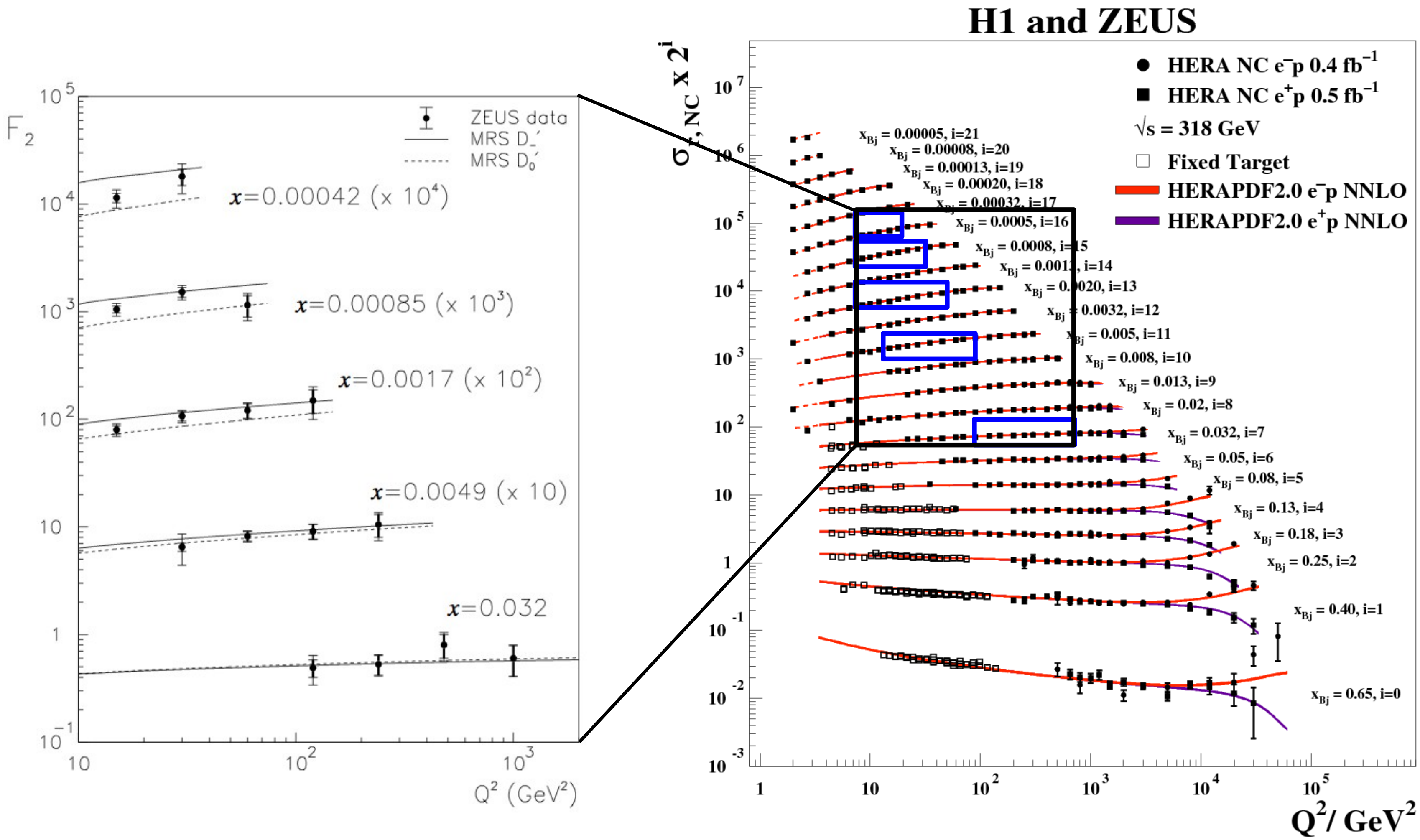
News on HERA proton structure and prospects from EIC

K. Wichmann @EPI23

DIS @ HERA

First: 1993 → Final: 2015



2007: HERA shutdown

→ 15th anniversary of start, 30th anniversary of end

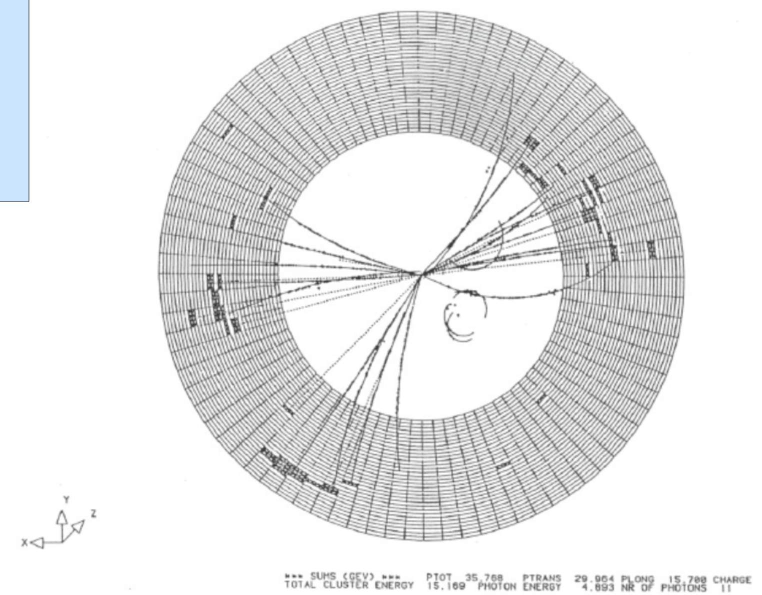
I'm still standing

Jets produced @ DESY for almost 45 years

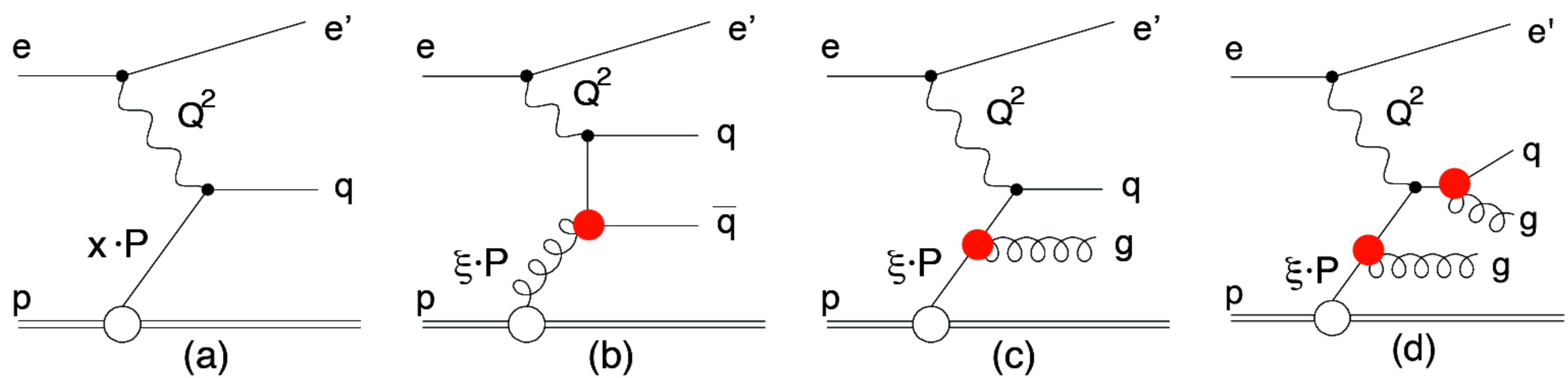
At HERA direct information on gluon and $\alpha_s(M_Z)$ comes from jet production

→ Possible simultaneous determination of parton densities and $\alpha_s(M_Z)$

Jets at PETRA, 1979



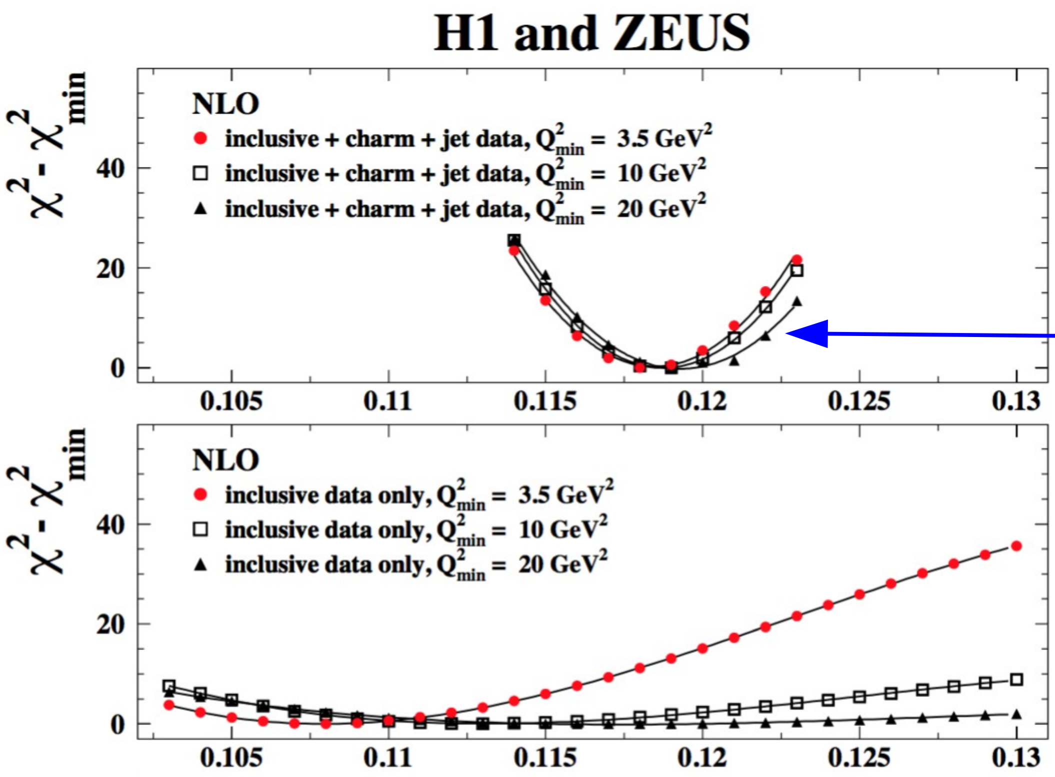
Jets at HERA



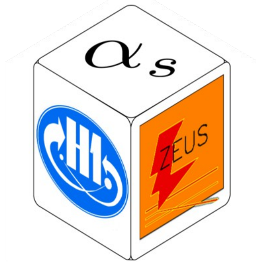
elweak coupling $\propto \alpha_S$ $\propto \alpha_S$ $\propto \alpha_S^2$

dijets trijets

Why study jets @ HERA?



- HERA inclusive data carry little information on $\alpha_s(M_Z)$
- Jet data sensitive to $\alpha_s(M_Z)$



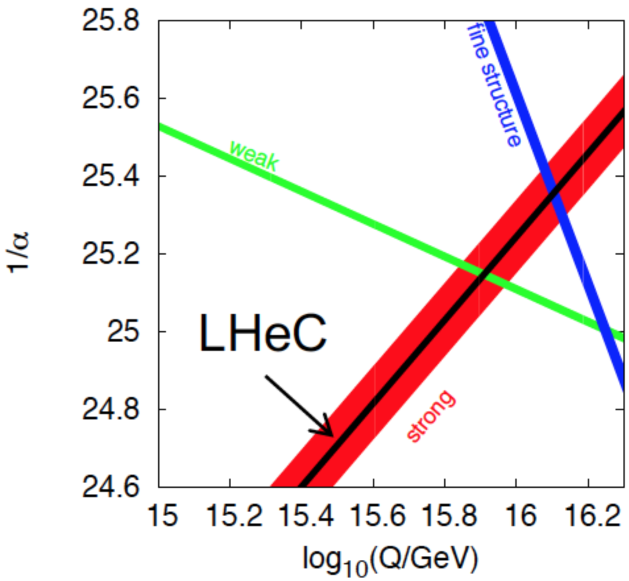
New NNLO calculations for HERA ep jet production available now

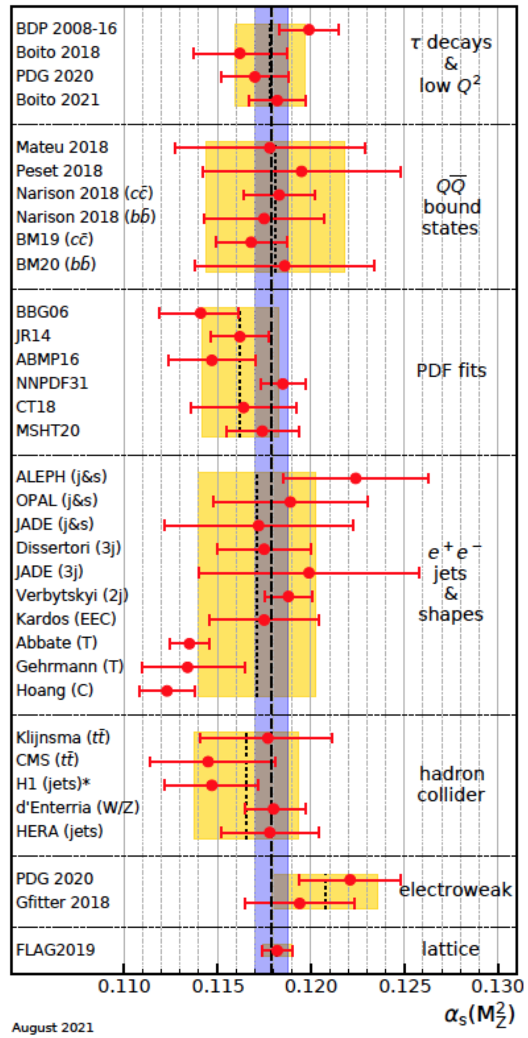
- Implemented in FastNLO and APPLEGRID → fast cross section calculation possible

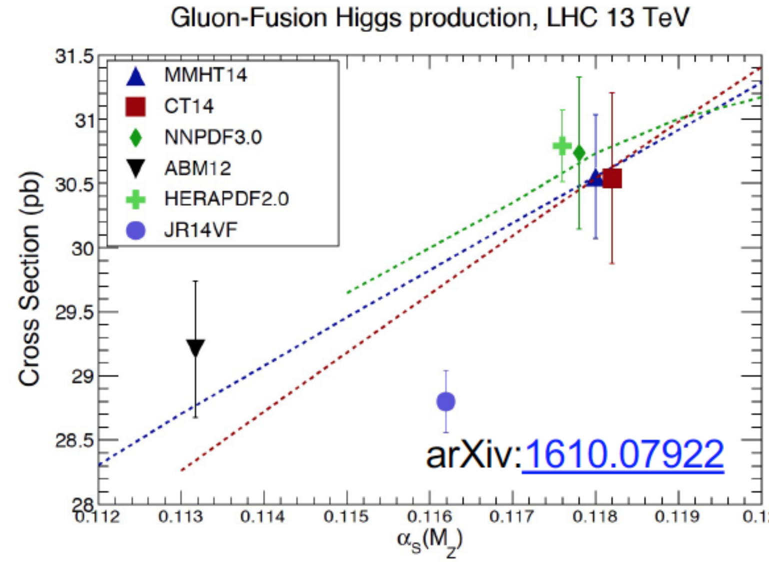
EPJ C 82, 243 (2022) arXiv:2112.01120

→ **Possible simultaneous determination of PDFs and $\alpha_s(M_Z)$ at NNLO**

Why look at α_s ?







- **αs** is least known coupling constant;

  needed to constrain GUT scenarios; cross section predictions, including Higgs; …

- **PDFs** and/or **αs** limit: precision SM and Higgs measurements, BSM searches, …

PDG21: αs = 0.1175 ± 0.0010 (w/o lattice)

- what is true **αs** central value and uncertainty?

  new precise determinations have important role to play

HERA jet data used in NNLO PDF fit

EPJC C82 (2022) 243

- Inclusive jets and dijets included
- Trijets from HERAPDF2Jets NLO excluded → no NNLO predictions
- H1 low Q^2 data added – particularly sensitive to $\alpha_s(M_Z)$
- Some data points excluded due theory limitations
  - Data at low scale $\mu = (pt^2 + Q^2) < 10$ GeV → scale variations are large (~25% NLO and ~10% NNLO)
  - 6 ZEUS dijet data points at low pt for which predictions are not truly NNLO

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
H1 HERA I normalised jets	1999 – 2000	150	15000	65.4	e^+p	319	yes	24	24
H1 HERA I jets at low Q^2	1999 – 2000	5	100	43.5	e^+p	319	no	28	20
H1 normalised inclusive jets at high Q^2	2003 – 2007	150	15000	351	e^+p/e^-p	319	yes	30	30
H1 normalised dijets at high Q^2	2003 – 2007	150	15000	351	e^+p/e^-p	319	yes	24	24
H1 normalised inclusive jets at low Q^2	2005 – 2007	5.5	80	290	e^+p/e^-p	319	yes	48	37
H1 normalised dijets at low Q^2	2005 – 2007	5.5	80	290	e^+p/e^-p	319	yes	48	37
ZEUS inclusive jets	1996 – 1997	125	10000	38.6	e^+p	301	no	30	30
ZEUS dijets 1998 –2000 &	2004 – 2007	125	20000	374	e^+p/e^-p	318	no	22	16

- QCD PDF fit with jet data
  - → With fixed $\alpha_s(M_Z)$
  - → With free $\alpha_s(M_Z)$ or doing $\alpha_s(M_Z)$ scan → **$\alpha_s(M_Z)$ value**

HERAPDF2.0 parameterisation

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

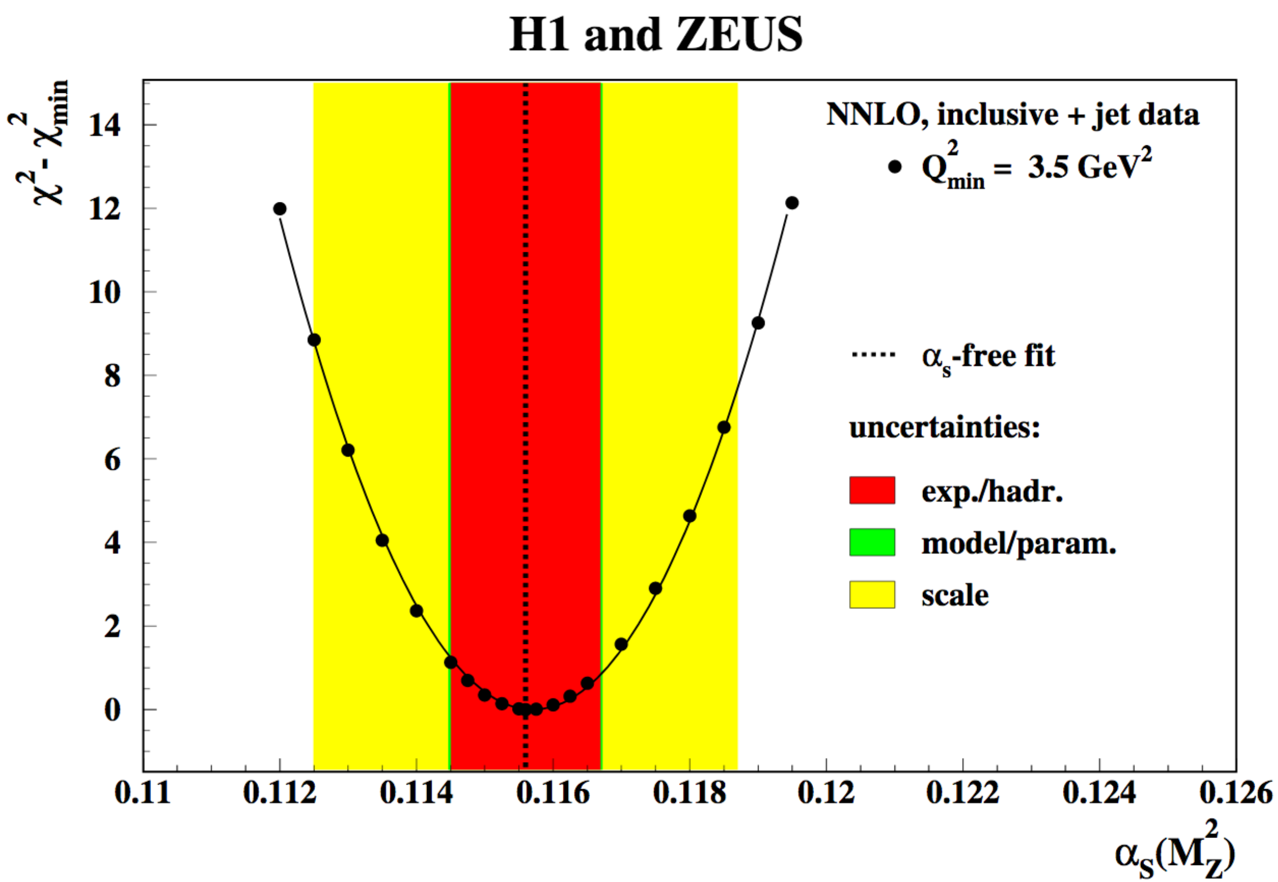
$$\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x), \\
x\bar{D}(x)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

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

α_s @ NNLO from HERA jets

• $\alpha_s(M_Z)$ determined with experimental, model, param. and hadr. uncertainties

• In fits with free $\alpha_s(M_Z)$ scale uncertainty important → calculated as 100% correlated between bins and data sets



$$\alpha_s(M_Z^2) = 0.1156 \pm 0.0011\,(\text{exp})\ {}^{+0.0001}_{-0.0002}\,(\text{model + parameterisation})$$
$$\pm\, 0.0029\,(\text{scale})$$

Comparison to other HERAPDF2.0 fits

- For previous NLO results scale uncertainty applied as 50% correlated and 50% uncorrelated between bins and data sets (due to inclusion of HQ and trijet data)
- Using the precious procedure at NNLO:

NNLO

$$\alpha_s(M_Z^2) = 0.1156 \pm 0.0011\ (\text{exp})\ {}^{+0.0001}_{-0.0002}\ (\text{model} + \text{parameterisation})$$

$$\pm 0.0022$$

HERAPDF2.0Jets NLO

$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0009(\text{exp}) \pm 0.0005(\text{model/parameterisation}) \pm 0.0012(\text{hadronisation})\ {}^{+0.0037}_{-0.0030}(\text{scale})\,.$$

Scale uncertainties reduced
→ as expected for NNLO calculations

comparison to other HERA DIS results

1. **H1** NNLO jet study using fixed PDFs, includes H1 inclusive-jet and di-jet:

H1 jets	$\mu > 2m_b$	$0.1170\ (9)_{\text{exp}}\ (7)_{\text{had}}\ (5)_{\text{PDF}}\ (4)_{\text{PDF}\alpha_s}\ (2)_{\text{PDFset}}\ (38)_{\text{scale}}$

with similar breakup of uncertainties and similar μ, new HERA result:

$$\alpha_s(M_Z^2) = 0.1156 \pm 0.0011\,(\text{exp+had+PDF})\ {}^{+0.0001}_{-0.0002}\ (\text{model + parameterisation})\ \pm 0.0029\ (\text{scale})$$

H1 also provided a **PDF+αs** fit to H1 inclusive and jet data

$$0.1147\ (11)_{\text{exp,NP,PDF}}\ (2)_{\text{mod}}\ (3)_{\text{par}}\ (23)_{\text{scale}}$$

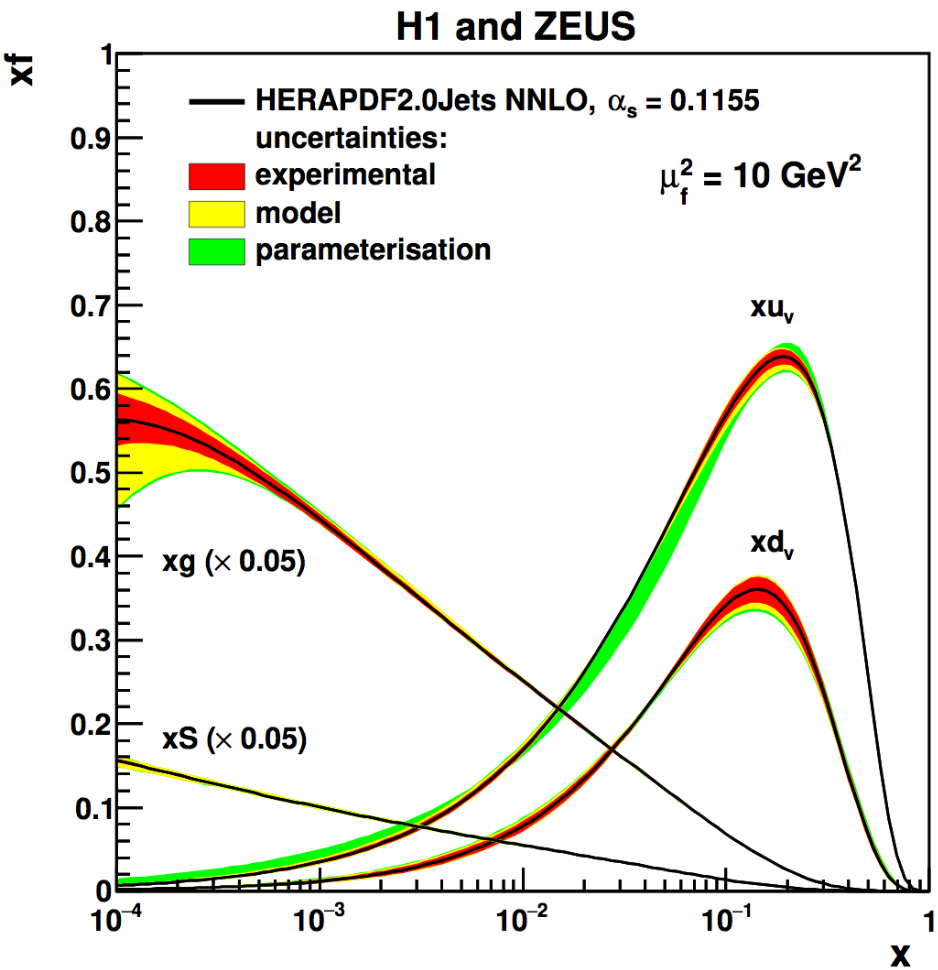
analysis required $Q^2 > \mathbf{10}\,\text{GeV}^2$; NEW HERA result re-evaluated with this cut (rather than $>\mathbf{3.5}\,\text{GeV}^2$), is:

$$\alpha_s(M_Z^2) = \boxed{0.1156} \pm 0.0011\ (\text{exp}) \pm 0.0002\ (\text{model + parameterisation}) \pm \boxed{0.0021\ (\text{scale})}$$

2. **NNLOJet+APPLfast** using fixed PDFs, includes H1+ZEUS inclusive-jet:

HERA inclusive jets	$\mu > 2m_b$	$0.1171\ (9)_{\text{exp}}\ (5)_{\text{had}}\ (4)_{\text{PDF}}\ (3)_{\text{PDF}\alpha_s}\ (2)_{\text{PDFset}}\ (33)_{\text{scale}}$

Fit with fixed $\alpha_s = 0.1155$



- **Experimental uncertainties:**
  - Hessian method
  - Conventional $\Delta\chi^2 = 1 \rightarrow 68\%$ CL

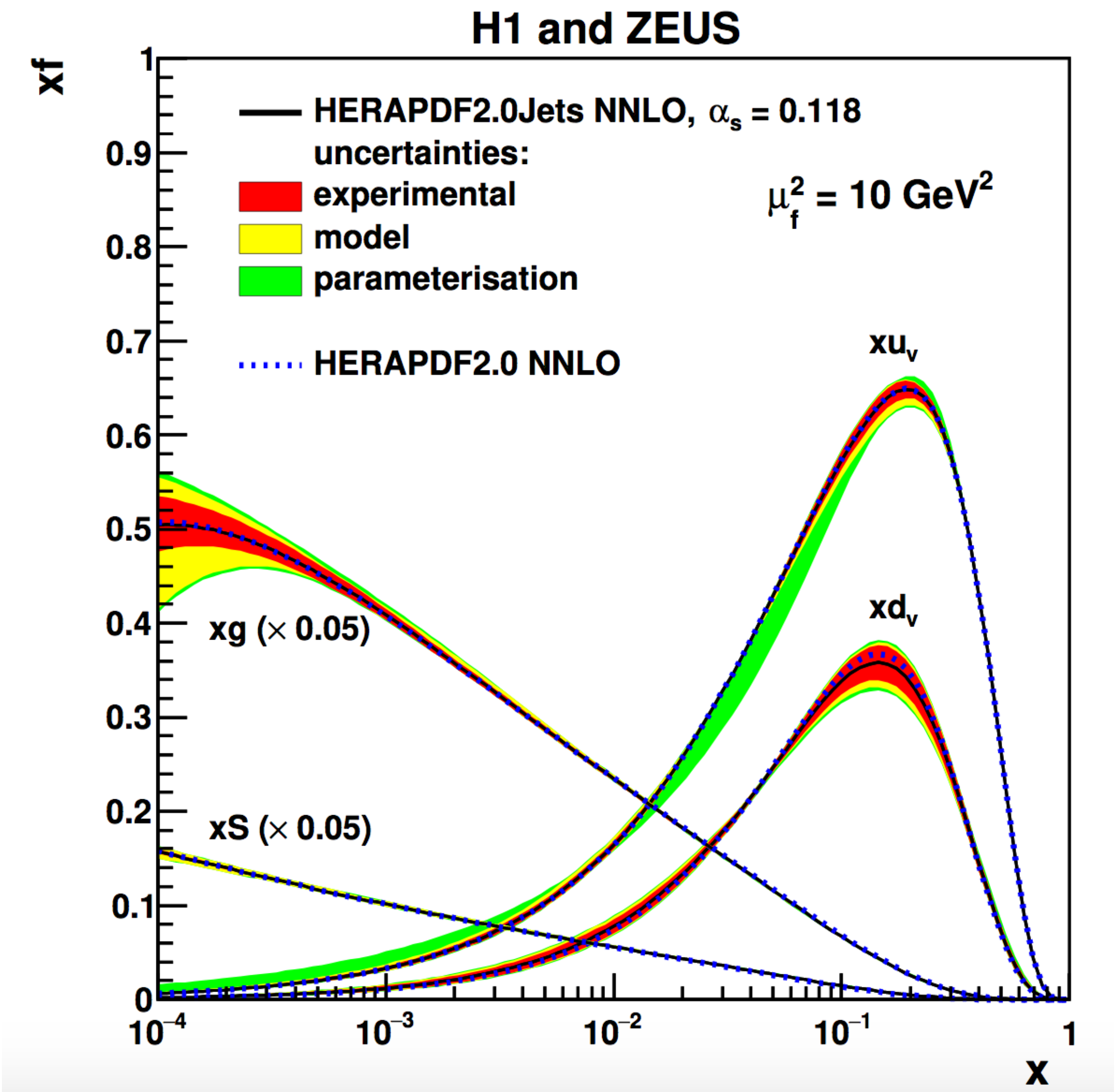
Parameter	Central value	Downwards variation	Upwards variation
Q^2_{min} [GeV^2]	3.5	2.5	5.0
f_s	0.4	0.3	0.5
M_c [GeV]	1.41	1.37*	1.45
M_b [GeV]	4.20	4.10	4.30
μ^2_{f0} [GeV^2]	1.9	1.6	2.2*

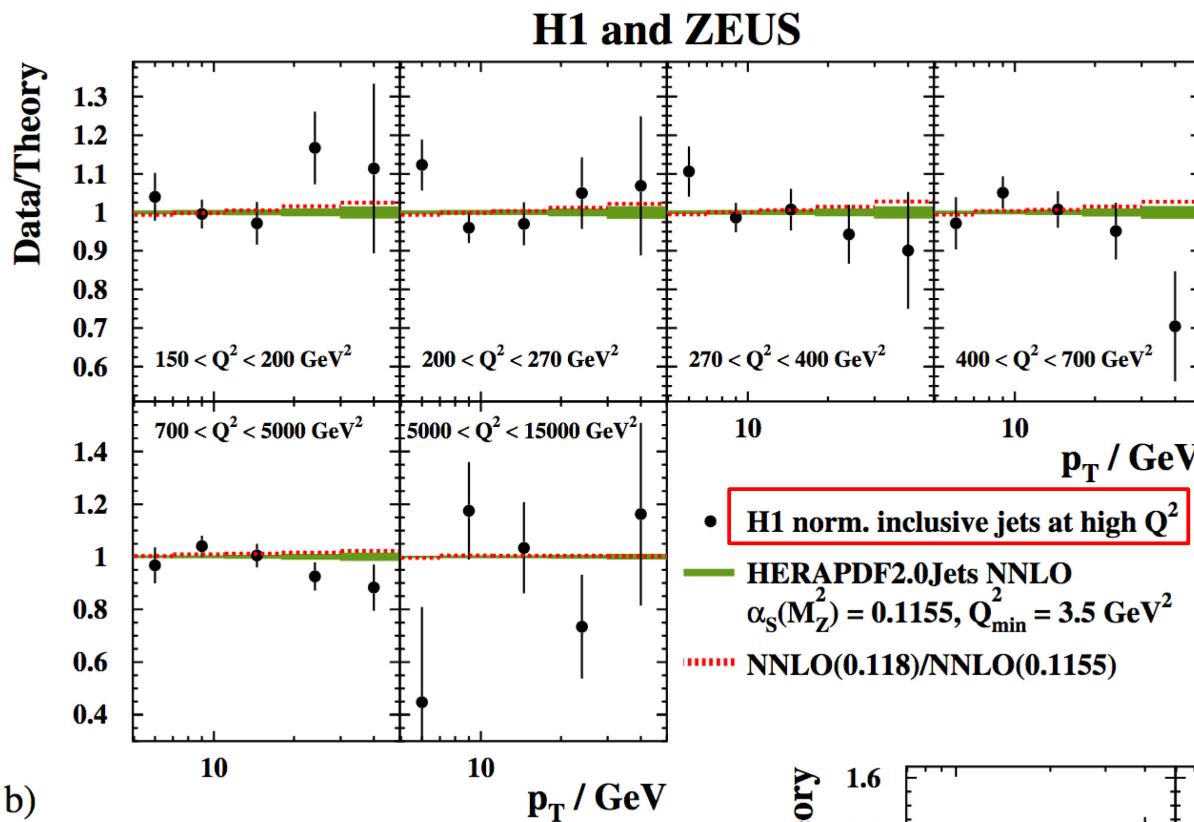
Adding D and E parameters to each PDF

- **Parametrisation uncertainties**
  - largest deviation
- **Model uncertainties**
  - all variations added in quadrature

Fit with fixed $\alpha_s = 0.118$

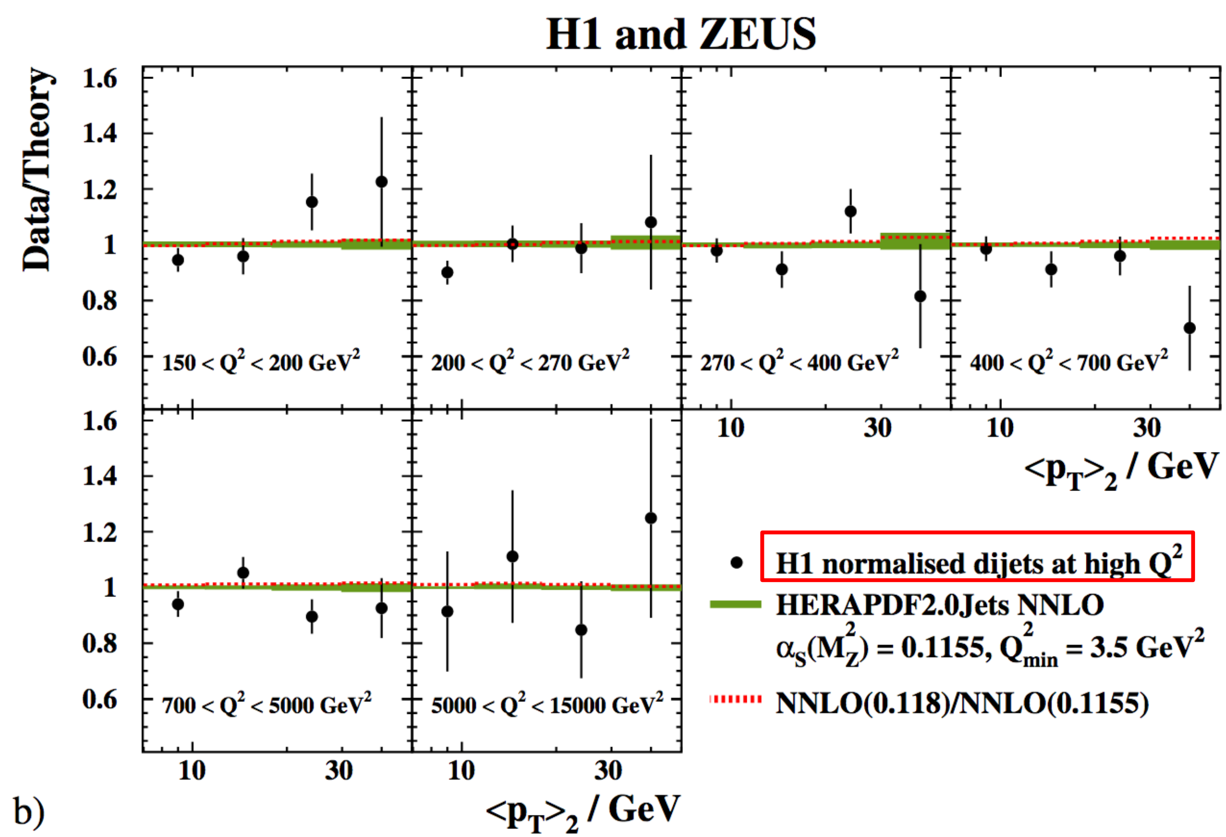
How does it compare to HERAPDF2.0? Well!



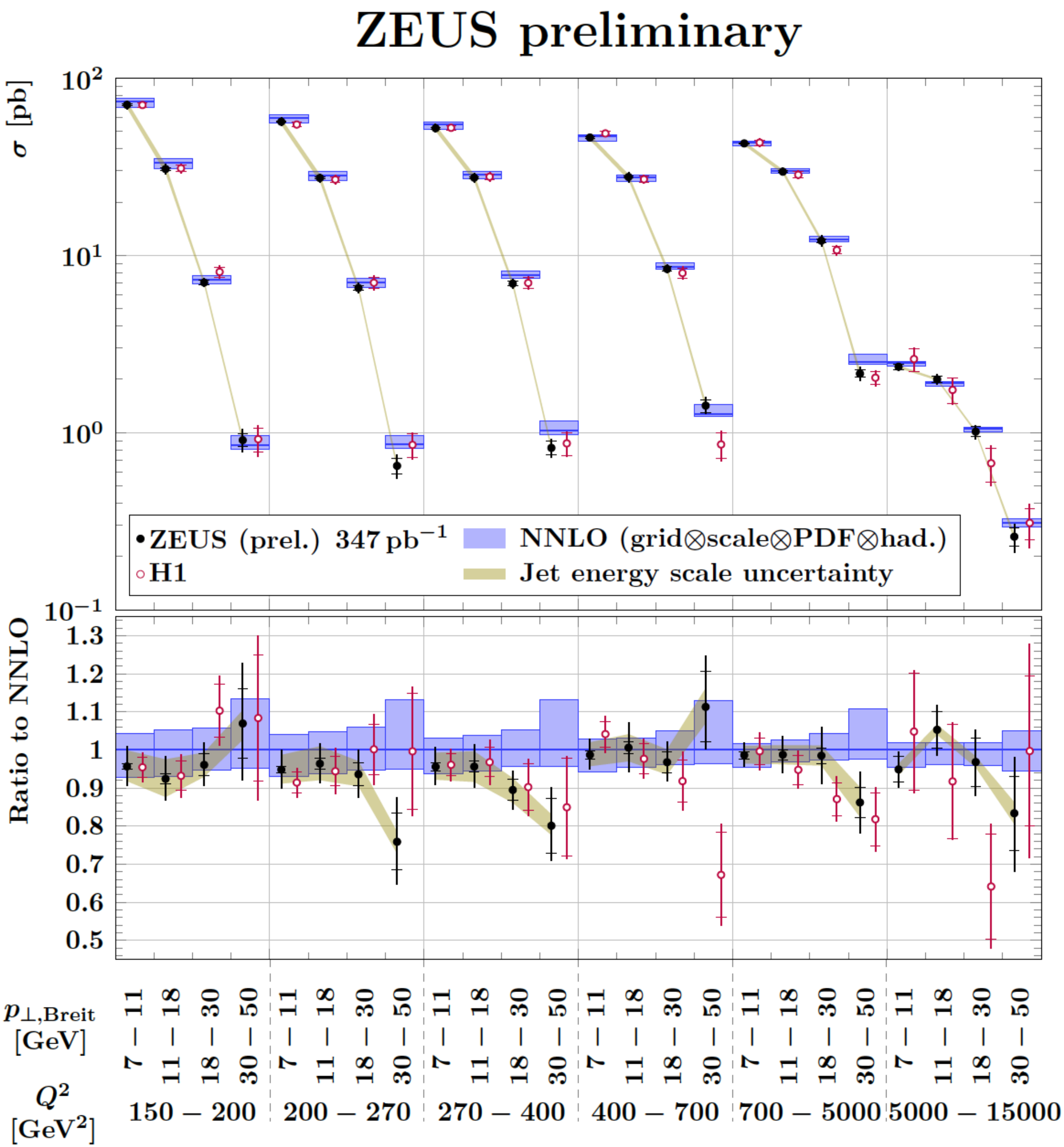


Comparison of theory predictions to H1 HERA II normalised jets @ high Q^2

→ good agreement for all data used in PDF fits



New ZEUS jet measurement



- New HERAII high-Q^2 inclusive jets results from ZEUS (15 years after shutdown)
- Phase-space and cuts identical to H1 high-Q^2 result → direct comparison possible

- Good agreement with H1 and with theory predictions → used in simultaneous PDF and α_s fit

ZEUS-prel-22-001

ZEUS-jets QCD fit @ NNLO

- Used jet data sets
  - HERAI ZEUS inclusive jets at high Q^2
  - HERAI+II ZEUS di-jets at high Q^2
  - *New HERAII ZEUS inclusive jets at high Q^2*

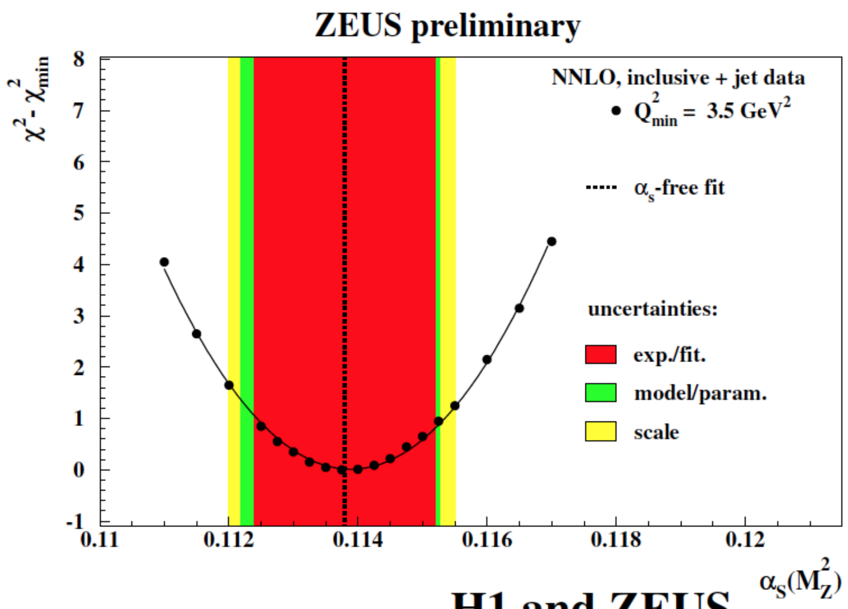
- Statistical correlations between ZEUS HERAII jet data sets taken into account via correlation matrix
- Fit method and settings follow exactly HERAPDF2 strategy

Results

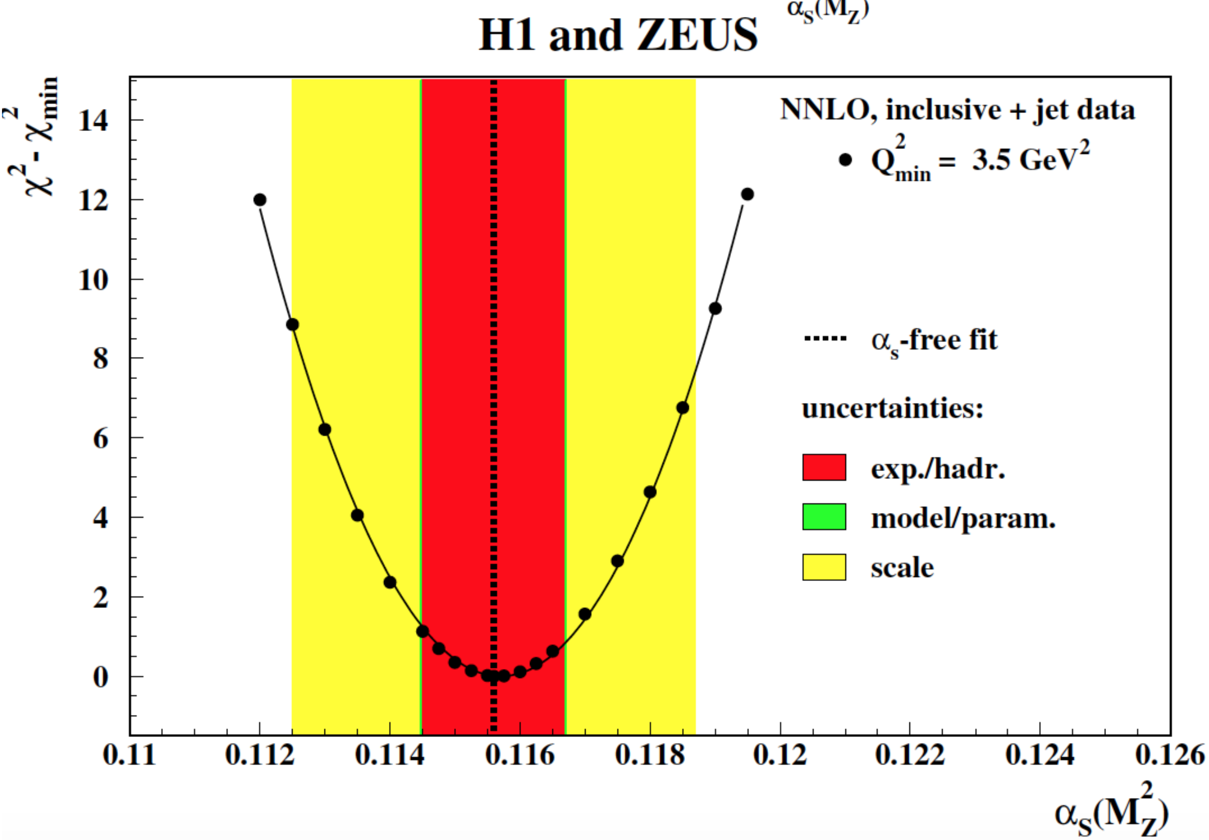
$$\alpha_s(M_Z^2) = 0.1138 \pm 0.0014 \text{ (exp/fit) } {}^{+0.0004}_{-0.0008} \text{ (model/parameterisation) } {}^{+0.0012}_{-0.0005} \textbf{ (scale)}$$

- *Note scale uncertainty!*

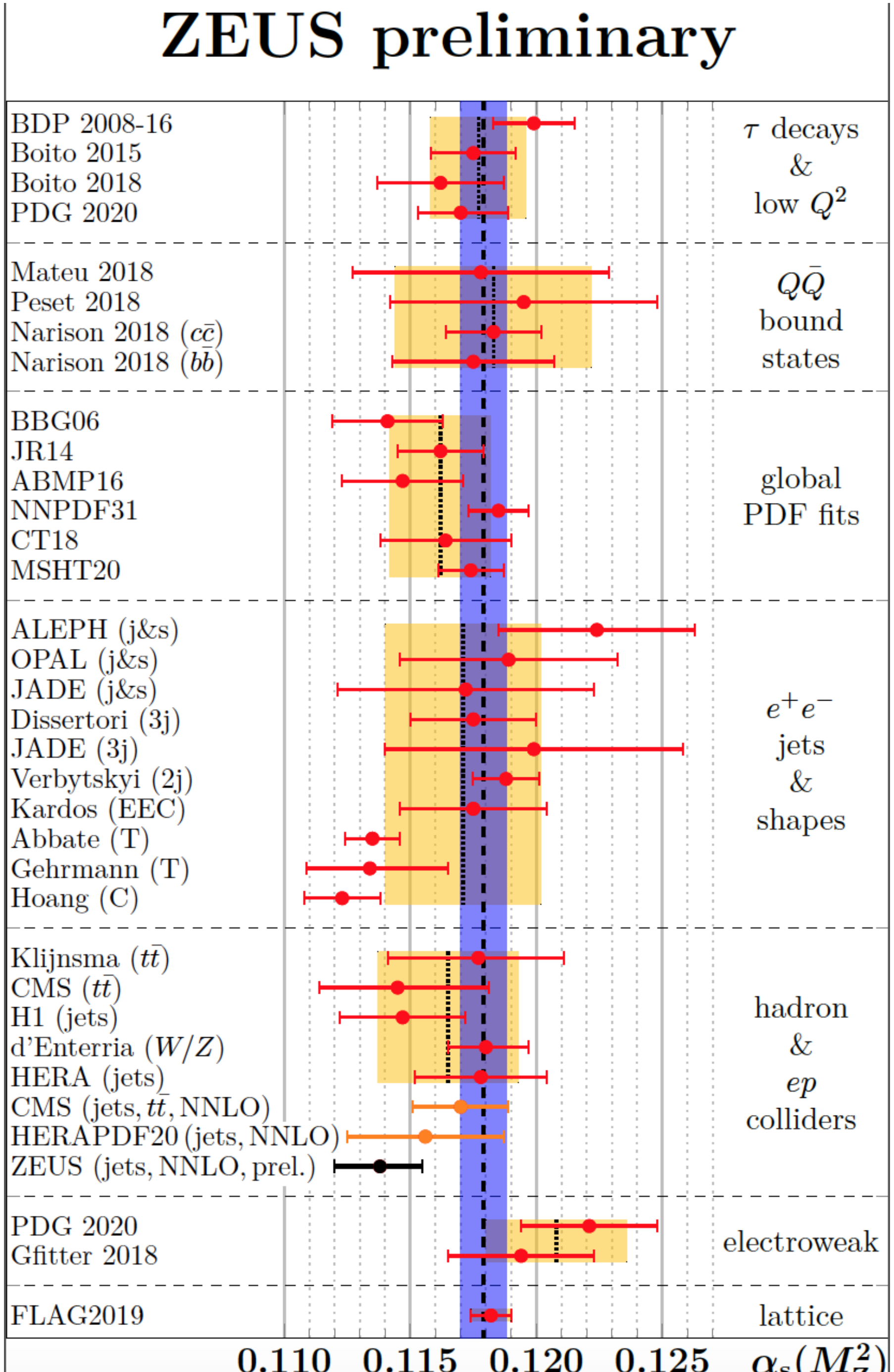
Comparison to HERAPDF2Jets NNLO



- Central value compatible with HERAPDF and with PDG world average
- Increased experimental uncertainty ← fewer jet datasets used



Significantly decreased scale uncertainty ← <u>absence of low Q2 jet data</u>



Conclusion

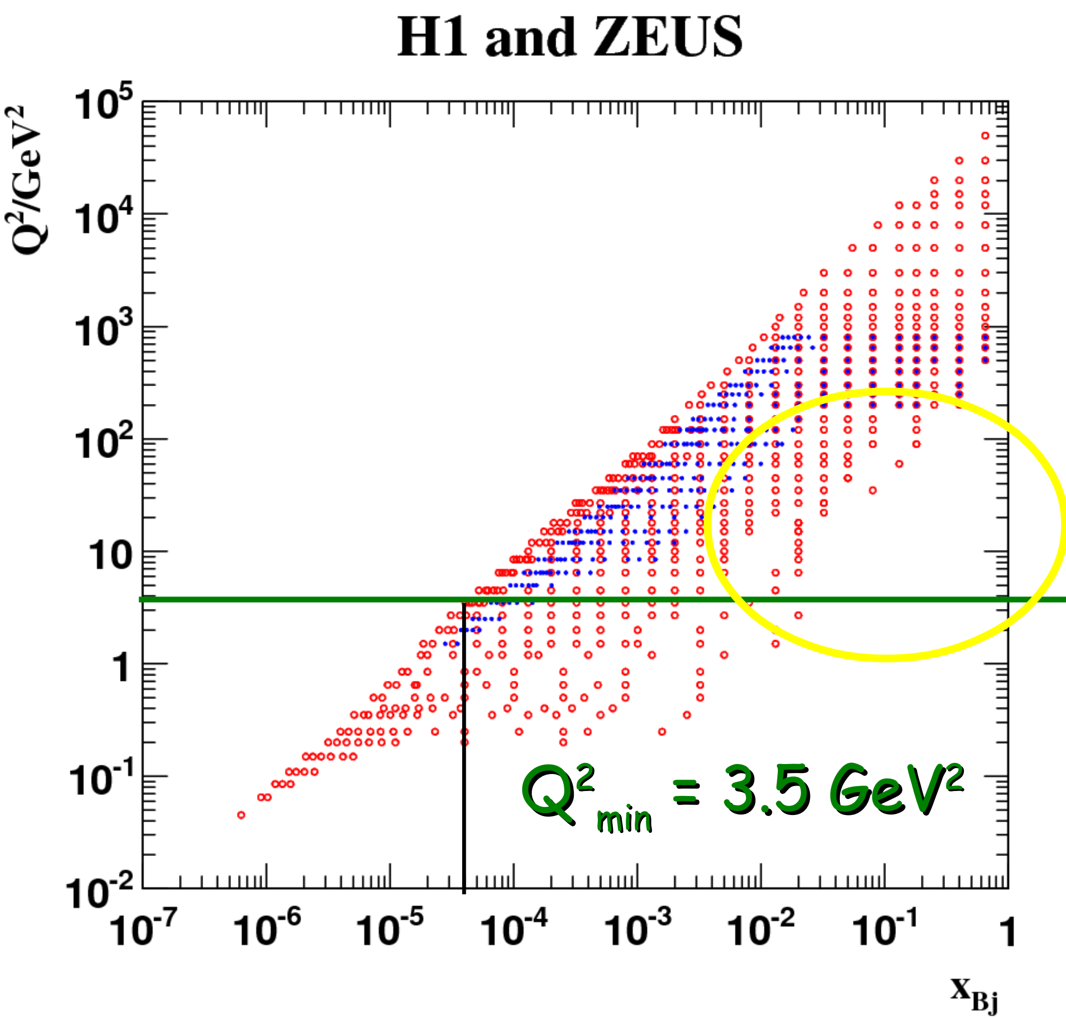
Reduced scale uncertainty →

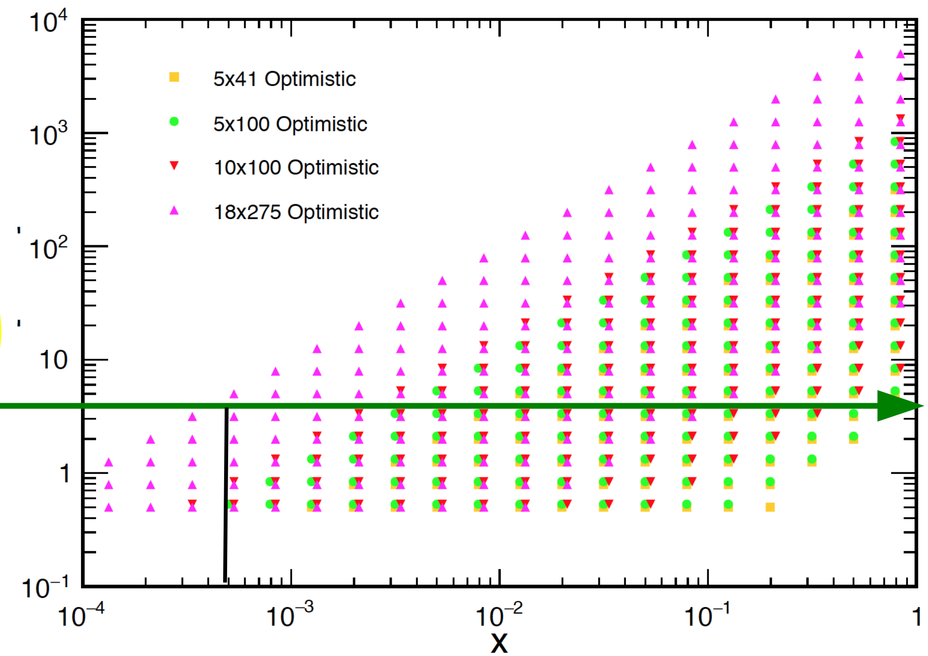
present analysis is one of the most precise measurements of $\alpha_s(M^2_Z)$ at hadron colliders so far†

†PTEP 2020, 8, 083C01 (2020)

New DIS data for PDFs:

HERA & ATHENA phase-space



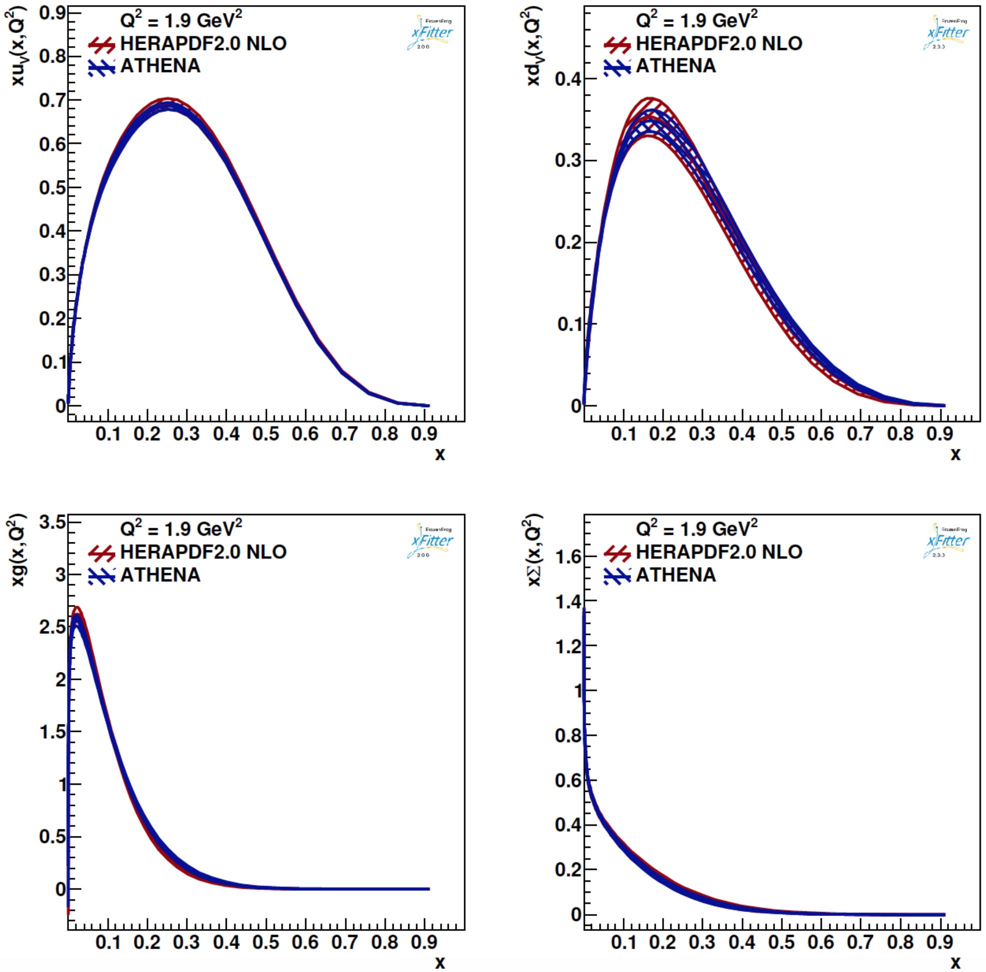


High-x region not covered by HERA → impact on high-x PDFs expected

HERAPDF philosophy: get PDFs with HERA data only → start with that

Fits with ATHENA pseudo-data

- ATHENA pseudo-data created using HERAPDF2 NLO
  → NC: 5 centre-of-mass energies
  → CC: only highest energy so far
  → "realistic" uncertainties estimation
- PDF fits "HERAPDF2-style" with DIS and DIS+EIC data

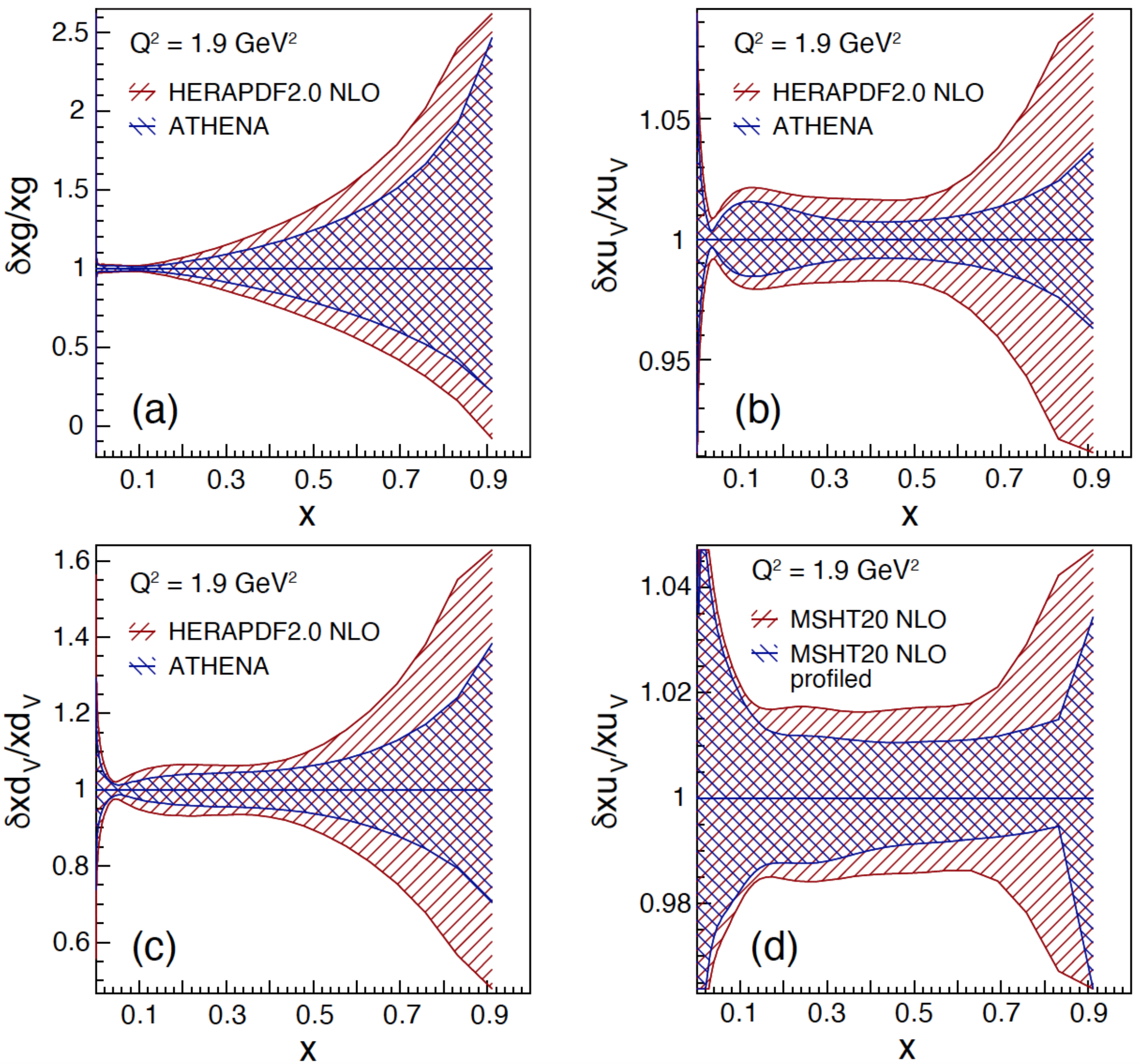


By design:

- Parton distributions agree very well

→ comparison of uncertainties crucial

Impact of EIC data on proton PDF



As expected for DIS-only fits:

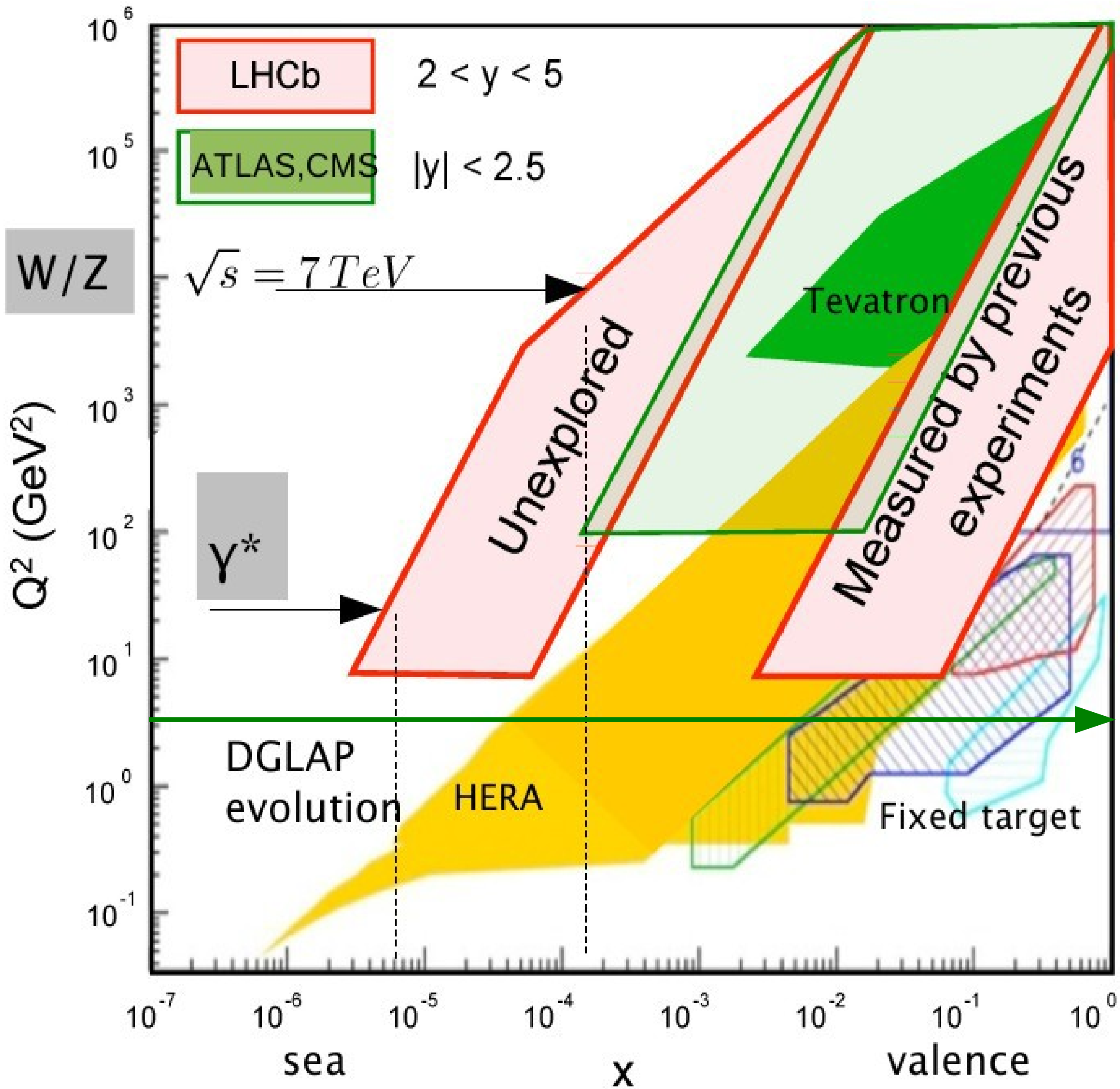
- Dramatic improvement of valence quarks at large x
- Improvement also for gluons/sea

For global fits:

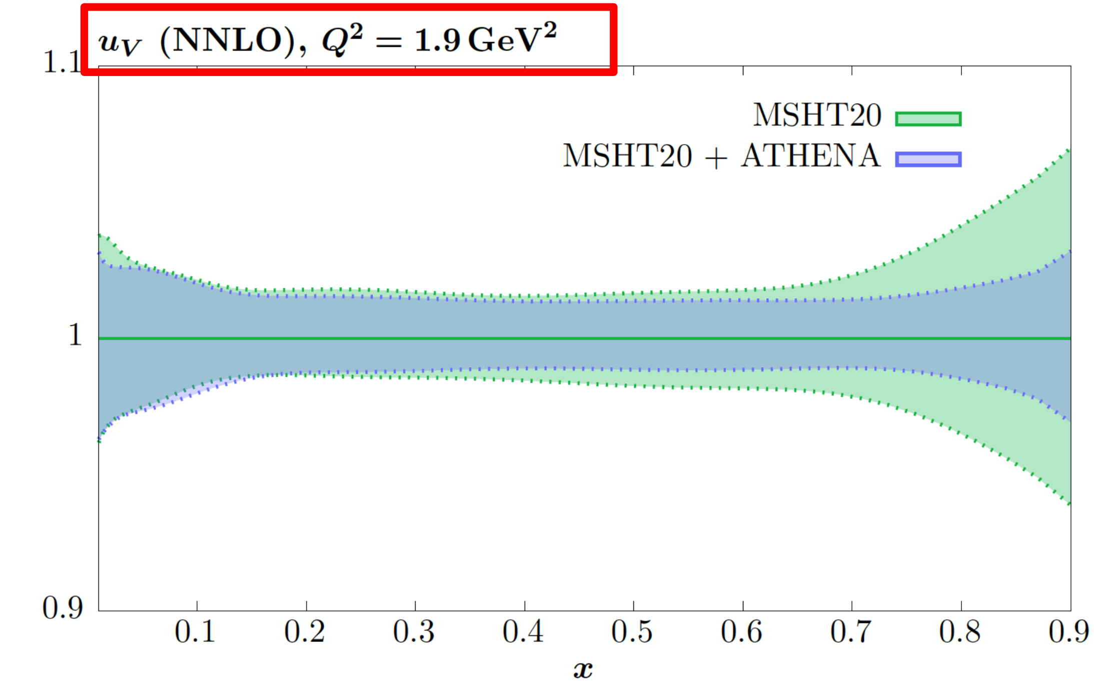
- Improvement smaller but clearly visible
- Done using profiling method → let's look at full fits

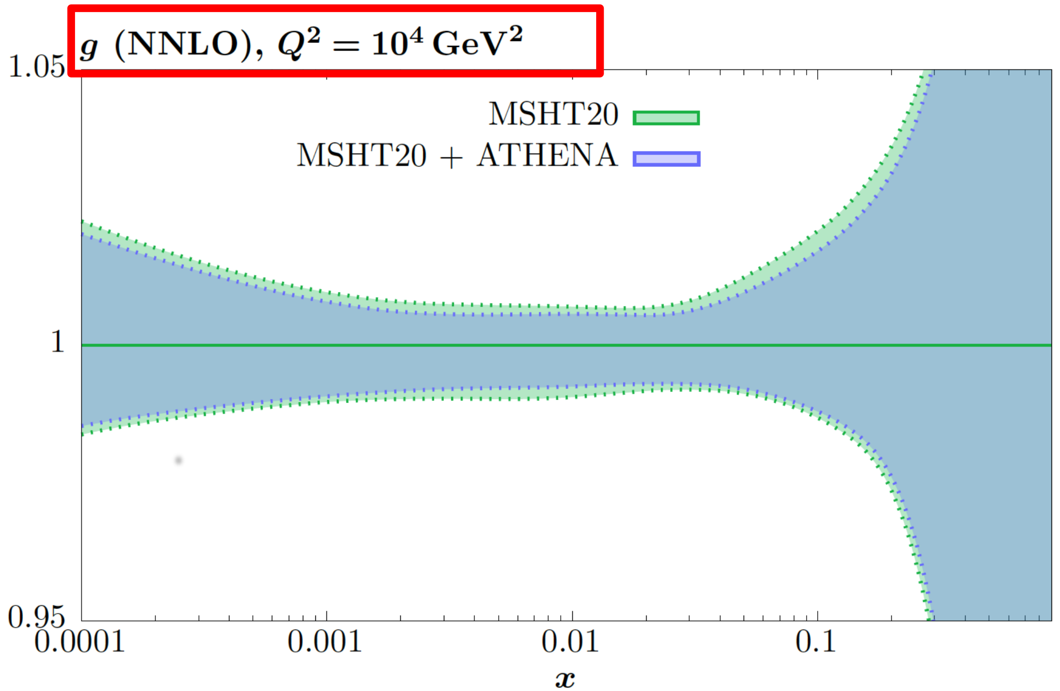
arxiv:1606.01736

Various data in other PDF sets



Impact of EIC data on global fits @NNLO

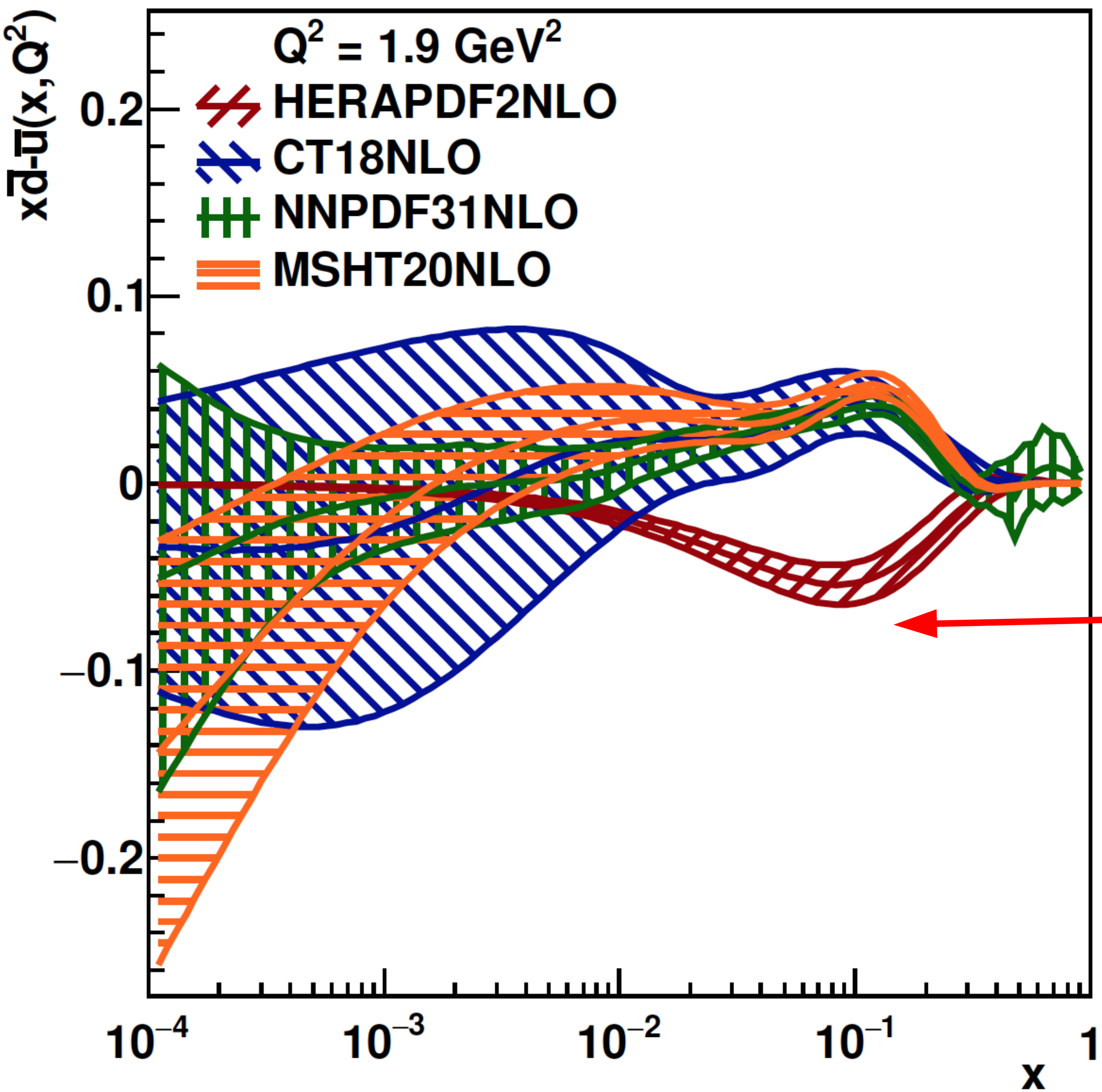




- Full fits with MSHT20 pseud-data
- Improvement significantly reduced compared with HERAPDF2.0
- Still significant effects present
  → biggest impact on up-valence distribution
  → small but valuable improvement on all parton species visible at all x and Q^2 values

Suppl. material to 1606.01736

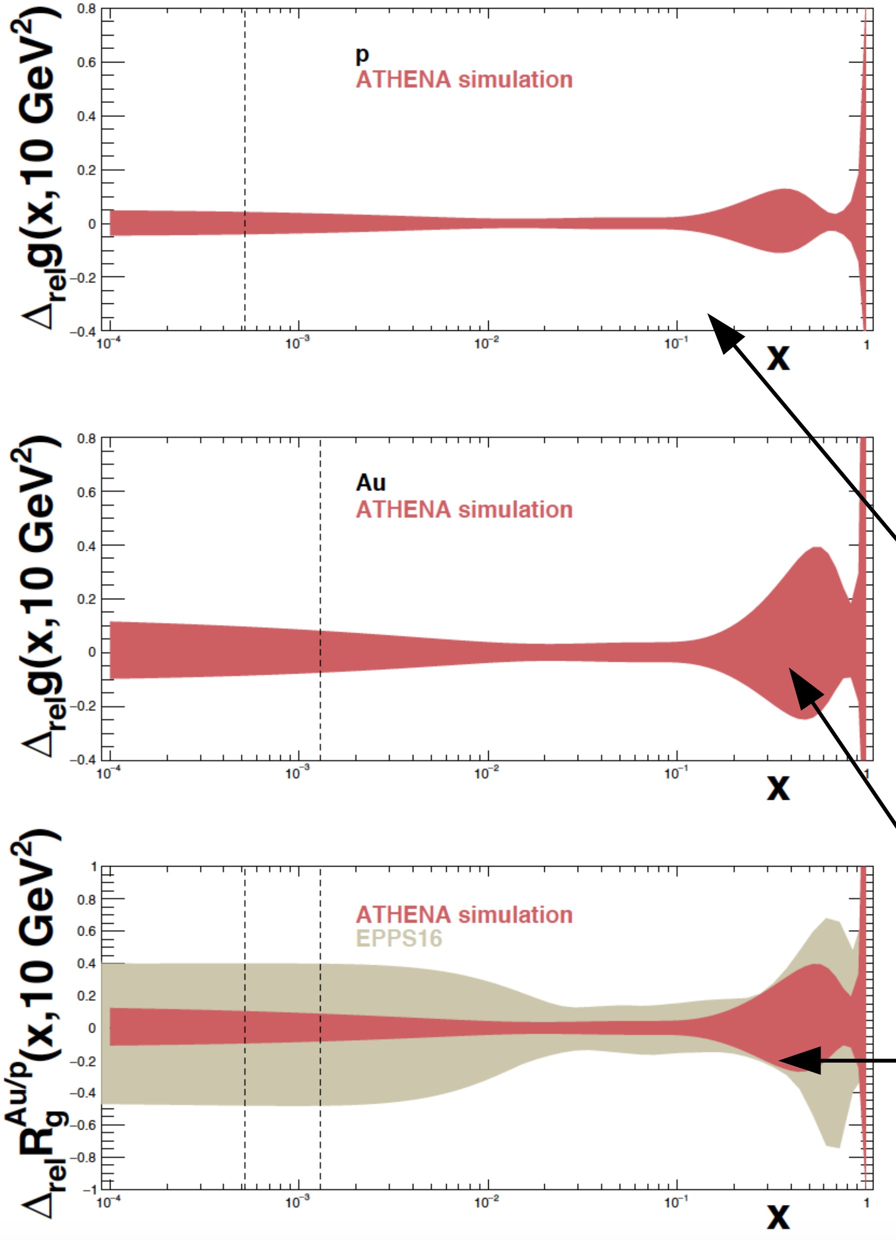
My private EIC wish list ...



HERA: only available high energy ep DIS data
→ all other fits include fixed target DIS data

Is that a real effect?

EIC, world's first e+A collider → will explore nuclear structure at unprecedented level, up to heaviest nuclei



- Nuclear PDFs studied in terms of nuclear modification factor R:

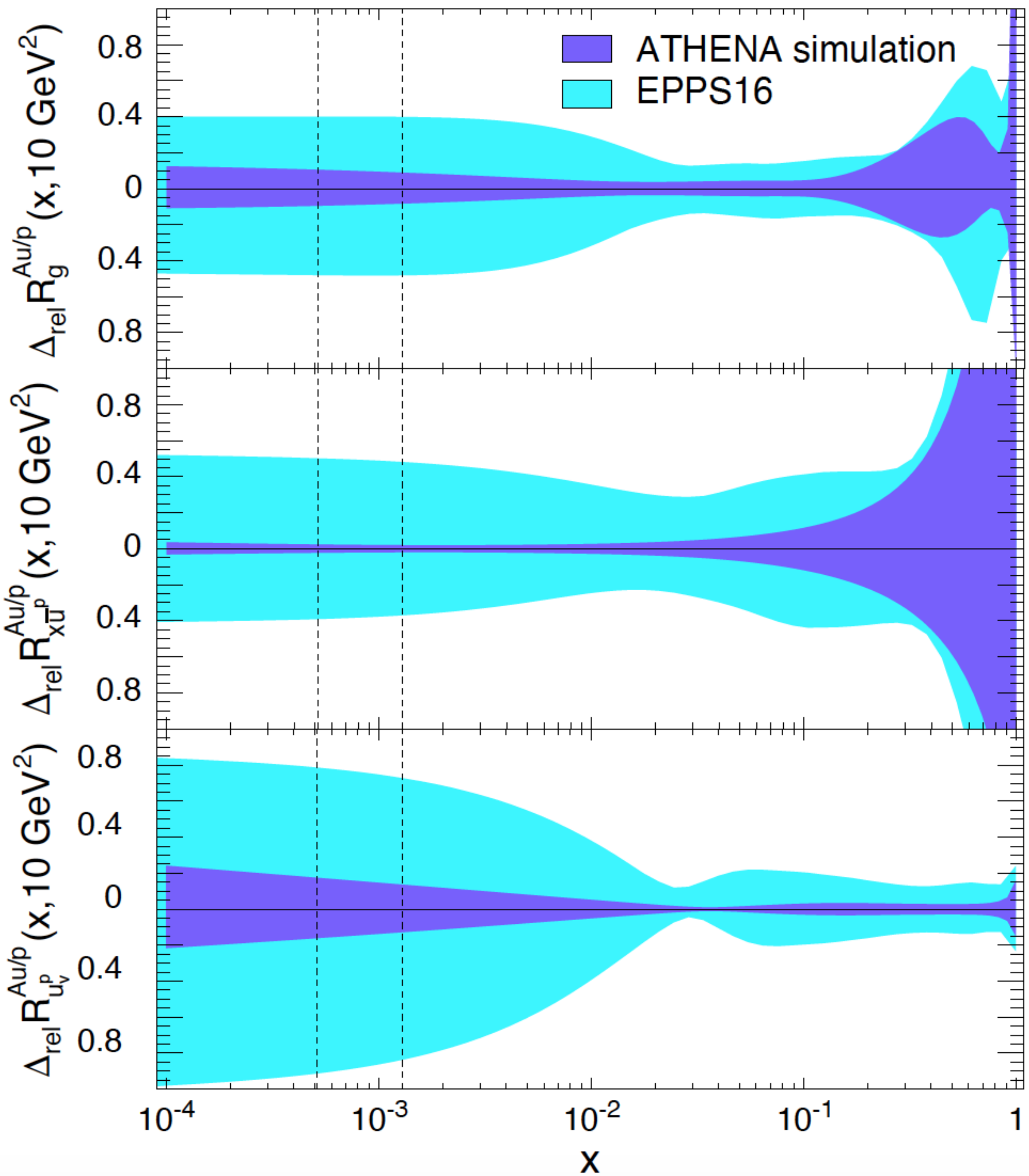
  It encodes deviations of nPDFs from simple scaling of free nucleon PDFs with atomic mass A after accounting for varying proton-to-neutron ratios using isospin symmetry

- Relative uncertainty of gluon in proton ATHENA-only fits
- Uncertainty of gluon in gold nucleus
- Nuclear modification factor formed from ratio of gluon in gold and proton

Suppl. material to 1606.01736

Impact of EIC data on nuclear PDF @NLO

arxiv:1606.01736



- Nuclear modification factors for gluon and u valence and u sea quarks

  → comparison with <u>EPPS16 (representative current global fit)</u>
  - Fixed target DIS and DY data
  - p+A at LHC
  - π^0 from PHENIX

Precision largely improved <u>with EIC data only</u>
→ factor of two @ x ~ 0.1

Beyond collinear PDFs:

TMD PDFs → towards global fits

S.Taheri Monfared, H.Jung, K.Wichmann

Motivation

- PB TMDs together with PB TMD parton shower allow very good description of measurements over wide kinematic range
  → excellent description of the DY spectrum in a wide range of p_T
  → also for jet multiplicity even much beyond reach of corresponding fixed-order calculation

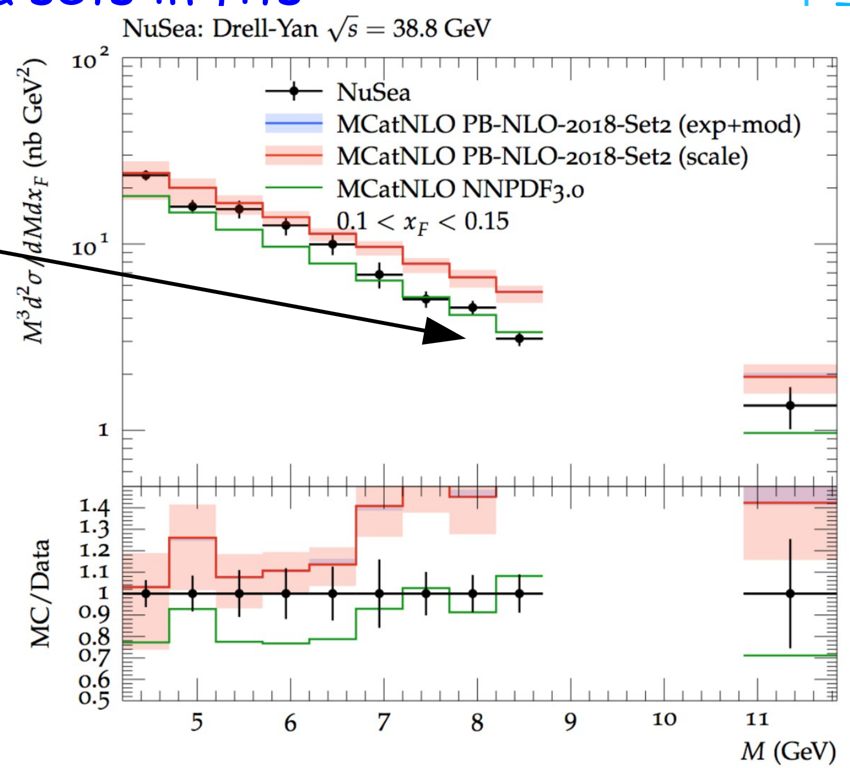
Is there still any room for improvement? YES!

- PB-TMD NLO fits use HERA DIS data
  → can be improved by including different data sets in fits

arXiv:2001.06488

- NuSea data studied
  → generally well described by PB-TMD + NLO
  → deteriorates for region of highest masses
    - large-x region - parton densities used in calculation poorly constrained
    - NNPDF3.0 fits better – more data used
  → can be improved in global fits

  → jet data constrain gluon at high x



TMDs-what is it? [Phys. Lett. B **772** (2017), 446-451], [JHEP **01** (2018), 070]

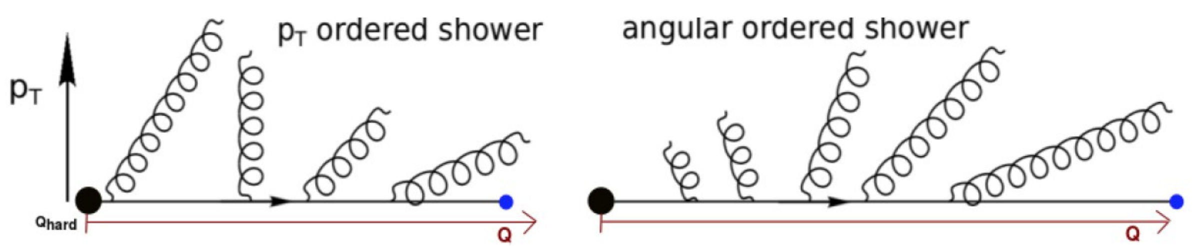
- TMDs : Transverse Momentum Dependent parton distributions
- extended collinear PDFs : transverse momentum effects from intrinsic k_t + evolution

Why TMD?

- fixed order calculations are limited in application
- small transverse momentum & small-x phenomena need TMDs

New approach: Parton Branching (PB) method

- evolution of TMDs and collinear PDFs at LO, NLO & NNLO
- automatically contain soft gluon resummation (at NLL identical to CSS approach)
- unique feature: backward evolution fully determines the TMD shower
- very successful for description of inclusive processes
  [Phys. Rev. D **100** (2019) no.7, 074027], [Eur. Phys. J. C **80** (2020) no.7, 598]



- Two angular ordered sets with different choice of scale in α_s:
  - set1: α_s(evolution scale)
  - **set2**: α_s(transverse momentum): similar quality as the NLO + NNLL prediction in $p_t(z)$ description

Fits using HERAPDF framework

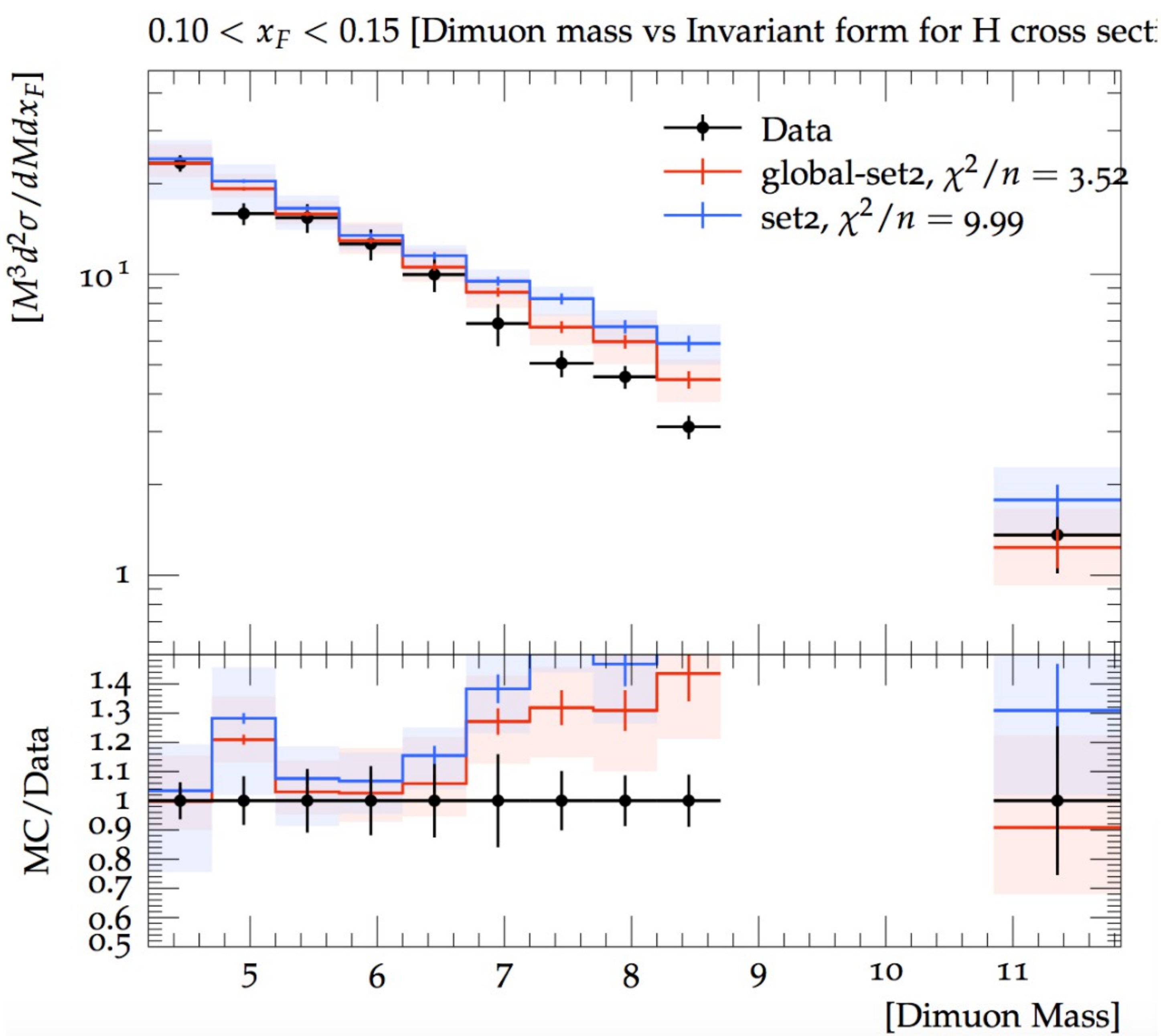
	Dataset	
HERA	HERA1+2 CCep	CC e+-p NC e+-p
	HERA1+2 CCem	
	HERA1+2 NCem	
	HERA1+2 NCep 820	
	HERA1+2 NCep 920	
	HERA1+2 NCep 460	
	HERA1+2 NCep 575	
HERA	ZEUS inclusive dijet 98-00/04-07 data	FastNLO jets
	H1 low Q2 inclusive jet 99-00 data	
	ZEUS inclusive jet 96-97 data	
	H1 normalised inclusive jets with unfolding	FastNLO ep jets normalised
	H1 normalised dijets with unfolding	
	H1 normalised trijets with unfolding	
Tevatron	CDF Z rapidity 2010	NC ppbar CC ppbar
	D0 W el nu lepton asymmetry ptl 25 GeV	
	D0 Z rapidity 2007	
	E866, high mass	NC pp
	E866, mid mass	
	E866, low mass	
LHC	CMS W muon asymmetry	CC pp NC pp
	CMS W muon asymmetry 8 TeV	
	CMS 7 TeV Z Boson rapidity 2	
	CMS 7 TeV Z Boson rapidity 3	
	CMS 7 TeV Z Boson rapidity 4	
	CMS 7 TeV Z Boson rapidity 5	

Total number of data point : 1501

Set1 → chi2/dof=1858/1484=1.25
Set2 → chi2/dof=1922/1484=1.29

- Started with HERA jets
- Added fixed target + CMS W/Z
- Good data description

Visible improvement for high masses



Message to take away

- Two new HERA α_s results

  → HERAPDF2.0Jets NNLO

$$\alpha_s(M_Z^2) = 0.1156 \pm 0.0011 \text{ (exp/fit) } {}^{+0.0001}_{-0.0002} \text{ (model/parameterisation)} \pm 0.0029 \text{ (scale)}$$

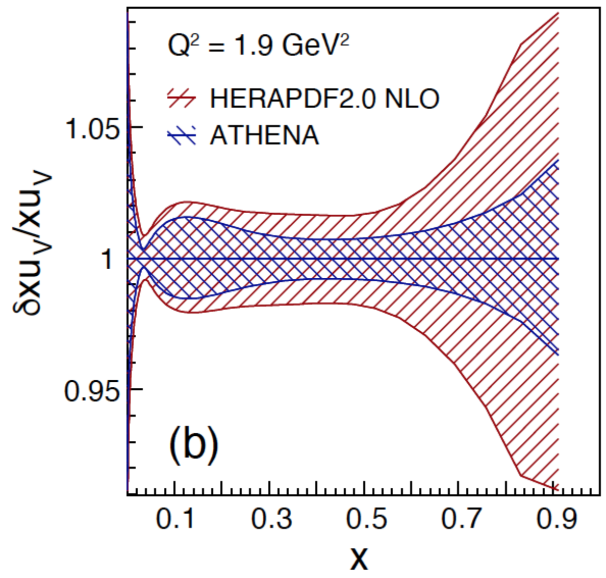
  → ZEUS new jet measurement + $\alpha_s(M_Z)$ fit

$$\alpha_s(M_Z^2) = 0.1138 \pm 0.0014 \text{ (exp/fit) } {}^{+0.0004}_{-0.0008} \text{ (model/parameterisation) } {}^{+0.0012}_{-0.0005} \text{ (scale)}$$

  → one of the most precise measurements of $\alpha_s(M_Z^2)$ at hadron colliders

- Using EIC data will make tremendous difference
  → proton PDFs, especially at high x
  → nPDFs constrained with 10% precision

- Parton Branching methods allows studying TMDs
  → global PB TMDs within reach



HERA still has something to say!

Additional slides

Updates in the procedure

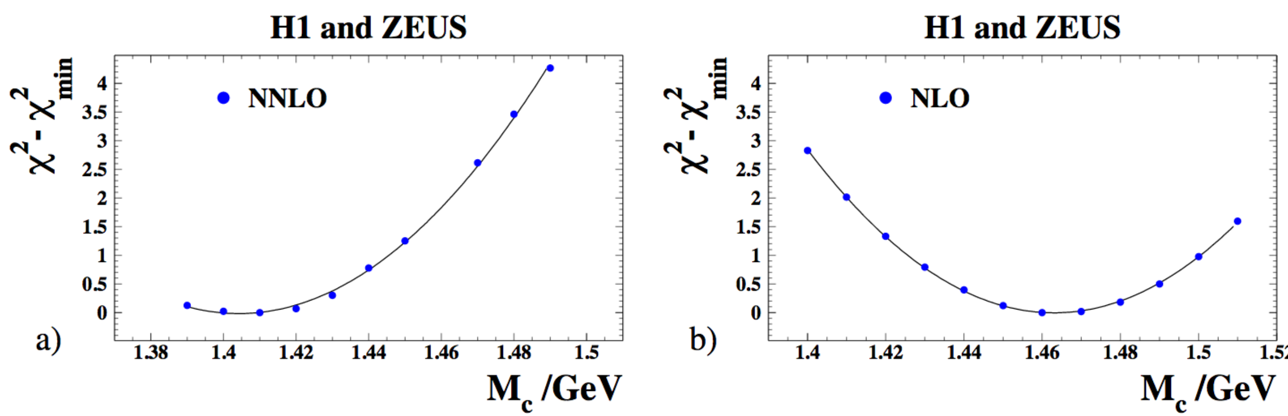
- scale choice changes:
- factorisation: $\mu F^2=(Q^2+pt^2)$
- cf. $\mu F^2=Q^2$ in previous NLO analysis; updated since not a good choice for low Q^2 jet data; change makes almost no difference for high Q^2 jets
- renormalisation: $\mu R^2=(Q^2+pt^2)$
- cf. $\mu R^2=(Q^2+pt^2)/2$ in previous NLO analysis
- NNLO fit with $\mu R^2=(Q^2+pt^2)$ gives $\Delta X^2= -$**15** cf. $\mu R^2=(Q^2+pt^2)/2$ and vice versa for NLO fit
- scale uncertainties treated as completely correlated between bins and datasets

† pt denotes pt^{jet} in the case of inclusive jet cross sections and <pt> for dijets

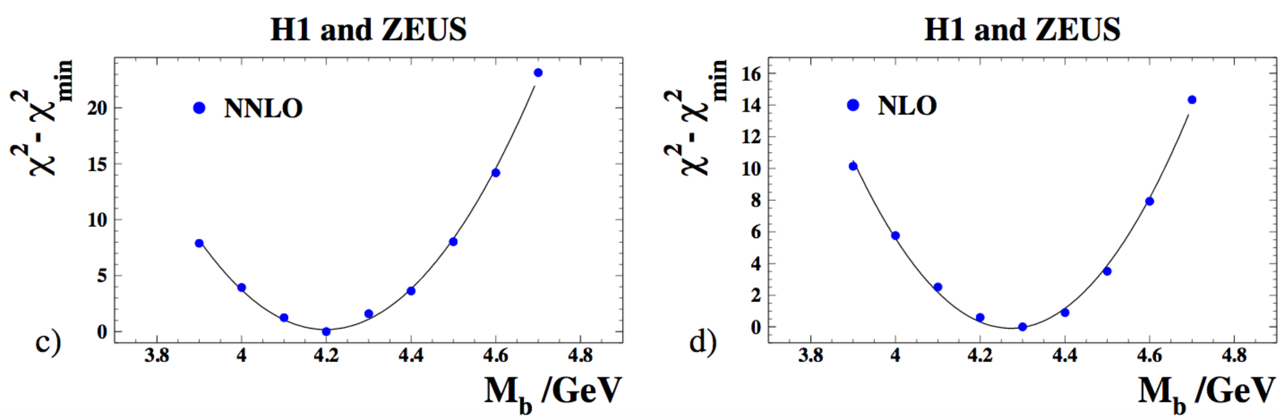
- improved treatment of hadronisation uncertainties; NOW included together with exp. systematics; treated as ½ correlated, ½ uncorrelated between bins and datasets
- (small) uncertainties on theory predictions included

Estimation of charm & beauty masses

- new HERA combined charm and beauty data: EPJ C78 (2018), 473
  → updated estimation of M_c and M_b
  → Heavy Quark (HQ) coefficient functions evaluated using Thorne-Roberts Optimised Variable Flavour Number Scheme



M_c = 1.41 +- 0.04 M_c = 1.46 +- 0.04

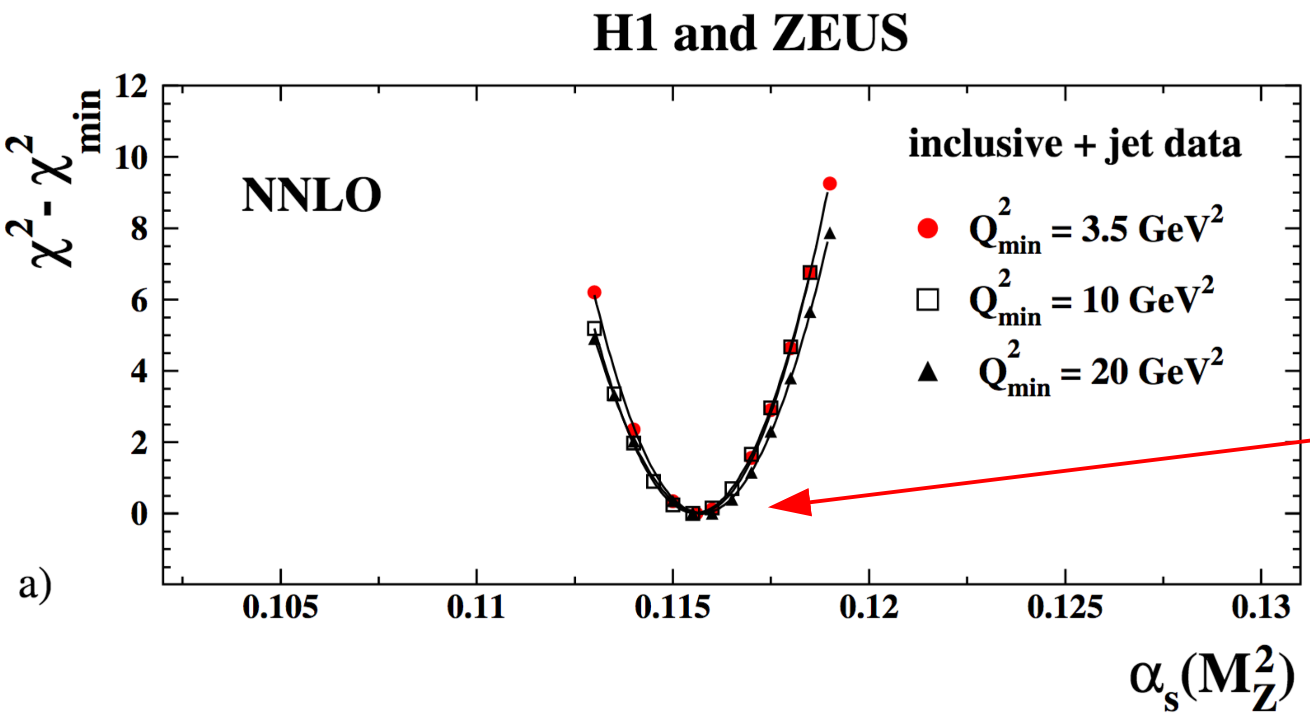


M_b = 4.2 +- 0.1 M_b = 4.3 +- 0.1

Checking robustness of results

• HERA data at low x and Q^2 may be subject to need for ln(1/x) resummation or higher twist effects (eg arXiv:1506.06042, 1710.05935)

→ χ^2 scans performed with harder Q^2 cuts

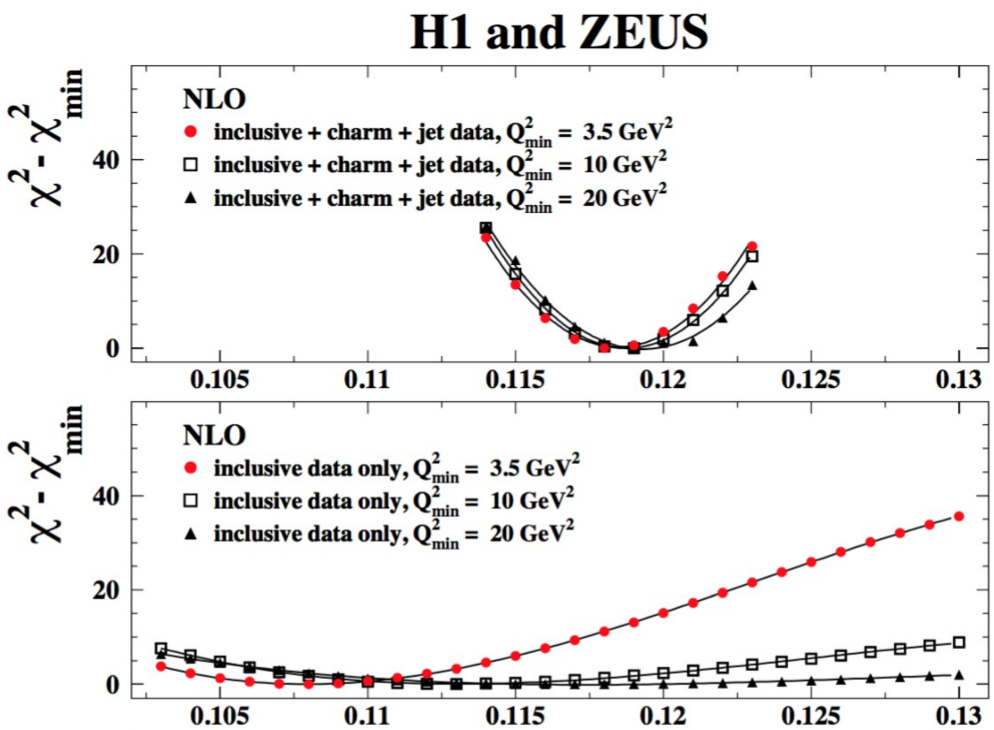


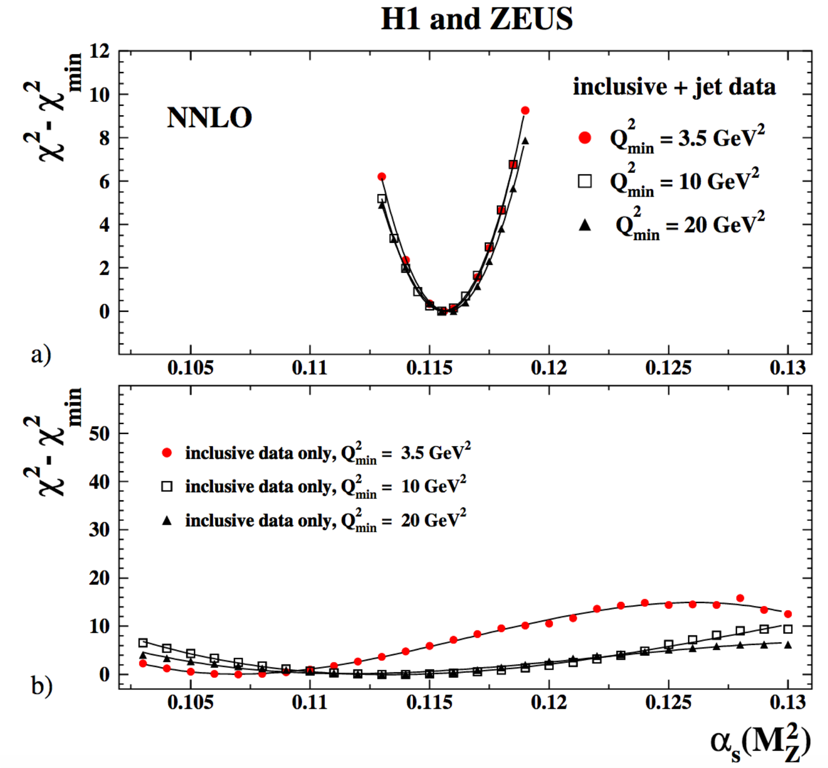
Q^2 cuts do not result in any significant change to the value of $\alpha_s(M_Z)$

- Alternative parameterisations checked
  - No negative gluon term and no NG but additional Dg parameter
    → both give the same result
    → consistent with nominal

$$\alpha_s(M_Z^2) = 0.1151 \pm 0.0010 \text{ (exp)}$$

Completing NLO picture

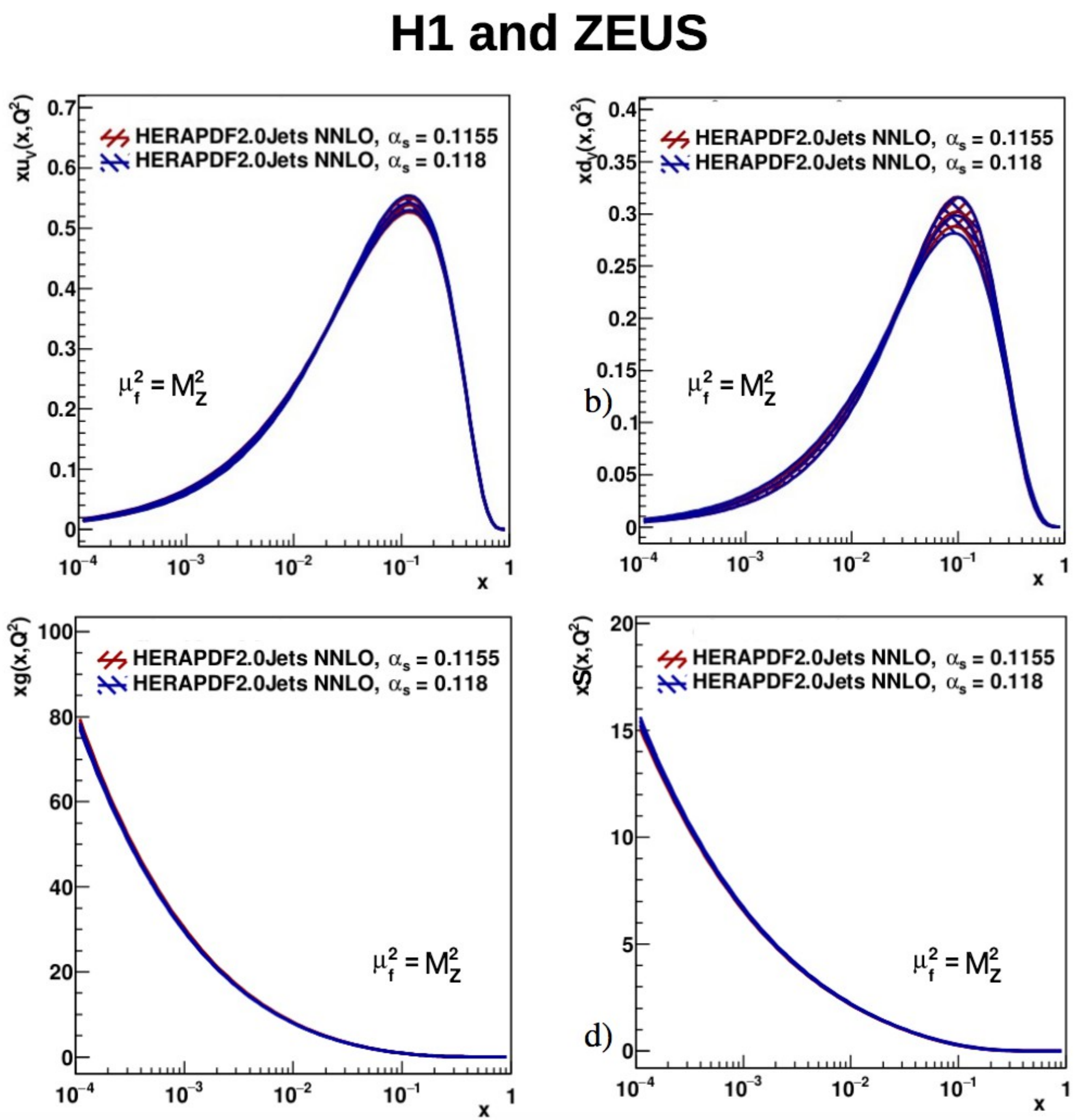




- Similar behavior and level of precision at NLO and NNLO
- However direct comparison of 2015 and 2022 results not possible
  → different scale choice and slightly different jet data sets
- After unifying (details in backup)

αs(Mz) = 0.1186 ± 0.0014 (exp) **NLO**
αs(Mz) = 0.1144 ± 0.0013 (exp) **NNLO**

… and how it compares to α_s = 0.1155



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

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

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

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

- 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:

(from A. Cooper-Sarkar, alpha-s 2022 workshop)

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

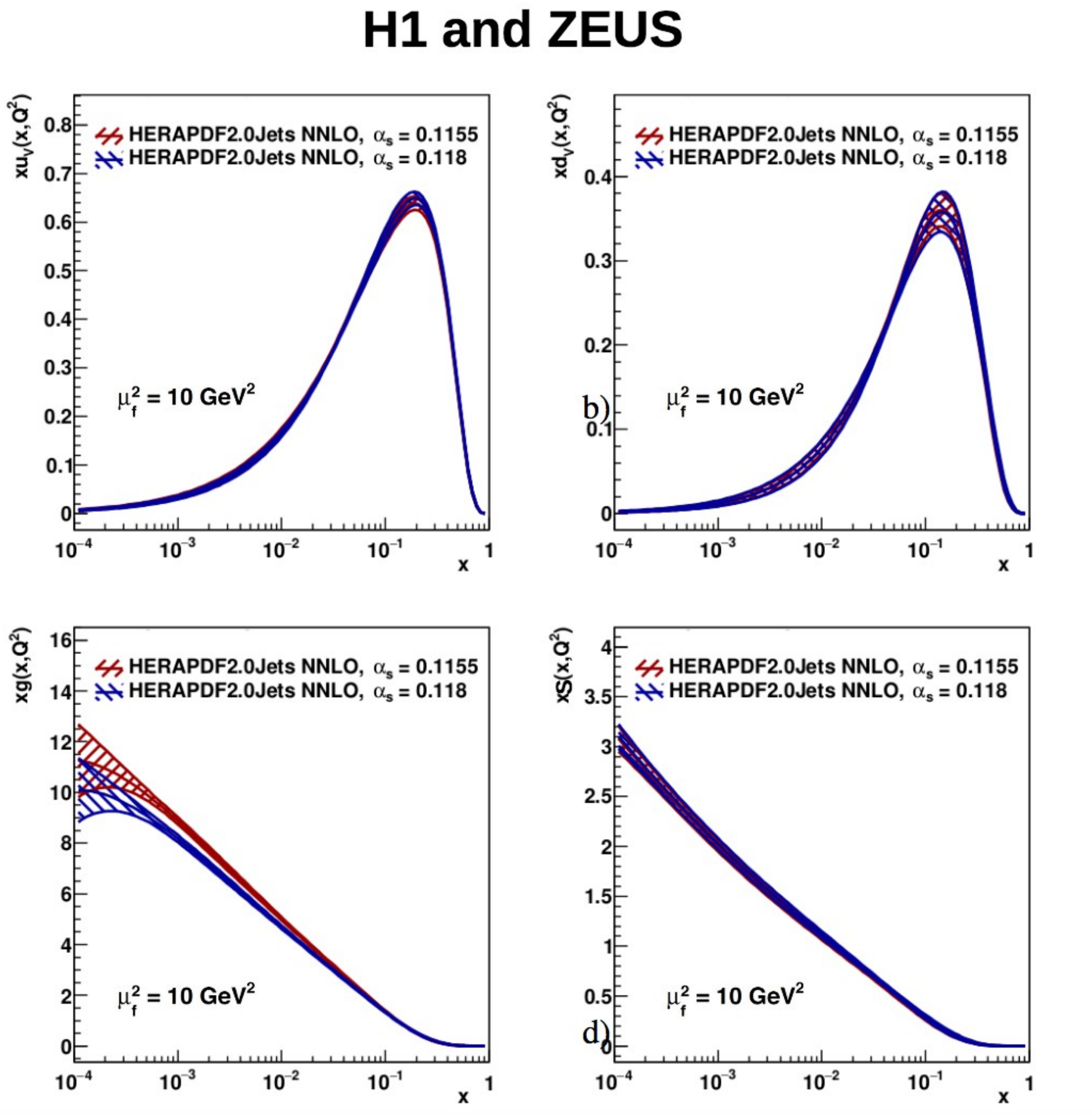
- choice of scale, $\mu_f^2 = \mu_r^2 = Q^2 + p_T^2$;
- exclusion of the H1 low-Q^2 inclusive and dijet data;
- exclusion of the low-p_T points from the H1 high-Q^2 inclusive jet data;
- exclusion of trijet data;
- exclusion of low-p_T points from the ZEUS dijet data;
- exclusion of data with $\mu <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

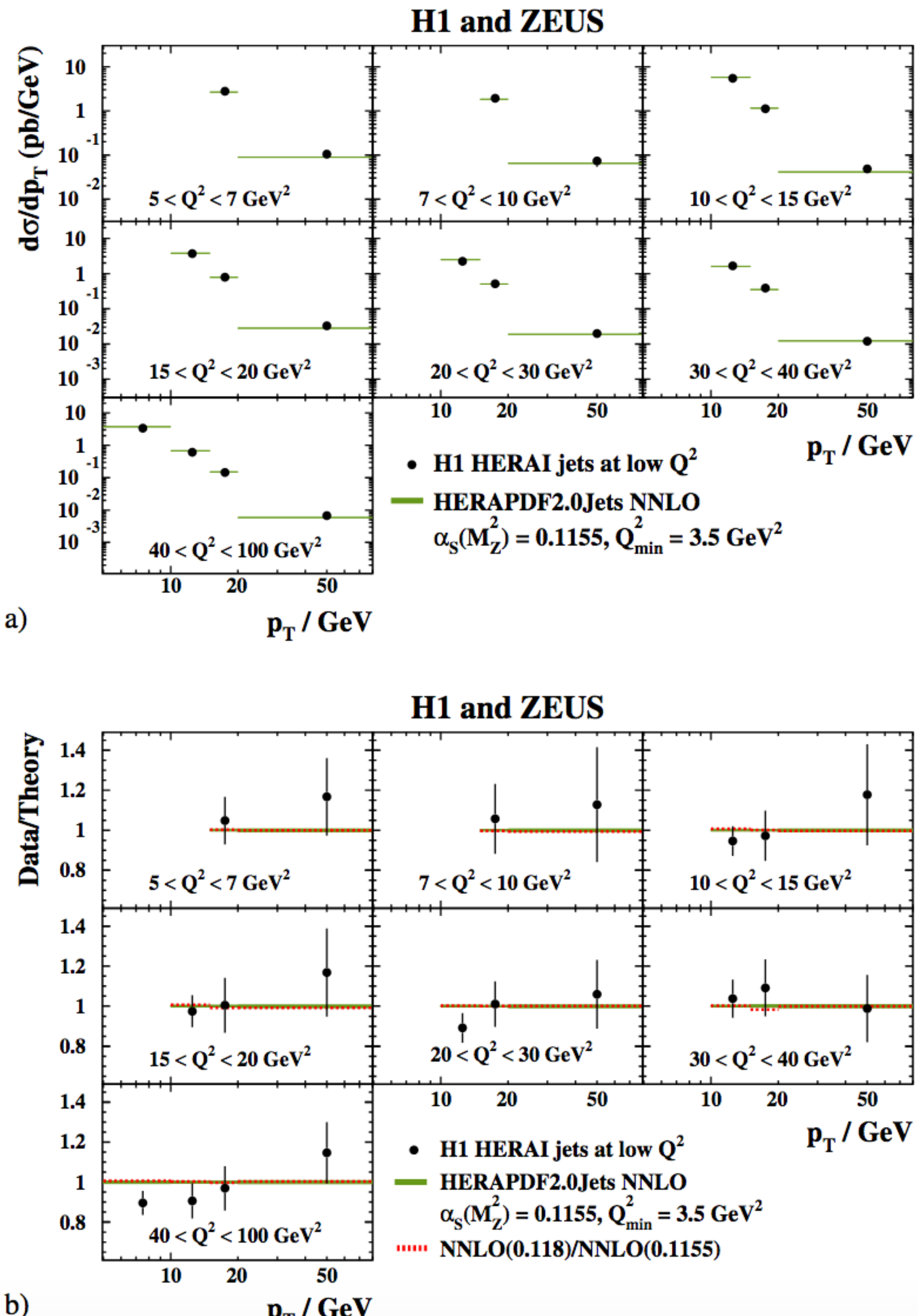
The values of $\alpha_S(M_Z)$ obtained for these conditions are:
0.1186 ± 0.0014(exp) NLO and 0.1144 ± 0.0013(exp) NNLO.
The change of the NNLO value from the preferred value of 0.1156 is mostly due to the exclusion of the H1 lowQ^2 data and the low-p_T points at high Q^2

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.

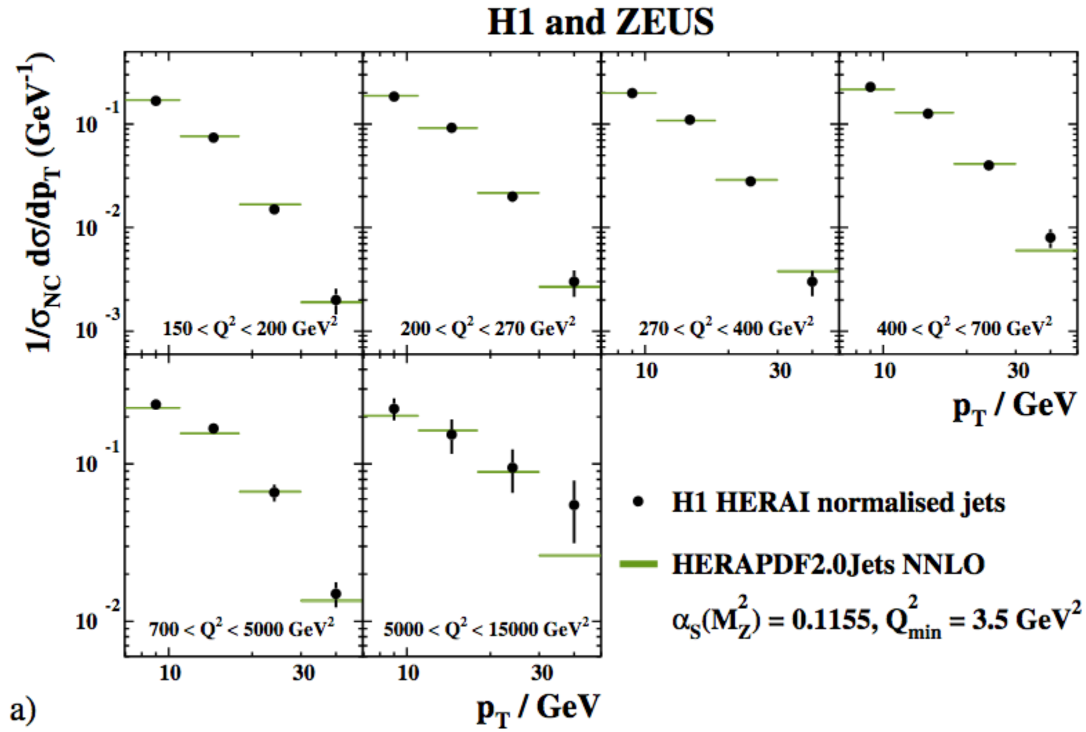
(from A. Cooper-Sarkar, alpha-s 2022 workshop)

… and how it compares to α_s = 0.1155

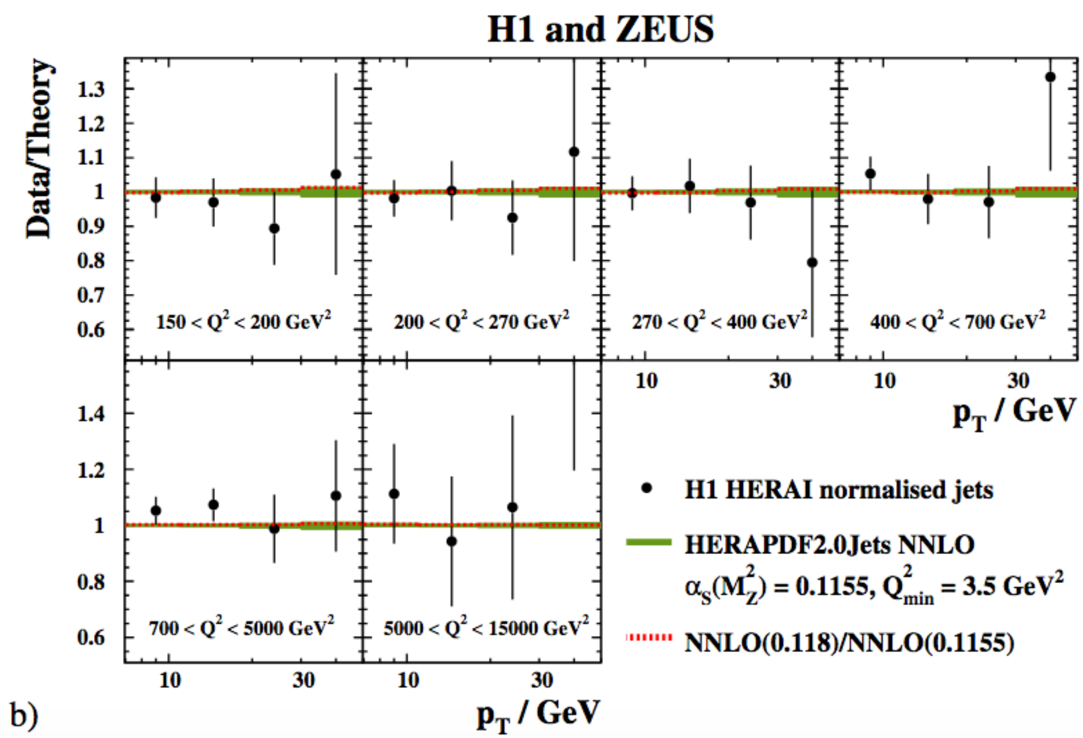




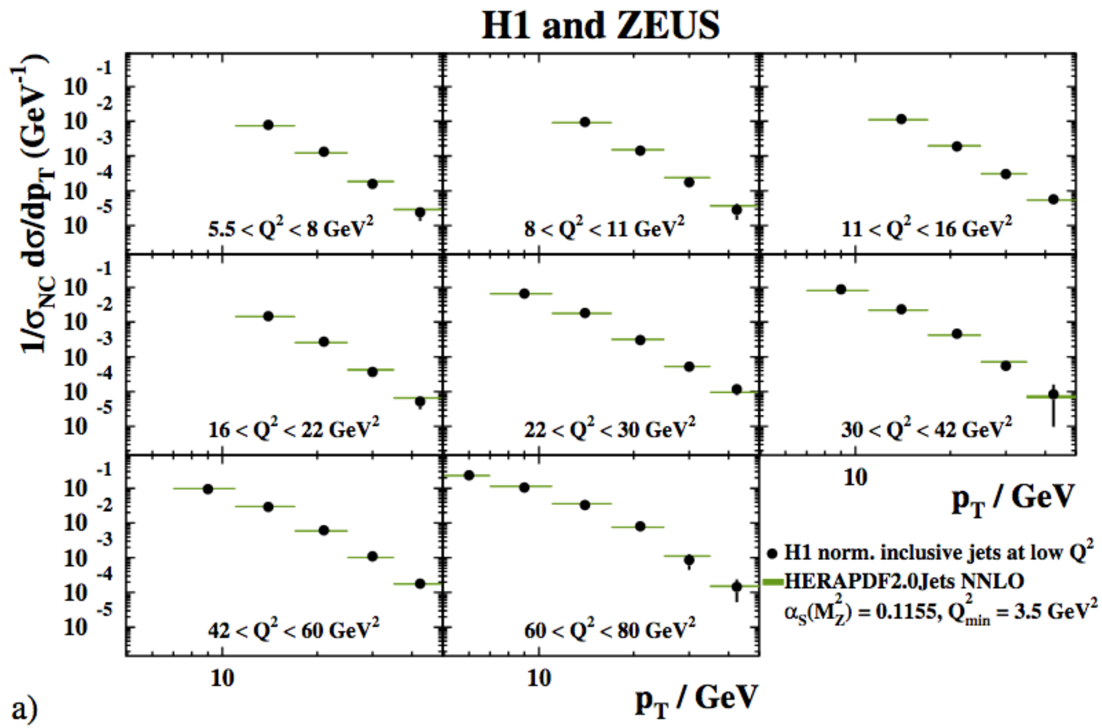
H1 and ZEUS
dσ/dp_T (pb/GeV)
5 < Q² < 7 GeV²
7 < Q² < 10 GeV²
10 < Q² < 15 GeV²
15 < Q² < 20 GeV²
20 < Q² < 30 GeV²
30 < Q² < 40 GeV²
40 < Q² < 100 GeV²
p_T / GeV
H1 HERAI jets at low Q²
HERAPDF2.0Jets NNLO
α_S(M_Z²) = 0.1155, Q²_min = 3.5 GeV²
a)
H1 and ZEUS
Data/Theory
5 < Q² < 7 GeV²
7 < Q² < 10 GeV²
10 < Q² < 15 GeV²
15 < Q² < 20 GeV²
20 < Q² < 30 GeV²
30 < Q² < 40 GeV²
40 < Q² < 100 GeV²
p_T / GeV
H1 HERAI jets at low Q²
HERAPDF2.0Jets NNLO
α_S(M_Z²) = 0.1155, Q²_min = 3.5 GeV²
NNLO(0.118)/NNLO(0.1155)
b)

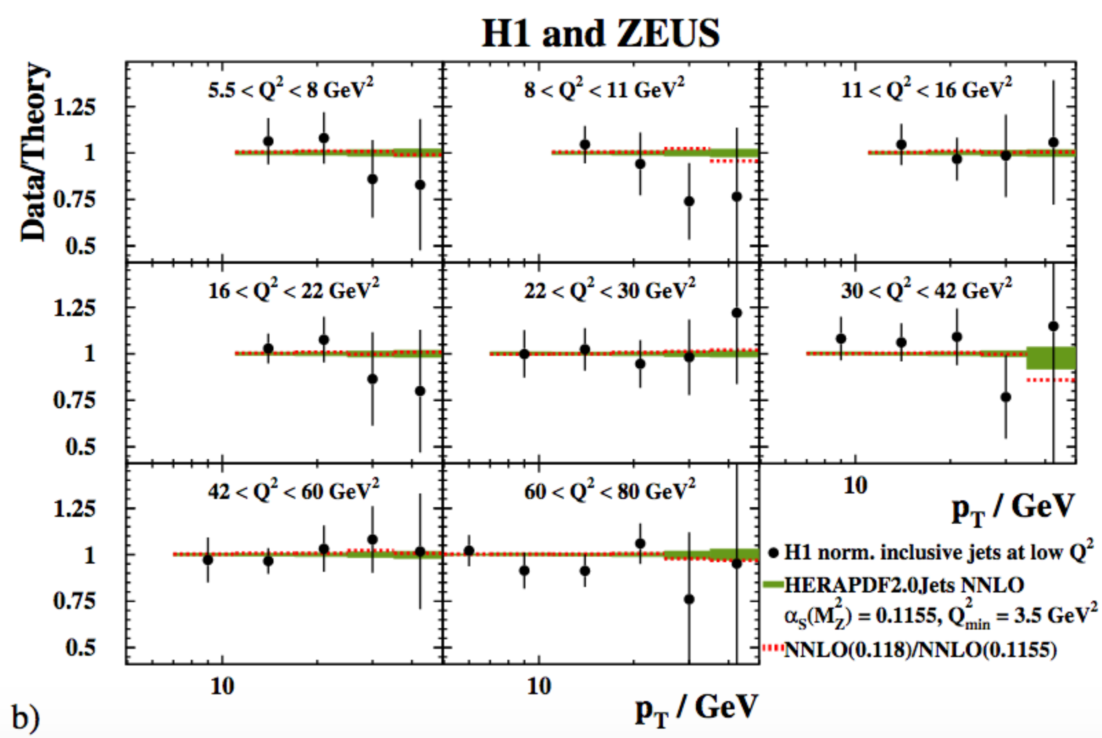


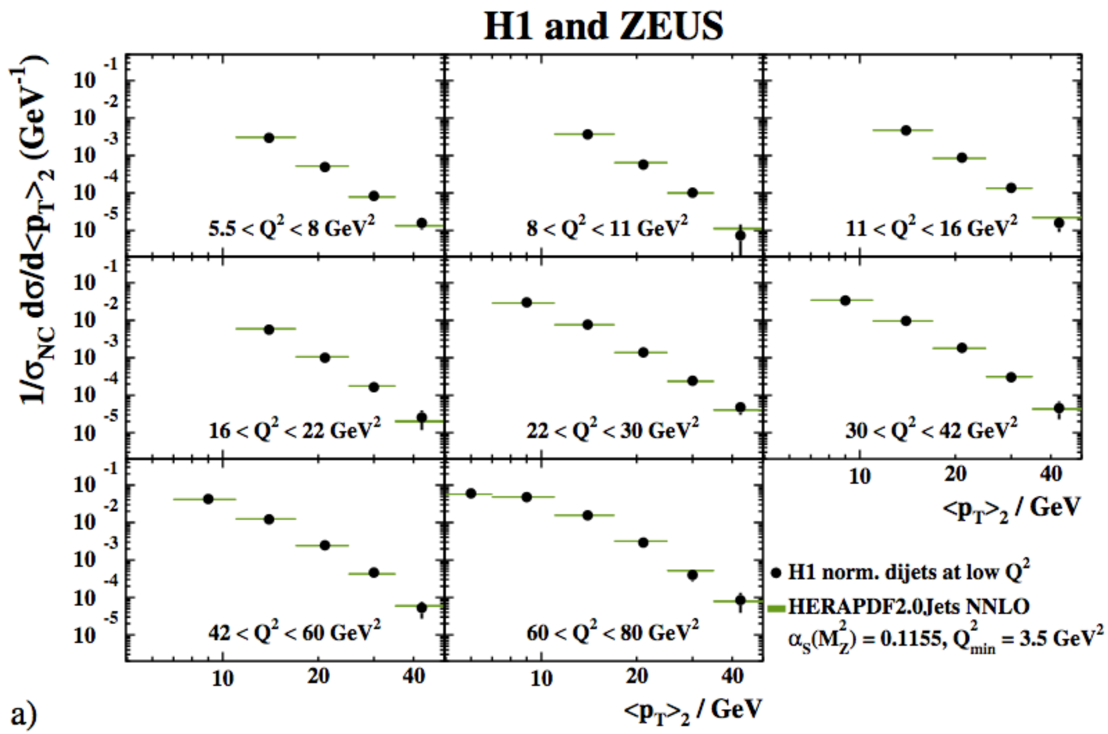
H1 and ZEUS
$1/\sigma_{NC}\, d\sigma/dp_T$ (GeV^{-1})
$150 < Q^2 < 200$ GeV^2
$200 < Q^2 < 270$ GeV^2
$270 < Q^2 < 400$ GeV^2
$400 < Q^2 < 700$ GeV^2
$700 < Q^2 < 5000$ GeV^2
$5000 < Q^2 < 15000$ GeV^2
p_T / GeV
H1 HERAI normalised jets
HERAPDF2.0Jets NNLO
$\alpha_S(M_Z^2) = 0.1155$, $Q^2_{min} = 3.5$ GeV^2
a)

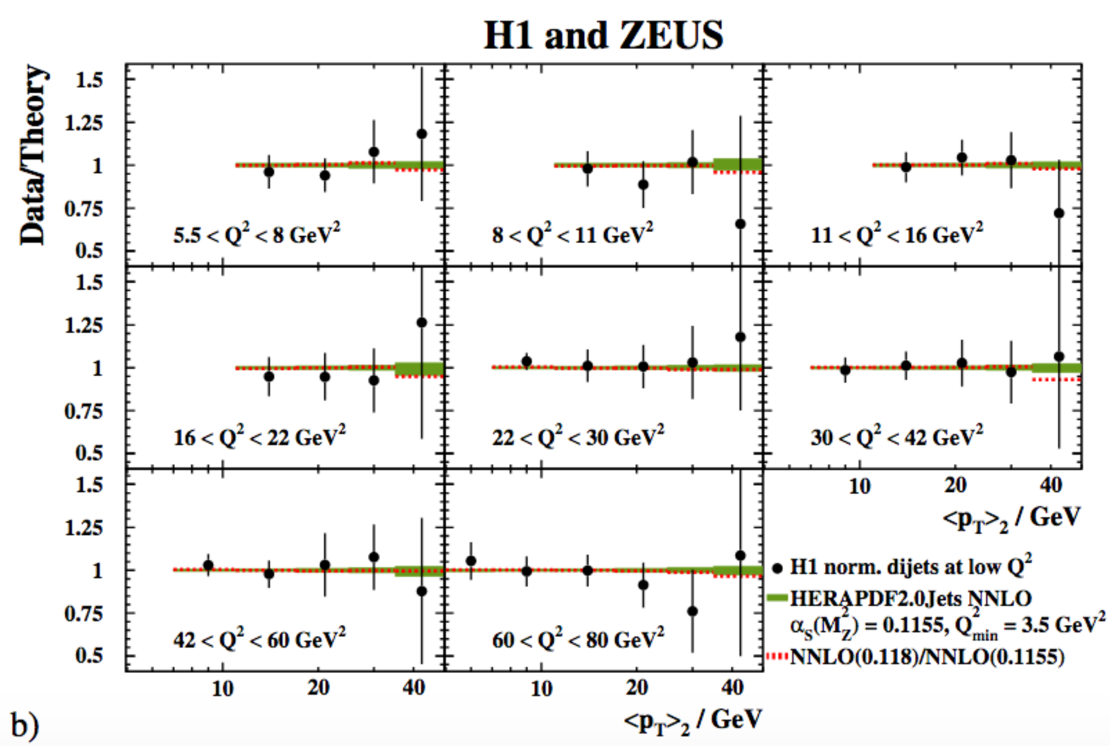


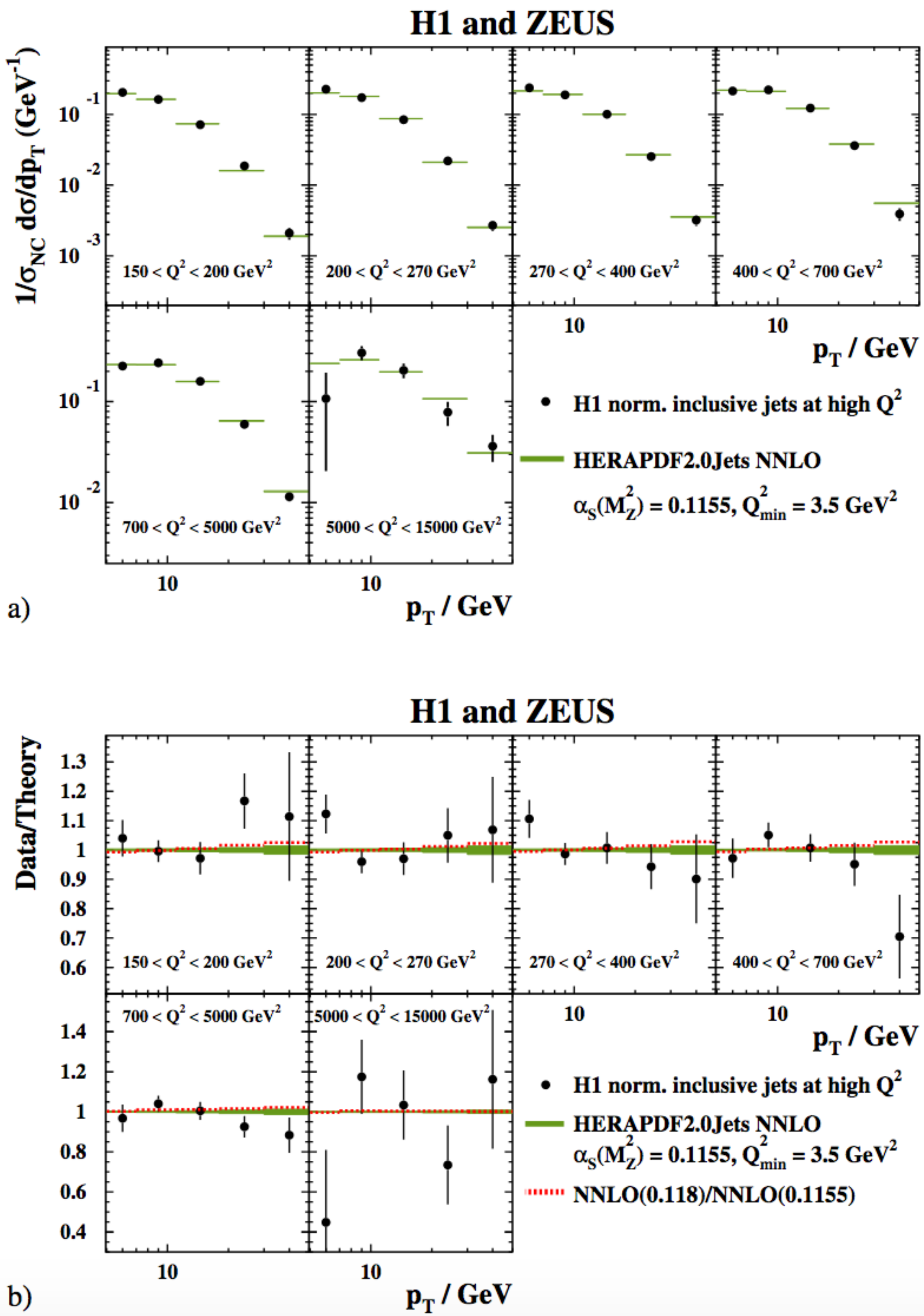
H1 and ZEUS
Data/Theory
$150 < Q^2 < 200$ GeV^2
$200 < Q^2 < 270$ GeV^2
$270 < Q^2 < 400$ GeV^2
$400 < Q^2 < 700$ GeV^2
$700 < Q^2 < 5000$ GeV^2
$5000 < Q^2 < 15000$ GeV^2
p_T / GeV
H1 HERAI normalised jets
HERAPDF2.0Jets NNLO
$\alpha_S(M_Z^2) = 0.1155$, $Q^2_{min} = 3.5$ GeV^2
NNLO(0.118)/NNLO(0.1155)
b)

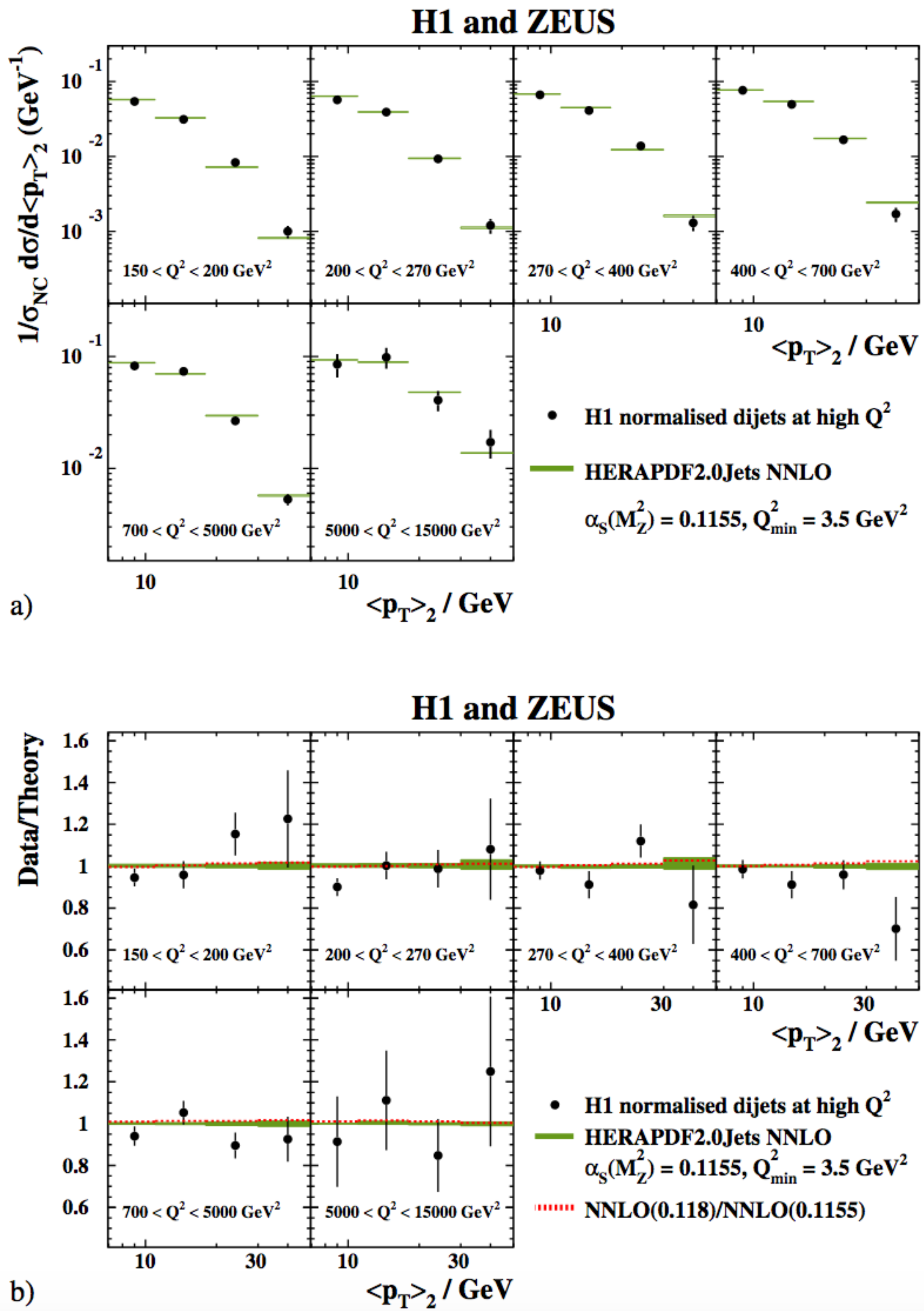

H1 and ZEUS
$1/\sigma_{NC}\, d\sigma/dp_T$ (GeV^{-1})
$5.5 < Q^2 < 8$ GeV^2
$8 < Q^2 < 11$ GeV^2
$11 < Q^2 < 16$ GeV^2
$16 < Q^2 < 22$ GeV^2
$22 < Q^2 < 30$ GeV^2
$30 < Q^2 < 42$ GeV^2
$42 < Q^2 < 60$ GeV^2
$60 < Q^2 < 80$ GeV^2
p_T / GeV
H1 norm. inclusive jets at low Q^2
HERAPDF2.0Jets NNLO
$\alpha_S(M_Z^2) = 0.1155$, $Q^2_{min} = 3.5$ GeV^2
a)

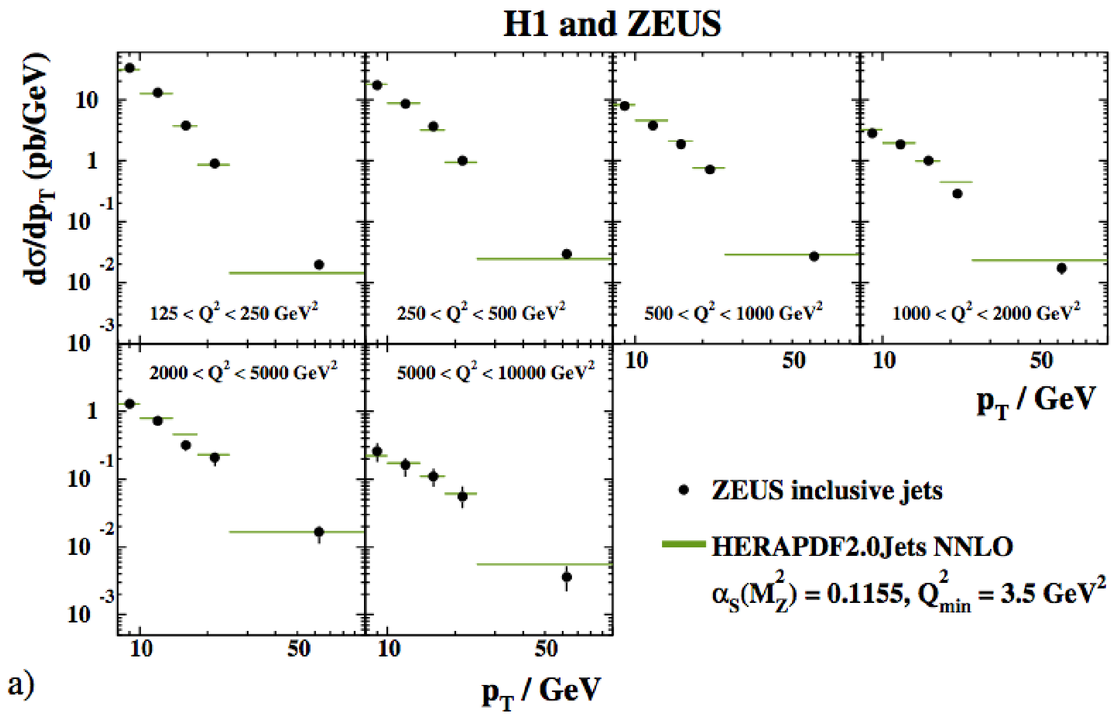

H1 and ZEUS
Data/Theory
$5.5 < Q^2 < 8$ GeV^2
$8 < Q^2 < 11$ GeV^2
$11 < Q^2 < 16$ GeV^2
$16 < Q^2 < 22$ GeV^2
$22 < Q^2 < 30$ GeV^2
$30 < Q^2 < 42$ GeV^2
$42 < Q^2 < 60$ GeV^2
$60 < Q^2 < 80$ GeV^2
p_T / GeV
H1 norm. inclusive jets at low Q^2
HERAPDF2.0Jets NNLO
$\alpha_S(M_Z^2) = 0.1155$, $Q^2_{min} = 3.5$ GeV^2
NNLO(0.118)/NNLO(0.1155)
b)

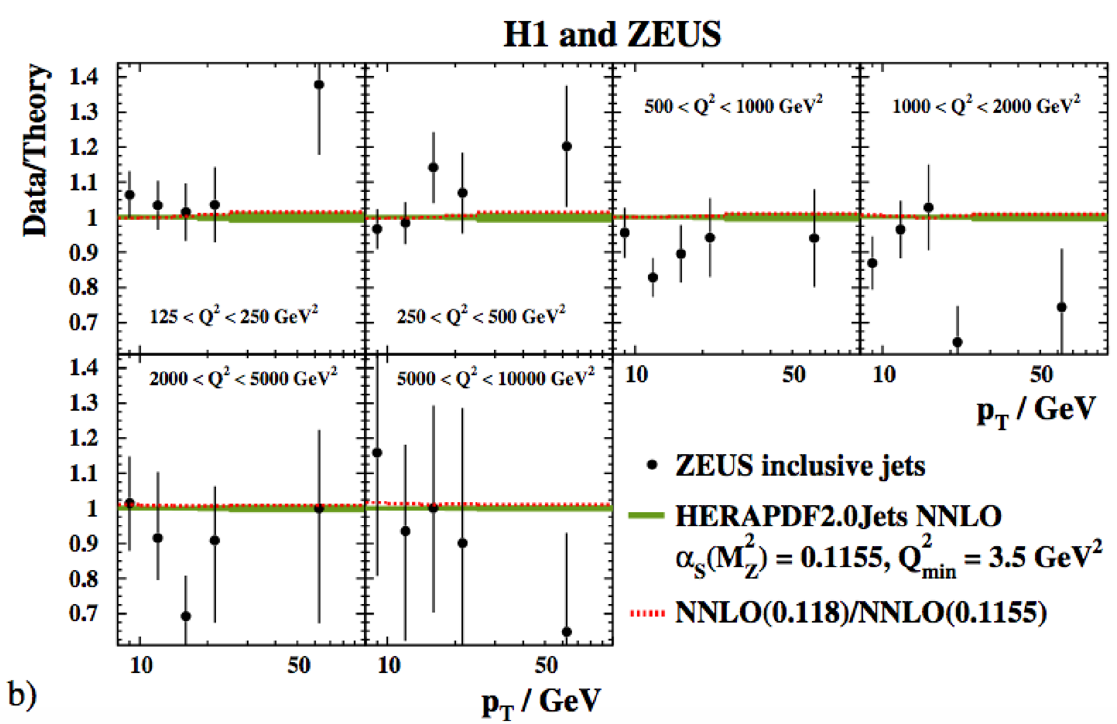

H1 and ZEUS
1/σNC dσ/d<pT>2 (GeV-1)
5.5 < Q2 < 8 GeV2
8 < Q2 < 11 GeV2
11 < Q2 < 16 GeV2
16 < Q2 < 22 GeV2
22 < Q2 < 30 GeV2
30 < Q2 < 42 GeV2
42 < Q2 < 60 GeV2
60 < Q2 < 80 GeV2
<pT>2 / GeV
H1 norm. dijets at low Q2
HERAPDF2.0Jets NNLO
αS(MZ2) = 0.1155, Q2min = 3.5 GeV2
a)

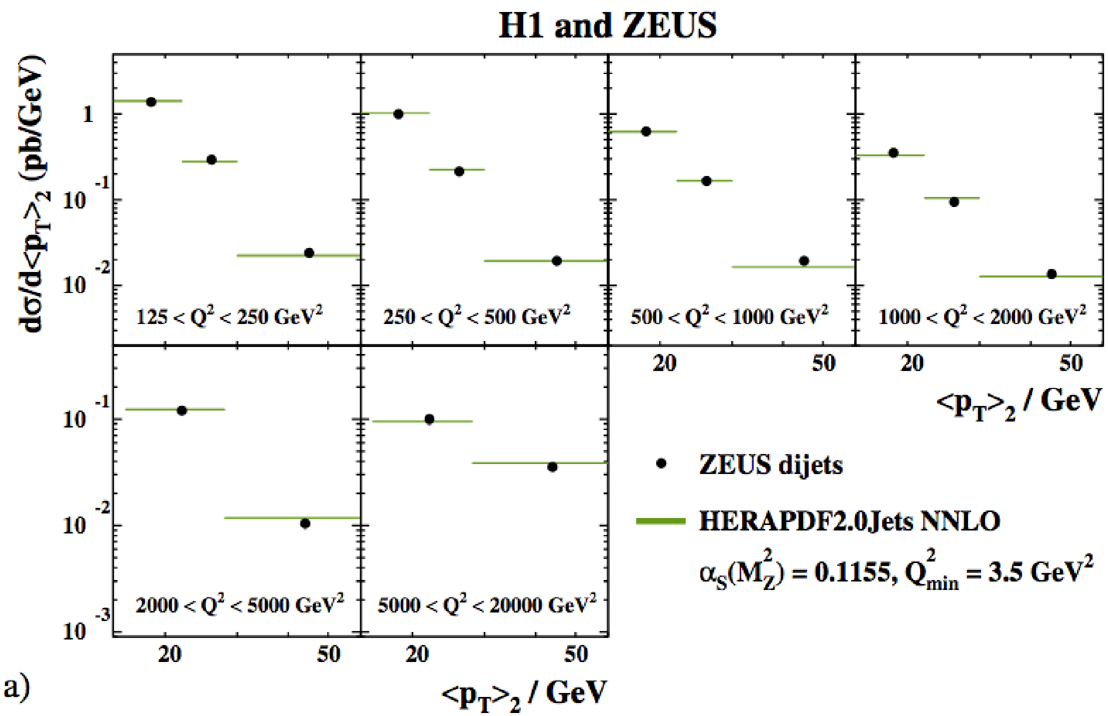

H1 and ZEUS
Data/Theory
5.5 < Q2 < 8 GeV2
8 < Q2 < 11 GeV2
11 < Q2 < 16 GeV2
16 < Q2 < 22 GeV2
22 < Q2 < 30 GeV2
30 < Q2 < 42 GeV2
42 < Q2 < 60 GeV2
60 < Q2 < 80 GeV2
<pT>2 / GeV
H1 norm. dijets at low Q2
HERAPDF2.0Jets NNLO
αS(MZ2) = 0.1155, Q2min = 3.5 GeV2
NNLO(0.118)/NNLO(0.1155)
b)

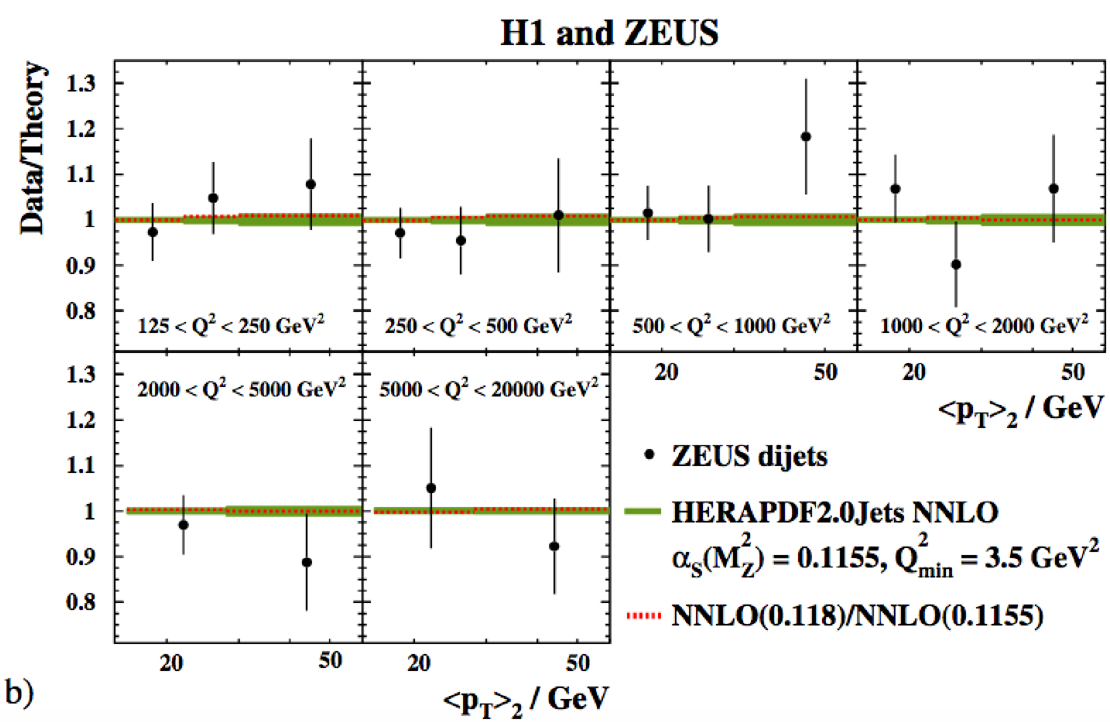

H1 and ZEUS
$1/\sigma_{NC}\, d\sigma/dp_T$ (GeV^{-1})
$150 < Q^2 < 200$ GeV^2
$200 < Q^2 < 270$ GeV^2
$270 < Q^2 < 400$ GeV^2
$400 < Q^2 < 700$ GeV^2
$700 < Q^2 < 5000$ GeV^2
$5000 < Q^2 < 15000$ GeV^2
p_T / GeV
H1 norm. inclusive jets at high Q^2
HERAPDF2.0Jets NNLO
$\alpha_S(M_Z^2) = 0.1155$, $Q^2_{min} = 3.5$ GeV^2
a)
H1 and ZEUS
Data/Theory
$150 < Q^2 < 200$ GeV^2
$200 < Q^2 < 270$ GeV^2
$270 < Q^2 < 400$ GeV^2
$400 < Q^2 < 700$ GeV^2
$700 < Q^2 < 5000$ GeV^2
$5000 < Q^2 < 15000$ GeV^2
p_T / GeV
H1 norm. inclusive jets at high Q^2
HERAPDF2.0Jets NNLO
$\alpha_S(M_Z^2) = 0.1155$, $Q^2_{min} = 3.5$ GeV^2
NNLO(0.118)/NNLO(0.1155)
b)


H1 and ZEUS
$1/\sigma_{NC}\, d\sigma/d\langle p_T\rangle_2$ (GeV^{-1})
150 < Q² < 200 GeV²
200 < Q² < 270 GeV²
270 < Q² < 400 GeV²
400 < Q² < 700 GeV²
700 < Q² < 5000 GeV²
5000 < Q² < 15000 GeV²
$\langle p_T\rangle_2$ / GeV
H1 normalised dijets at high Q²
HERAPDF2.0Jets NNLO
$\alpha_S(M_Z^2) = 0.1155$, $Q^2_{min} = 3.5$ GeV²
a)
H1 and ZEUS
Data/Theory
150 < Q² < 200 GeV²
200 < Q² < 270 GeV²
270 < Q² < 400 GeV²
400 < Q² < 700 GeV²
700 < Q² < 5000 GeV²
5000 < Q² < 15000 GeV²
$\langle p_T\rangle_2$ / GeV
H1 normalised dijets at high Q²
HERAPDF2.0Jets NNLO
$\alpha_S(M_Z^2) = 0.1155$, $Q^2_{min} = 3.5$ GeV²
NNLO(0.118)/NNLO(0.1155)
b)


H1 and ZEUS
dσ/dp_T (pb/GeV)
125 < Q² < 250 GeV²
250 < Q² < 500 GeV²
500 < Q² < 1000 GeV²
1000 < Q² < 2000 GeV²
2000 < Q² < 5000 GeV²
5000 < Q² < 10000 GeV²
p_T / GeV
ZEUS inclusive jets
HERAPDF2.0Jets NNLO
α_S(M_Z²) = 0.1155, Q²_min = 3.5 GeV²
a)

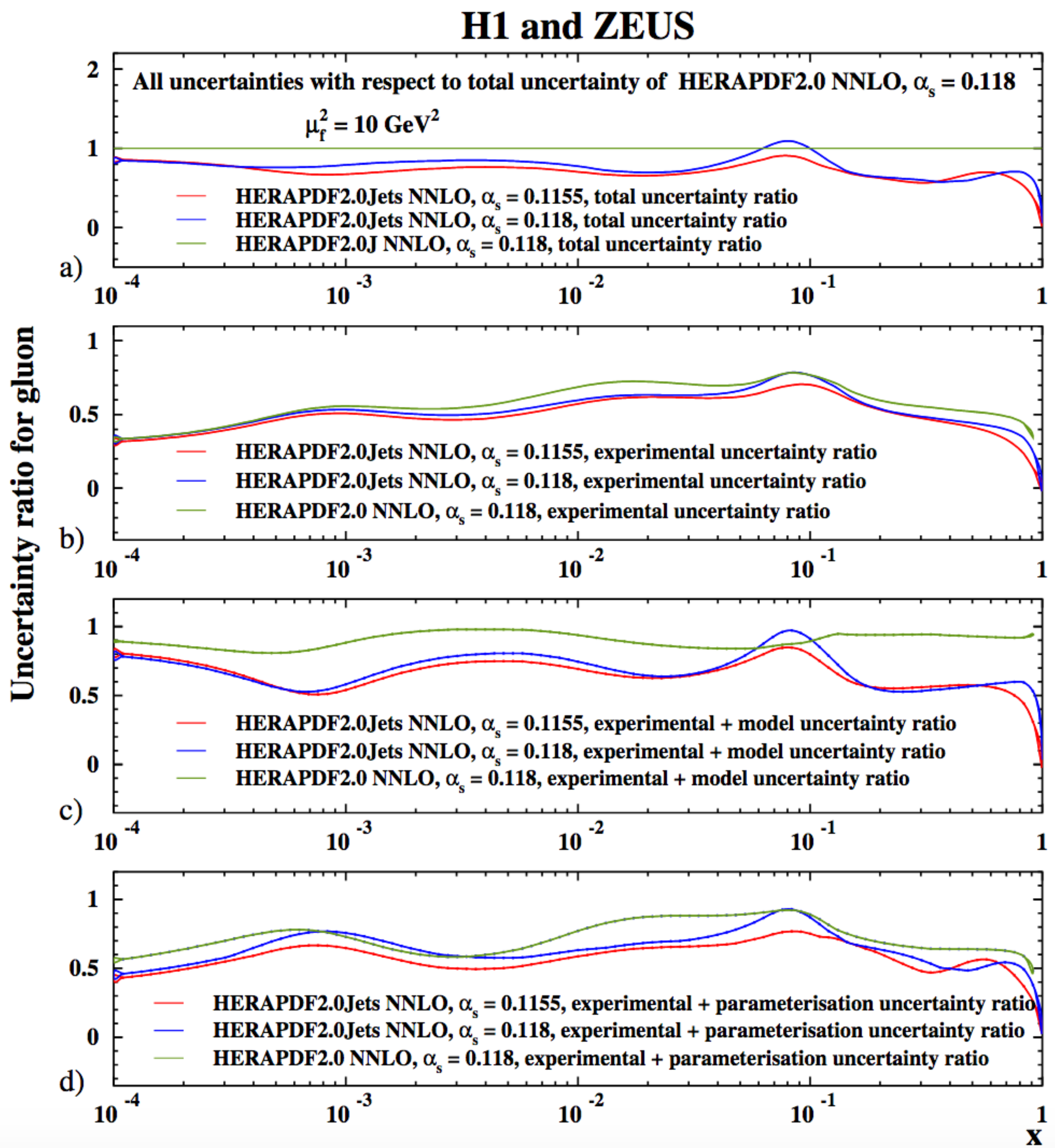

H1 and ZEUS
Data/Theory
125 < Q² < 250 GeV²
250 < Q² < 500 GeV²
500 < Q² < 1000 GeV²
1000 < Q² < 2000 GeV²
2000 < Q² < 5000 GeV²
5000 < Q² < 10000 GeV²
p_T / GeV
ZEUS inclusive jets
HERAPDF2.0Jets NNLO
α_S(M_Z²) = 0.1155, Q²_min = 3.5 GeV²
NNLO(0.118)/NNLO(0.1155)
b)


H1 and ZEUS
dσ/d<p_T>_2 (pb/GeV)
125 < Q^2 < 250 GeV^2
250 < Q^2 < 500 GeV^2
500 < Q^2 < 1000 GeV^2
1000 < Q^2 < 2000 GeV^2
2000 < Q^2 < 5000 GeV^2
5000 < Q^2 < 20000 GeV^2
<p_T>_2 / GeV
ZEUS dijets
HERAPDF2.0Jets NNLO
α_S(M_Z^2) = 0.1155, Q^2_min = 3.5 GeV^2
a)


H1 and ZEUS
Data/Theory
125 < Q^2 < 250 GeV^2
250 < Q^2 < 500 GeV^2
500 < Q^2 < 1000 GeV^2
1000 < Q^2 < 2000 GeV^2
2000 < Q^2 < 5000 GeV^2
5000 < Q^2 < 20000 GeV^2
<p_T>_2 / GeV
ZEUS dijets
HERAPDF2.0Jets NNLO
α_S(M_Z^2) = 0.1155, Q^2_min = 3.5 GeV^2
NNLO(0.118)/NNLO(0.1155)
b)

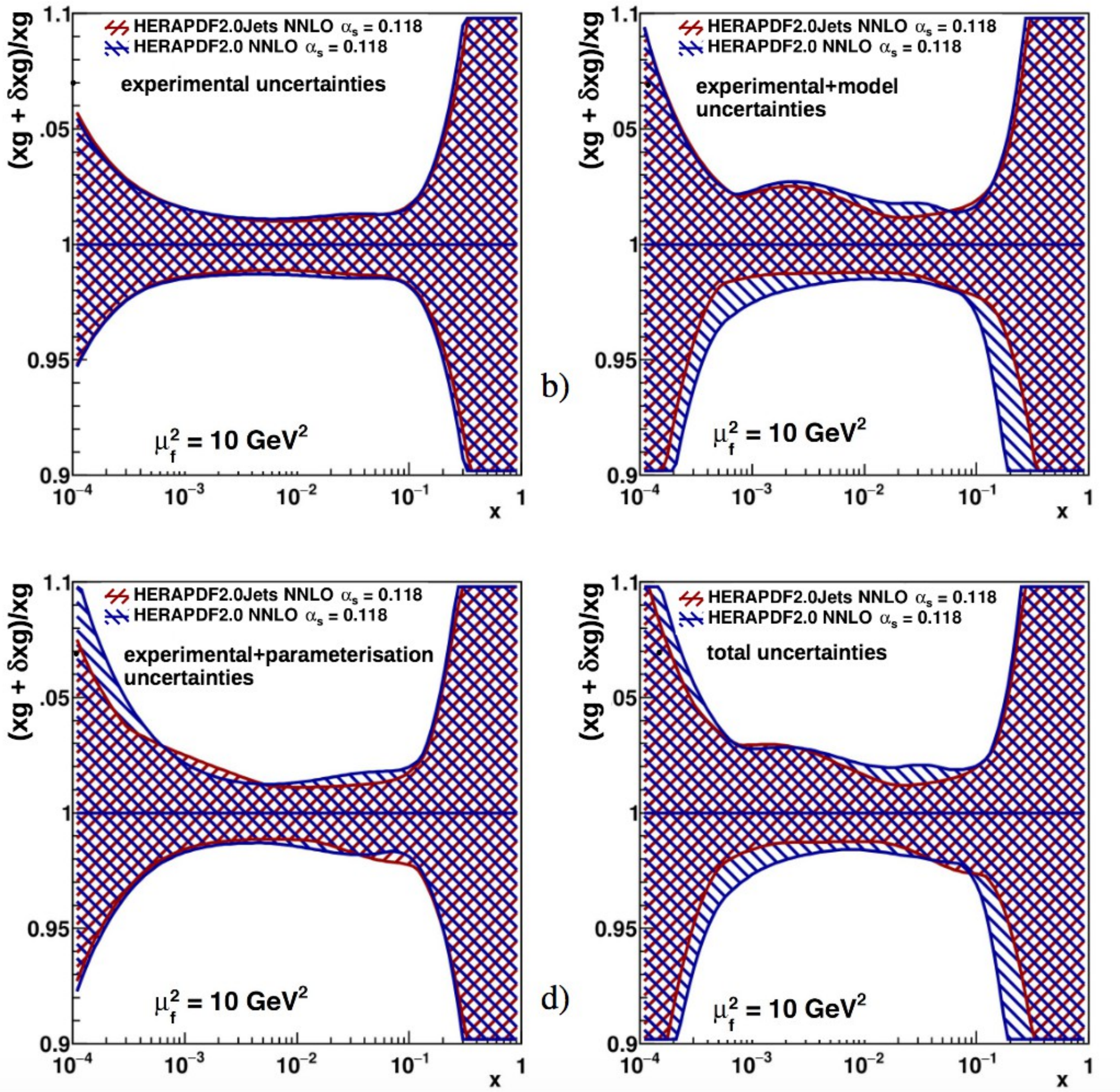
Uncertainties

- Reduction of low-x gluon ($x < 10^{-3}$) uncertainties due to reduced model/param uncertainties in variations of M_c and μ_f^2
- Reduction of high-x gluon ($x > 10^{-3}$) uncertainties due to reduced model/param/exp uncertainties
- The same for other scales



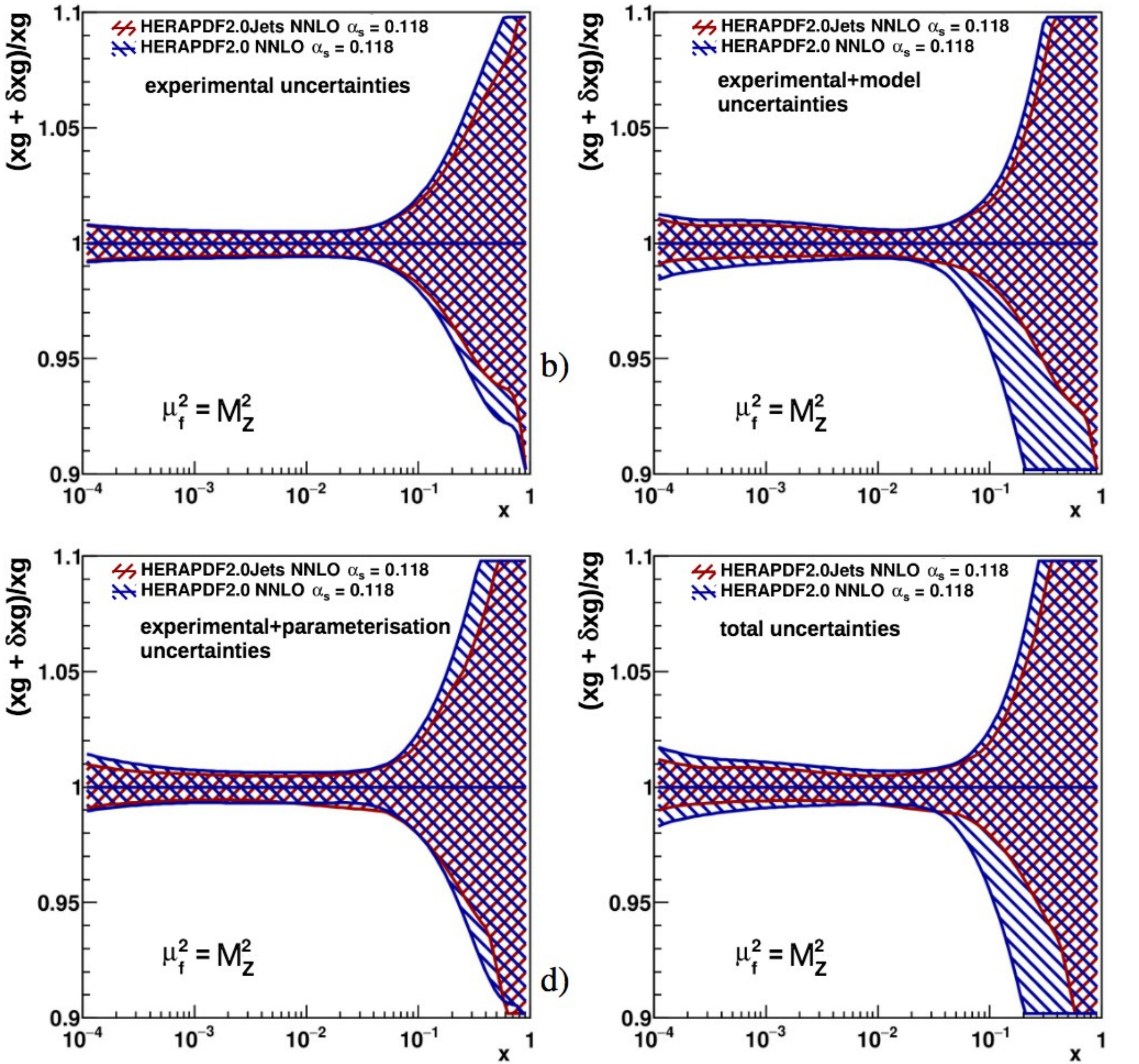
Uncertainties

H1 and ZEUS



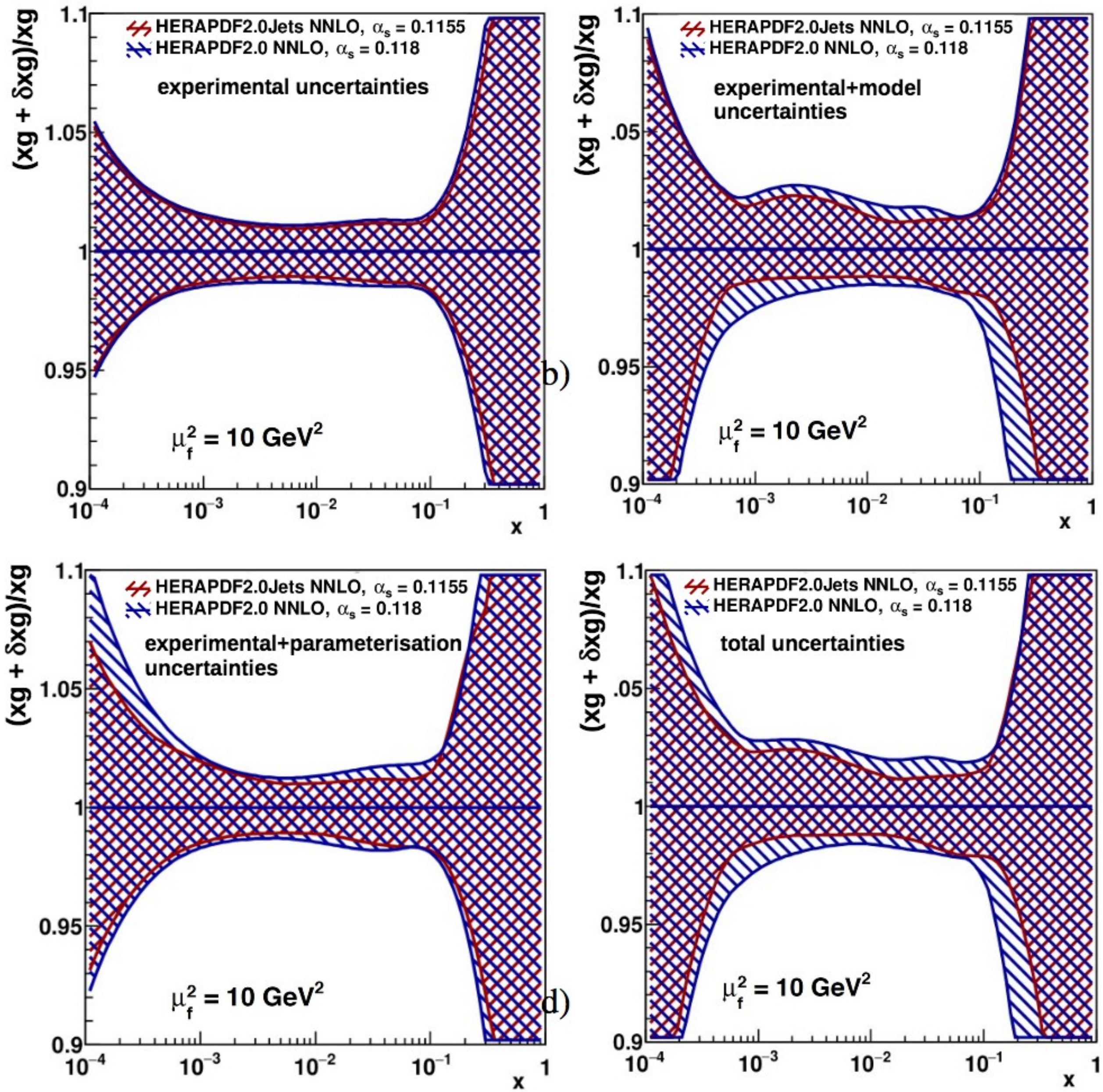
Uncertainties

H1 and ZEUS



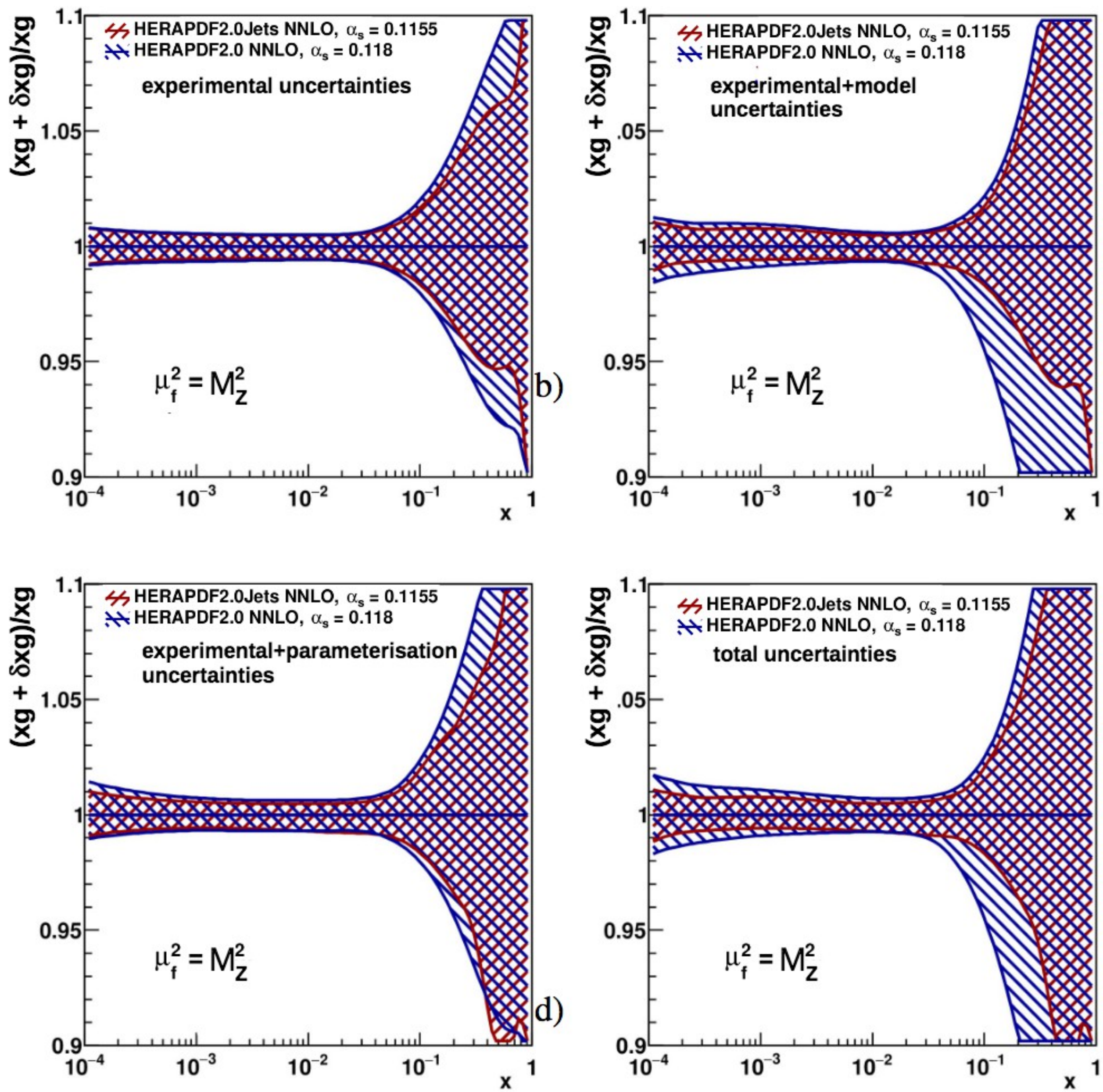
Uncertainties

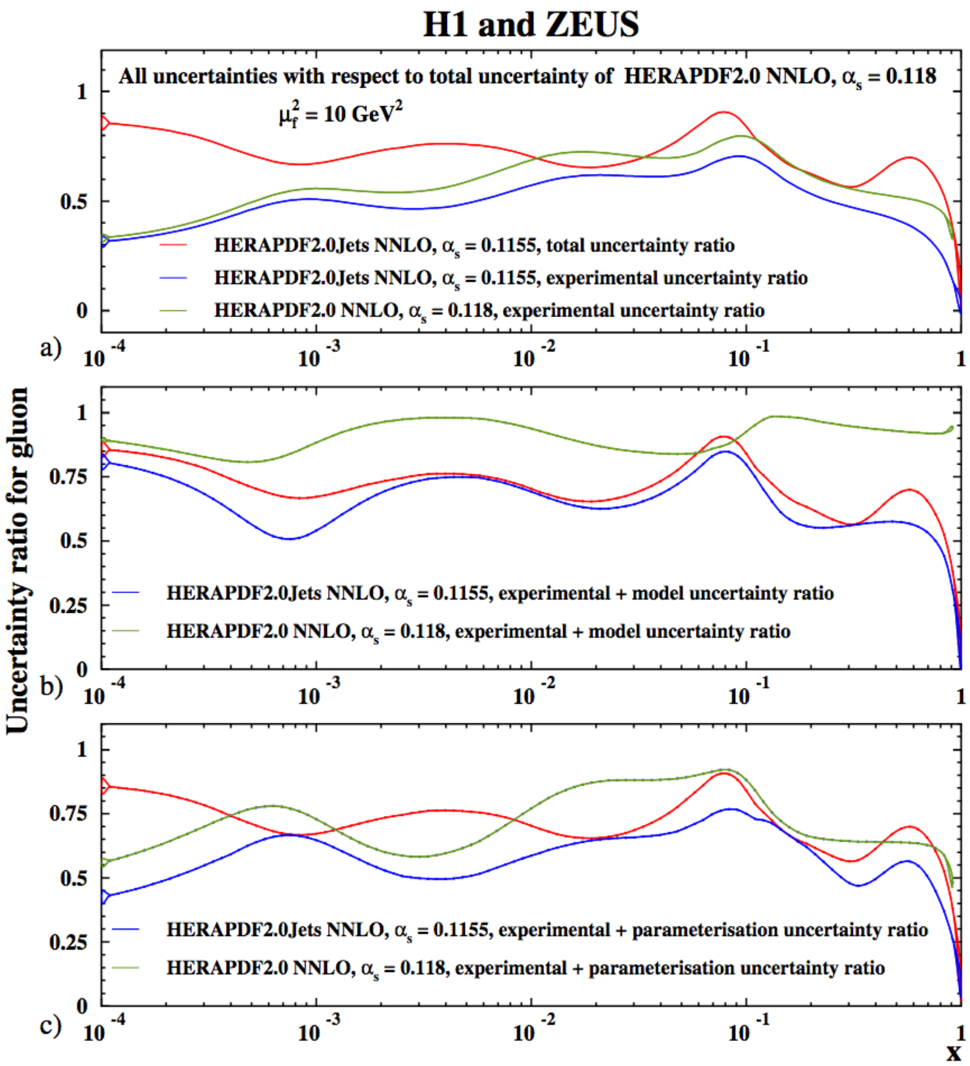
H1 and ZEUS

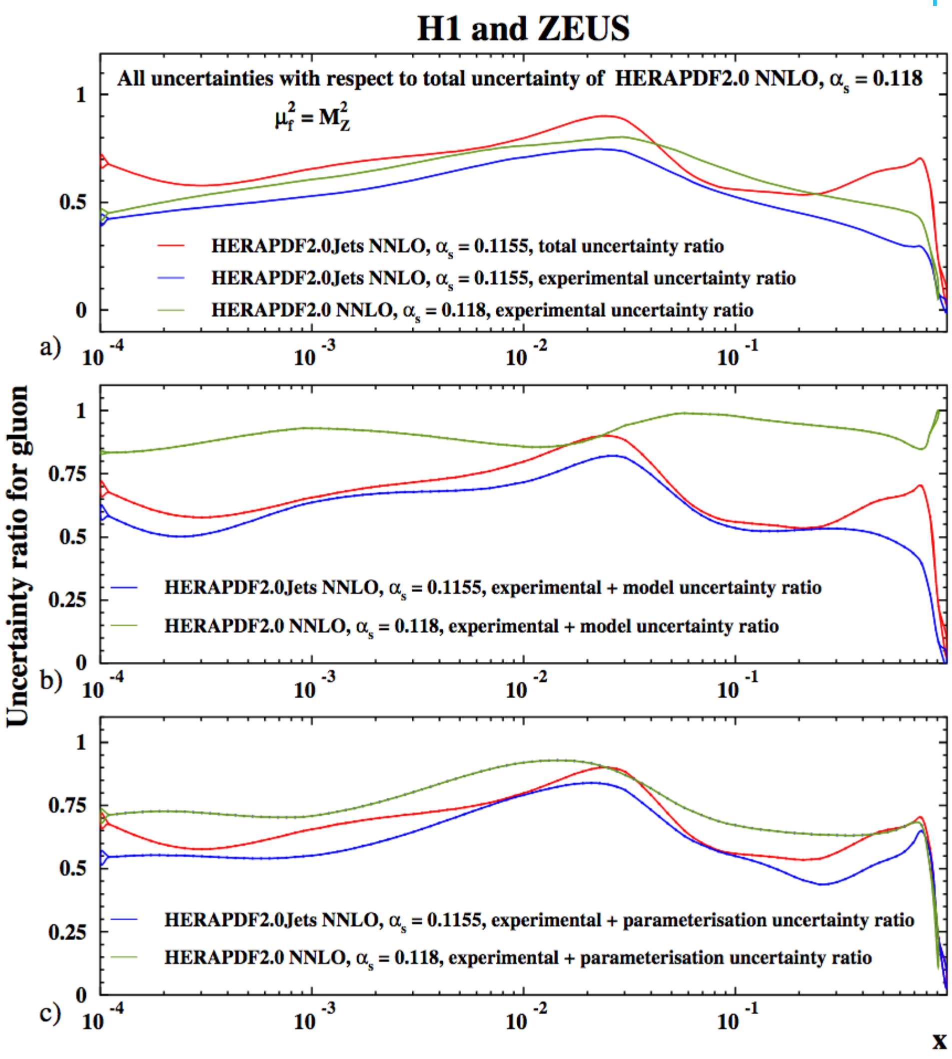


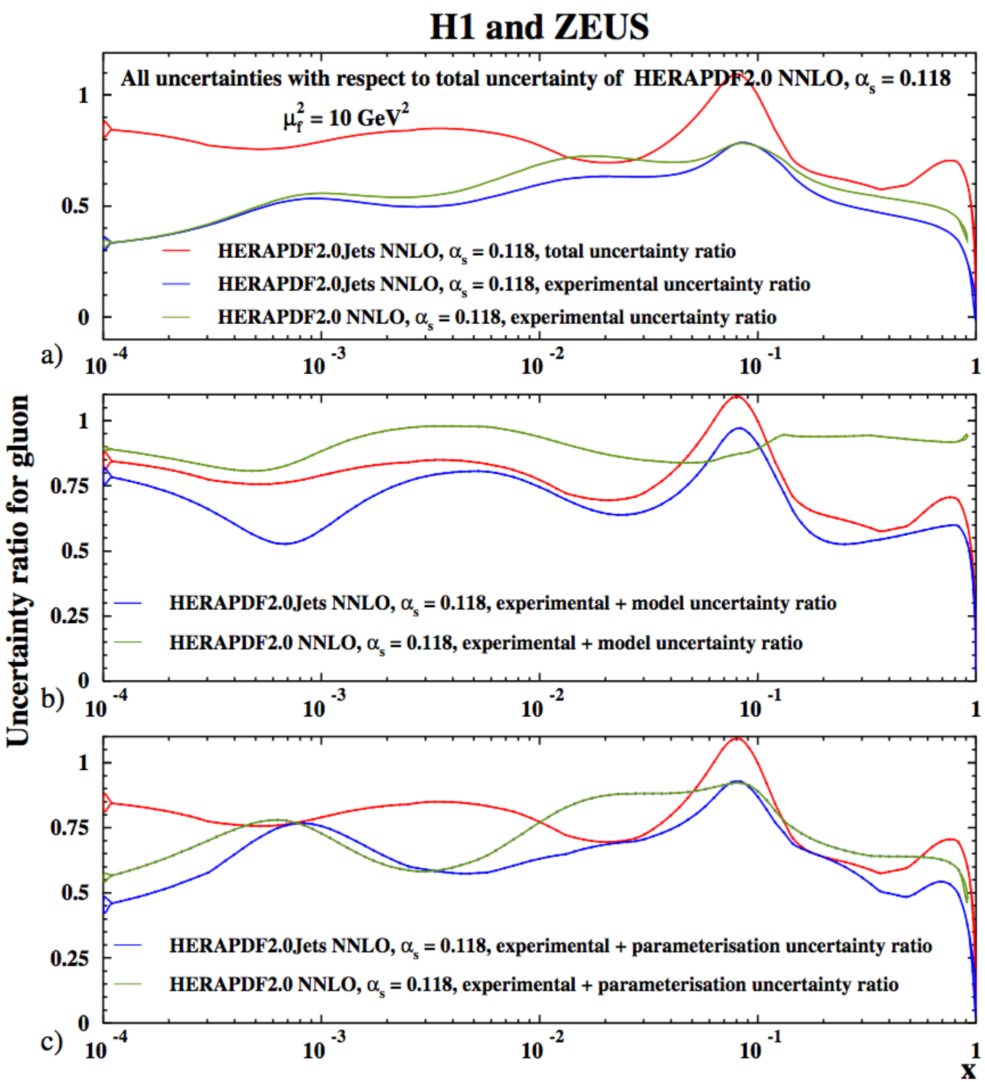
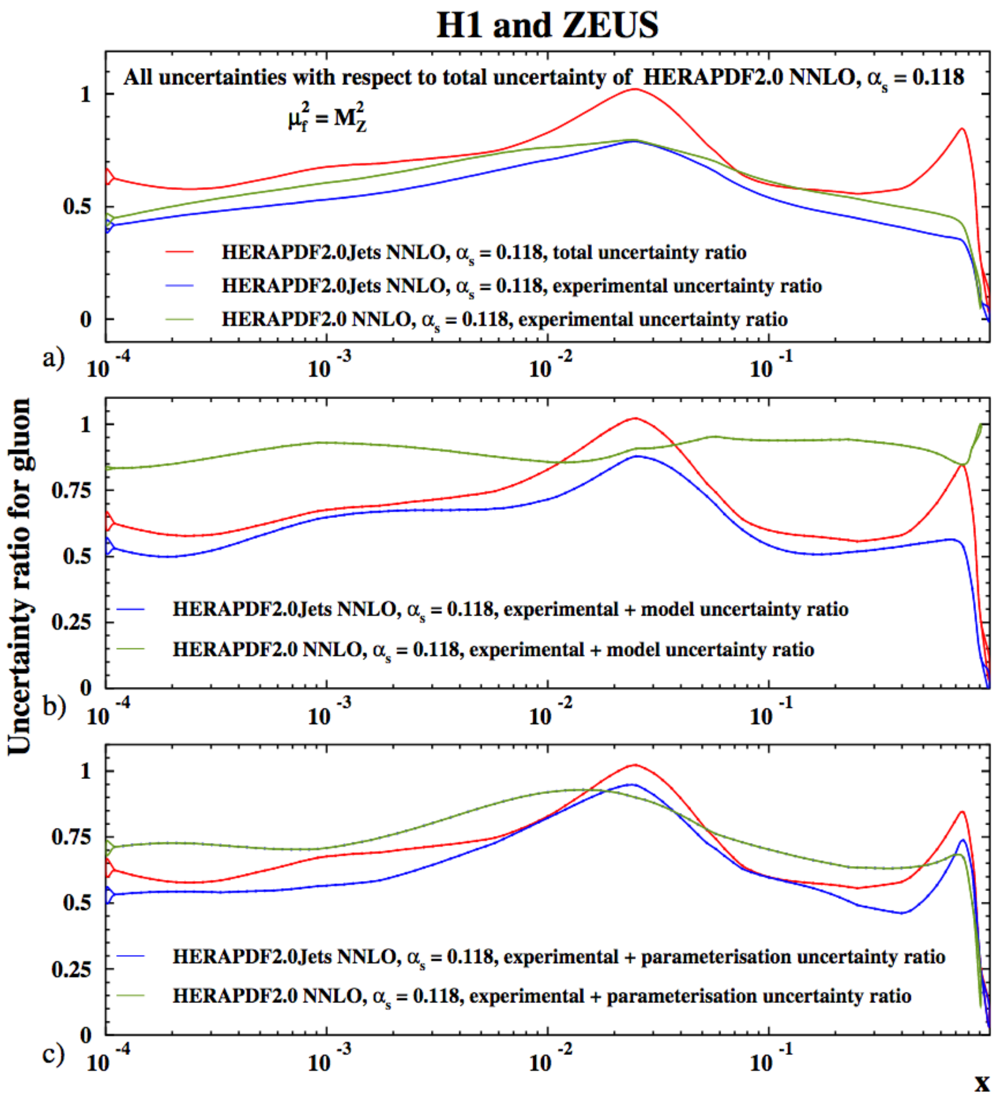
Uncertainties

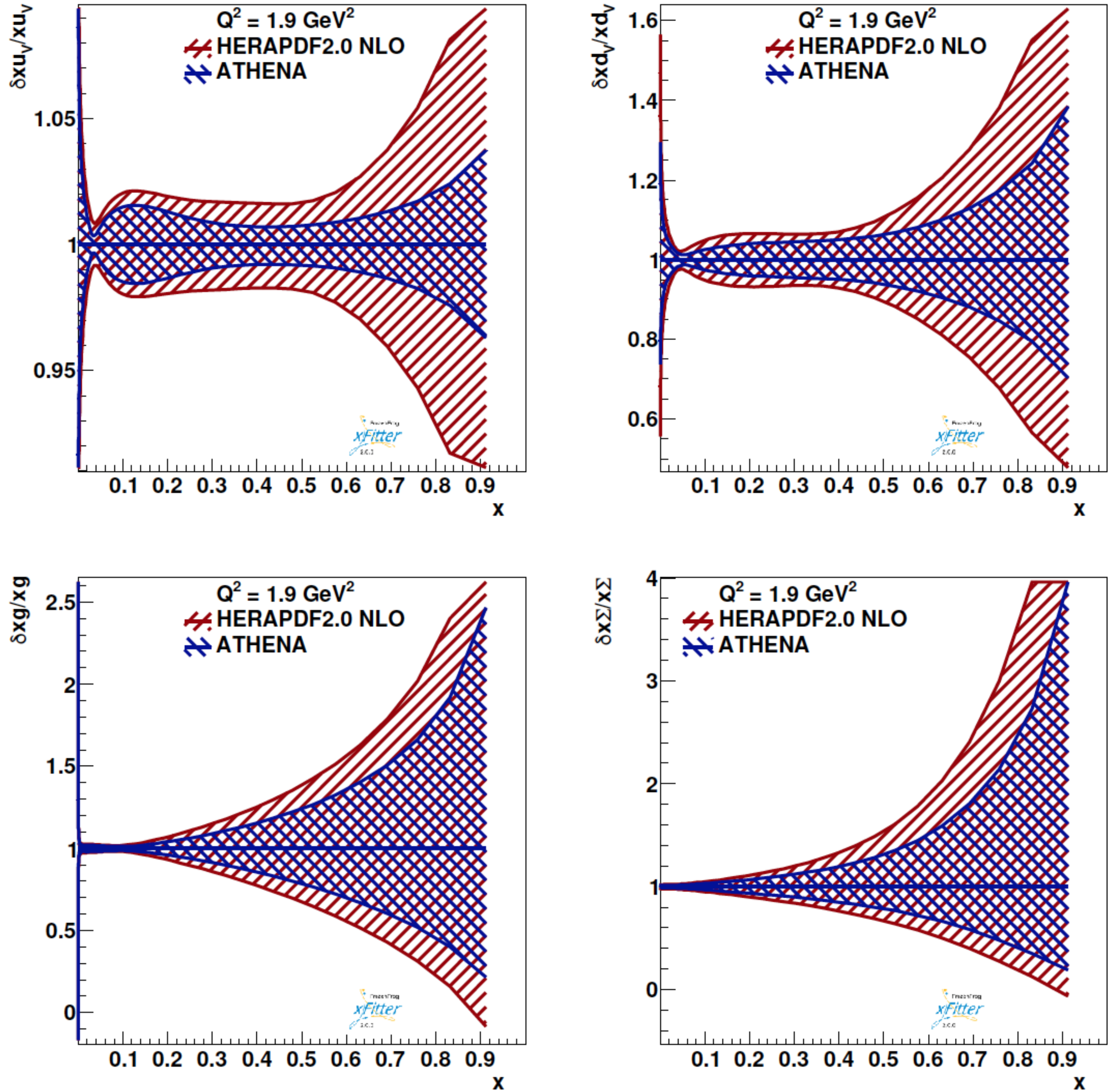
H1 and ZEUS




H1 and ZEUS
All uncertainties with respect to total uncertainty of HERAPDF2.0 NNLO, αs = 0.118
μf² = 10 GeV²
HERAPDF2.0Jets NNLO, αs = 0.1155, total uncertainty ratio
HERAPDF2.0Jets NNLO, αs = 0.1155, experimental uncertainty ratio
HERAPDF2.0 NNLO, αs = 0.118, experimental uncertainty ratio
HERAPDF2.0Jets NNLO, αs = 0.1155, experimental + model uncertainty ratio
HERAPDF2.0 NNLO, αs = 0.118, experimental + model uncertainty ratio
HERAPDF2.0Jets NNLO, αs = 0.1155, experimental + parameterisation uncertainty ratio
HERAPDF2.0 NNLO, αs = 0.118, experimental + parameterisation uncertainty ratio
Uncertainty ratio for gluon
a)
b)
c)
x

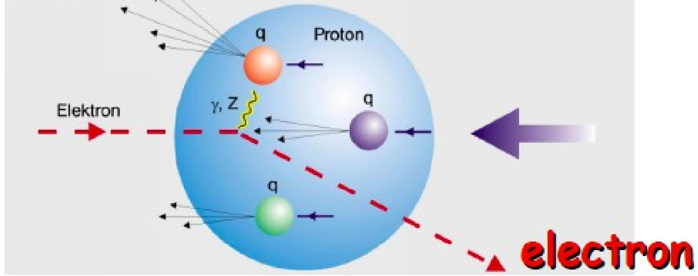

H1 and ZEUS
All uncertainties with respect to total uncertainty of HERAPDF2.0 NNLO, αs = 0.118
μf² = M²Z
HERAPDF2.0Jets NNLO, αs = 0.1155, total uncertainty ratio
HERAPDF2.0Jets NNLO, αs = 0.1155, experimental uncertainty ratio
HERAPDF2.0 NNLO, αs = 0.118, experimental uncertainty ratio
HERAPDF2.0Jets NNLO, αs = 0.1155, experimental + model uncertainty ratio
HERAPDF2.0 NNLO, αs = 0.118, experimental + model uncertainty ratio
HERAPDF2.0Jets NNLO, αs = 0.1155, experimental + parameterisation uncertainty ratio
HERAPDF2.0 NNLO, αs = 0.118, experimental + parameterisation uncertainty ratio
Uncertainty ratio for gluon
a)
b)
c)
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 = 0.118, total 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 = 0.118, experimental + model uncertainty ratio
HERAPDF2.0 NNLO, α_s = 0.118, experimental + model uncertainty ratio
HERAPDF2.0Jets NNLO, α_s = 0.118, experimental + parameterisation uncertainty ratio
HERAPDF2.0 NNLO, α_s = 0.118, experimental + parameterisation uncertainty ratio
Uncertainty ratio for gluon
a)
b)
c)
x

H1 and ZEUS
All uncertainties with respect to total uncertainty of HERAPDF2.0 NNLO, α_s = 0.118
$\mu_f^2 = M_Z^2$
HERAPDF2.0Jets NNLO, α_s = 0.118, total 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 = 0.118, experimental + model uncertainty ratio
HERAPDF2.0 NNLO, α_s = 0.118, experimental + model uncertainty ratio
HERAPDF2.0Jets NNLO, α_s = 0.118, experimental + parameterisation uncertainty ratio
HERAPDF2.0 NNLO, α_s = 0.118, experimental + parameterisation uncertainty ratio
Uncertainty ratio for gluon
a)
b)
c)
x

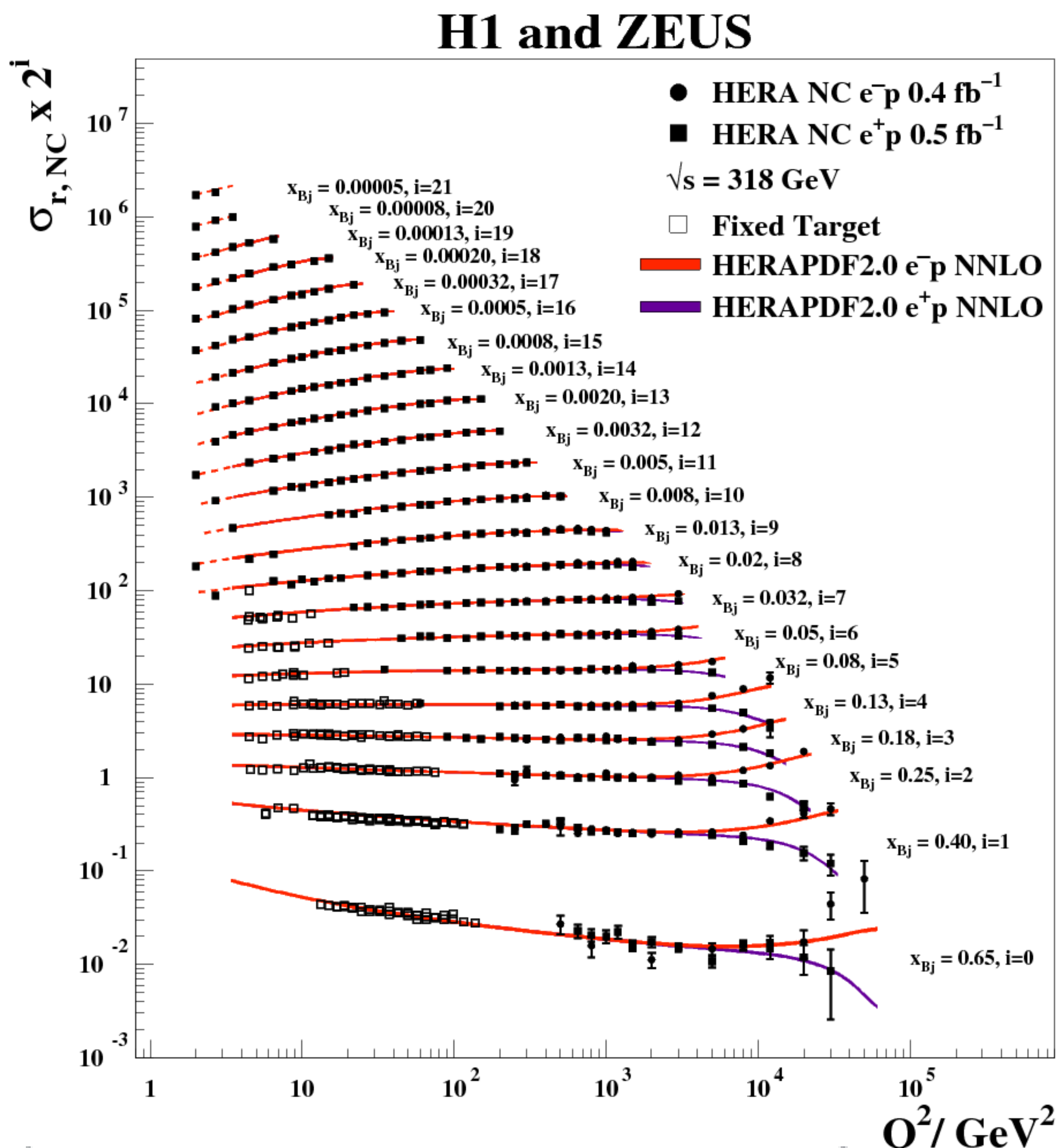


K. Wichmann @ EPIPHANY23

PDFs @ HERA



HERA combined inclusive DIS

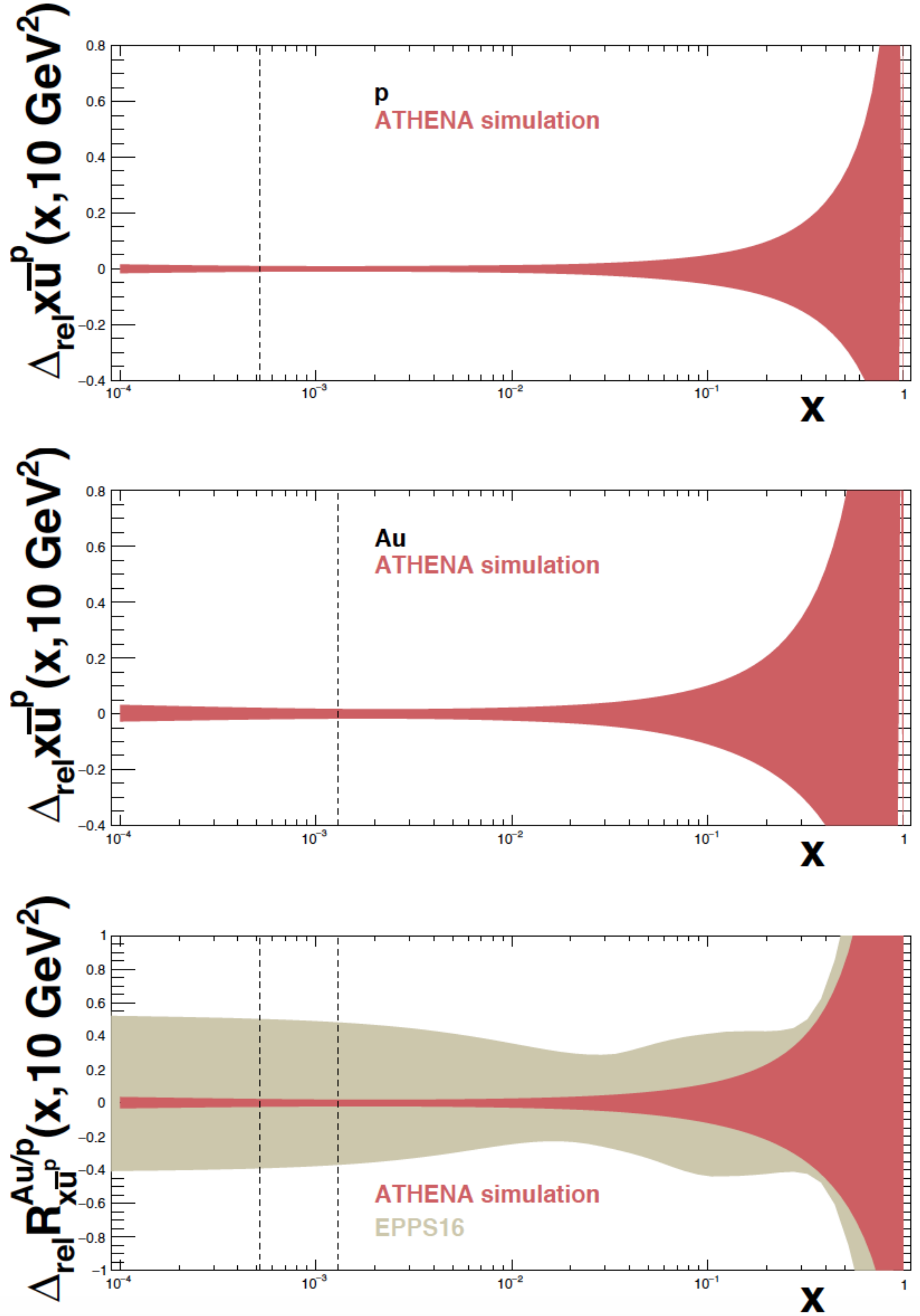


<u>HERA combined DIS data are core of every modern PDF extraction</u>

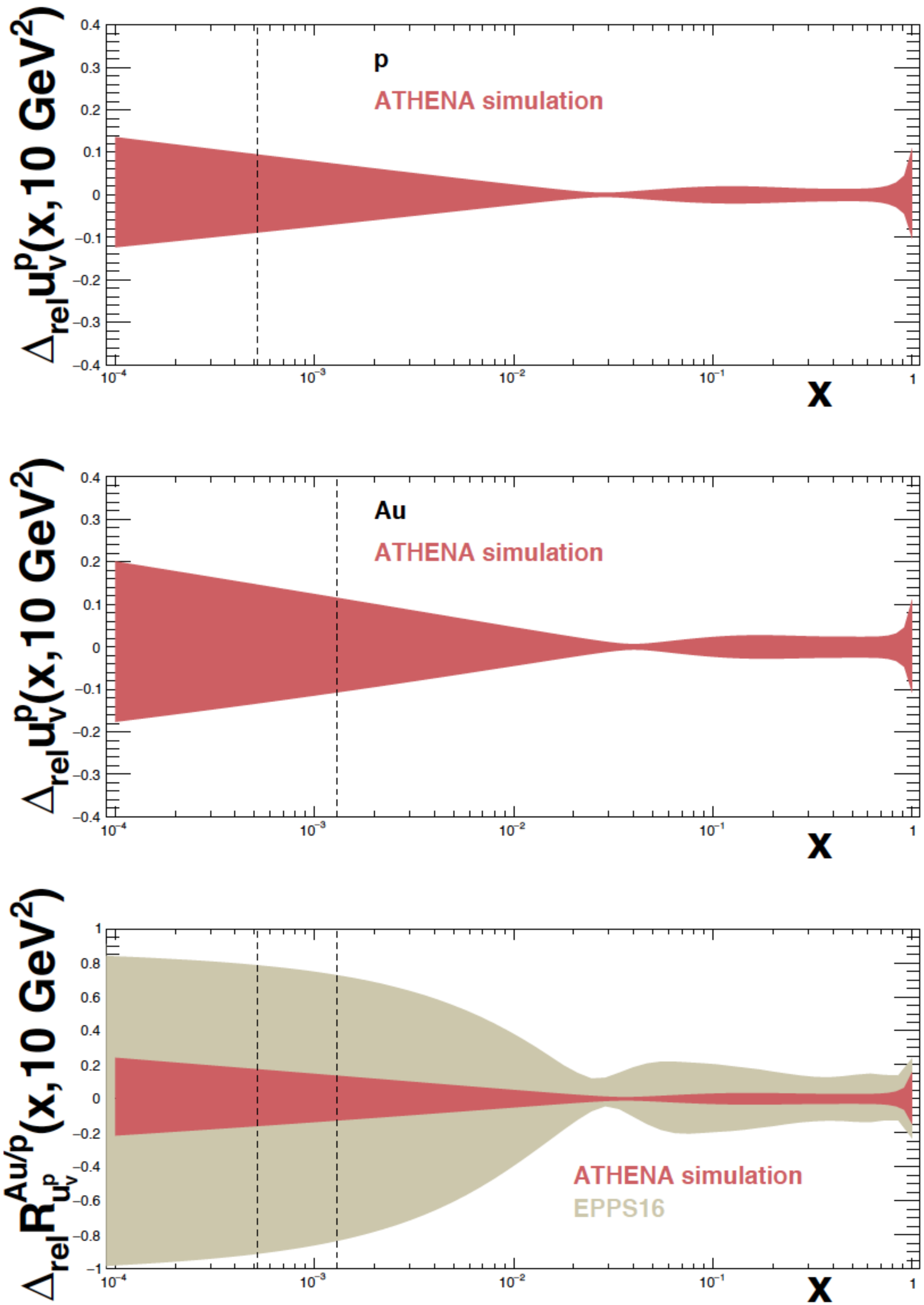
- 2927 data points combined to 1307
- impressive precision

HERAPDF approach uses ONLY HERA data in global QCD fit

Eur. Phys. J. **C75** (2015), 12, 580



p
ATHENA simulation
Au
ATHENA simulation
ATHENA simulation
EPPS16
$\Delta_{rel} x\bar{u}^{p}(x, 10\ GeV^2)$
$\Delta_{rel} R^{Au/p}_{x\bar{u}^{p}}(x, 10\ GeV^2)$
x


p
ATHENA simulation
$\Delta_{rel} u_v^p(x, 10\ GeV^2)$
x
Au
ATHENA simulation
$\Delta_{rel} u_v^p(x, 10\ GeV^2)$
x
ATHENA simulation
EPPS16
$\Delta_{rel} R_{u_v^p}^{Au/p}(x, 10\ GeV^2)$
x

How to obtain collinear/TMD PDFs form PB method? QCD fit to HERA data

Fitting procedure in a nutshell:

- parameterize collinear PDF at μ_0^2
- produce PB kernels for collinear & TMD distributions to evolve them to $\mu^2 > \mu_0^2$
  [Eur. Phys. J. C **74**, 3082 (2014)]
- perform fits to measurements using xFitter frame to extract the initial parametrization (with collinear coefficient functions at NLO)
- store the TMDs in a grid for later use in CASCADE3 [Eur. Phys. J. C **81**, no.5, 425 (2021)]
- plot collinear and TMD pdfs within TMDPLOTTER [arXiv:2103.09741]

5 FLNS:

- full coupled evolution with all flavors & $\alpha_s(M_Z^{n_f=5}) = 0.118$
- HERAPDF parametrization form
- using full HERAI+II inclusive DIS data ($3.5 < Q^2 < 50000$ GeV^2 & $4.10^{-5} < x < 0.65$)
- $\chi^2/dof = 1.21$

[Phys. Rev. D **99** (2019) no. 7, 074008]

4 FLNS:

- the same functional form & data as 5FL - parameters are re-fitted
- $m_b \to \infty$ & $\alpha_s(M_Z^{n_f=4}) = 0.1128$
- $\chi^2/dof = 1.25$

[arXiv:2106.09791]