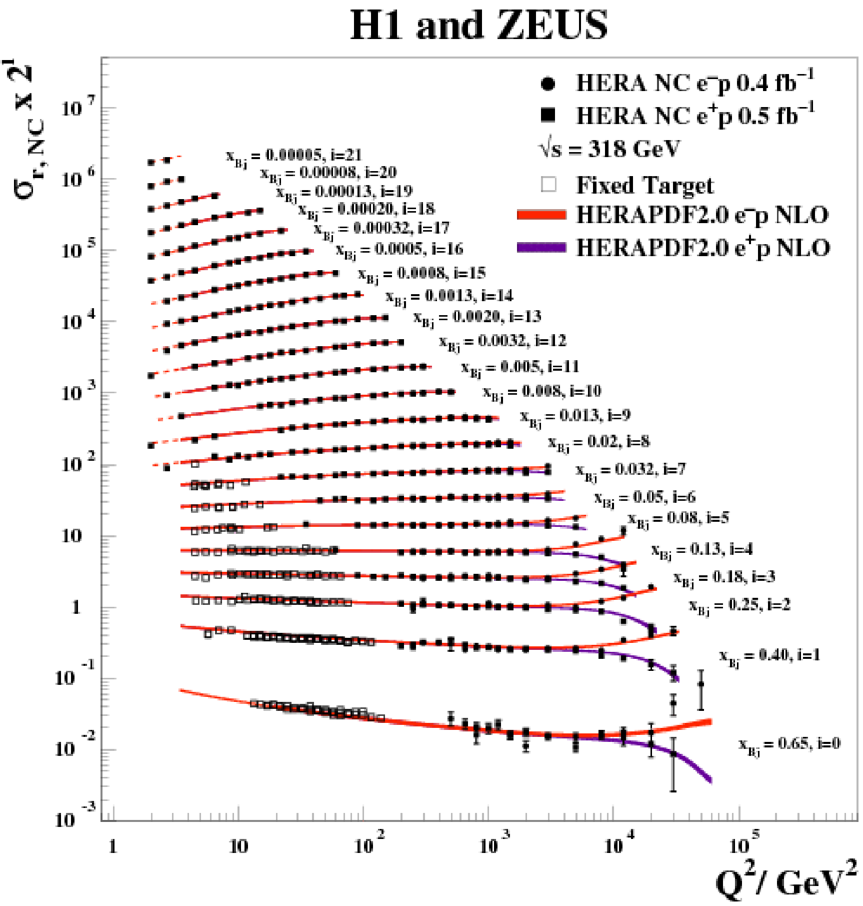
Enables an extraction of xF3

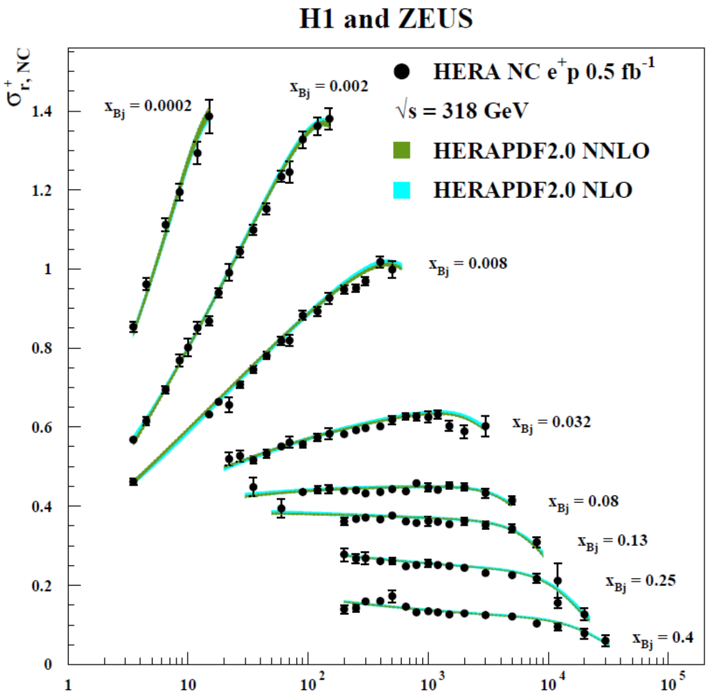


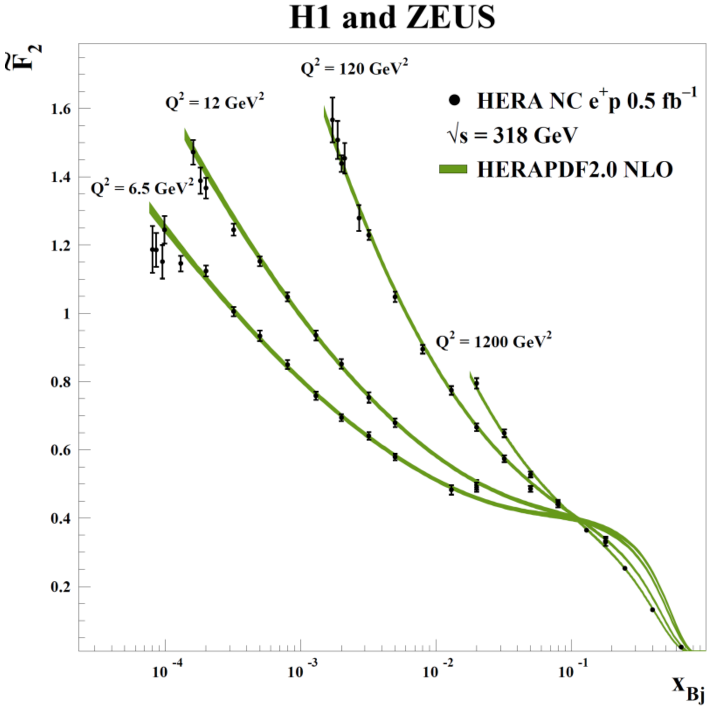
CCe^+/CCe^- difference at high Q^2 .. due to $(1-y)^2$ suppression at high y

These plots already show the QCD fit HERAPDF2.0









Scaling violations

Low-x rise of F2.. Let’s come back to this..

These plots already show the QCD fit HERAPDF2.0

The HERAPDF approach uses only HERA data

The combination of the HERA data yields a very accurate and consistent data set for 4 different processes: e^+p and e^-p Neutral and Charged Current reactions and for e^+p Neutral Current at 4 different beam energies

The use of the single consistent data set allows the usage of the conventional $\chi 2$ tolerance $\Delta\chi 2 = 1$ when setting 68%CL experimental errors

NOTE the use of a pure proton target means no need for heavy target/deuterium corrections.

d-valence is extracted from CC e^+p without assuming d in proton= u in neutron

All data are at high W (> 15 GeV), so high-x, higher twist effects are negligible.

These are the only PDFs for which this is true

HERAPDF evaluates model uncertainties and parametrisation uncertainties in addition to experimental uncertainties

HERAPDF1.0 was based on the combination of HERA-I data

HERAPDF1.5 included preliminary HERA-II data

HERAPDF2.0 is based on the new final combination of HERA-I and HERA-II data which supersedes the HERA-I combination and supersedes all previous HERAPDFs

HERAPDF specifications: parameterisation and χ2 definition

For the NLO and NNLO fits the central parametrisation at $Q^2_0 = 1.9$ GeV^2 is

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

QCD sum-rules constrain A_g, A_{uv}, A_{dv} $x\bar{s} = f_s x\bar{D}$ sets the size of the strange PDF and the constraints $B_{\bar{U}} = B_{\bar{D}}$ and $A_{\bar{U}} = A_{\bar{D}}(1-f_s)$ ensure $x\bar{u} \to x\bar{d}$ as $x \to 0$.

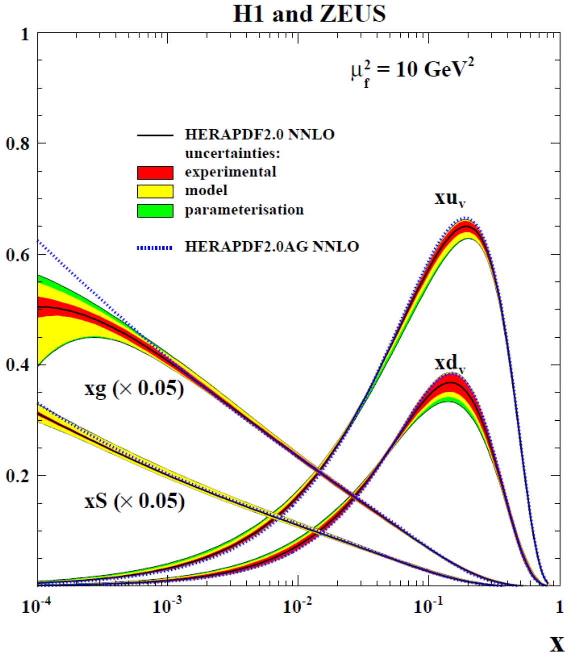
- There are 14 free parameters in the central fit determined by saturation of the χ2
- $\alpha_S(M_Z) = 0.118$ for central fits
- PDFs are evolved using the DGLAP equations using QCDNUM and convoluted with coefficient functions to evaluate structure functions and hence measurable cross sections
- Heavy quark coefficient functions are evaluated by the Thorne Roberts Optimized Variable Flavour Number scheme – this is the standard, unless otherwise stated
- Fixed Flavour Number PDFs are also available at NLO
- An LO fit with $\alpha_S(M_Z) = 0.130$ is also provided with an alternative gluon (AG) parametrisation
- The form of the χ2 accounts for 169 correlated uncertainties, 162 from the input data sets and 7 from the procedure of combination

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

HERAPDF specifications: sources of uncertainty

Experimental
Hessian uncertainties: 14 eigenvector pairs, evaluated with $\Delta\chi 2 = 1$
Cross checked uncertainties evaluated from the r.m.s. of MC replicas

Model: Variation of input assumptions
Variation of charm mass and beauty mass parameters is restricted using HERA charm and beauty data

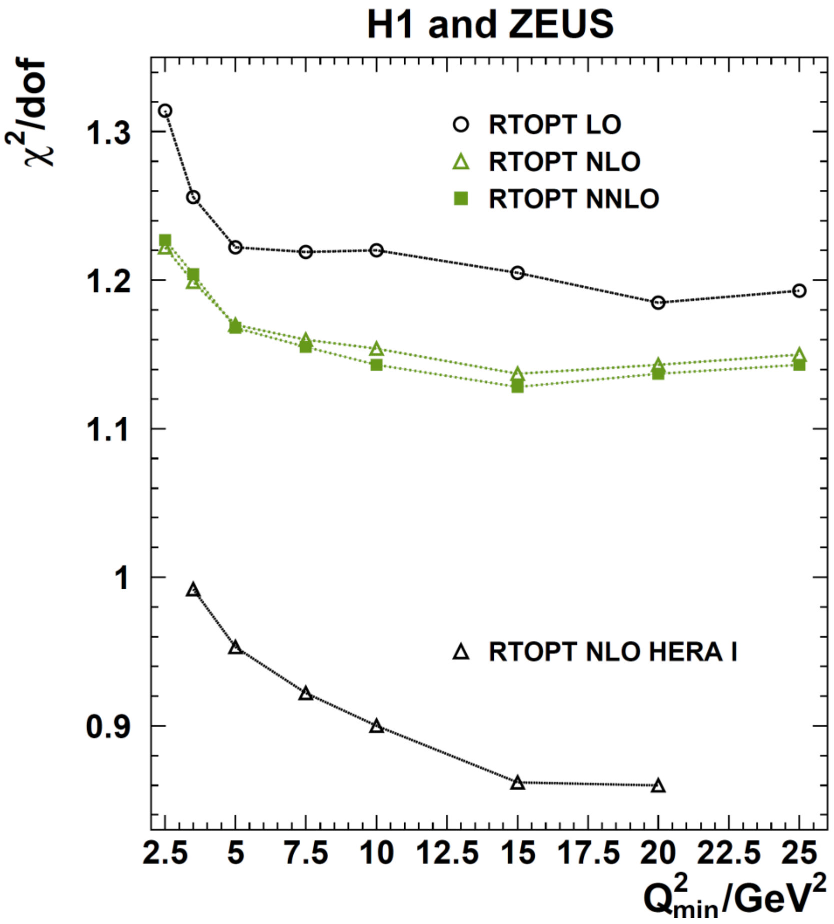


Variation	central	Upper	lower
f_s size and shape	0.4	0.5	0.3
M_c (NLO) GeV	1.43	1.49	1.37
M_c (NNLO) GeV	1.47	1.53	1.41
M_b GeV	4.5	4.25	4.75
Q^2_{min} GeV^2	3.5	2.5	5.0
Q^2_{min}(HiQ2)	10.0	7.5	12.5

Parametrisation
Variation of $Q^2_0 = 1.9 \pm 0.3$ GeV^2 and addition of 15th parameters

The value of $\alpha_S(M_Z)$ is not treated as an uncertainty. The central value is $\alpha_S(M_Z) = 0.118$
But PDFs are supplied for $\alpha_S(M_Z)$ values from 0.110 to 0.130 in steps of 0.001

HERAPDF specifications: minimum value of Q^2



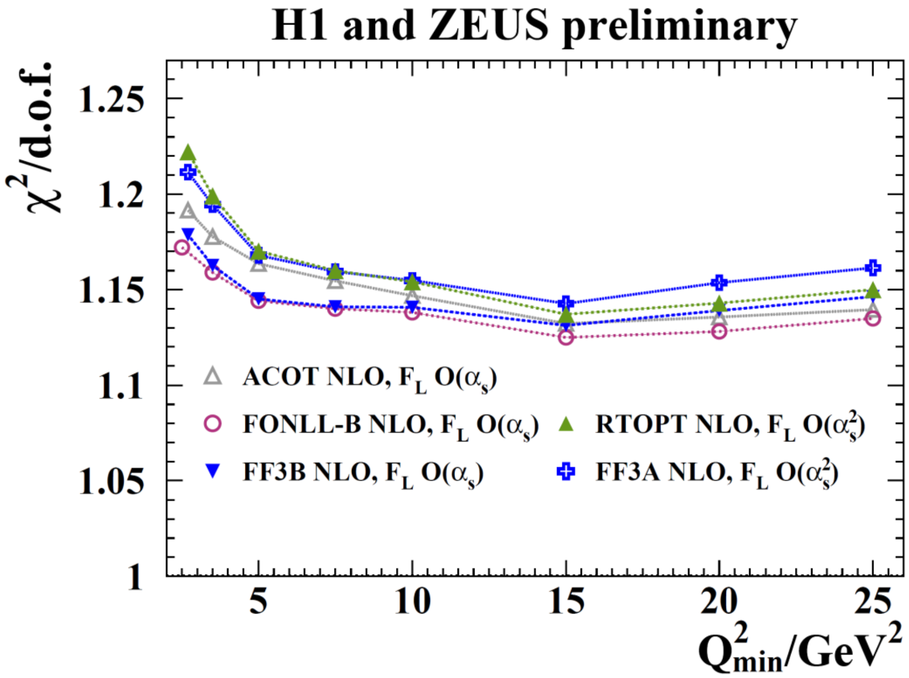
A minimum value of Q^2 for data allowed in the fit is imposed to ensure that pQCD is applicable. For HERAPDF the usual value is $Q^2 > 3.5$ GeV^2 but consider the variation of χ2 with this cut

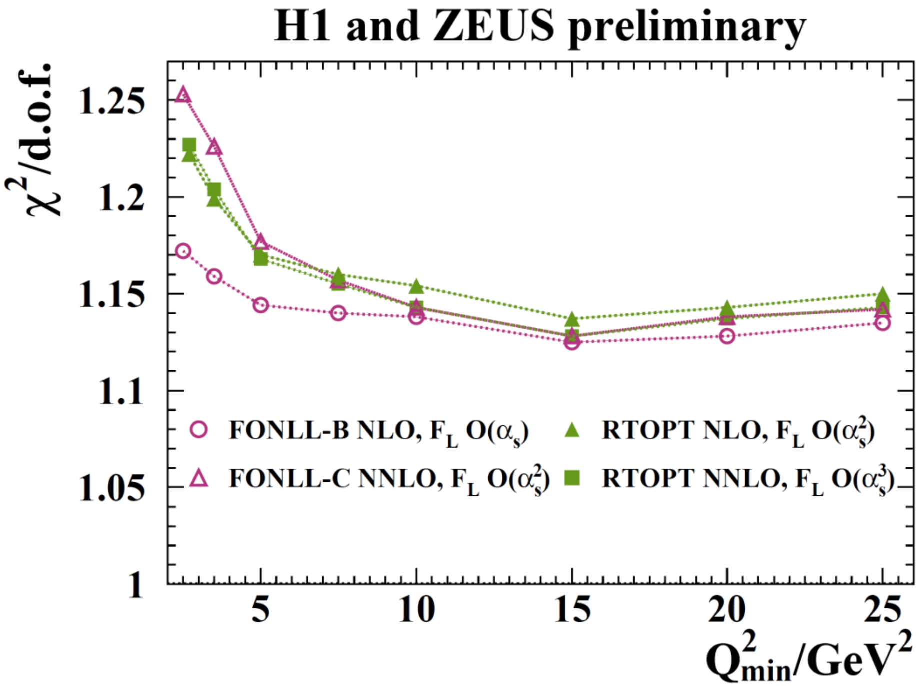
- The χ2 decreases with increase of Q^2 minimum until $Q^2_{min} \sim 10$ -15 GeV^2
- The same effect was observed in HERA-1 data
- This is independent of heavy flavour scheme (see next slide)
- NLO is obviously better than LO but NNLO is not significantly better than NLO, for RT

Fits for two Q^2 cuts will be presented: HERAPDF2.0: $Q^2 > 3.5$ and HERAPDF2.0HiQ2: $Q^2 > 10$ GeV^2

HERA kinematics is such that cutting out low Q^2 also cuts the lowest x values, thus HERAPDF2.0HiQ2 is used to assess possible bias in HERAPDF2.0 from including a kinematic region which might require treatment of: non-perturbative effects; ln(1/x) resummation; saturation etc.

Further remarks on dependence on Q^2_{min}
Compare heavy flavour schemes at NLO and compare NLO to NNLO





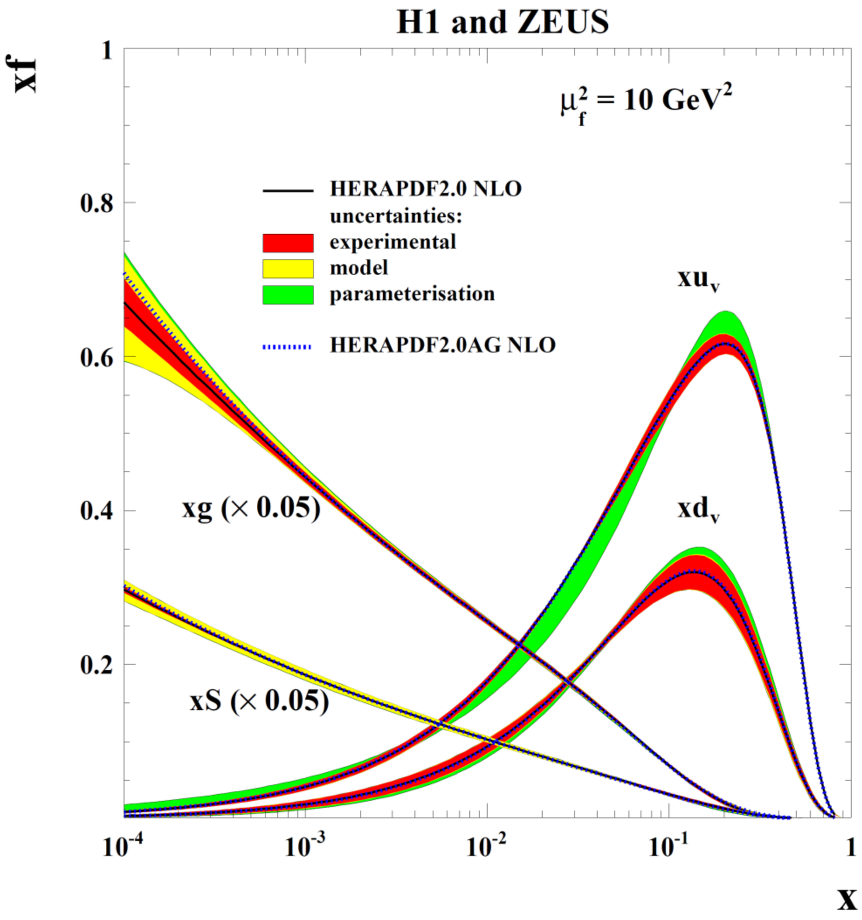
Treating F_L to $O(\alpha_S)$ – the same order as F_2 yields better χ2 than treating FL to $O(\alpha_S{}^2)$ almost independent of heavy flavour scheme

RTOPT NNLO is marginally worse than NLO

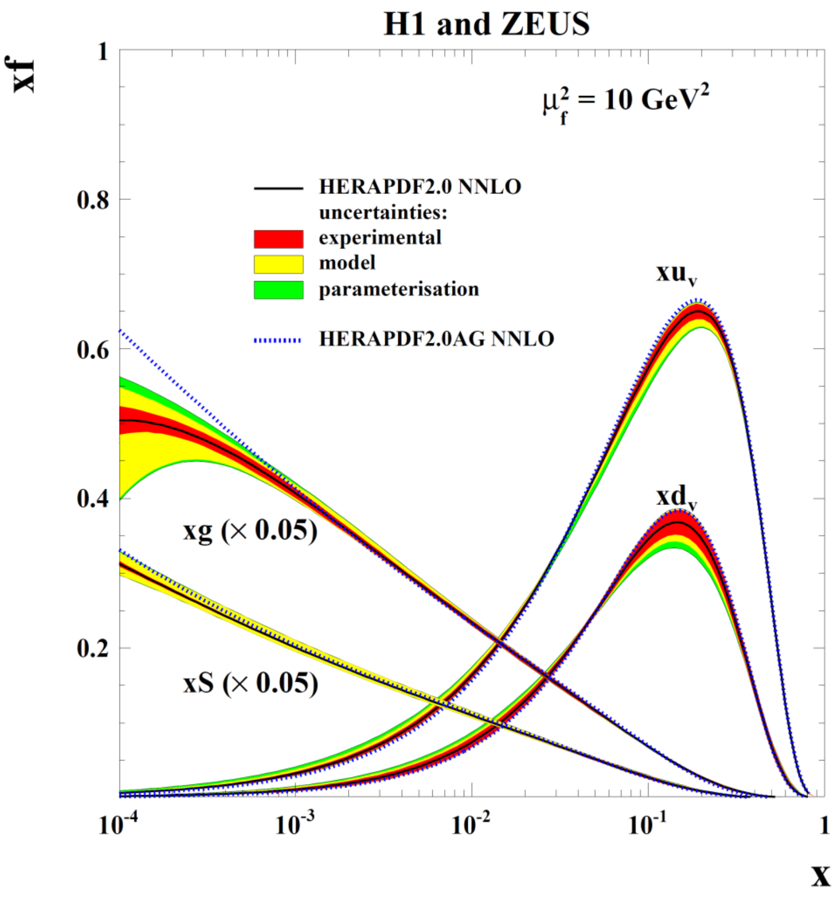
FONLL NNLO is a lot worse than NLO

HERAPDF2.0: NLO and NNLO fits

NLO



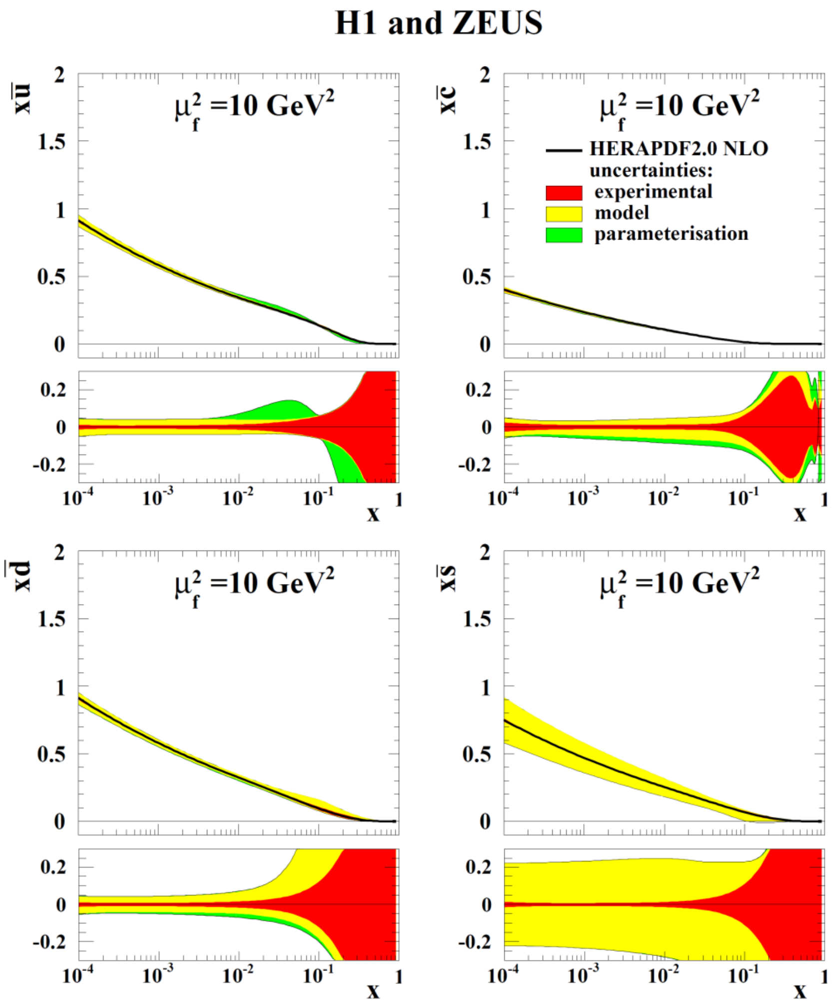
NNLO



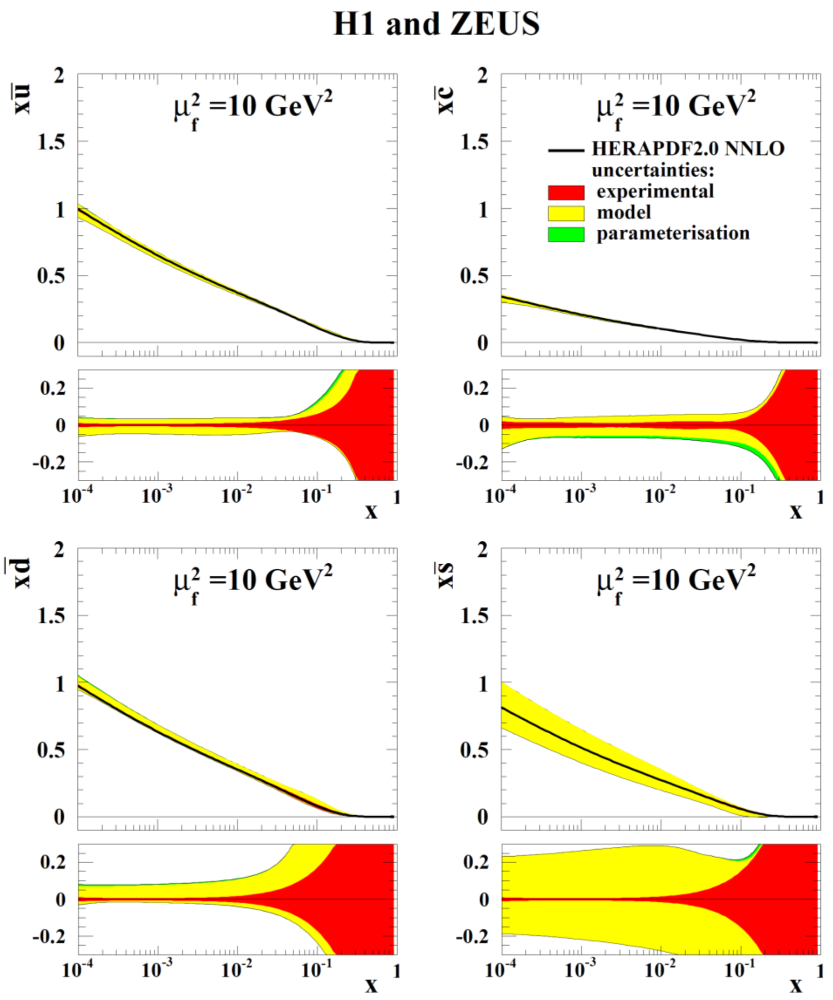
The HERAPDF2.0AG is an alternative gluon parametrisation which is positive definite for all x and all $Q^2 > Q^2_0$

HERAPDF2.0: NLO and NNLO fits

NLO

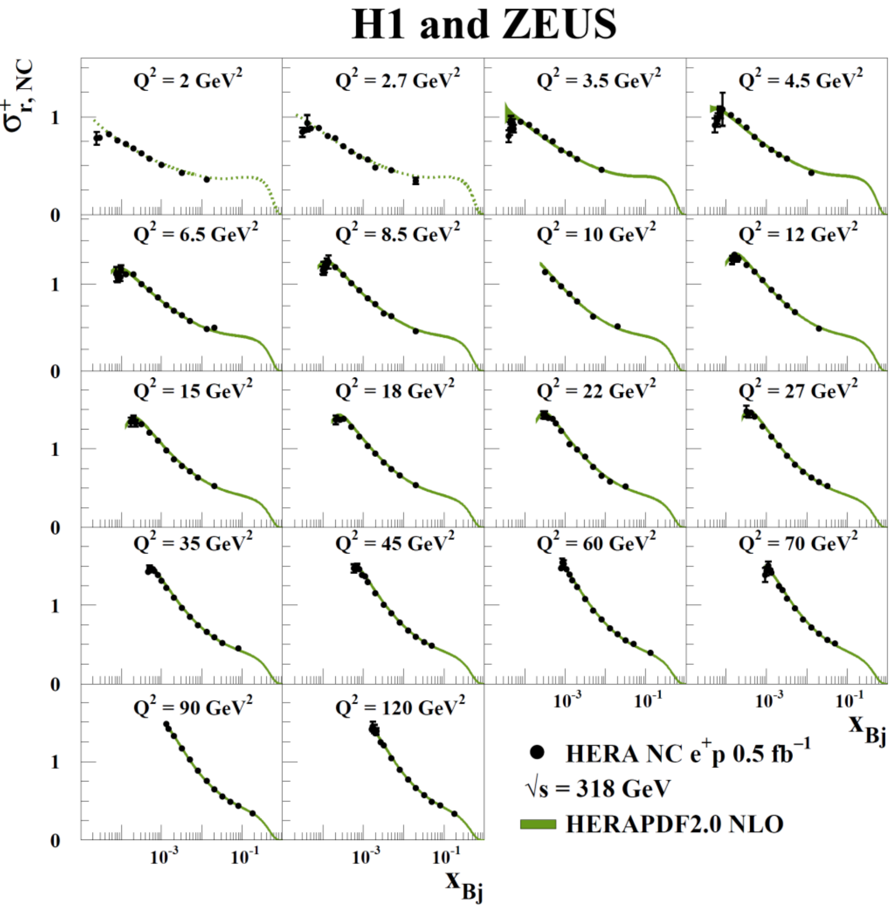


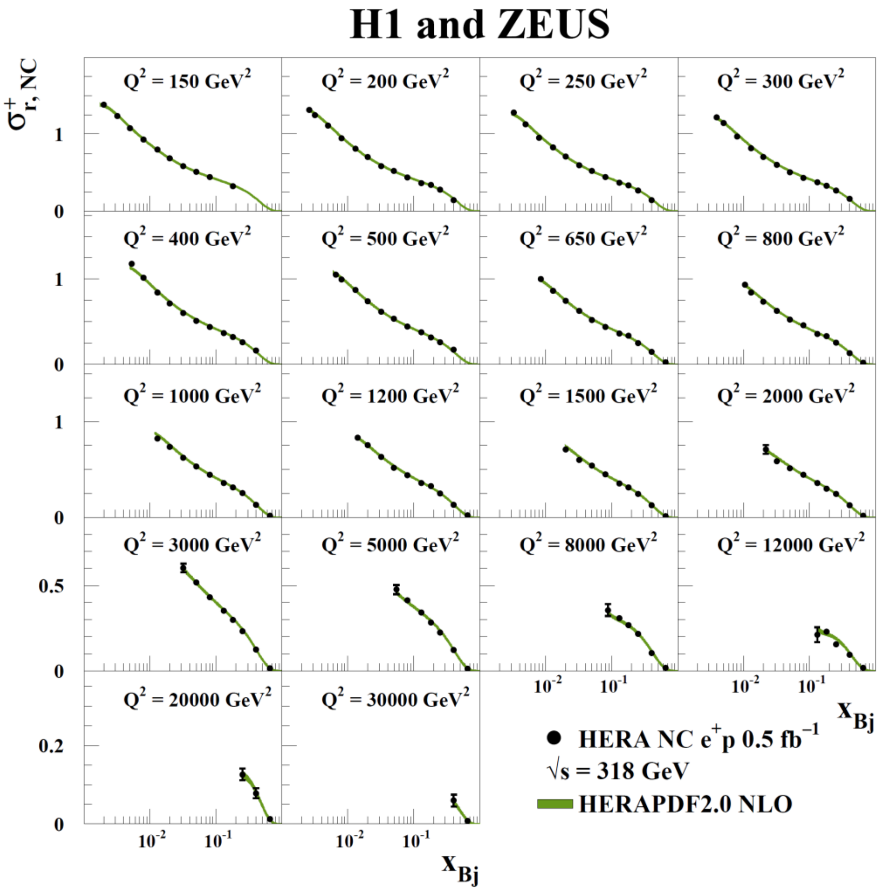
NNLO



Flavour break-up of the sea

HERAPDF2.0 compared to data

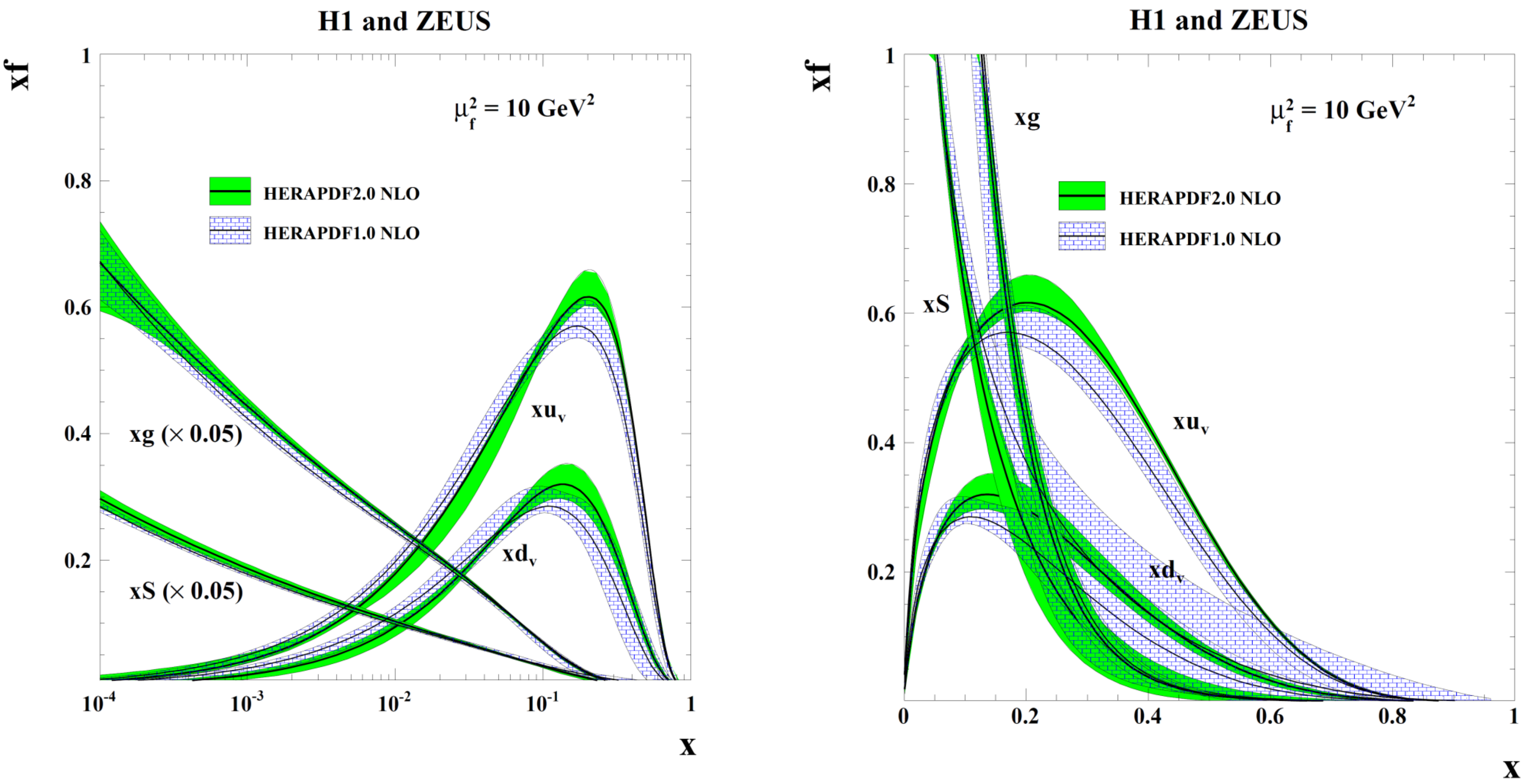




Here is the comparison to the NC e^+ data for $2 < Q^2 < 30000$ GeV^2

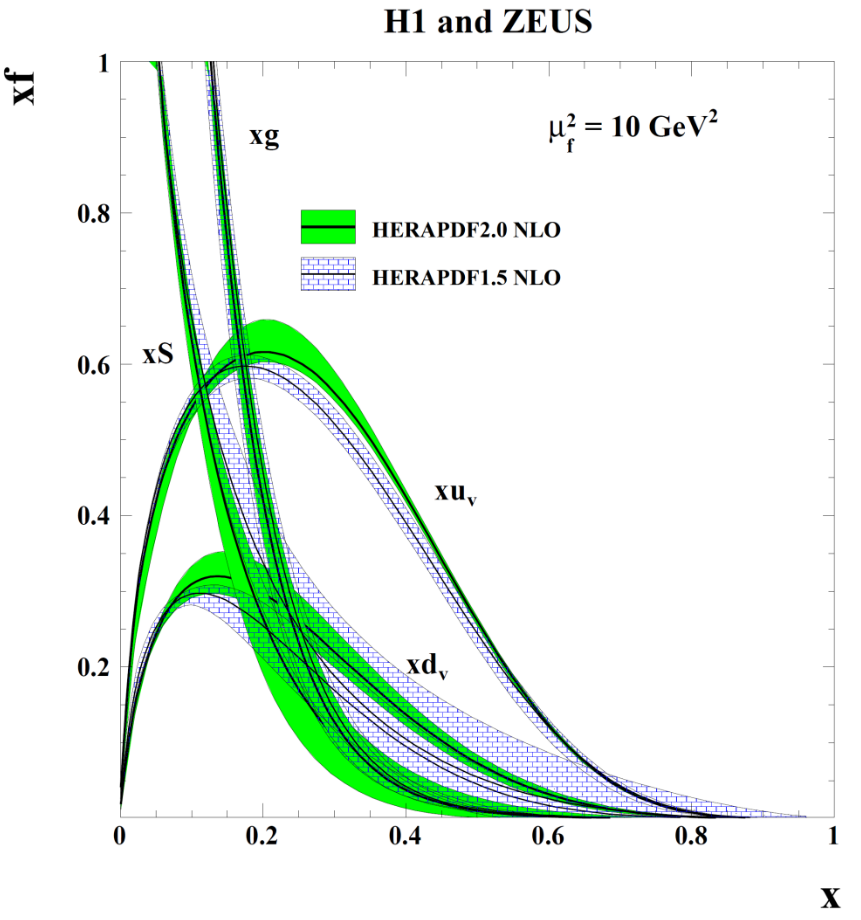
NLO and NNLO fits look very similar (check back to slide 6)

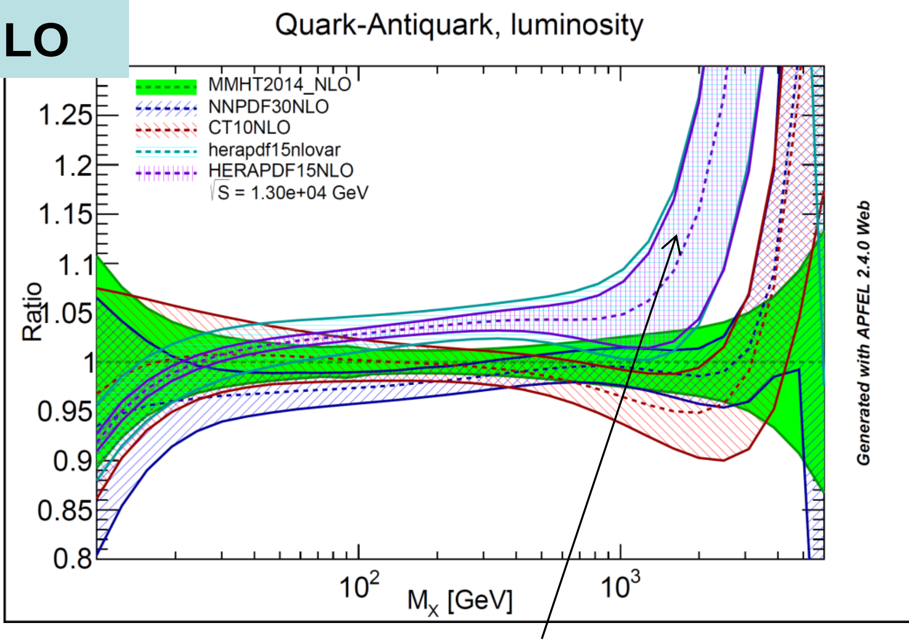
Compare HERAPDF2.0 to HERAPDF1.0 at NLO



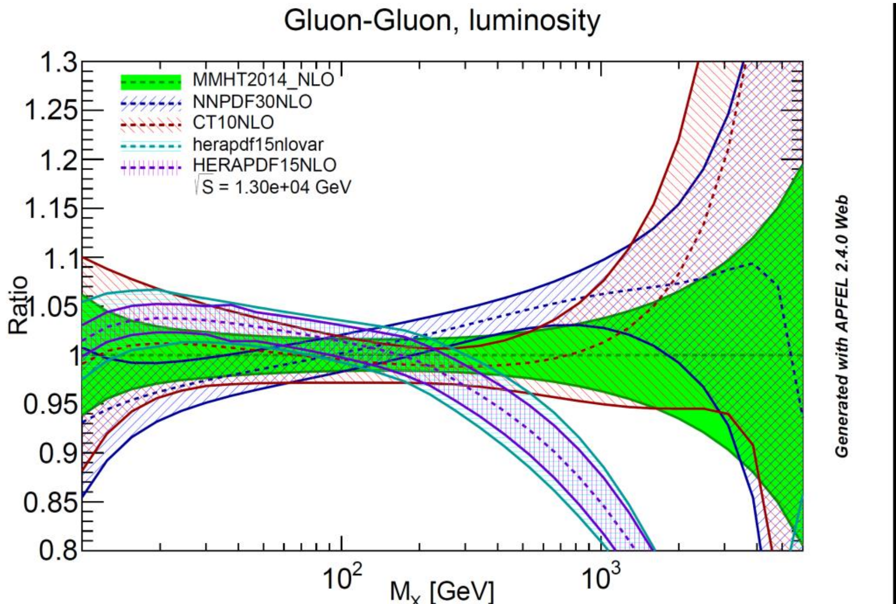
Much more high-x data
Substantial reductions in high-x uncertainty
Some change in valence shape

Compare HERAPDF2.0 to HERAPDF1.5 at NLO



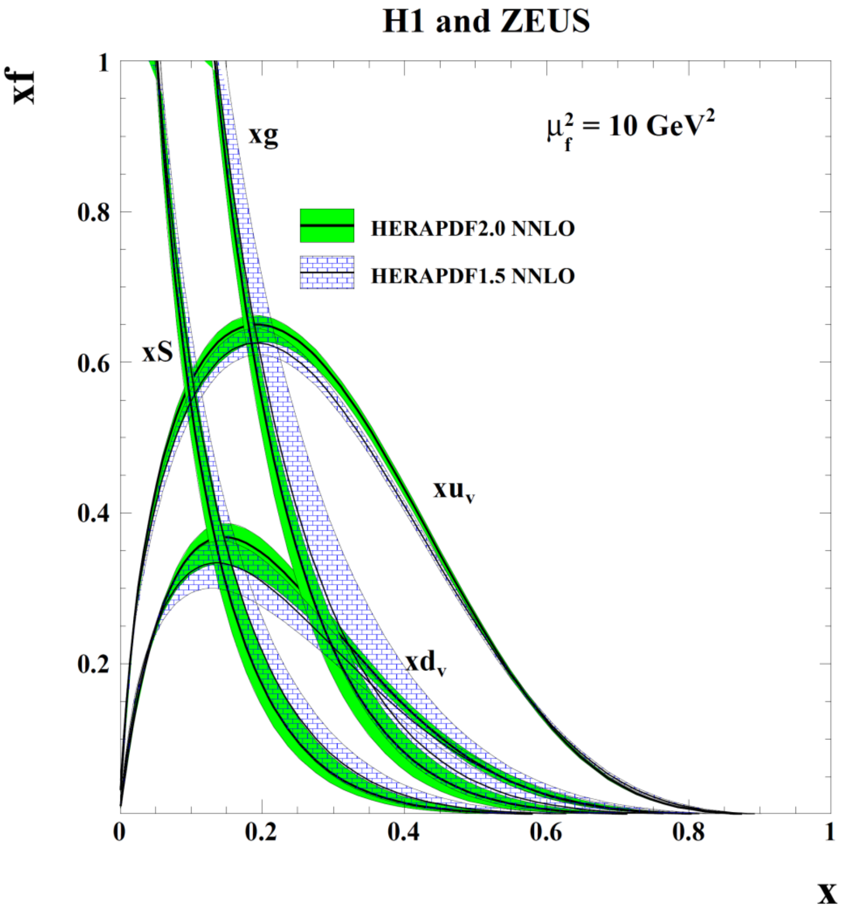


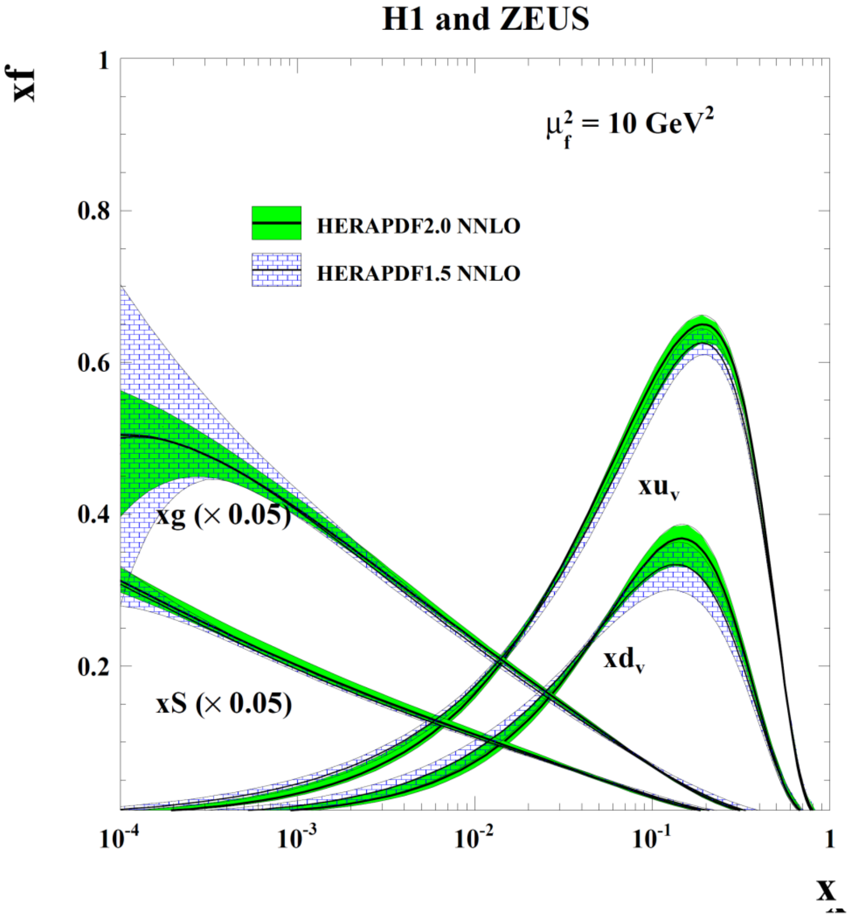
So the q-qbar luminosity at high-x comes down for HERAPDF2.0



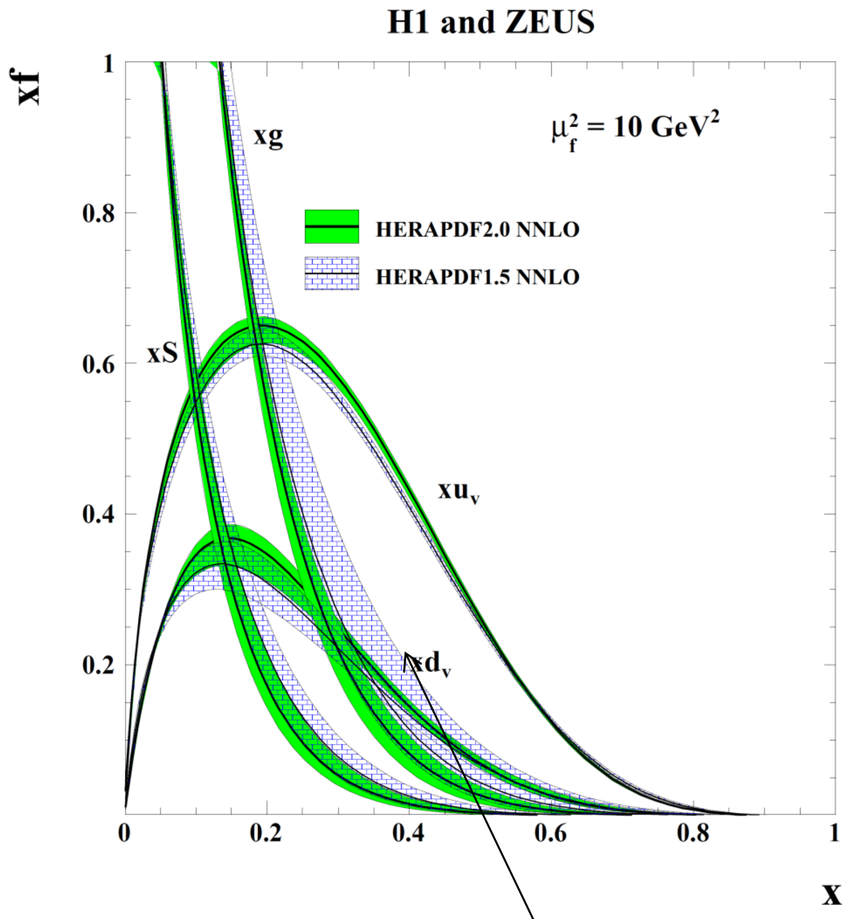
- HERAPDF1.0 and 1.5 had rather hard high-x sea, harder than the gluon (within large uncertainties).This is no longer the case and uncertainties are much reduced
- HERAPDF1.0 and 1.5 had a soft high-x gluon this moves to the top of its previous error band- but is still soft (at NLO)

Compare HERAPDF2.0 to HERAPDF1.5 at NNLO

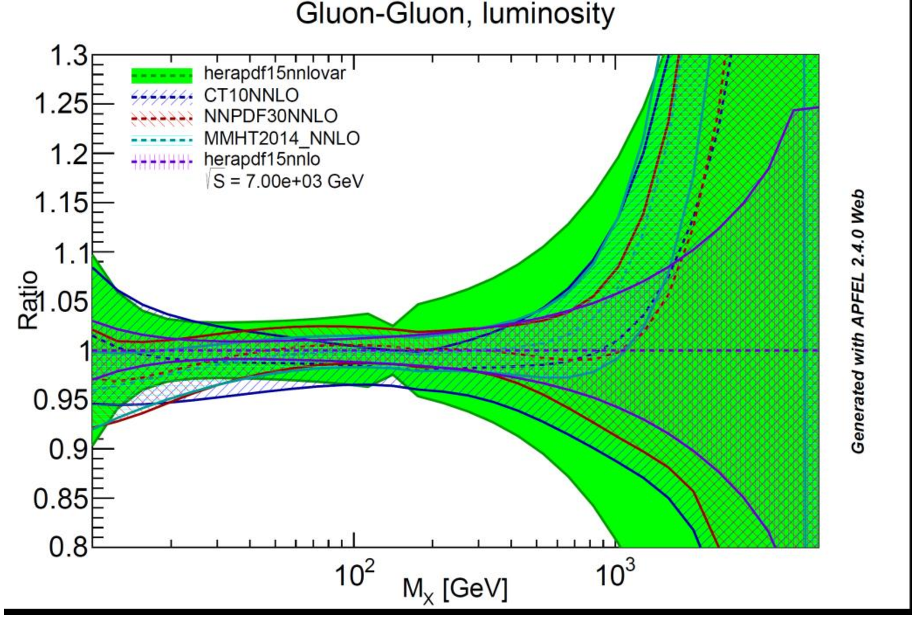




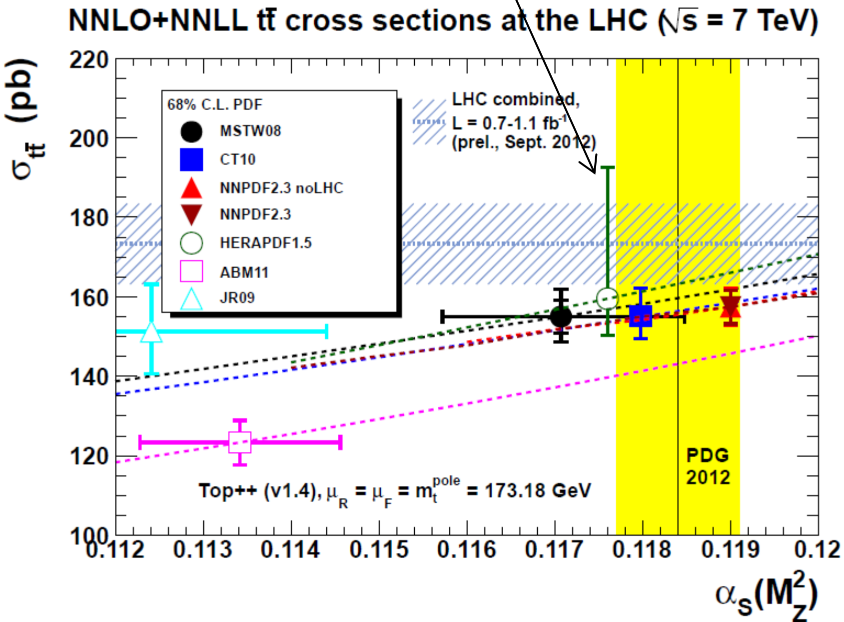
Reduction in gluon uncertainty both at low-x and high-x.
A lot of this reduction is because the model variation due to variation of Q^2 cut is not as dramatic now that we have more data.



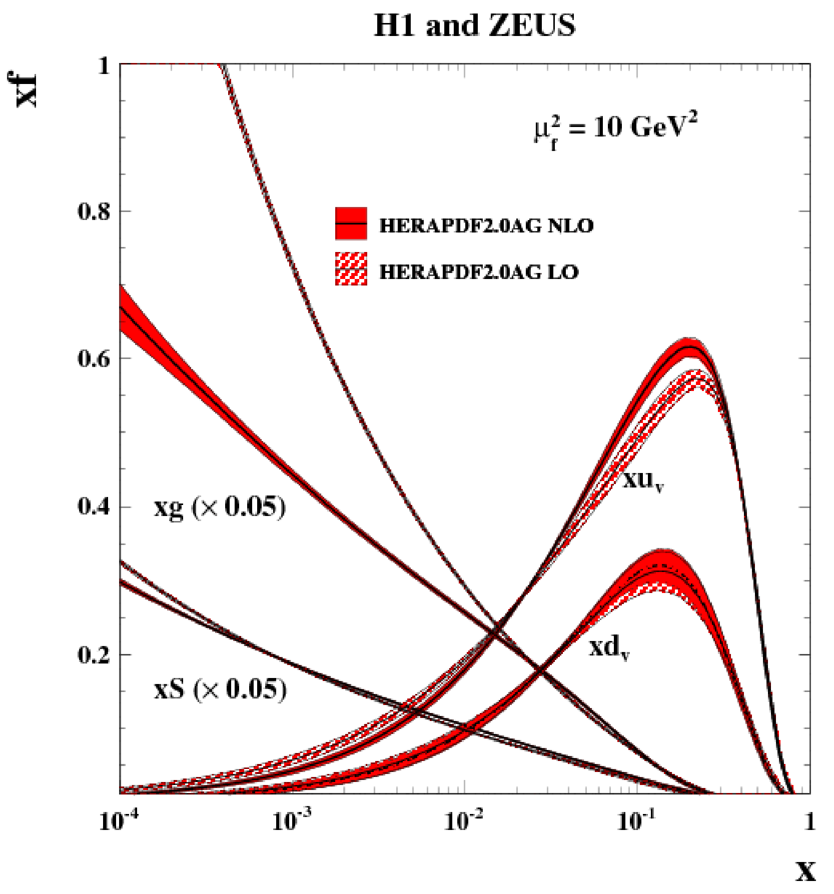
The HERAPDF1.5 gluon was not soft compared to global PDFs. However it had a large error band.
This uncertainty on the gluon decreases and ihe central value moves to the lower end of its previous error band



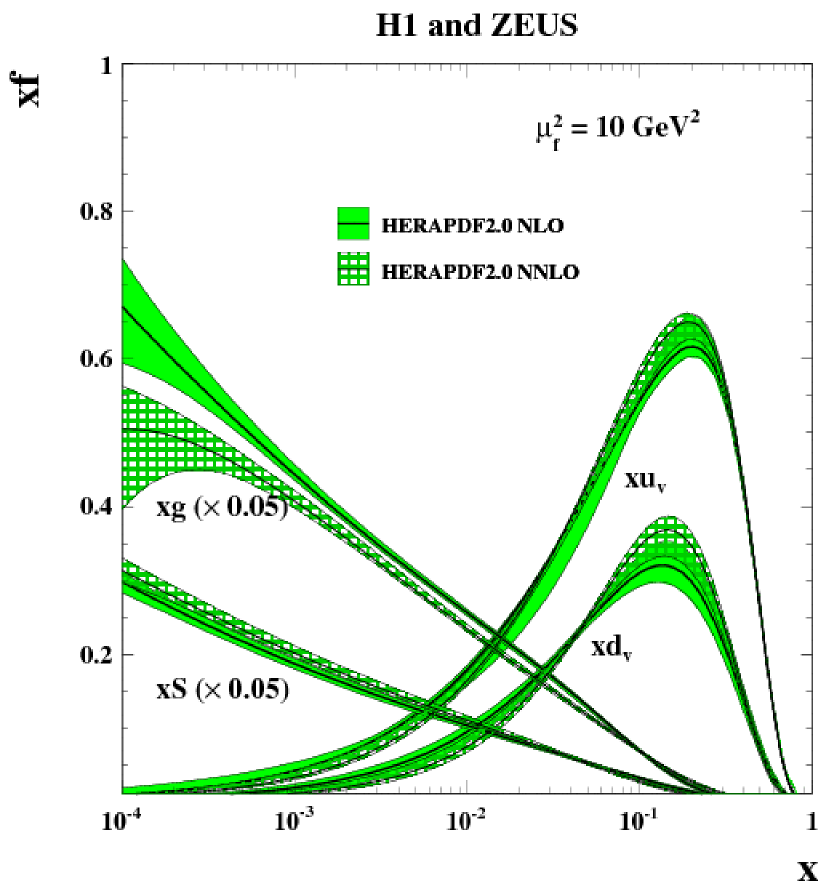
So this uncertainty on the g–g luminosity will also decrease and thus the uncertainty on the t-tbar cross section



HERAPDF2.0 at LO, NLO and NNLO

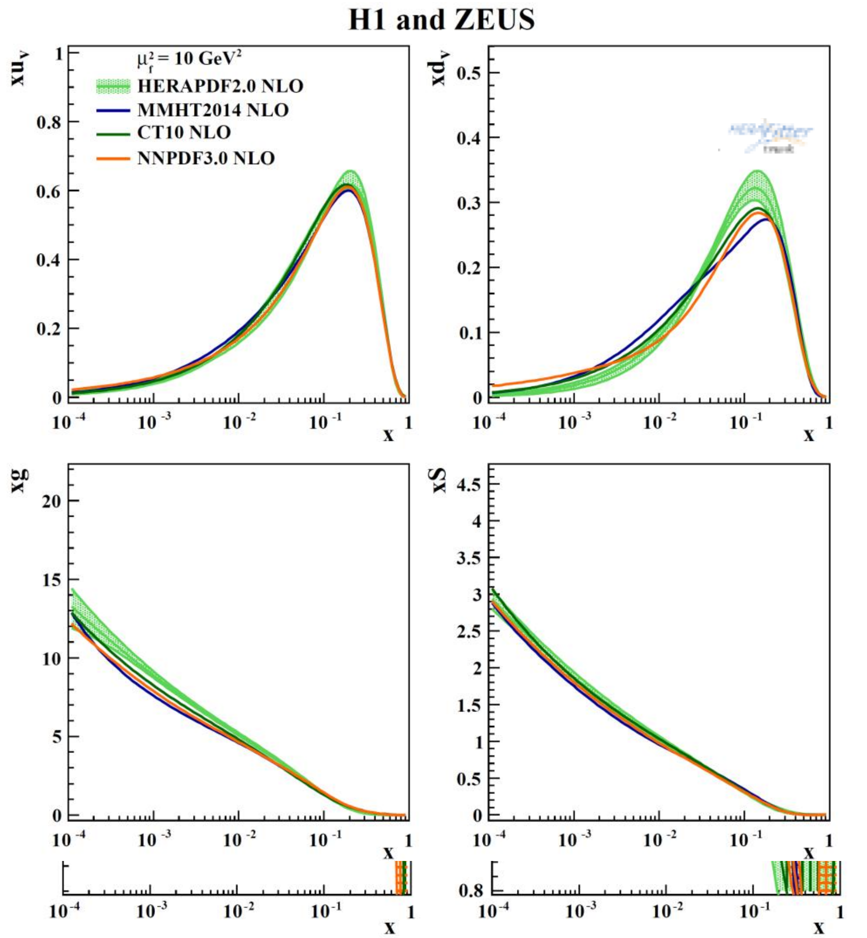


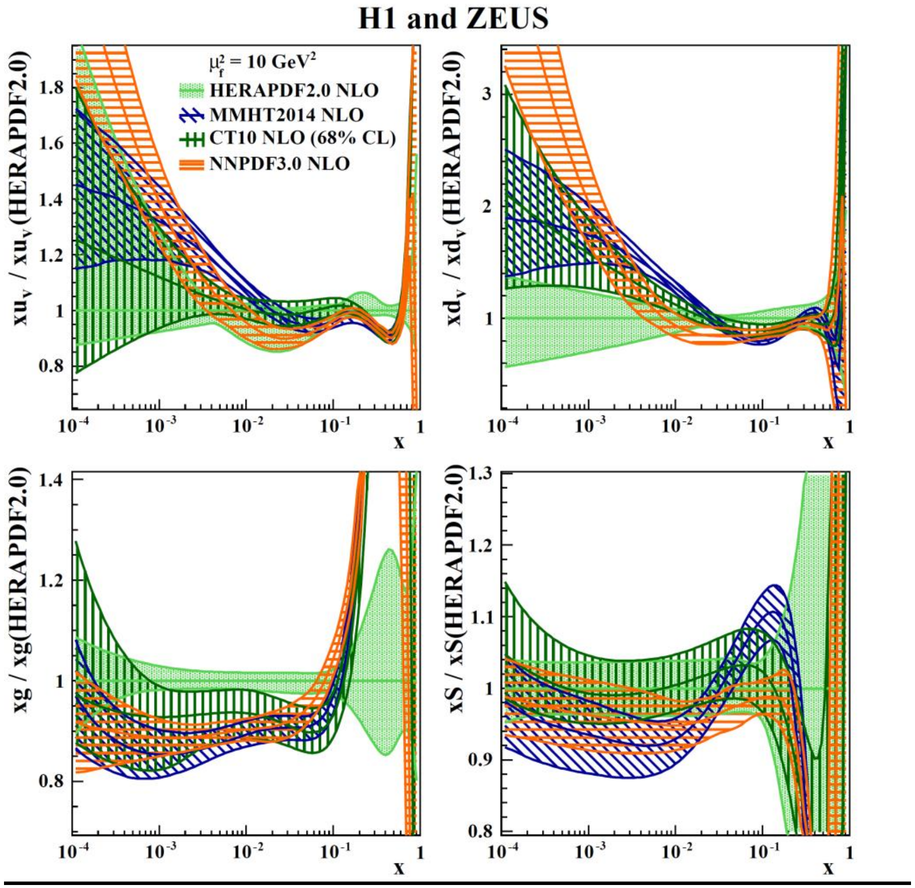
HERAPDF2.0 LO is only available with experimental uncertainties and is here compared to NLO also with experimental uncertainties.
In both cases the alternative gluon parametrisation is used



HERAPDF2.0 NLO and NNLo are compared with full uncertainties.
In both cases a more flexible gluon parametrisation with a term which allows the gluon to be negative at low-x and low Q^2 values is used

Compare HERAPDF2.0 to other PDFs at NLO

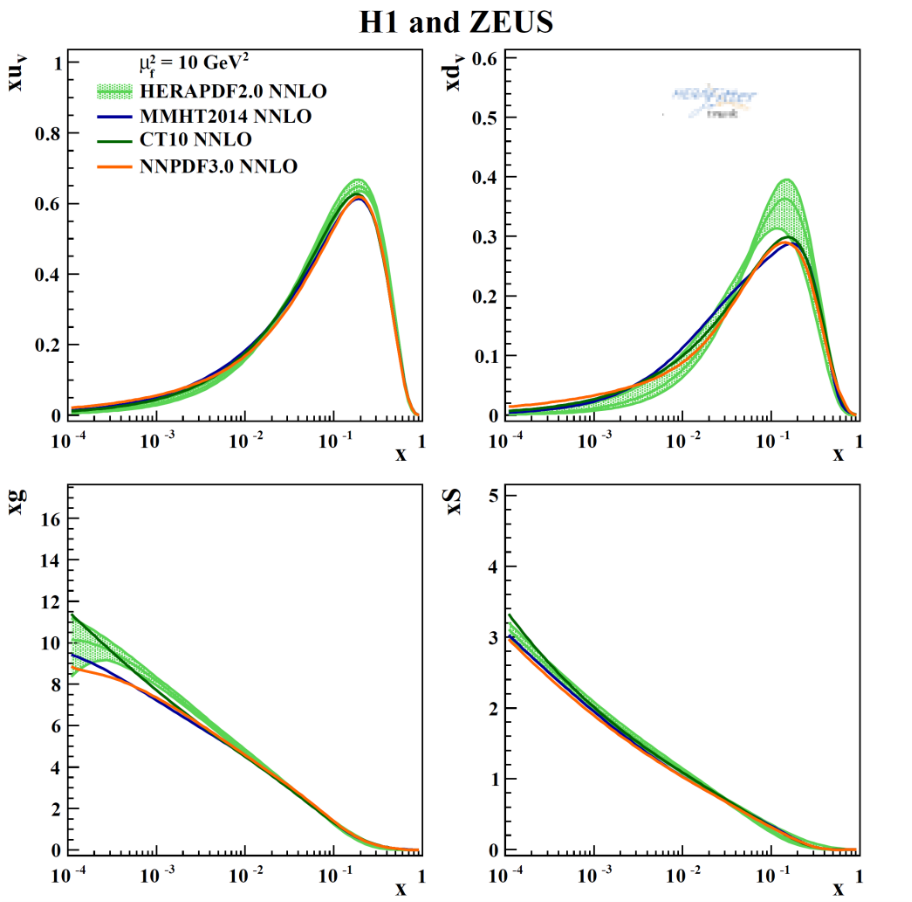


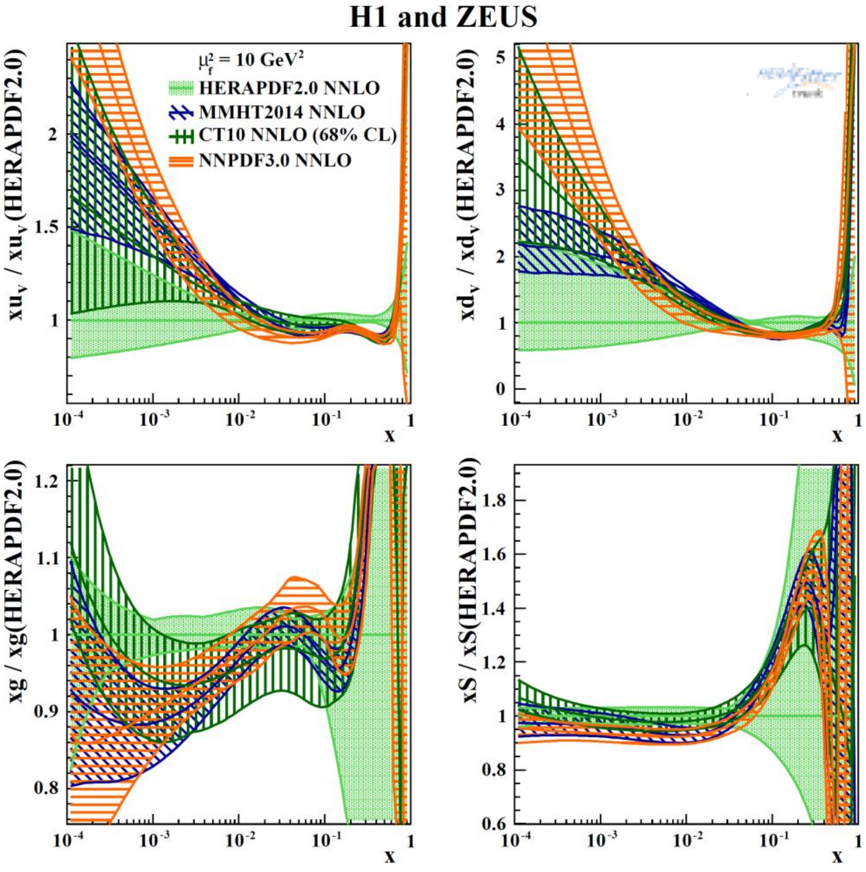


High-x valence shapes somewhat different– new high- x data and use of proton target only

Other PDFs have harder high-x gluon, but Sea is more compatible

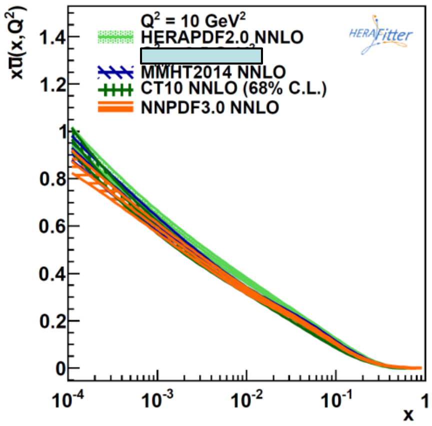
Compare HERAPDF2.0 to other PDFs at NNLO

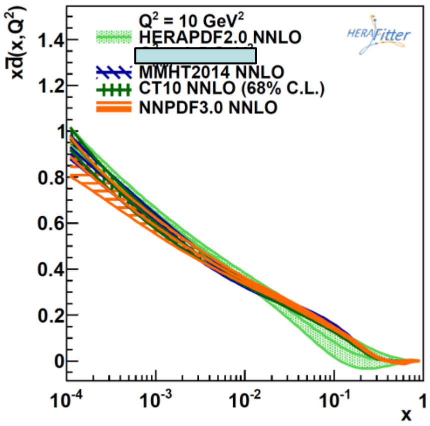


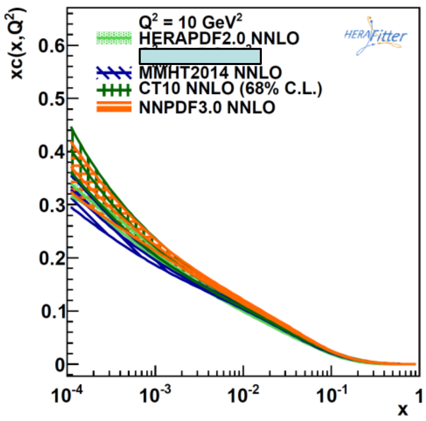


High-x valence shapes somewhat different – new high- x data and use of proton target only

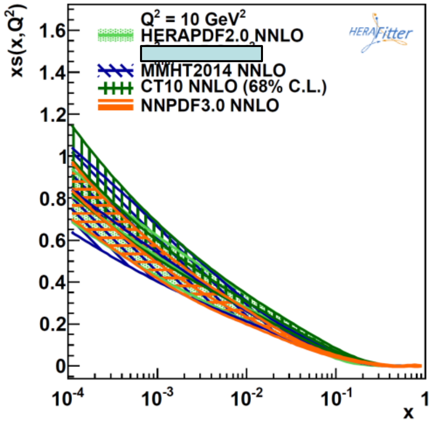
At NNLO gluon and Sea are both compatible with other PDFs



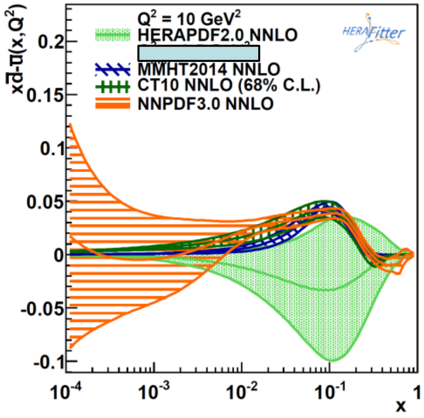


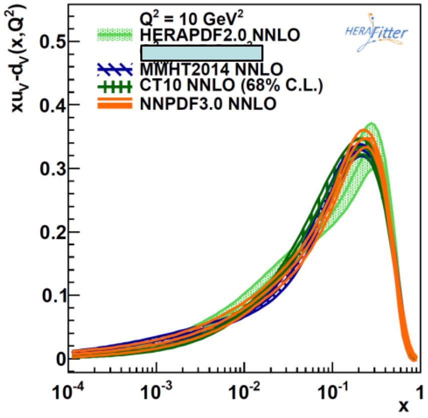


$u_{valence} - d_{valence}$ dominates the W-aymmmetry at Tevatron and LHC

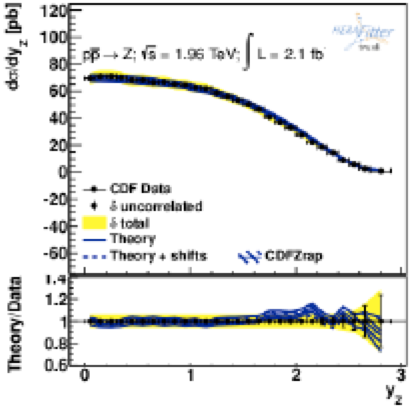


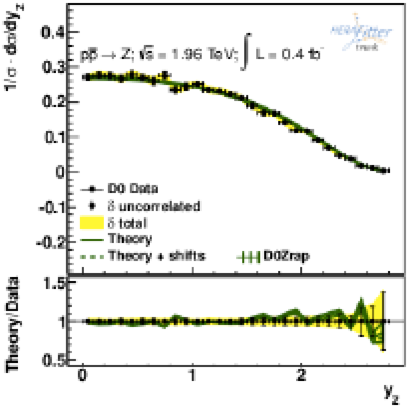
And here are more details on the flavour break up of the Sea
In particular
dbar-ubar is negative but with large uncertainties, which cover other PDFs



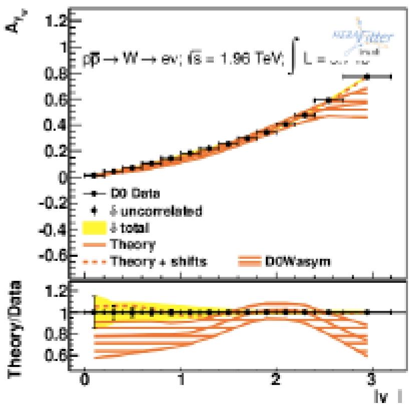


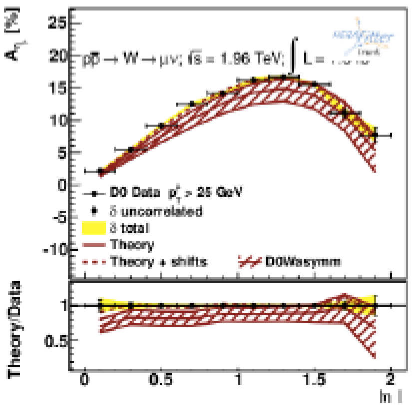
Compare HERAPDF2.0 to Tevatron and LHC W,Z data

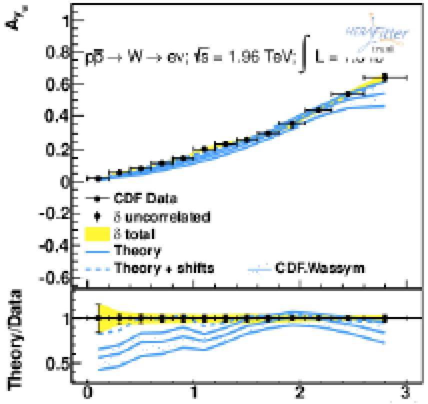


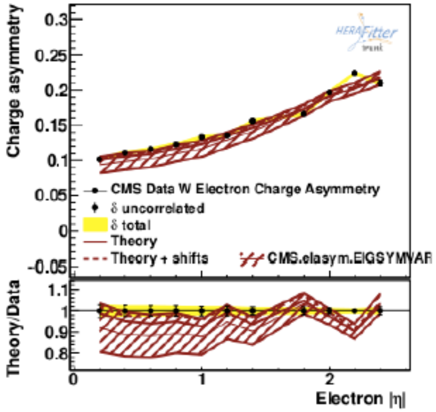


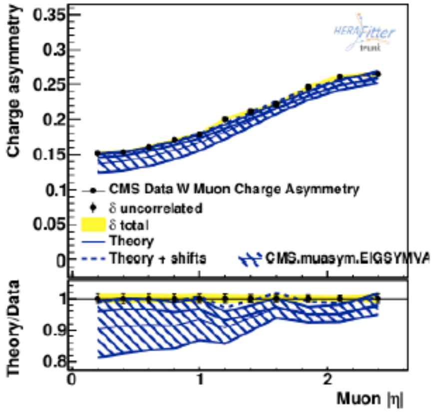
Similar level of agreement as the global PDFs





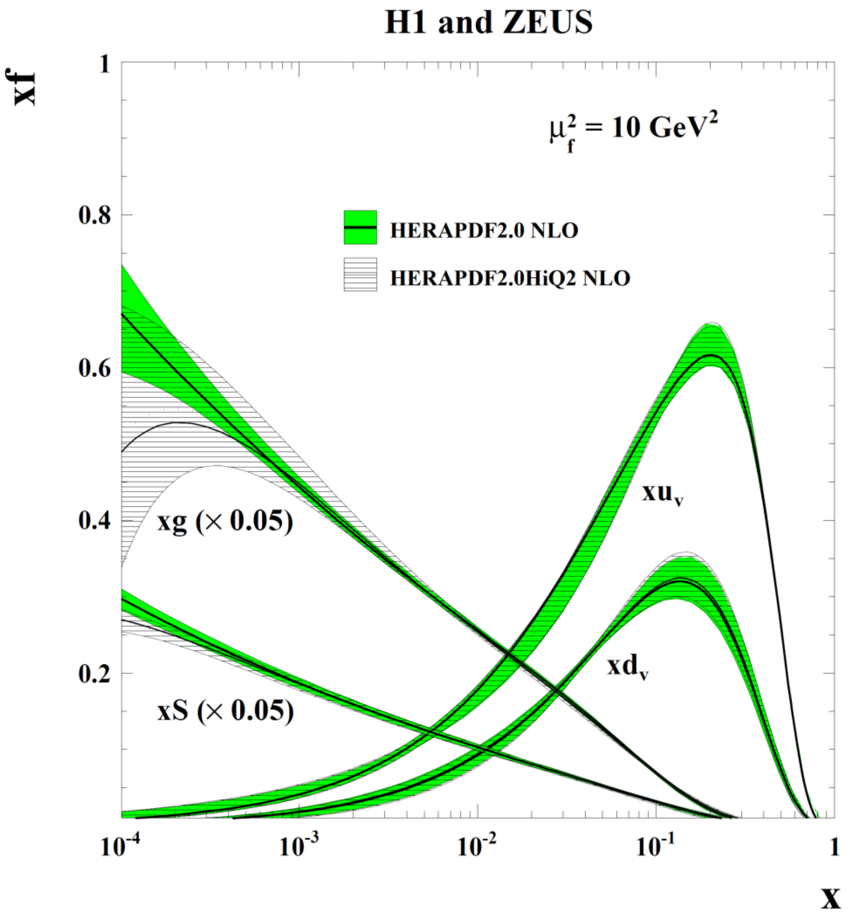


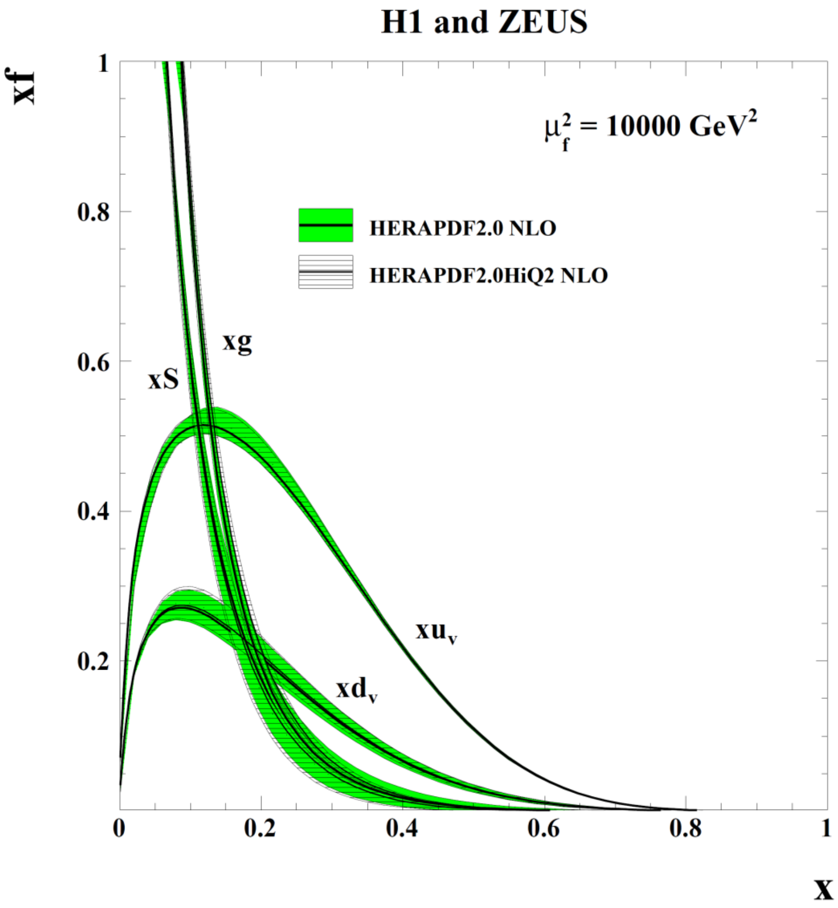




Thanks to V. Radescu

Compare HERAPDF2.0HiQ2, with Q2>10GeV^2 , to the standard fit at NLO

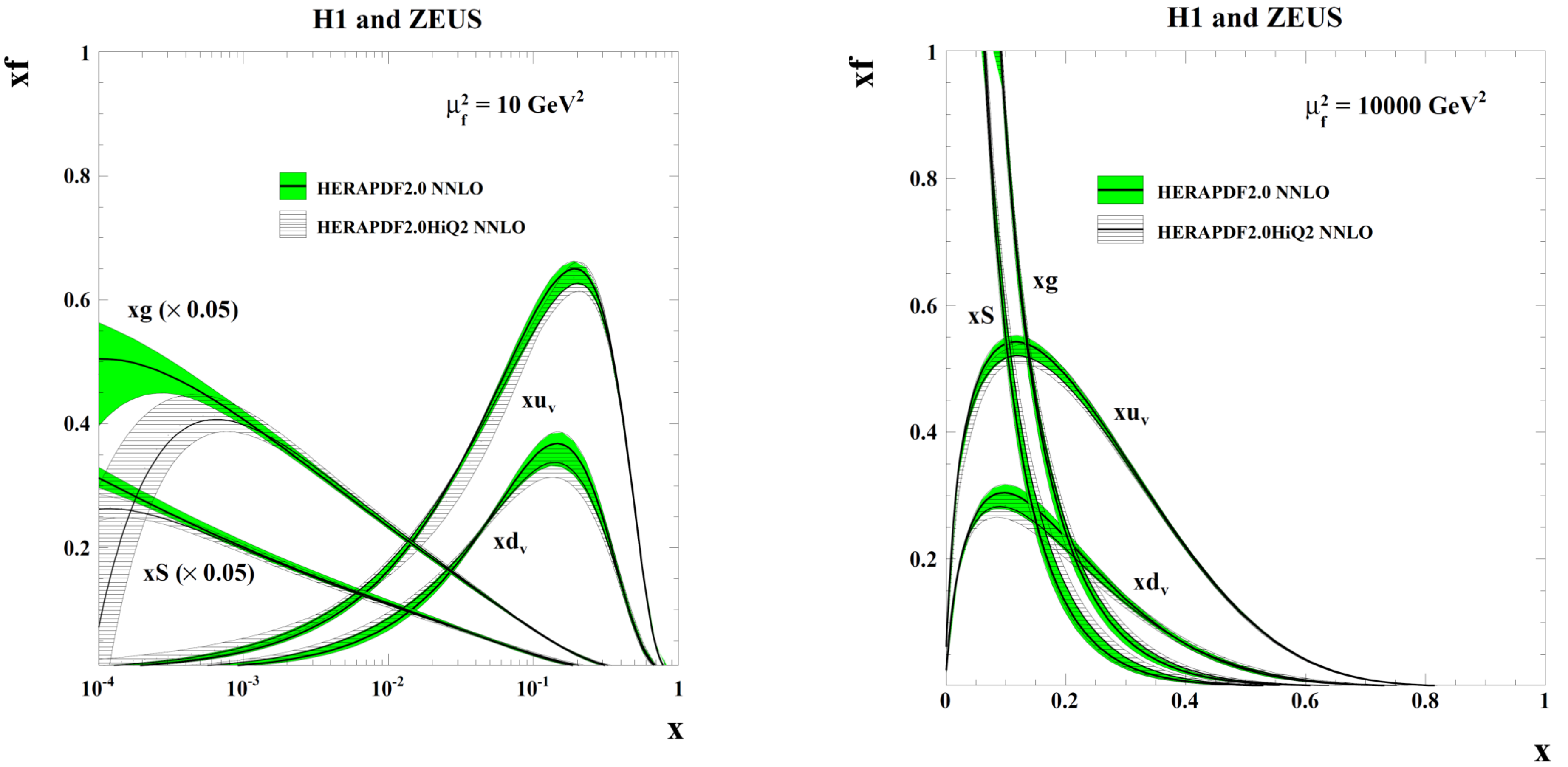




The purpose of this is to check for bias introduced by using low Q^2, low-x data in the fit. Fits are compatible. At large x all PDFs are similar for 2.0 and 2.0HiQ2 thus there is no bias at high scale due to the inclusion of the lower Q^2, lower x data This is also true at NNLO.

There is greater uncertainty at low-x for Sea and glue there is some small change of gluon and sea shape at low-x.

Compare HERAPDF2.0 with Q2>10GeV^2 to the standard fit at NNLO



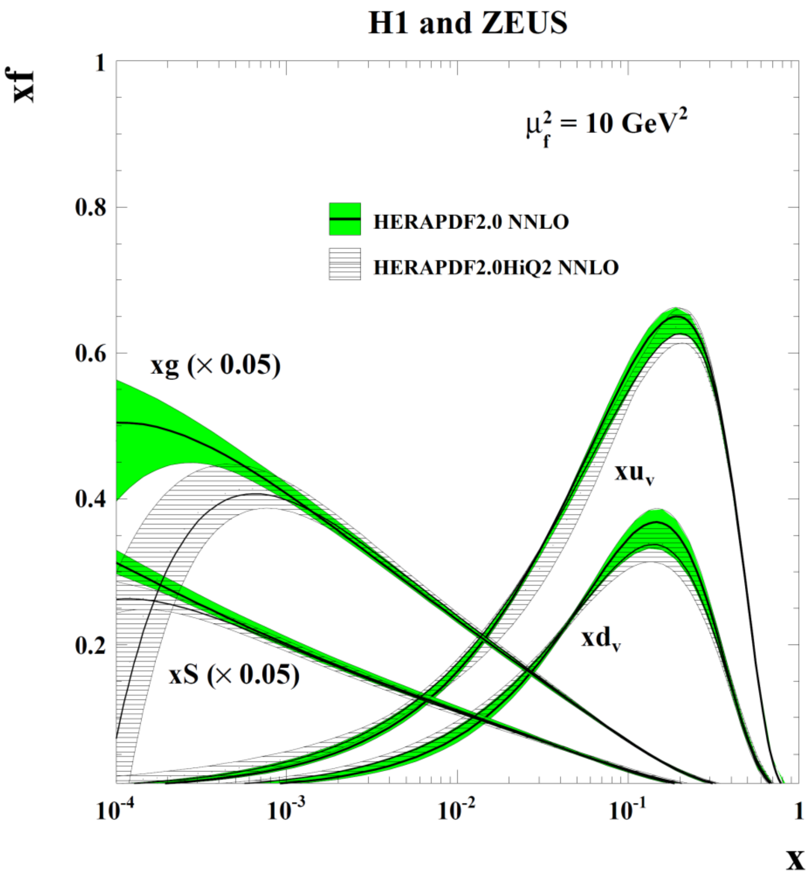
Fits are VERY compatible at high-x ---like in NLO case

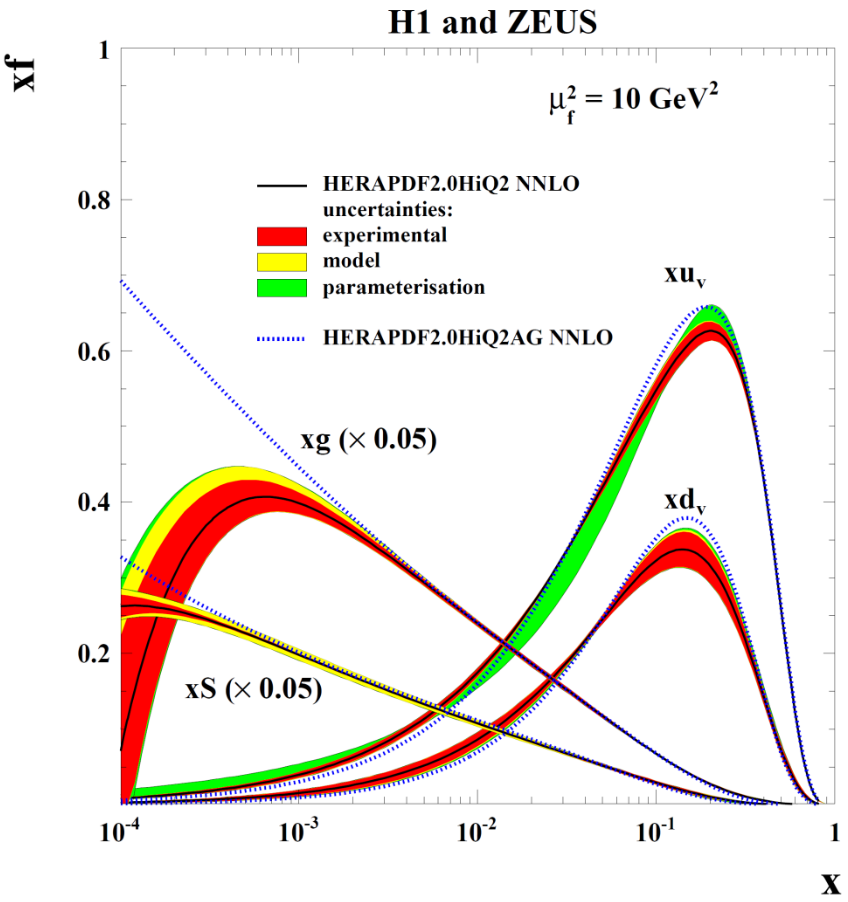
BUT the difference in shape for low-x Sea and gluon– has now become pronounced- fits are no longer compatible

There is still no bias from including the lower Q^2, lower x data in the fits if we move to LHC scales ---for the ATLAS,CMS kinematic regimes.

However at very low-x and moderate Q^2 --as in LHCb --the NNLOfit for Q$^2_{min}$=10 cannot be used--- the gluon becomes negative and so does the longitudinal cross section

Compare HERAPDF2.0 with Q2>10GeV^2 to the standard fit at NNLO





Fits are VERY compatible at high-x ---like in NLO case

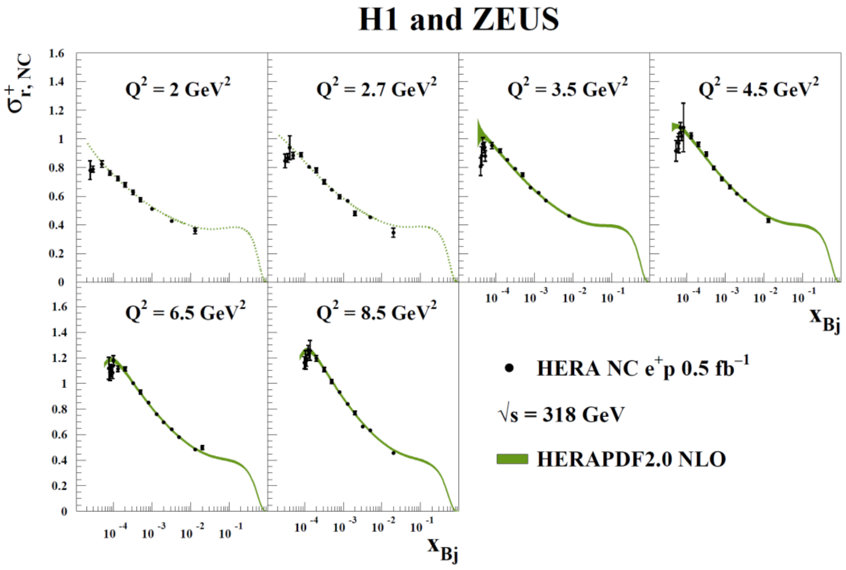
BUT the difference in shape for low-x Sea and gluon– has now become pronounced.

At very low-x and moderate Q^2 --as in LHCb --the NNLOfit for Q$^2_{min}$=10 gives a negative gluon and a negative longitudinal cross section, and thus is not fit for purpose.

Can use the HERAPDF2.0HiQ2AG– alternative gluon shape—$xg(x) = A_g\, x^{Bg}\, (1-x)^{Cg}\, (1+D_g x)$, which cannot be negative at any x for Q^2 > Q$^2_0$, but fit χ2 is larger by Δχ2~+30

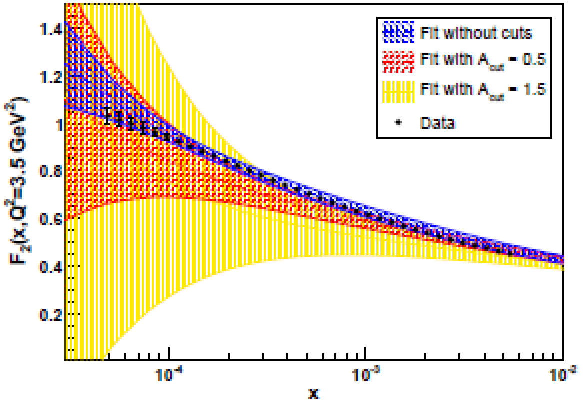
Does this indicate a breakdown of DGLAP at low x?

Low Q^2, low-x

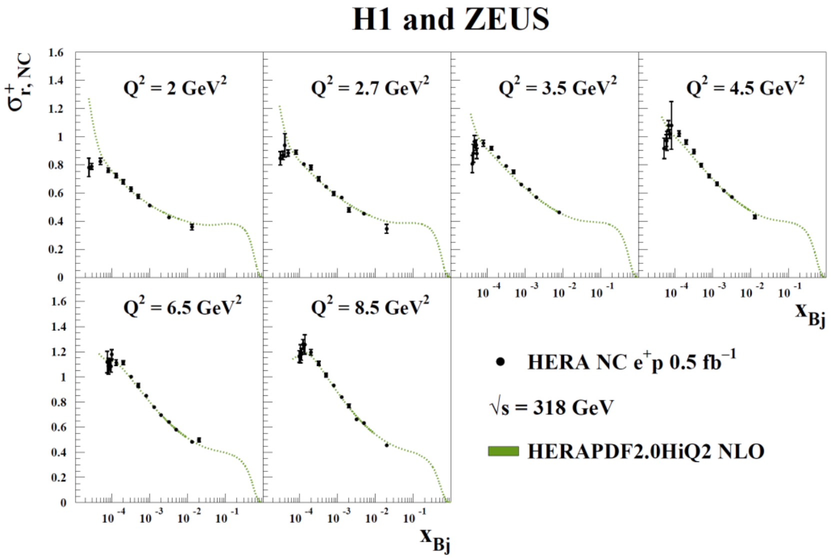


NLO

$Q^2>3.5$ GeV^2



Reminds us of this? arXiv:0910.3143. The fit evolves faster than the data– so going to higher order NNLO does not improve this



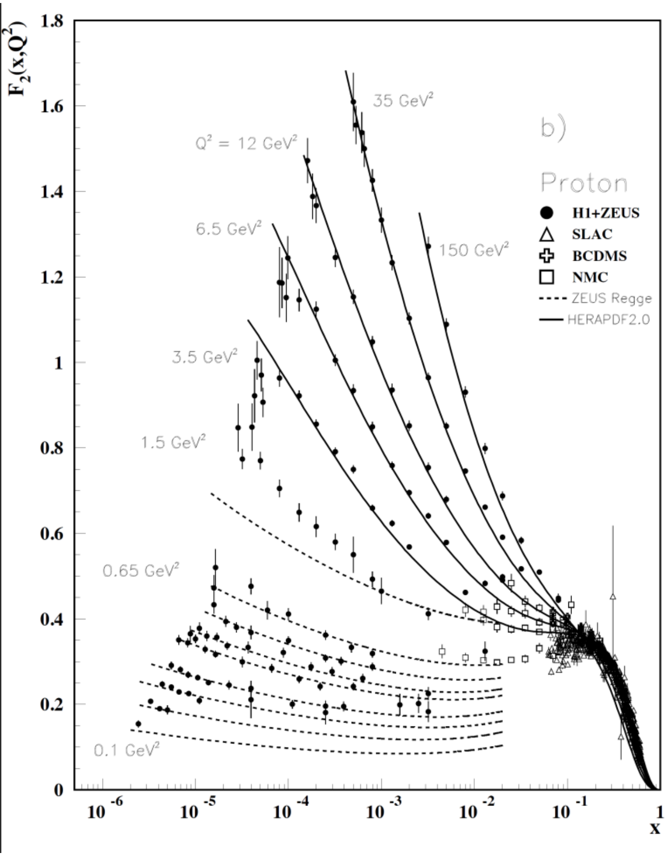
NLO

$Q^2>10$ GeV^2

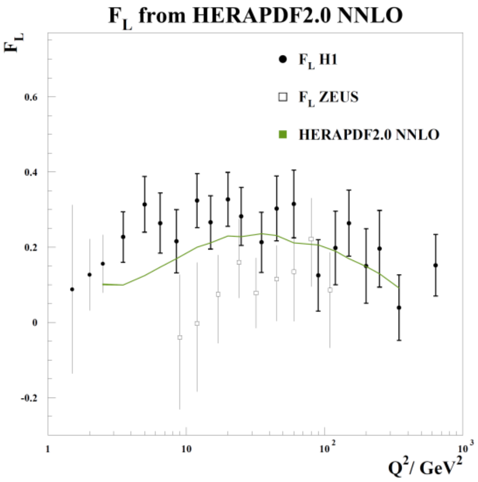
These are the comparisons of the fit to the NC e+p data at low Q^2

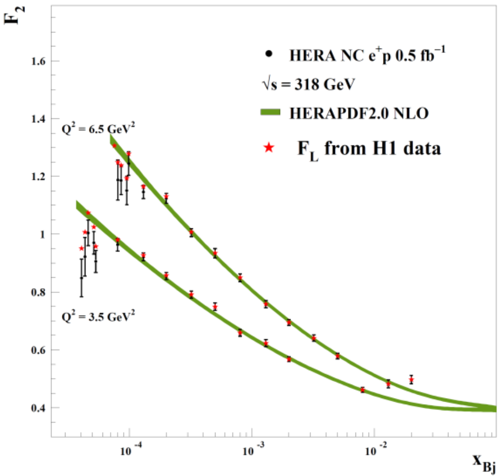
The fit with $Q^2>10$ misses the lower Q^2 data in a systematic matter undershooting the data – worse at low-x and low Q^2---and not describing the high-y turn over

There is a further interesting observation to be made about the high-y turn over.
It comes from the F_L term in the reduced cross-section
We can calculate F_2 by correcting the reduced cross section for F_L: $\sigma_{red} = F_2 - y^2/2\ F_L$
We use the HERAPDF2.0 predictions for F_L to do this correction

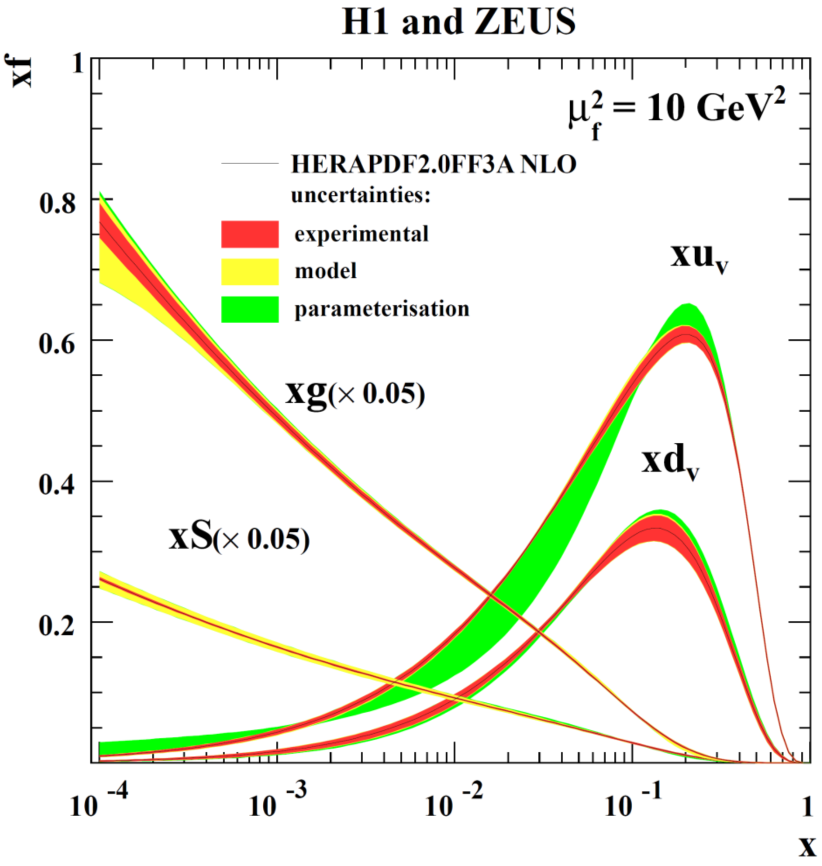


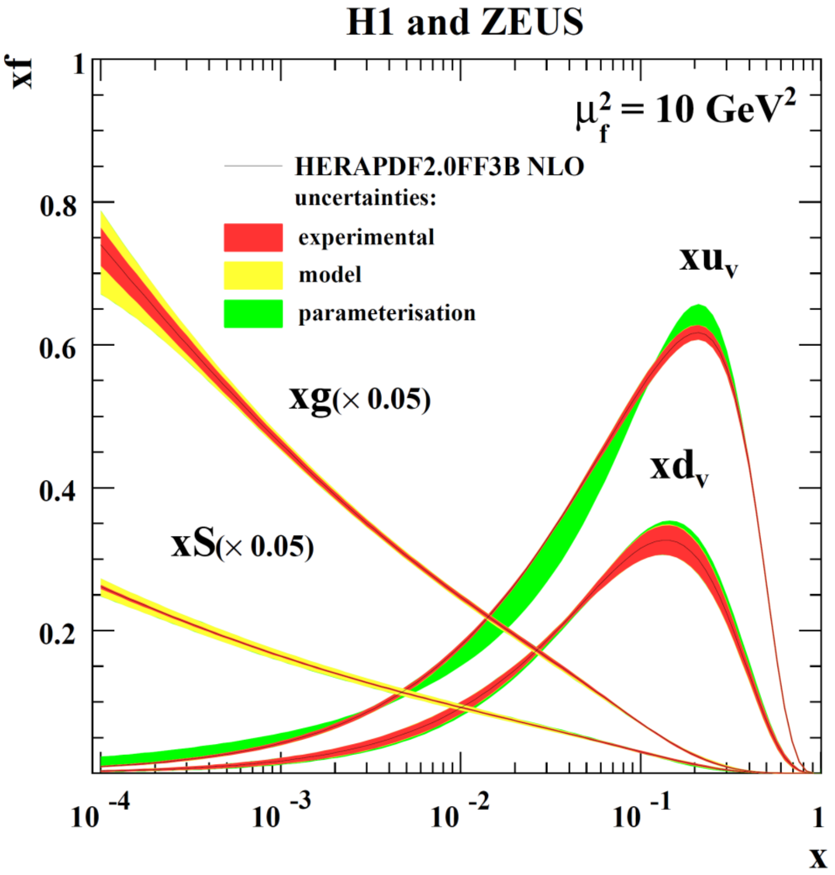
Here is the preliminary figure for the PDG2016 showing F_2 extracted this way.
It shows a turn over in F_2 at low x,Q^2, which is not predicted by NLO or NNLO QCD.
This turn over is there because the predicted values of F_L are low.
Compare the HERAPDF2.0 F_L to the measurements.
However even if we used the somewhat higher measured H1 values for F_L when making the correction to σ_{red} we still have a turn over in F_2.





HERAPDF2.0 Fixed Flavour Number PDFs



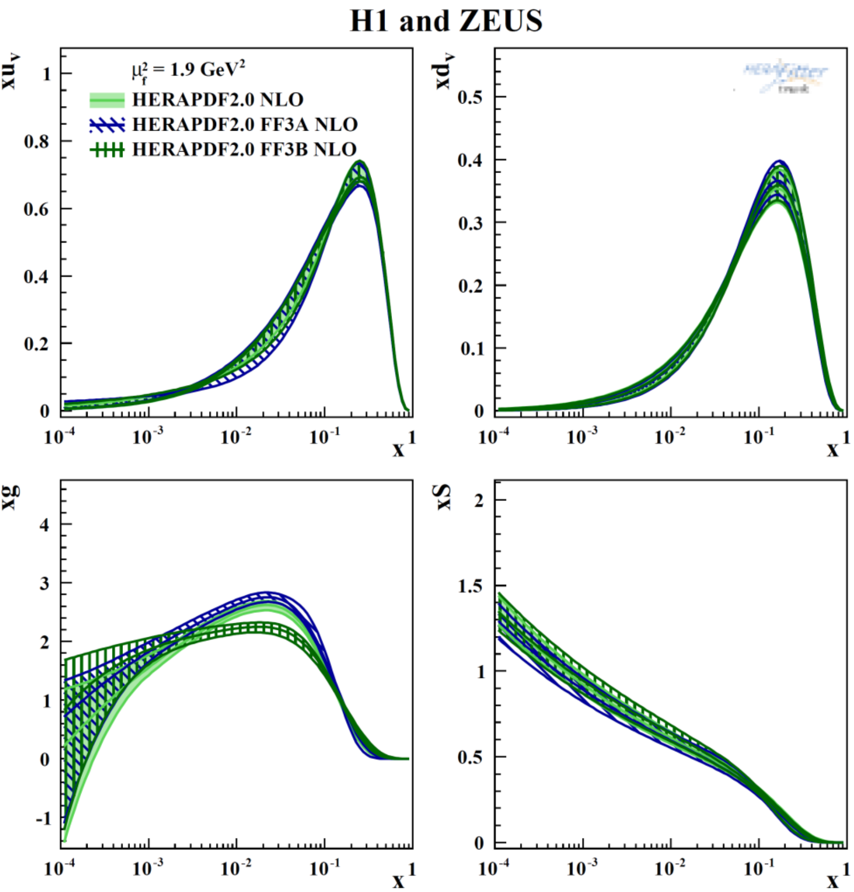


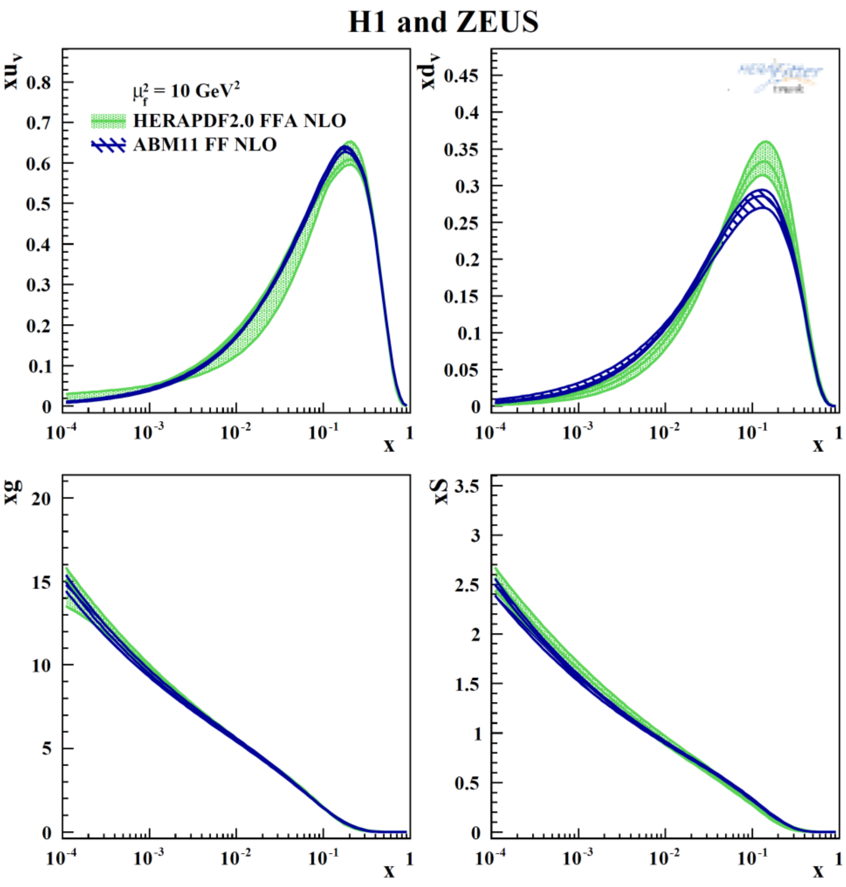
3 flavour running of α_s →

Variable-flavour running of α_s →

scheme	$\alpha_s(M_Z^2)$	F_L	m_c [GeV]	m_b [GeV]
FF3A	$\alpha_s^{N_F=3} = 0.106375$	$\mathcal{O}(\alpha_s^2)$	$m_c^{pole} = 1.44$	$m_b^{pole} = 4.5$
FF3B	$\alpha_s^{N_F=5} = 0.118$	$\mathcal{O}(\alpha_s)$	$m_c(m_c) = 1.26$	$m_b(m_b) = 4.07$

HERAPDF2.0 Fixed Flavour Number PDFs





Comparison of FF3A and FF3B to standard VFN scheme.

FF3A high-x gluon is softer.

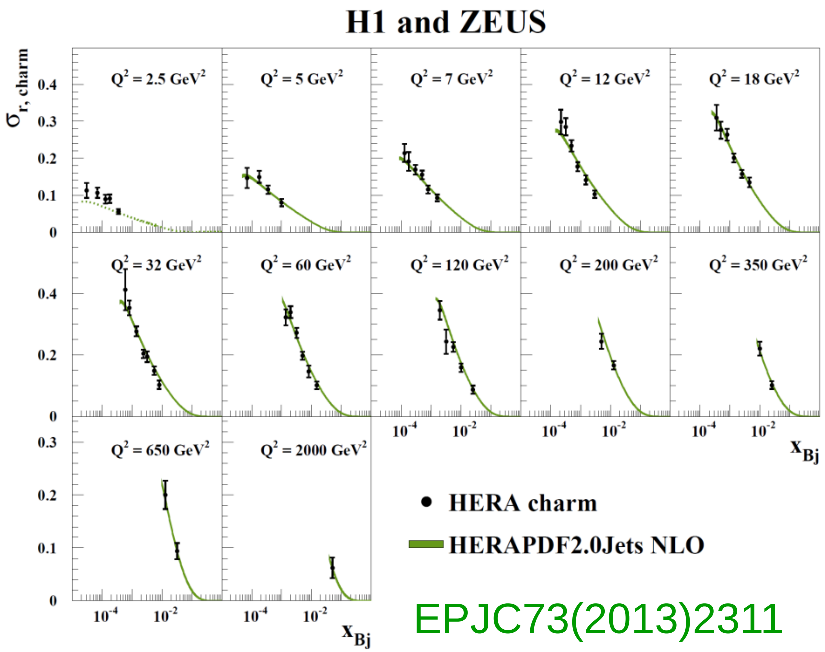
Difference in FF3A and FF3B gluon is due to treatment of O(α_s) in FL and due to the VFN running of α_s in FF3B

Comparison of FF3A to ABM

Similar difference of valence shape as noted for VFN schemes

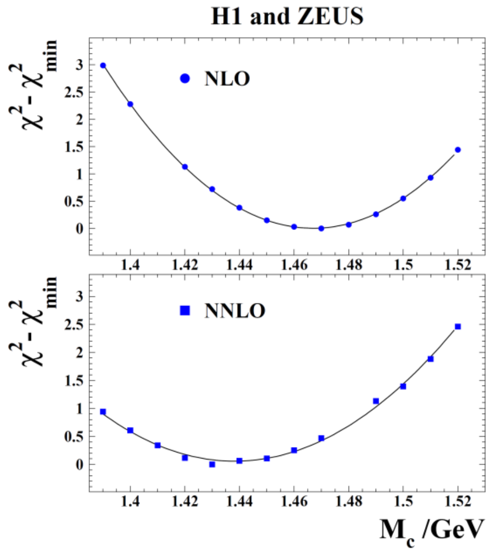
FF3A and ABM gluons are compatible

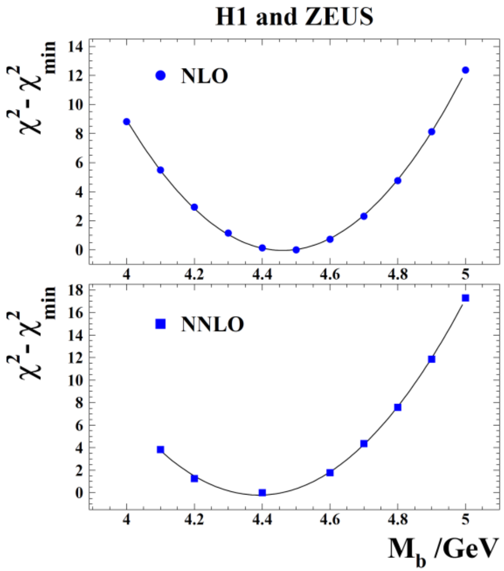
Adding more data to HERAPDF2.0: heavy flavour data



EPJC73(2013)2311

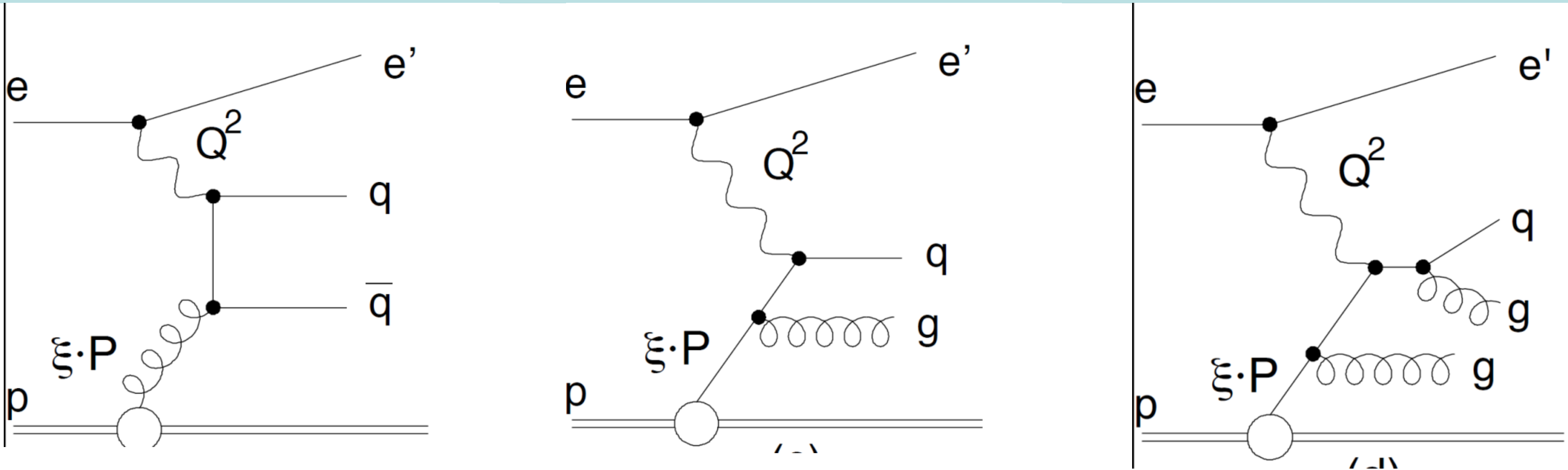
The data from the HERA charm combination is added to the fit.
The PDFs do not change significantly.
The main effect is to determine the optimal charm mass parameter and its variation as already done in the standard HERAPDF2.0.
This variation is much reduced compared to HERAPDF1.0





ZEUS and H1 data on beauty production EPJC75(2015)265
EPJ65C(2010)89
Are similarly used to determine the optimal beauty mass parameter and its variation

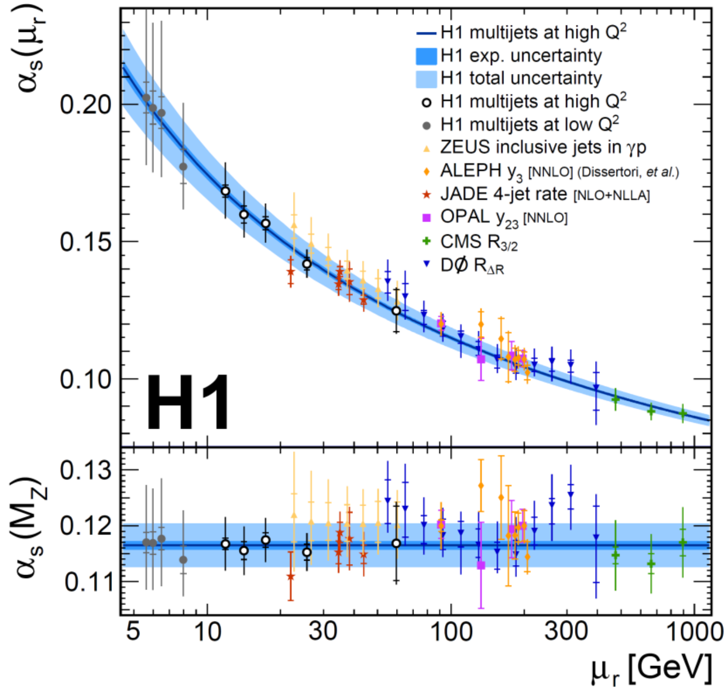
Adding more data to HERAPDF2.0: jet data (EPJC75(2015)2)



It is well known that jet data give a direct handle on the gluon PDF and can be used to measure $\alpha_S(M_Z)$

This recent publication of high Q^2 normalised inclusive jets, di-jets, tri-jets from H1 has been used for a measurement of

$\alpha_S(M_Z) = 0.1165 \pm 0.0008(\text{exp}) \pm 0.0038(\text{pdf,theory})$



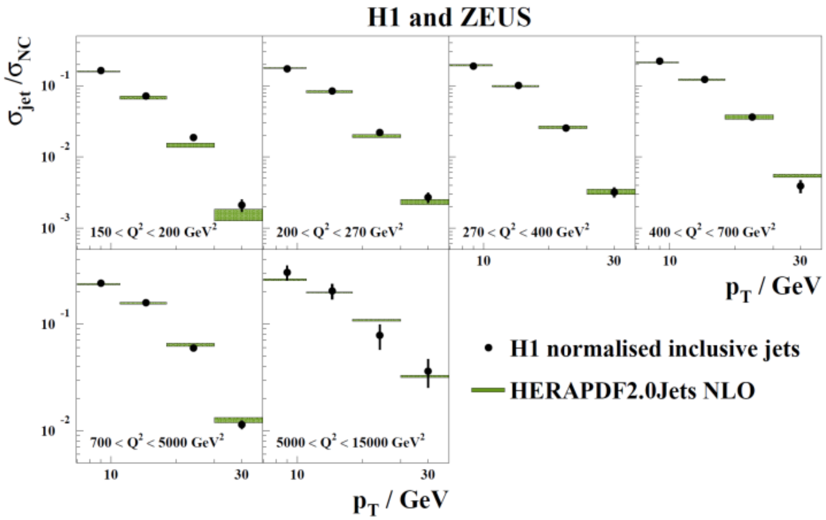
Seven data sets on inclusive jet, dijet, trijet production at low and high Q^2, from ZEUS and H1 have been added to the HERAPDF2.0 fit

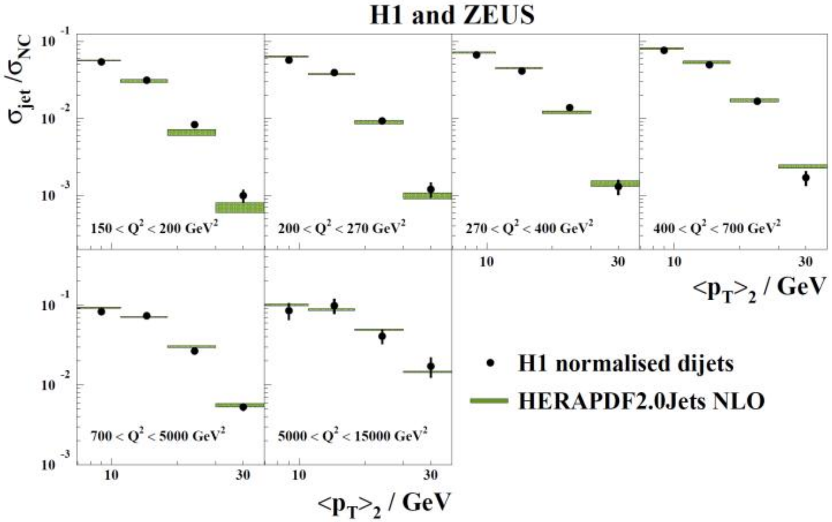
PLB547(2001)164, EPJC70(2010)965, EPJC67(2010)1, PLB653(2007)134 and **EPJC75(2015)2**

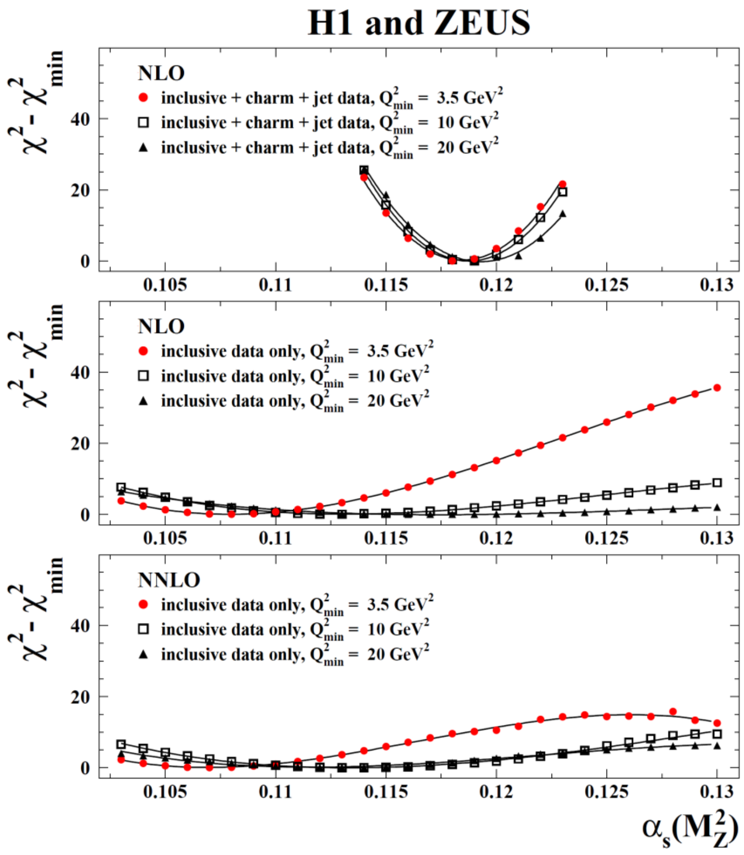
HERAPDF2.0Jets is based on inclusive + charm + jet data

The fits with and without jet data and charm data are very compatible for fixed $\alpha_S(M_Z)$

Let's look at freeing $\alpha_S(M_Z)$ --- first look at χ2 scans







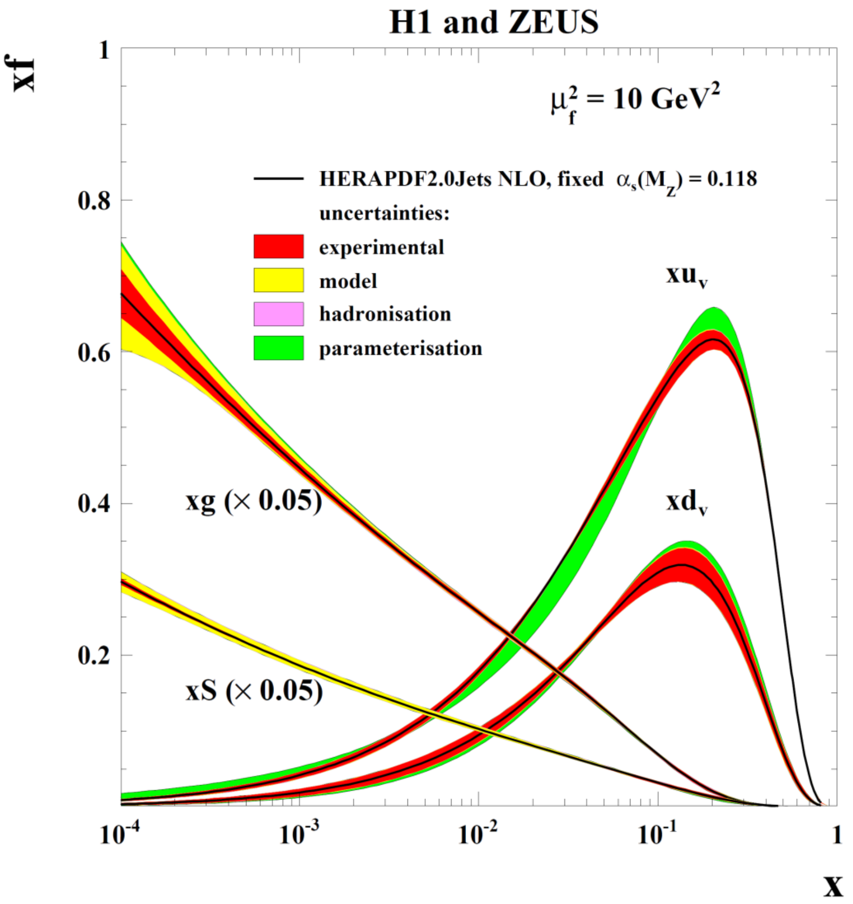
Inclusive data alone cannot determine $\alpha_S(M_Z)$ reliably either at NLO or at NNLO

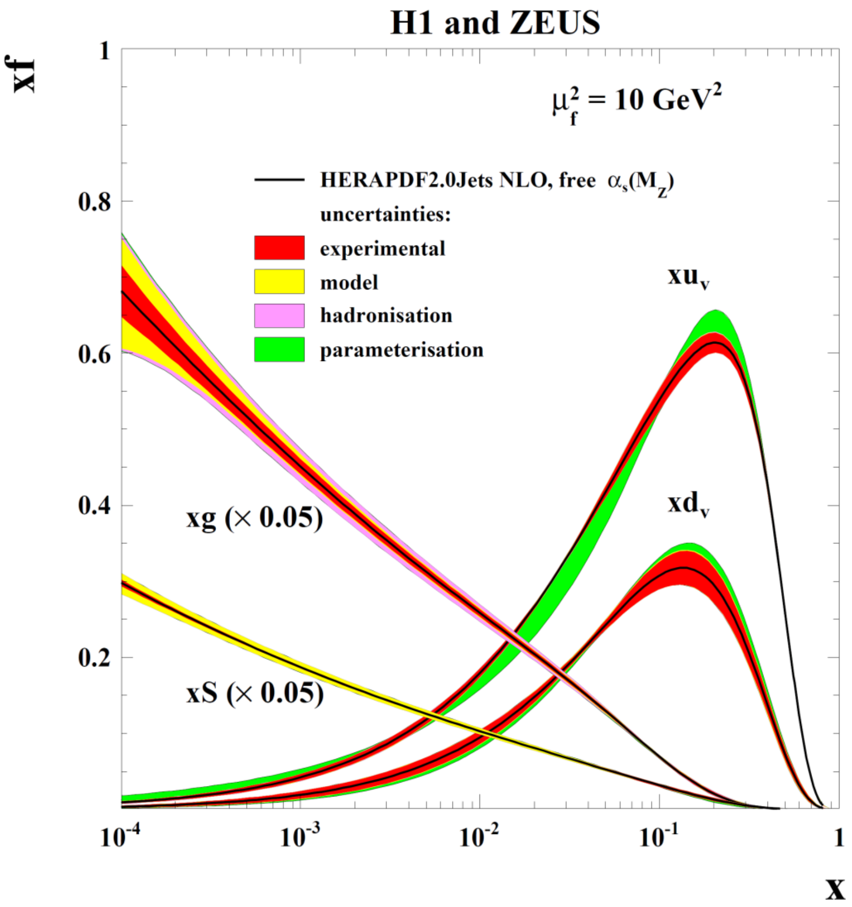
When jet data are added one can make a simultaneous fit for PDF parameters and $\alpha_S(M_Z)$ at NLO--- NNLO calculation still not available

HERAPDF2.0Jets is based on inclusive + charm + jet data

Fits are made with fixed and free $\alpha_S(M_Z)$

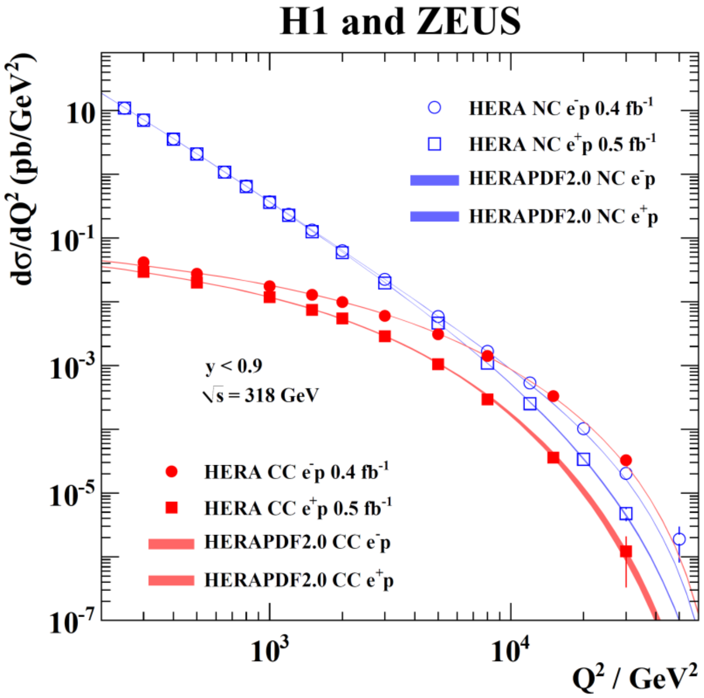
These PDFs are very similar since the fitted value is in agreement with the chosen fixed value. The uncertainties of gluon are not much larger when $\alpha_S(M_Z)$ is free since it is well determined. Scale uncertainties are not illustrated on the PDFs



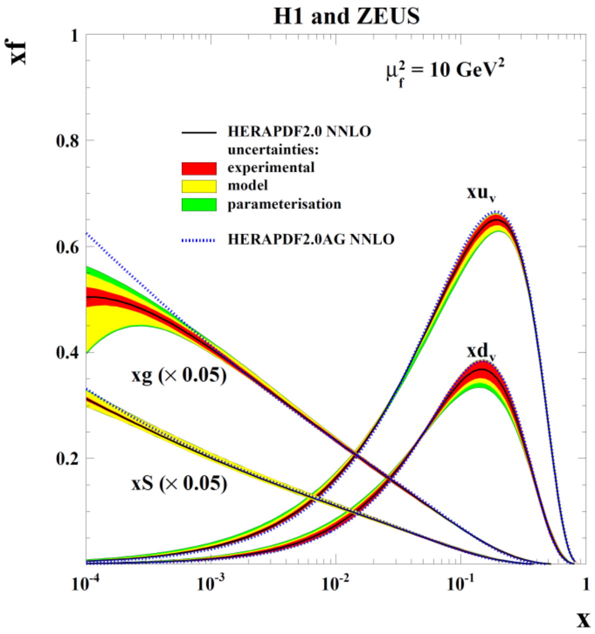


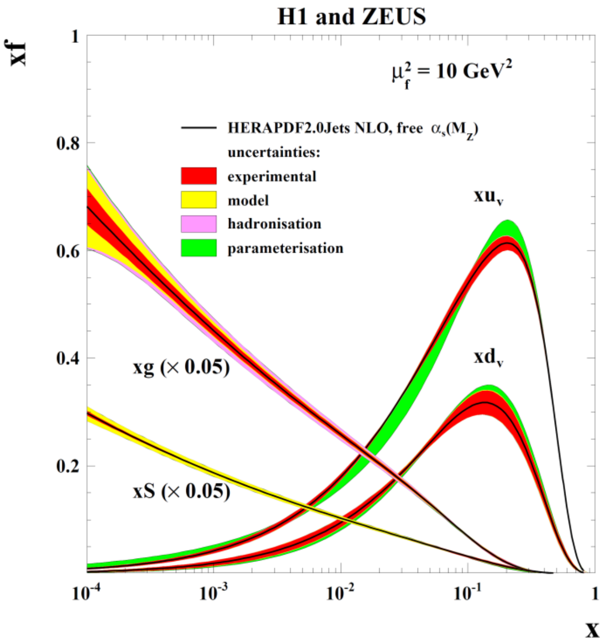
$$\alpha_S(M_Z) = 0.1183 \pm 0.0009_{(\mathrm{exp})} \pm 0.0005_{(\mathrm{model/param})} \pm 0.0012_{(\mathrm{had})}\ {}^{+0.0037}_{-0.0030}(\mathrm{scale})$$

Summary

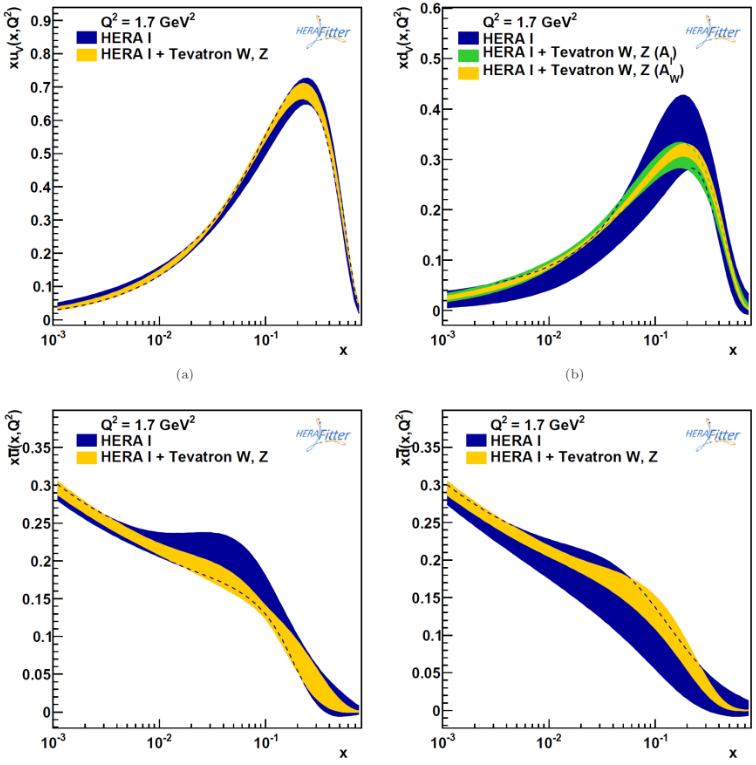


We have the FINAL Inclusive HERA-I and II combination
And the HERAPDF2.0 series based upon it





Outlook-1

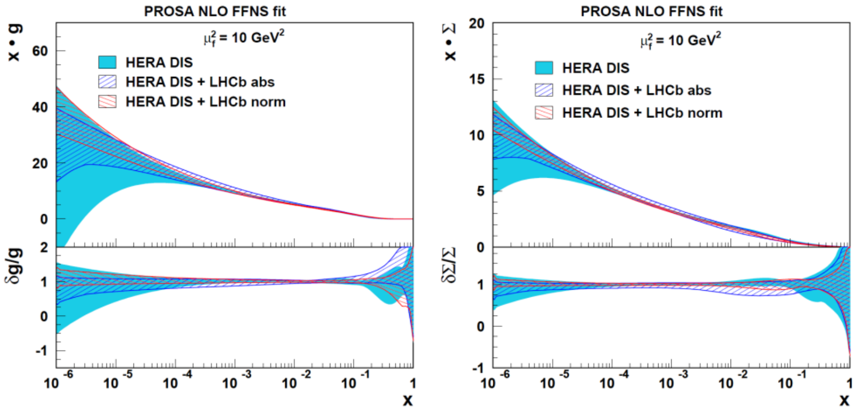


(a) (b) (c) (d)

HERAFitter is used within ATLAS and CMS to assess the impact of their data using the HERA-I combination as the base.
The HERAFitter groups and the PROSA group also use this platform

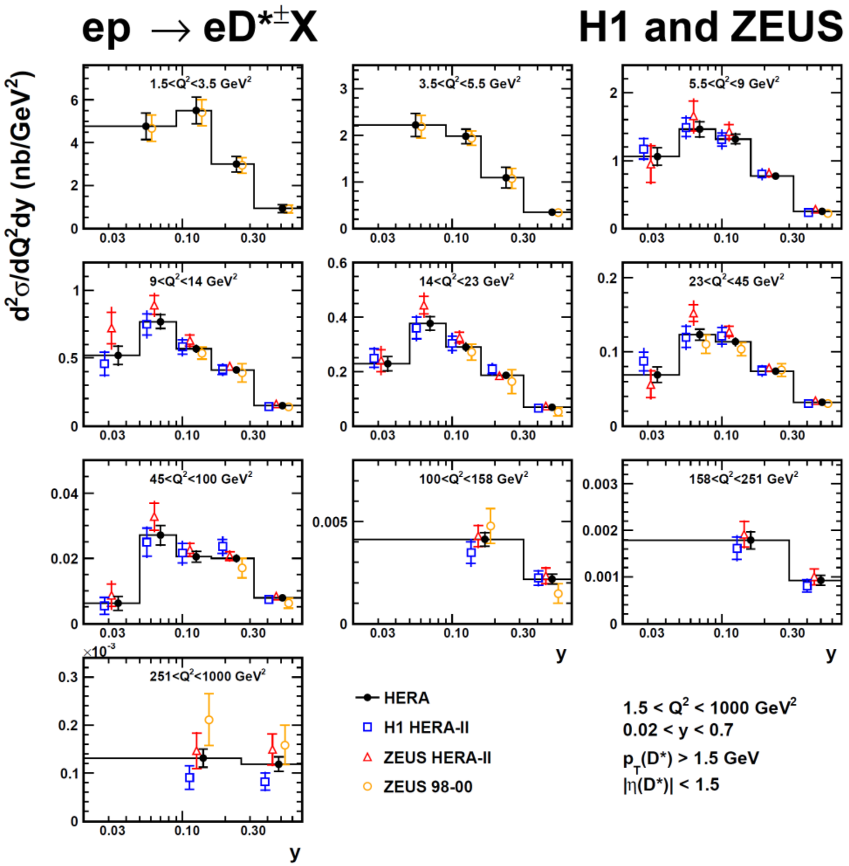
Recent examples of the use of HERAFitter arXiv1410.4412
based on the HERA-I combination
Now we should move to using the final HERA-I+II combination as the basis for such fits

arXiv:1503.05221
HERAFitter
HERA-I + Tevatron W-asymmetry data



arXiv:1503.04581
PROSA
HERA-1 inclusive +heavy flavour data +LHC-B heavy flavour data

Outlook-2



DESY-15-037,
arXiv:1503:06042

There is still data coming out of HERA
Recently the **D* HERA combination** was released.

There are more measurements to come.

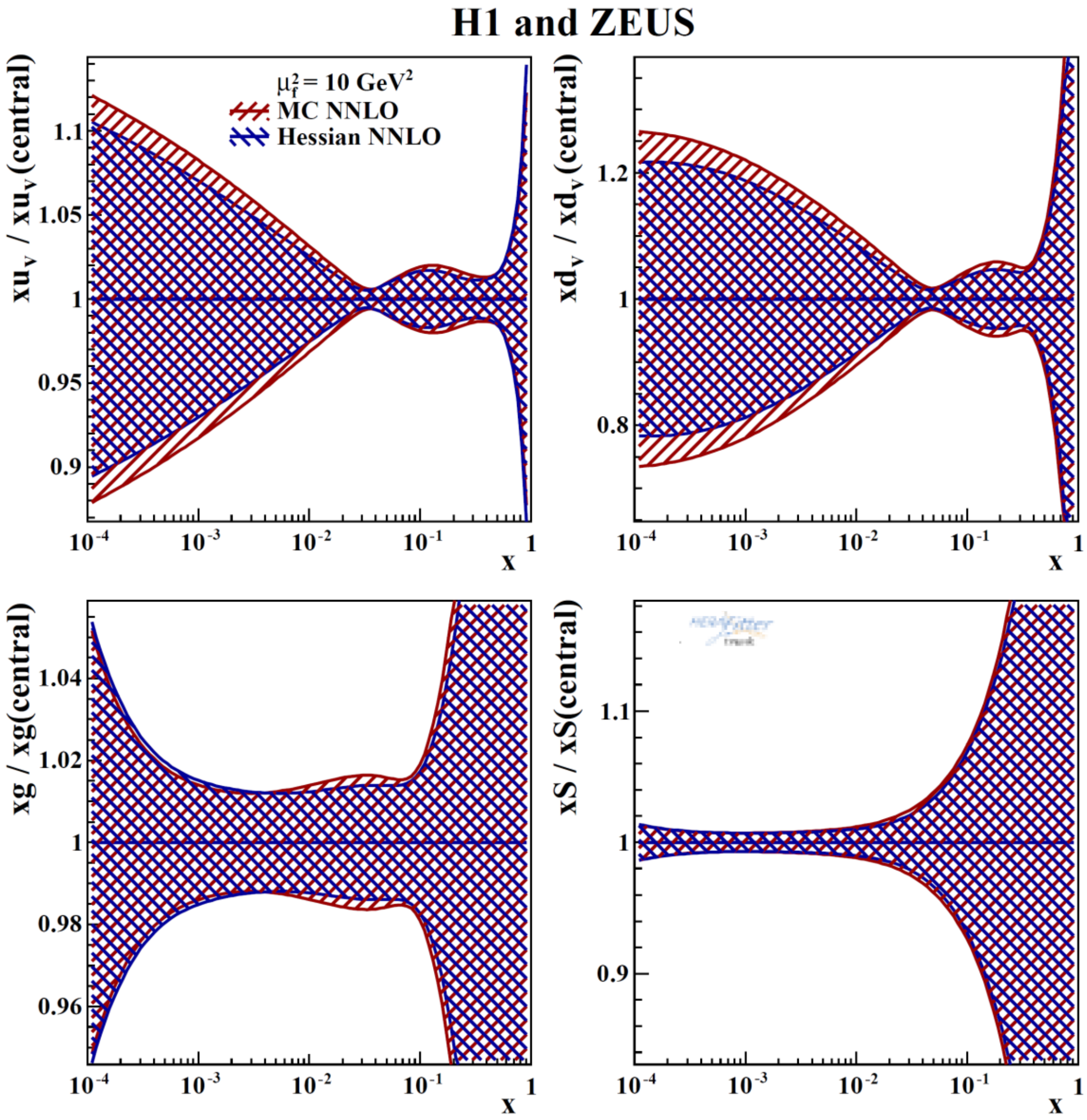
Results on heavy flavour
ZEUS:JHEP10(2014)003 D* at 3 different √s

Results on diffractive dijets:
H1:JHEP1503(2015)092 dijets AND
arXiv:1502.01683 dijets with leading proton
ZEUS-prel-14-004 dijets
Results on prompt γ:
ZEUS-prel-15-001 isolated γ
Results on vector mesons:
ZEUS-prel-14-003 Ratio of ψ(2s)/ψ(1s)

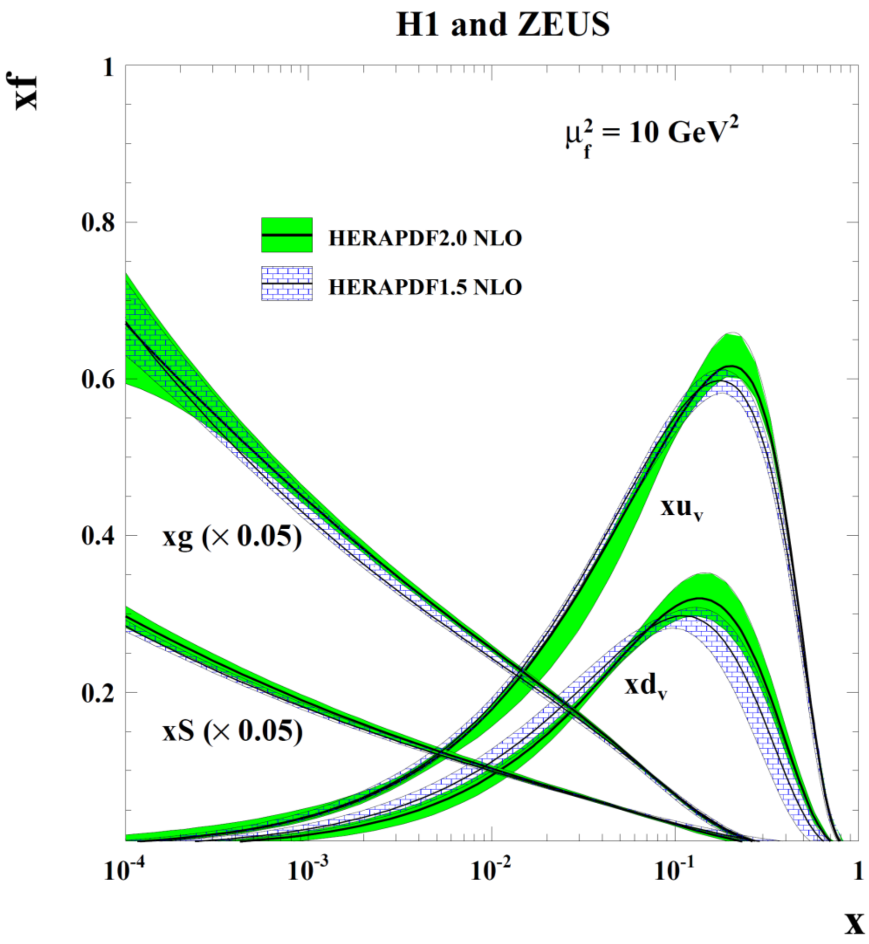
We are not done yet!

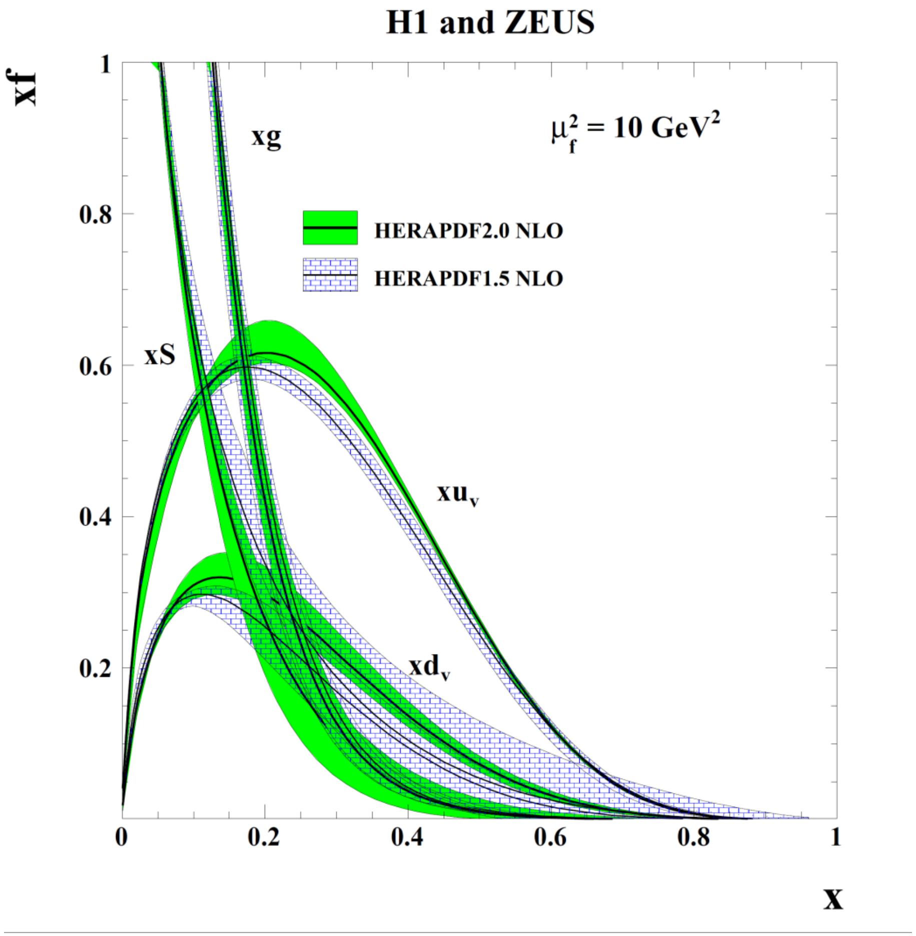
Back-up

Compare MC to Hessian uncertainties



Compare HERAPDF2.0 to HERAPDF1.5 at NLO

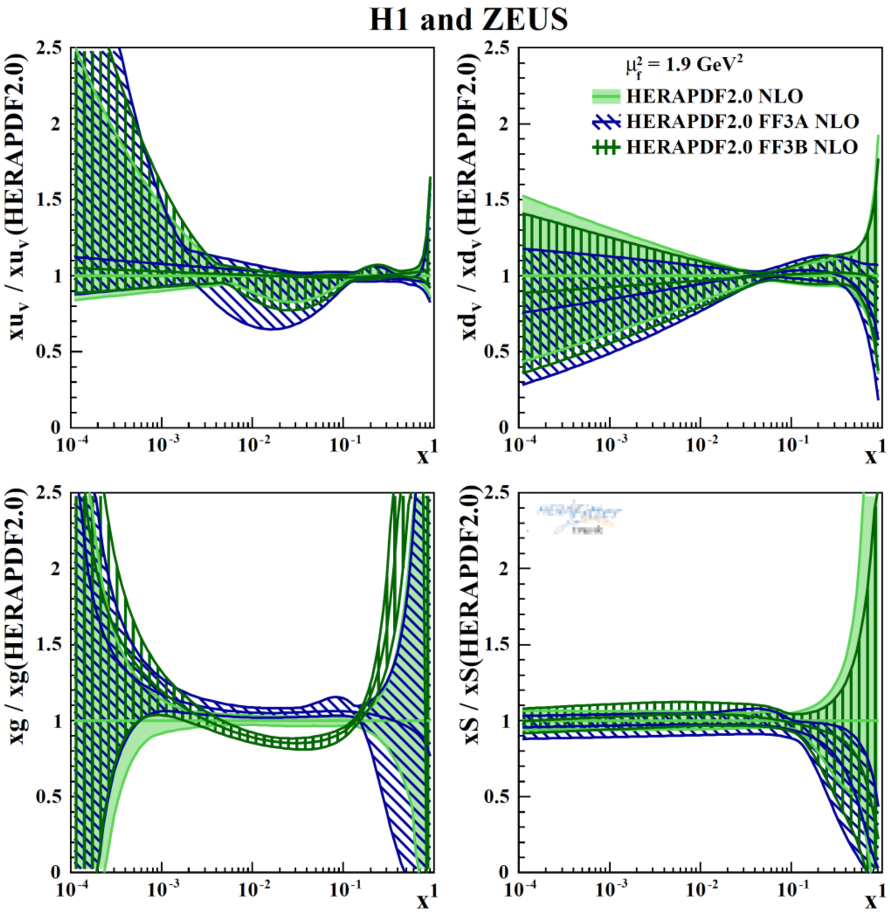


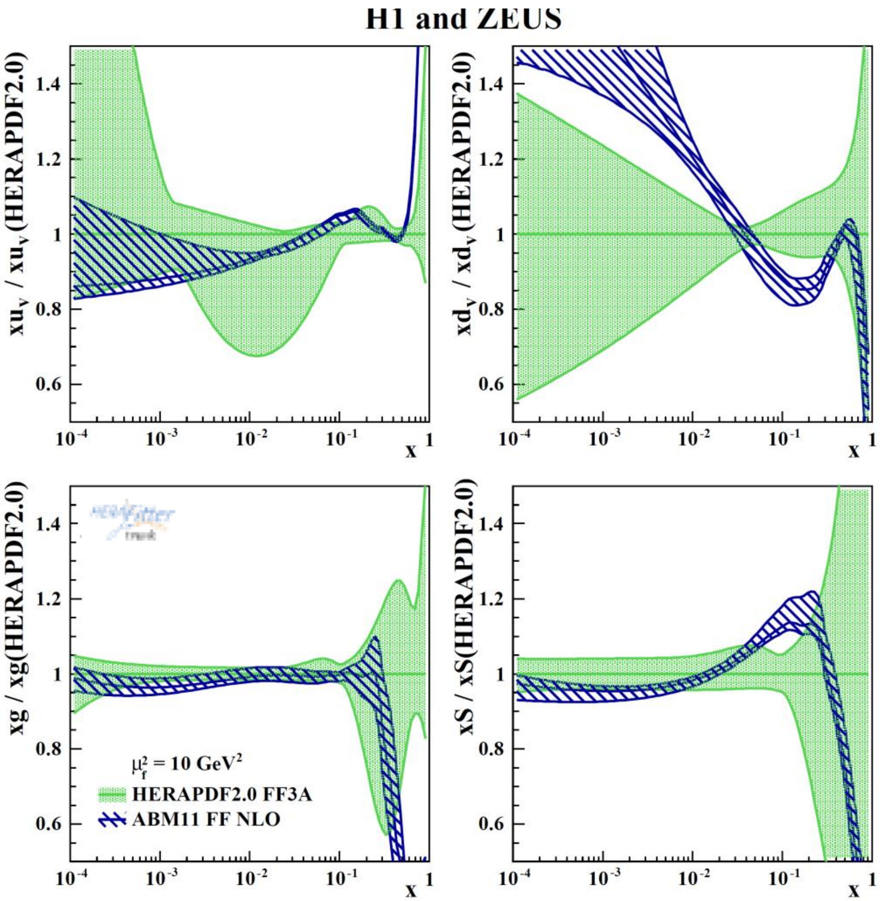


Some more high-x data

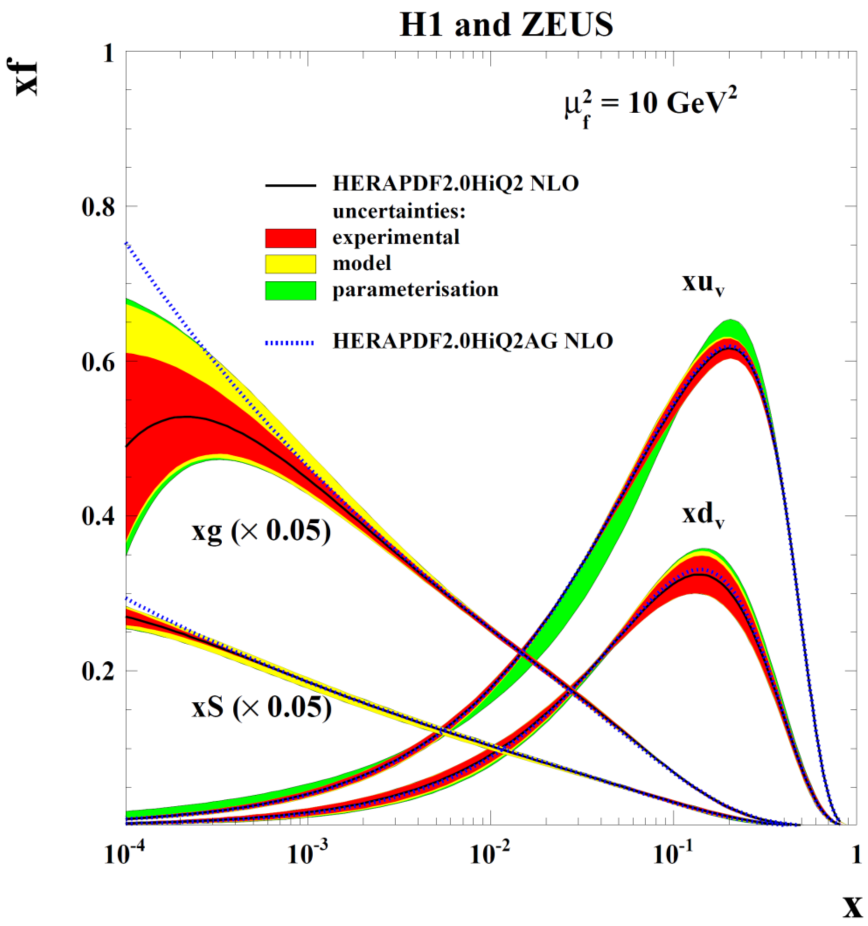
Still shows reductions in high-x uncertainty

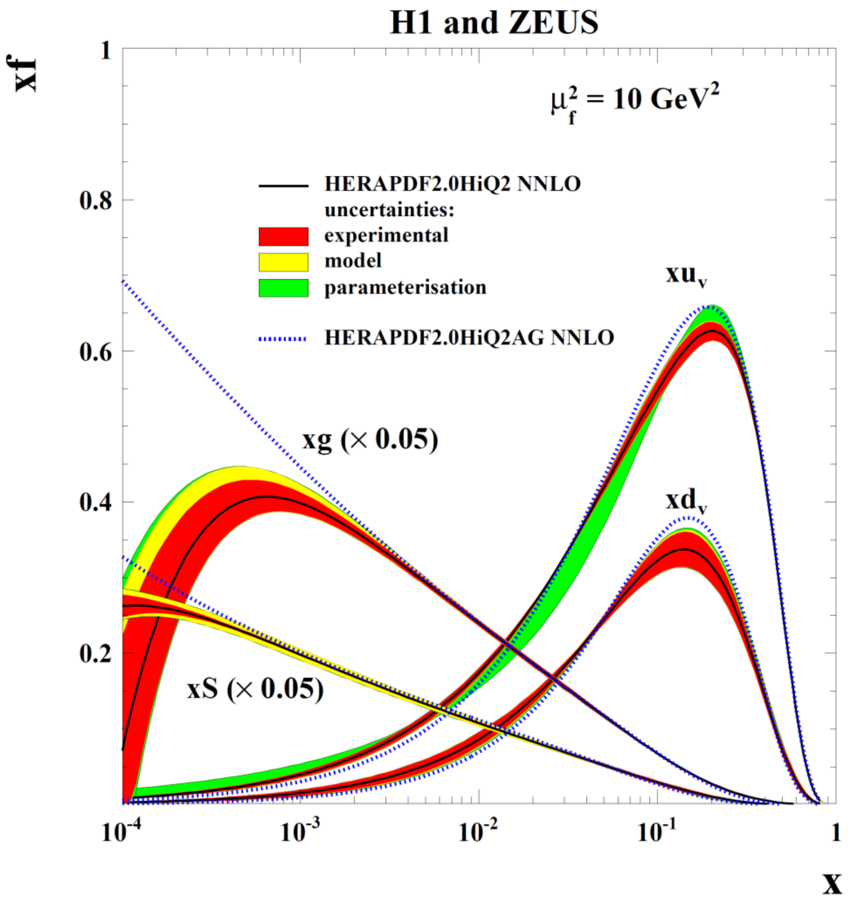
Some change in valence shape- but not so much as for 1.0


H1 and ZEUS
μ_f^2 = 1.9 GeV^2
HERAPDF2.0 NLO
HERAPDF2.0 FF3A NLO
HERAPDF2.0 FF3B NLO
xu_v / xu_v(HERAPDF2.0)
xd_v / xd_v(HERAPDF2.0)
xg / xg(HERAPDF2.0)
xS / xS(HERAPDF2.0)
0
0.5
1
1.5
2
2.5
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x
HERAFitter trunk


H1 and ZEUS
μ_f^2 = 10 GeV^2
HERAPDF2.0 FF3A
ABM11 FF NLO
xu_v / xu_v(HERAPDF2.0)
xd_v / xd_v(HERAPDF2.0)
xg / xg(HERAPDF2.0)
xS / xS(HERAPDF2.0)
0.6
0.8
1
1.2
1.4
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x
HERAFitter trunk

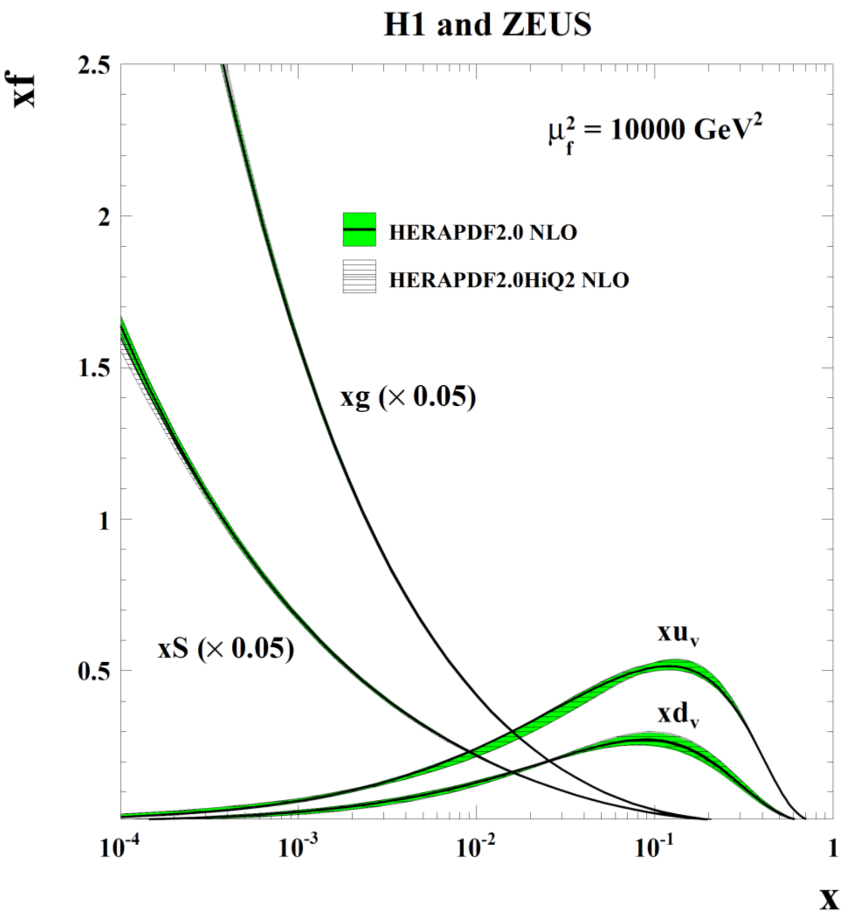
HERAPDF2.0HiQ2 at NLO and NNLO

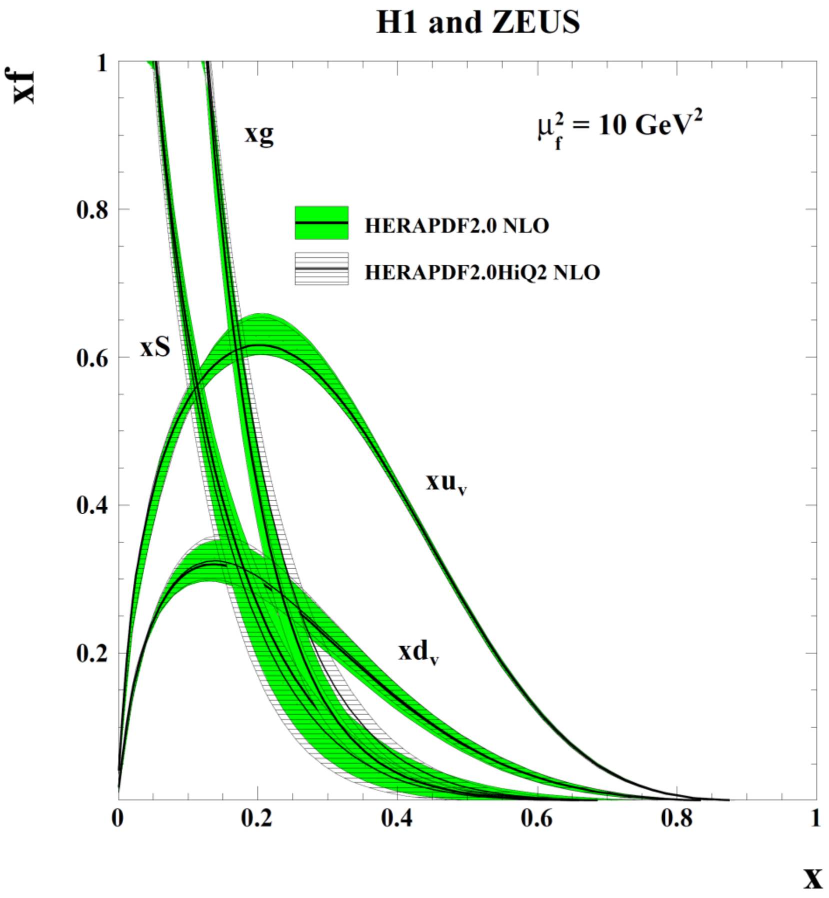




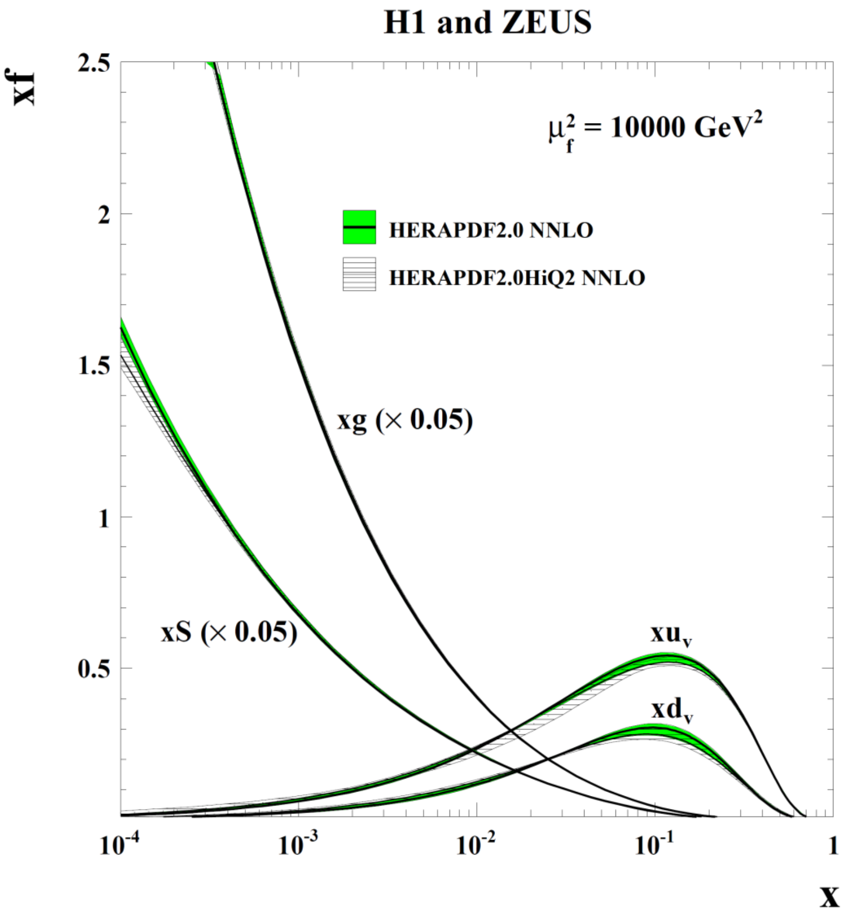
alternative gluon shape—$xg(x) = A_g\, x^{B_g}\, (1-x)^{C_g}\, (1+D_g x)$

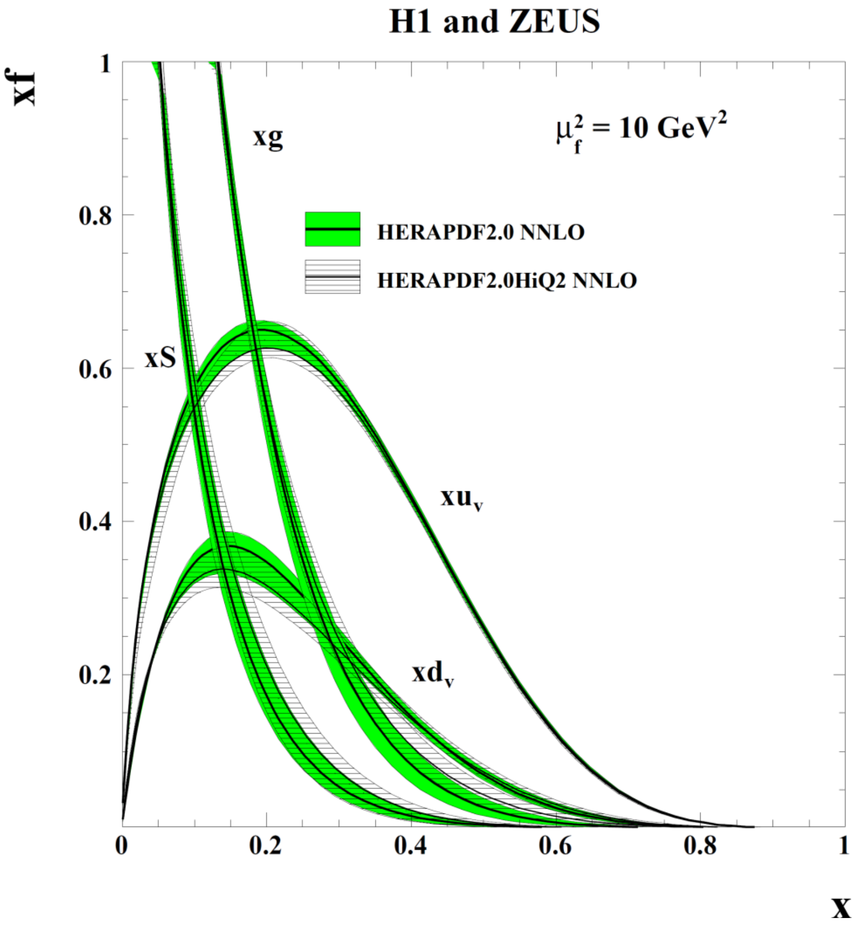
Compare HERAPDF2.0 to HERAPDF2.0HiQ2 at NLO

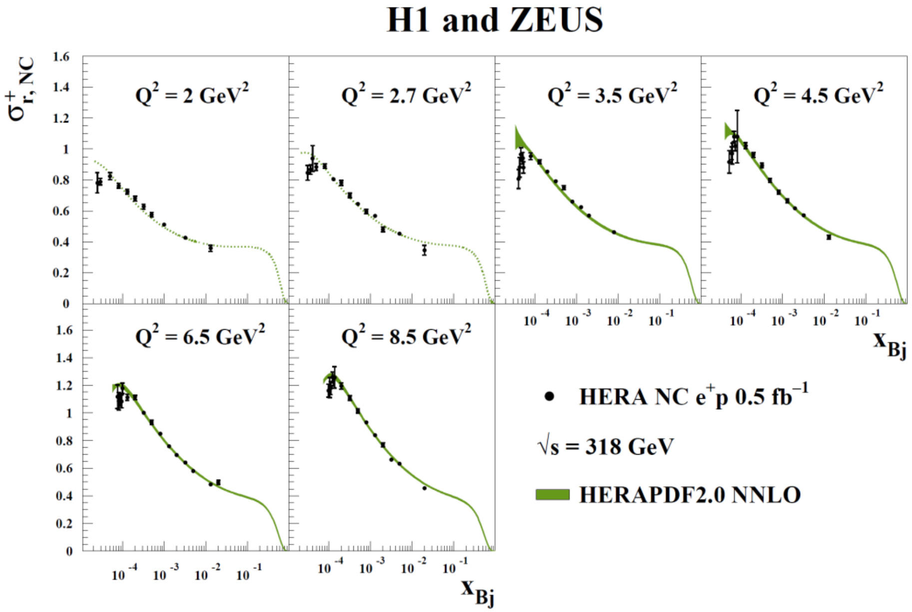




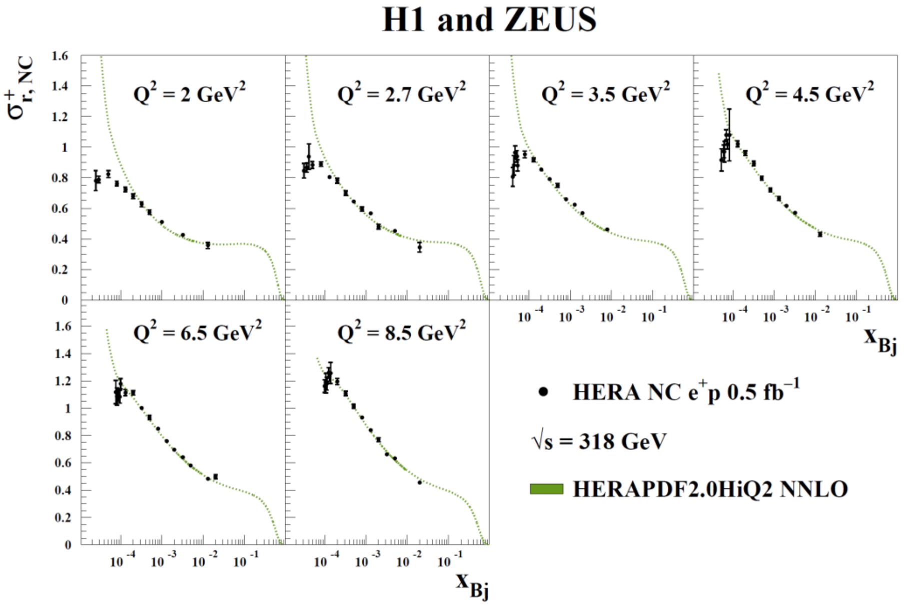
Compare HERAPDF2.0 to HERAPDF2.0HiQ2 at NNLO







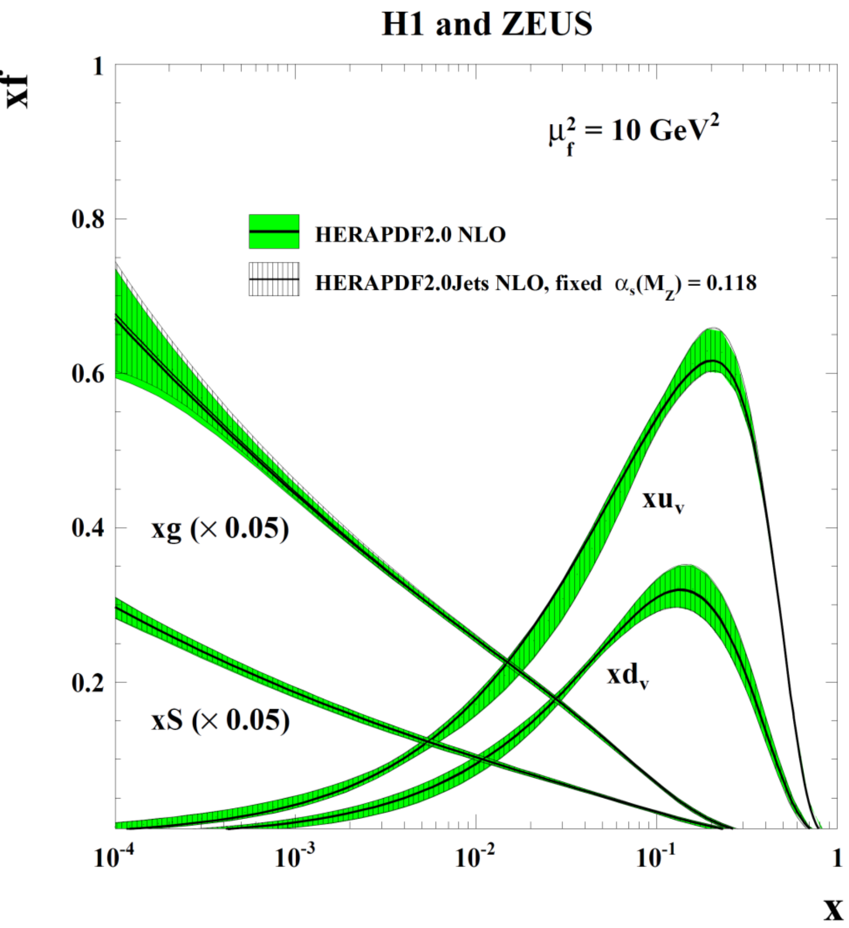
NNLO
$Q^2>3.5$ GeV^2

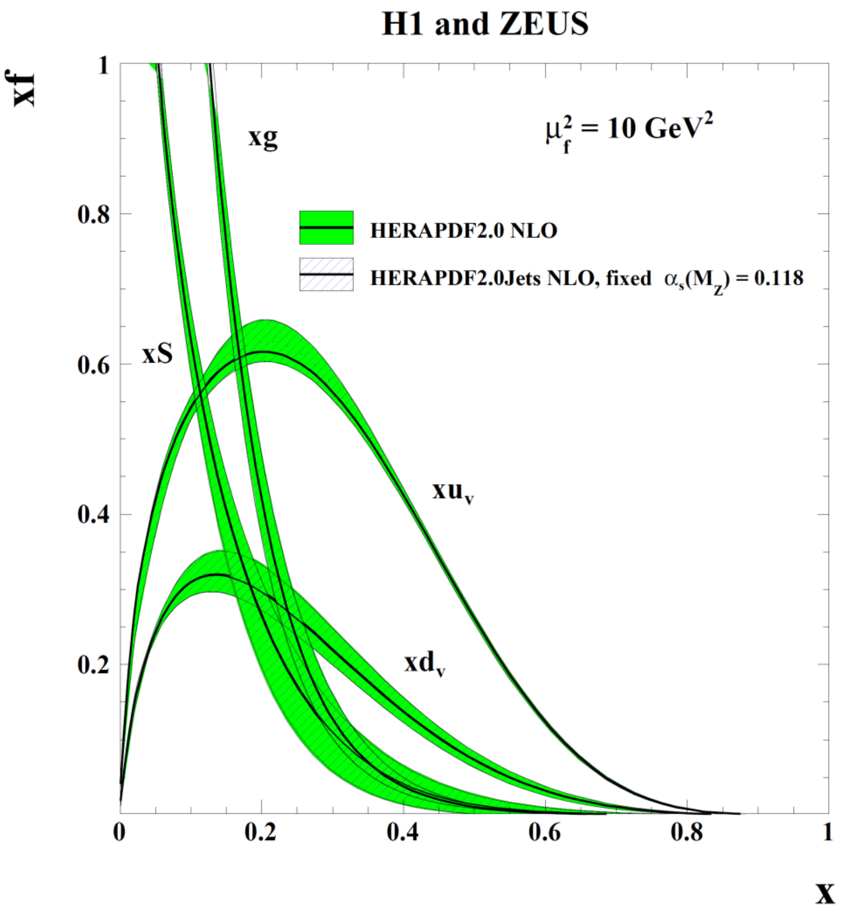


NNLO
$Q^2>10$ GeV^2

Going to higher orders does not improve the fit at low-Q^2, low-x

Comparison of HERAPDF2.0Jets to HERAPDF2.0

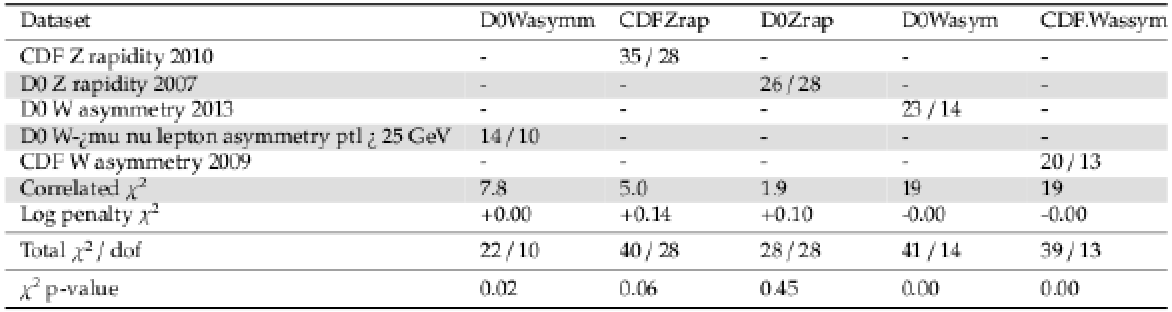




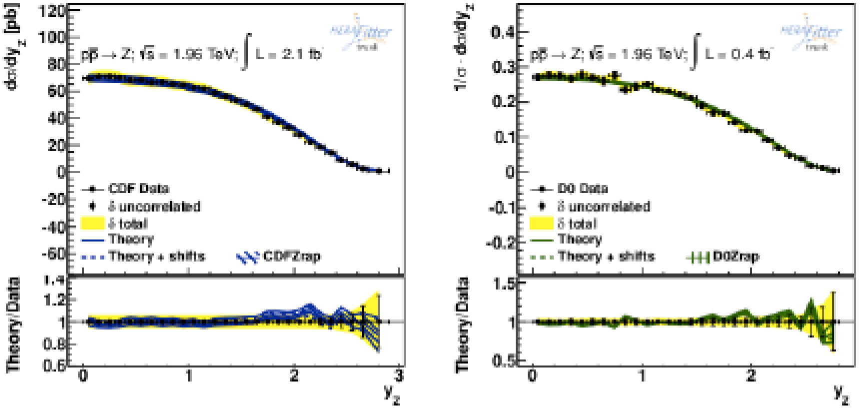
The fits with and without jet data and charm data are very compatible
The charm and jet data are very well fitted at NLO
There is only marginal further decrease in uncertainty due to these data when $\alpha_S(M_Z)$ is fixed

HERAPDF2.0 NLO (All uncerr) vs Tevatron Data

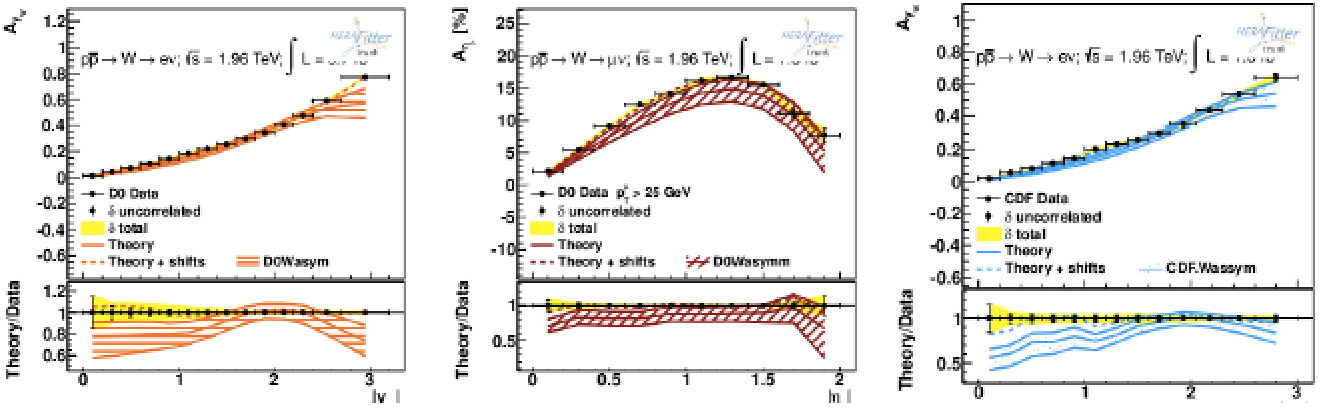
- Chi2



Dataset	D0Wasymm	CDFZrap	D0Zrap	D0Wasym	CDF.Wassym
CDF Z rapidity 2010	-	35 / 28	-	-	-
D0 Z rapidity 2007	-	-	26 / 28	-	-
D0 W asymmetry 2013	-	-	-	23 / 14	-
D0 W-¿mu nu lepton asymmetry ptl ¿ 25 GeV	14 / 10	-	-	-	-
CDF W asymmetry 2009	-	-	-	-	20 / 13
Correlated χ^2	7.8	5.0	1.9	19	19
Log penalty χ^2	+0.00	+0.14	+0.10	-0.00	-0.00
Total χ^2 / dof	22 / 10	40 / 28	28 / 28	41 / 14	39 / 13
χ^2 p-value	0.02	0.06	0.45	0.00	0.00

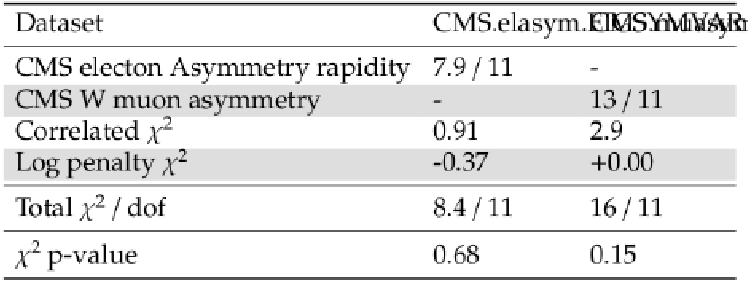


Similar level of agreement as the global PDFs



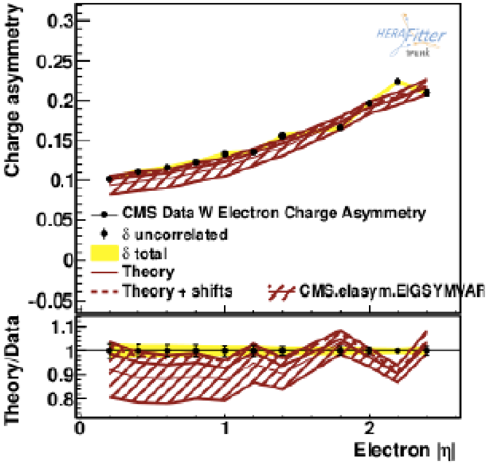
HERAPDF2.0 NLO (All uncerr) vs LHC data

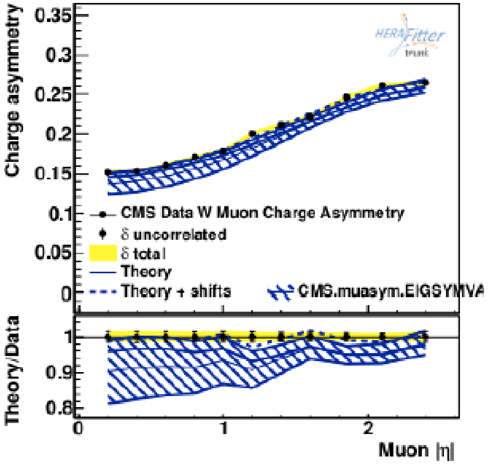
- Chi2

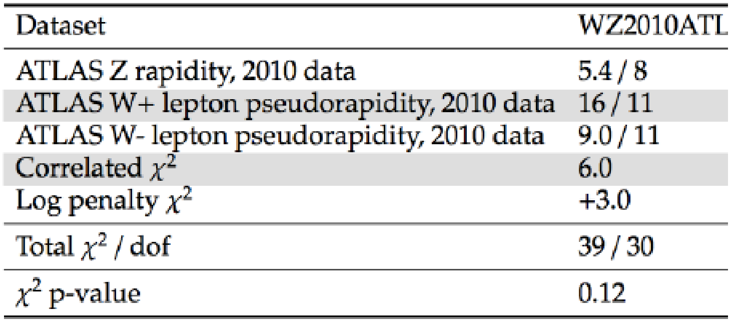


Dataset	CMS.elasym.EIGSYMVAR	CMS.muasym
CMS electon Asymmetry rapidity	7.9 / 11	-
CMS W muon asymmetry	-	13 / 11
Correlated χ^2	0.91	2.9
Log penalty χ^2	-0.37	+0.00
Total χ^2 / dof	8.4 / 11	16 / 11
χ^2 p-value	0.68	0.15

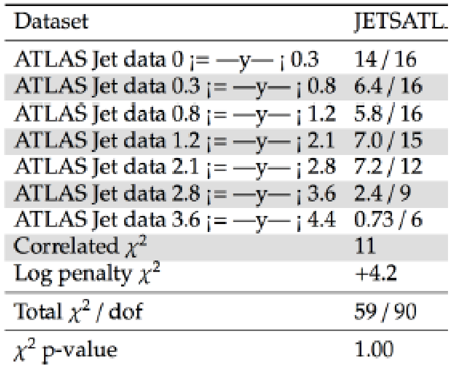
Similar level of agreement
as the global PDFs







Dataset	WZ2010ATL
ATLAS Z rapidity, 2010 data	5.4 / 8
ATLAS W+ lepton pseudorapidity, 2010 data	16 / 11
ATLAS W- lepton pseudorapidity, 2010 data	9.0 / 11
Correlated χ^2	6.0
Log penalty χ^2	+3.0
Total χ^2 / dof	39 / 30
χ^2 p-value	0.12



Dataset	JETSATL
ATLAS Jet data 0 ¡= —y— ¡ 0.3	14 / 16
ATLAS Jet data 0.3 ¡= —y— ¡ 0.8	6.4 / 16
ATLAS Jet data 0.8 ¡= —y— ¡ 1.2	5.8 / 16
ATLAS Jet data 1.2 ¡= —y— ¡ 2.1	7.0 / 15
ATLAS Jet data 2.1 ¡= —y— ¡ 2.8	7.2 / 12
ATLAS Jet data 2.8 ¡= —y— ¡ 3.6	2.4 / 9
ATLAS Jet data 3.6 ¡= —y— ¡ 4.4	0.73 / 6
Correlated χ^2	11
Log penalty χ^2	+4.2
Total χ^2 / dof	59 / 90
χ^2 p-value	1.00