Nuclear PDFs from the nCTEQ25 global analysis and potential impact of light ion collisions at the LHC

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With many thanks to all my nCTEQ collaborators

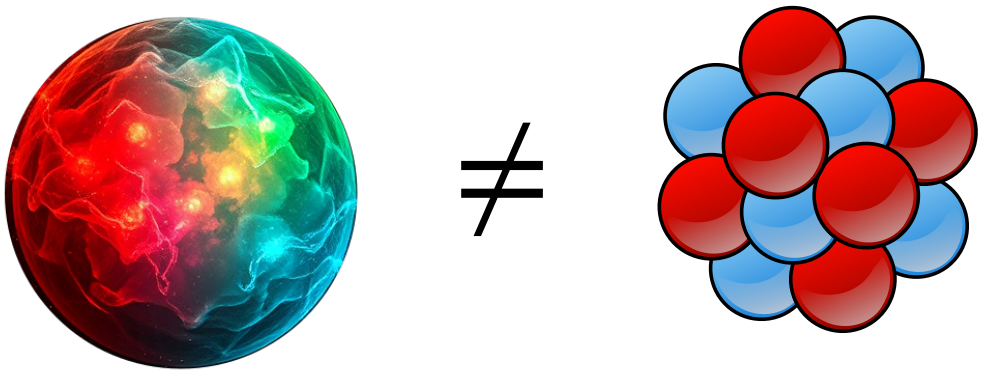
nCTEQ
nuclear parton distribution functions

2nd of December, 2025

Hadron structure and Nuclear PDFs

$$F_2^A \neq ZF_2^p + (A - Z)F_2^n$$

- Shadowing (low x), antishadowing (mid to high x), EMC effect (high x) and Fermi motion (very high x) very well tested experimentally
- Nuclear PDFs: Translation of modifications to universal quantaties



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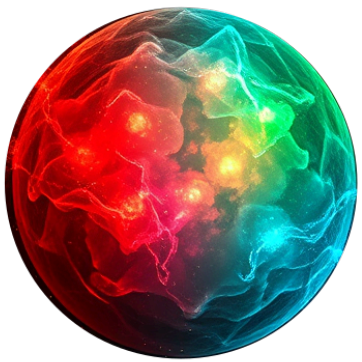
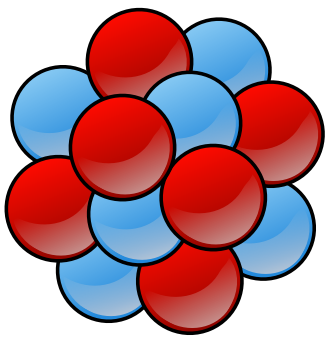


$\neq$



Physical Input for nuclear PDF determination

- Factorisation (PDFs as universal concept)
- **DGLAP** equations determine scaling and make the formalism predictive
- Isospin symetry: $d^{\frac{n}{A}}\left(x, Q^2\right) = u^{\frac{p}{A}}\left(x, Q^2\right)$ and vice versa
- Sum rules, e.g. $\int_0^1 (u(x) - \overline{u}(x))dx = 2$

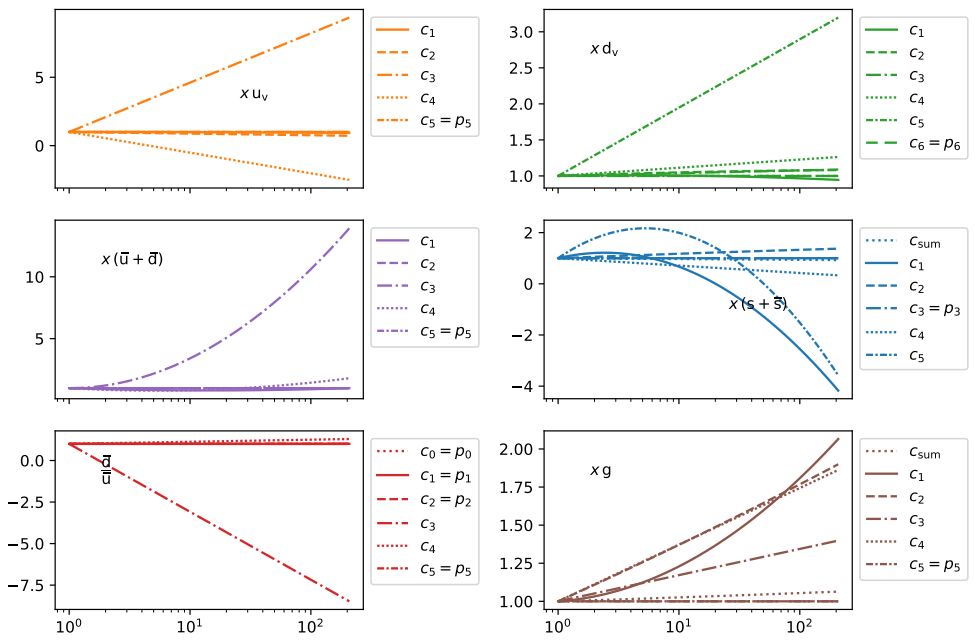
Hadron structure and Nuclear PDFs

- The model consists of a parametrisation in x at an initial scale Q_0:

$$f_k^A(x, \{c_k(A)\})$$

$$k = \{u_v, d_v, s + \bar{s}, g, etc\}$$

  - Fitted to experimental data
  - $c_k(A)$ is parametrised in A
- Parametrisation should be able to reproduce modifications found in measurements
- A - dependence as smooth parametrisation:
  - nCTEQ25: $c_A = p + a\ln(A) + b\ln(A)^2$
  - EPPS21: $y_i(A) = 1 + \left[y_{i(A_{\text{ref}})} - 1\right]\left(\frac{A}{A_{\text{ref}}}\right)^{\gamma_i}$
- nNNPDF3.0: A as input for neural network $\text{NN}_i\left(x, \ln\left(\frac{1}{x}\right), A\right)$

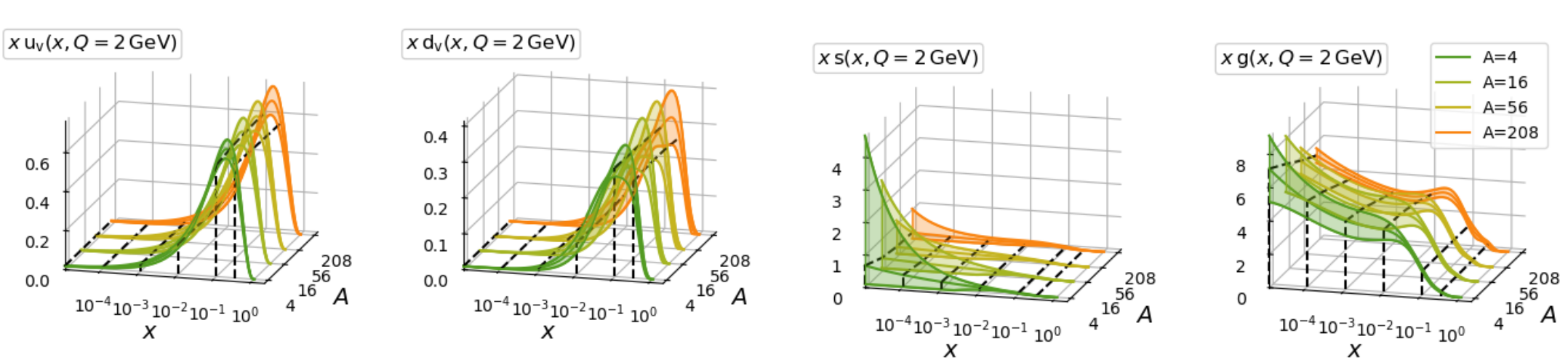


A- dependence of nuclear Parameters in nCTEQ25

nCTEQ25 global analysis

Overview

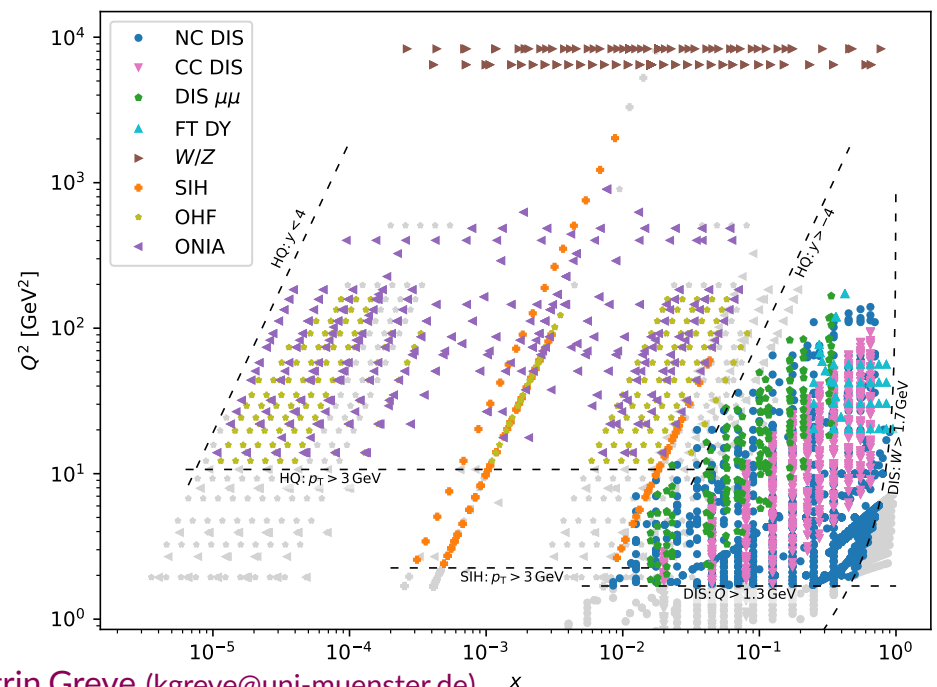
- Combination of old nCTEQ analyses (nCTEQ15HQ, nCTEQ15HIX etc.)
- + new Data, Parametrisation

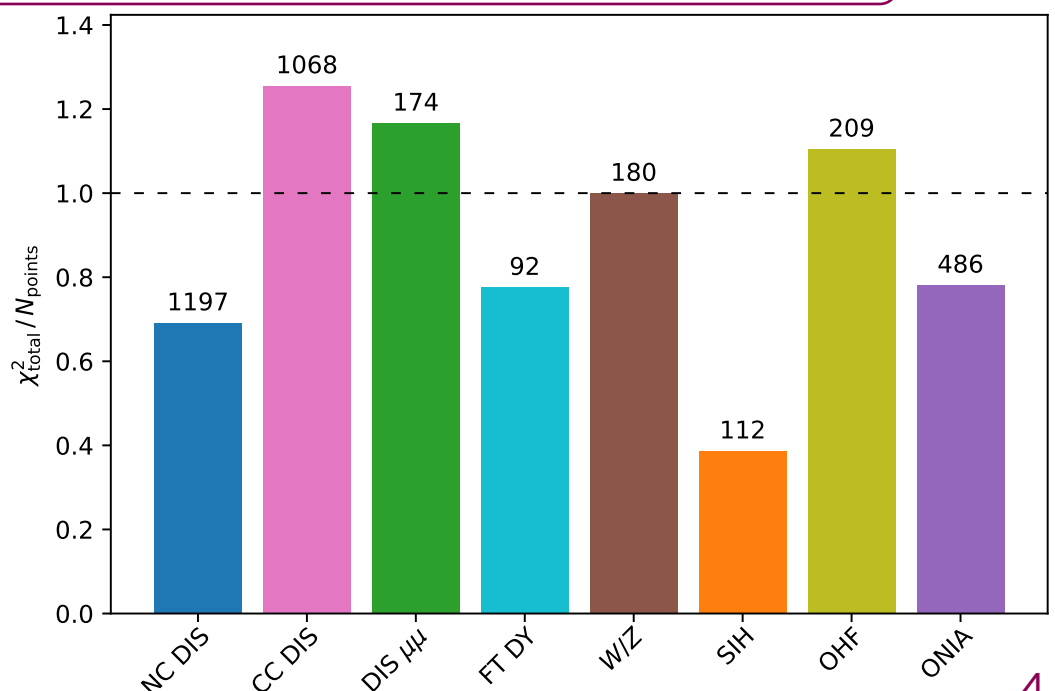


nCTEQ25 global analysis

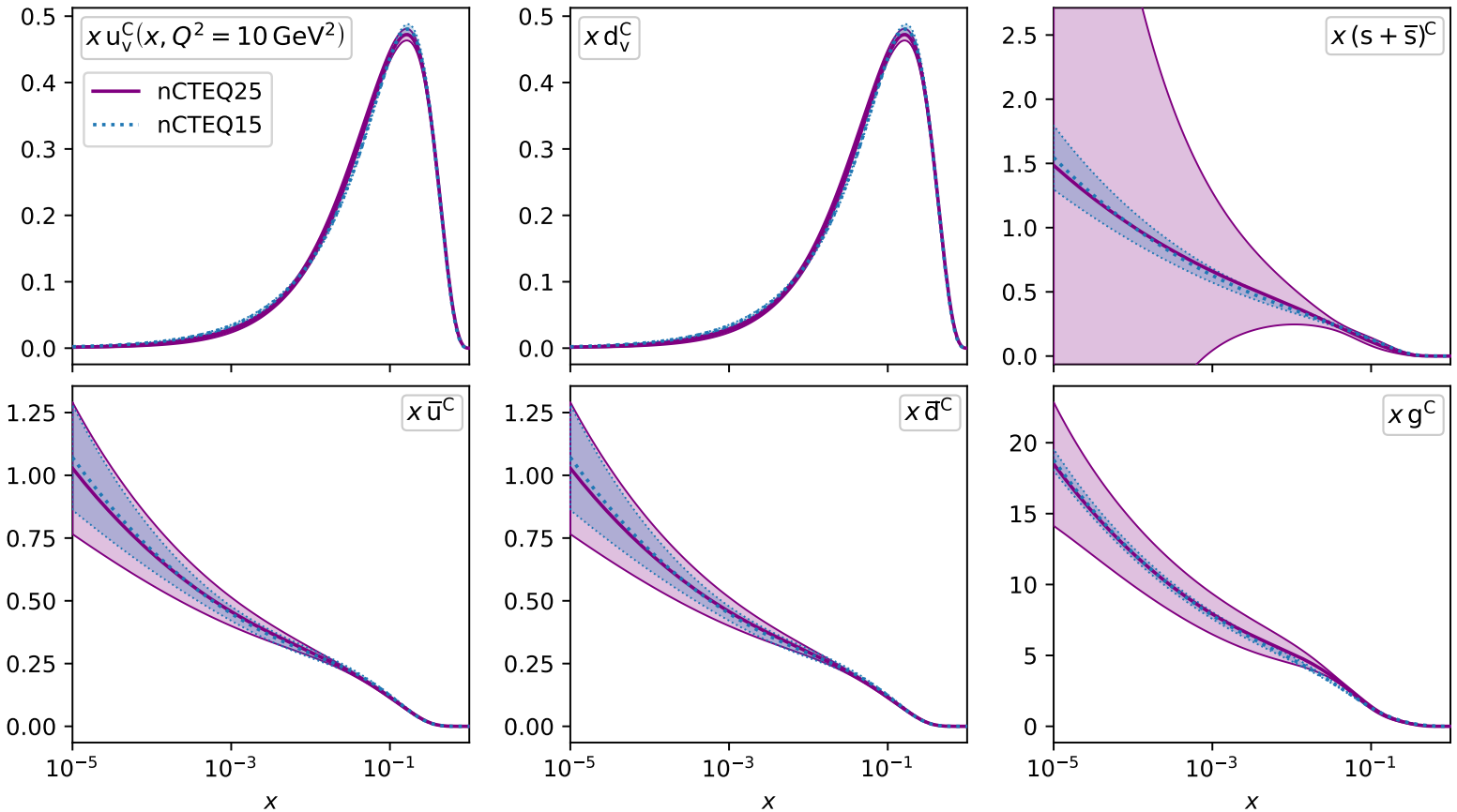
Overview

- Combination of old nCTEQ analyses (nCTEQ15HQ, nCTEQ15HIX etc.)
- + new Data, Parametrization
- 3518 included data points
- total χ^2/d.o.f. = 0.98
- 1079 points from hadron-hadron collisions





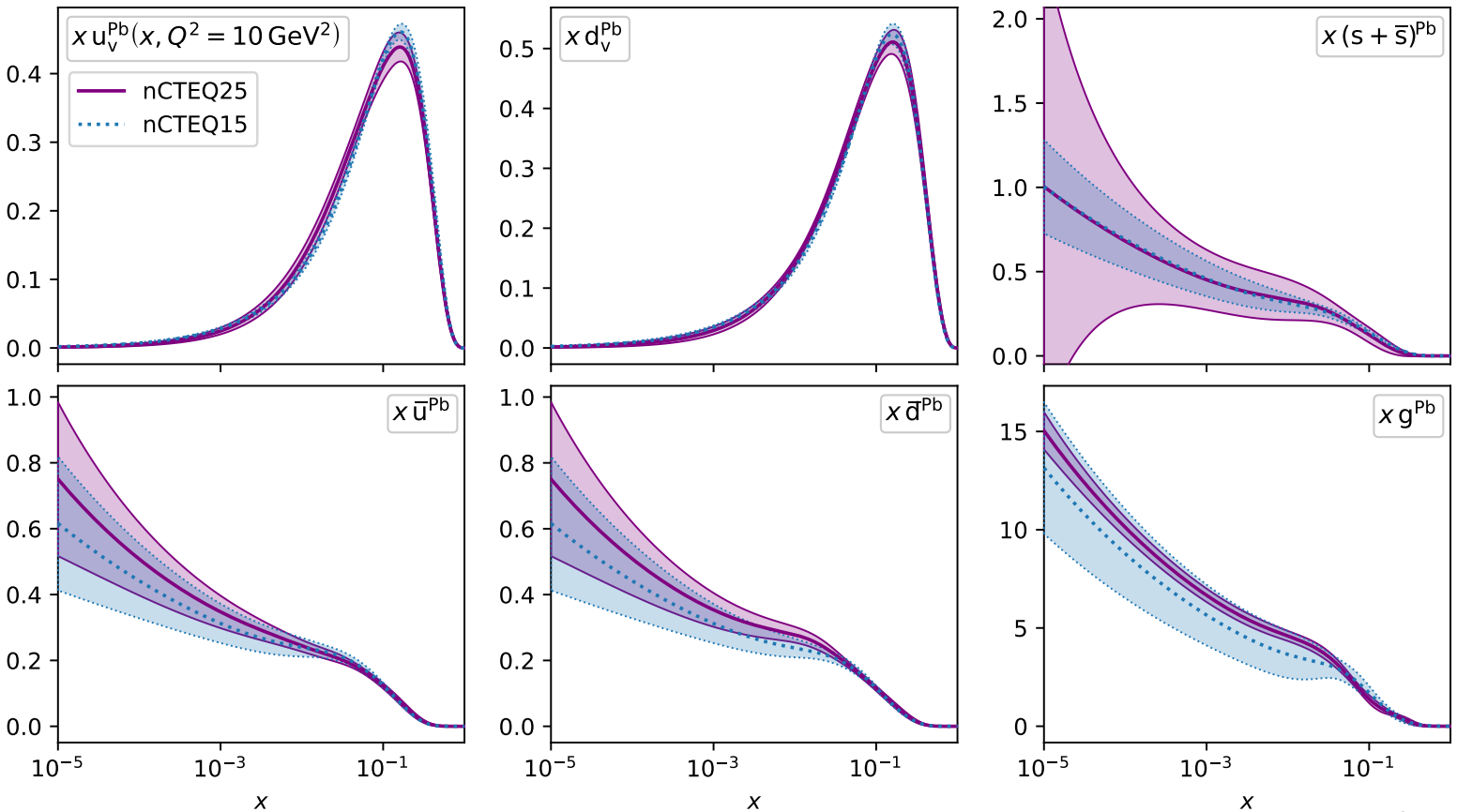
nCTEQ25 global analysis: $f^{C}(x, Q^2 = 10\ \mathrm{GeV}^2)$



- nCTEQ25 Parametrisation less restrictive compared to nCTEQ15[1]

[1] nCTEQ15 PDFs from [1]

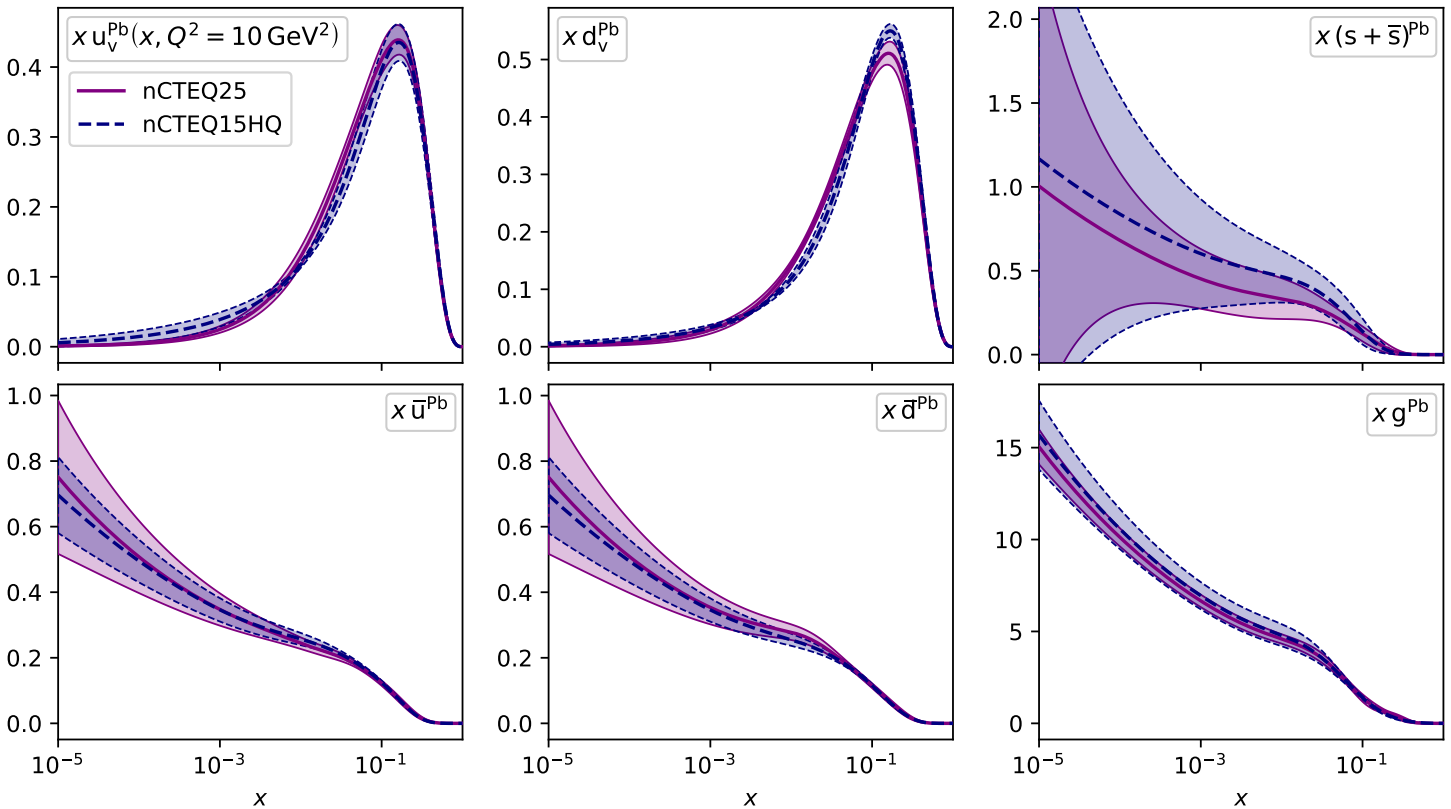
nCTEQ25 global analysis: $f^{\mathrm{Pb}}(x, Q^2 = 10\ \mathrm{GeV}^2)$



- nCTEQ25 Parametrisation less restrictive compared to nCTEQ15[1]
- HQ data as a constraint for gluon distribution (only heavy nuclei)

[1] nCTEQ15 PDFs from [1]

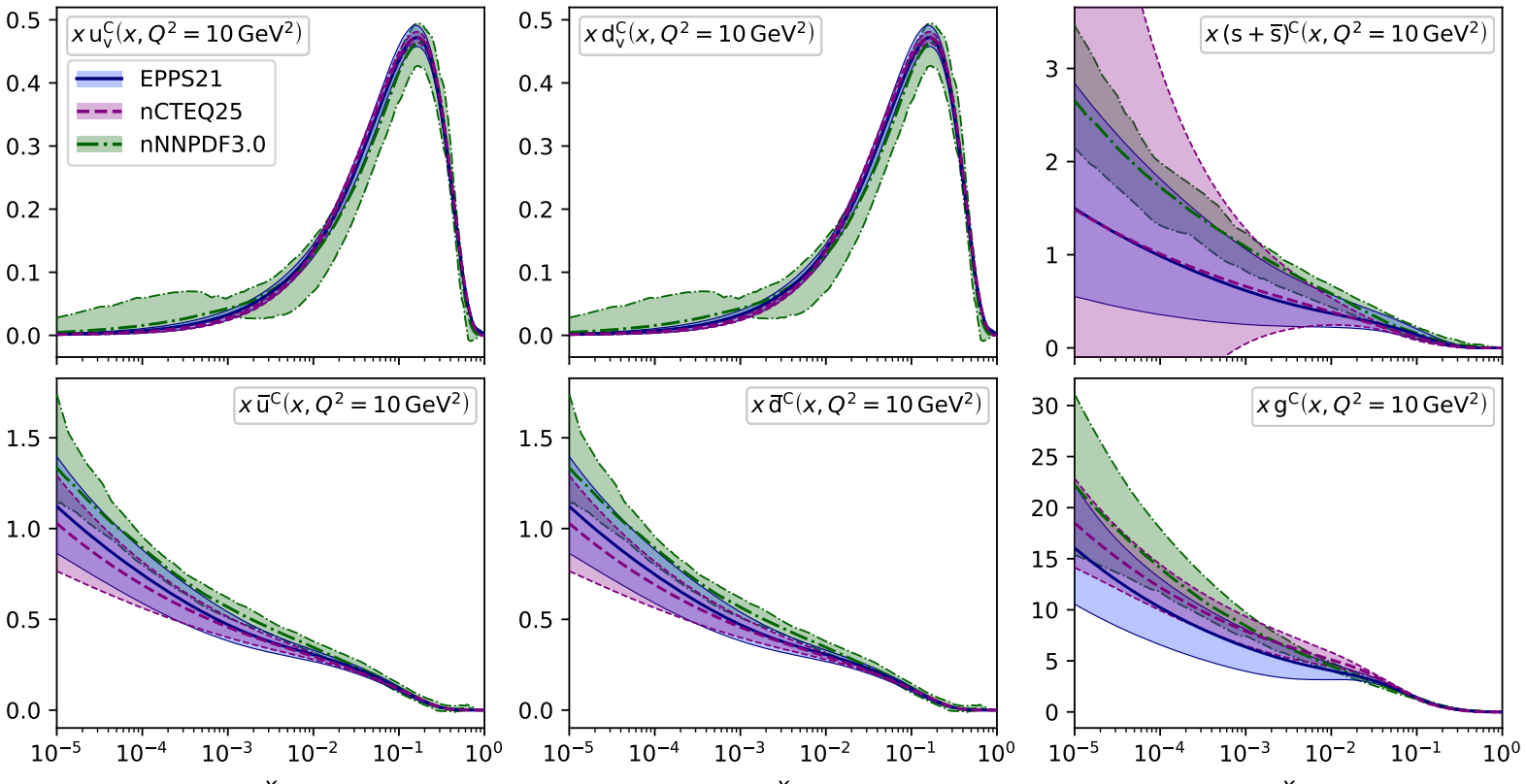
nCTEQ25 global analysis: $f^{\mathrm{Pb}}(x, Q^2 = 10\ \mathrm{GeV}^2)$



- nCTEQ15HQ, 2022[1], allowed for strange flexibility
  - Decreasing strange uncertainties towards nCTEQ25
- Are we finally in the era of realistic uncertainties?

[1] nCTEQ15HQ PDFs published in [2]

nCTEQ25 global analysis: $f^{C}(x, Q^2 = 10\ \mathrm{GeV}^2)$



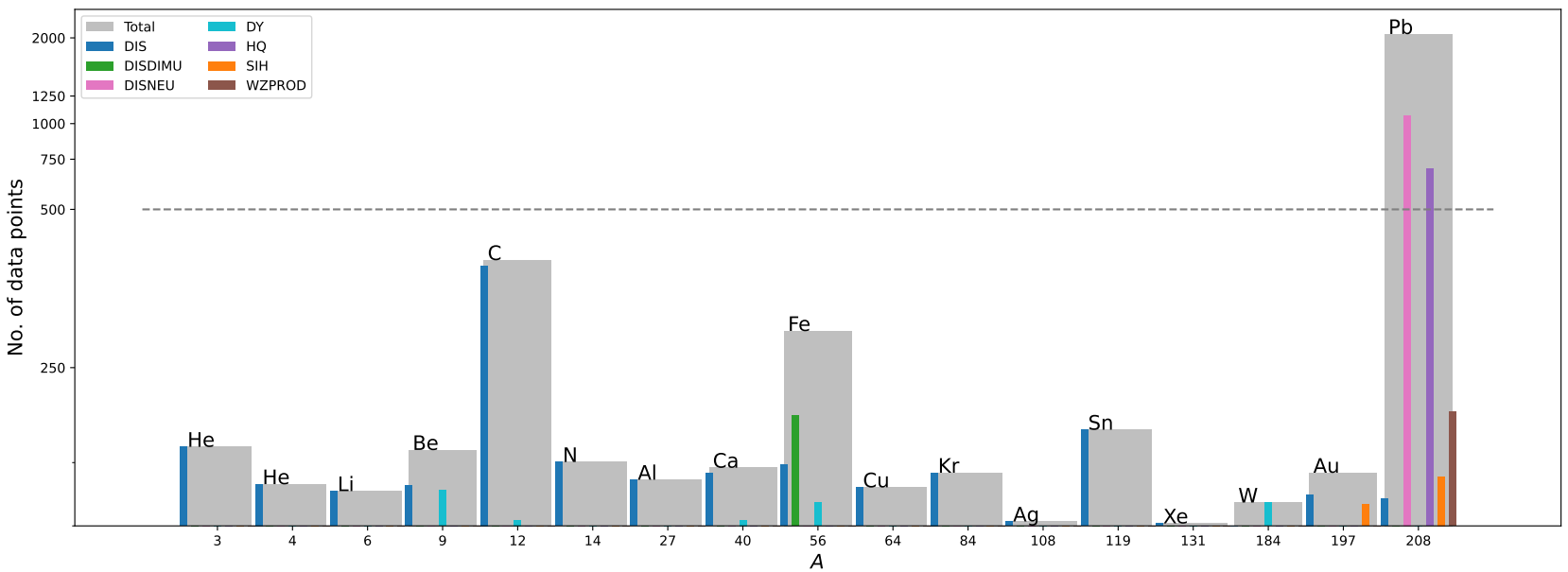
- Overall good agreement with EPPS21[1] and nNNPDF3.0 nuclear PDFs[2]
- New HQ data works as constraint for gluon distribution

[1] Published in [3]

[2] Published in [4]

Nuclear PDFs: Heavy data, light distributions?

- Vast amount of data from heavy ion collisions
- Hadron - hadron data only from heavy ions



Data used in nCTEQ25; distributed in A, presented on a log/lin scale.

Nuclear PDFs: Heavy data, light distributions?

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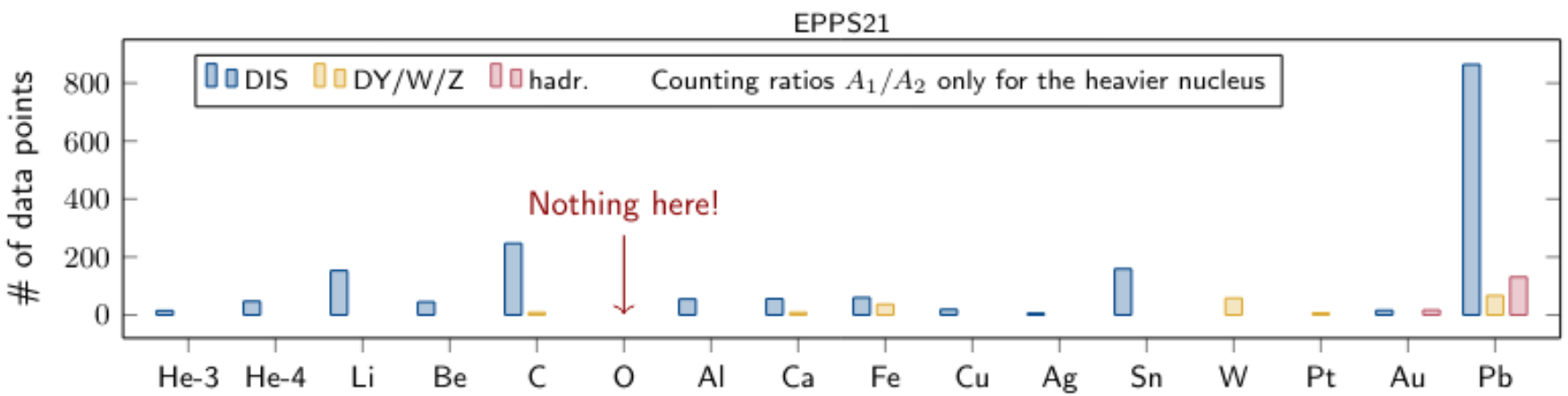
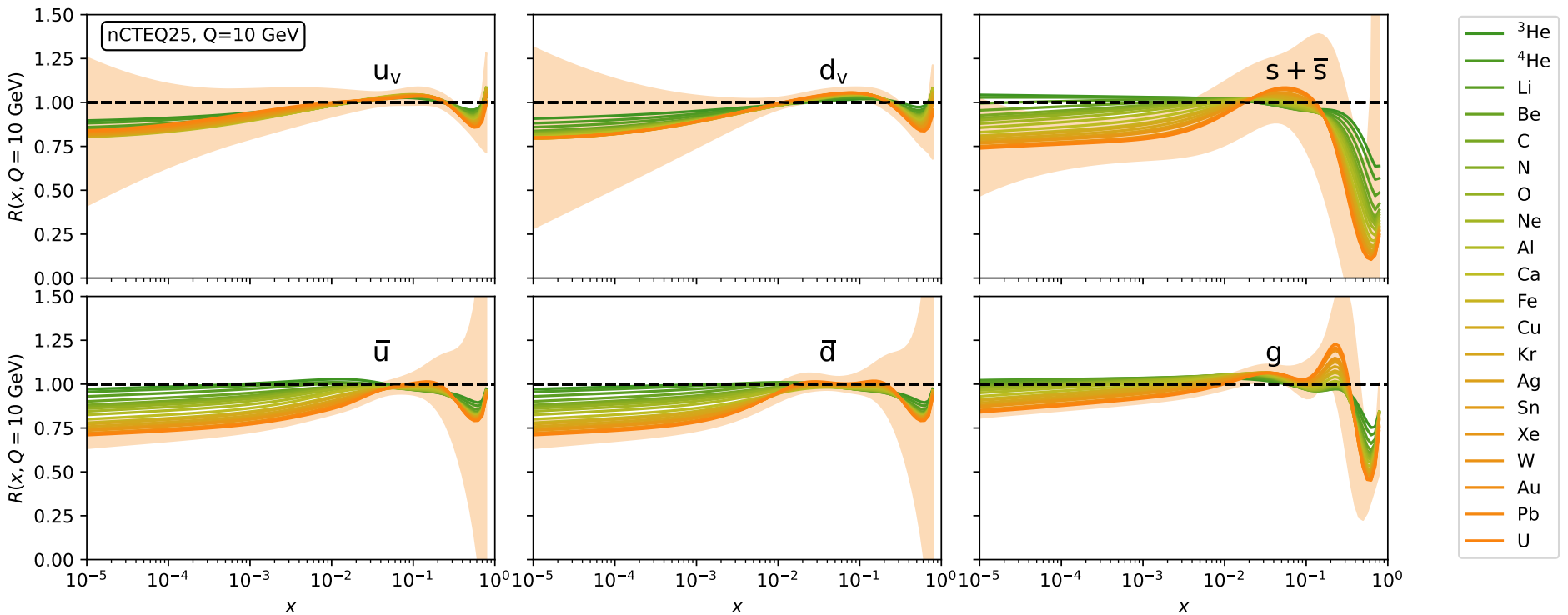


Data used in EPPS21; distributed in *A*.[1]

Same situation for all nuclear PDF groups
→ Missing data for light nuclei should be reflected in uncertainties

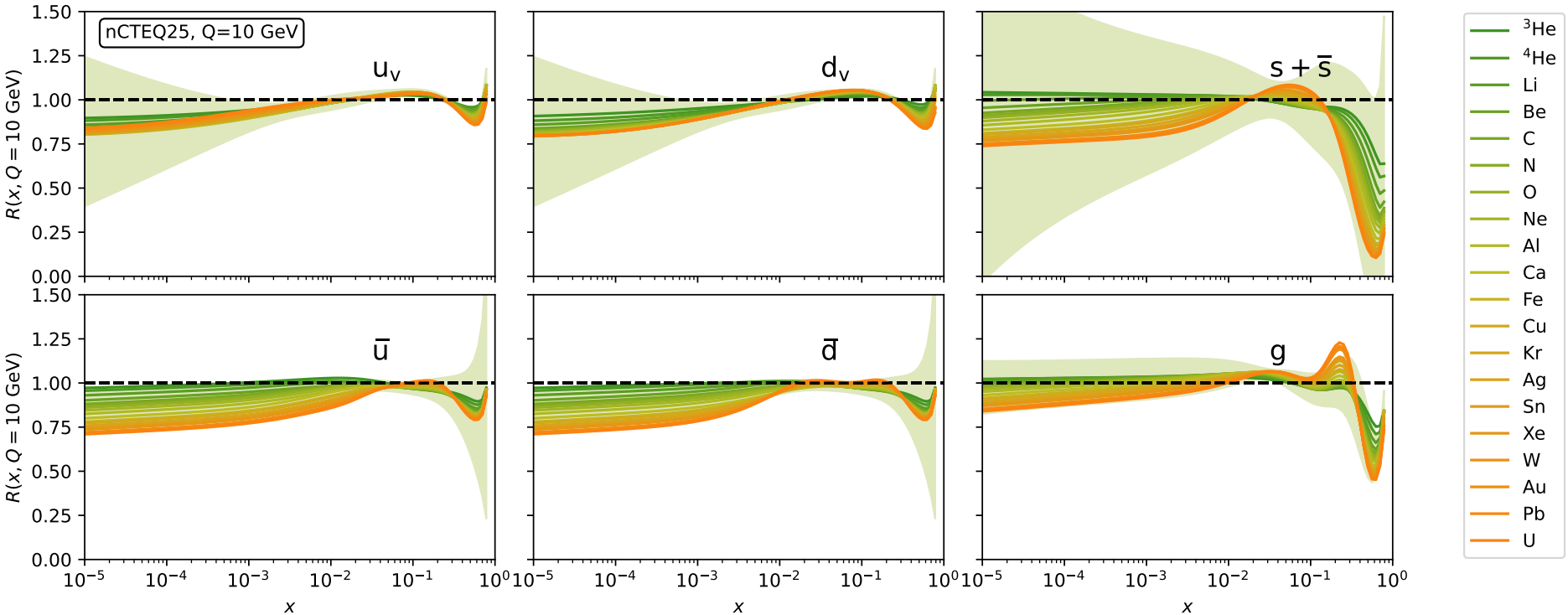
[1] Figure taken from EPPS21 talk at light ions 2024 [3].

Nuclear PDFs: Heavy data, light distributions?



Nuclear modification factors (uncertainty for Pb208)

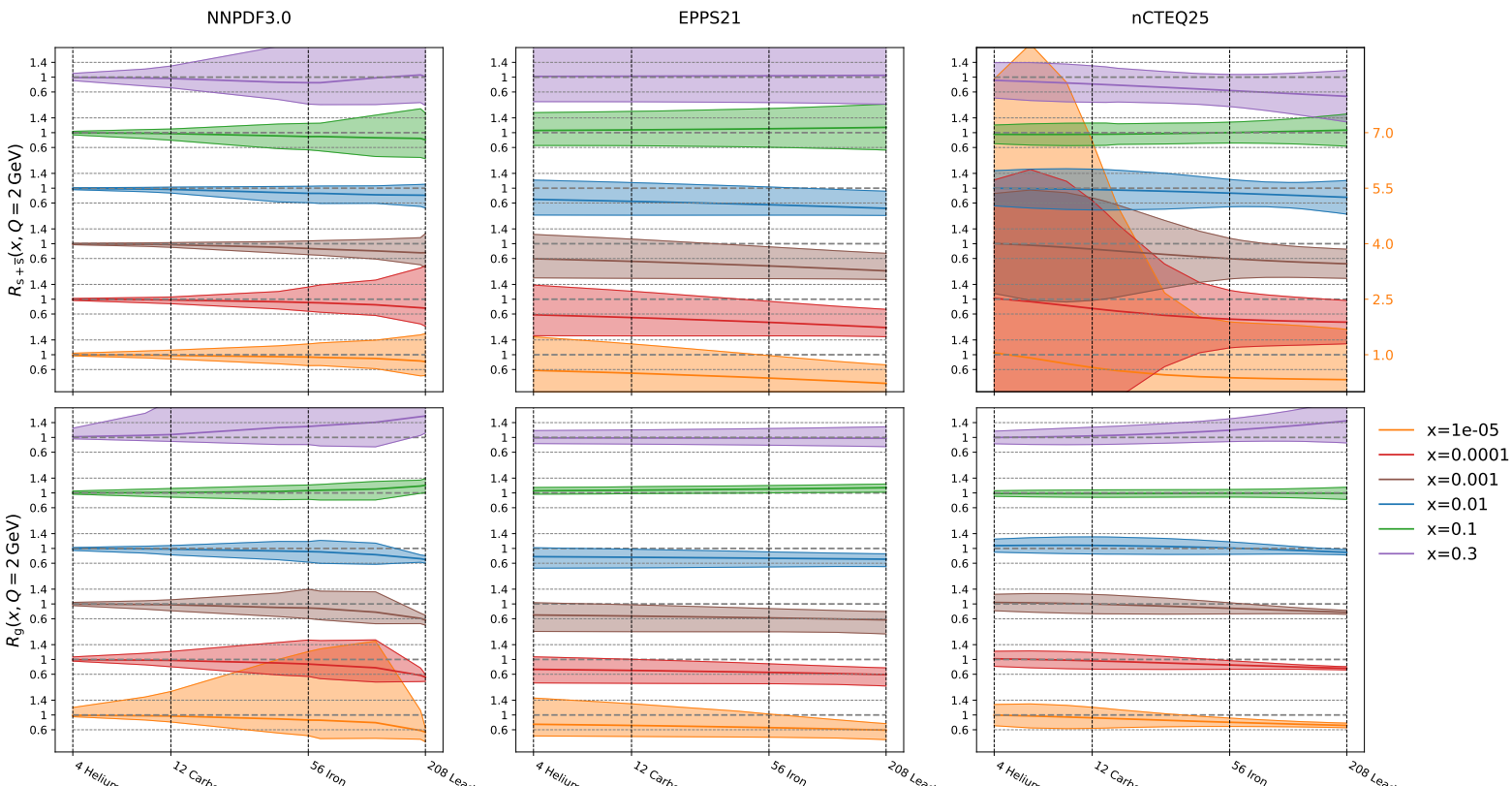
Nuclear PDFs: Heavy data, light distributions?



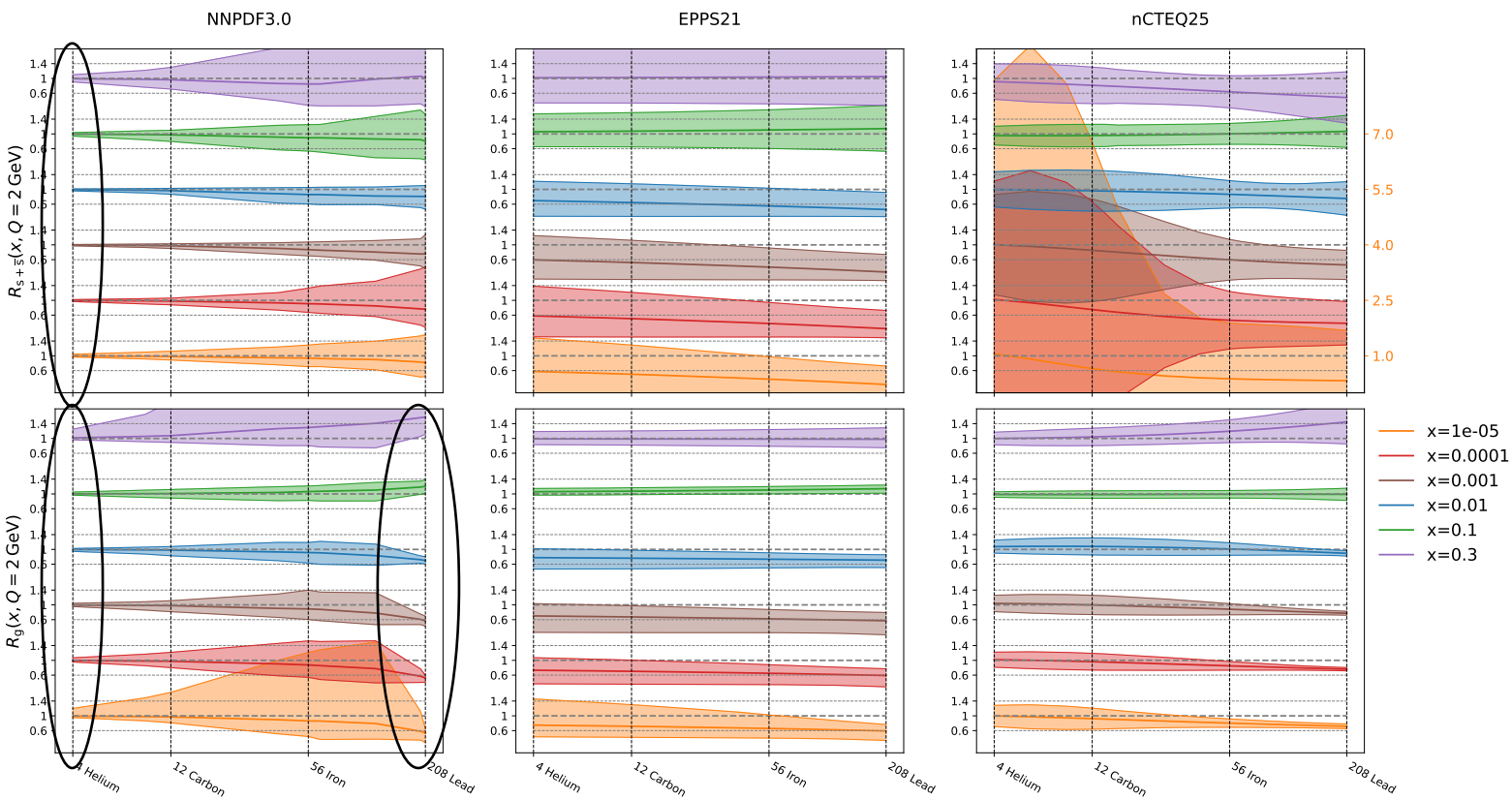
Nuclear modification factors (uncertainty for O16)

- For light nuclei at low x: both shadowing and antishadowing in gluon and strange distribution is consistent with the data

Nuclear PDFs: Heavy data, light distributions? $f(A, Q^2 = 2\ \mathrm{GeV}^2)$



Nuclear PDFs: Heavy data, light distributions? $f(A, Q^2 = 2\ \mathrm{GeV}^2)$

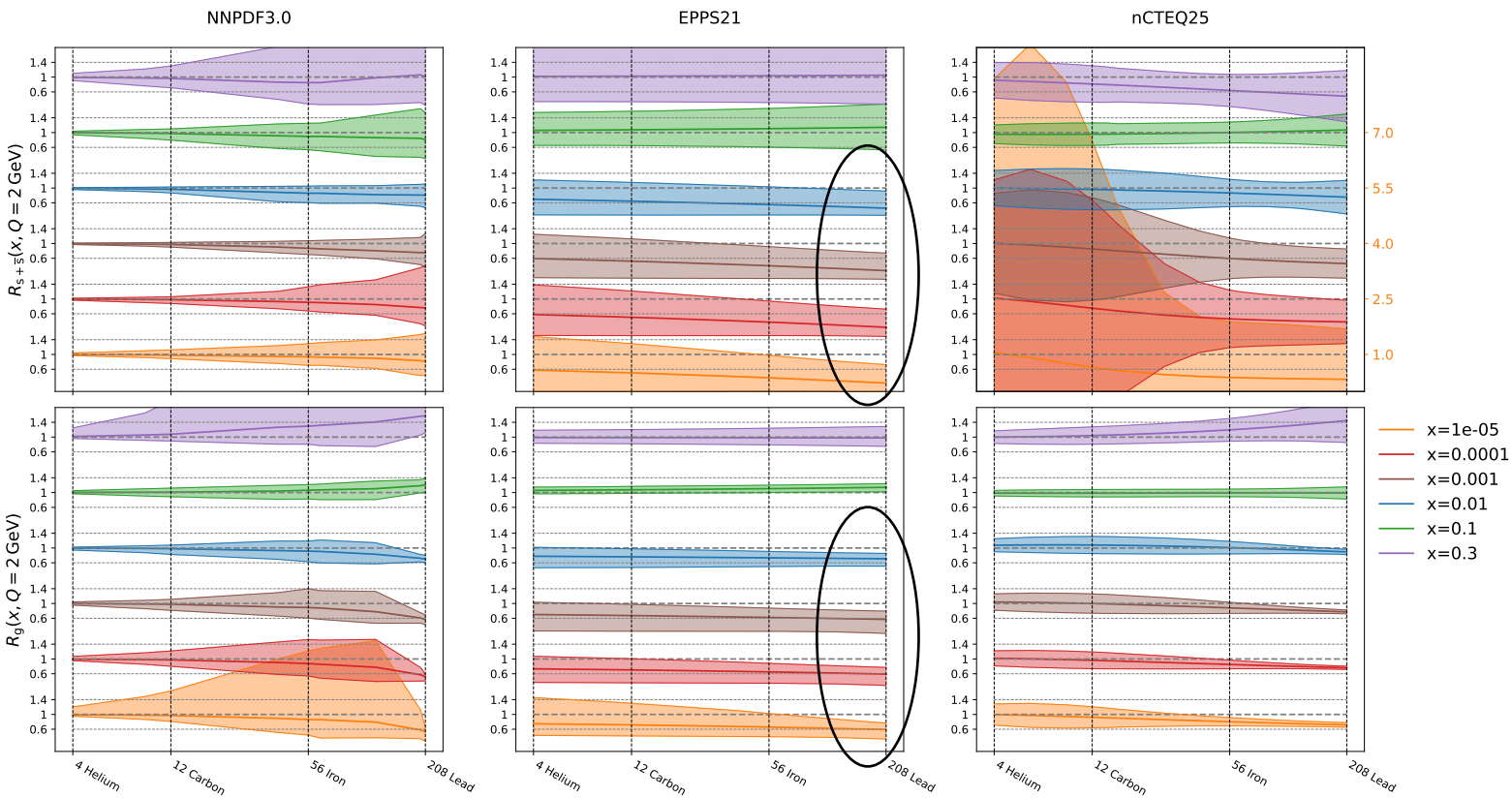


A behaviour for strange and gluon

- nNNPDF3.0
  - gluon: free proton boundary condition[1] + HQ data from heavy ion collisions
  - strange: free proton boundary condition + indirect constraints

[1] As mentioned in the nNNPDF3.0 relase paper [4]

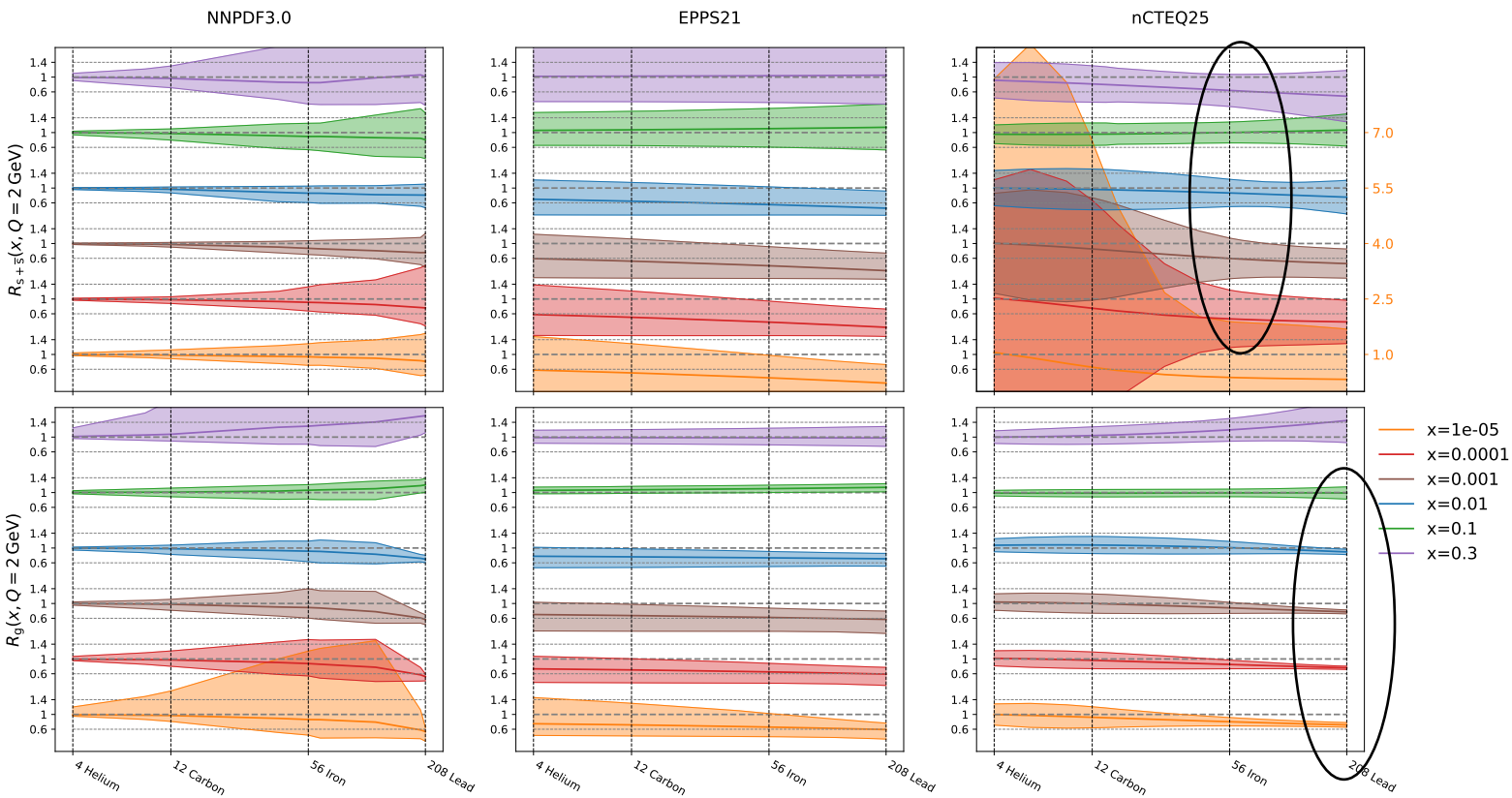
Nuclear PDFs: Heavy data, light distributions? $f(A, Q^2 = 2\ \mathrm{GeV}^2)$



A behaviour for strange and gluon

- EPPS21
  - gluon: HQ data from heavy ion collisions (low x)
  - strange: indirect constrains (e.g. HQ data from heavy ion collisions (low x))

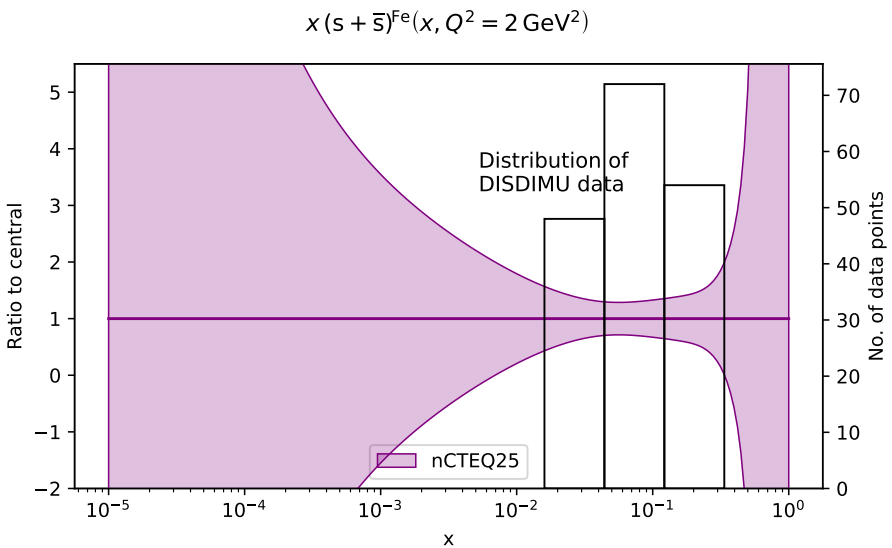
Nuclear PDFs: Heavy data, light distributions? $f(A, Q^2 = 2\ \mathrm{GeV}^2)$



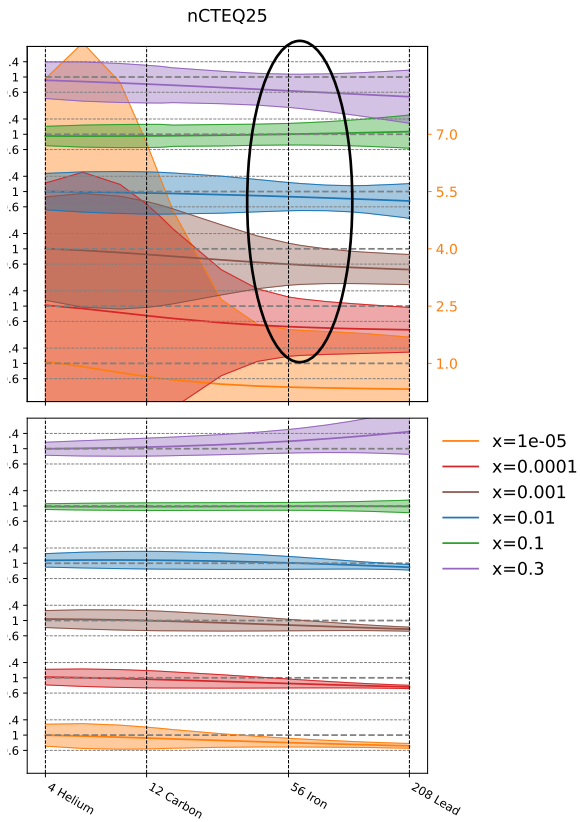
A behaviour for strange and gluon

- nCTEQ25:
  - gluon: HQ data from heavy ion collisions (low x)
  - strange: DISDIMU data for iron (high x)

Nuclear PDFs: Heavy data, light distributions? $f(A, Q^2 = 2\ \mathrm{GeV}^2)$



nCTEQ25 strange uncertainties in x vs. distribution of NuTev/Chorus dimuon data[1]

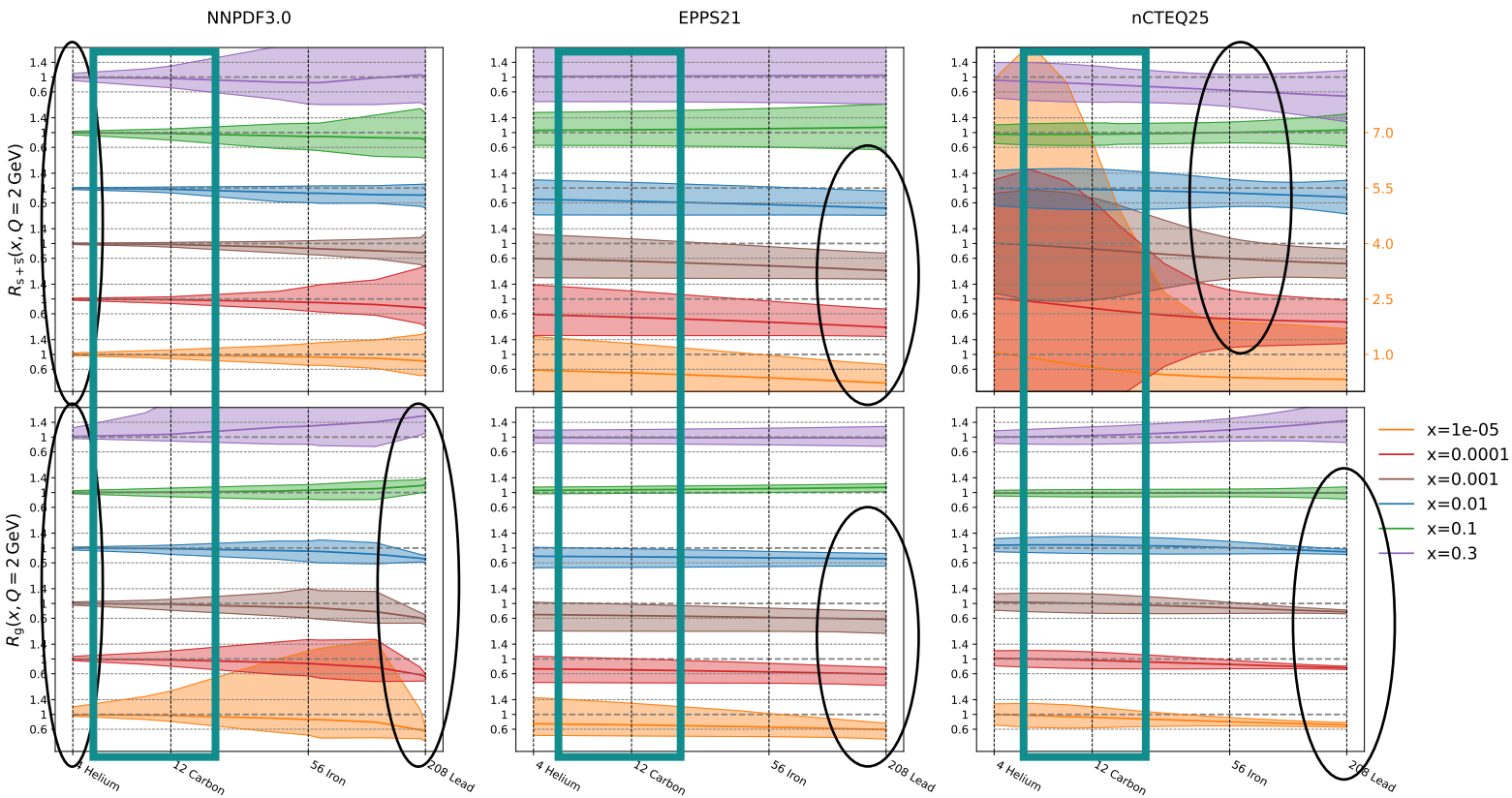


A behaviour for strange and gluon

- nCTEQ25:
  - gluon: HQ data from heavy ion collisions (low x)
  - strange: DISDIMU data for iron (high x)

[1] Data from [5]

Nuclear PDFs: Heavy data, light distributions? $f(A, Q^2 = 2\ \mathrm{GeV}^2)$



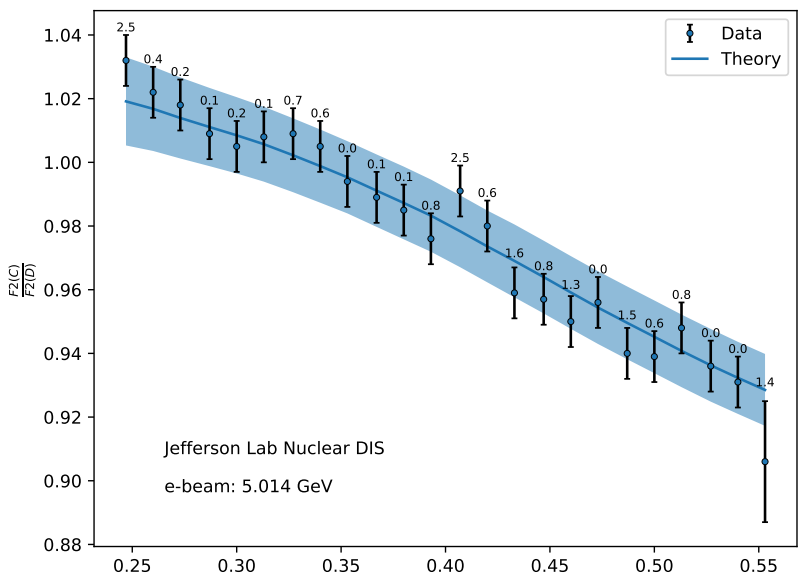
- Collaborations show very different uncertainty landscapes

What is missing everywhere:

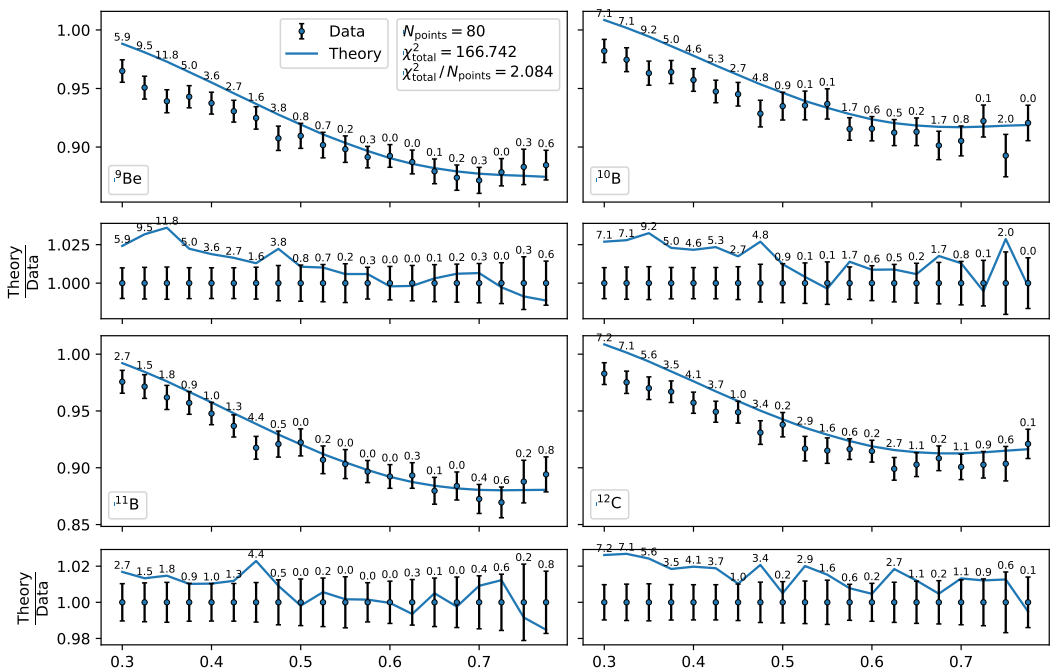
- light nuclei data!
- Oxygen data will help out here

Light data in nCTEQ25: Deep inlastic scattering

- DIS Data from New muon collaboration (1996)[1] and Jefferson Lab (2019[2] and 2009[3])
  - Predictions for new JLab data (2023)[4] (not used in the nCTEQ25 fit):



Jlab, 2009, $\frac{\sigma(C12)}{\sigma(D2)}$



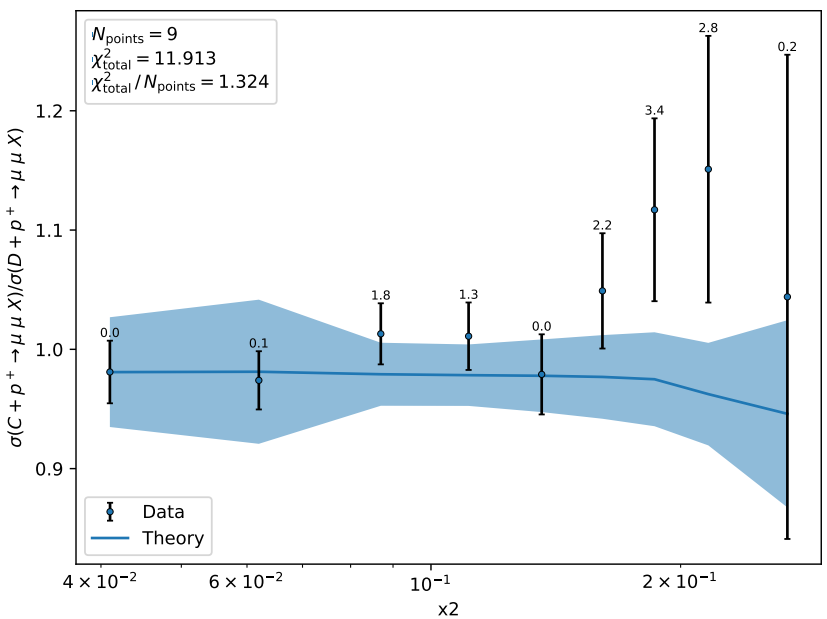
Jlab, 2023

[1] Data from [6]
[2] Data from [7]
[3] Data from [8]
[4] Data from [9]

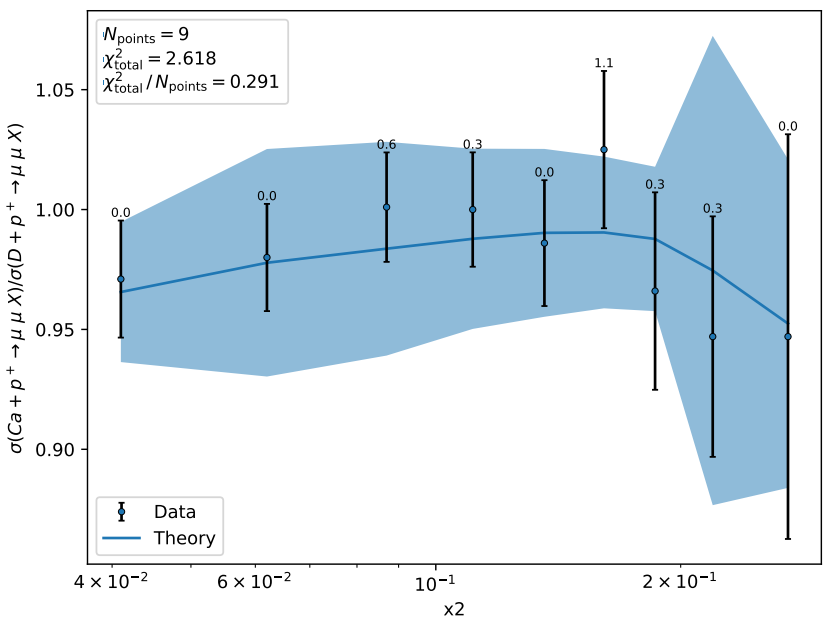
Light data in nCTEQ25: Hadron - hadron collisions

- Drell Yan data: Fermilab experiments E772, 1990[1]

$$\frac{\sigma(C+P\to\mu\mu X)}{\sigma(D+P\to\mu\mu)}$$



$$\frac{\sigma(Ca+P\to\mu\mu X)}{\sigma(D+P\to\mu\mu)}$$

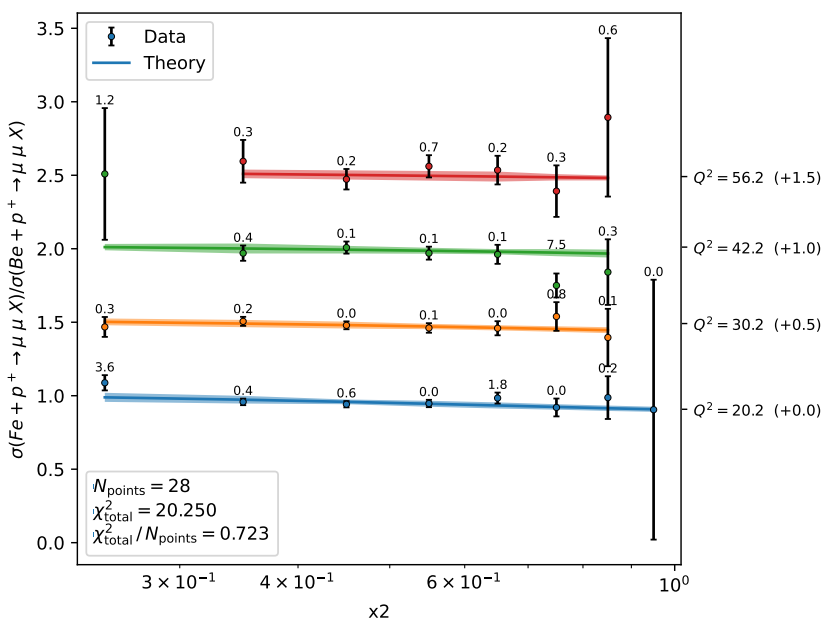


[1] Data from [10].

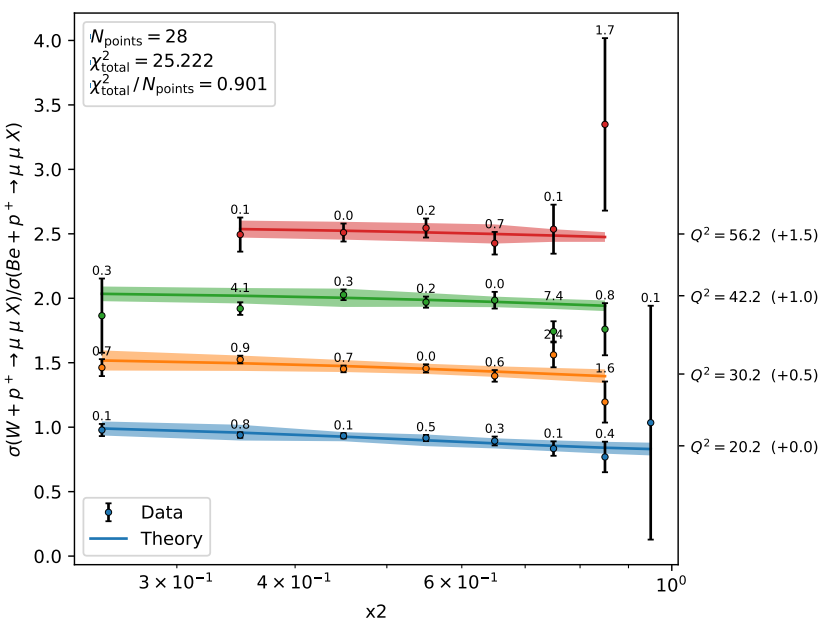
Light data in nCTEQ25: Hadron - hadron collisions

- Drell Yan data: Fermilab experiments E866, 1999[1]

$$\frac{\sigma(Fe+P\to\mu\mu X)}{\sigma(Be+P\to\mu\mu)}$$



$$\frac{\sigma(W+P\to\mu\mu X)}{\sigma(Be+P\to\mu\mu)}$$



[1] Data from [11].

Summary and Outlook

nCTEQ25: What we have seen

- Preliminary results of upcoming nCTEQ25 paper
- New fit, including more data
- Comparison to other nuclear PDF sets
- Detailed study of A-dependence
  - The different collaborations provide very different landscapes in A
  - Are we finally in the era of realistic uncertainties?

Outlook

- nuclear PDF groups want more light nuclei data!
- Oxygen data from LHC can help to constrain light nuclei regime
- SMOG data can help out too

Universität Münster

Thank You

nCTEQ

nuclear parton distribution functions

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[6] M. Arneodo and others, “The A dependence of the nuclear structure function ratios,” *Nucl. Phys. B*, vol. 481, pp. 3–22, 1996, doi: 10.1016/S0550-3213(96)90117-0.

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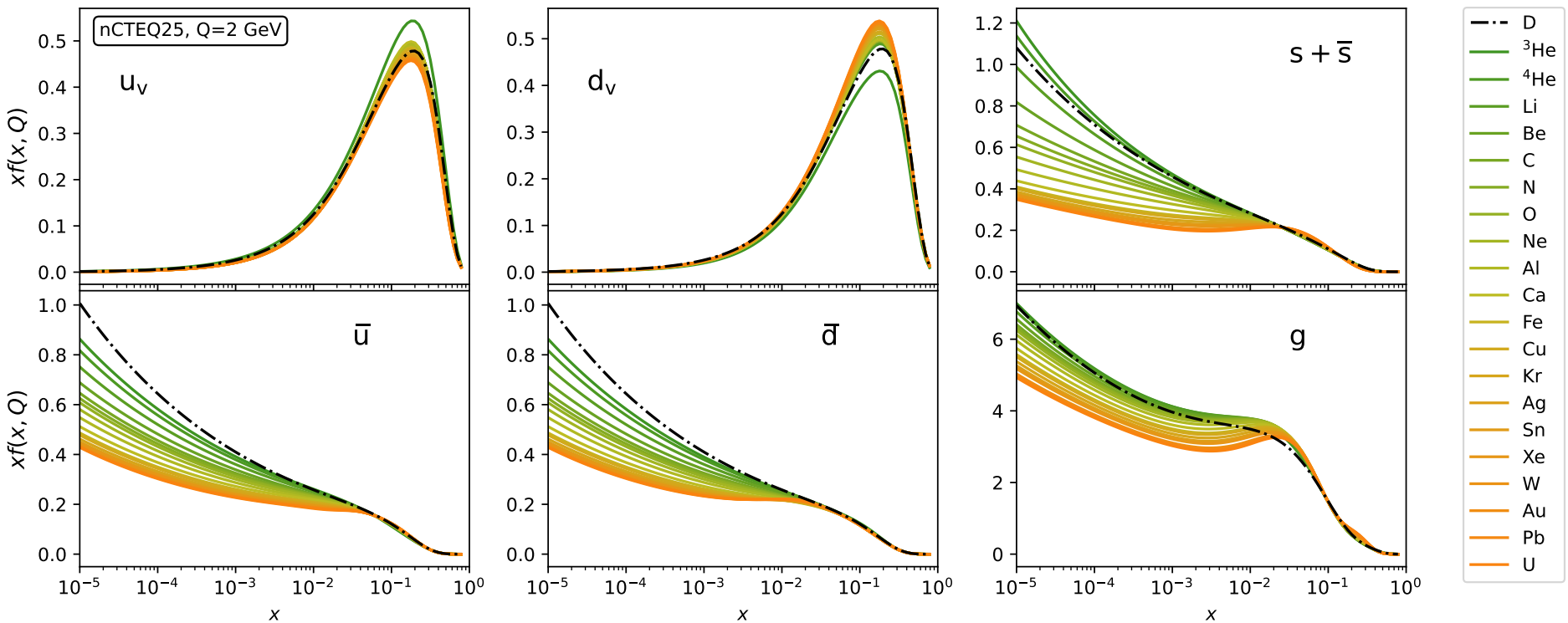
[9] A. Karki *et al.*, “First Measurement of the EMC Effect in ^{10}B and ^{11}B,” no. arXiv:2207.03850. arXiv, July 2023. doi: 10.48550/arXiv.2207.03850.

[10] D. M. Alde *et al.*, “Nuclear Dependence of Dimuon Production at 800 GeV,” *Physical Review Letters*, vol. 64, no. 21, pp. 2479–2482, May 1990, doi: 10.1103/PhysRevLett.64.2479.

[11] FNAL E866/NuSea Collaboration *et al.*, “Parton Energy Loss Limits and Shadowing in Drell-Yan Dimuon Production,” *Physical Review Letters*, vol. 83, no. 12, pp. 2304–2307, Sept. 1999, doi: 10.1103/PhysRevLett.83.2304.

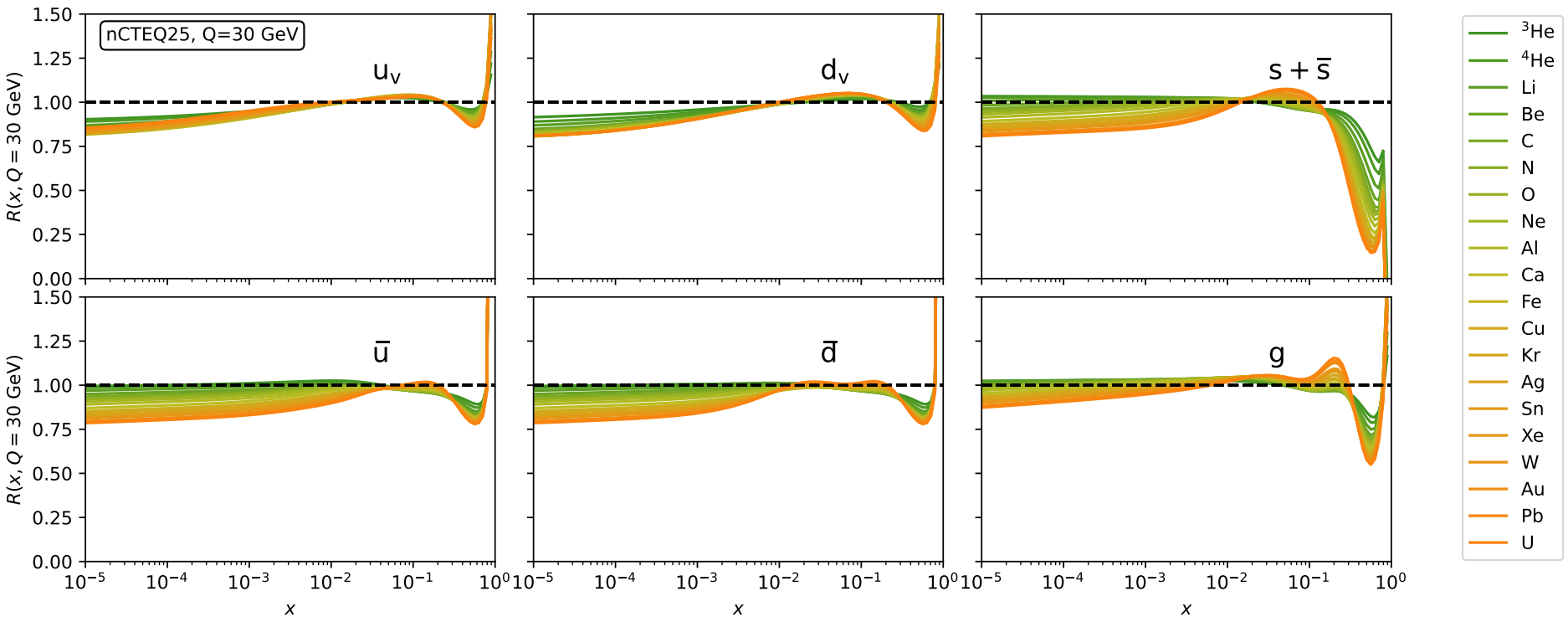
Backup

Nuclear PDFs: Heavy data, light distributions?

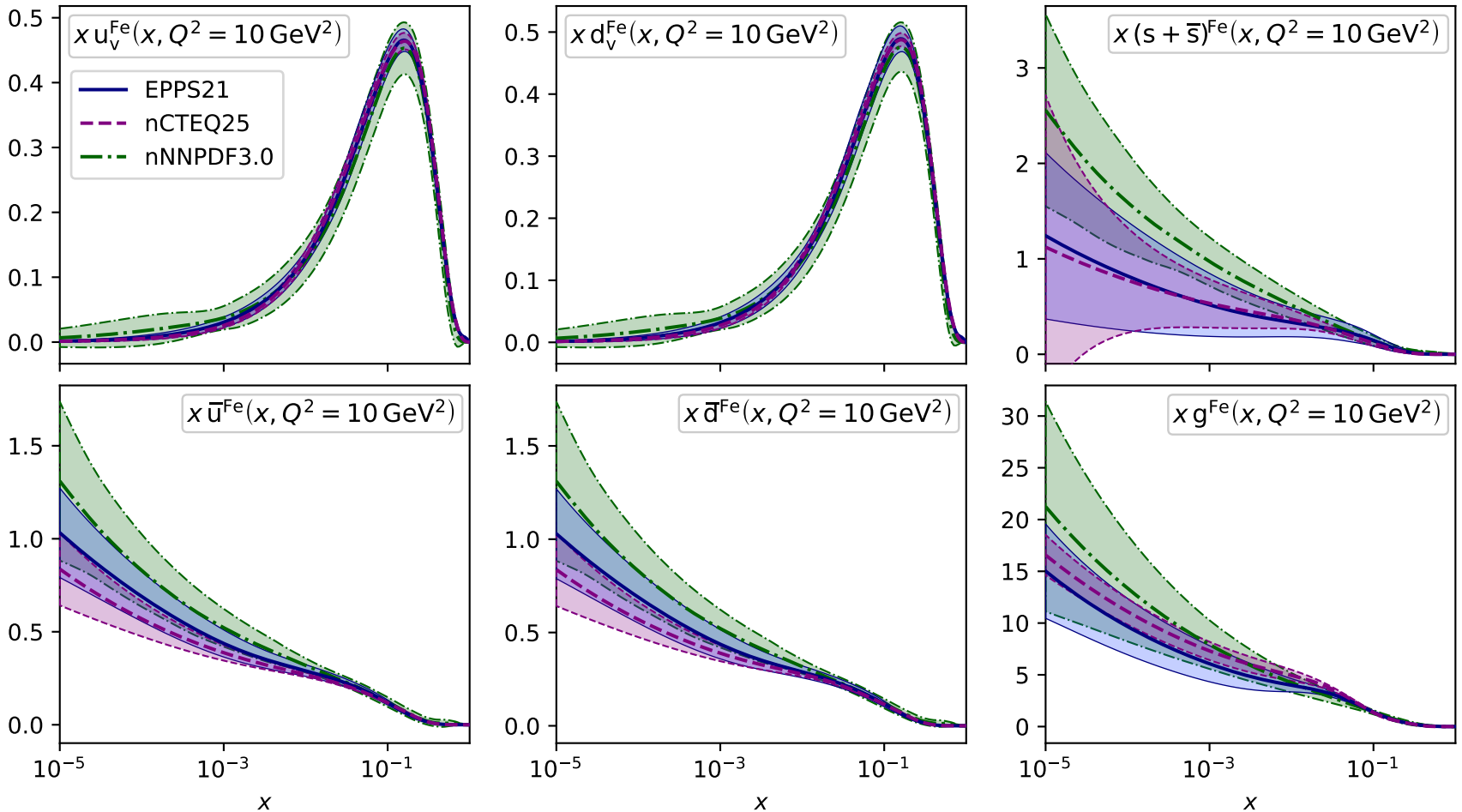


- The difference in PDFs between light nuclei is large
- For heavy nuclei only soft change, for light nuclei rapid change in A.

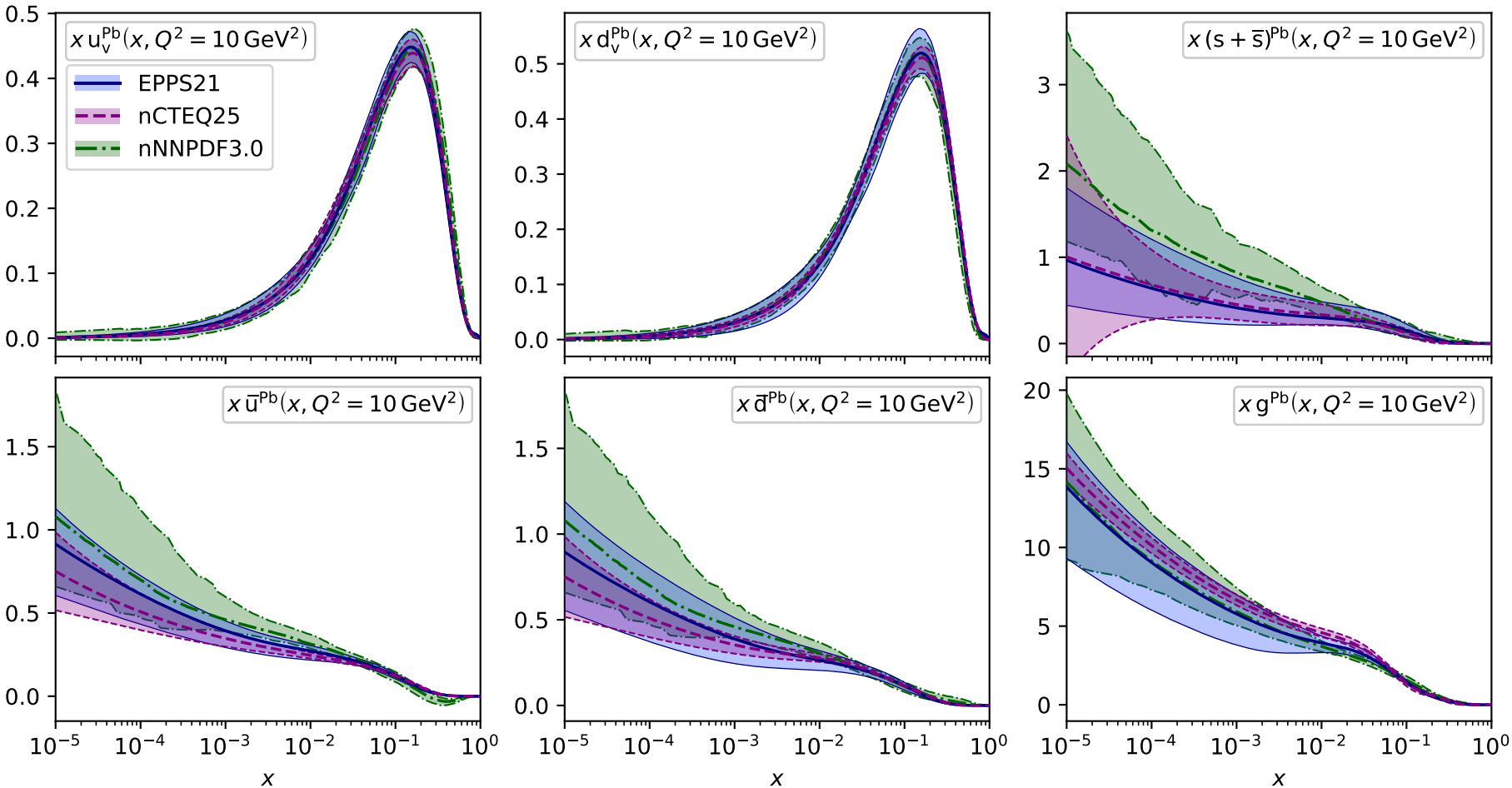
Nuclear PDFs: Heavy data, light distributions?



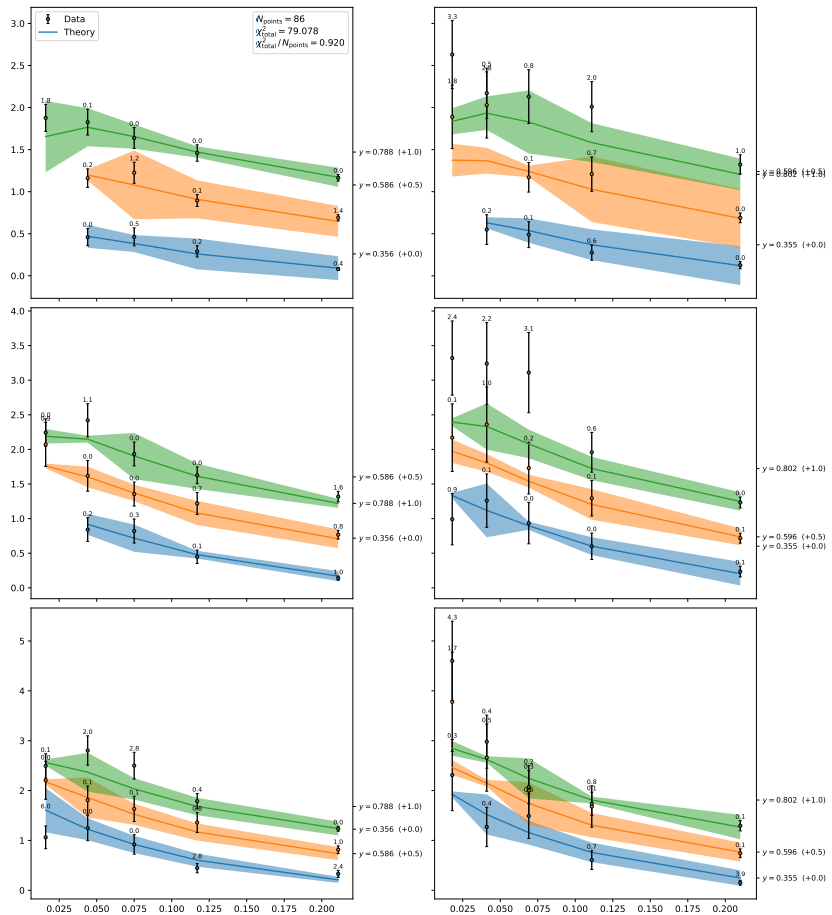
nCTEQ25 vs EPPS21 vs nNNPDF3.0 $f^{Fe}\left(x, Q^2 = 10GeV^2\right)$



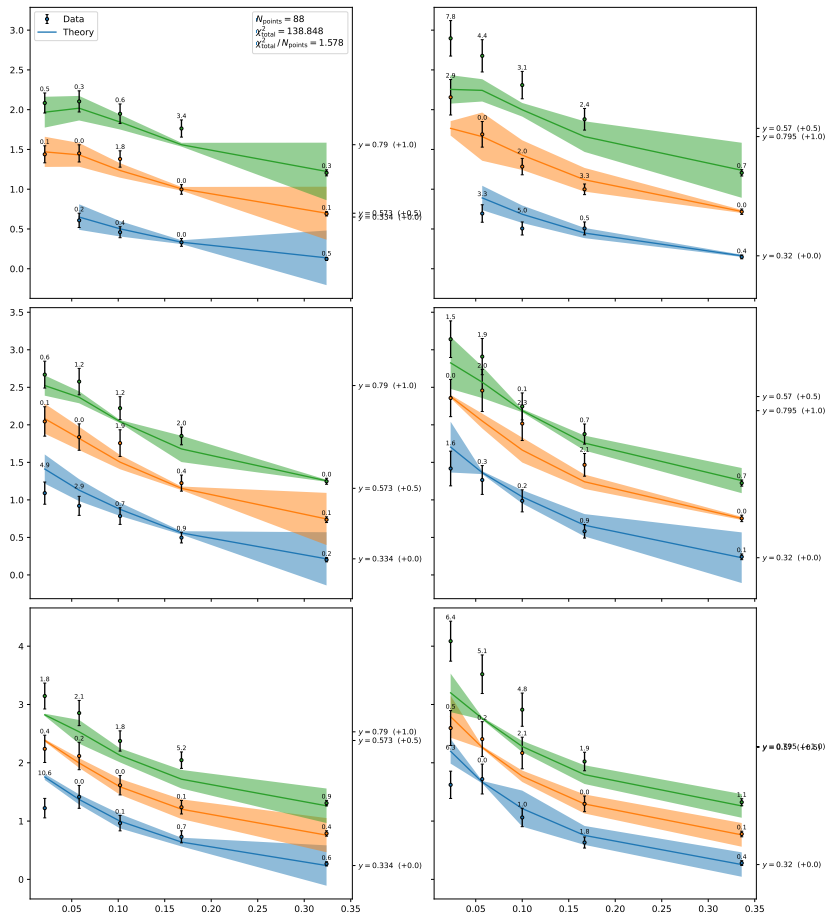
nCTEQ25 vs EPPS21 vs nNNPDF3.0 $f^{Pb}\left(x, Q^2 = 10GeV^2\right)$



Data vs. Theory DISDIMU



NuTeV/Chorus anti-neutrino (W^-) current



NuTeV/Chorus neutrino (W^+) current

Data vs. Theory JLab 2019