H1 and ZEUS HERAPDF2.0NNLO Jet QCD analysis using NNLOJet predictions

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In September 2020 we were told that the grids we had been using for the NNLO jet predictions had a bug.
Producing new grids took a lot longer than anticipated
We finally got the grids in May and have re-run the analysis

- Review what was agreed already in August2020
- Review what has changed?
- Review the NEW analysis
- All tables an figures in the paper

What did we agree?

- The data sets entering the fit – and the data points - 6 extra low-pt data points are for the H1 high Q2 inclusive jets have been added since the preliminary
- The jet scale to be used for the main fit: $Q^2 + p_t^2$ for both renormalisation and factorisation scales
- The treatment of hadronization uncertainties: the treatment of hadronisation uncertainties was recommended as ½ correlated and ½ uncorrelated. The correlated part was treated by the Hessian method AND correlated between all data sets. The hadronisation uncertainties for H1 data come from the H1 publications, for ZEUS a common value of 2% is used- which was already the value for the ZEUS dijets. This treatment is a change from preliminary for which the hadronization uncertainties were evaluated by offset method
- The treatment of scale uncertainties: **Fully correlated to be the main result and ½ correlated and ½ uncorrelated ONLY for comparison to NLO**. These uncertainties are quoted for $\alpha_S(M_Z)$. Scale uncertainties on the PDFs are negiligible.
- The treatment of model/parametrisation uncertainties and the choice of the central parametrisation

There was no need to change any of this for the new grids

However **there is a case to change the cut on $\mu = \sqrt{(pt^2 + Q^2)}$** which is applied to select the data points within each data set, because this cut was chosen in consideration of the size of scale uncertainties and these have changed somewhat

So what has changed?

1. With the new grids the first thing one notices is that the predictions have changed (for the same PDF) by a few % in the low Q^2, p_T parts of phase space

This leads to a lower χ2 of the fit for the same number of data points
Old grids, χ2/ndf=1601/1335
New grids, χ2/ndf=1587/1335
An improvement of 14 where 11 points of this comes from the H1 lowQ2 HERA-I and HERA-II jets (for fixed $\alpha_S(M_Z)$ =0.118)

2. One also notices that the scale uncertainties of the low Q^2, p_T jet data have decreased. This means we can use a reduced cut on $\mu = \sqrt{(pt^2+Q^2)}$, μ > 10 GeV, while still preserving NNLO scale uncertainties < 10%, and this in turn lets in 14 extra jet points to the fit (see slides 4,5)

New grids plus new μ cut, χ2 /ndf= 1619/1349
We note that the new grids came with estimates of the percentage uncertainty on the grid point, which we have taken as ½ correlated and ½ uncorrelated as recommended
New grids plus uncertainties plus new μ cut, χ2/ndf=1617/1349

BUT NOTE the PDFs barely change at all and neither does the fitted $\alpha_S(M_Z)$ it all looks much the same as what we had in August 2020

H1 HERA-II lowQ2 2 inclusive and dijets

These come as 48 data points in 8 groups (increasing in Q2) of 6 points (increasing in ET)

The NNLO scale uncertainties appeared large with the old grids

Showing only the largest variation for MuR down, where variation is applied to a fixed PDF (our own HERAPDF2.0)

NNLO Mur=1/2--old grids, blue points were selected by the old μ cut

0.31*,0.19*,0.11,0.077,0.052,0.024/ 0.29*,0.18*,0.11,0.076,0.051,0.022/
0.26*,0.17*,0.09,0.075,0.050,0.026/
0.24*,0.16*,0.10,0.07,0.05,0.023/ 0.22*,0.14*,0.10,0.075,0.044,0.025
/0.18*,0.13*,0.09,0.07,0.043,0.022/ 0.14*,0.11*,0.094,0.068,0.043,0.022/
0.13*,0.10*,0.087,0.063,0.047,0.023

NNLO Mur=1/2-new grids, green points can now be added to the blue

0.19*,0.13*,0.10,0.08,0.065,0.047/ 0.18*,0.13*,0.10,0.085,0.064,0.044/
0.15*,0.12*,0.10,0.08,0.064,0.045/
0.14*,0.11*,0.09,0.07,0.06,0.044/ 0.12*,0.11*,0.09,0.075,0.057,0.042
/0.11*,0.09*,0.08,0.07,0.056,0.041/ 0.09*,0.08*,0.08,0.069,0.054,0.038/
0.08*,0.07*,0.07,0.063,0.053,0.038

The OLD cut, $\mu = \sqrt{(pt^2+Q^2)} > 13.5$ GeV, cut out large scale variations at NNLO indicated by the ***. But the sensitivity to scale variation has changed**

The NEW cut, $\mu = \sqrt{(pt^2+Q^2)}$ **> 10 GeV, allows green points back in.**

To achieve scale variation < 10% we can lower the cut to μ > 10GeV

This is shown here for inclusive jets, but also applies to the dijets

48 points are cut to 37 for each data set

H1 HERA-1 low Q2 inclusive jets data set

There are 28 data points grouped as 7 groups of 4, where the 7 groups are of increasing Q2 and the 4 points within each groups are of increasing ET

The NNLO scale uncertainties appeared large with the old grids

Showing only the largest variation for MuR down, where variation is applied to a fixed PDF (our own HERAPDF2.0)

NNLO Mur=1/2—old grids, blue points were selected by the old μ cut

0.28*,0.13*,0.096,0.065 /0.26*,0.13*,0.087, 0.068 /0.23*,0.12,0.086,0.066 /**
0.21*,0.11,0.08, 0.06 /0.19**,0.11**,0.08, 0.06 /0.16**,0.10, 0. 077, 0.056 /**
0.12, 0.09,0.068,0.055/**

NNLO Mur=1/2—new grids, green points can now be added to the blue

0.17*,0.11*,0.095,0.07 /0.16*,0.11*,0.09, 0.07 /0.15*,0.10,0.088,0.07 /**
0.13*,0.10,0.08, 0.06 /0.11**,0.10**,0.08, 0.06 /0.11**,0.09, 0. 077, 0.06 /**
0.08, 0.07,0.067,0.055/**

The * indicates points that we have always cut -even at NLO using a k-factor criterion

The ** indicates the extra cut from using the OLD kinematic cut μ > 13.5GeV

This cut NLO scale variations >~24% and NNLO scale variations > ~10% (old grids)

However this has changed the NNLO scale variations have decreased (new grids)

NEW cut μ > 10GeV adds 4 extra points with NNLO scale variation ~<10% preserved.

Fitted data set now has 20 points

The HERAPDF2.0NNLO jets uses the following agreed jet data sets

ZEUS HERA I+II di-jets = 22 pts: but cut 6 low pt data points for which the NNLO corrections are effectively only NLO

ZEUS HERA-I (96/97) inclusive jets = 30 pts

H1 HERA1 inclusive normalised highQ2 = 24pts

H1 HERA1 inclusive lowq2 = 28pts -- -cut to 20pts, μ = √(pt²+Q²) > 10 GeV -H1

HERA-II normalised inclusive jets high Q2= 30pts (- 6 new points at low pt added)

H1 HERA-II normalised dijets high Q2 = 24pts

H1 HERA-II inclusive normalised low Q2 =48pts —cut to 37pts, μ = > 10 GeV

H1 2016 normalised dijets low Q2 = 48pts -- cut to 37pts, μ = > 10 GeV

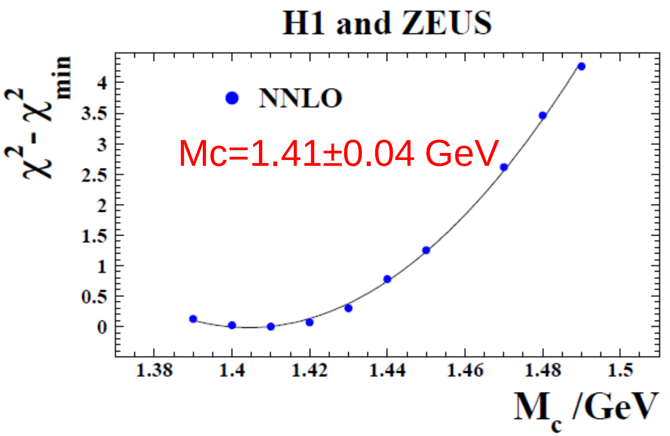
Data Set	taken from	to	Q^2[GeV^2] range from	to	$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV	norma-lised	all points	used points	Ref.
H1 HERA I normalised jets	1999	2000	150	15000	65.4	e^+p	319	yes	24	24	[9]
H1 HERA I jets at low Q^2	1999	2000	5	100	43.5	e^+p	319	no	28	20	[10]
H1 normalised inclusive jets at high Q^2	2003	2007	150	15000	351	e^+p/e^-p	319	yes	30	30	[13,14]
H1 normalised dijets at high Q^2	2003	2007	150	15000	351	e^+p/e^-p	319	yes	24	24	[14]
H1 normalised inclusive jets at low Q^2	2005	2007	5.5	80	290	e^+p/e^-p	319	yes	48	37	[13]
H1 normalised dijets at low Q^2	2005	2007	5.5	80	290	e^+p/e^-p	319	yes	48	37	[13]
ZEUS inclusive jets	1996	1997	125	10000	38.6	e^+p	301	no	30	30	[11]
ZEUS dijets 1998 –2000 &	2004	2007	125	20000	374	e^+p/e^-p	318	no	22	16	[12]

Table 1: *The data sets on jet production from H1 and ZEUS used for the HERAPDF2.0Jets NNLO its. The term normalised indicates that all cross sections are normalised to the respective NC inclusive cross sections.*

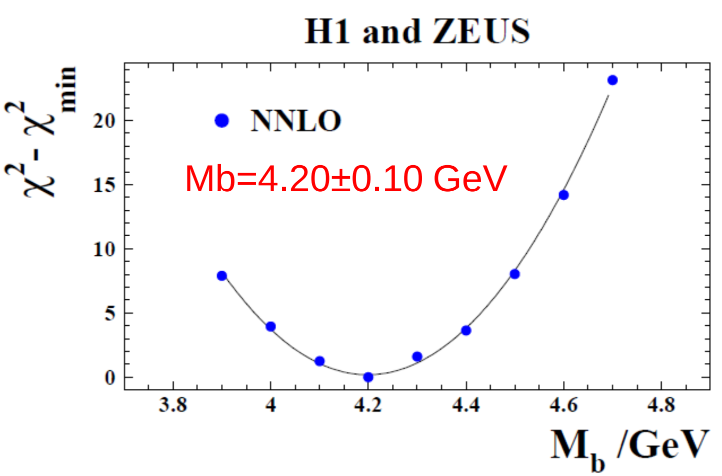
Since the publication of HERAPDF2.0 we also have **NEW HERA combined charm and beauty data Eur.Phys.J C78(2018)473**

This affects the evaluation of the optimal charm and beauty masses

One could use these data in the NNLO fit, however it is not clear that heavy flavour can be fully consistently treated at NNLO –and thus we do NOT do this

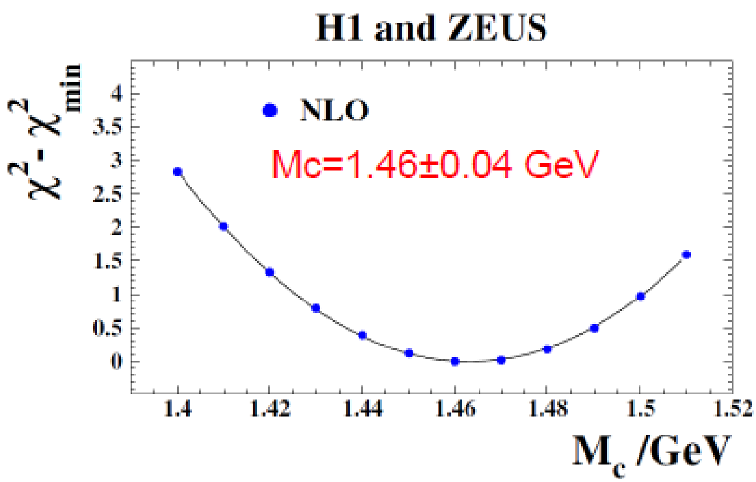


These scans are new since preliminary, where we just used the HERAPDF2.0 values

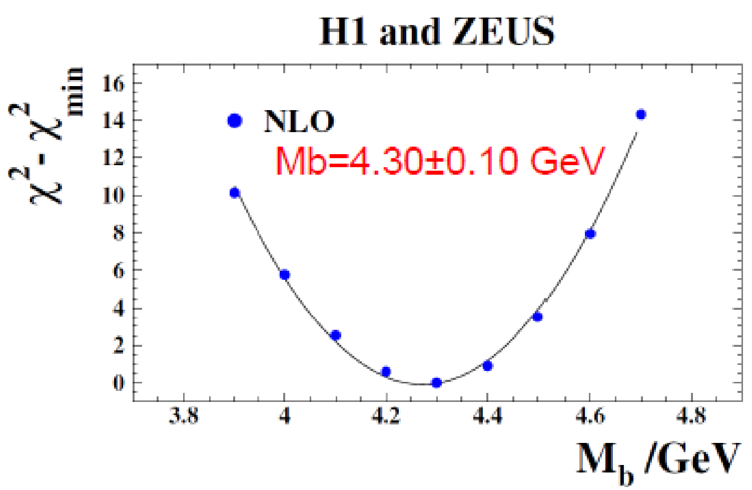


New Mc, Mb χ2 scans using inclusive and heavy flavour data are iterated:

- We start with $\alpha_S(M_Z)$ =0.118 as usual and the standard HERAPDF 2.0 parametrisation. perform the scan, adopt the resulting values
- And then fit for $\alpha_S(M_Z)$ including jet data
- Since the new value $\alpha_S(M_Z)$ =0.1156 is obtained we then revisit these scans obtaining very slightly different Mc, Mb values shown here and then
- refit for $\alpha_S(M_Z)$ using these new Mb, Mc value – $\alpha_S(M_Z)$ =0.1156 still favoured
- Then re-check parametrisation scan with new Mc,Mb, $\alpha_S(M_Z)$ =0.1156 AND jet data added— (after all there are 218 new jet data points)
- Previous parametrisation confirmed
- **Hence no further iterations needed**



Update to add NLO



We will also add the equivalent results at NLO since future LHC analyses may wish to use these

A reminder of the parametrisation

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

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

The effect of this negative term is investigated

Ubar=ubar

Dbar=dbar+sbar

- Additional constrains
  - A_{u_v}, A_{d_v}, A_g: constrained by the quark-number sum rules and momentum sum rule
  - $B_{\bar{U}} = B_{\bar{D}}$; $A_{\bar{U}} = A_{\bar{D}}(1-f_s)$ dbar=ubar at low-x
  - $x\bar{s} = \boxed{f_s} x\bar{D}$ at starting scale, f_s = 0.4

xFitter

3

As usual we start with a minimal number of parameters and add more one at a time until the χ2 no longer improves. Parametrisation variations adding extra parameters which can change PDF shape but do not improve χ2 are part of the uncertainty

A reminder about model/param uncertainties

Parameter	Central Value	Downwards variation	Upwards variation
Q^2_{min} [GeV^2]	3.5	2.5	5.0
f_s	0.4	0.3	0.5
M_c [GeV]	1.41	1.37*	1.45
M_b [GeV]	4.20	4.10	4.30
μ^2_{f0} [GeV^2]	1.9	1.6	2.2*

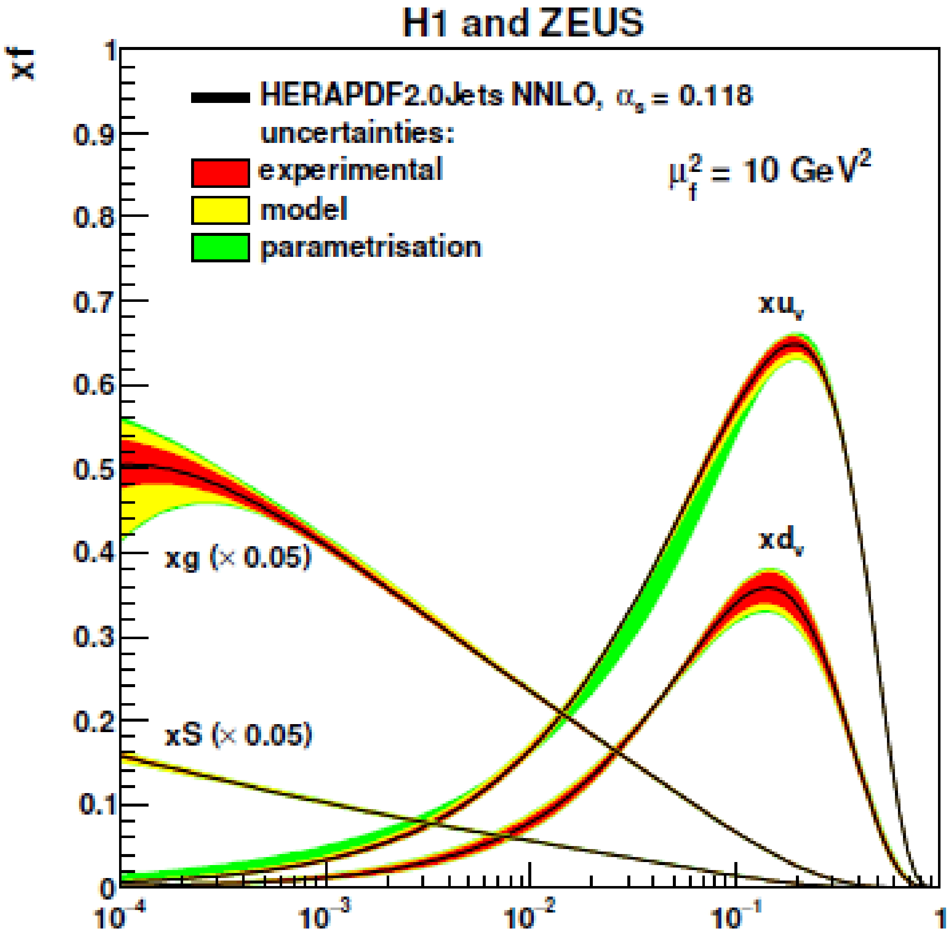
- We vary our input assumptions on the minimum Q^2 of data entering the fit, the fraction of strangeness in the sea, the charm and beauty quark pole masses. These variations give the model uncertainty
- We also vary the starting scale for evolution μ_{f0}^2 and this is considered part of the parametrisation uncertainty

However note

- The variation of M_c and μ_{f0}^2 are coupled because we require $\mu_{f0}^2 < M_c^2$
- For the central values this is fine (M_c^2=1.9881) and for μ_{f0}^2 varied downwards and central M_c this is fine **but**
- for μ_{f0}^2 varied up to 2.2 GeV ^{2} and central M_c it is not fine – we USED to combine this with the upper variation of M_c BUT the new value of M_c and its uncertainty make the upper variation of M_c=1.45, M_c^2=2.1025..too small
- Propose vary μ_{f0}^2 down ONLY and symmetrise
- Similarly for the M_c variations at central μ_{f0}^2, the M_c upward variation is fine but
- For M_c varied down to 1.37GeV, M_c^2=1.8769 is not fine
- We used to combine this variation with the downward variation of μ_{f0}^2 but we now propose to vary M_c up ONLY and symmetrise

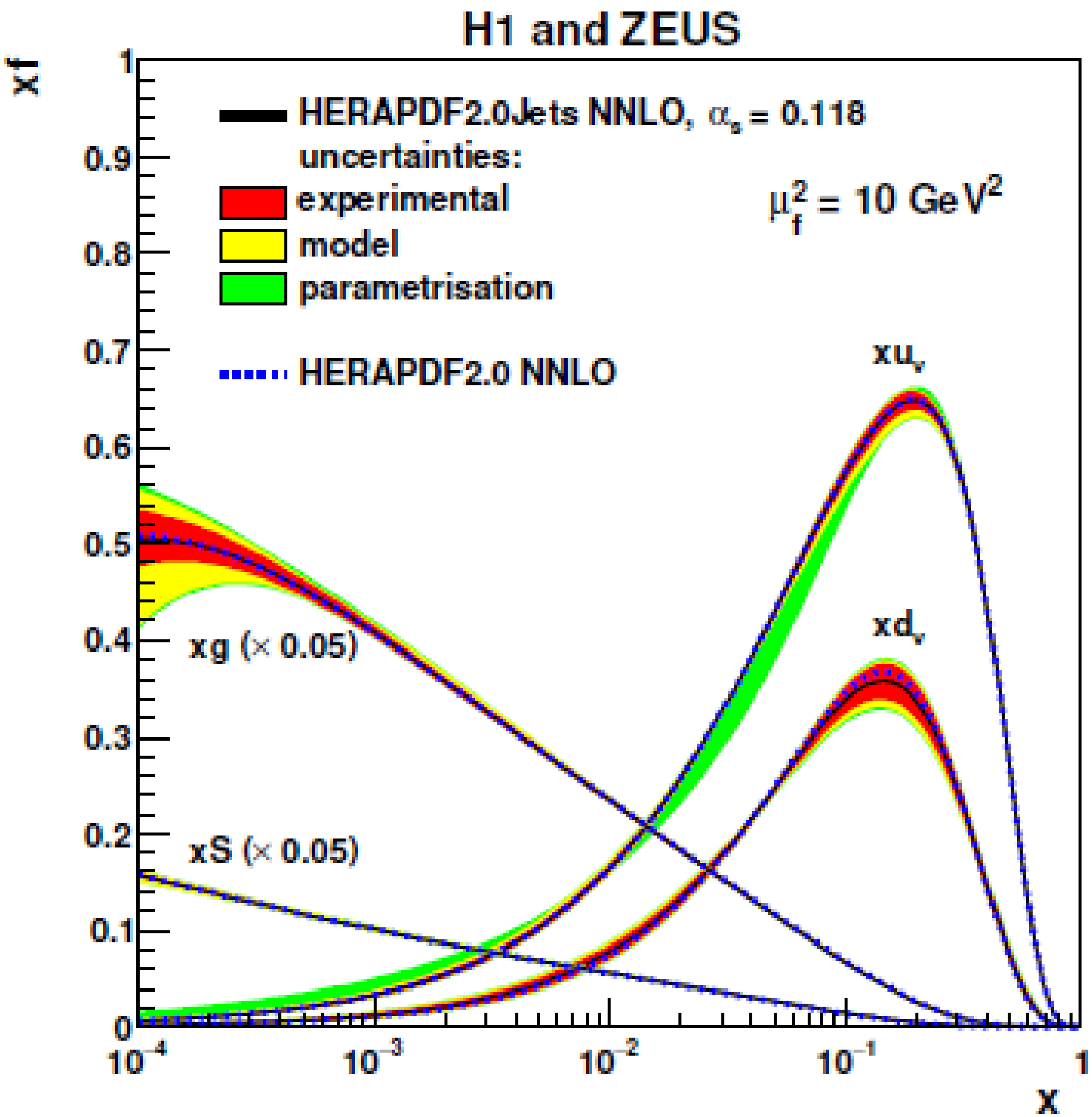
These propositions were agreed, note that the consequence is that we are no longer double counting some M_c and μ_{f0}^2 variations

NEW $\alpha_S(M_Z)$ =0.118 NNLOJets fit - SUMMARY PLOT



	Parameter	HERAPDF2.0 NNLO as=0.118	
2	'Bg'	-0.070319	0.043016
3	'Cg'	5.670899	0.482567
7	'Aprig'	0.161572	0.043068
8	'Bprig'	-0.391610	0.027755
9	'Cprig'	25.000000	0.000000
12	'Buv'	0.806334	0.028281
13	'Cuv'	4.844608	0.081284
15	'Euv'	10.242348	1.441602
22	'Bdv'	0.981522	0.092135
23	'Cdv'	4.622768	0.397334
33	'CUbar'	7.137838	1.347568
34	'DUbar'	1.458837	1.614989
41	'ADbar'	0.269978	0.010673
42	'BDbar'	-0.126504	0.004831
43	'CDbar'	8.036277	1.509073

NEW comparison to HERAPDF2.0 without jets

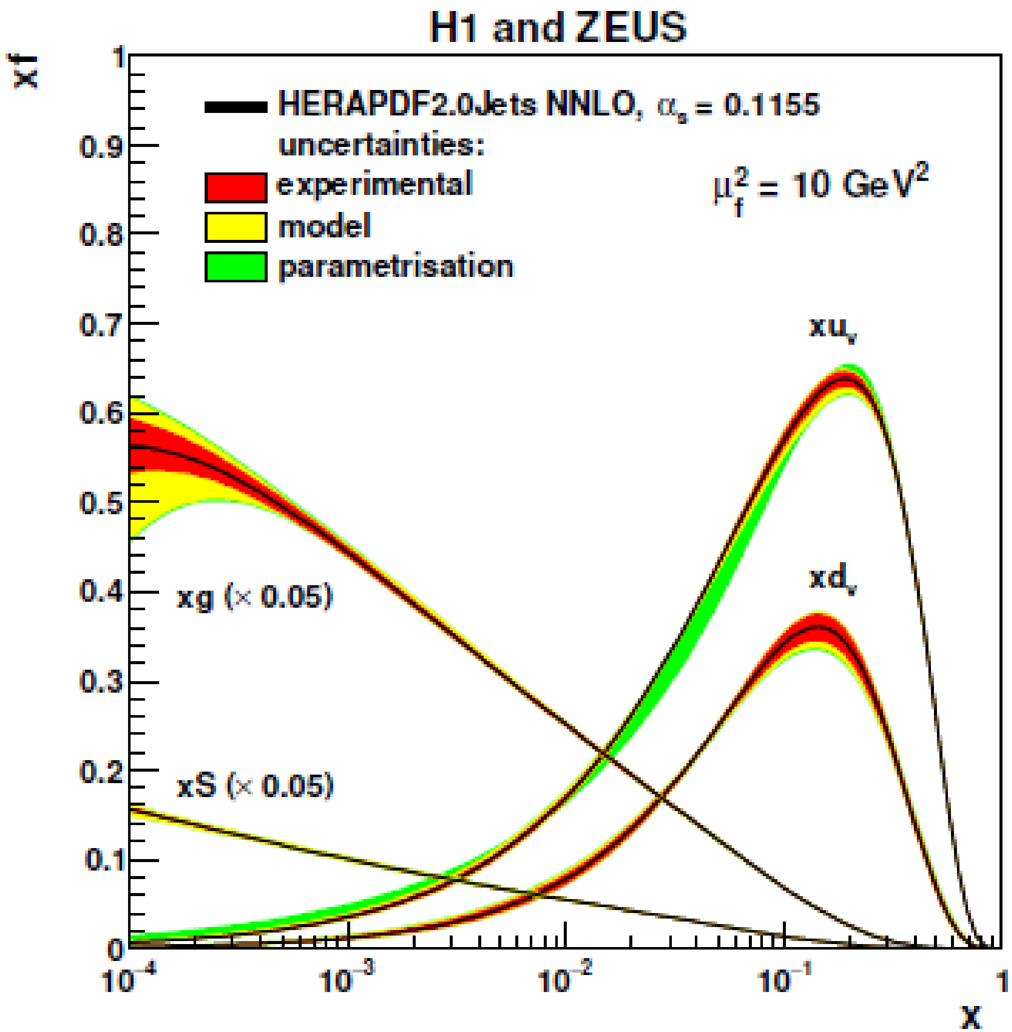


The new HERAPDF2.0Jets NNLO fit and the previous HERAPDf2.0NNLO fit are very similar if both are taken at $\alpha_S(M_Z)$ =0.118.

However the Jets fit favours $\alpha_S(M_Z)$ =0.1155

NEW $\alpha_S(M_Z)$ =0.1155 **NNLOJets fit - SUMMARY PLOT**

Anticipating the result of the free $\alpha_S(M_Z)$ fit

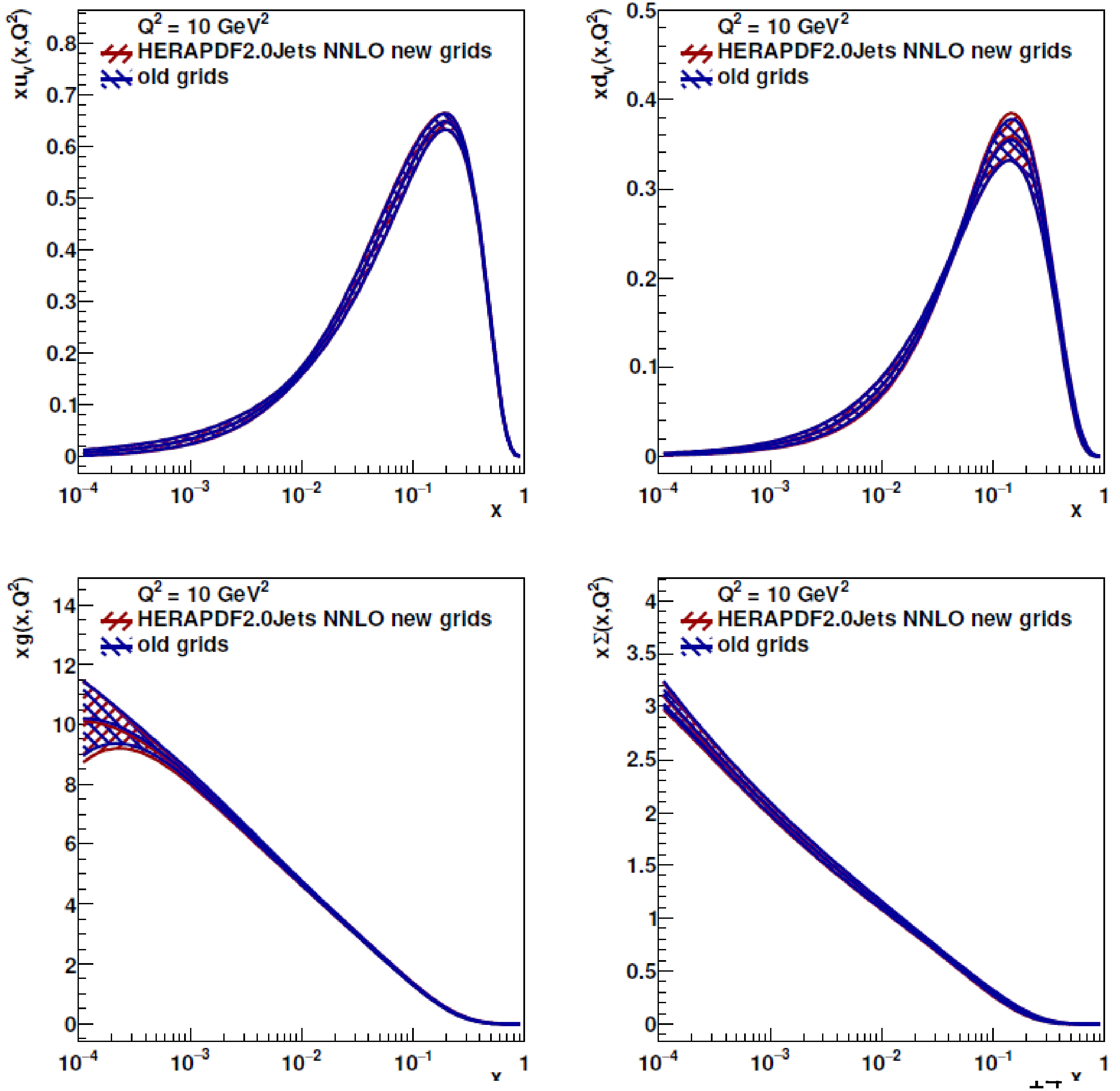


Parameter		HERAPDF2.0	NNLO as=0.1155
2	'Bg'	-0.085574	0.039648
3	'Cg'	6.171545	0.496131
7	'Aprig'	0.147903	0.040820
8	'Bprig'	-0.409380	0.028287
9	'Cprig'	25.000000	0.000000
12	'Buv'	0.781078	0.025867
13	'Cuv'	4.880050	0.080411
15	'Euv'	10.401539	1.289019
22	'Bdv'	0.983055	0.084572
23	'Cdv'	4.804735	0.380423
33	'CUbar'	7.125150	1.645404
34	'DUbar'	2.031948	2.222251
41	'ADbar'	0.262191	0.010036
42	'BDbar'	-0.128934	0.004725
43	'CDbar'	9.161993	1.693978
101	'alphas'	0.115500	0.000000

Compare PDFS using NEW/OLD grids and cuts

How much have the PDFS changed at fixed $\alpha_S(M_Z) = 0.118$?

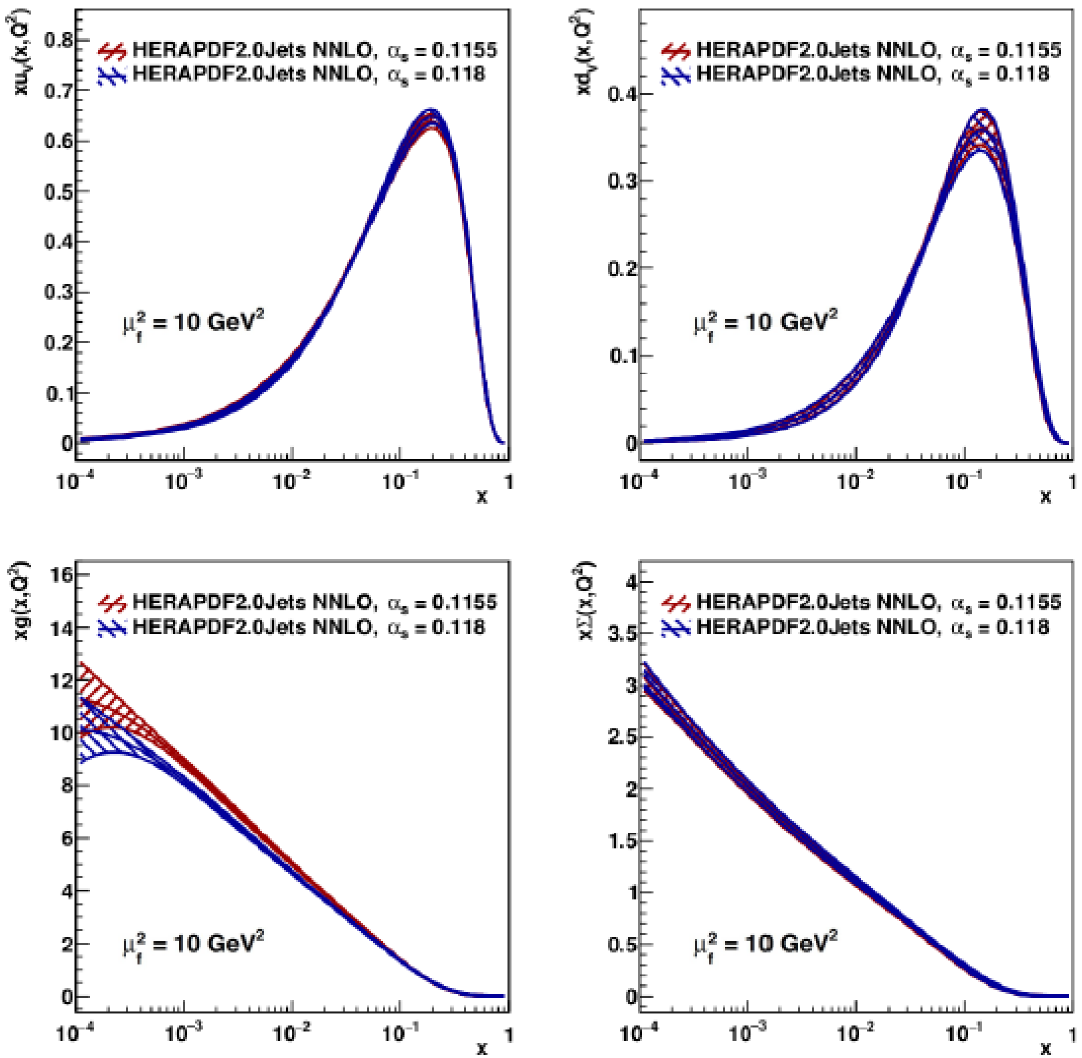
Barely at all



Does xFitter and the ZEUS/Oxford code still agree with the new jets? YES

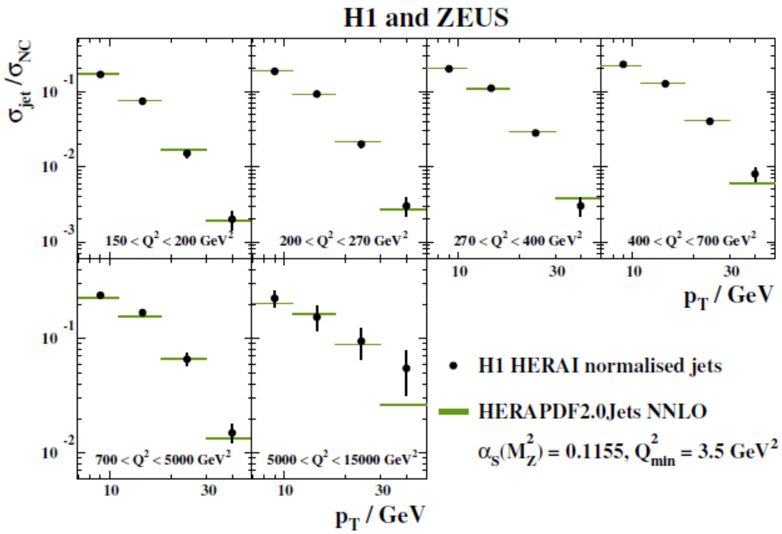
		xFitter		ZEUS/Oxford
2	'Bg'	-0.070319	0.043016	-0.065,0.044
3	'Cg'	5.670899	0.482567	5.99,0.54
7	'Aprig'	0.161572	0.043068	0.167, 0.115
8	'Bprig'	-0.391610	0.027755	-0.387,0.059
9	'Cprig'	25.000000	0.000000	
12	'Buv'	0.806334	0.028281	0.804, 0.028
13	'Cuv'	4.844608	0.081284	4.855, 0.085
15	'Euv'	10.242348	1.441602	10.5,1.4
22	'Bdv'	0.981522	0.092135	0.948,0.09
23	'Cdv'	4.622768	0.397334	4.47,0.39
33	'CUbar'	7.137838	1.347568	7.4,1.6
34	'DUbar'	1.458837	1.614989	2.1,2.4
41	'ADbar'	0.269978	0.010673	0.269,0.011
42	'BDbar'	-0.126504	0.004831	-0.127,0.005
43	'CDbar'	8.036277	1.509073	7.1,1.5
101	'alphas'	0.118000	0.000000	

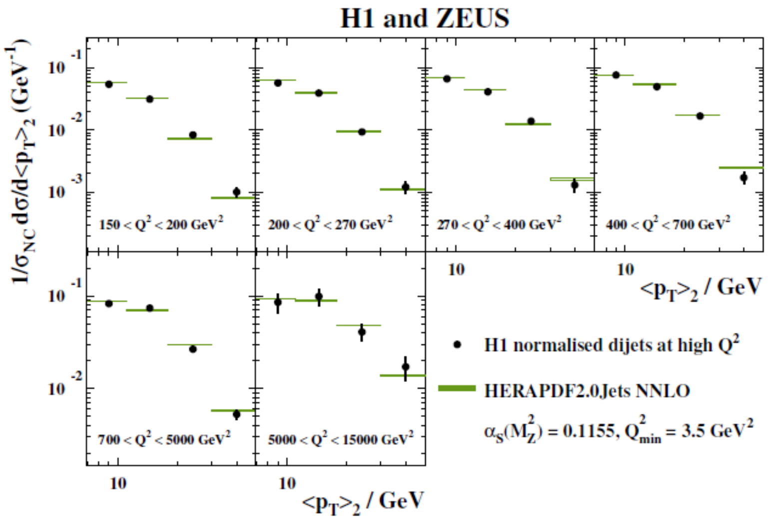
Compare new PDFs for the two values of $\alpha_S(M_Z)$



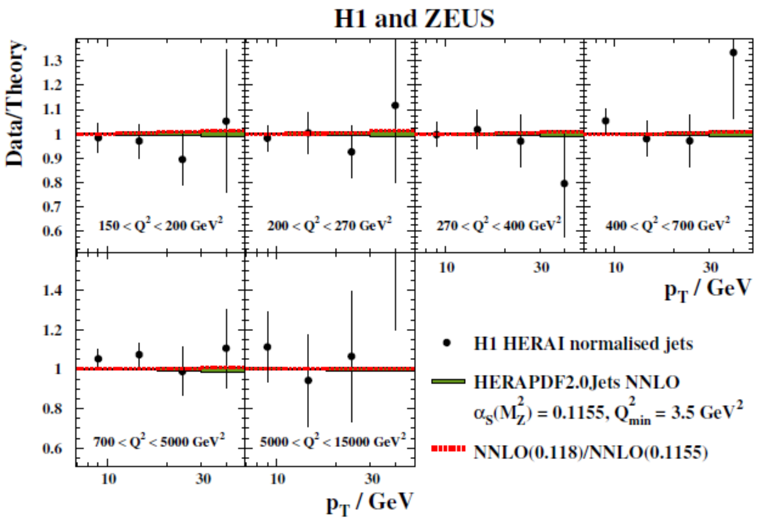
This plot is also made at scale Mz

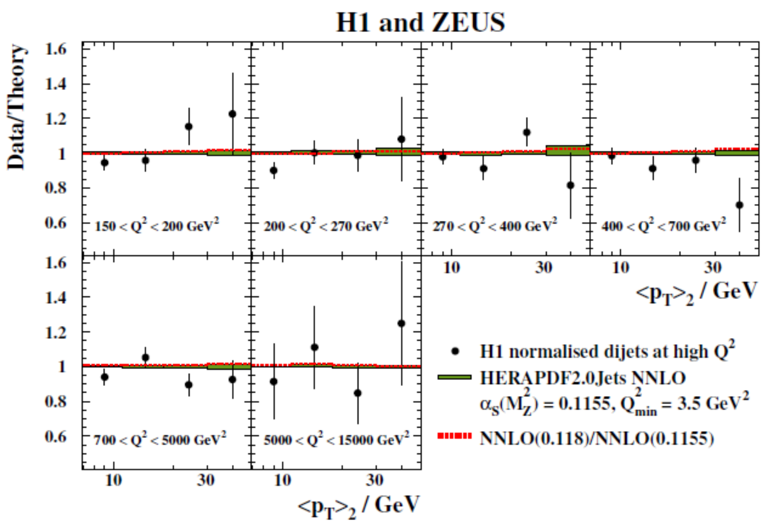
Examples of data and theory prediction and ratios for a couple of data sets—
The rest come in the full list of figures



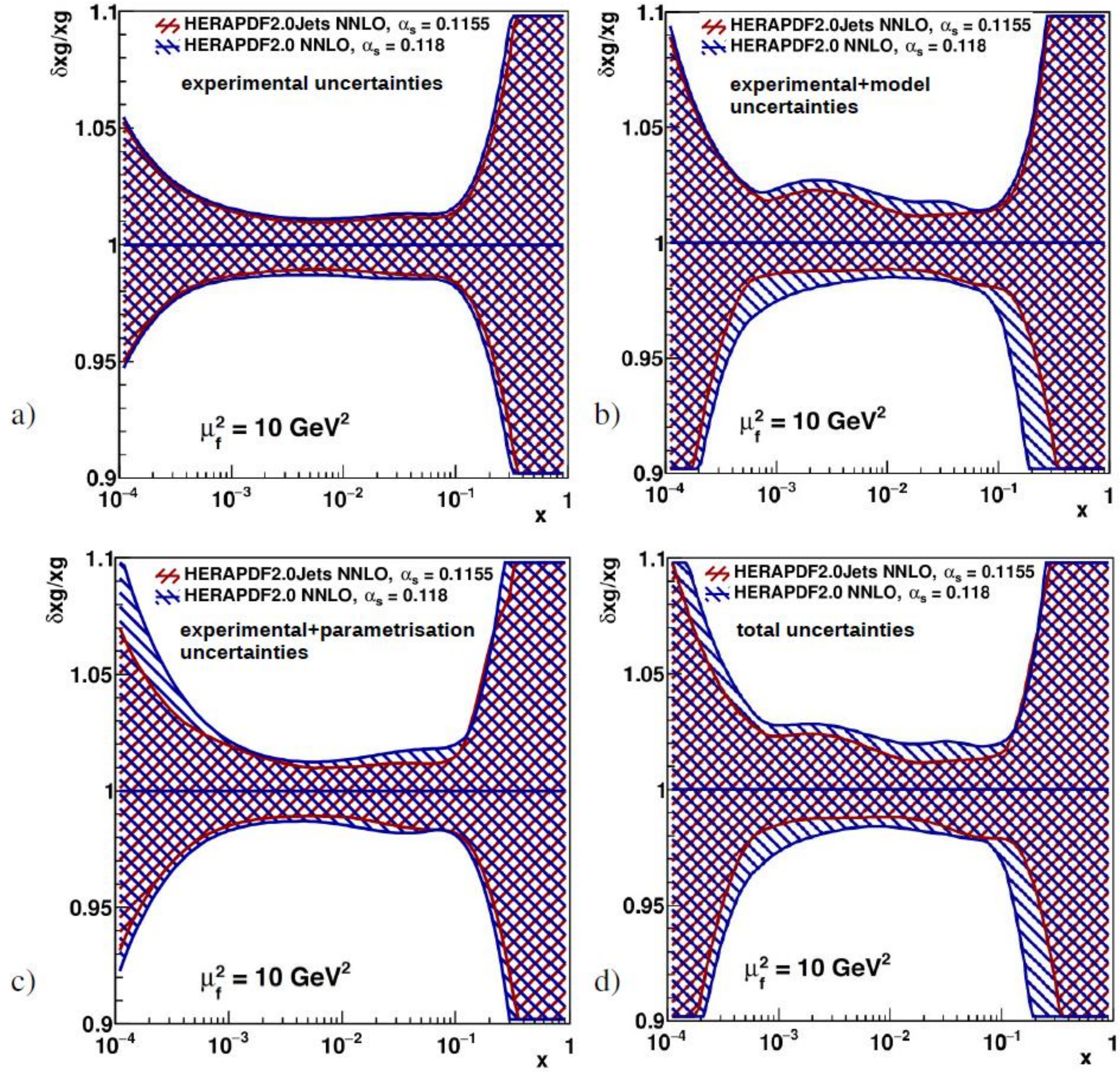


NEW format of ratios



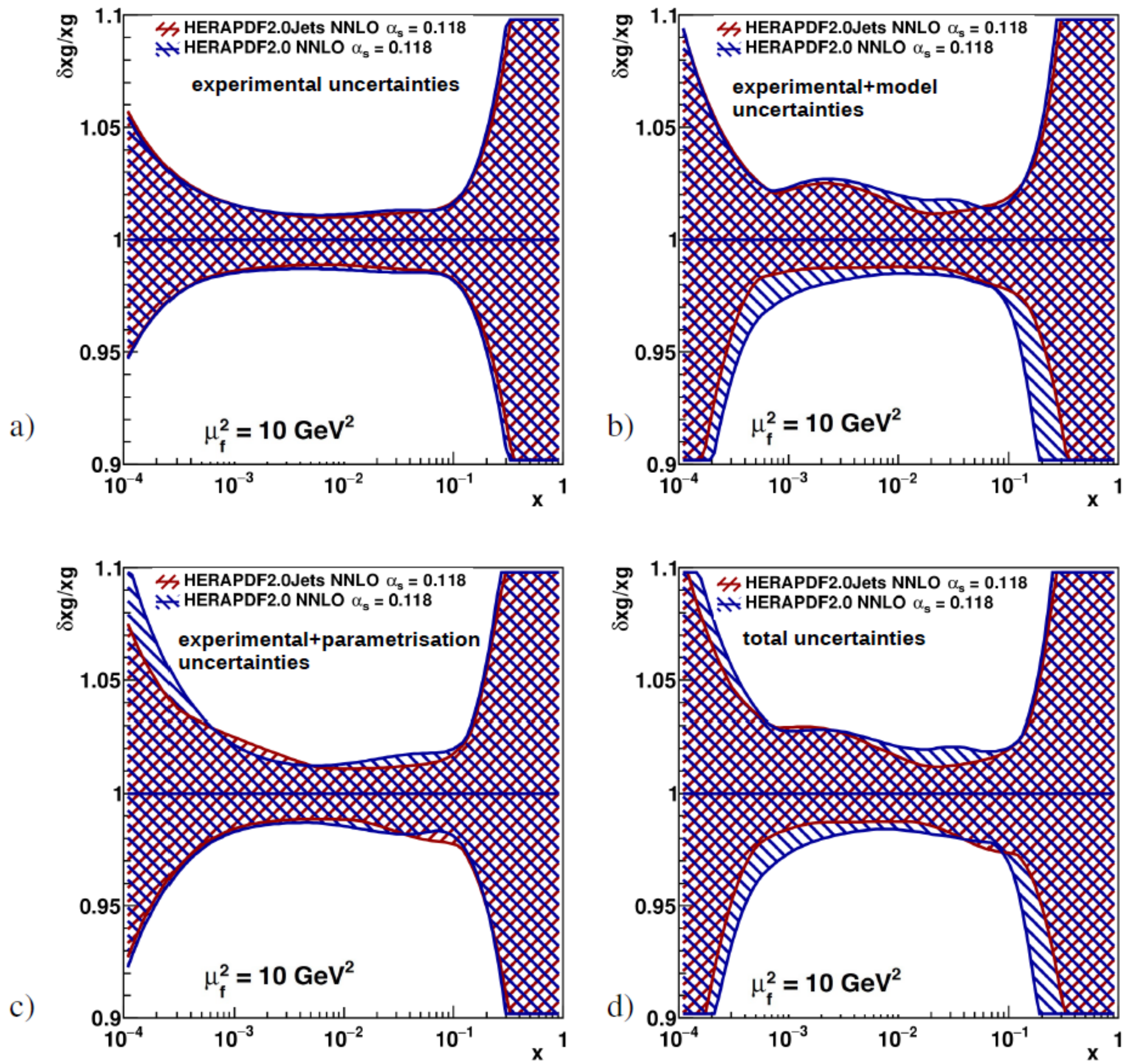


We also compare the uncertainties of the **new** Jets fit and the inclusive NNLO fit



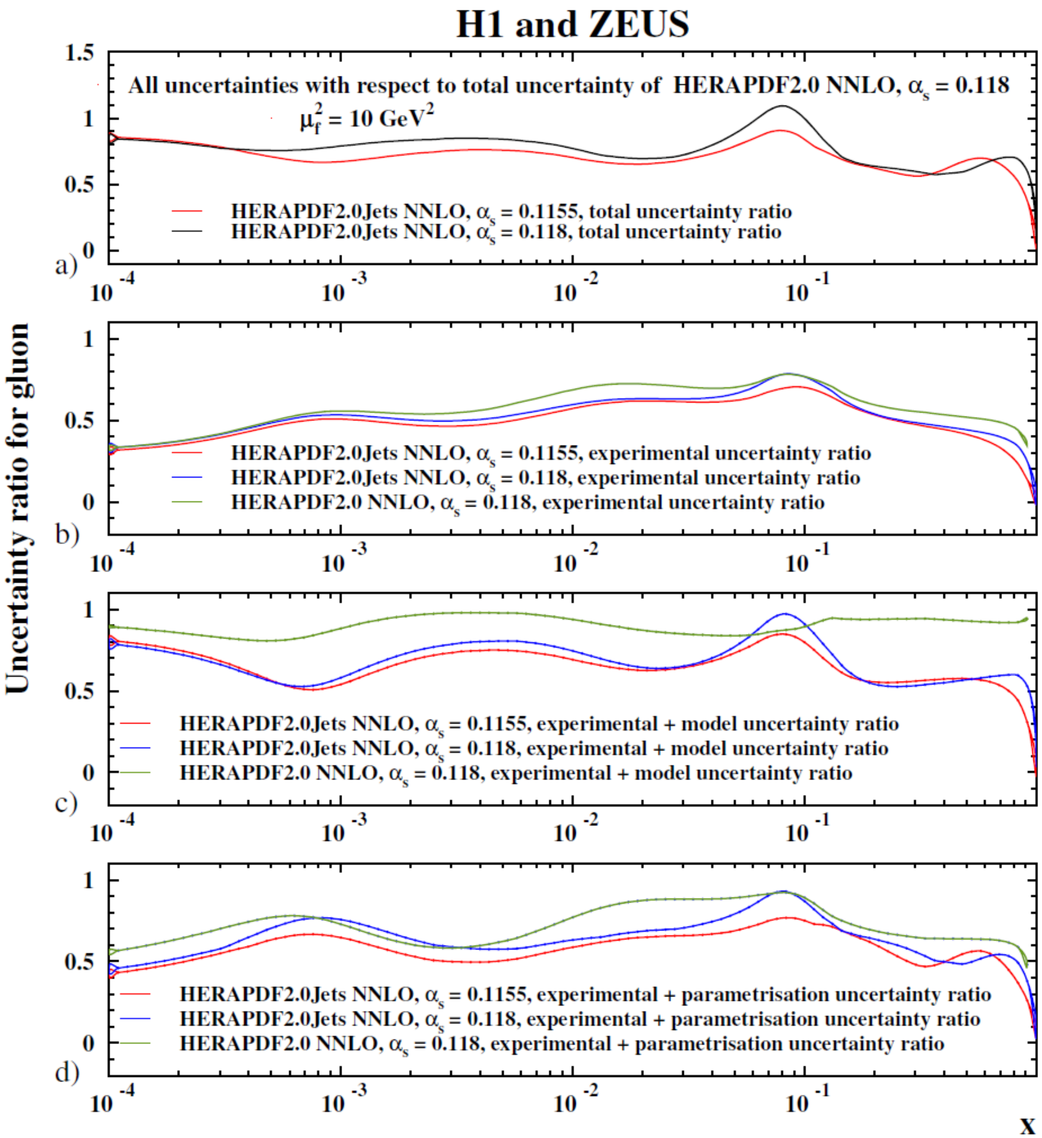
This plot is also made at scale Mz

And we add a version for which the PDFs before and after the inclusion of jets in the fit are compared at the same $\alpha_S(M_Z)$ =0.118



This plot is also made at scale Mz

Here are some new ways of showing this, where ratios of uncertainties for the new fits to the published HERAPDF2.0 NNLO at $\alpha_S(M_Z) = 0.118$ are shown



For total uncertainties

For the experimental uncertainties, which have barely changed

For the exp +model uncertainties, which have improved

For the exp+parametrisation uncertainties, which have improved a little

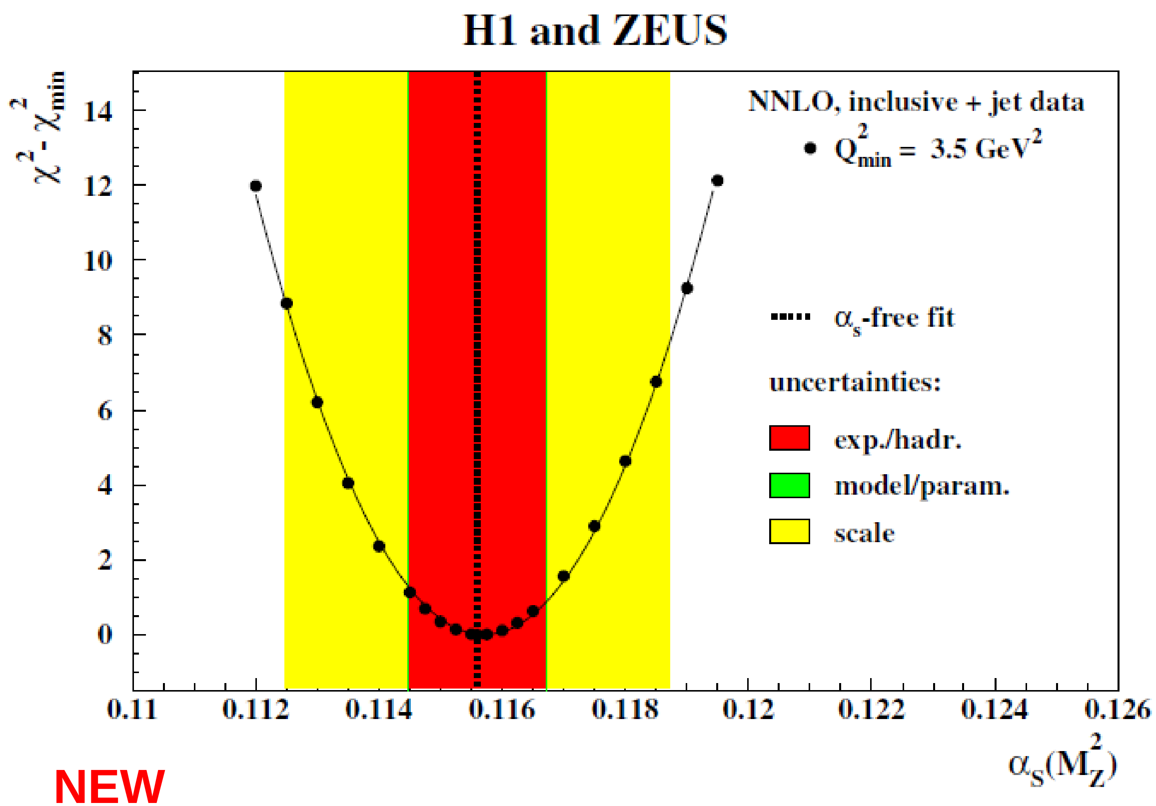
There is little difference between the uncertainties of the new fit for the two values of $\alpha_S(M_Z)$, but the best fit value gives marginally smaller uncertainties

Determination of $\alpha_S(M_Z)$ by simultaneous fit with PDFs

$\chi 2$=1614 for free $\alpha_s(M_Z)$ fit
1363 data points, 1348 degrees of freedom,
$\chi 2$/d.o.f =1.197

$\chi 2$=1617 for fixed $\alpha_s(M_Z)$=0.118
1363 data points, 1349 degrees of freedom,
$\chi 2$/d.o.f =1.199

Compare $\chi 2$/d.o.f =1363/1131 =1.205 for HERAPDF2.0NNLO



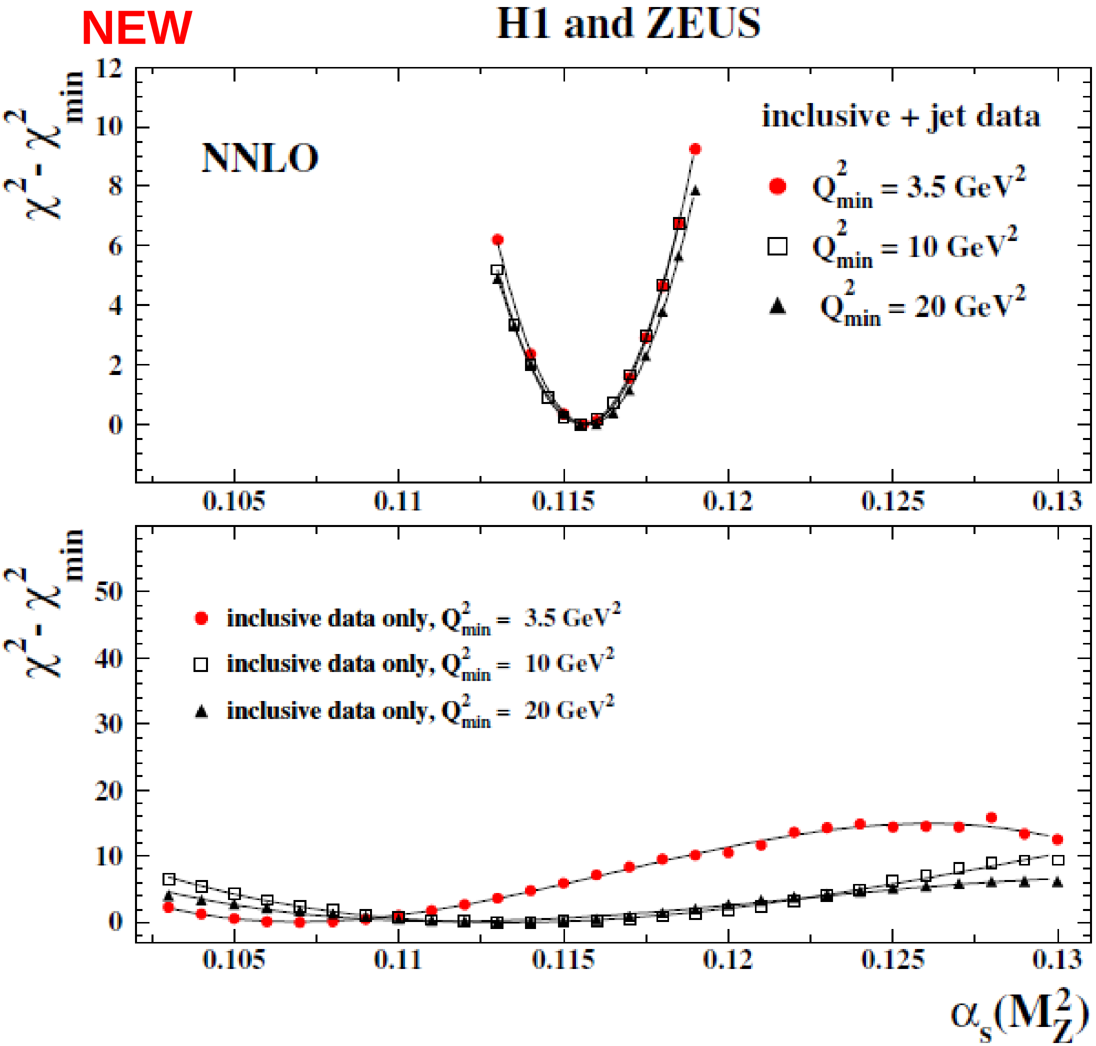
NEW

$$\alpha_s(M_Z) = 0.1156 \pm 0.0011(\text{exp})\ ^{+0.0001}_{-0.0002}(\text{model+parametrisation} \pm 0.0029(\text{scale})$$

The black points show the result of a scan of the chisq of the PDF fit for fixed values of $\alpha_S(M_Z)$. This is in perfect agreement with the simultaneous fit of $\alpha_S(M_Z)$ and PDF params. The fits are repeated with changes in model parameters and parametrisation choices and with changes in the choice of scale as discussed below

NOTE that (exp) now includes hadronization uncertainties

NEW



We also show scans of the χ2 vs $\alpha_S(M_Z)$ for harder cuts on the minimum Q^2 entering the fit and compare it with a similar plot in which inclusive only data are used– illustrating the power of jets, just as we did for NLO.

Note this has also been done both for cuts on just the inclusive data and also cutting the low Q^2 normalised jet data. Since the results are very similar it was decided to show the results for cutting inclusive data alone

A further check on the dependence of the value of $\alpha_S(M_Z)$ on the parametrisation was made such that the negative term in the gluon parametrisation was removed. The value $\alpha_S(M_Z)$ = 0.1151 ± 0.0010(exp) was obtained. The addition of a further (1+Dx) term multiplied into the main gluon term was also tried resulting in $\alpha_S(M_Z)$ = 0.1151 ± 0.0010(exp), both compatible with our central result.

Scale uncertainties

Scale uncertainties are determined by varying the factorisation and renormalisation scales up and down by a factor of two- both separately and simultaneously 7-point variation -and refitting. **The full scale uncertainties are obtained by taking the maximal upward and downward variations.**

The full scale uncertainty on $\alpha_S(M_Z)$ WAS $^{+0.0036}/_{-0.0034}$ using the old grids and it was dominated by the change in renormalisation scale.

The full scale uncertainty on $\alpha_S(M_Z)$ IS ± 0.0029 using the new grids and it is still dominated by the change in renormalisation scale

In our previous NLO analysis we had applied the scale uncertainties as ½ correlated and ½ uncorrelated between bins and data sets, and if we follow this procedure the scale uncertainty on $\alpha_S(M_Z)$ WAS $^{+0.0026}/_{-0.0024}$ And is NOW ± 0.0022

We wish to quote this uncertainty at NNLO **ONLY** when comparing to the NLO scale uncertainty which was $^{+0.0037}/_{-0.0030}$ in order to demonstrate that scale uncertainties are significantly reduced from NLO to NNLO.

Our present NNLO result using ½ correlated and ½ uncorrelated scale uncertainty

$\alpha_s(M_Z) = 0.1156 \pm 0.0011(\text{exp})\ ^{+0.0001}_{-0.0002}(\text{model+parametrisation} \pm 0.0022(\text{scale})$

where "exp" denotes the experimental uncertainty which is taken as the fit uncertainty, including the contribution from hadronisation uncertainties.

Maybe compared with the NLO result

$\alpha_S(M_Z) = 0.1183 \pm 0.0008(\text{exp}) \pm 0.0012(\text{had})\ ^{+0.0003}/_{-0.0005}(\text{mod/param})\ ^{+0.0037}/_{-0.003}(\text{scale})$

But note these analyses were done with differing choices of data set, scale etc. Some work was done on unifying this and is in backup, but we decided against including this in the paper

We wish to quote the full scale uncertainty as our main result and for comparison to other NNLO $\alpha_S(M_Z)$ extractions….from the **NEW** H1 NNLO jet study erratum

H1 jets		$2m_b$	$0.1170\ (9)_{\rm exp}\ (7)_{\rm had}\ (5)_{\rm PDF}\ (4)_{\rm PDF\alpha_s}\ (2)_{\rm PDFset}\ (38)_{\rm scale}$
H1 jets	μ >	28 GeV	$0.1166\ (19)_{\rm exp}\ (9)_{\rm had}\ (3)_{\rm PDF}\ (2)_{\rm PDF\alpha_s}\ (4)_{\rm PDFset}\ (21)_{\rm scale}$
H1 jets		42 GeV	$0.1172\ (23)_{\rm exp}\ (8)_{\rm had}\ (2)_{\rm PDF}\ (2)_{\rm PDF\alpha_s}\ (7)_{\rm PDFset}\ (14)_{\rm scale}$

Using a similar break up of uncertainties our result is

$$\alpha_S(M_Z) = 0.1156 \pm 0.0011(\text{exp+had+PDF})\ ^{+0.0001}_{-0.0002}(\text{model+parametrisation}) \pm 0.0029(\text{scale})$$

For μ > 10 GeV. In the paper we only compare the scale uncertainties because of the differing method of $\alpha_S(M_Z)$ extraction with fixed PDFs

Alternatively we may compare to the H1 result making a simultaneous PDF and $\alpha_S(M_Z)$ fit to just H1 inclusive and jet data, $0.1147\ (11)_{\rm exp,NP,PDF}\ (2)_{\rm mod}\ (3)_{\rm par}\ (23)_{\rm scale}$

but note this was for $Q^2 > 10$ GeV^2 on both inclusive and jets hence we have re-evaluated the scale uncertainty using this cut (rather than the default 3.5 GeV^2 cut)
We apply this cut both on inclusive data and on the jet data whose normalisations involve low Q^2.
Our comparable result is
$\alpha_S(M_Z)$ =**0.1156** ± *0.0011(exp,had,PDF)* ± *0.0002(mod/par)* ± ***0.0021*****(scale)**

There is also an update of the NNLOjet $\alpha_S(M_Z)$ extraction using fixed PDFs

HERA inclusive jets		
HERA inclusive jets	$2m_b$	$0.1171 \; (9)_{\rm exp} \; (5)_{\rm had} \; (4)_{\rm PDF} \; (3)_{\rm PDF\alpha_s} \; (2)_{\rm PDFset} \; (33)_{\rm scale}$
HERA inclusive jets	28 GeV	$0.1178 \; (15)_{\rm exp} \; (7)_{\rm had} \; (2)_{\rm PDF} \; (2)_{\rm PDF\alpha_s} \; (4)_{\rm PDFset} \; (19)_{\rm scale}$

Using a similar break up of uncertainties our result is

$\alpha_S(M_Z) = 0.1156 \pm 0.0011(\text{exp+had+PDF})\ ^{+0.0001}_{-0.0002}(\text{model+parametrisation}) \pm 0.0029(\text{scale})$

For μ > 10 GeV, again we will only compare scale uncertainties

This is the end of the new analysis

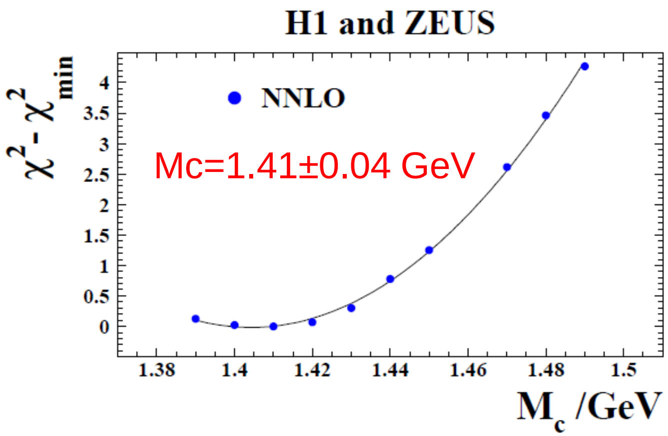
All proposed Tables and Figures are below.

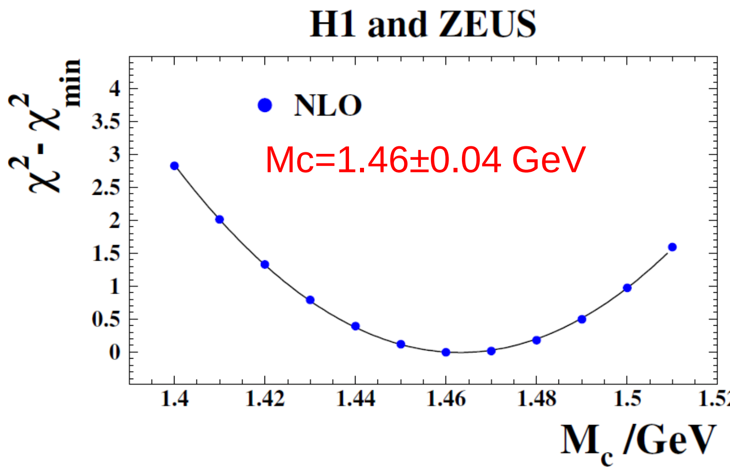
Data Set	taken	Q^2[GeV^2] range		$\mathcal{L}$	e^+/e^-	$\sqrt{s}$	norma-	all	used	Ref.
	from – to	from	to	pb^{-1}		GeV	lised	points	points	
H1 HERA I normalised jets	1999 – 2000	150	15000	65.4	e^+p	319	yes	24	24	[9]
H1 HERA I jets at low Q^2	1999 – 2000	5	100	43.5	e^+p	319	no	28	20	[10]
H1 normalised inclusive jets at high Q^2	2003 – 2007	150	15000	351	e^+p/e^-p	319	yes	30	30	[13,14]
H1 normalised dijets at high Q^2	2003 – 2007	150	15000	351	e^+p/e^-p	319	yes	24	24	[14]
H1 normalised inclusive jets at low Q^2	2005 – 2007	5.5	80	290	e^+p/e^-p	319	yes	48	37	[13]
H1 normalised dijets at low Q^2	2005 – 2007	5.5	80	290	e^+p/e^-p	319	yes	48	37	[13]
ZEUS inclusive jets	1996 – 1997	125	10000	38.6	e^+p	301	no	30	30	[11]
ZEUS dijets 1998 –2000 &	2004 – 2007	125	20000	374	e^+p/e^-p	318	no	22	16	[12]

Table 1: *The data sets on jet production from H1 and ZEUS used for the HERAPDF2.0Jets NNLO its. The term normalised indicates that all cross sections are normalised to the respective NC inclusive cross sections.*

Parameter	Central Value	Downwards variation	Upwards variation
Q^2_{min} [GeV^2]	3.5	2.5	5.0
f_s	0.4	0.3	0.5
M_c [GeV]	1.41	1.37*	1.45
M_b [GeV]	4.20	4.10	4.30
μ^2_{f0} [GeV^2]	1.9	1.6	2.2*

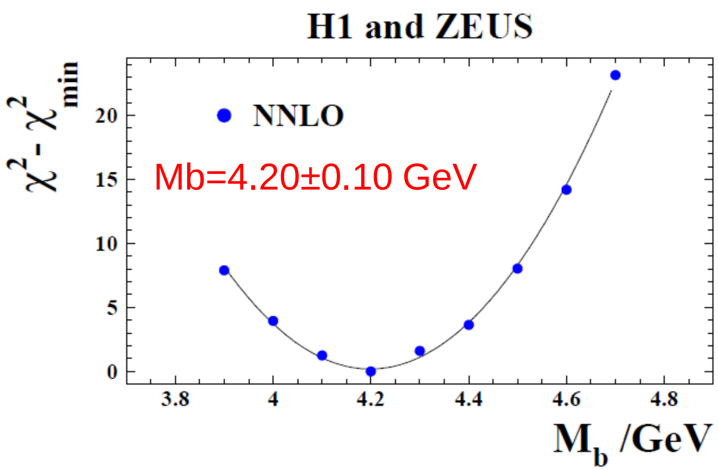
Table 2: *Central values of model input parameters and their one-sigma variations. It was not possible to implement the variations marked * because $\mu_{f0} < M_c$ is required, see Section 3.3. In these cases, the uncertainty on the PDF obtained from the other variation was symmetrised.*





NNLO Mc,Mb scans have not changed

Update to add NLO



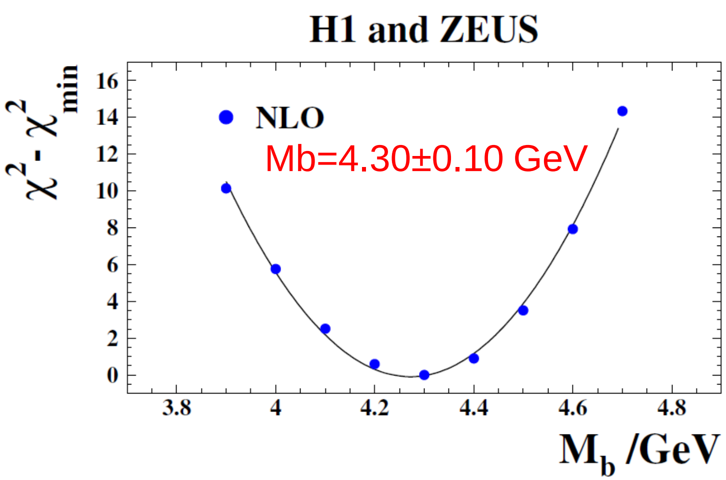
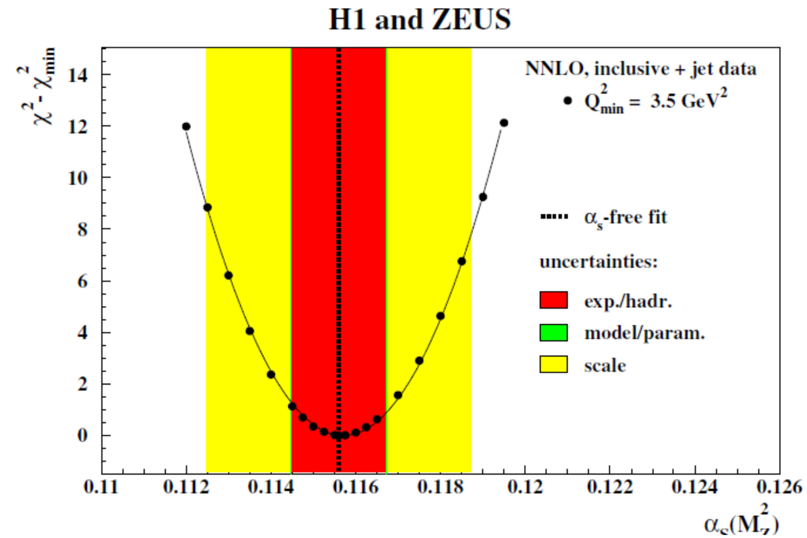
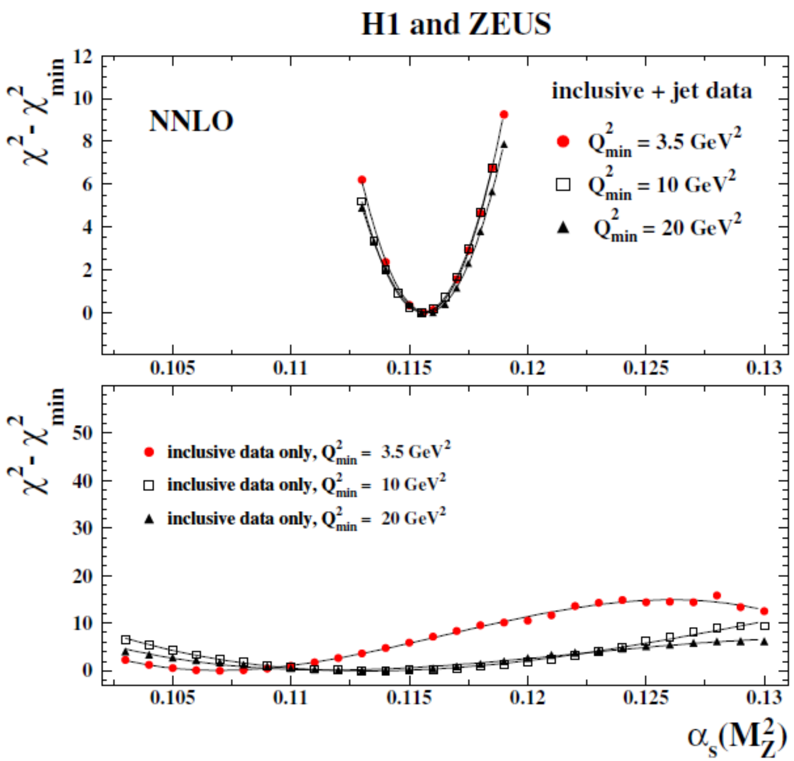


Figure 1: $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ vs. a) M_c with $M_b = 4.2$ GeV and b) M_b with $M_c = 1.41$ GeV for HERAPDF2.0Jets NNLO fits with fixed $\alpha_s(M_Z^2) = 0.1155$.

NEW

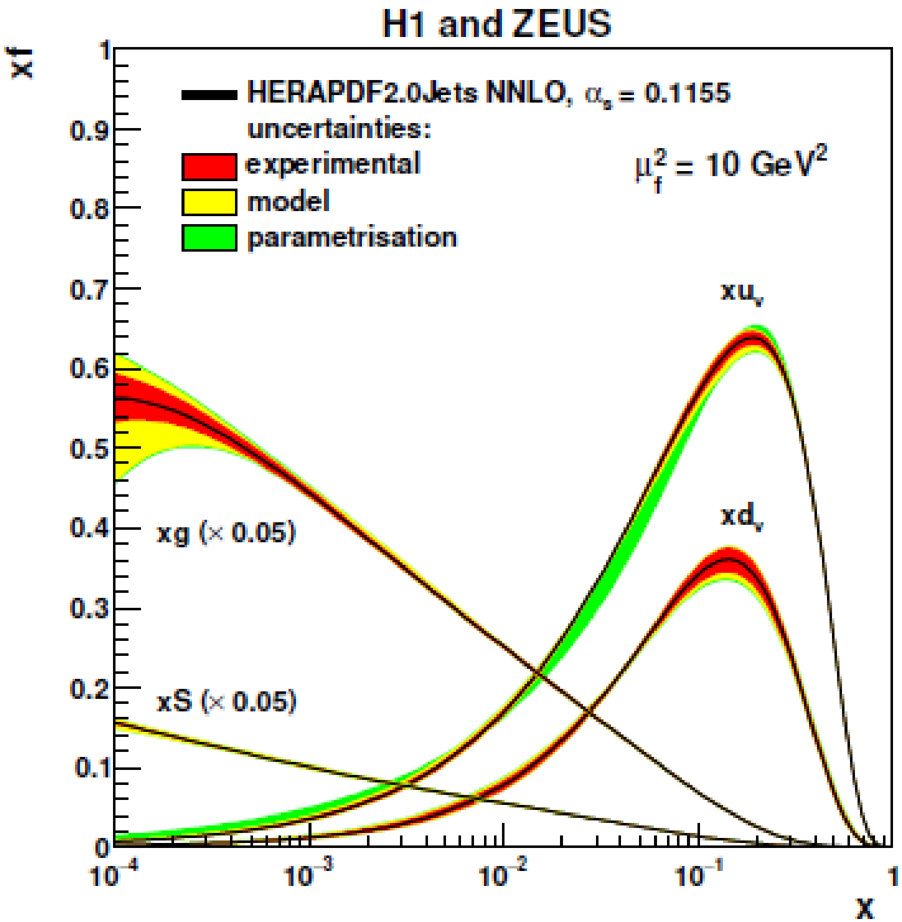


H1 and ZEUS
NNLO, inclusive + jet data
Q^2_{min} = 3.5 GeV^2
α_s-free fit
uncertainties:
exp./hadr.
model/param.
scale
$\chi^2 - \chi^2_{min}$
$\alpha_s(M_Z^2)$
0.11 0.112 0.114 0.116 0.118 0.12 0.122 0.124 0.126
0 2 4 6 8 10 12 14

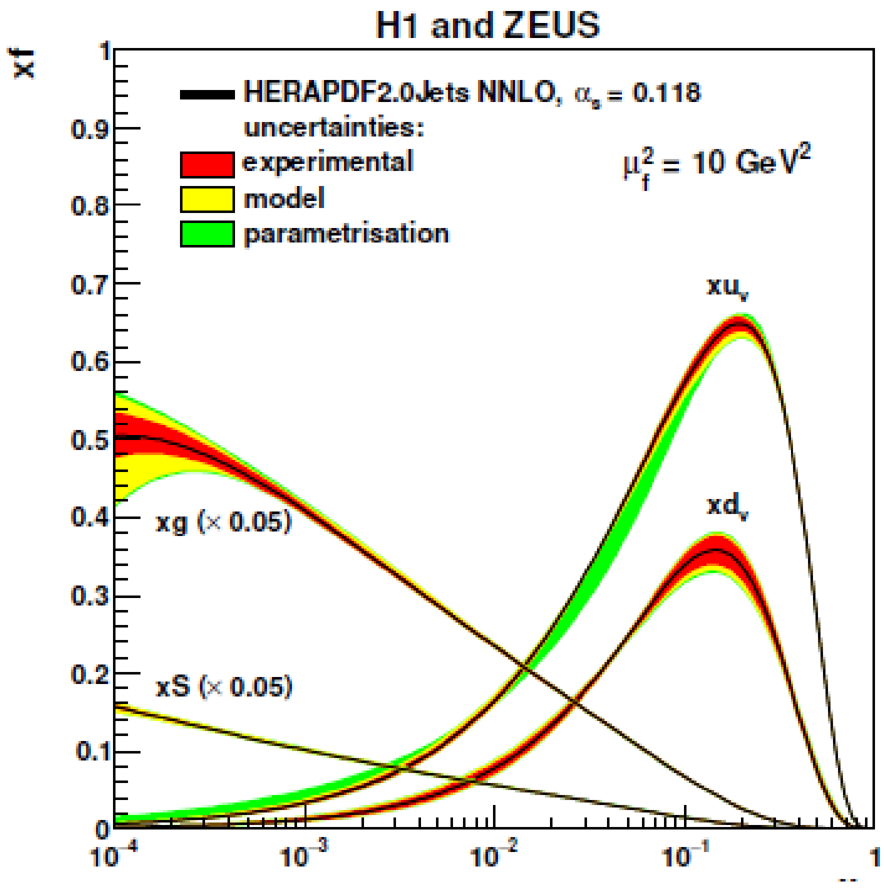


H1 and ZEUS
NNLO
inclusive + jet data
Q^2_{min} = 3.5 GeV^2
Q^2_{min} = 10 GeV^2
Q^2_{min} = 20 GeV^2
inclusive data only, Q^2_{min} = 3.5 GeV^2
inclusive data only, Q^2_{min} = 10 GeV^2
inclusive data only, Q^2_{min} = 20 GeV^2
$\chi^2 - \chi^2_{min}$
$\alpha_s(M_Z^2)$
0.105 0.11 0.115 0.12 0.125 0.13

NEW

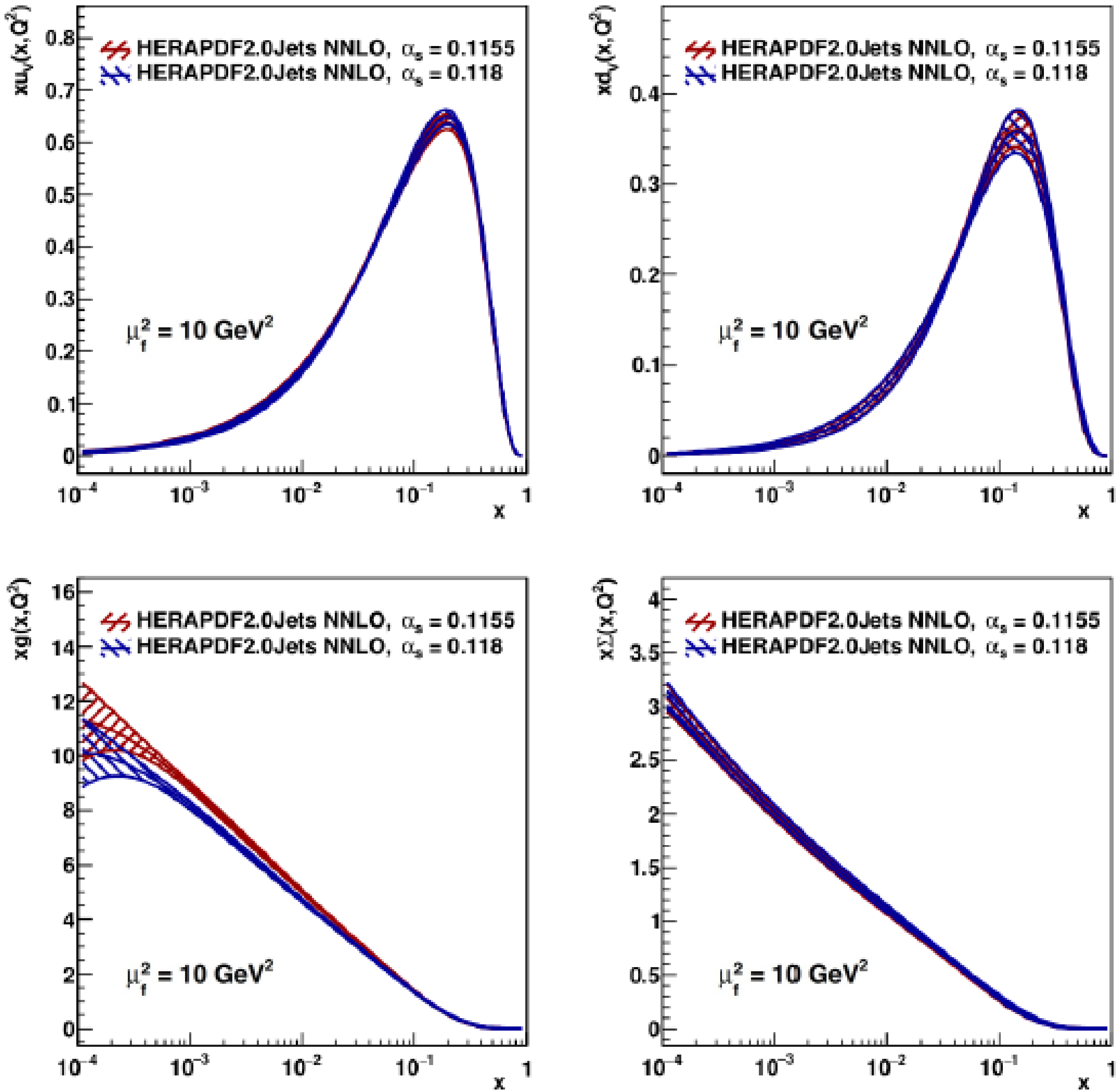


H1 and ZEUS
xf
HERAPDF2.0Jets NNLO, α_s = 0.1155
uncertainties:
experimental
model
parametrisation
μ_f^2 = 10 GeV^2
xu_v
xd_v
xg (× 0.05)
xS (× 0.05)
x



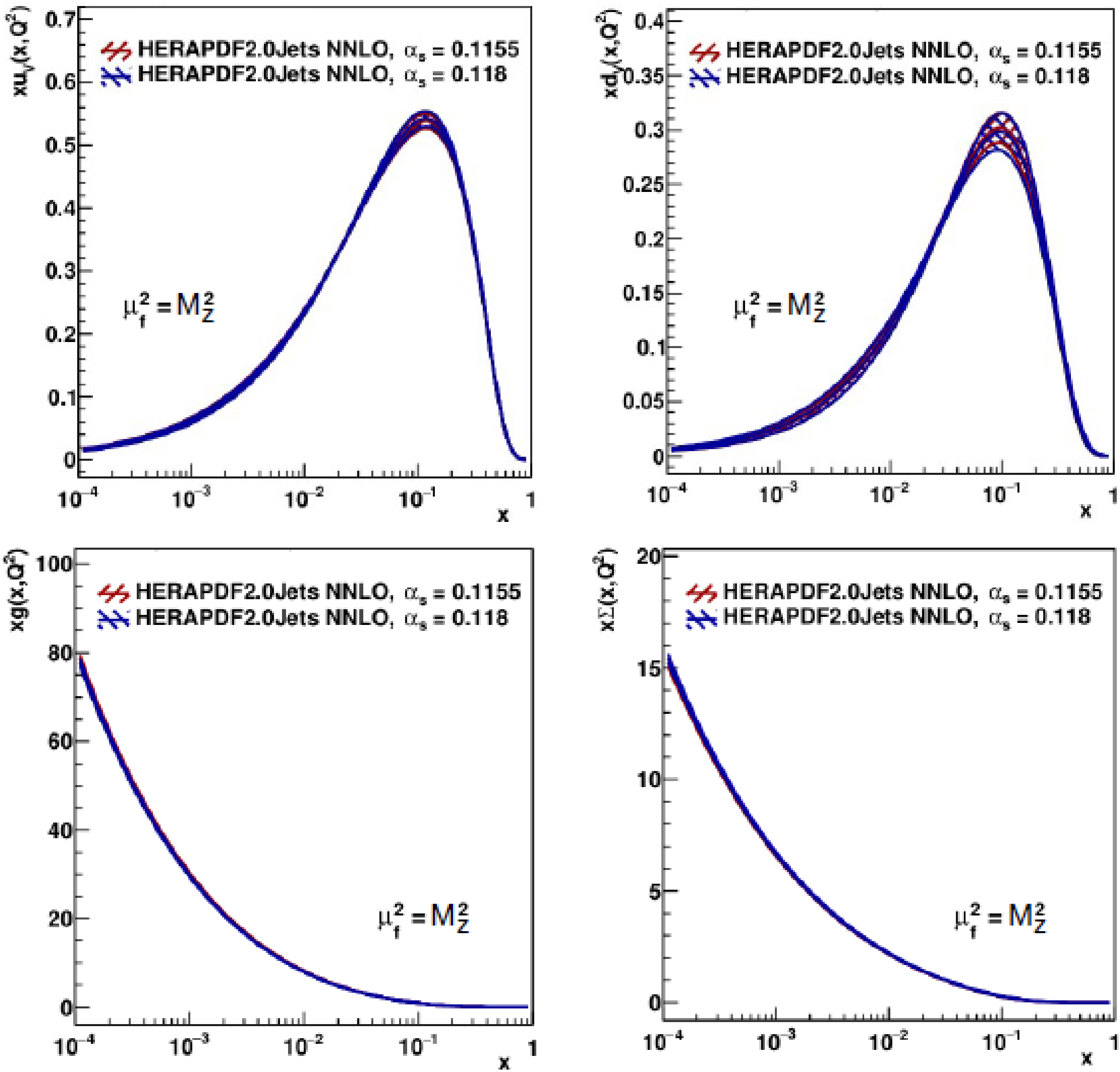
H1 and ZEUS
xf
HERAPDF2.0Jets NNLO, α_s = 0.118
uncertainties:
experimental
model
parametrisation
μ_f^2 = 10 GeV^2
xu_v
xd_v
xg (× 0.05)
xS (× 0.05)

NEW



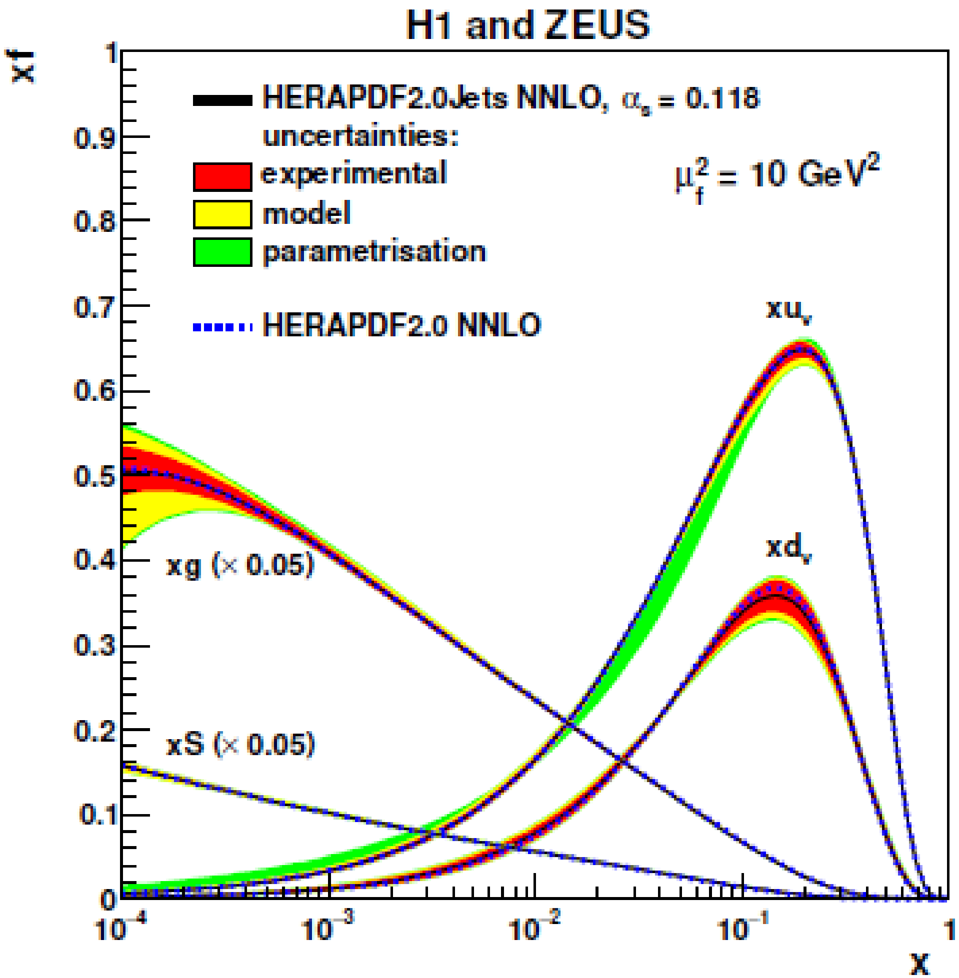
HERAPDF2.0Jets NNLO, $\alpha_s = 0.1155$
HERAPDF2.0Jets NNLO, $\alpha_s = 0.118$
$\mu_f^2 = 10\ GeV^2$
$xu_v(x,Q^2)$
$xd_v(x,Q^2)$
$xg(x,Q^2)$
$x\Sigma(x,Q^2)$
x

NEW



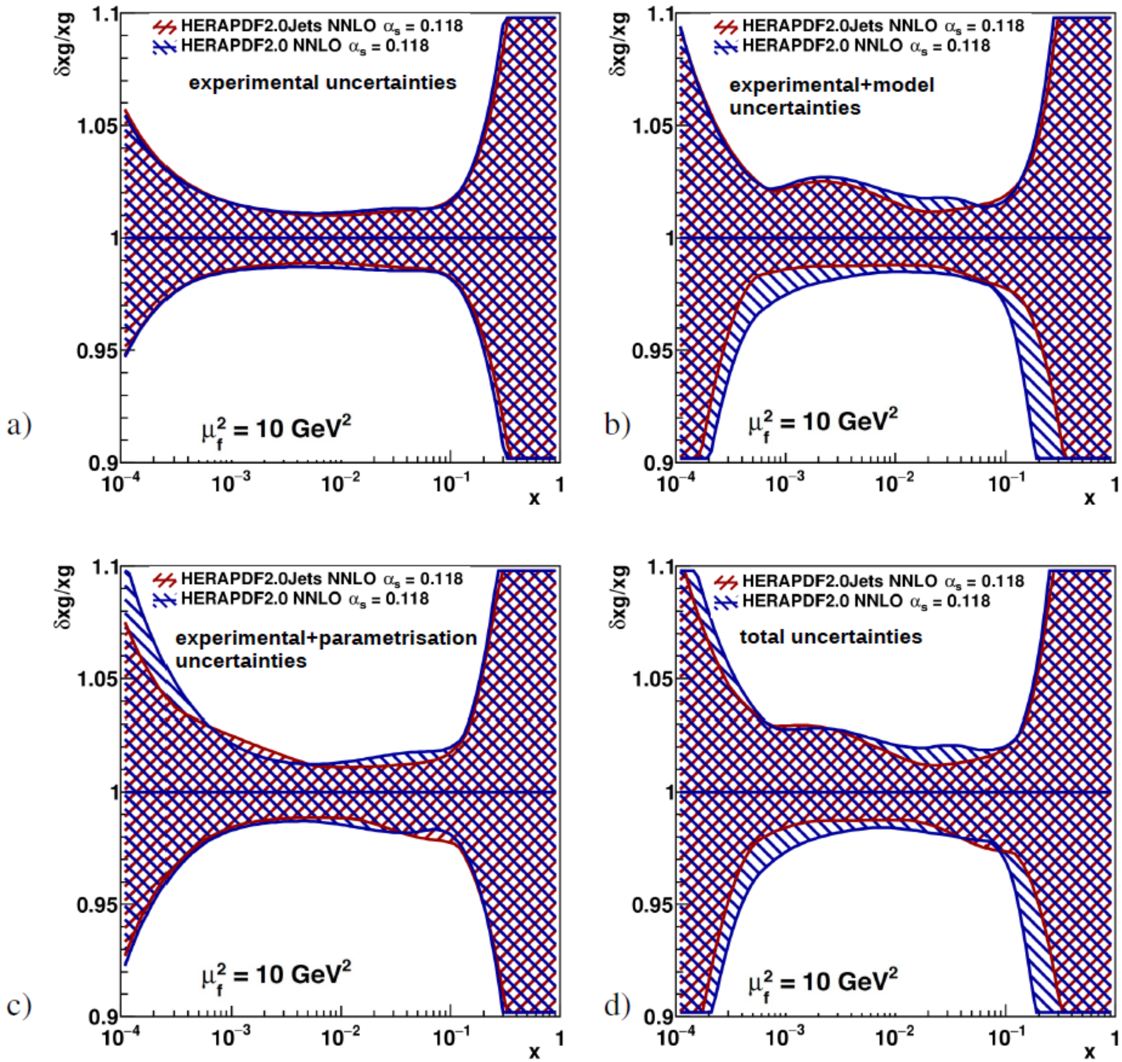
HERAPDF2.0Jets NNLO, α_s = 0.1155
HERAPDF2.0Jets NNLO, α_s = 0.118
$xu_v(x,Q^2)$
$xd_v(x,Q^2)$
$xg(x,Q^2)$
$x\Sigma(x,Q^2)$
$\mu_f^2 = M_Z^2$
x

NEW

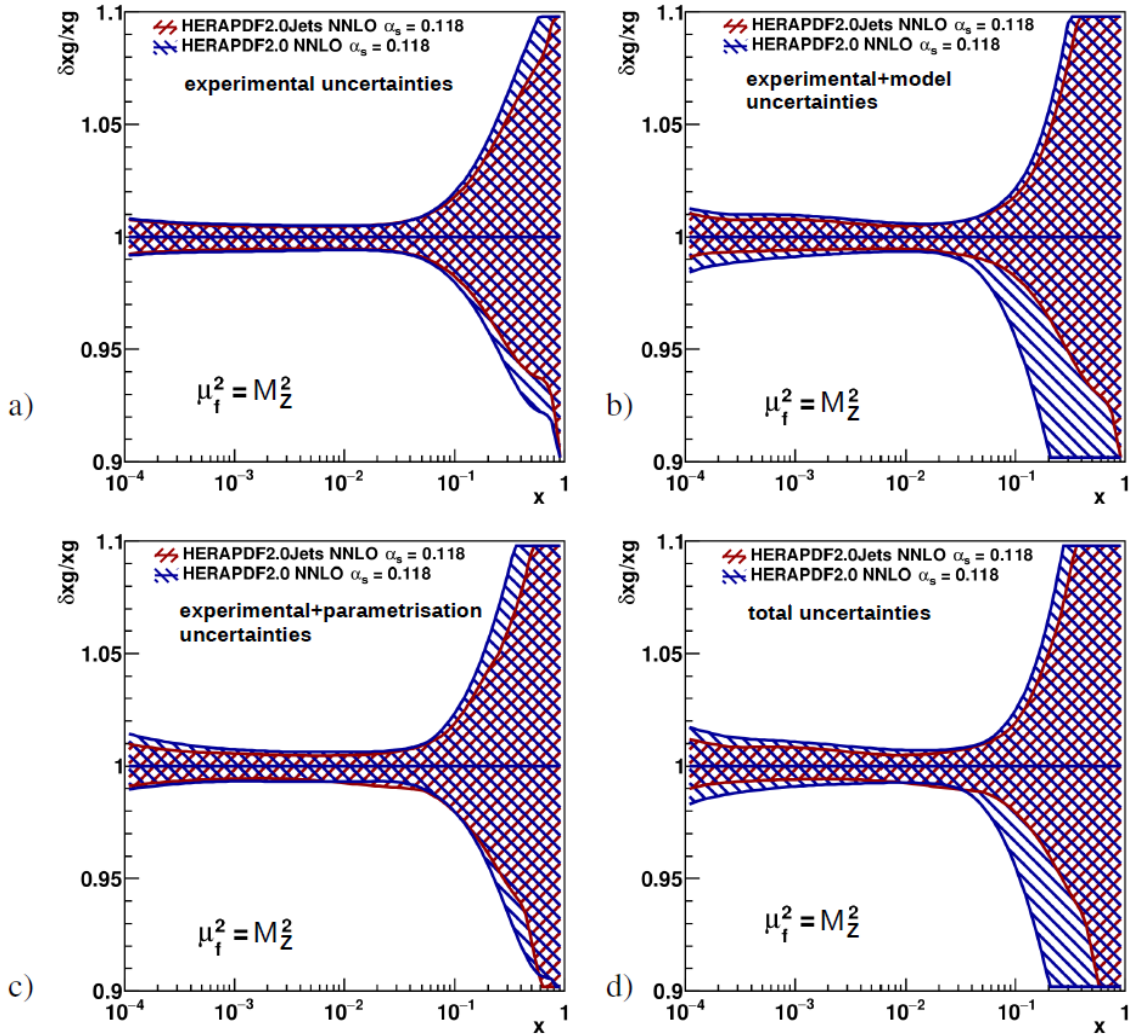


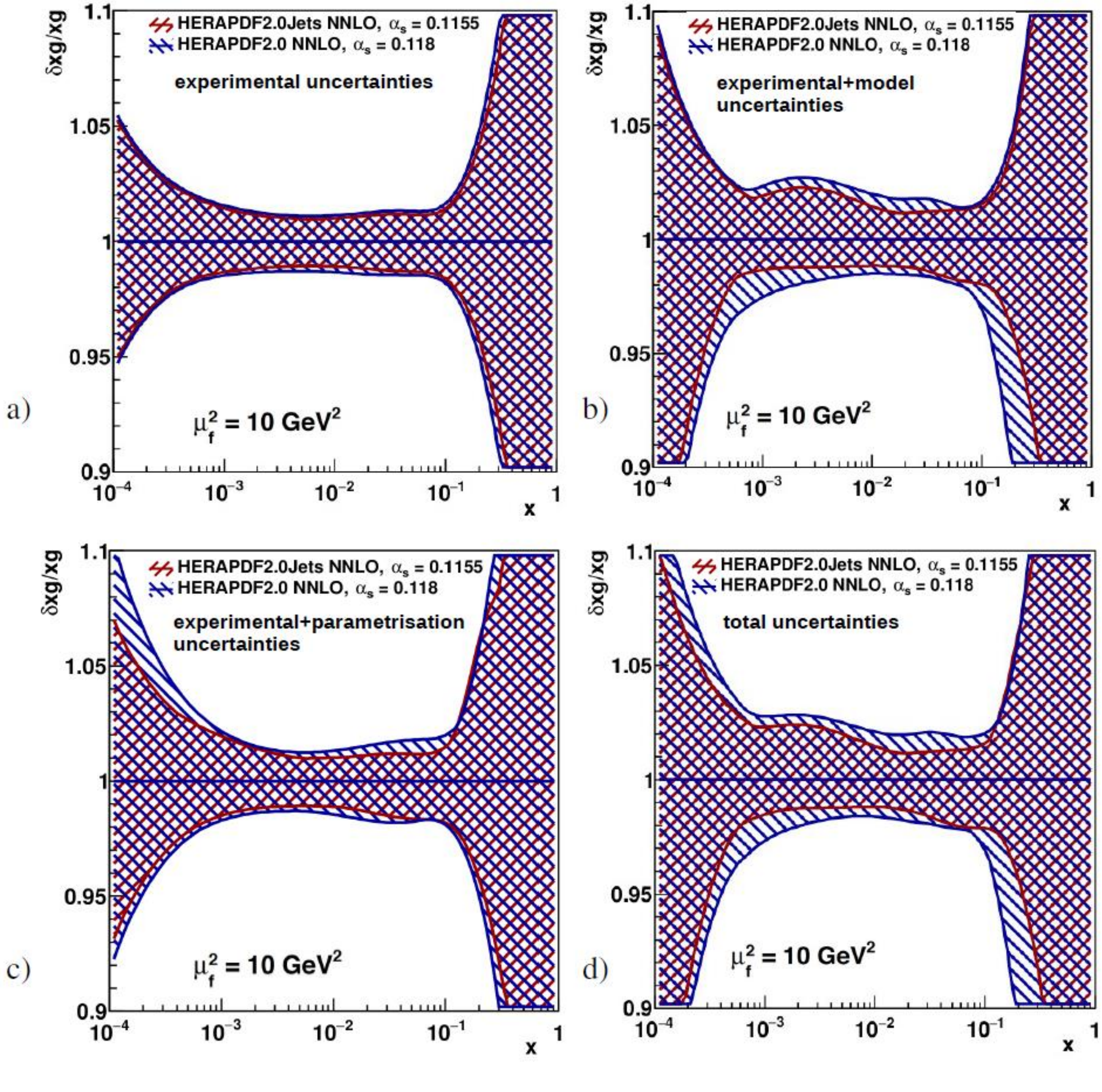
H1 and ZEUS
xf
HERAPDF2.0Jets NNLO, α_s = 0.118
uncertainties:
experimental
model
parametrisation
HERAPDF2.0 NNLO
μ_f^2 = 10 GeV^2
xu_v
xd_v
xg (× 0.05)
xS (× 0.05)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x

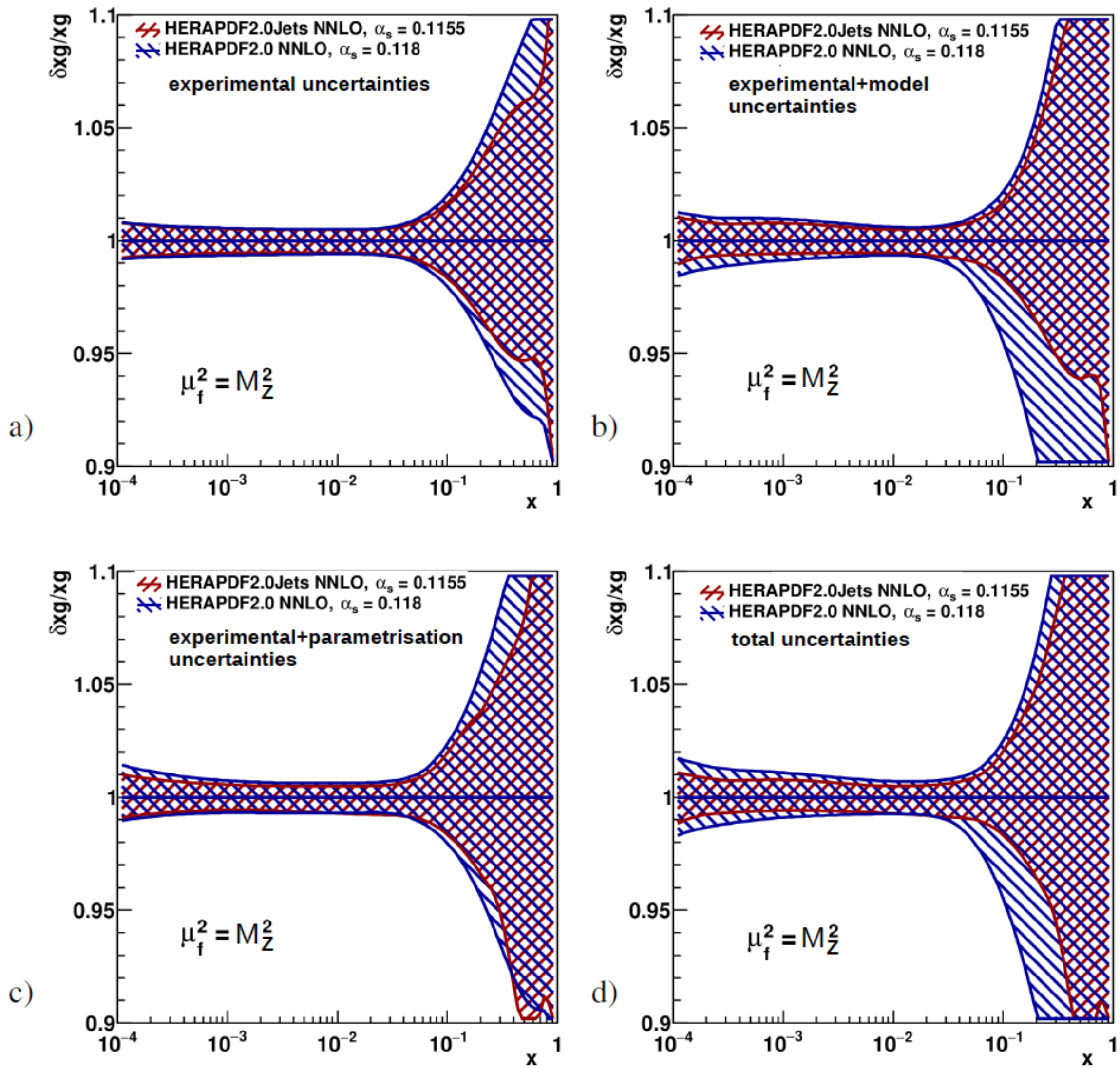
NEW

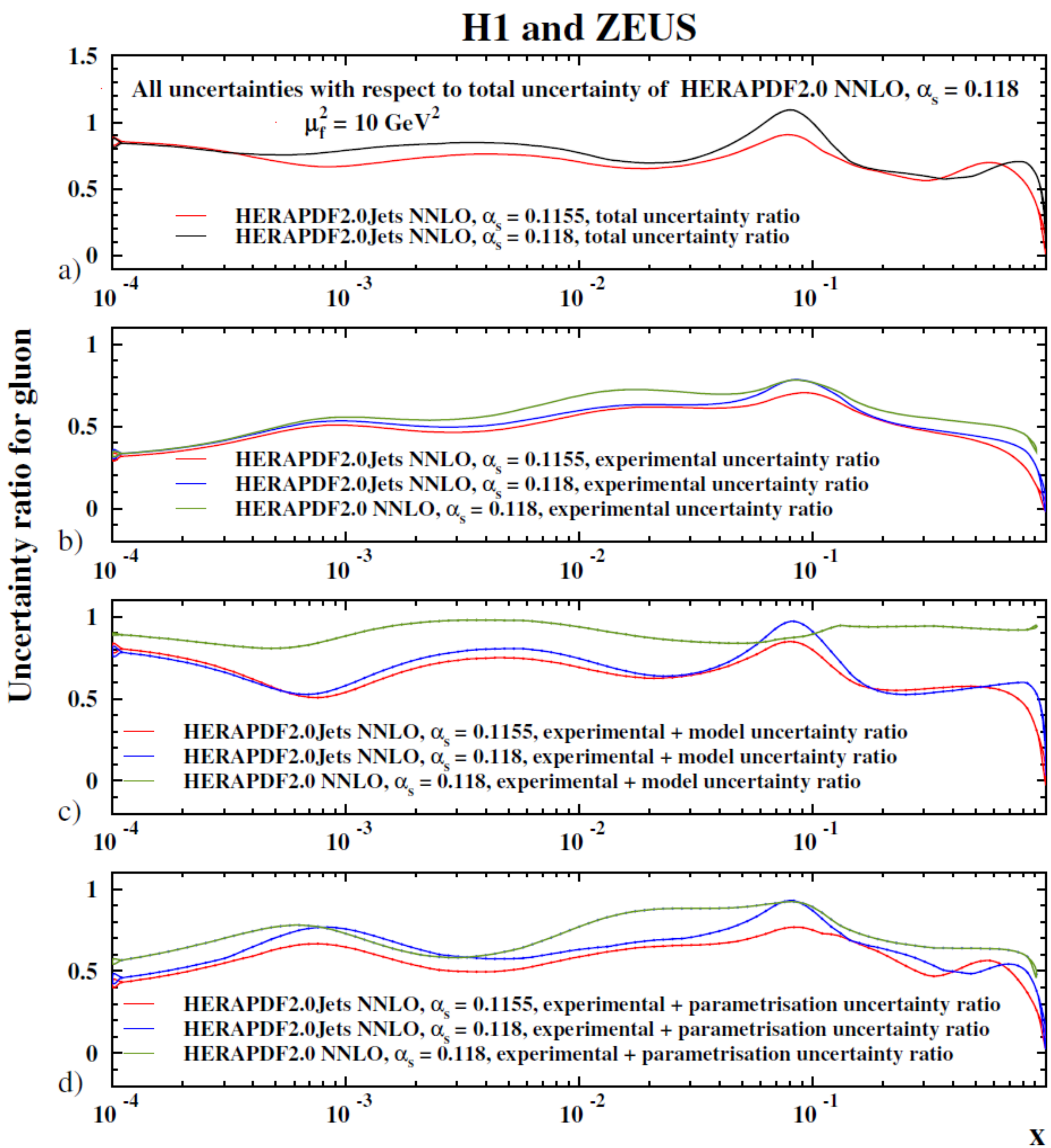


a)
HERAPDF2.0Jets NNLO α_s = 0.118
HERAPDF2.0 NNLO α_s = 0.118
experimental uncertainties
μ_f^2 = 10 GeV^2
b)
HERAPDF2.0Jets NNLO α_s = 0.118
HERAPDF2.0 NNLO α_s = 0.118
experimental+model uncertainties
μ_f^2 = 10 GeV^2
c)
HERAPDF2.0Jets NNLO α_s = 0.118
HERAPDF2.0 NNLO α_s = 0.118
experimental+parametrisation uncertainties
μ_f^2 = 10 GeV^2
d)
HERAPDF2.0Jets NNLO α_s = 0.118
HERAPDF2.0 NNLO α_s = 0.118
total uncertainties
μ_f^2 = 10 GeV^2
δxg/xg
x


HERAPDF2.0Jets NNLO α_s = 0.118
HERAPDF2.0 NNLO α_s = 0.118
experimental uncertainties
$\mu_f^2 = M_Z^2$
a)
experimental+model uncertainties
b)
experimental+parametrisation uncertainties
c)
total uncertainties
d)
$\delta xg/xg$
x

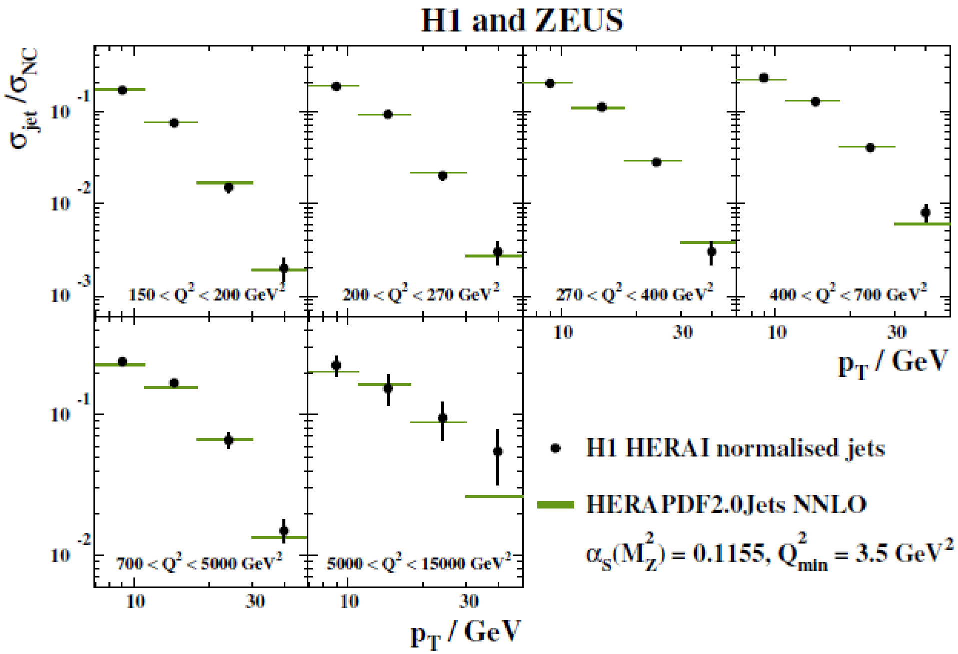

a)
HERAPDF2.0Jets NNLO, α_s = 0.1155
HERAPDF2.0 NNLO, α_s = 0.118
experimental uncertainties
μ_f^2 = 10 GeV^2
δxg/xg
x
b)
HERAPDF2.0Jets NNLO, α_s = 0.1155
HERAPDF2.0 NNLO, α_s = 0.118
experimental+model uncertainties
μ_f^2 = 10 GeV^2
δxg/xg
x
c)
HERAPDF2.0Jets NNLO, α_s = 0.1155
HERAPDF2.0 NNLO, α_s = 0.118
experimental+parametrisation uncertainties
μ_f^2 = 10 GeV^2
δxg/xg
x
d)
HERAPDF2.0Jets NNLO, α_s = 0.1155
HERAPDF2.0 NNLO, α_s = 0.118
total uncertainties
μ_f^2 = 10 GeV^2
δxg/xg
x

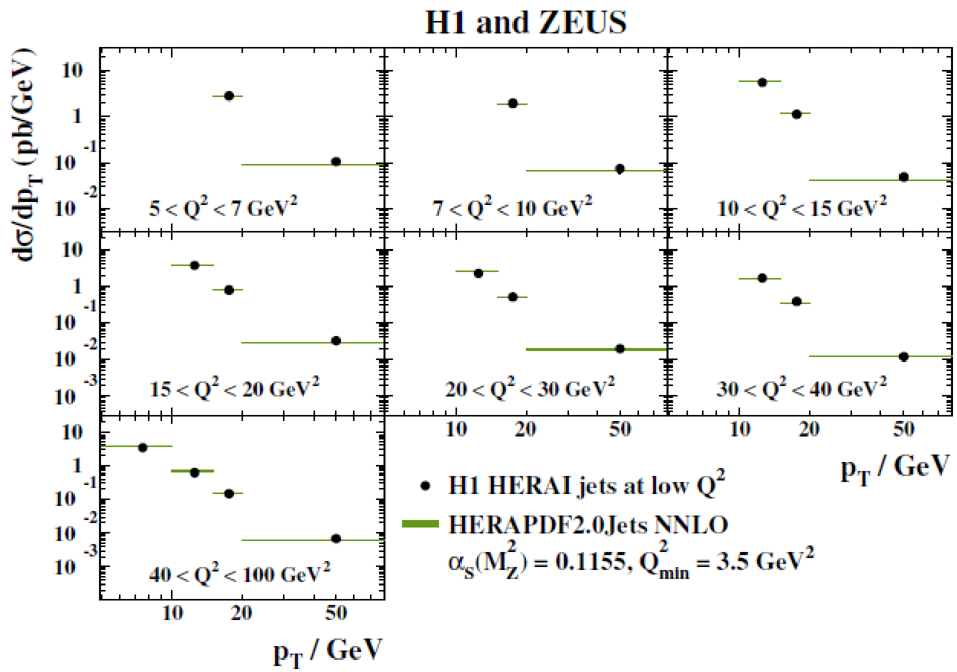

a)
HERAPDF2.0Jets NNLO, α_s = 0.1155
HERAPDF2.0 NNLO, α_s = 0.118
experimental uncertainties
$\mu_f^2 = M_Z^2$
b)
HERAPDF2.0Jets NNLO, α_s = 0.1155
HERAPDF2.0 NNLO, α_s = 0.118
experimental+model uncertainties
$\mu_f^2 = M_Z^2$
c)
HERAPDF2.0Jets NNLO, α_s = 0.1155
HERAPDF2.0 NNLO, α_s = 0.118
experimental+parametrisation uncertainties
$\mu_f^2 = M_Z^2$
d)
HERAPDF2.0Jets NNLO, α_s = 0.1155
HERAPDF2.0 NNLO, α_s = 0.118
total uncertainties
$\mu_f^2 = M_Z^2$
$\delta xg/xg$
x



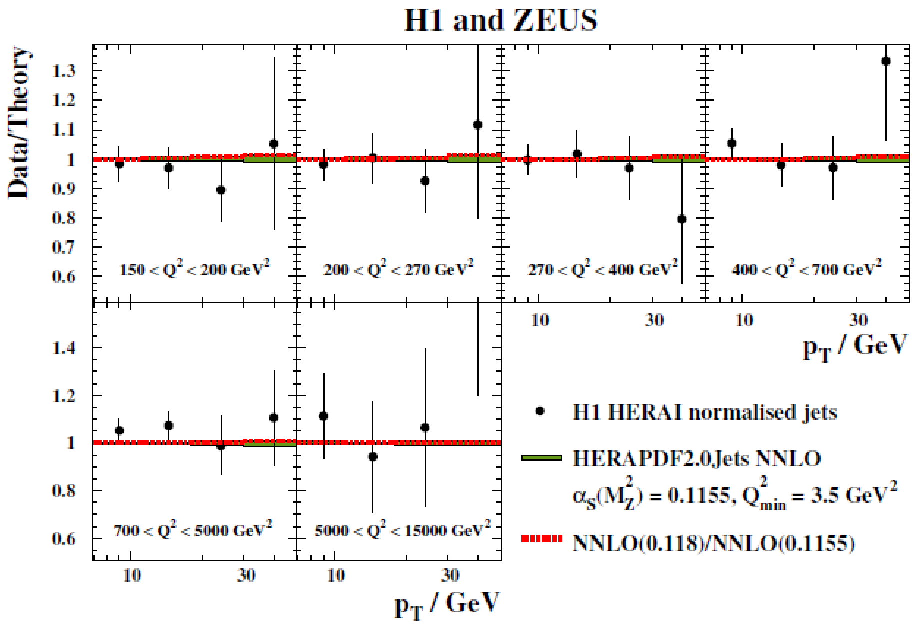
H1 and ZEUS
All uncertainties with respect to total uncertainty of HERAPDF2.0 NNLO, α_s = 0.118
μ_f^2 = 10 GeV^2
HERAPDF2.0Jets NNLO, α_s = 0.1155, total uncertainty ratio
HERAPDF2.0Jets NNLO, α_s = 0.118, total uncertainty ratio
HERAPDF2.0Jets NNLO, α_s = 0.1155, experimental uncertainty ratio
HERAPDF2.0Jets NNLO, α_s = 0.118, experimental uncertainty ratio
HERAPDF2.0 NNLO, α_s = 0.118, experimental uncertainty ratio
HERAPDF2.0Jets NNLO, α_s = 0.1155, experimental + model uncertainty ratio
HERAPDF2.0Jets NNLO, α_s = 0.118, experimental + model uncertainty ratio
HERAPDF2.0 NNLO, α_s = 0.118, experimental + model uncertainty ratio
HERAPDF2.0Jets NNLO, α_s = 0.1155, experimental + parametrisation uncertainty ratio
HERAPDF2.0Jets NNLO, α_s = 0.118, experimental + parametrisation uncertainty ratio
HERAPDF2.0 NNLO, α_s = 0.118, experimental + parametrisation uncertainty ratio
Uncertainty ratio for gluon
a)
b)
c)
d)
x

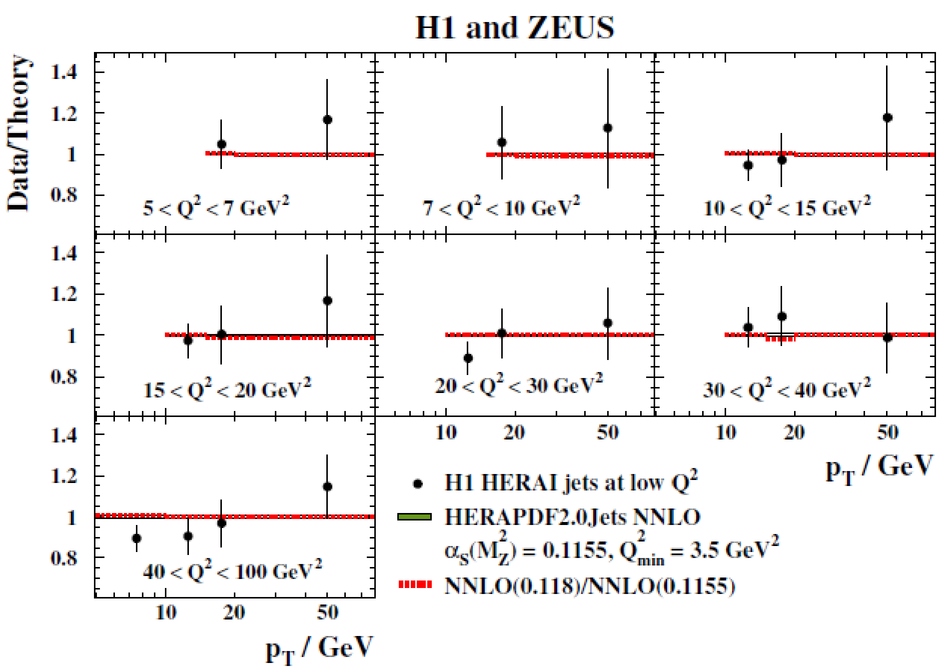
All data plots are NEW



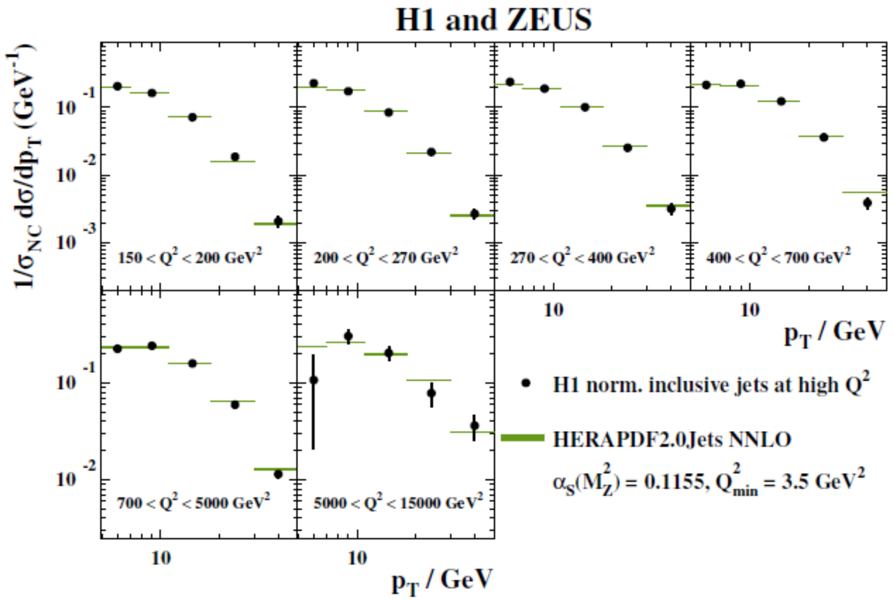


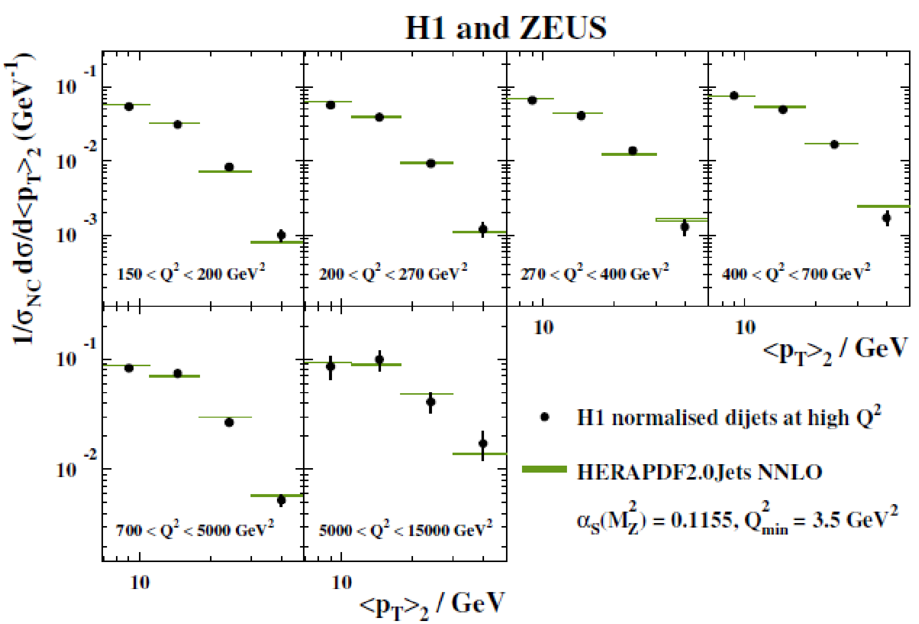
All data plots are NEW



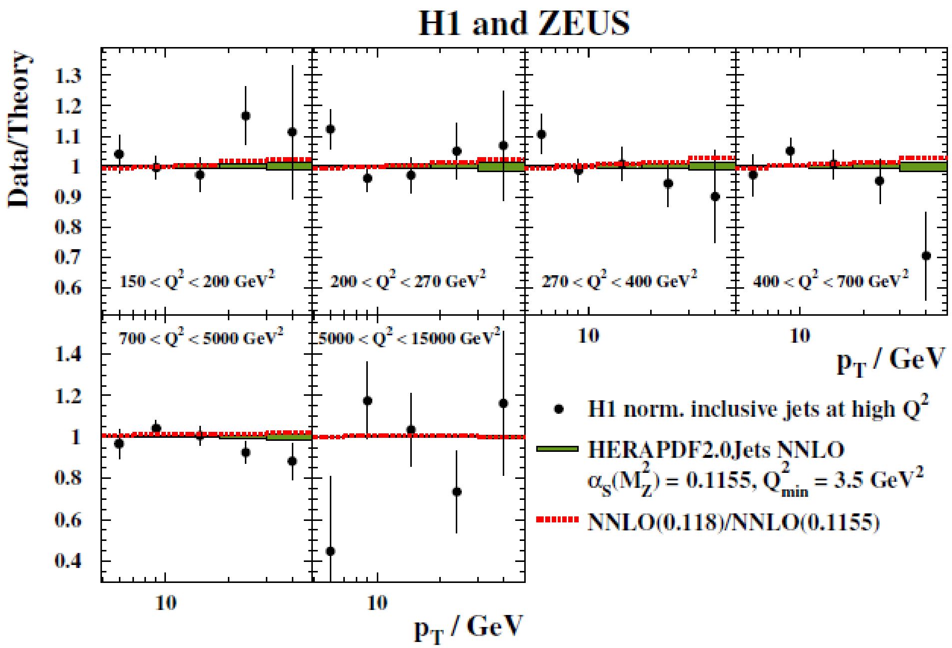


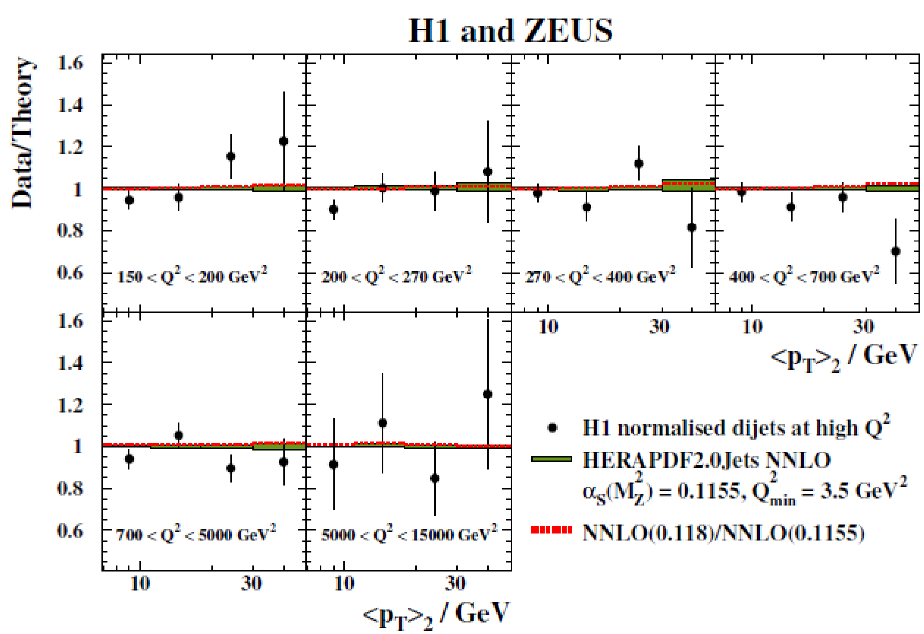
All data plots are NEW





All data plots are NEW





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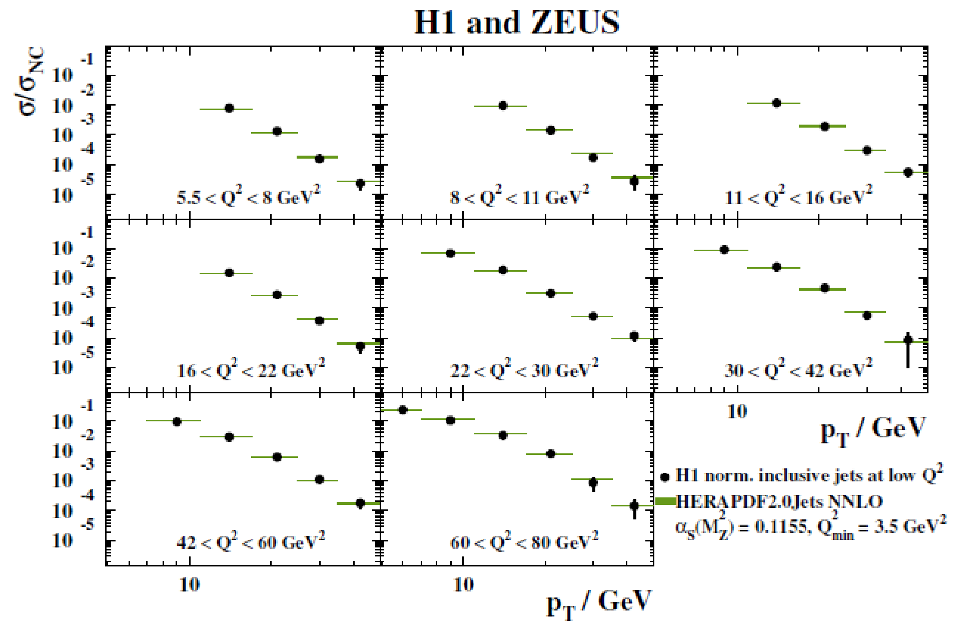
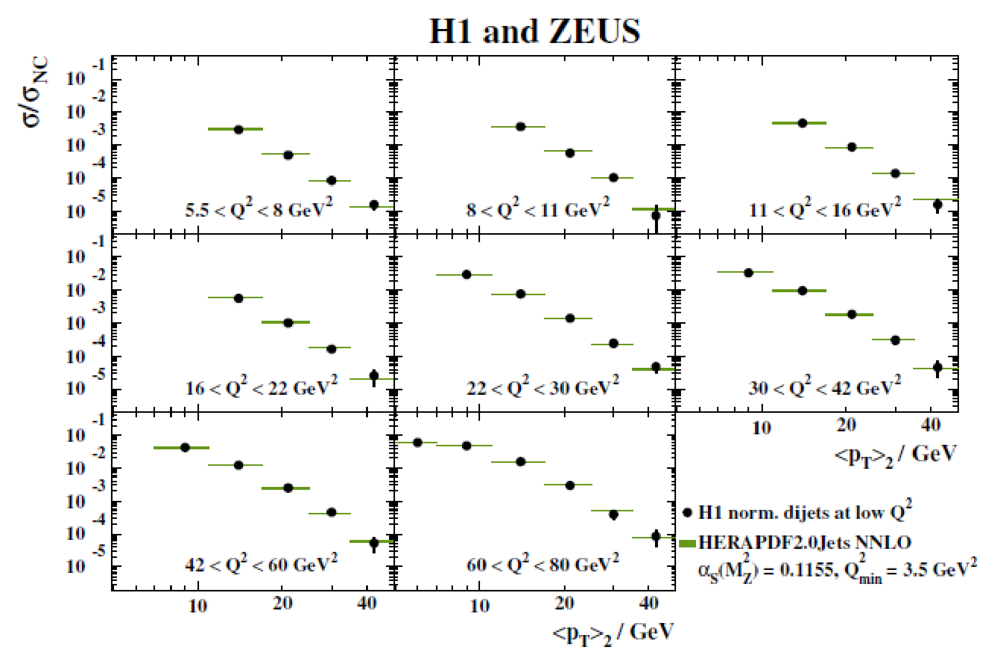
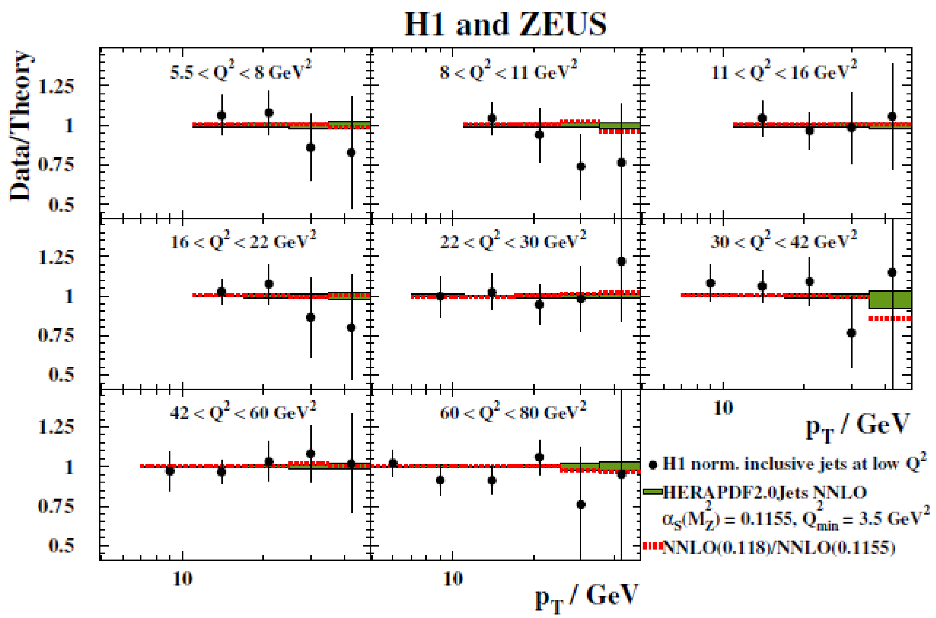
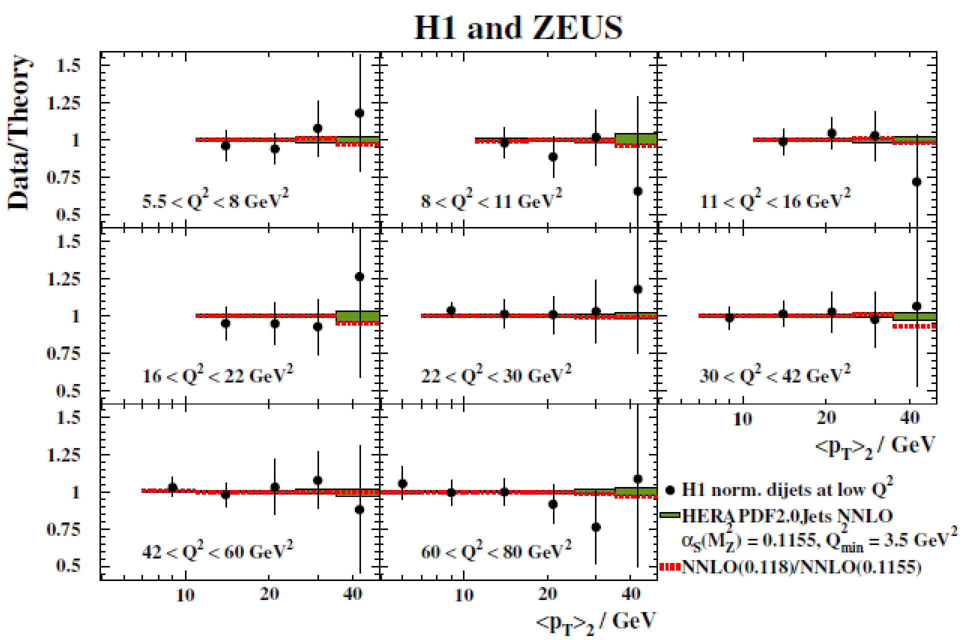


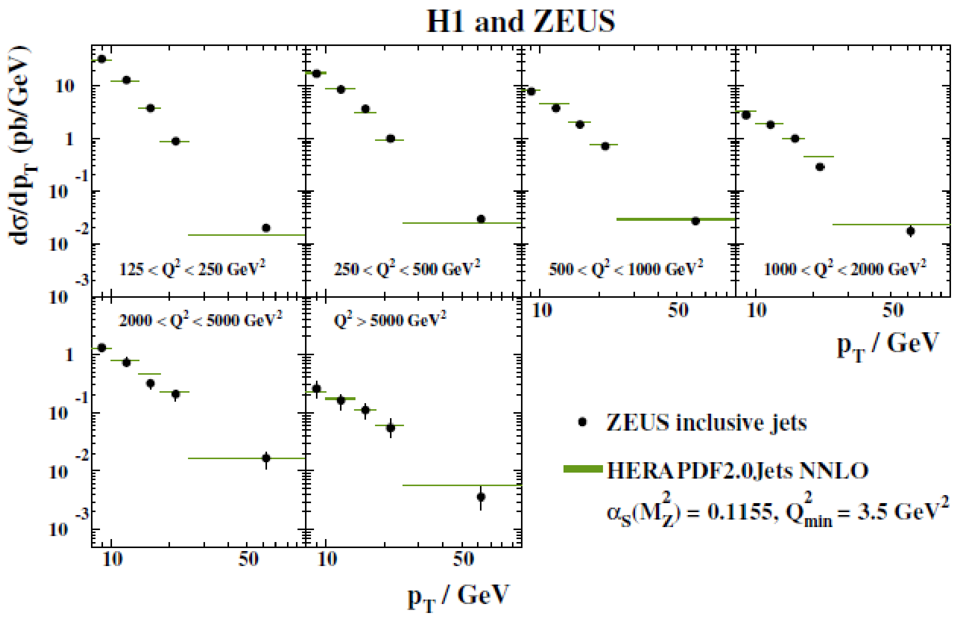


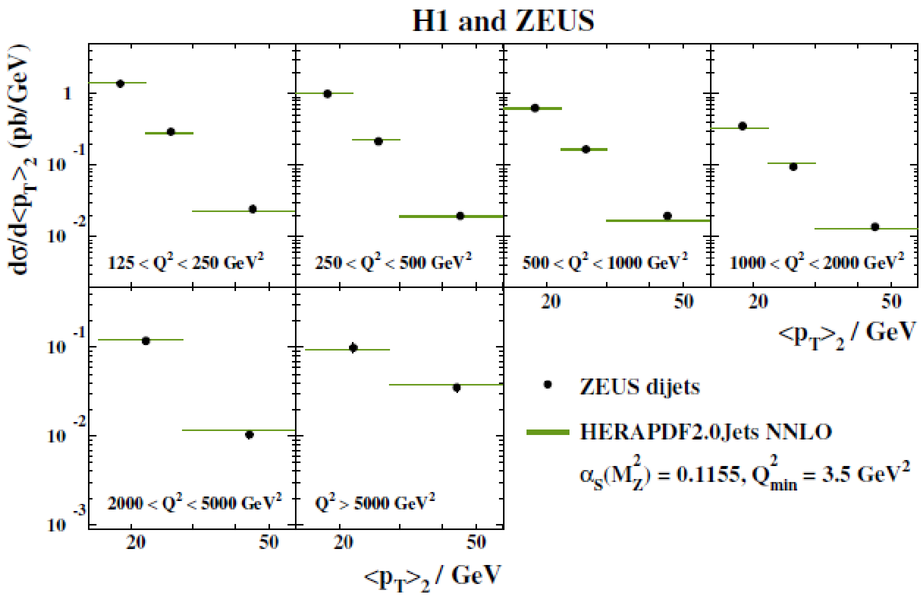
All data plots are NEW



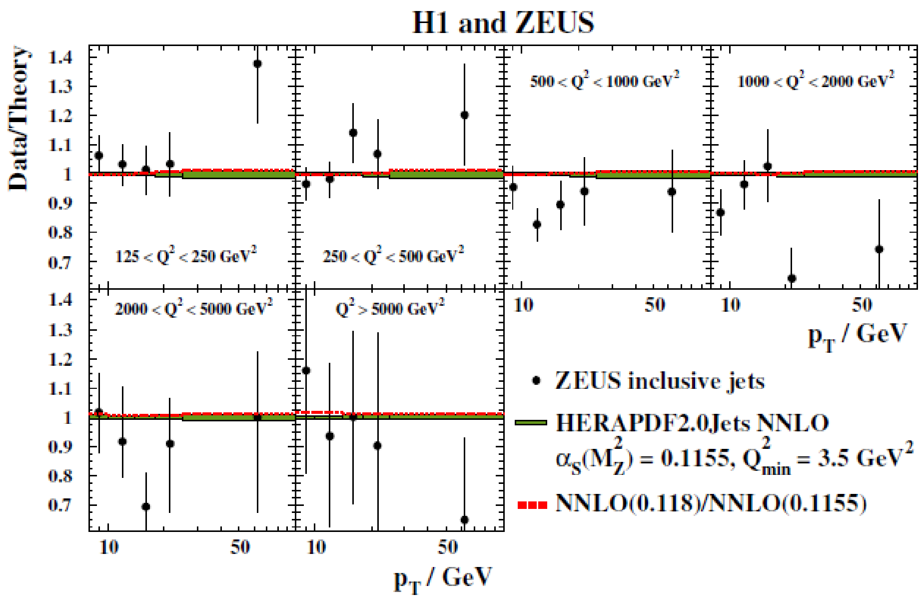


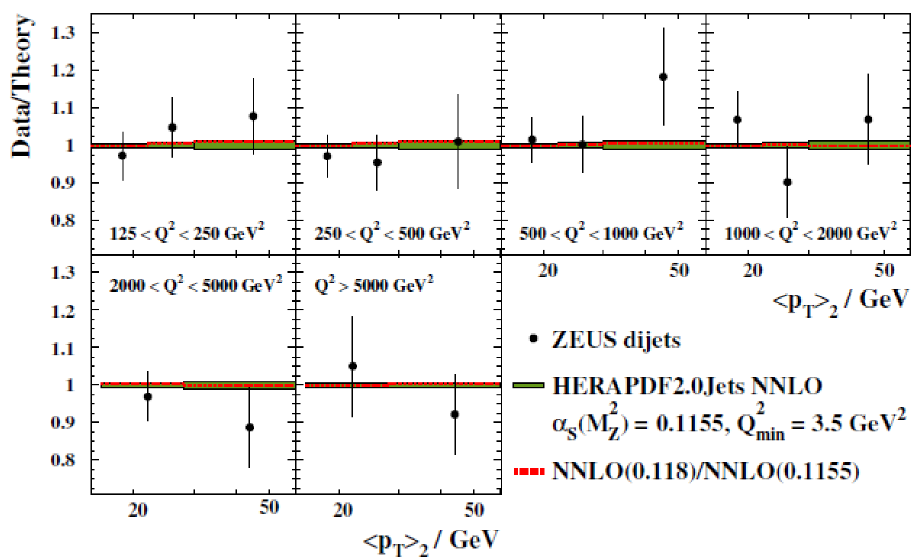
All data plots are NEW

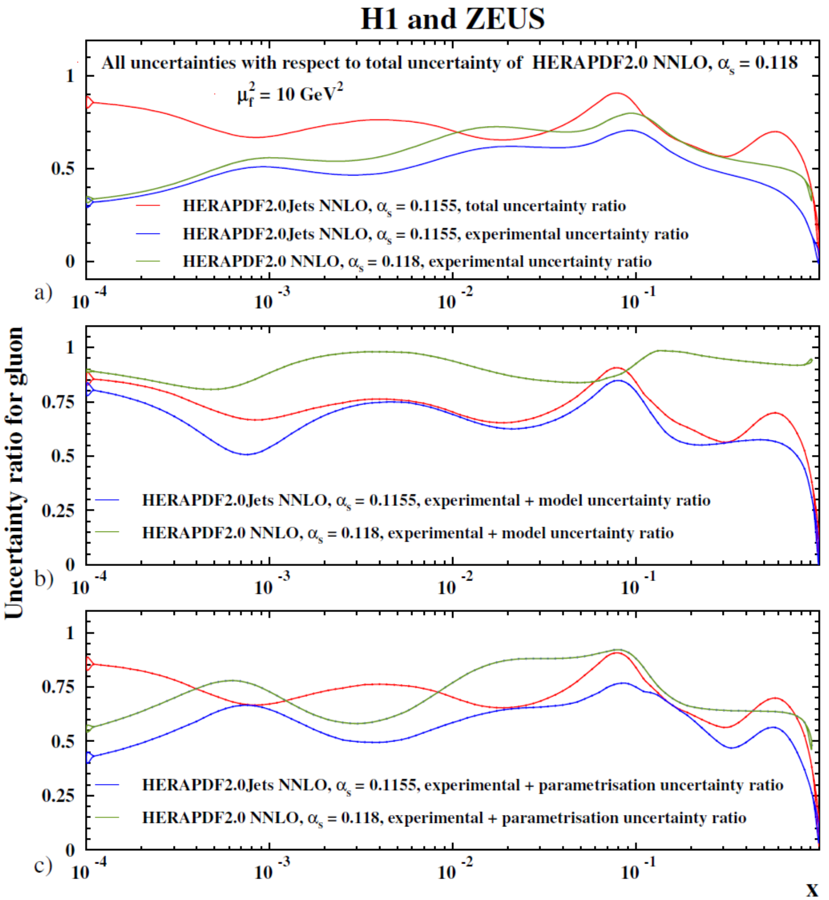


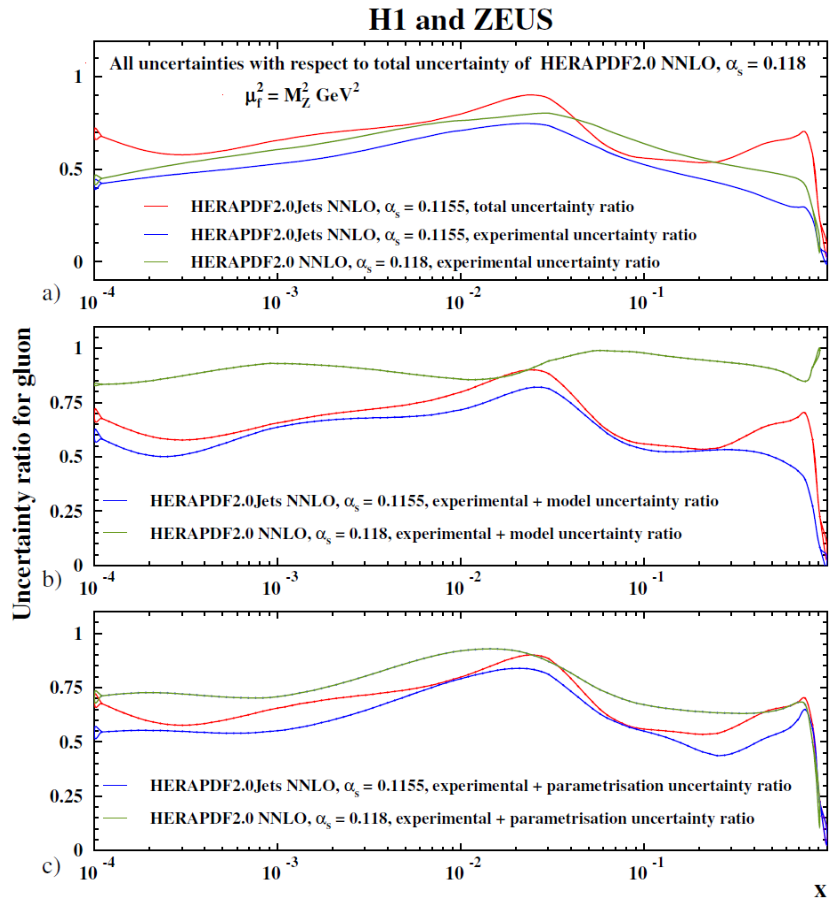


All data plots are NEW

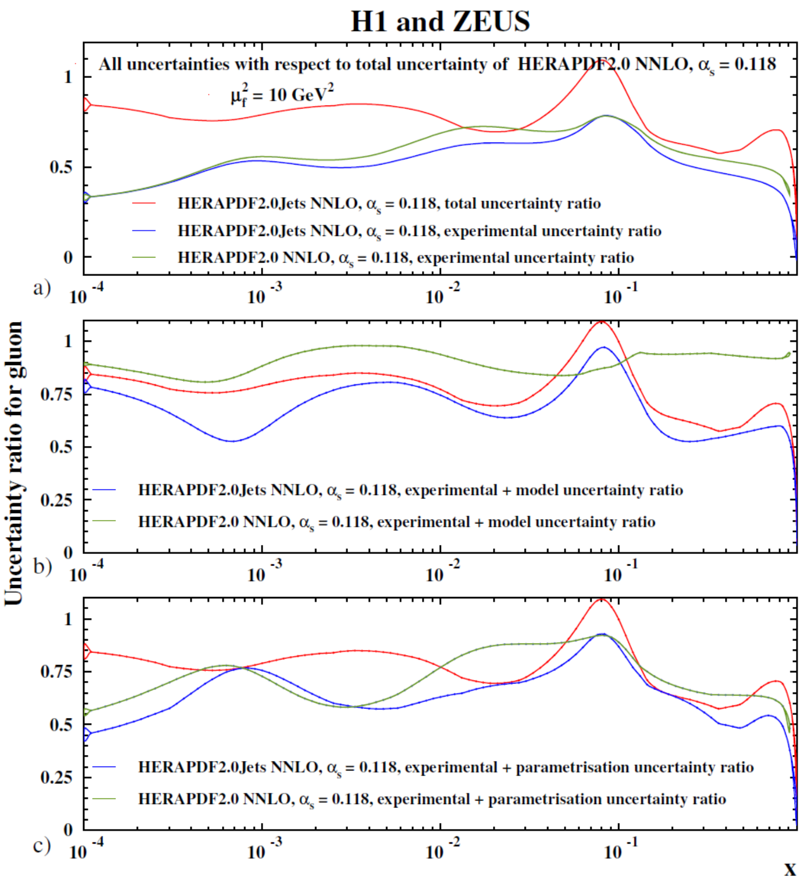


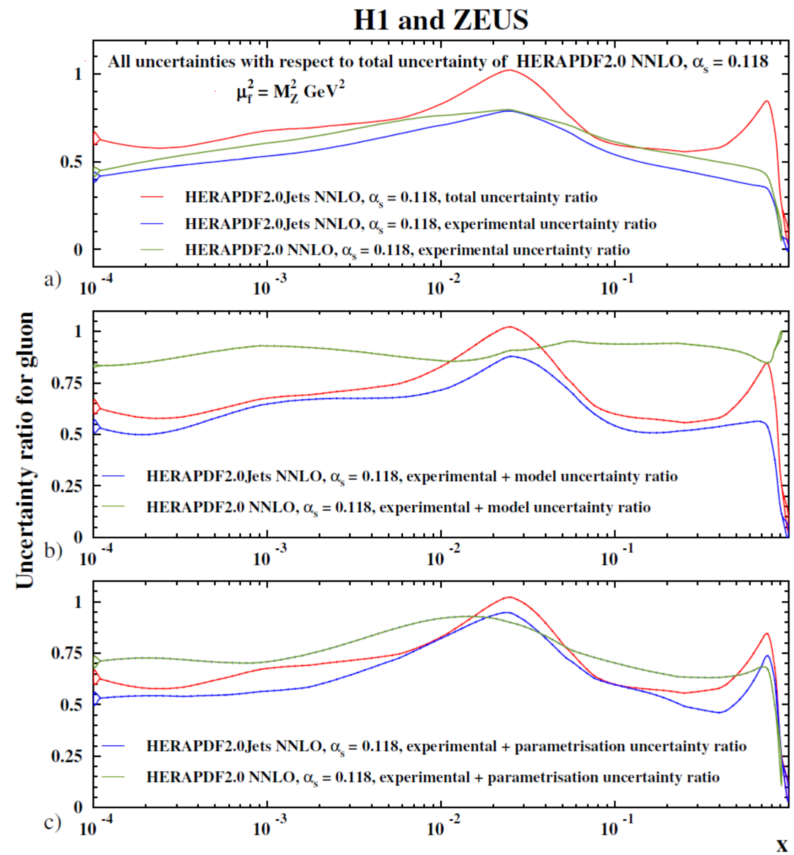






Additional material





Additional material

Retain some possible back-up slides?

Choice of HERA jet data sets

1. There had been an agreement about the jet data sets to be used way back in 2013 when work on the HERAPDF2.0 NLO Jets began. The H1 HERA-I inclusive and dijet data (sqrt(s)=300 GeV) data sets were omitted since it was considered that the same phase space was covered by later more accurate H1 data. Similarly
2. The ZEUS 98/00 inclusive data are also not included since they cover the same phase space as the ZEUS 96/97 inclusive set with similar accuracy (and they have some overlap with ZEUS dijets 98-06 which are included).
3. Checks have been made that the inclusion of these data sets make no significant difference to the fit – both these data sets can be fitted very easily with the parameters of the HERAPDF2.0NNLOJet fit which does not contain them.

For example, for the H1 HERA-I data he $\chi 2$ is 19.5 for 32 data points (4.5 for 16 inclusive 15.0 for 16 dijet)
If these data are then fitted the $\chi 2$ hardly changes --becoming 19 for 32 data points.

There is no visible change in PDFs indeed parameters shift only in the 4^{th} significant figure way below uncertainties. The value of $\alpha_S(M_Z)$ shifts by < ~0.0002.

There is a choice of scales to be made for the jets.

For HERAPDF2.0Jets NLO we chose renormalisation =(Q2+pt2)/2, factorisation =Q2
But it turns out that for NNLO jets a choice of renormalisation =(Q2+pt2) is better
(better= giving lower chisq Δχ2~ -15)
And for H1 HERA-II lowQ2 jets factorisation = (Q2+pt2) gives much more stability under scale variation than factorisation= Q2 for either of the above choices of renormalisation
This is quite understandable at lowQ2 and probably should have been used for the older low Q2 data set as well.

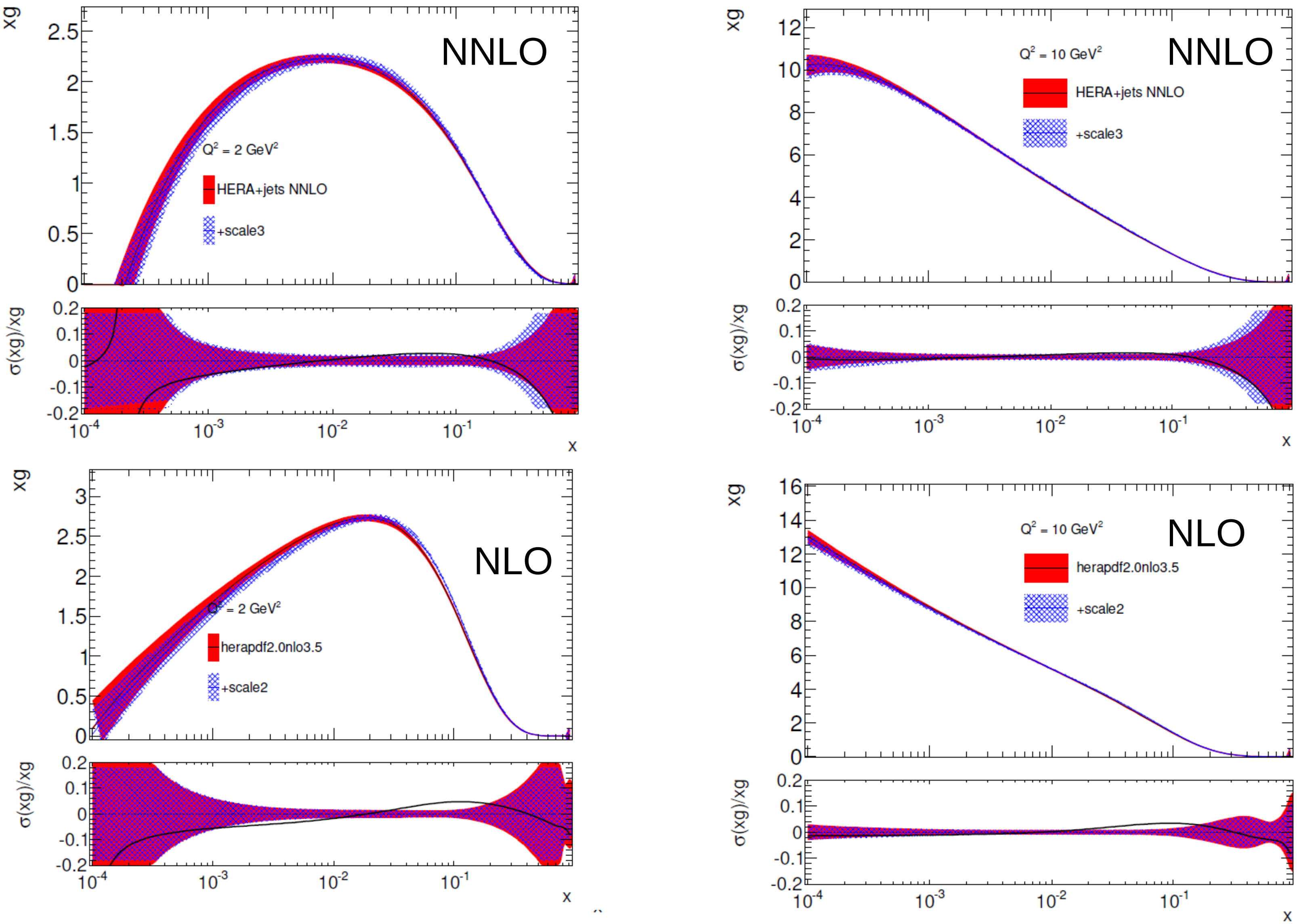
In fact the 'optimal' scale choice for NLO and NNLO is different – if optimal means lower chisq. (NLO has lower chisq Δχ2~ -15 for the old scale choice)
Since we are concentrating on NNLO we will use
Renormalisation= Q2 +pt2,
Factorisation=Q2+pt2
(in practice using Q2 or Q2+pt2 for high Q2 jets doesn't make a any significant difference

Of course scale variations are considered

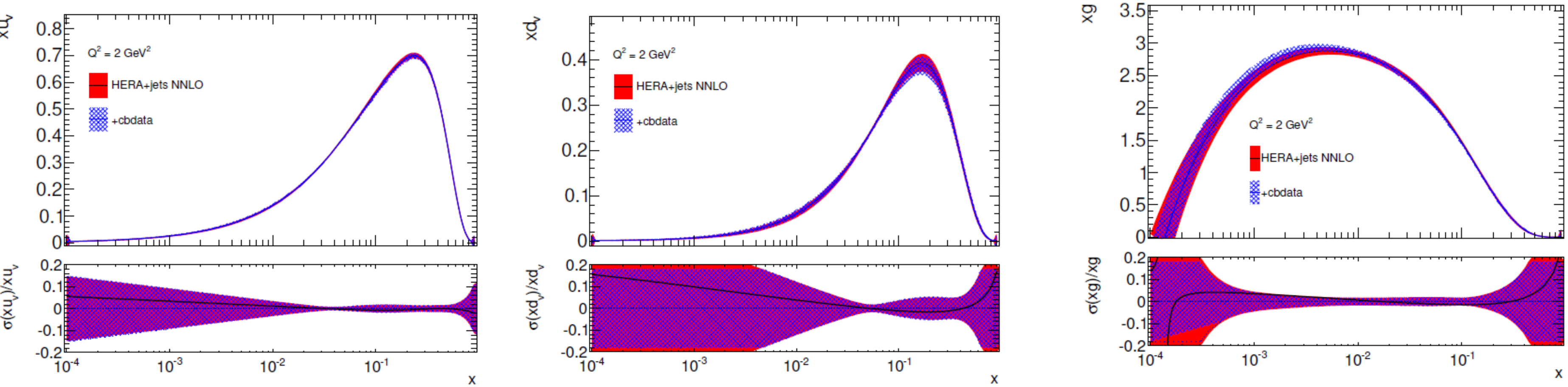
Effect of scale choice on PDFs

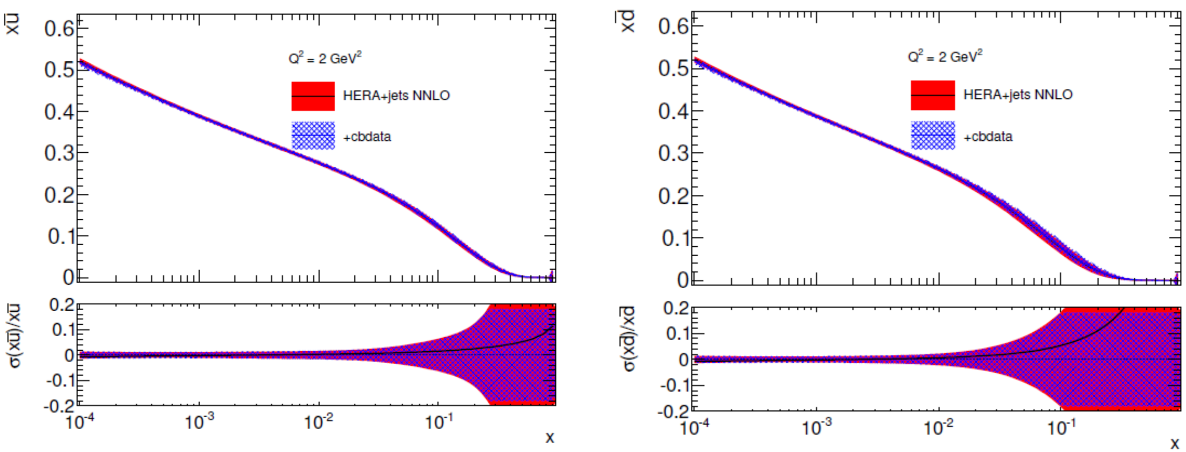
Compare scale 2=(Q2+pt2)/2 and Scale3=Q2+pt2. What do scale changes do?

Answer: very little if alphas is fixed



JUST for the record: we show the difference in PDFs with /without charm and beauty data





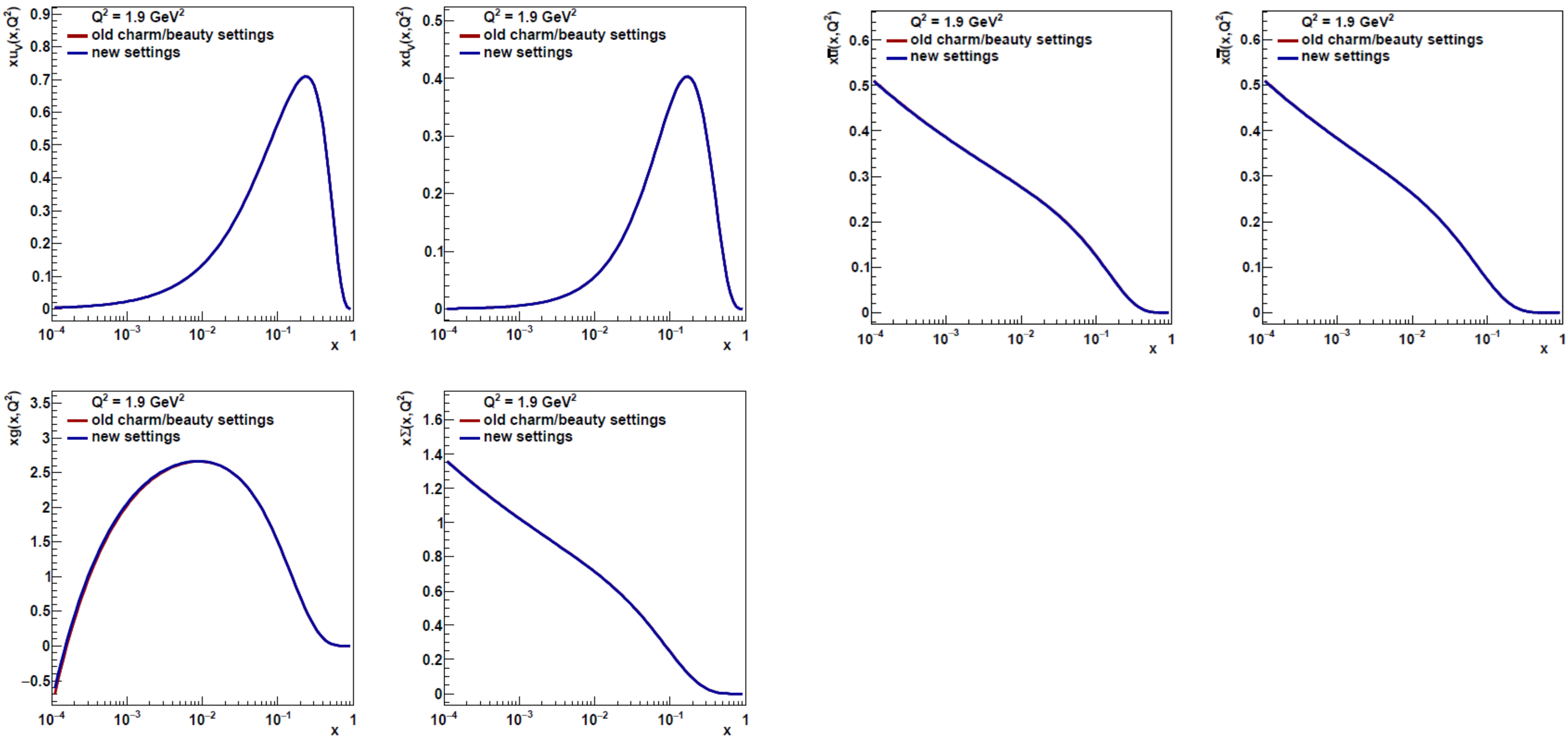
Only the gluon shows a visible but small difference

Note these two fits both have alphas=0.115

Message:

- Adding charm and beauty data has very small effect on gluon
- Fits to data very similar to those from charm/beauty data paper
- Change in Mc, Mb settings has little effect on PDF central values—but affects procedure for evaluation of uncertainty

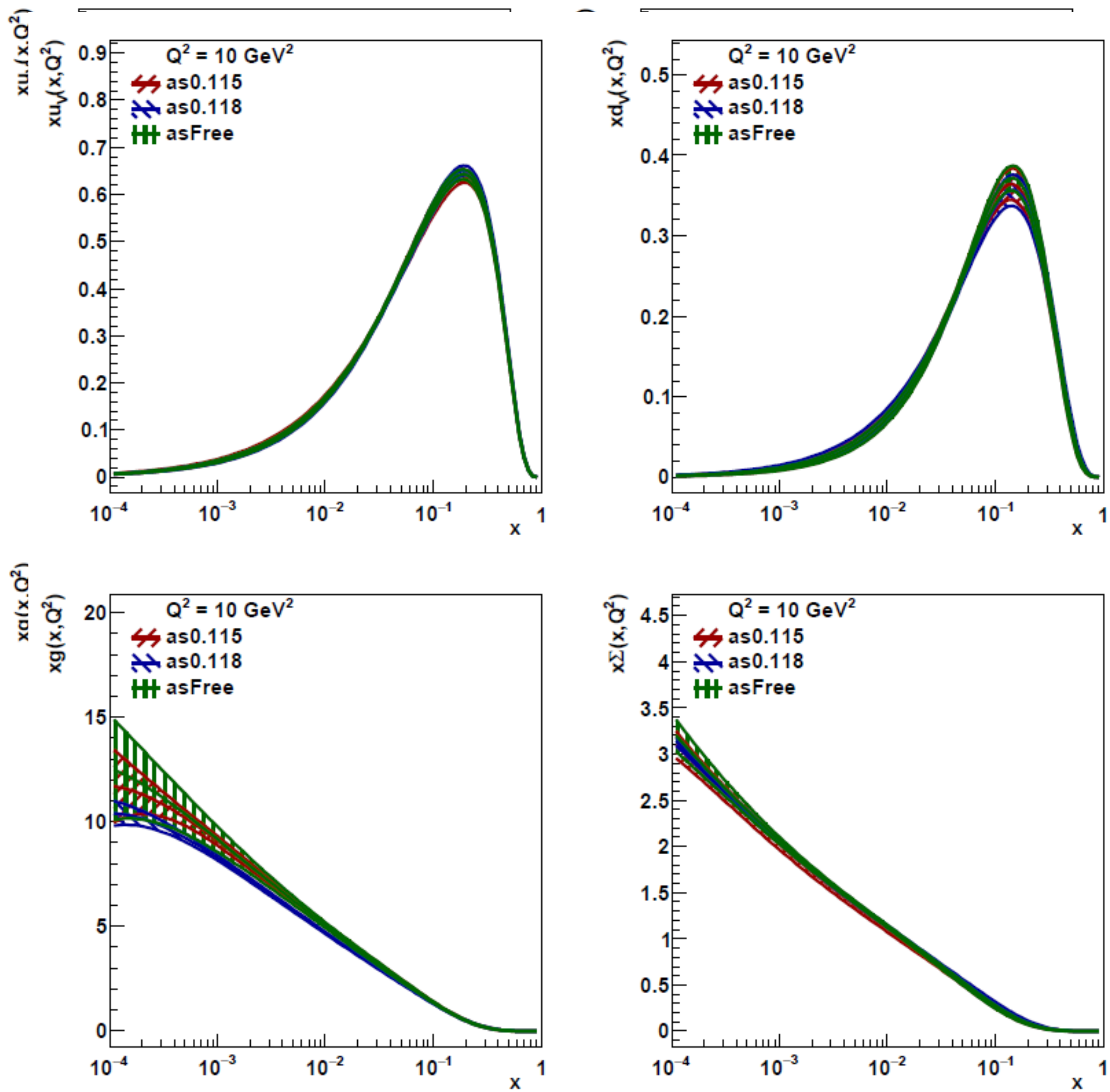
Compare PDFs fit to inclusive +jets at NNLO with new/old values of mc,mb settings.



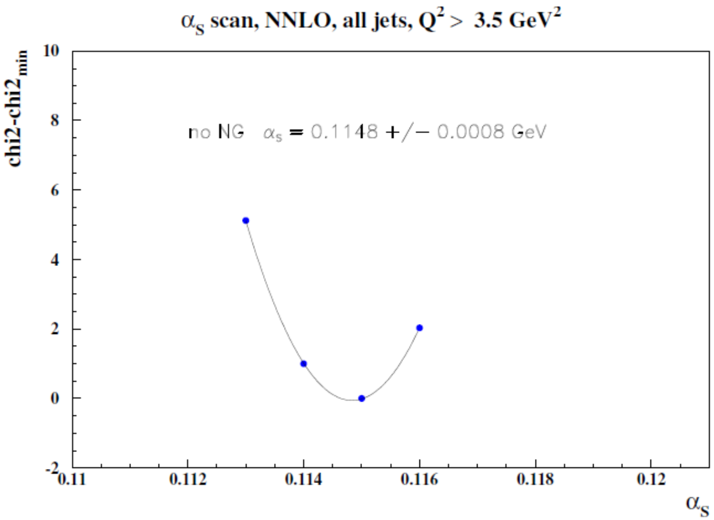
Message:

- New settings have negligible effect on PDFs

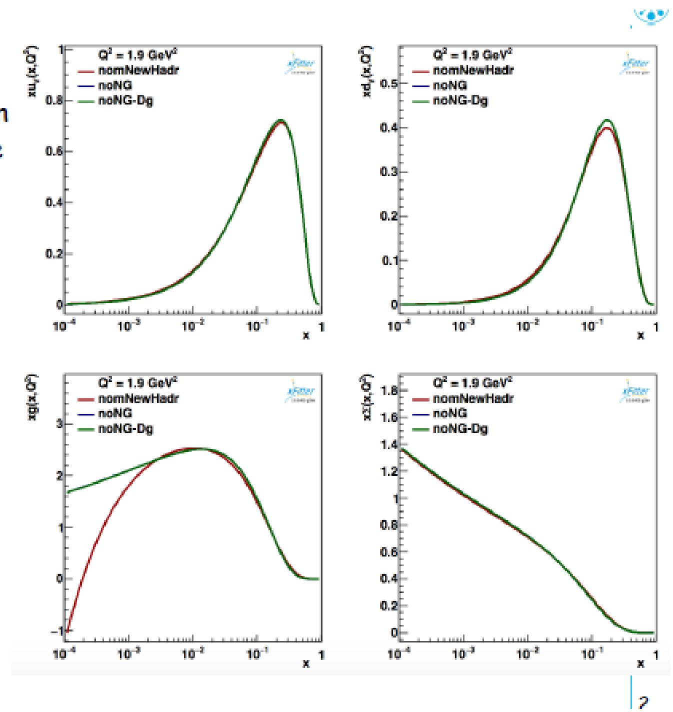
If you want to see what an alpha_s free fit looks like then it looks like this



A fit with no negative gluon term



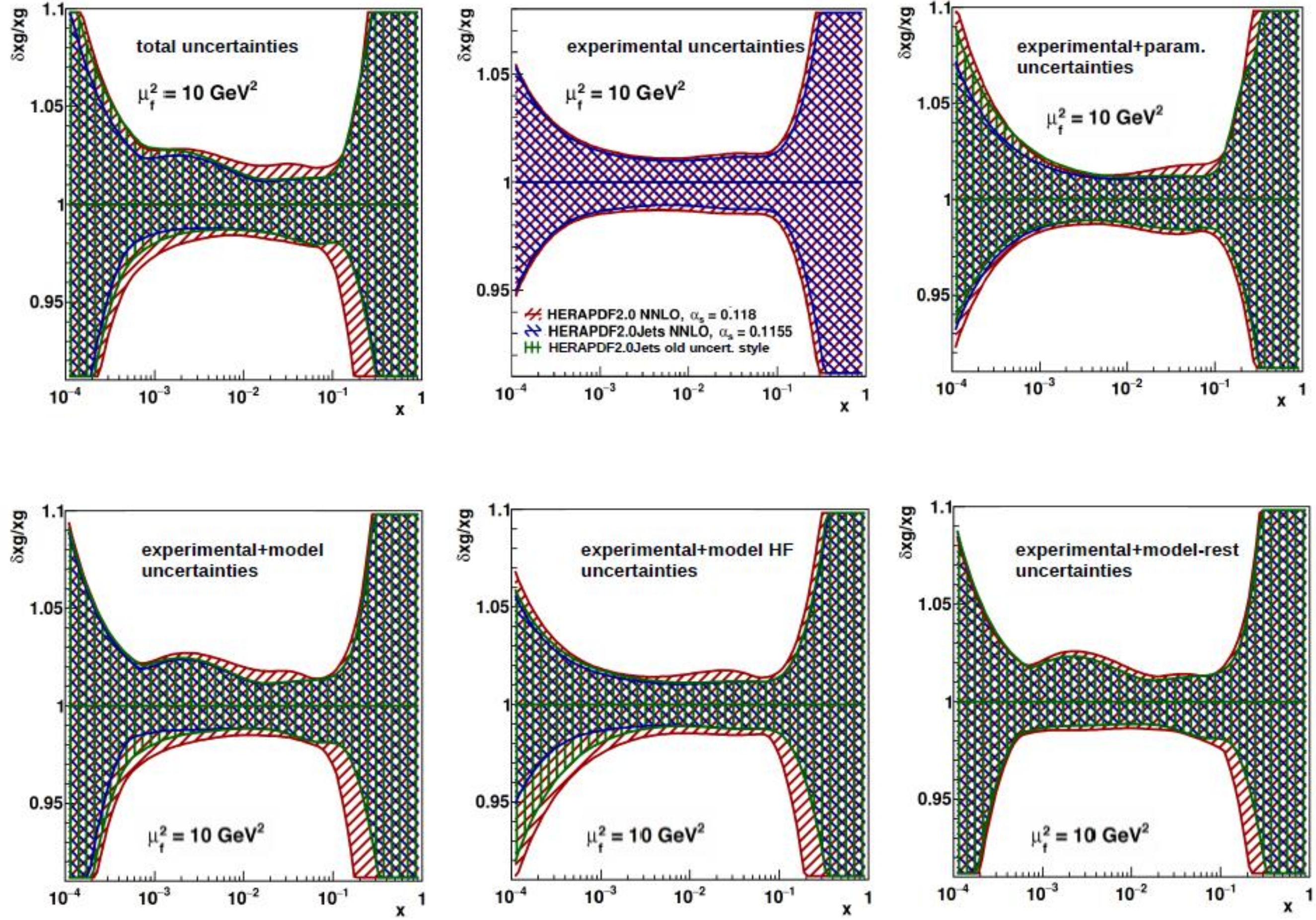
- Both alternative gluon parameterisation give essentially identical results
- Gluon obviously different
- α_s consistent → see



With no negative gluon term

$\alpha_s(M_Z) = 0.1152 \pm 0.0009$

Compatible with standard result (OLD SLIDE)



The story of how much of the change in uncertainty due to

1. Input of jet data
2. Change in range of the Mc and Mb uncertainties –part of 'model'
3. Change in procedure- not double counting

Red HERAPDF2.0NNLO
Blue HERAPDF2.0JETS NNLO
Green HERAPDF2.0JETS NNLO uncertainties treated old style Mc,Mb values and ranges, with double counting

The green shows us what would happen if we continued to double count. Nothing happens to experimental uncertainty (obviously) but for parametrisation uncertainties the improvement at low-x is mostly due to not double counting, whereas the improvement at middle/higher x is due to input of jet data. For model uncertainties the improvement at low-x is mostly due to not double counting HF, the improvement at middle/higher –x is due to input of jet data. Considering the total improvement of the uncertainties we can see that a substantial part of it does come from the input of jets (difference red to green)

Some remarks on NLO to NNLO comparison- (not in the paper)

Our present NNLO result using ½ correlated and ½ uncorrelated scale uncertainty

$\alpha_s(M_Z) = 0.1156 \pm 0.0011(\mathrm{exp})\ ^{+0.0001}_{-0.0002}(\mathrm{model+parametrisation}) \pm 0.0022(\mathrm{scale})$

where "exp" denotes the experimental uncertainty which is taken as the fit uncertainty, including the contribution from hadronisation uncertainties.

Maybe compared with the NLO result

$\alpha_S(M_Z) = 0.1183 \pm 0.0008(\mathrm{exp}) \pm 0.0012(\mathrm{had})^{+0.0003}/_{-0.0005}(\mathrm{mod/param})\ ^{+0.0037}/_{-0.003}(\mathrm{scale})$

BUT

- the choice of scale was different;
- the NLO result did not include the recently published H1 low-Q^2 inclusive and dijet data [28];
- the NLO result did not include the newly published low p_T points from the H1 high-Q^2 inclusive data;
- the NNLO result does not include trijet data;
- the NNLO result does not include the low p_T points from the ZEUS dijet data;
- the NNLO analysis imposes a stronger kinematic cut $\mu > 10$ GeV
- the treatment of hadronisation uncertainty differs.

All these changes with respect to the NLO analysis had to be made to create a consistent environment for a fit at NNLO. at the same time, an NLO fit cannot be done under exactly the same conditions as the NNLO fit since the H1 low Q^2 data cannot be well fitted at NLO. However, an NLO and an NNLO fit can be done under the common conditions:

An NLO and an NNLO fit can be done under the common conditions:

- choice of scale, $\mu_f^2 = \mu_r^2 = Q^2 + p_T^2$;
- exclusion of the H1 low-Q^2 inclusive and dijet data;
- exclusion of the low-p_T points from the H1 high-Q^2 inclusive jet data;
- exclusion of trijet data;
- exclusion of low-p_T points from the ZEUS dijet data;
- exclusion of data with μ < 10 GeV
- hadronisation uncertainties treated as correlated systematic uncertainties as done in the NNLO analysis.

The values of $\alpha_S(M_Z)$ obtained for these conditions are:
0.1186 ± 0.0014(exp) NLO and 0.1144 ± 0.0013(exp) NNLO.
The change of the NNLO value from the preferred value of 0.1156 is mostly due to the exclusion of the H1 lowQ^2 data and the low-p_T points at high Q^2

What do we mean when we say the H1 low Q^2 jets cannot be well fitted at NLO?
Simply this, that at NNLO the increase in overall $\chi 2$ of the fit when the 74 data pts of these data are added is ~80 (exact value depends on $\alpha_S(M_Z)$ and on scale choice)
Whereas at NLO the increase in overall $\chi 2$ of the fit when the 74 data pts of these data are added is ~180.

Physics message

Our primary interest was in the NNLO PDFs including jet data
Predictions for jet production at NNLO were not previously available.
There has not been a paper looking at this using combined HERA inclusive data and jet data from both collaborations. There is also new input from the recent HERA charm and beauty combination

We were focussed on the PDFs, but since the HERAPDF2.0NLO Jet fit had an $\alpha_S(M_Z)$ determination, we were interested to compare scale uncertainties from the new and the old fit.
We were pleased to see them reduce if evaluated in the same way.

We were slightly surprised to see the value of $\alpha_S(M_Z)$ decrease so much
Since the value of $\alpha_S(M_Z)$ is modified this also affects the PDF and is thus part of our PDF message.

Futhermore
the uncertainties on the gluon PDF are reduced in the new analysis. This is due both to the jet input AND due to the use of HERA combined heavy flavour data to set the range of uncertainty of Mc and Mb which triggered a re-evaluation of some of our procedures for the evaluation of model/parametrisation uncertainties

Is the HERAPDF2.0 still current?

There is still interest in a PDF which is based on a modern set of consistent data with well understood uncertainties

Plus it is ‘new physics free’

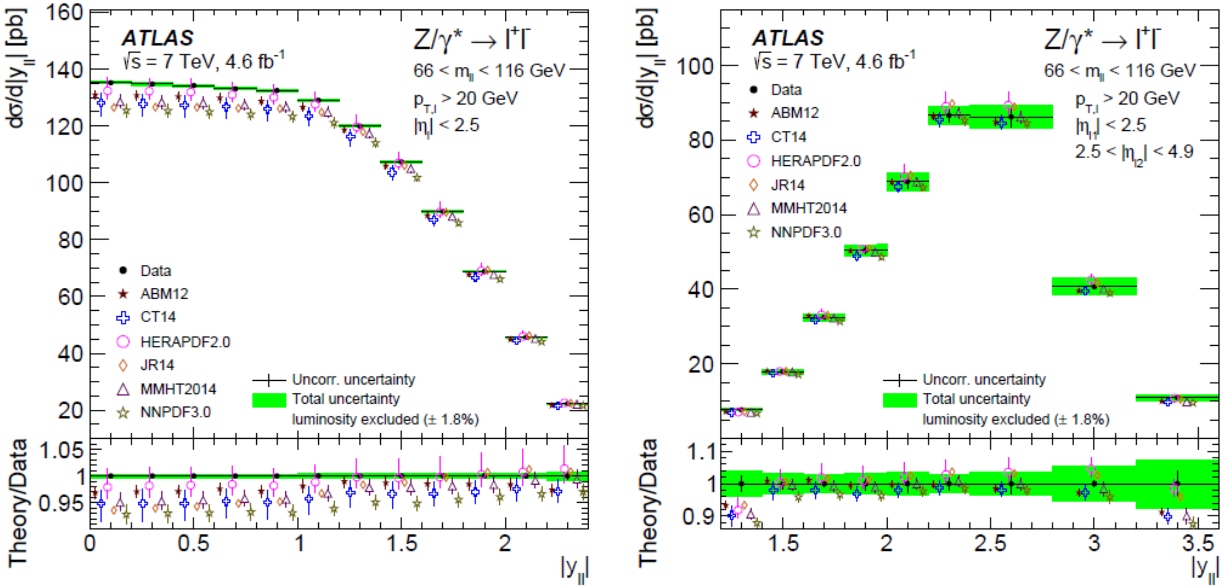
List of ATLAS papers which have used it and where the description is comparable to other current PDFs

1. ATLAS high precision W and Z at 7 TeV for various rapidity/mass regions 1612.03016
2. ATLAS W+/- and W-asymmetry at 8 TeV pseudorapidity 1904.05631
3. ATLAS Z+jets at 8 TeV vs rapidity for various pt regions 1907.067288
4. ATLAS jets at 8 TeV vs pt for various rapidity regions 1706.03192
5. ATLAS 8 TeV t-tbar data for various rapidity variables 1511.04711
6. ATLAS 8 TeV V+jets 2101.05905

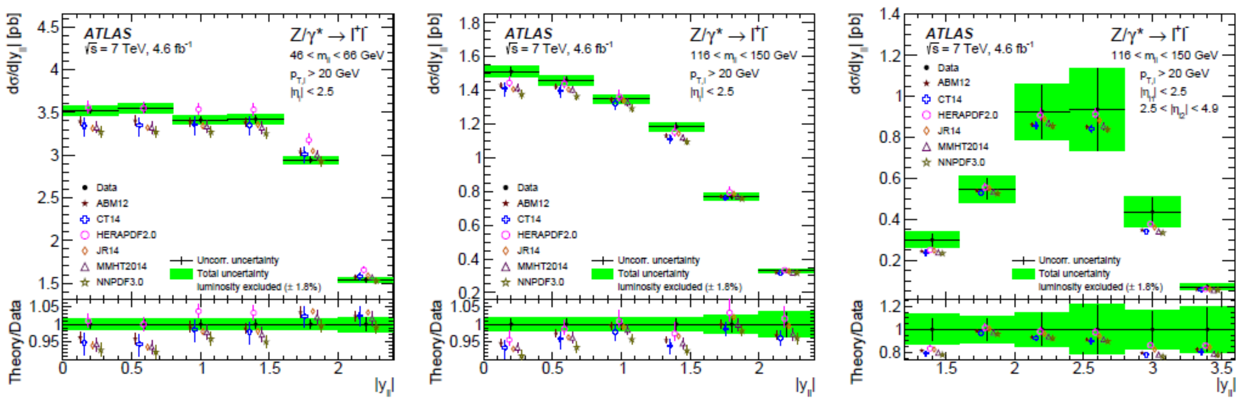
	P_{obs}			
Rapidity ranges	CT14	MMHT2014	NNPDF3.0	HERAPDF2.0
Anti-k_t jets $R = 0.4$				
$\lvert y\rvert < 0.5$	44%	28%	25%	16%
$0.5 \le \lvert y\rvert < 1.0$	43%	29%	18%	18%
$1.0 \le \lvert y\rvert < 1.5$	44%	47%	46%	69%
$1.5 \le \lvert y\rvert < 2.0$	3.7%	4.6%	7.7%	7.0%
$2.0 \le \lvert y\rvert < 2.5$	92%	89%	89%	35%
$2.5 \le \lvert y\rvert < 3.0$	4.5%	6.2%	16%	9.6%
Anti-k_t jets $R = 0.6$				
$\lvert y\rvert < 0.5$	6.7%	4.9%	4.6%	1.1%
$0.5 \le \lvert y\rvert < 1.0$	1.3%	0.7%	0.4%	0.2%
$1.0 \le \lvert y\rvert < 1.5$	30%	33%	47%	67%
$1.5 \le \lvert y\rvert < 2.0$	12%	16%	15%	3.1%
$2.0 \le \lvert y\rvert < 2.5$	94%	94%	91%	38%
$2.5 \le \lvert y\rvert < 3.0$	13%	15%	20%	8.6%

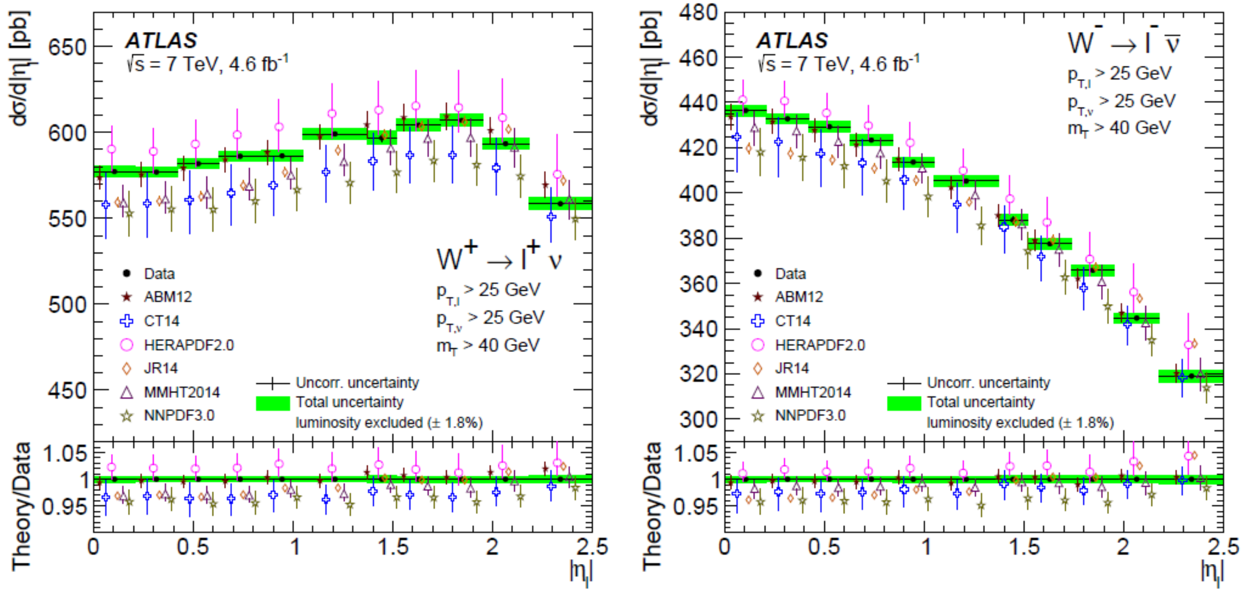
Table 2: Observed P_{obs} values evaluated for the NLO QCD predictions corrected for non-perturbative and electroweak effects and the measured inclusive jet cross-section of anti-k_t jets with $R = 0.4$ and $R = 0.6$. Only measurements with $p_{\text{T}} > 100$ GeV are included. The predictions are evaluated for various PDF sets. The default scale choice $p_{\text{T}}^{jet,max}$ is used.

Quantitative example for 8 TeV jets

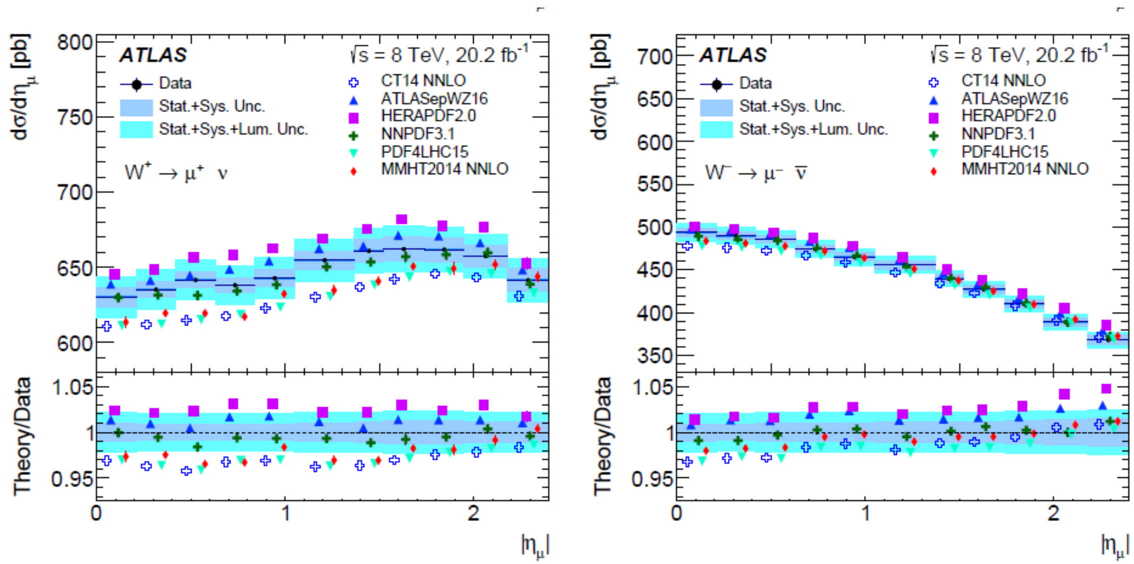


PDFs vs ATLAS Z/γ* for various rapidity/mass regions





PDFs vs ATLAS W± for vs rapidity for 7 and 8 TeV data



PDFs vs ATLAS Z+jets vs rapidity for various pt regions, 8 TeV data

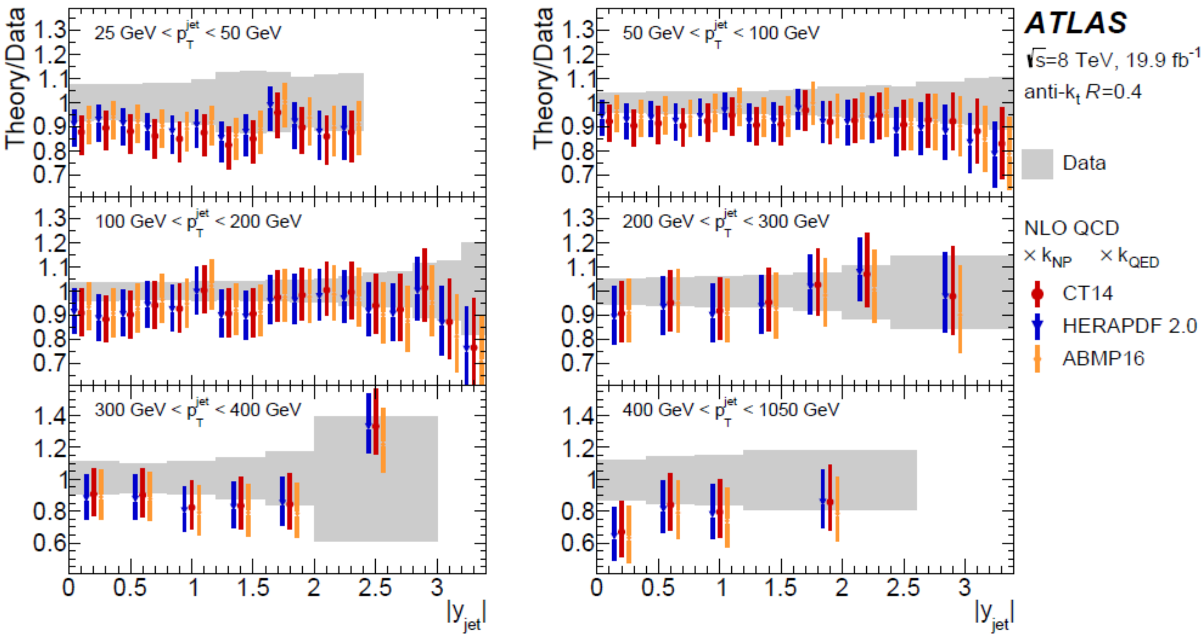


Figure 14: Ratio of the measured $Z+$jets production cross-section and the NLO QCD predictions, obtained using MCFM, corrected for the non-perturbative and QED radiation effects as a function of $|y_{\text{jet}}|$ and $p_{\text{T}}^{\text{jet}}$ bins. Theoretical predictions are calculated using various PDF sets. The coloured error bars represent the sum in quadrature of the effects of the PDF, scale, and α_{S} uncertainties, and the uncertainties from the non-perturbative and QED radiation corrections. The grey band shows the sum in quadrature of the statistical and systematic uncertainties in the measurement except for the luminosity uncertainty of 1.9%.

PDFs vs ATLAS jets vs pt for various rapidity regions for 7 TeV data

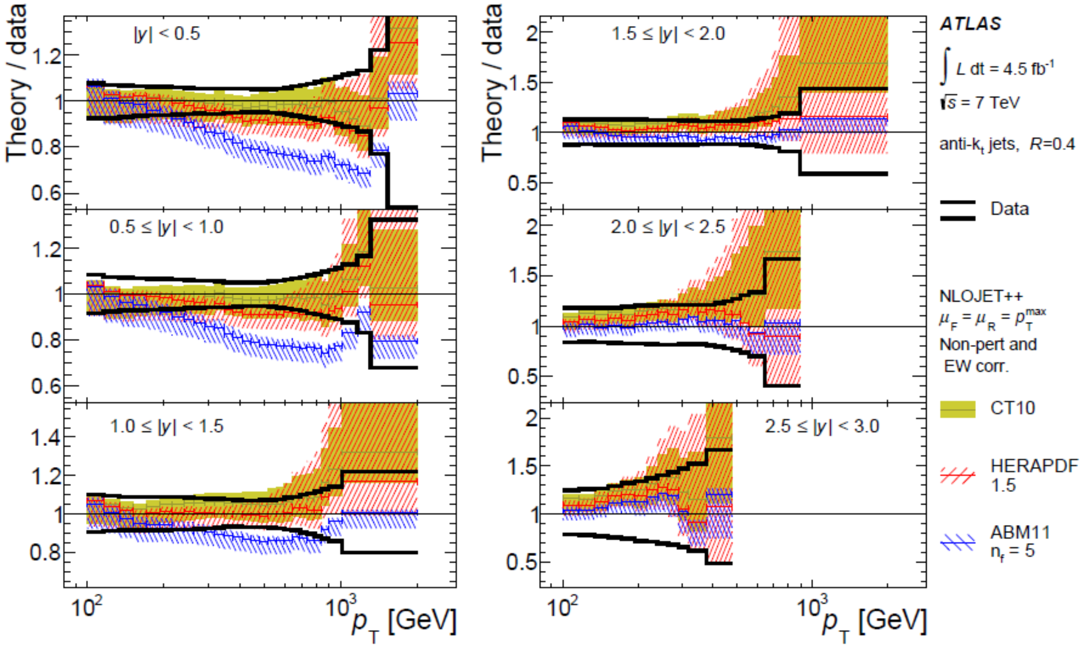


Figure 10. Ratio of NLO pQCD predictions to the measured double-differential inclusive jet cross-section, shown as a function of the jet p_T in bins of the jet rapidity, for anti-k_t jets with $R = 0.4$. The predictions are calculated using NLOJET++ with different NLO PDF sets, namely CT10, HERAPDF 1.5 and ABM11. Non-perturbative corrections and electroweak corrections are applied to the predictions. Their uncertainties are shown by the bands, including all the uncertainties discussed in section 5. The data lines show the total uncertainty except the 1.8% uncertainty from the luminosity measurement.

PDFs vs ATLAS jets vs ptjet for various rapidity regions for 8 TeV data

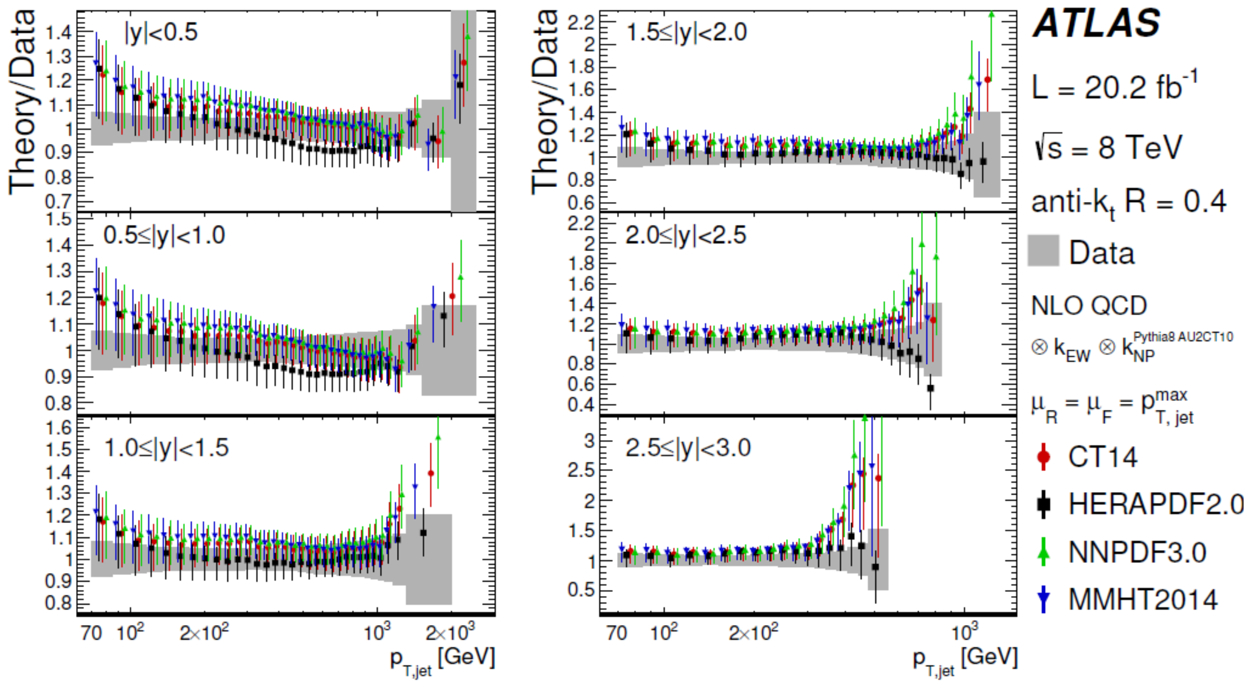
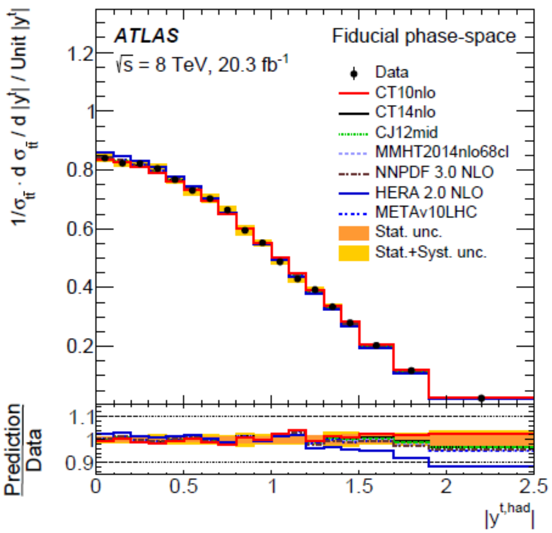
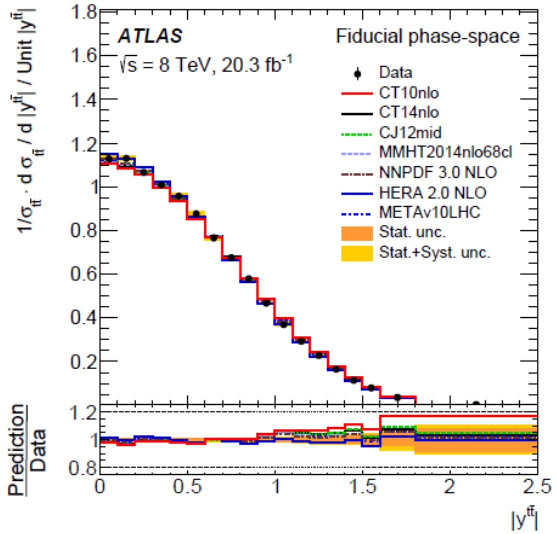


Figure 7: Ratio of the inclusive jet cross-section predicted by NLO QCD corrected for non-perturbative and electroweak effects to the cross-section in data as a function of the jet p_{T} in each jet rapidity bin. Shown are the predictions for various PDF sets for anti-k_t jets with $R = 0.4$. The points are offset in jet p_{T} for better visibility. The error bars indicate the total theory uncertainty. The grey band shows the total uncertainty in the measurement.

PDFs vs ATLAS for 8 TeV t-tbar data for various rapidity variables



(a)



(b)