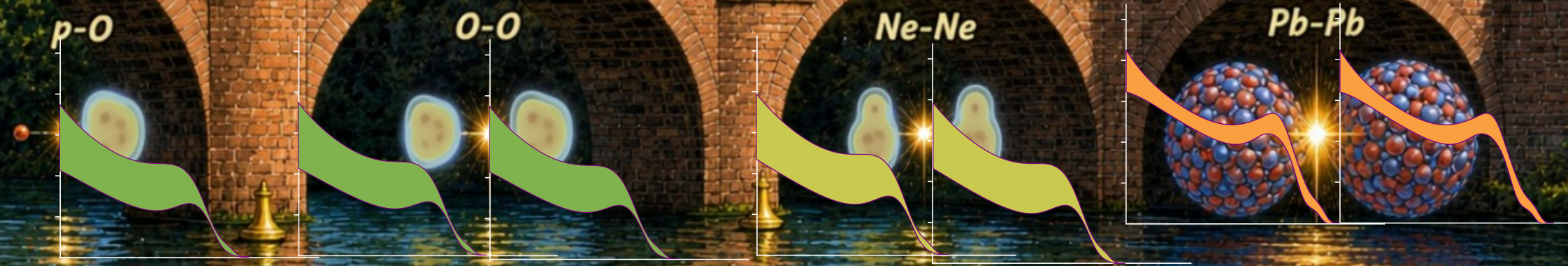


New global nuclear PDF analysis within the nCTEQ framework: nCTEQ26

Katrin Greve (kgreve@uni-muenster.de)



With many thanks to all my nCTEQ collaborators

September 22, 2026

Hadron structure and parton distributions

Factorisation:

$$F_2^{A,Z}(x, Q^2) = \sum_i f_i^{A,Z}(x, Q^2) \otimes C_{2,i}(x, Q^2)$$

$$\sigma = \int dx_1 \int dx_2 \sum_{i,j} f_{1,i}^{A,Z} f_{2,j}^{A,Z} \otimes \hat{\sigma}(x_1, x_2, Q^2)$$

nCTEQ26 Parametrisation in x :

$$f(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} \left(1 + c_3 \sqrt{x} + c_4 x\right) e^{c_5 \sqrt{x}}$$

- d_v : mixing with u_v : $d_v \rightarrow d_v + c_0 c_6 x^{c_7} u_v$
- $\frac{\bar{d}}{u} = c_0 x^{c_1} (1-x)^{c_2} + 1 + c_3 x (1-x)^{c_4}$
- Extension of CJ15 by $e^{c_5 \sqrt{x}}$

Theory input for (n)PDF determinations

- **DGLAP** equations determine scaling and make the formalism predictive
- Isospin symmetry: $d^{\frac{n}{A}}(x, Q^2) = u^{\frac{p}{A}}(x, Q^2)$ and vice versa
- Sum rules, e.g. $\int_0^1 (u(x) - \bar{u}(x)) dx = 2$

DGLAP:

$$\frac{\partial f_i(x, Q^2)}{\partial \log Q^2} = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(Q^2)\right) f_j(z, Q^2)$$

PDFs are not calculated analytically but derived from data by minimizing a loss function

Nuclear Structure

- **Shadowing** (low x), **Antishadowing** (mid to high x), **EMC effect** (high x) and **Fermi motion** (very high x) very well tested experimentally
- Nuclear PDFs: Encode modifications in universal quantities

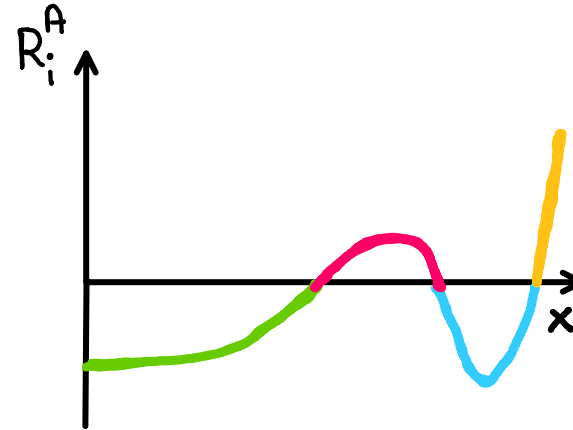
Review paper on nuclear PDFs:
(Klasen and Paukkunen 2024)

Nuclear structure

$$f_i^{A,Z}(x, Q^2) = Z \sum_i f_i^{p/A}(x, Q^2) + N \sum_i f_i^{n/A}(x, Q^2) \\ = R_i^A(x, Q^2) [Z f_i^p(x, Q^2) + N f_i^n(x, Q^2)]$$

$$\text{with } R_i^A = \frac{Z f_i^{p/A} + N f_i^{n/A}}{Z f_i^p + N f_i^n}$$

Fitted in nCTEQ26: $f_i^{p/A}(x, Q_0^2)$



nCTEQ26 Parametrisation in A :

$$c_k(A) = p + a \ln(A) + b \ln^2(A)$$

- Log behavior already observed in nCTEQ15
 - Allows for a rapid change in A for light nuclei and a milder change for heavy nuclei

Uncertainty estimation: Hessian approximation

Method:	Hessian	
Theory	Quadratic approximation of the χ^2 function around its minimum: $\chi^2 \approx \chi_0^2 + \sum_{i,j} H_{ij} (a_i - a_{i,0}) (a_j - a_{j,0})$ $= \chi_0^2 + \sum_i z_i^2$	
Uncertainty Observable	$(\delta X)^\pm =$ $\sqrt{\sum_k \left[\max_{\min} [X(s_k^+) - X(s_0), X(s_k^-) - X(s_0), 0] \right]^2}$	
used by	nCTEQ26/nCTEQ15HQ, EPPS21, TUJU21, KASAG20	

Uncertainty estimation: Hessian approximation

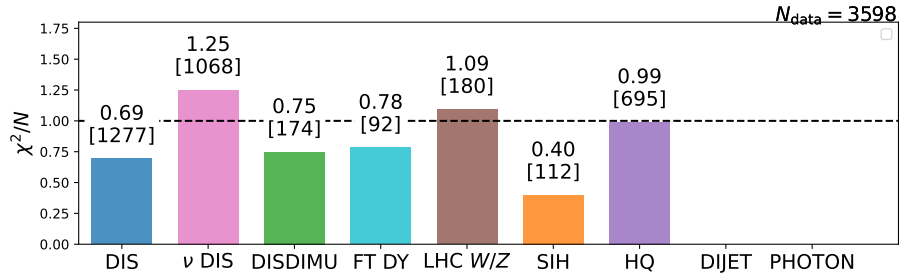
Method:	Hessian	Monte Carlo replicas ¹
Theory	Quadratic approximation of the χ^2 function around its minimum: $\chi^2 \approx \chi_0^2 + \sum_{i,j} H_{ij} (a_i - a_{i,0}) (a_j - a_{j,0})$ $= \chi_0^2 + \sum_i z_i^2$	Create replicas of fit, using sets of the data that is randomly shifted within the uncertainties: $D_i \rightarrow D_i (1 + \sigma_i R_i)$
Uncertainty Observable	$(\delta X)^\pm =$ $\sqrt{\sum_k \left[\min_{\max} [X(S_k^+) - X(S_0), X(S_k^-) - X(S_0), 0] \right]^2}$	Calculating X with all replicas; disregarding the highest/lowest ...%
used by	nCTEQ26/nCTEQ15HQ, EPPS21, TUJU21, KASAG20	nNNPDF3.0

¹Study on nuclear PDF uncertainty estimation using Monte Carlo Markov Chains: (Derakhshanian et al. 2026)
Katrin Greve (kgreve@uni-muenster.de)

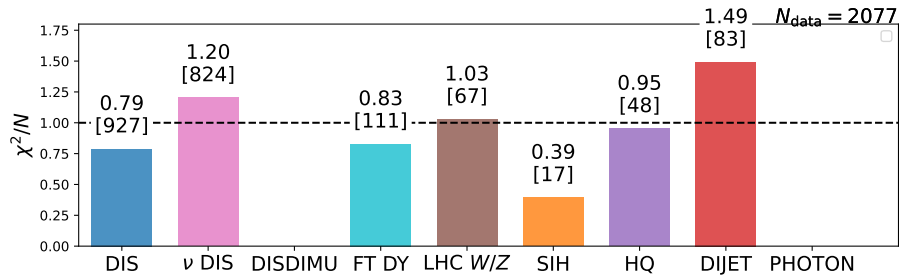
nCTEQ26 Fit quality

per type of experiment:

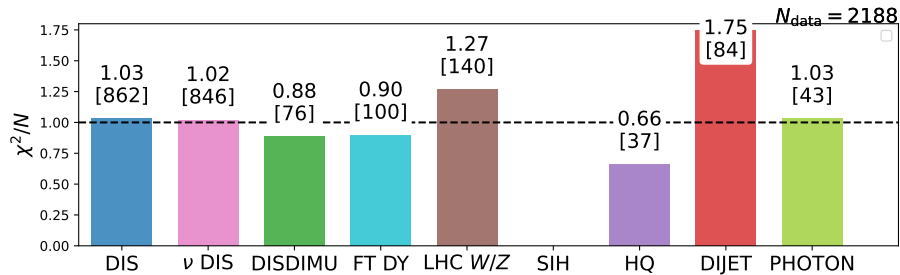
nCTEQ26



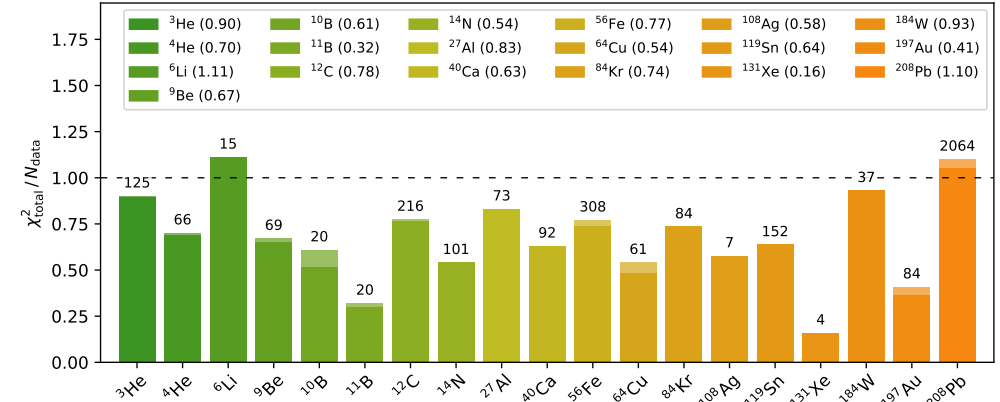
EPPS21



nNNPDF3.0



per Nuclei:

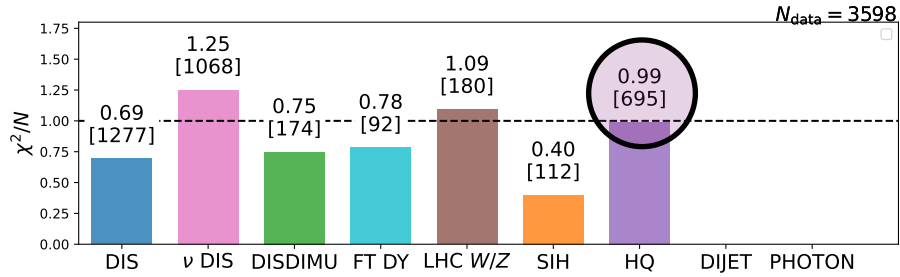


- DIS, Dimuons, HQ, FT DY, and SIH are generally well described
- nCTEQ26 & EPPS21: Agreement on “hard” and “easy-to-describe” data types
- DIJET data are generally hard to describe (nCTEQ26 prediction shown later)
- nCTEQ26 can describe the data over the whole range of A

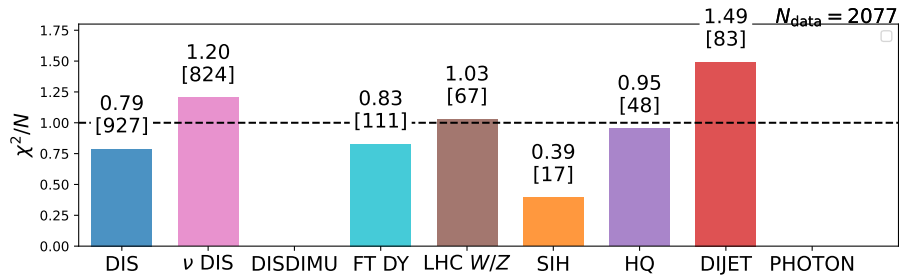
nCTEQ26 Fit quality

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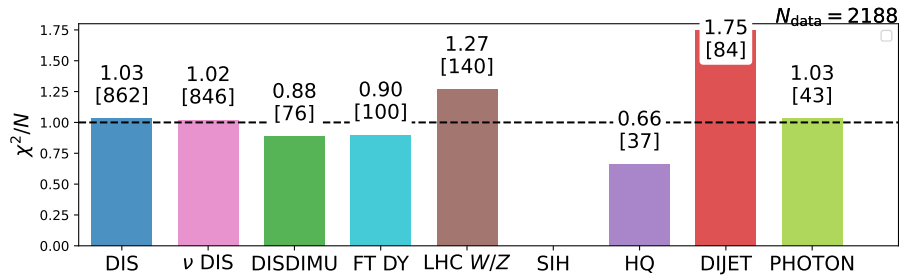
nCTEQ26



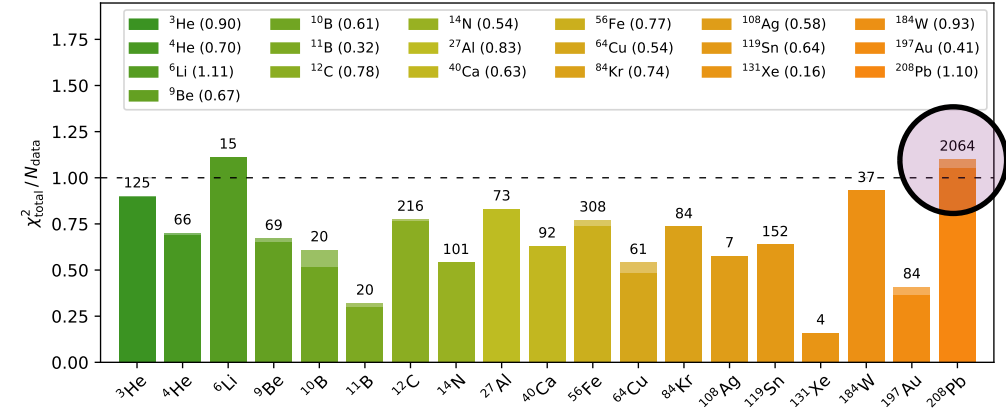
EPPS21



nNNPDF3.0

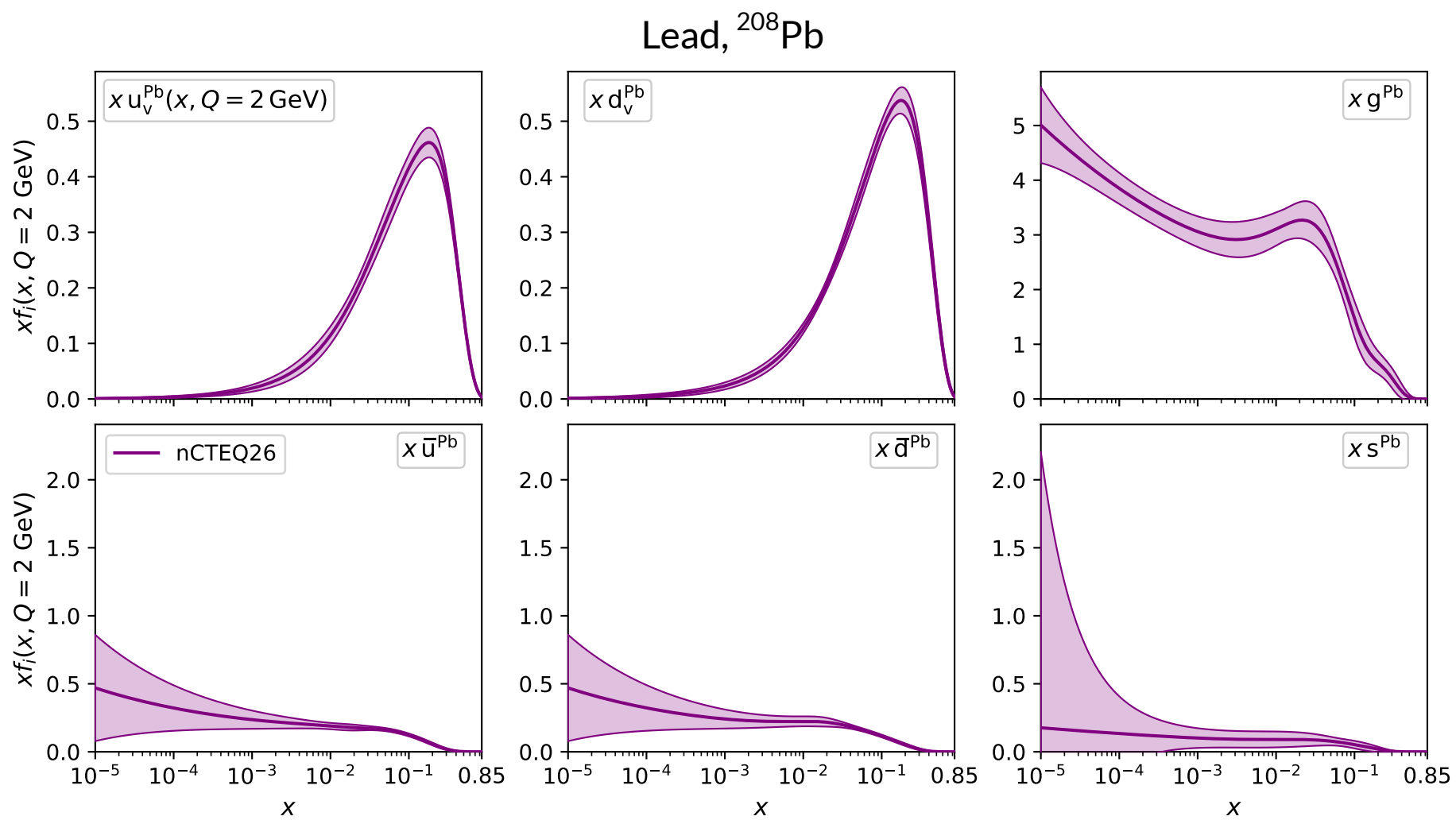


per Nuclei:



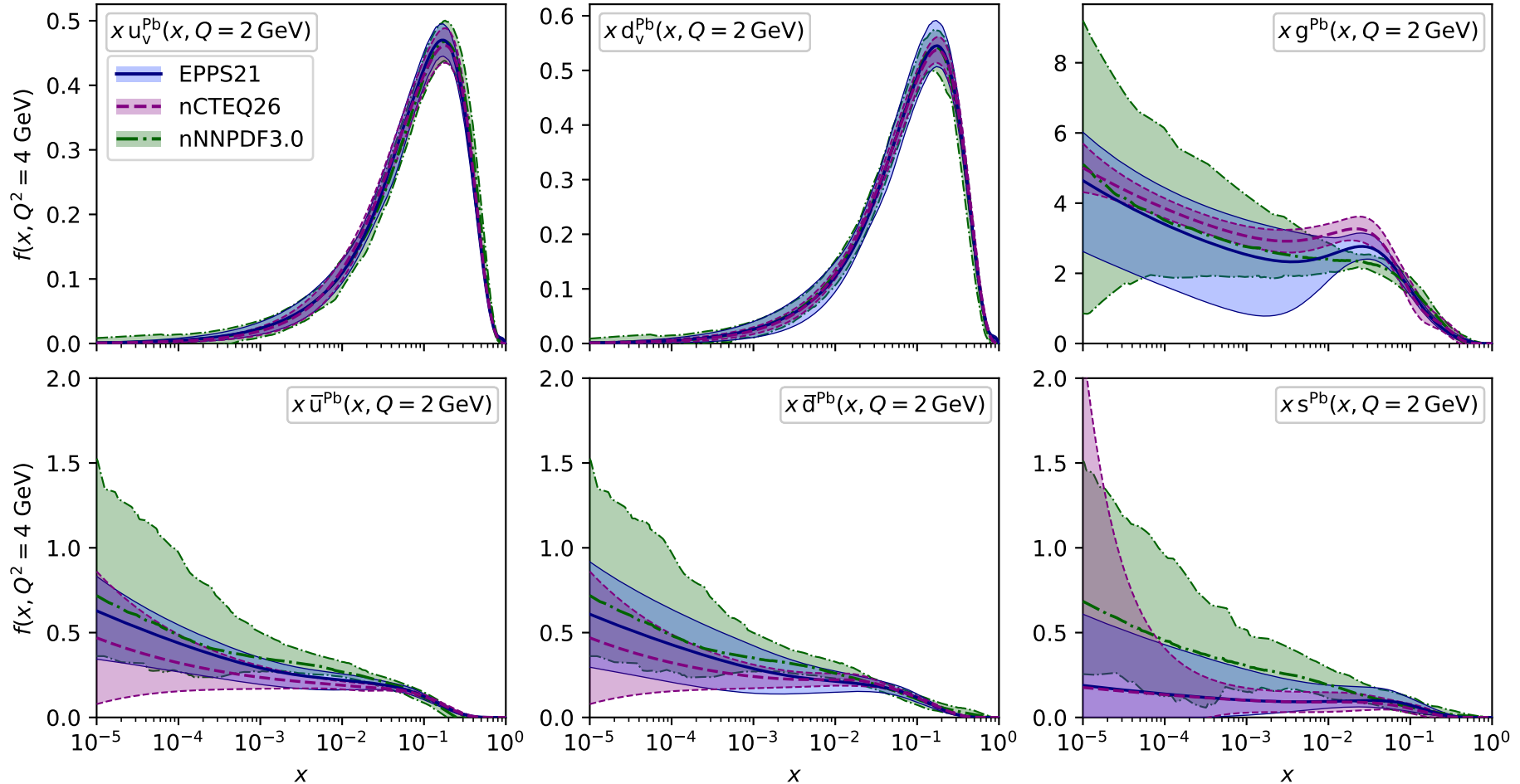
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Nuclear PDFs



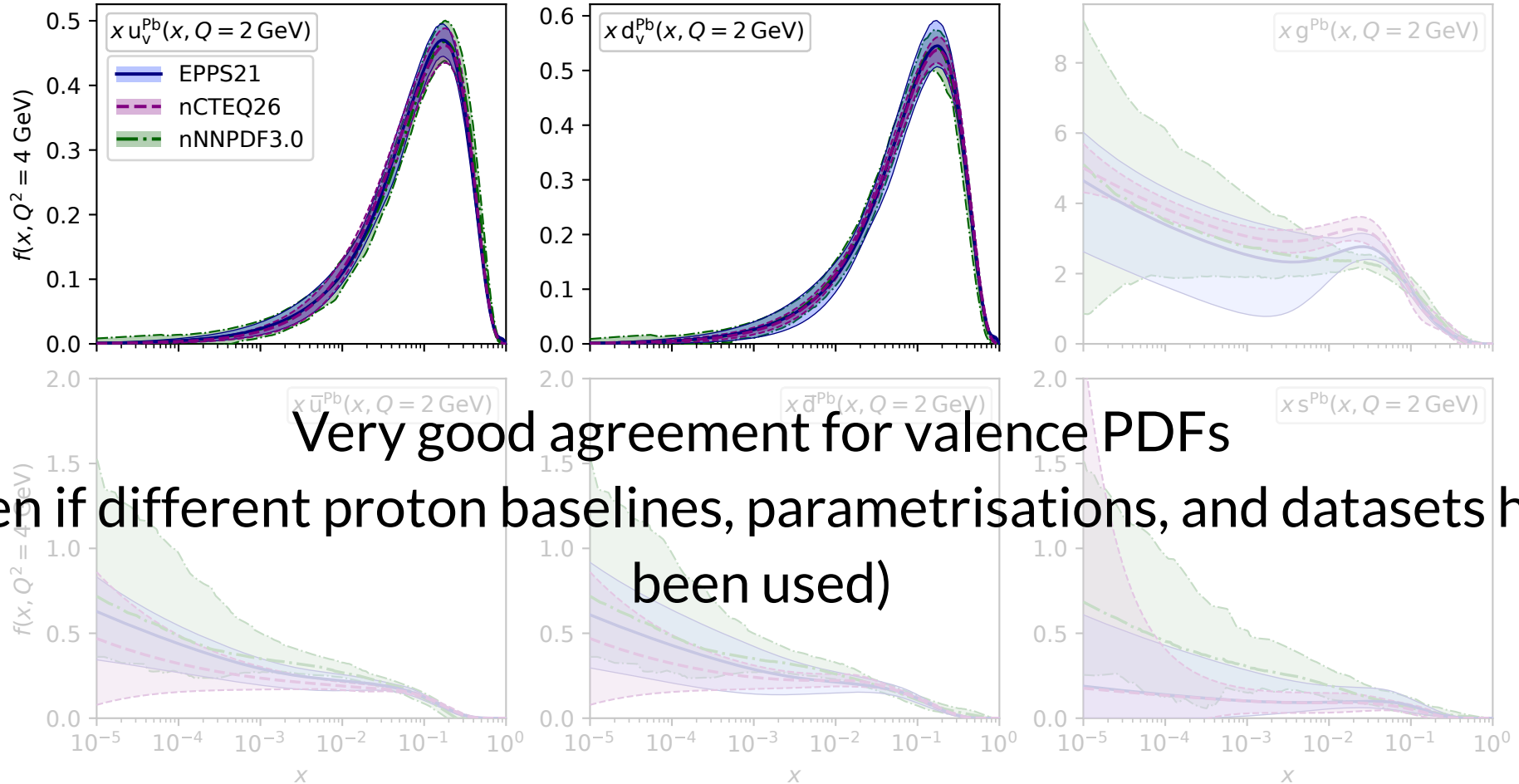
Nuclear PDFs

Lead, ^{208}Pb : Comparison with EPPS21 (Eskola et al. 2022) and nNNPDF3.0 (Khalek et al. 2022)



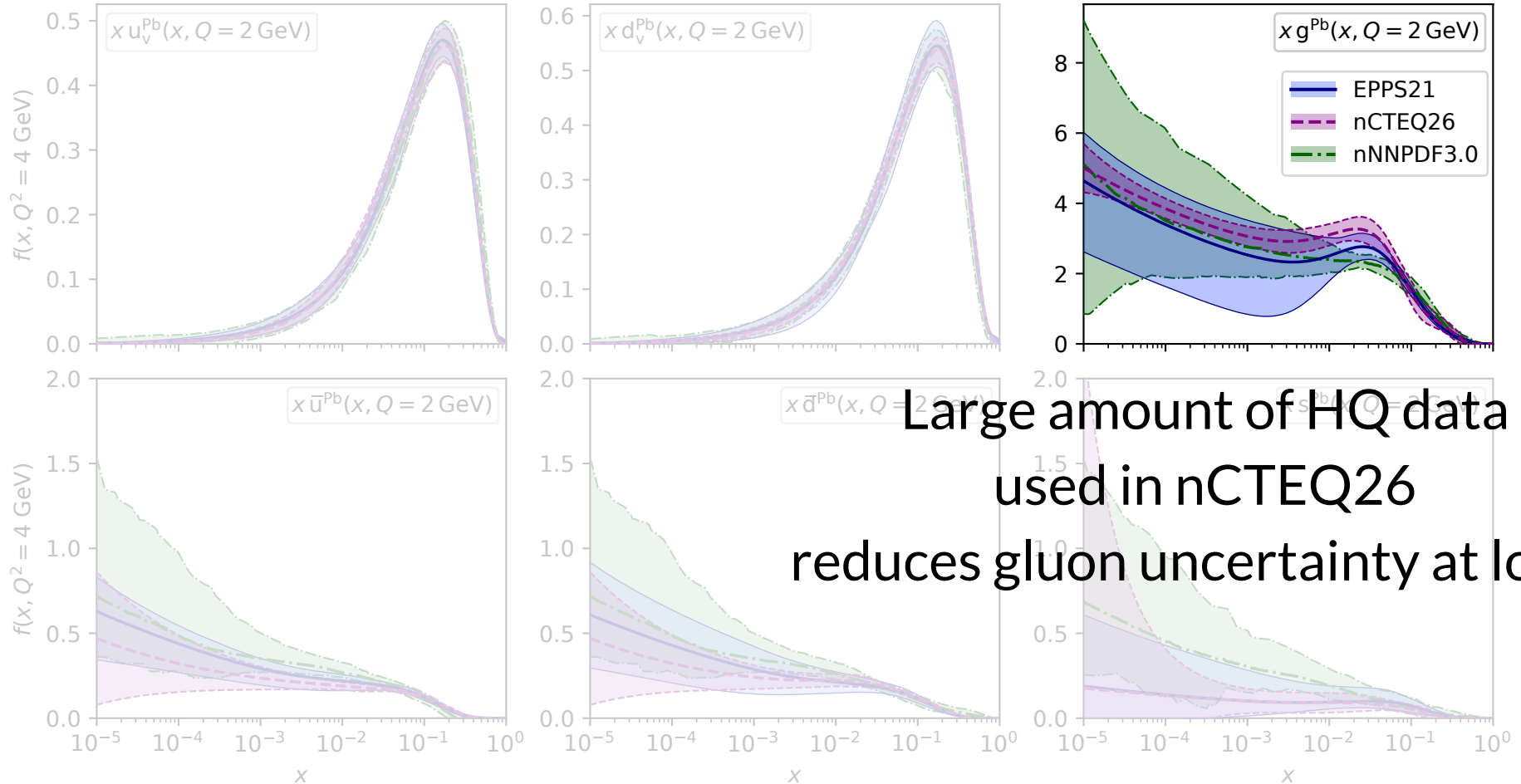
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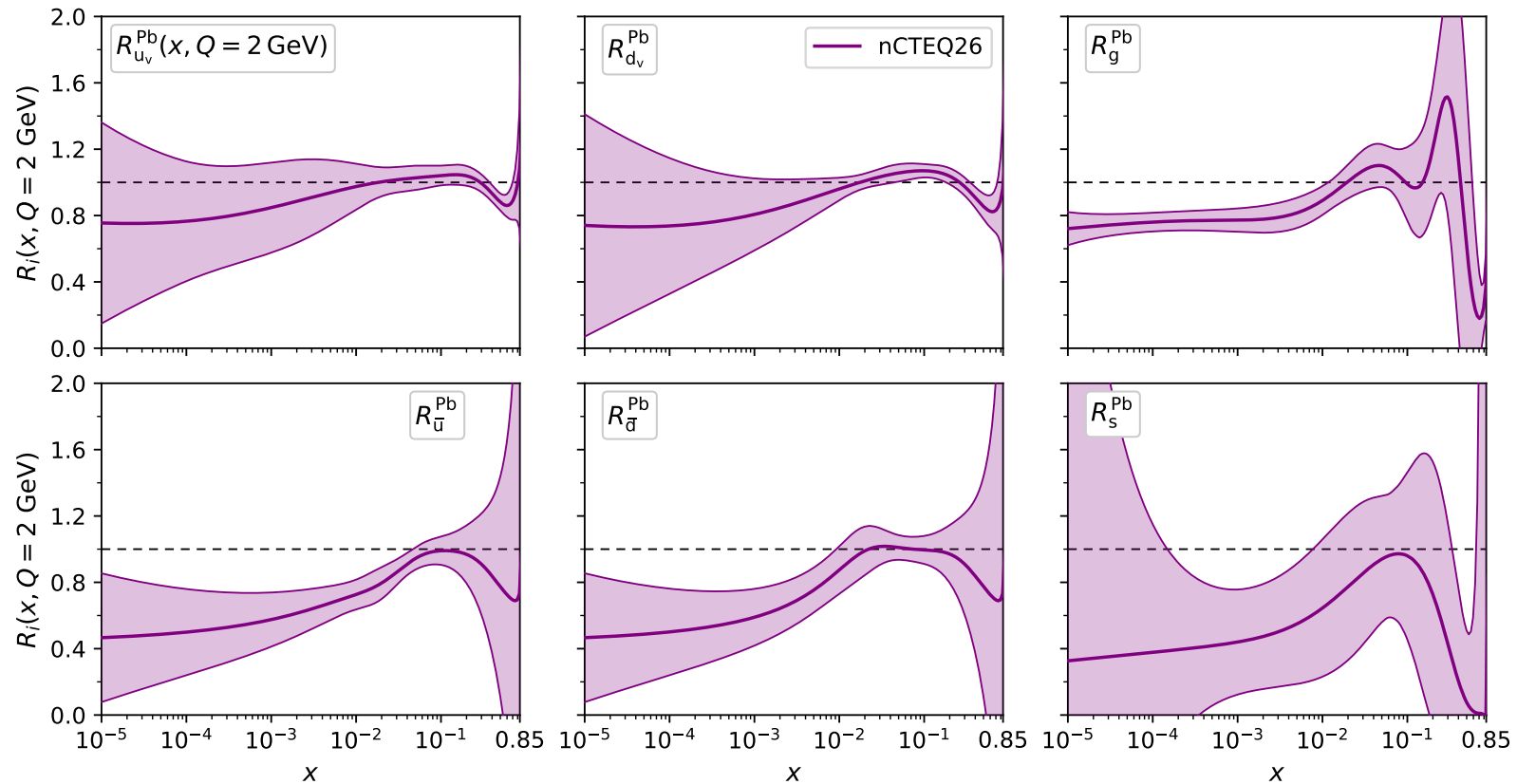
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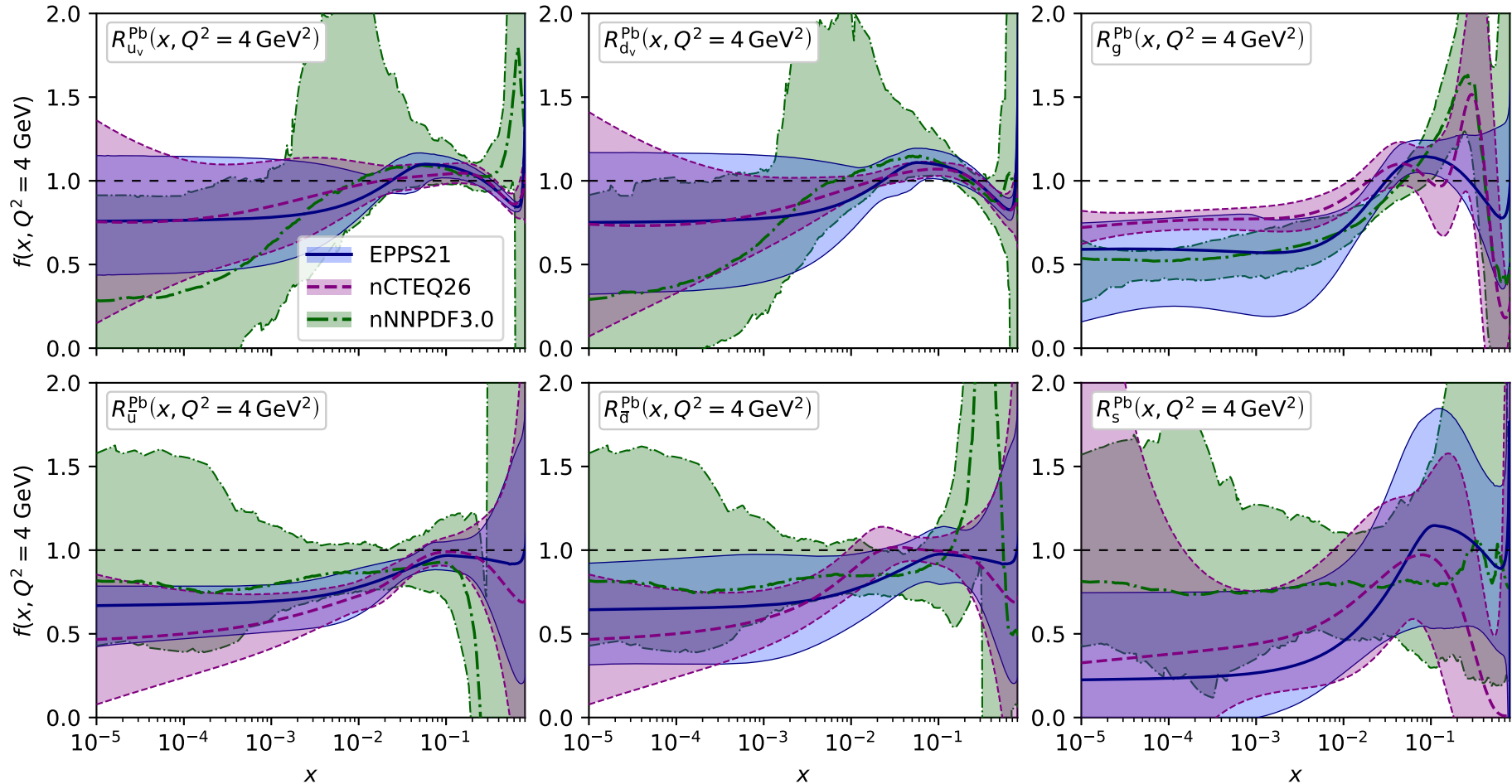


Nuclear modifications

Nuclear modification ratio: $R_i^A = \frac{Zf_i^{p/A} + Nf_i^{n/A}}{Zf_i^p + Nf_i^n}$, Lead ^{208}Pb

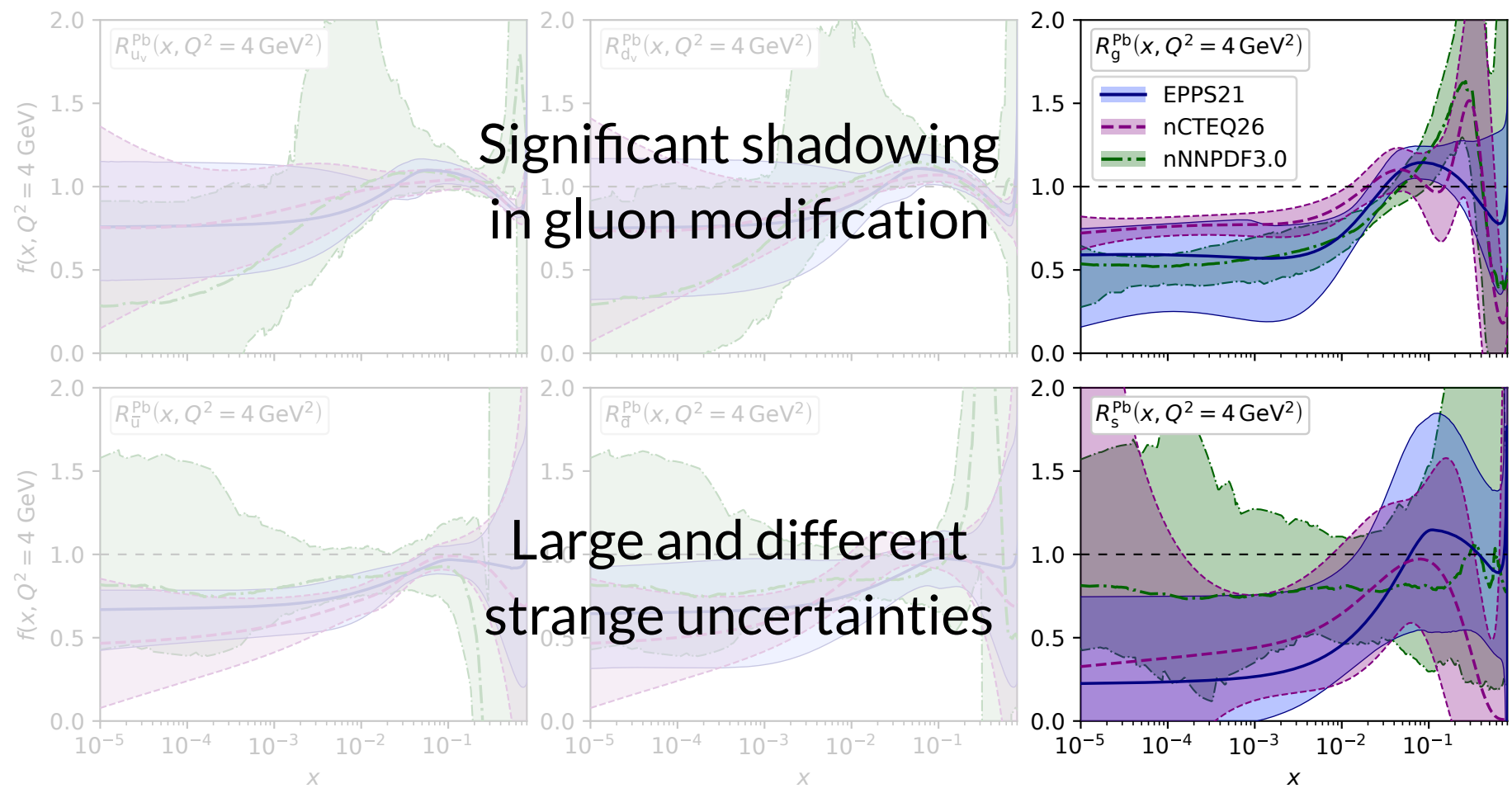


Nuclear modification ratio: Lead, ^{208}Pb

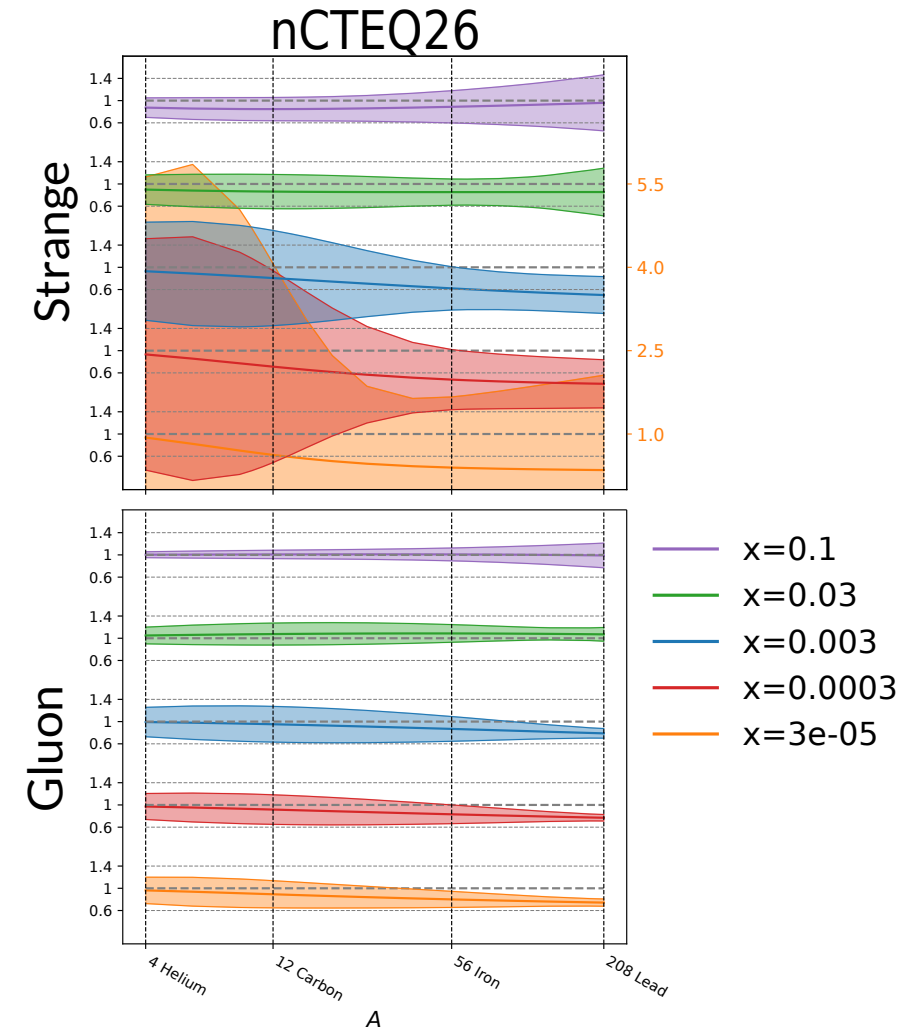


Nuclear modifications

Nuclear modification ratio: Lead, ^{208}Pb



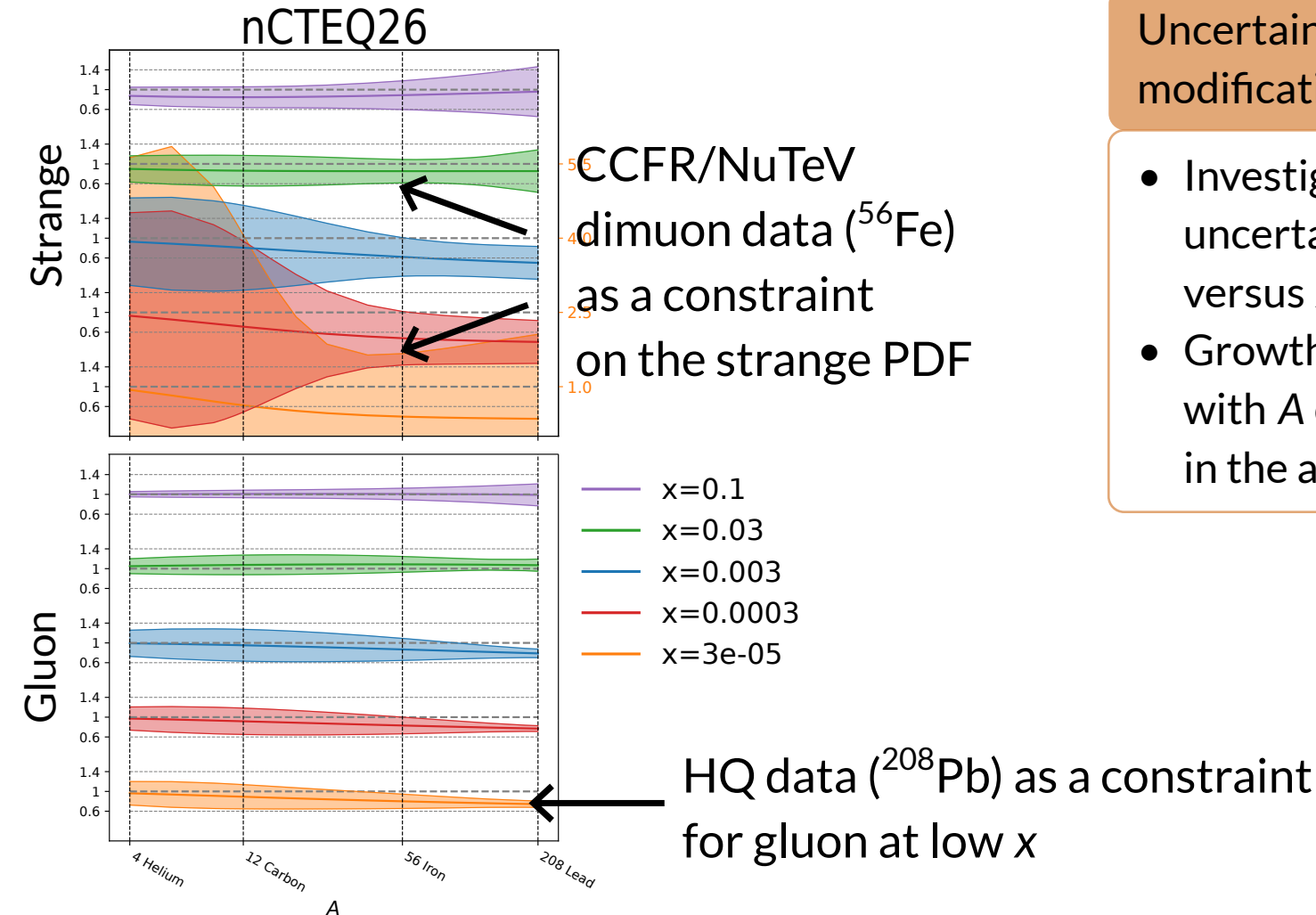
A-dependence



Uncertainty landscape in A of nuclear modification factors

- Investigation of the A-dependence of uncertainties: nuclear modifications versus A for different values of x

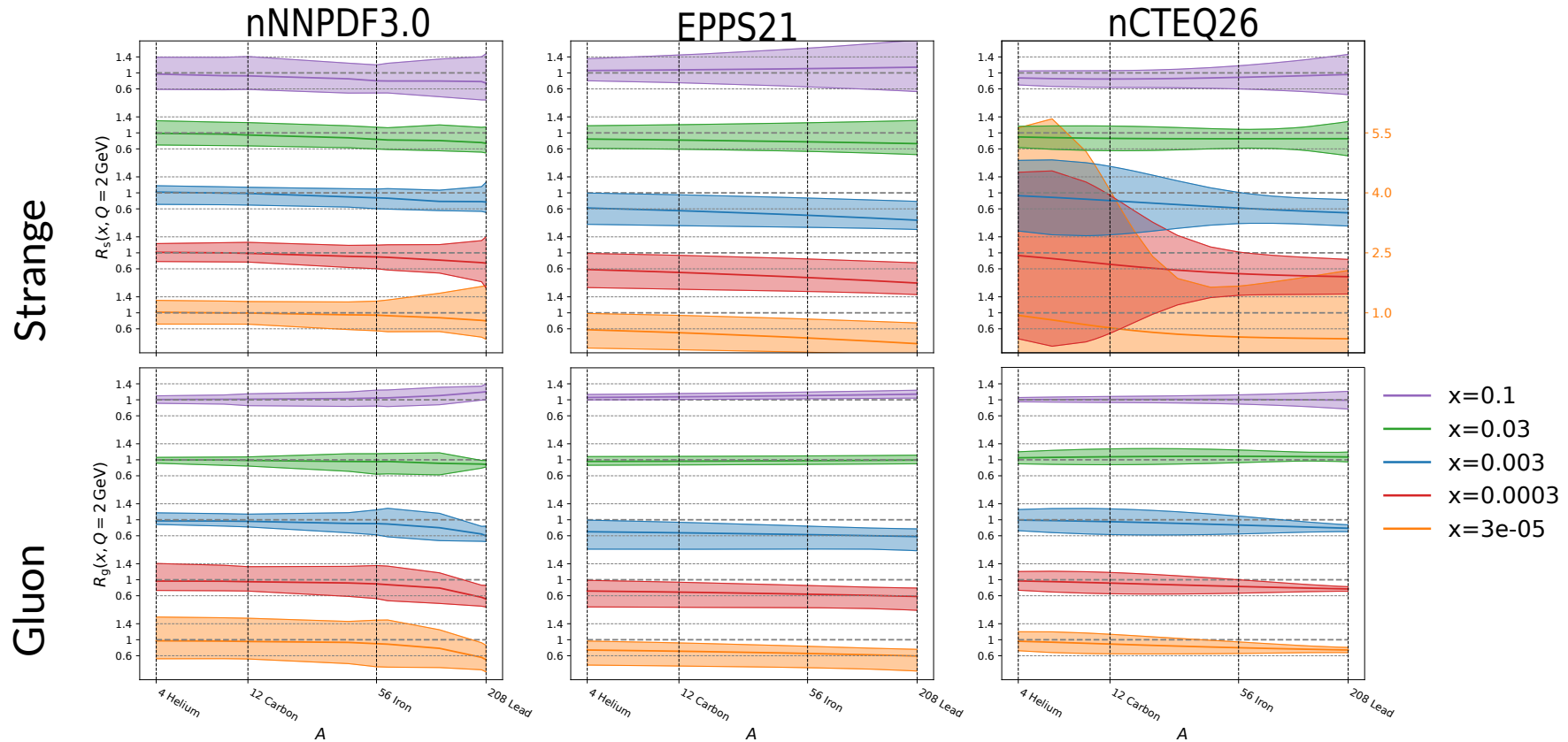
A-dependence



Uncertainty landscape in A of nuclear modification factors

- Investigation of the A-dependence of uncertainties: nuclear modifications versus A for different values of x
- Growth and decrease of uncertainties with A can be related to the data used in the analysis

A-dependence: Comparison with nNNPDF3.0 and EPPS21

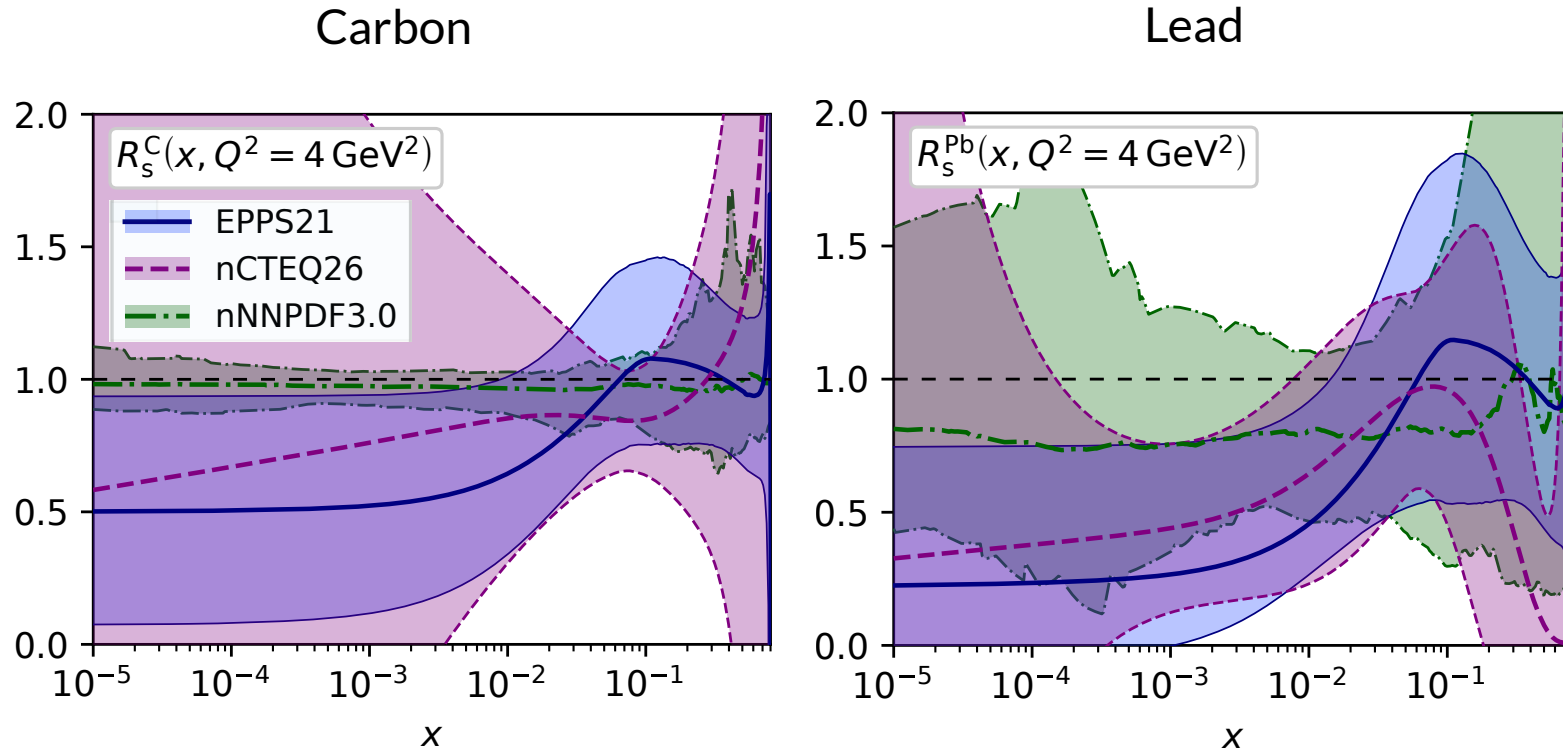


- Gluon: Trend of decreasing uncertainty bands towards large A for low x in all analyses, but especially pronounced in nCTEQ26
- Strange: The A dependence of uncertainties looks very different across the analyses

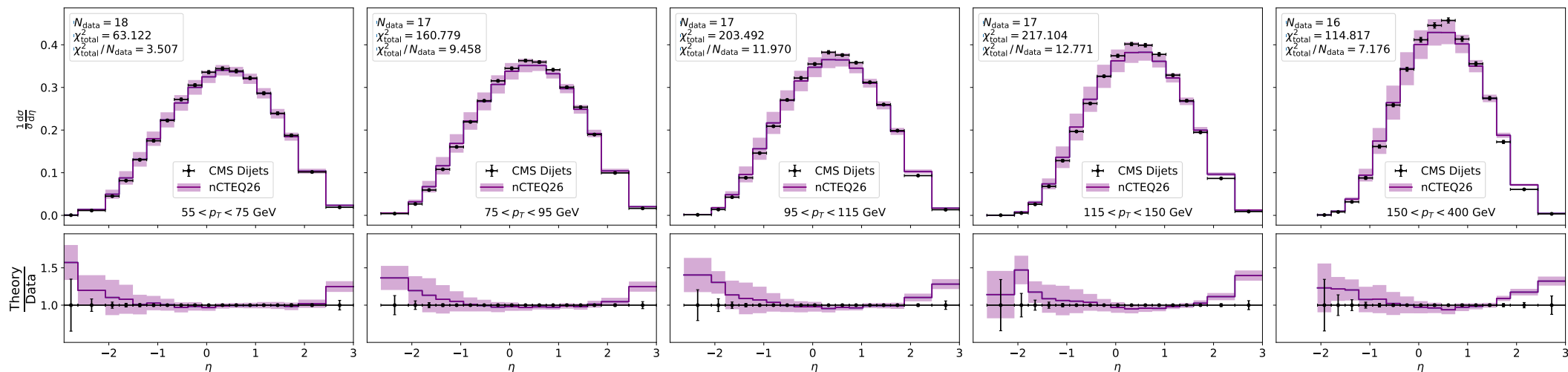
A-dependence: Comparison with nNNPDF3.0 and EPPS21

- The different evolution of uncertainty bands in A can be shown more explicitly with a 1 to 1 comparison of a light and a heavy nuclear modification

Strange nuclear modification ratio

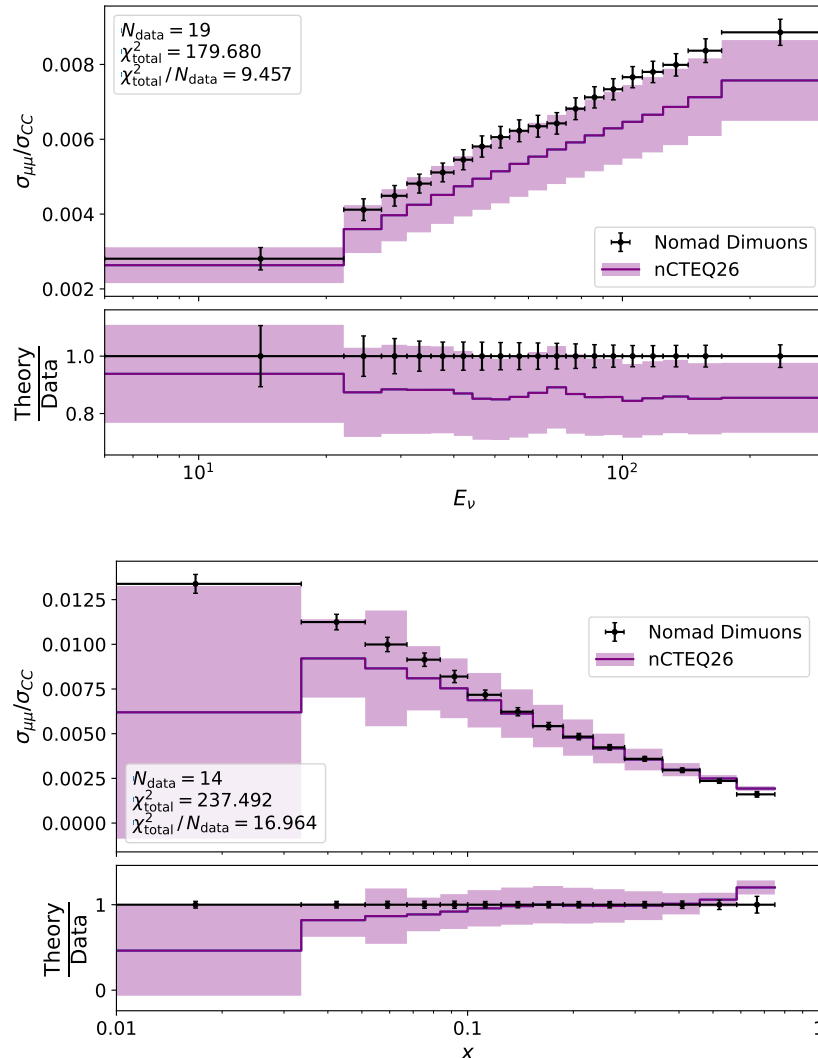


Predictions: CMS Dijets



- Central rapidity of $p\text{Pb}$ regime covered within nCTEQ26 uncertainties, but shape mismatch to data at kinematic edges
- Ratio to pp included in EPPS21 and nNNPDF3.0 (same shape mismatch)

Predictions: Nomad Dimuons



- E_ν distribution: data covered in 90% confidence level, upper end describes shape of the data, but nCTEQ26 overshoots the data in the whole E_ν range
- x distribution: Data is well described for large x but nCTEQ26 overshoots the data by far for the small x bins (which causes the overall disagreement in the E_ν distribution)
- Not included, because no fast prediction available (integration required)
- Very interesting data to gain more information on the strange PDF

Conclusion

- nCTEQ26 combines achievements from old nCTEQ analyses (nCTEQ15, nCTEQ15HQ, nCTEQ15WZSIH etc.) as well as completely new features (A Parametrisation, new Data, etc.)
- Wide range - from light to heavy - of data included
- Uncertainty landscape for strange and gluon differs significantly from other collaborations
 - Flexibility in A allows for large uncertainties in unconstrained regions and smaller uncertainties where the data lives
- Especially well constrained gluon PDF due to the large amount of HQ data
- Nuclear modifications for light and heavy nuclei look very different

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Outlook: What should be done with the nCTEQ26 PDFs?

1. Download from *lhapdf* or <https://ncteq.hepforge.org/ncteq26>
2. Predictions, Predictions, Predictions!
 - How well does the interpolation work for not included nuclei (e.g. oxygen or neon)?
 - How large is the contribution of the PDF uncertainty to the total one?
 - Can we describe A-A collisions with nCTEQ26 (e.g. Ne-Ne, O-O)?



Thank You

Bibliography

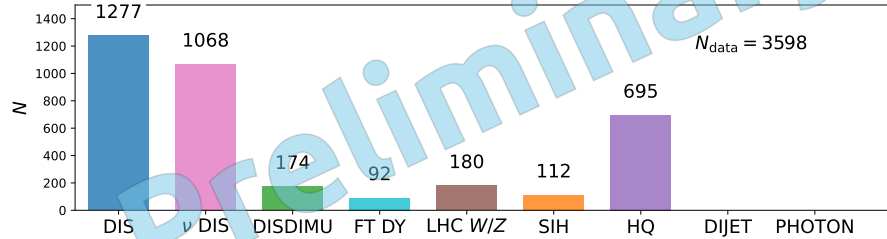
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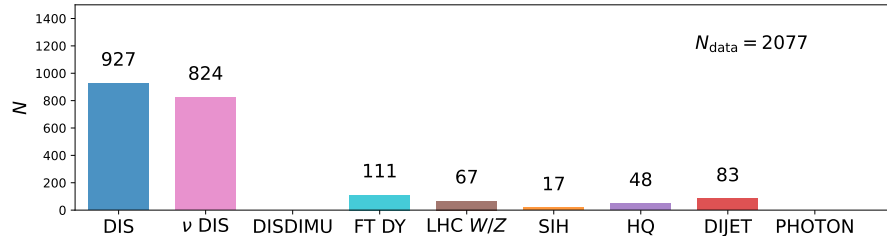
Backup

Data per type of experiment

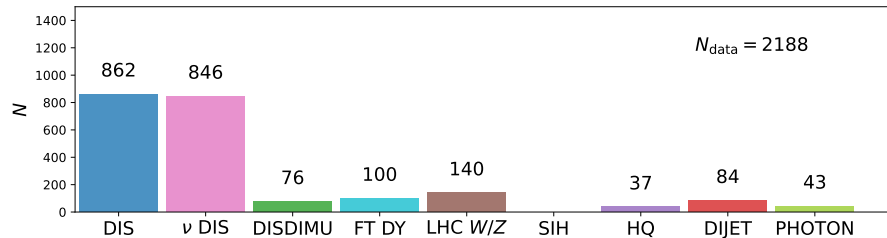
nCTEQ26



EPPS21

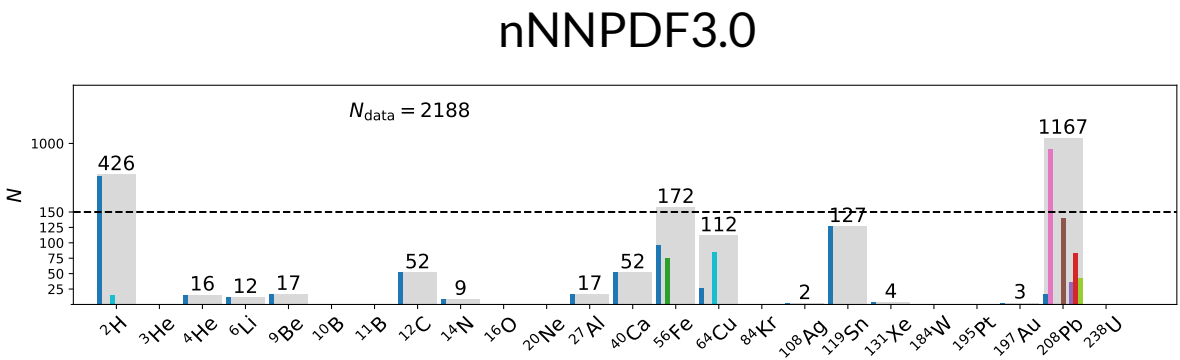
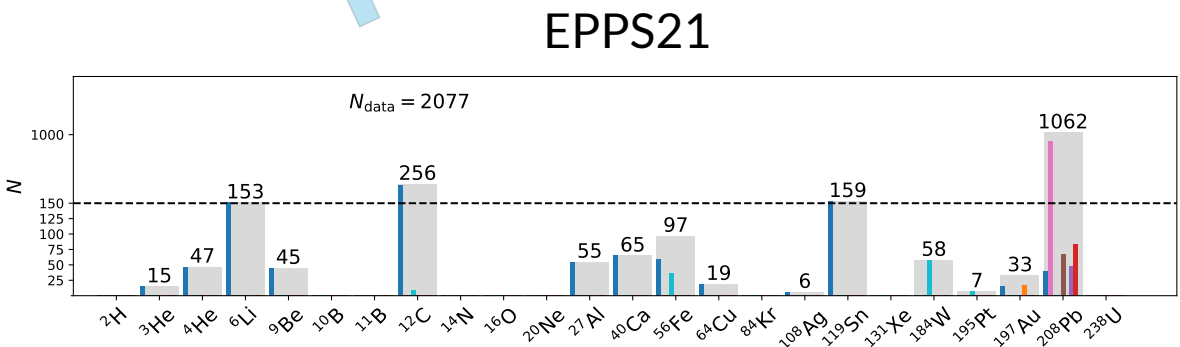
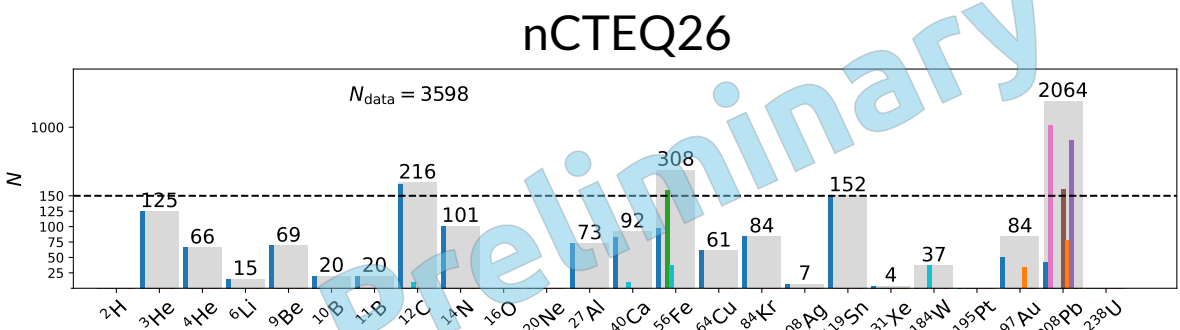


nNNPDF3.0



- Large amount of HQ data in nCTEQ26
- Other no. of data points comparable between the analyses
- DIJET data not included in nCTEQ26 (discussed later)

Global nuclear PDF analyses: Data per nuclei

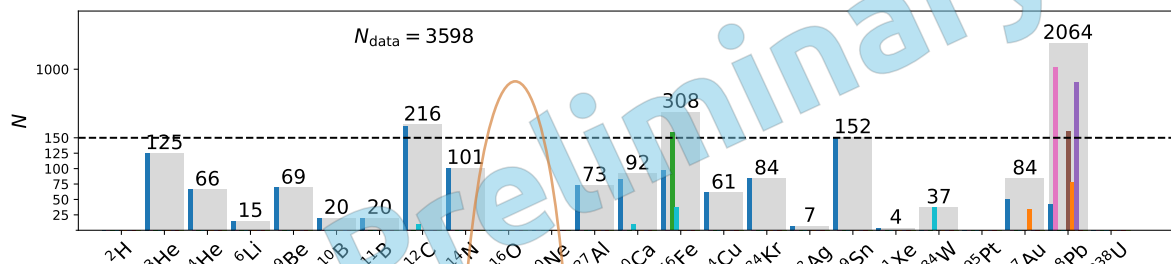


- DIS
- DISNEU
- DISDIMU
- FT DY
- LHC W/Z
- SIH
- HQ
- DIJET
- PHOTON

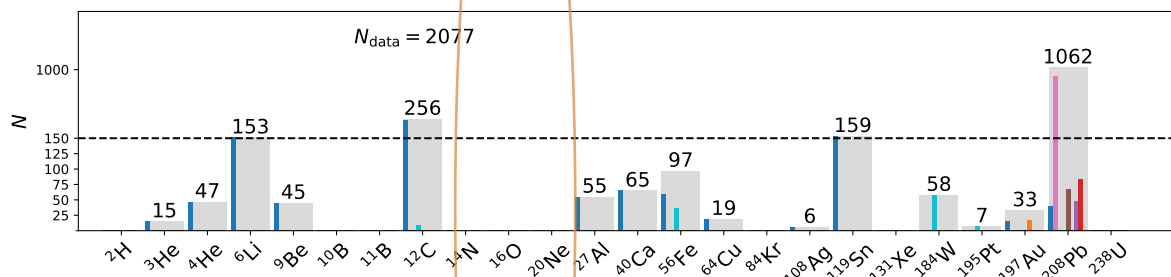
- Vast amount of data comes from lead collisions
- Light nuclei data is rare and comes only from FT DY and DIS, not from hadron-hadron collisions

Global nuclear PDF analyses: Data per nuclei

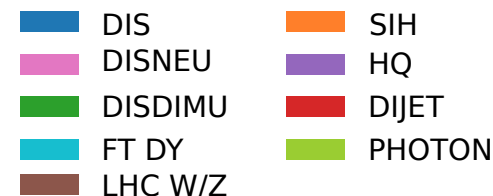
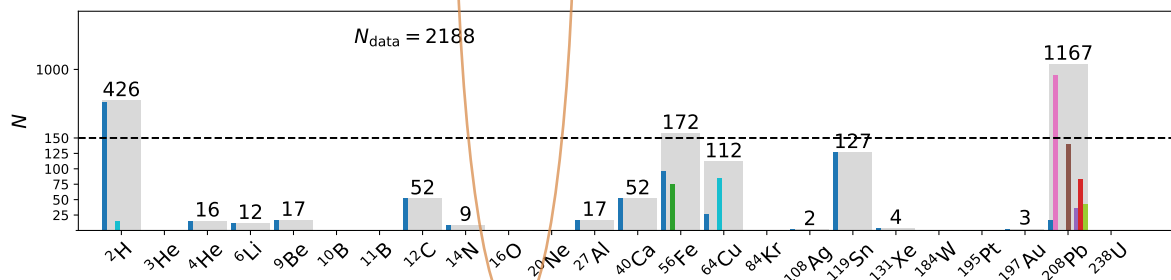
nCTEQ26



EPPS21



nNNPDF3.0

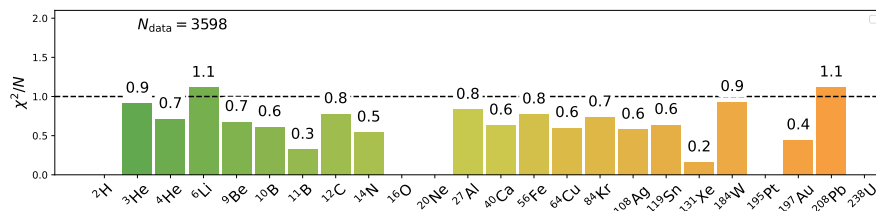


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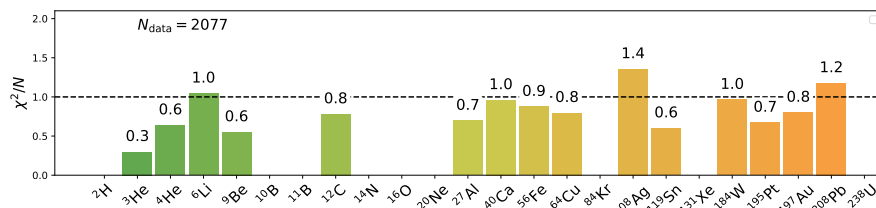
Global nuclear PDF analyses: Data per nuclei

NLO:

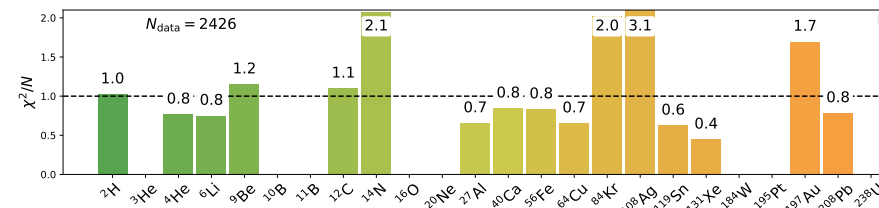
nCTEQ26



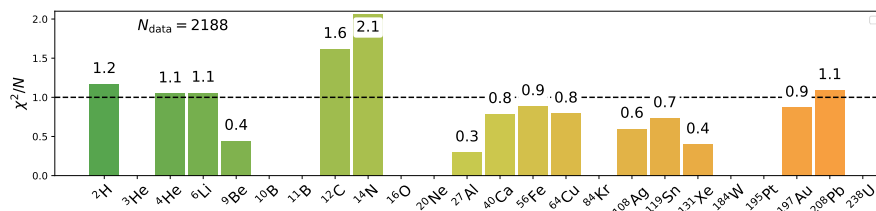
EPPS21



TUJU21 NNLO



nNNPDF3.0

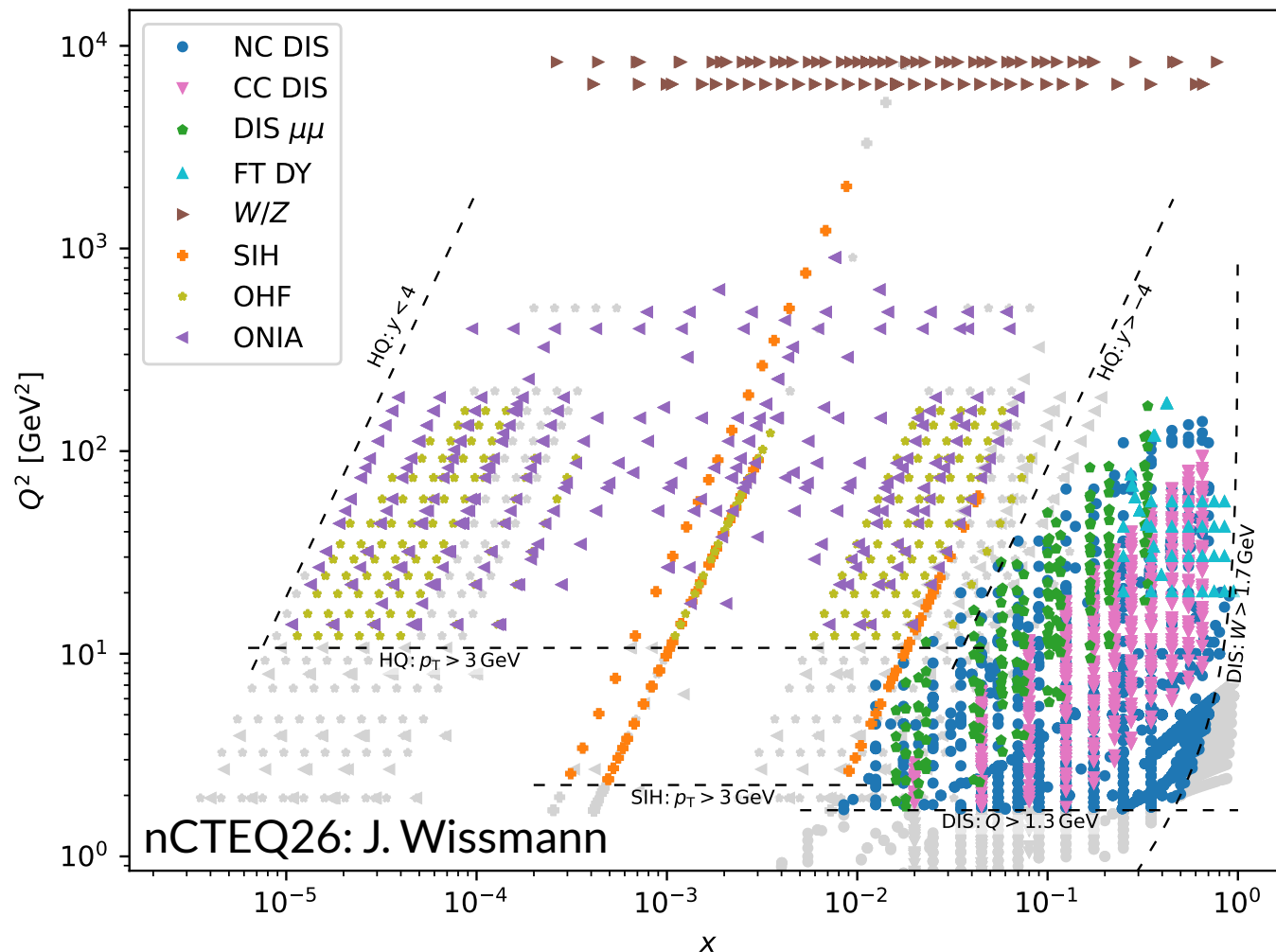


- Data can be described precisely over the whole range of A

Kinematic coverage in x and Q^2

Kinematic coverage of data used in nCTEQ26:

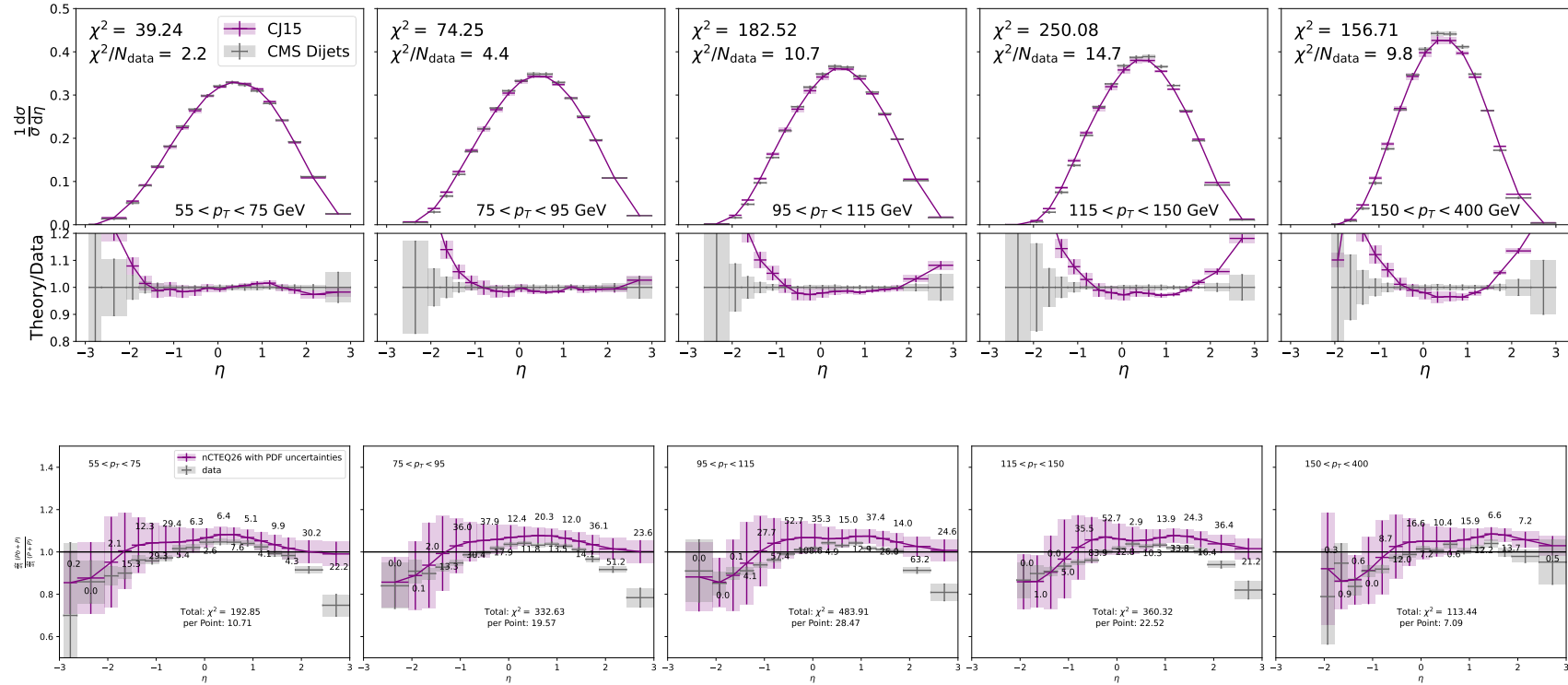
- DIS data covers low Q^2 -high x regime
- Inclusion of HQ and W/Z data gives access to low x regime
- W/Z data lives at particularly high scales Q^2



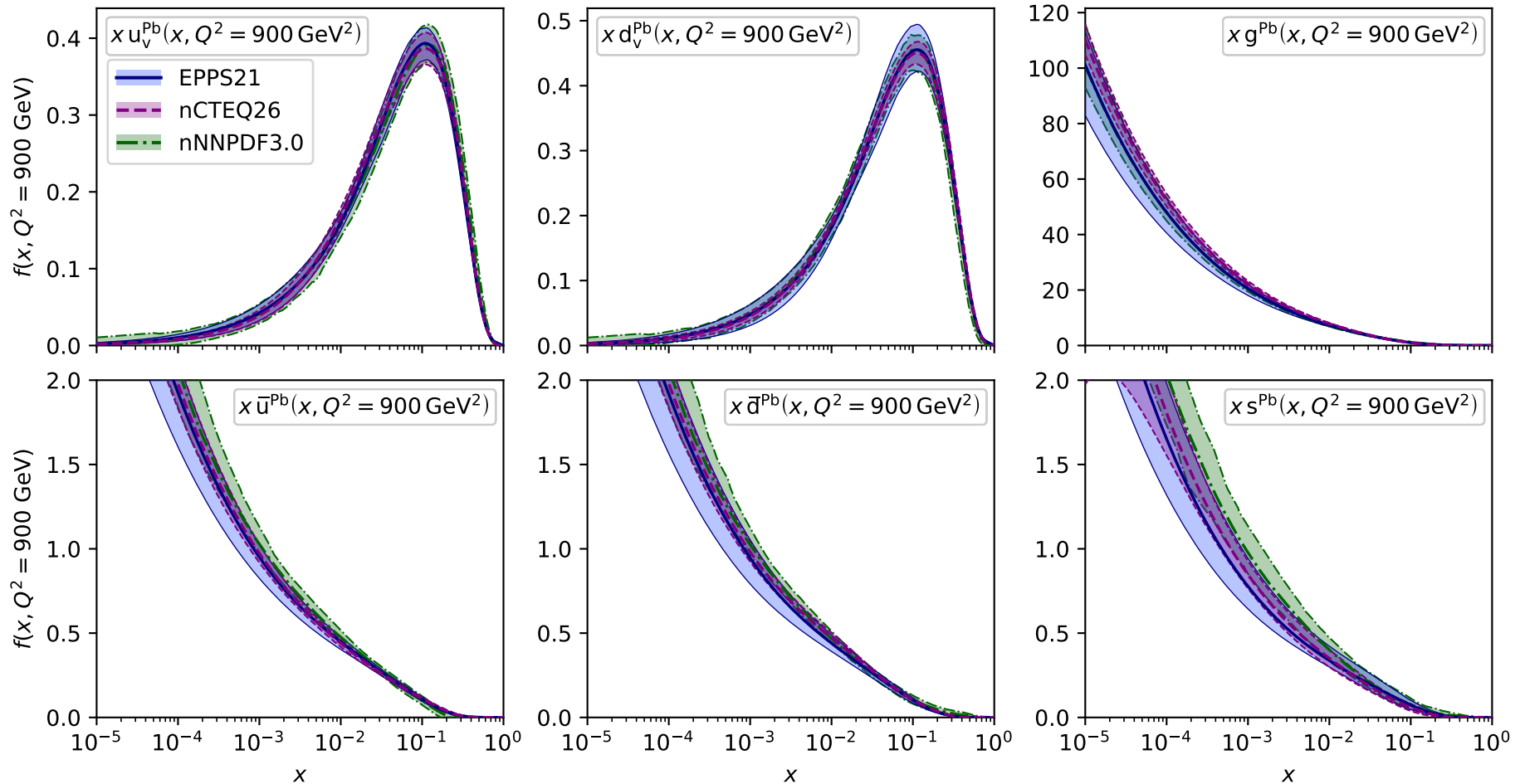
Overview

	nNNPDF3.0 (Khalek et al. 2022)	EPPS21 (Eskola et al. 2022)	nCTEQ26 (preliminary)	TUJU21 (Helenius et al. 2022)
Pert. order	NLO	NLO	NLO	NNLO
N_{data}	2188	2077	3598	2426
DIS	?	?	?	?
FT DY	?	?	?	?
LHC W/Z	?	?	?	?
Dijet	?	?	?	?
Photon	?	?	?	?
Dimuon	?	?	?	?
Uncertainty estimation	MC replicas	Hessian	Hessian	Hessian
N Parameters	268	24	36	16
N params. nuc. dep.	256	5	36	16

CJ15 predictions DIJET

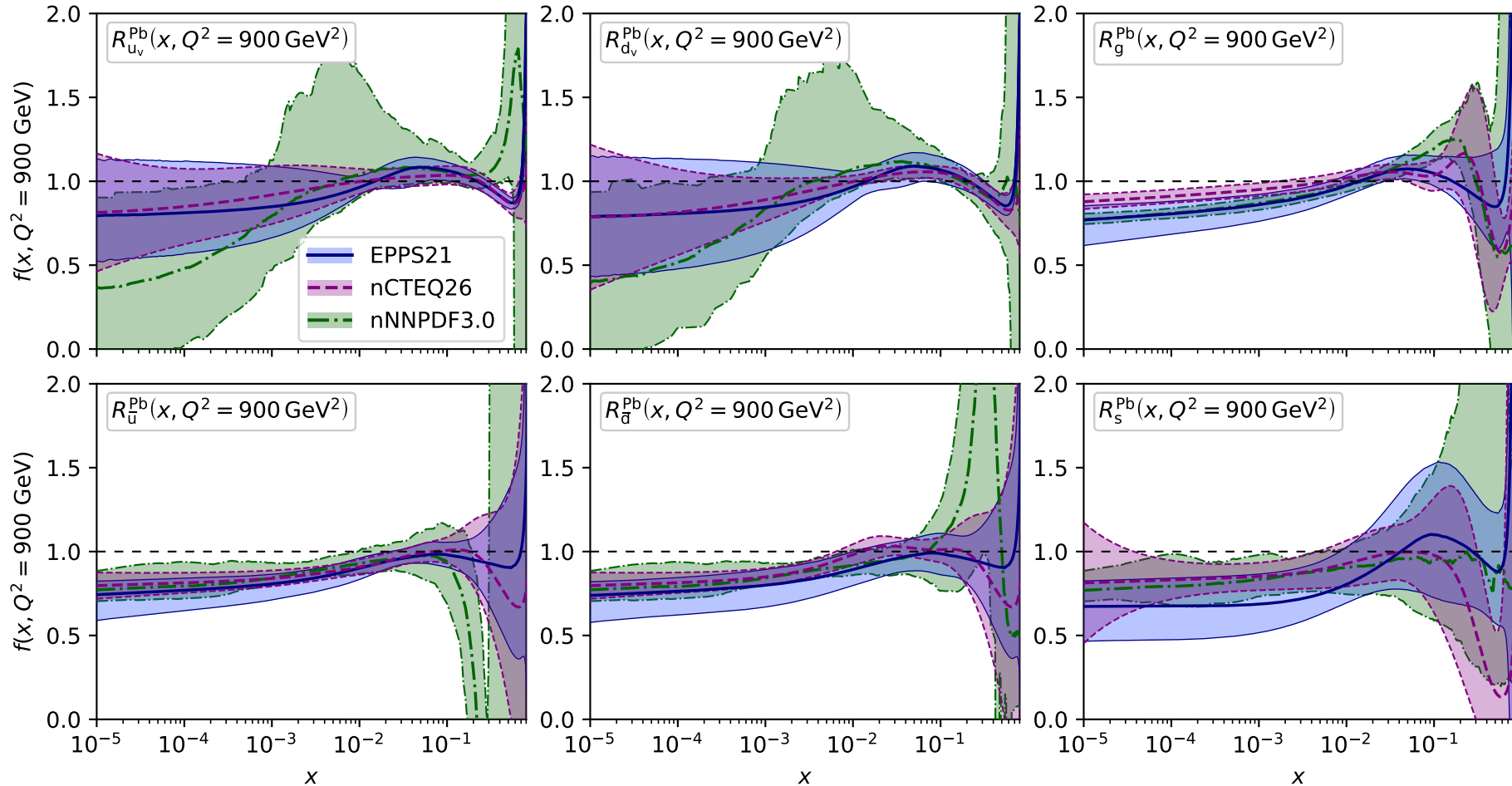


Nuclear pdfs Lead

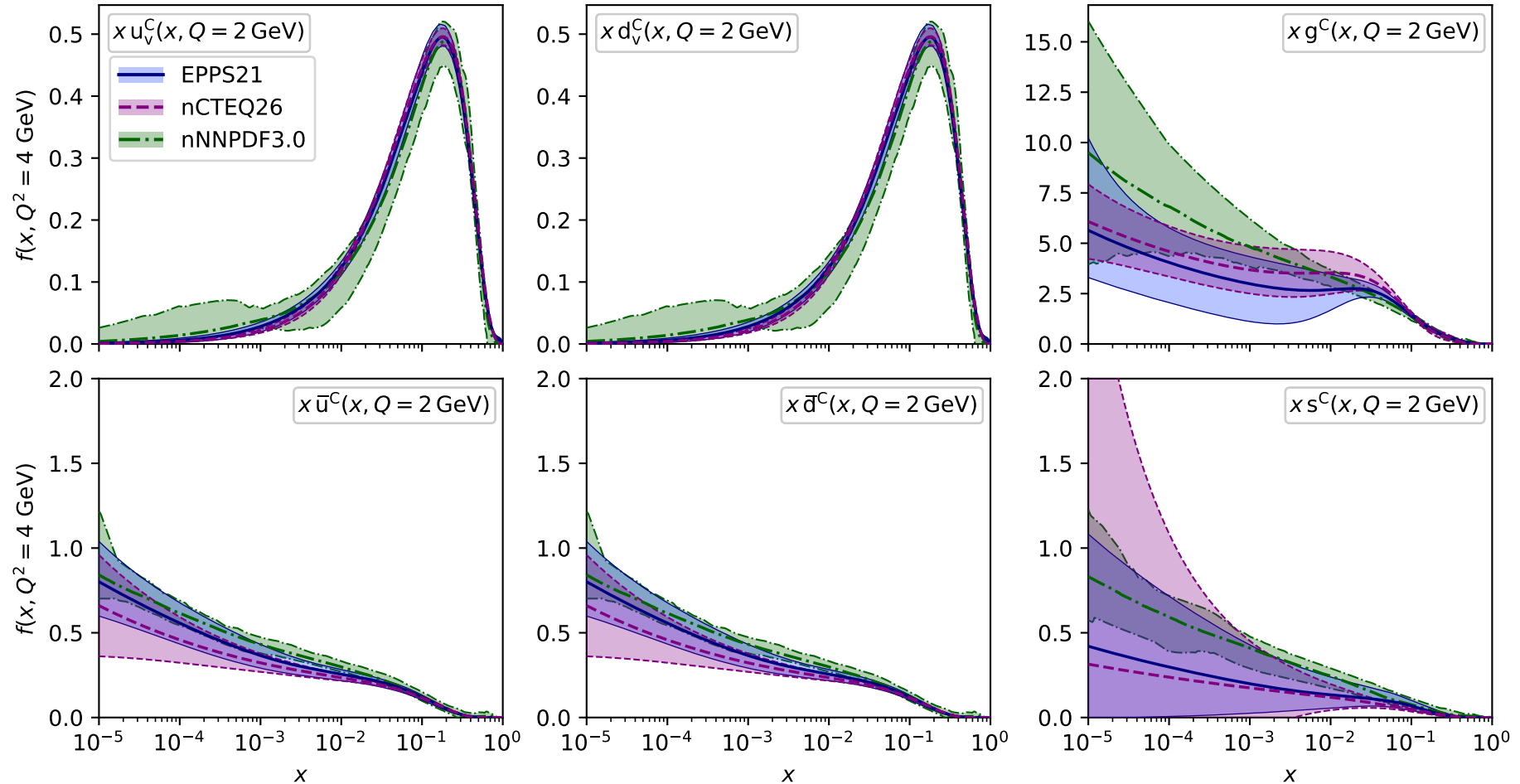


Nuclear modifications Lead 30 GeV

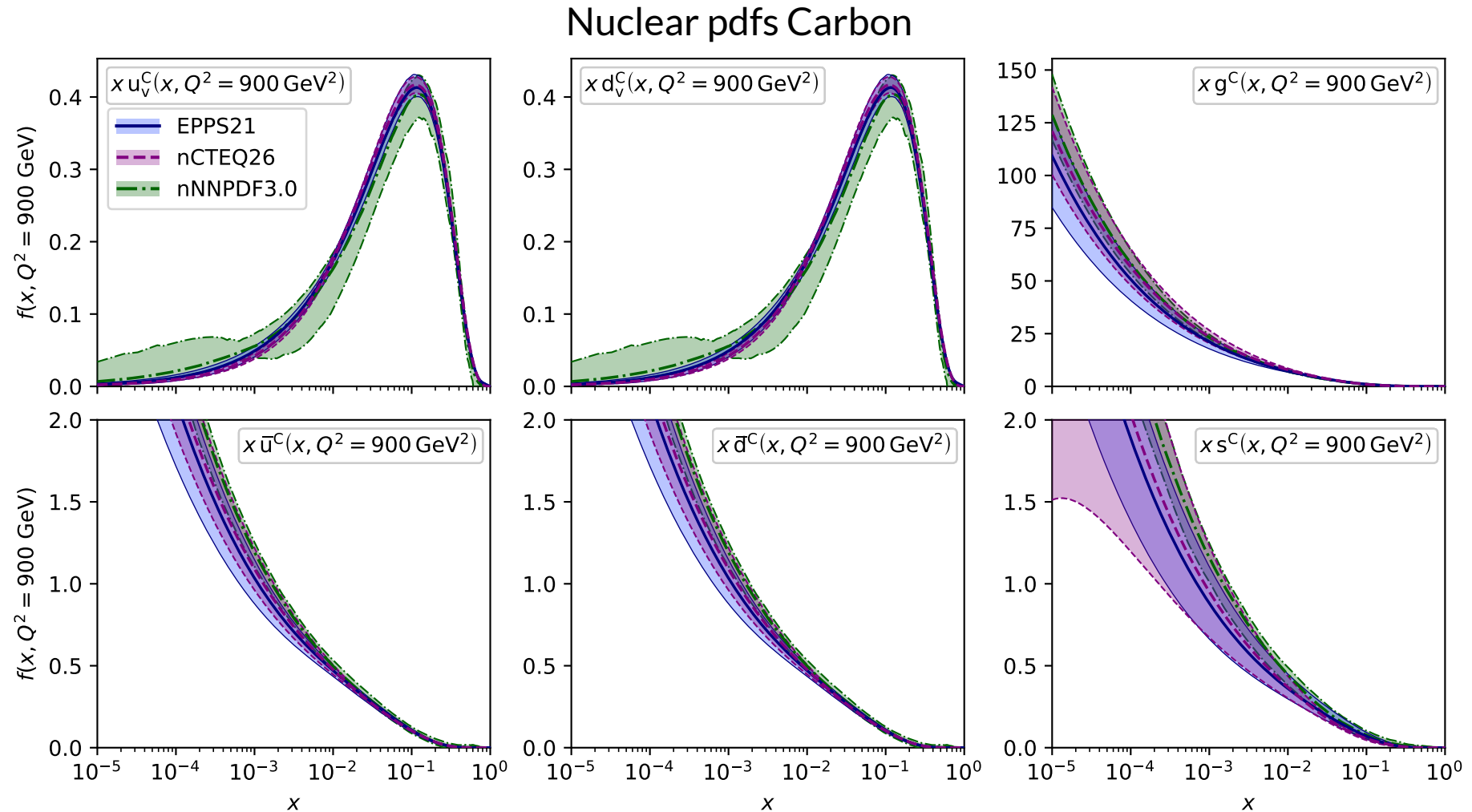
Nuclear modifications lead



Nuclear pdfs Carbon

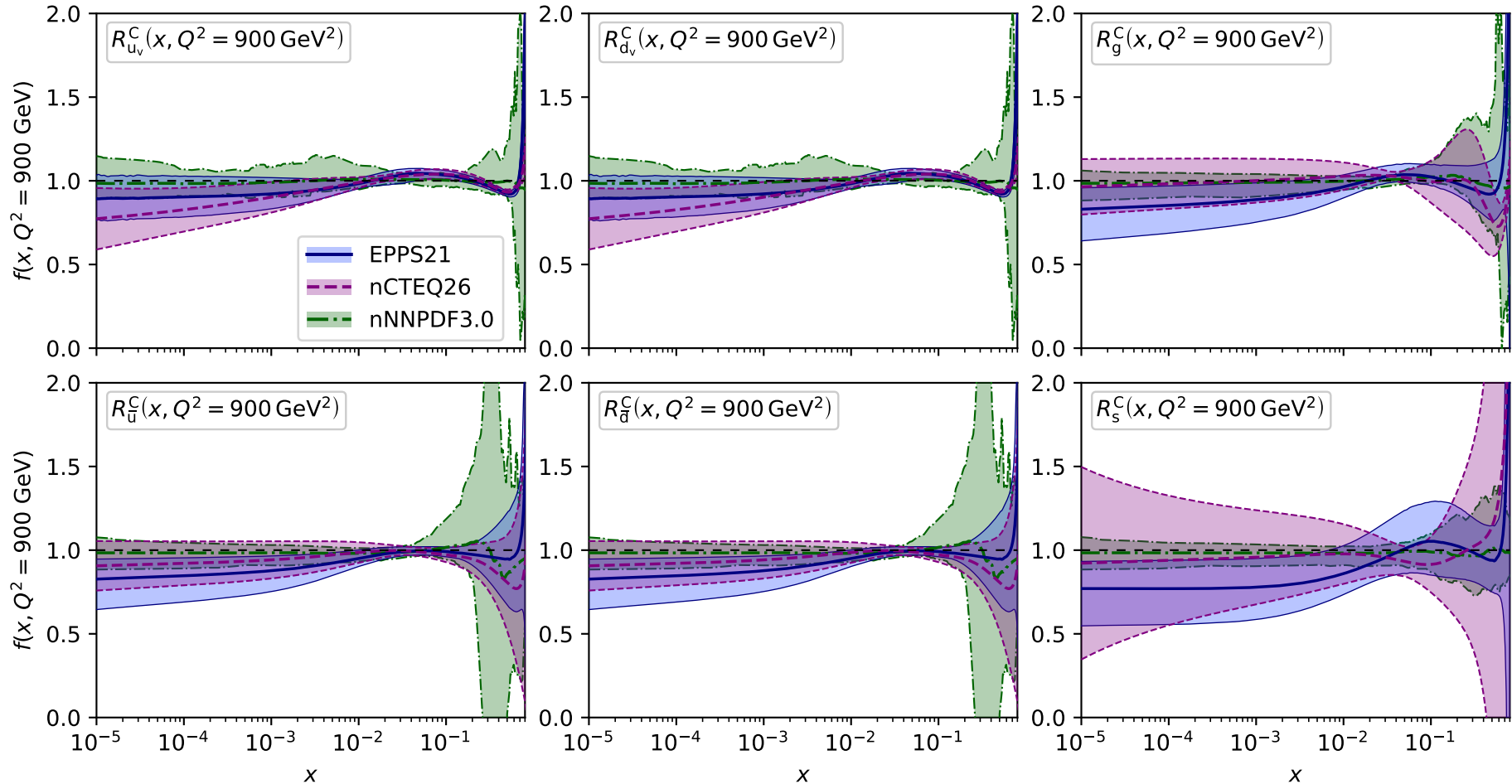


Nuclear PDFs Carbon 30 GeV



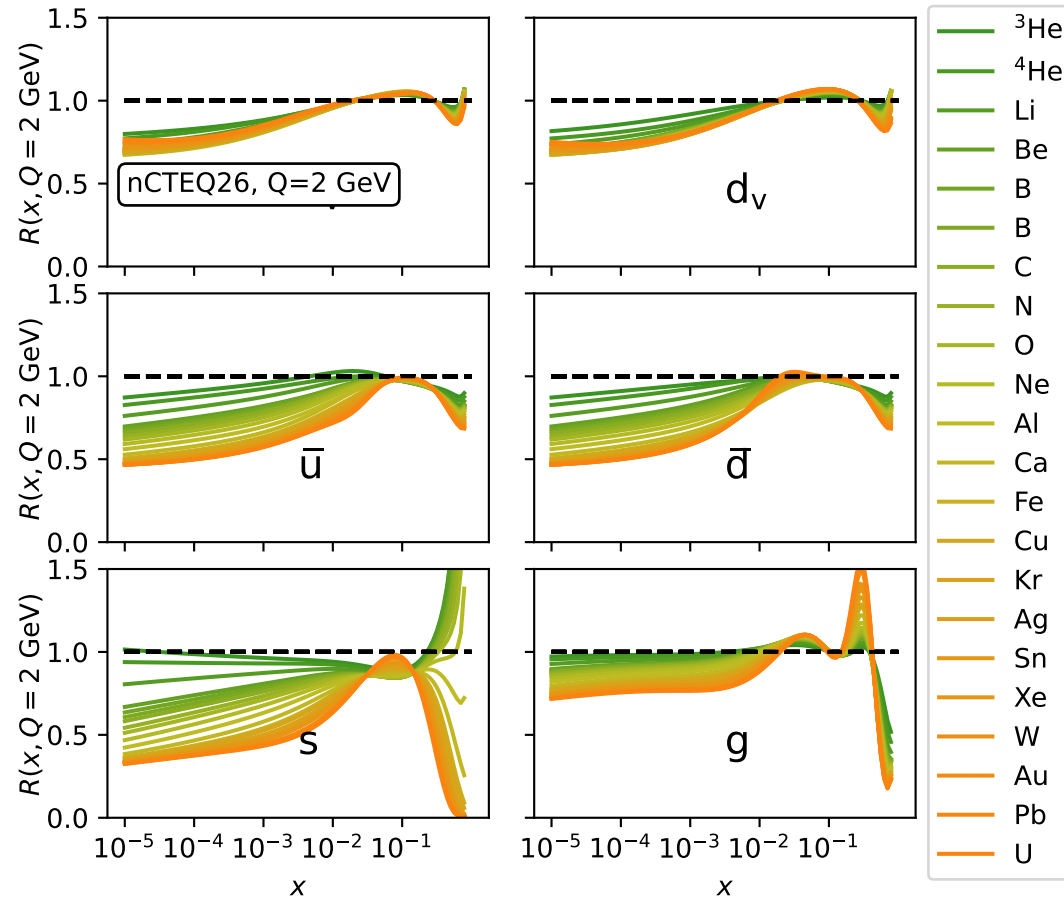
Nuclear modifications Carbon 30 GeV

Nuclear modifications carbon

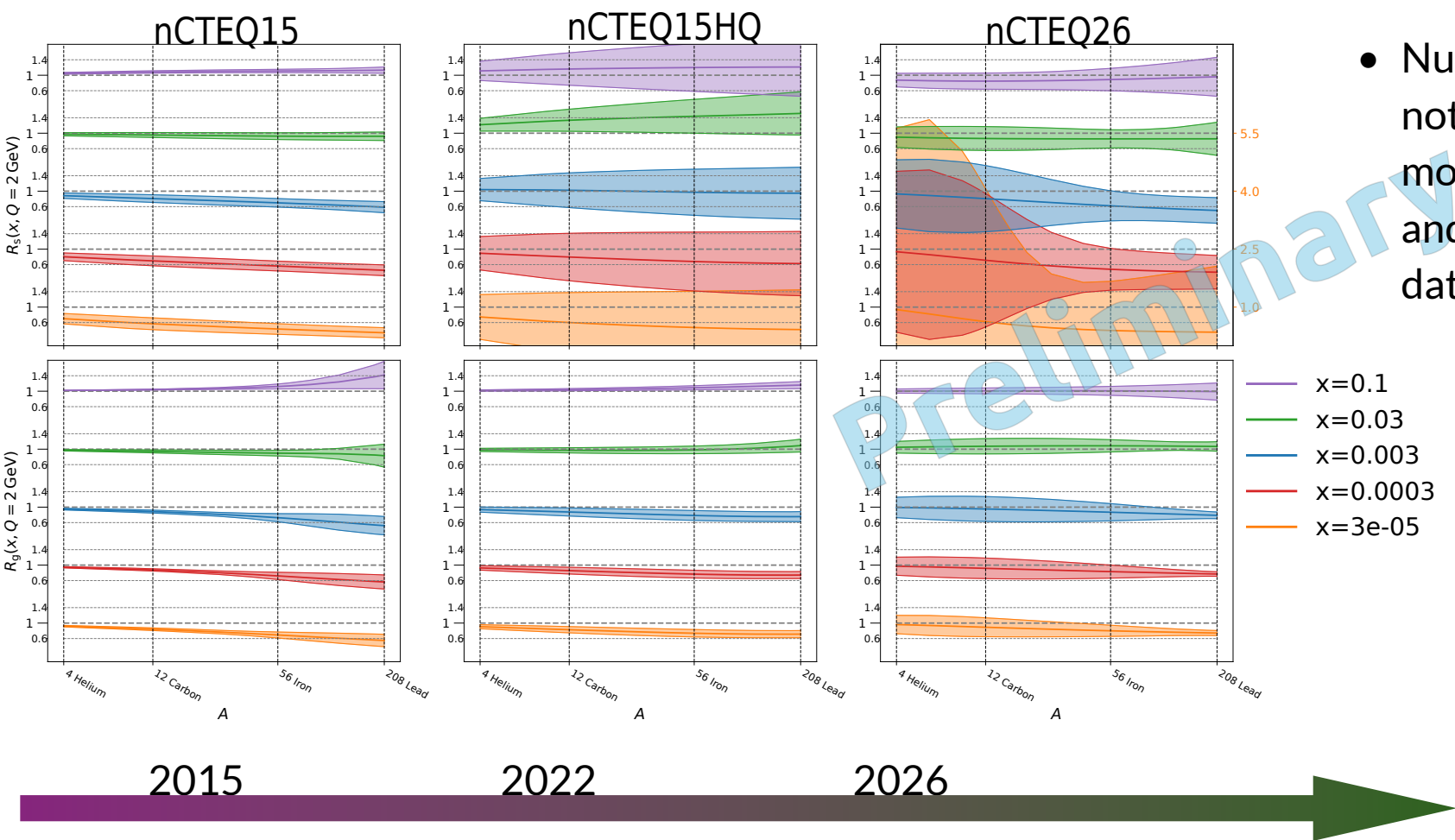


nCTEQ26 nuclear PDFs spektrum

A-dependence nuclear modification nCTEQ26

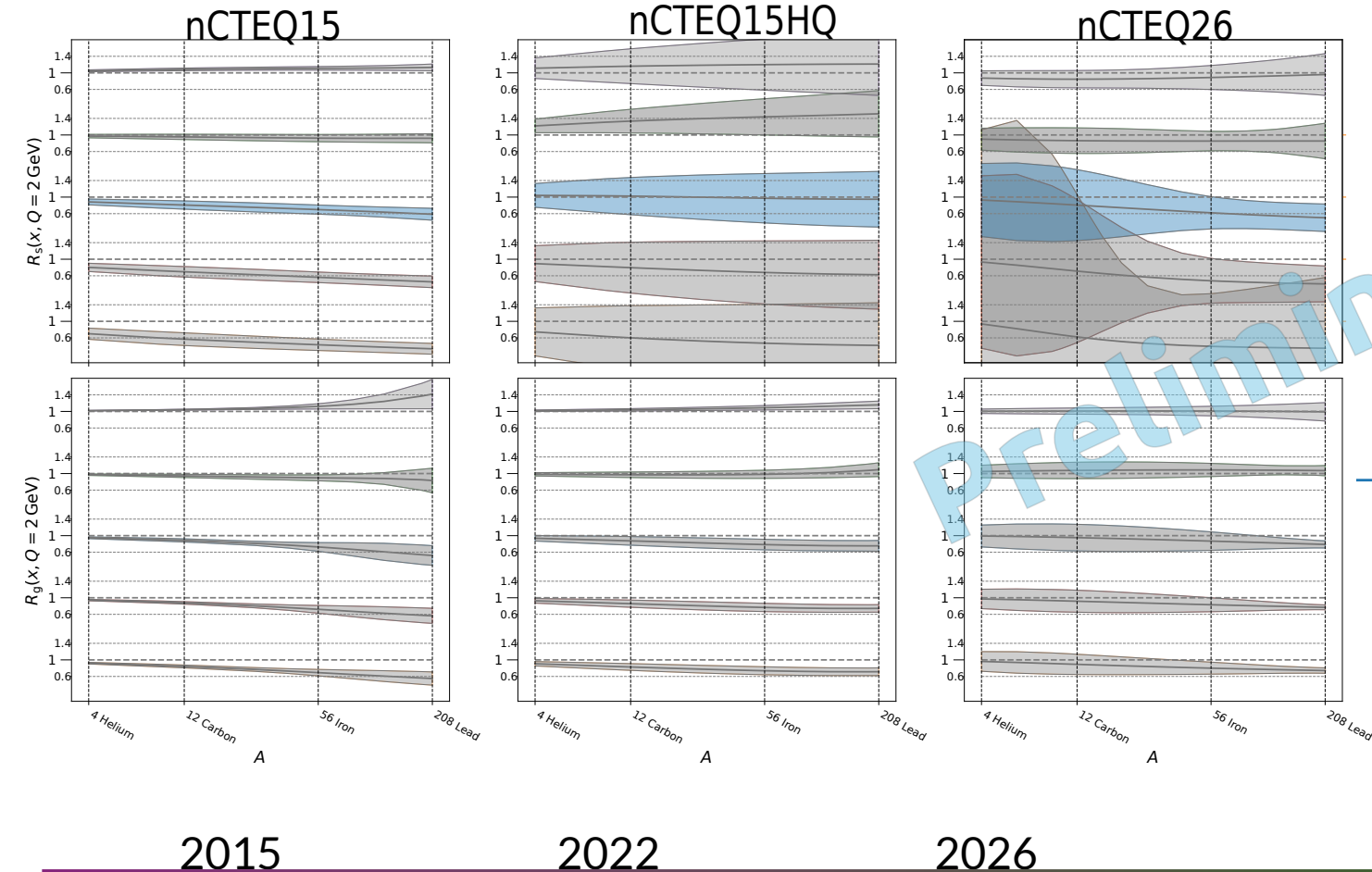


A-dependence: Evolution of nCTEQ nuclear uncertainties



- Nuclear uncertainties do not get monotonically more precise with time and inclusion of more data

A-dependence: Evolution of nCTEQ nuclear uncertainties



- Nuclear uncertainties do not get monotonically more precise with time and inclusion of more data

Uncertainties of old analyses are underestimated.
Did we reach the era of reliably uncertainties?