PDF + α_s fits using the CMS dijet data from LHC Run 1

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(performed within the APPLfast project)

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References 1

- **All results are from:**
  - **Jakob Stark's Master thesis:** ETP-KA/2021-2, KIT, Feb. 2021.
  - https://publish.etp.kit.edu/record/22044
- **Starting point:**
  - **Georg Sieber's PhD thesis:** IEKP-KA/2016-05, KIT, May 2016.
  - https://publish.etp.kit.edu/record/21328
- **CMS data:**
  - **Dijet production at 8 TeV:** SMP-16-011, EPJC 77 (2017) 746, arXiv:1705.02628.
  - **Dijet production at 7 TeV:** QCD-11-004, PRD 87 (2013) 112002, arXiv:1212.6660.
- **Theory input:**
  - **NNLOJET:** T. Gehrmann et al., RADCOR2017, PoS (2018) 074, arXiv:1801.06415.
  - **Dijets @ NNLO:** J. Currie et al., PRL 119 (2017) 152001, arXiv:1705.10271;
    A. Gehrmann-de Ridder et al., PRL 123 (2019) 102001, arXiv:190509047.
  - **EWK corrections:** S. Dittmaier et al., JHEP 11 (2012) 095, arXiv:1210.0438.

References 2

- **Essential tools:**
  - APPLfast interface: D. Britzger et al., EPJC 79 (2019) 845, arXiv:1906.05303.
  - fastNLO: D. Britzger et al., Proc. DIS2012 (2012) 217, arXiv:1208.3641.
  - APPLgrid: T. Carli et al., EPJC 66 (2010) 503, arXiv:0911.2985.
  - xfitter: S. Alekhin et al., EPJC 75 (2015) 304, arXiv:1410.4412.

Overview

Goals

- reproduce fitted results of G. Sieber[1] from CMS 8 TeV 3D dijet data with new version of xFitter and new theory program NNLOJET
- new theory calculations at NNLO and with an alternative scale definition (NNLOJET) for 3D dijets at 8 TeV
- simultaneous PDF and α_s fits at NNLO
- inclusion of CMS 2D dijet data at 7 TeV

include HERA1+2 combined inclusive DIS datasets into all fits

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

PDF parameterisation

A HERAPDF-like parametrization is used

Here: No negative gluon term
CMS: With negative gluon term

13-parameter fit (G. Sieber)

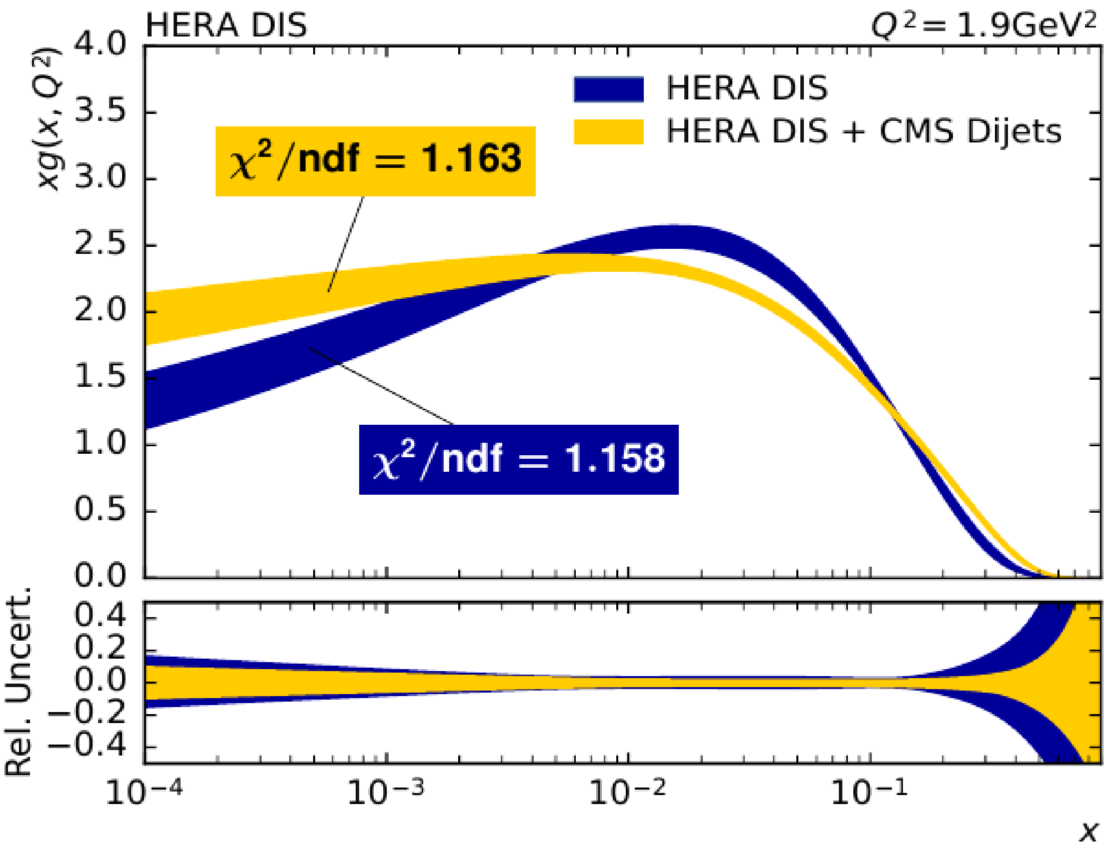
$$xg(x) = A_g\, x^{B_g}\, (1-x)^{C_g}\, (1 + E_g x^2)$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + D_{u_v} x)$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}}$$
$$x\bar{U}(x) = A_{\bar{U}}\, x^{B_{\bar{U}}}\, (1-x)^{C_{\bar{U}}}\, (1 + D_{\bar{U}} x)$$
$$x\bar{D}(x) = A_{\bar{D}}\, x^{B_{\bar{D}}}\, (1-x)^{C_{\bar{D}}}$$

$$f_s = 0.40$$

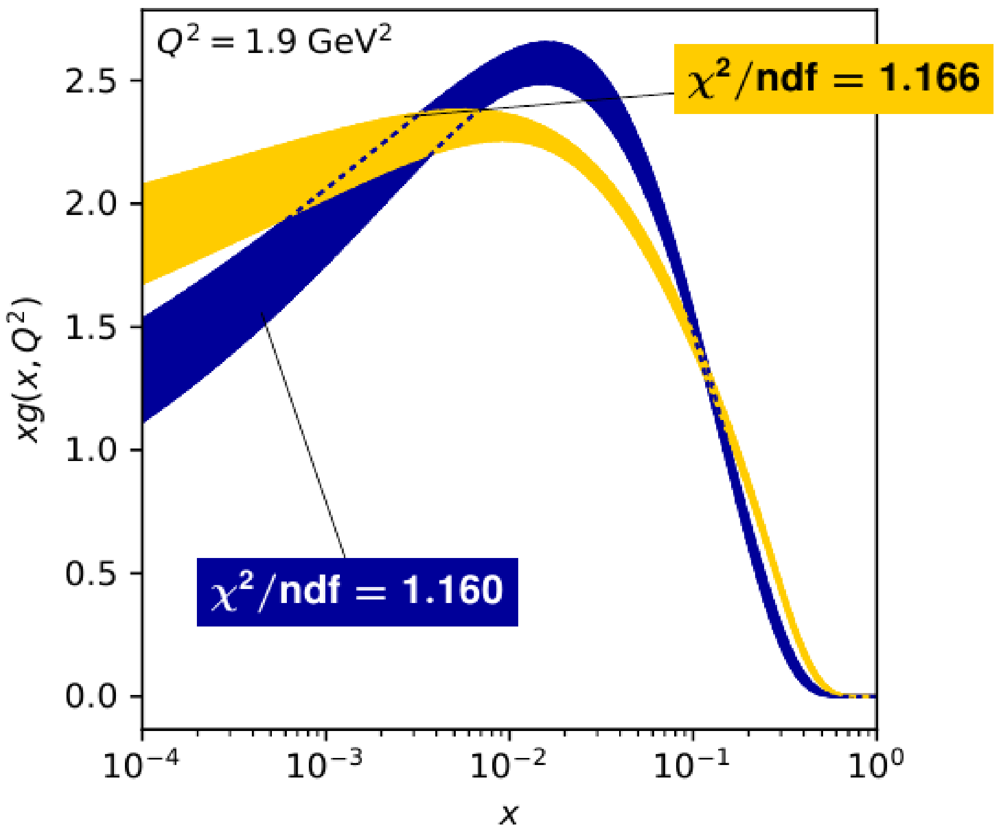
- uncolored A and $B_{\bar{U}}$ parameters are fixed by constraints
- use HERAPDF20 NNLO parameters as start values for DIS only fit
- use DIS only fit as start for fits with jet data included

Reproduction fits

original (G. Sieber 2016)



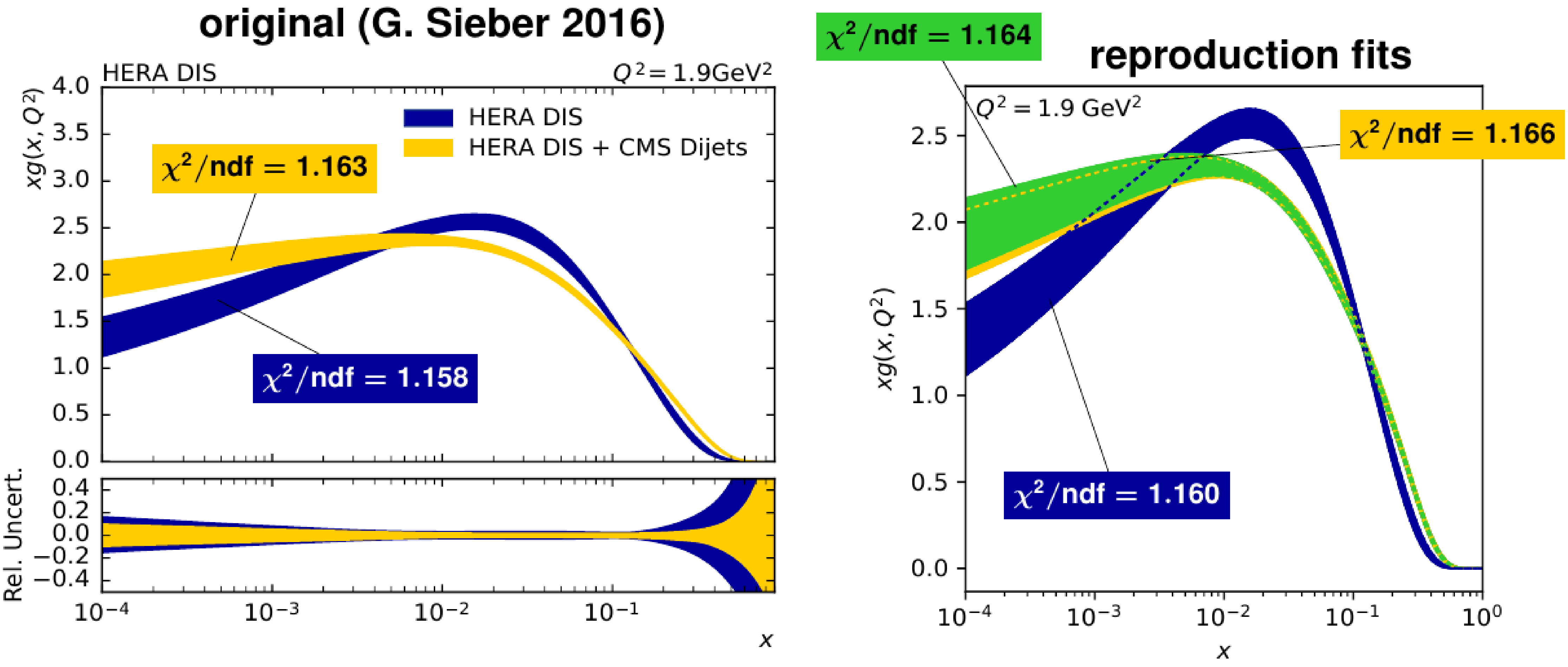
reproduction fits



✓ fit reproducible (yellow left vs. right)

⚠ Only experimental uncertainties

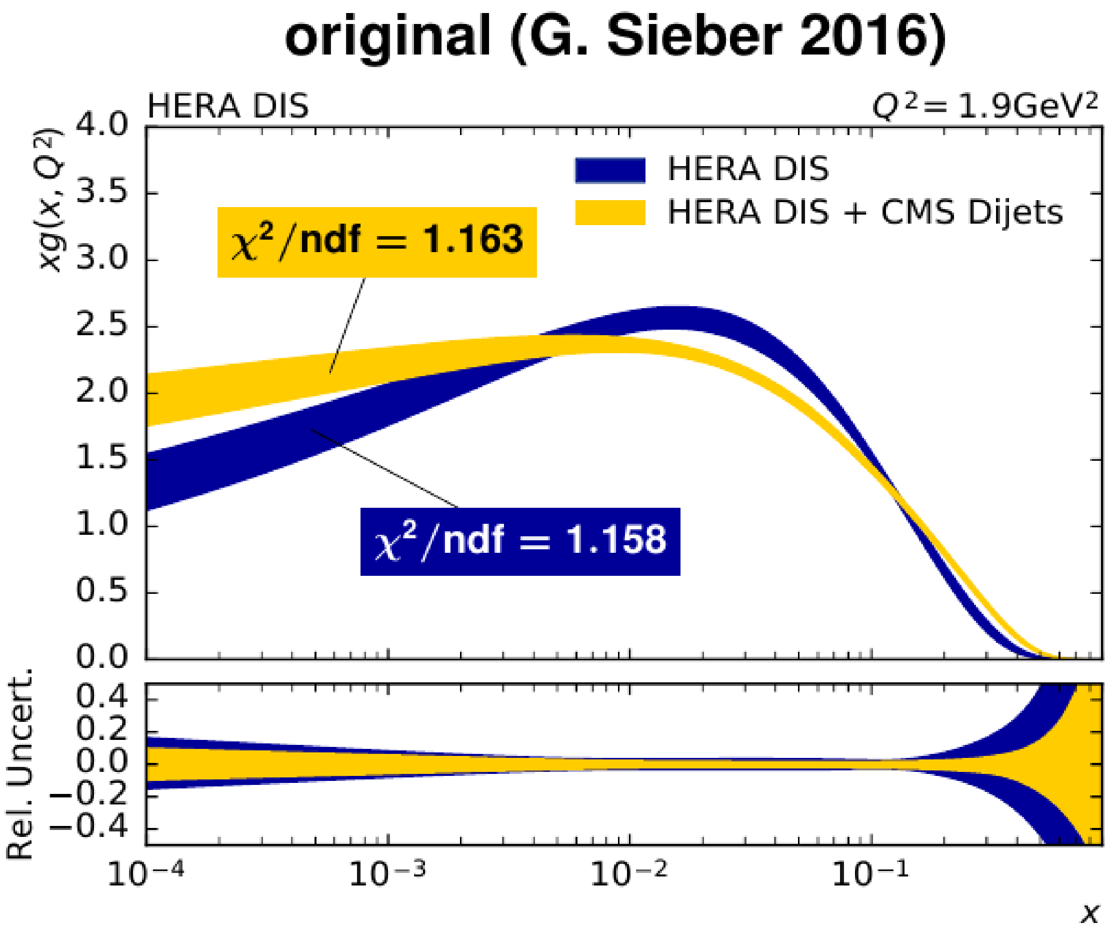
Reproduction fits

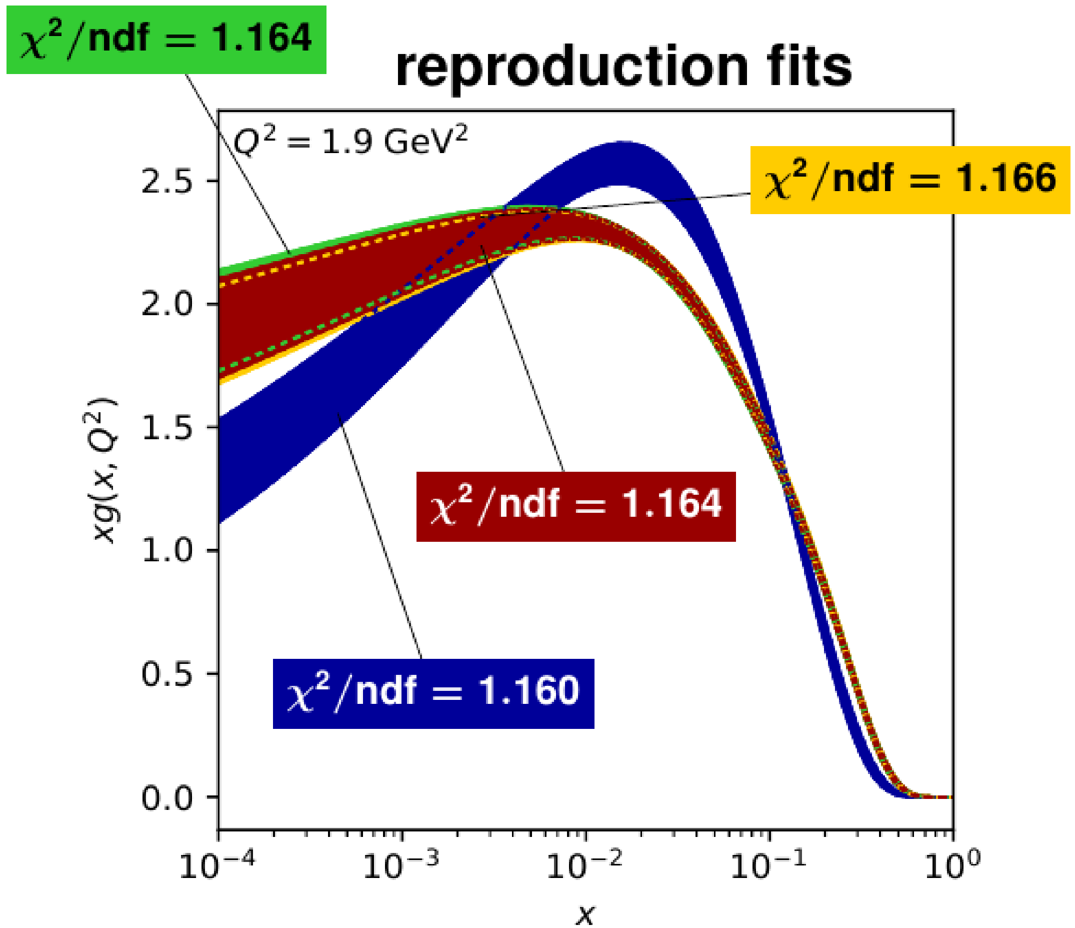


⚠ Only experimental uncertainties

- ✓ fit reproducible (yellow left vs. right)
- ✓ only small change if including EW corrections and final uncertainties

Reproduction fits





⚠ Only experimental uncertainties

- ✓ fit reproducible (yellow left vs. right)
- ✓ only small change if including EW corrections and final uncertainties
- ✓ good agreement between different NLOJET++ and NNLOJET

Scale choices

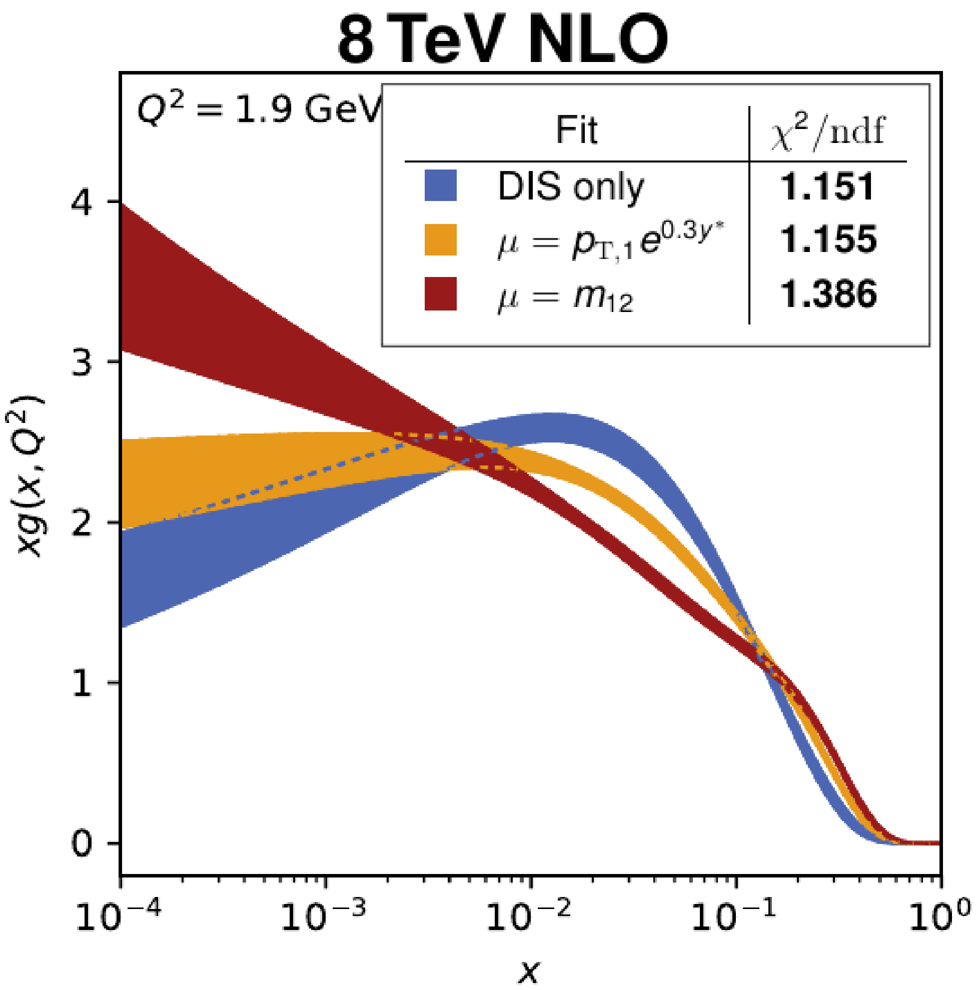
Produced new fastNLO grids filled from NNLOJET via APPLfast:
→ no fixed K factors

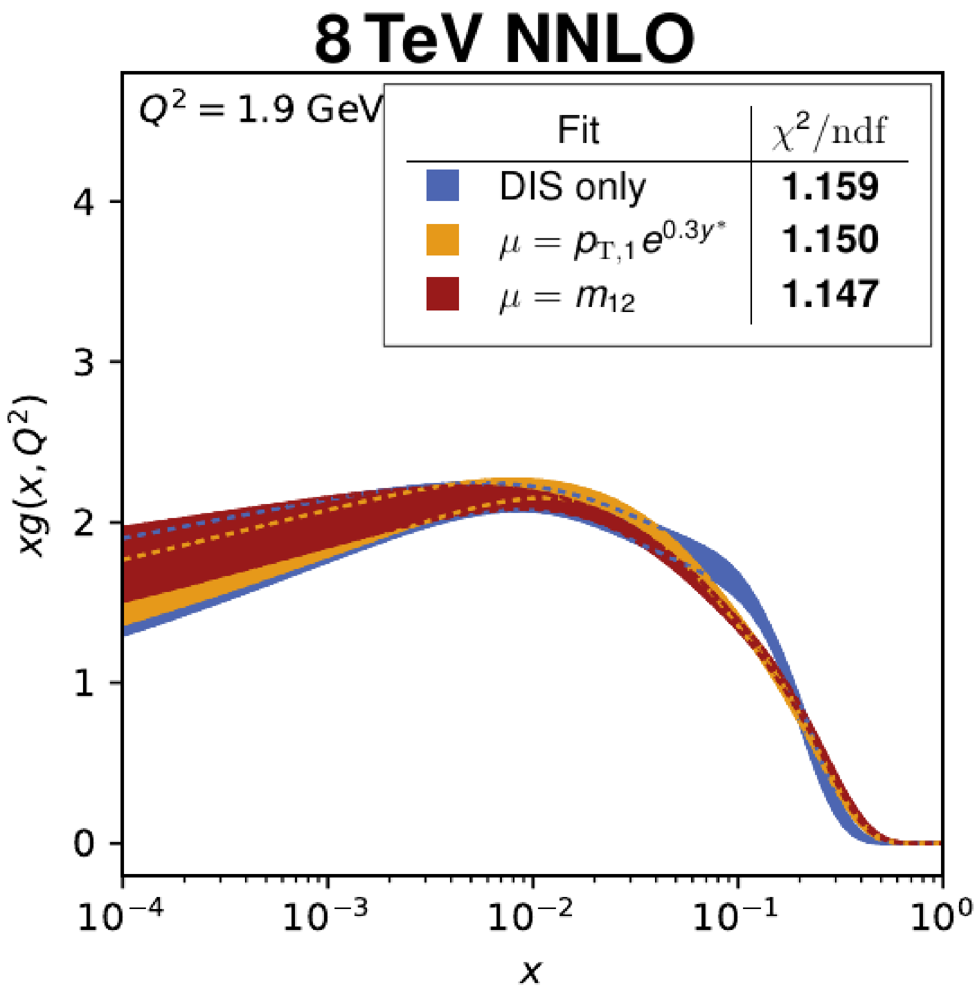
- contain NNLO contribution
- can change central scale definition between

$\mu = p_{\mathrm{T},1} e^{0.3y^*}$	"ptmax"	(used previously)
$\mu = m_{12}$	"m12"	(recommended by theory)

- in the following, increase DIS Q^2 cut from 7.5 to 10 GeV^2 (also recommended by theory)

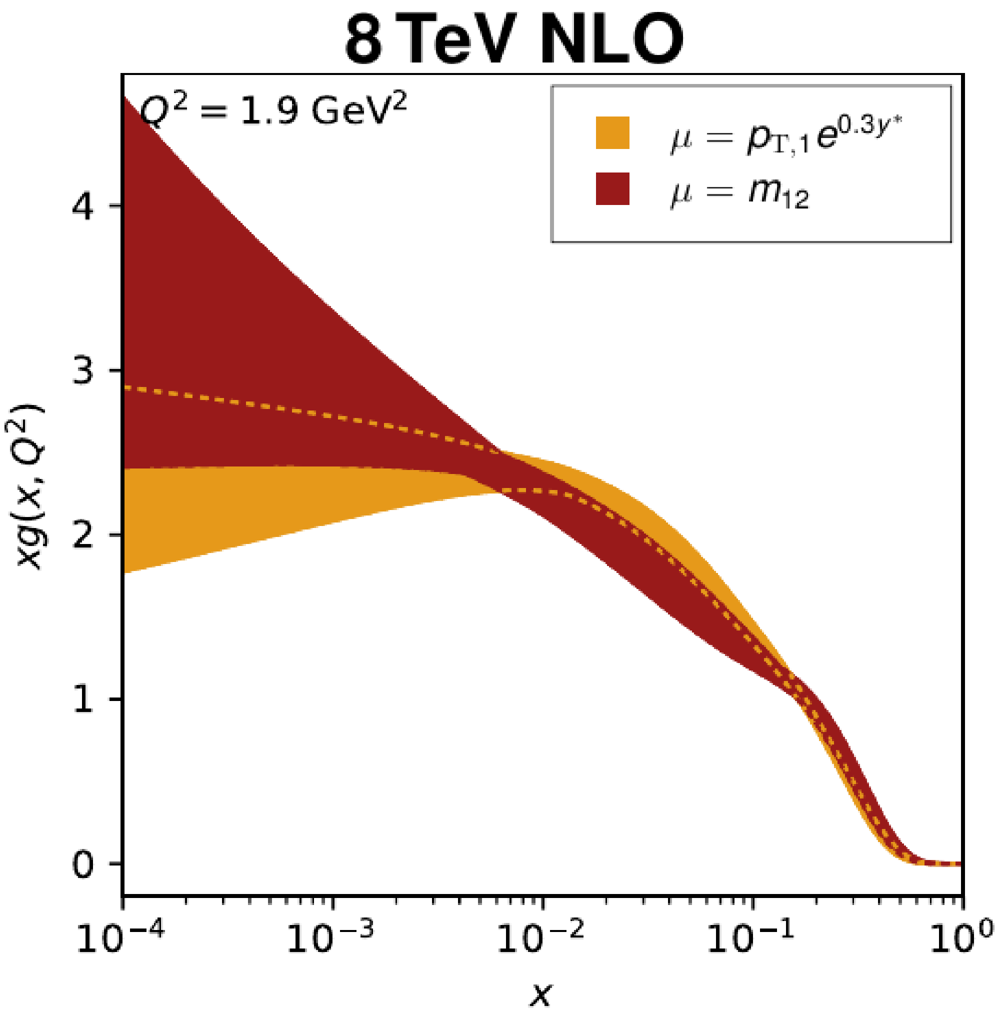
13 parameter fits – NLO vs. NNLO

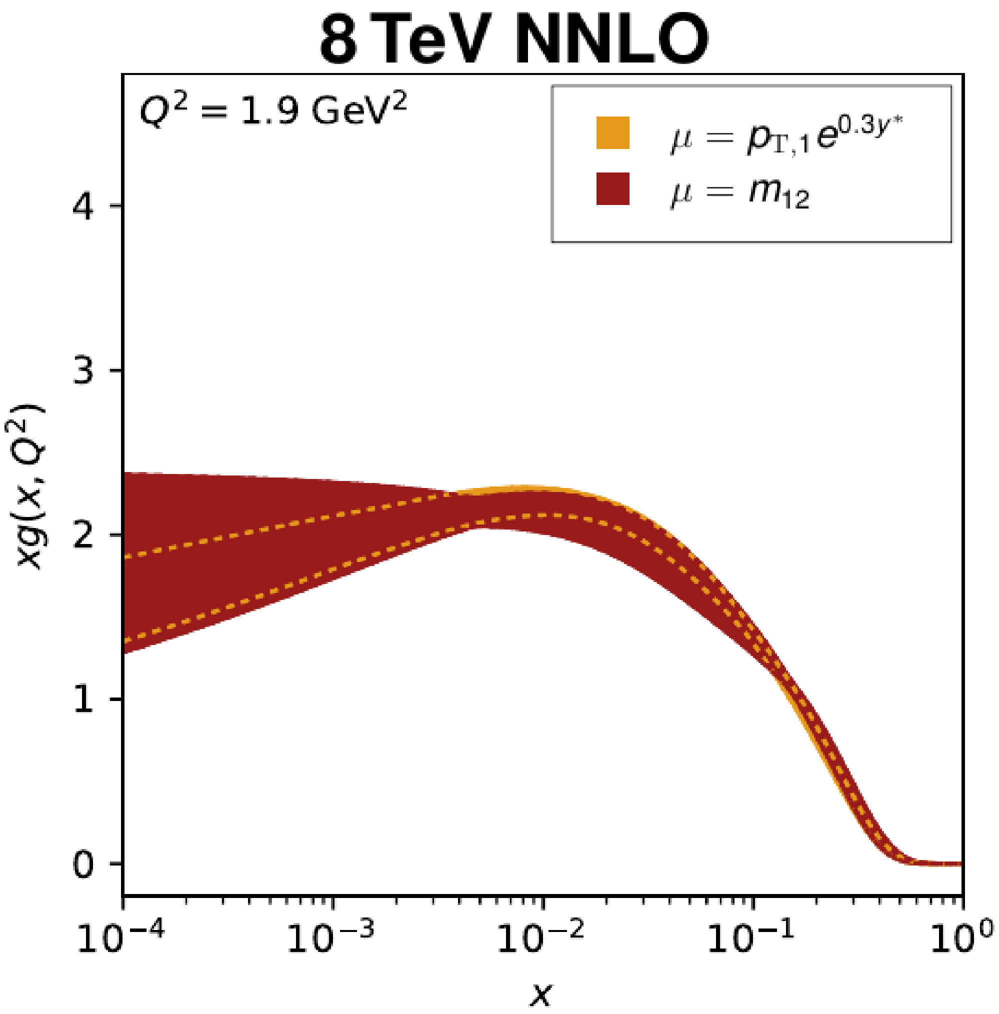




- NLO: significant differences between scales (ptmax vs. dijet mass)
- NNLO: both central scales agree very nicely
- m_{12} scale definition much smaller χ^2 in NNLO

Adding scale uncertainties

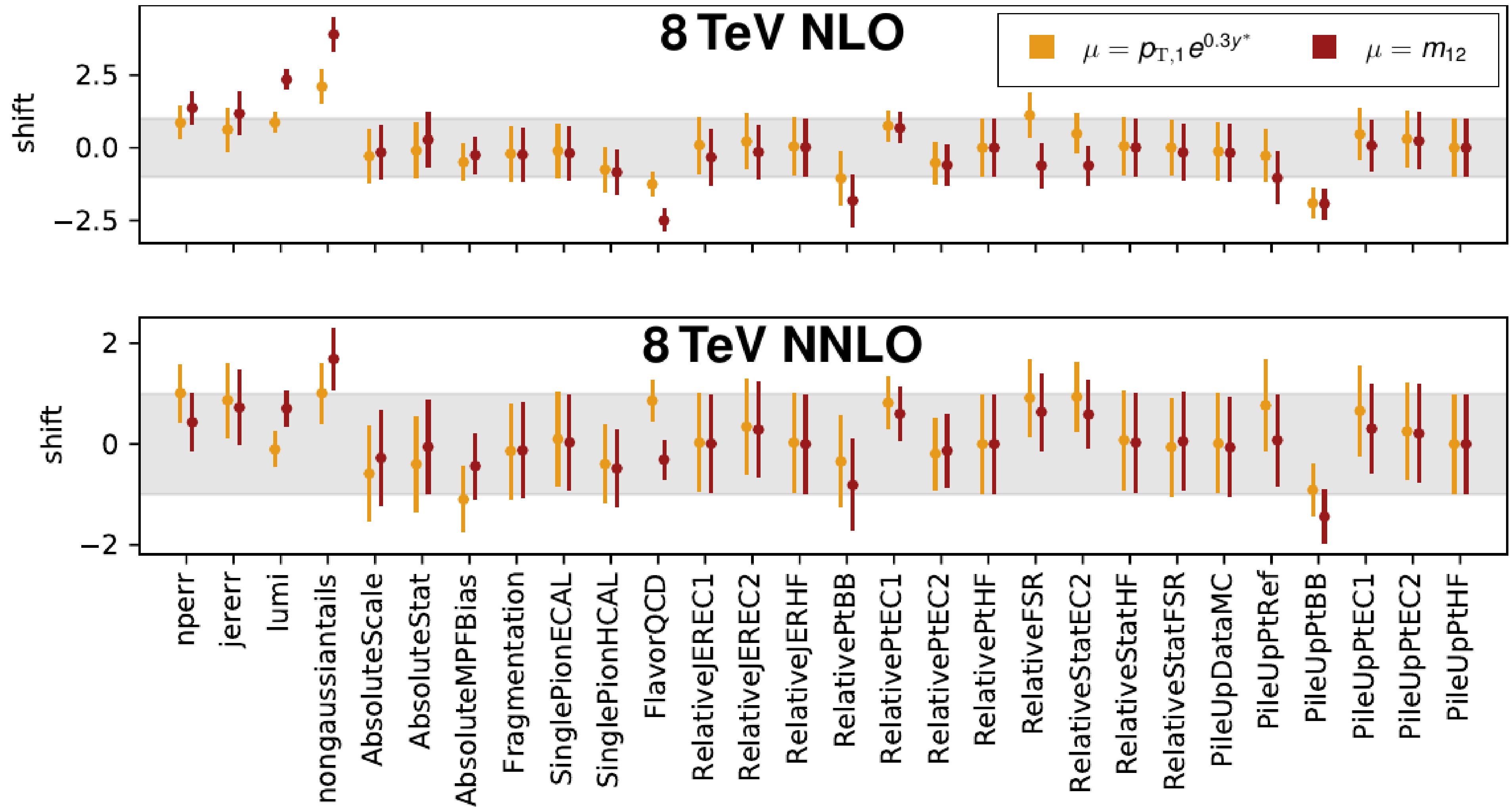




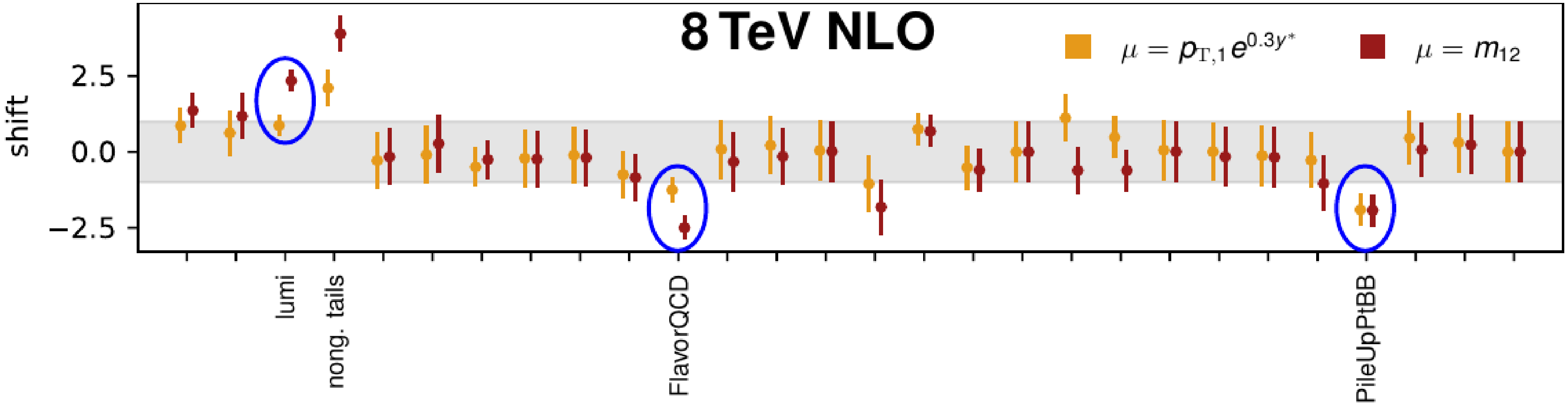
- maximum envelope of 6 scale variations[2]
- scale variation uncertainty considerably smaller in NNLO

[2] The bands show the combined scale and experimental uncertainties

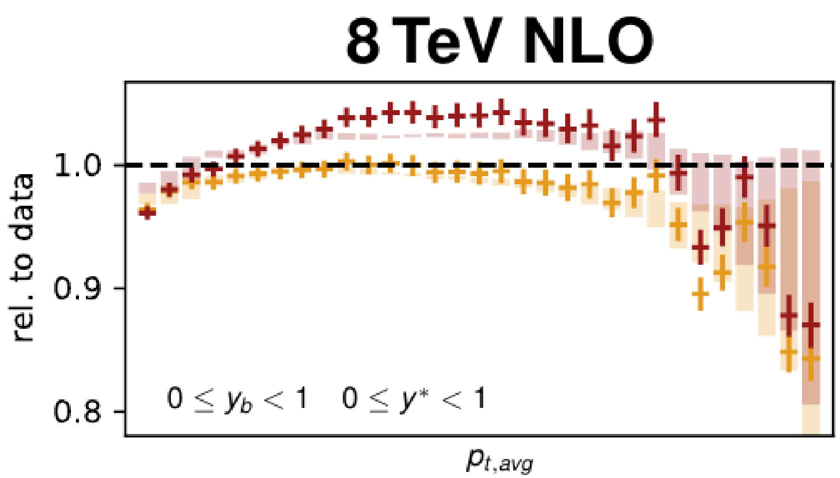
Pulls of fitted nuisance parameters



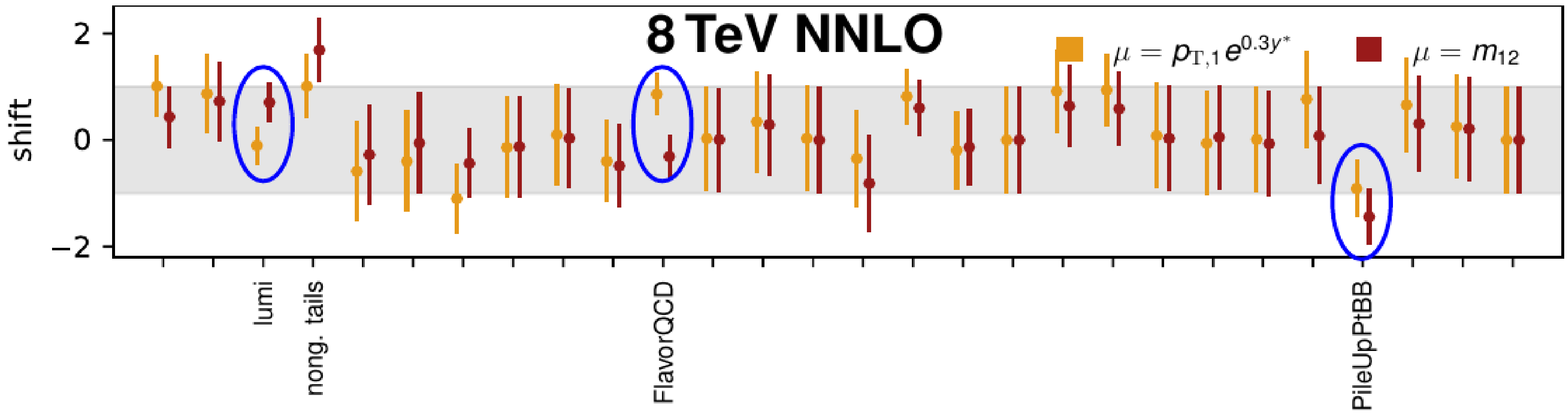
Pulls of fitted nuisance parameters



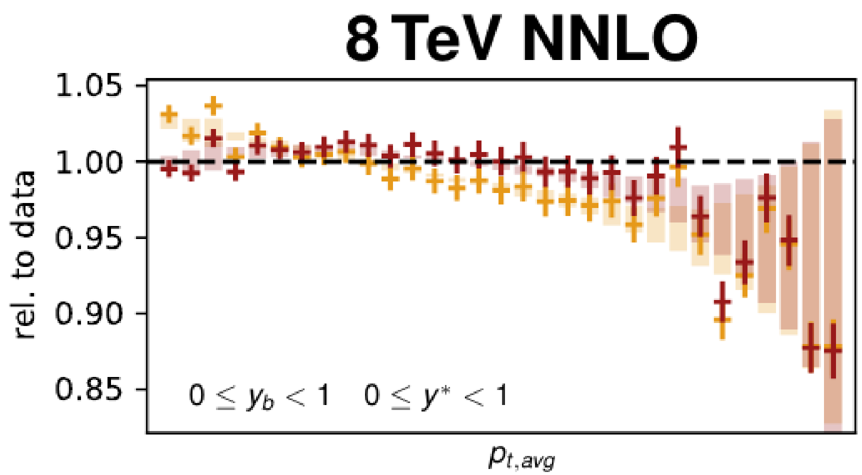
- curved distortion between prediction (crosses) and central data (black line)
- data is shifted towards predition (transparent bars)
- outliers in shifts produce distortion, lumi globally shifts data



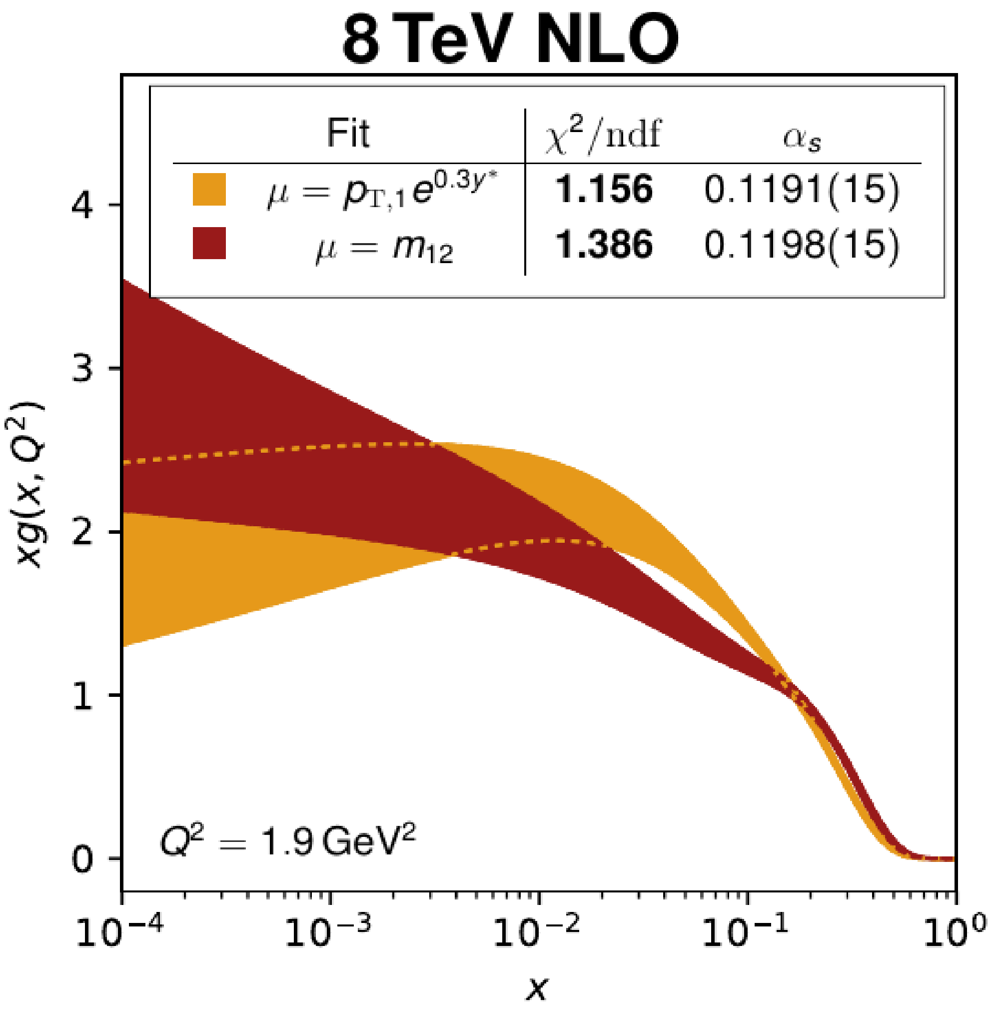
Pulls of fitted nuisance parameters

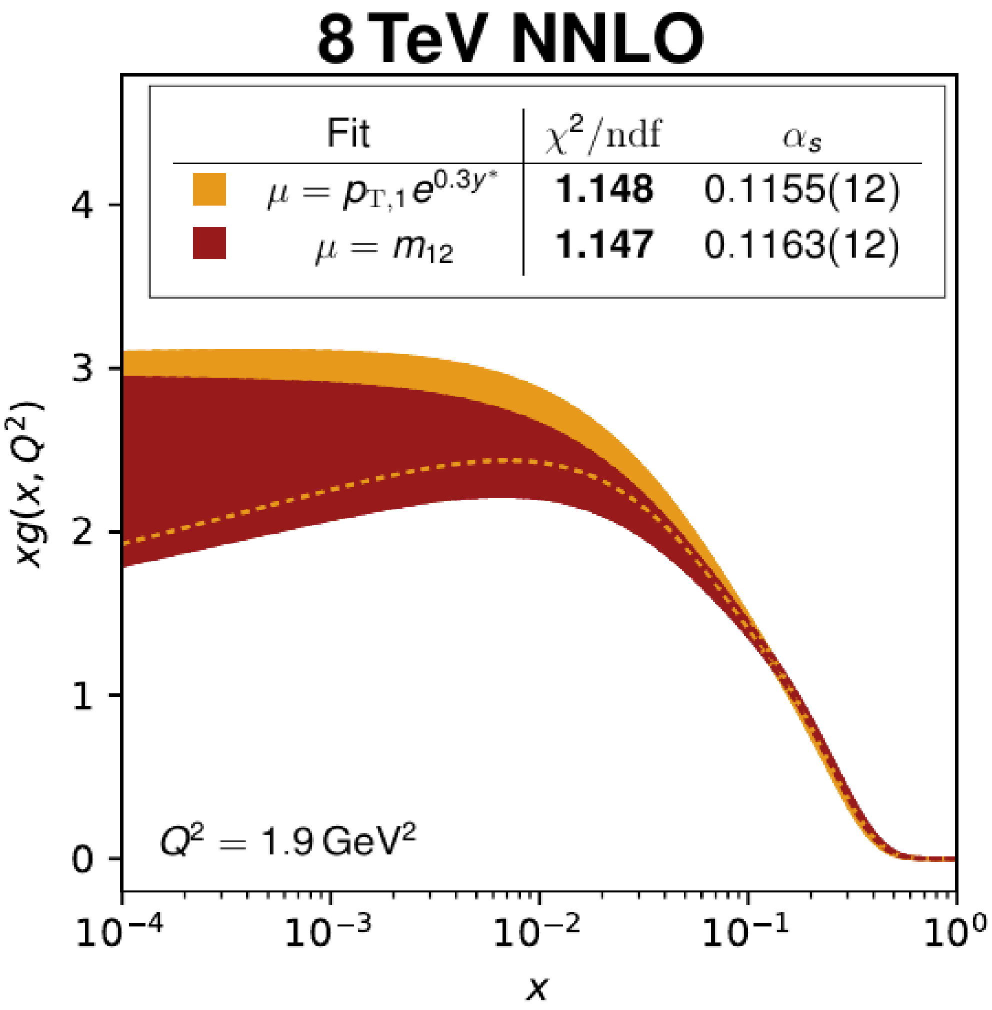


- curved distortion drastically reduced in NNLO
- previous outliers in shifts almost back in the gray 1-sigma region



Simultaneous PDF + α_s fits





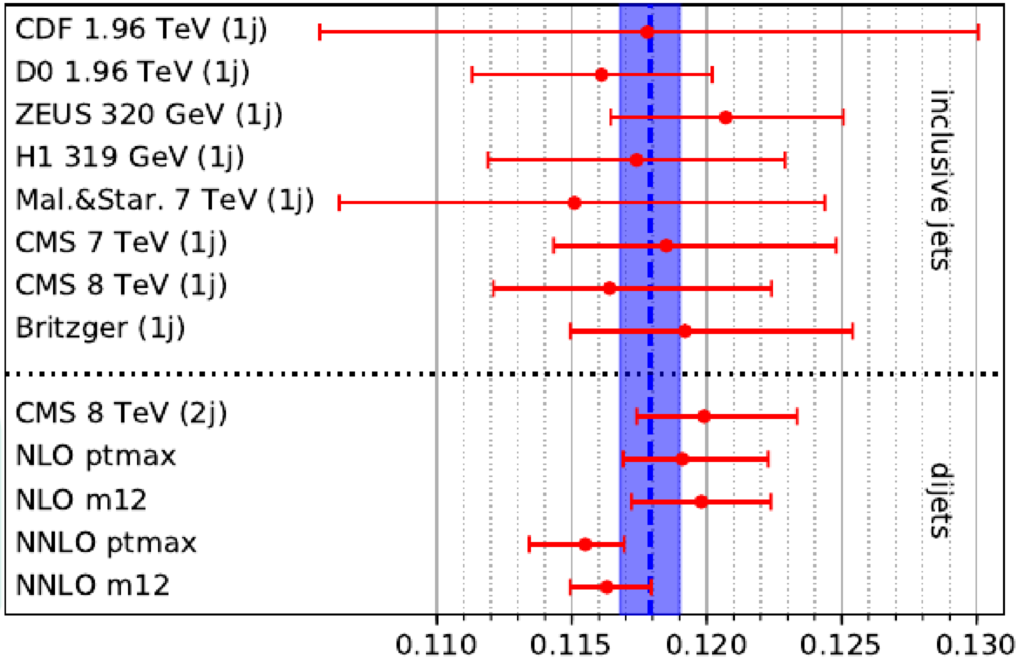
- no scale uncertainties shown here
- larger exp. uncertainty due to correlation of gluon PDF with α_s
- as before nice agreement between different scales at NNLO

Fitted α_s values

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

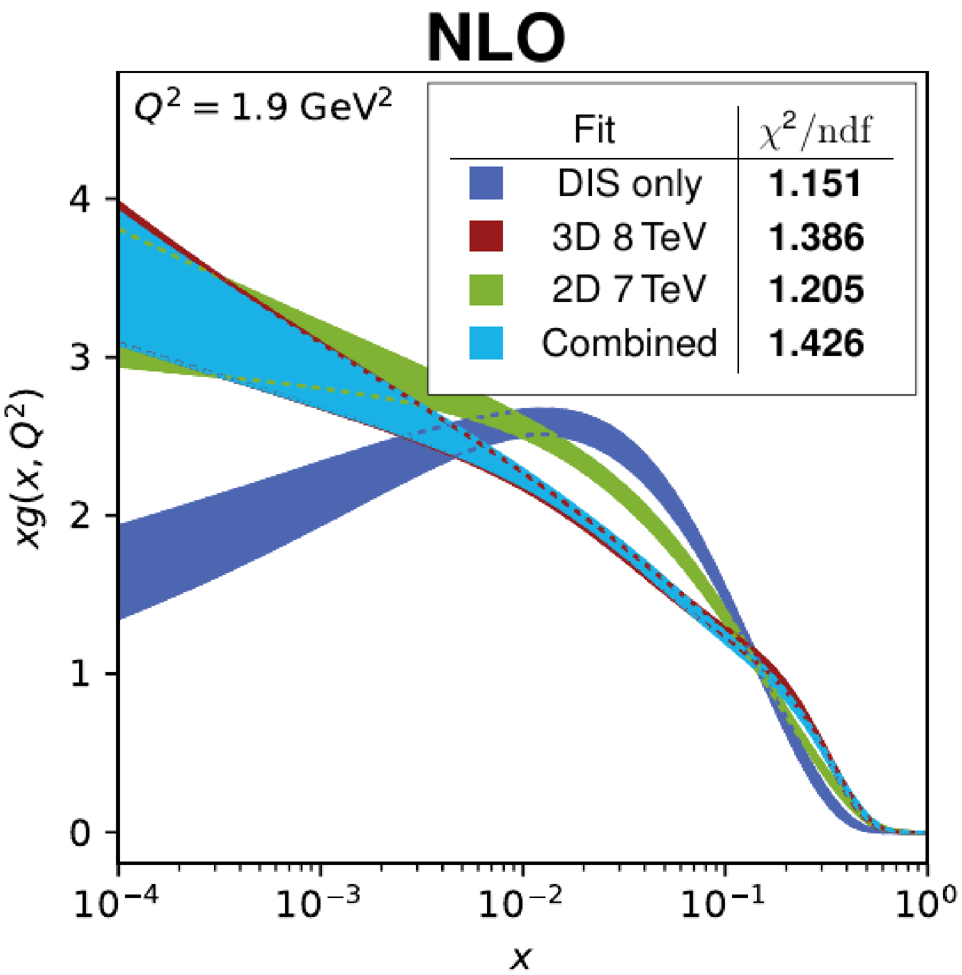
⚠ Only experimental and scale uncertainties

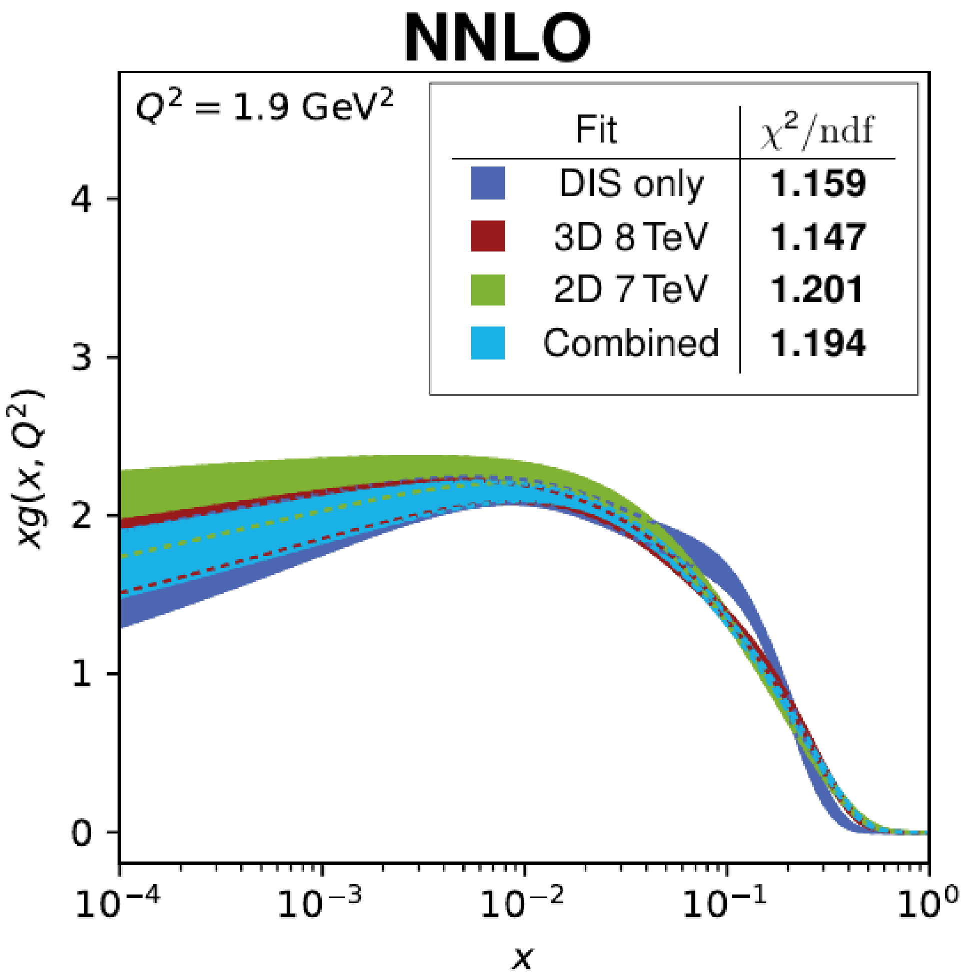


Comparison with other values obtained from jet cross sections and the world average (blue)

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

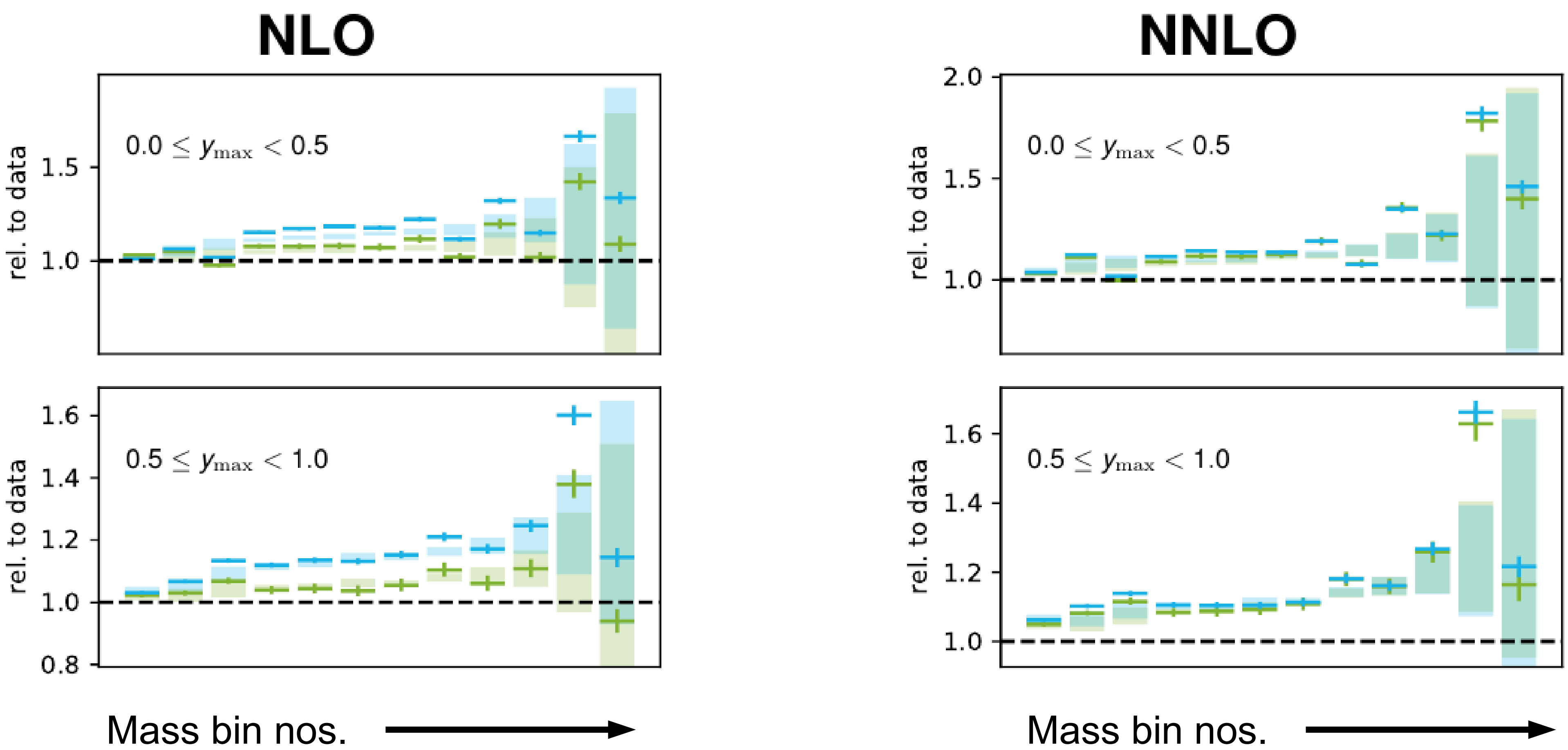
Including 7 TeV 2D dijet data





- use $\mu = m_{12}$ (dijet mass) scale for both datasets
- 7 & 8 TeV data compatible, 3D 8 TeV data dominates the combined fit
- NNLO results much more consistent

Including 7 TeV 2D dijet data



- crosses show the predictions of the 7 TeV only vs. the combined fit, bars show the shifted data
- slight normalization difference at NLO that decreases at NNLO

Conclusion

Reproduction of past dijet PDF fits at NLO

- 13 parameter fit of G. Sieber (2016) is reliably reproducible
- negligible impact from switch to new theory program NNLOJET and new xFitter version

PDF and α_s fits with new *fastNLO* tables

- good agreement between results with different scale definitions at NNLO
- scale uncertainty (on fitted PDFs and $\alpha_s(M_z)$) much smaller at NNLO

Inclusion of 7 TeV 2D dijet data

- 7 TeV 2D and 8 TeV 3D datasets yield compatible results at NNLO
- a combined fit is possible

Backup Slides

PDF parameterisation

$$xg(x) = A_g\, x^{B_g}\, (1-x)^{C_g}\, (1 + E_g x^2)$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + D_{u_v} x)$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}}$$
$$x\bar{U}(x) = A_{\bar{U}}\, x^{B_{\bar{U}}}\, (1-x)^{C_{\bar{U}}}\, (1 + D_{\bar{U}} x)$$
$$x\bar{D}(x) = A_{\bar{D}}\, x^{B_{\bar{D}}}\, (1-x)^{C_{\bar{D}}}$$

Here:
f_s = 0.40

$$A_{\overline{U}} = A_{\overline{D}}(1 - f_s)$$

CMS:
f_s = 0.31

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g} ,$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + D_{u_v} x + E_{u_v} x^2) ,$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}} (1 + D_{d_v} x) ,$$
$$x\overline{U}(x) = A_{\overline{U}} x^{B_{\overline{U}}} (1-x)^{C_{\overline{U}}} (1 + D_{\overline{U}} x) ,$$
$$x\overline{D}(x) = A_{\overline{D}} x^{B_{\overline{D}}} (1-x)^{C_{\overline{D}}} ,$$

χ^2 definition

`ExtraSystRescale` enables `Poisson`

$$\chi^2 = \sum_{i,j} \left(m_i - \Gamma_i^\alpha b_\alpha - \mu_i\right) C_{ij}^{-1} \left(m_j - \Gamma_j^\alpha b_\alpha - \mu_j\right) + \sum_\alpha b_\alpha^2 + \sum_i \log \frac{\Delta_{i,\mathrm{stat}}^2 + \Delta_{i,\mathrm{syst}}^2}{\mu_i^2(\delta_{i,\mathrm{stat}}^2 + \delta_{i,\mathrm{syst}}^2)}$$

$$C_{ij} = \rho_{ij}\Delta_{i,\mathrm{stat}}\Delta_{j,\mathrm{stat}} + \delta_{ij}\Delta_{i,\mathrm{syst}}\Delta_{j,\mathrm{syst}}$$

$$\Gamma_i^\alpha = \gamma_i^\alpha m_i$$

$$\Delta_{i,\mathrm{stat}} = \delta_{i,\mathrm{stat}}\sqrt{\mu_i m_i \exp(-\gamma_i^\alpha b_\alpha)}$$

$$\Delta_{i,\mathrm{syst}} = \delta_{i,\mathrm{syst}} m_i$$

`ExtraSystRescale`

`SysScale=Linear`

`StatScale=Poisson`

with theory predictions m_i, data points μ_i, uncertainties δ and γ and the correlation matrix ρ_{ij}

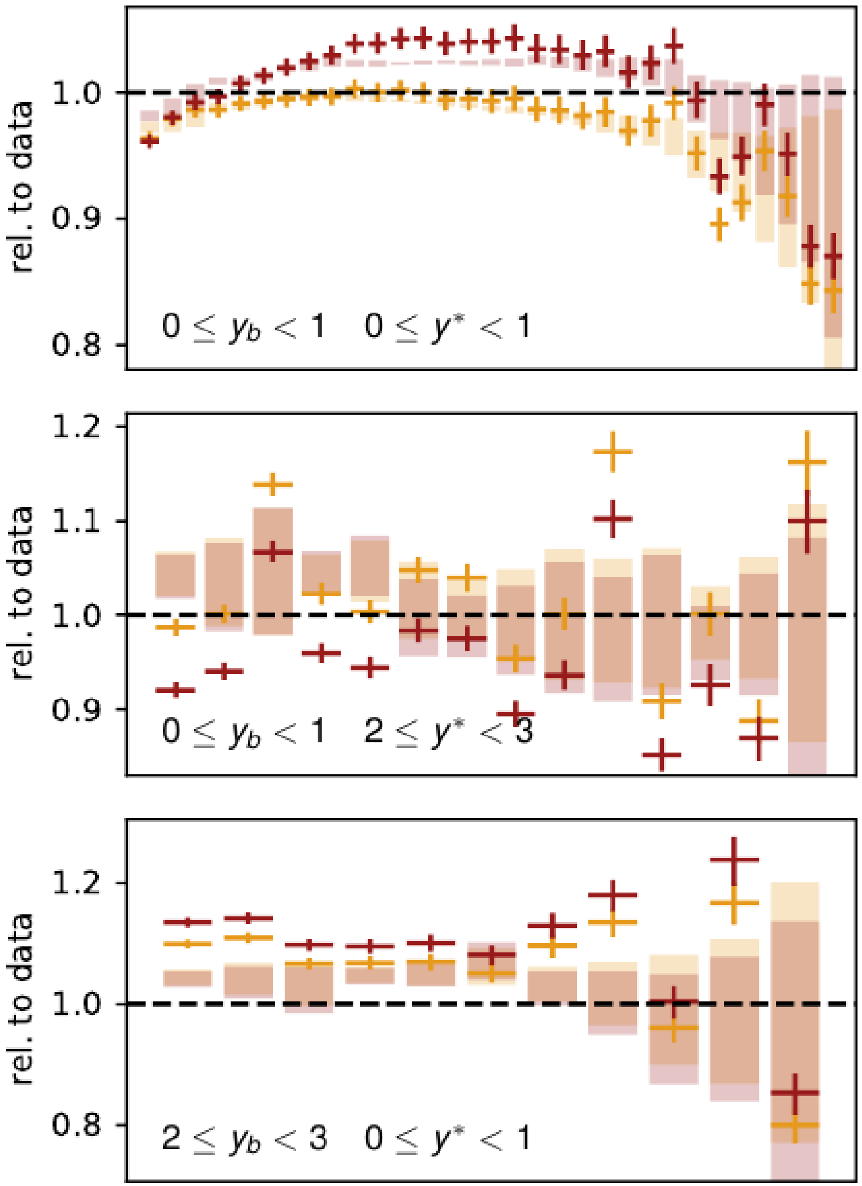
13 parameter fits – χ^2 values

		n_{data}	NLO HERA I+II Dis only	NLO with CMS dijets $\mu = p_{\mathrm{T},1} e^{0.3y^*}$	NLO with CMS dijets $\mu = m_{12}$	NNLO HERA I+II Dis only	NNLO with CMS dijets $\mu = p_{\mathrm{T},1} e^{0.3y^*}$	NNLO with CMS dijets $\mu = m_{12}$
HERA I+II	combined	1016	1106.14	1128.45	1181.30	1109.15	1116.89	1119.54
CMS 8 TeV dijets	yb0 ys0	31	–	13.71	35.82	–	17.79	16.70
	yb0 ys1	26	–	13.37	28.03	–	15.90	12.78
	yb0 ys2	14	–	23.23	76.82	–	20.97	23.38
	yb1 ys0	23	–	13.98	19.21	–	20.09	16.22
	yb1 ys1	17	–	20.33	27.45	–	25.70	20.40
	yb2 ys0	11	–	28.62	88.36	–	13.25	22.10
	combined	122	–	113.24	275.69	–	113.70	111.58
		correlated χ^2	50.96	69.88	115.15	55.48	63.96	63.17
		log penalty χ^2	-2.98	-11.96	-13.24	-1.74	-1.04	-3.95
		combined	1154.12	1299.63	1558.90	1162.89	1293.52	1290.33
		ndf	1003	1125	1125	1003	1125	1125
		p-value	6.13×10^{-4}	2.15×10^{-4}	3.24×10^{-4}	3.33×10^{-4}	4.16×10^{-4}	1.26×10^{-16}
		combined χ^2/ndf	**1.151**	**1.155**	**1.386**	**1.159**	**1.150**	**1.147**

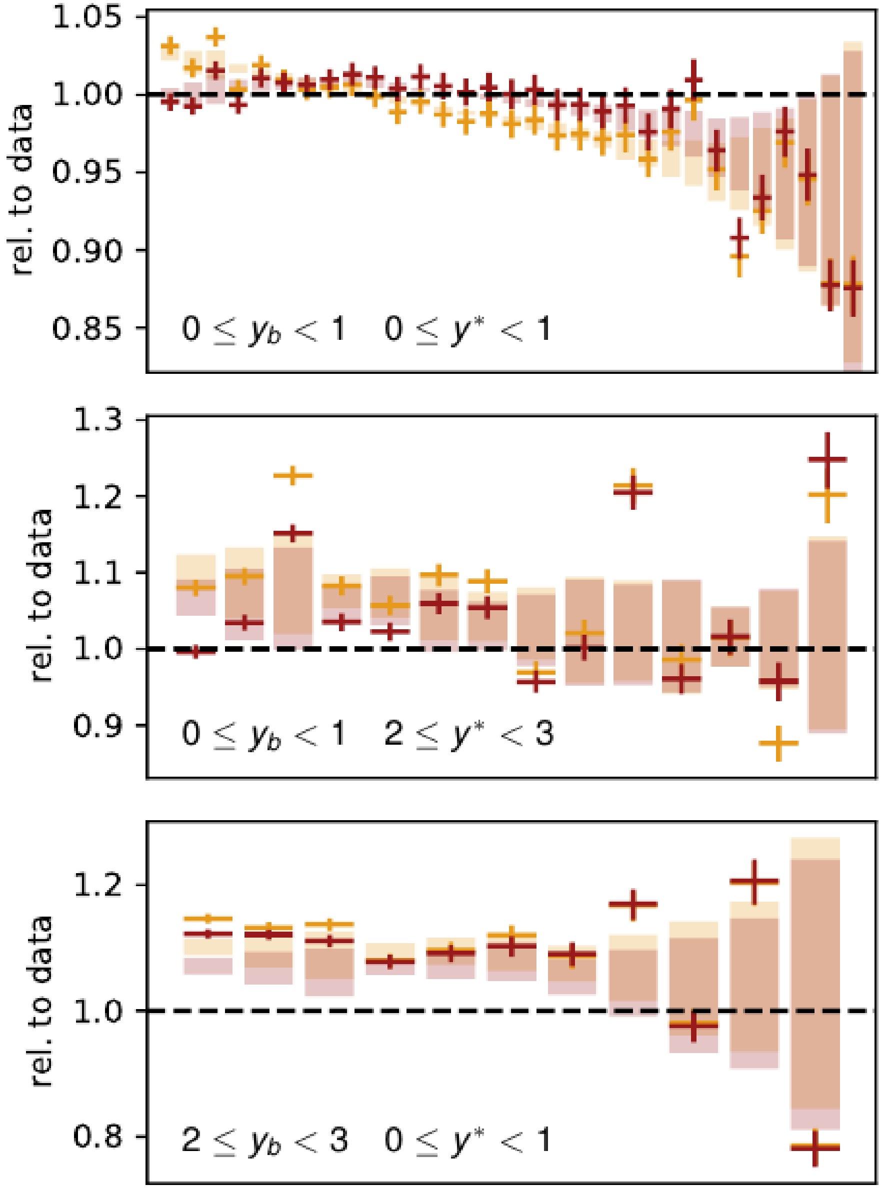
- differences in χ^2 considerably smaller in NNLO
  $\rightarrow$ scale dependency smaller in NNLO
- m_{12} way better in NNLO

Data description

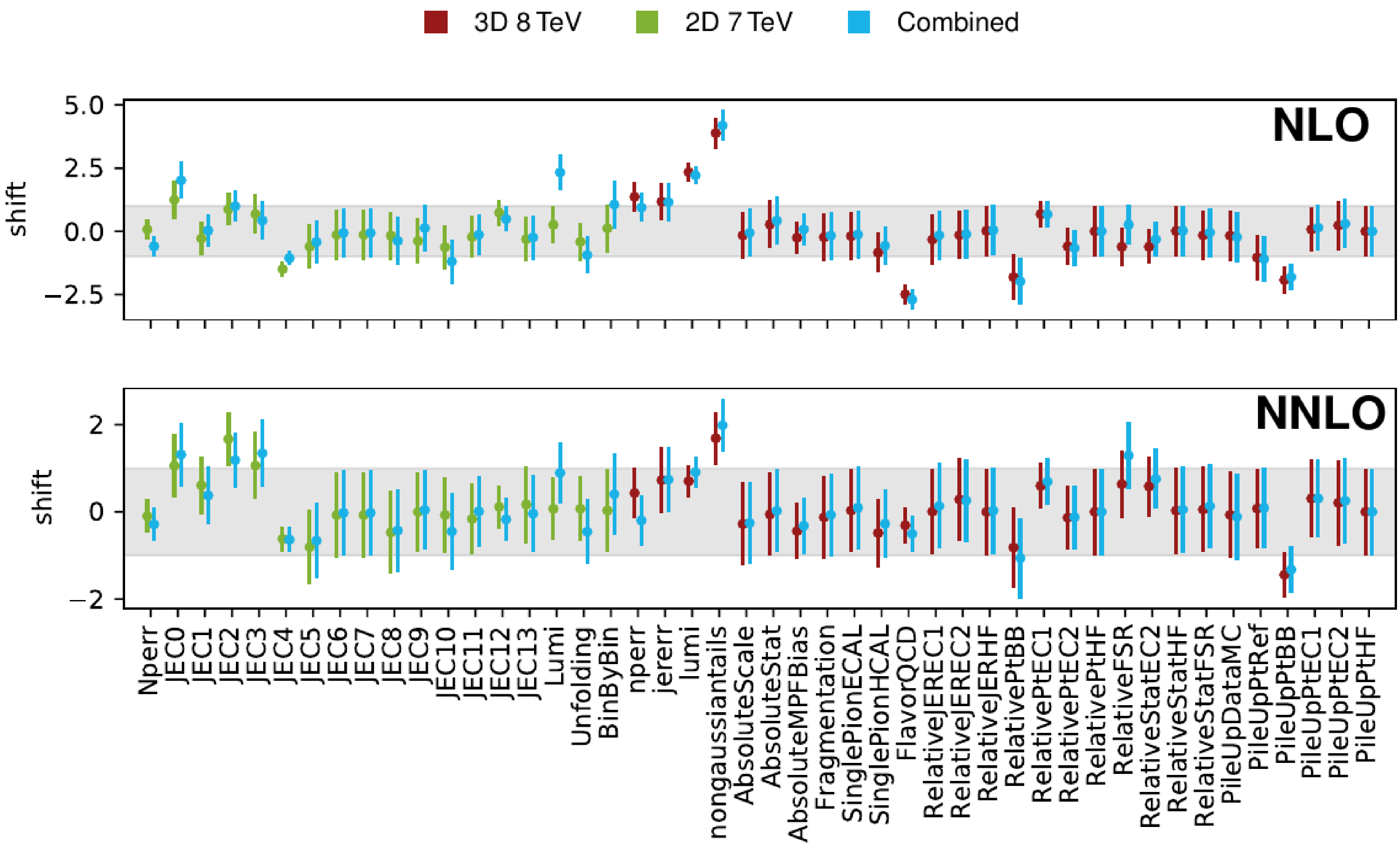
8 TeV NLO



8 TeV NNLO



Fitted nuisance parameters



Consistency of 3D 8 TeV & 2D 7 TeV

partial χ^2 values

NLO	CMS dijets 3D 8 TeV	CMS dijets 2D 7 TeV	Combined
HERA I+II	1181.30	1124.63	1178.64
CMS dijets 3D 8 TeV	275.69	–	283.74
CMS dijets 2D 7 TeV	–	94.24	97.36
Correlated χ^2	115.15	60.71	132.39

NNLO	CMS dijets 3D 8 TeV	CMS dijets 2D 7 TeV	Combined
HERA I+II	1119.54	1112.62	1120.46
CMS dijets 3D 8 TeV	111.58	–	111.93
CMS dijets 2D 7 TeV	–	93.31	103.04
Correlated χ^2	63.17	63.93	73.81

- NLO and NNLO only small change in partial χ^2 if including the other dataset
- Fitting both datasets together leads to similar results as fitting either of them alone

$\Downarrow$

Both dataset (plus theory calculations) can be called consistent

Exp. syst. uncertainties 8 TeV