Towards nNNPDF3.0: A global analysis of nuclear PDFs at NNLO

XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects

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Tuesday 13/04/2021

Outline

1

nNNPDF2.0

Overview - Parameterisation - Constraints

"nNNPDF2.0: Quark Flavor Separation in Nuclei from LHC Data"

— *arXiv:2006.14629*

Towards nNNPDF3.0

CMS 5 TeV dijets - DY at NNLO

2

"Phenomenology of NNLO jet production at the LHC and its impact on parton distributions"

— *arXiv:2005.11327*

Electron Ion collider Impact

Talk on Thursday

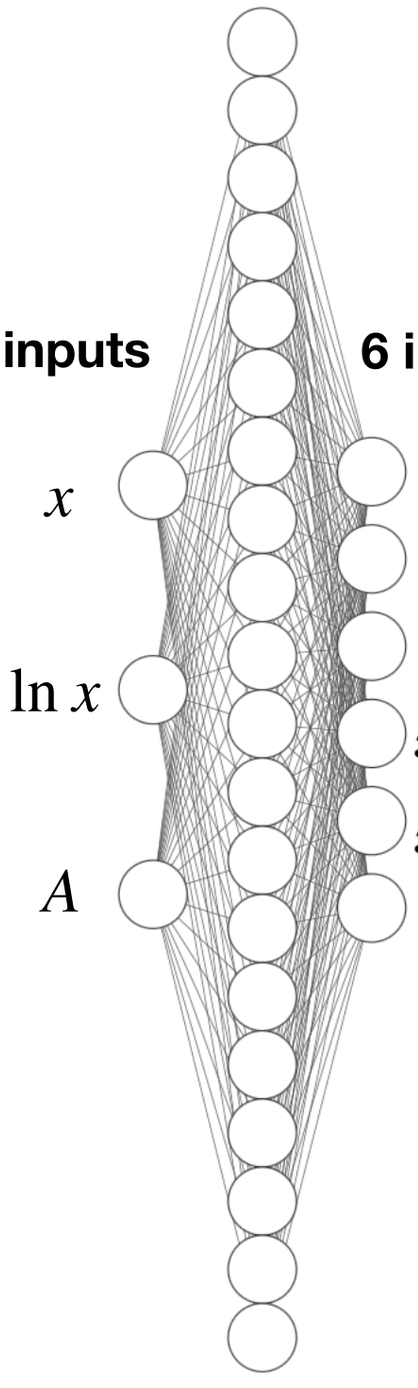
"Self-consistent determination of proton and nuclear PDFs at the Electron Ion Collider"

— *arXiv:2102.00018*

Overview

Order	DSSZ12 NLO	KA15 NNLO	nCTEQ15 NLO	EPPS16 NLO	TUJU19 NNLO	nNNPDF1.0 NLO & NNLO	nNNPDF2.0 NLO	nNNPDF3.0 NLO & **NNLO**
Neutral current DIS $\ell + A/\ell + d$	✔	✔	✔	✔	✔	✔	✔	✔
Dell-Yan dilepton $p + A/p + d$	✔	✔	✔	✔				
RHIC pions $d + Au/p + p$	✔		✔	✔				
Charged current DIS $\nu + A$	✔			✔	✔		✔	✔
Drell-Yan dilepton $\pi + A$				✔				
LHC (di)jet (5 TeV) $p + Pb$				✔				✔ **(k-factors)**
LHC W, Z (5, 8 TeV) $p + Pb$				✔			✔	✔ **(k-factors)**
LHC D^0 $p + Pb$								✔
Q_0	1.0	1.41	1.3	1.3	1.3	1.0	1.0	1.0
Q cut in DIS	1.0	1.0	2.0	1.3	1.87	1.87	1.87	1.87
Datapoints	1579	1479	708	1811	2336	451	1467	
Error analysis	Hessian	Hessian	Hessian	Hessian	Hessian	Monte Carlo	Monte Carlo	Monte Carlo
Free Proton Baseline	MSTW08	JR09	CTEQ6.1	CT14nlo	HERA2.0	NNPDF3.1	NNPDF3.1	NNPDF4.0
Heavy quark effects	✔		✔	✔	✔	✔	✔	✔
Flavour separation	✔		Some	✔			✔	✔
Parametrization	Modification Ratio in Mellin space	Modification Ratio	Proton pdf parametrised with A	Modification Ratio	Proton pdf parametrised with A	Neural Network With A as input	Neural Network With A as input	Neural Network With A as input
Reference	PR D.100.096015	PR D.93.014026	PR D.93.085037	EPJ C77 163	PR D.100.096015	EPJ C79 471	JHEP 09 (2020) 183	

nNNPDF2.0 Parameterisation



$$\Sigma = \sum_i^{n_f} f_i^+ \text{ (Singlet)} \qquad V = \sum_i^{n_f} f_i^- \text{ (Valence)}$$

$$T_3 = u^+ - d^+ \qquad V_3 = u^- - d^-$$

$$T_8 = u^+ + d^+ - 2s^+$$

6 independent flavours, 256 free parameters, $\mu_0 = 1$ GeV

$$\begin{aligned}
x\Sigma^{(p/A)}(x,Q_0) &= x^{\alpha_\Sigma}(1-x)^{\beta_\Sigma}\mathrm{NN}_\Sigma(x,A)\,,\\
xT_3^{(p/A)}(x,Q_0) &= x^{\alpha_{T_3}}(1-x)^{\beta_{T_3}}\mathrm{NN}_{T_3}(x,A)\,,\\
xT_8^{(p/A)}(x,Q_0) &= x^{\alpha_{T_8}}(1-x)^{\beta_{T_8}}\mathrm{NN}_{T_8}(x,A)\,,\\
xV^{(p/A)}(x,Q_0) &= B_V x^{\alpha_V}(1-x)^{\beta_V}\mathrm{NN}_V(x,A)\,,\\
xV_3^{(p/A)}(x,Q_0) &= B_{V_3} x^{\alpha_{V_3}}(1-x)^{\beta_{V_3}}\mathrm{NN}_{V_3}(x,A)\,,\\
xg^{(p/A)}(x,Q_0) &= B_g x^{\alpha_g}(1-x)^{\beta_g}\mathrm{NN}_g(x,A)\,.
\end{aligned}$$

Sum Rules

$$f_i^{p/A} = N_i x^\alpha (1-x)^\beta NN_i(x,A)$$

$$f_i^A = Z f_i^{p/A} + (A-Z) f_i^{n/A}$$

$$f_{u(d),\bar{u}(\bar{d})}^{n/A} = f_{d(u),\bar{d}(\bar{u})}^{p/A}$$ **SU(2) isospin symmetry**

nNNPDF2.0 Constraints

$$\chi^2 = \sum_{i,j=1}^{N_{\rm dat}} (D_i - T_i)(\mathrm{cov}_{t_0})^{-1}_{ij}(D_j - T_j)$$

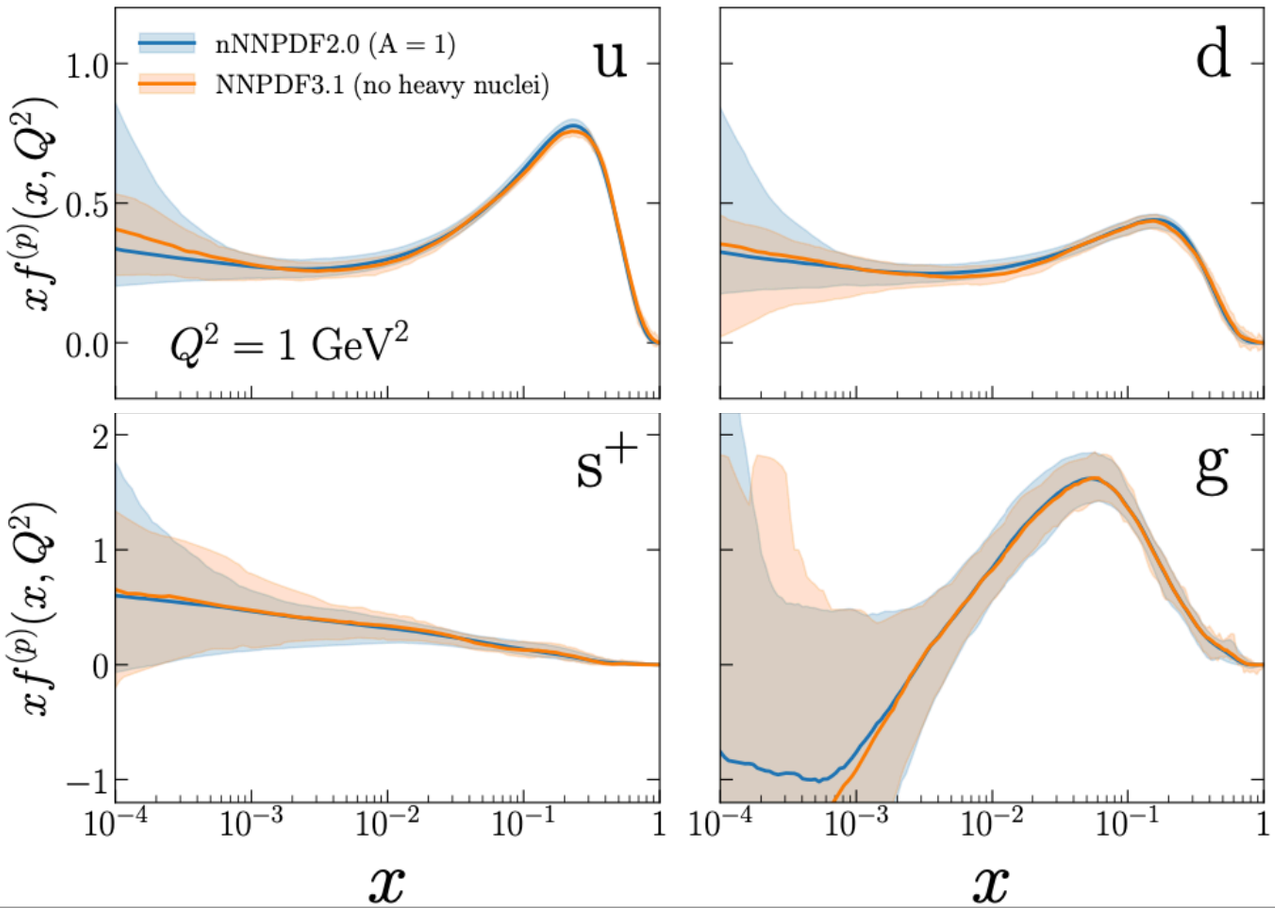
$$+\lambda_{bc} \sum_{m}^{n_f} \sum_{l=1}^{N_x} \left(f_m^{(p/A)}(x_l, Q_0, A=1) - f_m^{(p)}(x_l, Q_0) \right)^2 \longrightarrow \textbf{A=1 Boundary condition}$$

Member-by-member correlation

$$+\lambda_{pos} \sum_{k}^{N_{\rm pos}} \max(0, -O_k^{pos}) \longrightarrow$$

Positivity constraint for $x \in [10^{-7},1]$

$$F_2^u,\ F_2^d,\ F_2^s,\ d^2_{M^2y}\sigma^{DY}_{u\bar{u}},\ d^2_{M^2y}\sigma^{DY}_{d\bar{d}},\ d^2_{M^2y}\sigma^{DY}_{s\bar{s}},\ F_L^l$$



Sum Rules

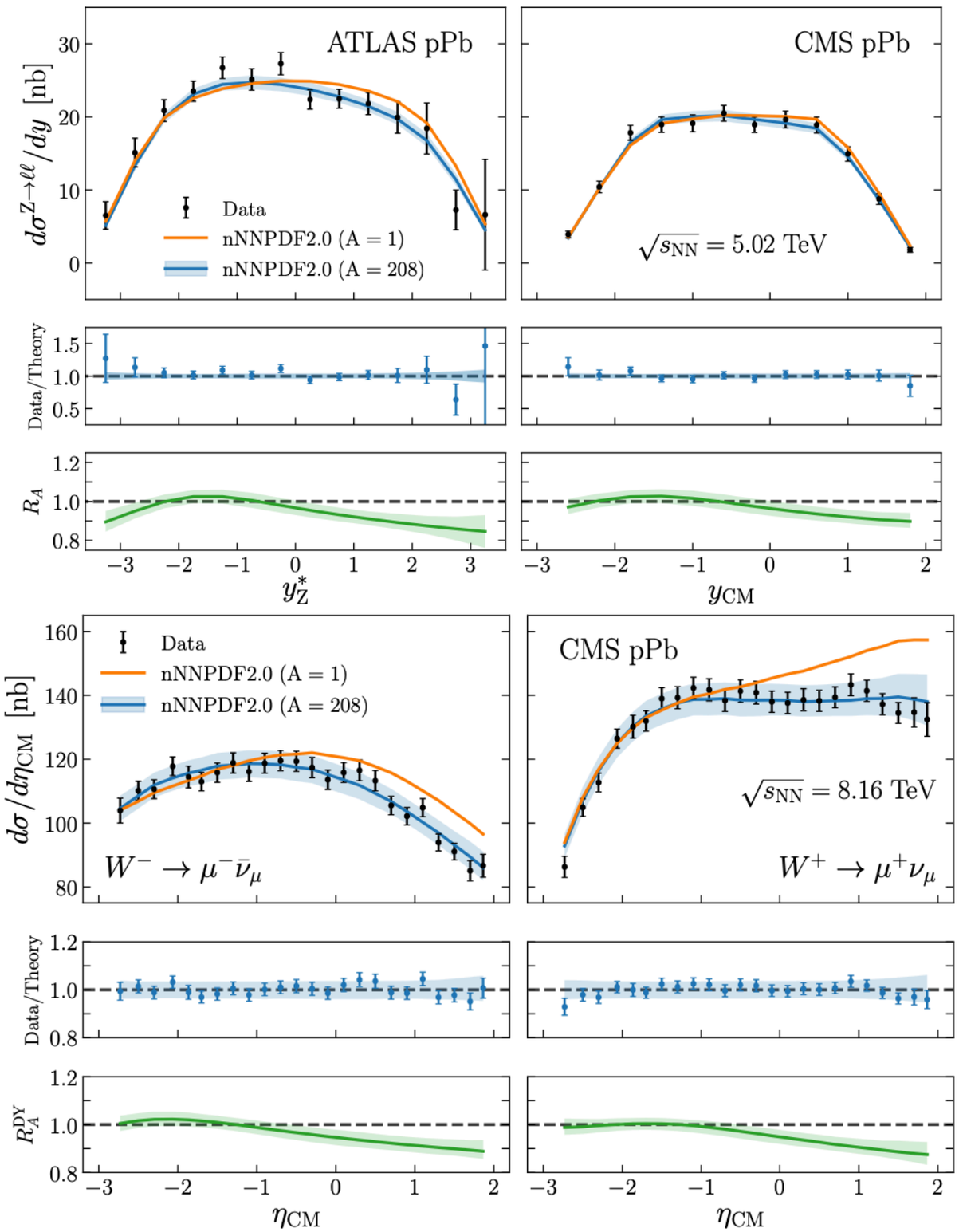
$$B_g(A) = \frac{1 - \int_0^1 dx\, x\Sigma^{(p/A)}(x, Q_0)}{\int_0^1 dx\, x g^{(p/A)}(x, Q_0)}$$

$$B_{V_3}(A) = \frac{1}{\int_0^1 dx\, V_3^{(p/A)}(x, Q_0, A)}$$

$$B_V(A) = \frac{3}{\int_0^1 dx\, V^{(p/A)}(x, Q_0, A)}$$

nNNPDF2.0 Results

		nNNPDF2.0 (DIS)	nNNPDF2.0	EPPS16nlo
Dataset	$n_{\rm dat}$	$\chi^2/n_{\rm dat}$	$\chi^2/n_{\rm dat}$	$\chi^2/n_{\rm dat}$
NuTeV ($\bar{\nu}$Fe)	37	0.946	1.094	*0.639*
NuTeV (νFe)	39	0.287	0.264	*0.381*
CHORUS ($\bar{\nu}$Pb)	423	0.938	0.97	1.107
CHORUS (νPb)	423	1.007	1.015	1.024
ATLAS$^{\rm 5TEV}$ Z	14	*1.469*	1.134	1.12
CMS$^{\rm 5TeV}$ W$^-$	10	*1.688*	1.078	0.857
CMS$^{\rm 8TeV}$ W$^-$	24	*1.453*	0.72	*0.825*
CMS$^{\rm 5TeV}$ W$^+$	10	*2.32*	1.125	1.211
CMS$^{\rm 8TeV}$ W$^+$	24	*3.622*	0.772	*0.951*
CMS$^{\rm 5TeV}$ Z	12	*0.58*	0.52	0.639
Total	**1467**	**1.013**	**0.976**	**0.896**

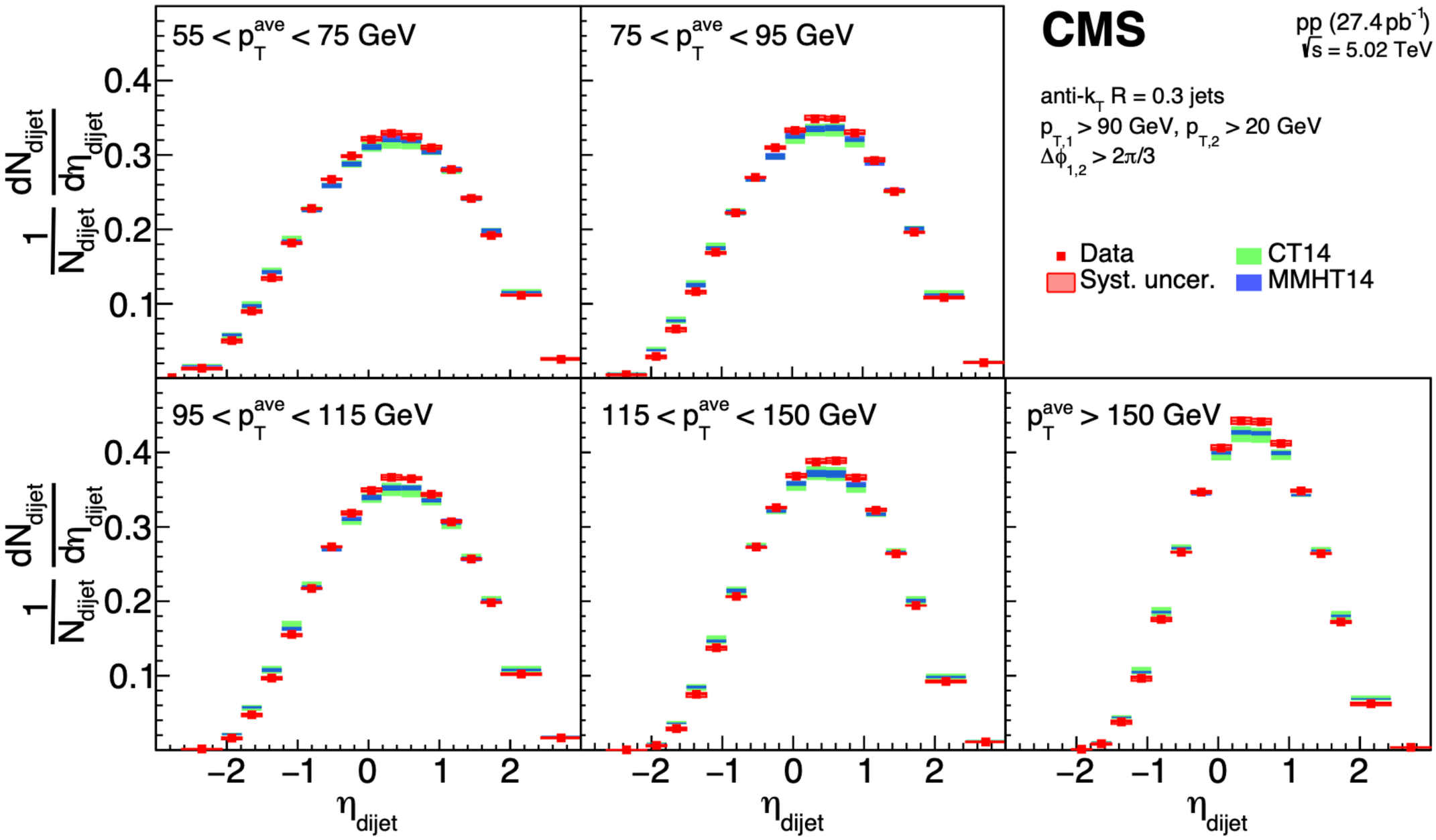


Towards nNNPDF3.0

		nNNPDF3.0	
Order		NLO & **NNLO**	
Neutral current DIS	$\ell + A/\ell + d$	✔	
Dell-Yan dilepton	$p + A/p + d$		
RHIC pions	$d + Au/p + p$		
Charged current DIS	$\nu + A$	✔	
Drell-Yan dilepton	$\pi + A$		
LHC (di)jet (5 TeV)	$p + Pb$	✔ **(k-factors)**	**Main Focus**
LHC W, Z (5, 8 TeV)	$p + Pb$	✔ **(k-factors)**	
LHC D^0	$p + Pb$	✔	
Q_0		1.0	
Q cut in DIS		1.87	
Datapoints			
Error analysis		Monte Carlo	
Free Proton Baseline		NNPDF4.0	
Heavy quark effects		✔	
Flavour separation		✔	
Parametrization		Neural Network With A as input	
Reference			

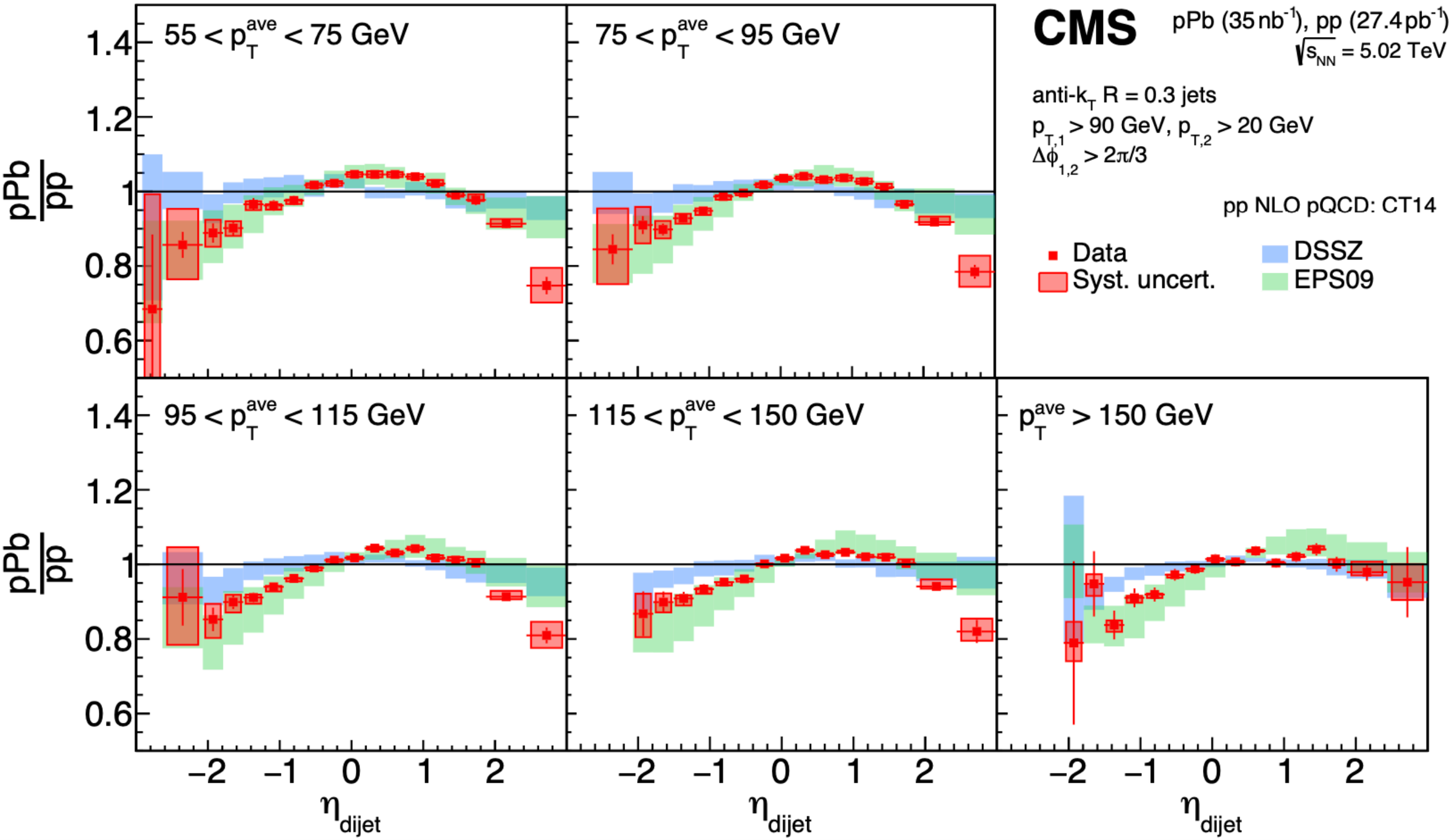
CMS Dijet
pp and pPb at 5 TeV

p-p CMS 5 TeV


55 < p_T^ave < 75 GeV
75 < p_T^ave < 95 GeV
95 < p_T^ave < 115 GeV
115 < p_T^ave < 150 GeV
p_T^ave > 150 GeV
1/N_dijet dN_dijet/dη_dijet
η_dijet
CMS
pp (27.4 pb^-1)
√s = 5.02 TeV
anti-k_T R = 0.3 jets
p_T,1 > 90 GeV, p_T,2 > 20 GeV
Δφ_1,2 > 2π/3
Data
Syst. uncer.
CT14
MMHT14

p-Pb CMS 5 TeV

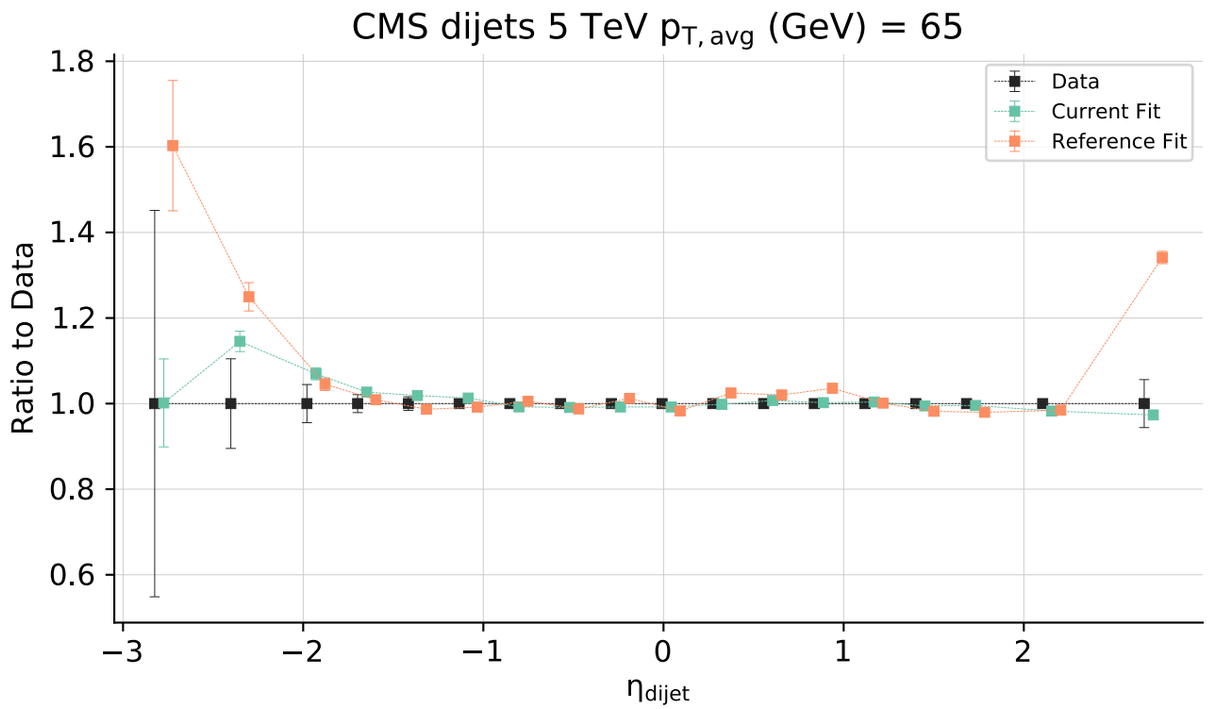
Both spectra (See slide 3) and $R_{\mathrm{pPb}}^{\mathrm{norm.}} = \dfrac{\frac{1}{\mathrm{d}\sigma^{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}^{\mathrm{ave}}}\,\mathrm{d}^2\sigma^{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}^{\mathrm{ave}}\mathrm{d}\eta_{\mathrm{dijet}}}{\frac{1}{\mathrm{d}\sigma^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}^{\mathrm{ave}}}\,\mathrm{d}^2\sigma^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}^{\mathrm{ave}}\mathrm{d}\eta_{\mathrm{dijet}}}$.

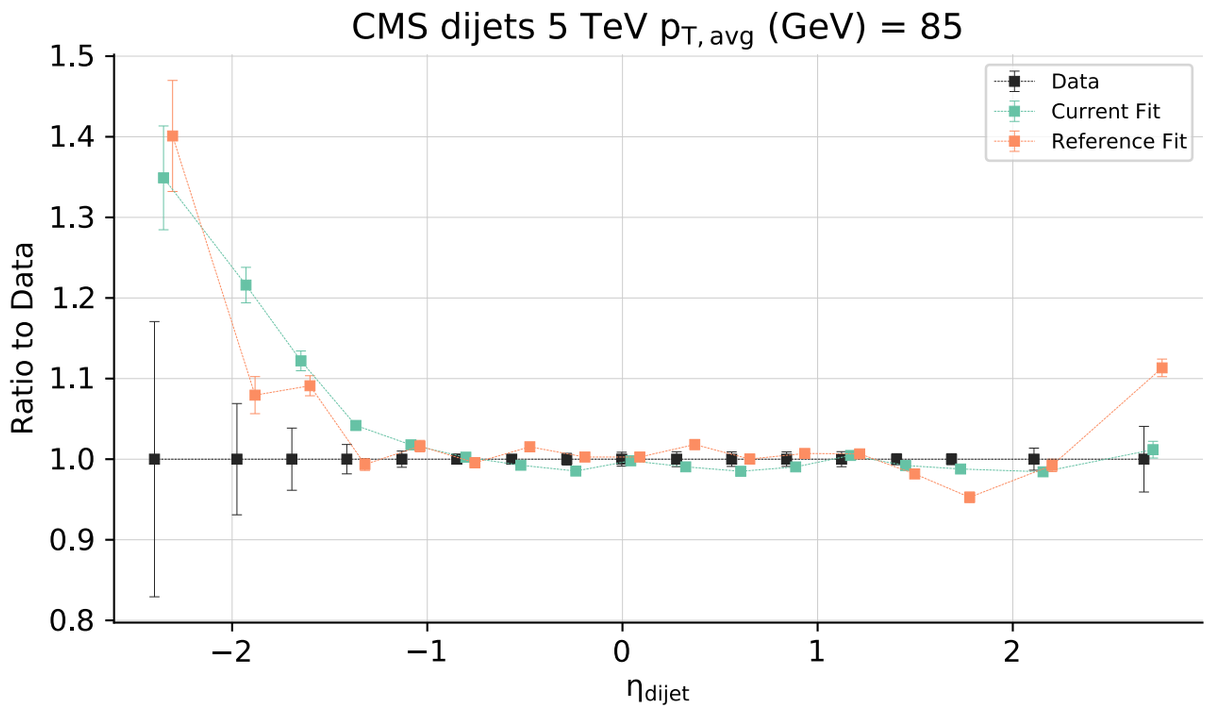


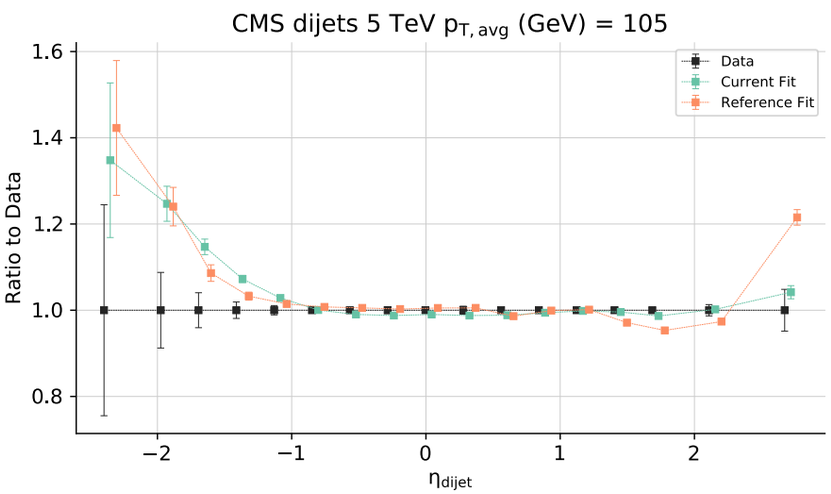
NNPDF3.1 +dijet + pp CMS 5 TeV

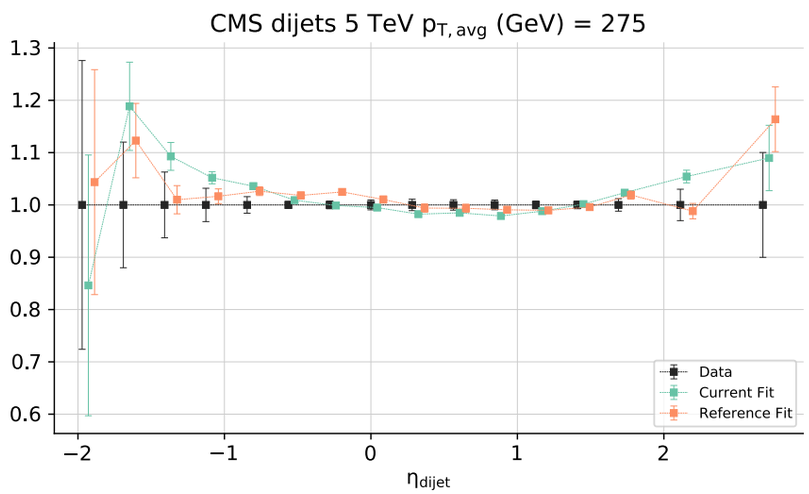
— **NLO** $(\chi^2_{tot}/N = 1.42)$, $(\chi^2_{dataset}/N = 2.51)$

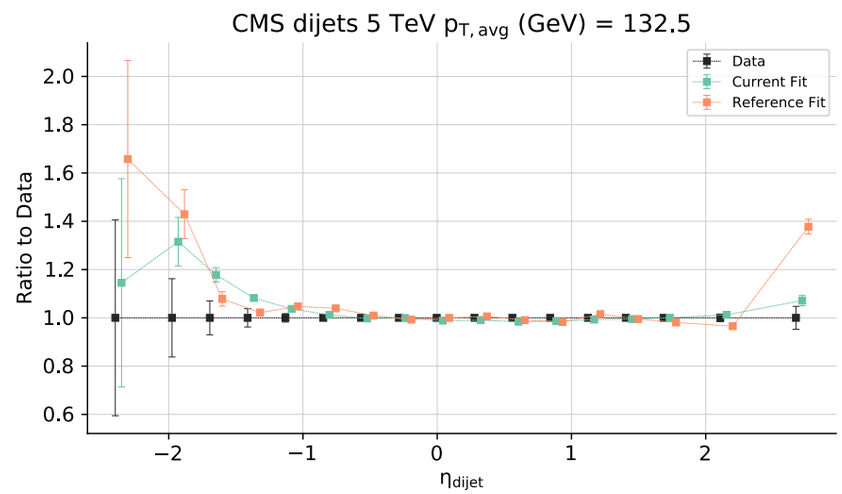
— **NNLO** $(\chi^2_{tot}/N = 1.41)$, $(\chi^2_{dataset}/N = 6.91)$





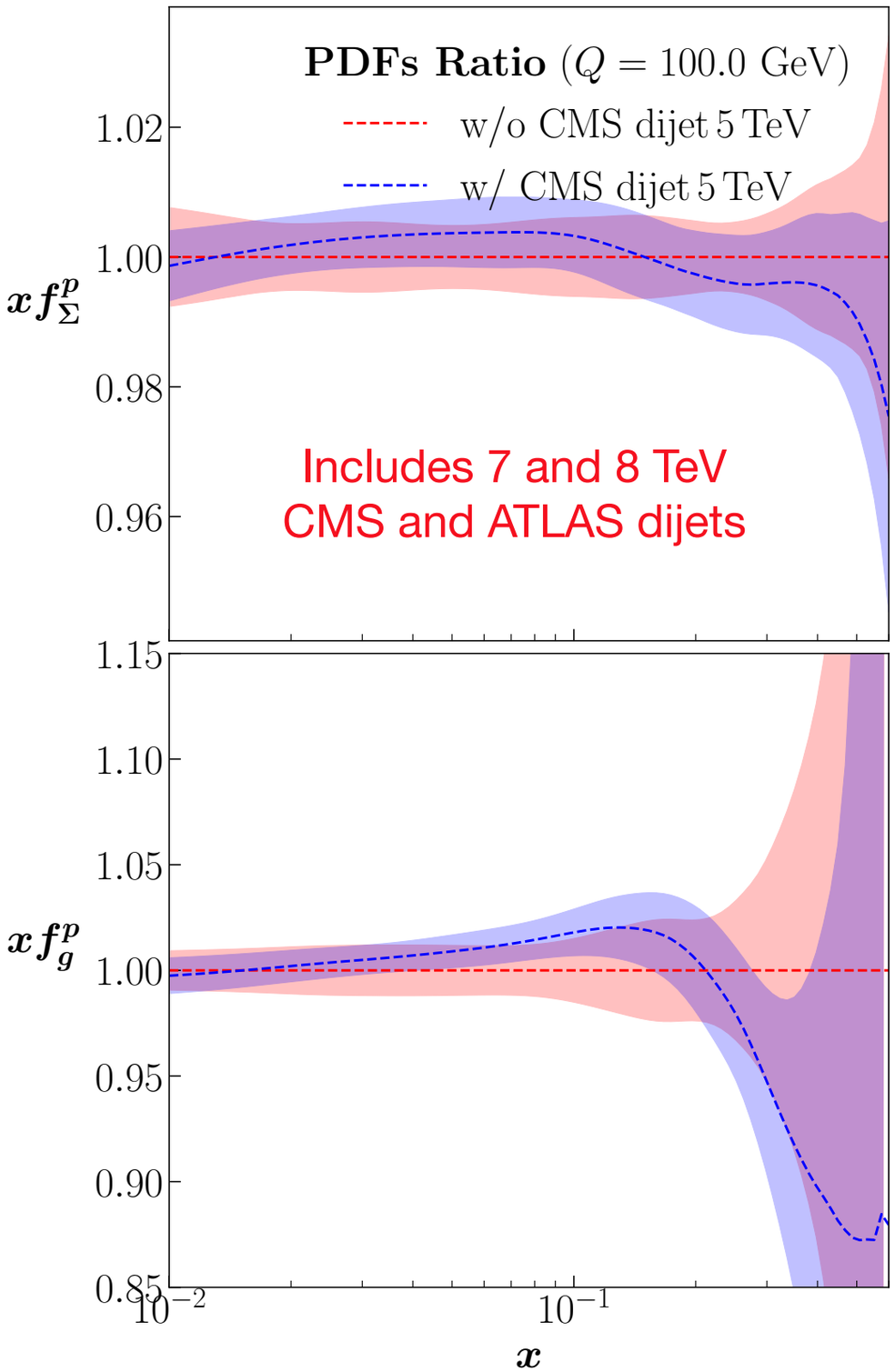




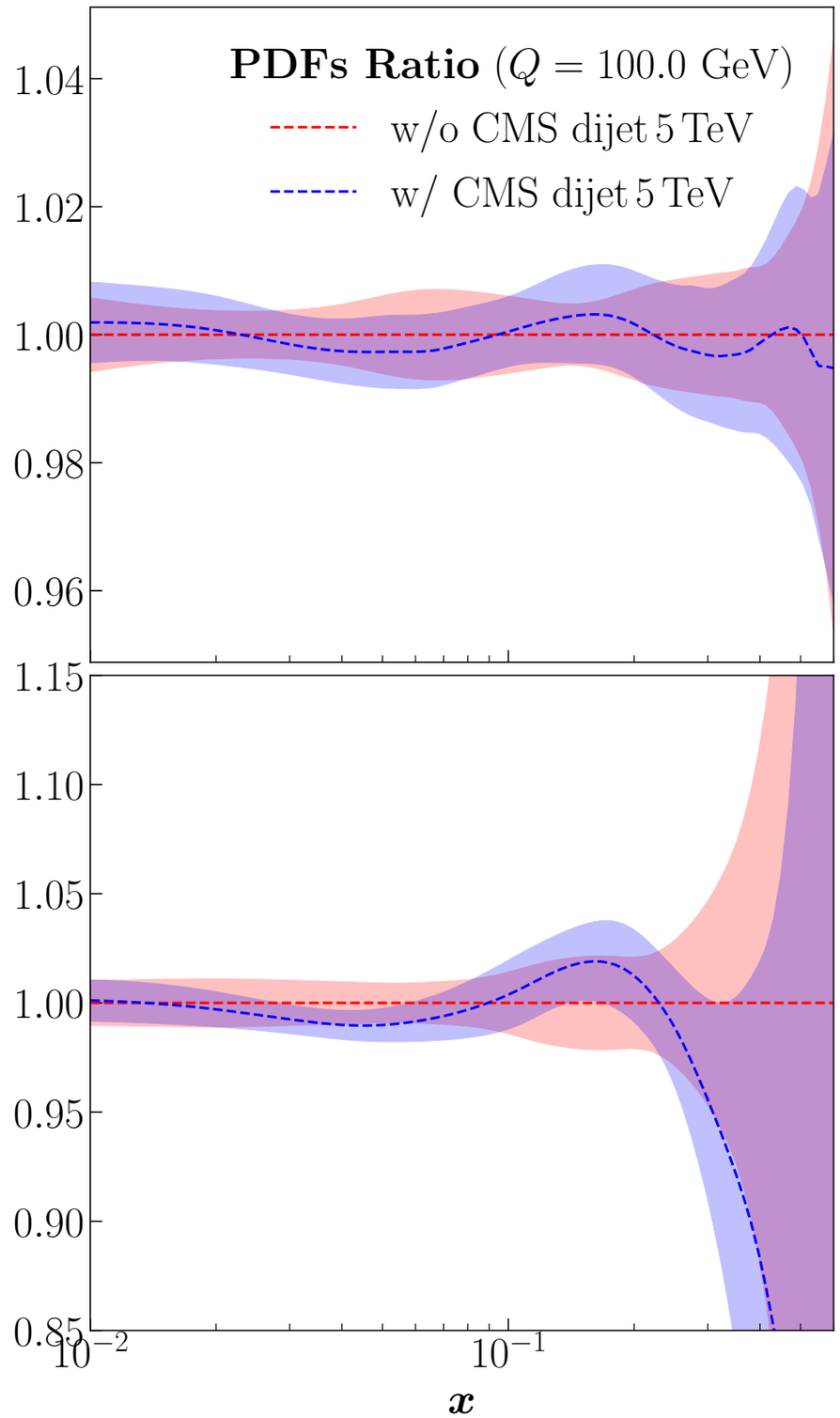


NNPDF3.1 +dijet + pp CMS 5 TeV

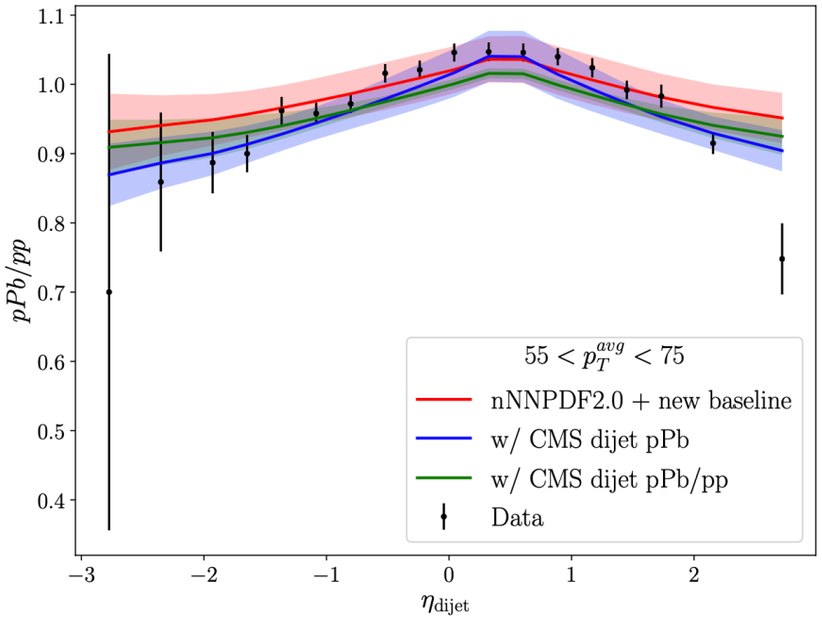
NLO

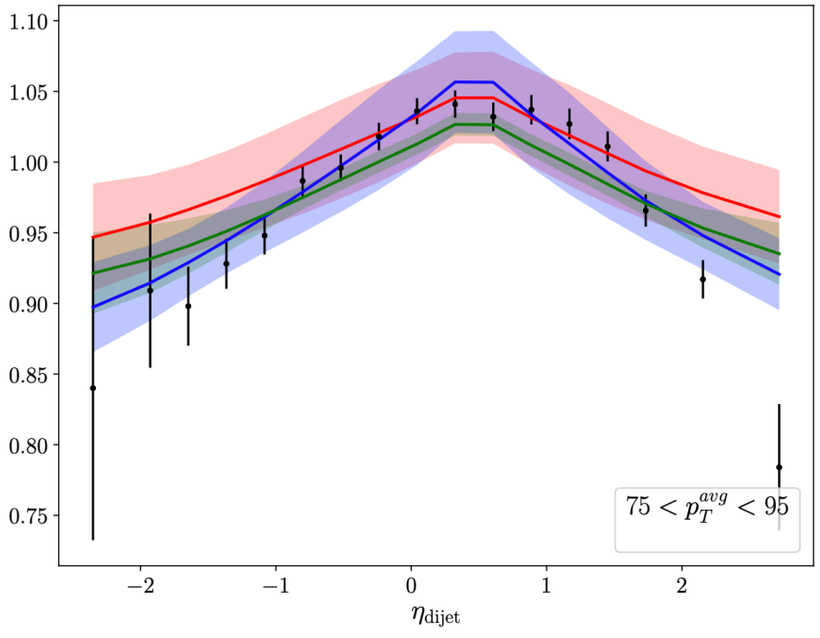


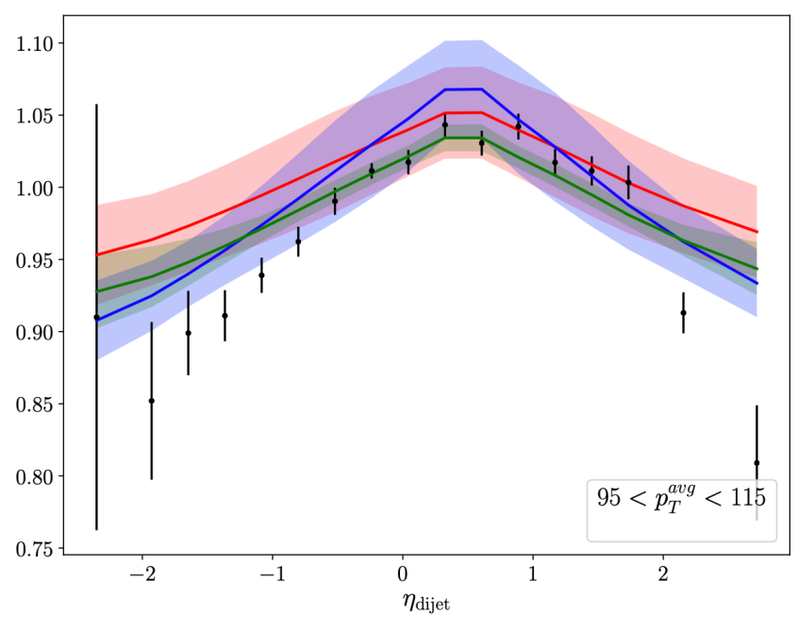
NNLO

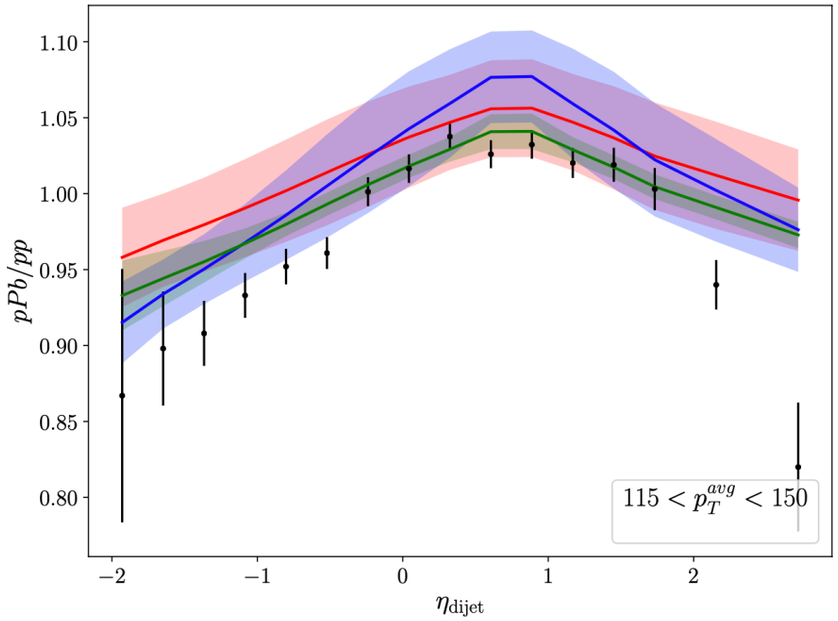


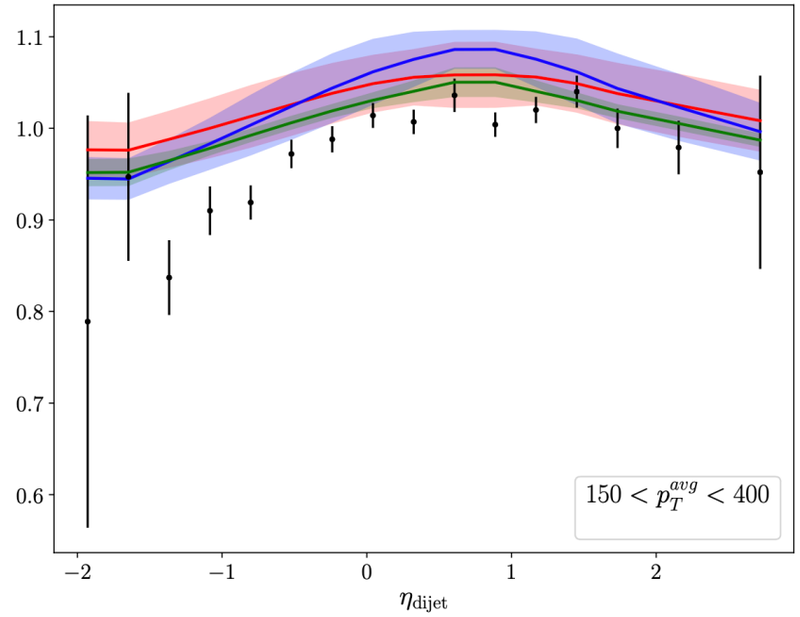
nNNPDF2.0 + pPb CMS 5 TeV





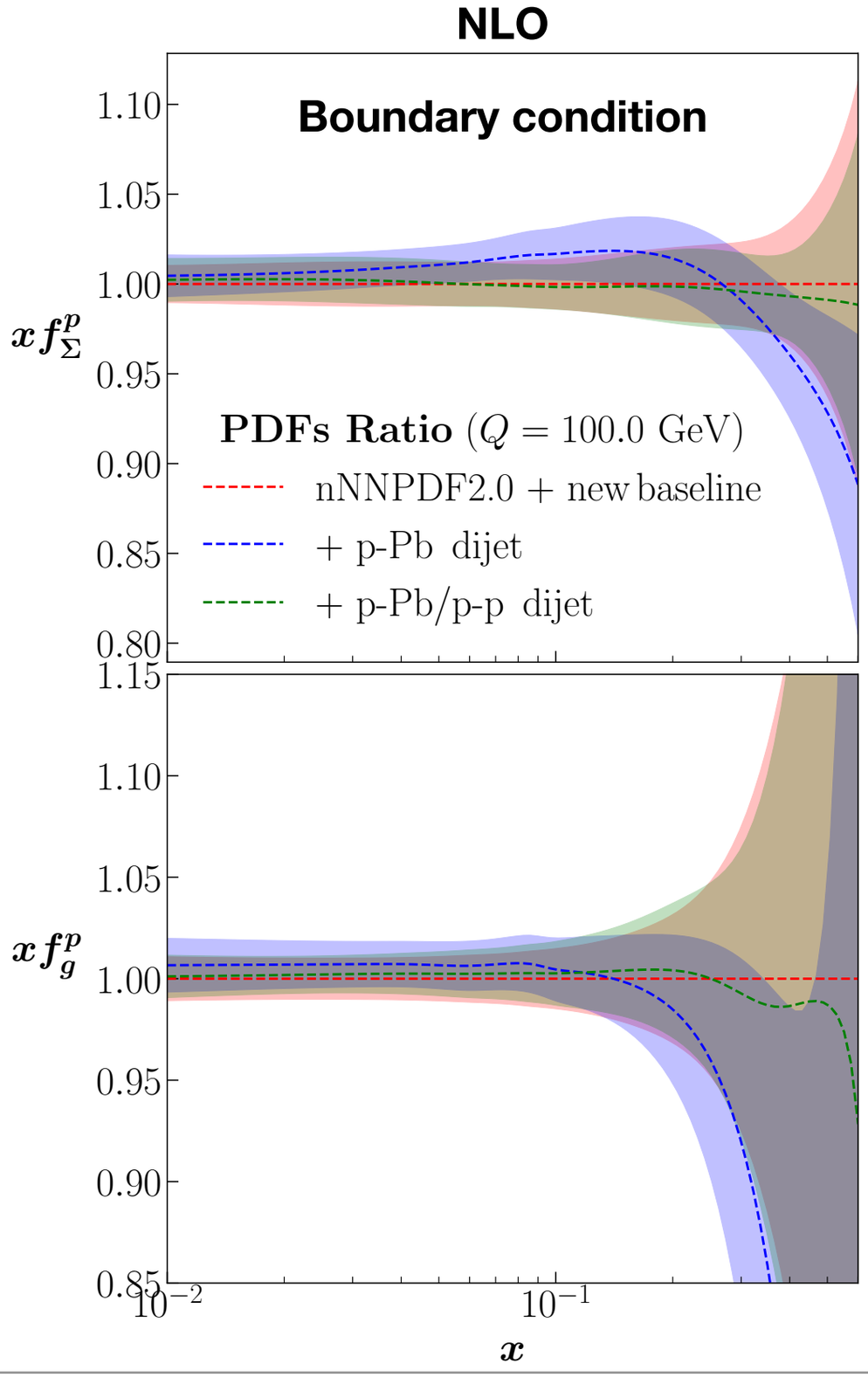


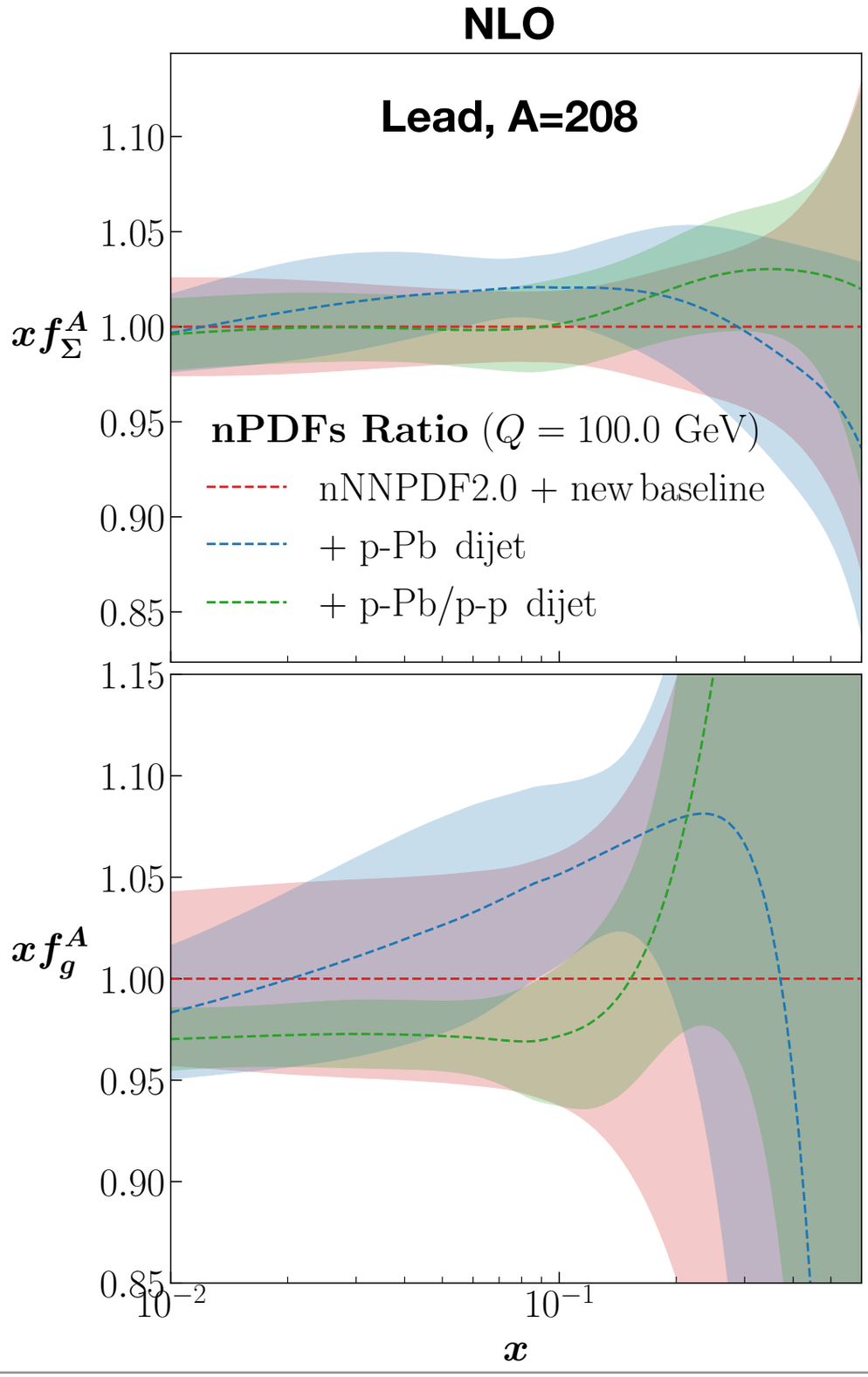




- **w/o dijet** $\rightarrow \chi^2_{dataset}/N = [6.47]$
- **w/ CMS dijet pPb** $\rightarrow \chi^2_{dataset}/N = [6.16]$
- **w/ CMS dijet pPb/pp** $\rightarrow \chi^2_{dataset}/N = 3.85$

nNNPDF2.0 + pPb CMS 5 TeV





PDF and nPDF fit quality

Dataset	w/o (NLO)	w/ (NLO)	w/o (NNLO)	w/ (NNLO)
CMS 5 TeV (pp)	**[5.87]**	**2.51**	**[12.04]**	**6.91**
CMS 5 TeV (pPb)	**[11.07]**	**3.53 [9.86]**	**—**	**—**
CMS 5 TeV (pPb/pp)	**[6.47]**	**3.85 [6.16]**	**—**	**—**

No tension is recorded between pp CMS 5 TeV dijet and the 7 and 8 TeV already considered in

"Phenomenology of NNLO jet production at the LHC and its impact on parton distributions"

— arXiv:2005.11327

(More on this in the appendix)

A word on the pA Drell-Yan at NNLO

QCD K-factors

$$\sigma^{\mathrm{NLO}}\left(pA \to \ell\ell\right) = \hat{\sigma}^{\mathrm{NLO}}\left(pp \to \ell\ell\right) \otimes \overbrace{f_p^{\mathrm{NLO}} \otimes f_A^{\mathrm{NLO}}}^{\mathscr{L}_{pA}^{\mathrm{NLO}}}$$

Not trivial with the available MC generators

$$K_{\mathrm{pA}}^{\mathrm{NNLO}} = \hat{\sigma}^{\mathrm{NNLO}}\left(pp \to \ell\ell\right) \otimes \mathscr{L}_{pA}^{\mathrm{NNLO}} \Big/ \hat{\sigma}^{\mathrm{NNLO}}\left(pp \to \ell\ell\right) \otimes \mathscr{L}_{pA}^{\mathrm{NLO}}$$

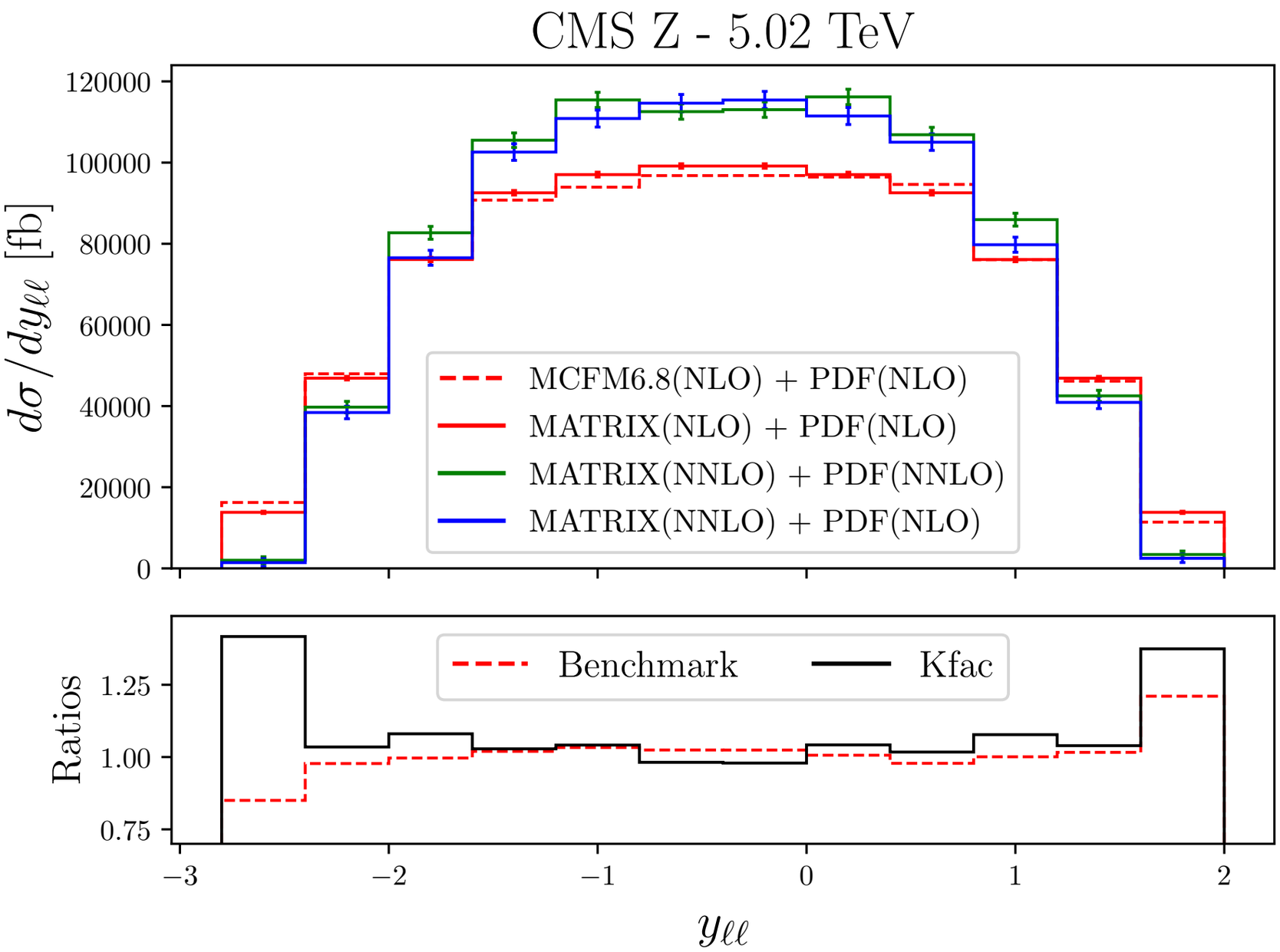
$$\approx \hat{\sigma}^{\mathrm{NNLO}}\left(pp \to \ell\ell\right) \otimes \mathscr{L}_{pp}^{\mathrm{NNLO}} \Big/ \hat{\sigma}^{\mathrm{NNLO}}\left(pp \to \ell\ell\right) \otimes \mathscr{L}_{pp}^{\mathrm{NLO}}$$

$$\approx K_{\mathrm{pp}}^{\mathrm{NNLO}}$$ **(With the appropriate pA kinematics)**

$$\sigma^{\mathrm{NNLO}}\left(pA \to \ell\ell\right) \approx K_{\mathrm{pp}}^{NNLO} \cdot \hat{\sigma}^{\mathrm{NNLO}}\left(pp \to \ell\ell\right) \otimes \overbrace{f_p^{\mathrm{NLO}} \otimes f_A^{\mathrm{NLO}}}^{\mathscr{L}_{pA}^{\mathrm{NLO}}}$$

CMS Z pPb 5 TeV

We started computing $K_{\mathrm{pp}}^{\mathrm{NNLO}}$ Using MATRIX [arXiv:1711.06631]



Will improve with increased accuracy

nNNPDF3.0 Status

CMS pPb dijet at 5 TeV

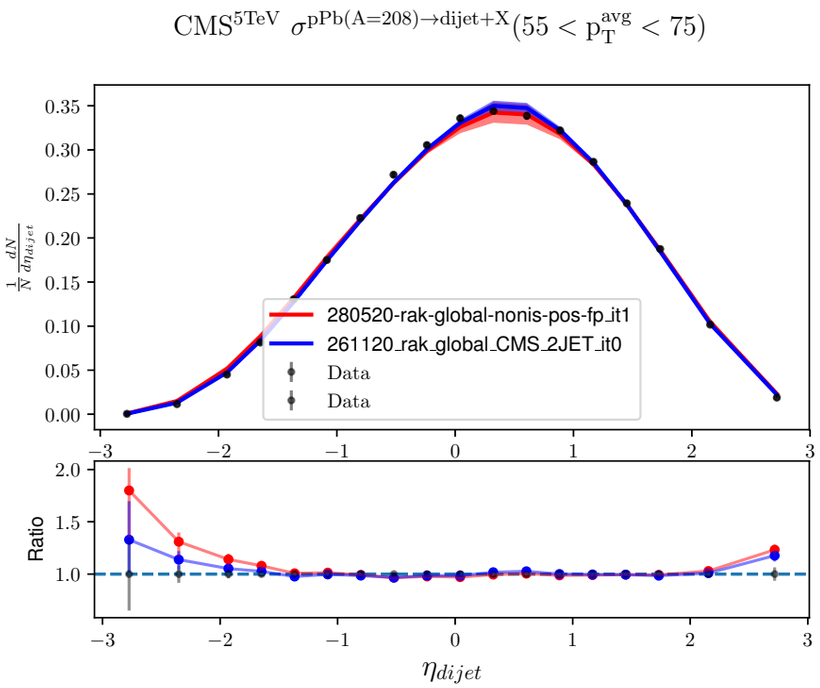
- Problem with the observable? Systematic uncertainties and missing correlations might be crucial to describe well this dataset.
- Inability to describe its pp data with NNPDF3.1 seems the main bottleneck to be able to fit pPb data with nNNPDF2.0
- NNLO k-factors need investigation.
- In order to include this dataset, we would need to cut out the extreme rapidity bins.

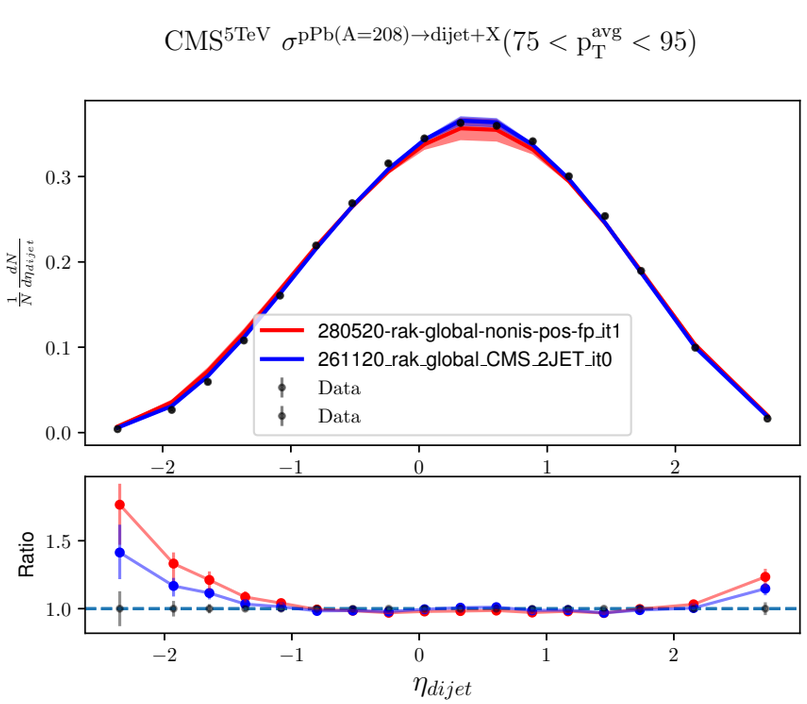
Drell-Yan at NNLO

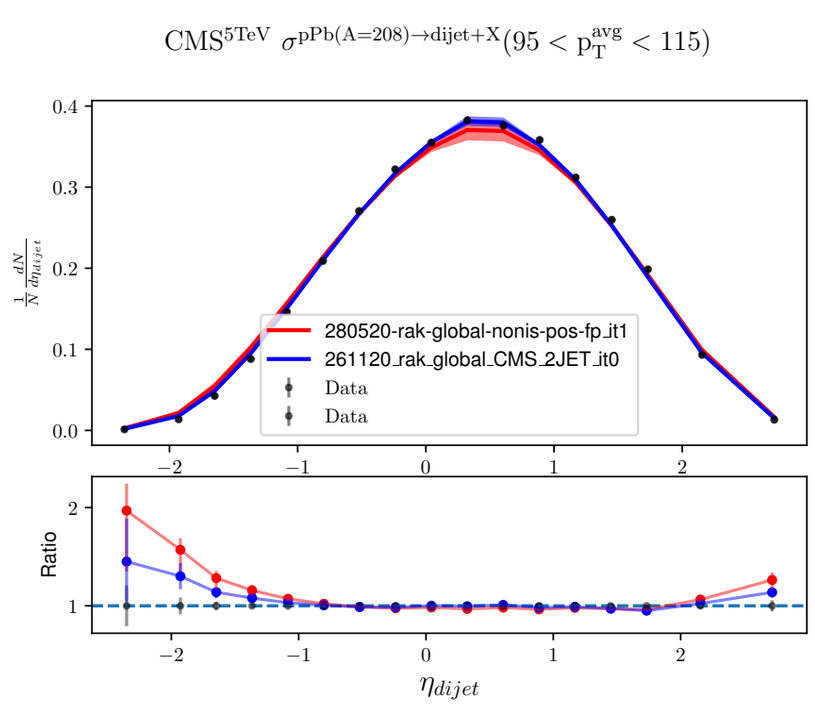
- CMS pPb Z at 5 TeV — completed ✔
- ATLAS pPb Z at 5 TeV — on the way
- ATLAS pPb $W^{\pm}$ at 5 and 8 TeV — on the way

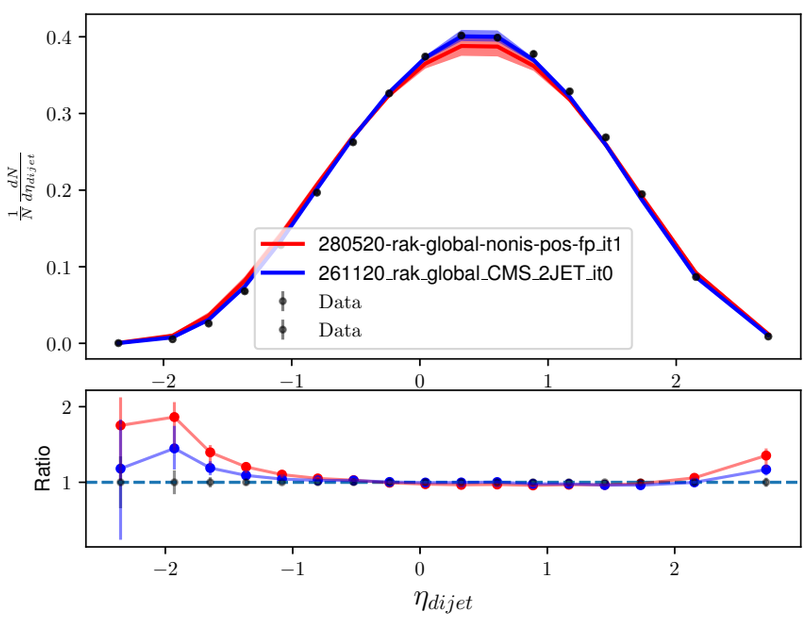
Appendix

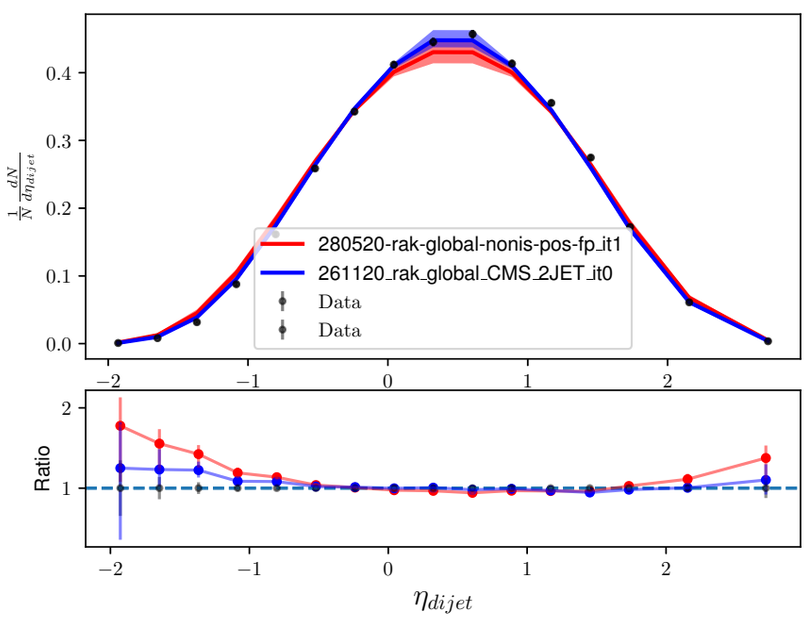
nNNPDF2.0 + p-Pb CMS











Dijet Paper

Experiment	Measurement	$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	R	Distribution	$n_{\rm dat}$
ATLAS	Inclusive jets	7	4.5	0.6	$d^2\sigma/dp_T d\|y\|$	140
CMS	Inclusive jets	7	4.5	0.7	$d^2\sigma/dp_T d\|y\|$	133
ATLAS	Inclusive jets	8	20.2	0.6	$d^2\sigma/dp_T d\|y\|$	171
CMS	Inclusive jets	8	19.7	0.7	$d^2\sigma/dp_T d\|y\|$	185
ATLAS	Dijets	7	4.5	0.6	$d^2\sigma/dm_{jj} d\|y^*\|$	90
CMS	Dijets	7	4.5	0.7	$d^2\sigma/dm_{jj} d\|y_{\rm max}\|$	54
CMS	Dijets	8	19.7	0.7	$d^3\sigma/dp_{T,\rm avg} dy_b dy^*$	122

	$\rm NLO_{QCD}$	$\rm NNLO_{QCD}$
baseline (NNPDF3.1 w/o jets)	b	bn
ATLAS & CMS jets 7-8 TeV	ja	jan
ATLAS & CMS dijets 7-8 TeV	da	dan

Absence of correlation

+ EW corrections considered in the paper

NNPDF3.1 w/ CMS dijet 5 TeV

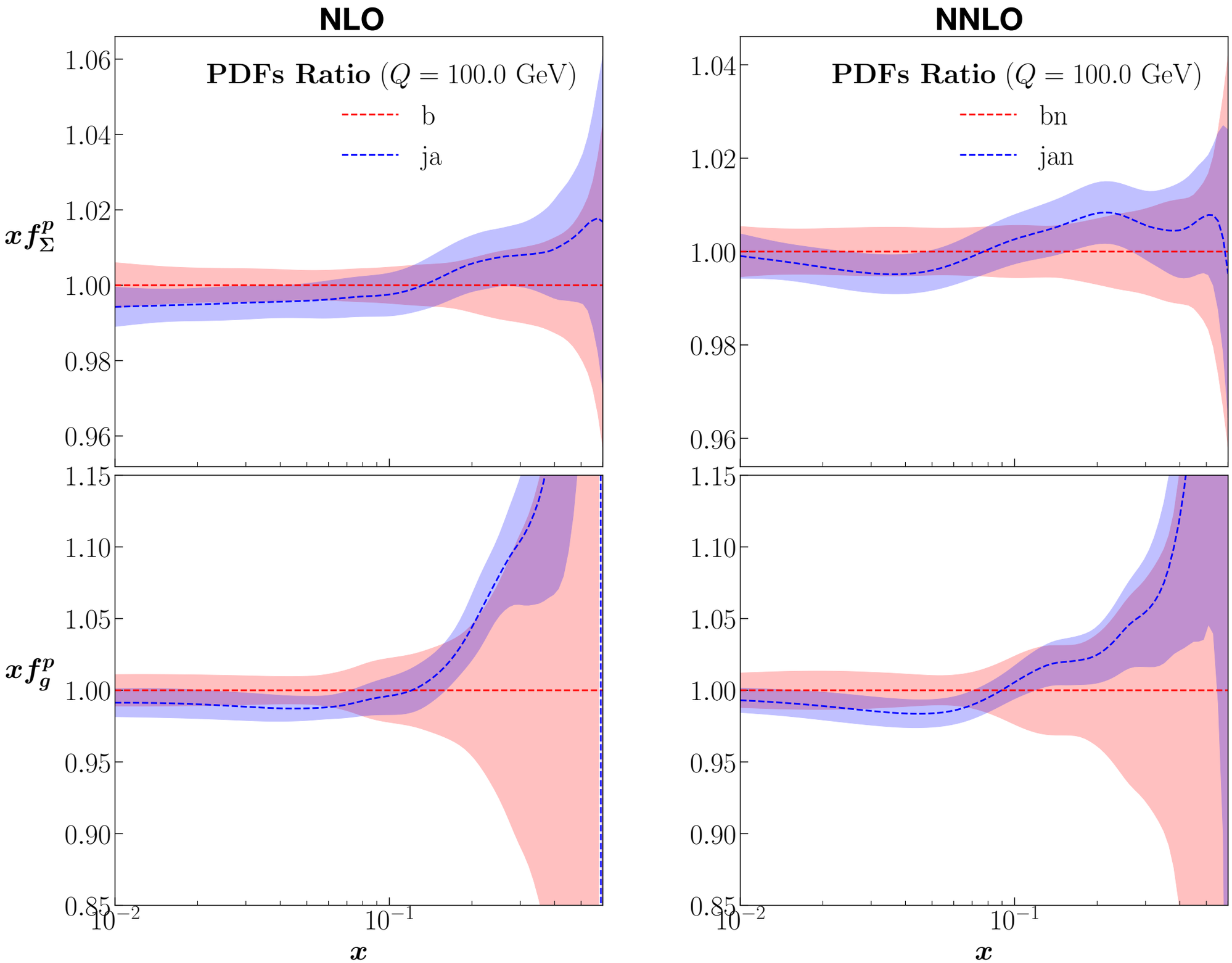
NNPDF3.1
+ 7 and 8 TeV Dijet (paper)
± CMS dijet 5 TeV

$$K_{\mathrm{NNLO}}^{\mathrm{QCD}} \equiv \frac{\sum_{ij} \widetilde{\sigma}_{ij}^{\mathrm{NNLO}} \otimes \mathcal{L}_{ij}^{\mathrm{NNLO}}}{\sum_{ij} \widetilde{\sigma}_{ij}^{\mathrm{NLO}} \otimes \mathcal{L}_{ij}^{\mathrm{NNLO}}},$$

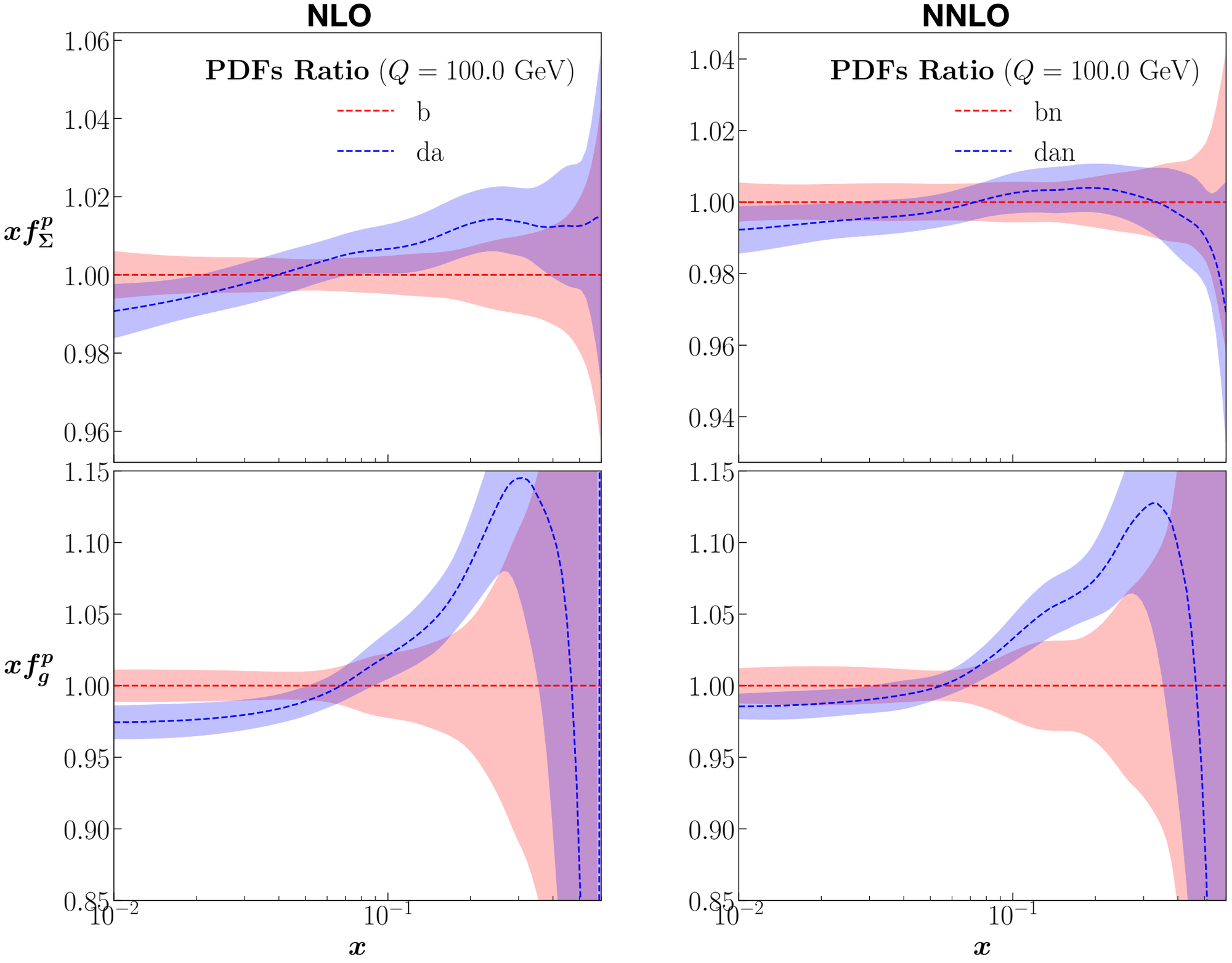
$\chi^2/\mathrm{n_{dat}}$

Dataset	n_{dat}	w/o (NLO)	w/ (NLO)	w/o (NNLO)	w/ (NNLO)
DIS NC	2113	1.28	1.31	1.25	1.27
DIS CC	81	1.24	1.25	1.15	1.16
Drell-Yan	440	1.36	1.33	1.21	1.24
$Z\ p_T$	120	2.22	2.26	1.11	1.09
Top pair	25	1.67	1.11	1.27	1.27
Dijets (all)	351	3.27	2.43	4.21	3.00
ATLAS 7 TeV	90	1.03	1.01	1.98	1.91
CMS 7 TeV	54	1.58	2.03	1.75	1.92
CMS 8 TeV	122	3.87	3.61	1.48	1.55
CMS 5 TeV	**85**	**[5.87]**	**2.51**	**[12.04]**	**6.91**
Total		1.37	1.42	1.24	1.41

Single Jet


NLO
NNLO
PDFs Ratio ($Q = 100.0$ GeV)
b
ja
bn
jan
$x f_\Sigma^p$
$x f_g^p$
x
1.06
1.04
1.02
1.00
0.98
0.96
1.15
1.10
1.05
1.00
0.95
0.90
0.85
10^{-2}
10^{-1}

Dijet


NLO
NNLO
PDFs Ratio ($Q = 100.0$ GeV)
b
da
bn
dan
$x f_\Sigma^p$
$x f_g^p$
x
1.06
1.04
1.02
1.00
0.98
0.96
0.94
1.15
1.10
1.05
0.95
0.90
0.85
10^{-2}
10^{-1}