HERAPDF2.0 NNLOJets

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on behalf of H1 and ZEUS
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Completing the HERAPDF2.0 family of PDFs
HERAPDF2.0LO, NLO and NNLO
HERAPDF2.0Jets only at NLO

Updating HERAPDF2.0Jets with NNLO predictions for jets from NNLOJET (Gehrmann et al) as implemented in the ApplFast system

Addition of new low Q^2 jet data

New PDFs at NNLO for $\alpha_s(M_Z)$= 0.118 and 0.115

$\alpha_s(M_Z)$ at NNLO is significantly lower than at NLO

Jets allow us to constrain $\alpha_s(M_Z)$

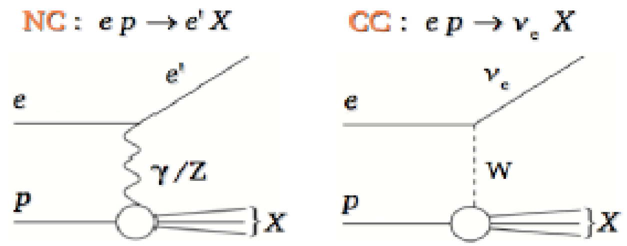
Free $\alpha_s(M_Z)$ fit at NNLO

$\alpha_s(M_Z)=0.1150 \pm 0.0008_{(exp)}\ ^{+0.0002}_{-0.0005(model/param)} \pm 0.0006_{(had)} \pm 0.0027_{(scale)}$

Compare the NLO result as published

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

The HERAPDF2.0 is the PDF which comes from QCD fits of the combined HERA $e^{\pm}p$ scattering data **Phys Rev D93(2016)092002**



- 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

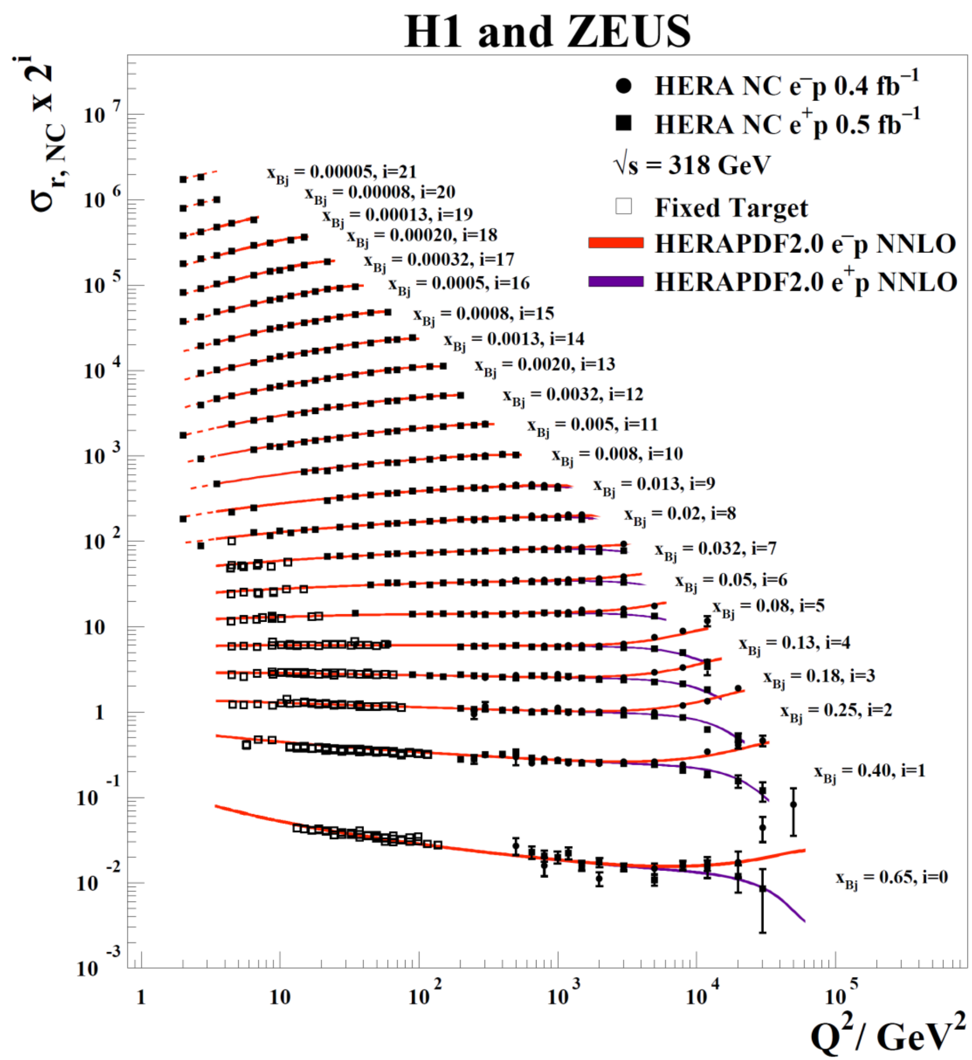
LO expressions

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

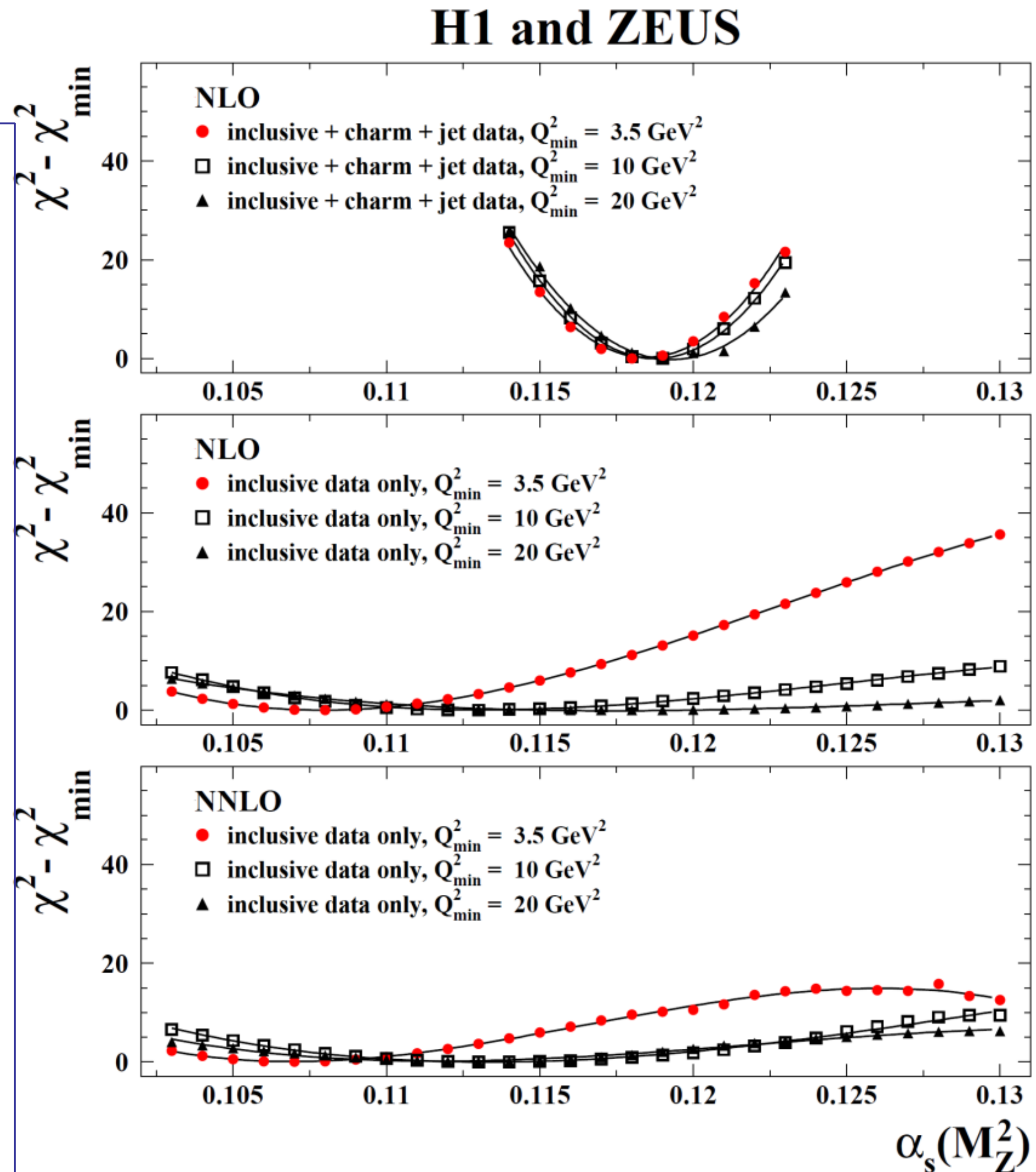


Gluon from the scaling violations: DGLAP equations tell us how the partons evolve

Why add Jet data?

The main effect of jet data is to allow a determination of $\alpha_S(M_Z)$
Inclusive data alone cannot give a precise determination because the shape of the gluon PDF and the value of $\alpha_S(M_Z)$ are coupled through the DGLAP equation.
However, jet cross sections depend on the gluon PDF and $\alpha_S(M_Z)$ in a different way such that a simultaneous fit of inclusive and jet production data can give much improved constraints on both.

We have done this at NLO BUT in 2015 the NNLO calculation was not available … this is what we can now complete



Jet Data sets used in the present NNLO analysis

Strong overlap with those used in the NLO analysis

Data Set	published	Q^2[GeV^2] range from	to	$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV	norma-lised	all points	used points
H1 high Q^2 HERA I incl. jets	2007	150	15000	65.4	e^+p	301	yes	24	24
H1 low Q^2 HERA I dijets	2010	5	100	43.5	e^+p	301	no	22	16
H1 high Q^2 HERA II incl. jets	2014	150	15000	351	e^+p/e^-p	319	yes	24	24
H1 high Q^2 HERA II dijets	2014	150	15000	351	e^+p/e^-p	319	yes	24	24
H1 low Q^2 HERA II incl. jets	2016	5	80	290	e^+p/e^-p	319	yes	48	32
H1 low Q^2 HERA II dijets	2016	5	80	290	e^+p/e^-p	319	yes	48	32
ZEUS incl. jets HERA I	2002	125	10000	38.6	e^+p	301	no	30	30
ZEUS dijets HERA I and II	2010	125	20000	374	e^+p/e^-p	318	no	22	16

These data sets are new and were not used in the 2015 NLO analysis

However as well as adding new data sets we have to subtract some data

- Trijets- there are no NNLO predictions
- Data at low scale $\mu = (pt^2 + Q^2) < 13.5$ fro which scale variations are large (~25% NLO and ~10% NNLO)
- 6 Dijet data points at low pt for which predictions are unreliable

Further points:

- The new 2016 lowQ^2 jets have some systematic correlations to the older 2014 high Q^2 jets– these are implemented
- All statistical correlation matrices for these jet data sets are implemented by default.

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

Factorisation scale

At NLO we used factorisation scale= Q^2 but this is not a good choice for low Q^2 jets, we have many more low Q^2 jet data points now – from the H1 2016 data- so we move to a choice factorisation scale $=(Q^2+pt^2)$ for all jets- this makes almost no difference to high Q^2 jets

Renormalisation scale

For HERAPDF2.0Jets NLO we chose renormalisation $=(Q^2+pt^2)/2$

For HERAPDF2.0Jets NNLO jets a choice of renormalisation $=(Q^2+pt^2)$

Results in a lower $\chi2$, $\Delta\chi2\sim -15$

In fact the 'optimal' scale choice for NLO and NNLO is different – if optimal is defined by lower $\chi2$. At NLO $\Delta\chi2\sim -15$ for the old scale choice.

We also explore the consequences of scale variation.

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 χ2 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.

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

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

HERAPDF2.0Jets fits add HERA Jet data to this.

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 $x \to 0$.

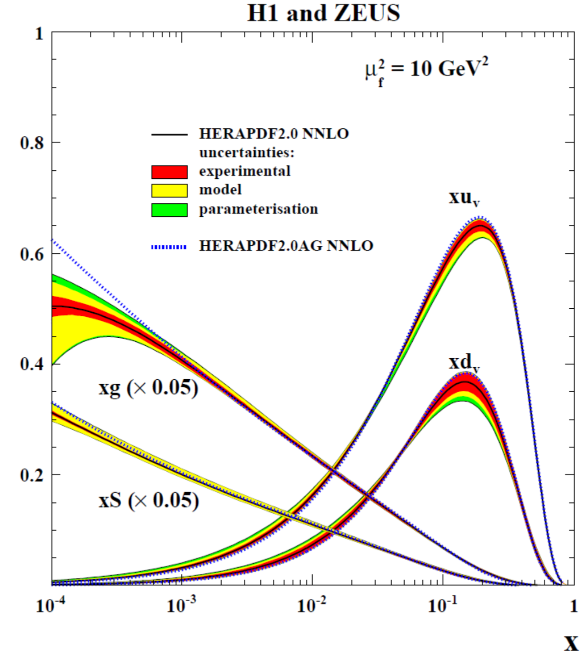
- There are 14 free parameters in the central fit determined by saturation of the χ2
- But extra D and E parameters are added to all flavours of PDF for parametrisation uncertainty plus Ag'=0 for no negative gluon term is also checked.
- $\alpha_S(M_Z)$ = 0.118, 0.115, free $\alpha_S(M_Z)$
- PDFs are 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
- Jet predictions from NNLOJet (T.Gehrmann et al) via Applfast

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



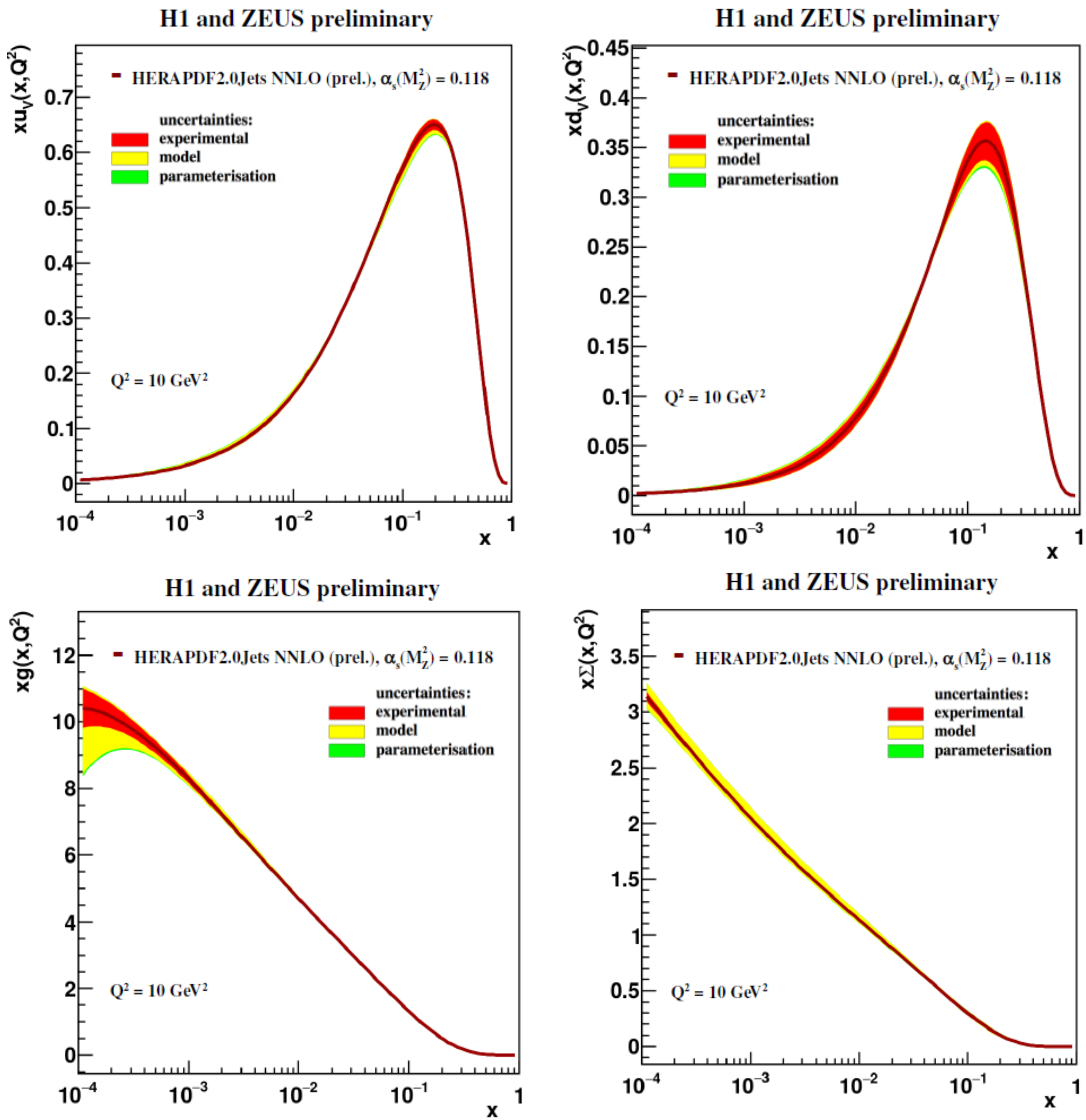
Parametrisation
Variation of $Q^2_0 = 1.9 \pm 0.3\ GeV^2$ and addition of 15^{th} parameters

When jets are included we also evaluate a hadronisation uncertainty from offsetting the corrections given for each jet data set

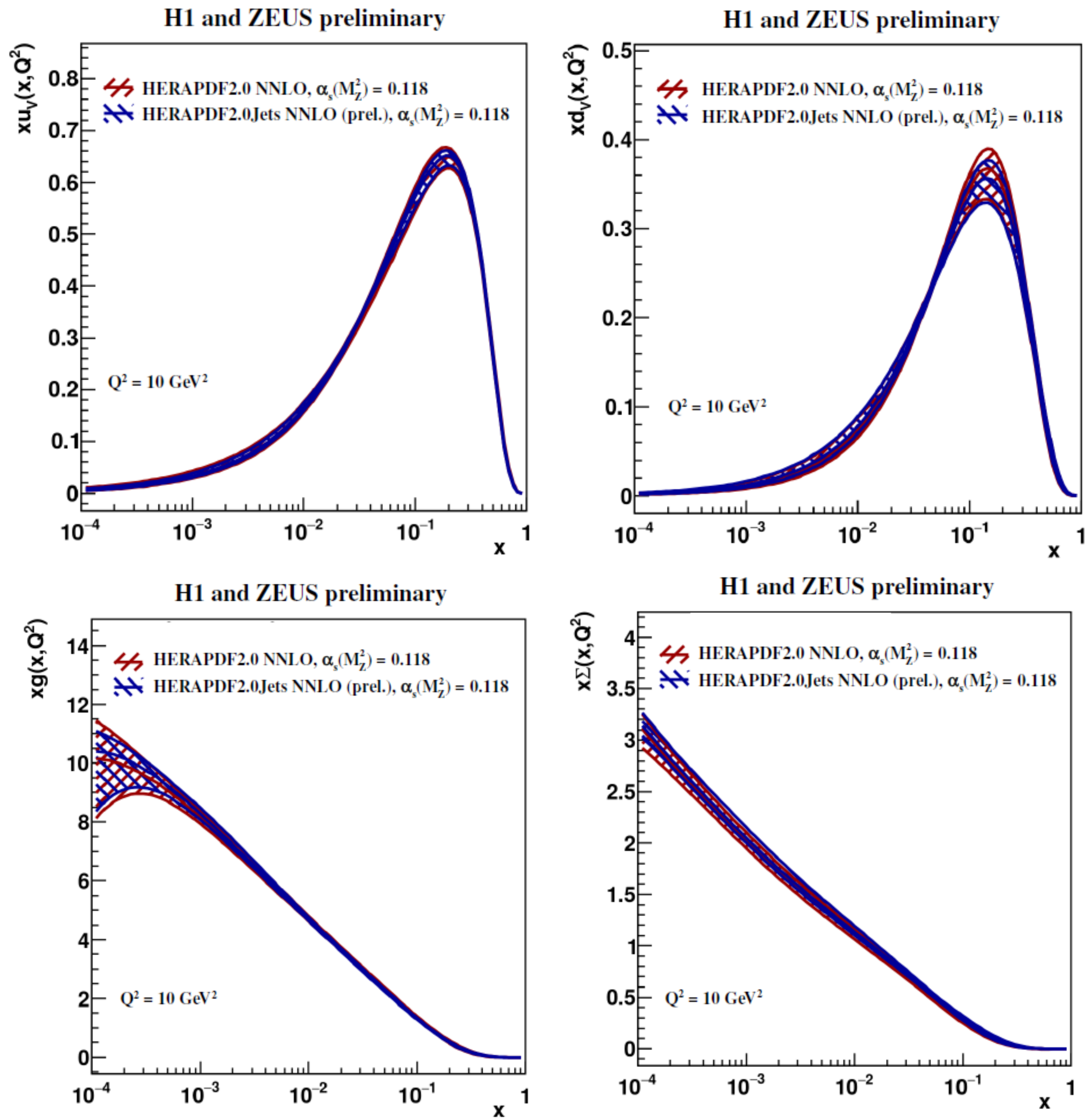
First we determine PDFs by making fits with the fixed value of

$\alpha_s(M_Z) = 0.118$

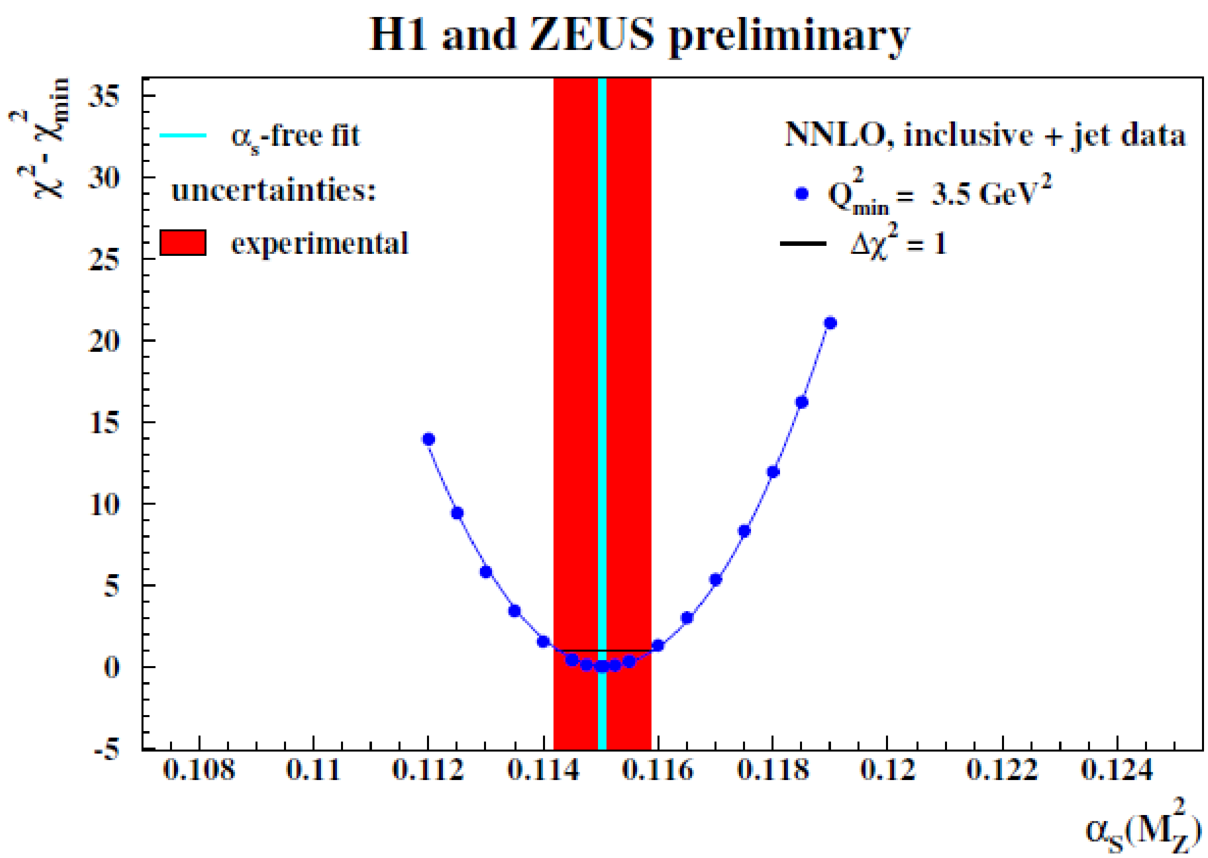
HERAPDF2.0Jets NNLO



Now compare HERAPDF2.0 NNLO to HERAPDF2.0Jets NNLO both with $\alpha_s(M_Z)$ =0.118



The standard value of $\alpha_s(M_Z)$ for HERAPDF fits is $\alpha_s(M_Z)$ =0.118 but we also perform fits with free $\alpha_s(M_Z)$, since the jet data enable us to constrain it.



Here we compare the result of a fit with free $\alpha_s(M_Z)$, to a χ2 scan over fixed $\alpha_s(M_Z)$ values, showing perfect agreement in the minimum and uncertainty

However the fitted experimental uncertainty is not the whole story.

The experimental, model, parametrisation and hadronisation uncertainties are also determined for these fits.

In addition, in fits with free $\alpha_s(M_Z)$ scale uncertainty becomes important:

Scale uncertainty is determined from the usual procedure

This was to vary factorisation and renormalisation scales both separately and simultaneously by a factor of two taking the maximal positive and negative deviations. These are assumed to be 50% correlated and 50% uncorrelated.

This gives scale uncertainty $^{+0.0026}$ / $_{-0.0027}$ by far the largest uncertainty.

To summarise the value of $\alpha_s(M_Z)$ determined from these fits with all uncertainties is:

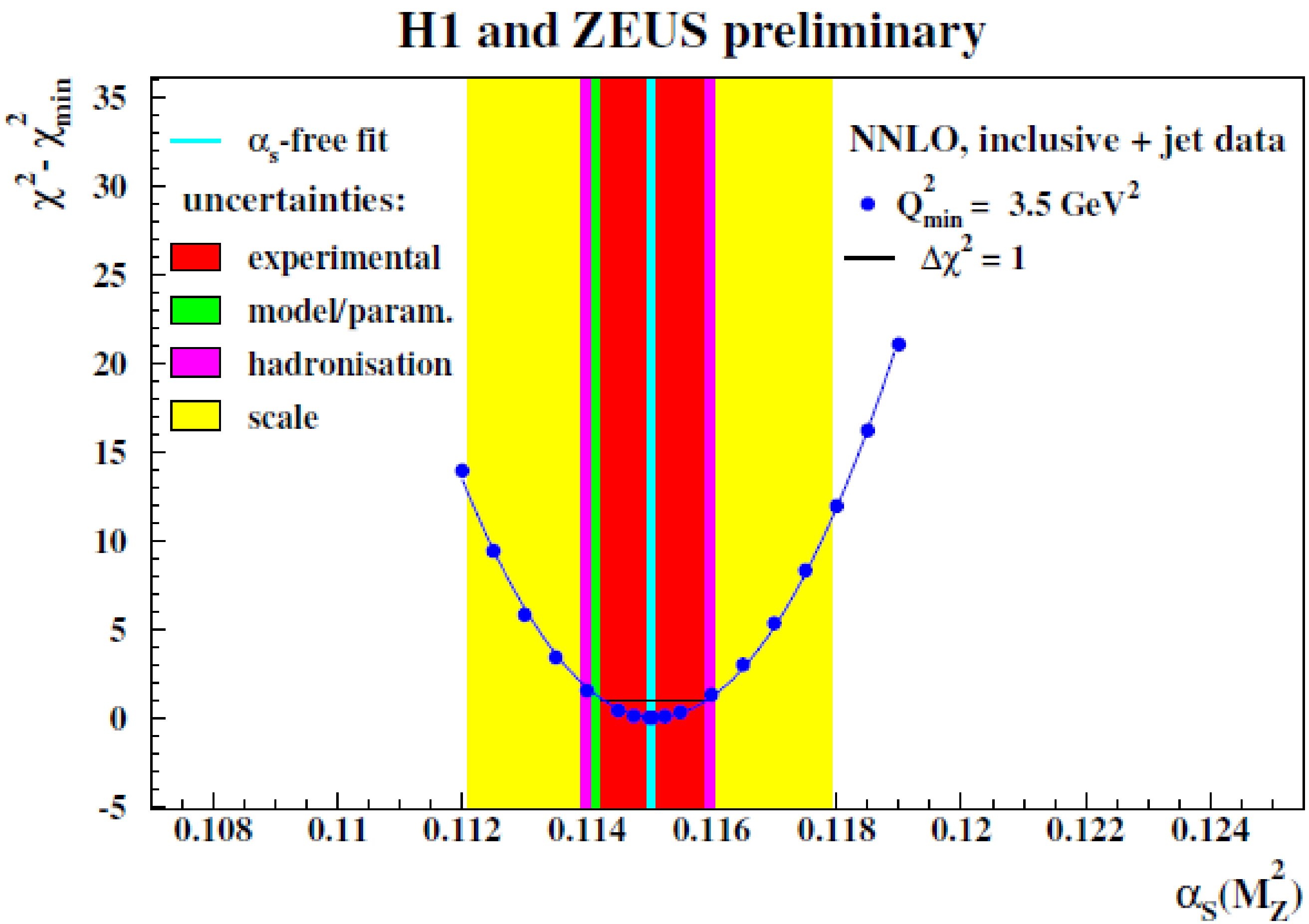
$$\alpha_s(M_Z)=0.1150 \pm 0.0008_{(exp)} {}^{+0.0002}_{-0.0005(model/param)} \pm 0.0006_{(had)} \pm 0.0027_{(scale)}$$

$\chi2$=1599 for free $\alpha_s(M_Z)$ fit, using1343 data points, 1328 degrees of freedom

$\chi2$/d.o.f =1.203

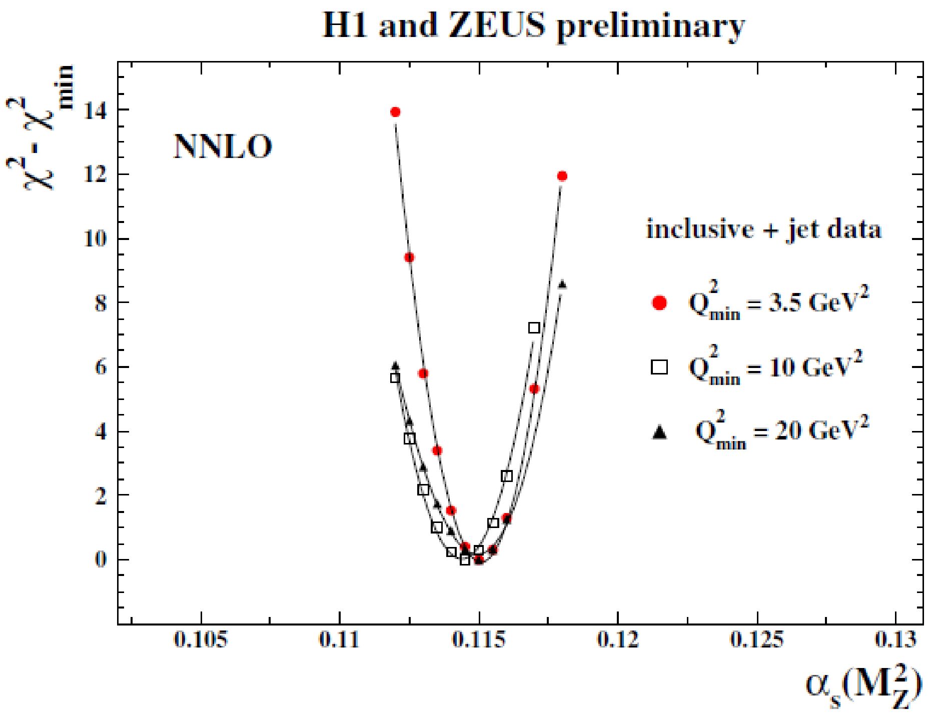
Compare $\chi2$/d.o.f =1.205 for HERAPDF2.0NNLO (with only 1131 degrees of freedom)

So to summarise all these uncertainties:



$\alpha_s(M_Z)=0.1150 \pm 0.0008_{(exp)}\ {}^{+0.0002}_{-0.0005(model/param)} \pm 0.0006_{(had)} \pm 0.0027_{(scale)}$

Since it is well known that HERA data at low x and Q^2 may be subject to the need for ln(1/x) resummation or higher twist effects we also perform χ2 scans with harder Q^2 cuts



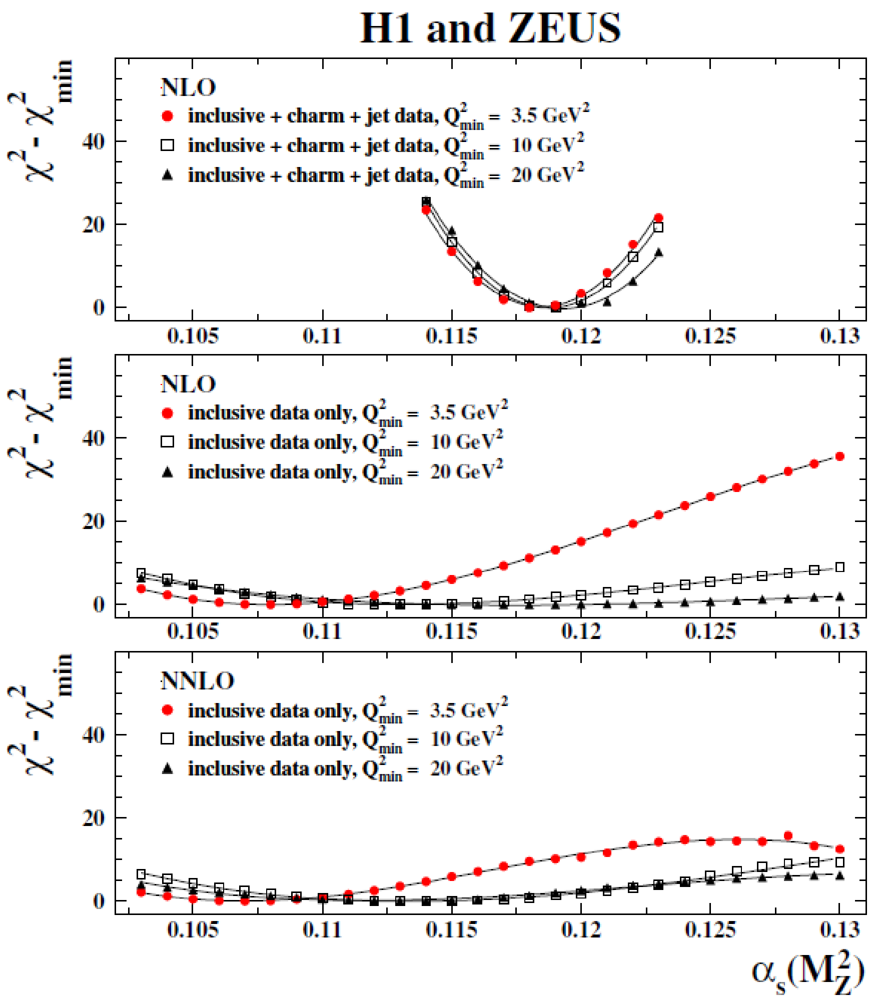
The Q^2 cuts do not result in any significant change to the value of $\alpha_s(M_Z)$ that is determined

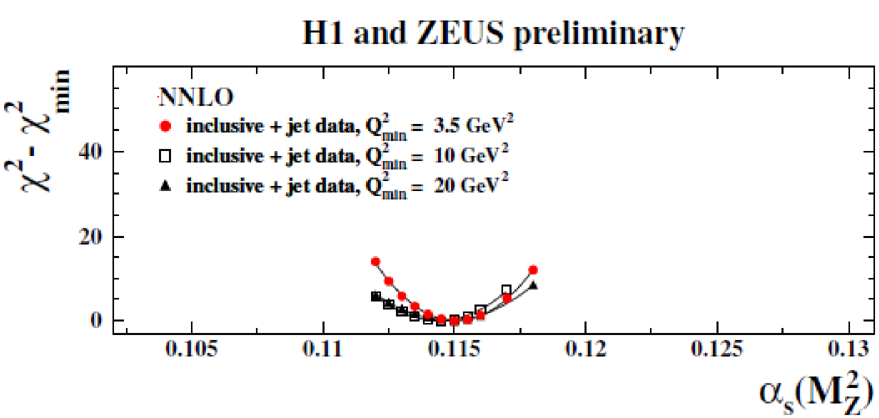
The central values from the three scans are:

$\alpha_s(M_Z)$ = 0.1150 ± 0.0008 Q^2>3.5 GeV^2

$\alpha_s(M_Z)$ = 0.1144 ± 0.0010 Q^2>10 GeV^2

$\alpha_s(M_Z)$ = 0.1148 ± 0.0010 Q^2>20 GeV^2





These scans over the NNLO inclusive +jet data are compared to the published scans done at NLO and to the corresponding scans using only inclusive data.

Just as at NLO the jet data help to constrain $\alpha_s(M_Z)$. There is a similar level of accuracy at NNLO and NLO and $\alpha_s(M_Z)$ clearly moves lower at NNLO –

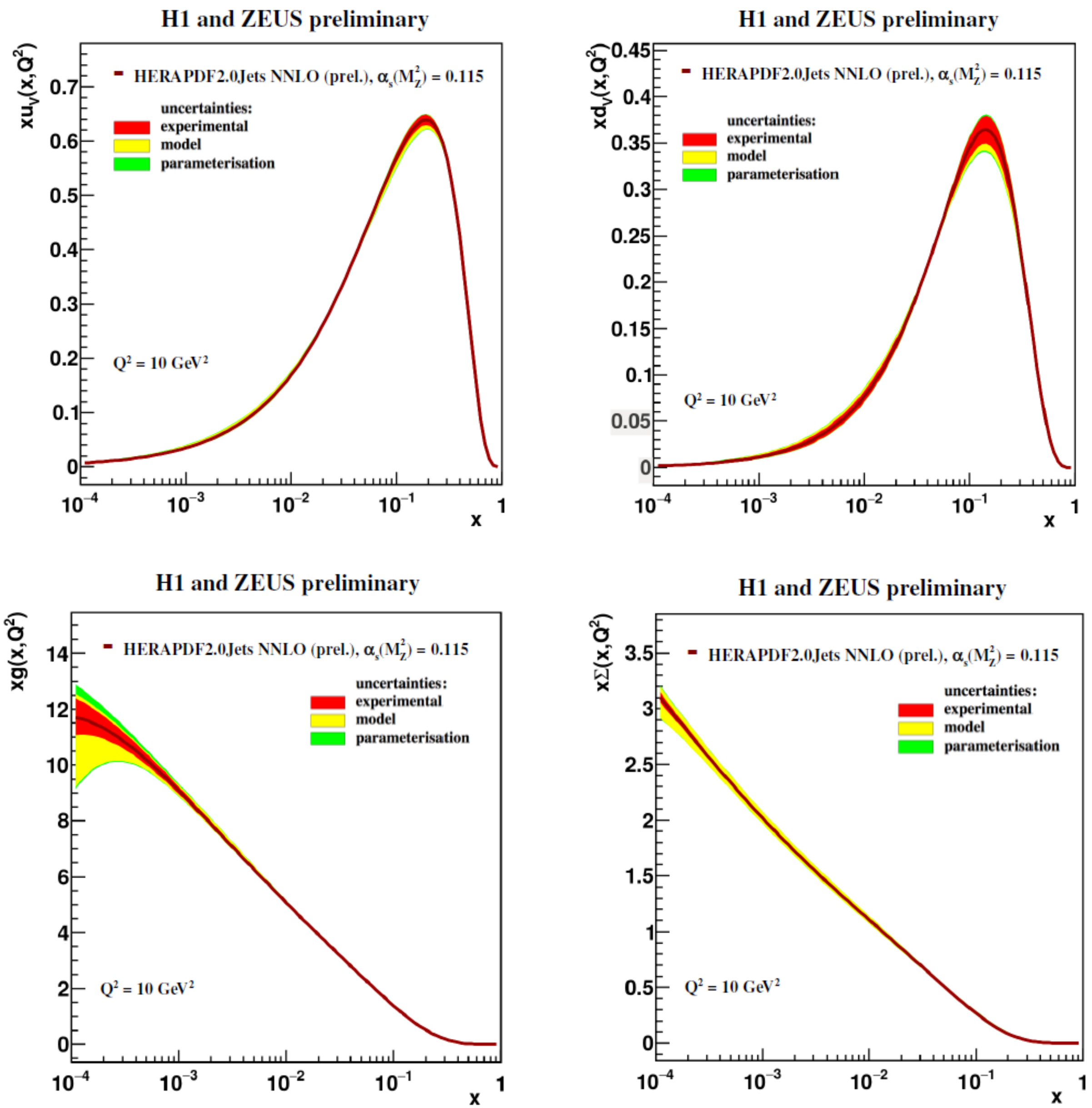
But note we are using a different scale now– our scale uncertainty studies show that with the old scale choice used at NLO the NNLO result would be even lower → $\alpha_s(M_Z) \sim 0.1135$.
So this IS a systematic shift.

The NNLO result is:
$\alpha_s(M_Z)=0.1150 \pm 0.0008_{(exp)}\,^{+0.0002}_{-0.0005(model/param)} \pm 0.0006_{(had)} \pm 0.0027_{(scale)}$

Compare the NLO result
$\alpha_s(M_Z)=0.1183 \pm 0.0009_{(exp)} \pm 0.0005_{(model/param)} \pm 0.0012_{(had)}\,^{+0.0037}_{-0.0030(scale)}$

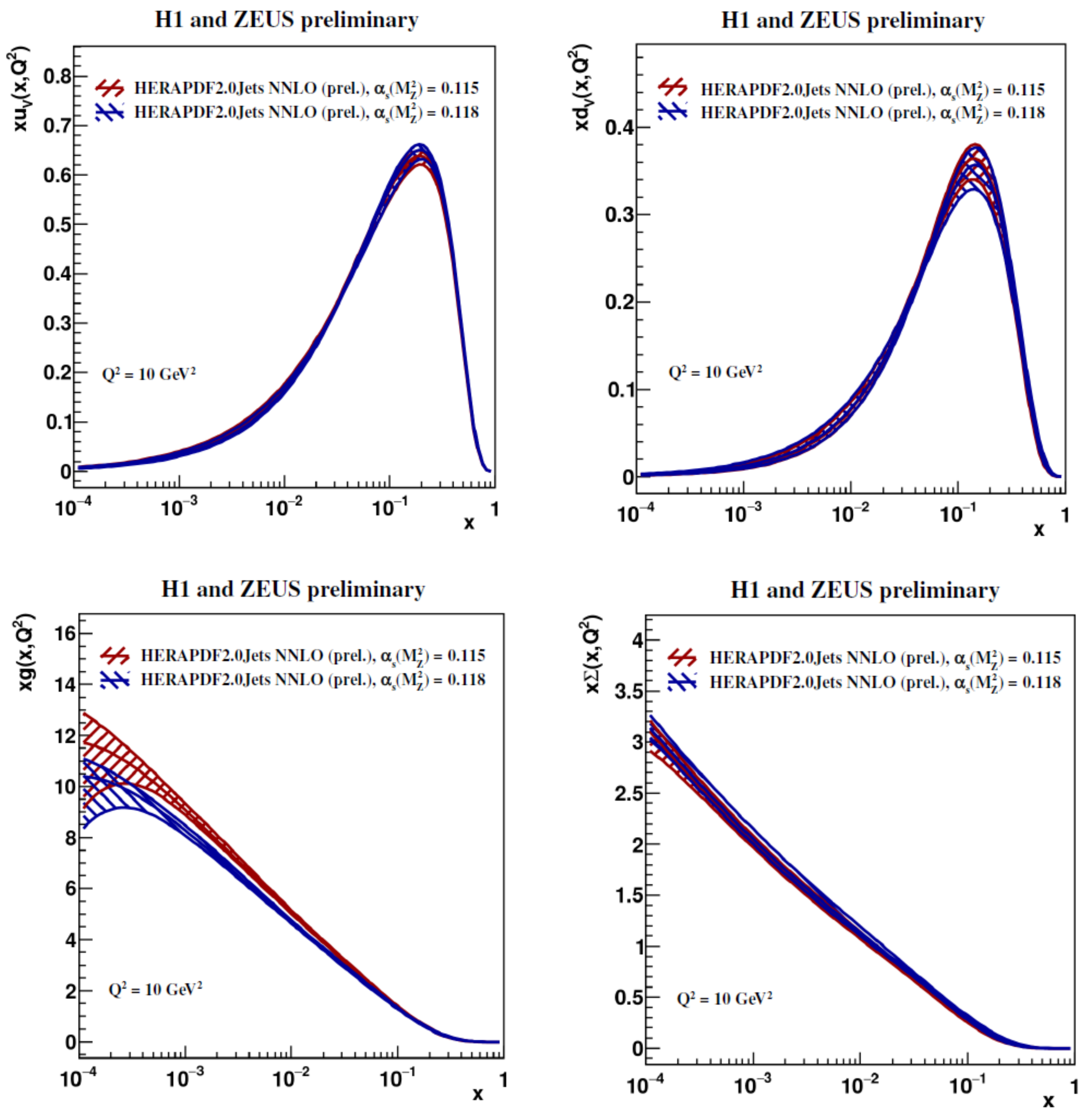
So now produce PDFs with the fixed value

$\alpha_s(M_Z) = 0.115$



Compare PDFs for

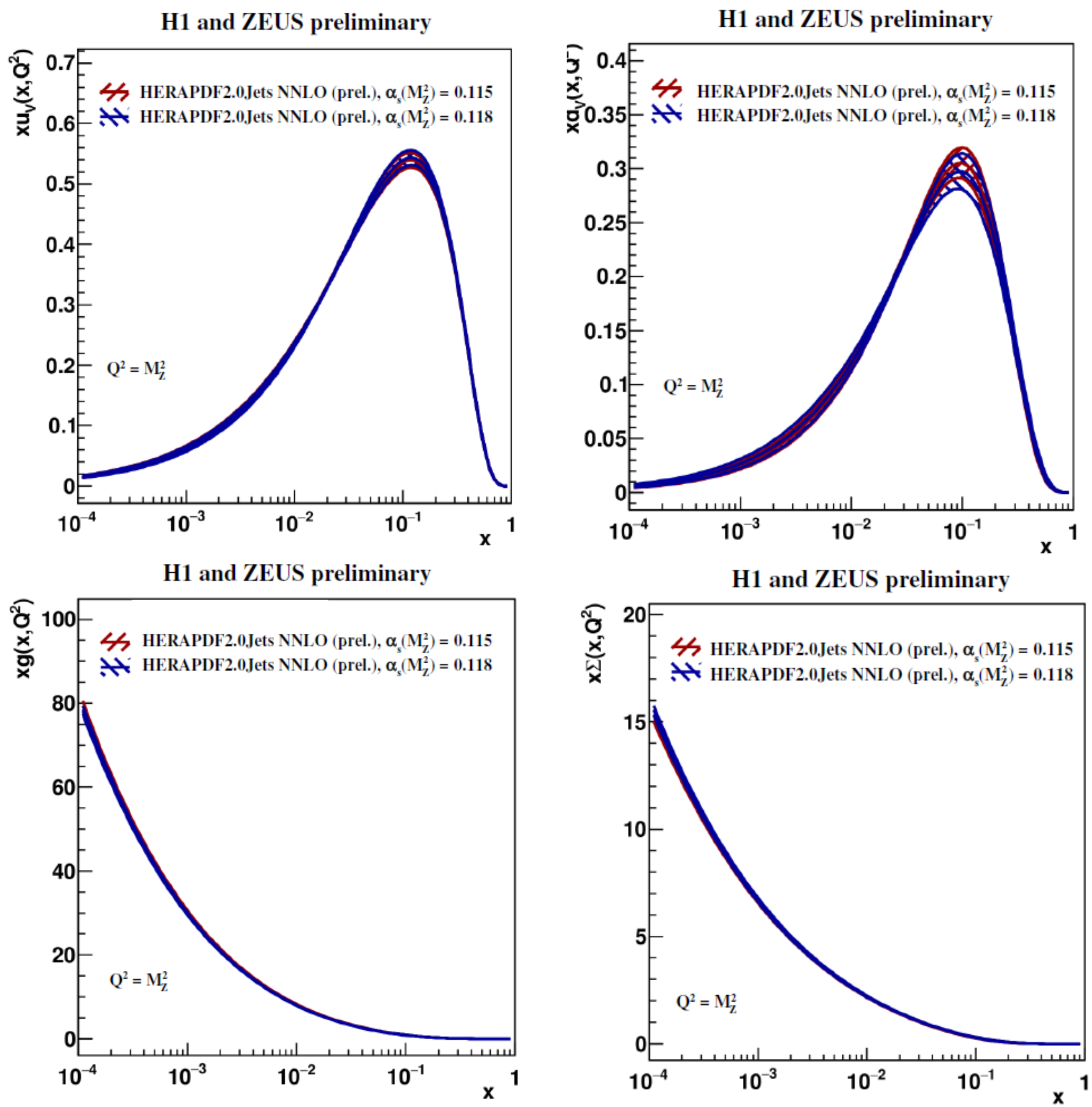
$\alpha_s(M_Z)$ =0.115 and
$\alpha_s(M_Z)$ =0.118

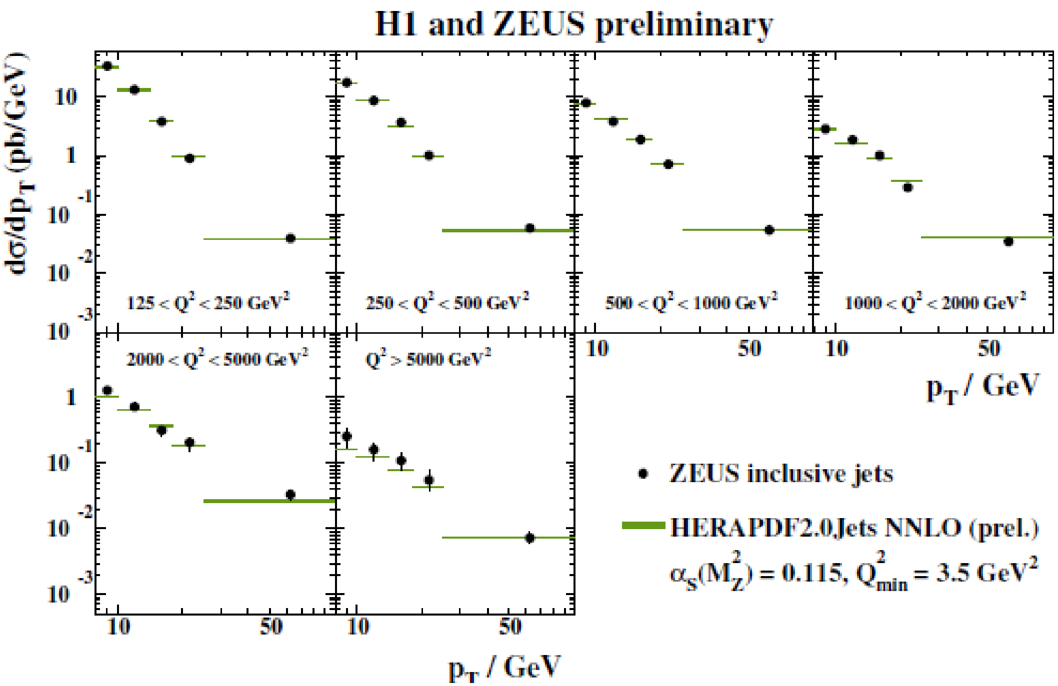


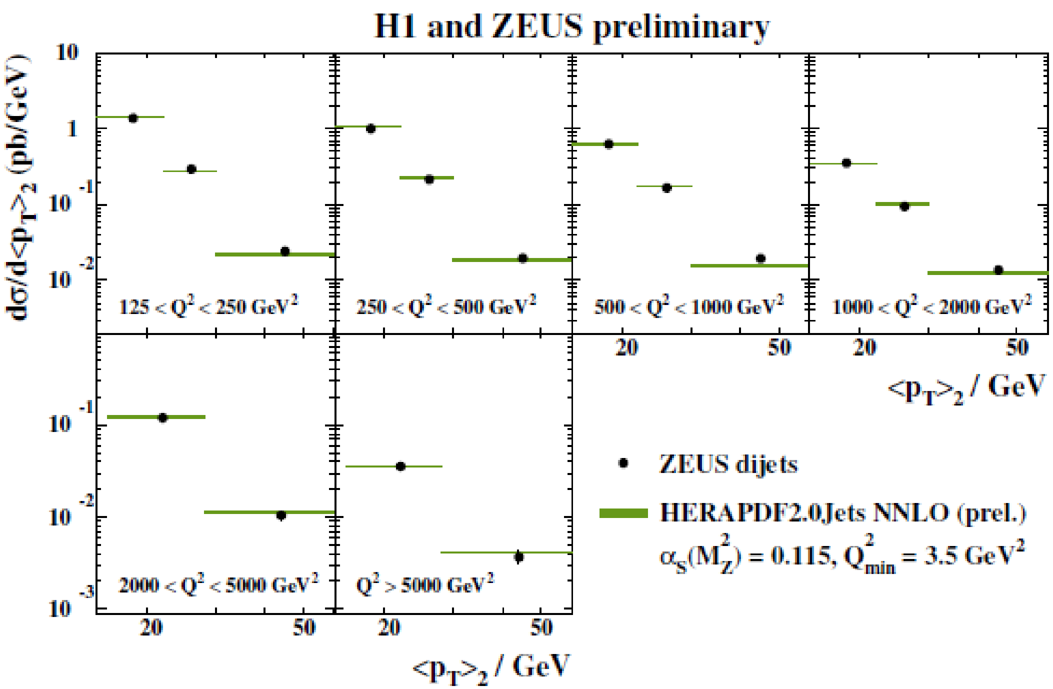
Compare PDFs for

$\alpha_s(M_Z)$ =0.115 and
$\alpha_s(M_Z)$ =0.118

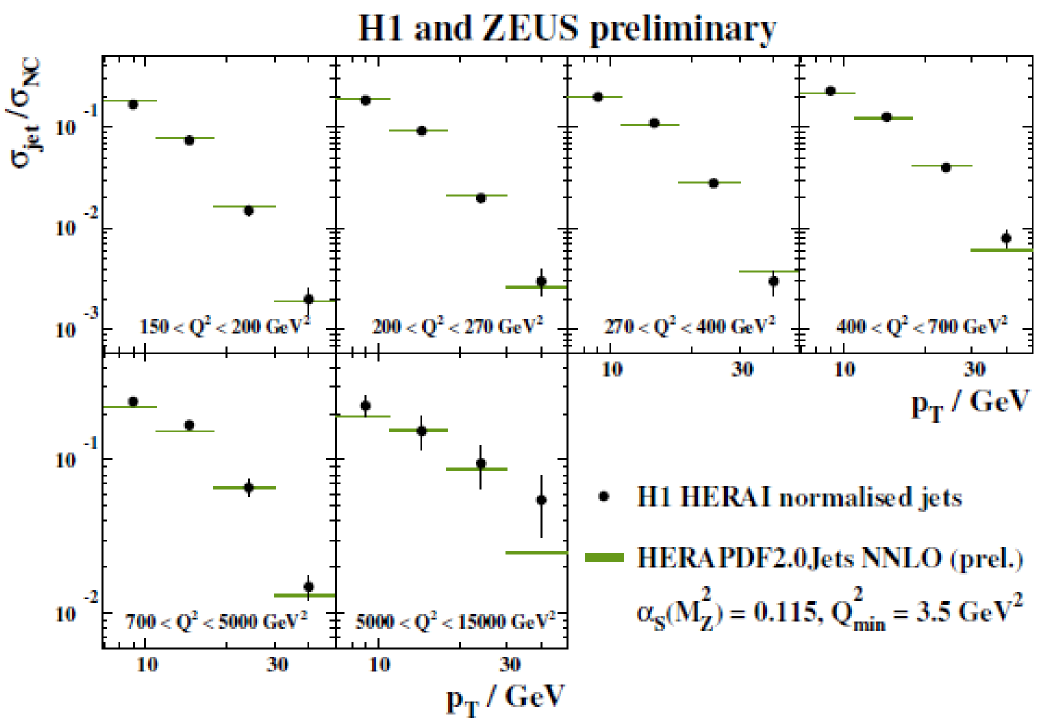
At high scale $Q^2 = M_z^2$

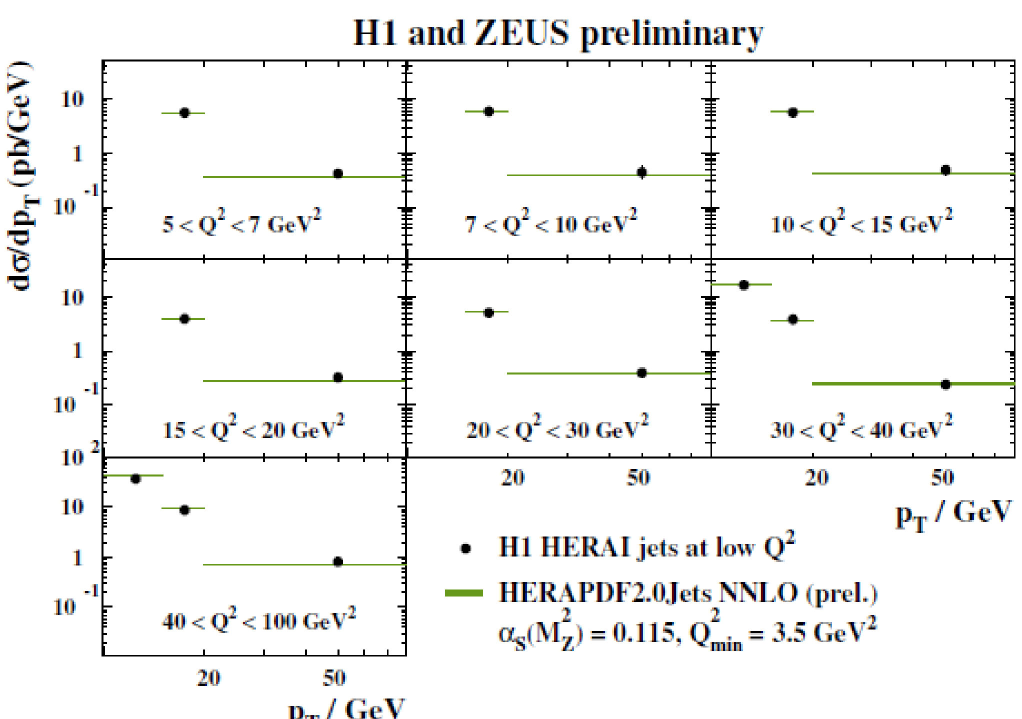






Now compare the HERAPDF2.0 Jets NNLO fit with $\alpha_s(M_Z)$=0.115 to the jet data





Now compare the HERAPDF2.0 Jets NNLO fit with $\alpha_s(M_Z)=0.115$ to the jet data

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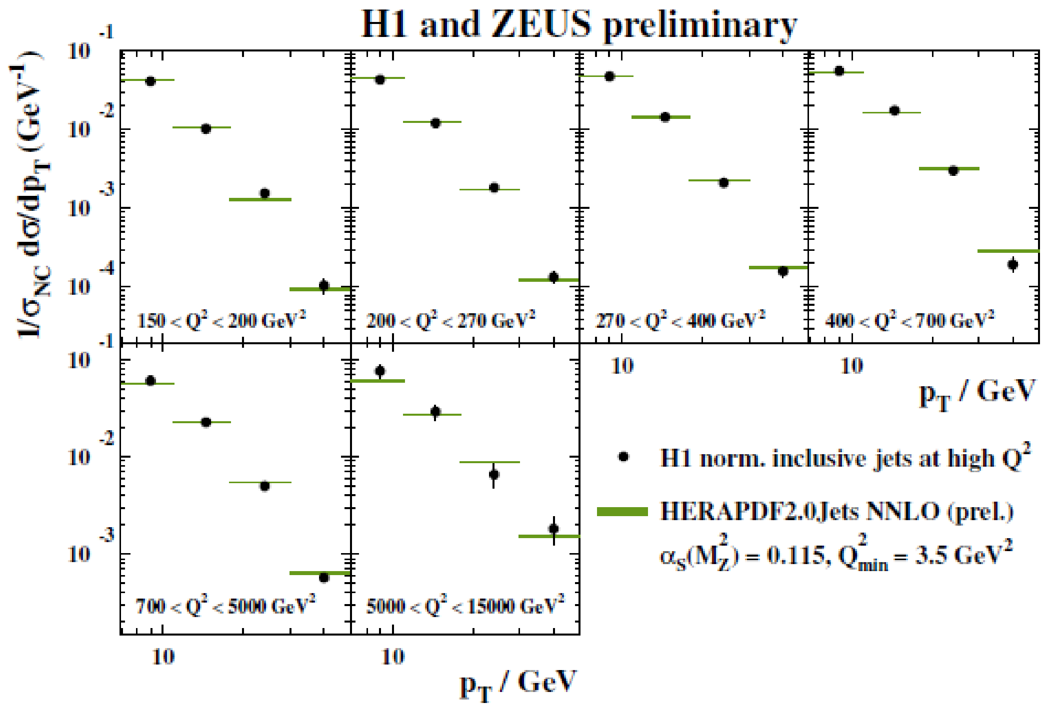

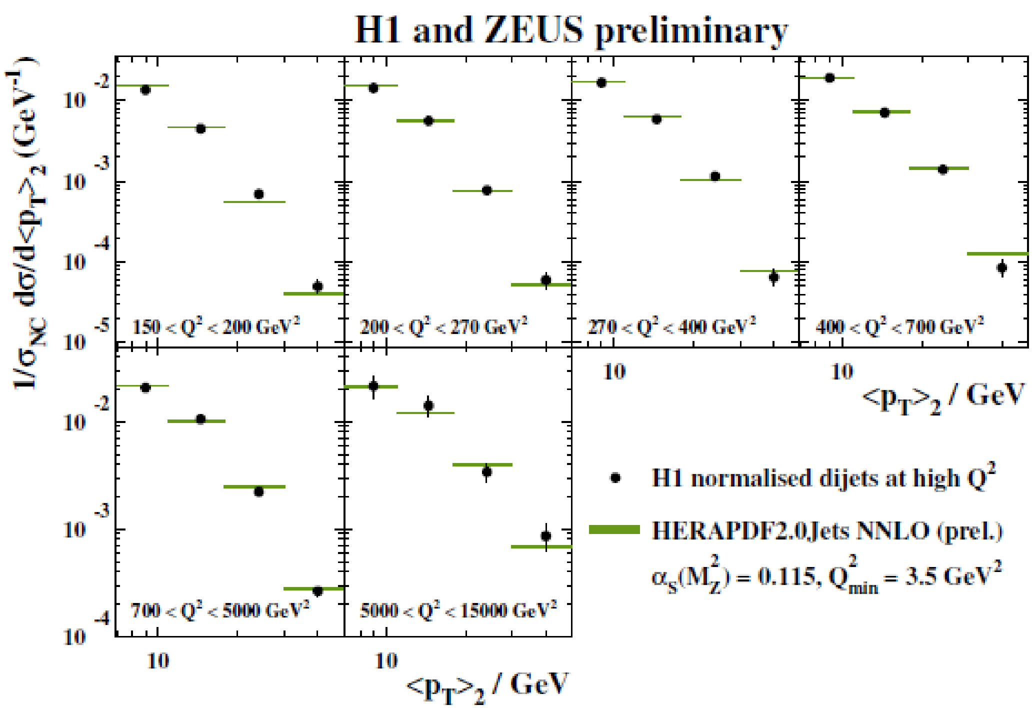

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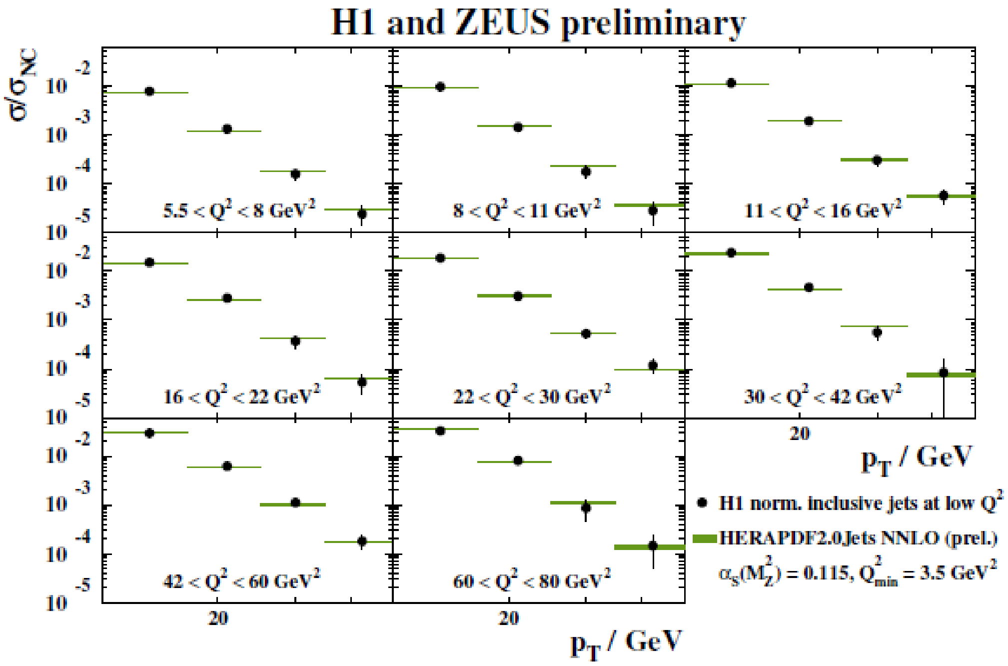

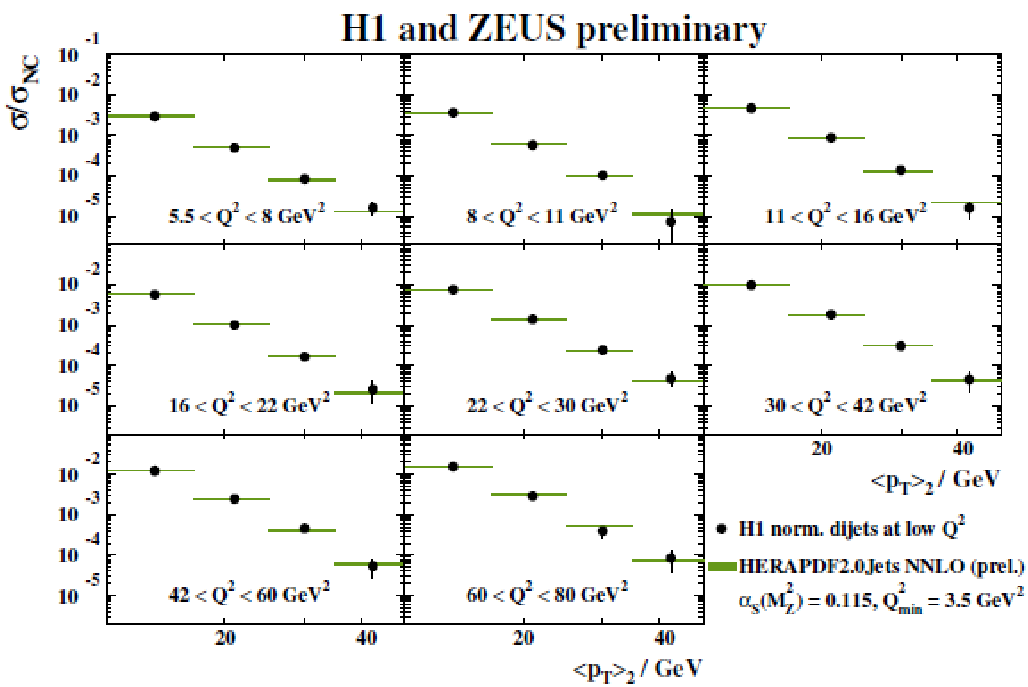

Conclusions

We have completed the HERAPDF2.0 family by performing an NNLO fit including jet data.
This results in two new PDF sets:
HERAPDF2.0JetsNNLO $\alpha_s(M_Z) = 0.118$ – the PDG value
HERAPDF2.0JetsNNLO $\alpha_s(M_Z) = 0.115$ – The value favoured by our own fit

The Jet data allow us to constrain $\alpha_s(M_Z)$. Our NNLO value is

$$\alpha_s(M_Z)=0.1150 \pm 0.0008_{(exp)} {}^{+0.0002}_{-0.0005(model/param)} \pm 0.0006_{(had)} \pm 0.0027_{(scale)}$$

Compare the NLO result

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

There is a systematic shift downwards at NNLO even taking scale variation into account