HERAPDF2.0 and Diffractive PDFs

A M Cooper-Sarkar on behalf of H1 and ZEUS
ICHEP2020

Two studies using predictions for Jet production at NNLO from the HERA ep collider experiments ZEUS and H1

1. Updating HERAPDF2.0NLOJets with NNLO predictions for Jets from NNLOJet as implemented in the ApplFast system ZEUS-prel-19-001 , H1-prelim-19-041

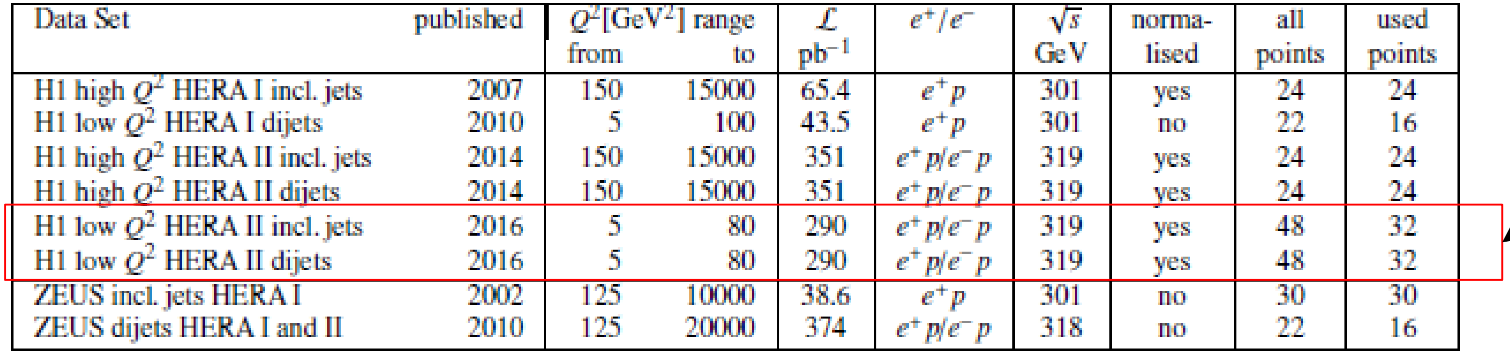
2. Diffractive PDFS at NNLO using H1 inclusive diffractive cross sections and diffractive jet production data H1-prelim-19-013

HERAPDF2.0NNLO is updated with Jet data

At the time of the 2015 publication (1506.06042) NNLO predictions were not available

Jet Data sets used in the present NNLO analysis

Strong overlap with those used in the NLO analysis, but more recent low Q^2 inclusive and dijet data are added. These have extra sensitivity to $\alpha_s(M_Z)$.



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 had to subtract some data

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

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 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 χ2, Δχ2~ -15

In fact the 'optimal' scale choice for NLO and NNLO is different – if optimal is defined by lower χ2. At NLO Δχ2~ -15 for the old scale choice.

We also explore the consequences of scale variation.

The HERAPDF approach uses only HERA data

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

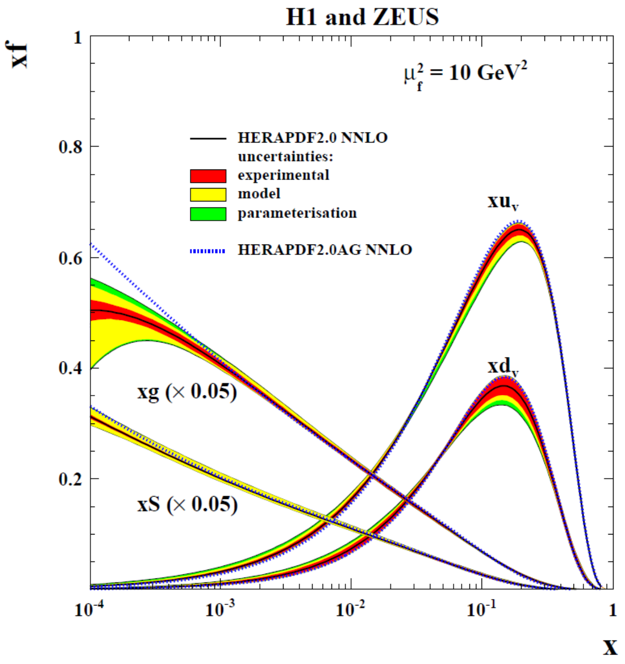
HERAPDF2.0Jets fits add HERA Jet data to this.

All choices of parametrisation, starting scale for evolution, mc, mb, cuts etc are as for the published HERAPDF2.0 (arXIV:1506.06042~)

Experimental
Hessian uncertainties: 14 eigenvector pairs, evaluated with Δχ2 = 1

Model: Variation of input assumptions
Variation of charm mass and beauty mass, Q^2_{min}, strangeness fraction

Parametrisation
Variation of Q^2_0 and addition of 15th parameter(s)



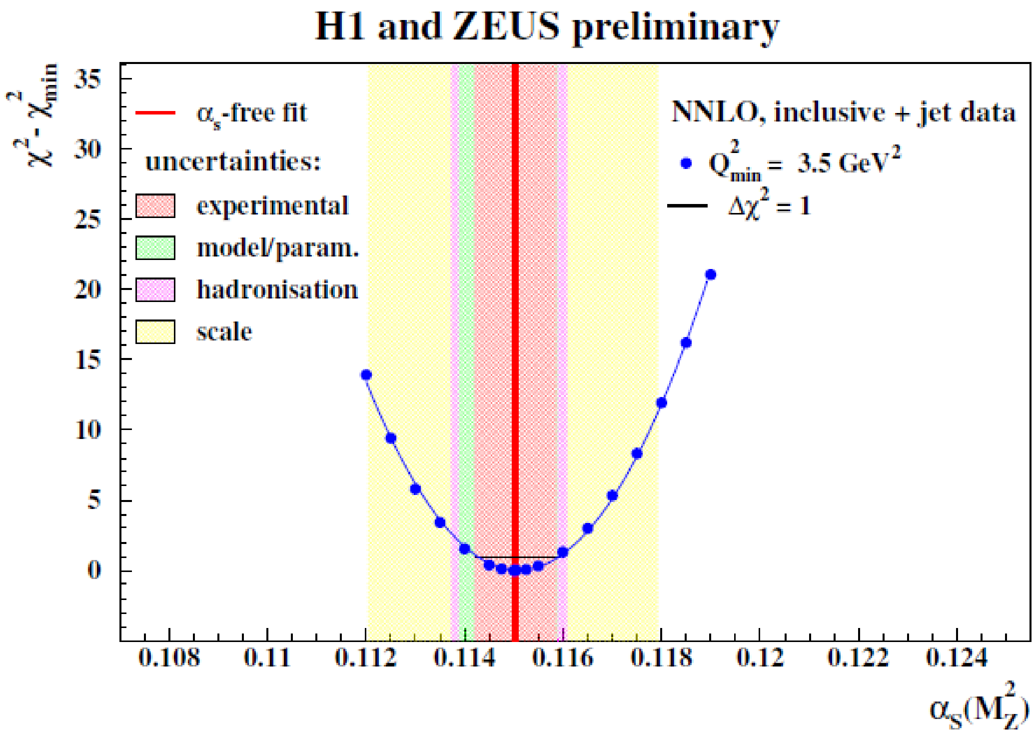
When jets are included we also evaluate a hadronisation uncertainty from offsetting the corrections given for each jet data set

The standard value of $\alpha_s(M_Z)$ for HERAPDF fits is $\alpha_s(M_Z)$ =0.118 but we also perform simultaneous fits for the PDFs with free $\alpha_s(M_Z)$.

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:

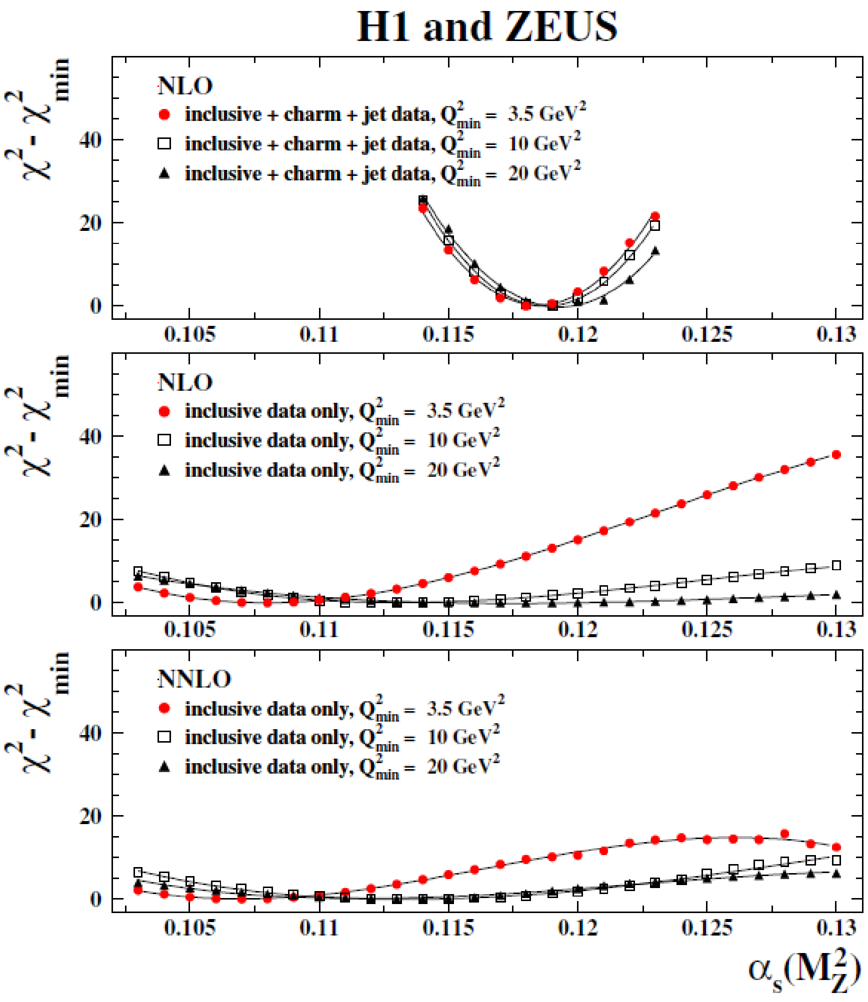
The result for $\alpha_s(M_Z)$ from the fit is compared with fits made scanning the χ2 w.r.t fixed values of $\alpha_s(M_Z)$.

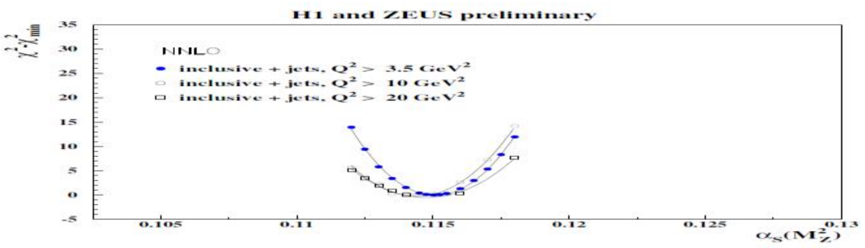


Scale uncertainty $^{+0.0026}$ / $_{-0.0027}$ is **by far the largest uncertainty**

Determined as for the NLO fit: factorisation and renormalisation scales are subject to 7-point variation by a factor of two taking the maximal positive and negative deviations. These are assumed to be 50% correlated and 50% uncorrelated.

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





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.

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 ~ $\alpha_s(M_Z)$ =0.1135.

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

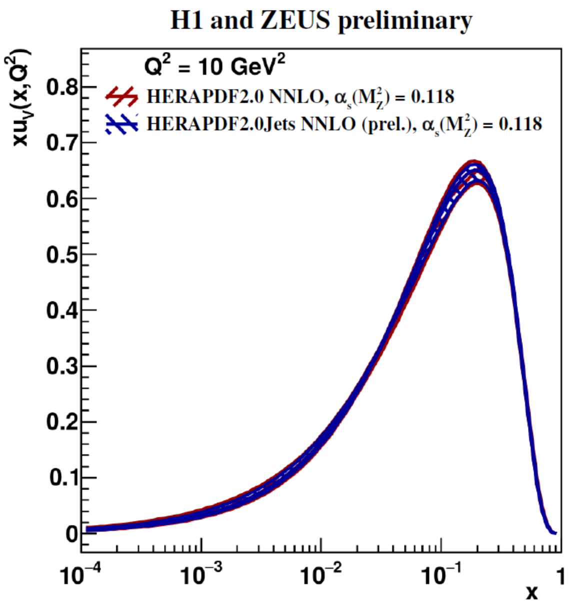
Compare the NLO result
$\alpha_s(M_Z)=0.1183 \pm 0.0009_{(exp)} \pm 0.0005_{(model/param)} \pm 0.0012_{(had)}{}^{+0.0037}_{-0.0030(scale)}$

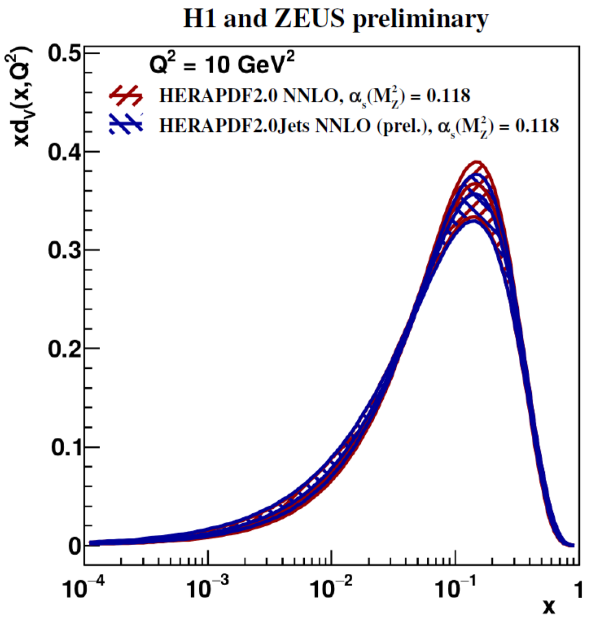
Scale uncertainty is reduced NLO to NNLO

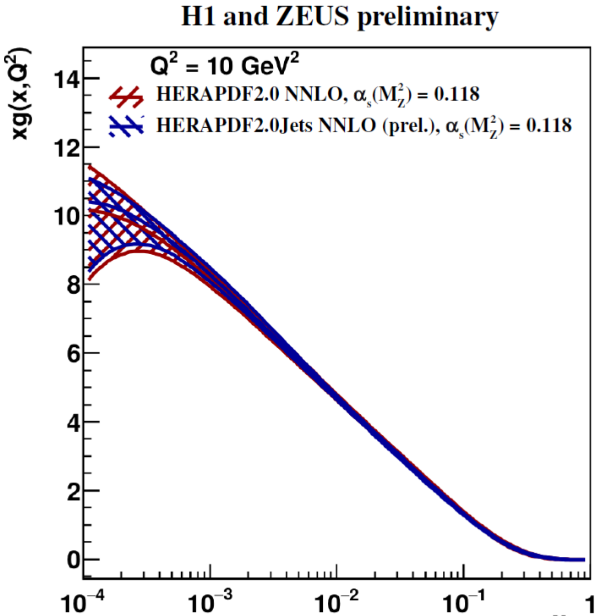
Now compare the new PDF
HERAPDF2.0Jets NNLO
to HERAPDF2.0 NNLO
both with $\alpha_s(M_Z) = 0.118$

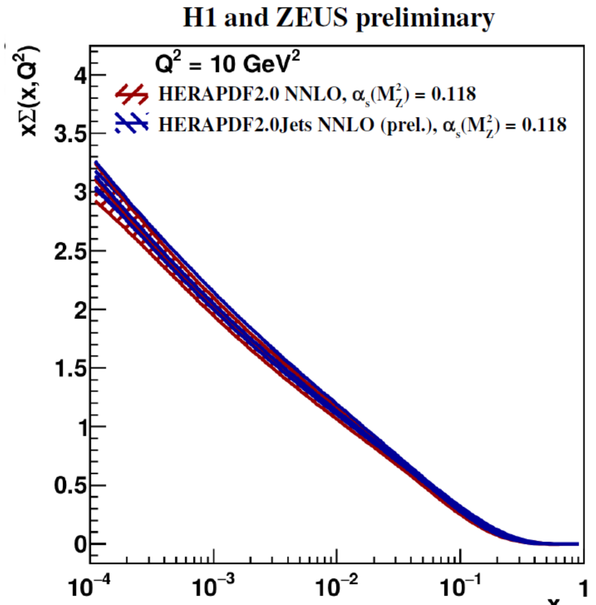
Very similar at fixed $\alpha_s(M_Z)$
Clearly the jet data are very compatible with the inclusive Data

Some reduction in gluon PDF uncertainty


H1 and ZEUS preliminary


H1 and ZEUS preliminary

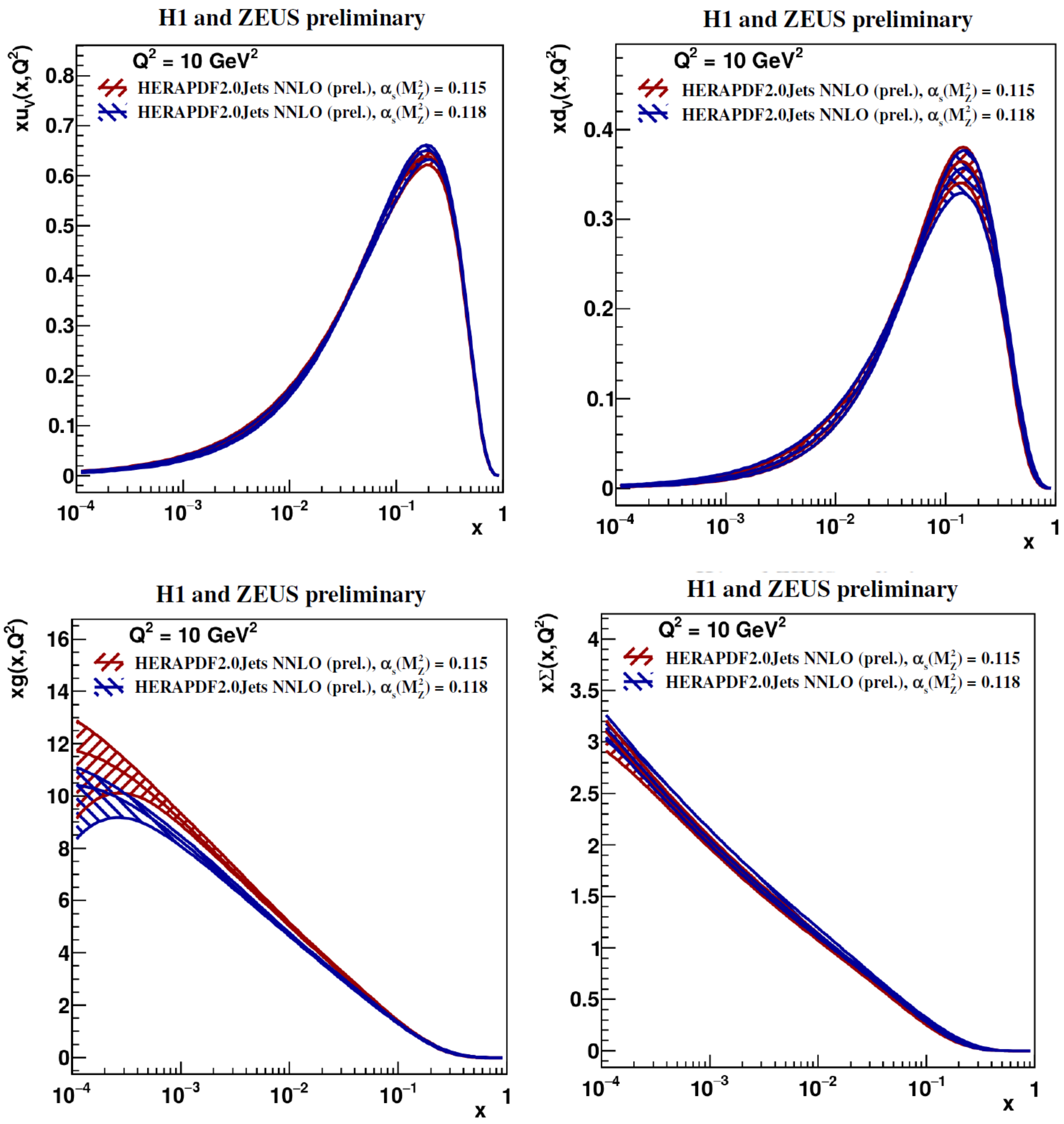

H1 and ZEUS preliminary

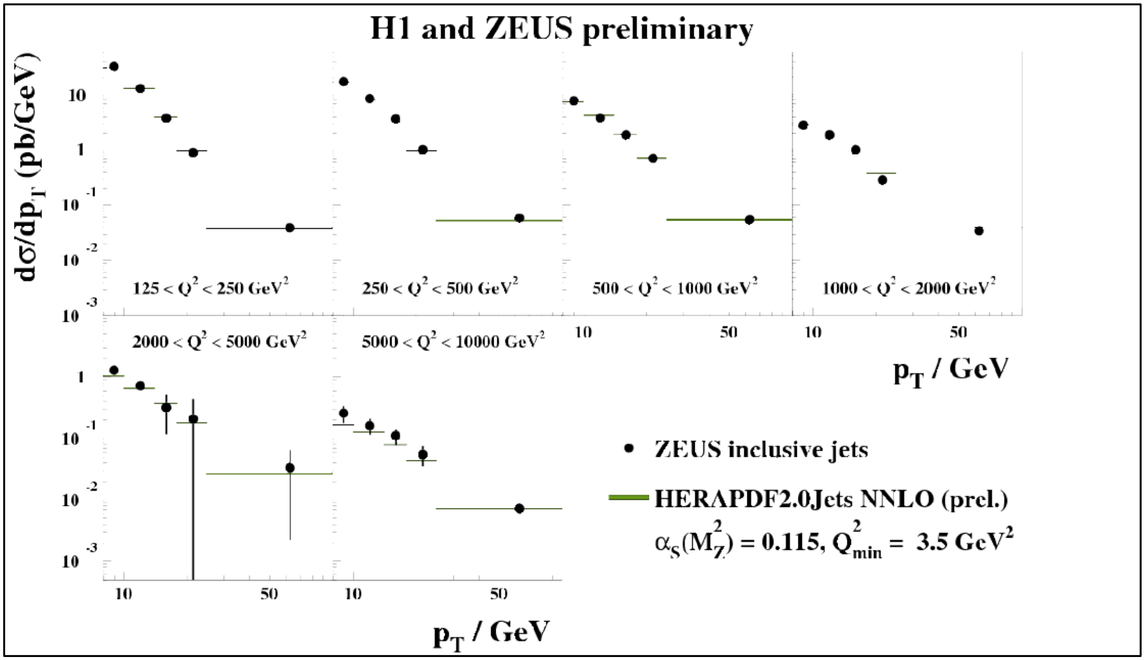

H1 and ZEUS preliminary

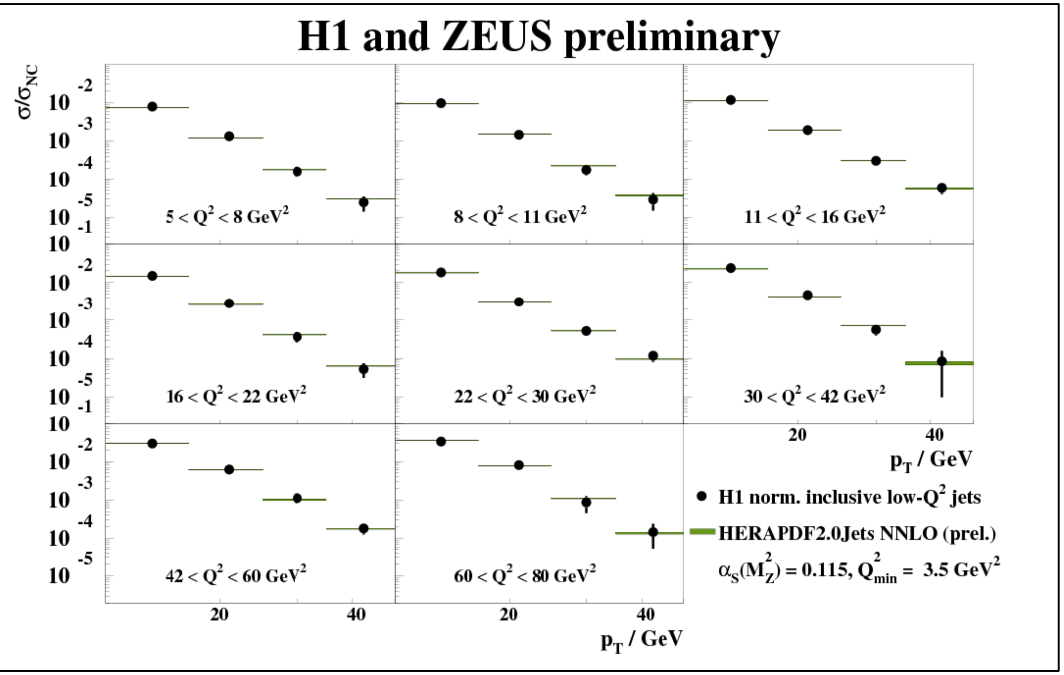
But the jet data prefer lower $\alpha_s(M_Z)$ at NNLO so let's compare the PDFs

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

We obtain a somewhat differing gluon shape as expected from a change in $\alpha_s(M_Z)$.







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

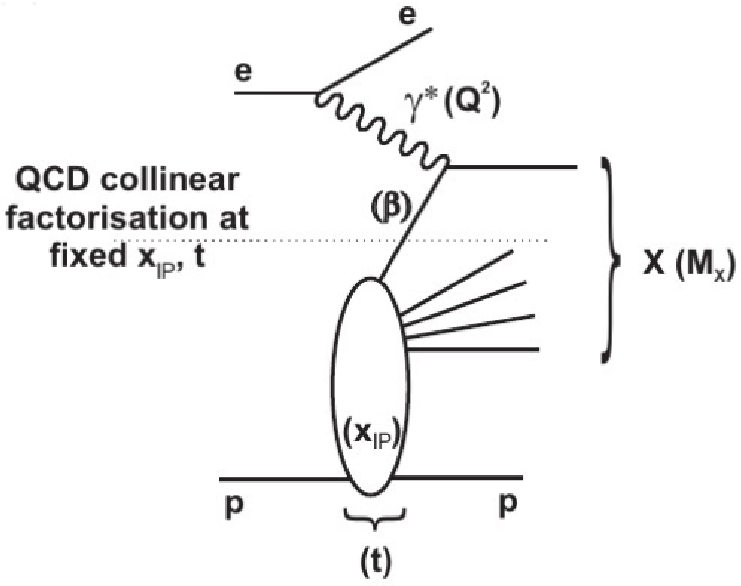
Since this is a short talk these comparisons are only shown for a subset of data

Here we show the ZEUS inclusive data form HERA-I and H1 inclusive normalised low Q2 jets from HERA-II

Many more comparisons in ZEUS-prel-`19-001

Diffractive Production in ep

In diffractive events the beam proton stays intact or dissociates into low mass hadronic system Y



At HERA about 10% of low-x events are diffractive

DIS variables:

$$Q^2 = -(k - k')^2 \qquad y = \frac{p \cdot q}{p \cdot k}$$

Diffractive variables:

$$x_{I\!P} = 1 - \frac{E'_p}{E_p} \qquad t = (p - p')^2$$

Mass: $M_X^2 = Q^2 \left(\frac{1}{\beta} - 1 \right)$

At LO: The momentum fraction entering the hard subprocess with respect to the diffractive exchange

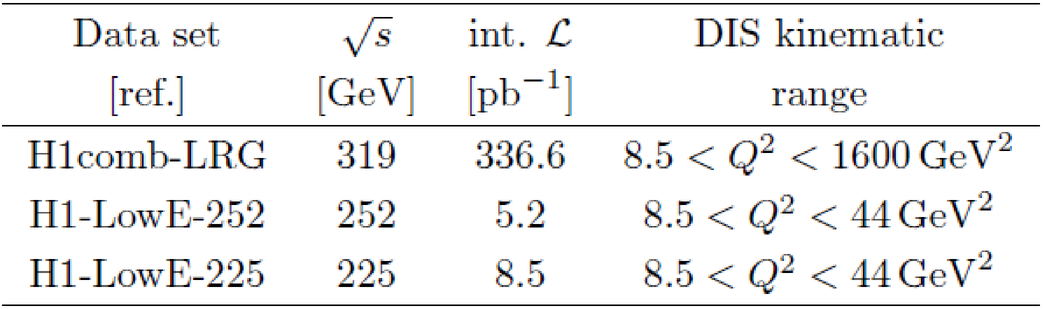
$$\beta = \frac{x_{Bj}}{x_{I\!P}} = \frac{Q^2}{s y x_{I\!P}}$$

2

What we are really doing here is determining the PDFs of the colourless exchanged ‘Pomeron’, rather than those of the proton

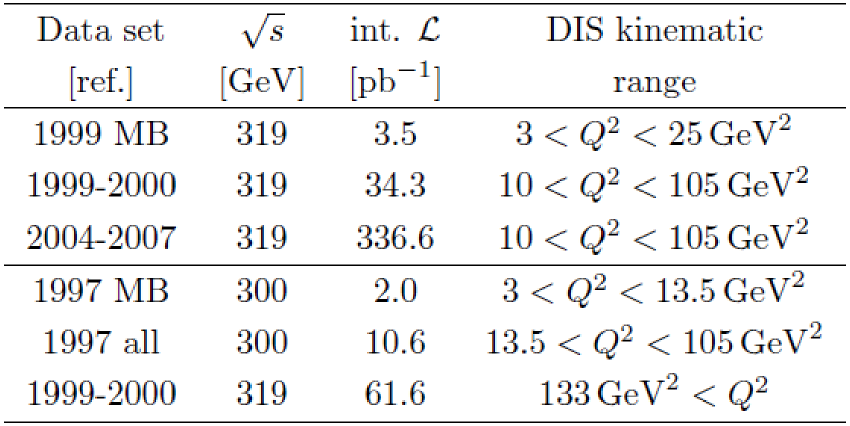
The data fitted are both inclusive diffractive data and diffractively produced dijet data.

There is a 40 times higher luminosity in inclusive diffractive data
and a 6 times higher luminosity for diffractive dijet data



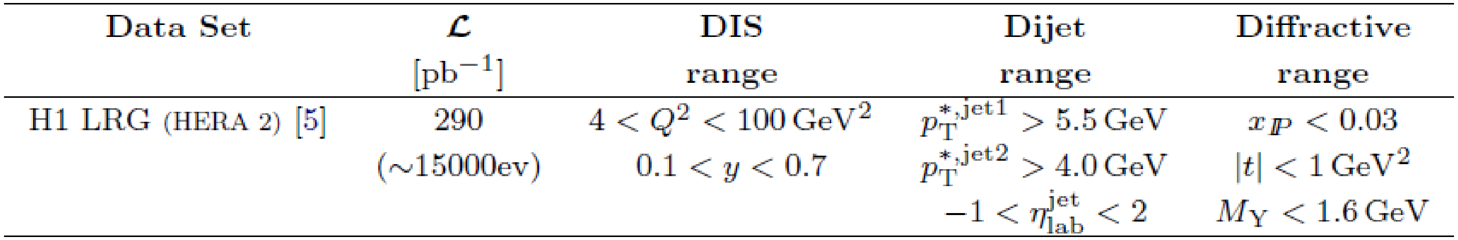
Data set [ref.]	$\sqrt{s}$ [GeV]	int. $\mathcal{L}$ [pb^{-1}]	DIS kinematic range
H1comb-LRG	319	336.6	$8.5 < Q^2 < 1600\,\mathrm{GeV}^2$
H1-LowE-252	252	5.2	$8.5 < Q^2 < 44\,\mathrm{GeV}^2$
H1-LowE-225	225	8.5	$8.5 < Q^2 < 44\,\mathrm{GeV}^2$

arXiv:1203.4495
arXiv:1107.3420



Data set [ref.]	$\sqrt{s}$ [GeV]	int. $\mathcal{L}$ [pb^{-1}]	DIS kinematic range
1999 MB	319	3.5	$3 < Q^2 < 25\,\mathrm{GeV}^2$
1999-2000	319	34.3	$10 < Q^2 < 105\,\mathrm{GeV}^2$
2004-2007	319	336.6	$10 < Q^2 < 105\,\mathrm{GeV}^2$
1997 MB	300	2.0	$3 < Q^2 < 13.5\,\mathrm{GeV}^2$
1997 all	300	10.6	$13.5 < Q^2 < 105\,\mathrm{GeV}^2$
1999-2000	319	61.6	$133\,\mathrm{GeV}^2 < Q^2$

Details of the combined data arXiv:1203.4495



Data Set	$\mathcal{L}$ [pb^{-1}]	**DIS** **range**	**Dijet** **range**	**Diffractive** **range**
H1 LRG (HERA 2) [5]	290 (~15000ev)	$4 < Q^2 < 100\,\mathrm{GeV}^2$ $0.1 < y < 0.7$	$p_T^{*,\mathrm{jet1}} > 5.5\,\mathrm{GeV}$ $p_T^{*,\mathrm{jet2}} > 4.0\,\mathrm{GeV}$ $-1 < \eta_{\mathrm{lab}}^{\mathrm{jet}} < 2$	$x_{I\!P} < 0.03$ $\|t\| < 1\,\mathrm{GeV}^2$ $M_Y < 1.6\,\mathrm{GeV}$

arXiv:1412.0928

The diffractive structure functions are a convolution of the Pomeron ‘flux’ and Pomeron PDF plus a similar term for Reggeon exchange

- Regge factorisation ansatz

$$f_i^D(z,\mu^2,x_{I\!P},t) = f_{I\!P/p}(x_{I\!P},t)\, f_{i/I\!P}(z,\mu^2) + n_{I\!R} f_{I\!R/p}(x_{I\!P},t)\, f_{i/I\!R}(z,\mu^2)$$

- **Pomeron PDF** $f_{i/I\!P}(z,\mu^2)$

times z=1 regulator: $\exp\left(-\frac{0.01}{1-z}\right)$

	Gluon at μ_0	Singlet at μ_0 $(u=d=s=\bar{u}=\bar{d}=\bar{s})$
H1 Fit2006A	$A_g \quad (1-z)^{C_g}$	$A_q\, z^{B_q} (1-z)^{C_q}$
H1 Fit2006B	A_g	
H1 Fit2007Jets ZEUS SJ **H1 Fit2019 NNLO**	$A_g\, z^{B_g} (1-z)^{C_g}$	

- **Reggeon PDF** $f_{i/I\!R}(z,\mu^2)$

$\longrightarrow$ only few % at $x_{IP} = 0.03$

$\longrightarrow$ Fixed to the pion PDF (GRV NLO as default)

$\longrightarrow$ The overall normalization $n_{I\!R}$ taken as free parameter

$$f_{\mathbb{P}/p}(x_{\mathbb{P}},t) \propto \left(\frac{1}{x_{\mathbb{P}}}\right)^{2[\alpha_{\mathbb{P}}(0)+\alpha'_{\mathbb{P}}t]-1} e^{B^0_{\mathbb{P}}t} \Rightarrow \frac{\mathrm{d}\sigma}{\mathrm{d}t} \propto \mathrm{e}^{-B|t|}$$

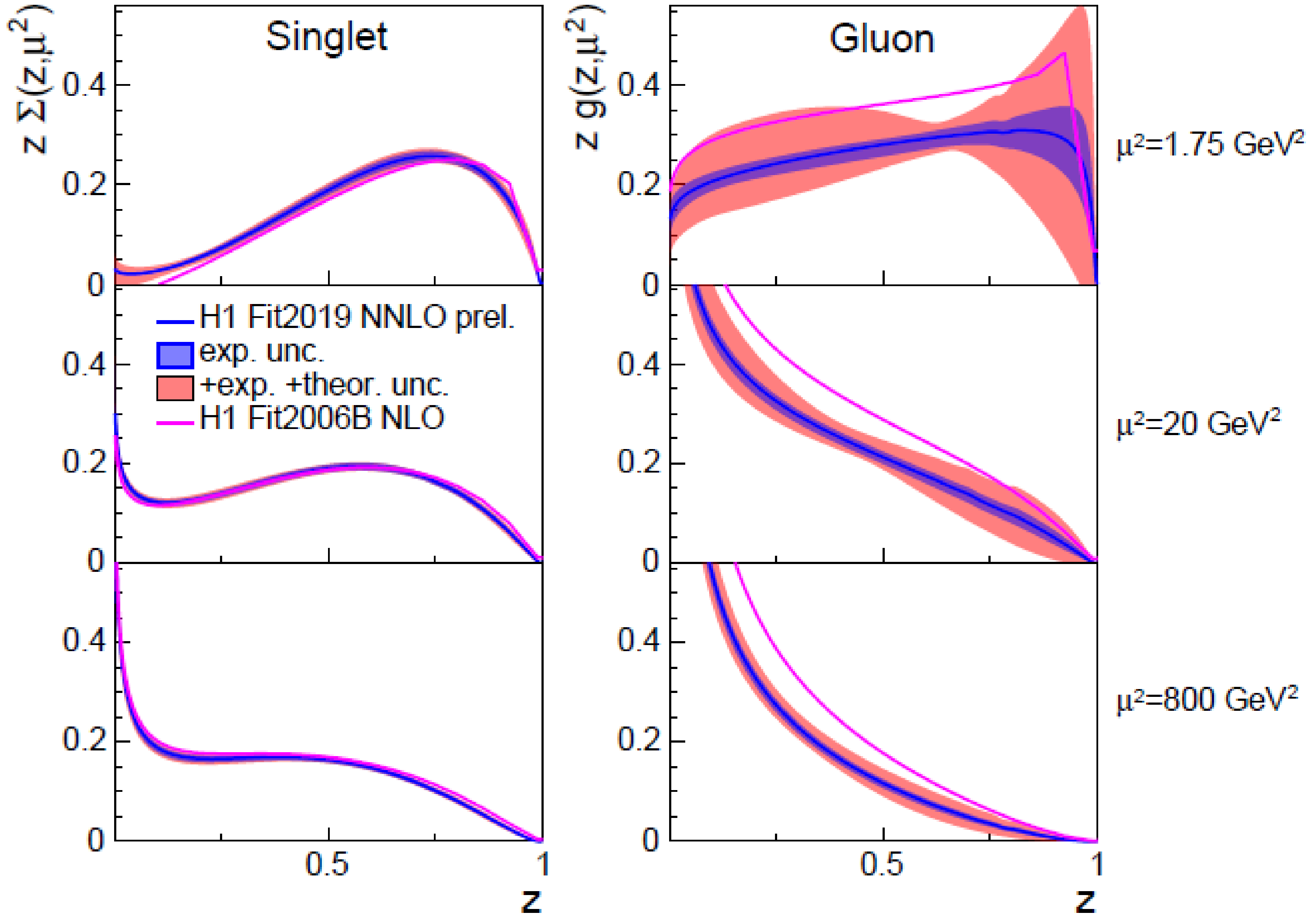
- t-integrated version: $f_{\mathbb{P}/p}(x_{\mathbb{P}}) \propto \left(\frac{1}{x_{\mathbb{P}}}\right)^{2\alpha_{\mathbb{P}}(0)-1-2\frac{\alpha'_{\mathbb{P}}}{B^0_{\mathbb{P}}}}$

~1.2, Fitted

~0.01, Fixed

	Parameter	Value	Source
Pomeron slope	$\alpha'_{\mathbb{P}}$	$0.04^{+0.08}_{-0.06}$ GeV^{-2}	H1 FPS HII [arXiv:1010.1476]
Pomeron B-slope	$B^0_{\mathbb{P}}$	$5.73^{+0.84}_{-0.93}$ GeV^{-2}	H1 FPS HII [arXiv:1010.1476]
Reggeon intercept	$\alpha_{\mathbb{R}}(0)$	0.5 ± 0.1	H1 LRG HI [hep-ex/9708016]
Reggeon slope	$\alpha'_{\mathbb{R}}$	$0.3^{+0.6}_{-0.3}$ GeV^{-2}	H1 FPS HI [hep-ex/0606003]
Reggeon B-slope	$B^0_{\mathbb{R}}$	$1.6^{+0.4}_{-1.6}$ GeV^{-2}	H1 FPS HI [hep-ex/0606003]
charm mass	m_c	1.4 ± 0.2 GeV	PDG2004
bottom mass	m_b	4.5 ± 0.5 GeV	PDG2004
strong coupling	$\alpha_S(M_Z^2)$	0.118 ± 0.002	PDG2004
staring scale of ev.	μ_0	$1.15^{+0.24}_{-0.15}$ GeV	

- The QCD scale varied by a factor of 2 (dominant unc. together with μ_0 variation)
- **8 parameters fitted:** 6 of pomeron PDF + $\alpha_{\mathbb{P}}(0)$ & $n_{\mathbb{R}}$

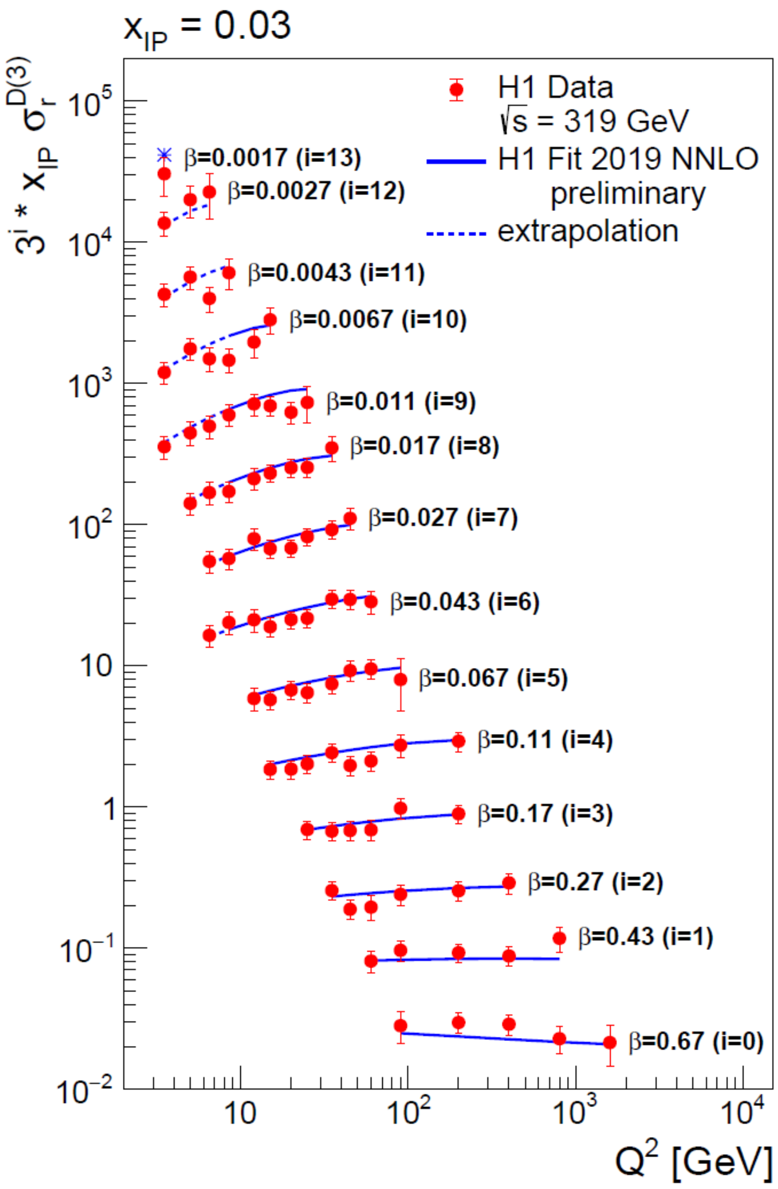


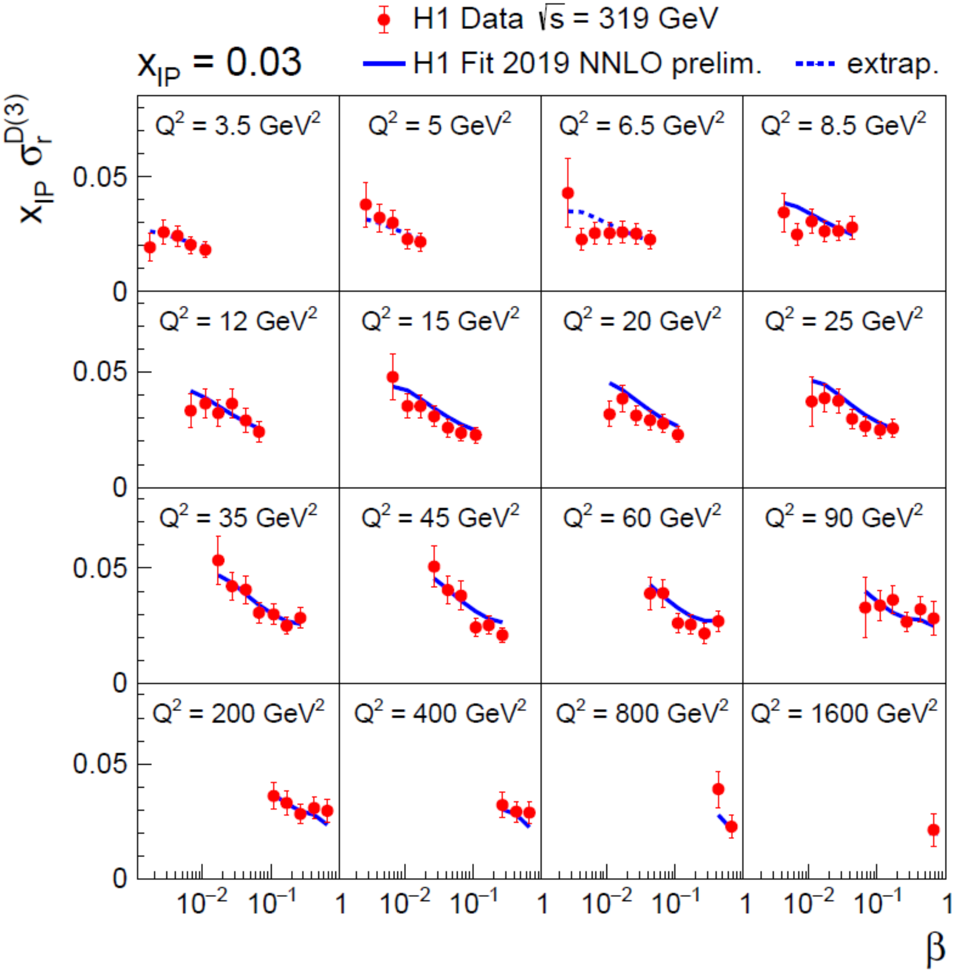
The singlet and gluon DPDFs are compared for the new H1Fit2019 NNLO and the previous H1 Fit2006B NLO

The gluon DPDF is considerably (~25%) reduced at NNLO

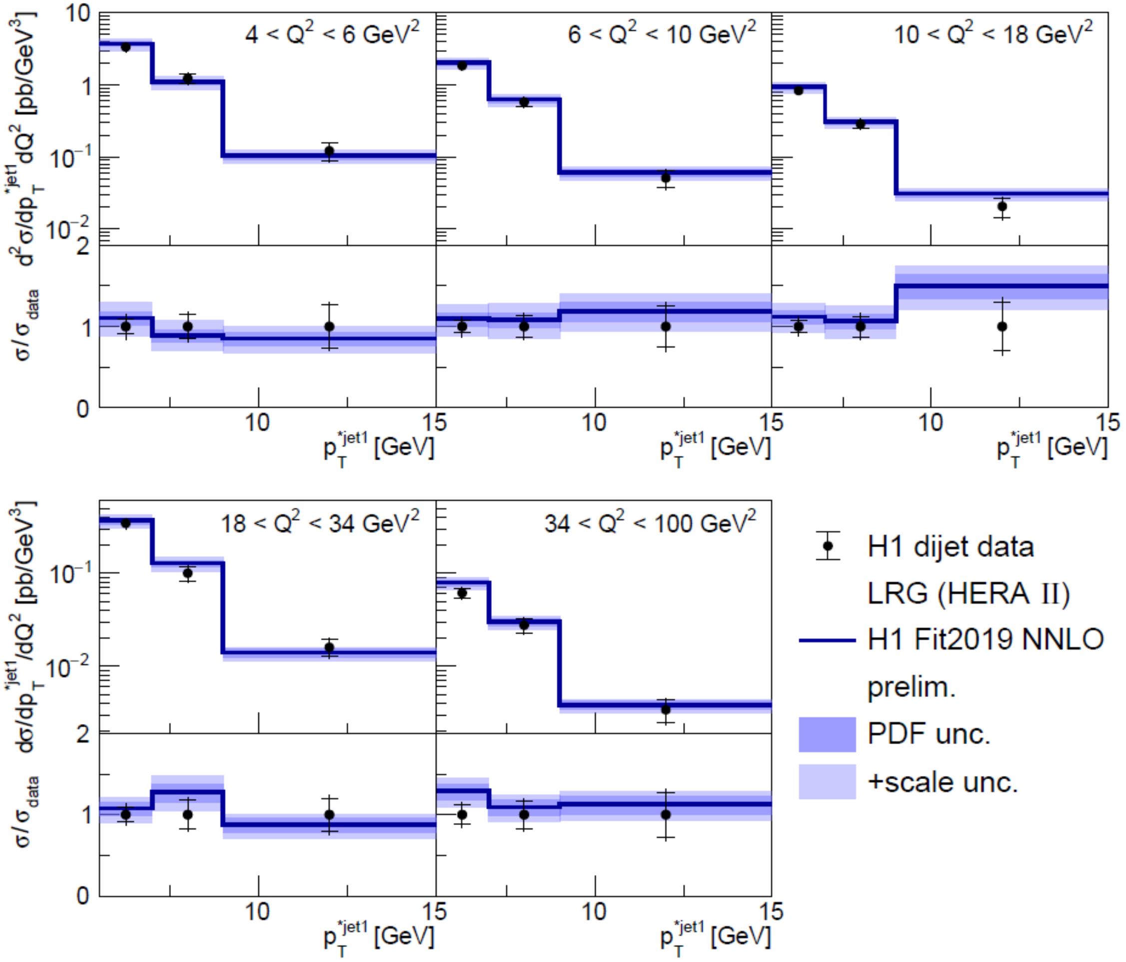
Nevertheless the gluon PDF in the Pomeron is dominant as found in previous DPDF analyses

Comparison of fit to inclusive DDIS data as a function of β and Q^2 for fixed x_P

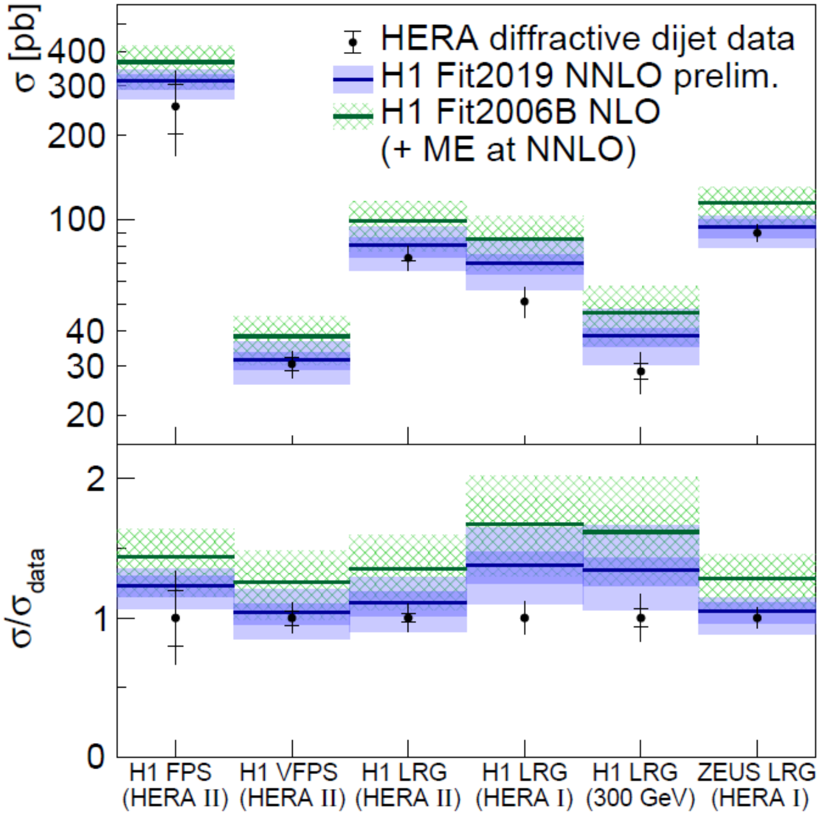




Comparison of fit to double differential dijet data



But the fit can also be used to predict cross sections for diffractive jet production which are not inputs to the fit



The NLO PDF overpredicts these cross sections

Many more data/fit comparisons in H1-prelim-19-013

Summary

The HERAPDF2.0 family is completed 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 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

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

Scale uncertainty is reduced and there is a shift of $\alpha_s(M_Z)$ downwards at NNLO even taking scale variation into account

Diffractive parton distributions DPDFs are extracted at NNLO for the first time

The NNLO DPDF has a lower gluon compared to the NLO analysis

Jet data are well fitted together with the inclusive data- -factorisation works

Predictions for other HERA diffractive jet cross sections are very successful- unlike at NLO

Backup

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 $\alpha_s(M_Z)$.

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:

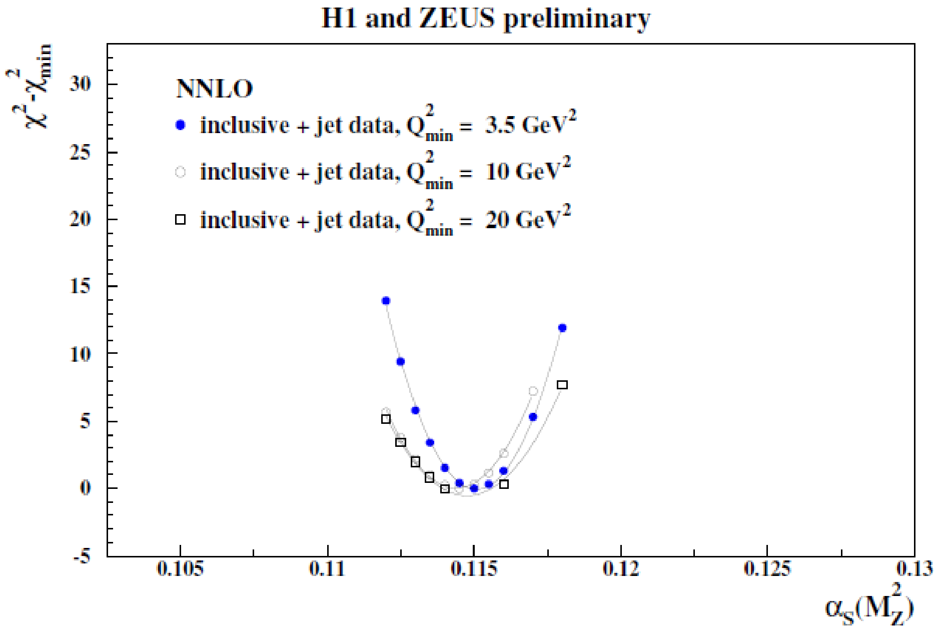
$$\alpha_s(M_Z)=0.1150 \pm 0.0008_{(exp)} {}^{+0.0002}_{-0.0005(model/param)} \pm 0.0006_{(had)} \pm 0.0027_{(scale)}$$

$\chi2$=1598.5 for free $\alpha_s(M_Z)$ fit, using1343 data points, 1328 degrees of freedom
$\chi2$/d.o.f =1.203

$\chi2$=1601.3 for fixed $\alpha_s(M_Z)$=0.118 fit, using1343 data points, 1329 degrees of freedom
$\chi2$/d.o.f =1.205

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

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 scans with Q^2 cuts



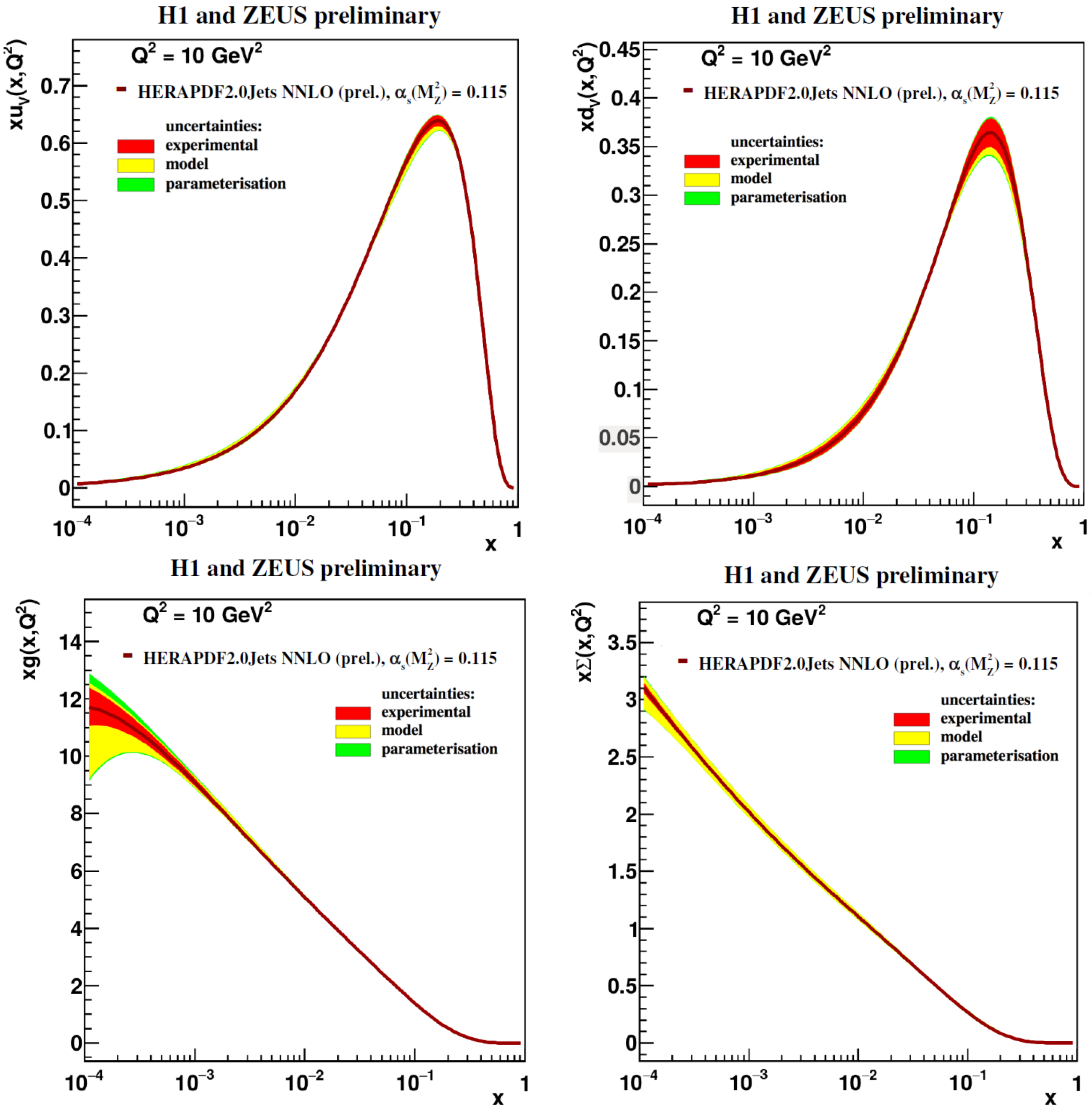
The Q2 cuts do not result in any significant change to the value of $\alpha_s(M_Z)$ that is determined

The central values from the three scans are:

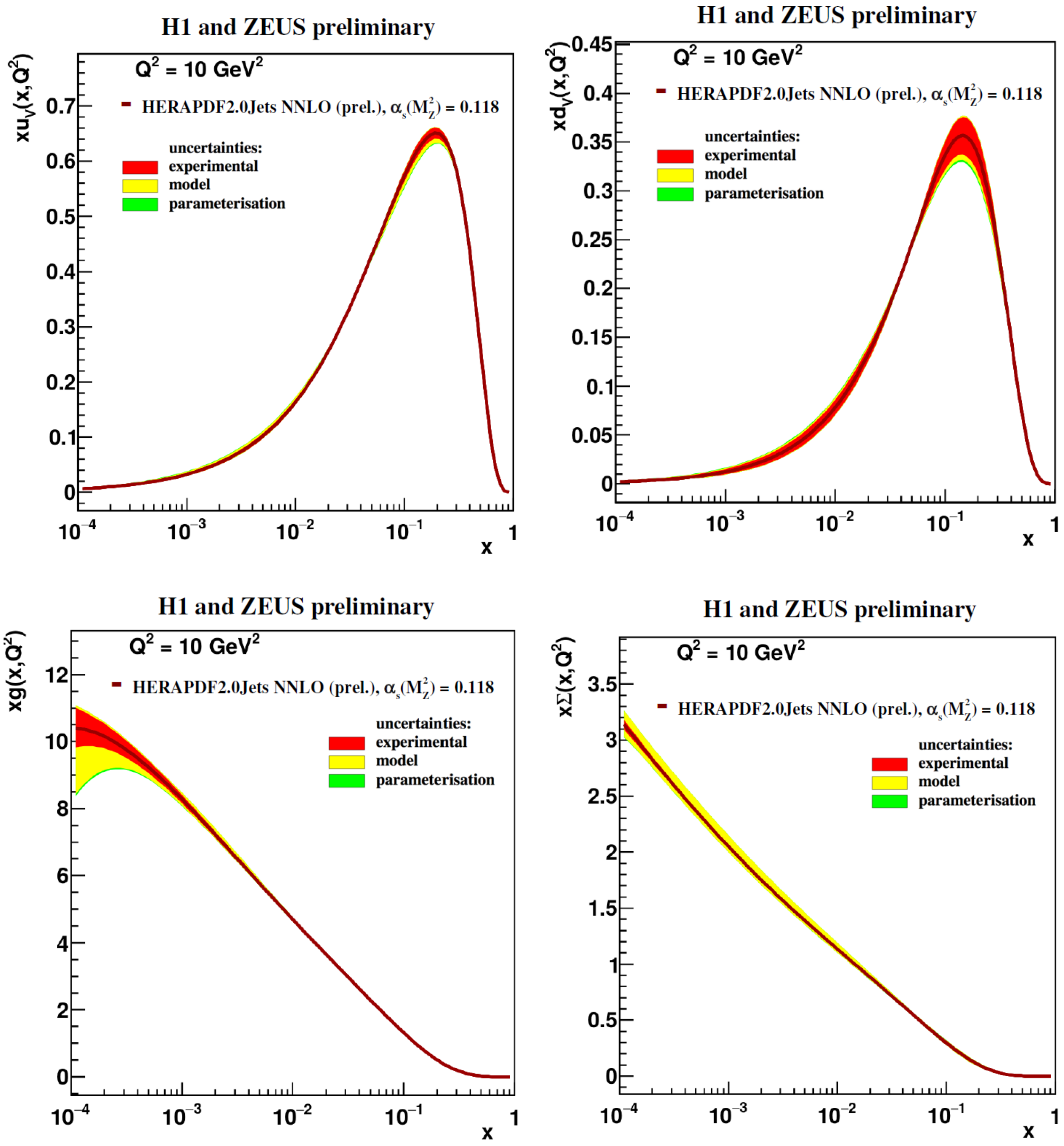
$\alpha_s(M_Z) = 0.1150 \pm 0.0008$ Q^2>3.5 GeV^2
$\alpha_s(M_Z) = 0.1144 \pm 0.0010$ Q^2>10 GeV^2
$\alpha_s(M_Z) = 0.1148 \pm 0.0010$ Q^2>20 GeV^2

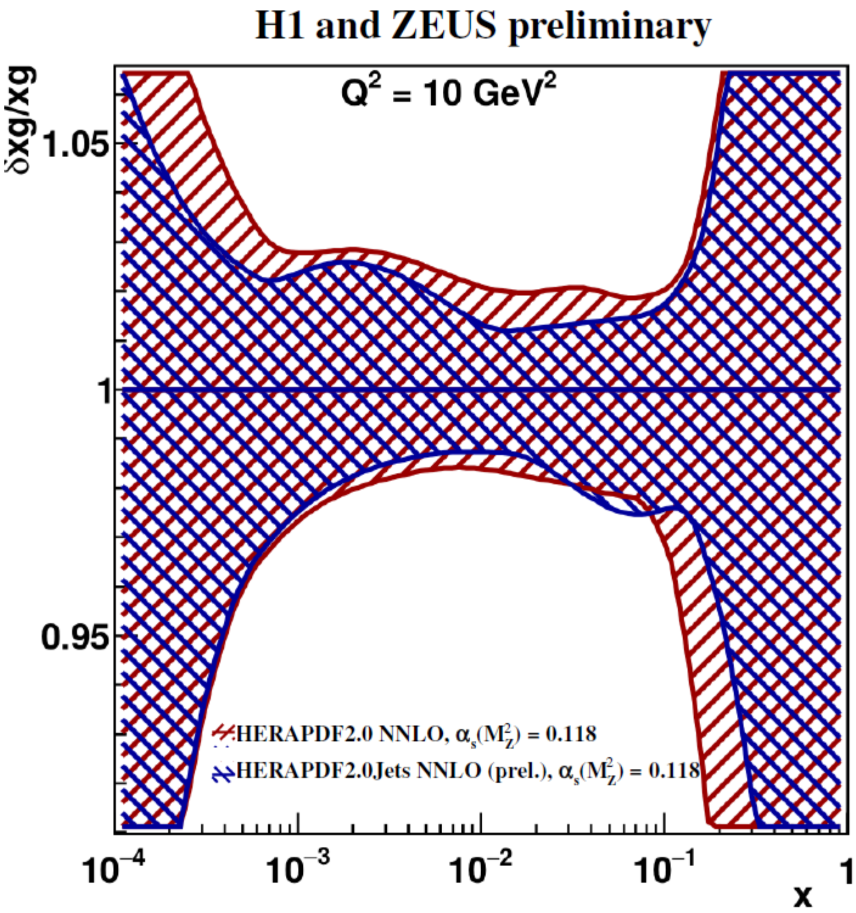
Now for the PDFs

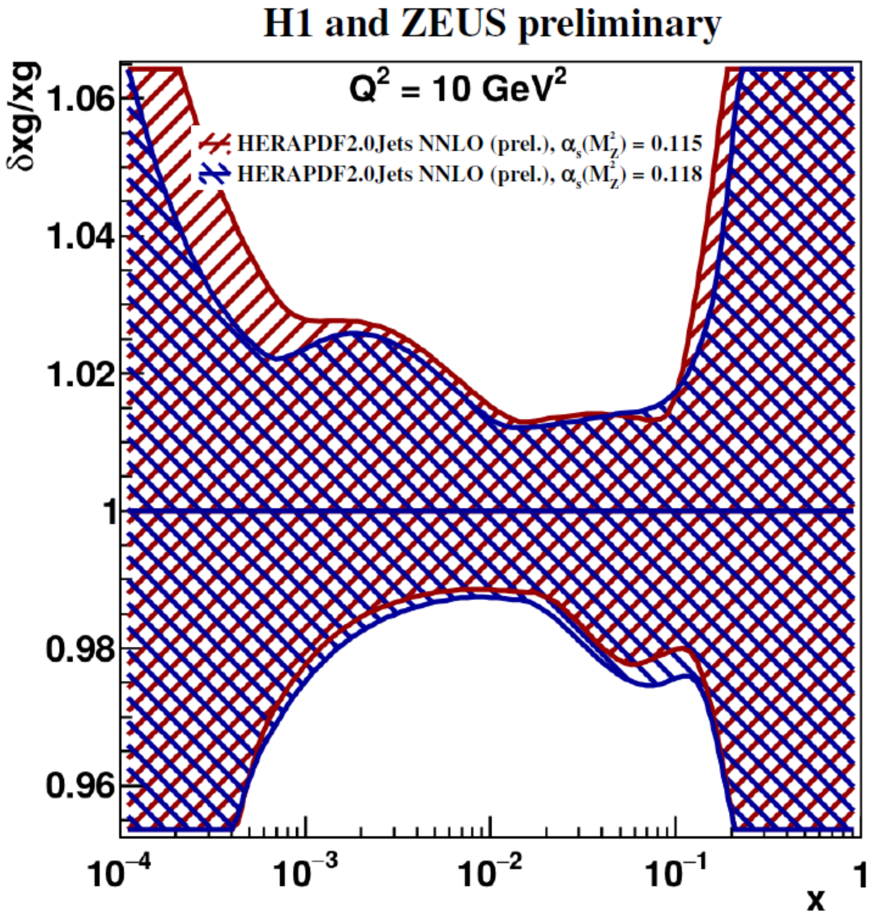
$\alpha_s(M_Z) = 0.115$



$\alpha_s(M_Z)$ =0.118



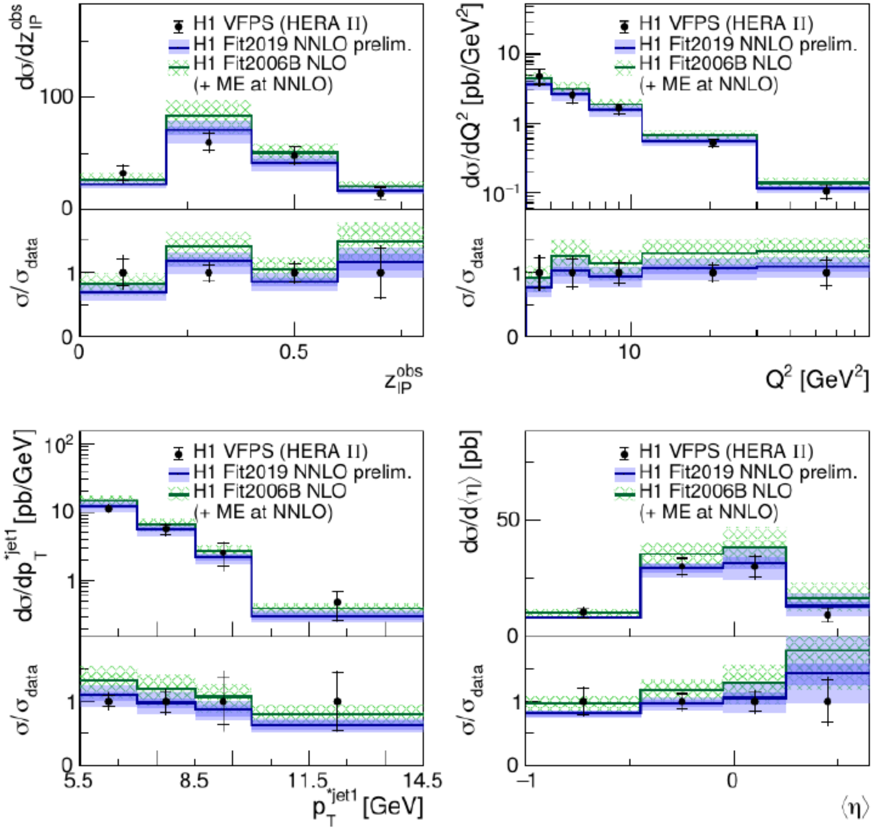

H1 and ZEUS preliminary
Q^2 = 10 GeV^2
δxg/xg
1.05
1
0.95
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x
HERAPDF2.0 NNLO, $\alpha_s(M_Z^2)$ = 0.118
HERAPDF2.0Jets NNLO (prel.), $\alpha_s(M_Z^2)$ = 0.118


H1 and ZEUS preliminary
Q^2 = 10 GeV^2
δxg/xg
1.06
1.04
1.02
1
0.98
0.96
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x
HERAPDF2.0Jets NNLO (prel.), $\alpha_s(M_Z^2)$ = 0.115
HERAPDF2.0Jets NNLO (prel.), $\alpha_s(M_Z^2)$ = 0.118

Data set	process	χ^2/n_{data}
H1comb-LRG	inclusive NC DDIS	$192/191$
H1-LowE-225	inclusive NC DDIS	$19/12$
H1-LowE-252	inclusive NC DDIS	$10/13$
H1 LRG (HERA 2)	dijet production	$12/15$
all		$235/231$
		$[n_{\mathrm{dof}} = 223]$

Dijet cross sections (H1 VFPS)

- The data based on Very Forward Proton Spectrometer (VFPS) do not contain any proton dissociation and are in many ways systematically independent to the LRG-based data
- Good description of the kinematic variables z_{IP}, Q^2, p_T^{jet1}, $<\eta>$



Dijet cross sections (ZEUS LRG)

- The H1 Fit2019 NNLO based predictions agree well with the ZEUS dijet data [arXiv:0708.1415]

- At LO the $z_{I\!P}^{\mathrm{obs}}$ directly related to the pomeron momentum fraction entering ME

$$z_{I\!P}^{\mathrm{obs}} = \frac{Q^2 + M_{12}^2}{Q^2 + M_X^2}$$