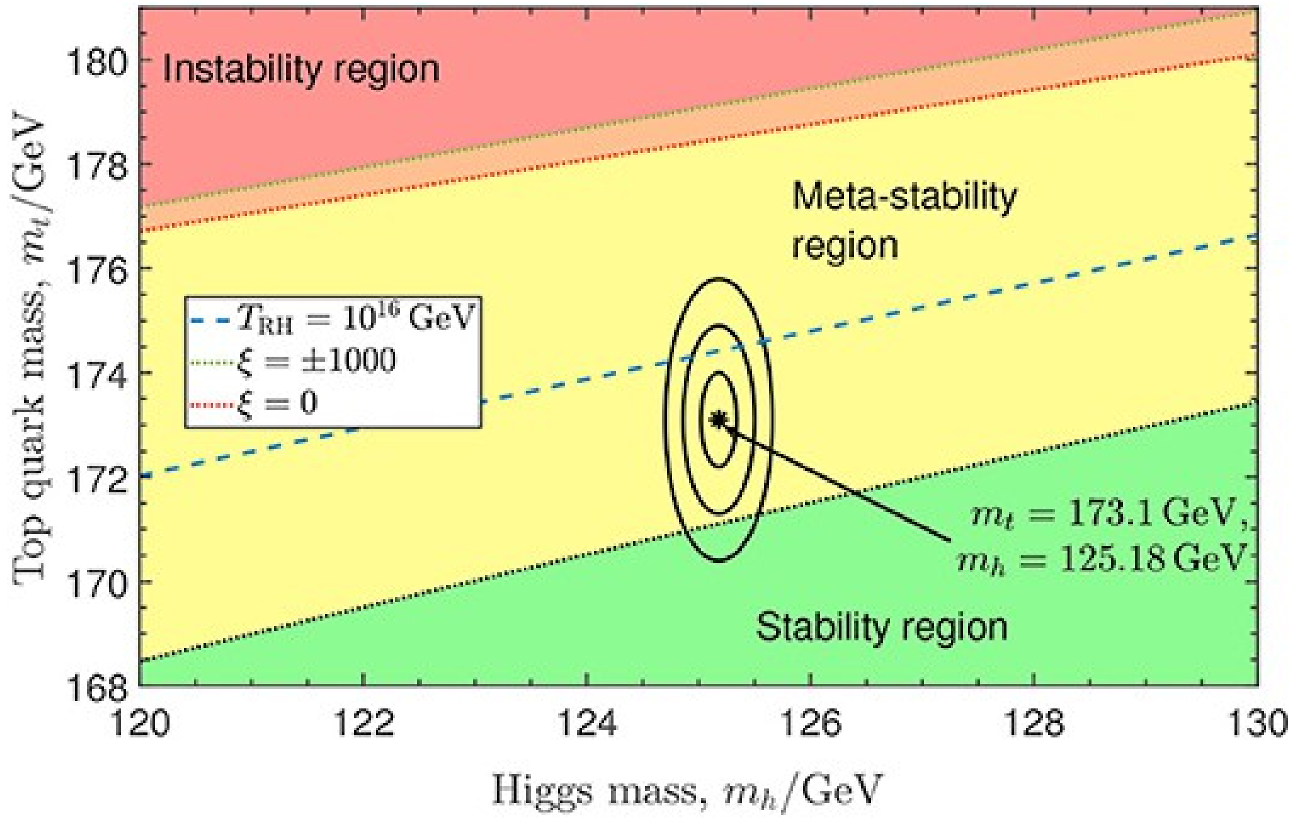
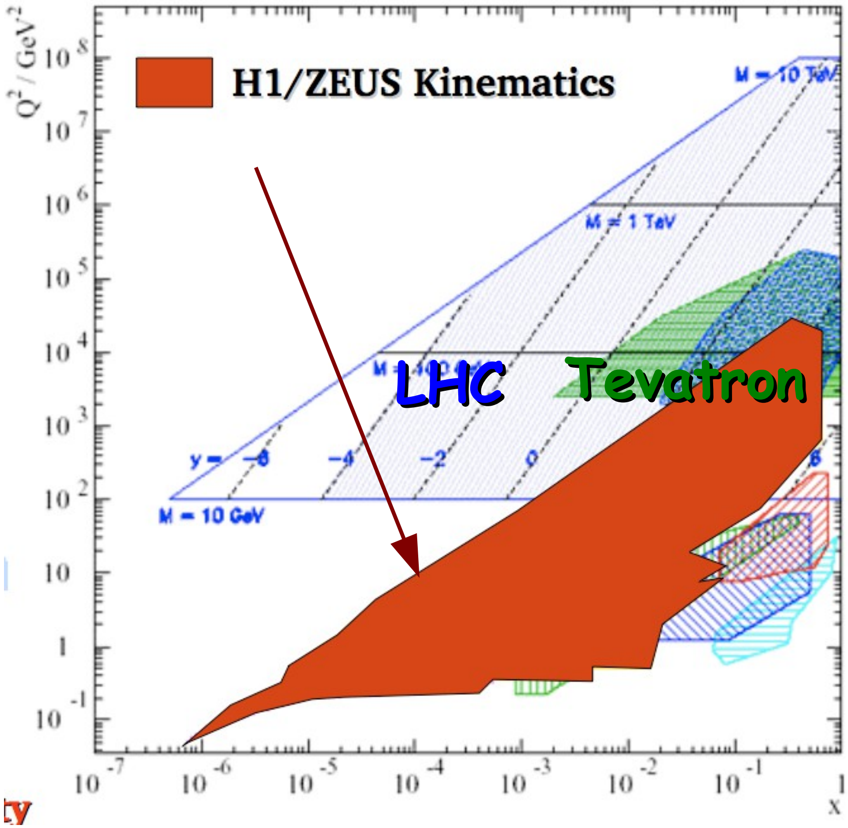
Proton structure and HERA data ...

... or rather: will we tunnel?



Proton structure

- PDFs used in interactions with proton: LHC, Tevatron, HERA
- Precision of many measurements often limited by PDF uncertainty
    - Higgs/top properties

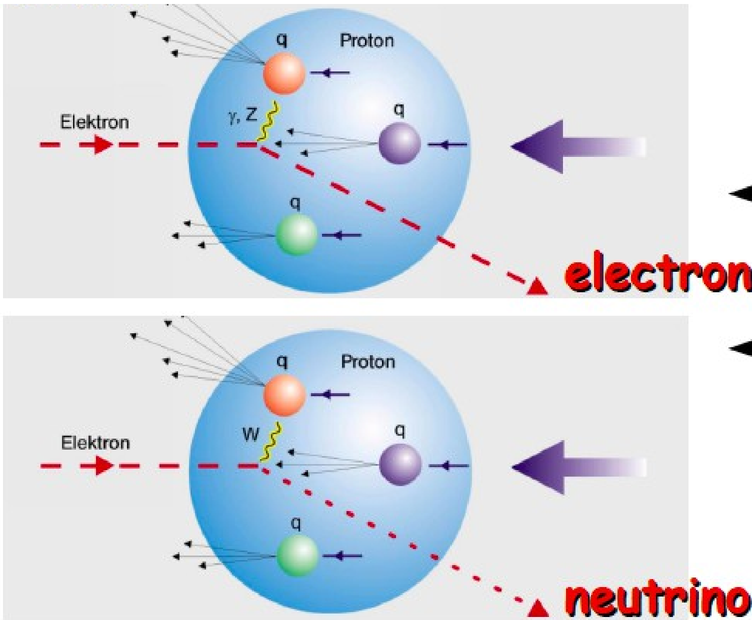


Inclusive measurements from HERA are core of every parton density extraction

HERA accelerator

Two colliding experiments

Deep Inelastic Scattering @ HERA

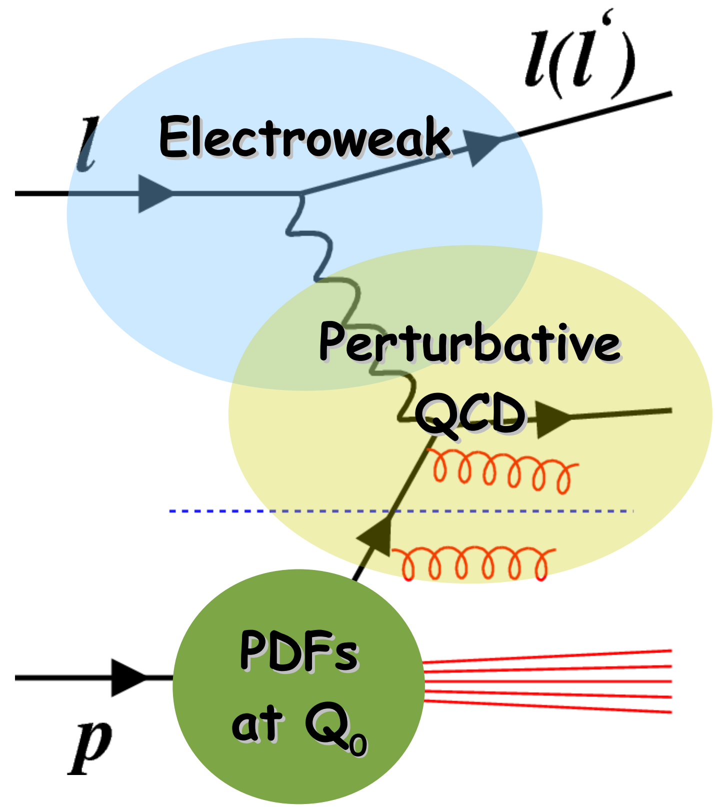


Neutral Current (NC)

γ, Z^0 exchange

Charged Current (CC)

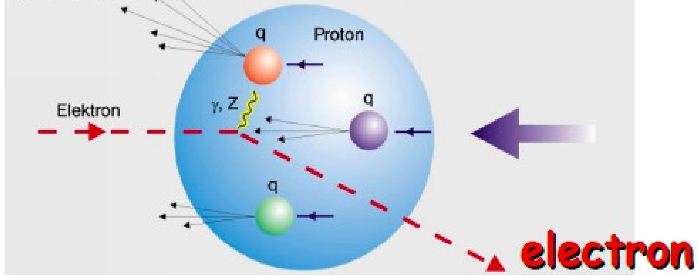
$W^{\pm}$ exchange



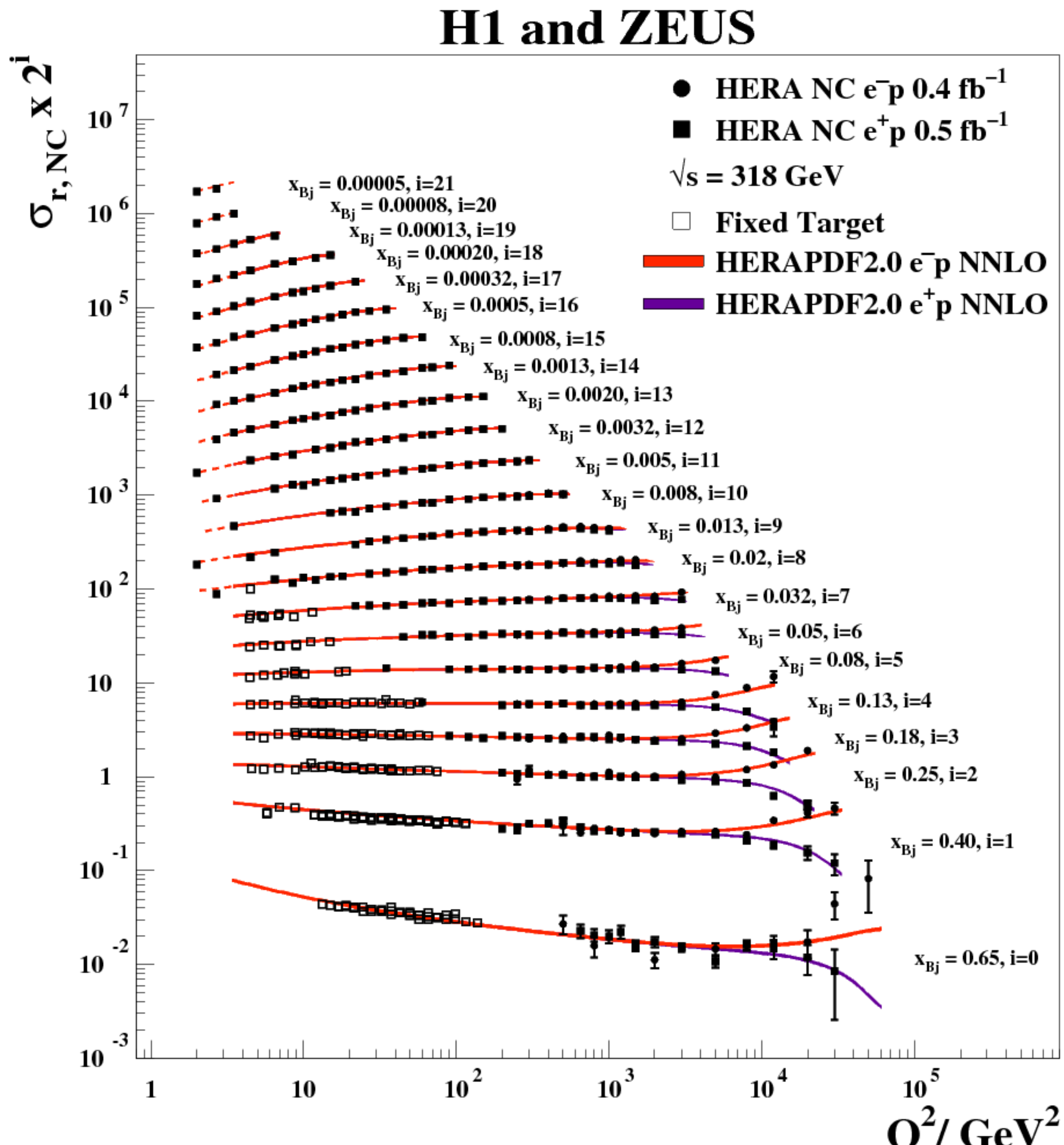
$$Q^2 = -q^2 = -(k-k')^2$$

$$x = \frac{Q^2}{2p\cdot q} \qquad y = \frac{p\cdot q}{p\cdot k}$$

$$s = (p+k)^2 \qquad Q^2 = x_{Bj}\cdot y\cdot s$$



HERA combined inclusive DIS



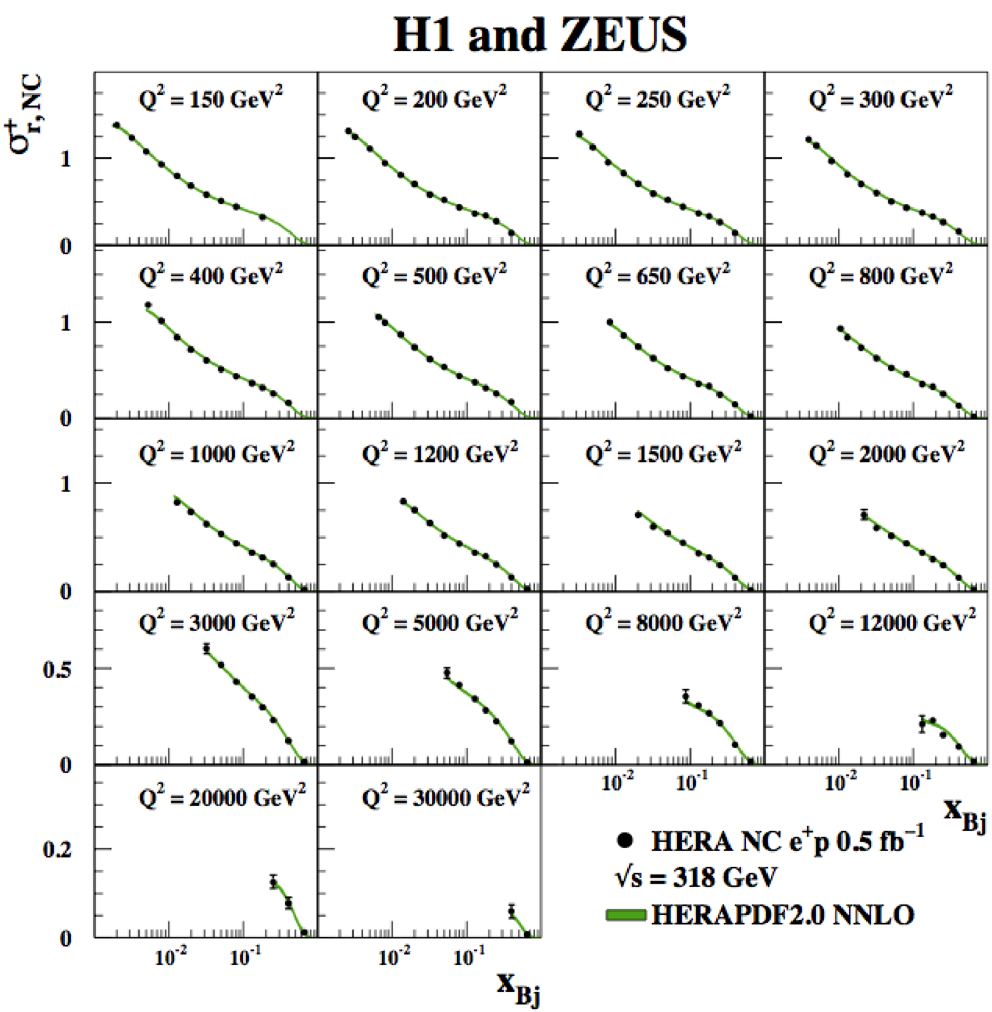
HERA combined DIS data are core of every modern PDF extraction

- 2927 data points combined to 1307
- Impressive precision
- Beautiful QCD and EW effects clearly seen

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

Neutral Current

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2 \mp Y_-xF_3 - y^2F_L\right]$$



Proton structure functions

$$F_2 = x\sum e_q^2[q(x)+\bar{q}(x)]$$

- Sensitive to quarks

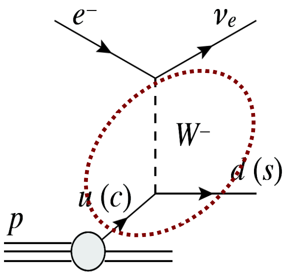
$$xF_3 = x\sum 2e_q a_q[q(x)-\bar{q}(x)]$$

- Sensitive to valence distributions

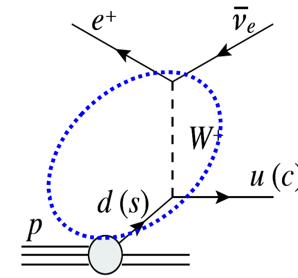
$$F_L \sim \alpha_S\, x\, g$$

- Sensitive to gluon

- Gluon also from scaling violation and charm+jet data

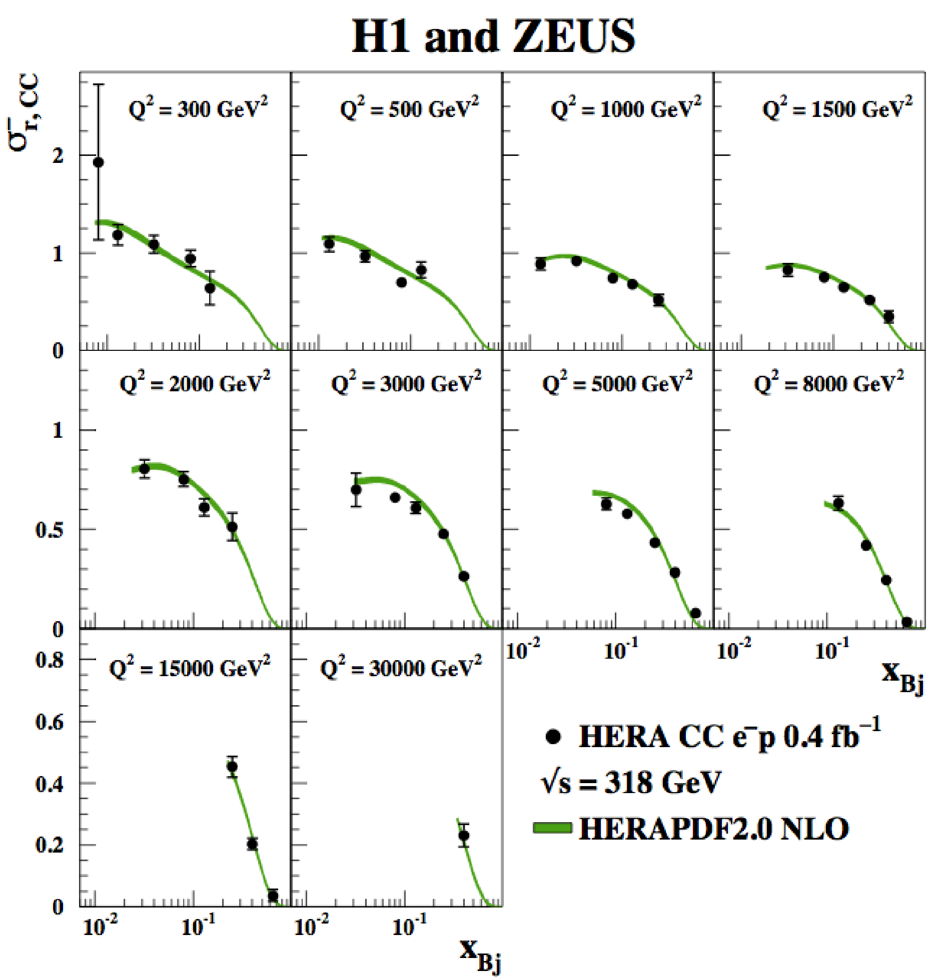


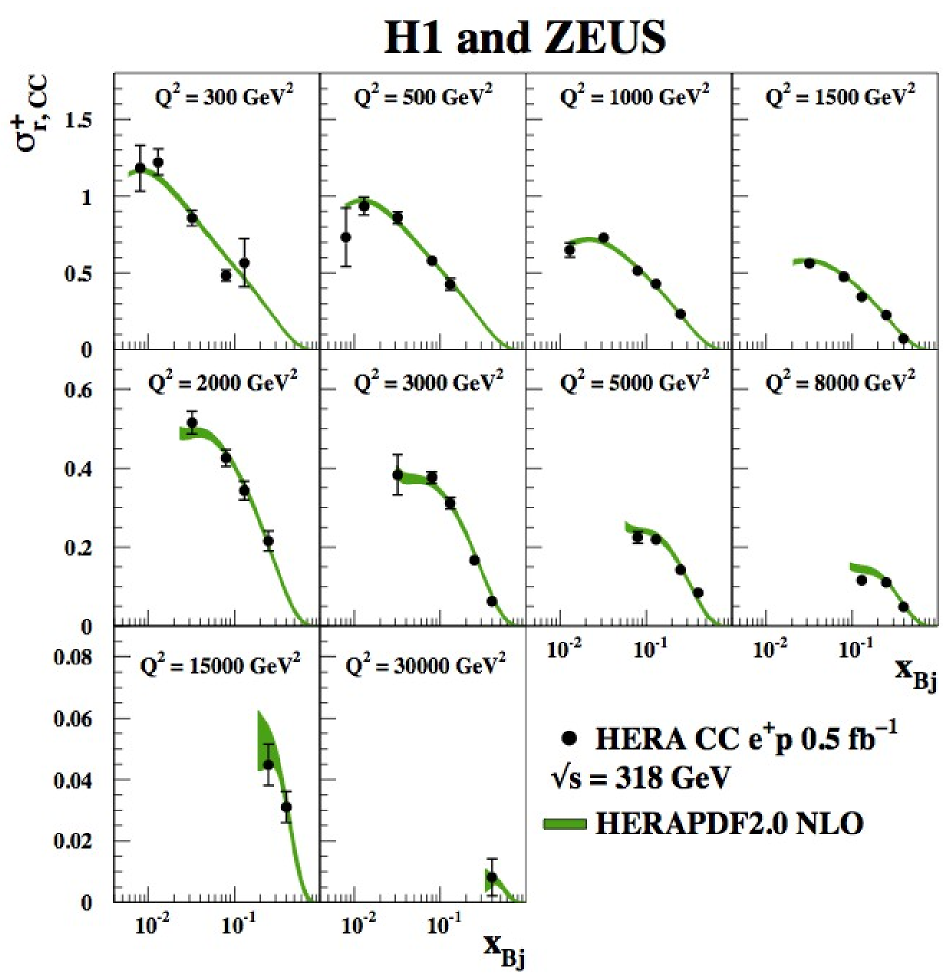
Charge Current: flavor decomposition



$$\sigma^-_{CC} \sim x[u + c] + x(1-y)^2[\bar{d} + \bar{s}]$$

$$\sigma^+_{CC} \sim x[\bar{u} + \bar{c}] + x(1-y)^2[d + s]$$





Global analysis of parton distributions

Goal: determination of the ***input distributions*** (for light quarks and gluons):

Method: Parametrizations $xf(x, Q_0^2) = Nx^a(1-x)^b \, \text{function}(x)$

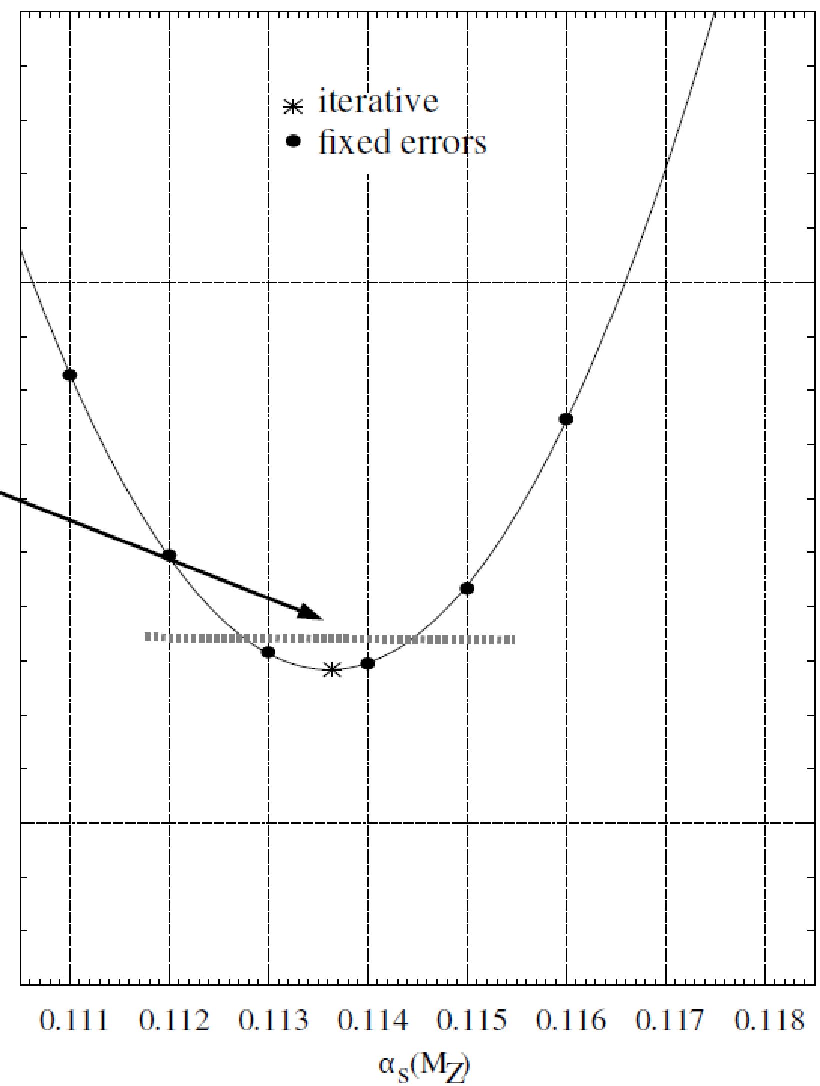
and usual *statistical estimation* (fits):

$$\chi^2(p) = \sum_{i=1}^{N} \left(\frac{\text{data}(i) - \text{theory}(i,p)}{\text{error}(i)} \right)^2$$

Position of minimum gives the value and curvature gives the error (region within a certain "tolerance" $\Delta\chi^2 = 1$)

(Monte Carlo methods can also be used)

Usually the chi-square definition is more sophisticated, experimental correlations are also treated, etc.



HERAPDF philosophy

HERAPDF approach uses only HERA data in global QCD fit

HERAPDF2.0 parameterisation

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

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

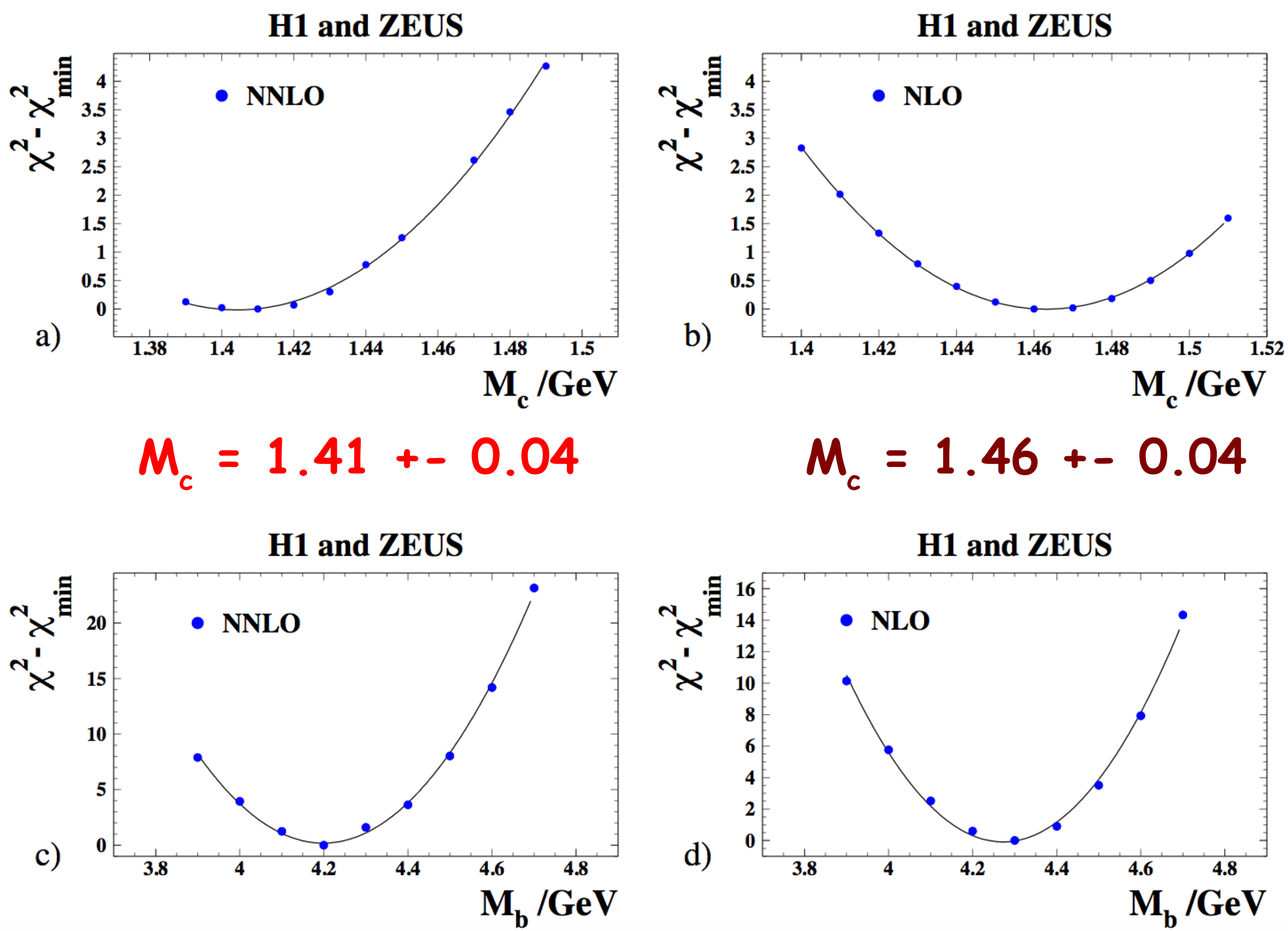
- Additional constrains
  - A_{u_v}, A_{d_v}, A_g: constrained by the quark-number sum rules and momentum sum rule
  - $B_{\bar{U}} = B_{\bar{D}}$
  - $x\bar{s} = f_s x\bar{D}$ at starting scale, f_s = 0.4

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



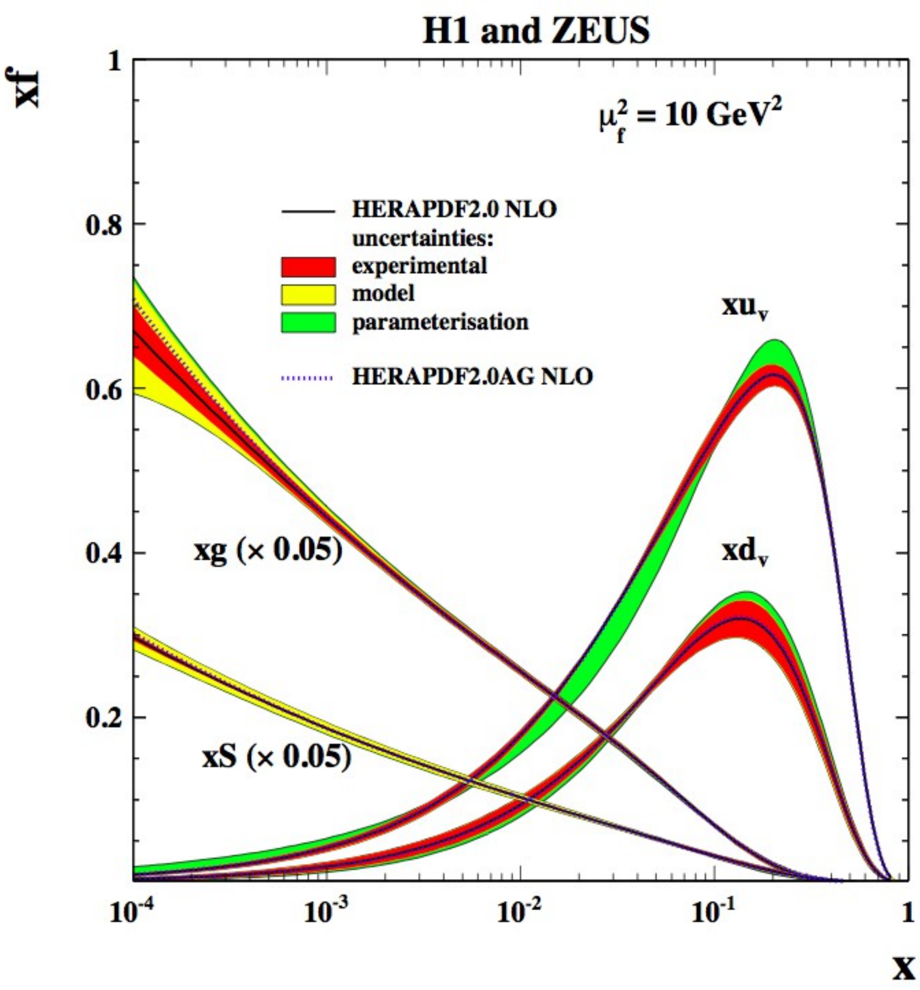
M_c = 1.41 +- 0.04 M_c = 1.46 +- 0.04

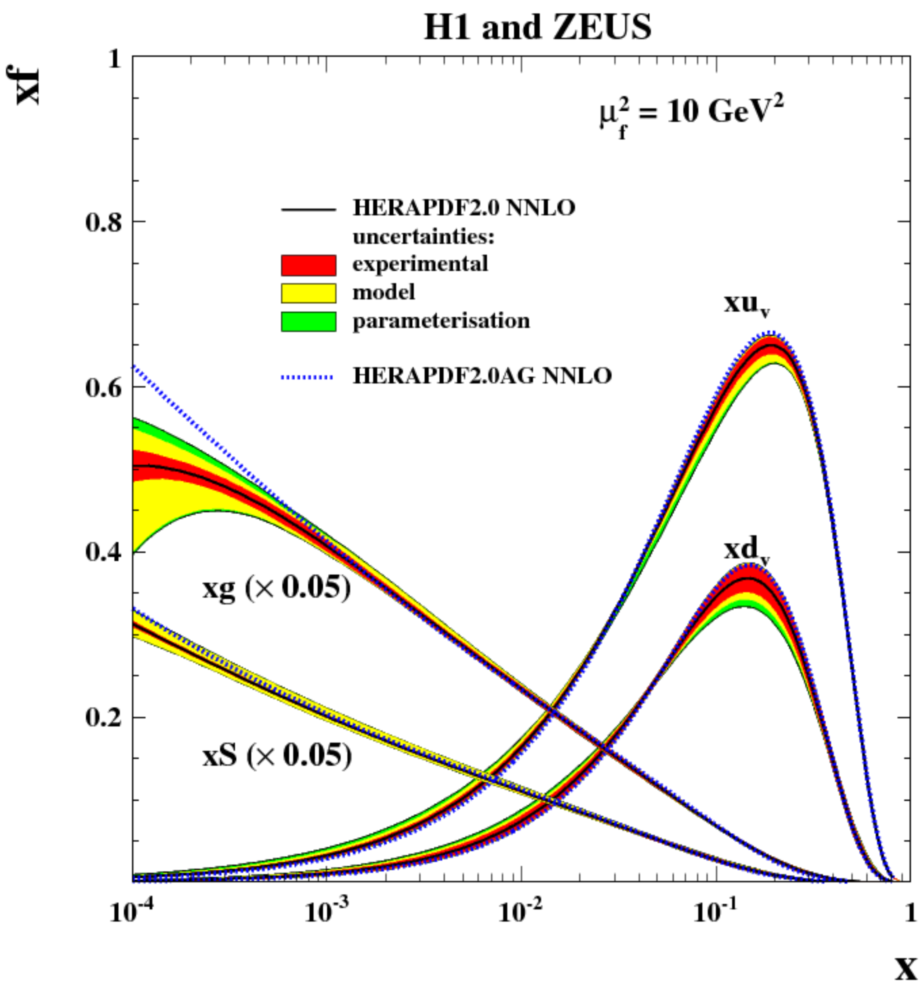
M_b = 4.2 +- 0.1 M_b = 4.3 +- 0.1

EPJC C82 (2022) 243

HERAPDF2 NLO & NNLO parton densities

NLO **NNLO**





HERAPDF2.0 extracted

with experimental, model and parametrization uncertainties

K. Wichmann @ Bad Honnef 23

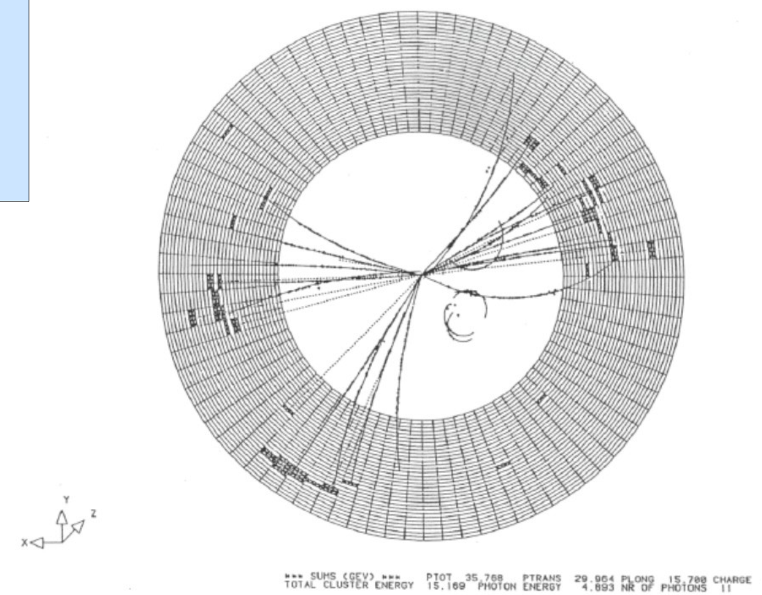
Including HERA jet data

Jets produced @ DESY for almost 45 years

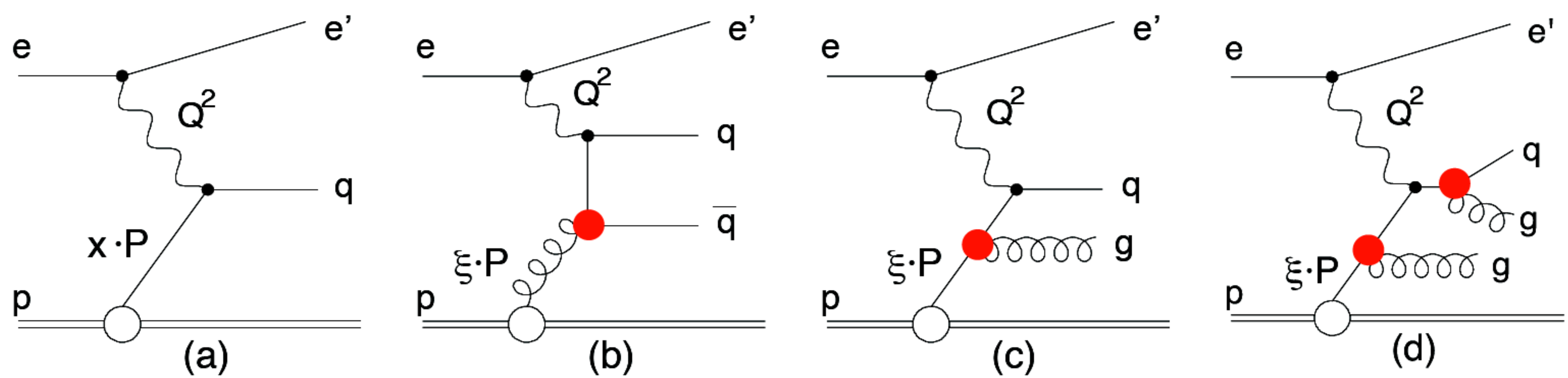
At HERA direct information on gluon and $\alpha_s(M_Z)$ comes from jet production

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

Jets at PETRA, 1979



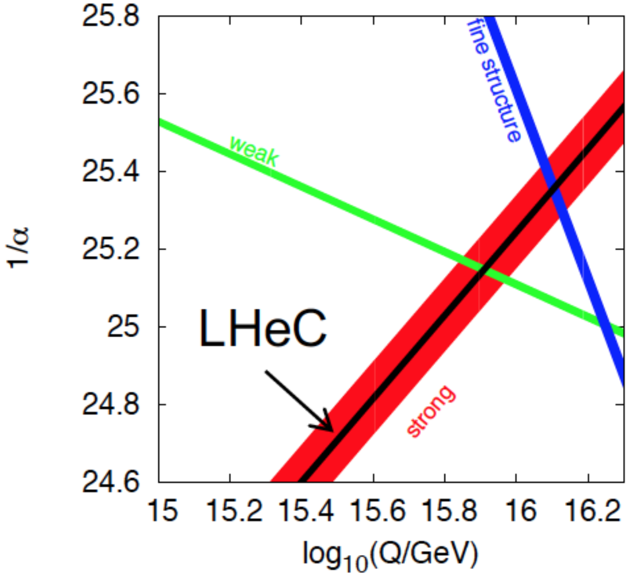
Jets at HERA

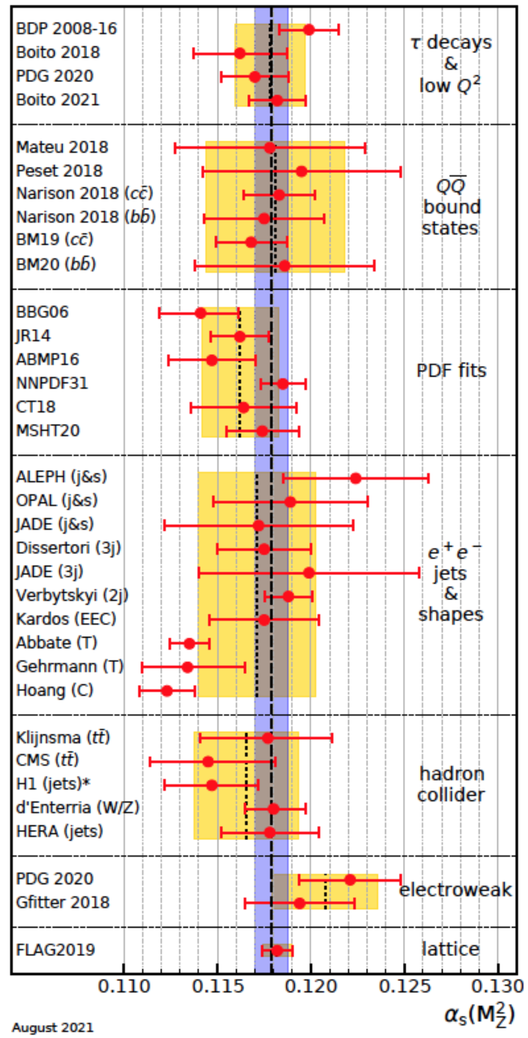


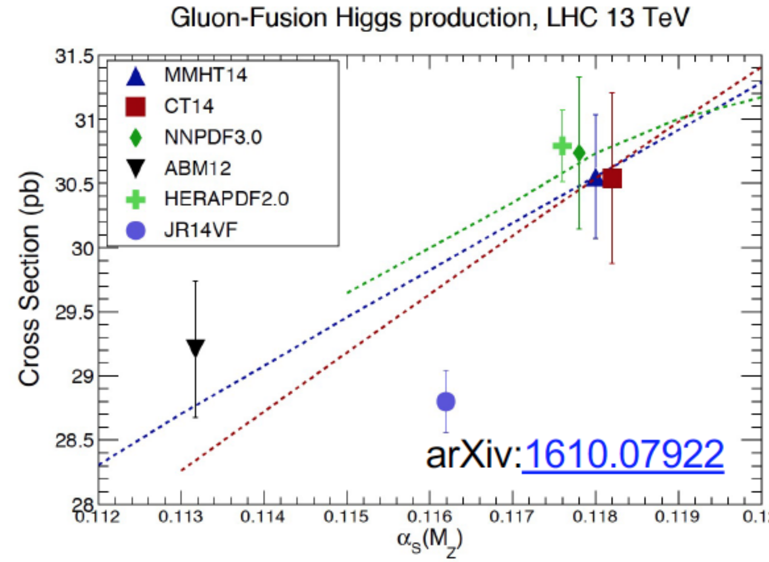
elweak coupling $\propto \alpha_S$ $\propto \alpha_S$ $\propto \alpha_S^2$

dijets trijets

Why look at α_s ?







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

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

  …

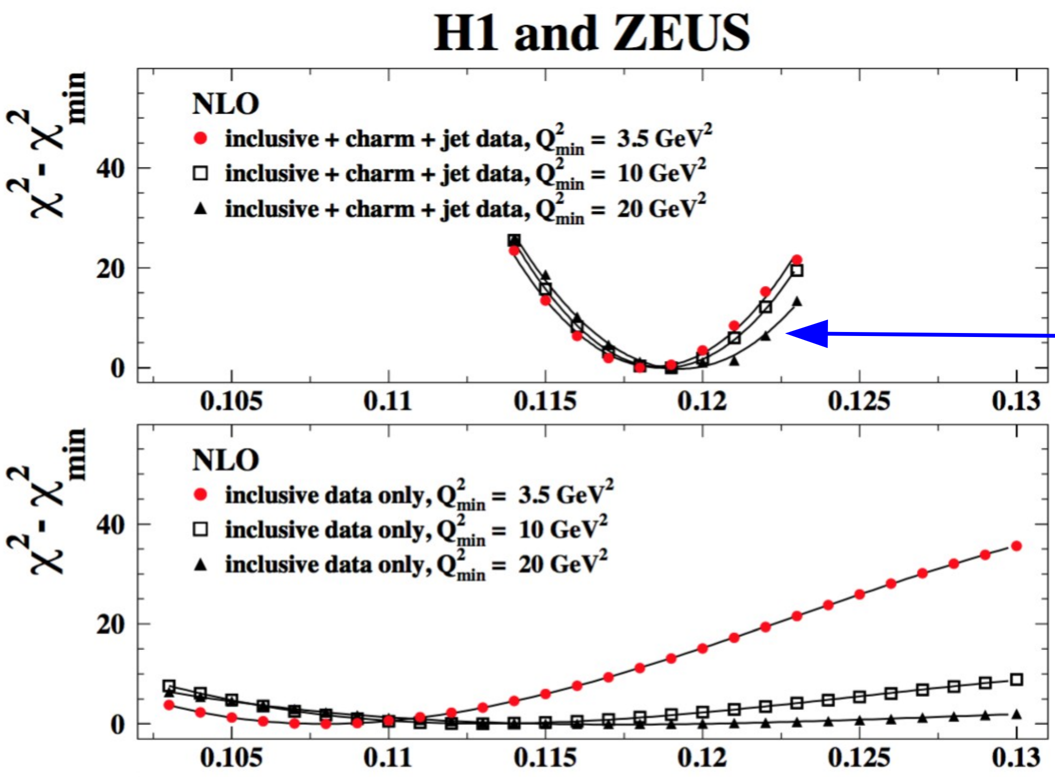
- **PDFs** and/or **αs** limit: precision SM and Higgs measurements, BSM searches, …

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

Why study jets @ HERA? And anywhere else



- 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

HERA jet data used in NNLO PDF fit

EPJC C82 (2022) 243

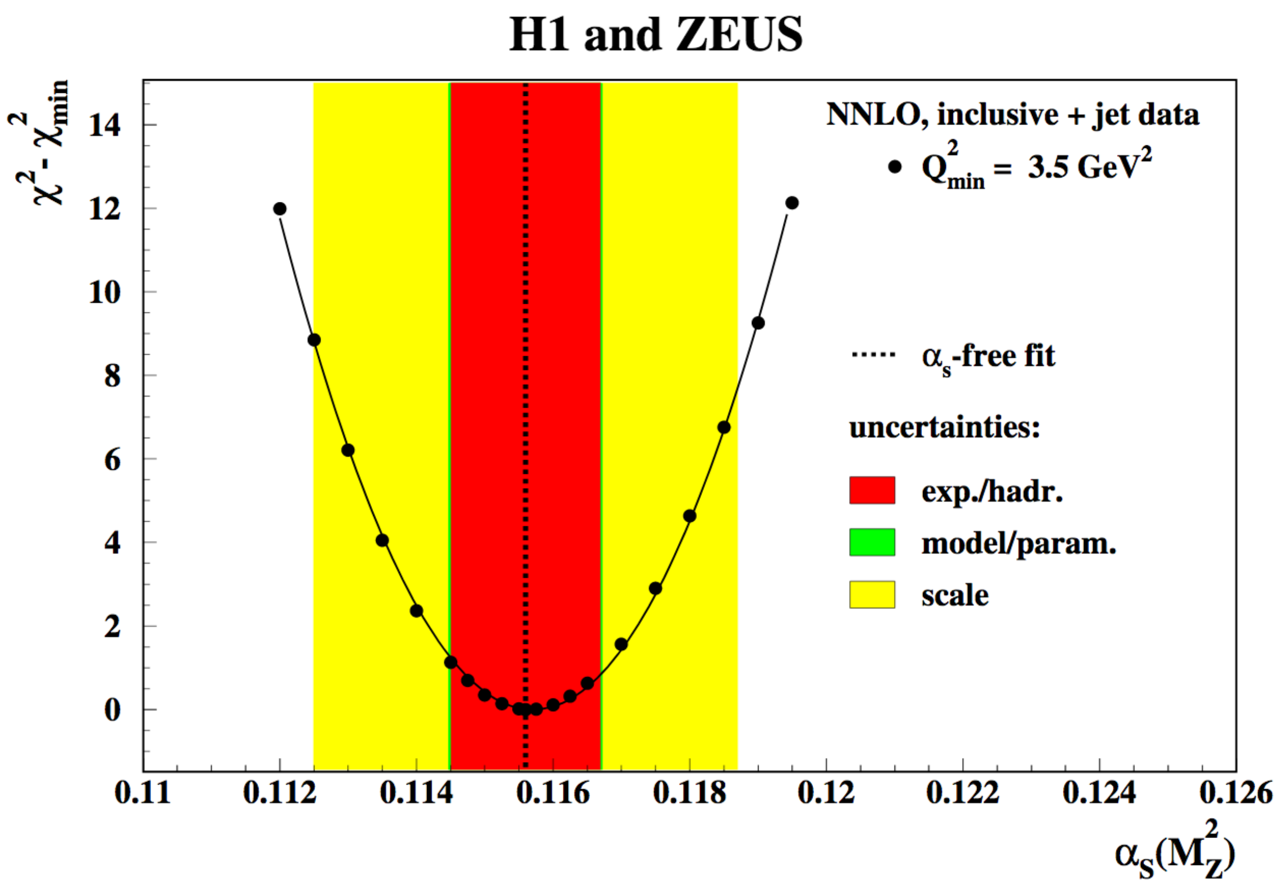
- Inclusive jets and dijets included
- Trijets from HERAPDF2Jets NLO excluded → no NNLO predictions
- H1 low Q^2 data added – particularly sensitive to $\alpha_s(M_Z)$
- Some data points excluded due theory limitations
  - Data at low scale $\mu = (pt_2 + Q_2) < 10$ GeV → scale variations are large (~25% 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	Normalised	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

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 previous procedure at NNLO:

NNLO

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

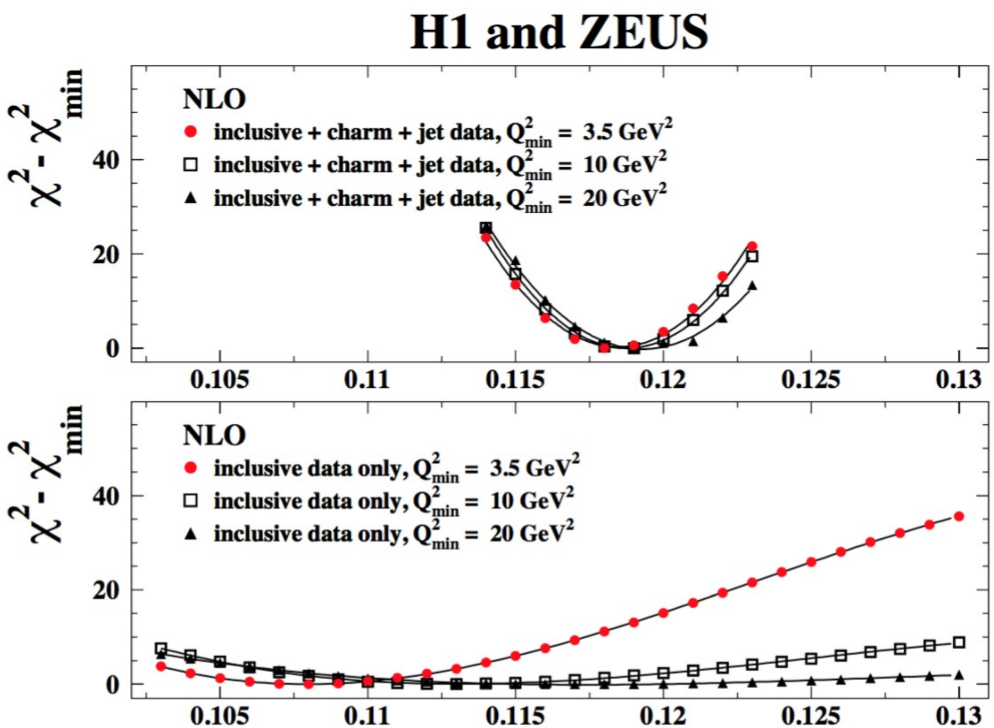
$$\pm 0.0022$$

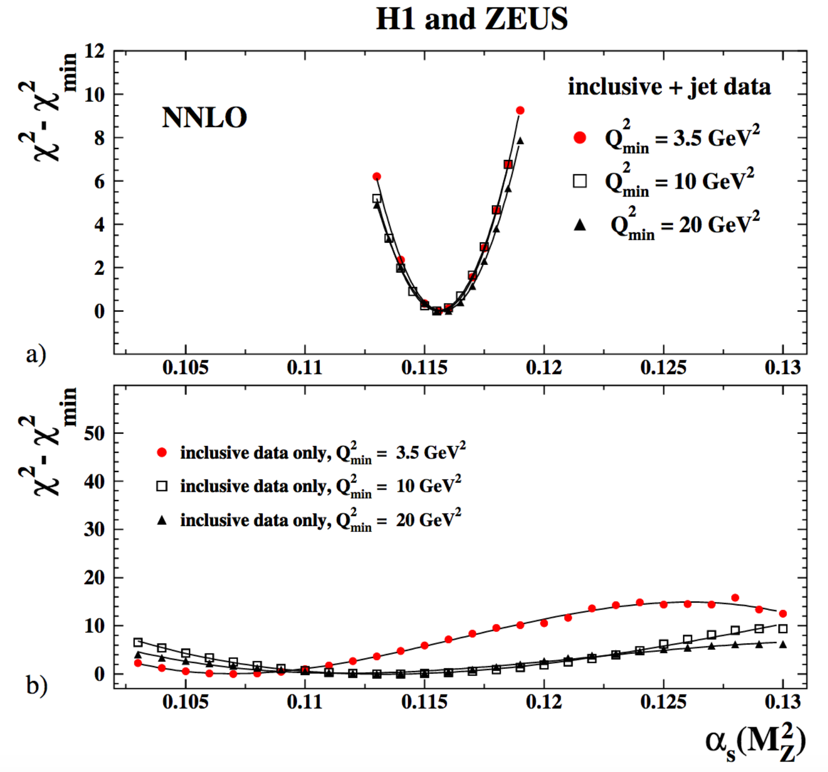
HERAPDF2.0Jets NLO

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

Scale uncertainties reduced
→ as expected for NNLO calculations

Completing NLO picture



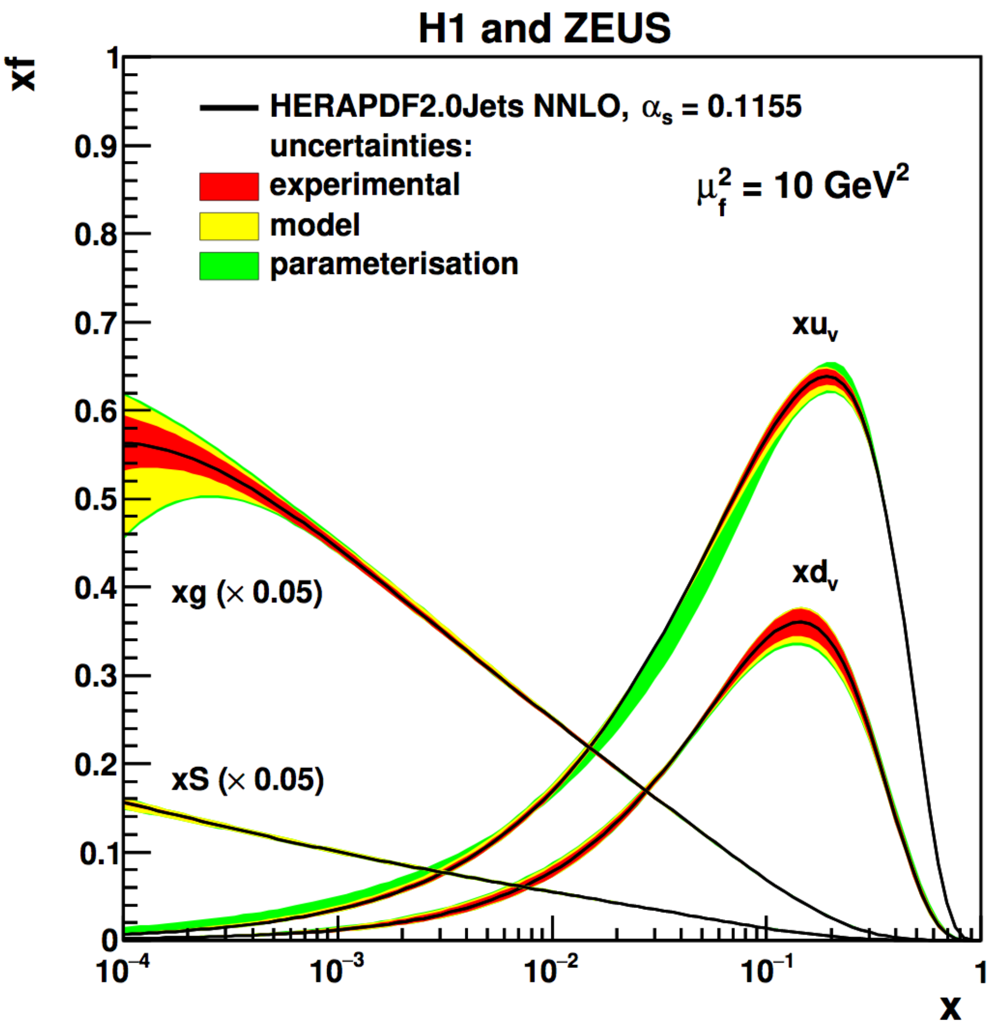


- Similar behavior and level of precision at NLO and NNLO
- However direct comparison of 2015 and 2022 results not possible
  → different scale choice and slightly different jet data sets
- After unifying (details in backup)

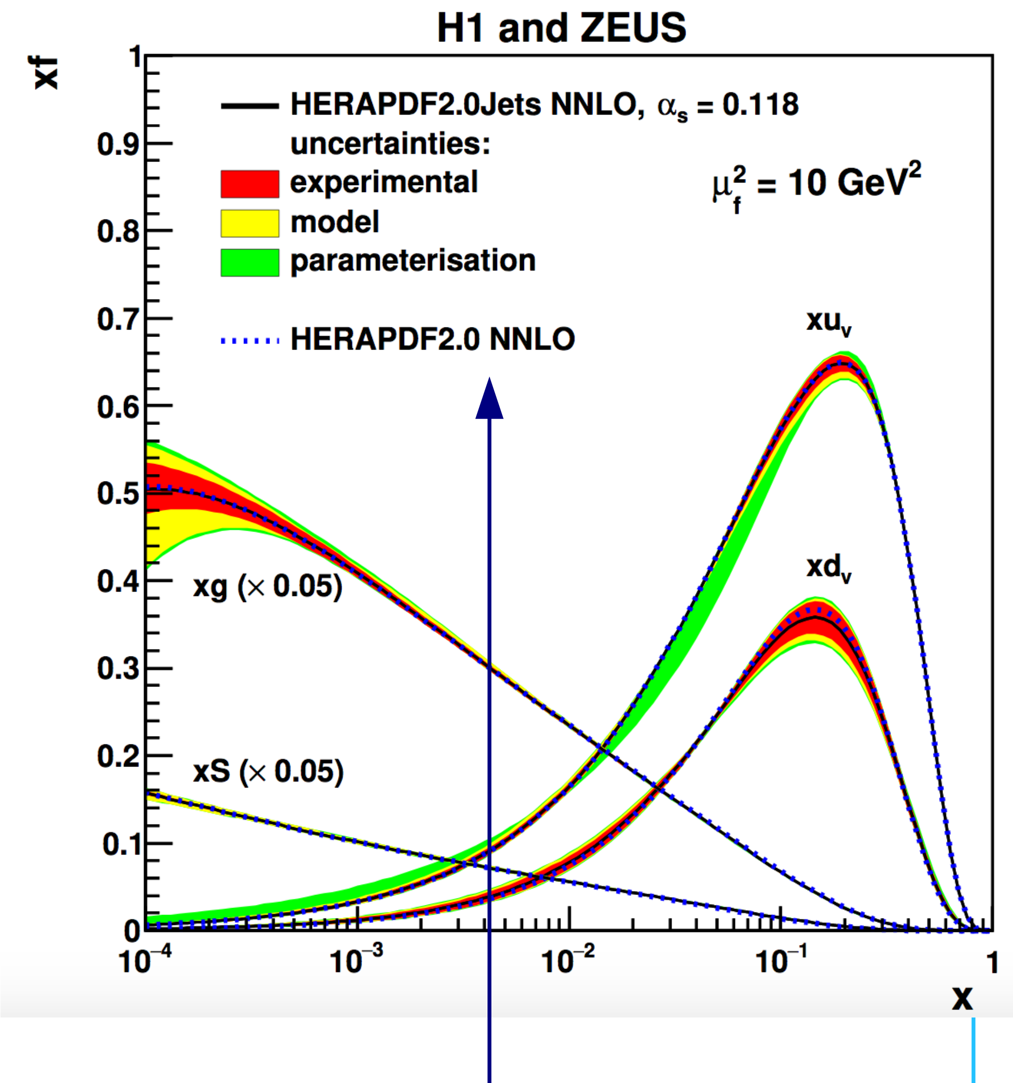
αs(Mz) = 0.1186 ± 0.0014 (exp) **NLO**
αs(Mz) = 0.1144 ± 0.0013 (exp) **NNLO**

Fits with fixed α_s

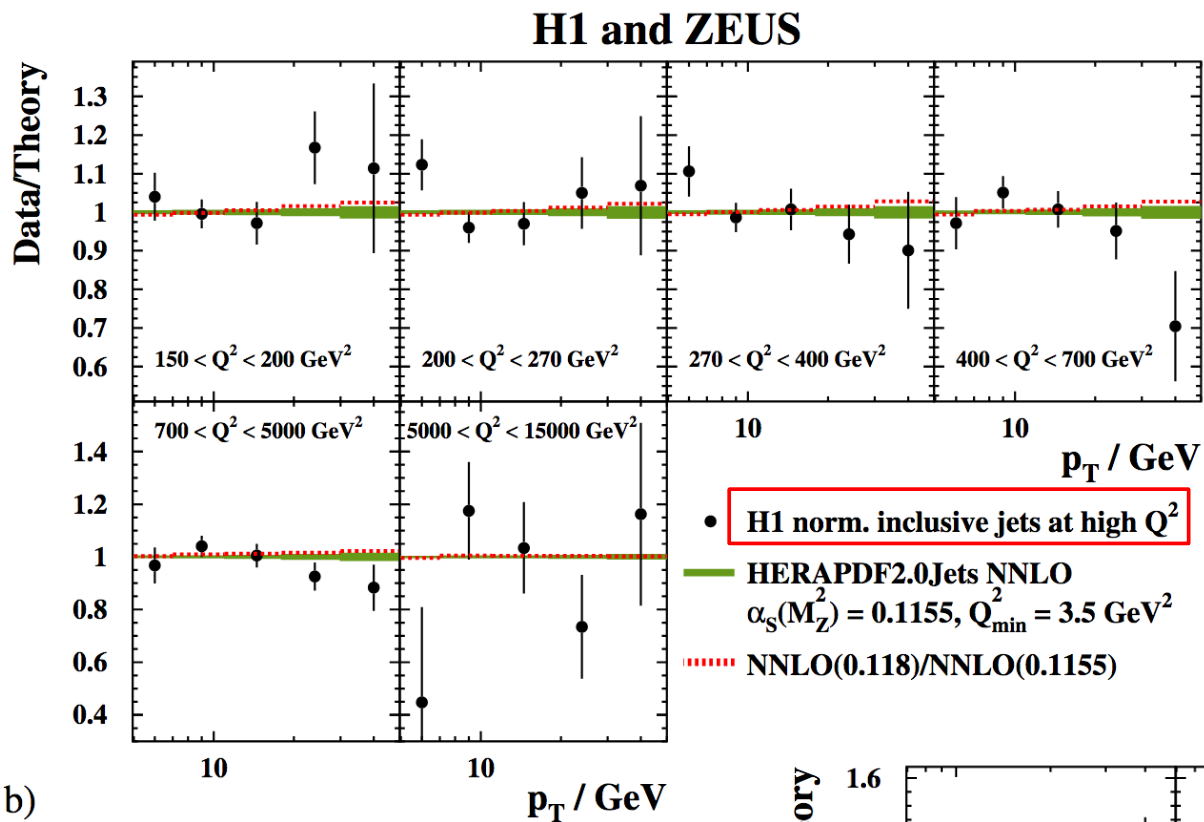
0.1155 **0.118**



a)

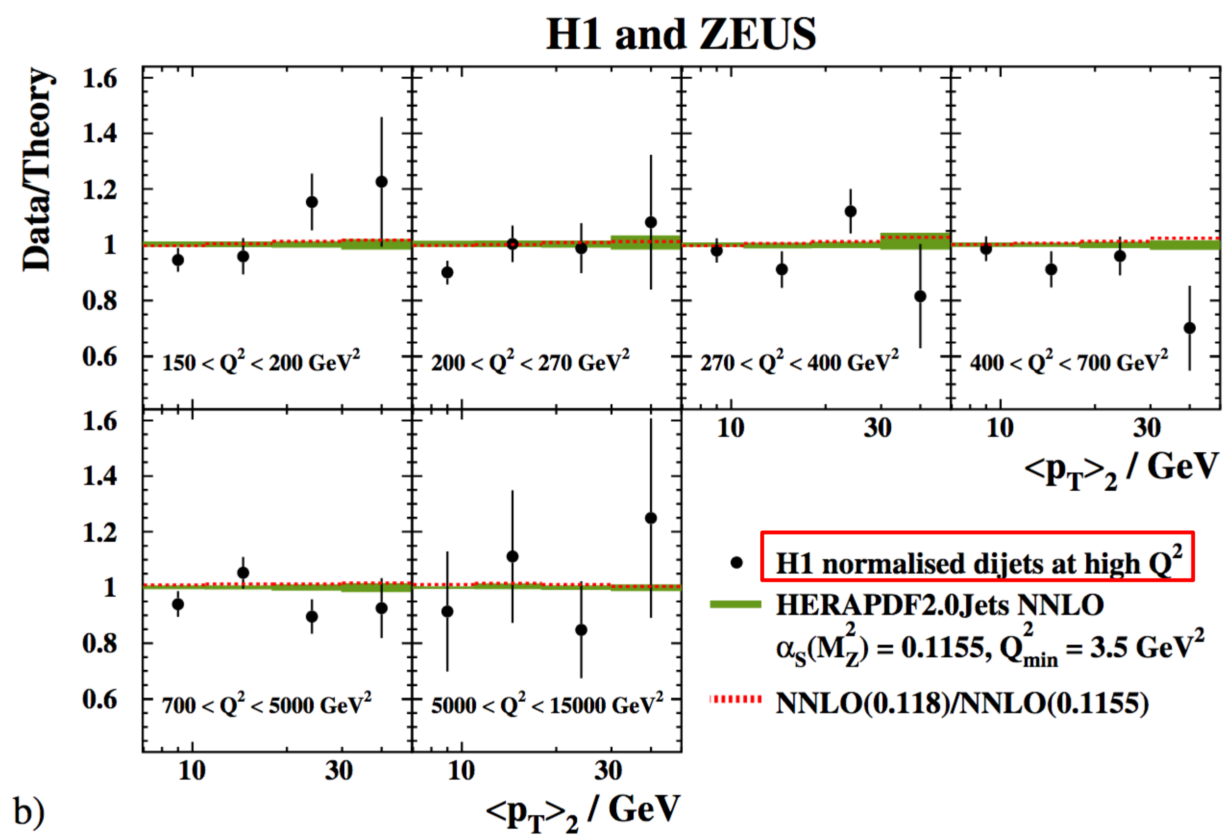


compatible with HERAPDF2 NNLO



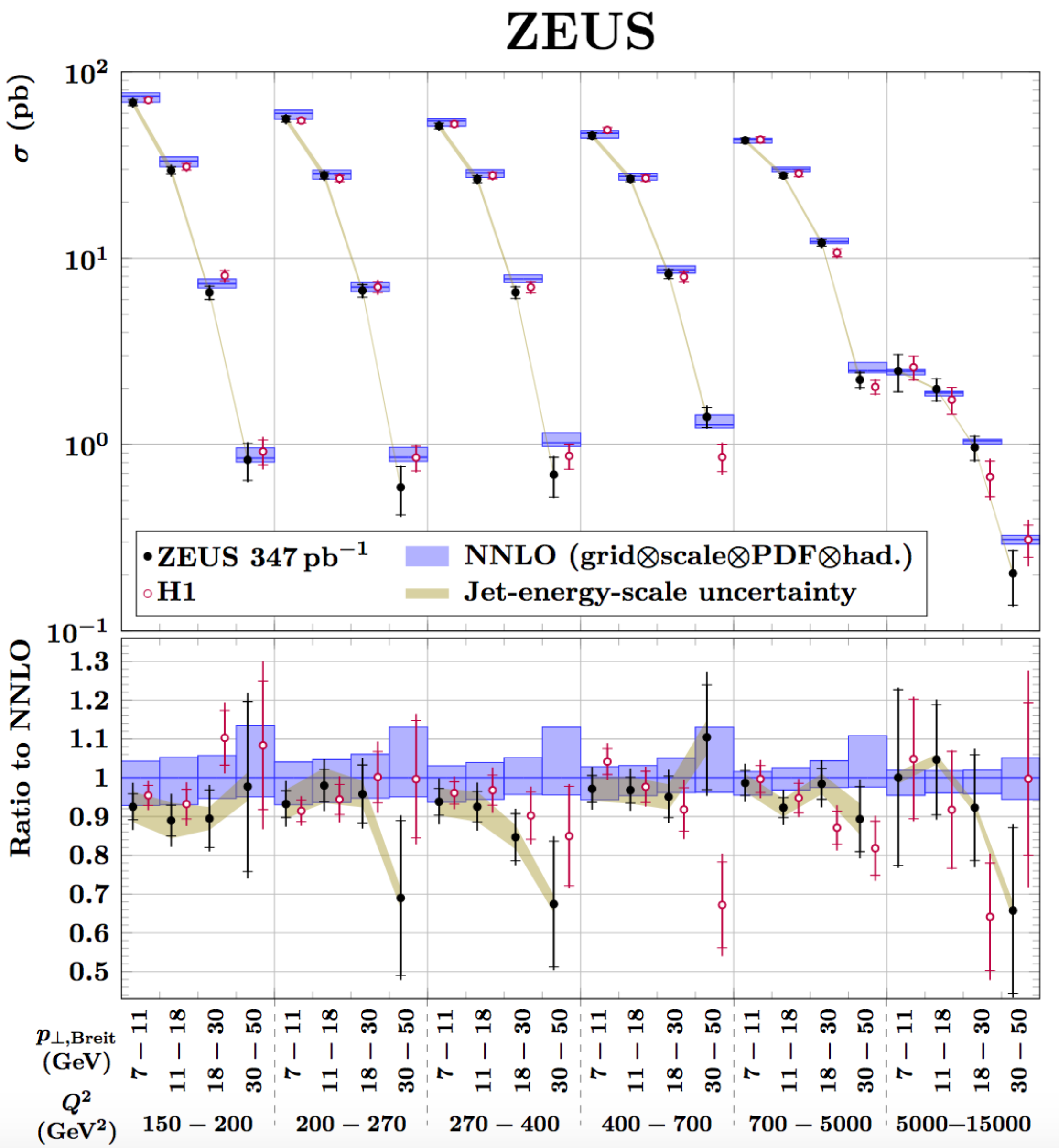
Comparison of theory predictions to H1 HERA II normalised jets @ high Q^2

→ good agreement for all data used in PDF fits



New ZEUS jet measurement

arxiv:2309.02889, submitted to EPJC



- New HERAII high-Q^2 inclusive jets results from ZEUS (16 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-jets QCD fit @ NNLO

xFitter

- 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

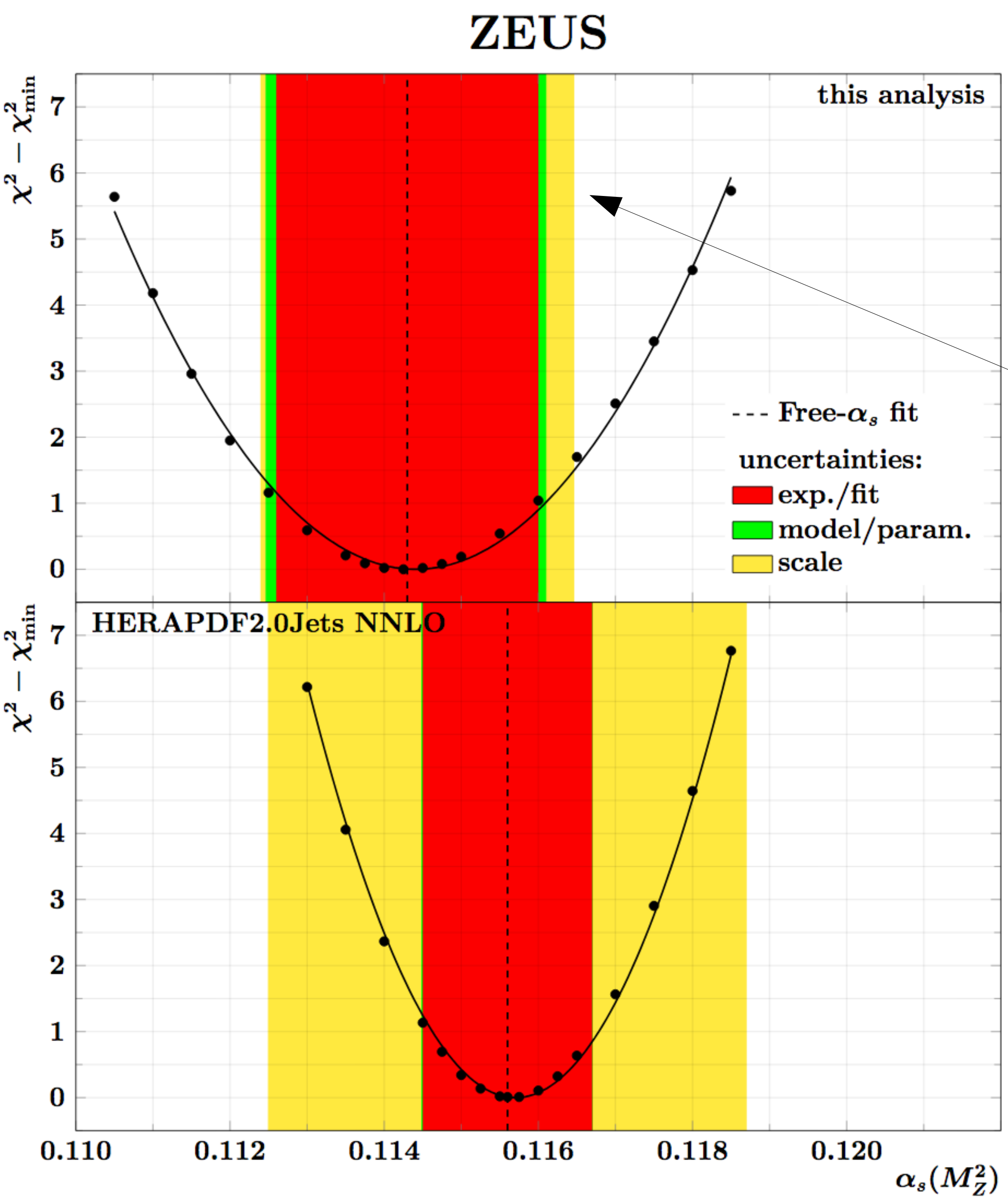
$$\alpha_s(M_Z^2) = 0.1142 \pm 0.0017\ (\text{exp./fit})\ {}^{+0.0006}_{-0.0007}\ (\text{model/parameterisation})\ {}^{+0.0006}_{-0.0004}\ (\text{scale})$$

- *Note scale uncertainty!*
  - Calculated as 50%-correlated and 50%-uncorrelated

$$\text{NNLO: } \alpha_s(M_Z^2) = 0.1142 \pm 0.0017\ (\text{exp./fit})\ {}^{+0.0006}_{-0.0007}\ (\text{model/param.})\ {}^{+0.0006}_{-0.0004}\ (\text{scale})$$

$$\text{NLO: } \alpha_s(M_Z^2) = 0.1159 \pm 0.0017\ (\text{exp./fit})\ {}^{+0.0007}_{-0.0009}\ (\text{model/param.})\ {}^{+0.0012}_{-0.0009}\ (\text{scale})$$

Comparison to HERAPDF2Jets NNLO



- Central value compatible with HERAPDF and world average
- Increased experimental uncertainty ← fewer jet datasets used
- Scale uncertainty here calculated as 100% correlated

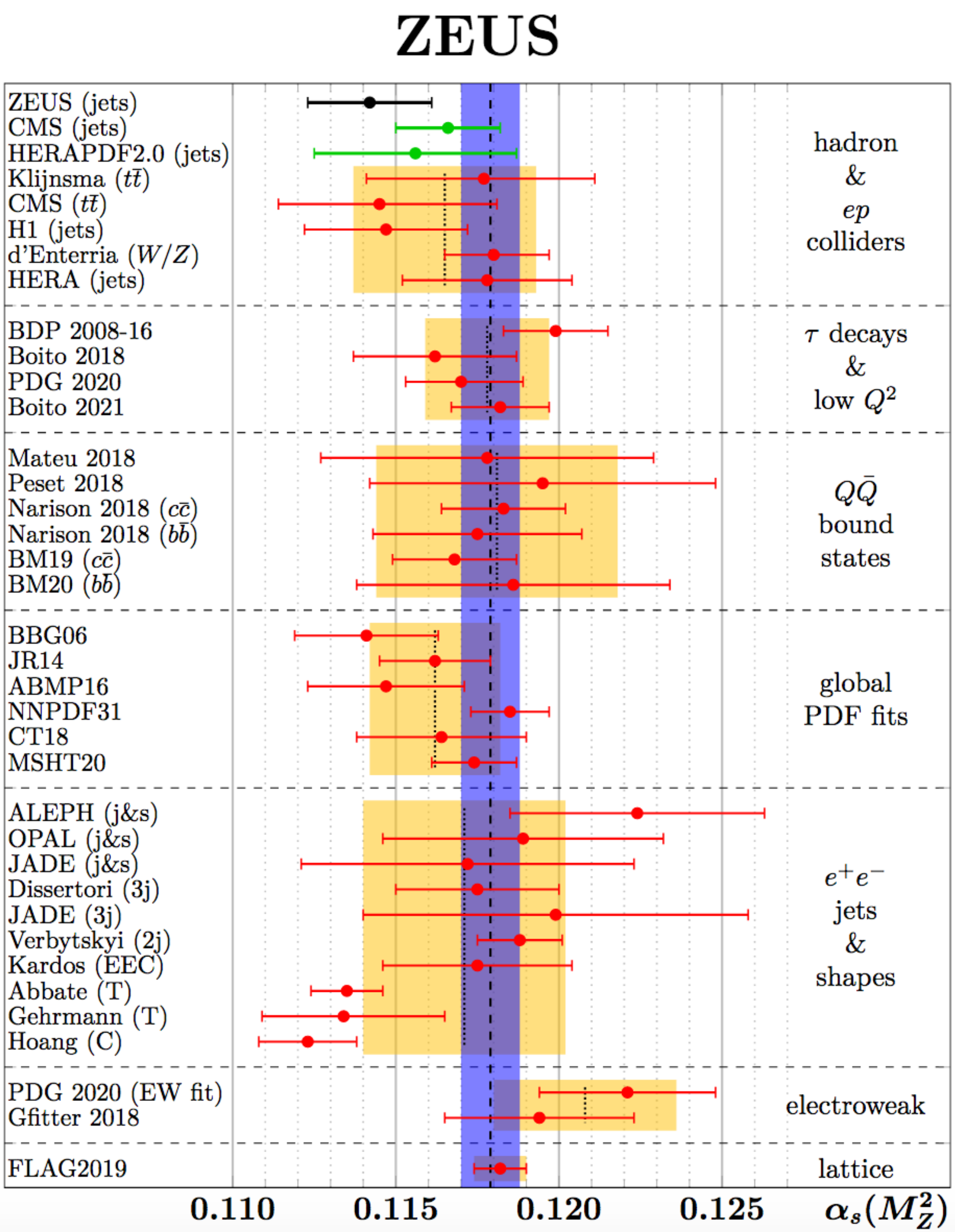
$$^{+0.0012}_{-0.0005}\ \text{(scale)}$$

to compare to HERAPDF2Jets

Significantly decreased scale uncertainty

- absence of low Q2 jet data
- 50%-correlated and 50%-uncorrelated uncert.

Comparison to other α_s estimations



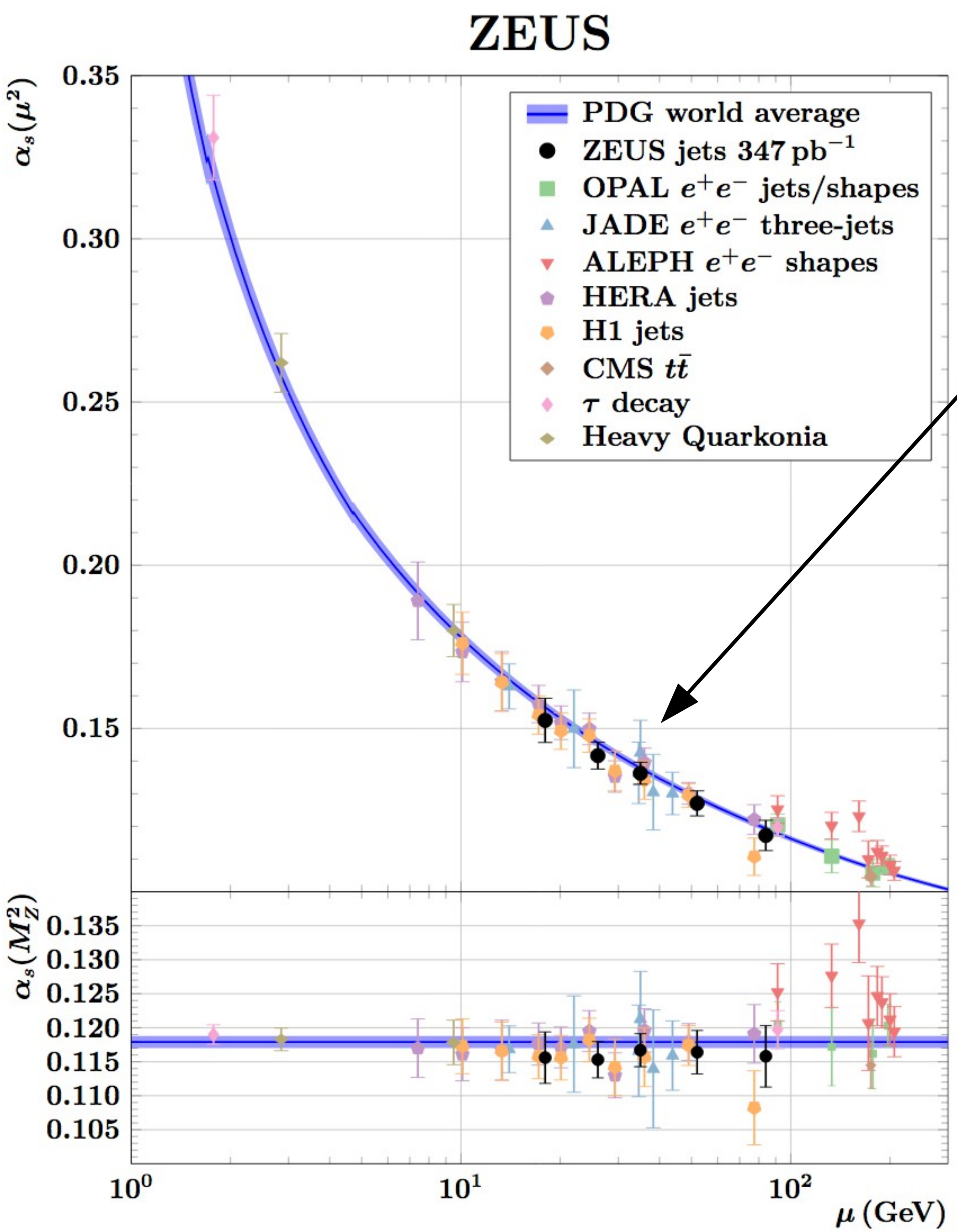
Reduced scale uncertainty

→

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)

Running of strong coupling



- Running of strong coupling expected from theory and confirm by various measurements
- ZEUS measured α_s in 5 energy bins
  - → All values very well compatible with result of global determination

- Measurements consistent with each other and with theory expectations

Dependence of strong coupling on energy scale consistent with previous measurements and perturbative QCD expectation

New DIS data for PDFs:

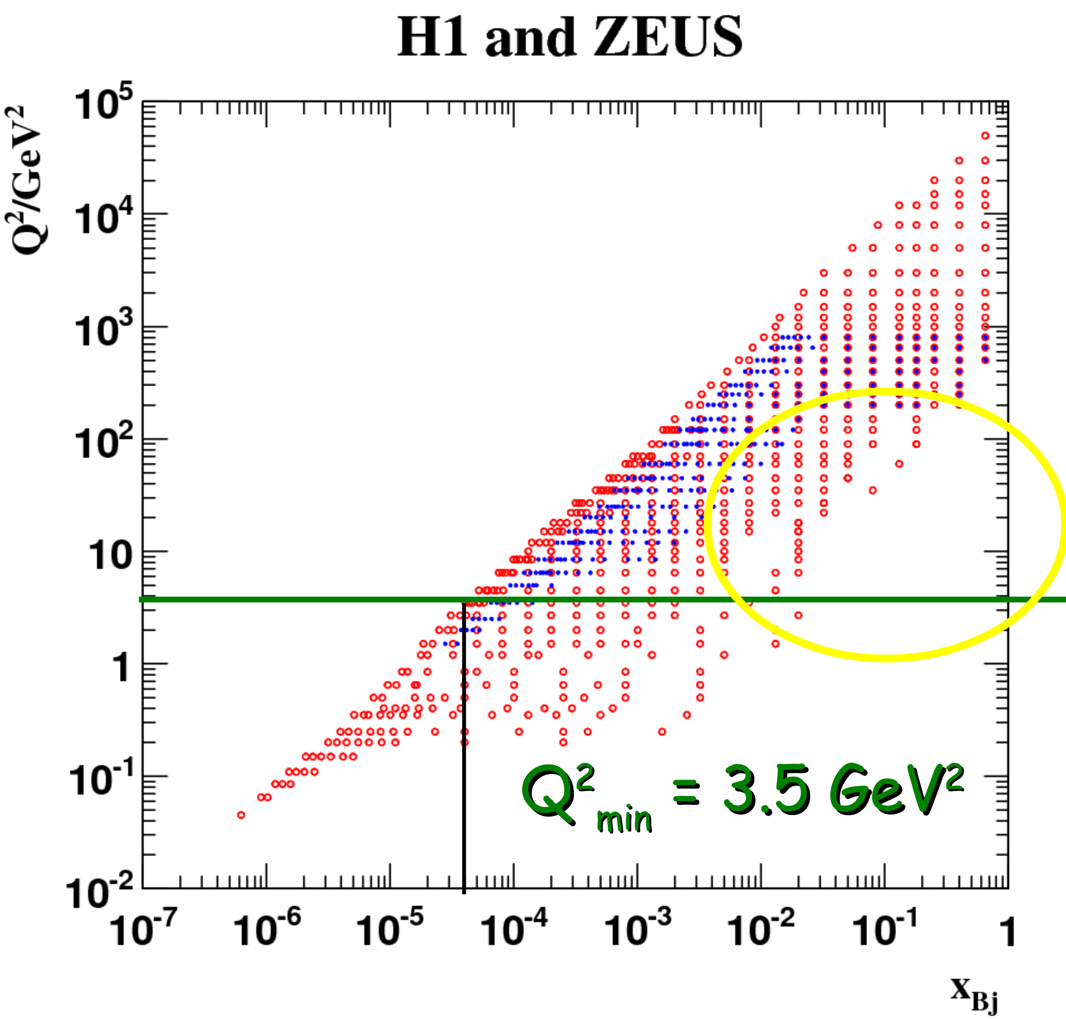
EIC

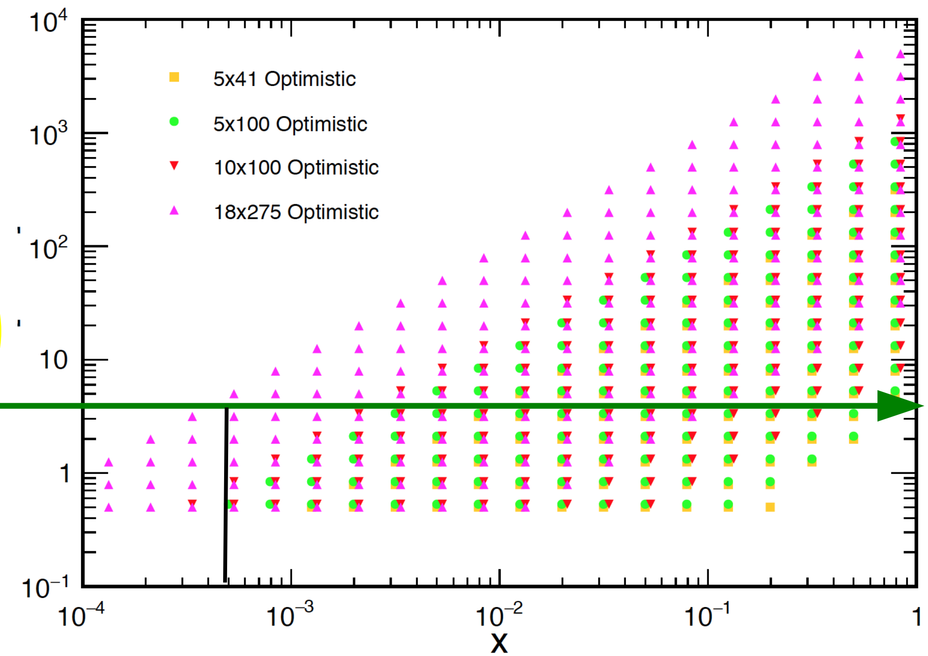
EIC & Collinear PDFs

→ sneak preview, more in F. Giuli's talk & poster on Tuesday

arXiv:2309.11269, submitted to EPJC

HERA & ATHENA phase-space



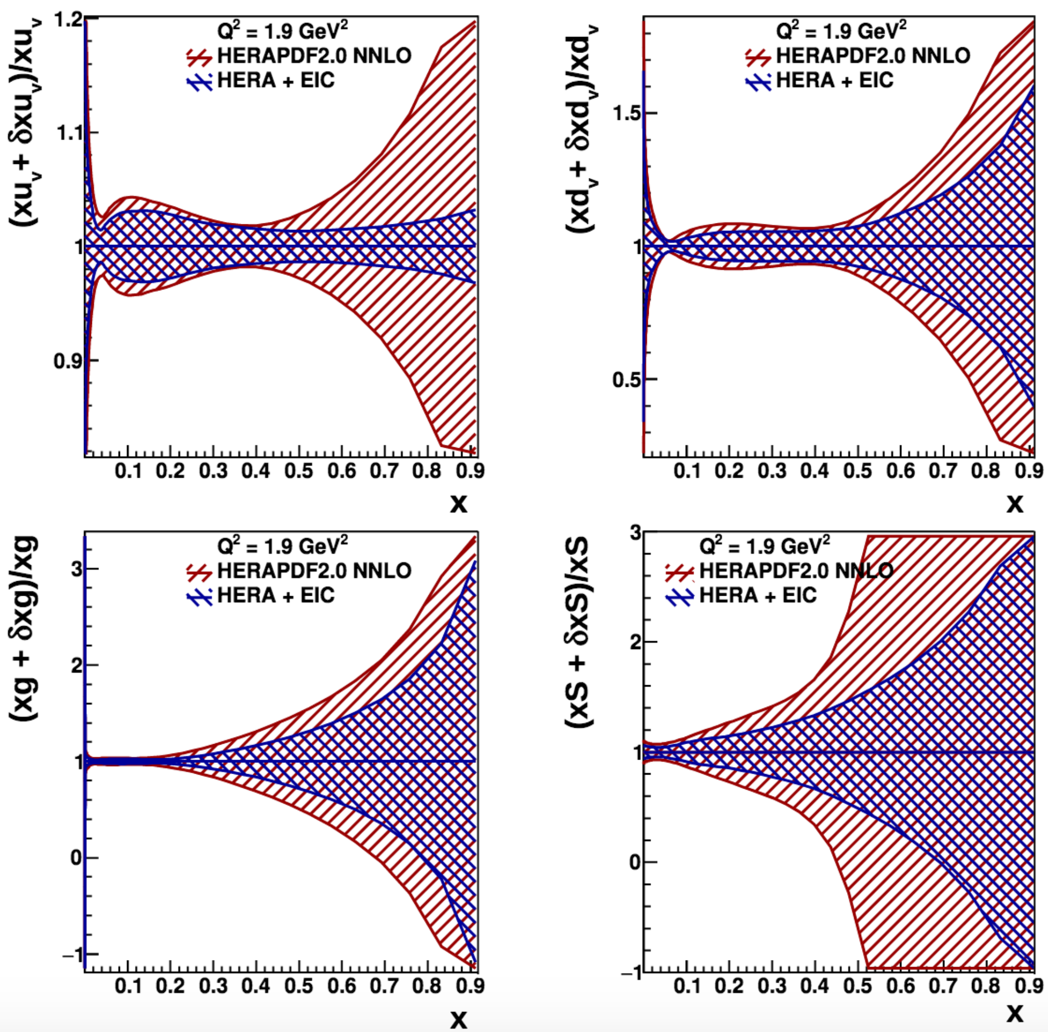


High-x region not covered by HERA → impact on high-x PDFs expected

HERAPDF philosophy: get PDFs with HERA data only

Fits with ATHENA pseudo-data

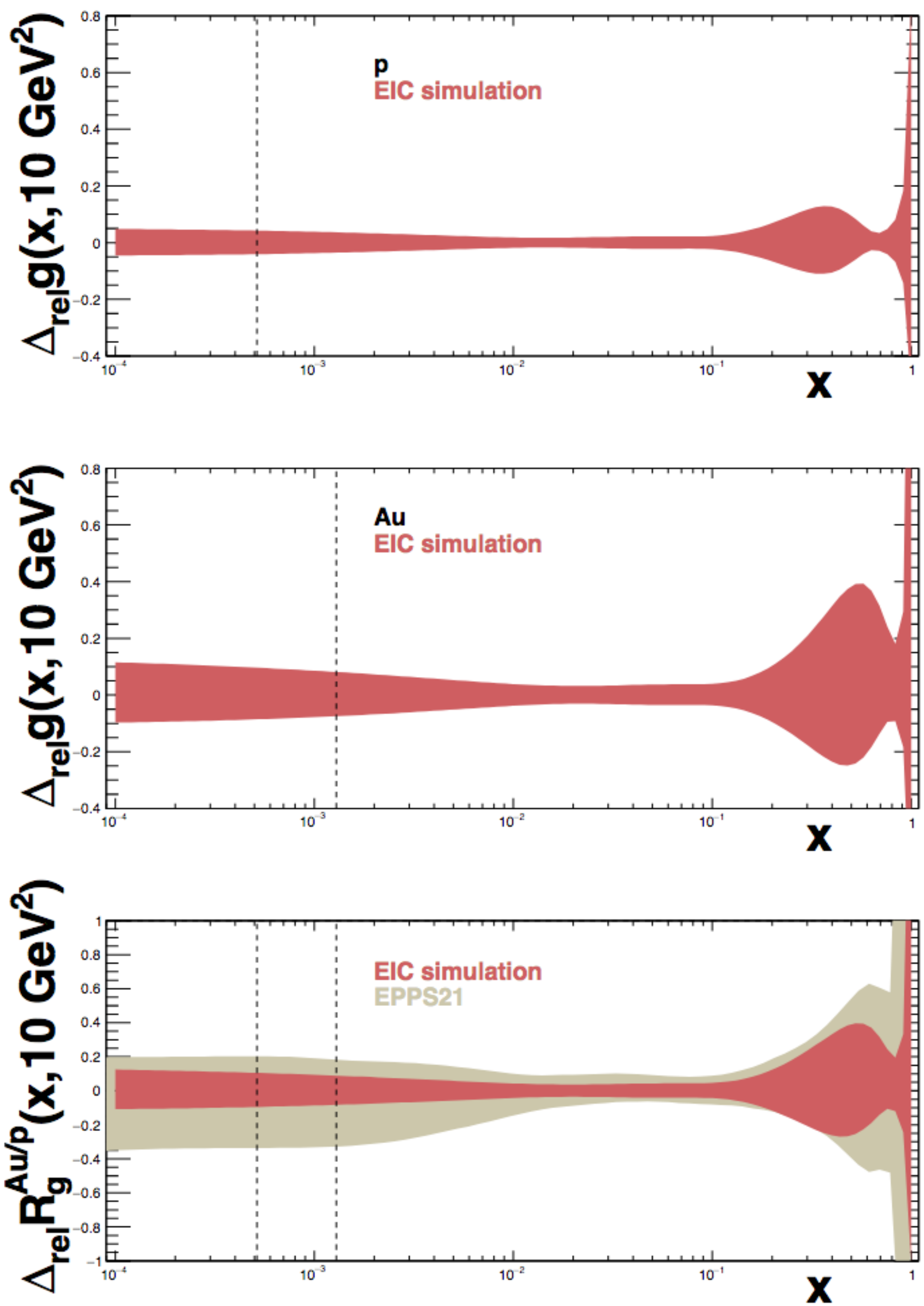
- ATHENA pseudo-data created using HERAPDF2 NNLO
  → NC: 5 centre-of-mass energies
  → CC: only highest energy so far
  → "realistic" uncertainties estimation
- PDF fits "HERAPDF2-style" with DIS and DIS+EIC data



<u>As expected for DIS-only fits:</u>

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

Impact of EIC data on nuclear PDF @NLO



- Nuclear modification factors for gluon (fo u valence and u sea quarks similar picture)

→ comparison with <u>EPPS21 (representative current global fit)</u>

- Fixed target DIS and DY data
- p+A at LHC
- π^0 from PHENIX

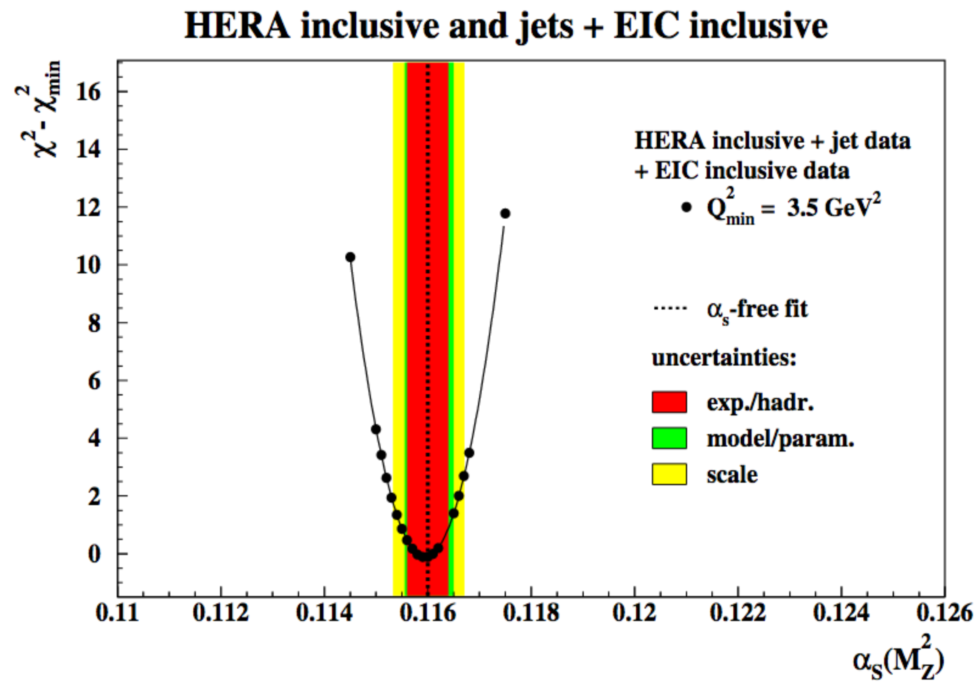
Precision largely improved <u>with EIC data only</u>
→ factor of two @ x ~ 0.1

EIC & strong coupling

→ sneak preview, more in Z. Demiroglu's talk & poster on Tuesday

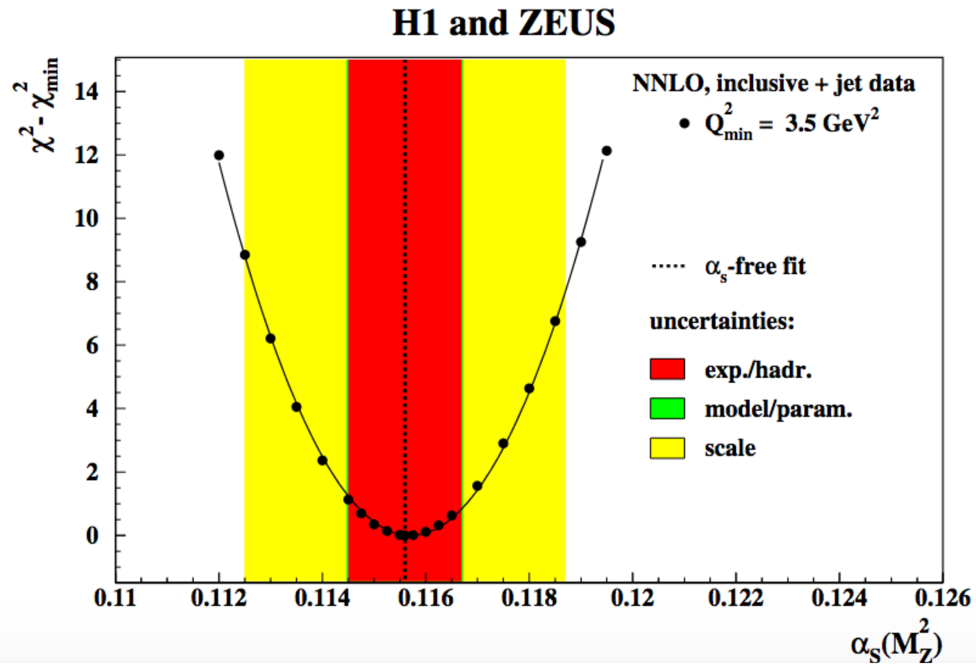
arXiv:2309.11269, accepted by EPJC

Simultaneous PDF and α_s fits with HERA DIS + jets and EIC DIS



$$\alpha_s(M_Z^2) = 0.1160 \pm 0.0004\ (\text{exp})\ ^{+0.0003}_{-0.0002}\ (\text{model} + \text{parameterisation}) \pm 0.0005\ (\text{scale})$$

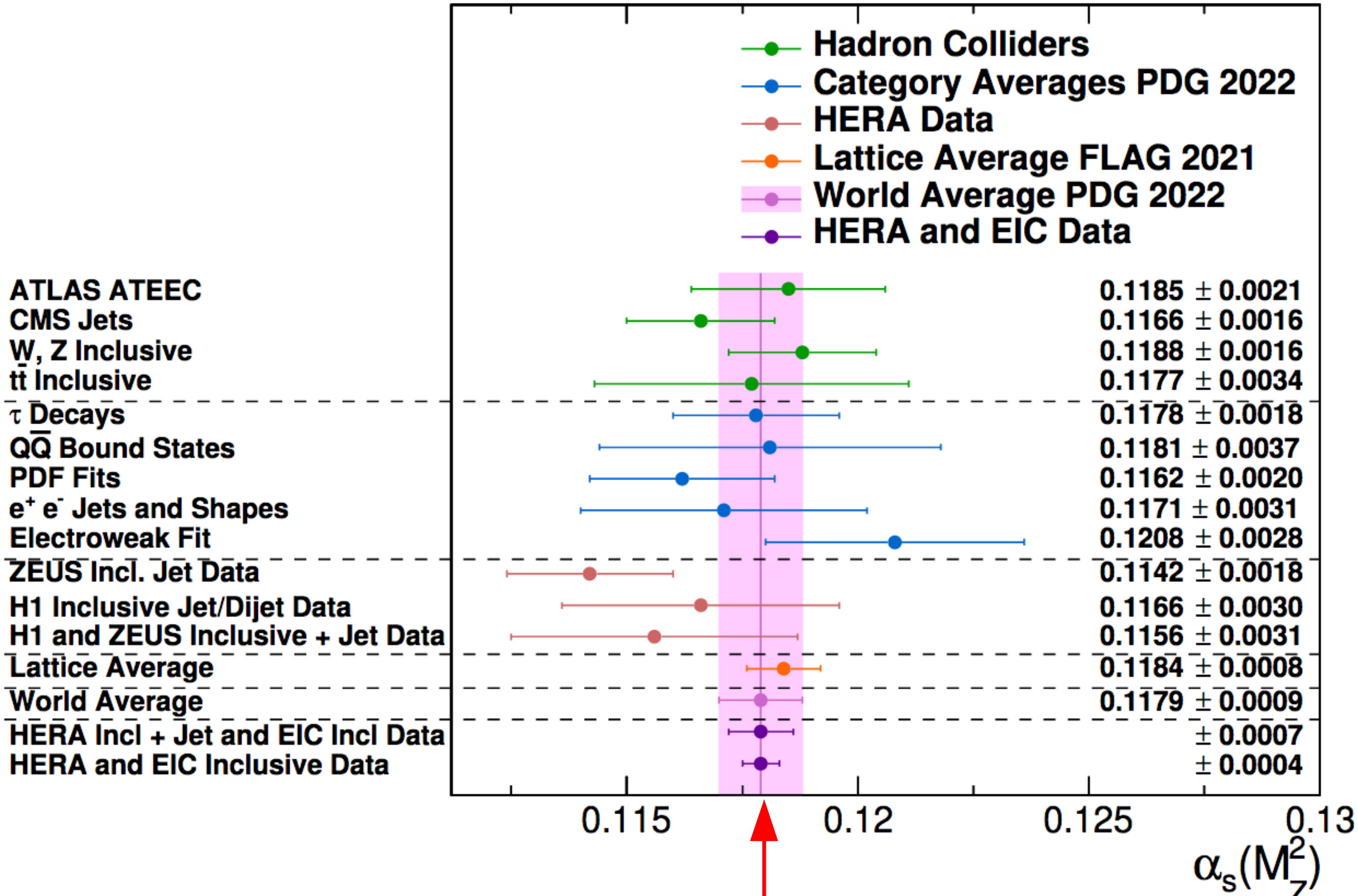
→ stunning improvement in uncertainties, also in scale uncertainty!



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

Simultaneous PDF and α_s fits with <u>only inclusive data</u> from HERA and EIC

→ stunning improvement possible due to kinematic phase-space and high-x quark evolution



below 0.4%!

$$\alpha_s(M_Z^2) = 0.1159 \pm 0.0004\ (\text{exp})\ ^{+0.0002}_{-0.0001}\ (\text{model} + \text{parameterisation})$$

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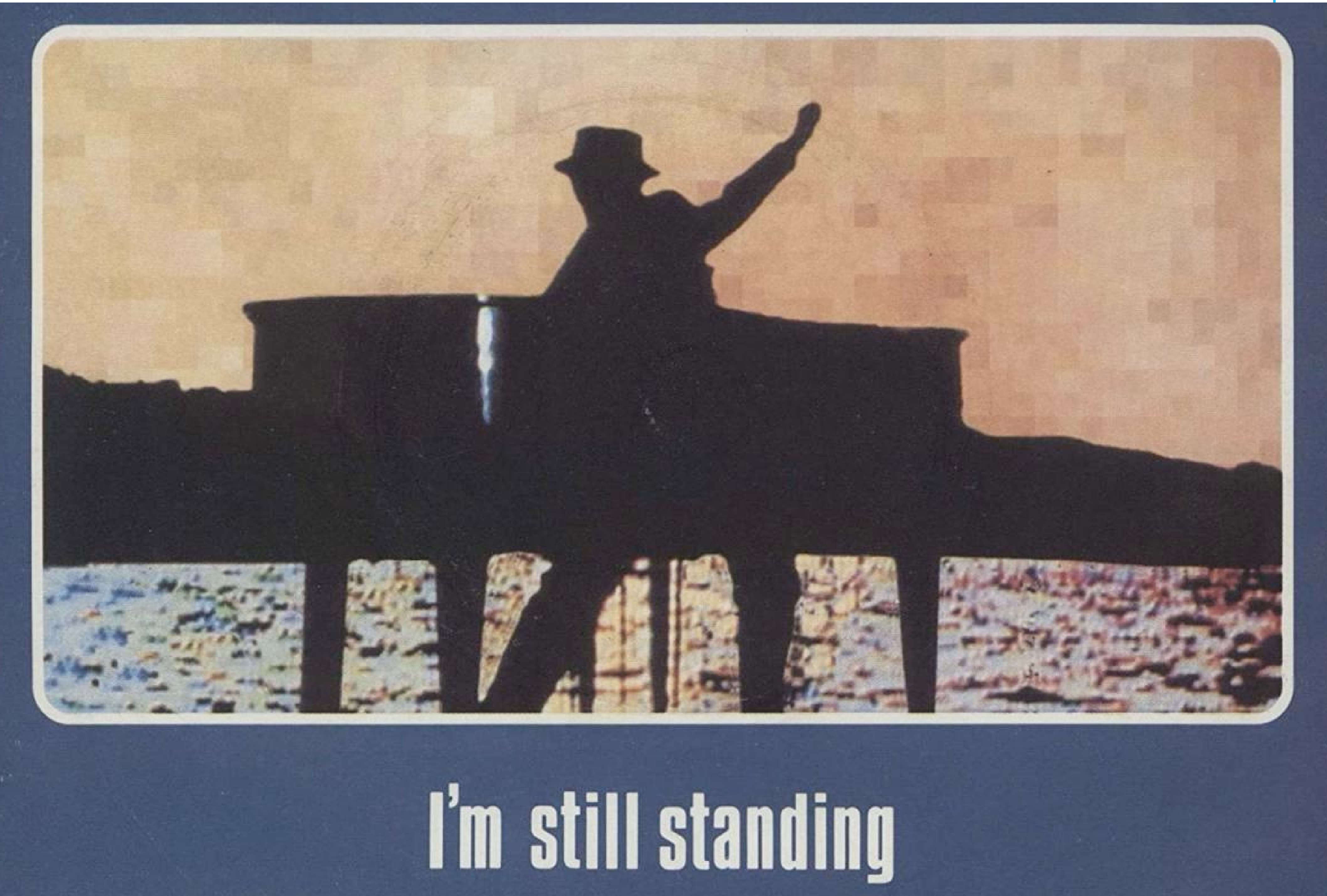
Message to take away: completely subjective



Message to take away: completely subjective

- HERA still has something to say!

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

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

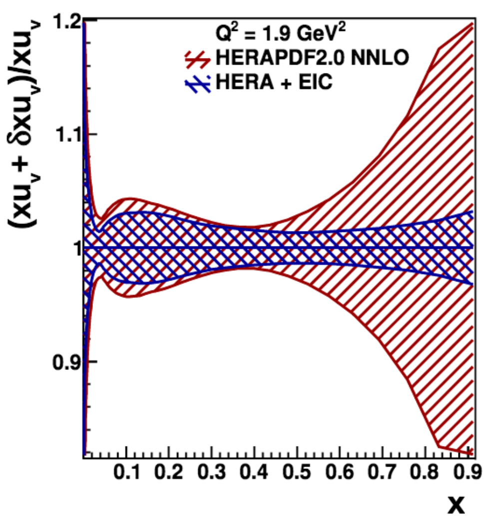
  → **one of the most precise measurements of $\alpha_s(M^2_Z)$ at hadron colliders**

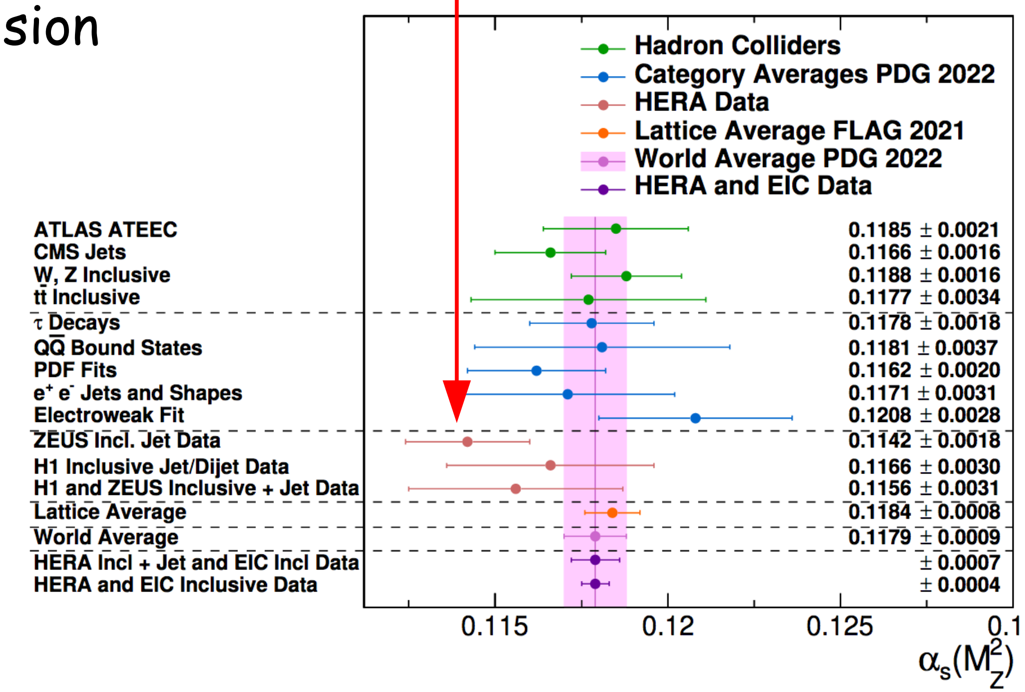
- Using EIC data will make tremendous difference

  → proton PDFs, especially at high x

  → nPDFs constrained with 10% precision

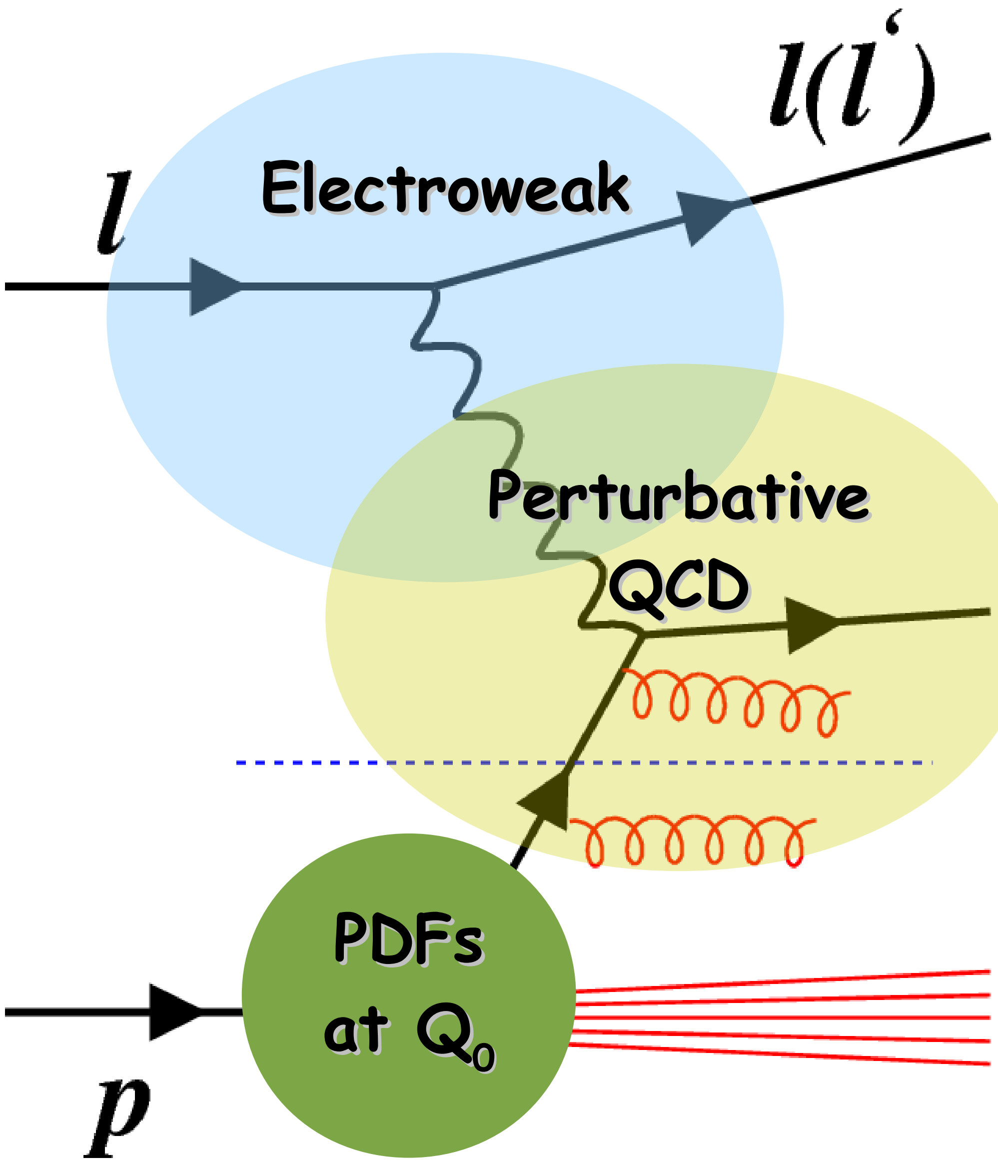
  → $\alpha_s(M_Z)$ determination





Additional slides

Deep Inelastic Scattering @ HERA

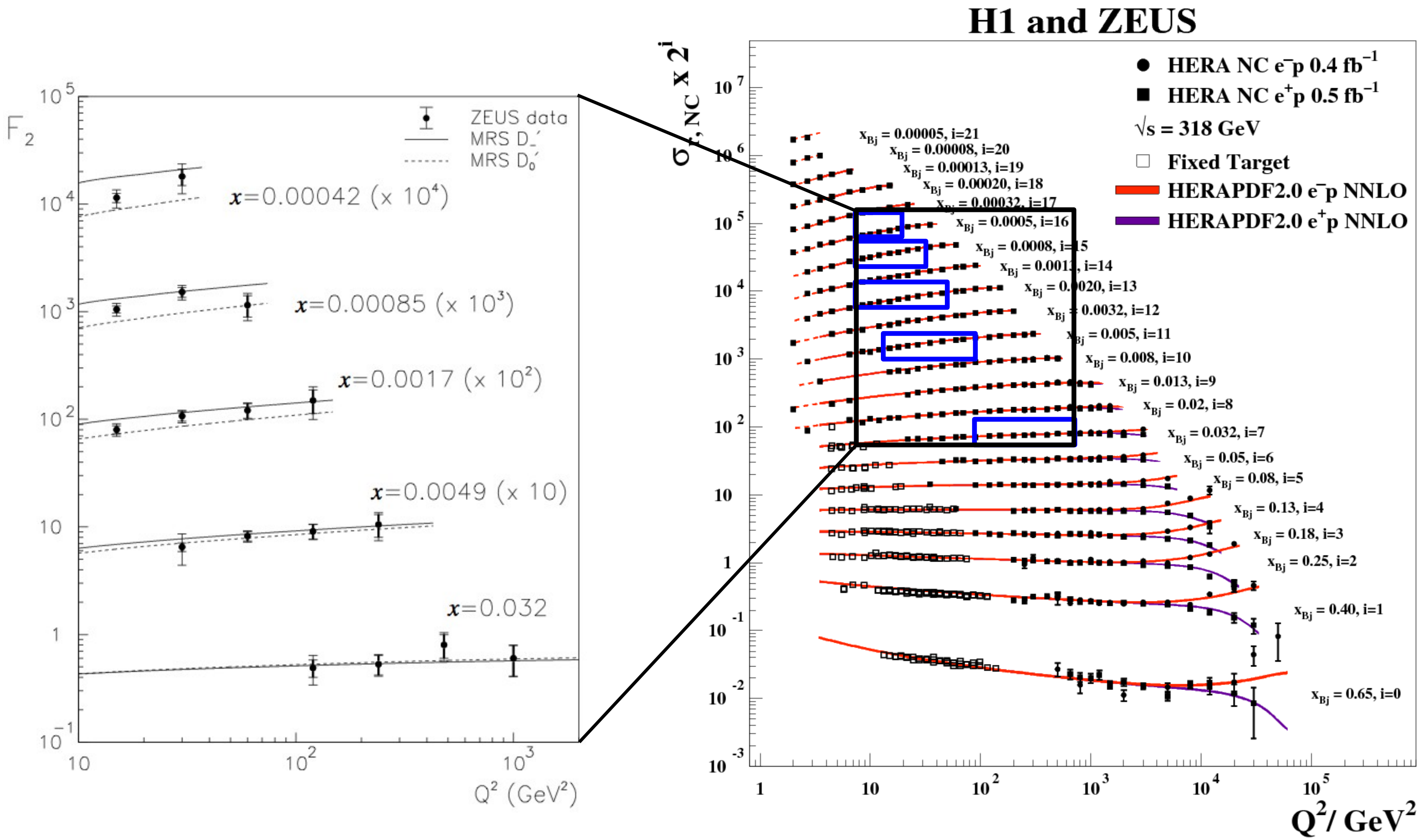


- Fix pQCD & PDFs
  ! Test Electroweak
- Fix Electroweak
  ! Test pQCD & PDFs

- Fix Electroweak & pQCD
  ! Determine PDFs

DIS @ HERA

First: 1993 → Final: 2015

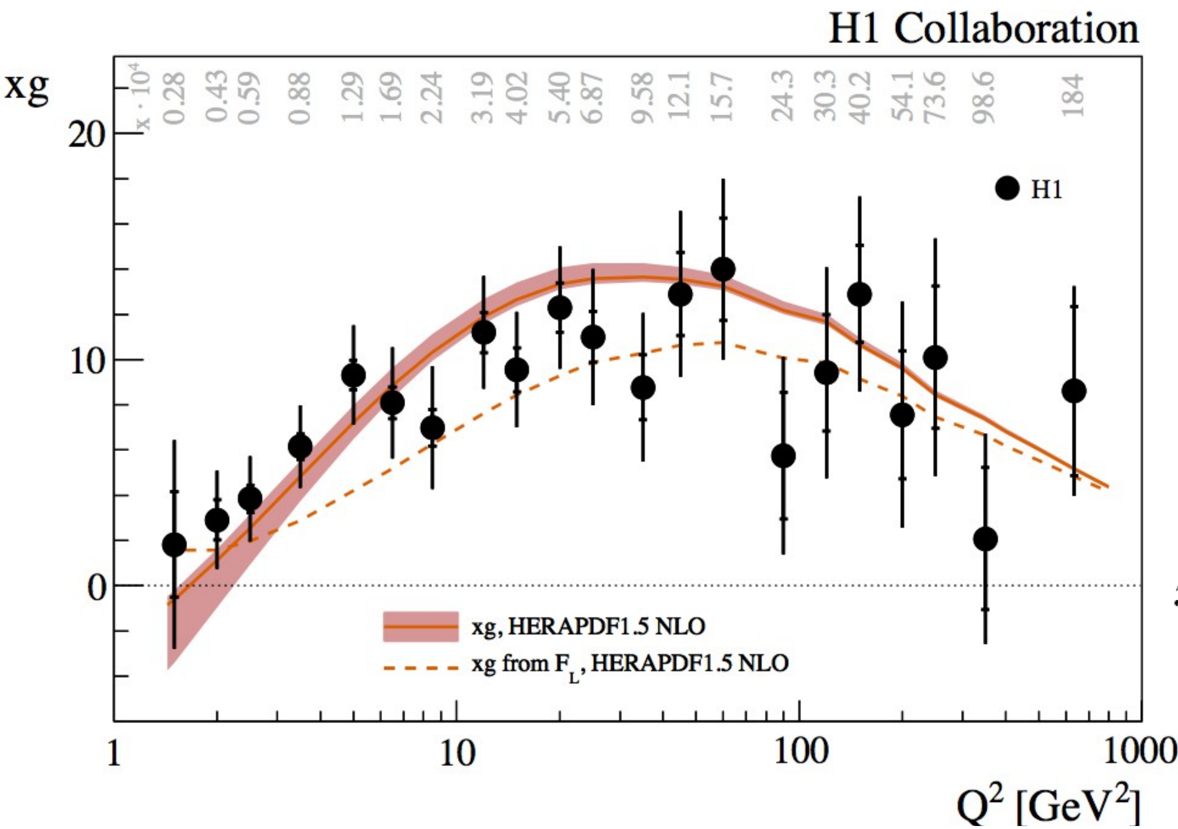


2007: HERA shutdown

→ 16th anniversary of end, 31st anniversary of start

Gluon from F_L

- H1 performed direct extraction of gluon density from F_L measurement @NLO

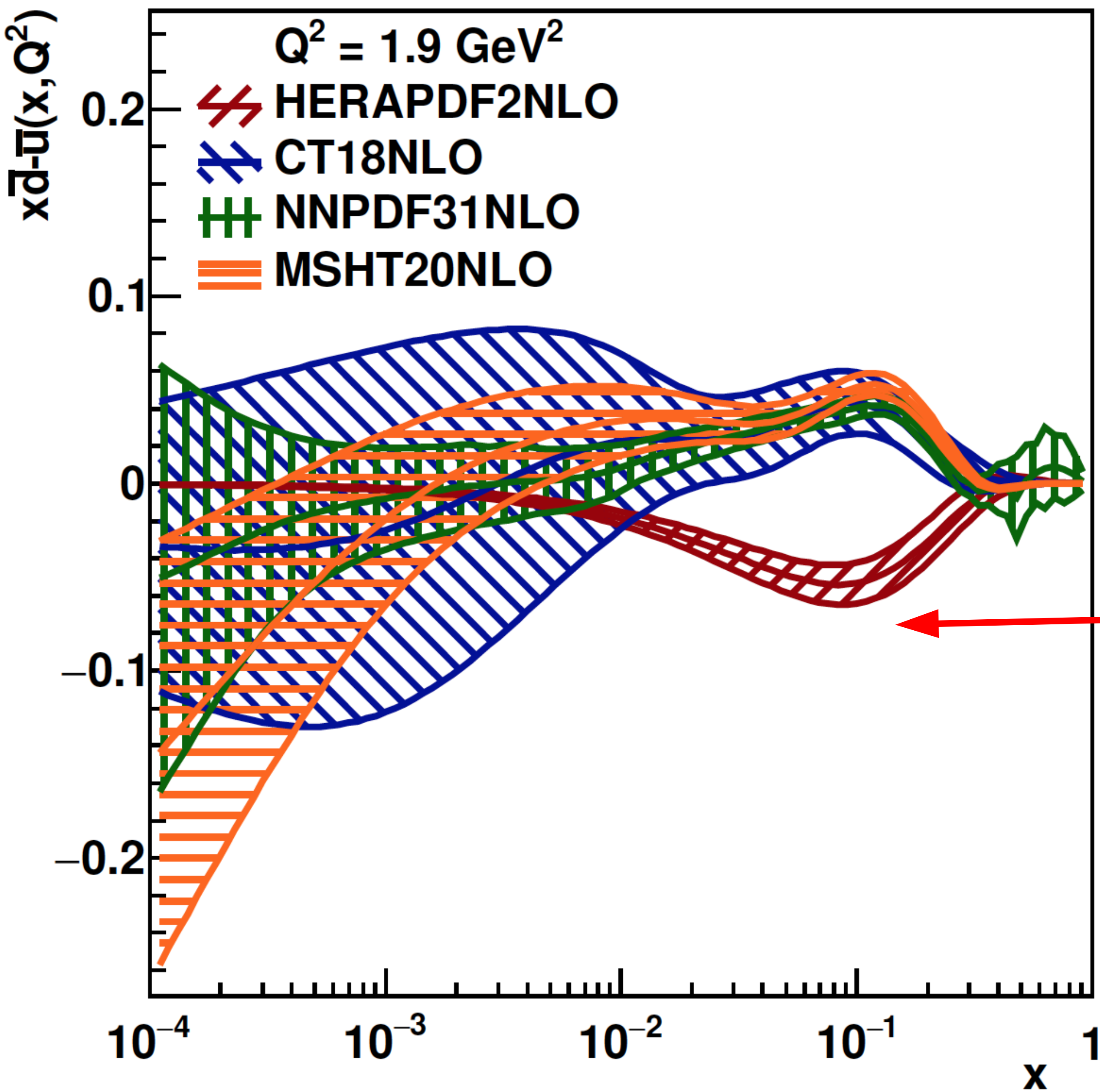


- Direct extraction of gluon density from F_L using approximation

$$xg(x, Q^2) \approx 1.77 \frac{3\pi}{2\alpha_S(Q^2)} F_L(ax, Q^2)$$

Gluon approximated from F_L agrees with gluon determined from scaling violations

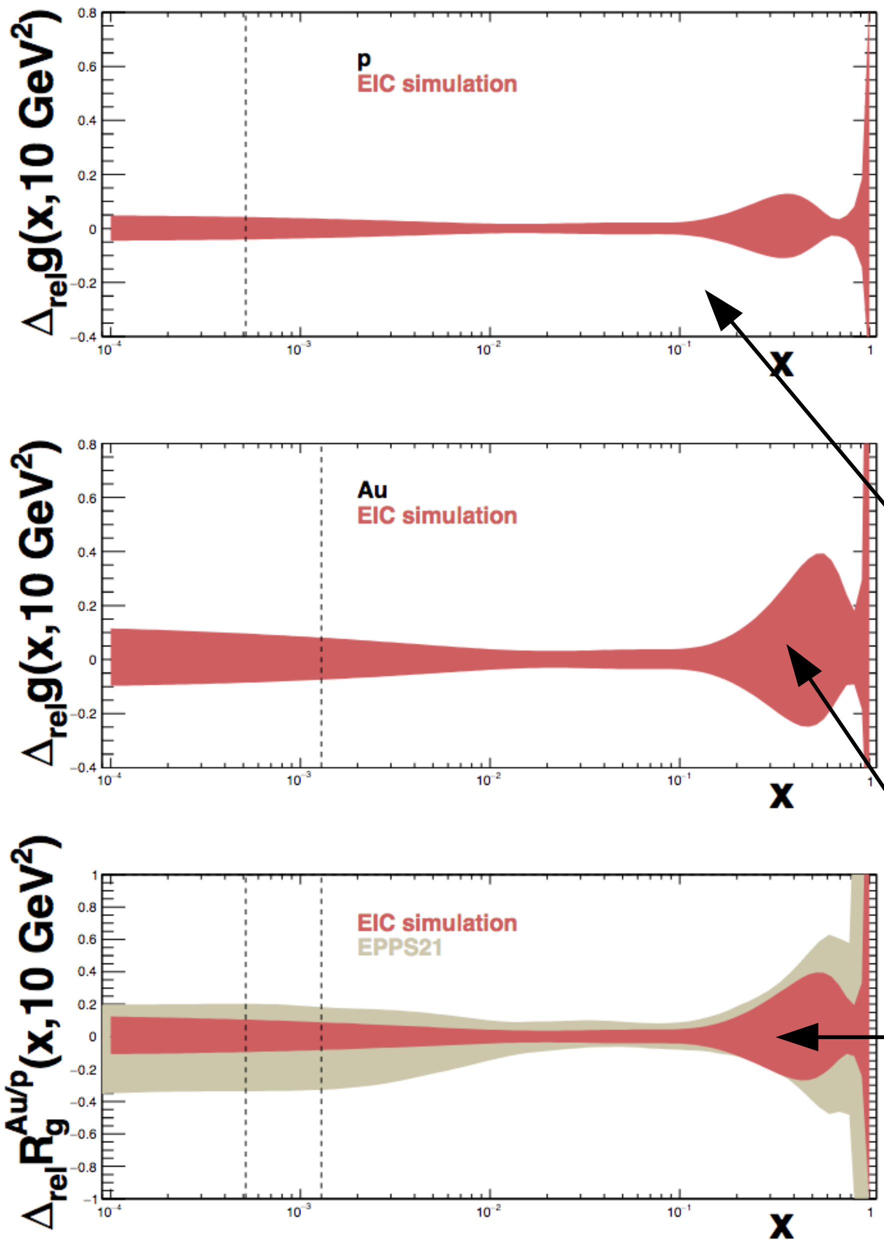
My private EIC wish list ...



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

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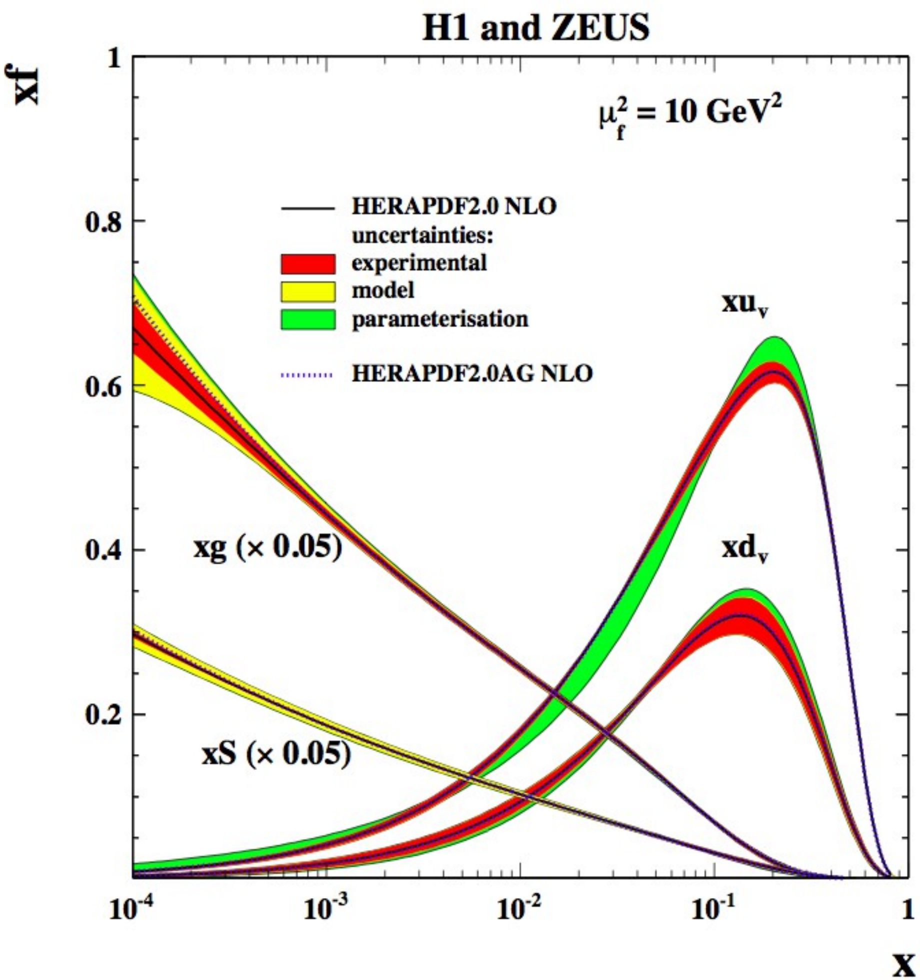
Color decomposition of uncertainties



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

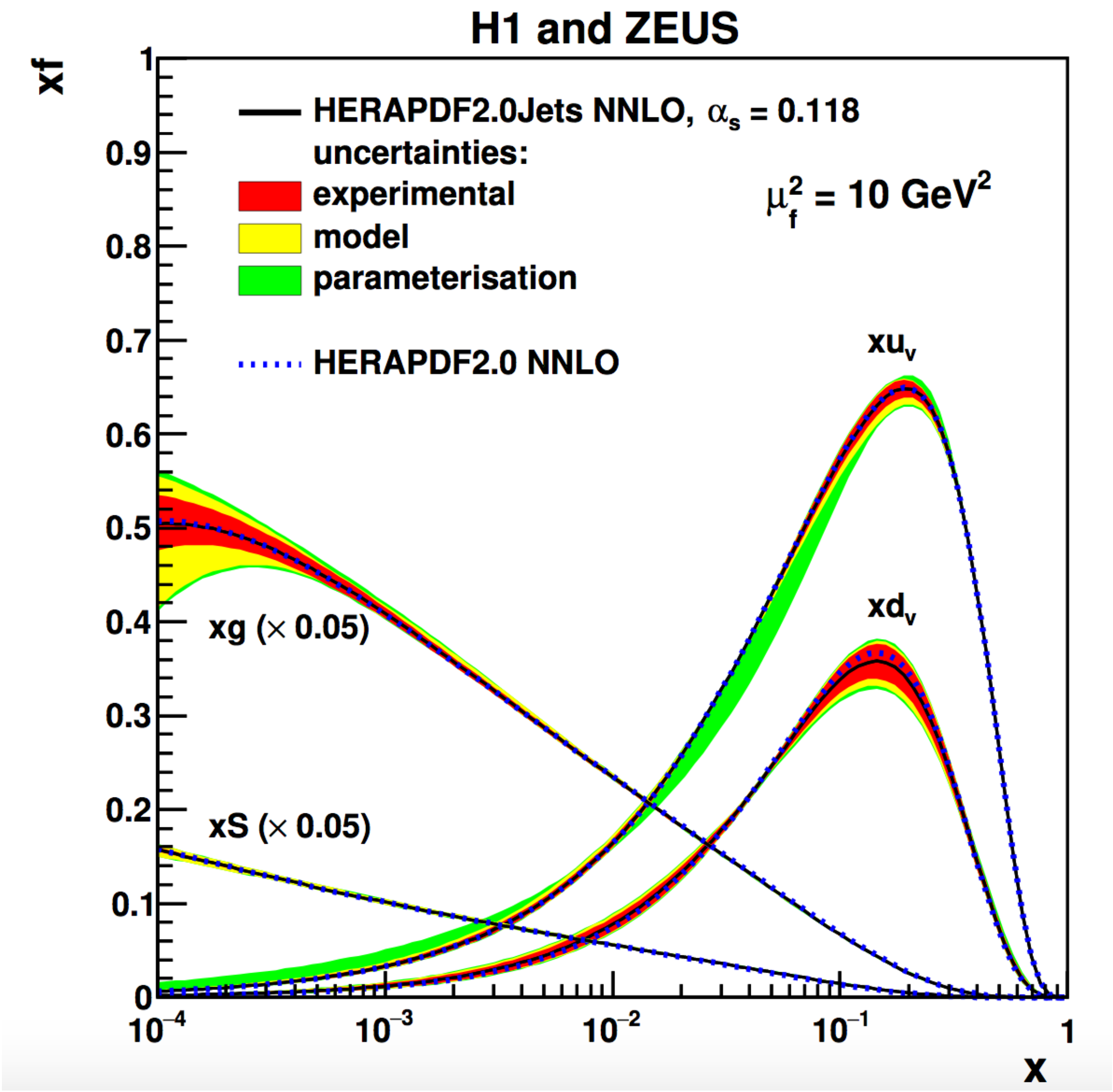
Variation	Standard Value	Lower Limit	Upper Limit
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_{min} [GeV^2] HiQ2	10.0	7.5	12.5
M_c(NLO) [GeV]	1.47	1.41	1.53
M_c (NNLO) [GeV]	1.43	1.37	1.49
M_b [GeV]	4.5	4.25	4.75
f_s	0.4	0.3	0.5
μ_{f_0} [GeV]	1.9	1.6	2.2

Adding D and E parameters to each PDF

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

Fit with fixed α_s = 0.118

How does it compare to HERAPDF2.0? Well!



comparison to other HERA DIS results

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

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

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

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

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

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

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

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

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

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

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

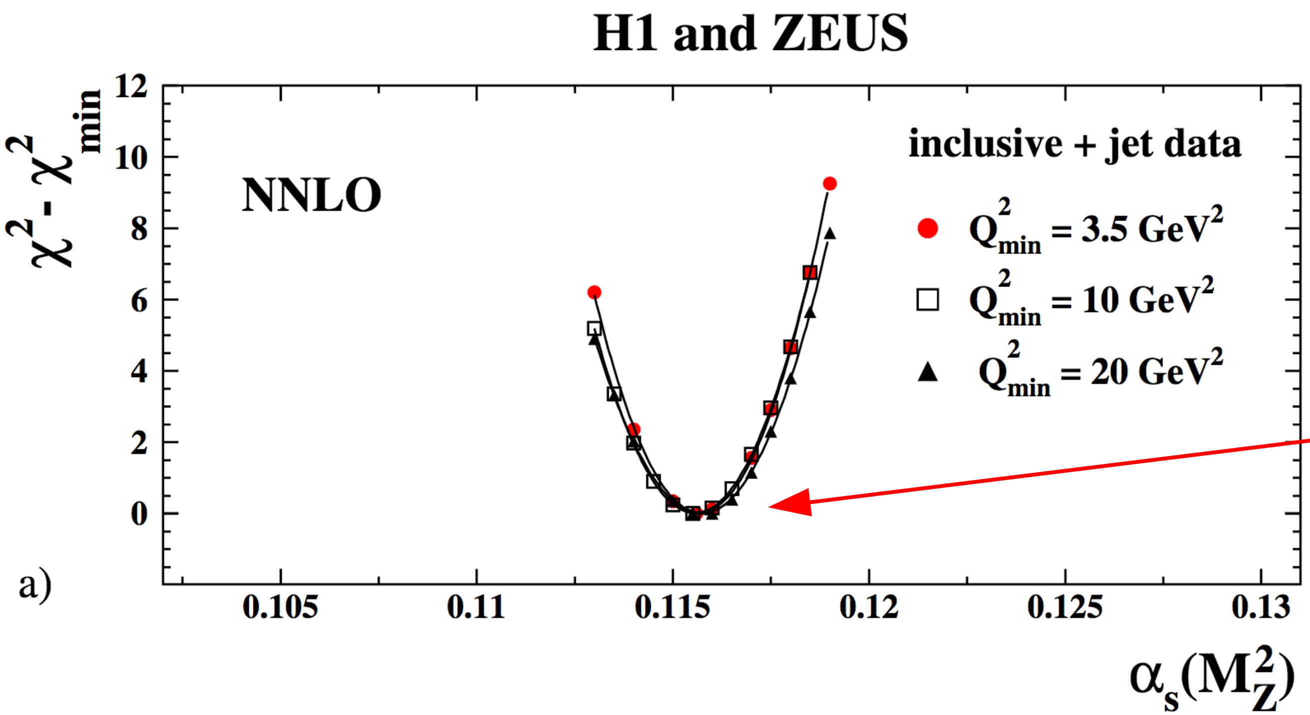
† pt denotes pt^{jet} in the case of inclusive jet cross sections and <pt> for dijets

- 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

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

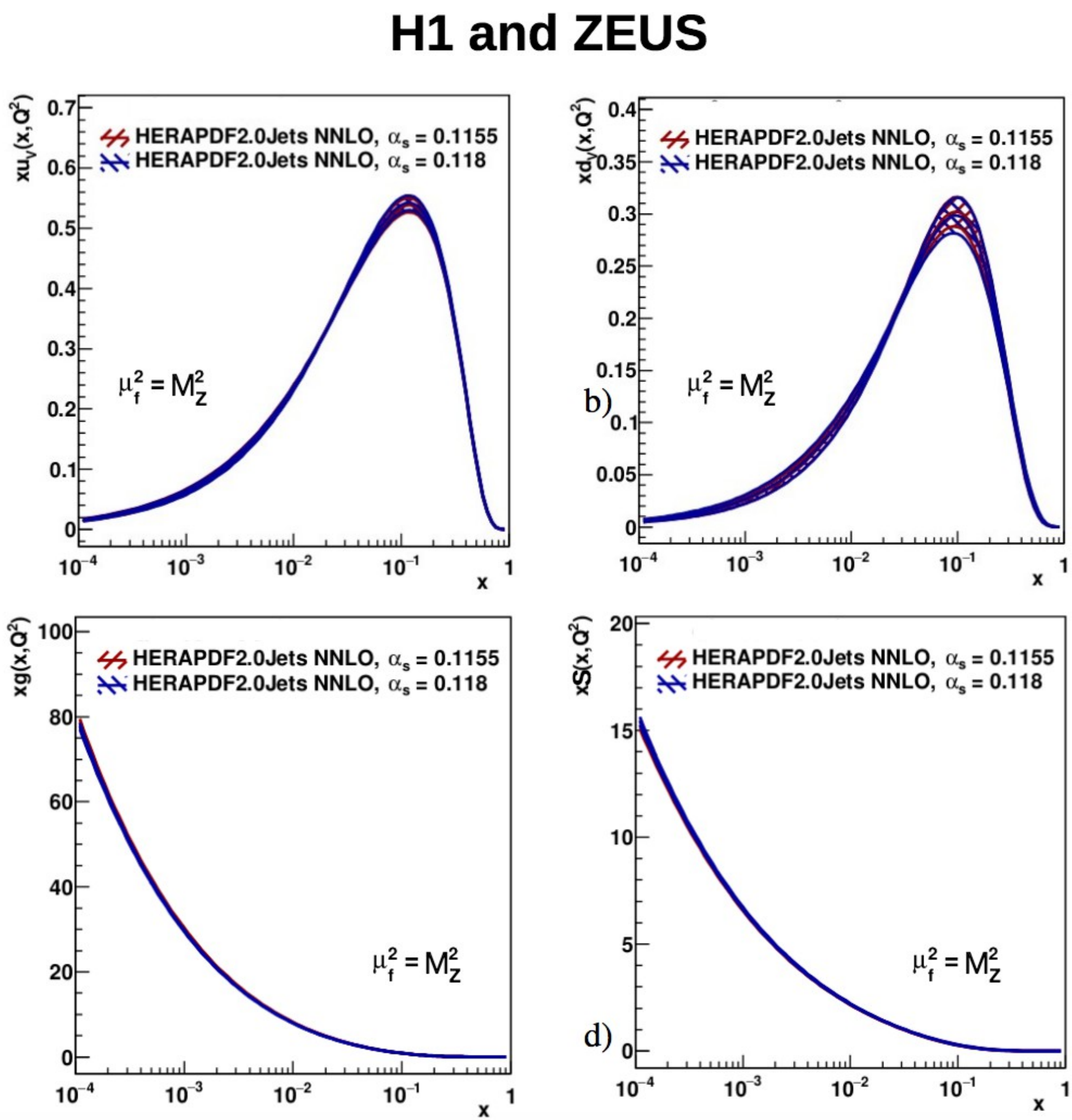


Q^2 cuts do not result in any significant change to the value of $\alpha_s(M_Z)$

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

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

… and how it compares to α_s = 0.1155



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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:

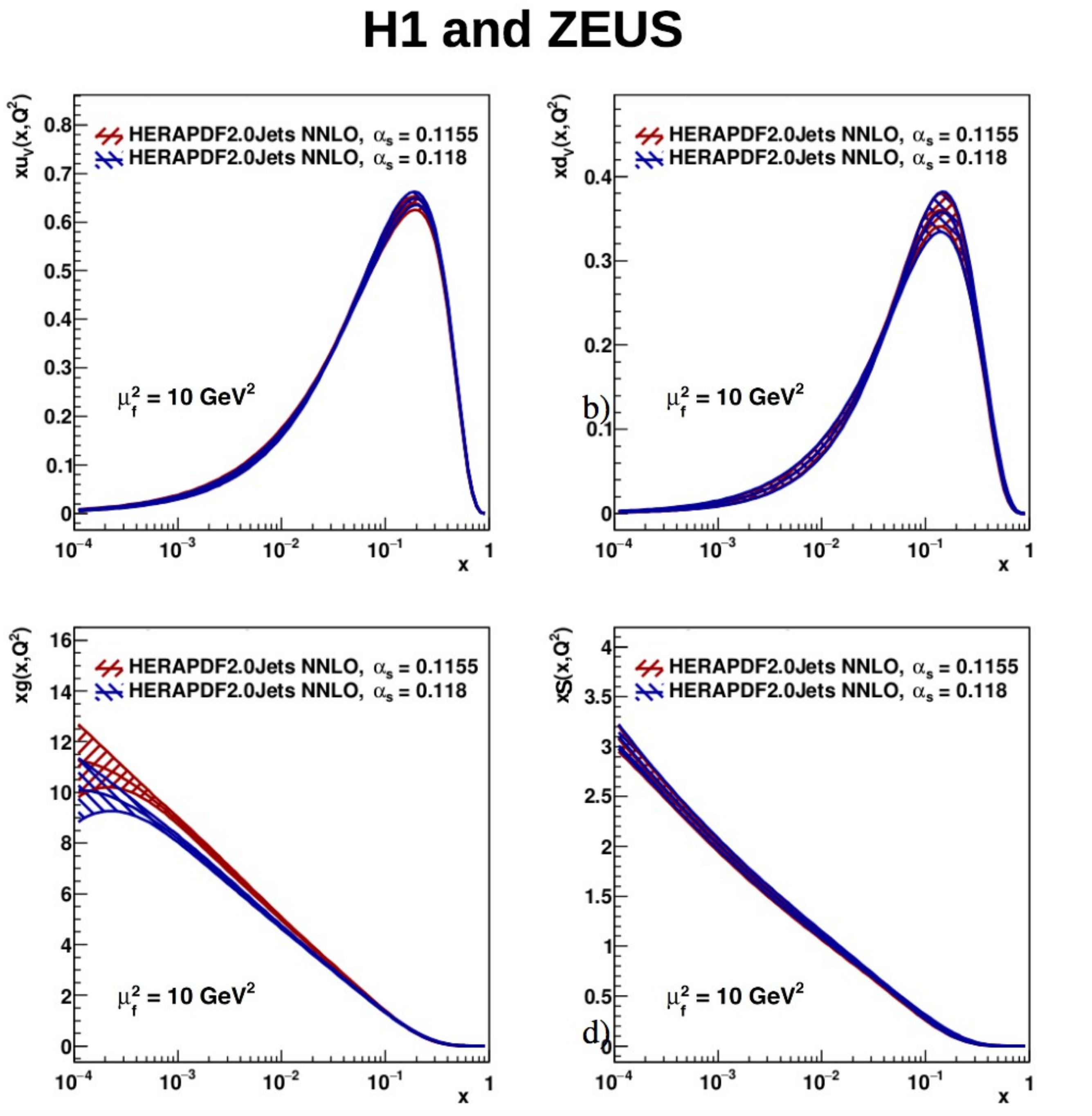
- choice of scale, $\mu_f^2 = \mu_r^2 = Q^2 + p_T^2$;
- exclusion of the H1 low-Q^2 inclusive and dijet data;
- exclusion of the low-p_T points from the H1 high-Q^2 inclusive jet data;
- exclusion of trijet data;
- exclusion of low-p_T points from the ZEUS dijet data;
- exclusion of data with $\mu <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

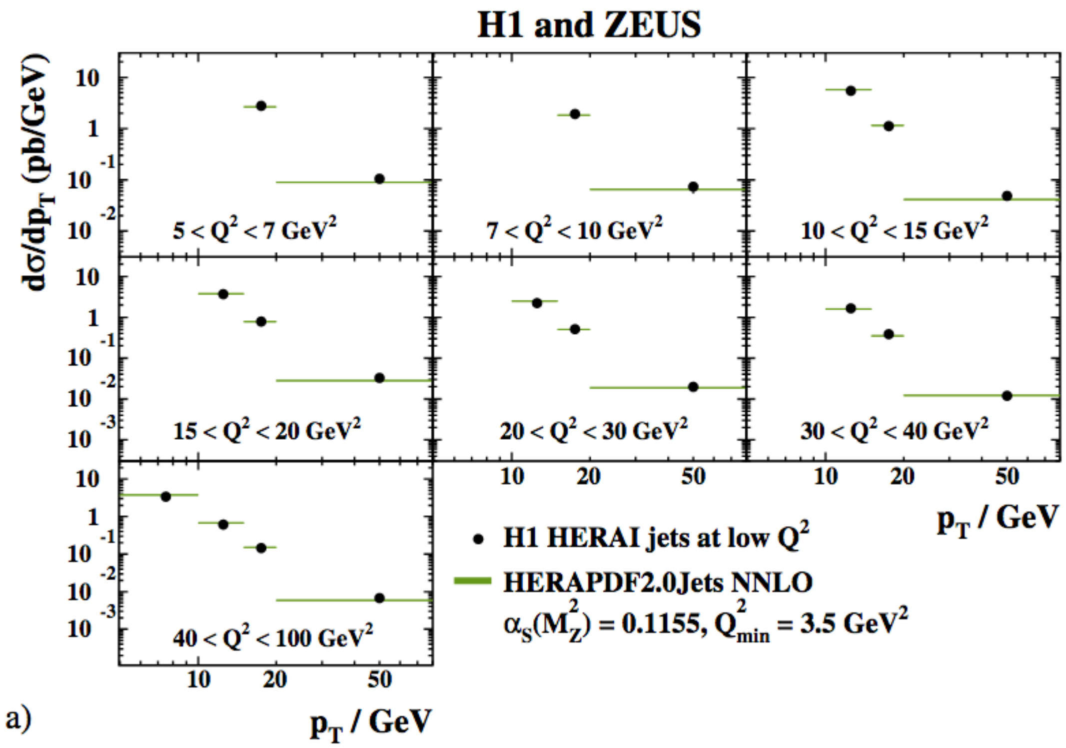
The values of $\alpha_S(M_Z)$ obtained for these conditions are:
0.1186 ± 0.0014(exp) NLO and 0.1144 ± 0.0013(exp) NNLO.
The change of the NNLO value from the preferred value of 0.1156 is mostly due to the exclusion of the H1 lowQ^2 data and the low-p_T points at high Q^2

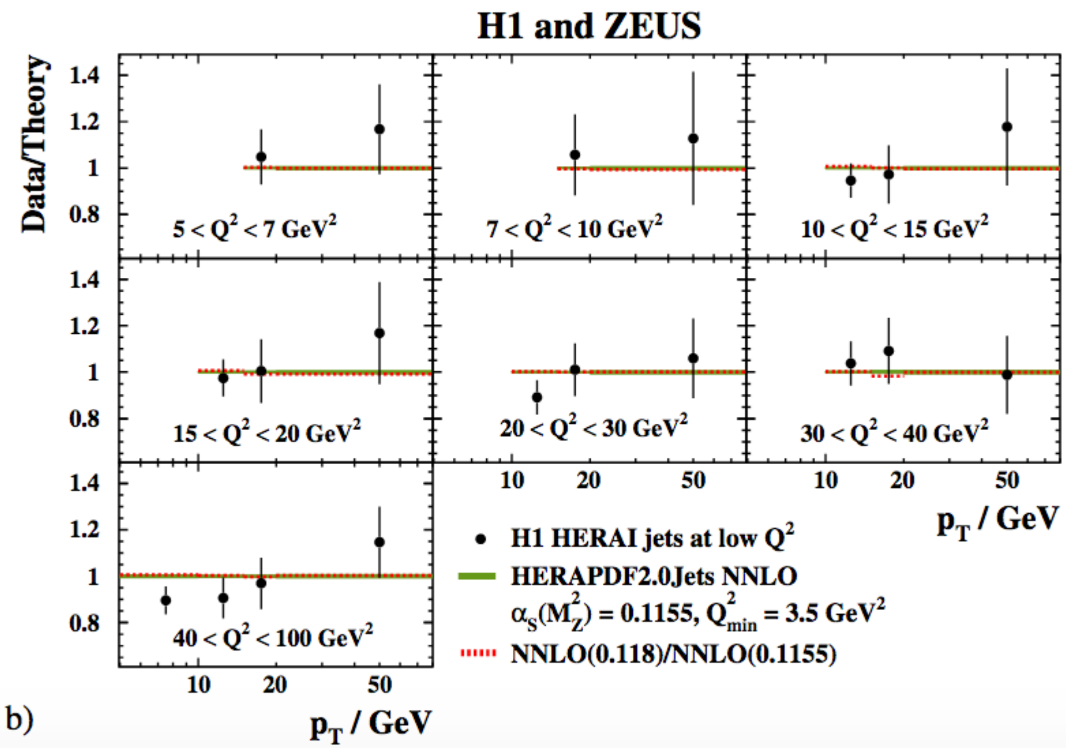
What do we mean when we say the H1 low Q^2 jets cannot be well fitted at NLO?
Simply this, that at NNLO the increase in overall $\chi 2$ of the fit when the 74 data pts of these data are added is ~80 (exact value depends on $\alpha_S(M_Z)$ and on scale choice)
Whereas at NLO the increase in overall $\chi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

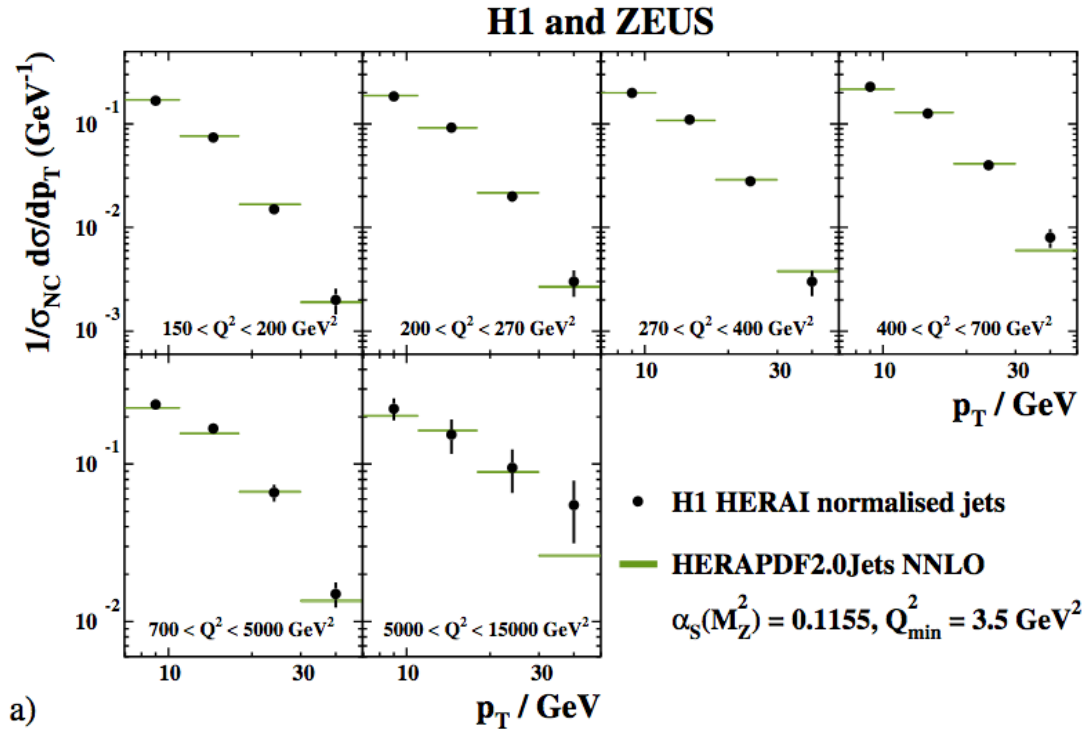
(from A. Cooper-Sarkar, alpha-s 2022 workshop)

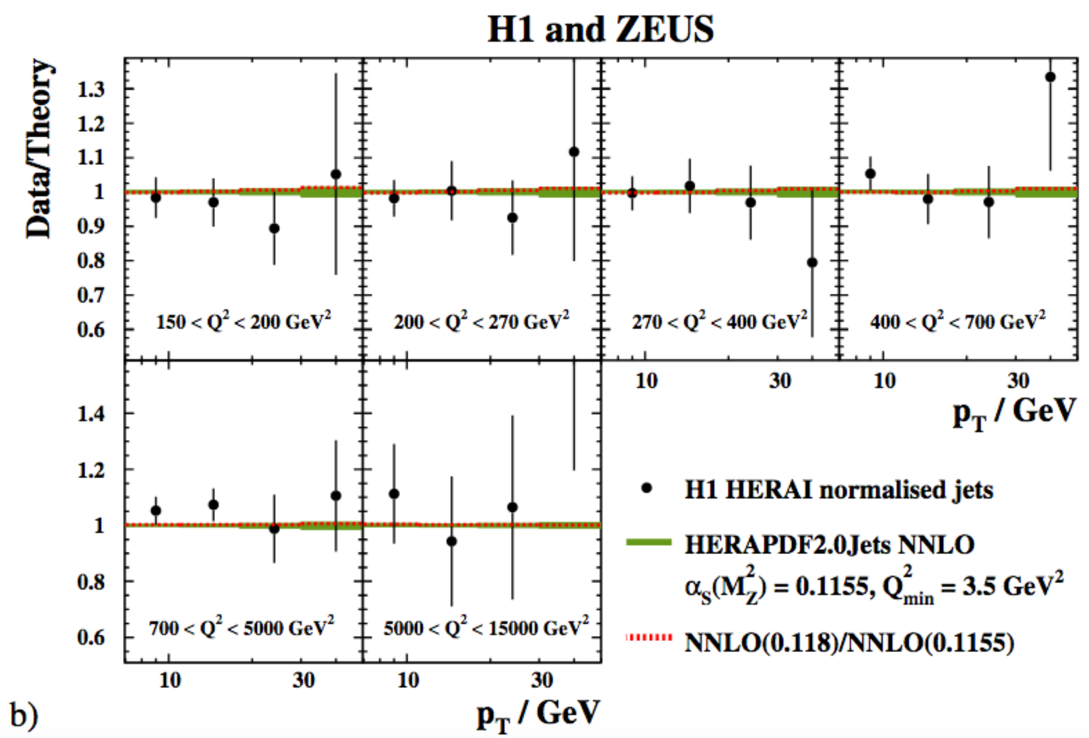
… and how it compares to α_s = 0.1155

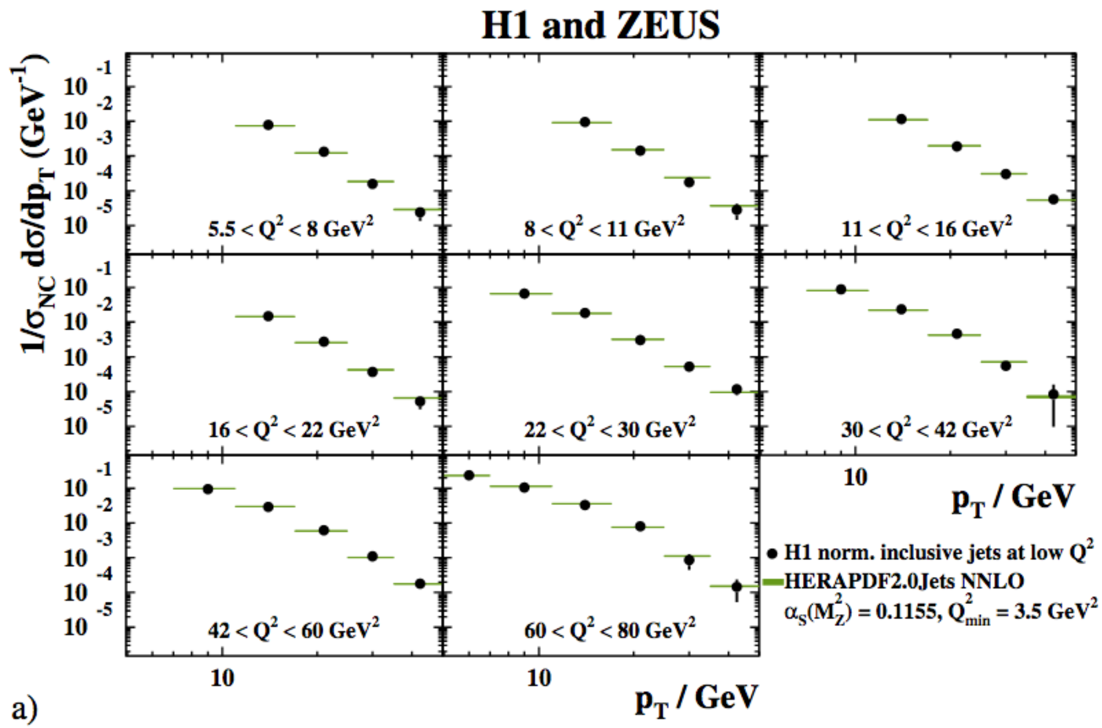



H1 and ZEUS
dσ/dp$_T$ (pb/GeV)
5 < Q^2 < 7 GeV^2
7 < Q^2 < 10 GeV^2
10 < Q^2 < 15 GeV^2
15 < Q^2 < 20 GeV^2
20 < Q^2 < 30 GeV^2
30 < Q^2 < 40 GeV^2
40 < Q^2 < 100 GeV^2
p$_T$ / GeV
H1 HERAI jets at low Q^2
HERAPDF2.0Jets NNLO
$\alpha_S(M_Z^2)$ = 0.1155, Q^2_{min} = 3.5 GeV^2
a)

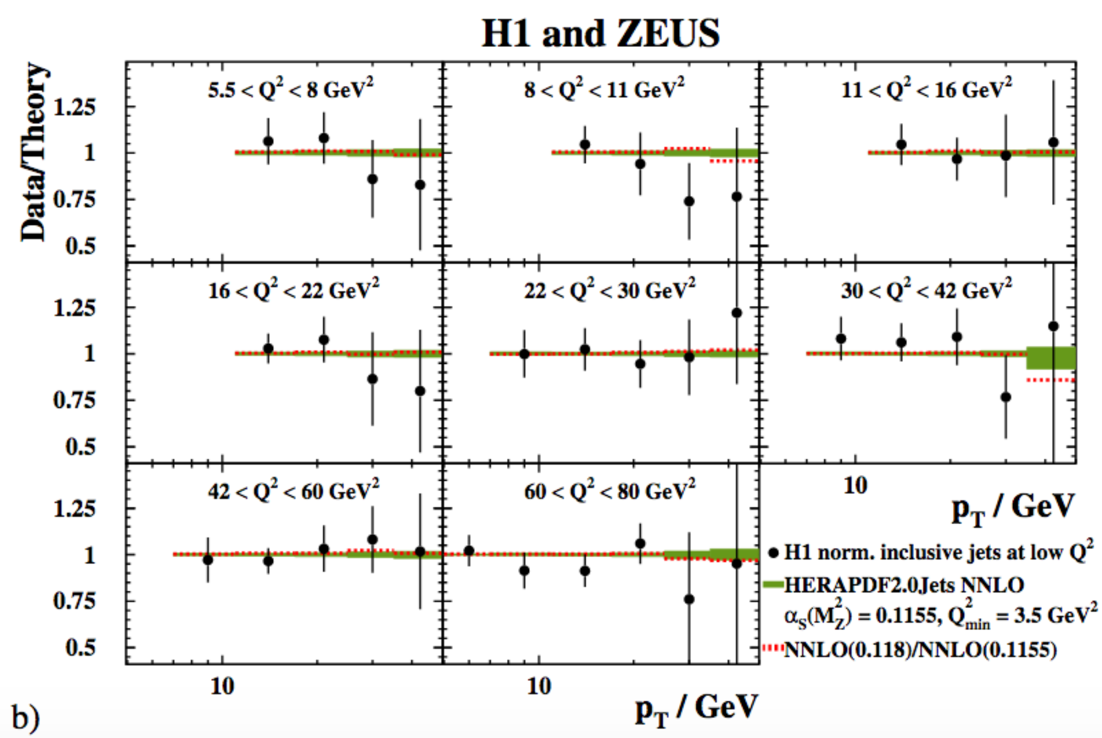

H1 and ZEUS
Data/Theory
5 < Q^2 < 7 GeV^2
7 < Q^2 < 10 GeV^2
10 < Q^2 < 15 GeV^2
15 < Q^2 < 20 GeV^2
20 < Q^2 < 30 GeV^2
30 < Q^2 < 40 GeV^2
40 < Q^2 < 100 GeV^2
p$_T$ / GeV
H1 HERAI jets at low Q^2
HERAPDF2.0Jets NNLO
$\alpha_S(M_Z^2)$ = 0.1155, Q^2_{min} = 3.5 GeV^2
NNLO(0.118)/NNLO(0.1155)
b)


H1 and ZEUS
$1/\sigma_{NC}\, d\sigma/dp_T\ (GeV^{-1})$
150 < Q² < 200 GeV²
200 < Q² < 270 GeV²
270 < Q² < 400 GeV²
400 < Q² < 700 GeV²
700 < Q² < 5000 GeV²
5000 < Q² < 15000 GeV²
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)

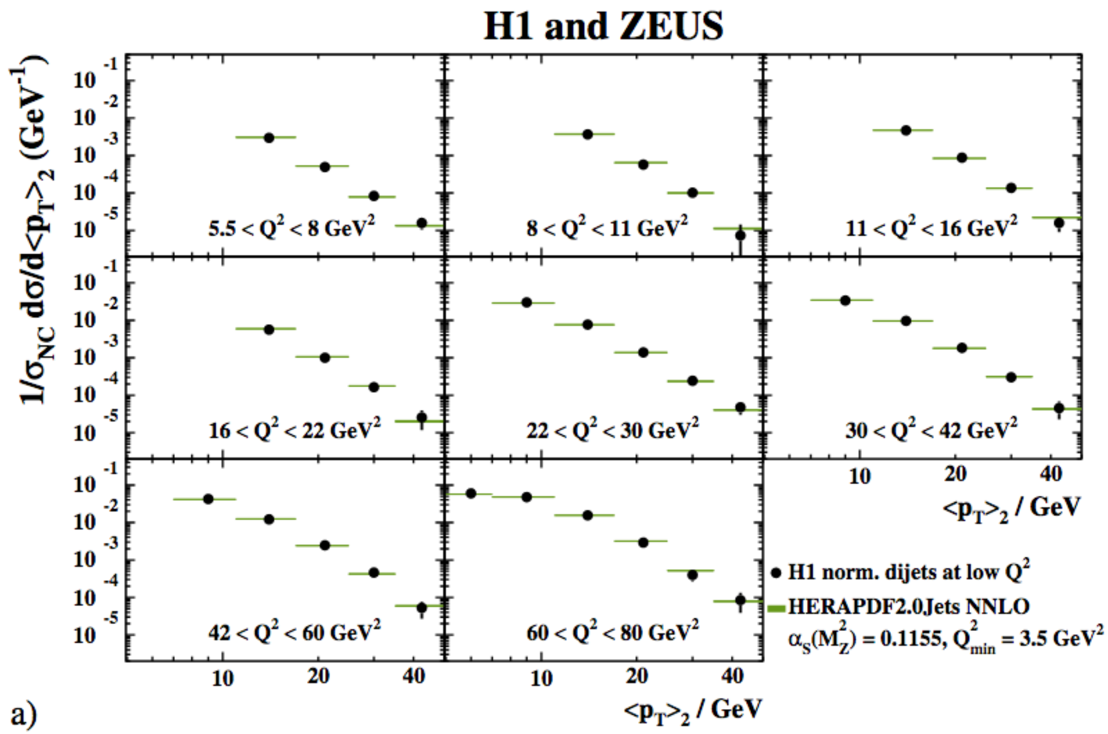

H1 and ZEUS
Data/Theory
150 < Q² < 200 GeV²
200 < Q² < 270 GeV²
270 < Q² < 400 GeV²
400 < Q² < 700 GeV²
700 < Q² < 5000 GeV²
5000 < Q² < 15000 GeV²
p_T / GeV
H1 HERAI normalised jets
HERAPDF2.0Jets NNLO
$\alpha_S(M_Z^2) = 0.1155,\ Q^2_{min} = 3.5\ GeV^2$
NNLO(0.118)/NNLO(0.1155)
b)

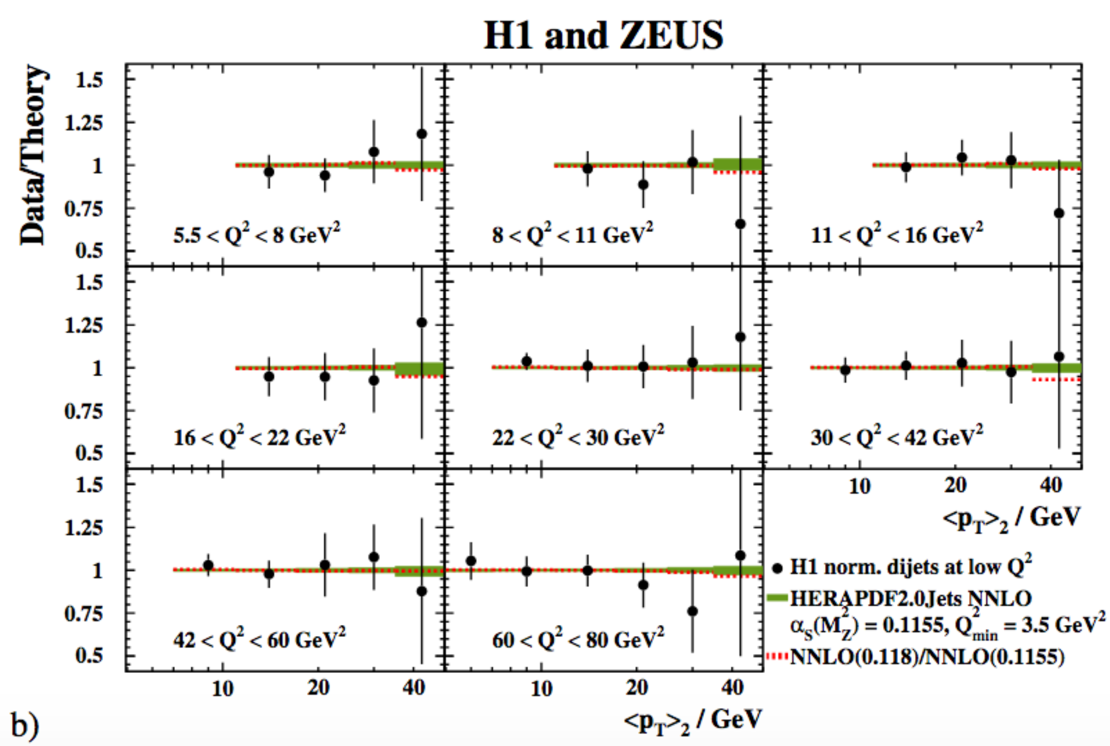


H1 and ZEUS
$1/\sigma_{NC}\, d\sigma/dp_T\ (GeV^{-1})$
$5.5 < Q^2 < 8\ GeV^2$
$8 < Q^2 < 11\ GeV^2$
$11 < Q^2 < 16\ GeV^2$
$16 < Q^2 < 22\ GeV^2$
$22 < Q^2 < 30\ GeV^2$
$30 < Q^2 < 42\ GeV^2$
$42 < Q^2 < 60\ GeV^2$
$60 < Q^2 < 80\ GeV^2$
p_T / GeV
H1 norm. inclusive jets at low Q^2
HERAPDF2.0Jets NNLO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





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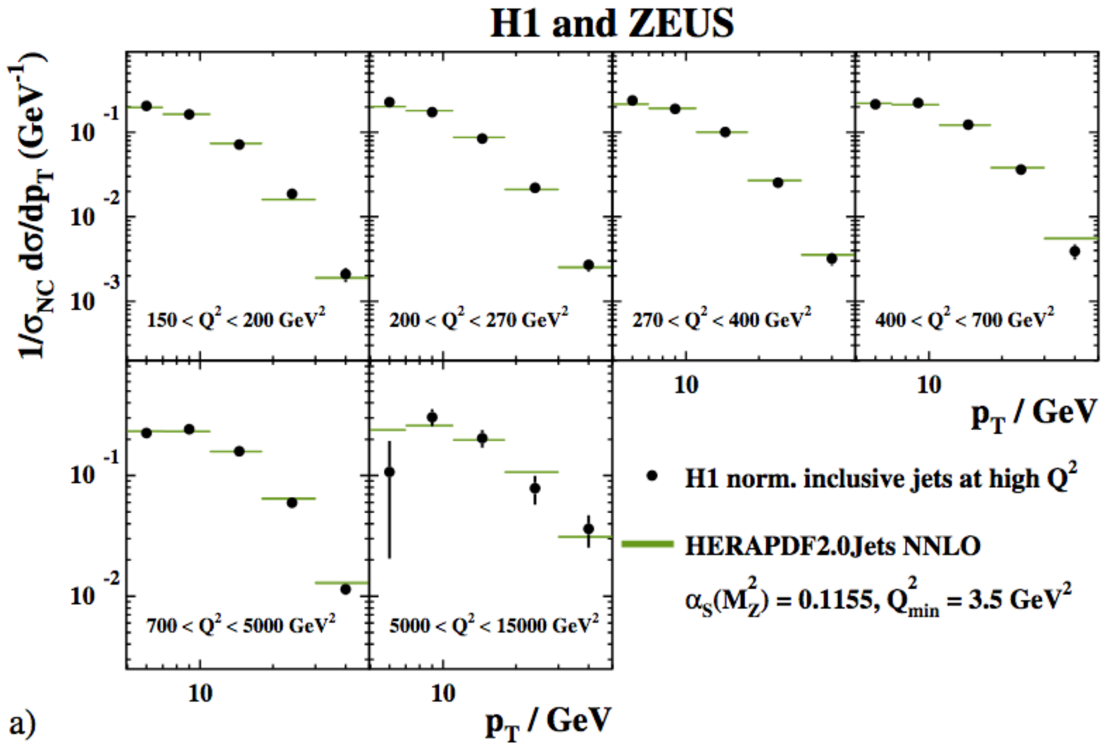
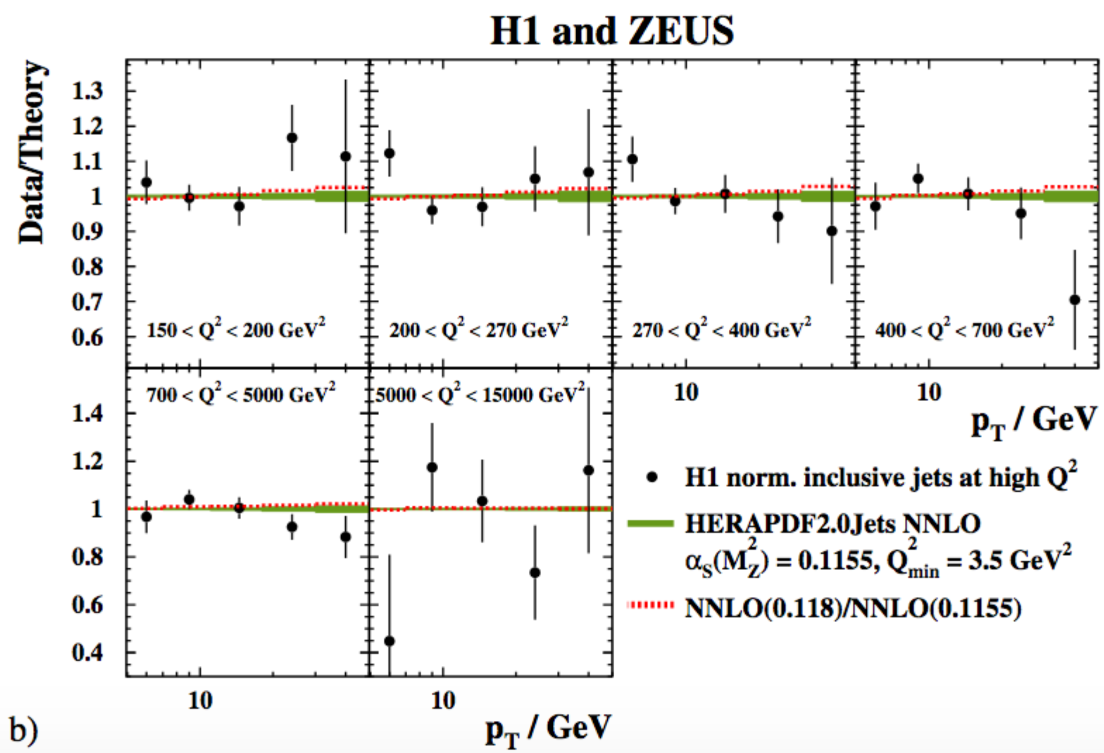
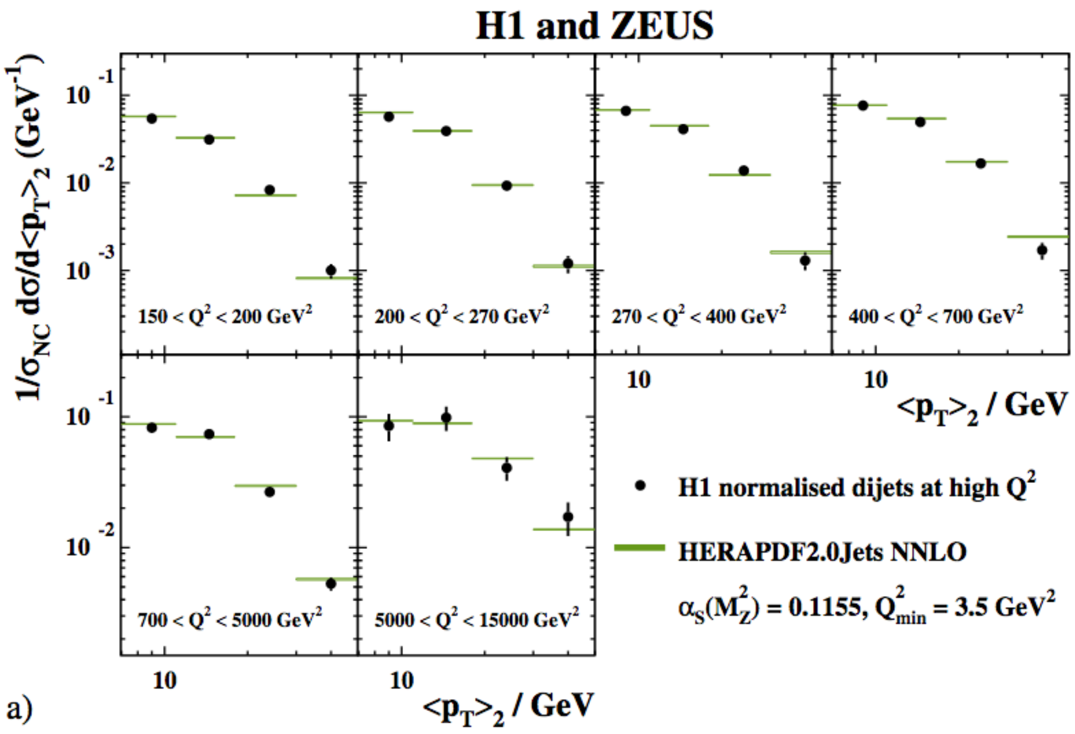

H1 and ZEUS
1/σNC dσ/dpT (GeV-1)
150 < Q2 < 200 GeV2
200 < Q2 < 270 GeV2
270 < Q2 < 400 GeV2
400 < Q2 < 700 GeV2
700 < Q2 < 5000 GeV2
5000 < Q2 < 15000 GeV2
pT / GeV
H1 norm. inclusive jets at high Q2
HERAPDF2.0Jets NNLO
αS(M2Z) = 0.1155, Q2min = 3.5 GeV2

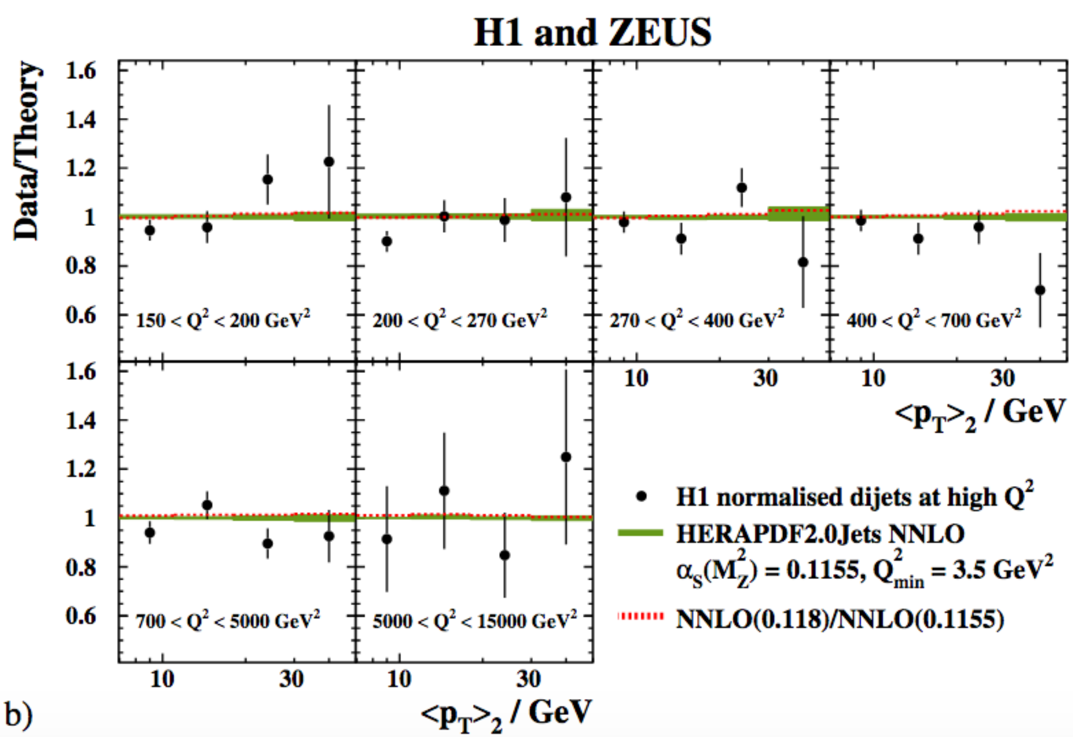
a)


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
pT / GeV
H1 norm. inclusive jets at high Q2
HERAPDF2.0Jets NNLO
αS(M2Z) = 0.1155, Q2min = 3.5 GeV2
NNLO(0.118)/NNLO(0.1155)

b)



a)



b)

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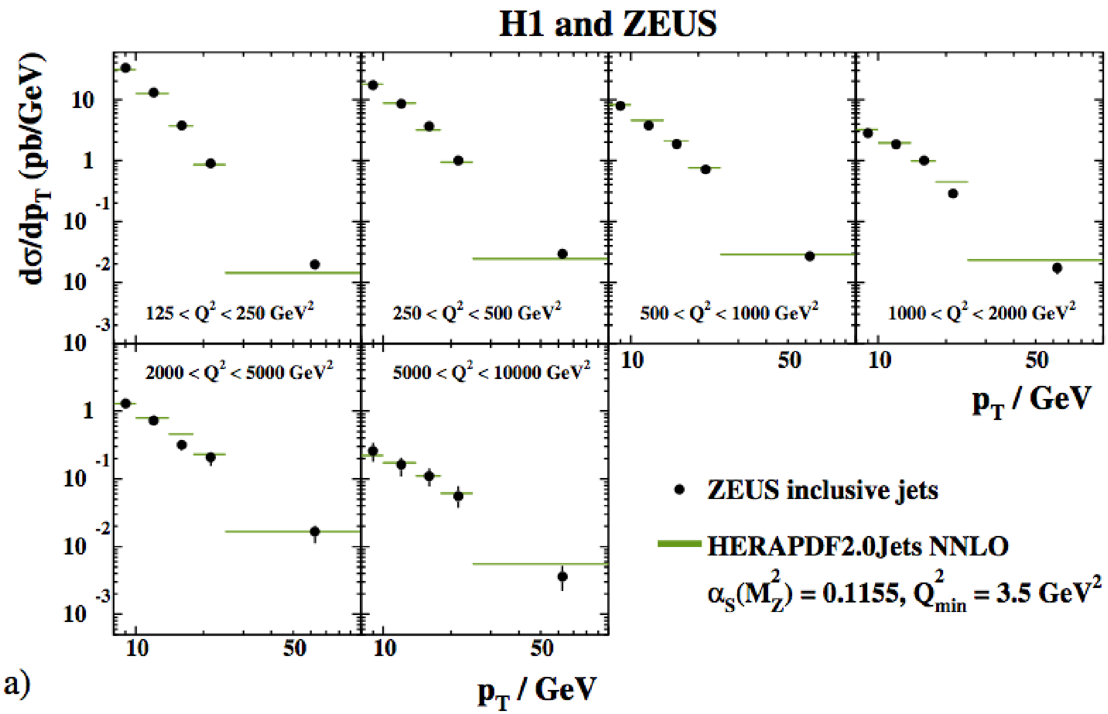
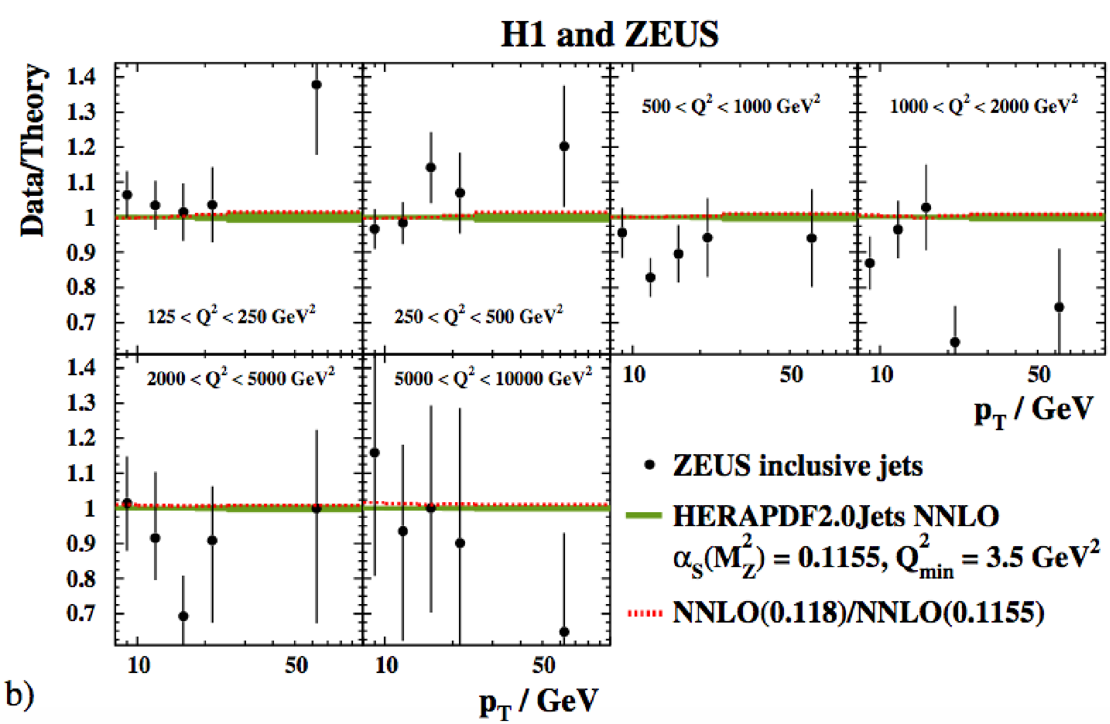
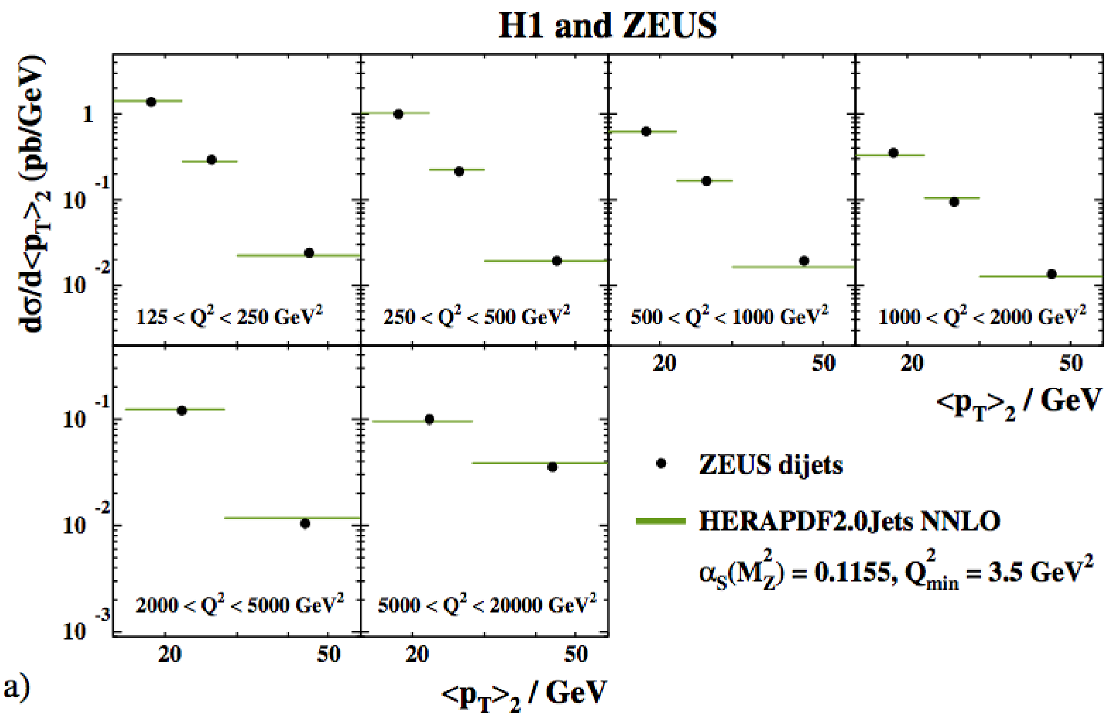
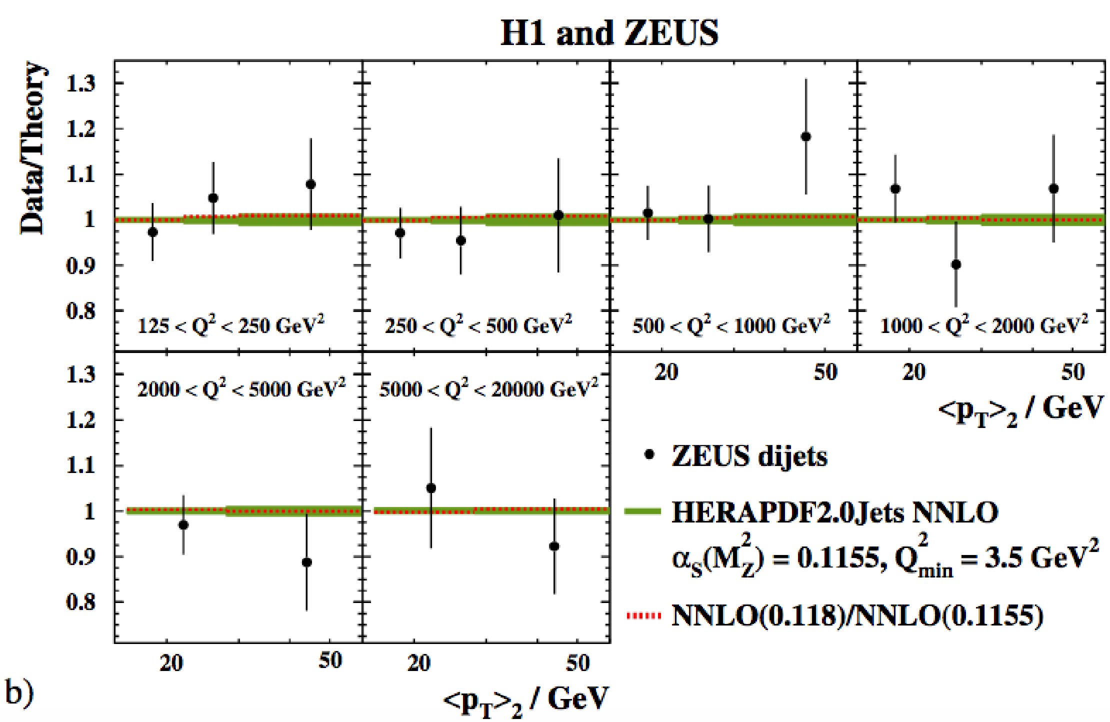

H1 and ZEUS
dσ/dp_T (pb/GeV)
125 < Q² < 250 GeV²
250 < Q² < 500 GeV²
500 < Q² < 1000 GeV²
1000 < Q² < 2000 GeV²
2000 < Q² < 5000 GeV²
5000 < Q² < 10000 GeV²
p_T / GeV
ZEUS inclusive jets
HERAPDF2.0Jets NNLO
α_S(M_Z²) = 0.1155, Q²_min = 3.5 GeV²

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)

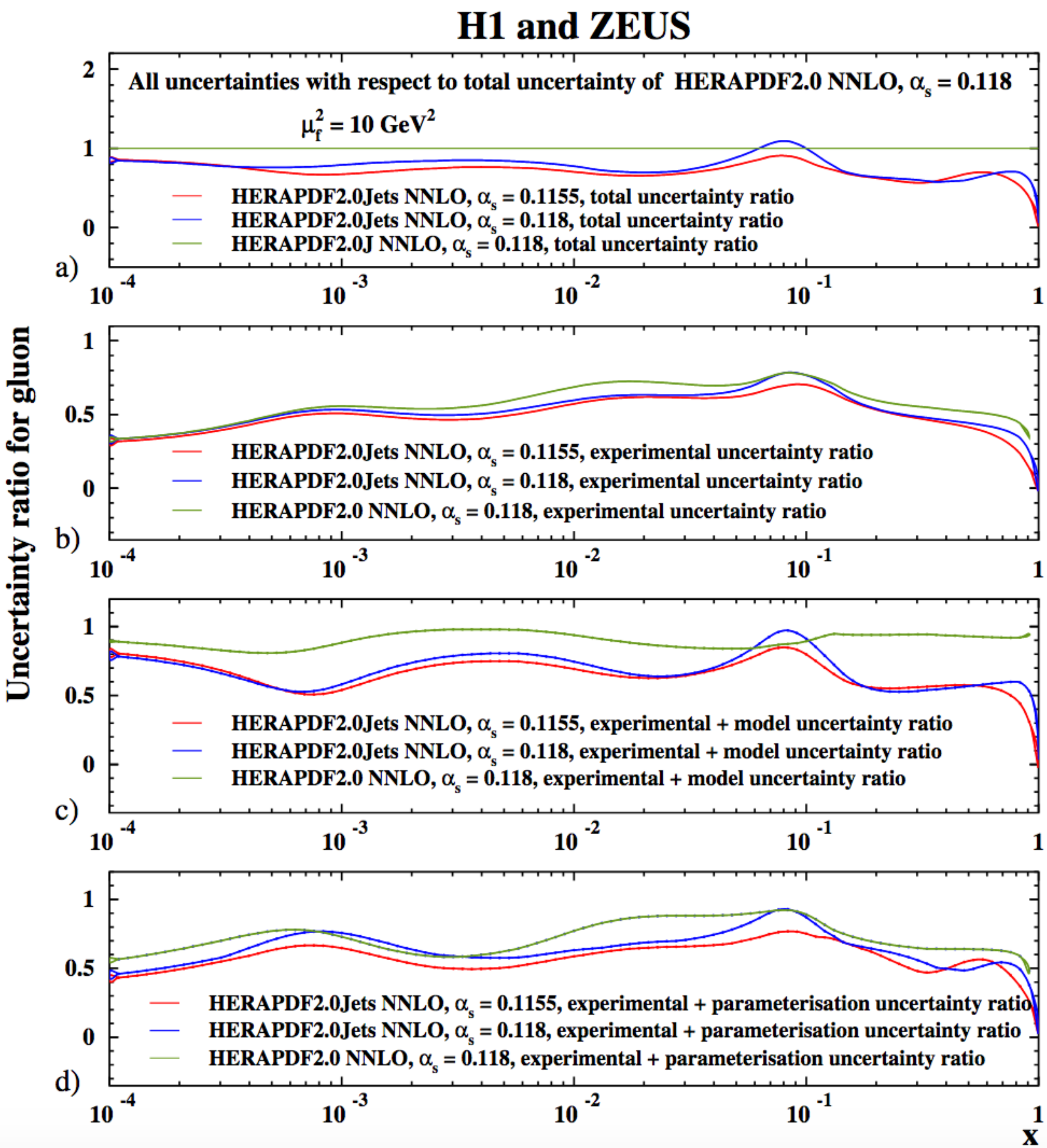
b)


H1 and ZEUS
dσ/d<p_T>_2 (pb/GeV)
125 < Q² < 250 GeV²
250 < Q² < 500 GeV²
500 < Q² < 1000 GeV²
1000 < Q² < 2000 GeV²
2000 < Q² < 5000 GeV²
5000 < Q² < 20000 GeV²
<p_T>_2 / GeV
ZEUS dijets
HERAPDF2.0Jets NNLO
α_S(M_Z²) = 0.1155, Q²_min = 3.5 GeV²
a)

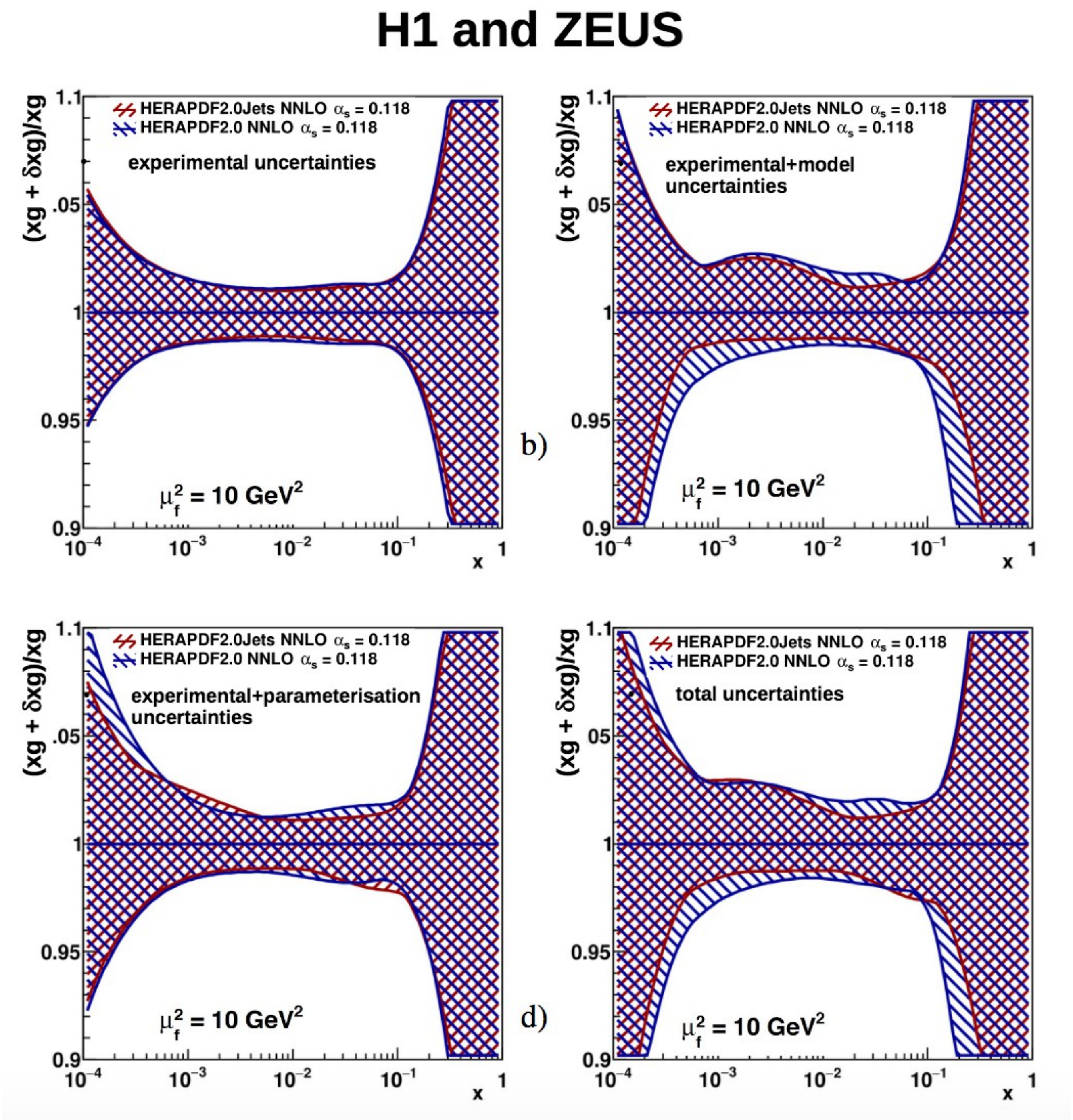

H1 and ZEUS
Data/Theory
125 < Q² < 250 GeV²
250 < Q² < 500 GeV²
500 < Q² < 1000 GeV²
1000 < Q² < 2000 GeV²
2000 < Q² < 5000 GeV²
5000 < Q² < 20000 GeV²
<p_T>_2 / GeV
ZEUS dijets
HERAPDF2.0Jets NNLO
α_S(M_Z²) = 0.1155, Q²_min = 3.5 GeV²
NNLO(0.118)/NNLO(0.1155)
b)

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

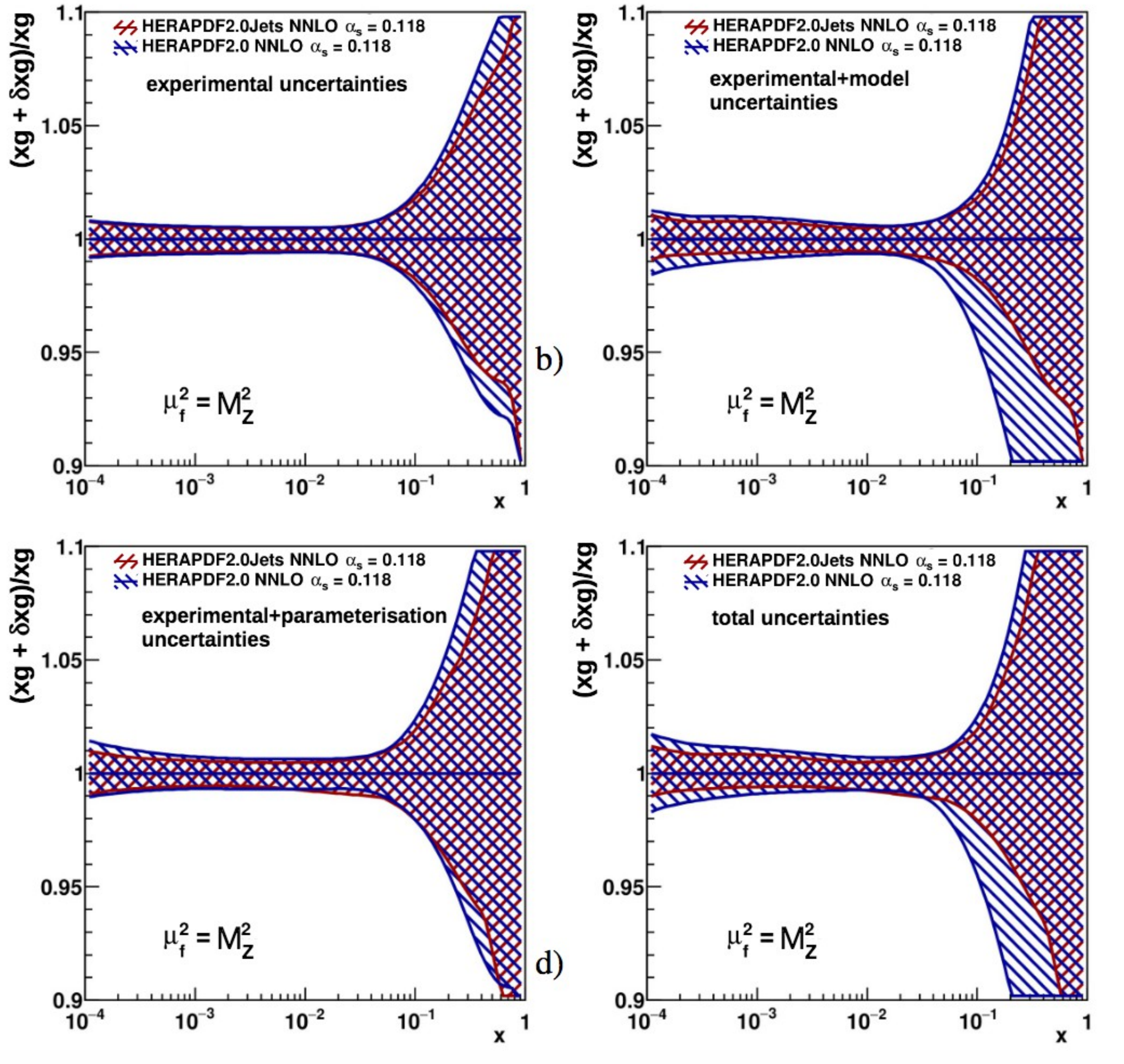


Uncertainties



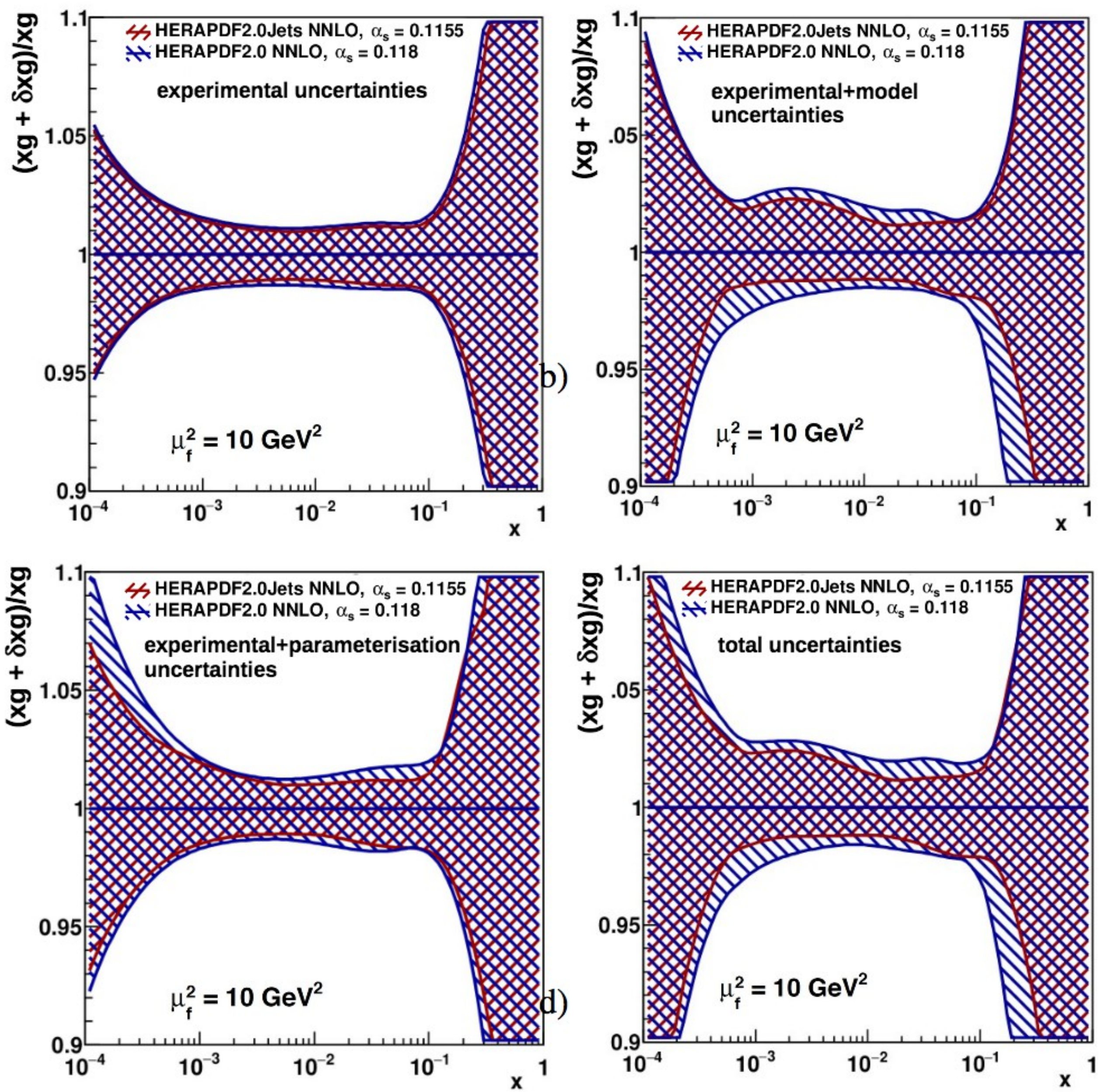
Uncertainties

H1 and ZEUS



Uncertainties

H1 and ZEUS



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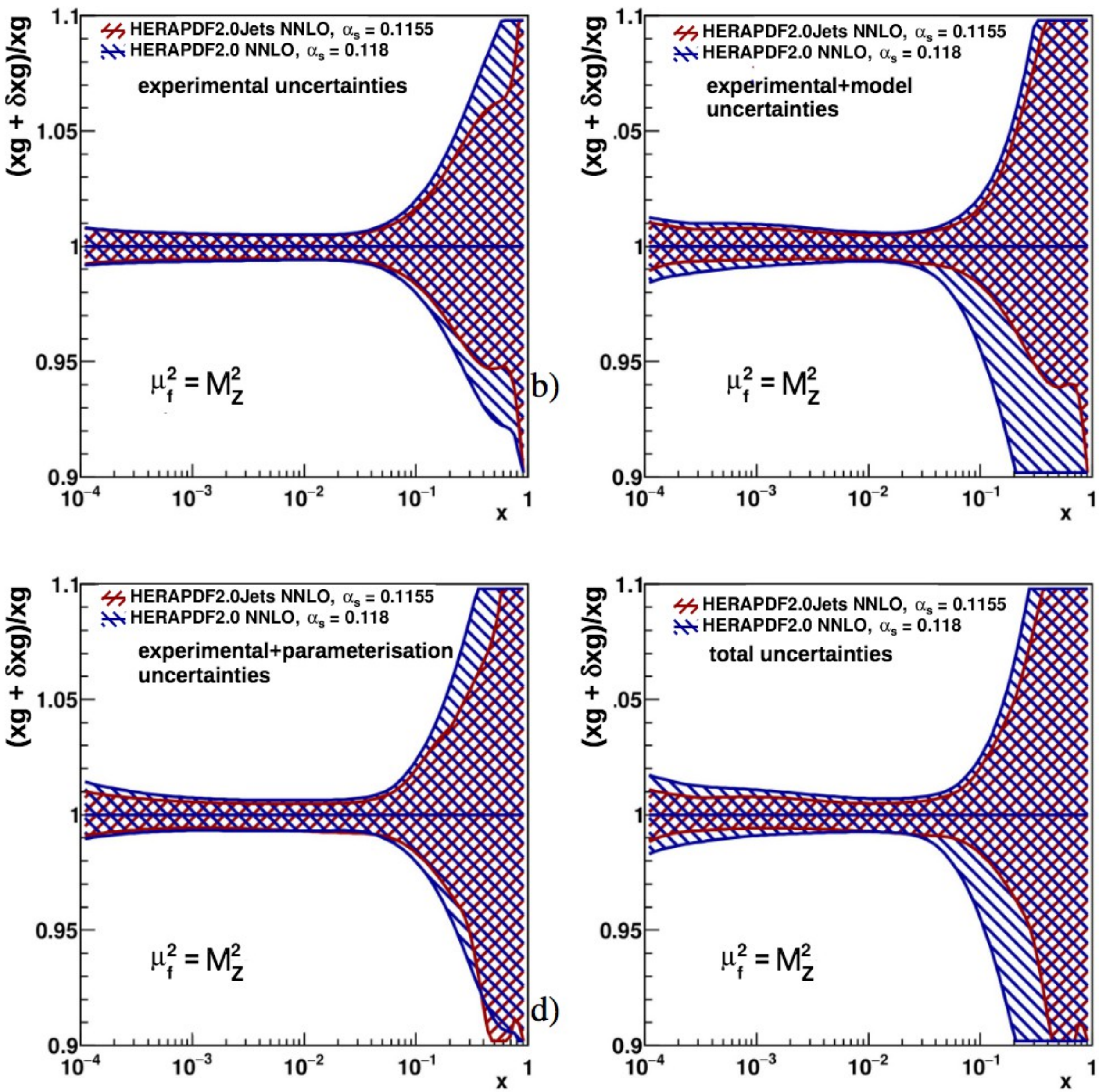
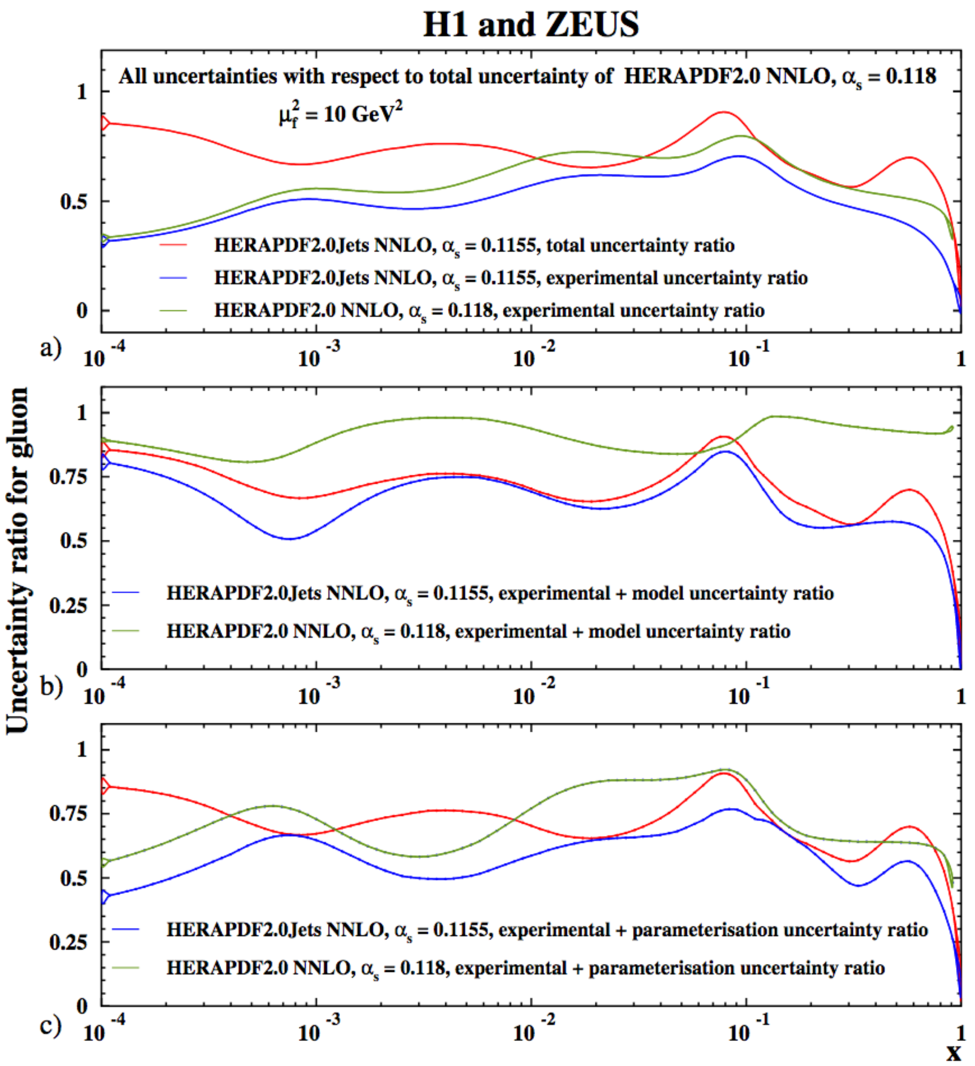
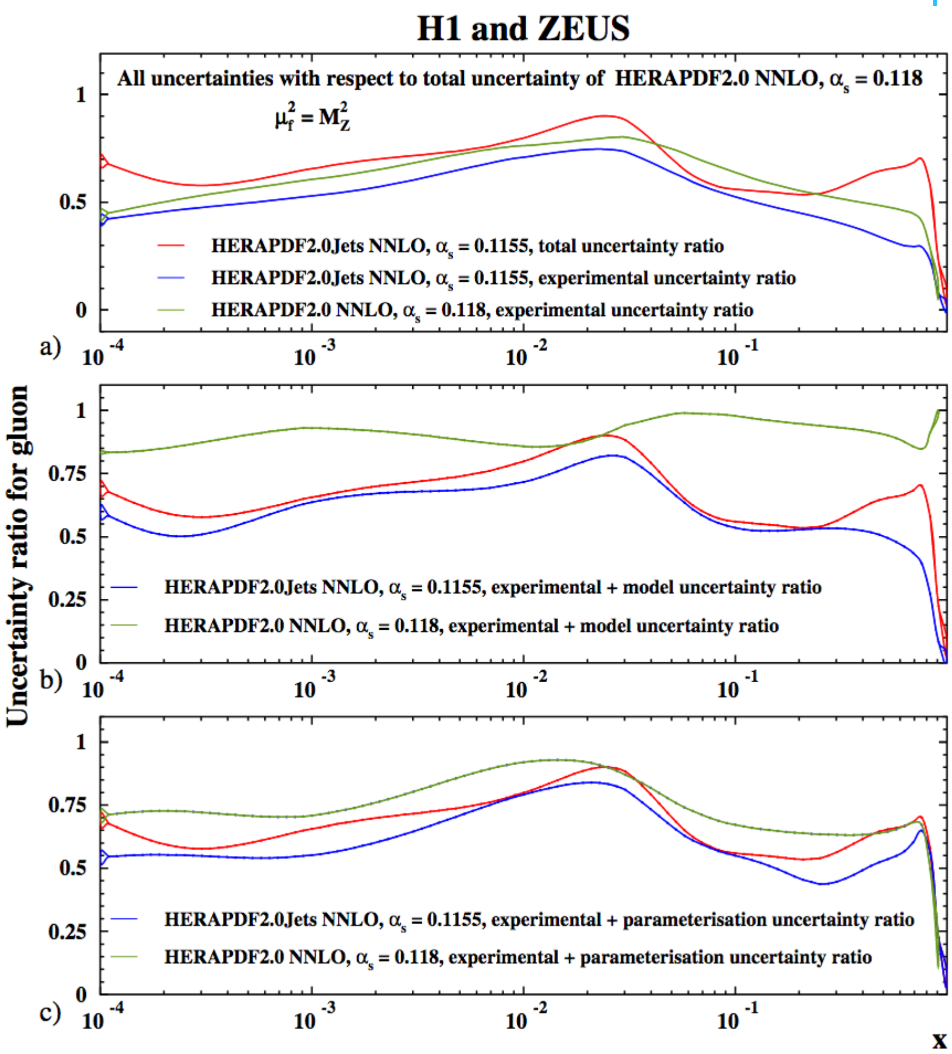
Uncertainties

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
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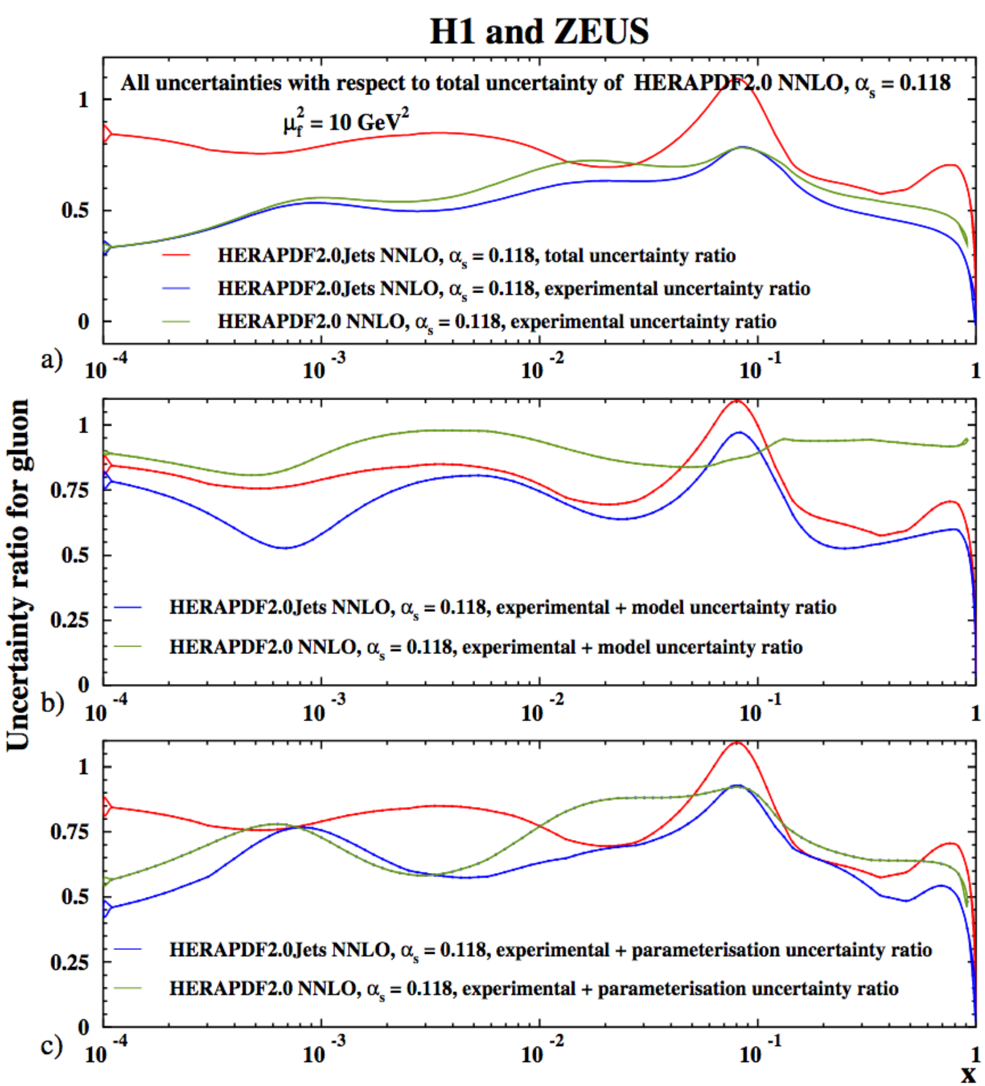
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Uncertainty ratio for gluon
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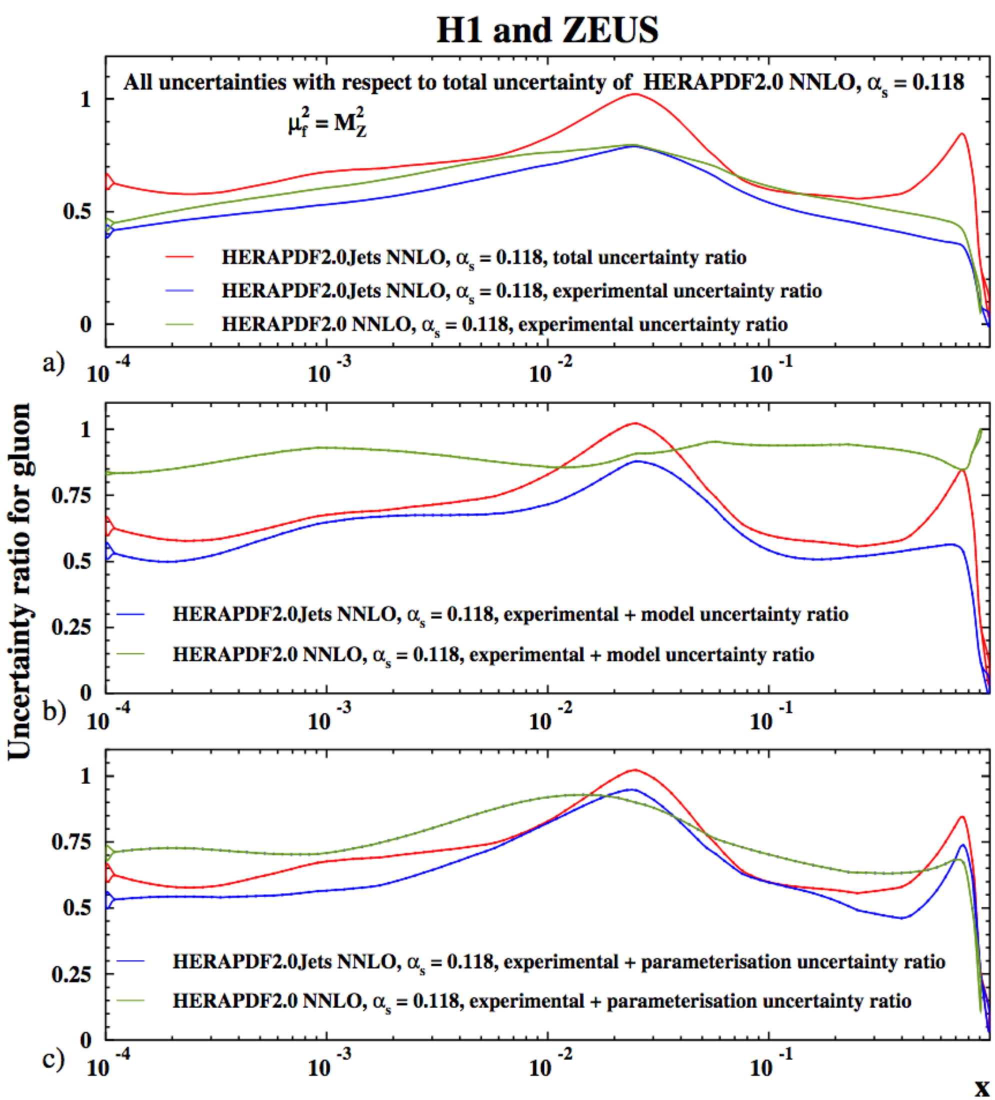
H1 and ZEUS
All uncertainties with respect to total uncertainty of HERAPDF2.0 NNLO, αs = 0.118
μf² = MZ²
HERAPDF2.0Jets NNLO, αs = 0.118, total uncertainty ratio
HERAPDF2.0Jets NNLO, αs = 0.118, experimental uncertainty ratio
HERAPDF2.0 NNLO, αs = 0.118, experimental uncertainty ratio
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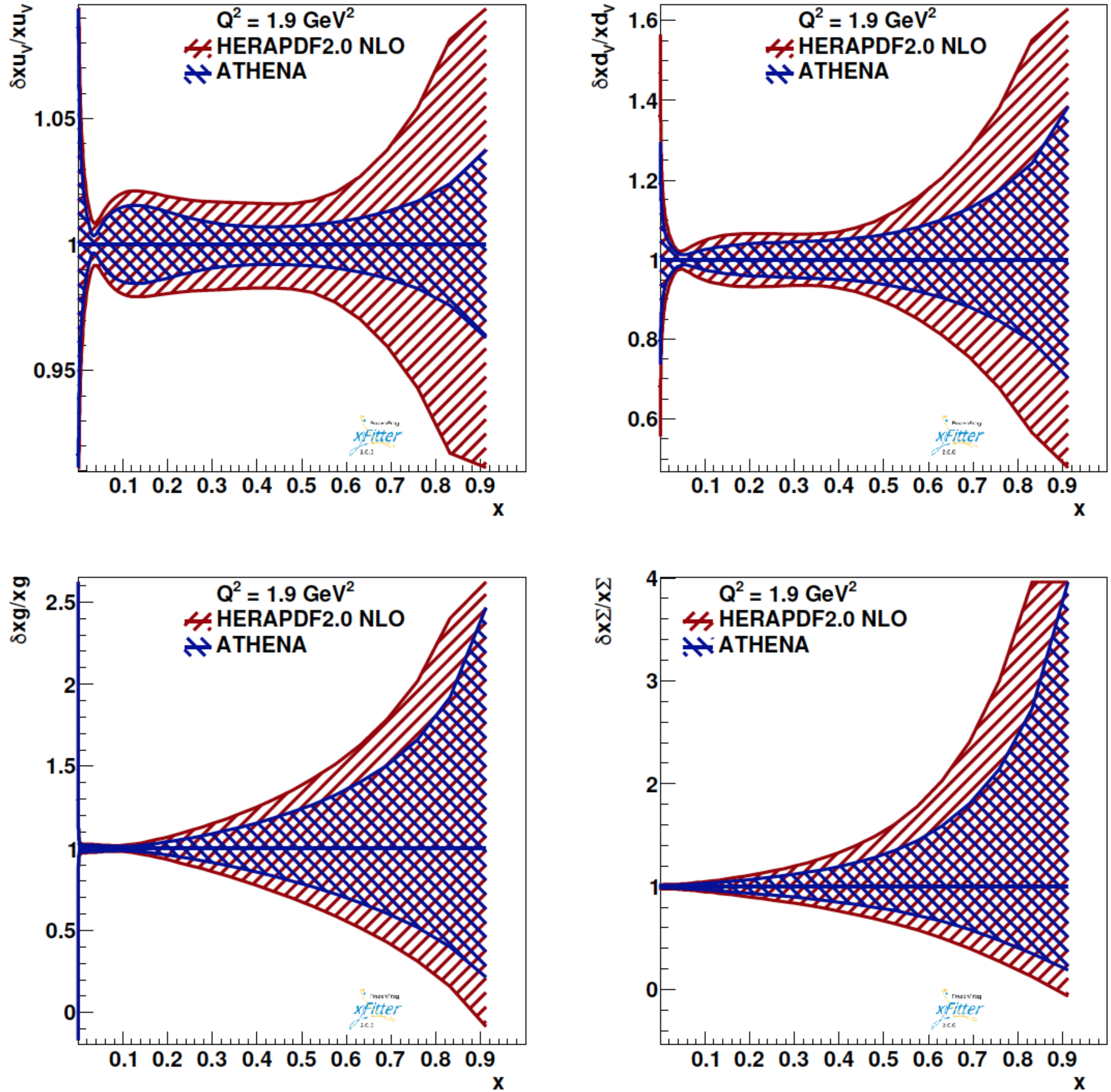
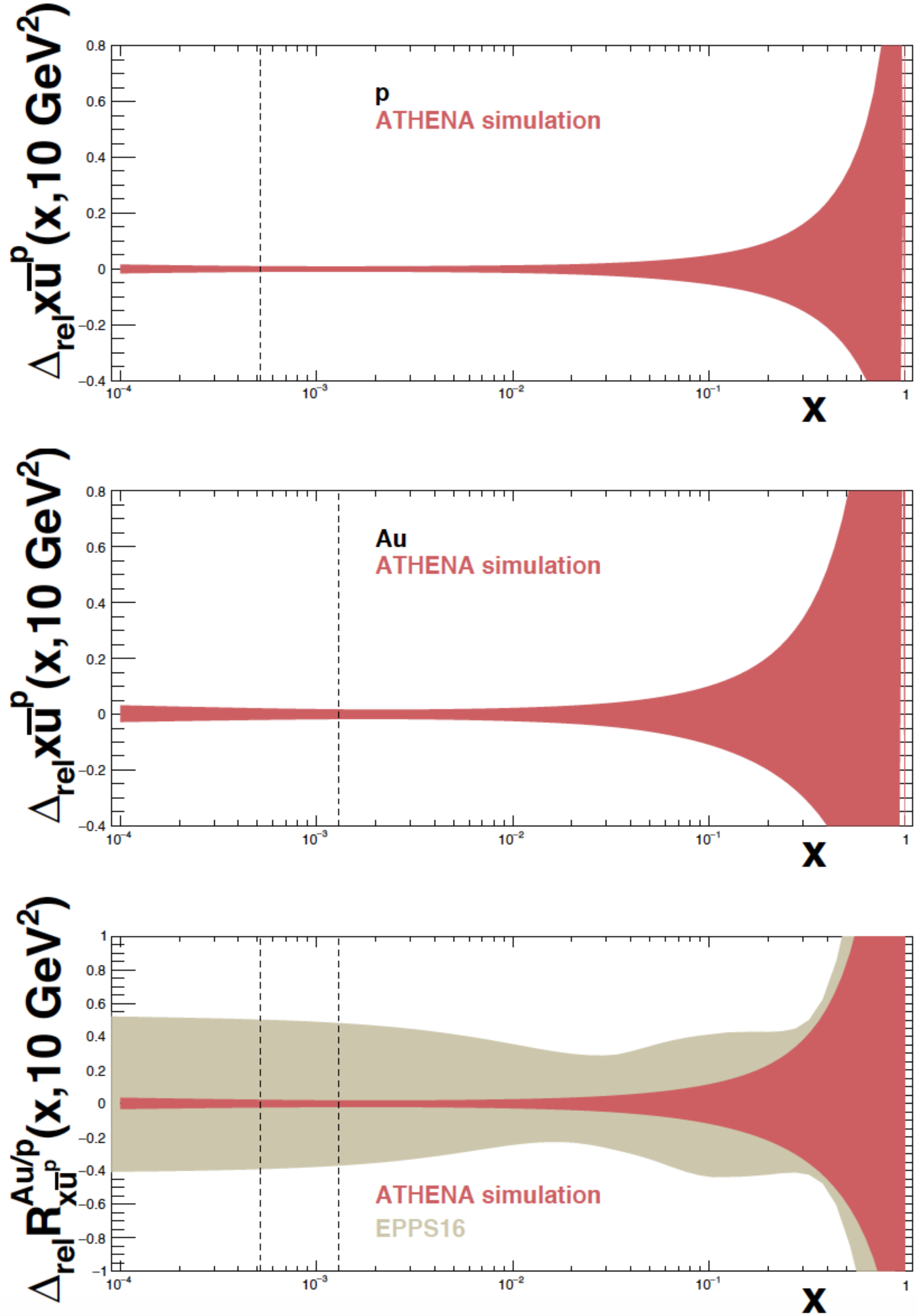
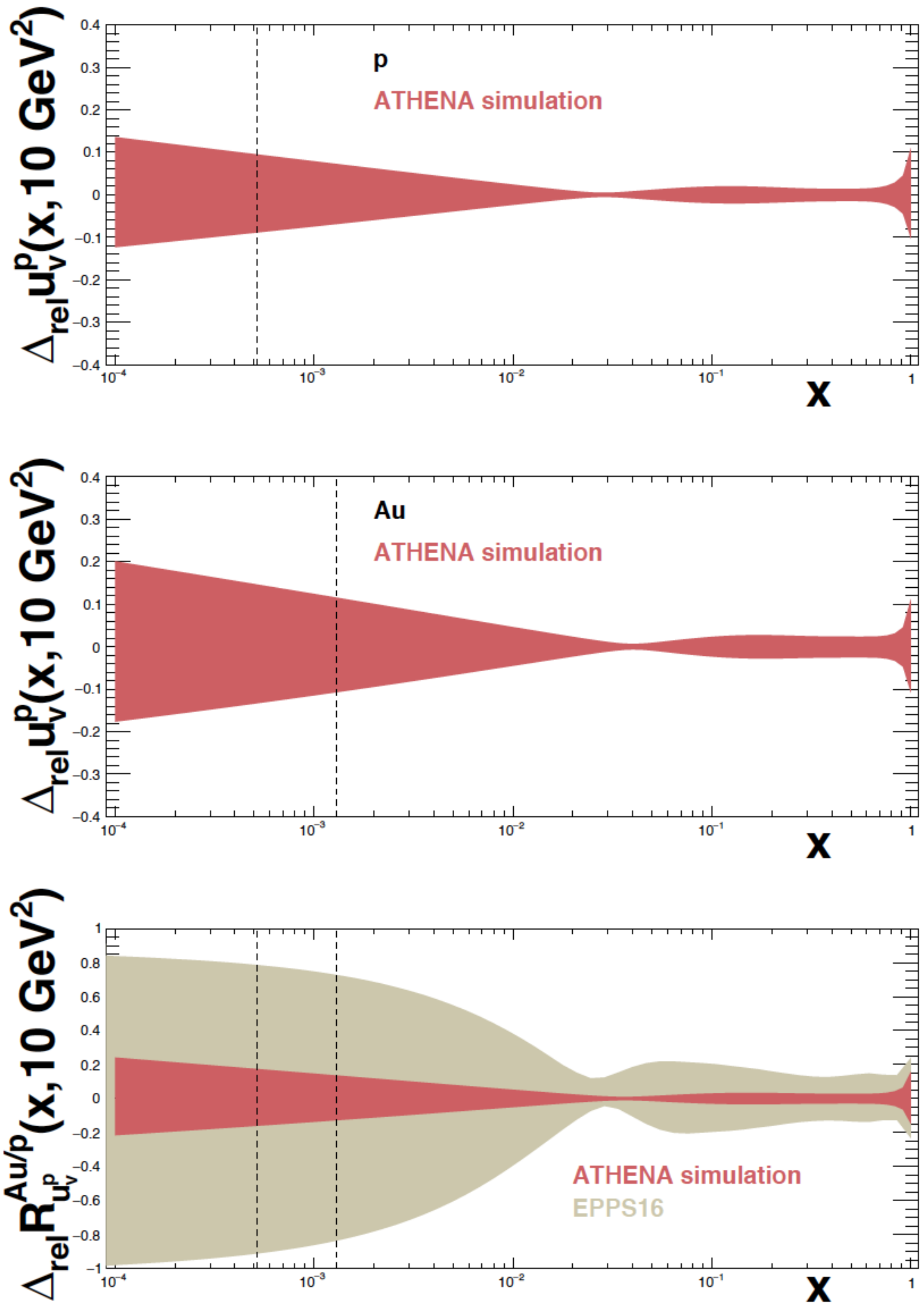
HERAPDF2.0 NNLO, αs = 0.118, experimental + parameterisation uncertainty ratio
Uncertainty ratio for gluon
a)
b)
c)
x



K. Wichmann @ Bad Honnef 23


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


p
ATHENA simulation
Au
ATHENA simulation
ATHENA simulation
EPPS16
x
x
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 & $4.10^{-5} < x < 0.65$)
- χ^2/dof=1.21

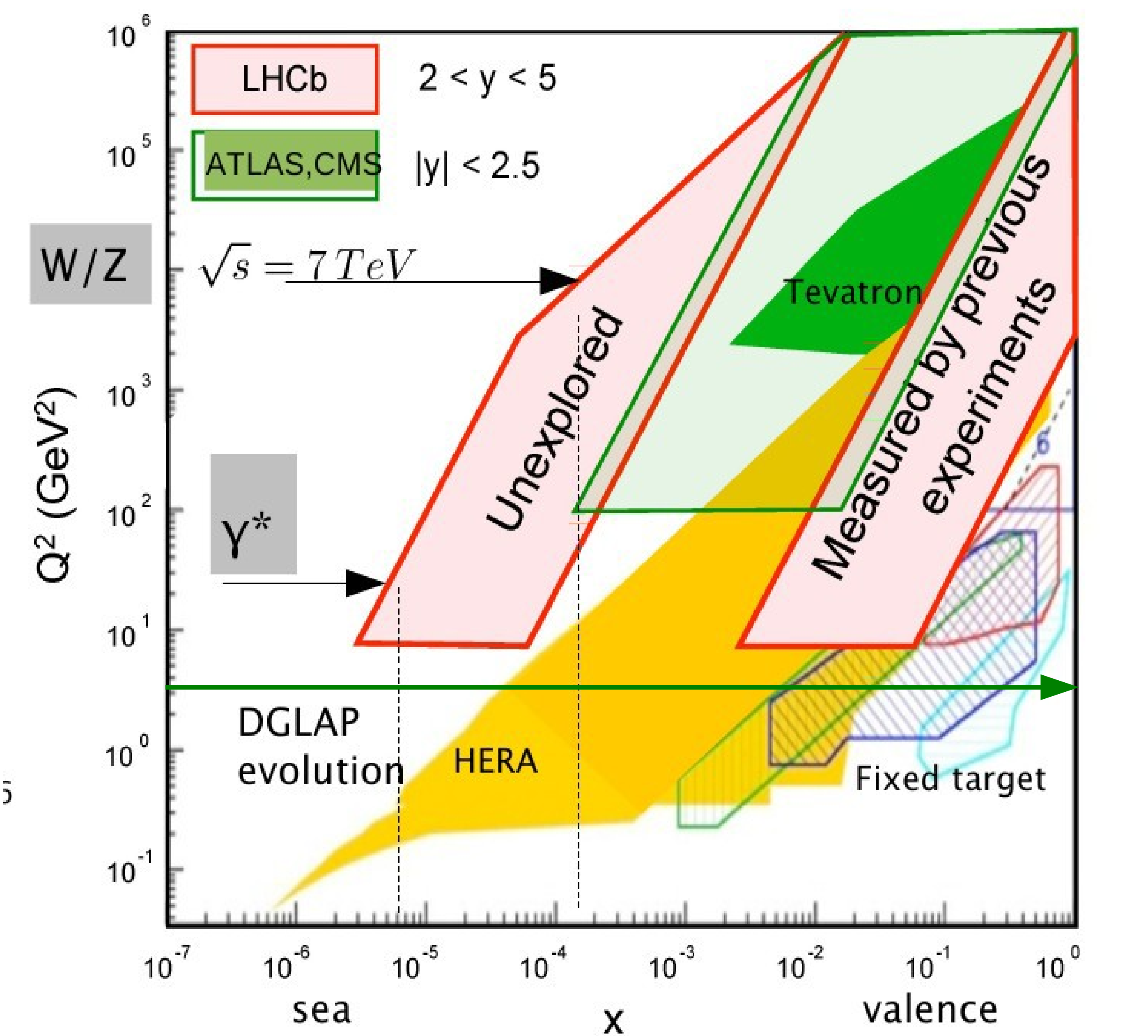
[Phys. Rev. D **99** (2019) no. 7, 074008]

4 FLNS:

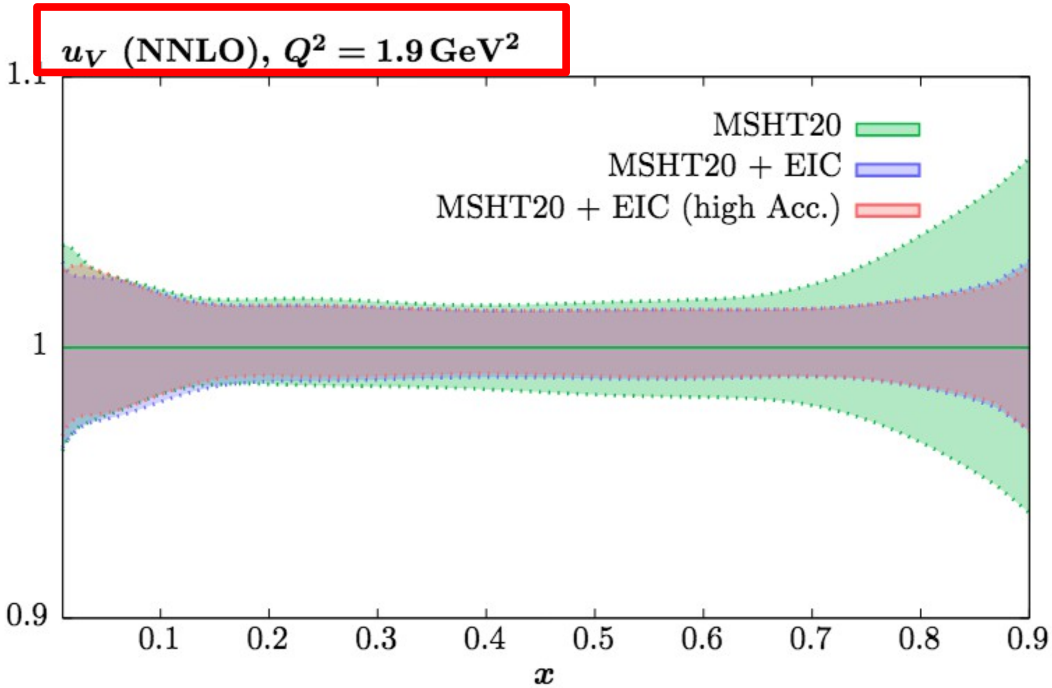
- the same functional form & data as 5FL - parameters are re-fitted
- $m_b \to \infty$ & $\alpha_s(M_Z^{n_f=4}) = 0.1128$
- $\chi^2/dof = 1.25$

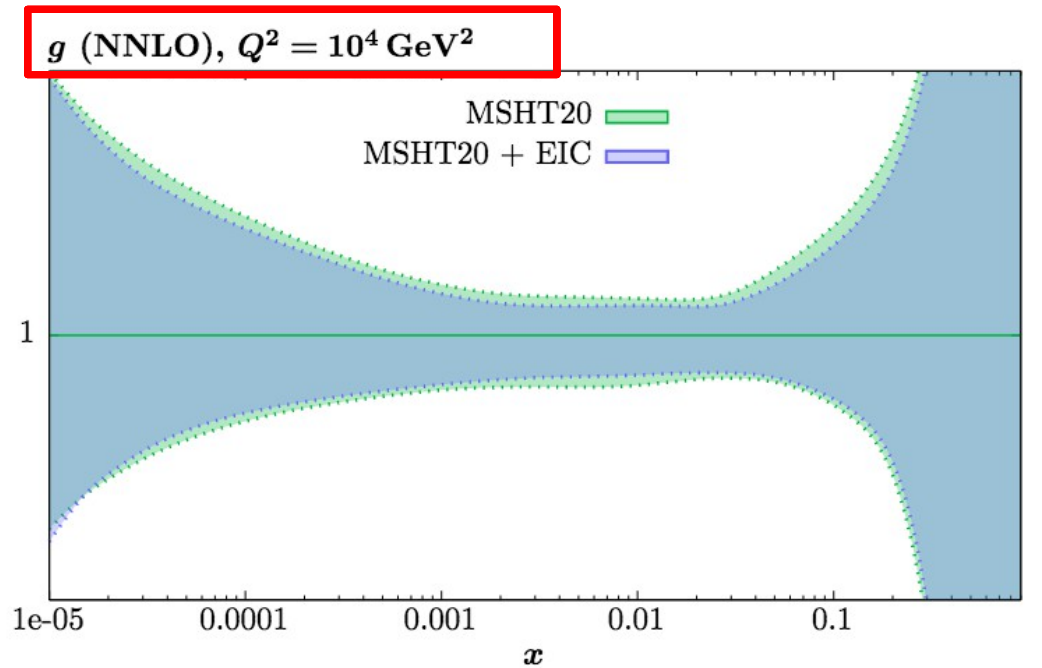
[arXiv:2106.09791]

Various data in other PDF sets



Impact of EIC data on global fits @NNLO

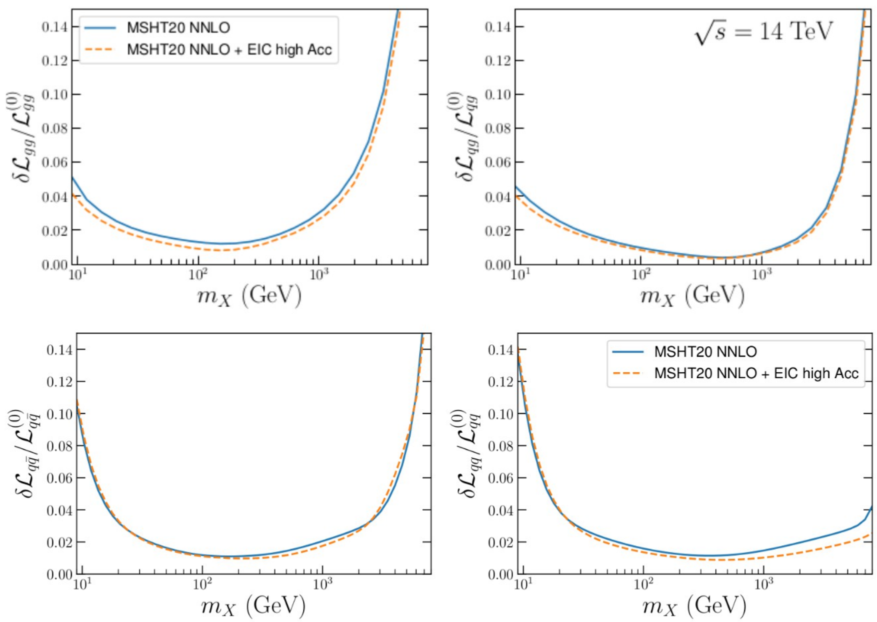


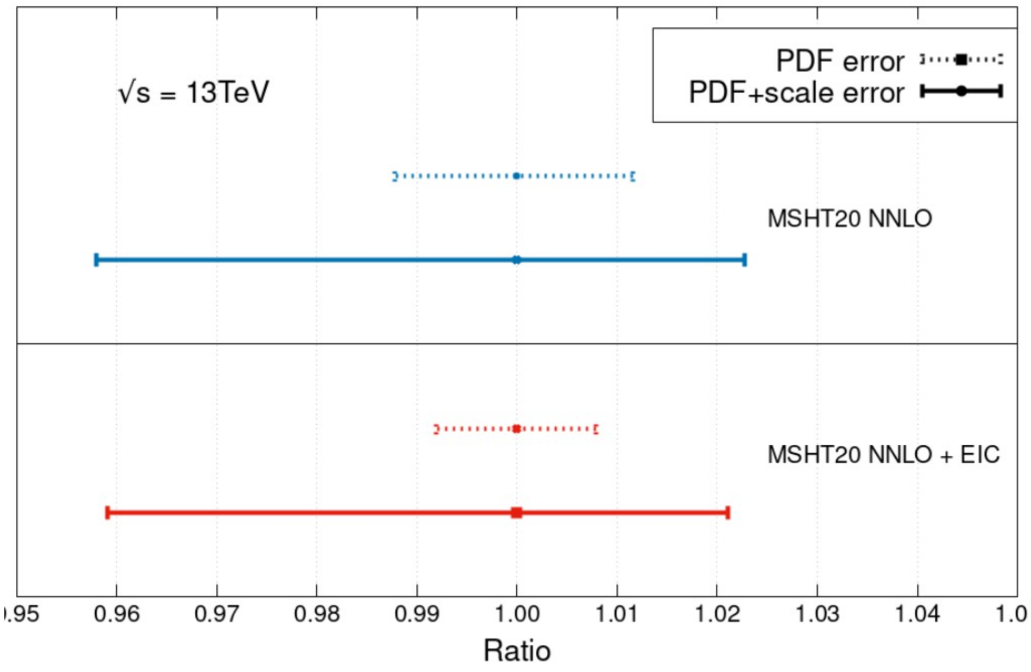


- Full fits with MSHT20 pseud-data
- Improvement significantly reduced compared with HERAPDF2.0
- Still significant effects present
  → biggest impact on up-valence distribution
  → small but valuable improvement on all parton species visible at all x and Q^2 values

arXiv:2309.11269, submitted to EPJC

Impact of EIC data on global fits @NNLO





- relatively mild improvement for luminosities
  → consistent with changes seen in PDF uncertainties.