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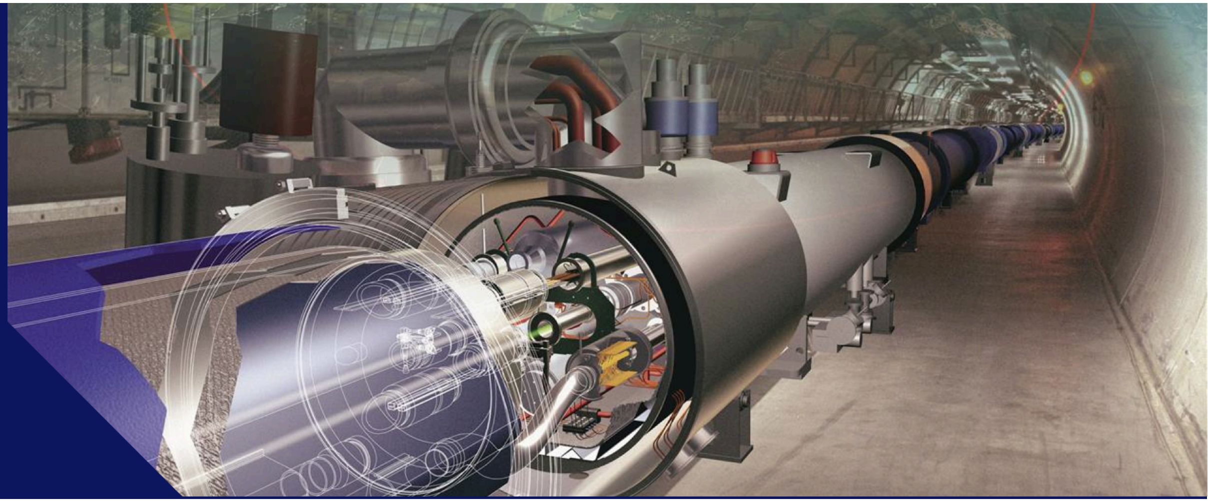
17 – 18 Sept. 2019



HERAPDF2.0Jets NNLO

completion of the HERAPDF2.0 family of PDFs and extraction of $\alpha_s(M_Z)$

Claire Gwenlan, Oxford

on behalf of the
H1, ZEUS, NNLOJet and APPLfast
collaborations

UNIVERSITY OF OXFORD

ZEUS

H1

overview

H1prelim-19-041

ZEUS-prel-19-001

- **completing the HERAPDF2.0 family of PDFs**
- previously produced (arXiv:1506.06042): HERAPDF2.0LO, NLO and NNLO; **HERAPDF2.0Jets were only at NLO**

- **HERAPDF2.0Jets updated here with NNLO jet predictions from NNLOJet,** as implemented in **APPLfast**
- plus addition of new H1 low Q^2 jet data

- **NEW** PDFs at NNLO QCD for $\alpha_s(M_Z)$=0.118 and 0.115
- **PLUS** free $\alpha_s(M_Z)$ fit, with preferred value significantly lower at NNLO than at NLO

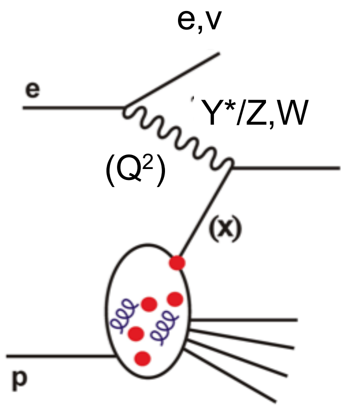
- **NNLO:**

$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0008\,(\mathrm{exp})^{+0.0002}_{-0.0005}\,(\mathrm{model/par.}) \pm 0.0006\,(\mathrm{had}) \pm 0.0027\,(\mathrm{scale})$$

- **NLO result**, as published:

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

HERA and DIS



- Kinematic variables:

$$Q^2 = -q^2 = -(k-k')^2$$ Virtuality of the exchanged boson

$$x = \frac{Q^2}{2p\cdot q}$$ Bjorken scaling parameter

$$y = \frac{p\cdot q}{p\cdot k}$$ Inelasticity parameter

$$s = (k+p)^2 = \frac{Q^2}{xy}$$ Invariant c.o.m.

Neutral Current:

LO expressions

$$\frac{d^2\sigma^{\pm}_{NC}}{dx dQ^2} = \frac{2\alpha\pi^2}{xQ^4}\left(Y_+F_2 \mp Y_- xF_3 - y^2 F_L\right)$$

$$F_2 \sim \sum_i e_i^2 (xq_i + x\bar{q}_i)$$ quarks pdfs

$$xF_3 \sim \sum_i (xq_i - x\bar{q}_i)$$ valence quarks

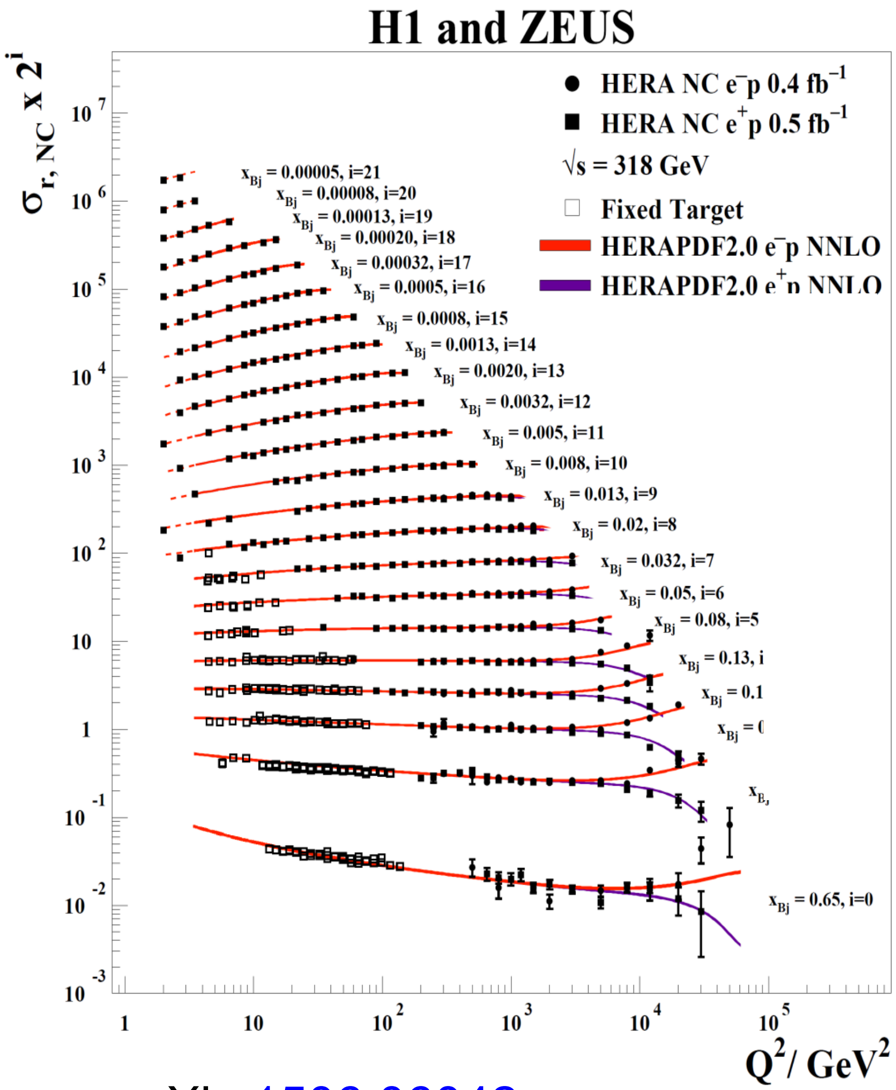
$$F_L \sim \alpha_s \times g$$ gluon via $\mathcal{O}(\alpha s)$

Charged Current:

$$\frac{d^2\sigma^{-}_{CC}}{dx dQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^2}{M_W^2+Q^2}\left(u + c + (1-y^2)(\bar{d}+\bar{s})\right)$$

$$\frac{d^2\sigma^{+}_{CC}}{dx dQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^2}{M_W^2+Q^2}\left(\bar{u} + \bar{c} + (1-y^2)(d+s)\right)$$

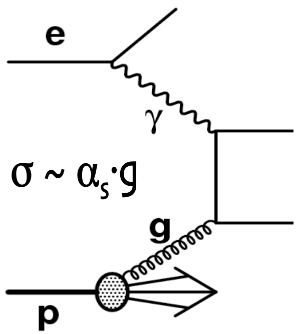
flavour decomposition



arXiv:[1506.06042]

why jet data?

simultaneous fit of DIS inclusive and jet cross sections **allows determination of αs(Mz)**

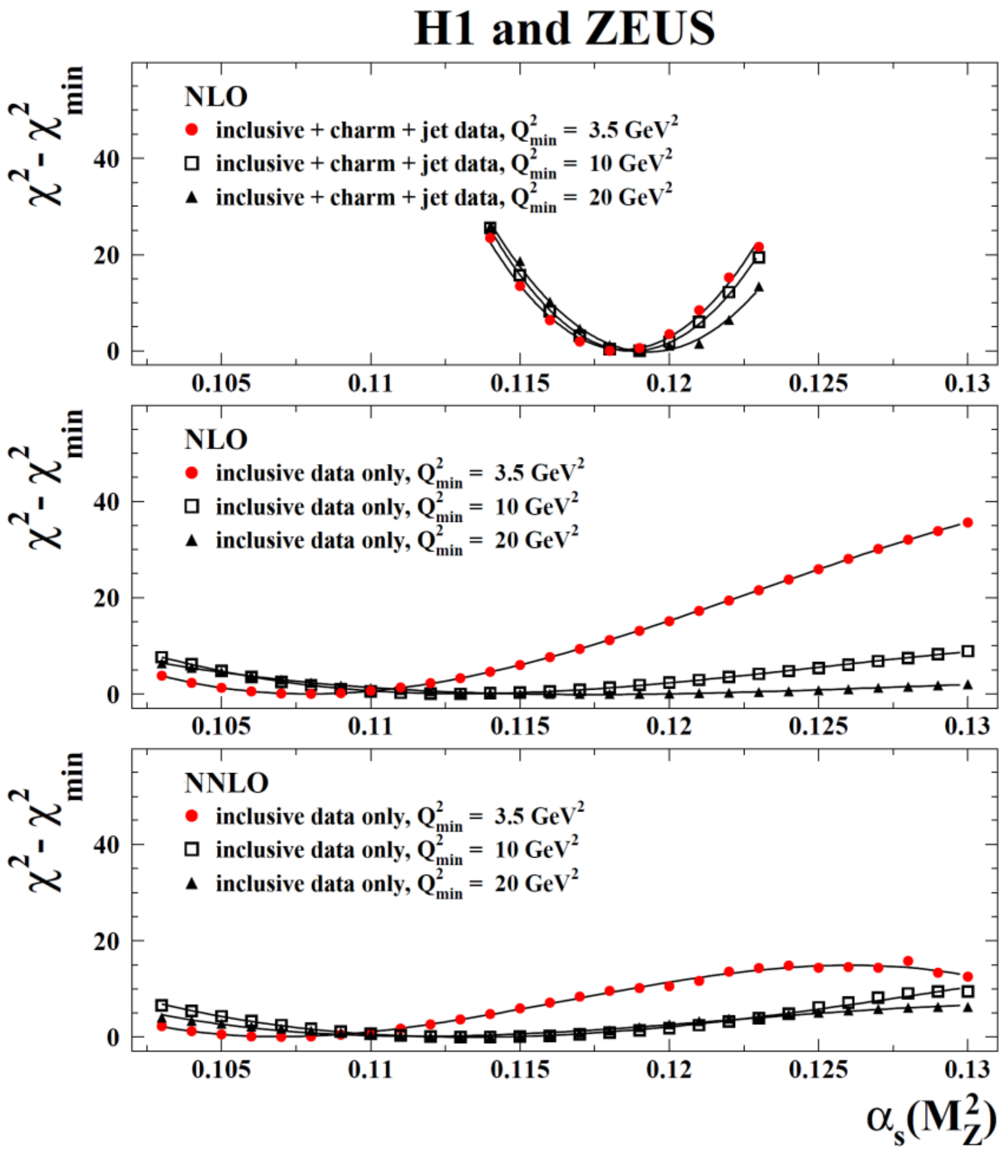


different dependencies on gluon and αs gives improved constraints on both

previous result at NLO → arXiv:1506.06042

NOW:

NNLO QCD calculations for DIS jets available in **NNLOJet** (arXiv:1606.03991, 1703.05977), and implemented in **APPLfast** (arXiv:1906.05303)



jet data used in the current NNLO analysis

strong overlap with those used in previous NLO QCD analysis

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	16
H1 normalised inclusive jets at high Q^2	2003 – 2007	150	15000	351	e^+p/e^-p	319	yes	30	24
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	32
H1 normalised dijets at low Q^2	2005 – 2007	5.5	80	290	e^+p/e^-p	319	yes	48	32
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

low Q^2 H1 datasets added (published 2016) that were not used in the previous NLO analysis

some other data sets removed cf. NLO analysis:

- trijet data, since no NNLO QCD calculations;
- 6 dijet data points at low pt, since predictions unreliable;
- low scale data $\mu = \sqrt{(Q^2 + pt^2)} < 13.5$ GeV, for which scale variations large

all systematic and statistical correlations implemented

scale choice for jet data

factorisation scale choice is $\mu_F^2=(Q^2+pt^2)$

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 jet data

renormalisation scale choice is $\mu_R^2=(Q^2+pt^2)$

cf. $\mu_R^2=(Q^2+pt^2)/2$ in previous NLO analysis

NB, optimal scale choice – where 'optimal' here means lower X^2 – is different for NLO vs NNLO;

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

consequences of scale changes also explored

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

HERA PDF approach

- **HERAPDF uses only HERA data**
- combination of HERA data yields very precise and consistent dataset for 4 different processes: **e+p** and **e–p neutral** and **charged current** reactions; also, for e+p, neutral current at 4 beam energies
- single consistent dataset; conventional $\mathbf{X}^2$ tolerance, $\Delta\mathbf{X}^2 = 1$
- use of proton target means no need for heavy target/deuterium corrections
- d-valence extracted from CC e+p without assuming d in proton = u in neutron
- all data at W >15 GeV, so high-x higher twist effects negligible
- **HERAPDF** evaluates model and parameterisation uncertainties in addition to experimental uncertainties
- **HERAPDF2.0** based on **FINAL combination of HERA I and HERA II data**, which supercedes the HERA I combination and all previous HERAPDFs
- **HERAPDF2.0Jets** add HERA jet data to this

HERAPDF parameterisation

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

QCD sum rules constrain Ag, Auv, Adv

$x\bar{s} = f_s x\bar{D}$ sets size of strange PDF

constraints $B_{\bar{U}} = B_{\bar{D}}$ and $A_{\bar{U}} = A_{\bar{D}}(1-f_s)$ ensure $x\bar{u} \rightarrow x\bar{d}$ as $x \rightarrow 0$

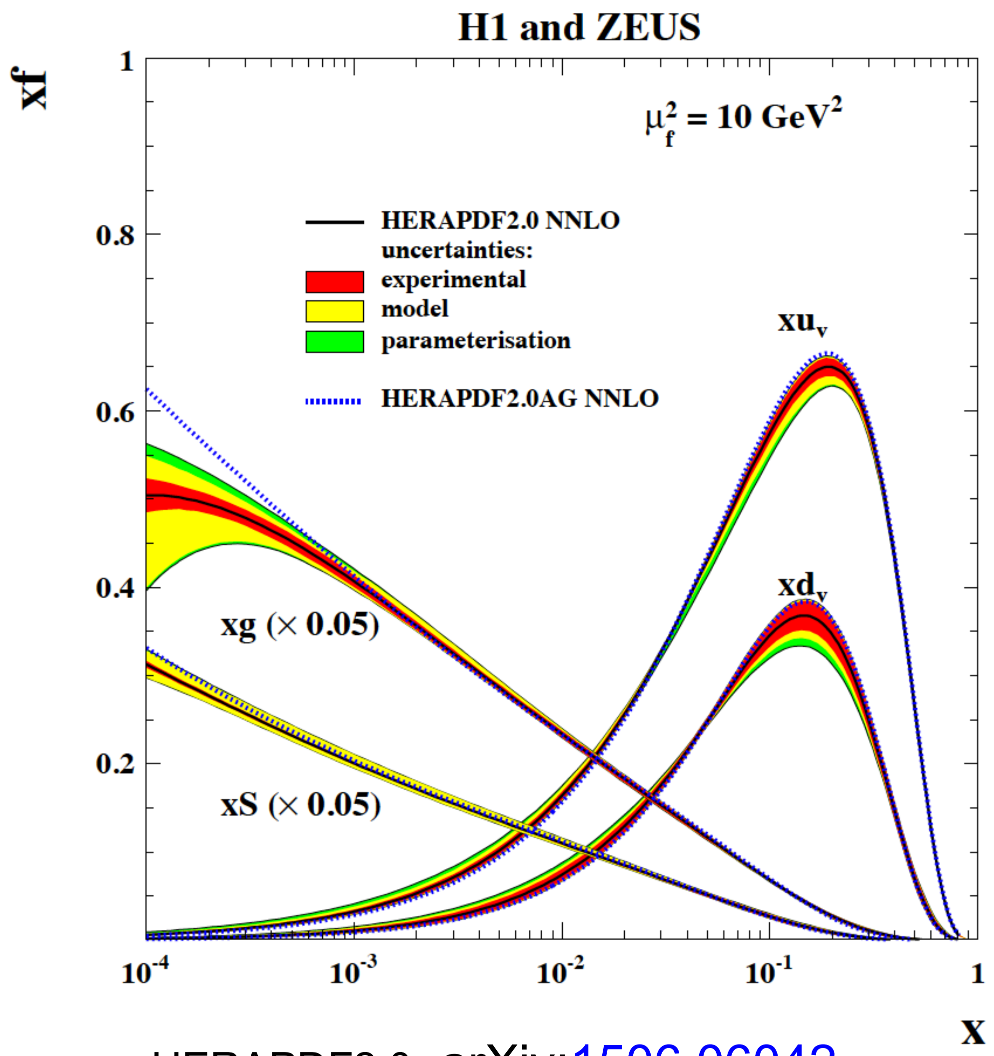
- **14 free parameters in central fit,** established by saturation of **X**^{2}
- extra D, E parameters added to all PDF flavours for parameterisation uncertainties, Ag'=0 also checked
- QCDNUM used for QCD DGLAP evolution, within xFitter framework, and cross checked with independent code
- Thorne-Roberts Optimised Variable Flavour Number Scheme (RT-VFN)
- jet predictions from NNLOJet (arXiv:1606.03991, 1703.05977) interfaced to APPLfast (arXiv:1906.05303)
- $\alpha_s(M_Z)$=0.118, 0.115; **plus free α_s fit**

HERAPDF sources of uncertainty

experimental:
Hessian uncertainties: 14 eigenvector pairs evaluated with $\Delta X^2=1$; cross checked uncertainties using rms of MC replicas

model:
variation of input assumptions; and c,b masses
fs = 0.4 ± 0.1
Mc = 1.43 ± 0.06 GeV
Mb = 4.5 ± 0.25 GeV
Q^2min = $3.5_{-1}^{+1.5}$ GeV

parameterisation:
variation of Q^2_0=1.9 ± 0.3 GeV^2, plus addition of 15th parameter(s)
(variations as for HERAPDF2.0 analysis)

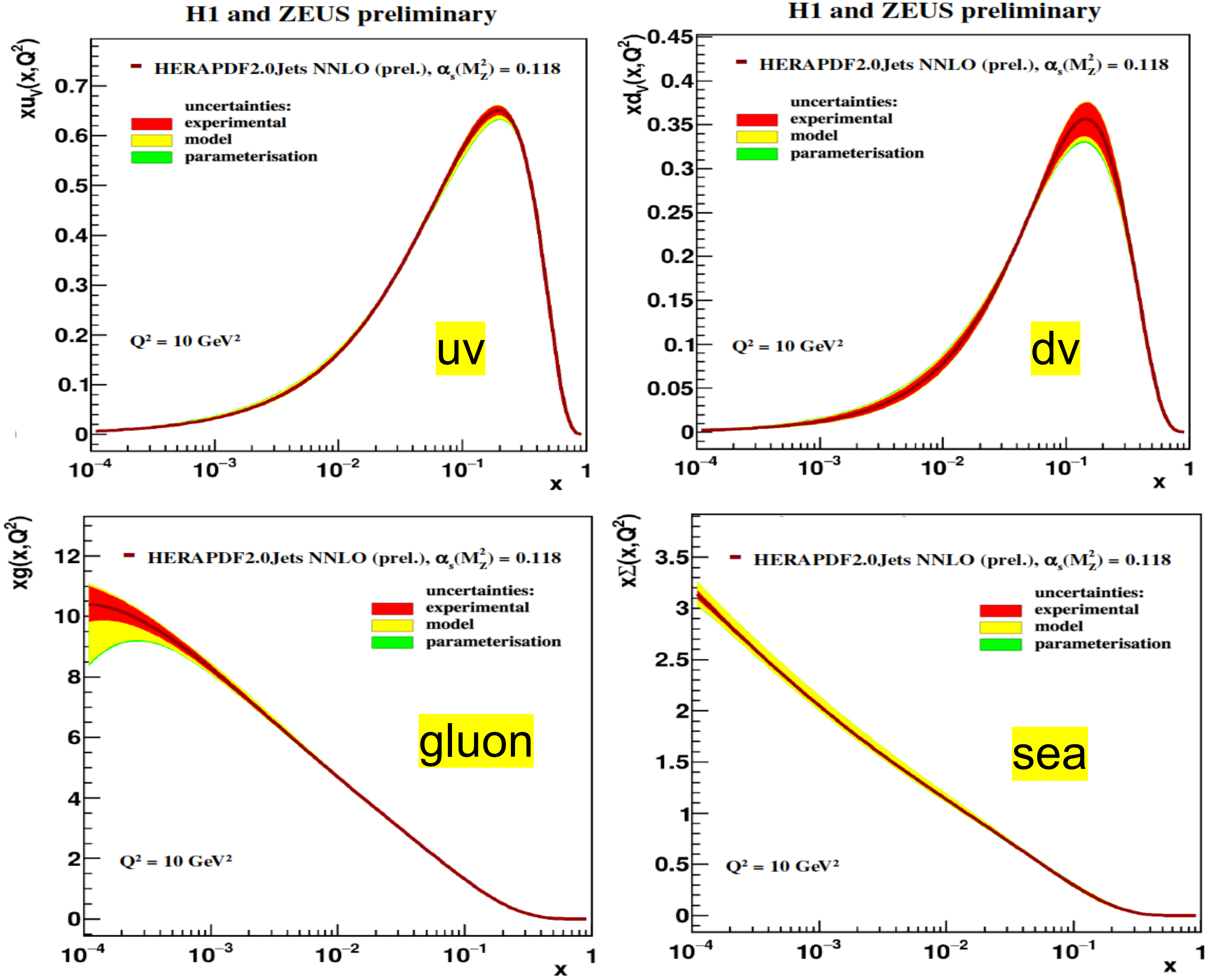


HERAPDF2.0, arXiv:1506.06042

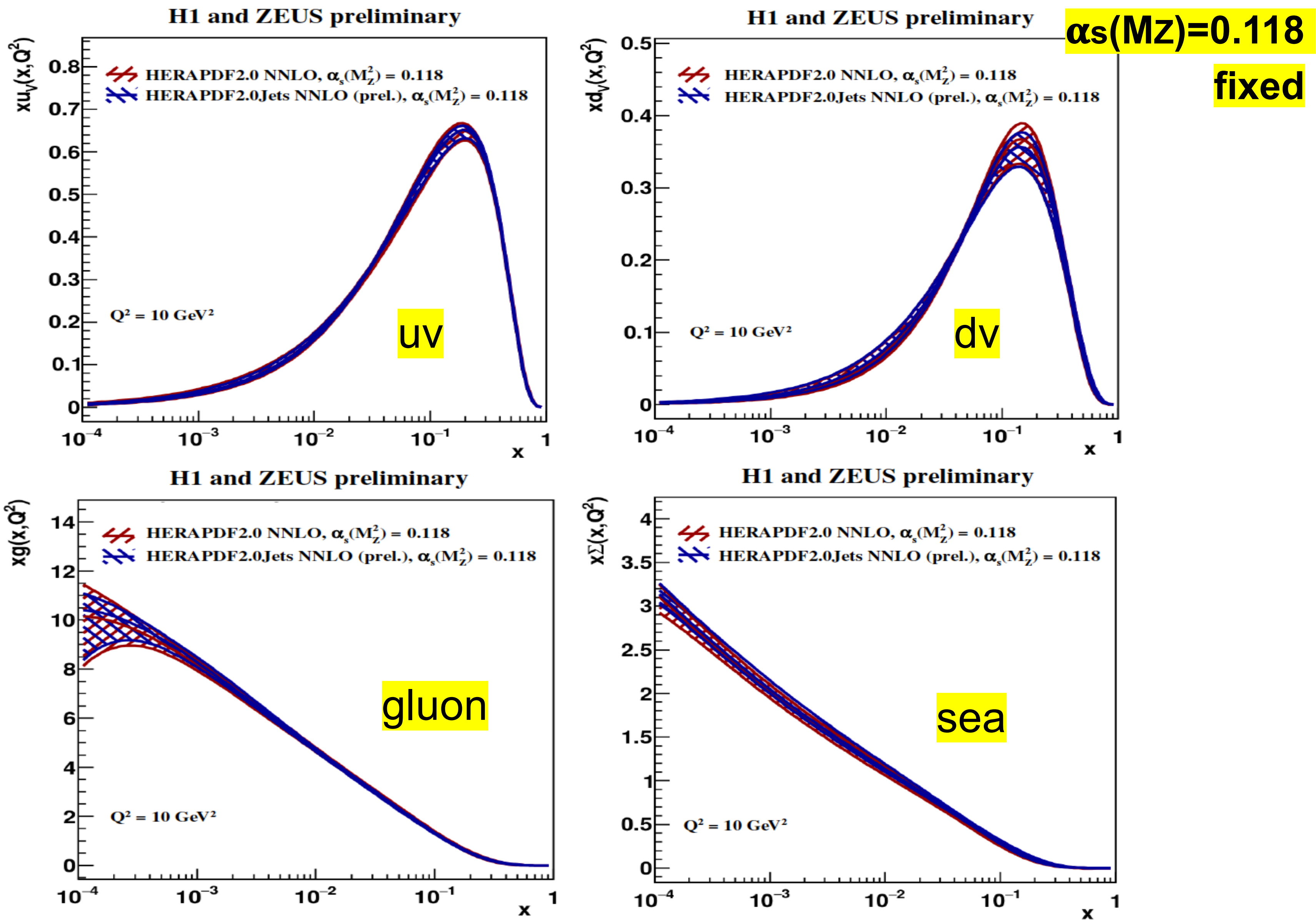
NB, for **jet cross sections**, hadronisation uncertainties also included

HERAPDF2.0Jets NNLO

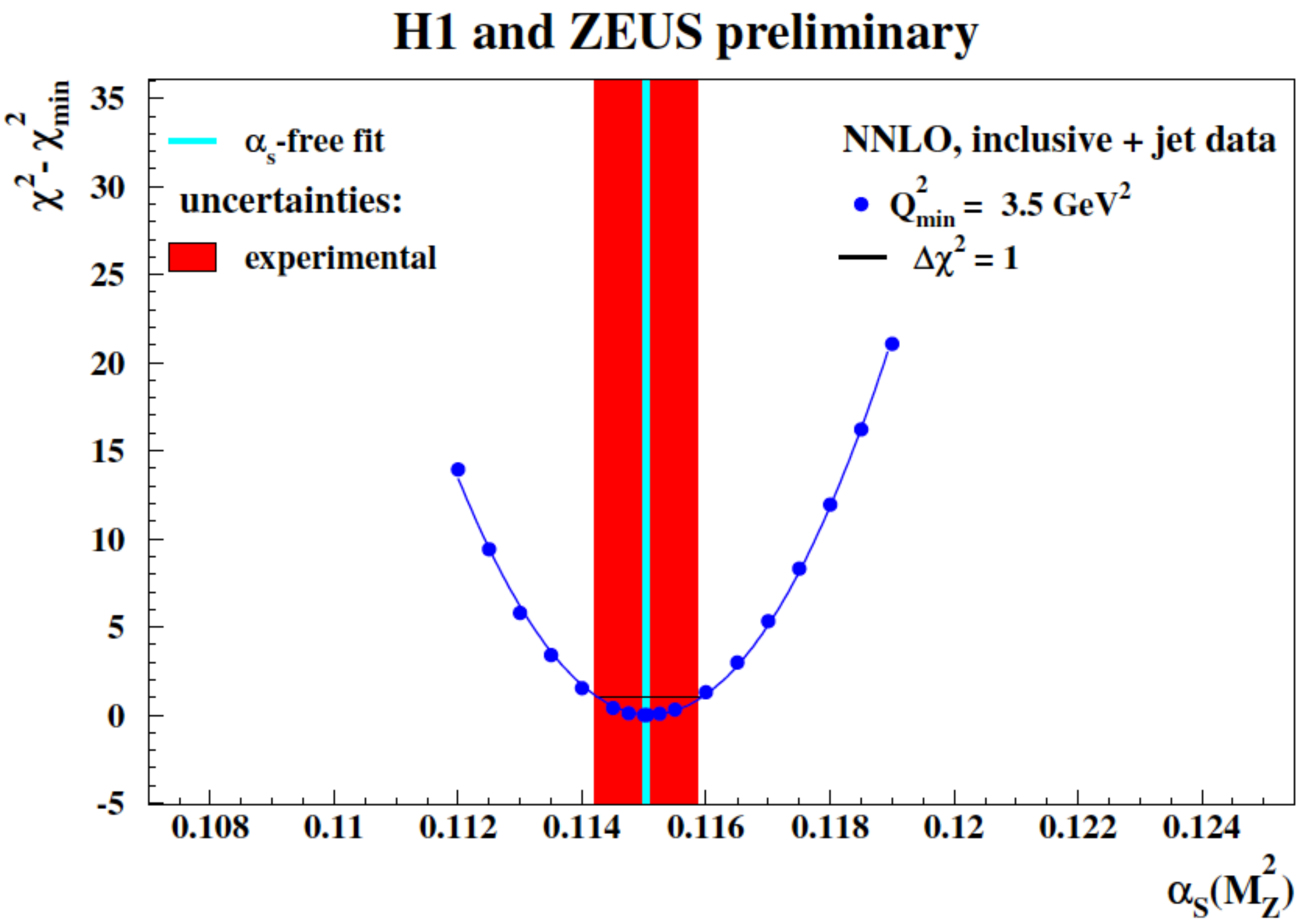
αs(Mz)=0.118 fixed



HERAPDF2.0 vs HERAPDF2.0Jets NNLO



HERAPDF2.0Jets NNLO α_s fits

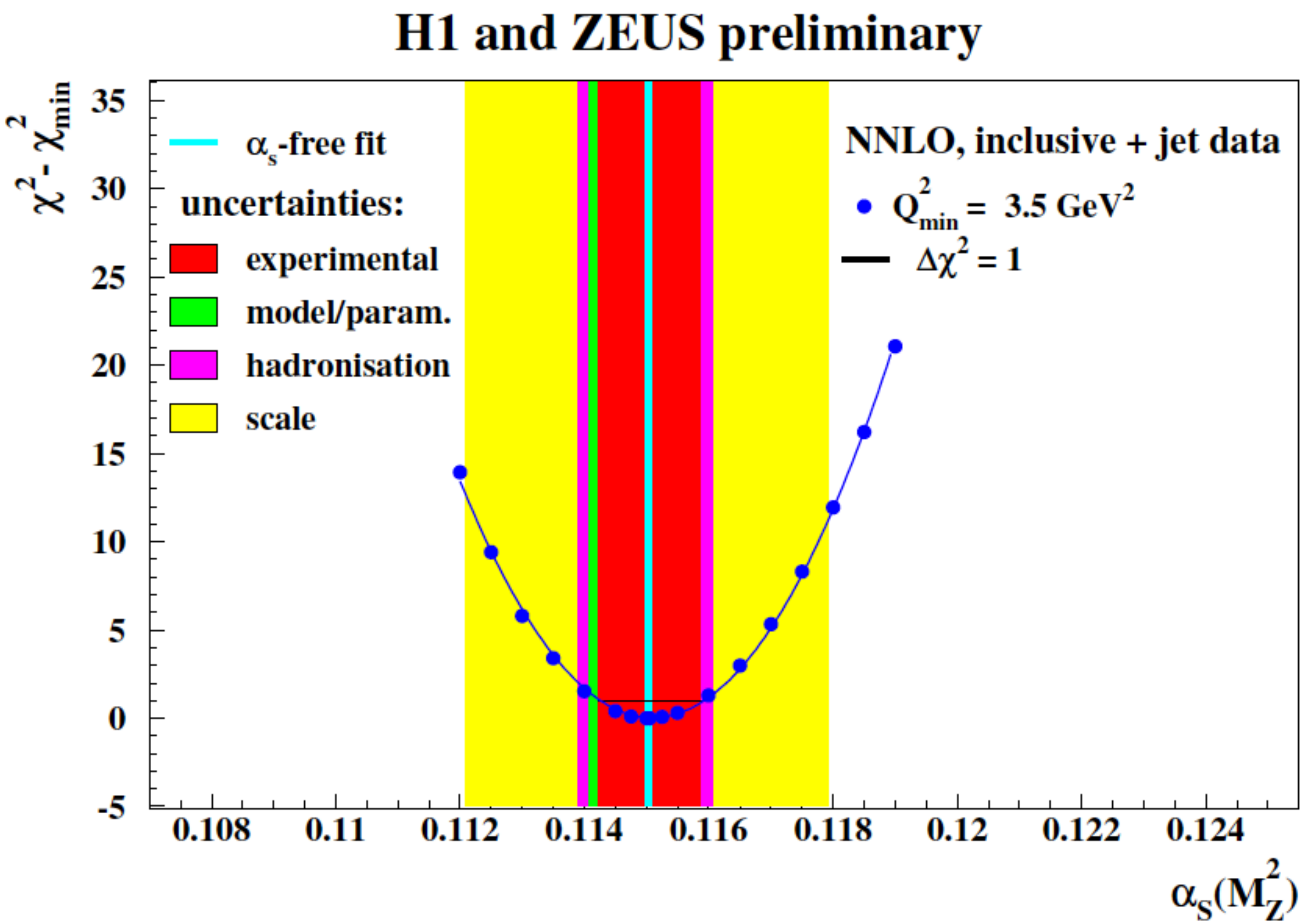


standard HERAPDF value is $\alpha_s(M_Z)=0.118$ (shown on previous slides)

fits also performed with **free $\alpha_s(M_Z)$**, compared here to **X^2 scan over fixed $\alpha_s(M_Z)$**

perfect agreement in minimum and uncertainty

HERAPDF2.0Jets NNLO α_s fits

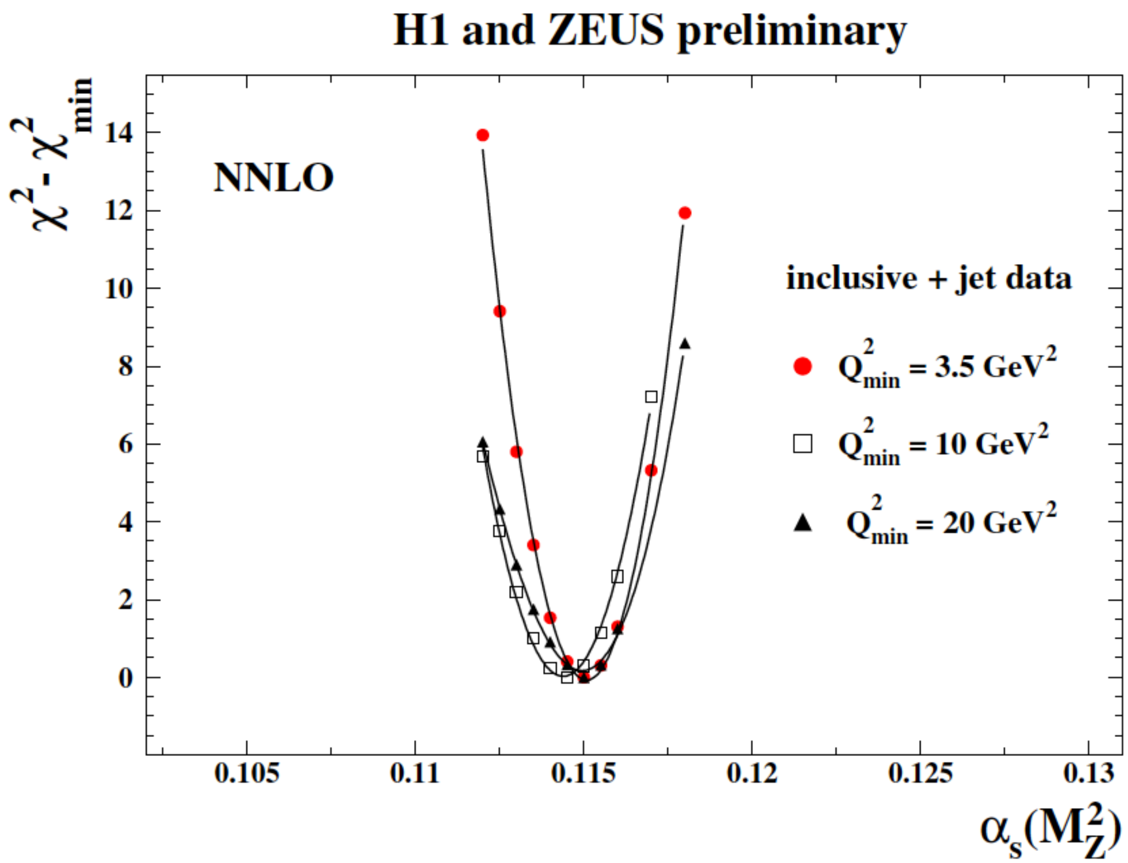


and with full uncertainties:

$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0008\,(\text{exp})^{+0.0002}_{-0.0005}\,(\text{model/par.}) \pm 0.0006\,(\text{had}) \pm 0.0027\,(\text{scale})$$

[NB, scale uncertainty dominates; 7-point variation considered, with μR, μF varied by factor of 2]

sensitivity to minimum Q^2 cut



central values from the 3 scans:

$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0008\,(\mathrm{exp}) \quad Q^2 > 3.5\,\mathrm{GeV}^2$$

$$\alpha_s(M_Z^2) = 0.1144 \pm 0.0010\,(\mathrm{exp}) \quad Q^2 > 10\,\mathrm{GeV}^2$$

$$\alpha_s(M_Z^2) = 0.1148 \pm 0.0010\,(\mathrm{exp}) \quad Q^2 > 20\,\mathrm{GeV}^2$$

EG, arXiv:1506.06042, 1710.05935

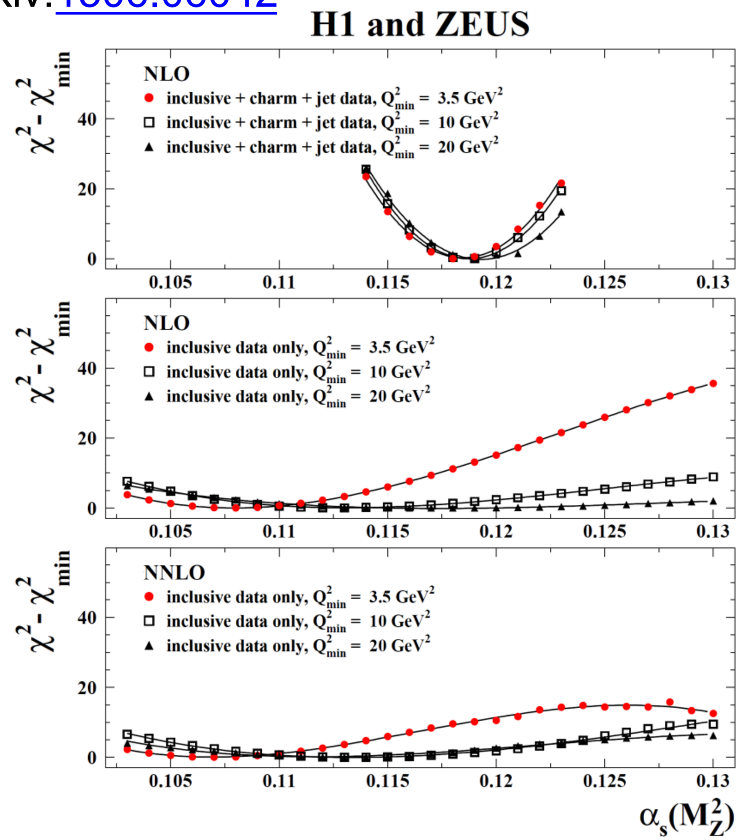
HERA data at low x, Q^2 may be subject to need for ln(1/x) resummation or higher twist effects;

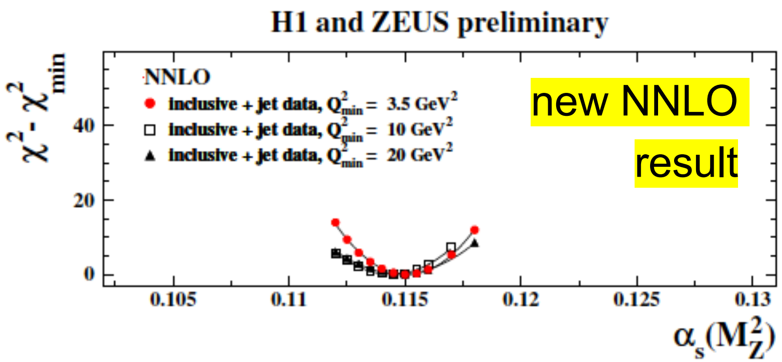
X^2 scans also performed with harder minimum Q^2 cuts

no significant change to extracted value of αs(Mz)

comparison to previous NLO result

arXiv:1506.06042





NNLO scans using inclusive and jet data are compared to previously published scans at NLO, plus corresponding scans using only inclusive data

similar level of precision at NNLO and NLO

smaller value of **αs**(Mz) preferred at NNLO

NB, conclusion holds independent of updated scale choices; with old scales, NNLO result would be even lower at 0.1135

NNLO:

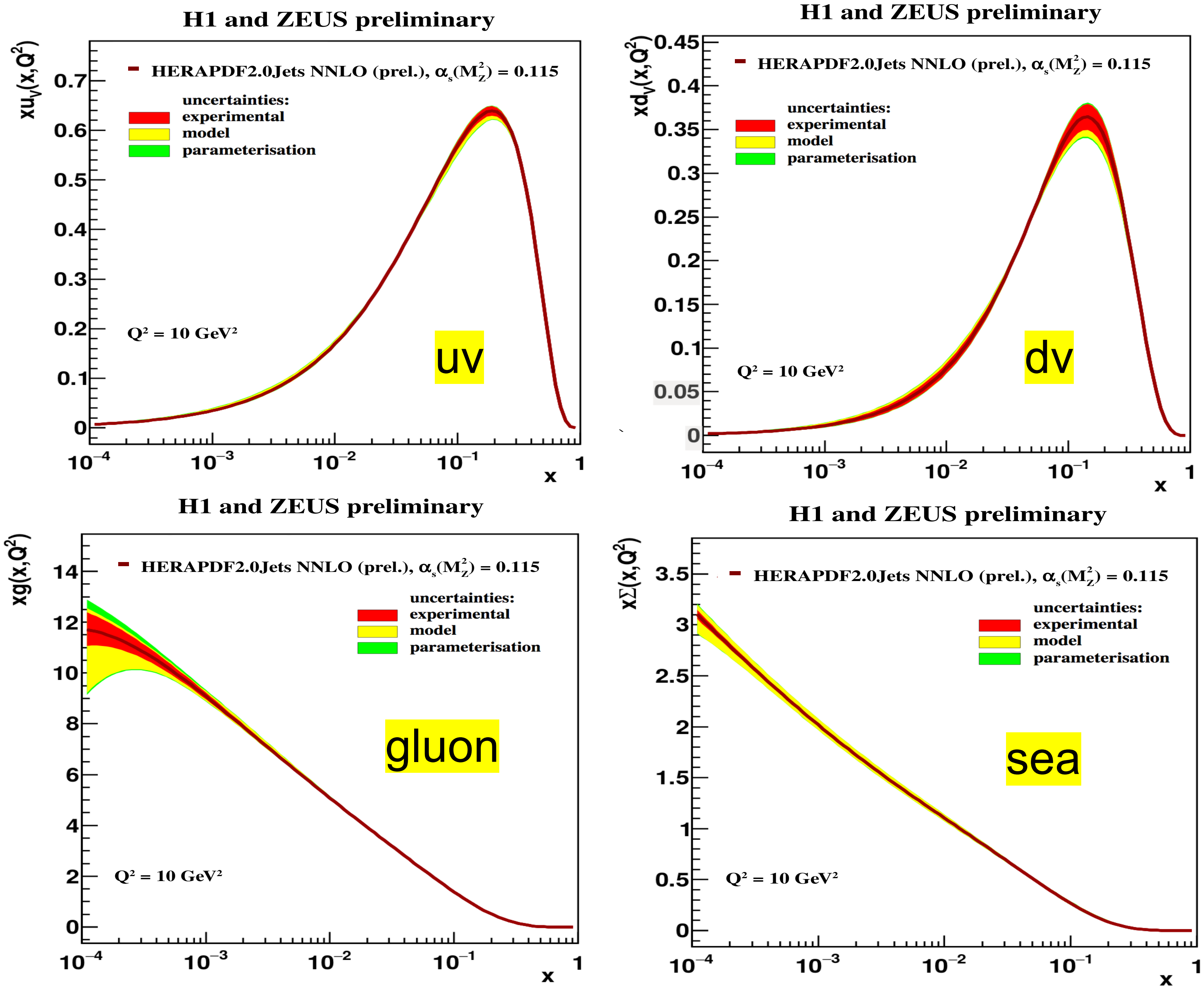
$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0008\,(\mathrm{exp})^{+0.0002}_{-0.0005}\,(\mathrm{model/par.}) \pm 0.0006\,(\mathrm{had}) \pm 0.0027\,(\mathrm{scale})$$

cf. **NLO:** arXiv:1506.06042

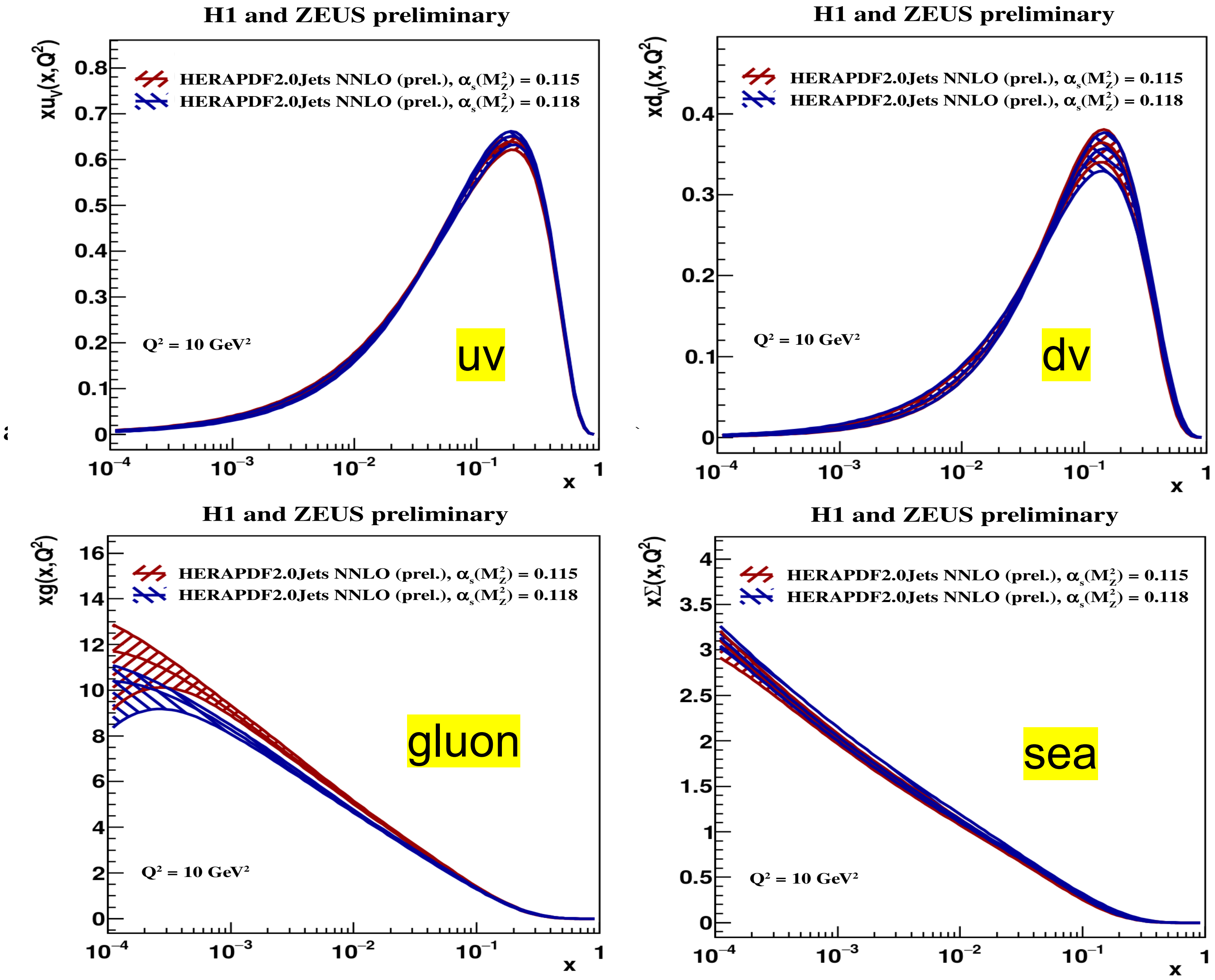
$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0009\,(\mathrm{exp}) \pm 0.0005\,(\mathrm{model/par.}) \pm 0.0012\,(\mathrm{had})^{+0.0037}_{-0.0030}\,(\mathrm{scale})$$

HERAPDF2.0Jets NNLO

αs(Mz)=0.115 fixed

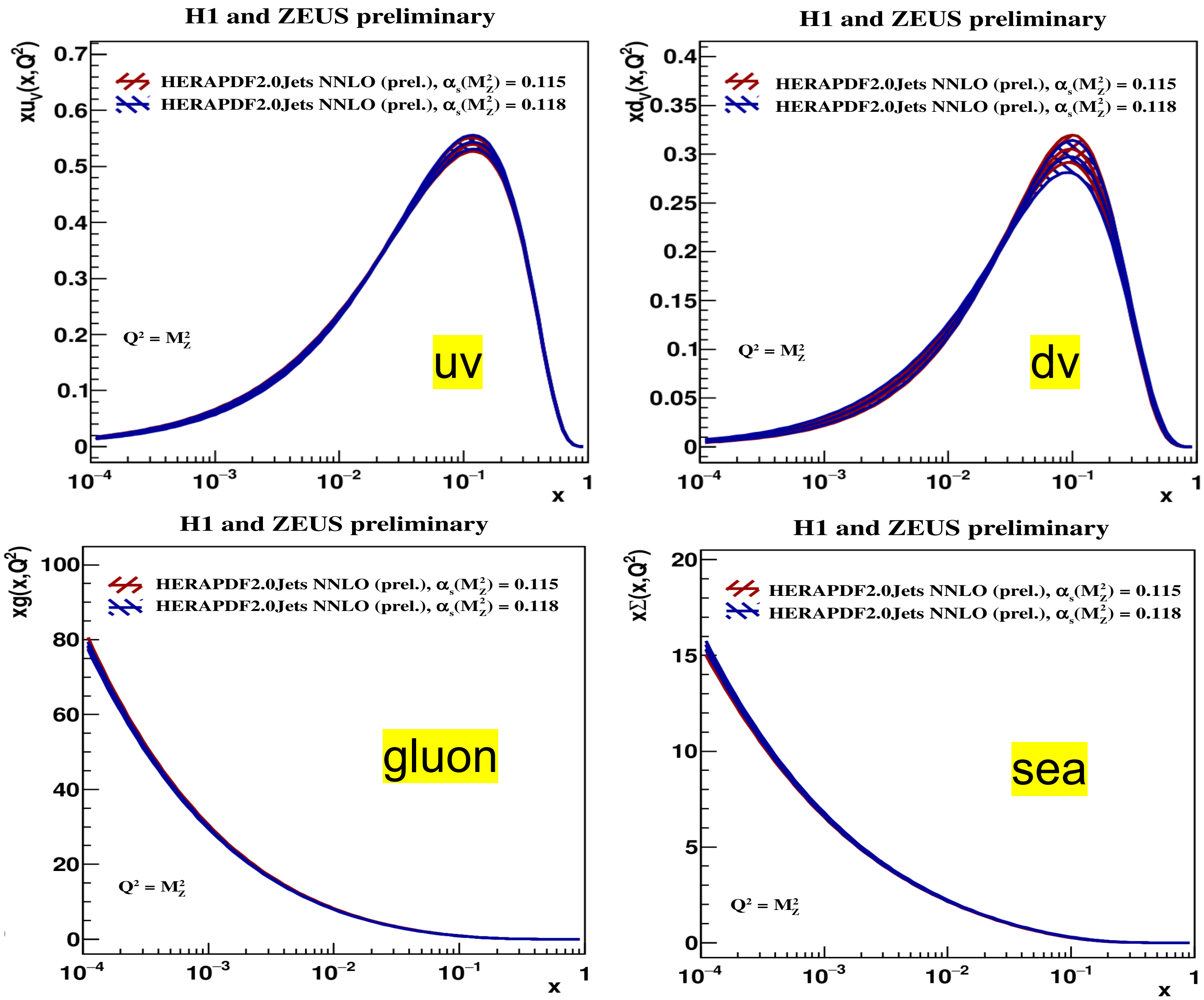


comparison of $\alpha_s(M_Z)$=0.115 and 0.118

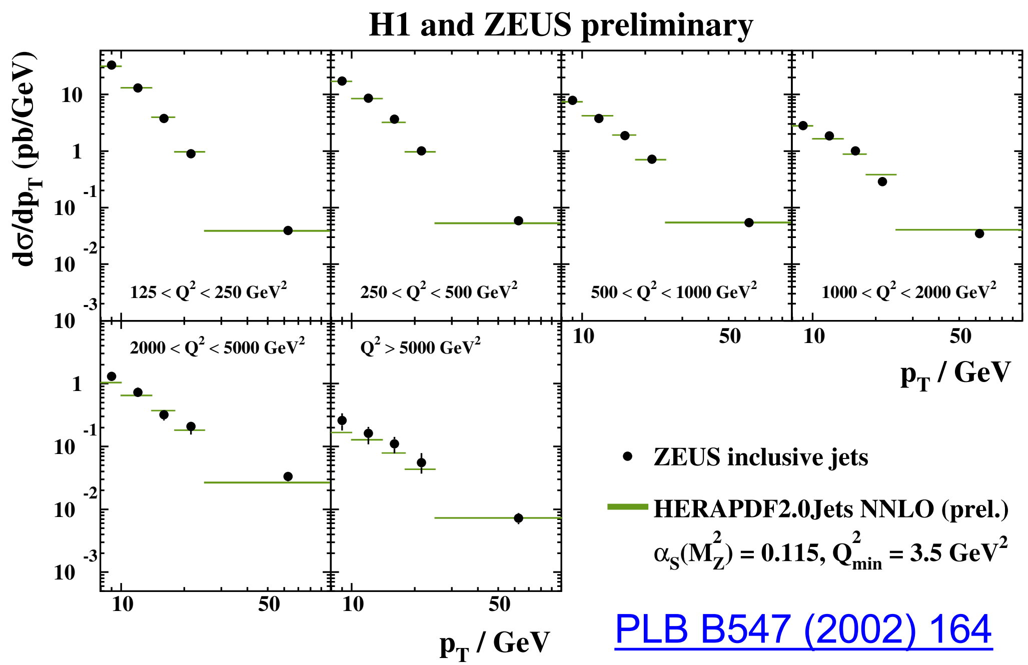


comparison of $\alpha_s(M_Z)$=0.115 and 0.118

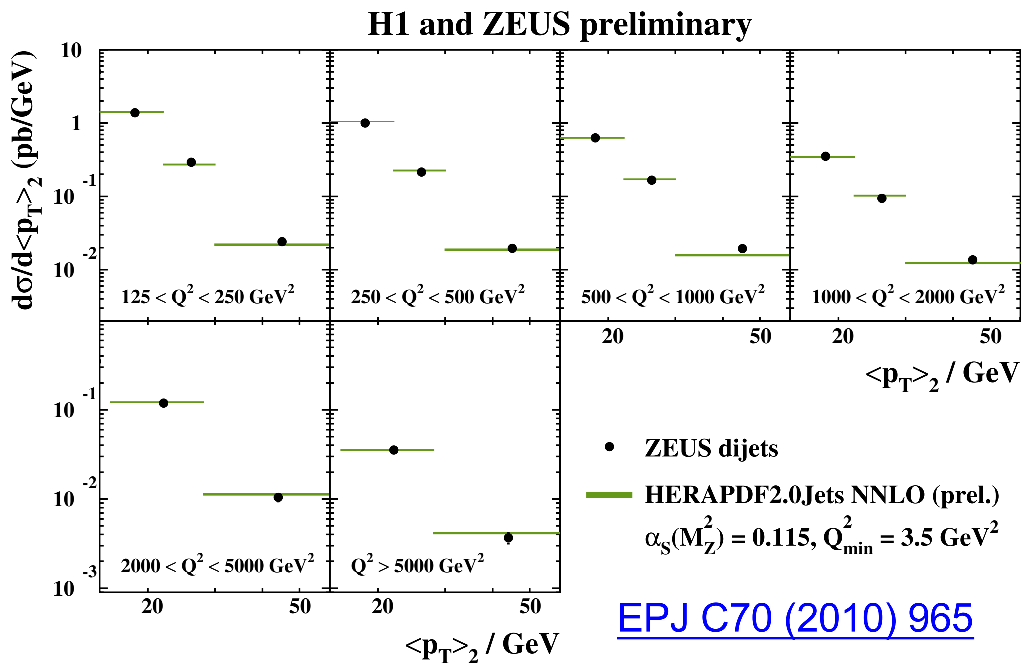
at higher scale $Q^2=M_Z^2$



cf. HERA jet data



PLB B547 (2002) 164



EPJ C70 (2010) 965

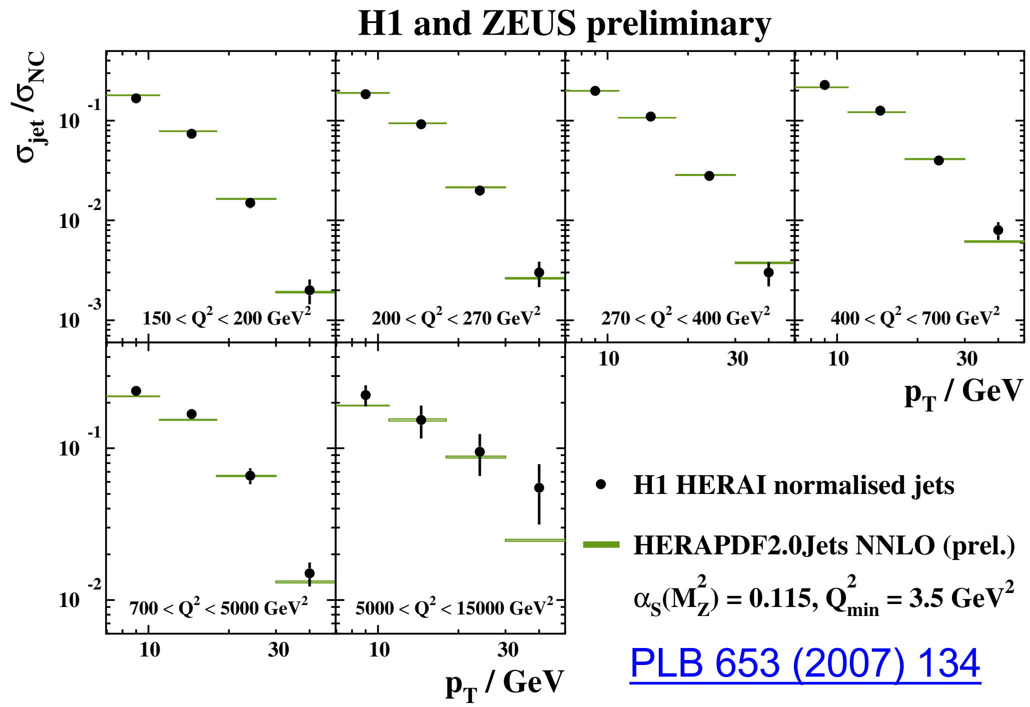
HERAPDF2.0JetsNLO

$\alpha_s(M_Z)=0.115$

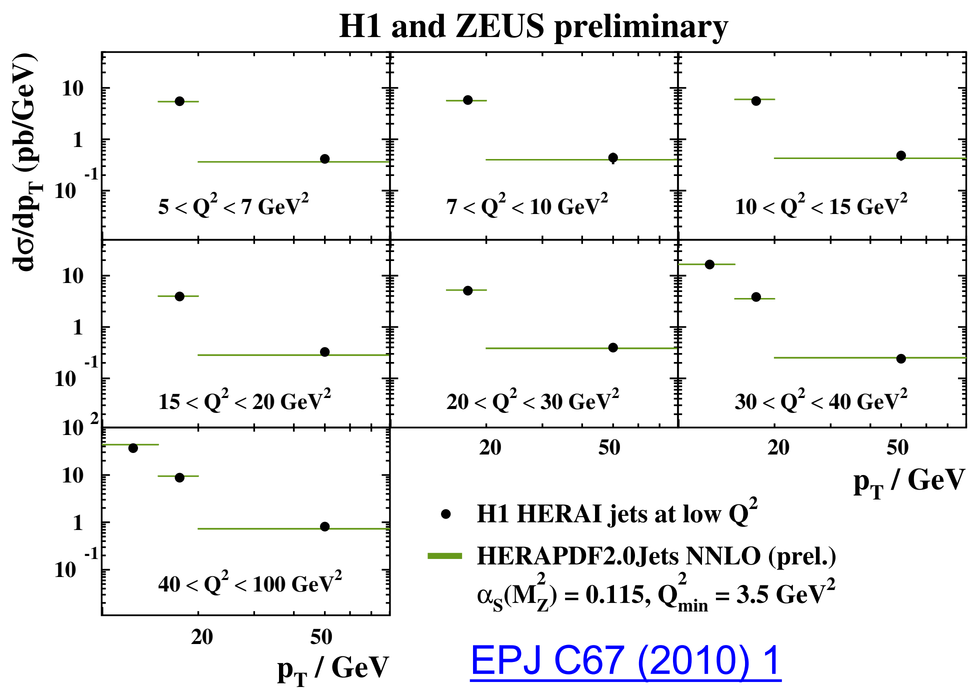
cf. HERA jet data

HERAPDF2.0JetsNLO

$\alpha_s(M_Z)=0.115$



PLB 653 (2007) 134

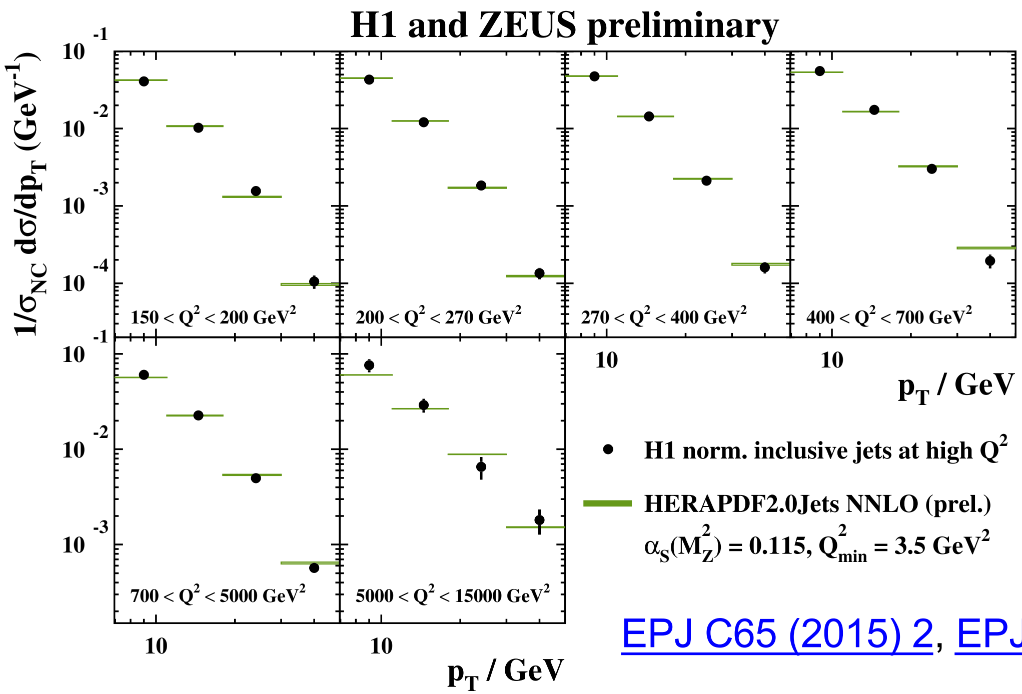


EPJ C67 (2010) 1

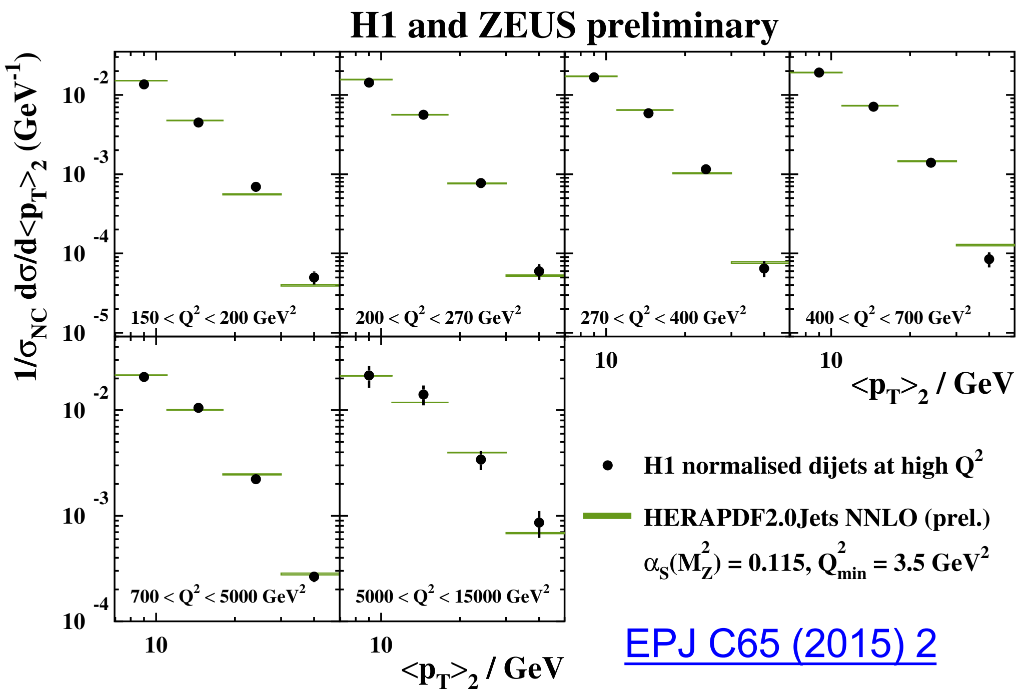
cf. HERA jet data

HERAPDF2.0JetsNLO

$\alpha_s(M_Z)=0.115$



EPJ C65 (2015) 2, EPJ C77 (2017) 215



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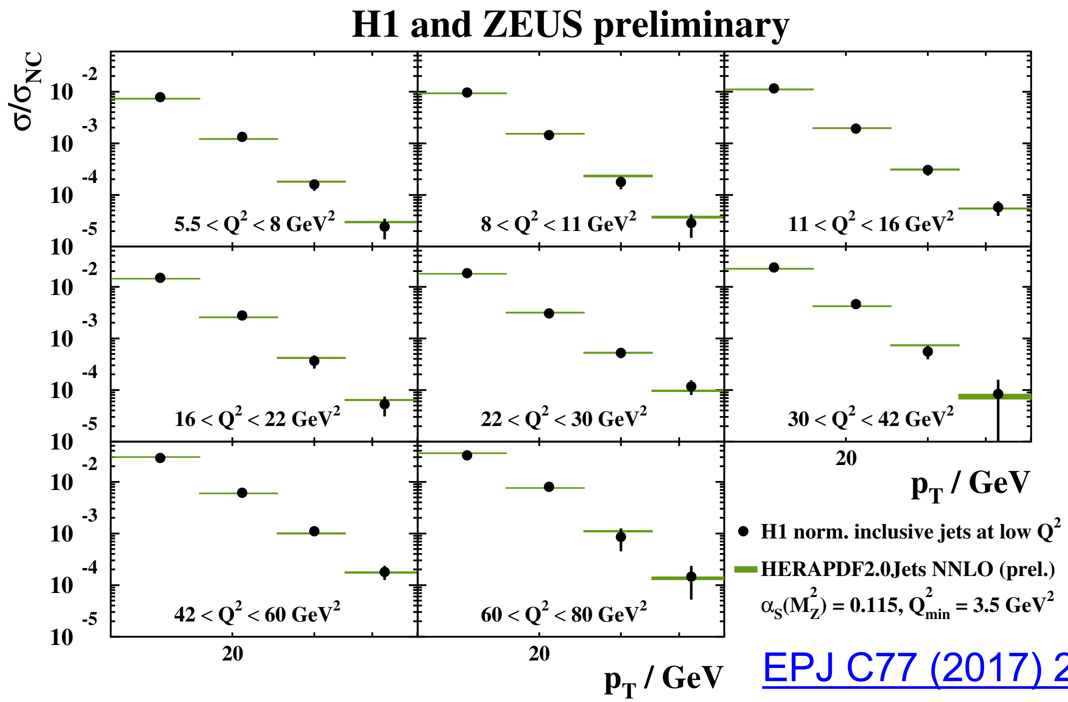
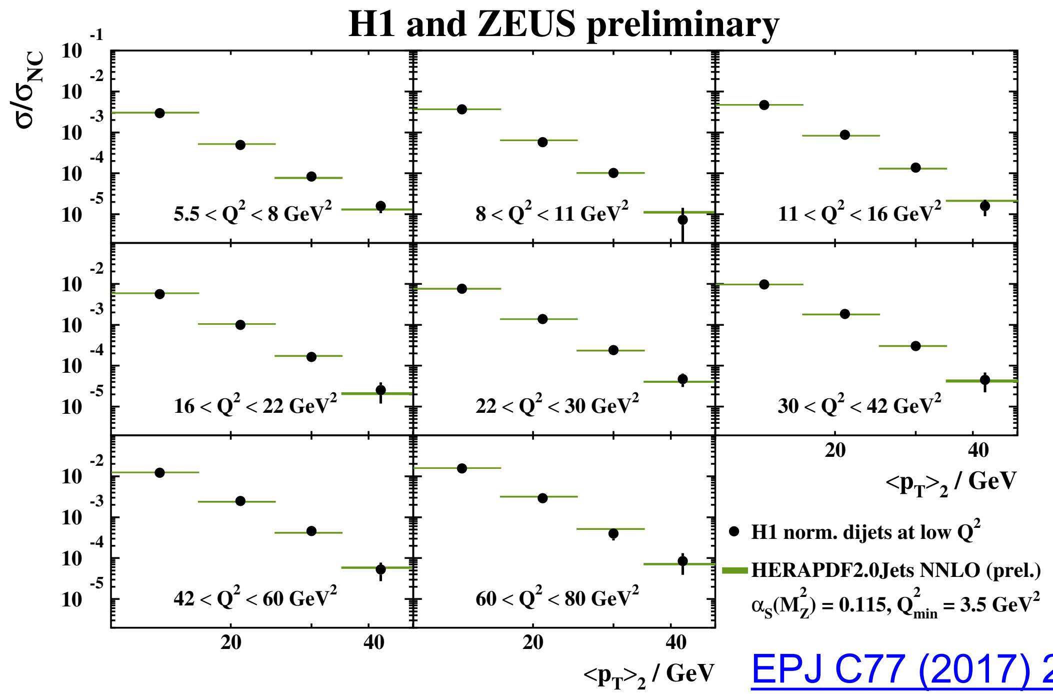
EPJ C65 (2015) 2



EPJ C77 (2017) 215



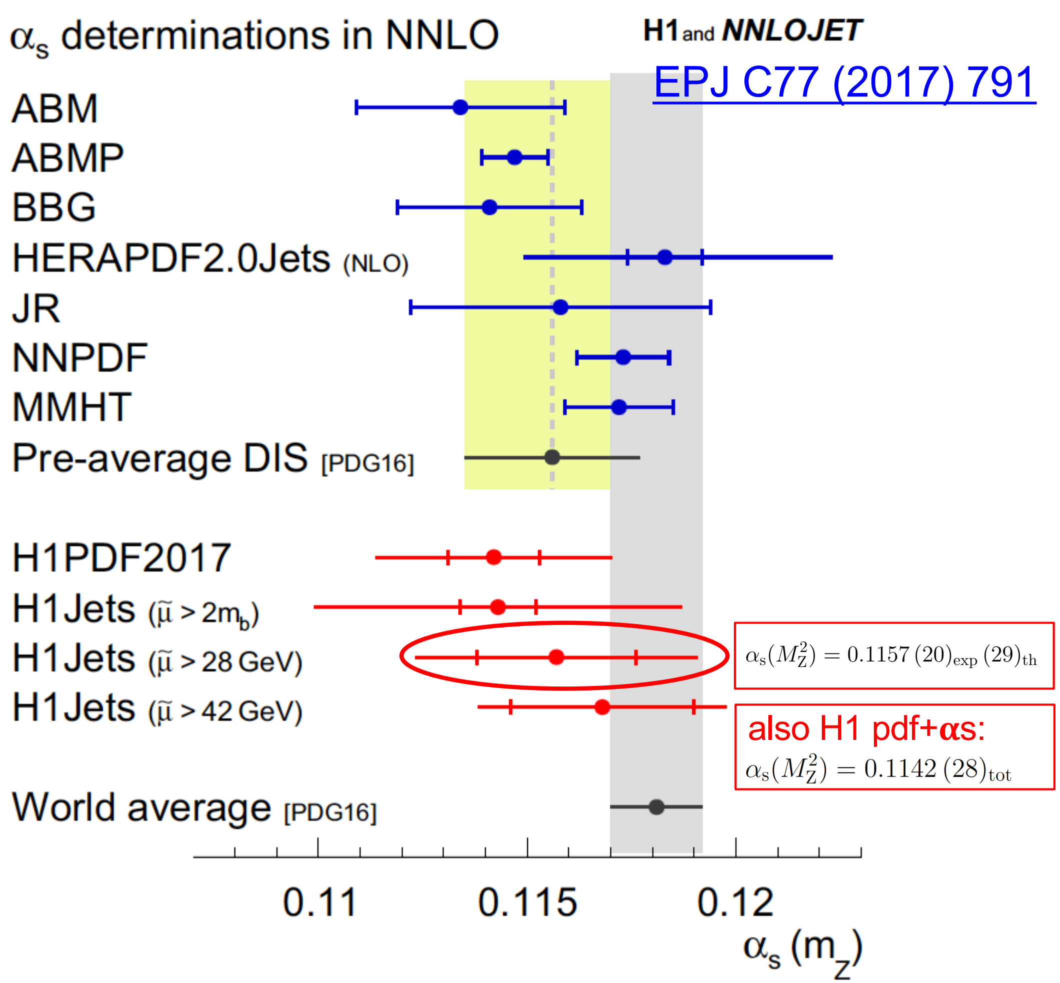
EPJ C77 (2017) 215

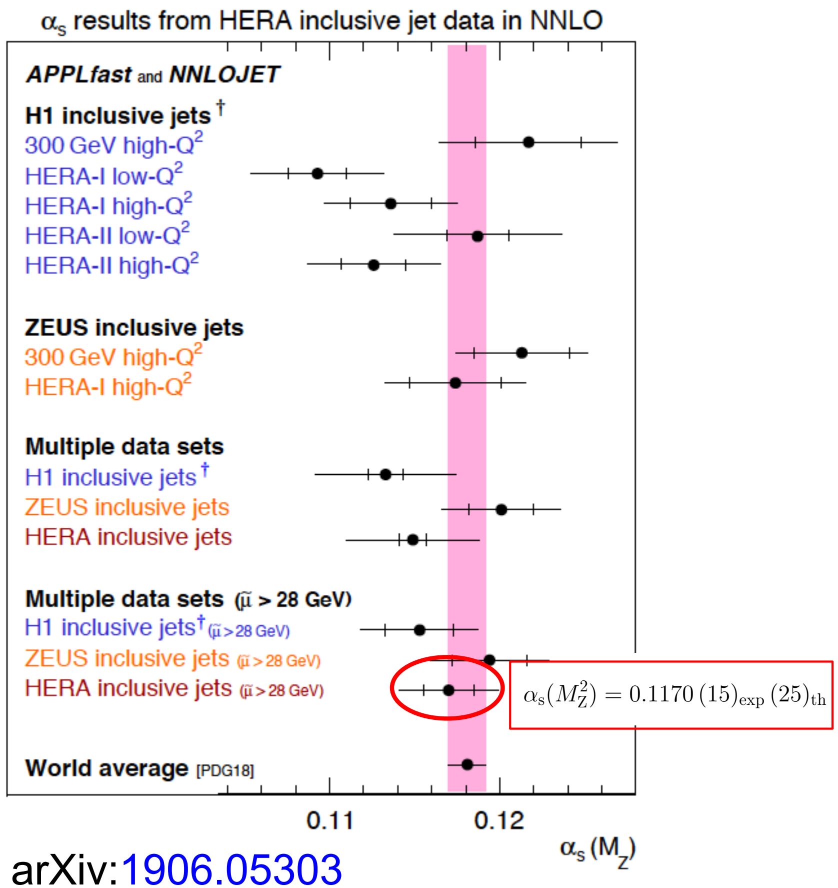
cf. HERA jet data

HERAPDF2.0JetsNLO

$\alpha_s(M_Z)=0.115$

cf. other NNLO determinations





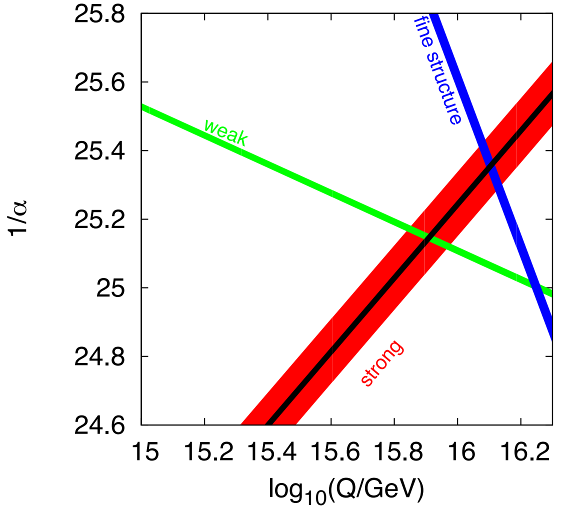
arXiv:1906.05303

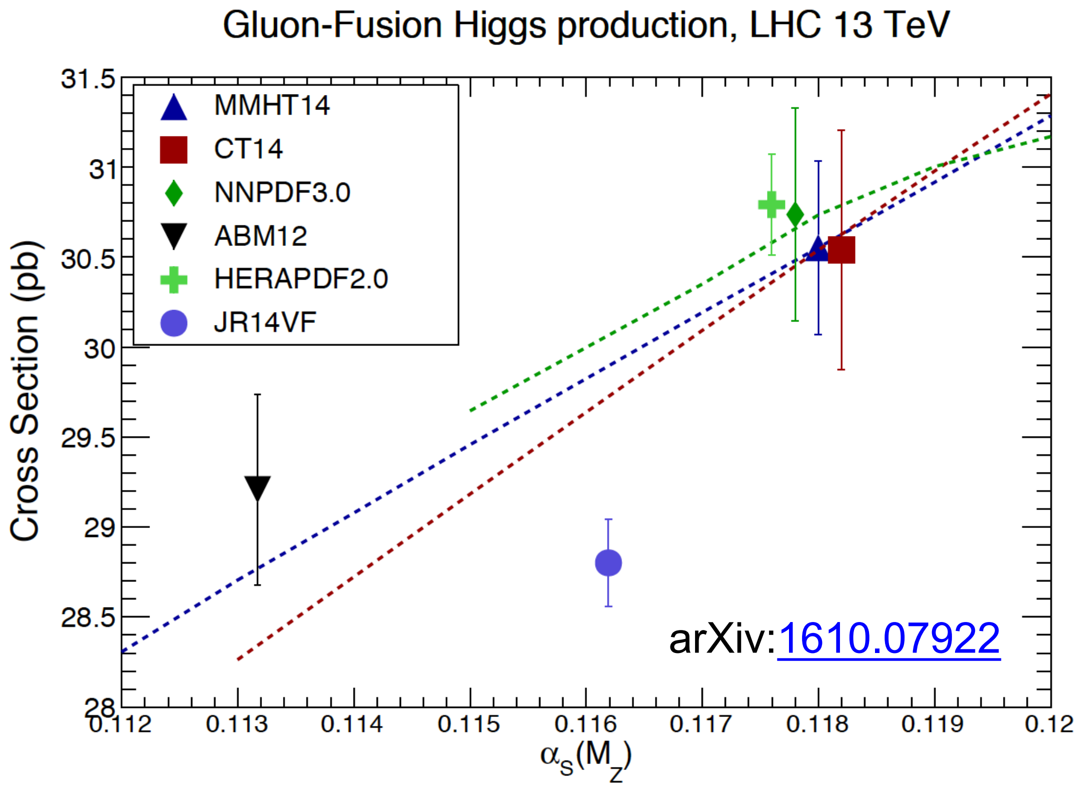
NNLOJet+APPLfast colls., **new result**,

HERA **inclusive** jets

NNLO (this analysis): $\alpha_s(M_Z^2) = 0.1150\,(8)_{\rm exp}\,(28)_{\rm th}$

impact at LHC





- α_S is least known coupling constant;

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

PDG18: $\alpha_S = 0.1181 \pm 0.0011$

($\alpha_S = 0.1174 \pm 0.0016$; w/o lattice QCD)

- what is true central value and uncertainty?

  new precise determinations have important role to play

summary

HERAPDF2.0 family of PDFs completed by performing an NNLO fit including HERA DIS jet data

possible only due to recent **theoretical** and **grid technology** developments (NNLOJet, APPLfast)

TWO new PDF sets:

HERAPDF2.0JetsNNLO $\alpha_s(M_Z)$=0.118 (the PDG value)

HERAPDF2.0JetsNNLO $\alpha_s(M_Z)$=0.115 (value favoured by our new fits)

the jet data allows us to constrain $\alpha_s(M_Z)$; NNLO value:

$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0008\,(\mathrm{exp})^{+0.0002}_{-0.0005}\,(\mathrm{model/par.}) \pm 0.0006\,(\mathrm{had}) \pm 0.0027\,(\mathrm{scale})$$

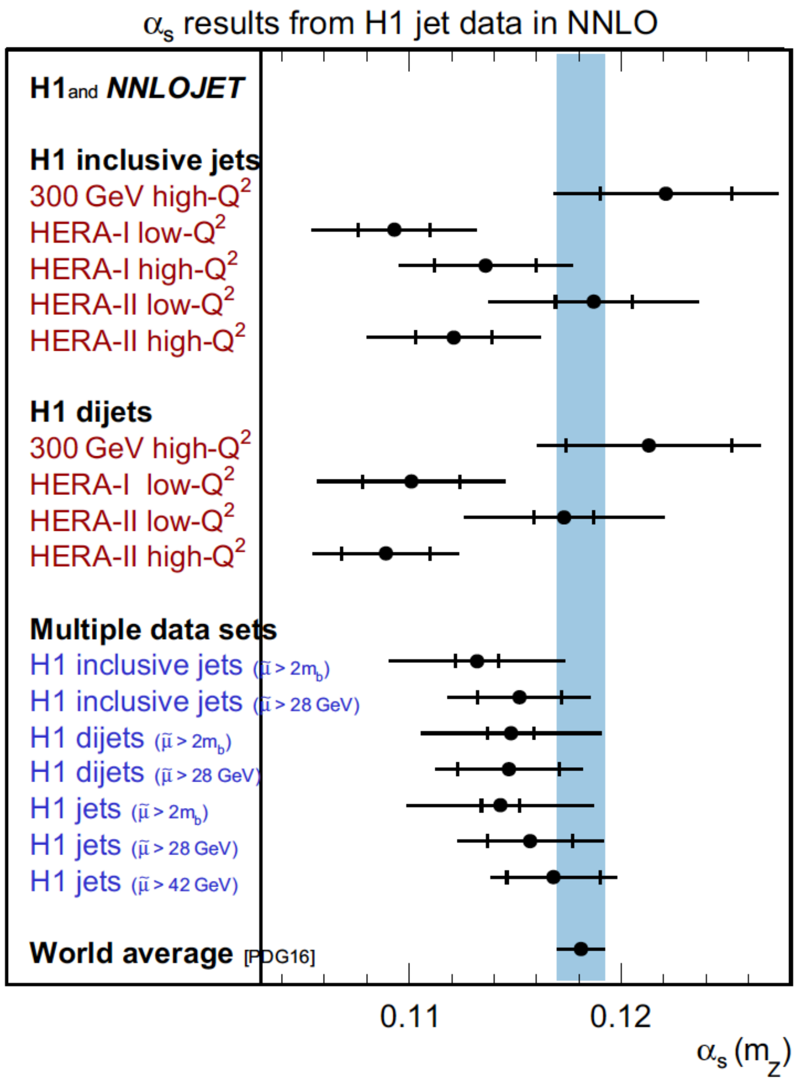
cf. NLO value:

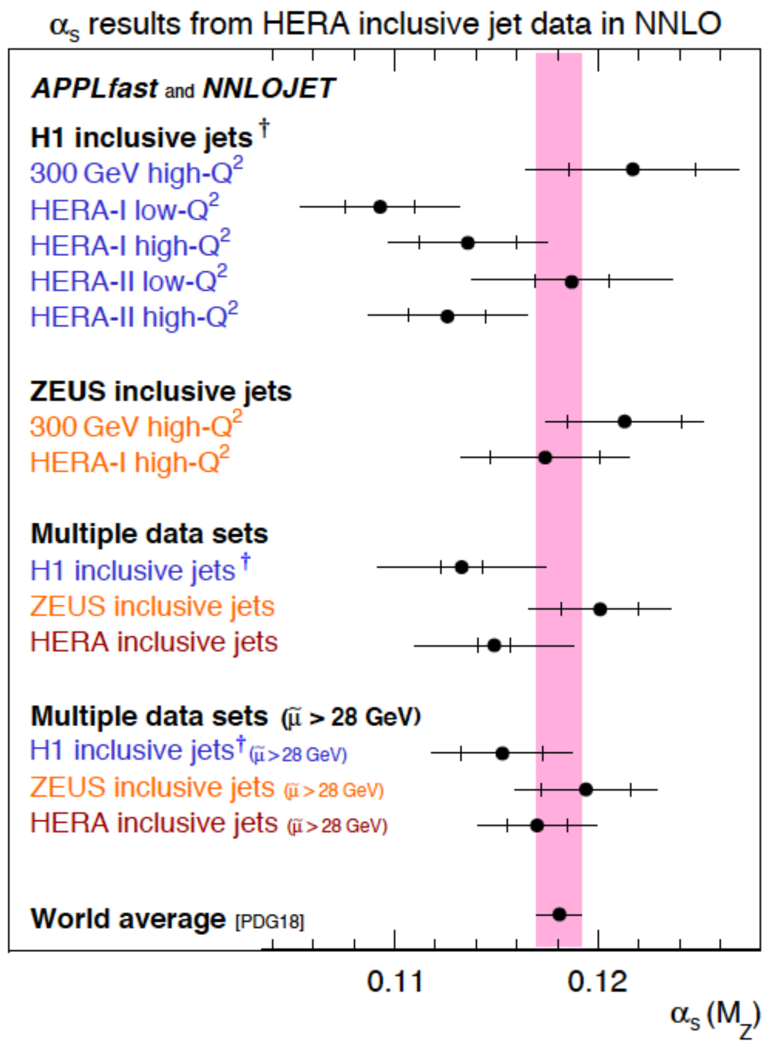
$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0009\,(\mathrm{exp}) \pm 0.0005\,(\mathrm{model/par.}) \pm 0.0012\,(\mathrm{had})^{+0.0037}_{-0.0030}\,(\mathrm{scale})$$

systematic shift downwards at NNLO even taking scale change into account

extras

cf. other NNLO results using HERA jets





H1, NNLOJet, APPLfast colls., EPJ C77 (2017) 791

NNLOJET+APPLfast, arXiv:1906.05303