Alpha-s 2025 Workshop

Precise Determination of the Strong Coupling Constant from Dijet Cross Sections up to the Multi-TeV Range

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Based on:
Phys. Rev. Lett. 135, 031903 (2025)

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Outline

- Motivation
- Theory
- Datasets
- Fit Methodology
- Results
- Summary

Motivation

- **Coupling constants of the SM**
  - **Great precision for α or G_F**
  - **Least known SM parameter α_s**
    - Enters all LHC processes
    - Significant source of uncertainty

Electromagnetic

$\alpha \approx 1/137$

$\Delta\alpha/\alpha = 0.15 \cdot 10^{-9}$

Weak

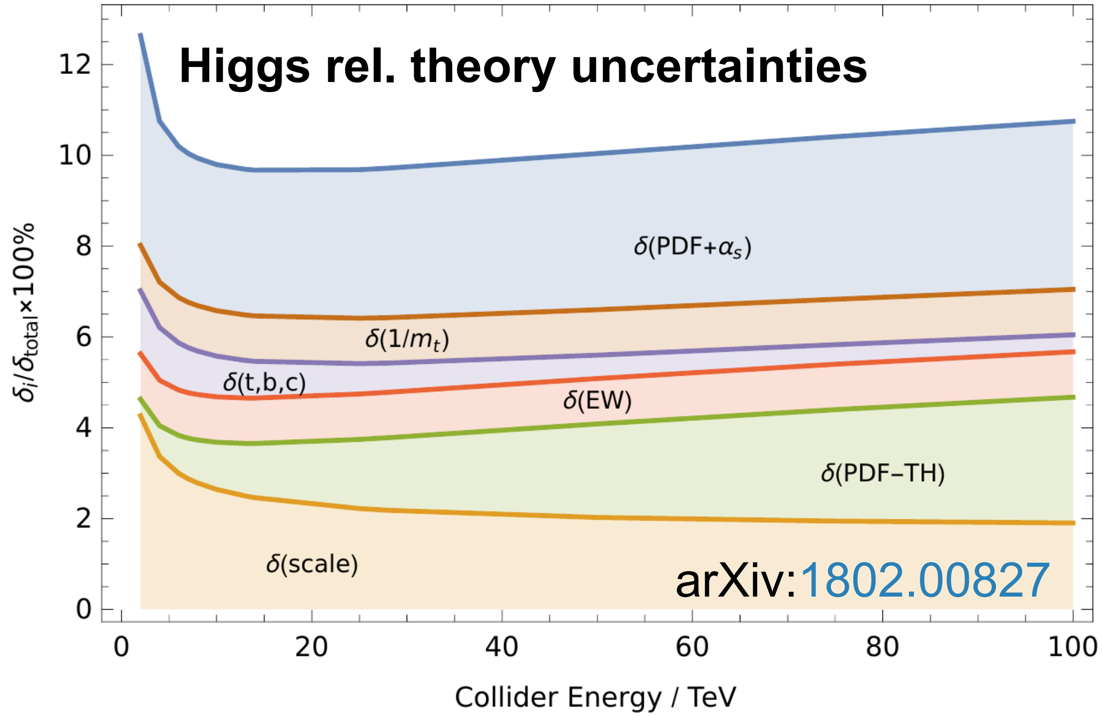
$G_F \approx 1.17 \cdot 10^{-5}/\mathrm{GeV}^2$

$\Delta G_F/G_F = 0.51 \cdot 10^{-6}$

Strong

$\alpha_s \approx 0.118$

$\Delta\alpha_s/\alpha_s = 0.76 \cdot 10^{-2}$

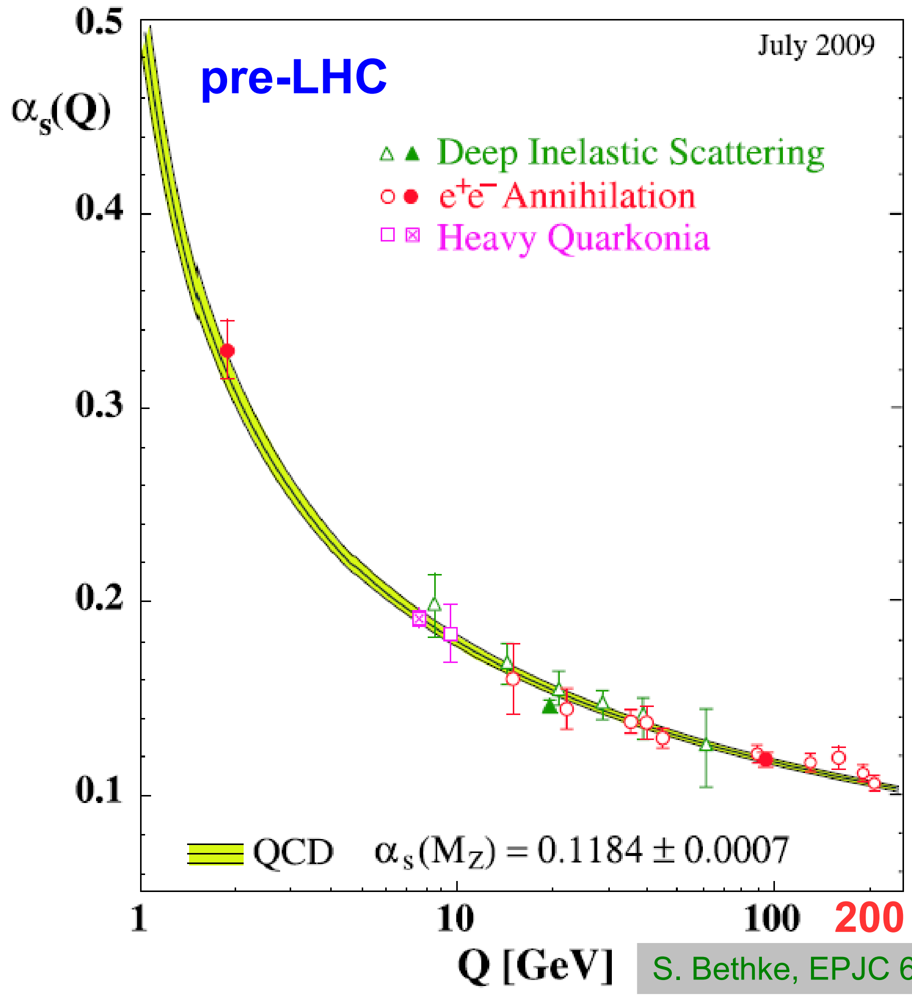


Motivation

- **Coupling constants of the SM**
  - **Great precision for α or G_F**
  - **Least known SM parameter α_s**
    - Enters all LHC processes
    - Significant source of uncertainty
  - **Scale dependence predicted**
    - Running of α_s tested only up to ~200 GeV pre LHC
    - Need highest-energy probe to further advance into asymptotic regime

Nobel prize 2004

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \alpha_s(\mu^2)\beta_0 \ln\left(\frac{Q^2}{\mu^2}\right)}$$



S. Bethke, EPJC 64 (2009).

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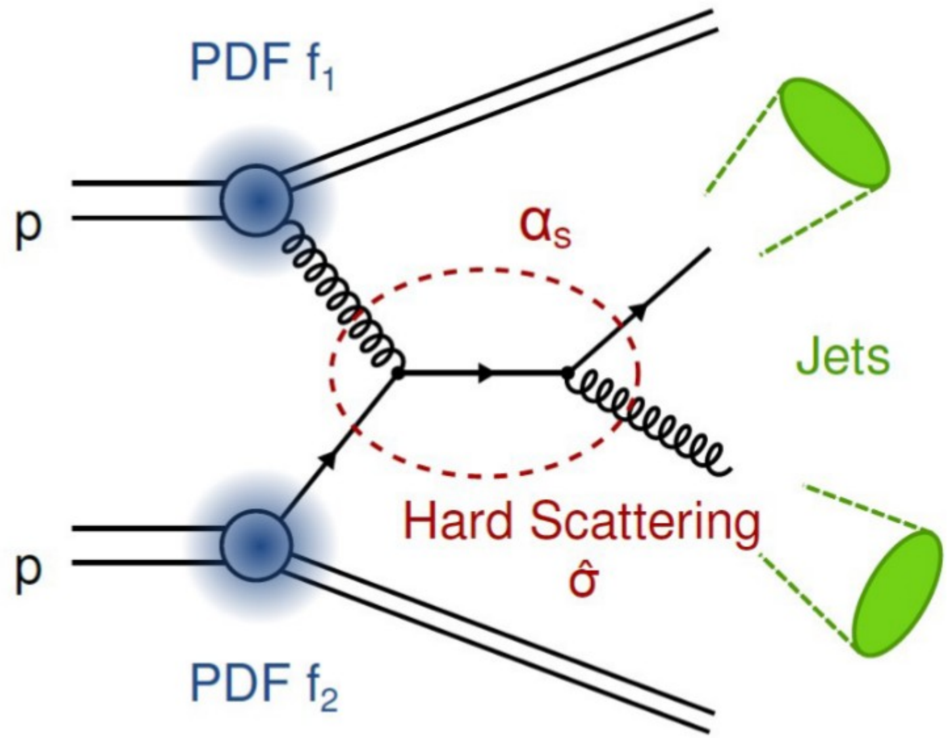
  - **Scale dependence predicted**
    - **Running of α_s tested only up to ~200 GeV pre LHC**
    - **Need highest-energy probe to further advance into asymptotic regime**
- **Latest progress**
  - **NNLO accuracy for predictions of jet cross-sections**

M. Czakon et al., JHEP10 (2019) 262;
M. Czakon et al., Phys. Rev. Lett. 127 (2021) 152001;
X. Chen et al., JHEP09 (2022) 025, JHEP10 (2022) 040.

→ tomorrow's talk by R. Poncelet on 3-jets & today's talks by V. Guglielmi & C. Glasman

Dijet production at the LHC



Huge cross section of dijet production
→ large reach in energy scale
Sensitive to $\alpha_s(m_Z)$ already at LO pert. QCD
All partonic processes present already at LO
→ good convergence

Motivation

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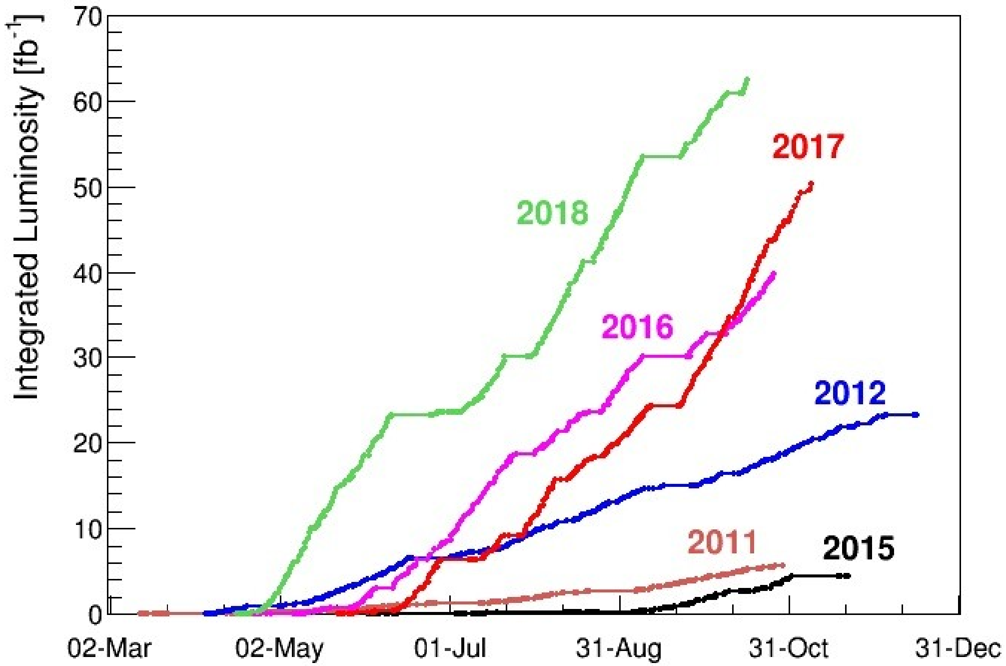
    - Need highest-energy probe to further advance into asymptotic regime
- Latest progress
  - NNLO accuracy for predictions of jet cross sections
  - Huge LHC datasets at 13 TeV (and 13.6 TeV)

LHC luminosity of Run 1 & 2

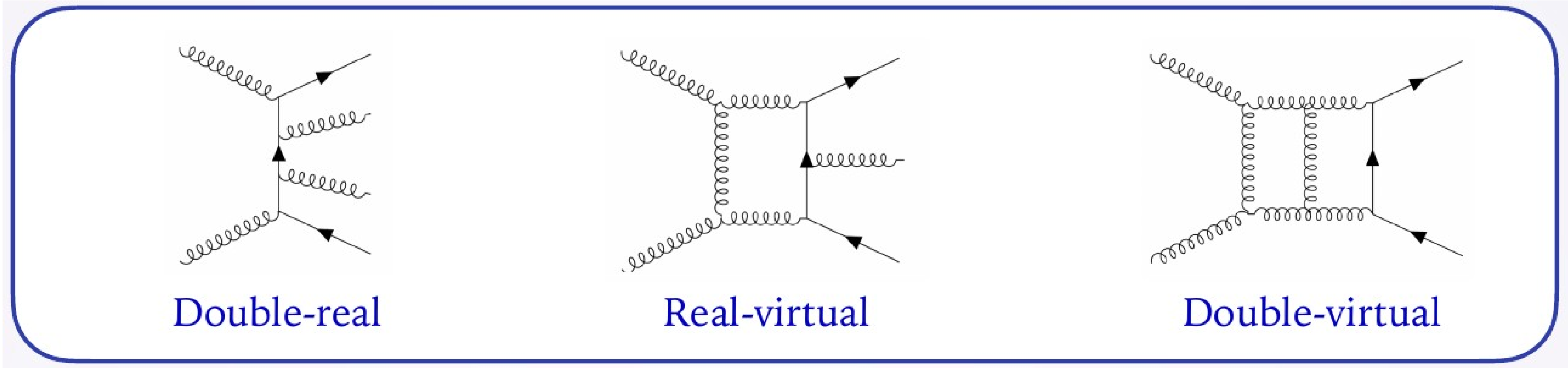


CERN

Total luminosity Run 2 at 13 TeV: 160 fb^{-1}

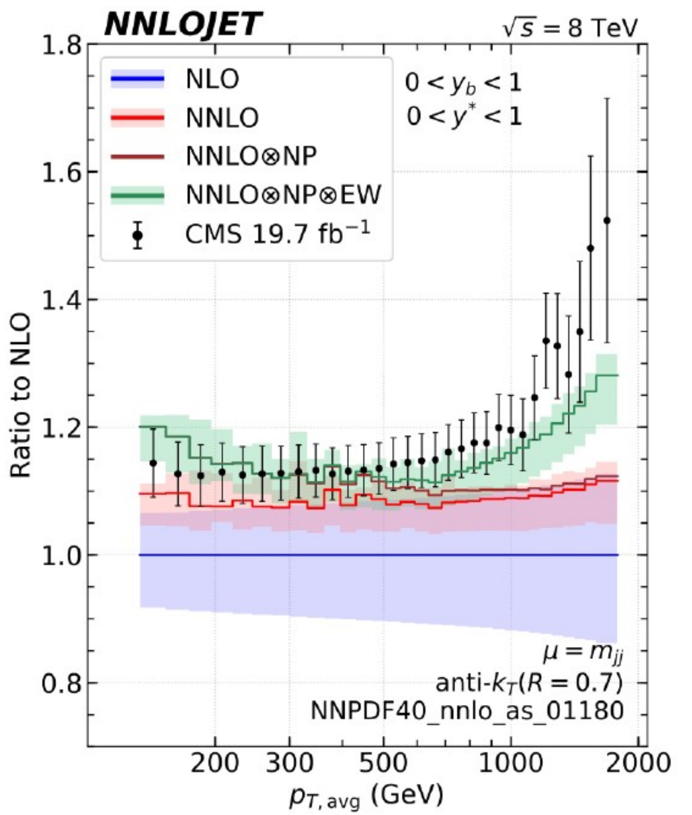
(Run 3 to finish by June 2026 …
Up to now: ~318 fb^{-1} at 13.6 TeV)

NNLO corrections for dijet process



- **NNLO parton-level cross sections obtained with NNLOJET**
  (pp) arXiv:1905.09047, 1705.10271;
  (ep) arXiv:1703.05977, 1606.03991

A. Huss et al., arXiv:2503.22804.

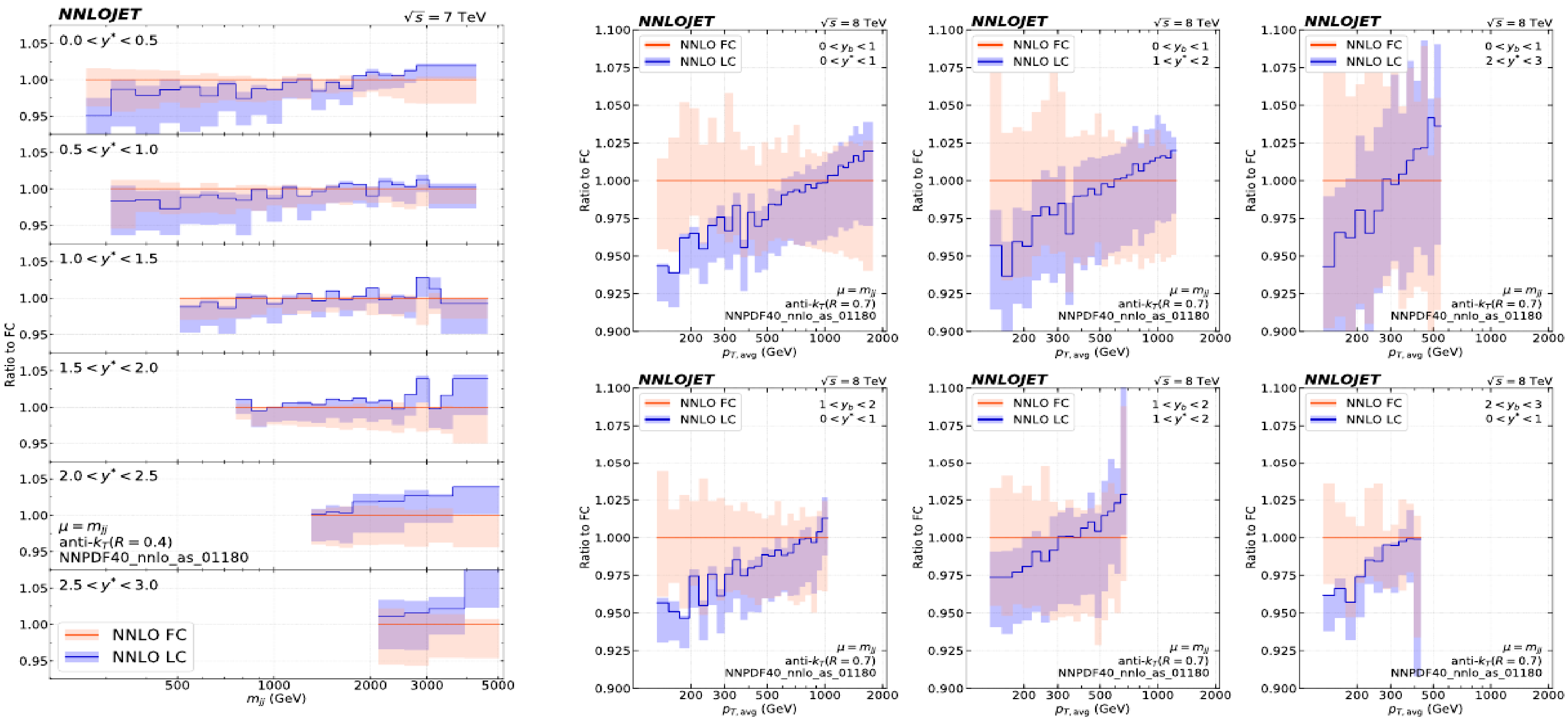


- **Reduced renormalization and factorization scale dependence**
- **Include sub-leading colour contributions**
  → used in this work for the first time, in α_s determination with LHC data (arXiv:1907.12911, 2204.10173, 2208.02115)

Sub-leading colour contributions

- **Sub-leading colour corrections are small**
  → but can be important for dijet production and precision determinations of α_s

used in this work for the first time in α_s determination with LHC jet data



ATLAS 7TeV and CMS 8 TeV NNLO dijet predictions: leading color vs. full color (arXiv:2204.10173)

Interpolation grids

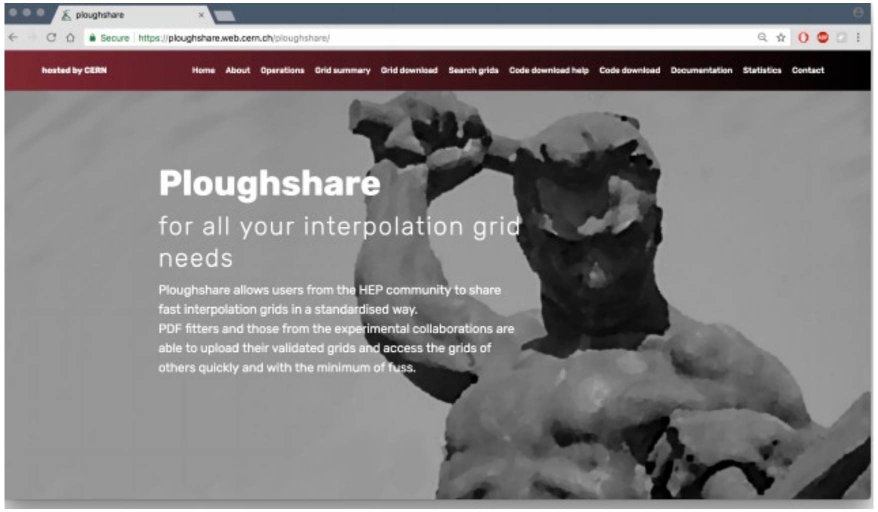
- Fit algorithm for α_s requires (re-)calculation of cross sections for varying $\alpha_s(M_Z)$, PDFs, scales
- NNLOJET interfaced to APPLfast library for fast recomputation

Britzger et al., EPJC 79 (2019) 845, EPJC 82 (2022) 930.

- APPLfast: Generic interface between NNLOJet and both APPLgrid and fastNLO

APPLgrid, Carli et al., Eur. Phys. J. C, 2010, 66, 503.
fastNLO, Britzger et al., arXiv:1208.3641.

  - pQCD coefficients stored in interpolation grids with
    - typically sub-permille accuracy in reproducing full calculation and
    - percent level statistical precision of numerical integrations in NNLOJet
- New fastNLO grids have been submitted to Ploughshare and are available in both formats
(2 CMS grids waiting for more server disk space ...)



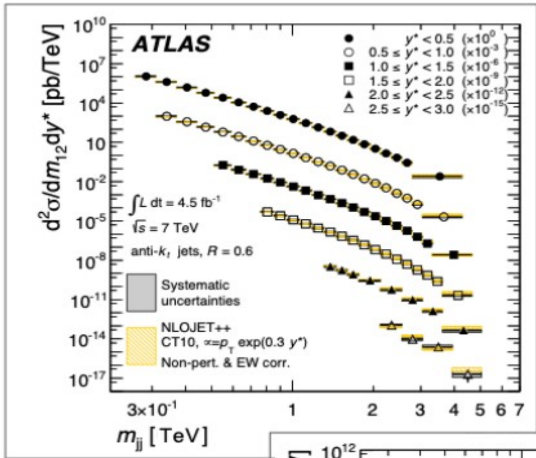
https://ploughshare.web.cern.ch/

LHC dijet data

➤ Abundant production of jets, typically well described by pQCD calculations

Data	$\sqrt{s}$ [TeV]	$d\sigma$	R	$\mathcal{L}$
ATLAS	7	$\frac{d^2\sigma}{dm_{jj}dy^*}$	0.6	$4.5\,\mathrm{fb}^{-1} \pm 1.8\,\%$
CMS	7	$\frac{d^2\sigma}{dm_{jj}dy_{max}}$	0.7	$5.0\,\mathrm{fb}^{-1} \pm 2.2\,\%$
CMS	8	$\frac{d^3\sigma}{d\langle p_T\rangle_{1,2}dy^*dy_b}$	0.7	$19.7\,\mathrm{fb}^{-1} \pm 2.6\,\%$
ATLAS	13	$\frac{d^2\sigma}{dm_{jj}dy^*}$	0.4	$3.2\,\mathrm{fb}^{-1} \pm 2.1\,\%$
CMS	13	$\frac{d^2\sigma}{dm_{jj}dy_{max}}$	0.8	$33.5\,\mathrm{fb}^{-1} \pm 1.2\,\%$
CMS	13	$\frac{d^3\sigma}{dm_{jj}dy^*dy_b}$	0.8	$29.6\,\mathrm{fb}^{-1} \pm 1.2\,\%$

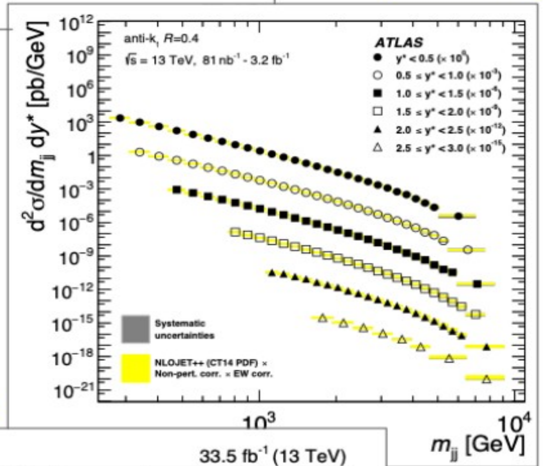
used for additional fit variant
(2D and 3D cannot be used simultaneously due to unknown correlations)

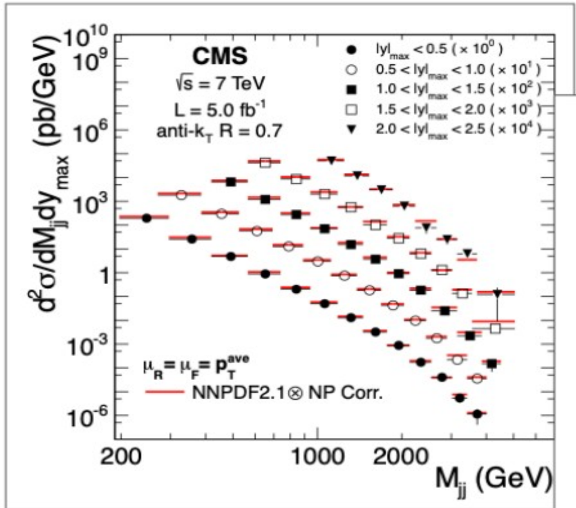


arXiv:1312.3524

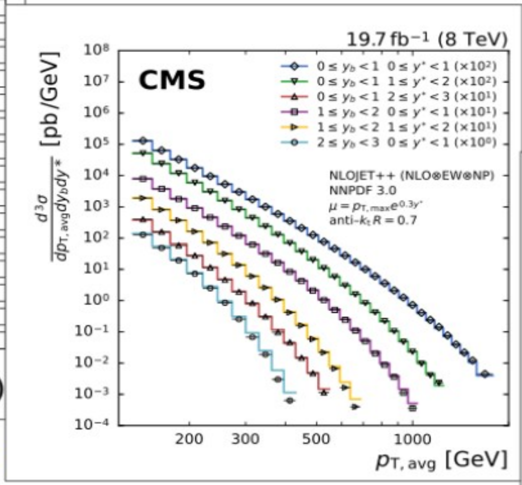
y* = |y1−y2|/2
yb = |y1+y2|/2

arXiv:1711.02692



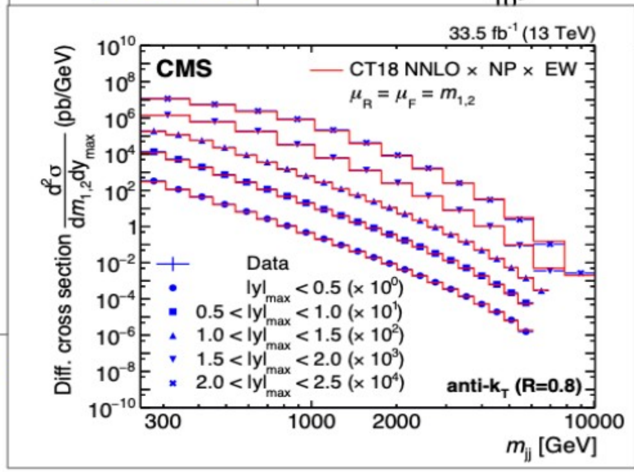


arXiv:1212.6660



arXiv:2312.16669

arXiv:1705.02628



selection: **ymax** or **y*** = |y1-y2|/2 < 2 ; **yb** = |y1+y2|/2 < 1 :

367 LHC cross sections used in α_s determination

LHC dijet data

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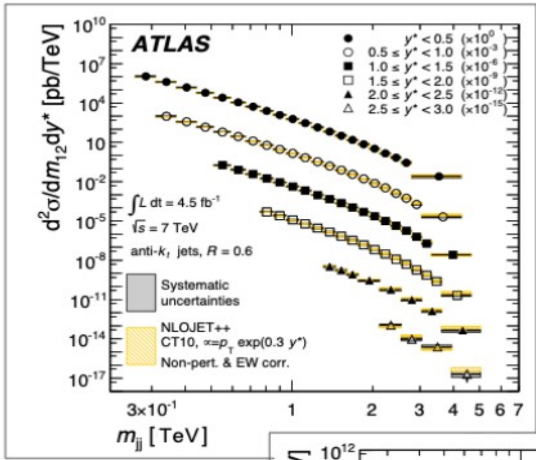
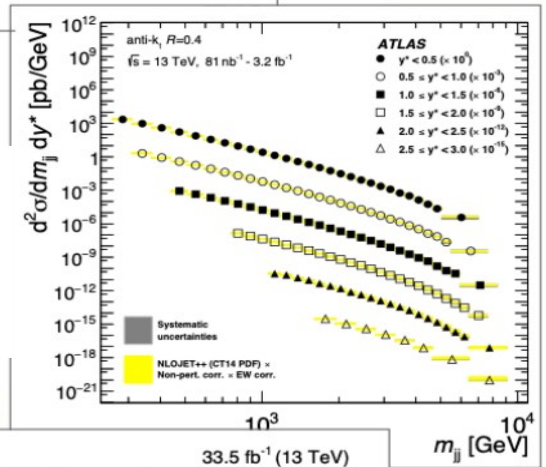


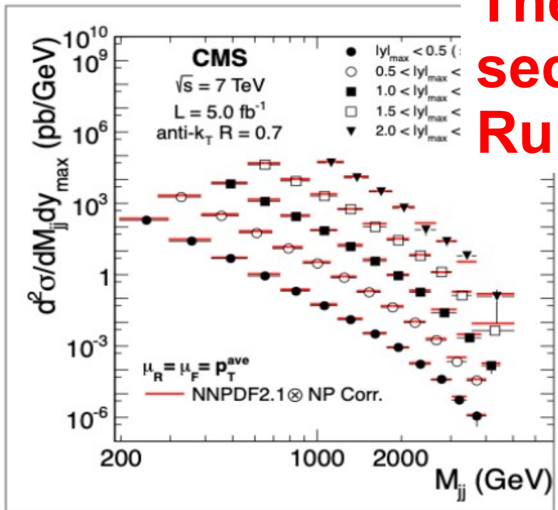
arXiv:1312.3524

$y^* = |y_1 - y_2|/2$
$y_b = |y_1 + y_2|/2$

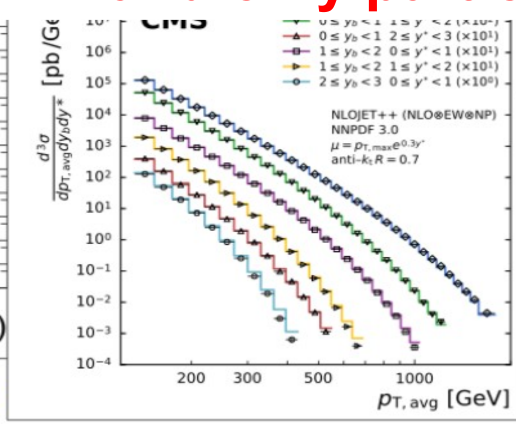
arXiv:1711.02692



These are all LHC dijet cross sections available at the time: Run 1 and only part of Run 2!



arXiv:1212.6660



arXiv:1705.02628

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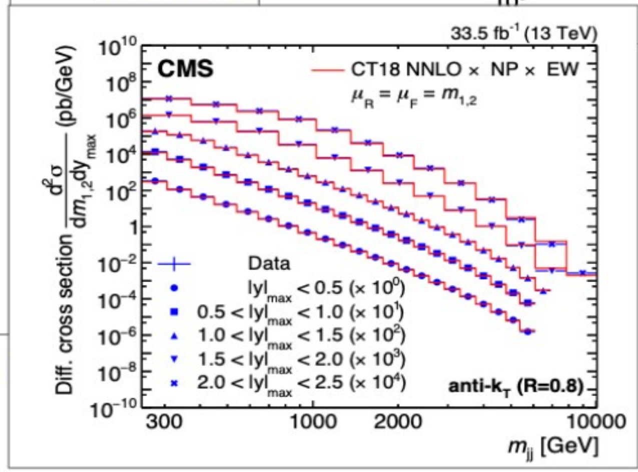

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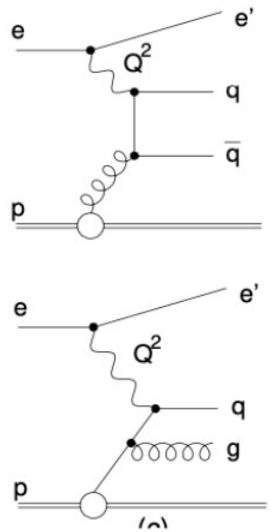
367 LHC cross sections used in α_s determination

HERA dijet data

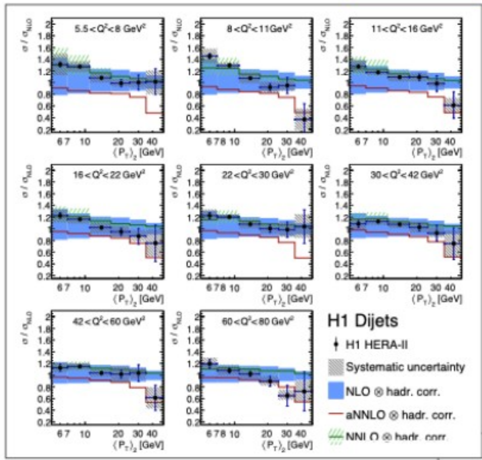
- ➤ Analysis further extended including data for dijet production in neutral-current DIS taken at the HERA *ep* collider

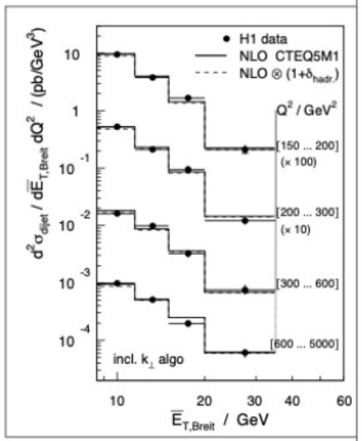


Data set	$\sqrt{s}$ [GeV]	Cuts
H1 300 GeV high-Q^2 [15]	300	–
H1 HERA-I low-Q^2 [16]	320	$\mu > 2m_b$
H1 HERA-II low-Q^2 [19]	320	$\mu > 2m_b$
H1 HERA-II high-Q^2 [18]	320	–
ZEUS HERA-I+II high-Q^2 [17]	320	$\langle p_T \rangle_{1,2} > 15$ GeV

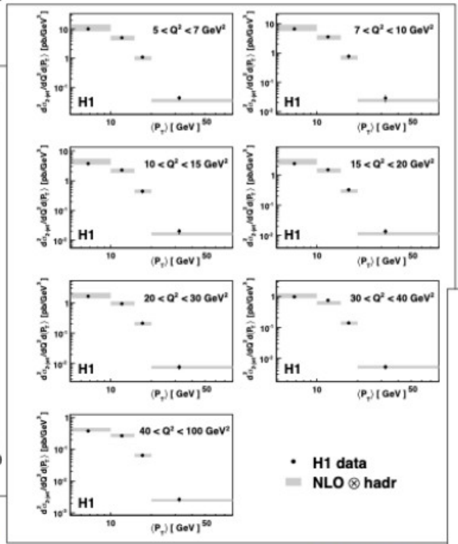
k_t with $R = 1.0$

arXiv:1611.03421



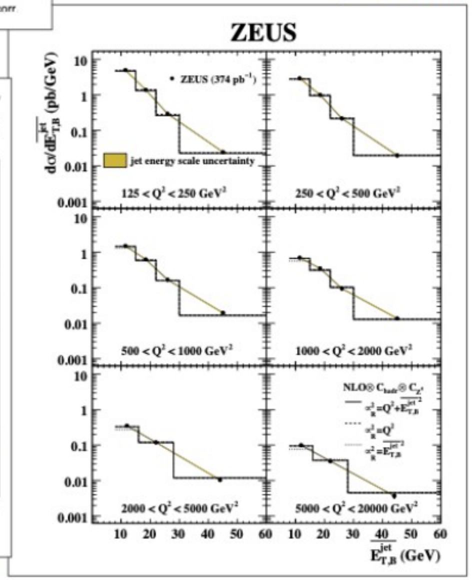


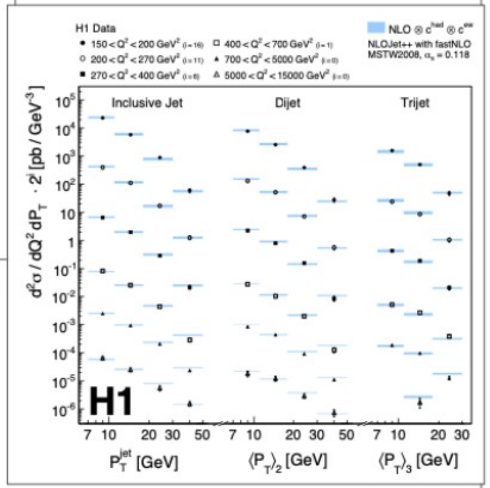
arXiv:0010054



arXiv:0911.5678

arXiv:1010.6167





arXiv:1406.4709

- ➤ Used in previous α_s extractions at NLO and/or NNLO → well understood data and theory

119 HERA cross sections used in α_s determination

Fit methodology

- **Determination of $\alpha_s(M_Z)$ in χ^2 minimisation (MIGRAD)**

$$\chi^2 = \sum_{i,j} \log \frac{\varsigma_i}{\sigma_i} \left(V_{\mathrm{exp}} + V_{\mathrm{NP}} + V_{\mathrm{NNLOstat}} + V_{\mathrm{PDF}}\right)^{-1}_{ij} \log \frac{\varsigma_j}{\sigma_j}$$

ζ_i	LHC or HERA jet data
σ_i	NNLO theory
V	covariance matrices

- **Cross section sensitive to α_s**

$$d\sigma = \sum_{a,b} \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} f_a(x_1, \mu_F) f_b(x_2, \mu_F) d\hat{\sigma}_{ab}(\mu_R, \mu_F) . c_{NP} . c_{EW}$$

pdfs

matrix element (ME) / partonic cross section

non-pertubative (NP) and electroweak (EW) correction factors

where both the **pdfs** and **ME** depend on α_s:

$$d\hat{\sigma}_{ab}(\alpha_s) = \left(\frac{\alpha_s(\mu)}{2\pi}\right)^2 d\hat{\sigma}_{ab,\mathrm{LO}} + \left(\frac{\alpha_s(\mu)}{2\pi}\right)^3 d\hat{\sigma}_{ab,\mathrm{NLO}} + \left(\frac{\alpha_s(\mu)}{2\pi}\right)^4 d\hat{\sigma}_{ab,\mathrm{NNLO}} + \mathcal{O}(\alpha_s^5(\mu))$$

$$f_a(x, \mu, \alpha_s) = (\Gamma(\mathcal{P}, \mu, \mu_0, \alpha_s) \otimes f_{\mu_0})_a$$

where Γ are the DGLAP kernels evaluated at 3-loop with 5 active flavours using Apfel++

- **Starting scale of PDF evolution with DGLAP set to μ_0 = 90 GeV**
- **x dependence of $f(x,\mu_0)$ obtained from PDF4LHC21**

Uncertainties

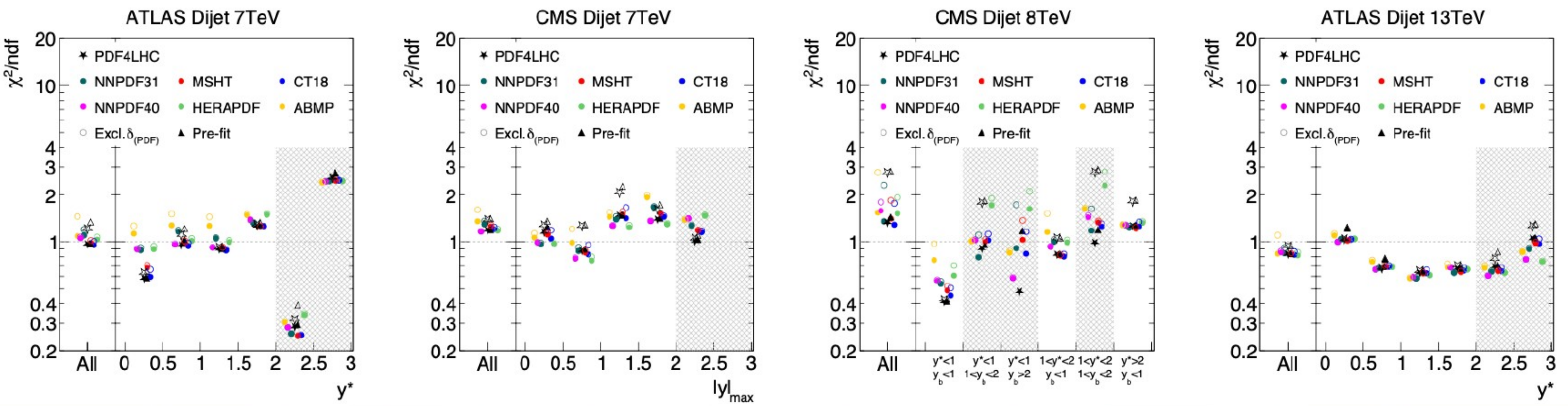
- $\alpha_s(m_Z)$ fit uncertainties: (fit,PDF)
- (Encoded in covariance matrices V and consist of...)
  - Experimental (exp): including stat. and syst. correlations as reported by the experiments
  - Non-perturbative (NP): provided by the LHC collaborations (using different MC models)
  - NNLO statistical: arising from MC integration in NNLOJET (typically at percent level or less)
  - PDF uncertainties: obtained from the relevant PDF set and evaluated at μ_0

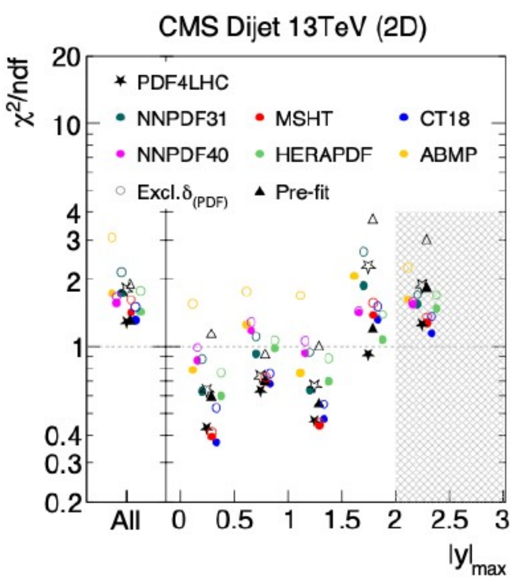
- Starting scale of the PDF evolution: (μ_0)
  - Varied by factors of 0.5 and 2 about the nominal value of μ_0=90 GeV
  - Also covers uncertainty arising from $\alpha_s(M_Z)$ variation in the original PDF

- Scale uncertainties: (μ_R, μ_F)
  - Renormalization μ_R and factorization scale μ_F varied by factors of 0.5, 1 or 2: 7-point variation
  - Nominal scales: LHC $\mu_R=\mu_F=m_{jj}$; HERA $\mu_R=\mu_F=\sqrt{Q^2+\langle p_T\rangle^2_{1,2}}$
  - Scale variations for LHC and HERA considered uncorrelated (added in quadrature for HERA+LHC fits)

Consistency study

Comprehensive study assessing consistency of NNLO predictions and data





Plotting χ^2/ndf values of α_s fits to individual y^*, y_b, y_{max} bins

- **pre- and post-fit χ^2 values reasonable (some exceptions at larger *y*) (open symbols: pre-fit)**
- **χ^2 using different PDFs reasonably consistent → PDFs are consistent**
- **PDF uncertainties are only mildly important**
- **Fit to all *y*-ranges of individual data without significant increase in χ^2**

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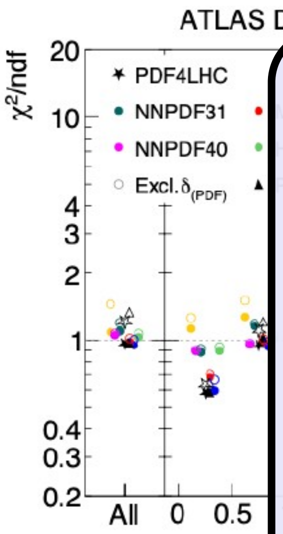
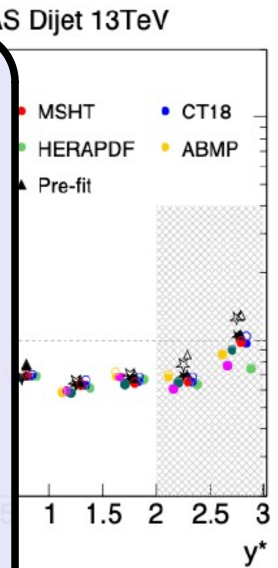
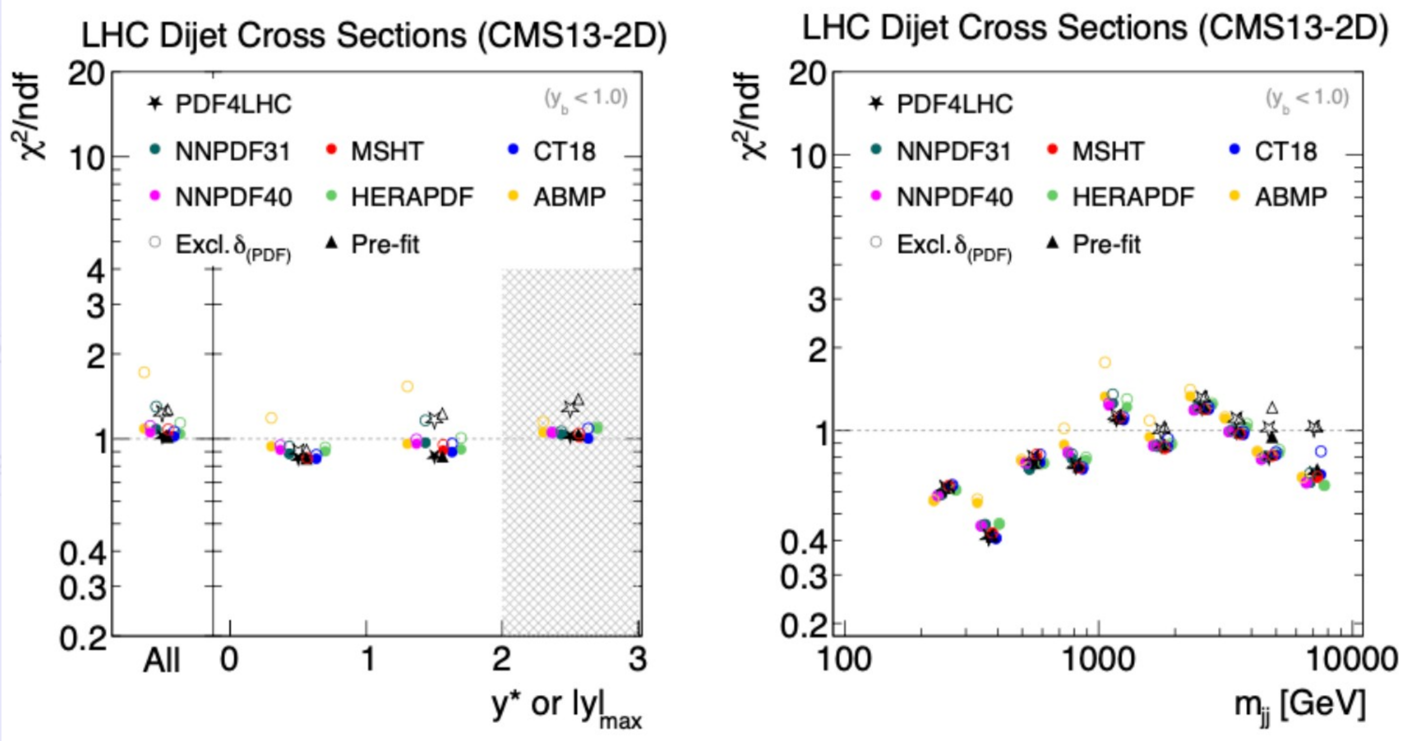


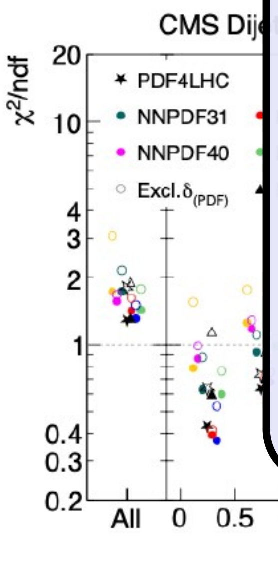


All selected LHC data points taken together



All LHC datasets together: excellent χ^2/ndf values around unity

No tensions observed vs. rapidity or dijet mas



Fit results

- Perform fits to
  - each individual data set
  - all LHC data sets (with either CMS 2D or 3D)

$\alpha_s(m_Z)$ (fit,PDF) (μ_0) (μ_R,μ_F)

Data set	χ^2/n_{dof}	$\alpha_s(m_Z)$
ATLAS 7 TeV	74.7/ 77	0.1193 (33) (4) (6)
ATLAS 13 TeV	87.7/106	0.1145 (32) (4) (16)
CMS 7 TeV	50.7/ 45	0.1151 (39) (1) (9)
CMS 8 TeV	37.0/ 56	0.1173 (25) (1) (11)
CMS 13 TeV (2D)	71.6/ 78	0.1209 (25) (2) (20)
CMS 13 TeV (3D)	137.7/112	0.1181 (20) (1) (15)
LHC dijets (CMS13-2D)	335.3/366	0.1178 (14) (1) (17)
LHC dijets (CMS13-3D)	397.9/400	0.1172 (14) (1) (14)

- α_s from individual data sets
  - all fits with good χ^2
  - exp.+PDF uncertainties: ±0.0020 to ±0.0033
  - data sets with larger integrated luminosities or higher √s yield smaller uncertainties
  - α_s determination using all 5 LHC dijet datasets yields reduced experimental uncertainties (benefits from independent measurements, extended kinematic ranges and multiple √s)

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- α_s including HERA + LHC data
  - good consistency between LHC and HERA
  - further reduced experimental uncertainties
  - increased scale uncertainty (since HERA is at lower scale)

Data set	χ^2/n_{dof}	$\alpha_s(m_Z)$
HERA	92.8/118	0.1177 (14) (1) (34)
LHC+HERA (CMS13-2D)	428.4/485	0.1180 (10) (1) (22)
LHC+HERA (CMS13-3D)	491.0/519	0.1177 (10) (1) (24)

Comparison to PDG24

- **LHC dijet data**
  - **excellent consistency with world average**

- **Main $\alpha_s(m_Z)$ results**
  - **all *5 LHC dijet data* sets taken together (*using CMS 13TeV 2D*)**

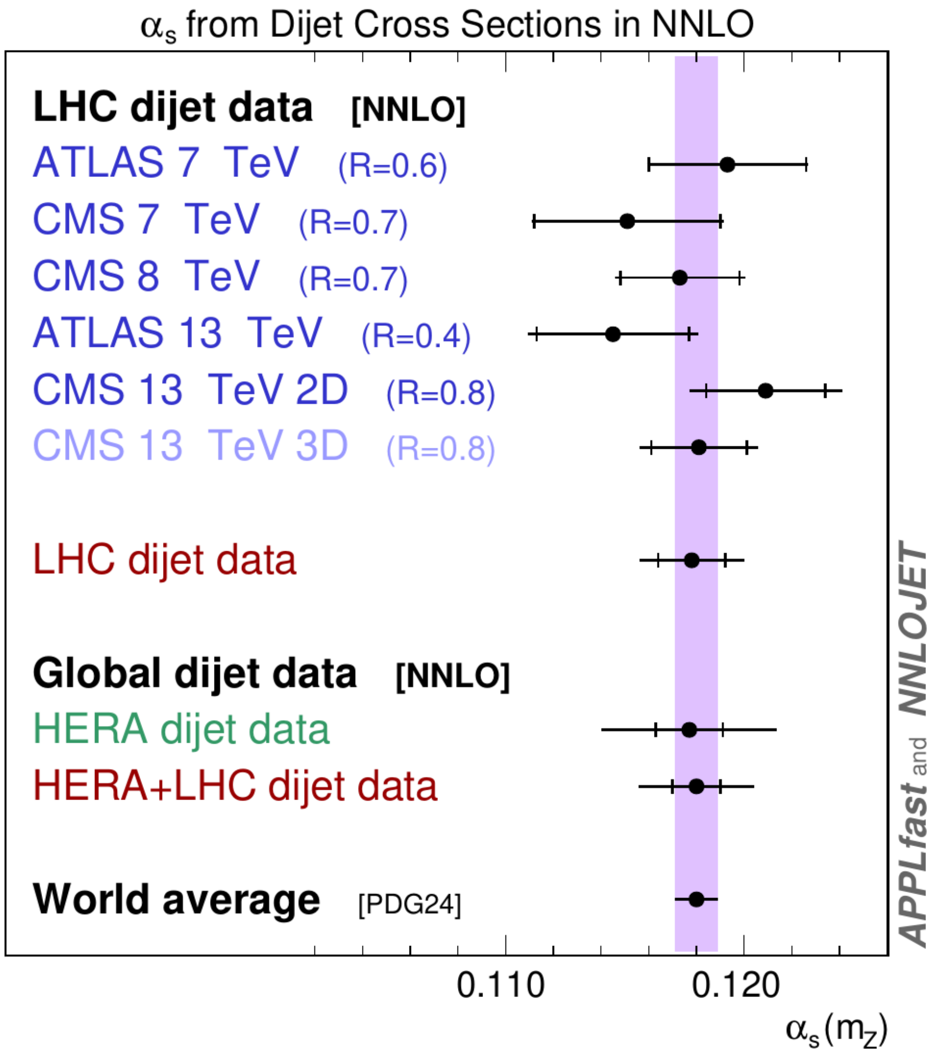
$$\alpha_s(m_Z) = 0.1178\,(14)_{(\mathrm{fit,PDF})}\;(1)_{(\mu_0)}\;(17)_{(\mu_R,\mu_F)}$$

  - **$\alpha_s(m_Z)$ using *HERA* dijet data**

$$\alpha_s(m_Z) = 0.1177\,(14)_{(\mathrm{fit,PDF})}\,(1)_{(\mu_0)}\,(34)_{(\mu_R,\mu_F)}$$

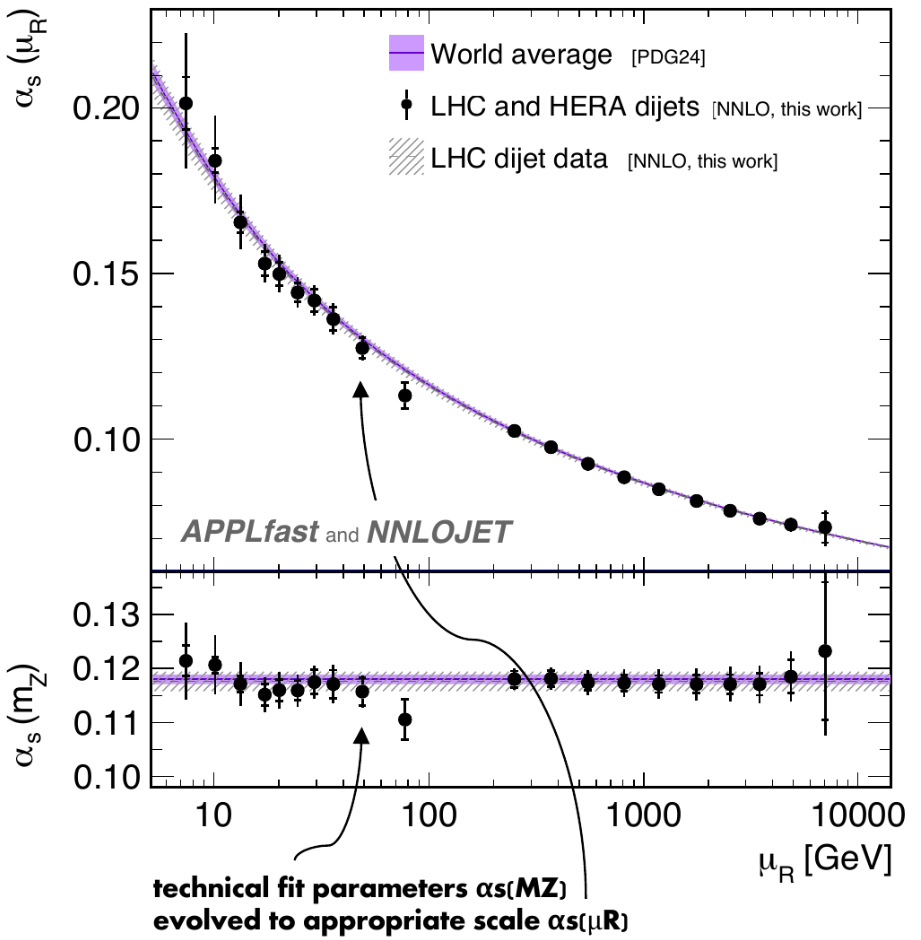
  - **$\alpha_s(m_Z)$ using *LHC and HERA* dijet data**

$$\alpha_s(m_Z) = 0.1180\,(10)_{(\mathrm{fit,PDF})}\,(1)_{(\mu_0)}\,(22)_{(\mu_R,\mu_F)}$$



Running coupling

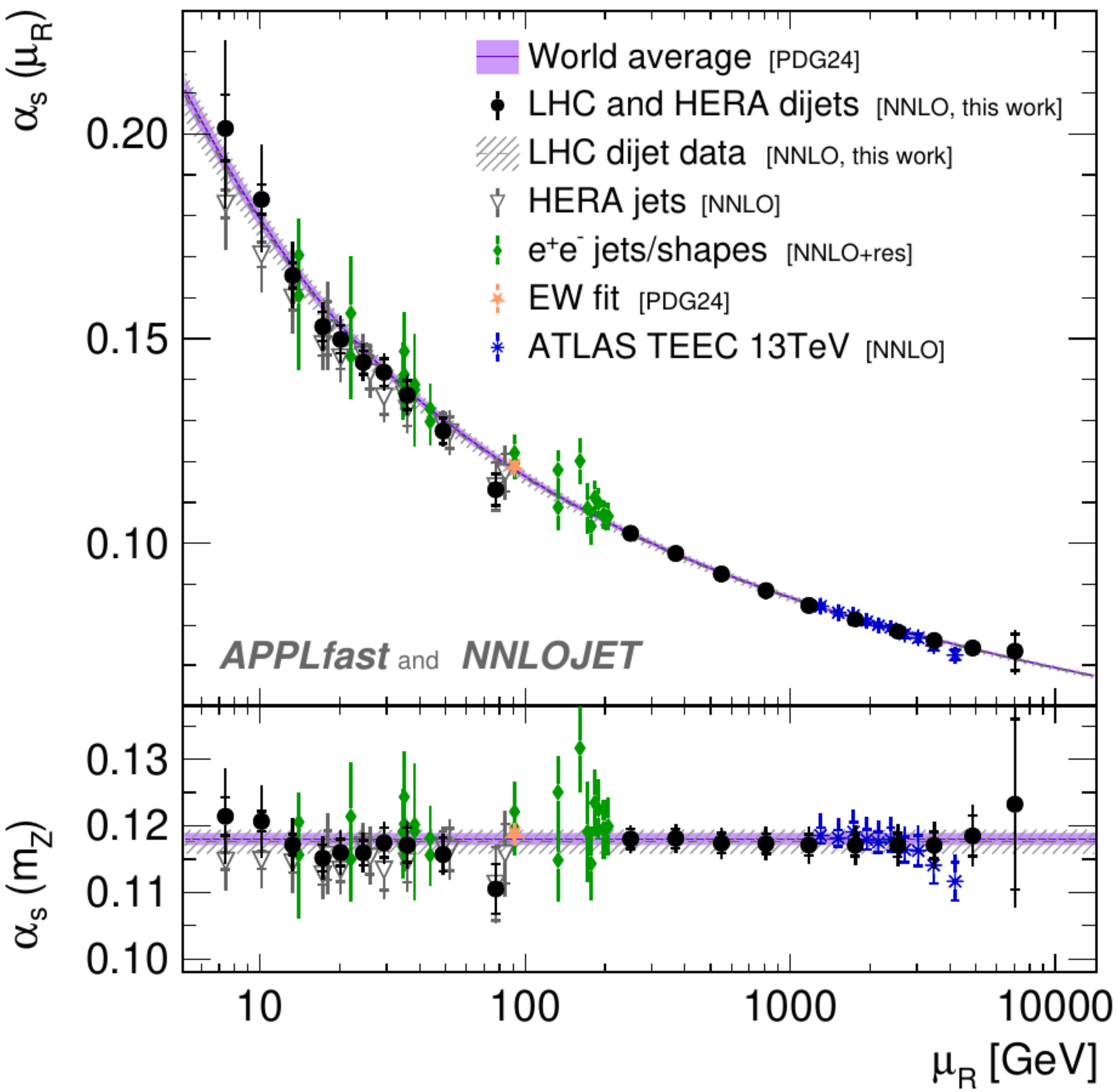
- Test the **running** of α_s
  - Each cross-section measurement is assigned a single **representative μ_R** value
    → group the data into **20 distinct μ_R intervals**
  - **Single fit** to **all dijet data**, where for each of the individual ranges a separate $\alpha_s(m_Z)$ value is used in the prediction
  - Assumes running to be valid within the very **limited range** covered by the interval
    (plus small extent in DGLAP from μ_0=90 to μ_F=μ_R)



- Results
  - **Consistent with the expectation from the RGE running** at all scales, from about **7 GeV to 7 TeV**
  - Theo. and experimental uncertainties of **similar size** (albeit scale uncertainty always dominates)

Scales up to 7 TeV probed for the first time

Comparison to other data



Huge range in scale μ_R covering 3 orders of magnitude with rather small uncertainties

Summary

- Strong coupling α_s determined from dijet data for the first time based on complete NNLO calculations (including sub-leading color contributions)
- Using multiple LHC dijet datasets from ATLAS and CMS at 7, 8 and 13 TeV, $\alpha_s(m_Z)$ is determined to

$$\alpha_s(m_Z) = 0.1178\,(22)_{(\mathrm{tot})}$$

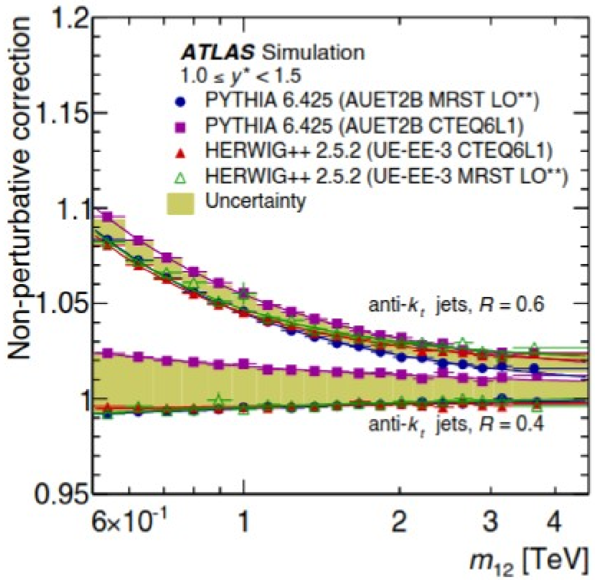
- Including dijet cross sections from HERA, we performed a comprehensive and precise test of the QCD RGE running of α_s, probing a range of scales from 7 GeV to 7 TeV
- Only LHC Run 1 and partial data of Run 2 used so far
  → can be extended substantially with full Run 2 & Run 3 data

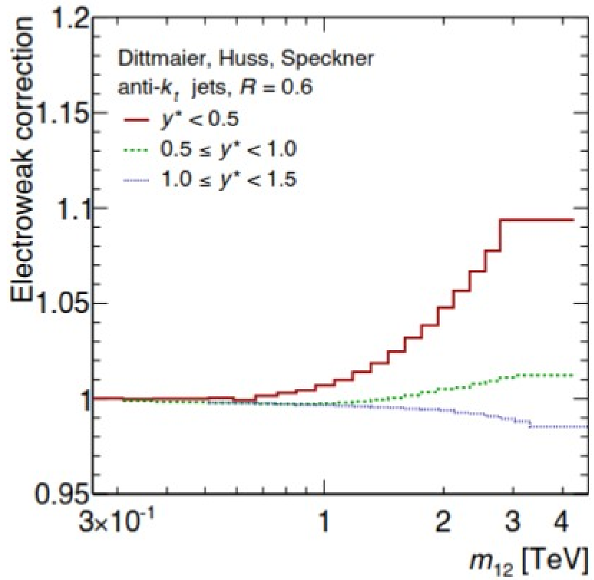
Thank you for your attention!

Backup

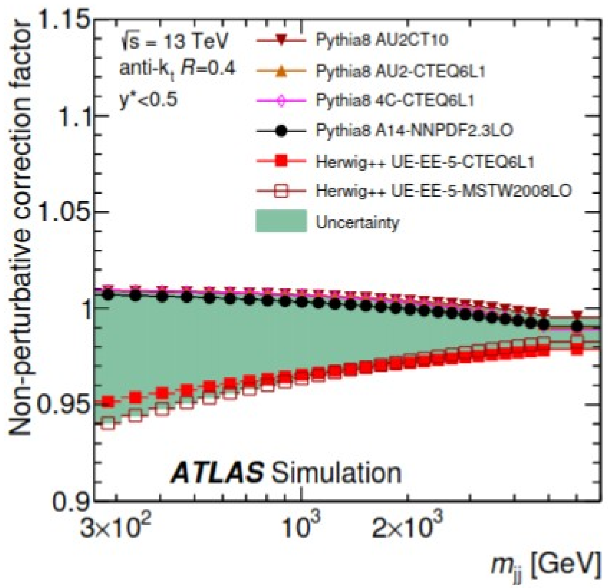
EW and NP corrections (ATLAS)

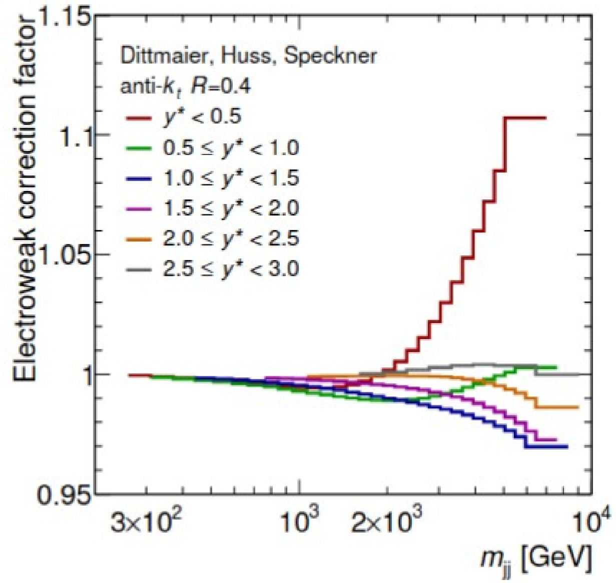
7 TeV





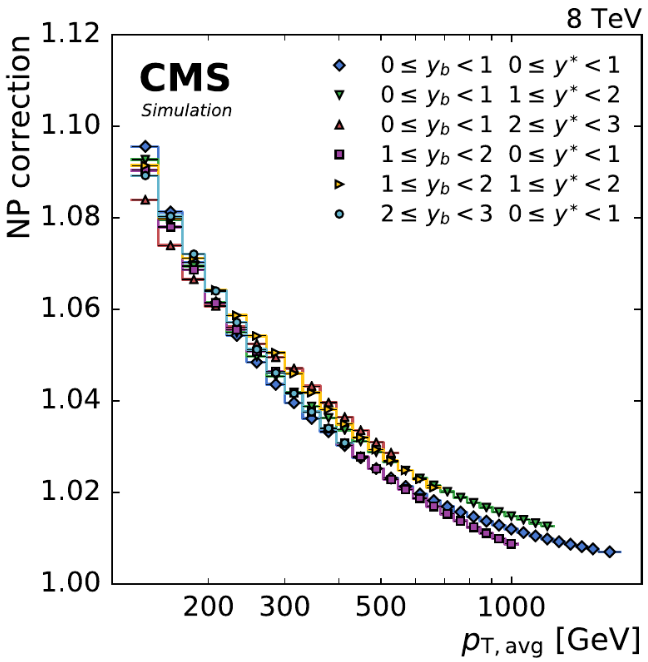
13 TeV

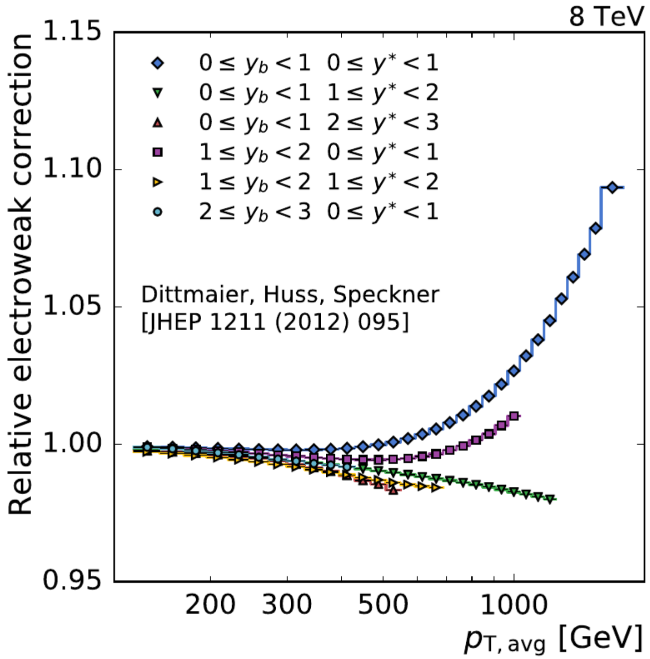




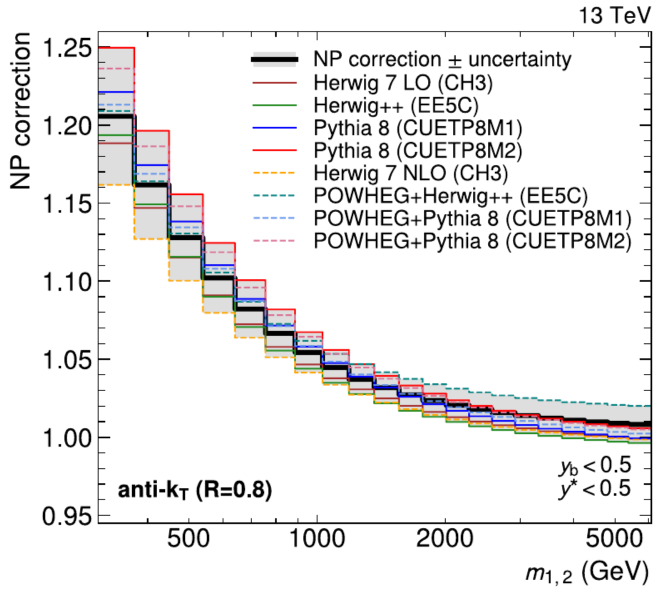
EW and NP corrections (CMS)

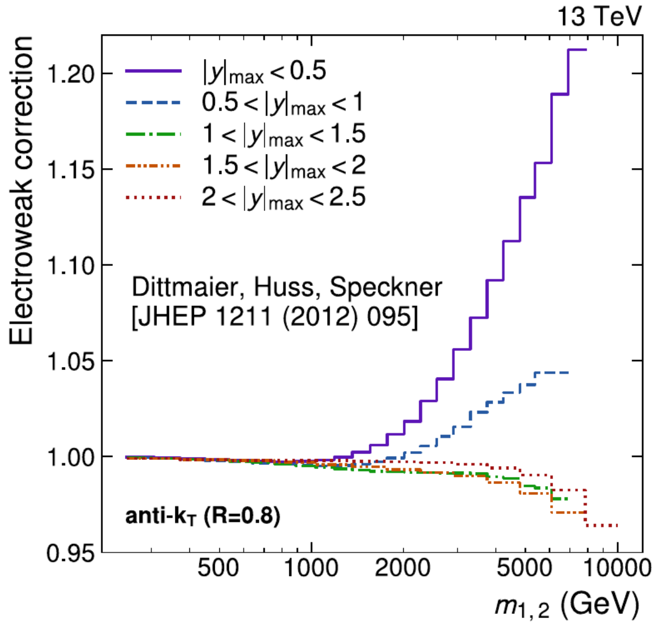
8 TeV





13 TeV





Numerical results

μ_R dependence

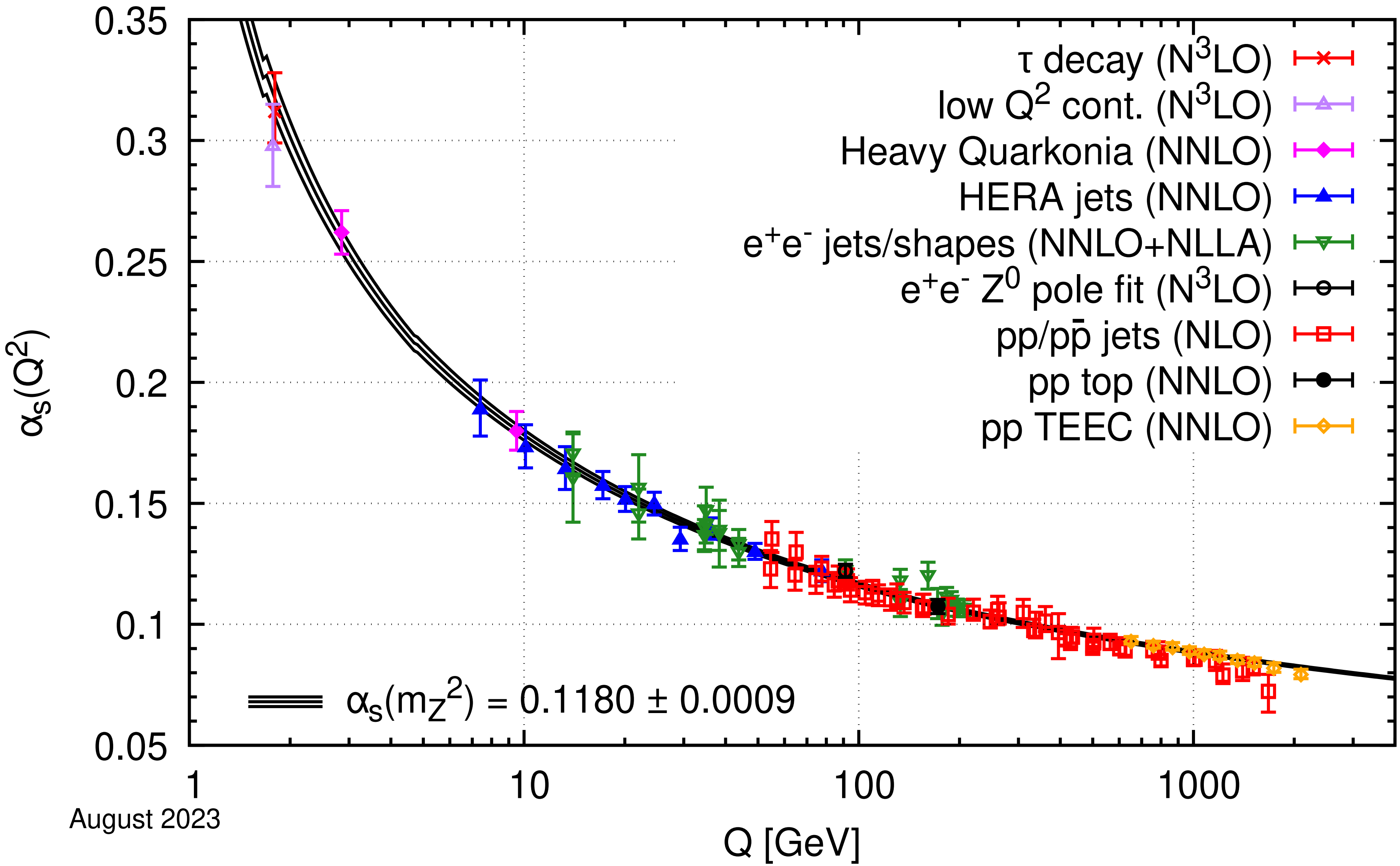
μ_R^{avg} [GeV]	$\alpha_s(m_Z)$	$\alpha_s(\mu_R)$
7.4	0.1214 (28) (1) (66)	0.2013 (82) (4) (196)
10.1	0.1207 (15) (1) (53)	0.1840 (37) (2) (130)
13.3	0.1171 (15) (0) (37)	0.1654 (31) (0) (77)
17.2	0.1151 (20) (0) (26)	0.1530 (36) (1) (47)
20.1	0.1160 (20) (1) (27)	0.1498 (34) (1) (46)
24.5	0.1159 (18) (0) (23)	0.1442 (29) (1) (37)
29.3	0.1175 (23) (0) (22)	0.1418 (33) (0) (32)
36.0	0.1171 (26) (0) (24)	0.1362 (35) (1) (33)
49.0	0.1157 (26) (1) (16)	0.1275 (31) (1) (20)
77.5	0.1105 (37) (3) (12)	0.1131 (39) (3) (12)
250	0.1180 (15) (1) (14)	0.1025 (11) (1) (11)
370	0.1181 (15) (1) (16)	0.0975 (10) (1) (11)
550	0.1174 (15) (1) (19)	0.0925 (9) (1) (12)
810	0.1173 (15) (2) (21)	0.0885 (9) (1) (11)
1175	0.1171 (16) (2) (23)	0.0848 (8) (1) (12)
1760	0.1171 (17) (2) (25)	0.0813 (8) (1) (12)
2545	0.1171 (18) (2) (27)	0.0783 (8) (1) (12)
3490	0.1171 (20) (2) (29)	0.0760 (8) (1) (12)
4880	0.1185 (31) (3) (34)	0.0742 (12) (1) (13)
7040	0.1232 (128) (12) (37)	0.0734 (43) (4) (13)

Correlations

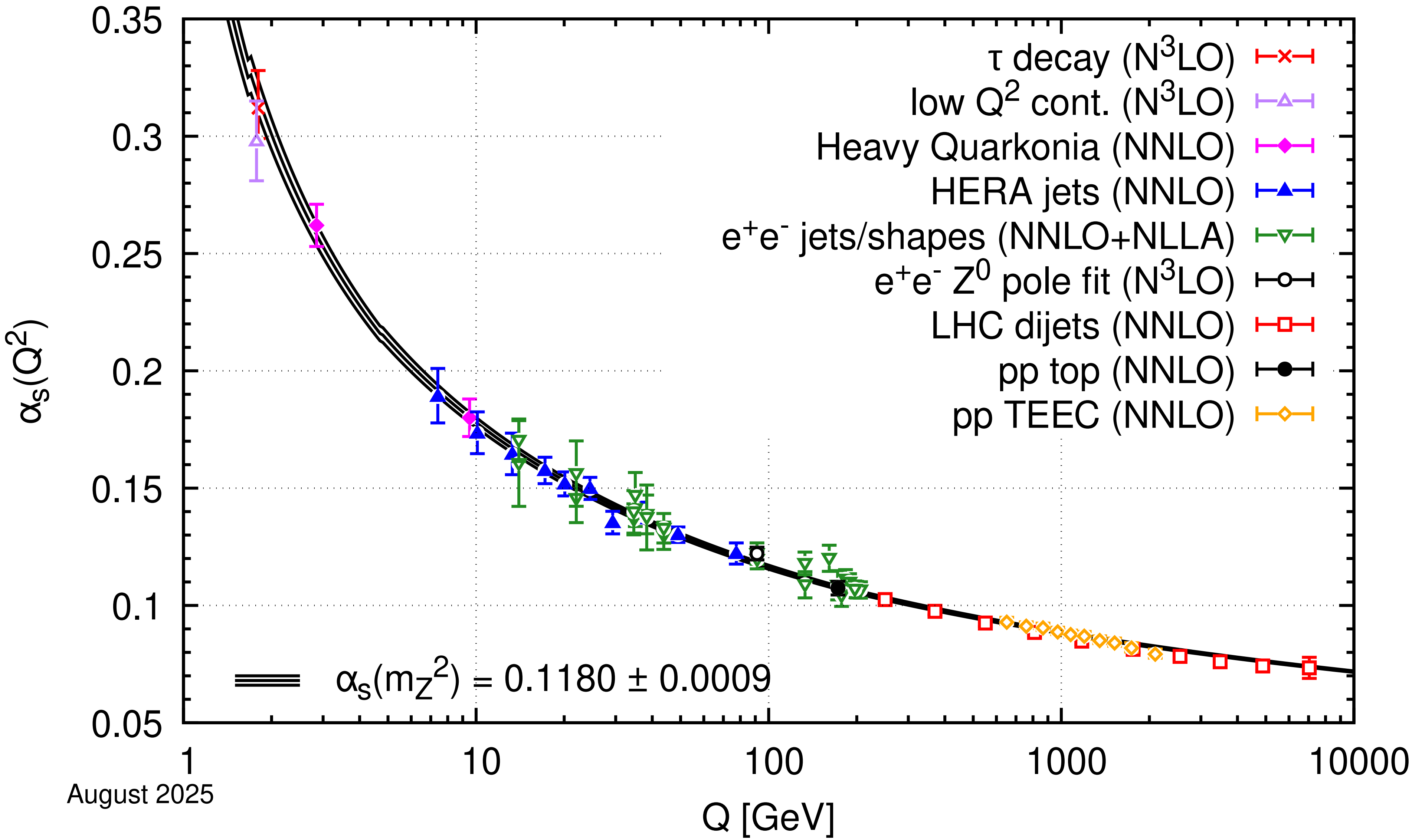
μ_R [GeV]	Correlations																			
7.4	–	56	29	21	19	22	15	17	16	12	2	1	-1	-2	-3	-3	-3	-3	-1	0
10.1	56	–	65	50	49	50	37	38	36	23	9	8	5	2	0	-2	-3	-3	-2	0
13.3	29	65	–	58	52	54	40	45	39	23	11	11	9	7	5	2	1	0	0	1
17.2	21	50	58	–	48	52	39	44	41	24	9	9	8	7	5	3	2	1	1	1
20.1	19	49	52	48	–	52	39	38	41	24	9	9	9	8	7	5	4	2	1	1
24.5	22	50	54	52	52	–	55	49	53	36	10	11	11	10	9	7	5	3	2	1
29.3	15	37	40	39	39	55	–	41	44	33	6	8	9	10	9	8	7	5	3	1
36.0	17	38	45	44	38	49	41	–	39	28	5	6	8	8	8	8	7	5	3	1
49.0	16	36	39	41	41	53	44	39	–	31	4	5	6	7	8	7	6	5	3	1
77.5	12	23	23	24	24	36	33	28	31	–		1	2	2	3	4	4	3	2	1
250	2	9	11	9	9	10	6	5	4	0	–	90	87	83	78	71	64	54	36	9
370	1	8	11	9	9	11	8	6	5	1	90	–	95	91	87	80	72	61	40	10
550	-1	5	9	8	9	11	9	8	6	2	87	95	–	97	93	88	80	67	45	11
810	-2	2	7	7	8	10	10	8	7	2	83	91	97	–	97	93	86	74	49	12
1175	-3	0	5	5	7	9	9	8	8	3	78	87	93	97	–	97	92	80	55	14
1760	-3	-2	2	3	5	7	8	8	7	4	71	80	88	93	97	–	96	87	62	17
2545	-3	-3	1	2	4	5	7	7	6	4	64	72	80	86	92	96	–	92	70	21
3490	-3	-3	0	1	2	3	5	5	5	3	54	61	67	74	80	87	92	–	78	27
4880	-1	-2	0	1	1	2	3	3	3	2	36	40	45	49	55	62	70	78	–	30
7040	0	0	1	1	1	1	1	1	1	1	9	10	11	12	14	17	21	27	30	–

TABLE V. Correlations of the (fit,PDF) uncertainty from the fit of 20 $\alpha_s(m_Z)$ parameters to HERA and LHC dijet data.

PDG 2023 α_s running



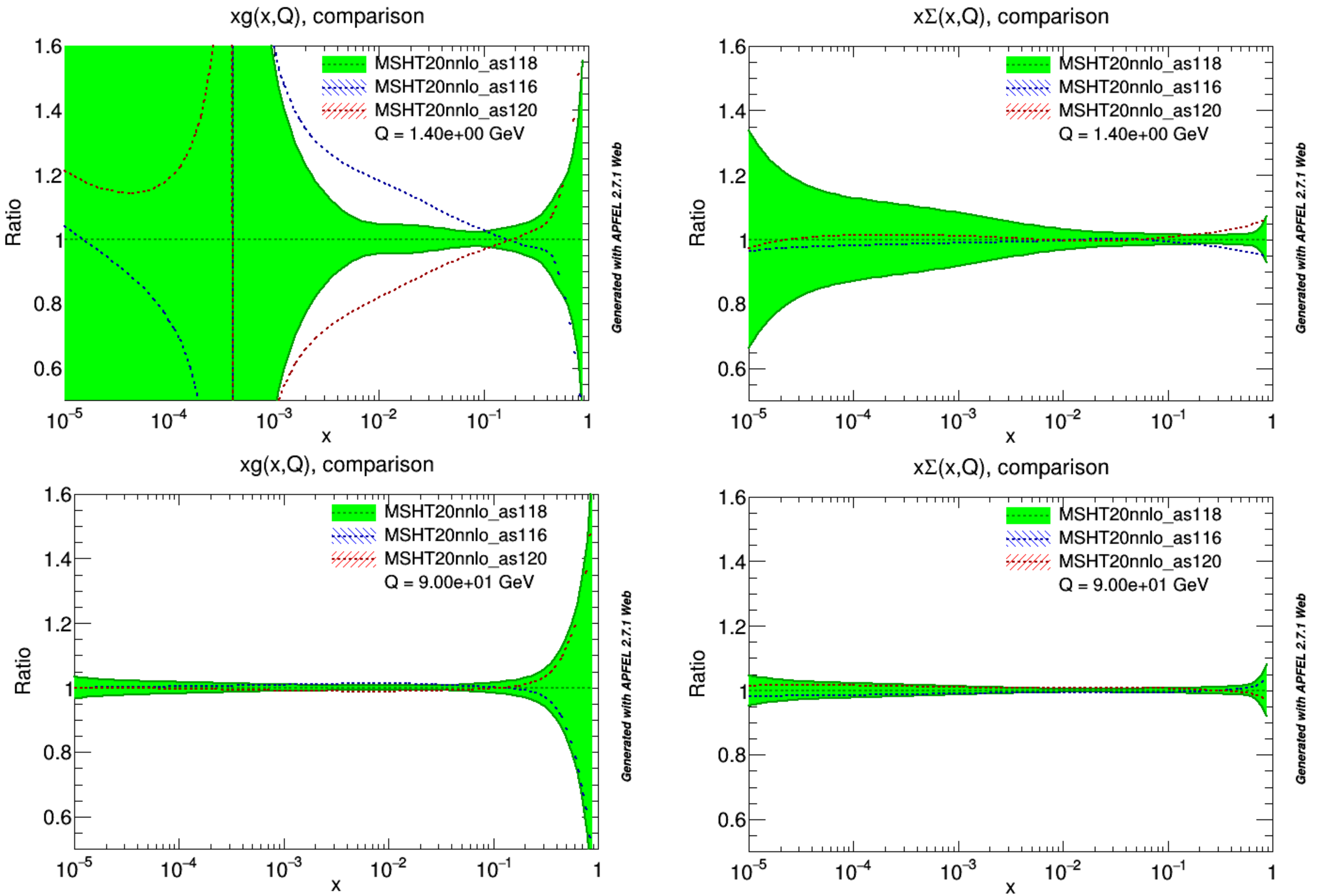
PDG 2025 α_s running



PDF dependence

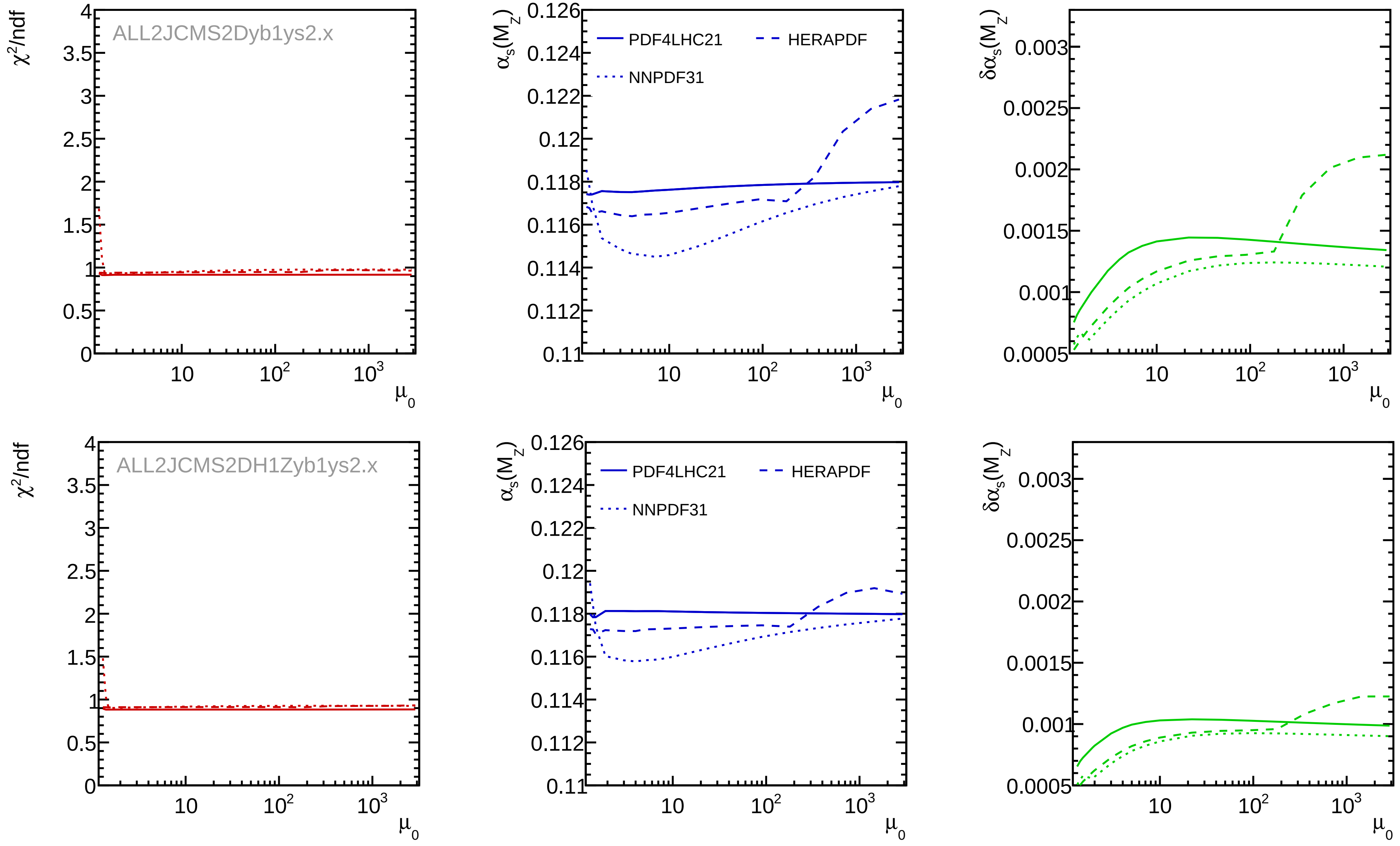
μ_F = 1.4 GeV

μ_F = 90 GeV

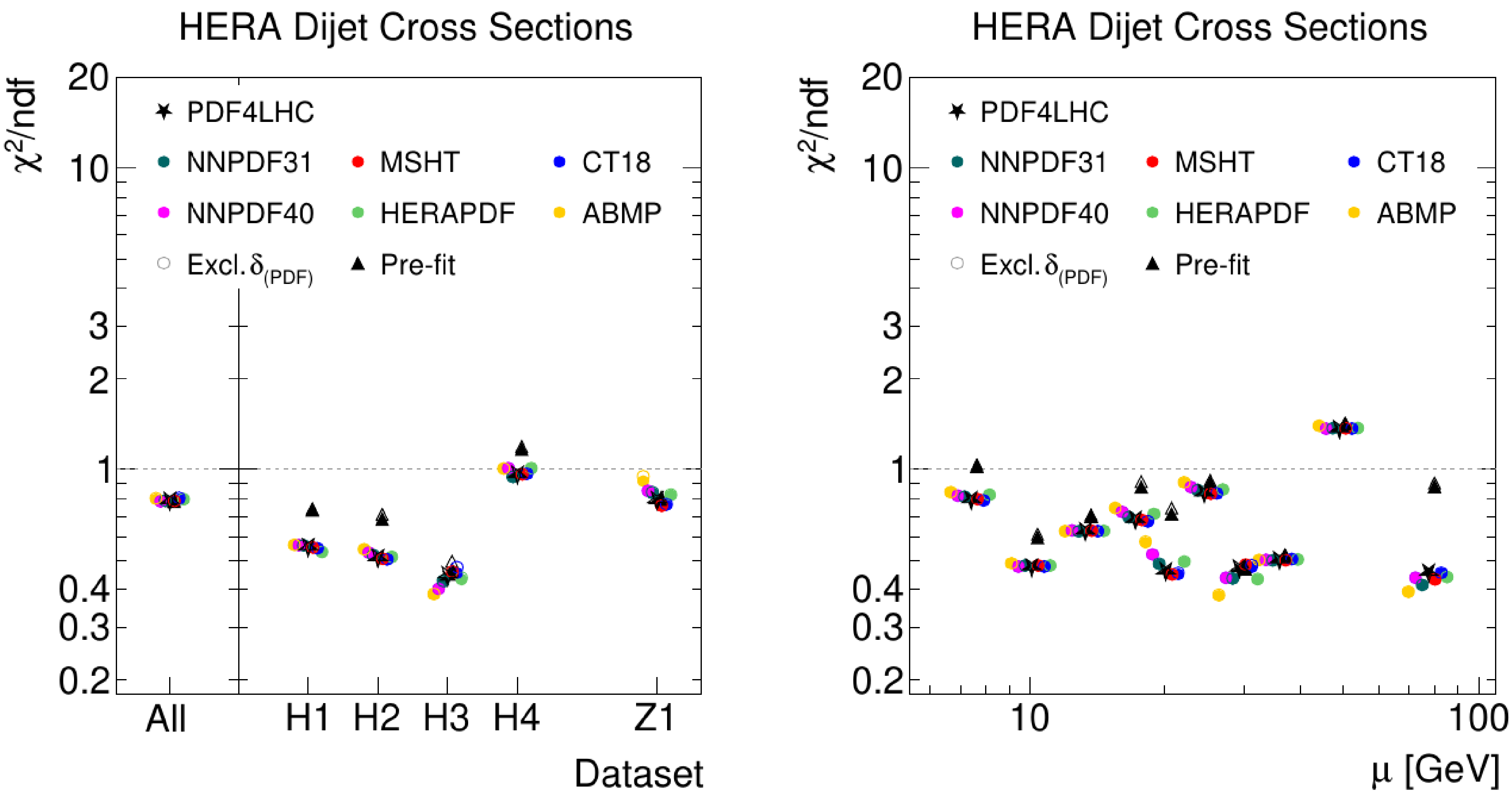


μ_0 dependence

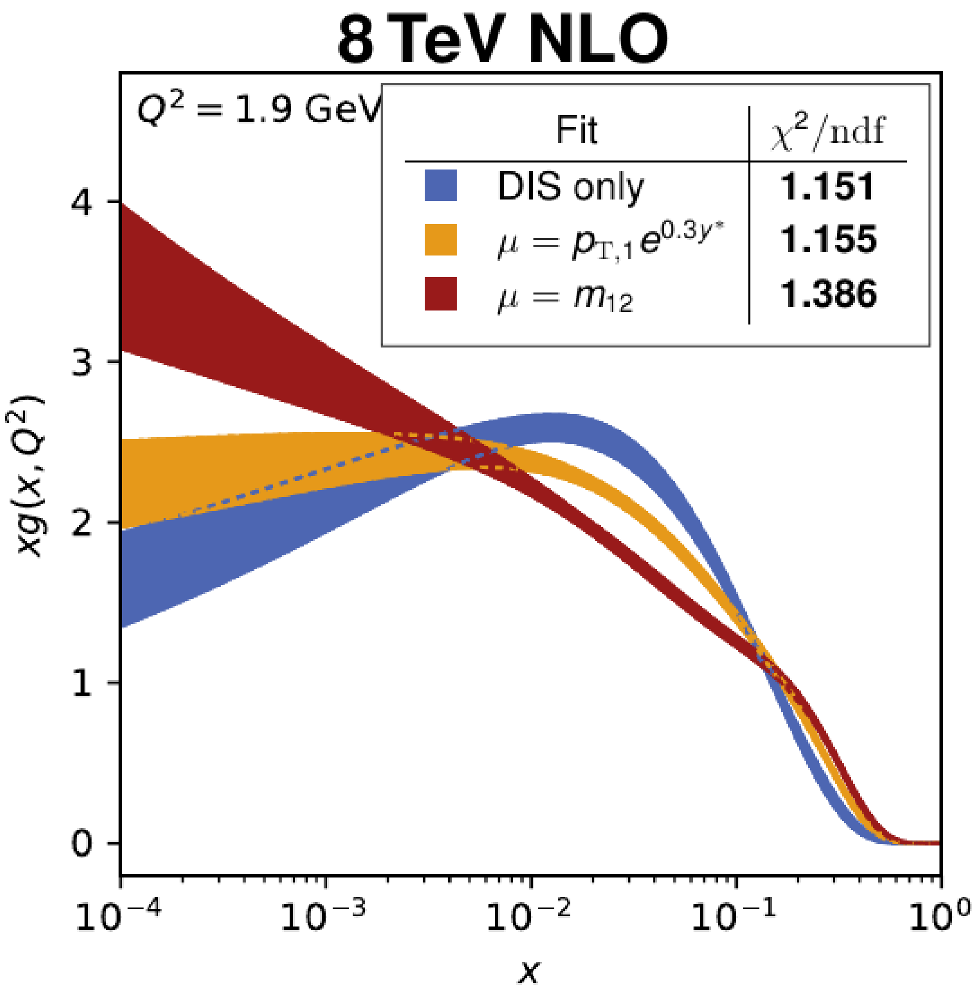
(Extreme) Variation of μ_F starting scale μ_0

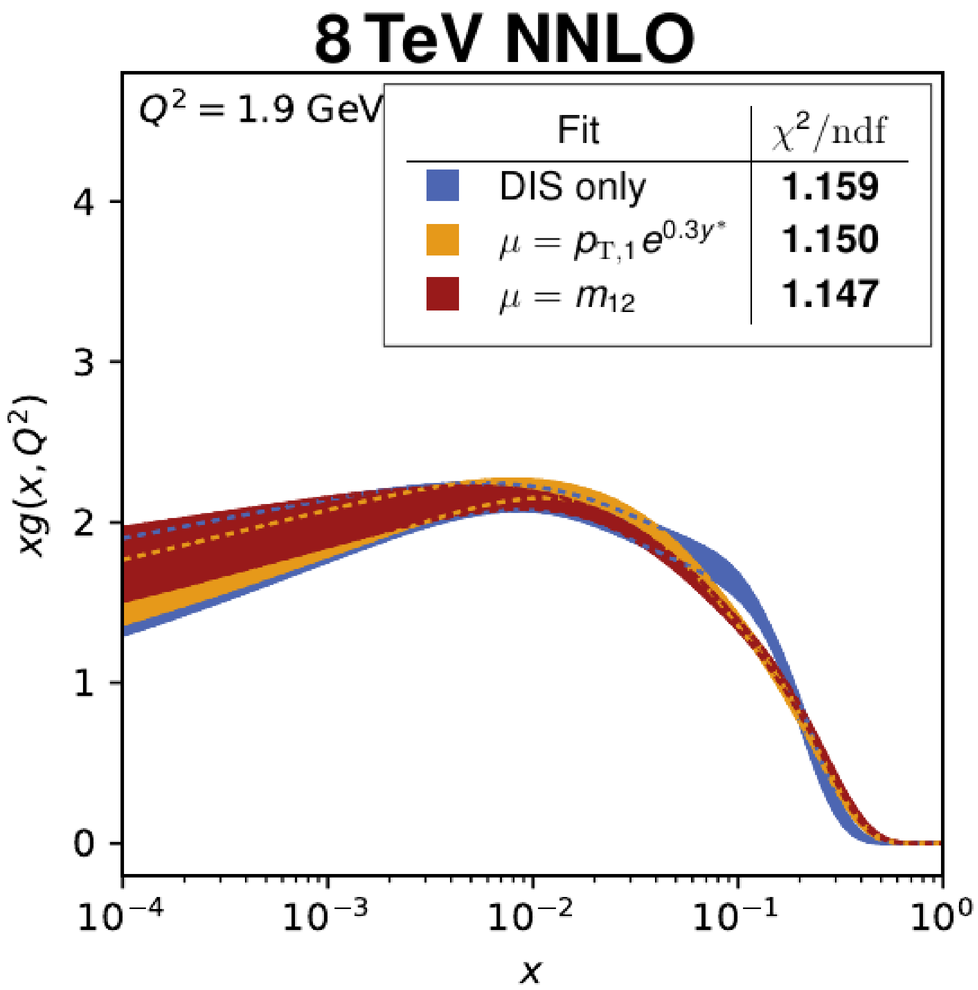


Consistency study for HERA data



PDF only fit: NLO vs. LC-NNLO

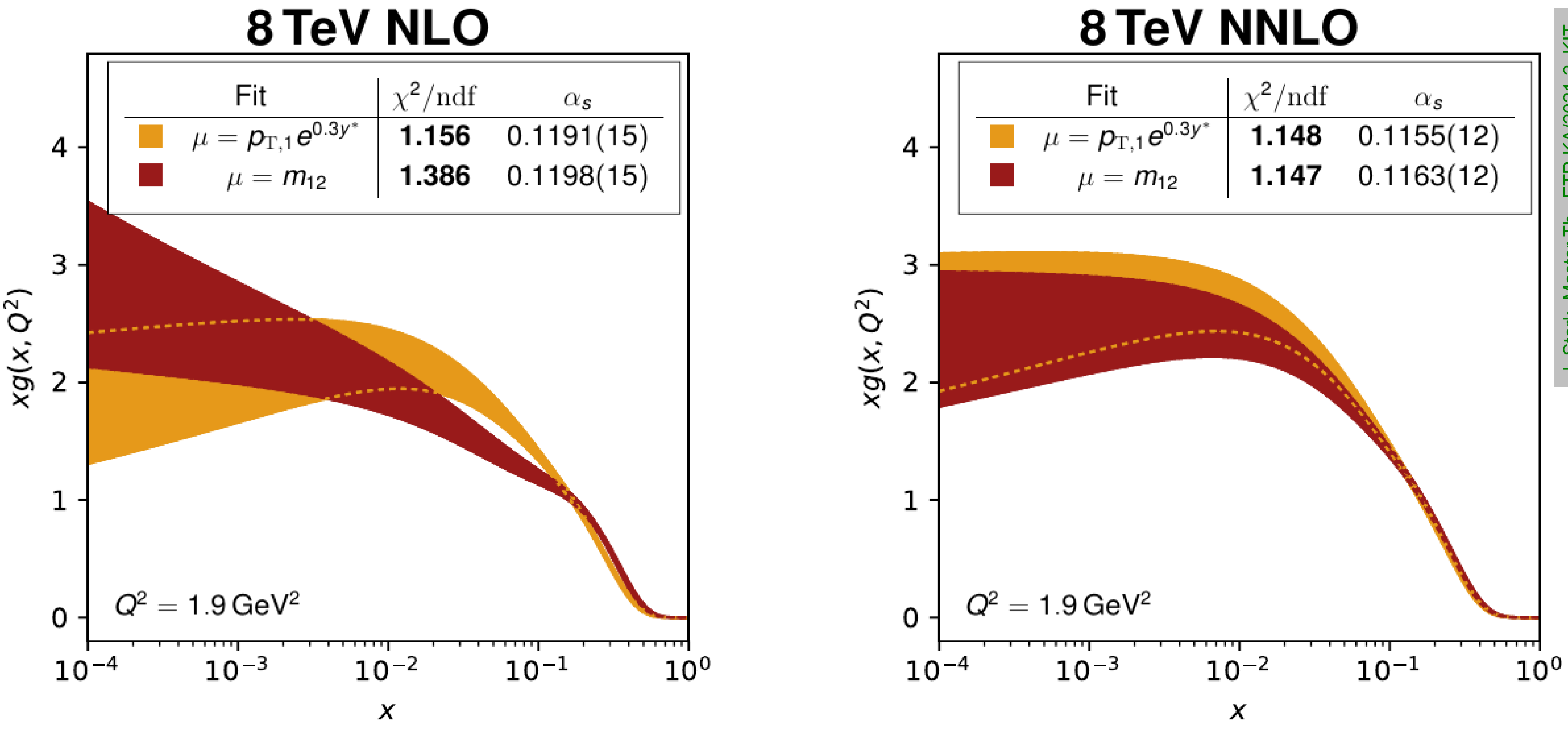




- NLO: significant differences between scales (ptmax vs. dijet mass)
- NNLO: both central scales agree very nicely
- m_{12} scale definition much smaller χ^2 in NNLO

From J. Stark, Master Thesis ETP-KA/2021-2, KIT.
Presented at CERN Theory Workshop, KR, May 2025.

PDF+α_s fit: Only exp. uncertainty



J. Stark, Master Th., ETP-KA/2021-2, KIT.

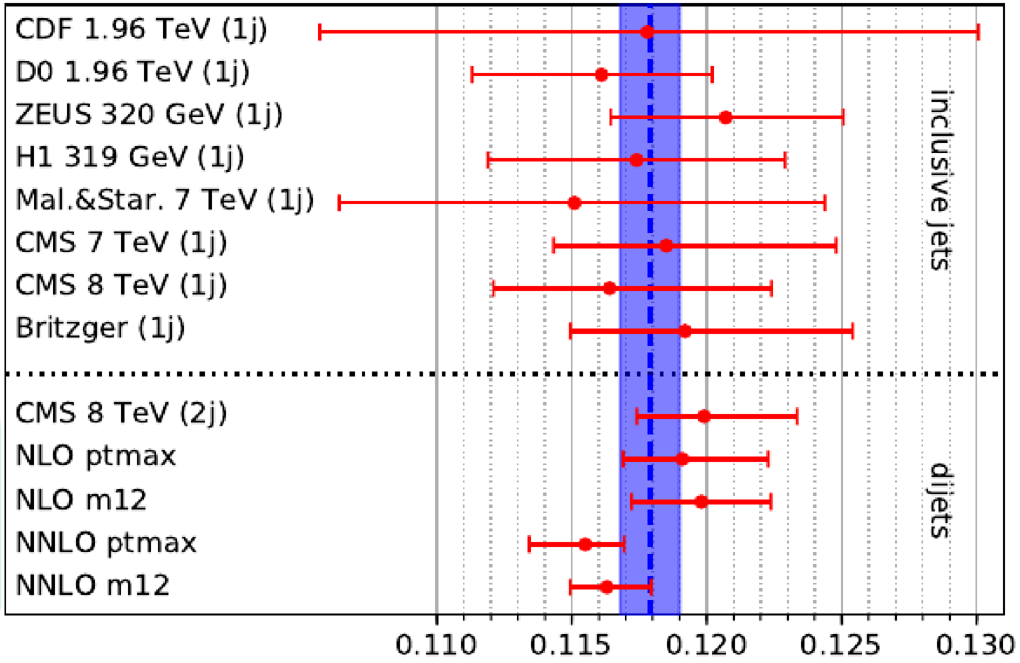
- no scale uncertainties shown here
- larger exp. uncertainty due to correlation of gluon PDF with α_s
- as before nice agreement between different scales at NNLO

PDF+α_s fit: Exp. & scale uncertainty

Fitted $\alpha_s(M_Z)$ values

NLO	$\mu = p_{T,1} e^{0.3y^*}$	$0.1191 \pm 0.0015(\text{exp})^{+0.0028}_{-0.0016}(\text{scale})$
	$\mu = m_{12}$	$0.1198 \pm 0.0015(\text{exp})^{+0.0021}_{-0.0021}(\text{scale})$
NNLO	$\mu = p_{T,1} e^{0.3y^*}$	$0.1155 \pm 0.0012(\text{exp})^{+0.0008}_{-0.0017}(\text{scale})$
	$\mu = m_{12}$	$0.1163 \pm 0.0013(\text{exp})^{+0.0010}_{-0.0004}(\text{scale})$

⚠ Only experimental and scale uncertainties



Comparison with other values obtained from jet cross sections and the world average (blue)

- as expected, smaller α_s values at NNLO
- scale uncertainties: maximal envelope of 6 scale variations
- experimental and especially scale uncertainties smaller at NNLO

Remark: It was not aimed for a new, fully flexible fit with xfitter
→ no parameterisation or model uncertainties.

J. Stark, Master Th., ETP-KA/2021-2, KIT.