# Towards nNNPDF3.0: A global analysis of nuclear parton distributions at NNLO

# and the impact of the Electron Ion Collider

**9th Workshop of the APS Topical Group on Hadronic Physics**

Rabah Abdul Khalek

Tuesday 15/04/2021

# Outline

1

**nNNPDF2.0 and NNPDF3.1**

**Parameterisation - Constraints**

*"Parton distributions from high-precision collider data"*

— *arXiv:1706.00428*

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

— *arXiv:2006.14629*

2

**Electron Ion collider Impact**

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

— *arXiv:2102.00018*

*"Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report"*

— *arXiv:2103.05419*

3

**Towards nNNPDF3.0**

**CMS 5 TeV dijets - DY at NNLO**

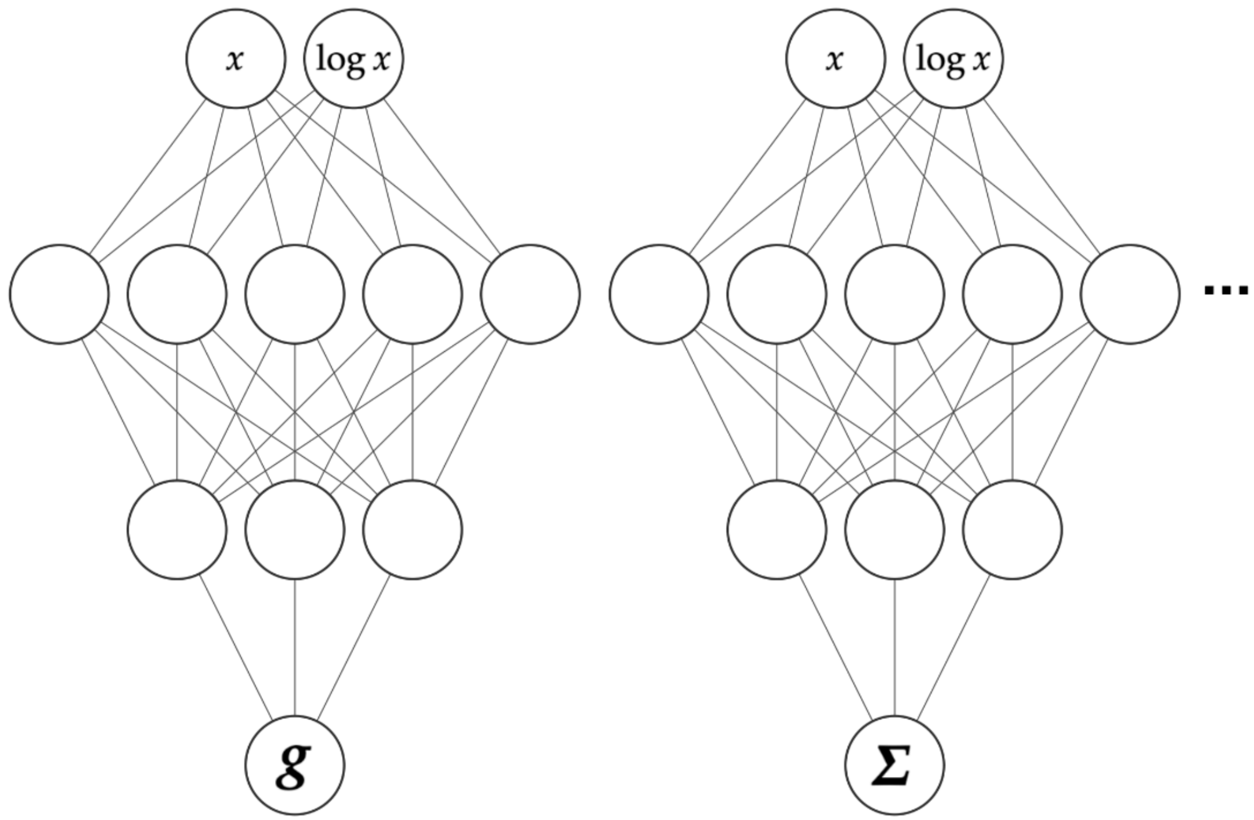
*"Phenomenology of NNLO jet production at the LHC and its impact on parton distributions"*

— *arXiv:2005.11327*

# NNPDF3.1 Parameterisation

NNPDF3.1 parameterisation basis: $\{\boldsymbol{g} \quad \boldsymbol{\Sigma} \quad \boldsymbol{T_3} \quad \boldsymbol{T_8} \quad \boldsymbol{V} \quad \boldsymbol{V_3} \quad \boldsymbol{V_8} \quad (\boldsymbol{c}^+)\}$

and $\boldsymbol{b} = \boldsymbol{t} = 0$ at $Q_0 = 1\ (1.65)$ GeV




$$\Sigma = \sum_i^{n_f} f_i^+ \text{ (Singlet)}$$

$$T_3 = u^+ - d^+$$

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

$$V = \sum_i^{n_f} f_i^- \text{ (Valence)}$$

$$V_3 = u^- - d^-$$

$$V_8 = u^- + d^- - 2s^-$$

$$f_i(x, Q_0) = A_i \hat{f}_i(x, Q_0), \quad \hat{f}_i(x, Q_0) = x^{\alpha_i}(1-x)^{\beta_i} NN_i(x)$$

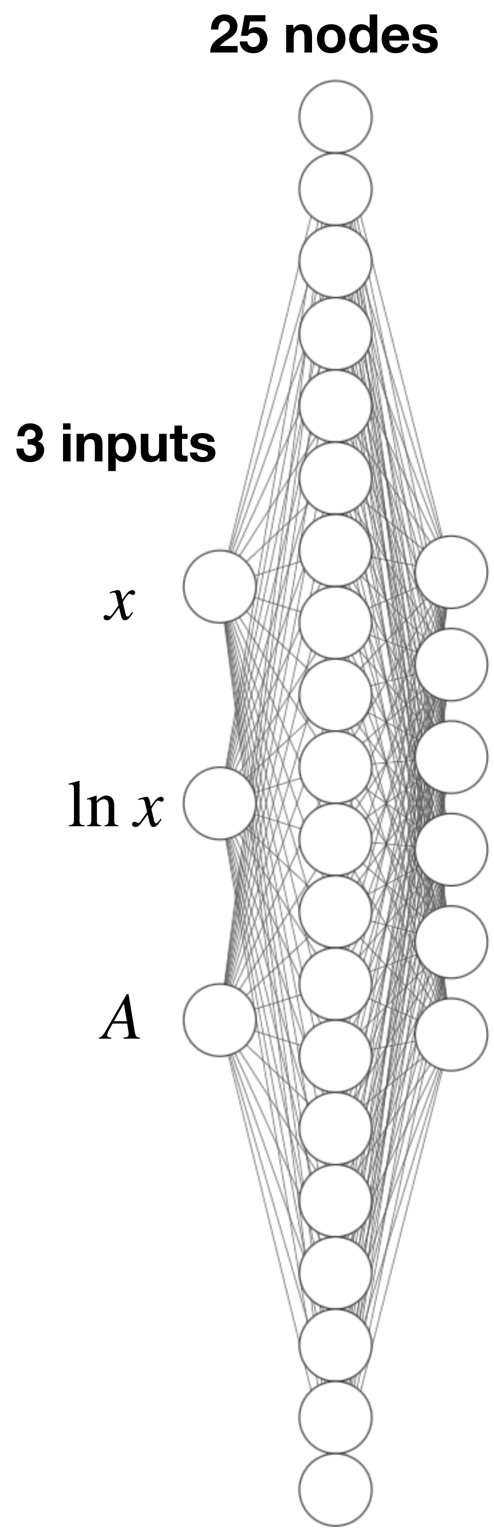
$$A_g = \frac{1 - \int_0^1 dx x\Sigma(x, Q_0)}{\int_0^1 dx x\hat{g}(x, Q_0)}, \quad A_\Sigma = A_{T_3} = A_{T_8} = 1$$

$$A_V = \frac{3}{\int_0^1 dx \hat{V}(x, Q_0)}, \quad A_{V_3} = \frac{1}{\int_0^1 dx \hat{V}_3(x, Q_0)}, \quad A_{V_8} = \frac{3}{\int_0^1 dx \hat{V}_8}$$

# nNNPDF2.0 Parameterisation

nNNPDF2.0 parameterisation basis: $\{g \quad \Sigma \quad T_3 \quad T_8 \quad V \quad V_3\}$

and $b = t = 0$ at $Q_0 = 1$ GeV




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

**6 independent flavours, 256 free parameters**

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

Sum Rules

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

# nNNPDF2.0 Constraints

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

**Common with NNPDF3.1**

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

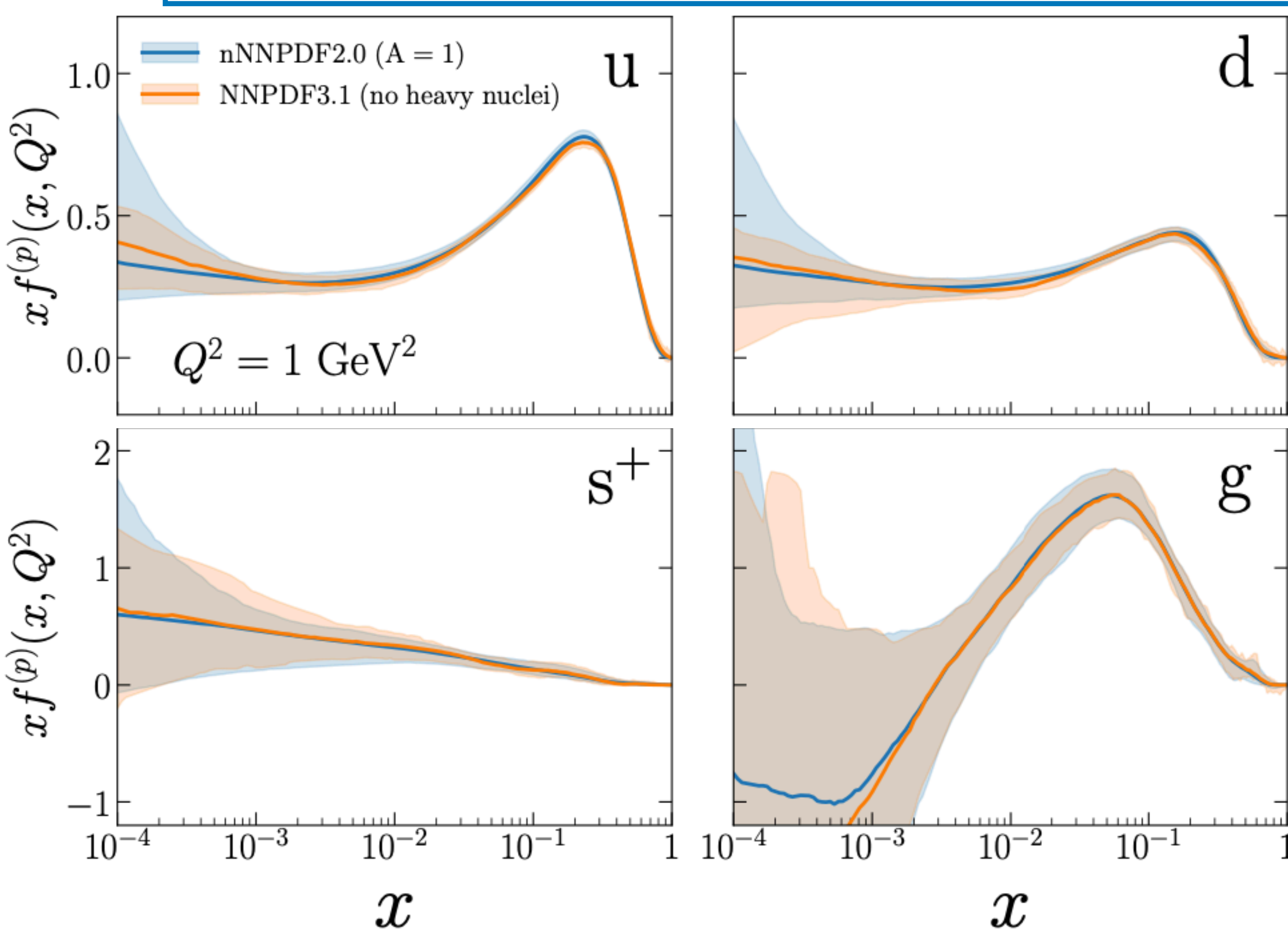
**nNNPDF2.0 A=1 Boundary condition**
**Member-by-member correlation**

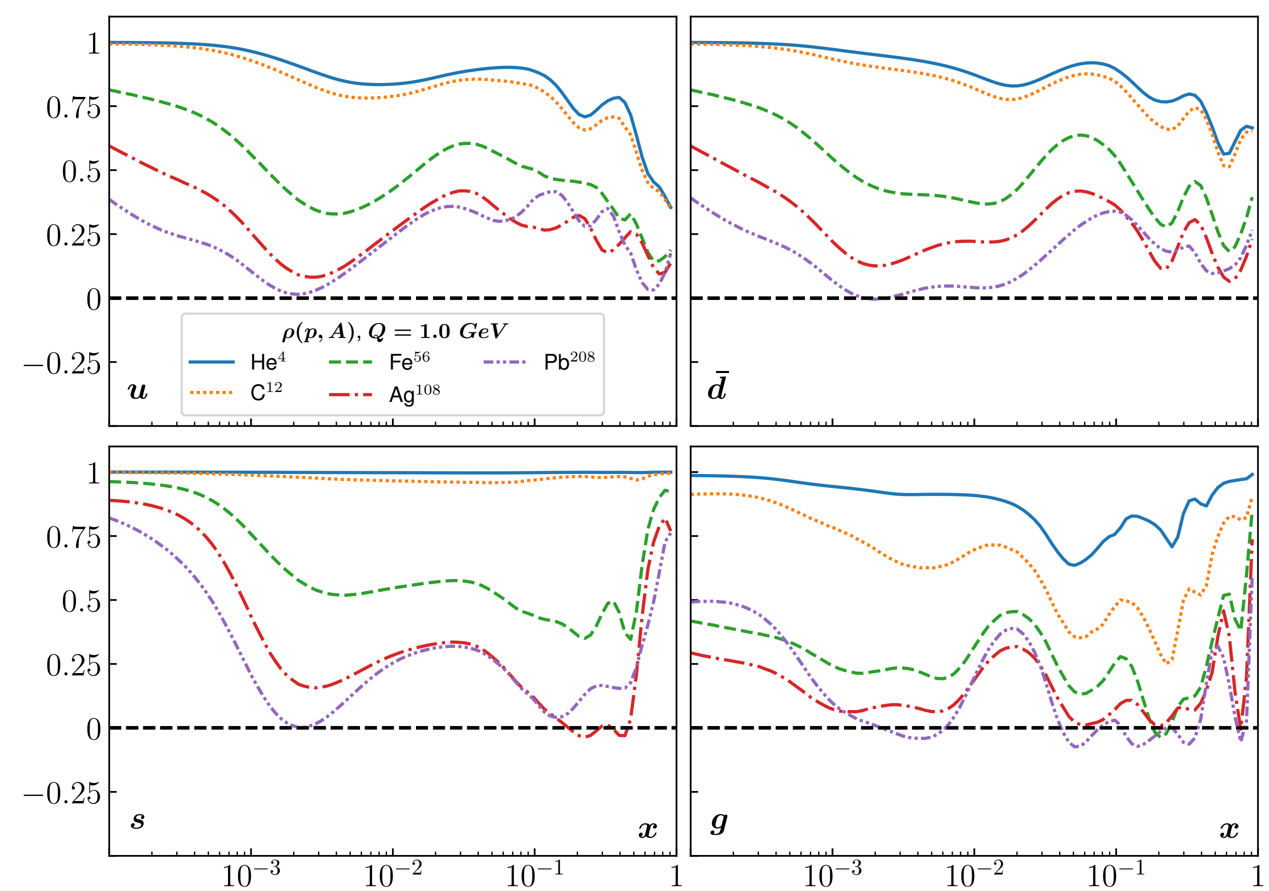
$$+\lambda_{pos} \sum_{k}^{N_{\rm pos}} \max(0, -O_k^{pos}) \longrightarrow$$

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

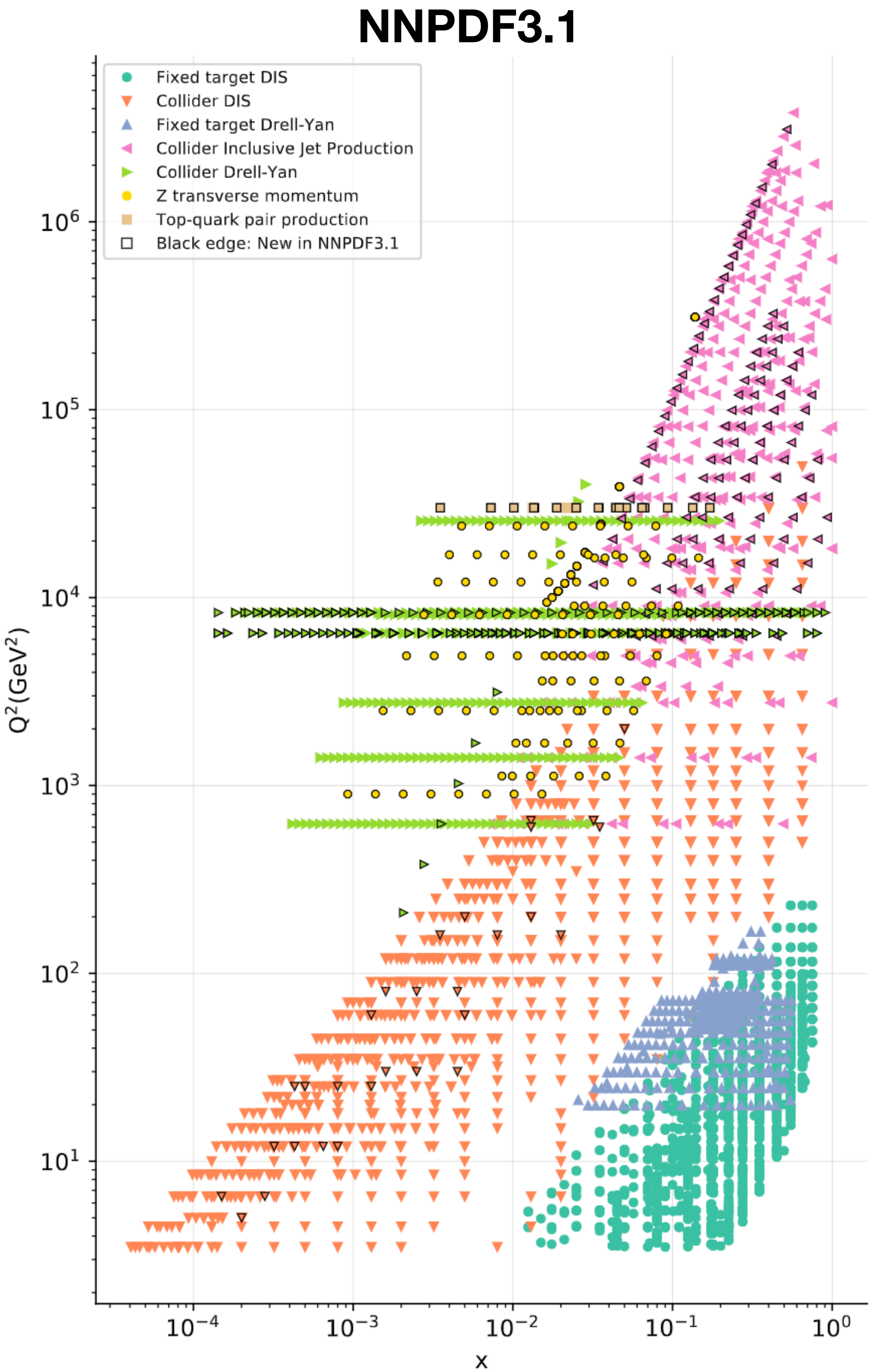
$$F_2^u,\ F_2^d,\ F_2^s,\ d^2_{M^2y}\sigma^{DY}_{u\bar{u}},\ d^2_{M^2y}\sigma^{DY}_{d\bar{d}},\ d^2_{M^2y}\sigma^{DY}_{s\bar{s}},\ F_L^l$$

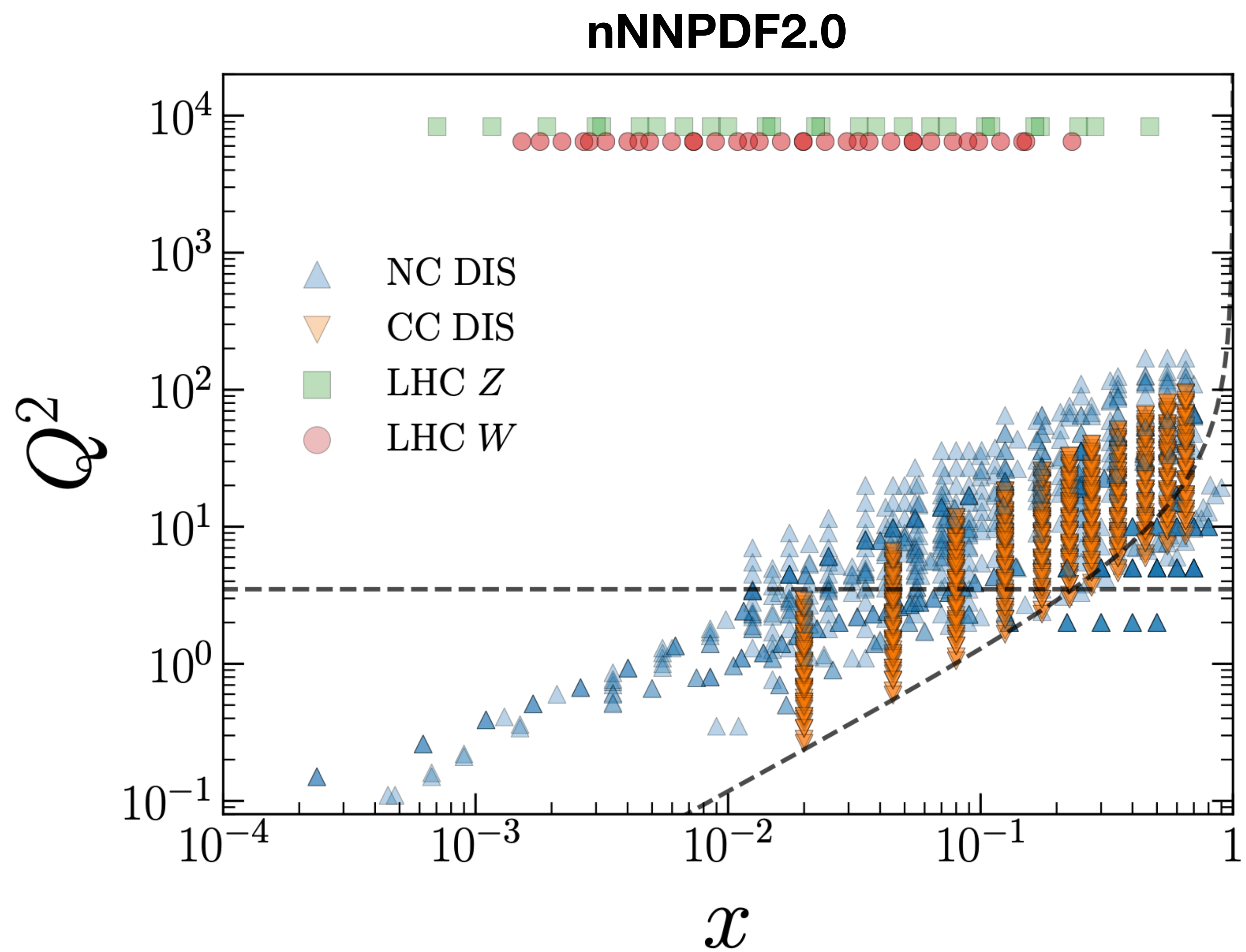
**Common with NNPDF3.1**



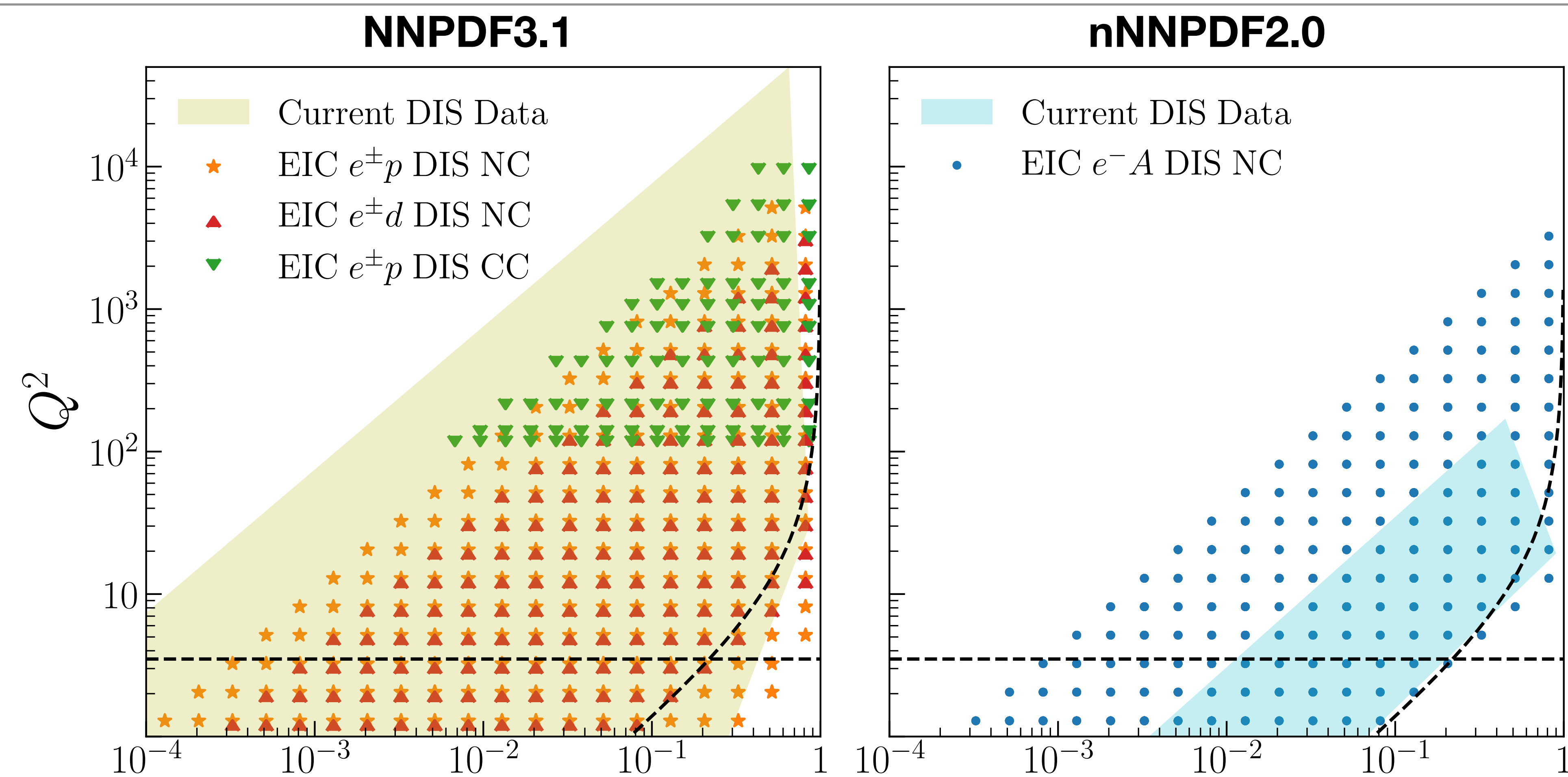
# Kinematic coverage

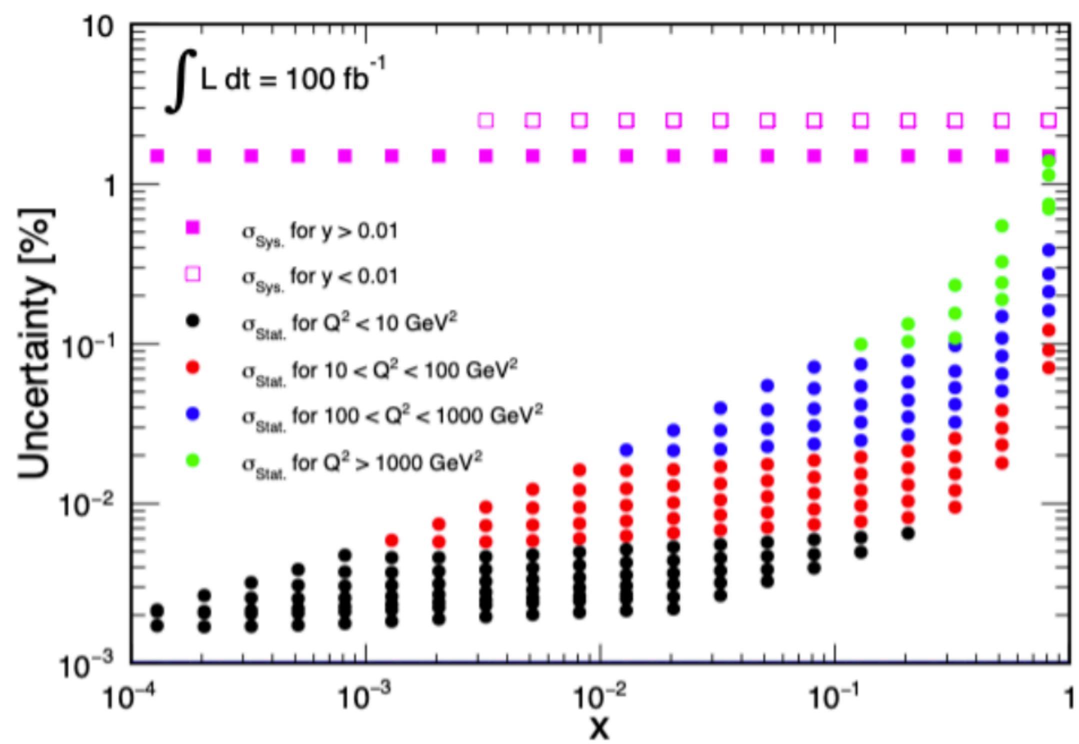


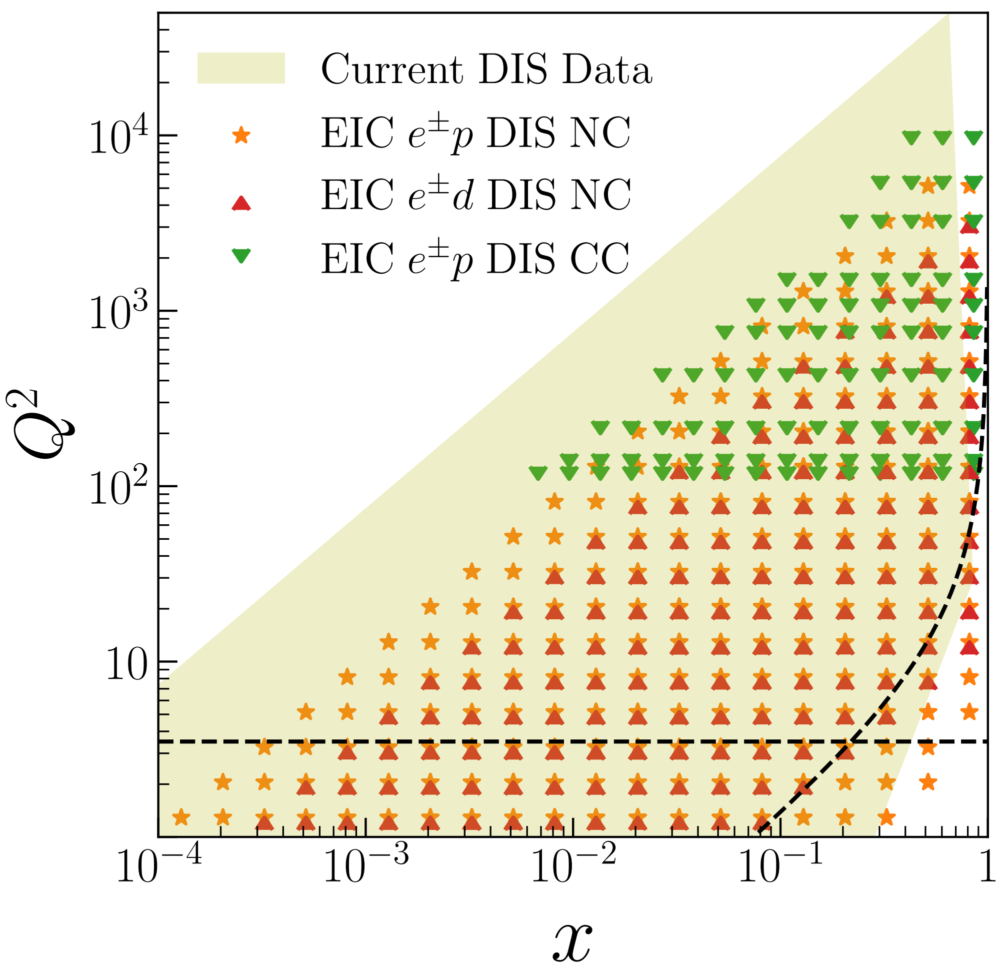
# Impact of the Electron-Ion Collider On NNPDF3.1 and nNNPDF2.0

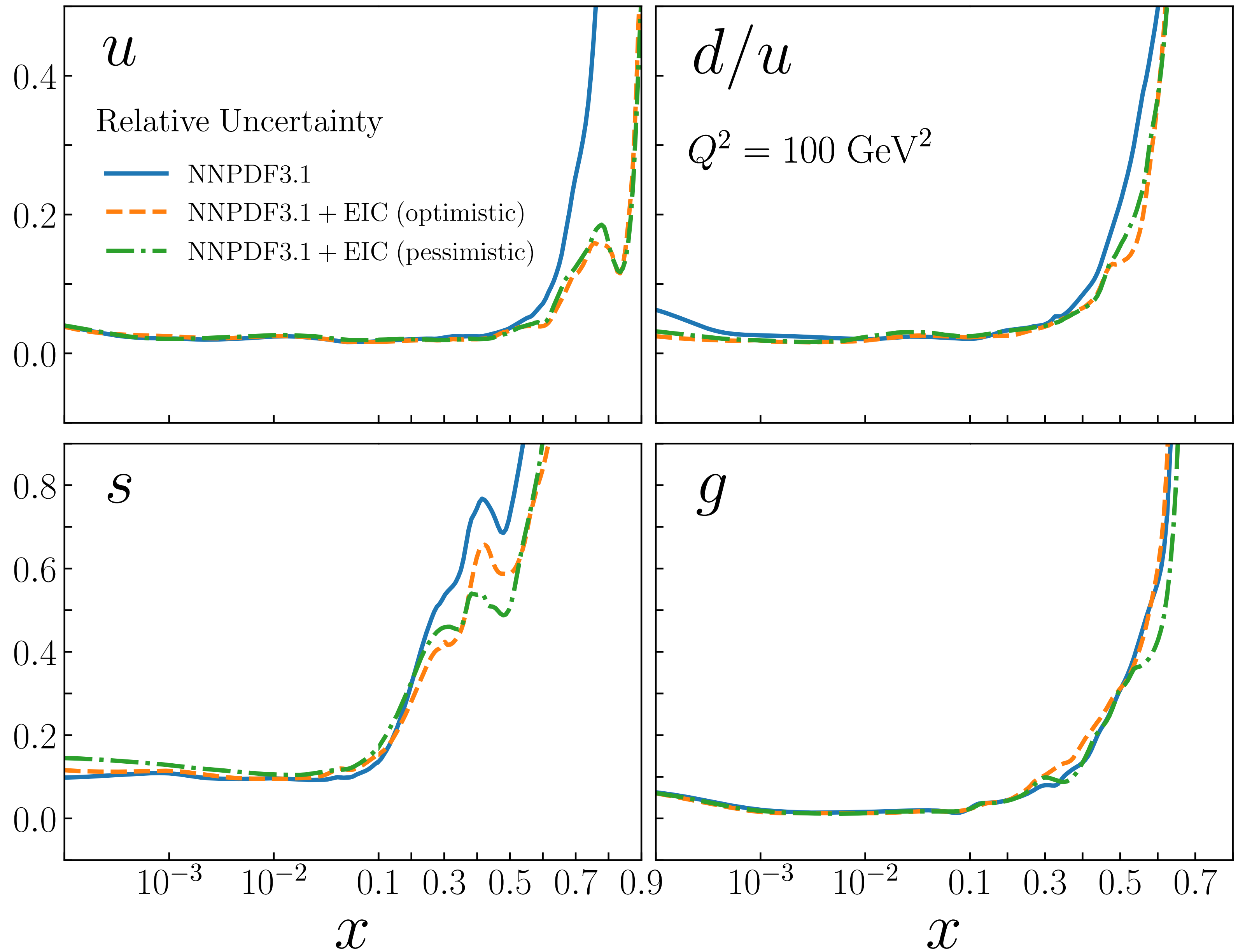
# EIC Kinematic coverage



# EIC impact on PDFs

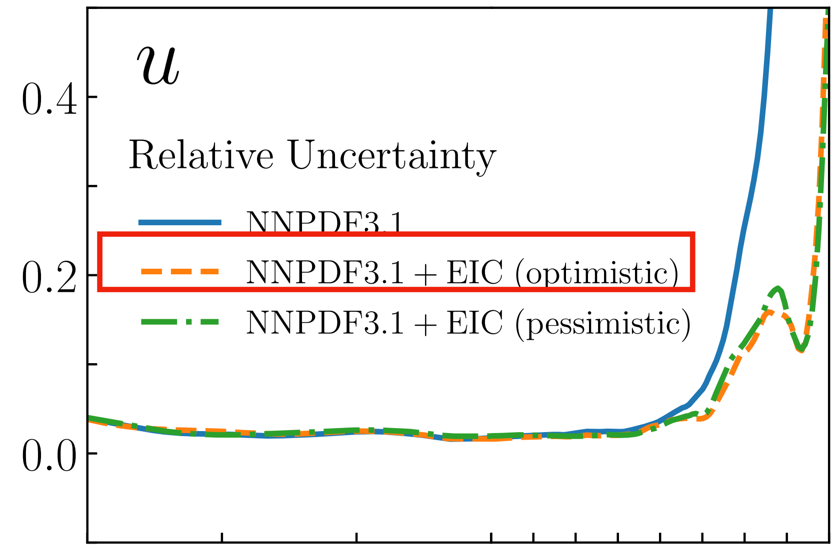



- **EIC could reduce the uncertainty of the light quark PDFs of the proton at large x**
- **Size of this reduction is similar for both the optimistic and pessimistic scenarios.**

# EIC impact on PDFs

**We take NNPDF3.1 + EIC (optimistic)**
**To be the boundary condition in**
**nNNPDF2.0 + EIC (optimistic)**




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

**Common with NNPDF3.1**

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

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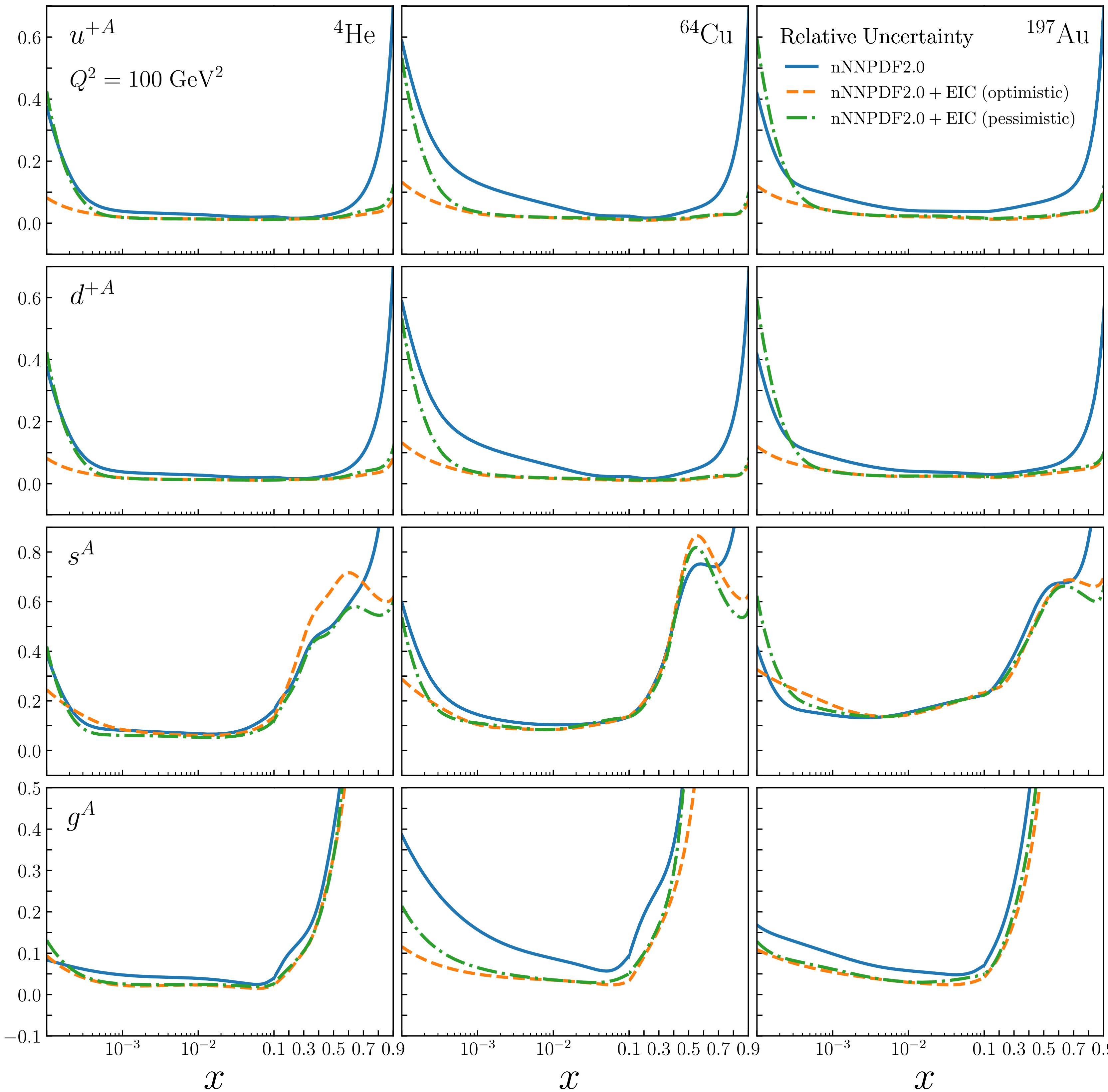
$$+\lambda_{pos} \sum_{k}^{N_{\rm pos}} \max(0, -O_k^{pos}) \longrightarrow$$

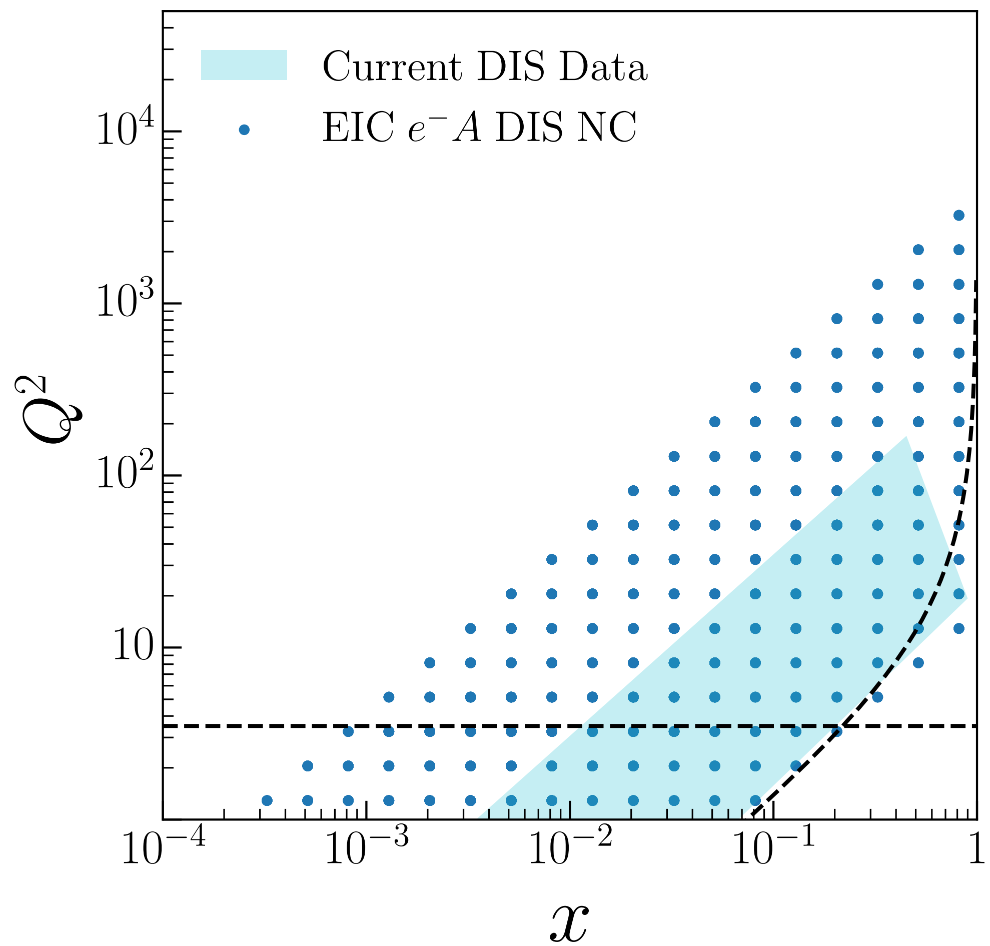
**Positivity constraint for** $x \in [10^{-7}, 1]$

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

**Common with NNPDF3.1**

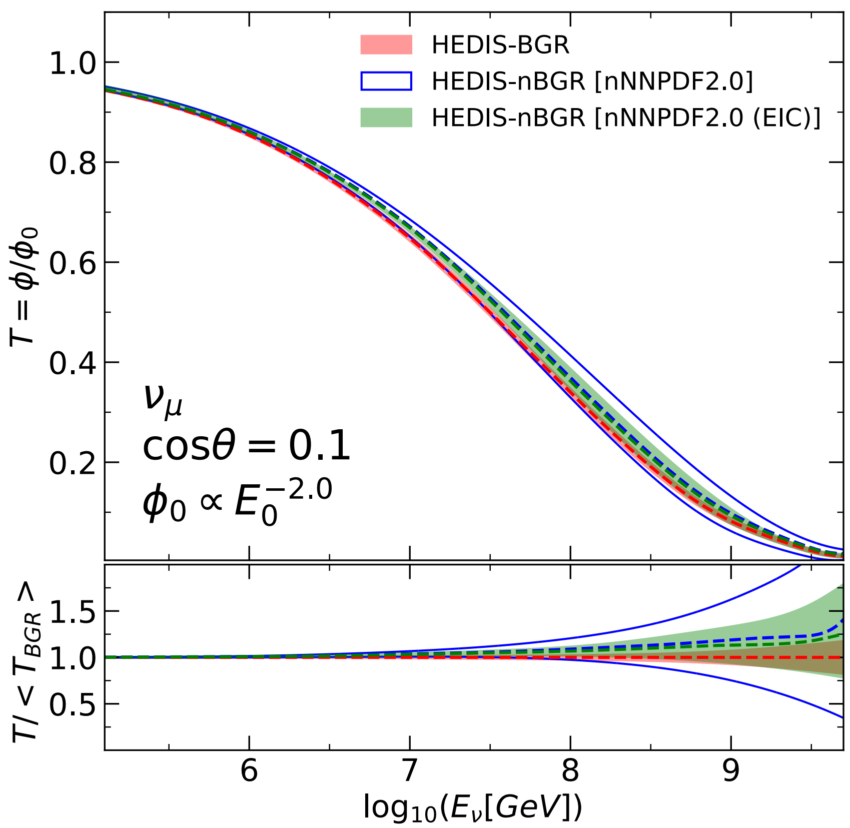
# EIC impact on nPDFs

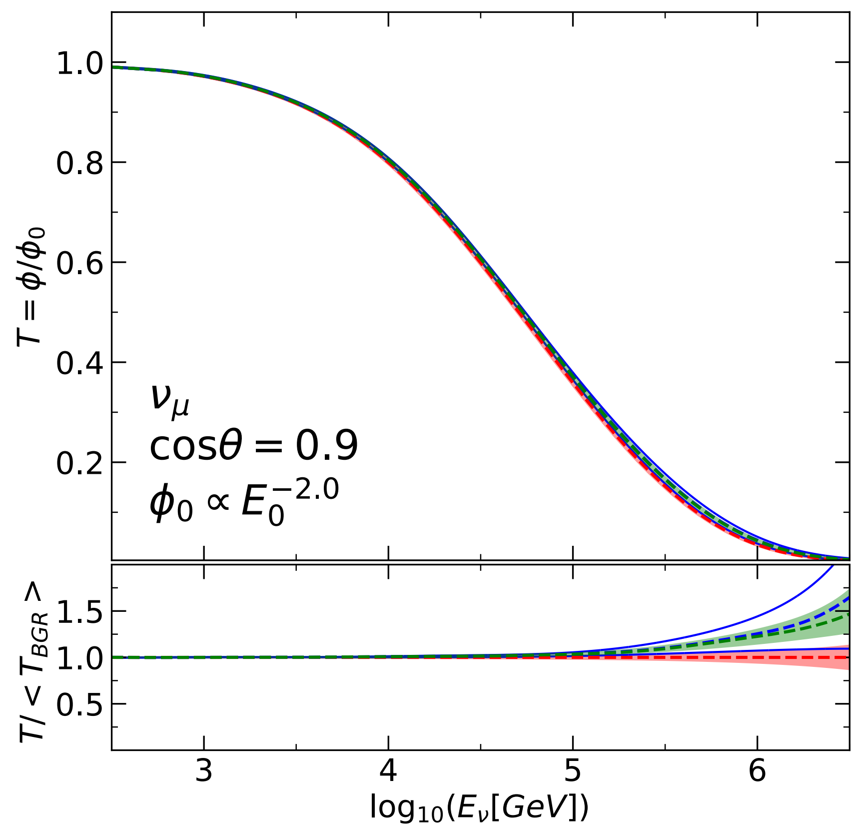


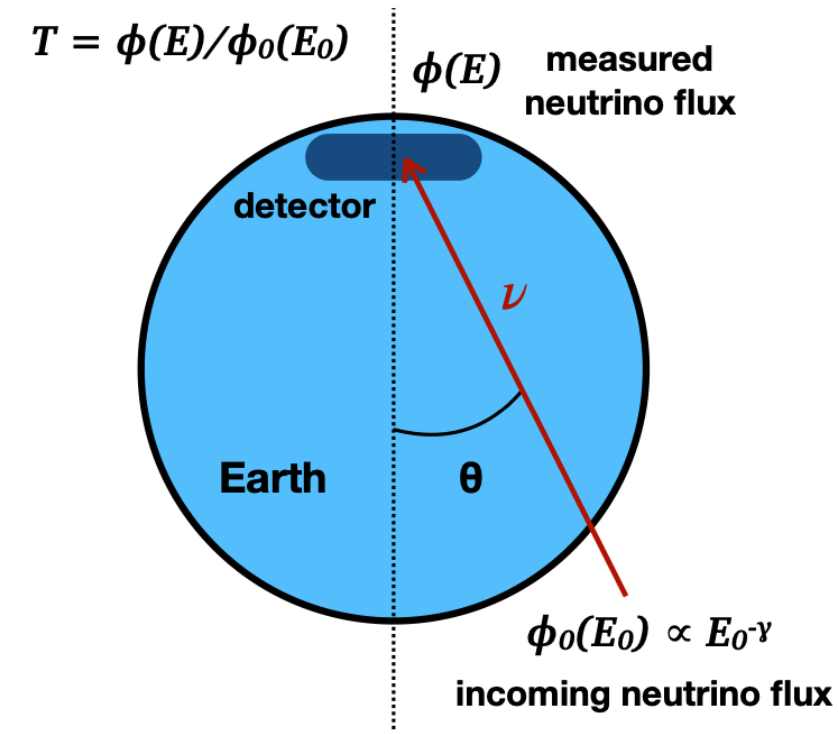



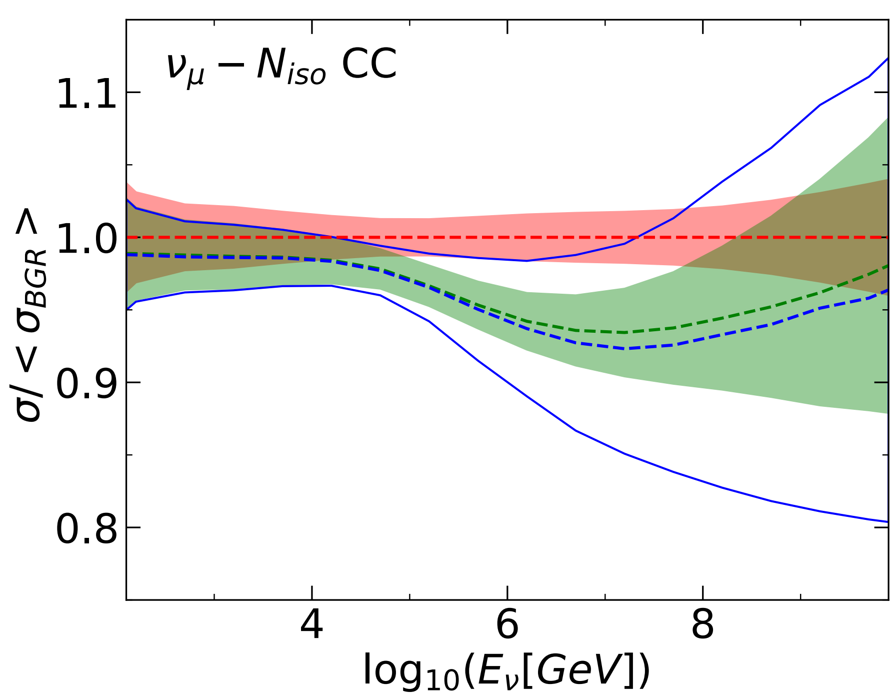

- **Reduction of nPDF uncertainties for nuclei in a wide range of atomic mass A values both at small and large-x.**
- **At large-x region, nPDF benefit from the increased precision of the baseline proton PDFs.**

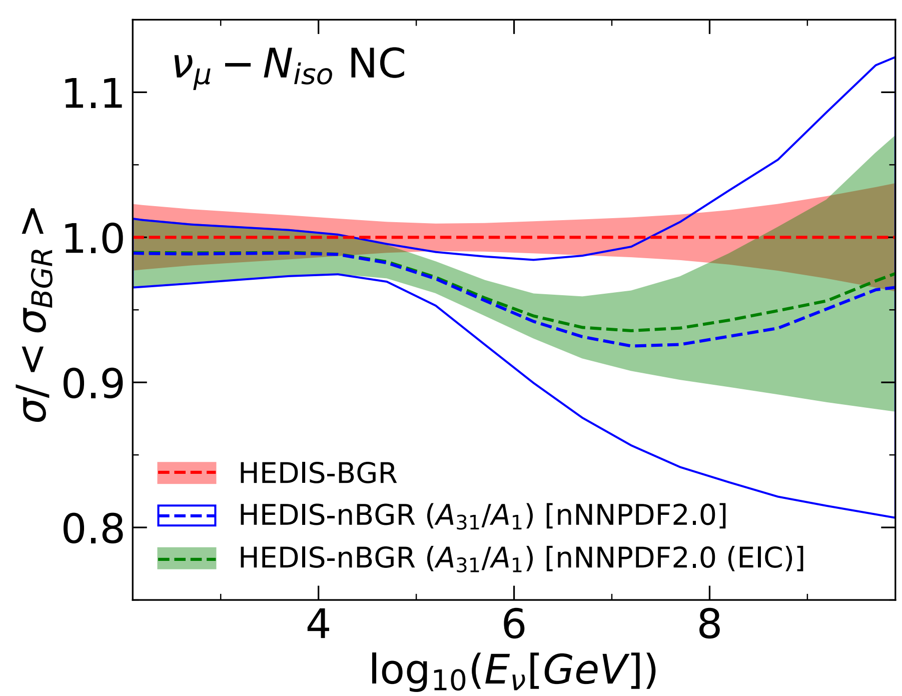
# Implications



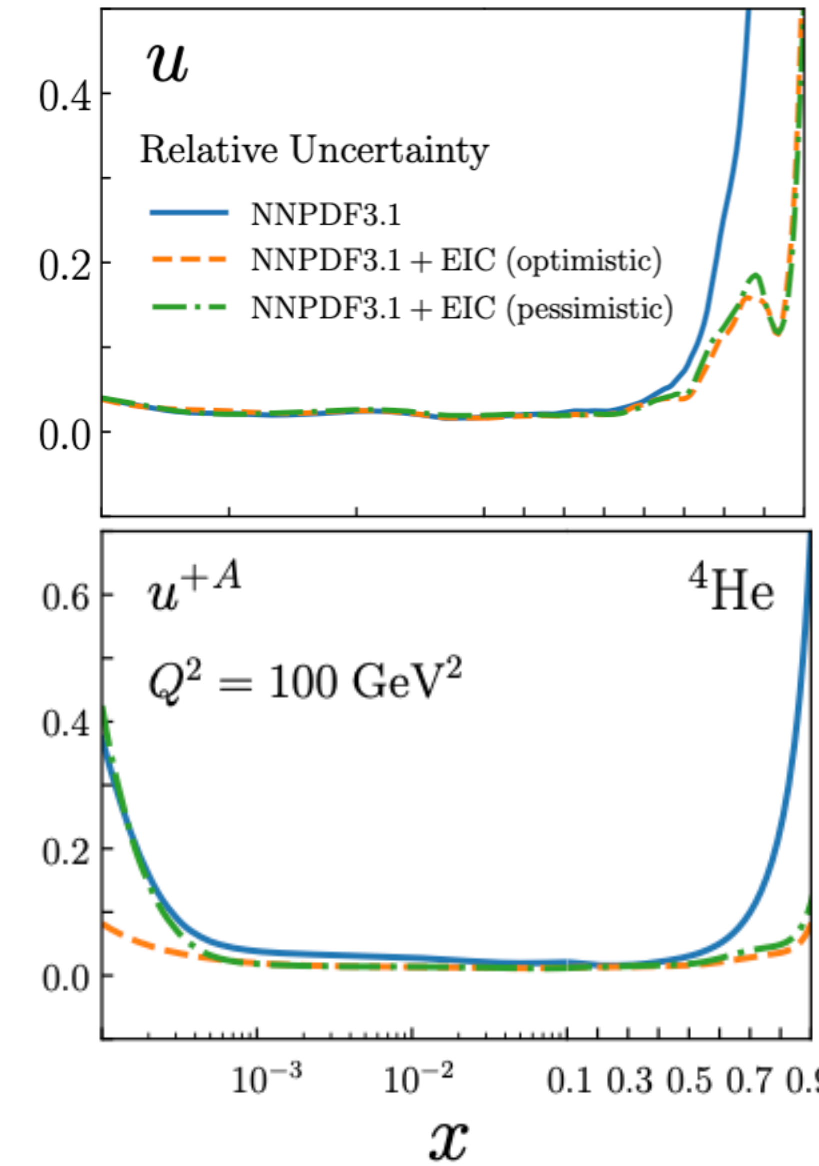

**We average the earth nuclei by**
$A \sim 31,\ Z \sim 15$

**For the HEDIS-BGR proton a variant of NNPDF3.1 used**

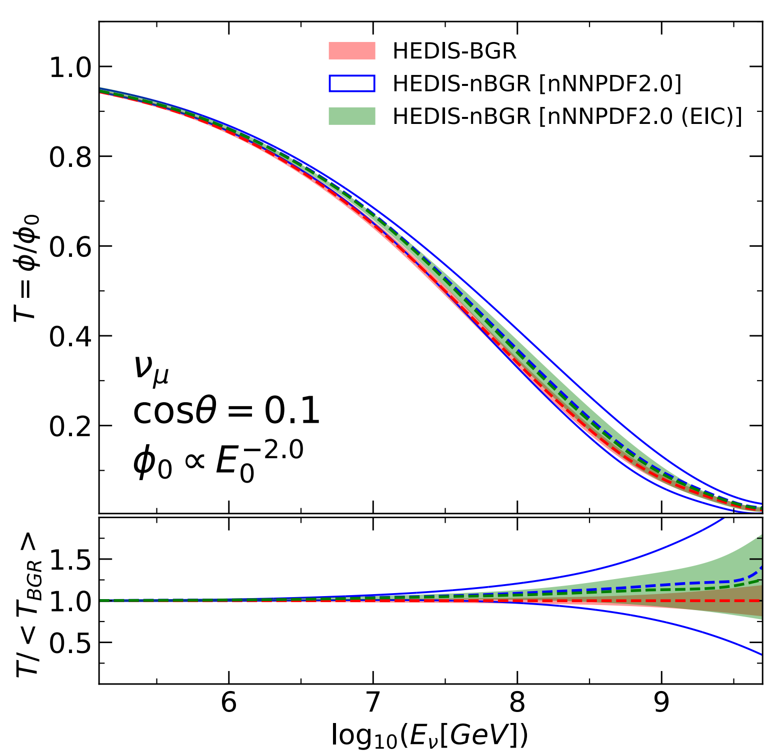
**the EIC pseudodata is seen to reduce the uncertainty of the prediction for a nuclear target by roughly a factor of two for**
$E_\nu \simeq 10^6$ GeV

# EIC Conclusions

- EIC could reduce the uncertainty of the light quark PDFs of the proton at large x
- Size of this reduction is similar for both the optimistic and pessimistic scenarios.




- Reduction of nPDF uncertainties for nuclei in a wide range of atomic mass A values both at small and large-x.
- At large-x region, nPDF benefit from the increased precision of the baseline proton PDFs.



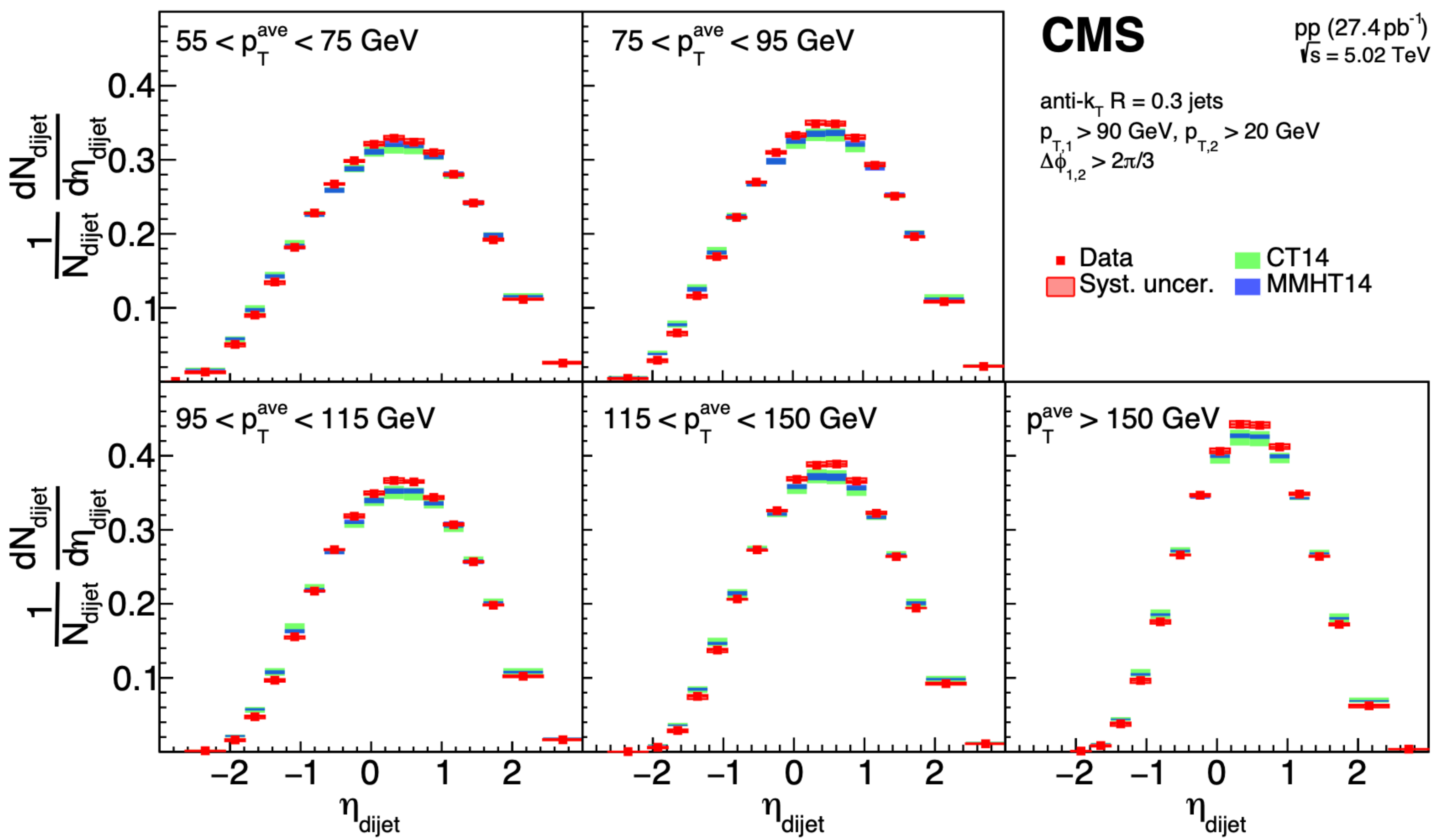

- Improve the modelling of the interactions of ultra-high energy cosmic neutrinos with matter.
- nuclear PDF uncertainties may no longer encompass the difference between $\nu A$ predictions obtained on a proton and on a nuclear target.
- importance of carefully accounting for nuclear PDF effects in high-energy neutrino astrophysics.

# 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)** | **Current 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

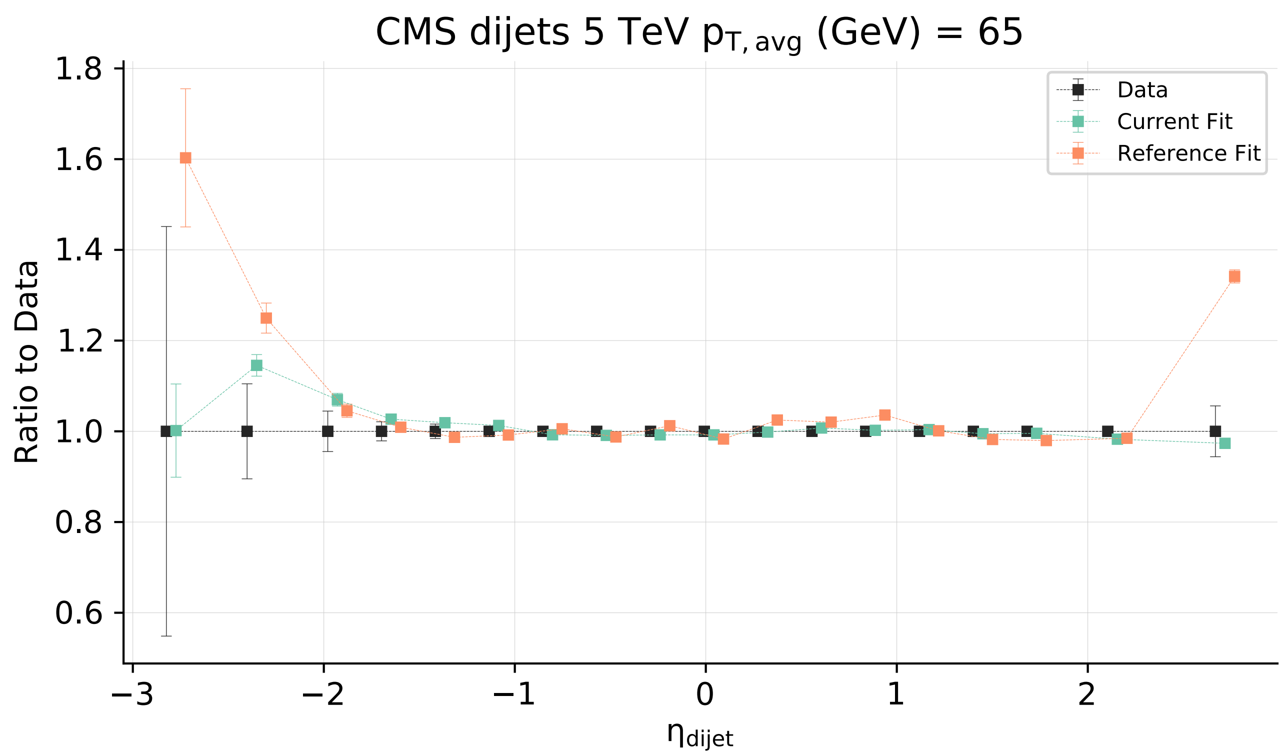


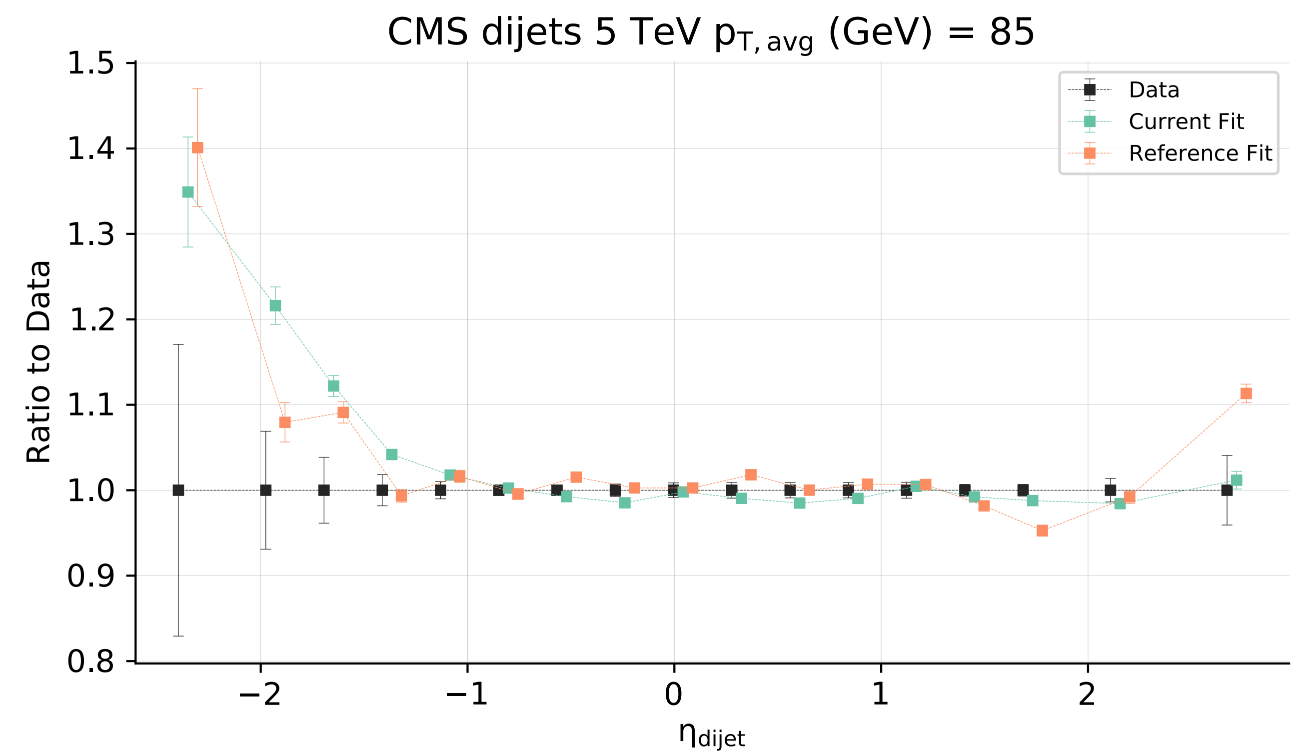
CMS
pp (27.4 pb$^{-1}$)
$\sqrt{s}$ = 5.02 TeV
anti-$k_T$ R = 0.3 jets
$p_{T,1}$ > 90 GeV, $p_{T,2}$ > 20 GeV
$\Delta\phi_{1,2} > 2\pi/3$
Data
Syst. uncer.
CT14
MMHT14
$55 < p_T^{ave} < 75$ GeV
$75 < p_T^{ave} < 95$ GeV
$95 < p_T^{ave} < 115$ GeV
$115 < p_T^{ave} < 150$ GeV
$p_T^{ave} > 150$ GeV
$\frac{1}{N_{dijet}} \frac{dN_{dijet}}{d\eta_{dijet}}$
$\eta_{dijet}$

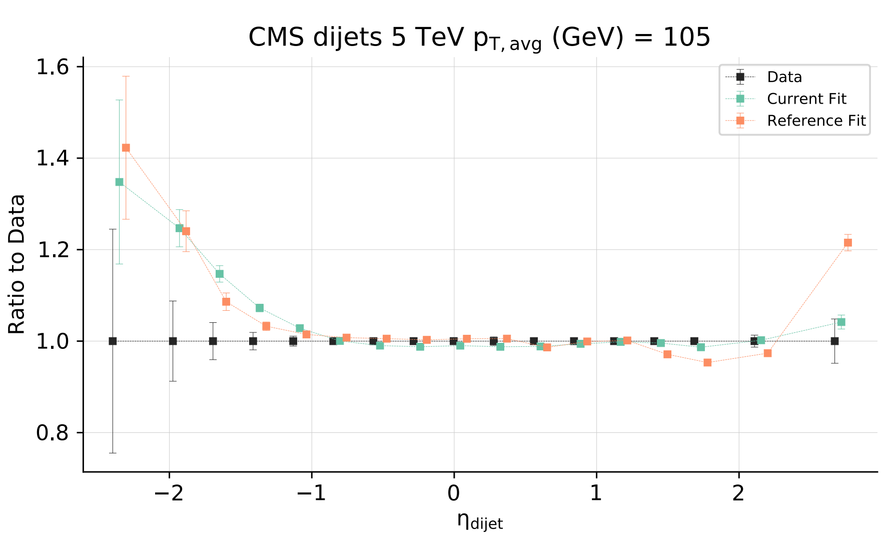
# NNPDF3.1$^{+dijet}$ + pp CMS 5 TeV

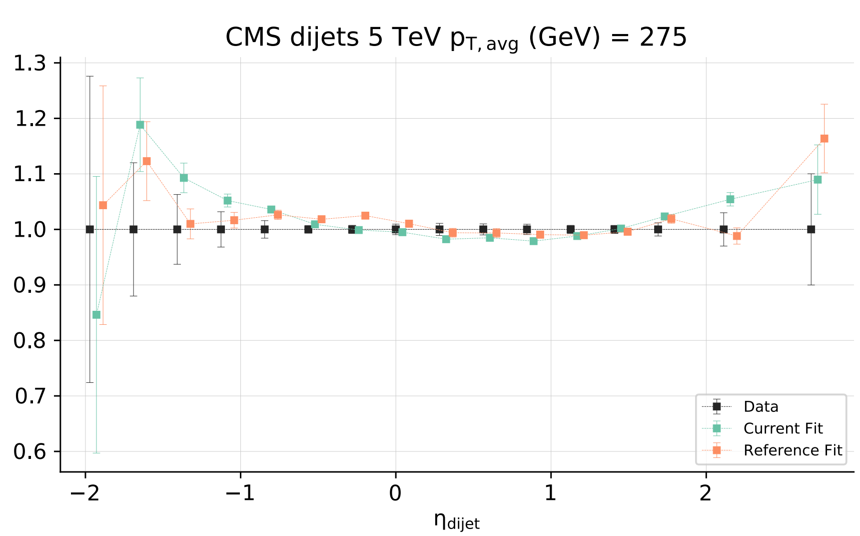
**— NLO** $(\chi^2_{tot}/N = 1.42), (\chi^2_{dataset}/N = 2.51)$

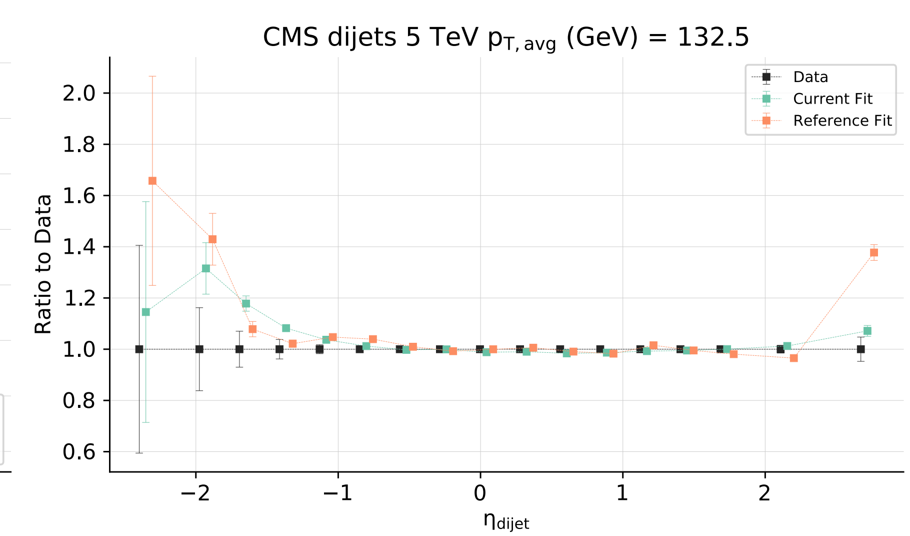
**— NNLO** $(\chi^2_{tot}/N = 1.41), (\chi^2_{dataset}/N = 6.91)$



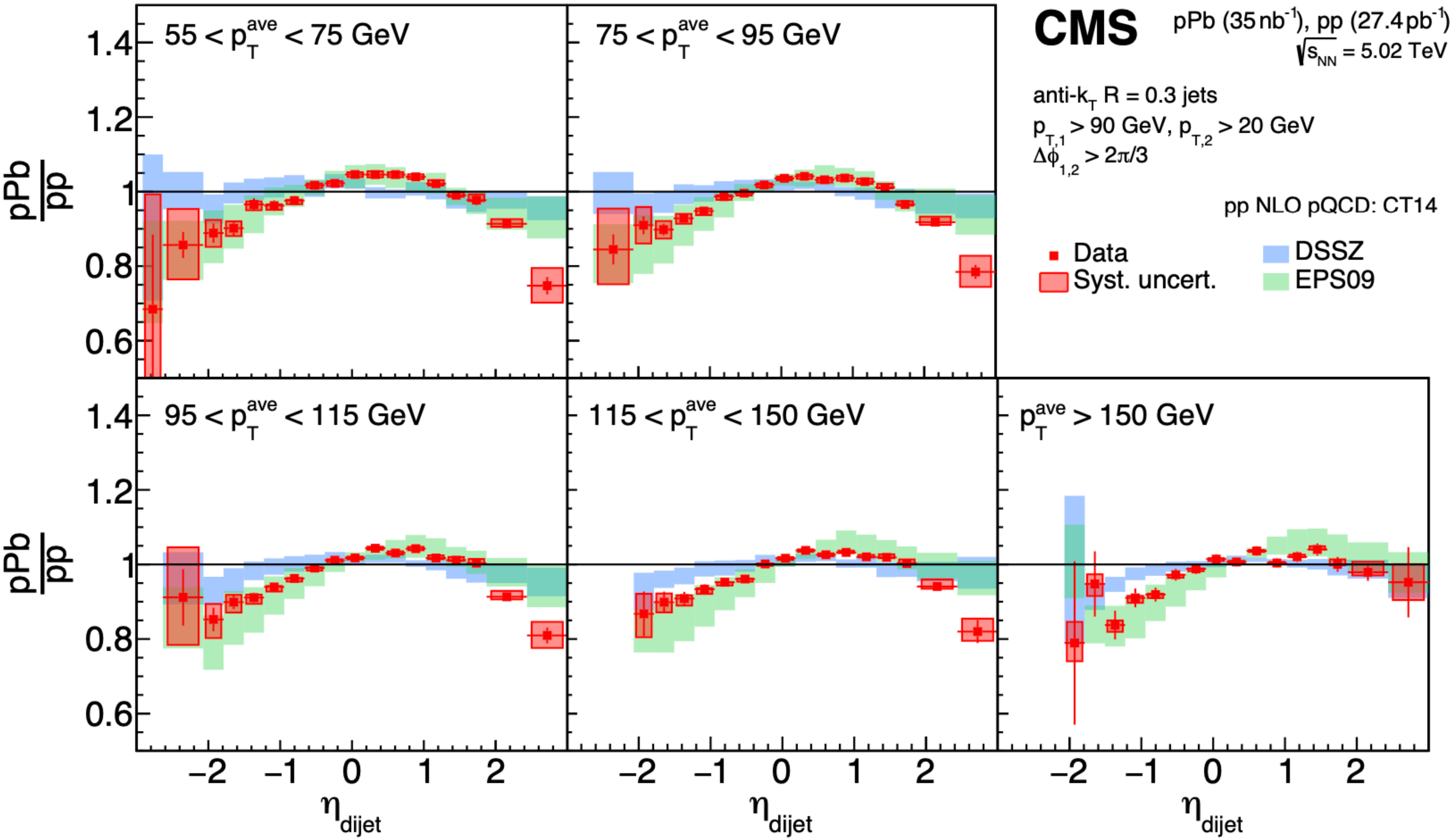



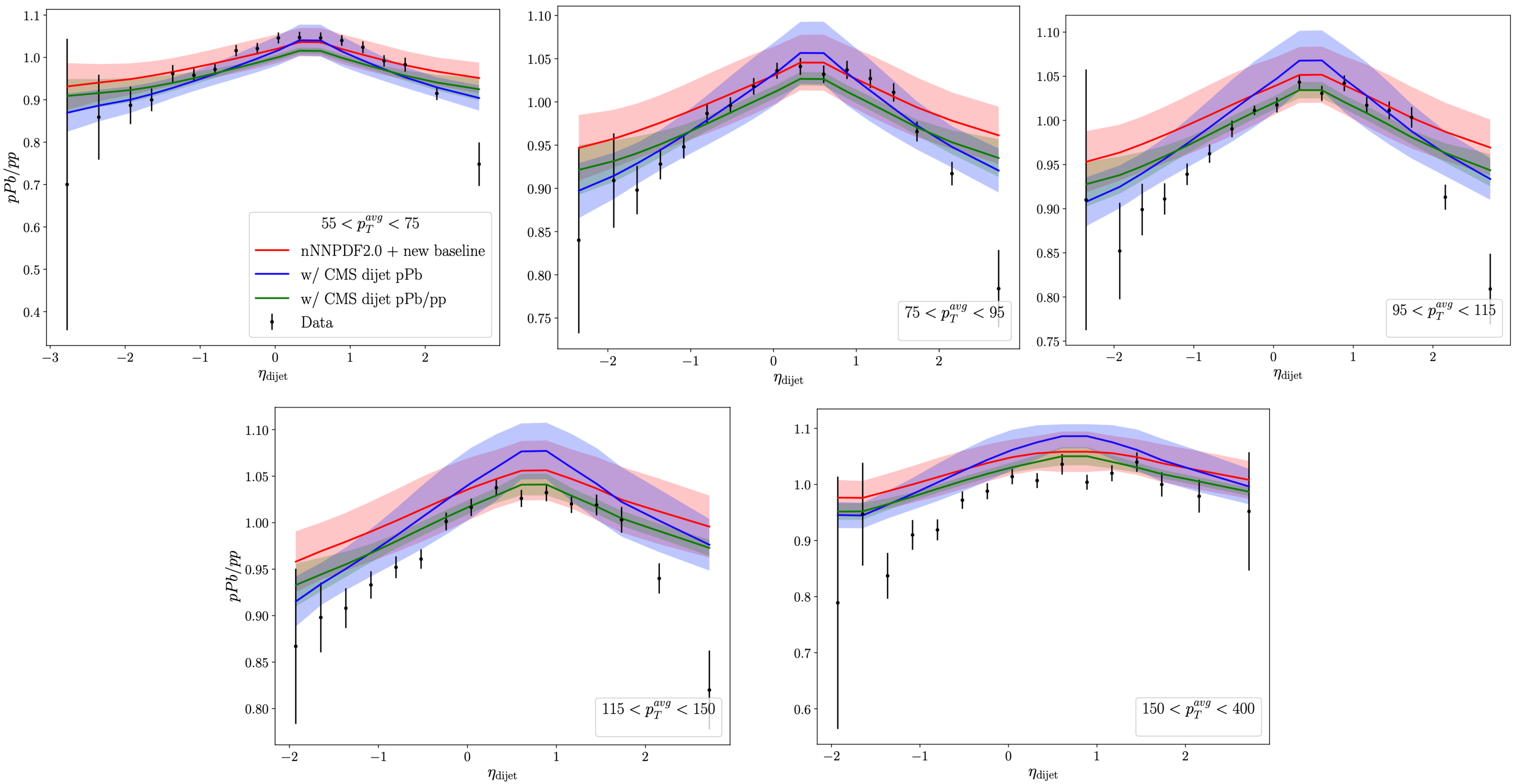



# p-Pb CMS 5 TeV

**Both spectra (See slide 3) and** $R^{\text{norm.}}_{\text{pPb}} = \frac{\frac{1}{d\sigma^{\text{pPb}}/dp_T^{\text{ave}}} d^2\sigma^{\text{pPb}}/dp_T^{\text{ave}} d\eta_{\text{dijet}}}{\frac{1}{d\sigma^{\text{pp}}/dp_T^{\text{ave}}} d^2\sigma^{\text{pp}}/dp_T^{\text{ave}} d\eta_{\text{dijet}}}.$



# nNNPDF2.0 + pPb CMS 5 TeV




**— w/o dijet** $\rightarrow \chi^2_{dataset}/N = [6.47]$

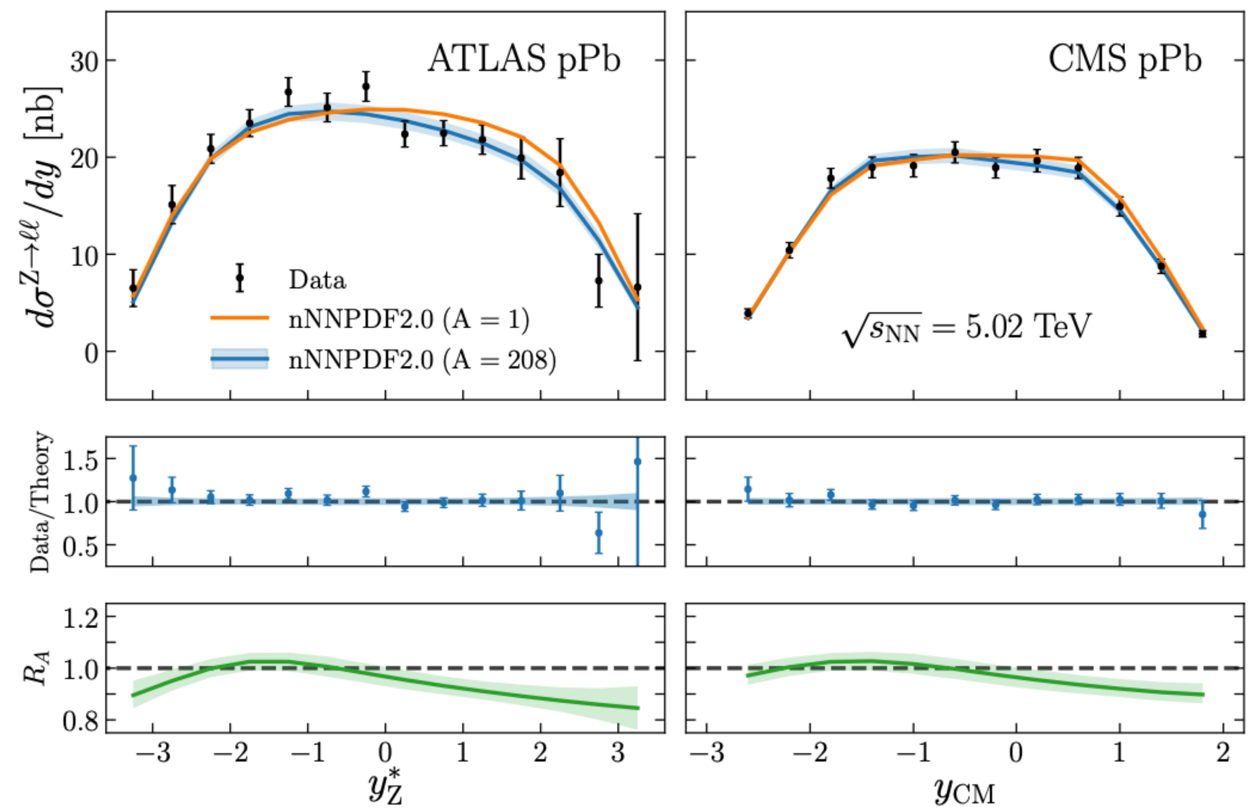
**— w/ CMS dijet pPb** $\rightarrow \chi^2_{dataset}/N = [6.16]$

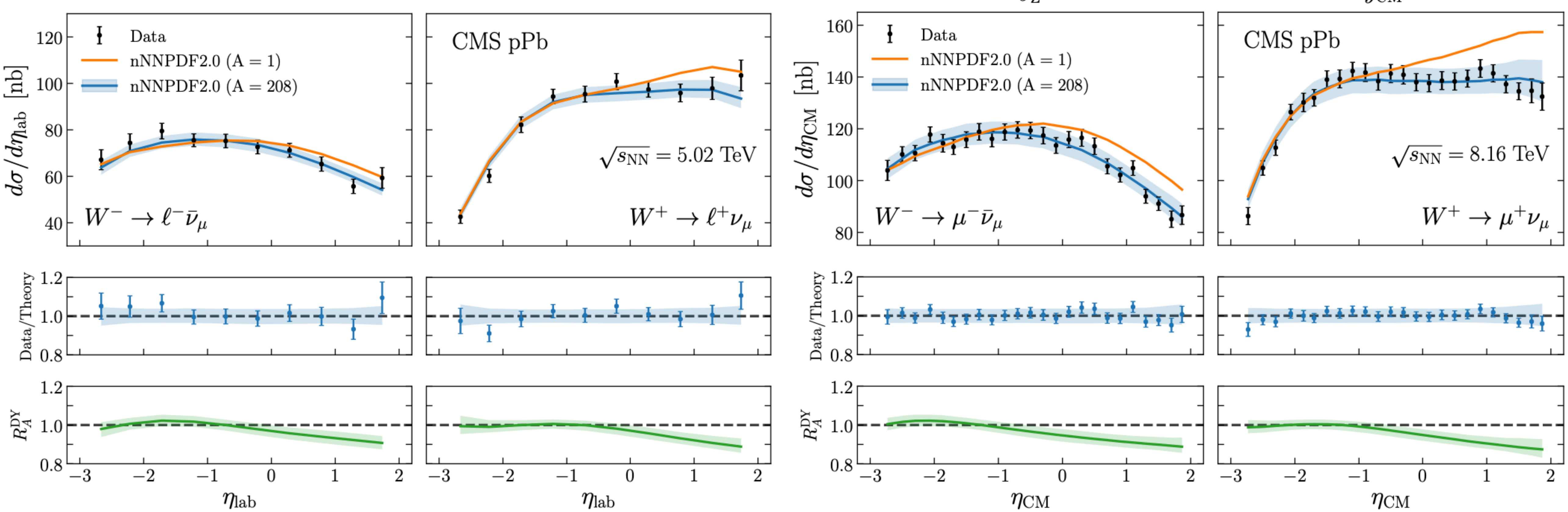
**— w/ CMS dijet pPb/pp** $\rightarrow \chi^2_{dataset}/N = 3.85$

# A word on the pA Drell-Yan at NNLO

# nNNPDF2.0 Results

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



# Towards nNNPDF3.0: 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**

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

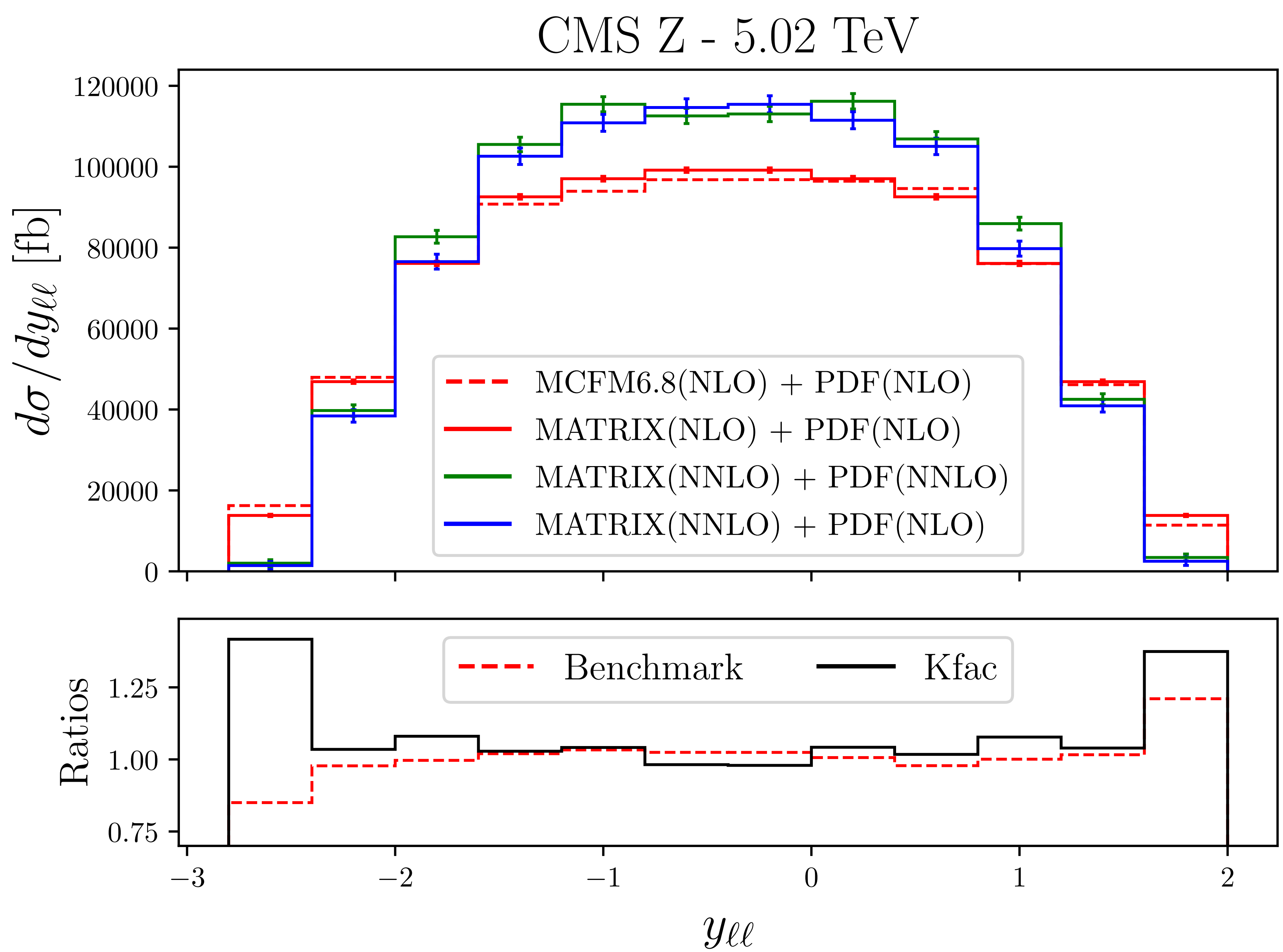
$$\approx \hat{\sigma}^{\mathrm{NNLO}}\left(pp \to \ell\ell\right) \otimes \mathscr{L}_{pp}^{\mathrm{NNLO}} \Big/ \hat{\sigma}^{\mathrm{NNLO}}\left(pp \to \ell\ell\right) \otimes \mathscr{L}_{pp}^{\mathrm{NLO}}$$

$\approx K_{\mathrm{pp}}^{\mathrm{NNLO}}$ **(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 $K_{\text{pp}}^{\text{NNLO}}$ Using MATRIX [arXiv:1711.06631]**




**Will improve with increased accuracy**

# nNNPDF3.0 Status

## CMS pPb dijet at 5 TeV

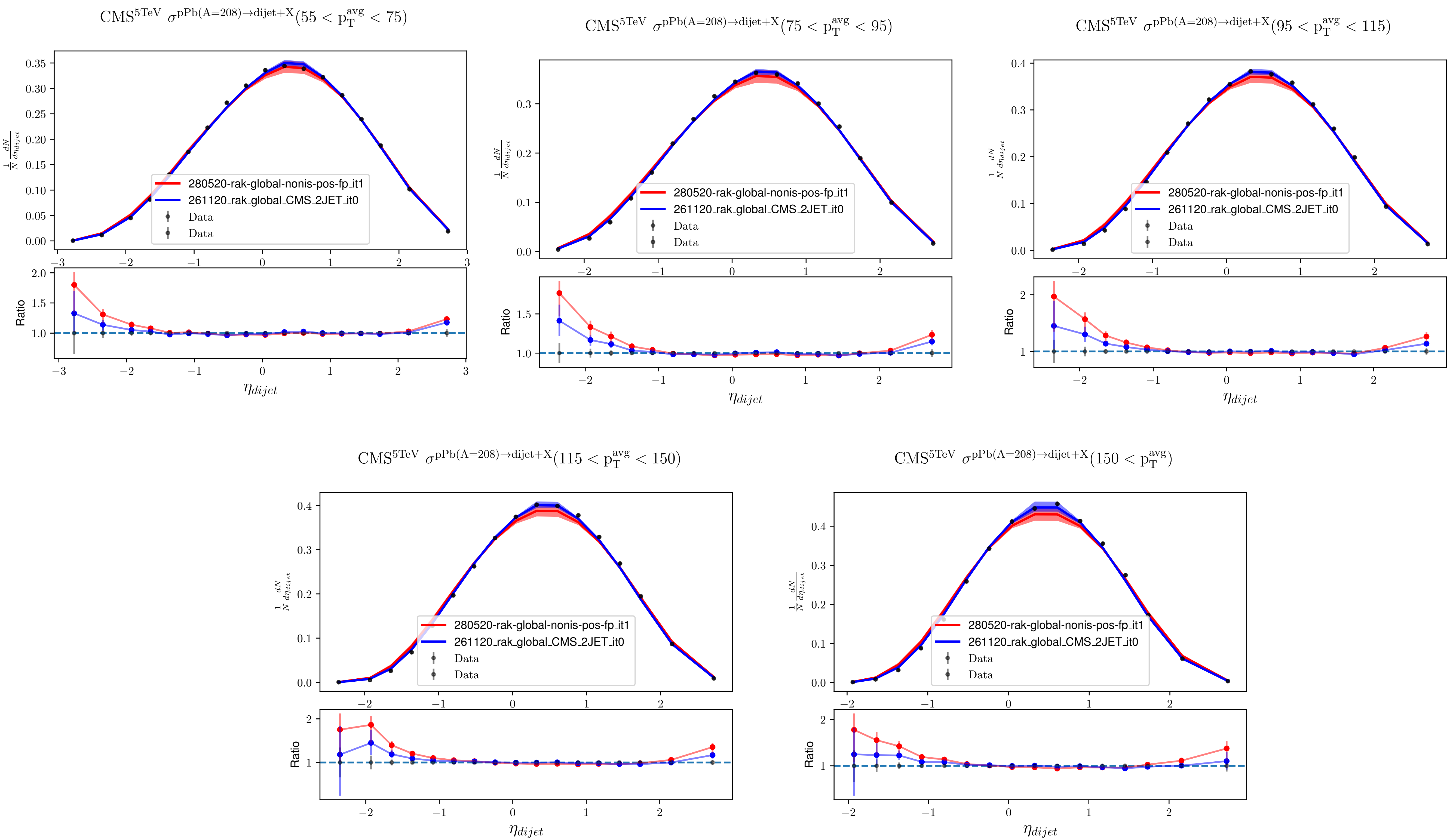
- Problem with the observable? Systematic uncertainties and missing correlations might be crucial to describe well this dataset.
- Inability to describe its pp data with NNPDF3.1 seems the main bottleneck to be able to fit pPb data with nNNPDF2.0
- NNLO k-factors need investigation.
- In order to include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

## Drell-Yan at NNLO

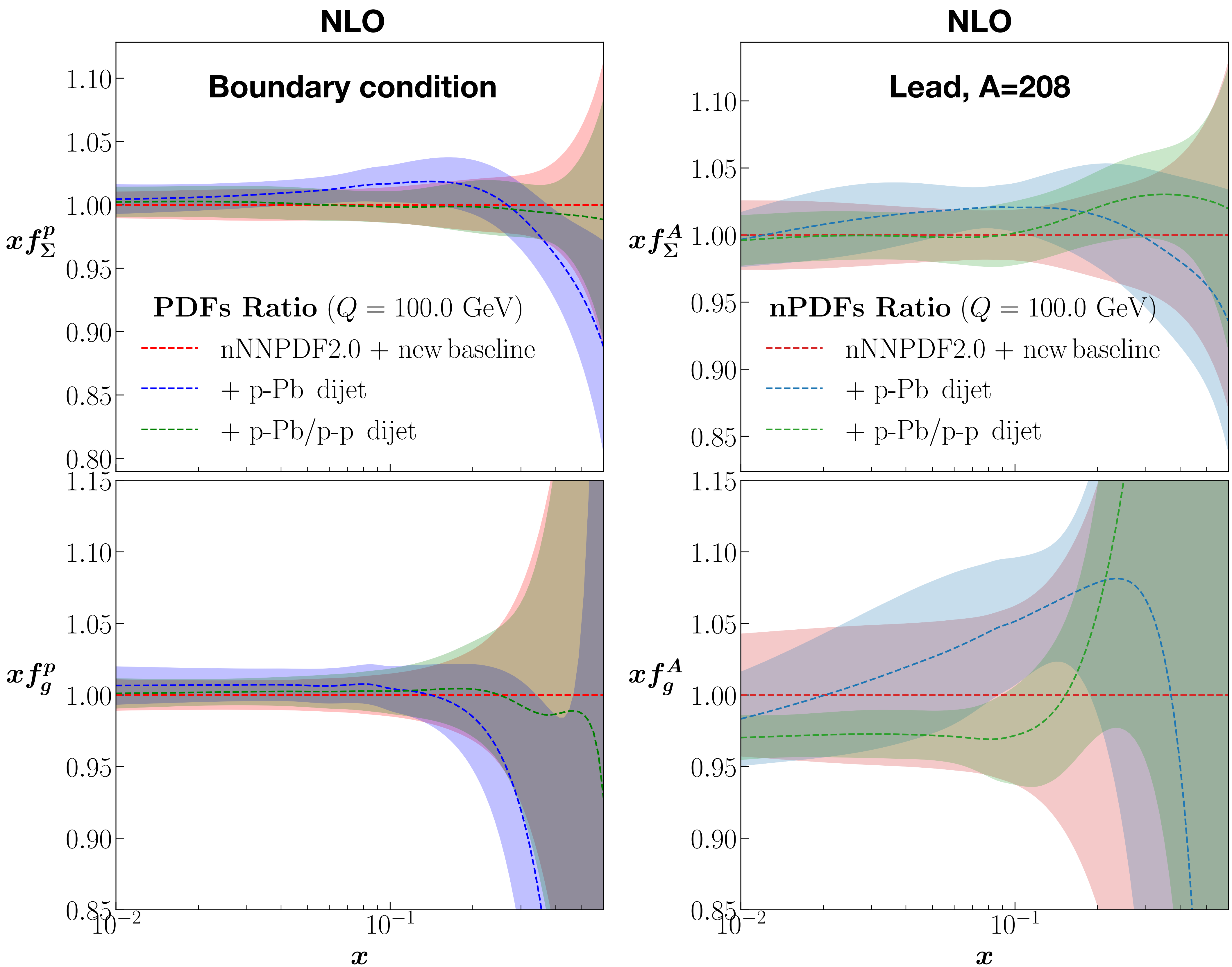
- CMS pPb $Z$ at 5 TeV — completed ✔
- ATLAS pPb $Z$ at 5 TeV — on the way
- ATLAS pPb $W^{\pm}$ at 5 and 8 TeV — on the way

# Appendix

# nNNPDF2.0 + p-Pb CMS



# 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)*

# Dijet Paper

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

**+ EW corrections considered in the paper**

**Absence of correlation**

# NNPDF3.1 w/ CMS dijet 5 TeV

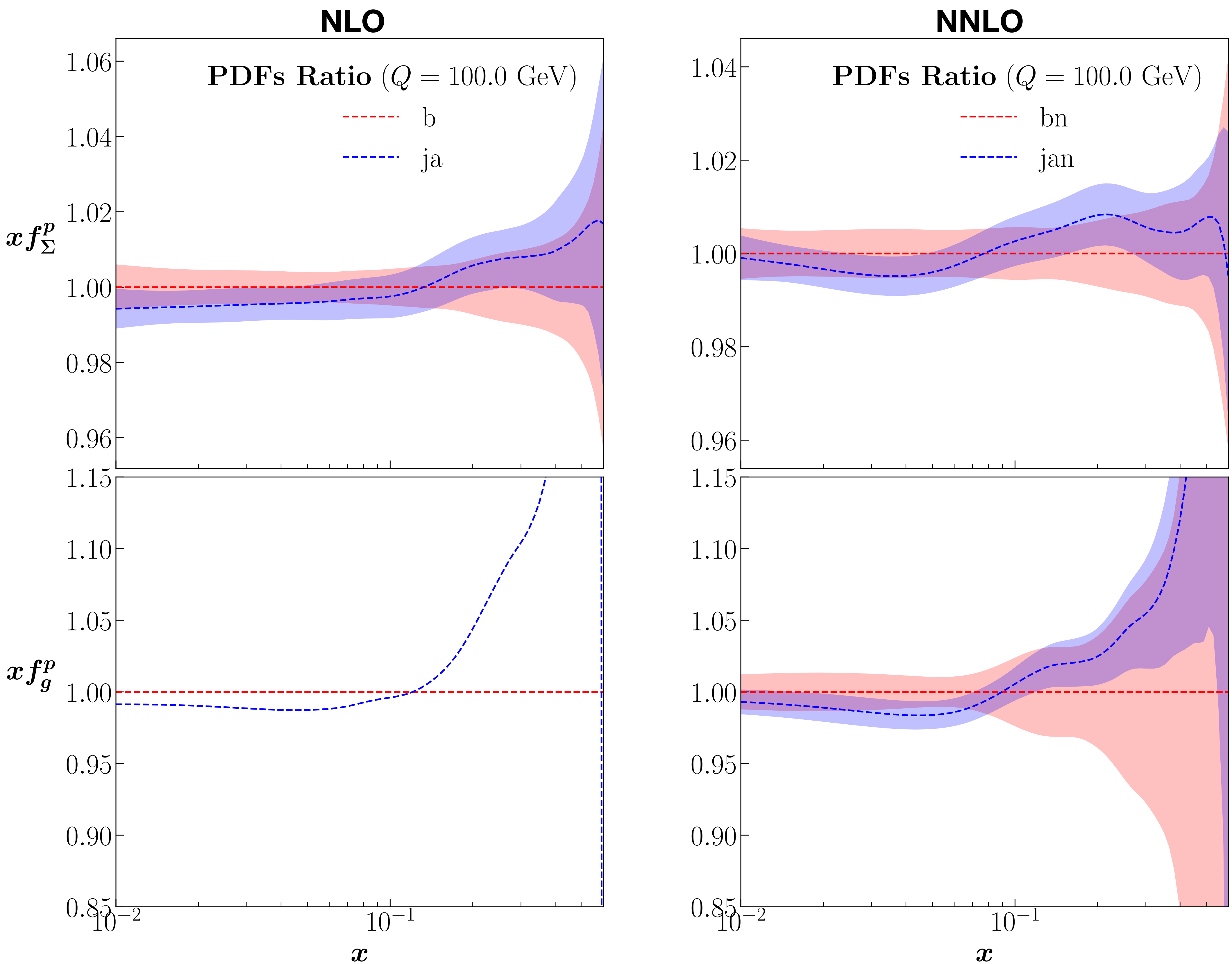
**NNPDF3.1**
**+ 7 and 8 TeV Dijet (paper)**
**± CMS dijet 5 TeV**

$$K^{\rm QCD}_{\rm NNLO} \equiv \frac{\sum_{ij} \tilde{\sigma}^{\rm NNLO}_{ij} \otimes \mathcal{L}^{\rm NNLO}_{ij}}{\sum_{ij} \tilde{\sigma}^{\rm NLO}_{ij} \otimes \mathcal{L}^{\rm NNLO}_{ij}},$$

$\chi^2/\mathrm{n}_{\mathrm{dat}}$

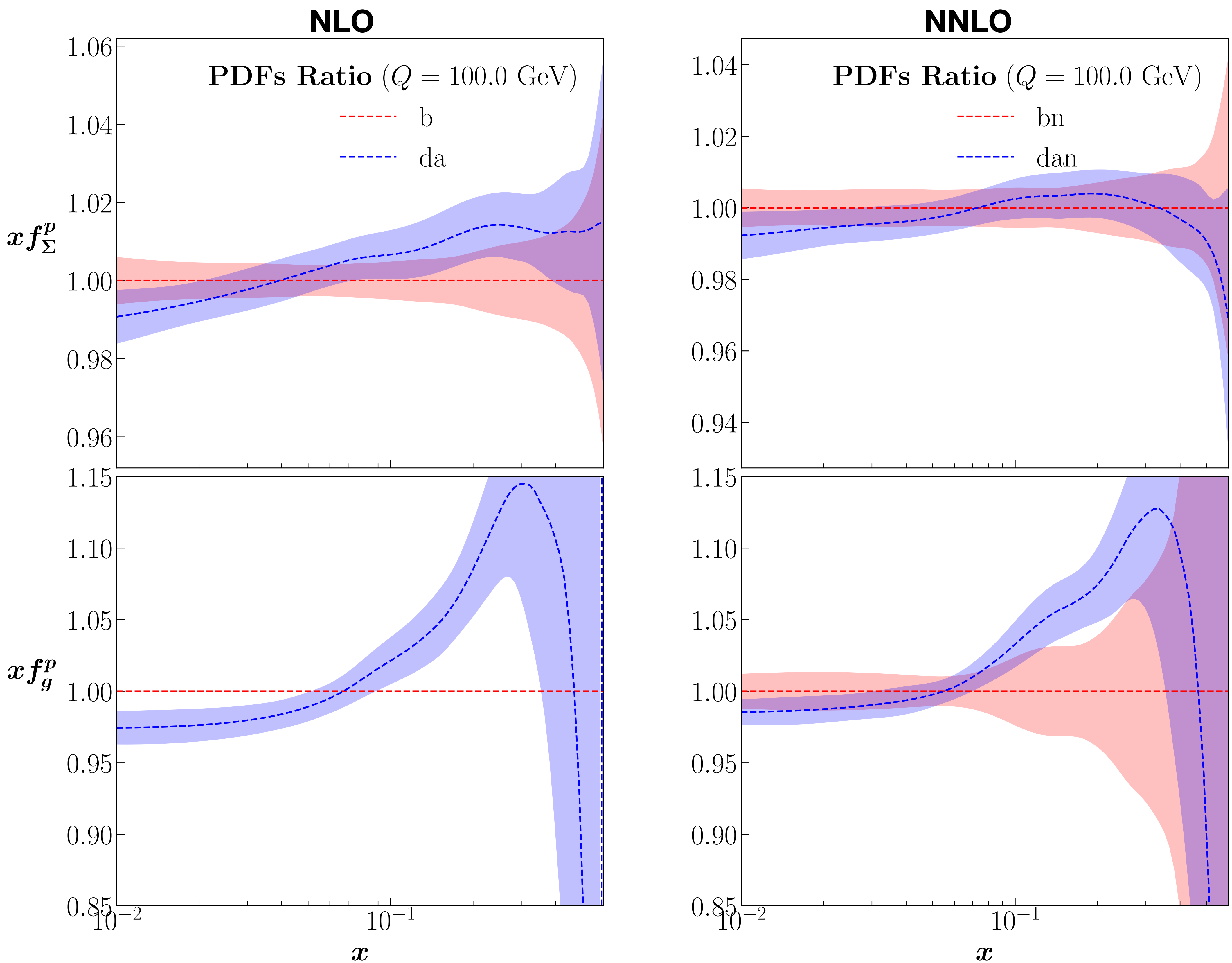
| Dataset | $n_{\rm dat}$ | w/o (NLO) | w/ (NLO) | w/o (NNLO) | w/ (NNLO) |
|---|---|---|---|---|---|
| DIS NC | 2113 | 1.28 | 1.31 | 1.25 | 1.27 |
| DIS CC | 81 | 1.24 | 1.25 | 1.15 | 1.16 |
| Drell-Yan | 440 | 1.36 | 1.33 | 1.21 | 1.24 |
| $Z\ p_T$ | 120 | 2.22 | 2.26 | 1.11 | 1.09 |
| Top pair | 25 | 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
PDFs Ratio ($Q = 100.0$ GeV)
bn
jan
$xf^p_\Sigma$
$xf^p_g$
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
$10^{-2}$
$10^{-1}$
$x$

# Dijet



NLO
NNLO
PDFs Ratio ($Q$ = 100.0 GeV)
b
da
bn
dan
$xf^p_\Sigma$
$xf^p_g$
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
$10^{-2}$
$10^{-1}$
$x$