Universität Münster

nCTEQ
nuclear parton distribution functions

nCTEQ global analysis of nuclear PDFs

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nCTEQ collaboration
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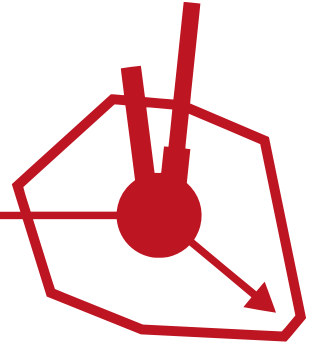
DIS2026

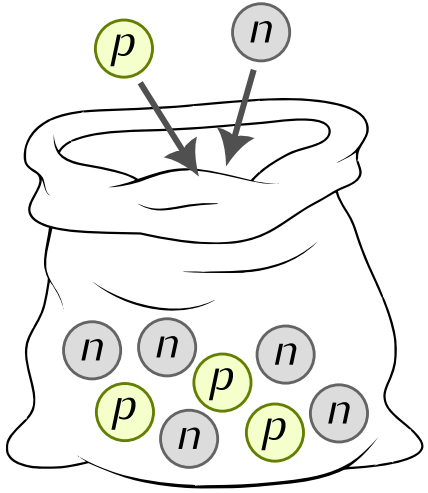


living.knowledge

Foundations

Structure of nuclei

- Nuclei made up of protons and neutrons ...

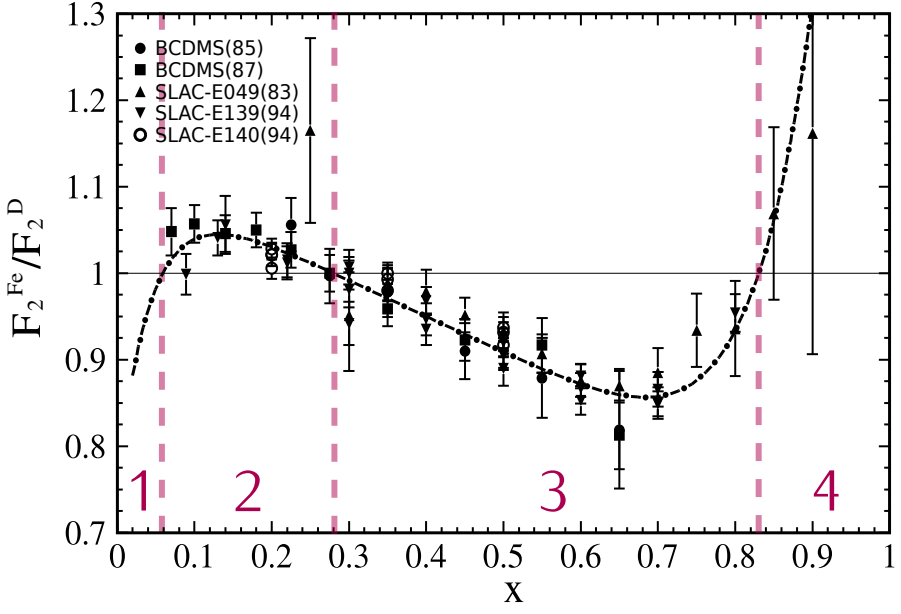


- Free nucleon approximation

$$Af^A \approx Zf^p + Nf^n$$

Structure of nuclei

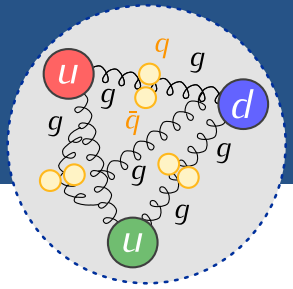
- Nuclear modification:



- 1 shadowing
- 2 anti-shadowing
- 3 EMC effect
- 4 Fermi motion

- Underlying dynamics still to be fully theoretically understood
- Can be parametrized and incorporated into nuclear structure determinations

Theoretical framework: proton PDFs

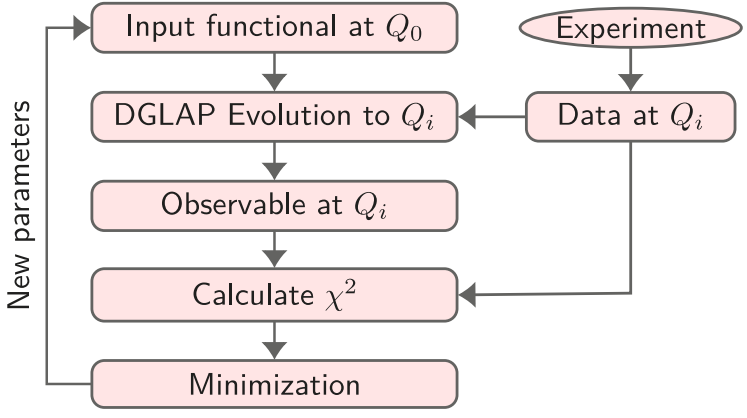


- We rely on collinear factorisation
- PDF μ perturbatively evolved with DGLAP equations
- PDF x dependence not calculable in pQCD

  - Constrained through *number* and *momentum* sum rules and fitted from data
  - Assume parametrization[a] in x at a chosen input scale $\mu = Q_0$:

$$x f_i(x, Q_0) = N(1-x)^{p_{i,1}} x^{p_{i,2}} P(x, p_{i,3}, \dots)$$

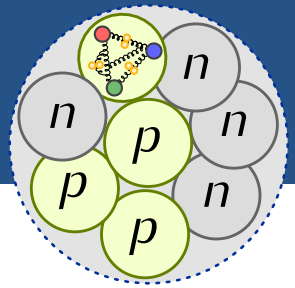
  - Set $p_{i,j}$, calculate theoretical predictions, compare to data, iterate:



  - Until reaching best fit

[a] NNPDF collaboration use NN to avoid parametrization bias.

Theoretical framework: nuclear PDFs



- Nuclear modification can be incorporated into PDF determinations
  - Introduce the notion of bound PDF for flavour i: $f_i^{p/A}(x, \mu, A)$, with A-dependent x parametrization at $\mu = Q_0$
  - $x \in (0, A)$, but $x > 1$ region typically negligible
  - $f_i^{p/A}$ fulfils the usual evolution equations and sum rules
  - $f_i^{n/A}$ from isospin symmetry, i.e. $f_{d,u}^{n/A} = f_{u,d}^{p/A}$

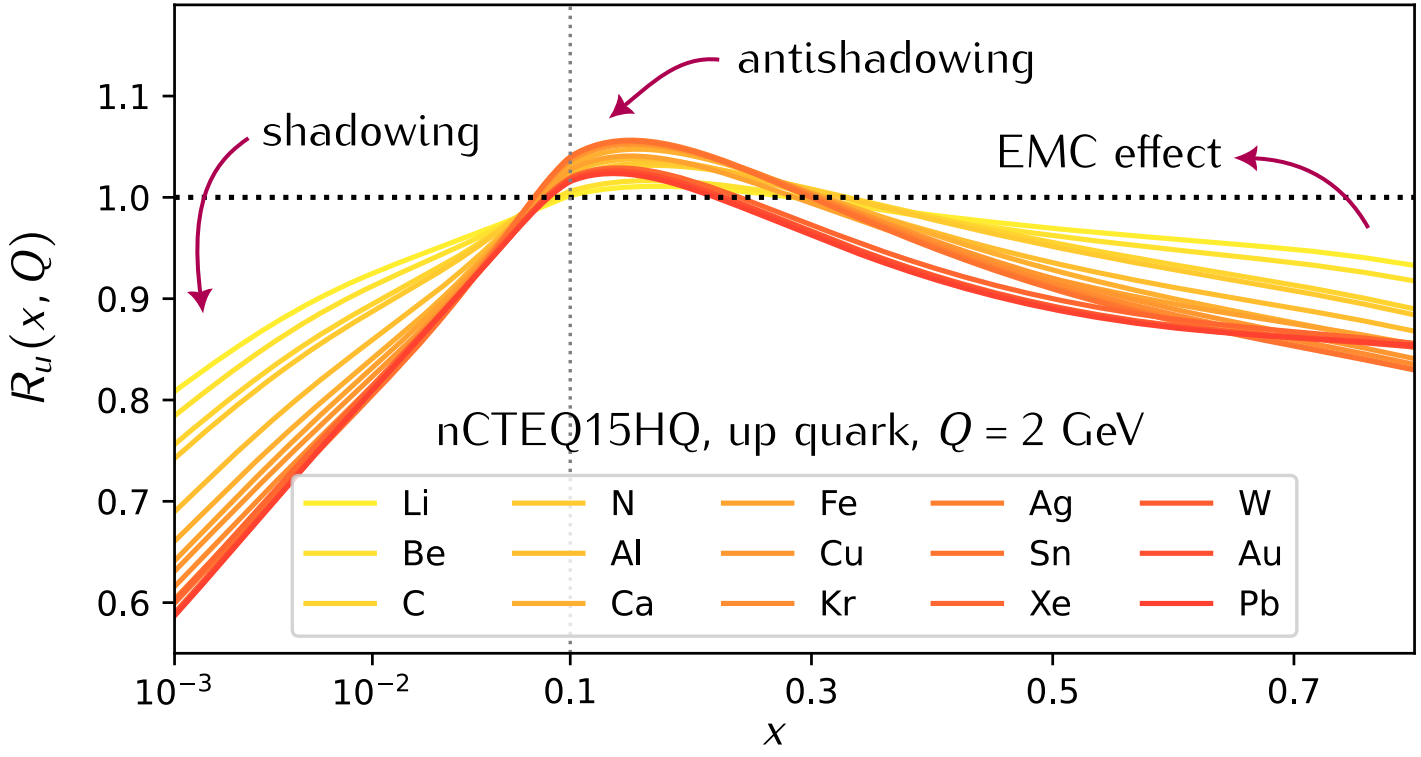
$$f_i^{(A,Z)}(x, \mu) = \frac{Z}{A} f_i^{p/A}(x, \mu, A) + \frac{A - Z}{A} f_i^{n/A}(x, \mu, A)$$

  - $f_i^{(A,Z)}$ replaces f_i^p in the factorization formula[a]

[a] Proof of factorization for collisions of nuclei not yet available.

Theoretical framework: nuclear PDFs

- Example dependence on A



The Story So Far

From nCTEQ15 onwards

- nCTEQ15
  - mostly NC DIS, some FT DY, a handfull of SIH (740 pts)

- nCTEQ15 upgrades
  - nCTEQ15WZ ('20): + LHC W/Z data (+120 pts)
  - nCTEQ15HIX ('20): + JLAB NC DIS data + relaxed DIS cuts (+336 pts)
  - nCTEQ15WZSIH ('21): + LHC W/Z and SIH data (+232 pts)
  - nCTEQ15HQ ('22): + LHC W/Z + HQ data (+668 pts)
  - nCTEQ15NU[a] ('22): + LHC W/Z + SIH data + CC DIS (+1206 pts)
  - nCTEQ15SRC ('23): nCTEQ15HIX with SRC-inspired PDF parametrization

[a] Denoted BaseDimuChorus in the publication.

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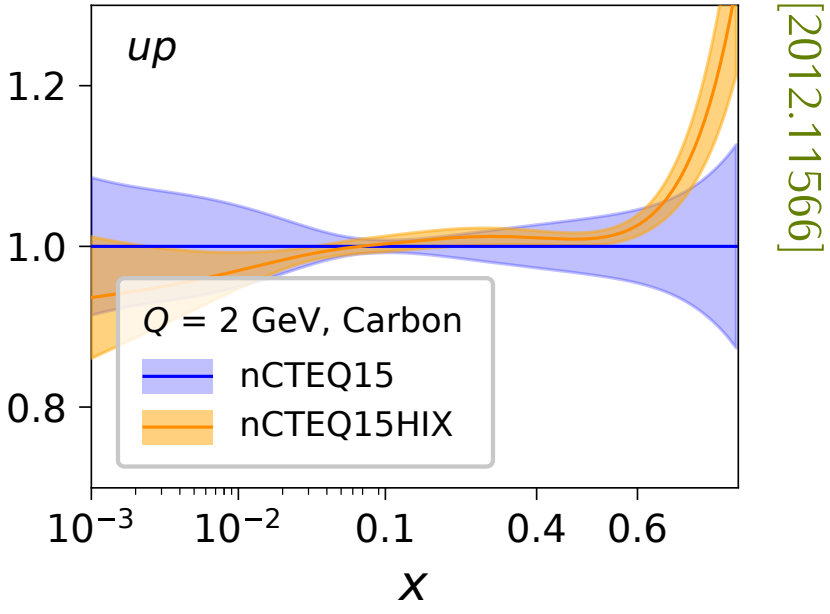
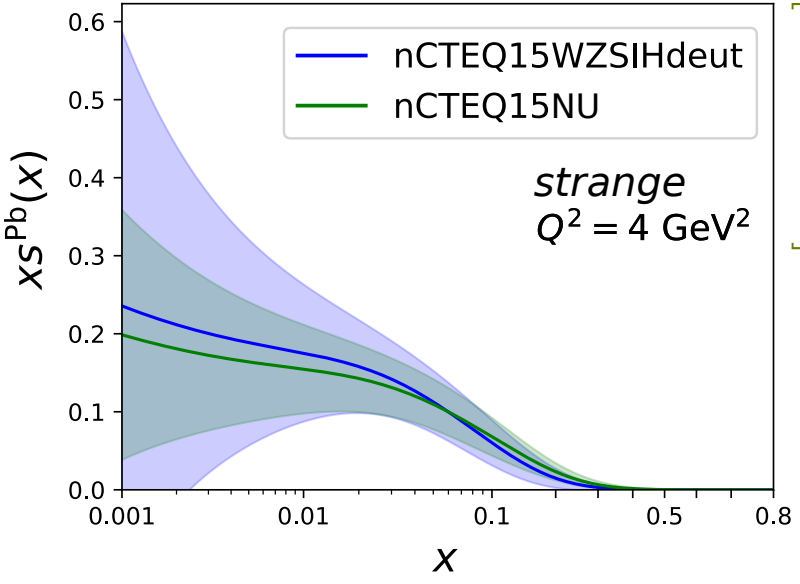
Key improvements

- **Valence**: nCTEQ15HIX includes very precise JLAB data (+336 pts)
  - and explores impact of TMCs, HT, deuteron correction, high-x rescaling



Key improvements

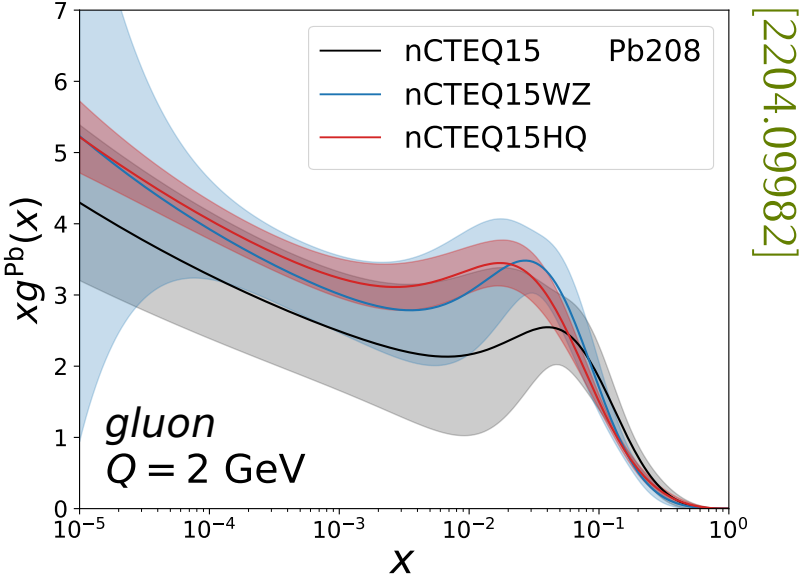
- **Valence**: nCTEQ15HIX includes very precise JLAB data (+336 pts)
- **Strange**: nCTEQ15NU adds bulk of CC DIS data (+1206 pts)
  - constraining strange across a broad range of x



[2204.13157]

Key improvements

- **Valence**: nCTEQ15HIX includes very precise JLAB data (+336 pts)
- **Strange**: nCTEQ15NU adds bulk of CC DIS data (+1206 pts)
- **Gluon**: nCTEQ15HQ adds quarkonium and open HQ data (+668 pts)
  - providing a handle on gluon with unprecedentend low-x reach



[2204.09982]

nCTEQ26

Setup

- We[a] combine all our past efforts into a global analysis
  - Include all data considered so far + bonus W/Z and HQ data
    - NC & CC DIS, FT DY, LHC W/Z, SIH, HQ
  - Extend the Q and W cuts from (2,3.5) GeV to (1.3,1.7) GeV (~ 3600 pts)
  - Upgrade our proton baseline to CJ15
  - Synchronize our parametrization, e.g. $xg(x,Q_0) = c_0 x^{c_1}(1-x)^{c_2}(1+c_3\sqrt{x}+c_4 x)$
    - with upgraded A dependence

$$c_j(A) = p_j + a_j(1 - A^{-b_j}) \quad \Rightarrow \quad c_j(A) = p_j + a_j \ln A + b_j \ln^2 A$$

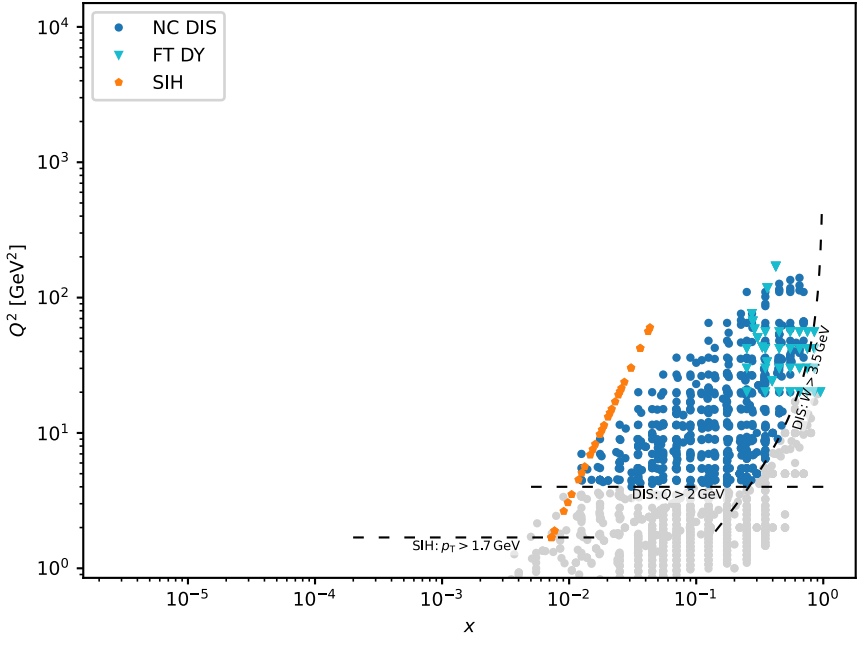
  - Further setup
    - NLO QCD, SACOT-χ, open ~ 35 parameters, Hessian with tolerance, deuteron correction & higher twist (CJ15), TMCs, ...

[a] nCTEQ collaborators: Accardi, Derakhshanian, Duwentäster, **Greve**, **TJ**, Keppel, Klasen, Kovařík, **Kusina**, Leger, Morfín, Muzakka, Niehues, Olness, Owens, Risse, Ruiz, Schienbein, **Wissmann**, Yu

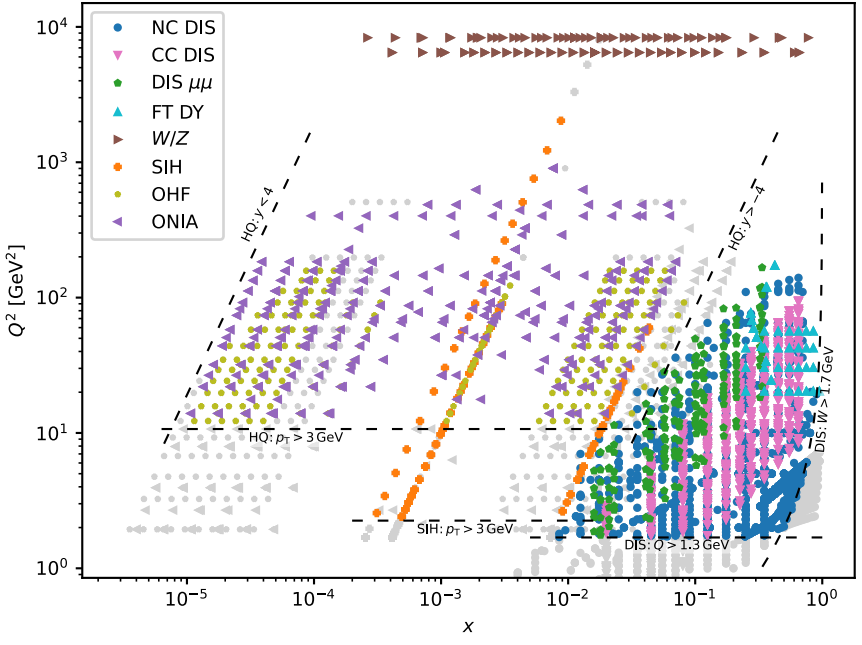
Data selection: kinematic coverage

- Since nCTEQ15 we expanded on variety, amount, x-reach, ...

nCTEQ15

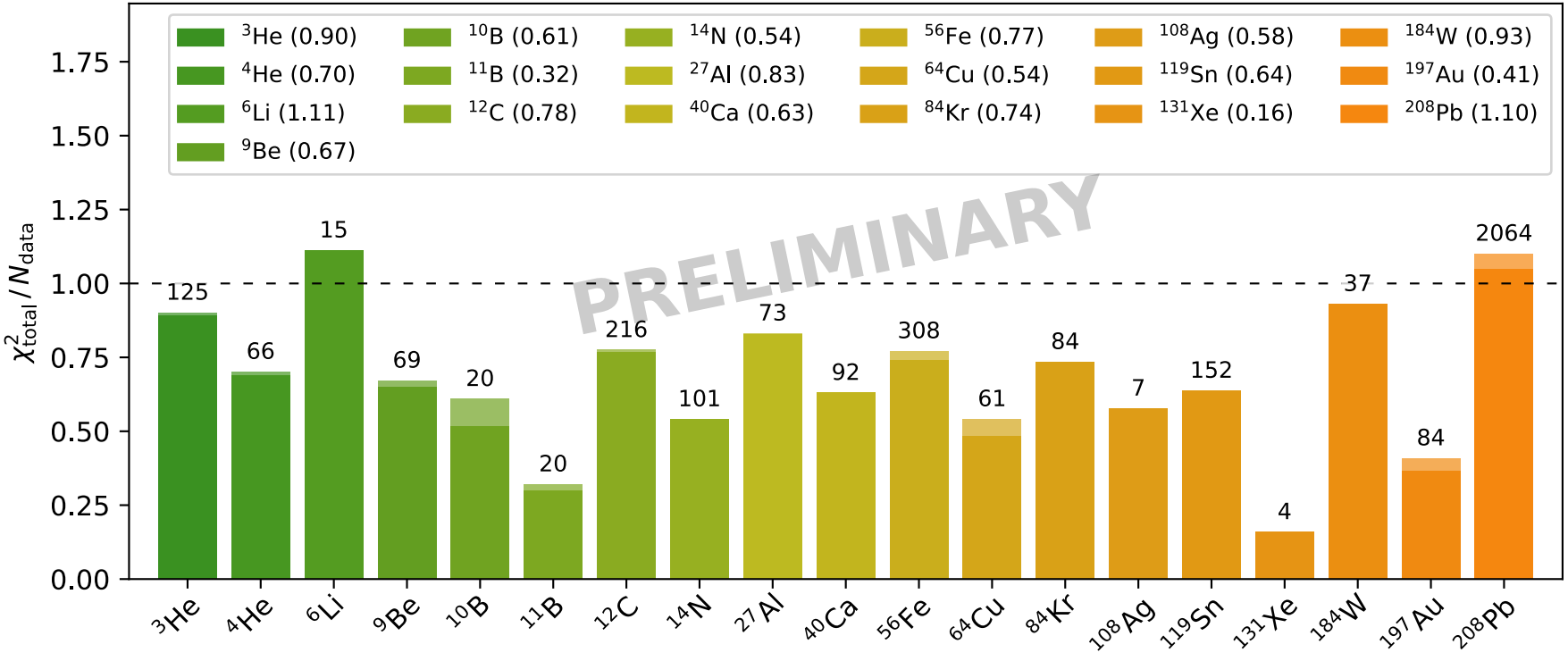


nCTEQ26



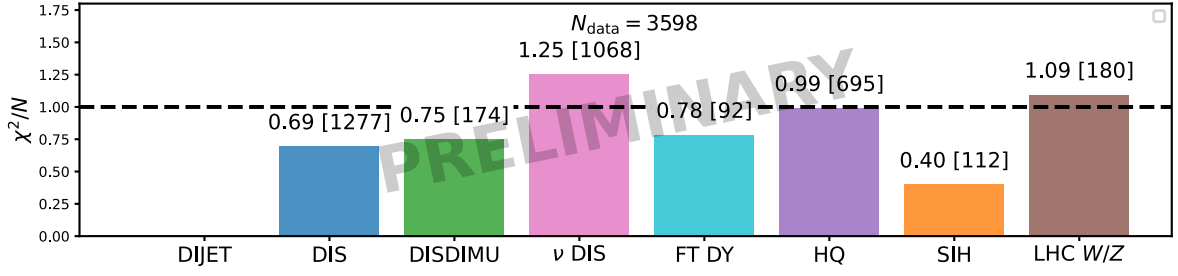
Data selection: nuclear A coverage

- Extensive A coverage

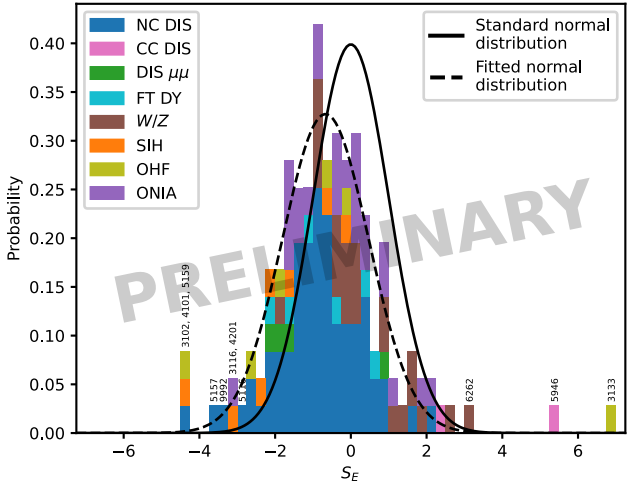


Results: data description quality

- Overall excellent fit with $\chi^2/N_{\text{dof}} = 0.98$
- Each experiment type well described
  - νDIS in slight tension
  - SIH overfitted



- Well-behaved pull distribution
  - Consistent with an optimal fit
  - Only a handful of outliers



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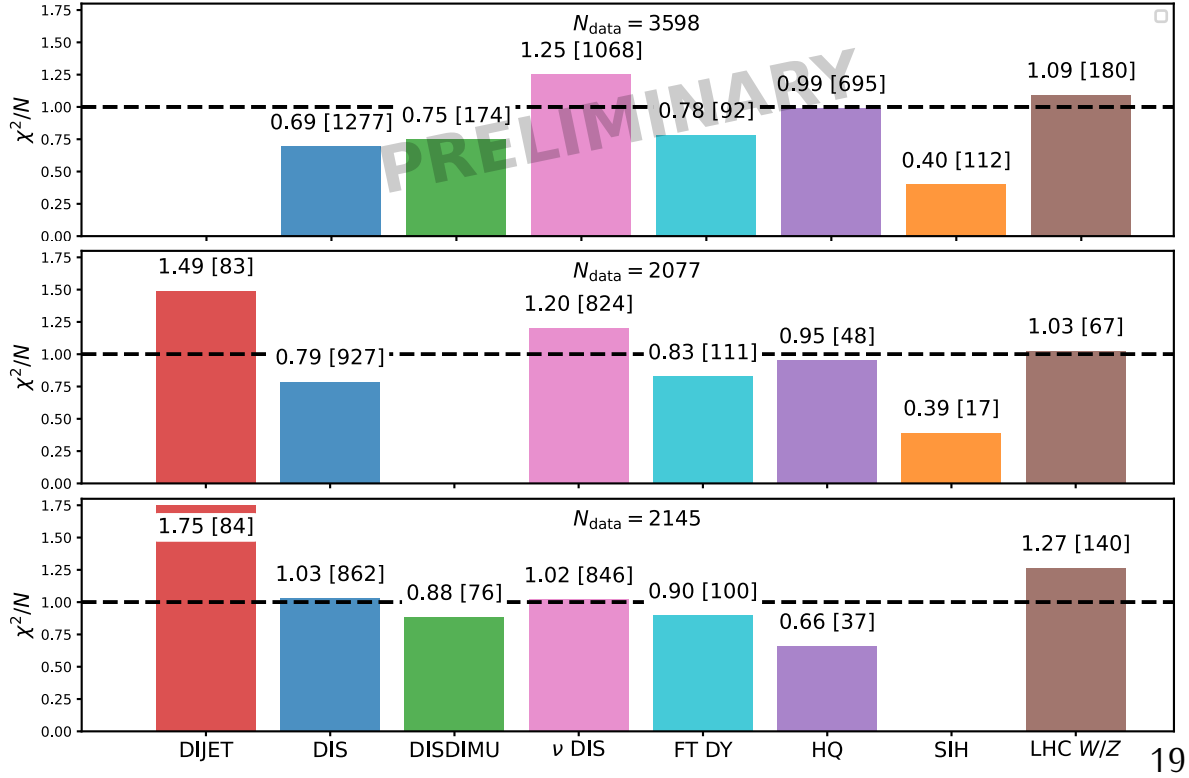
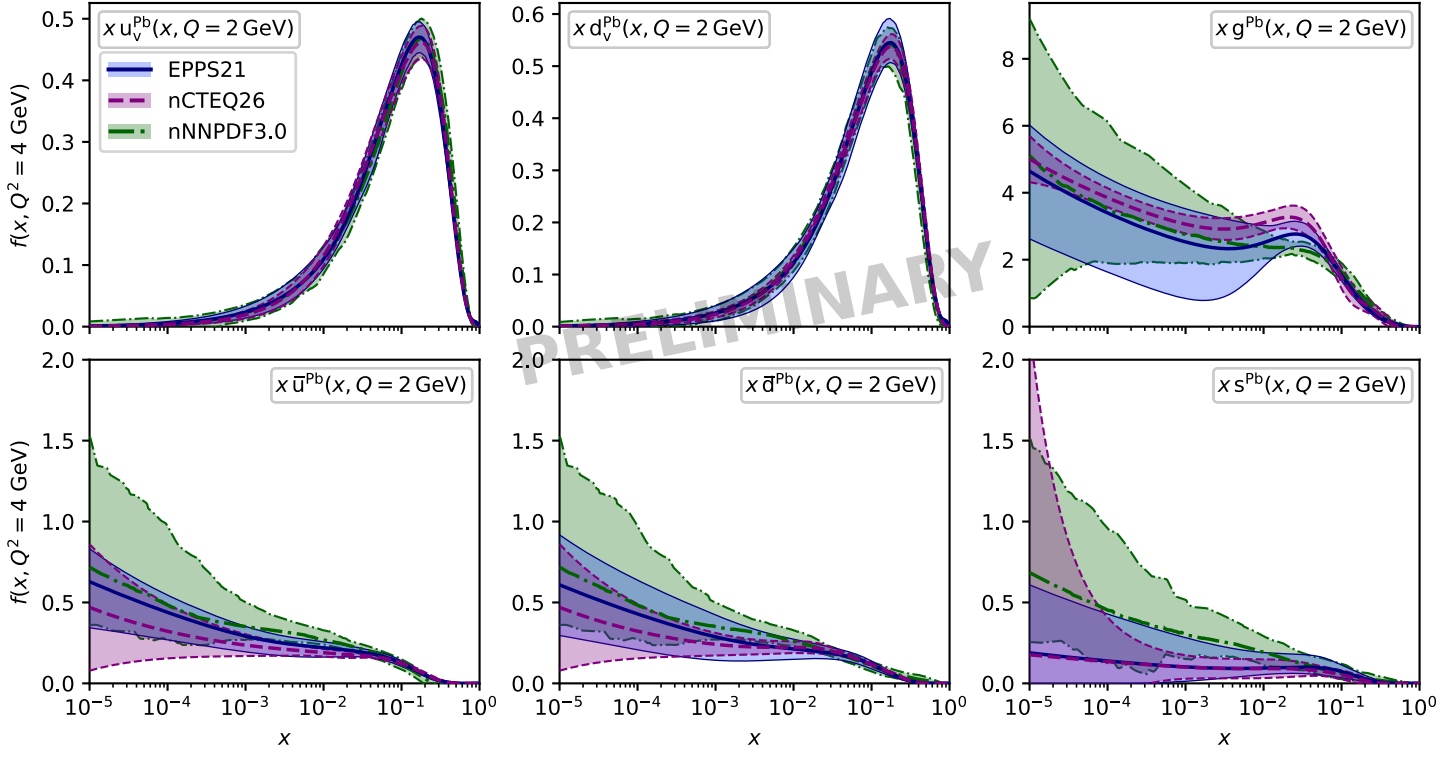
  - nCTEQ26:
  - EPPS21:
  - nNNPDF3.0:



Results: Lead PDFs

- PDFs consistent with other extractions, with most notable differences in gluon and strange



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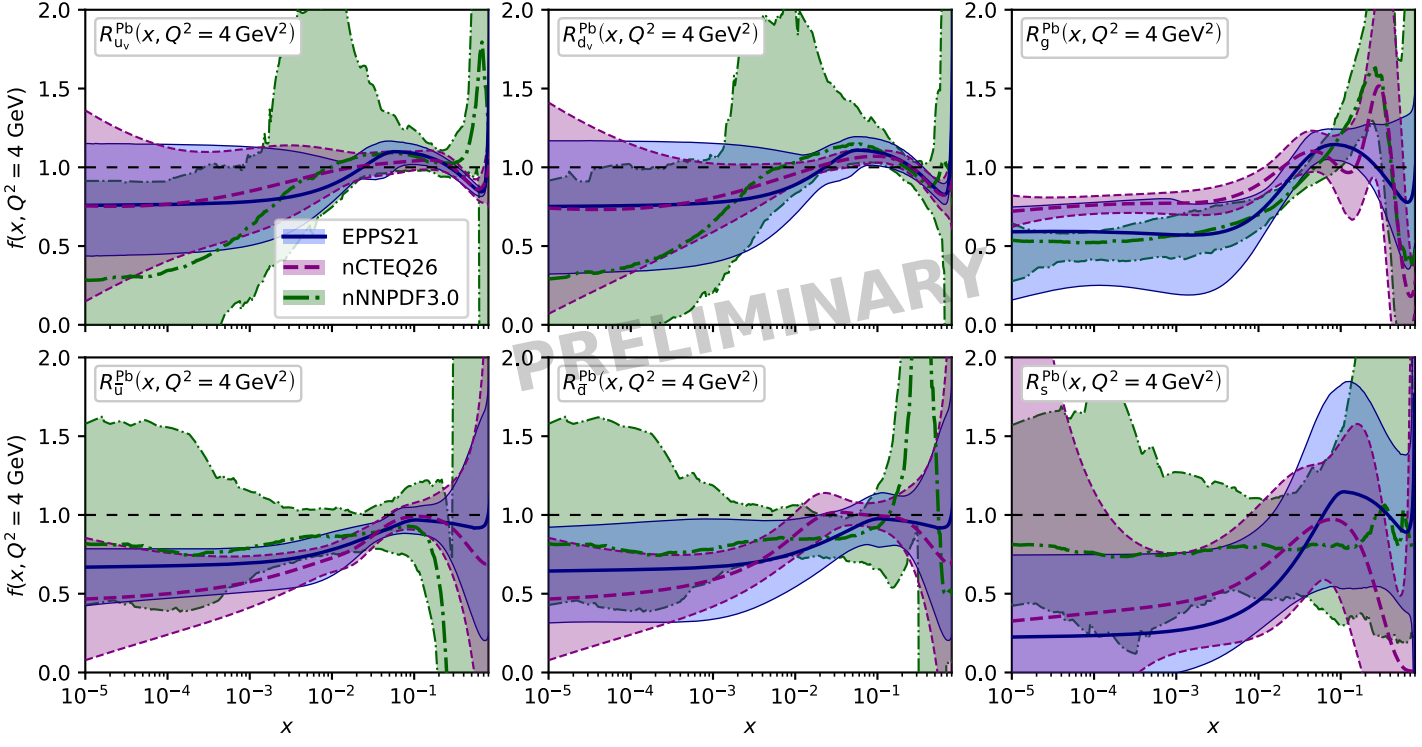

Results: A dependence

- New A dependence:

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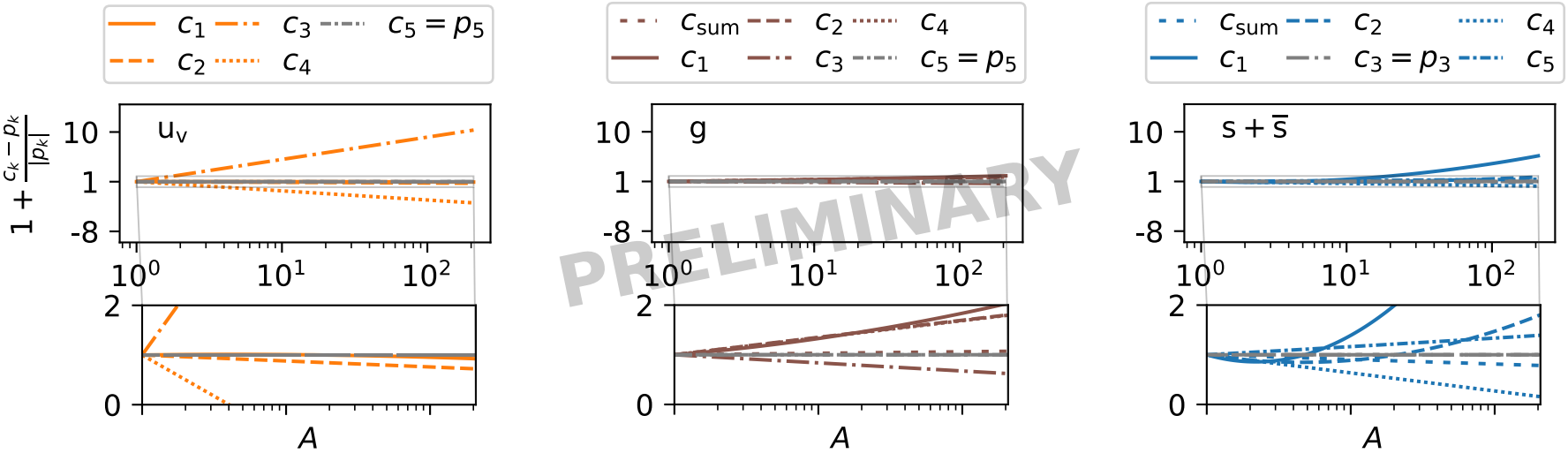
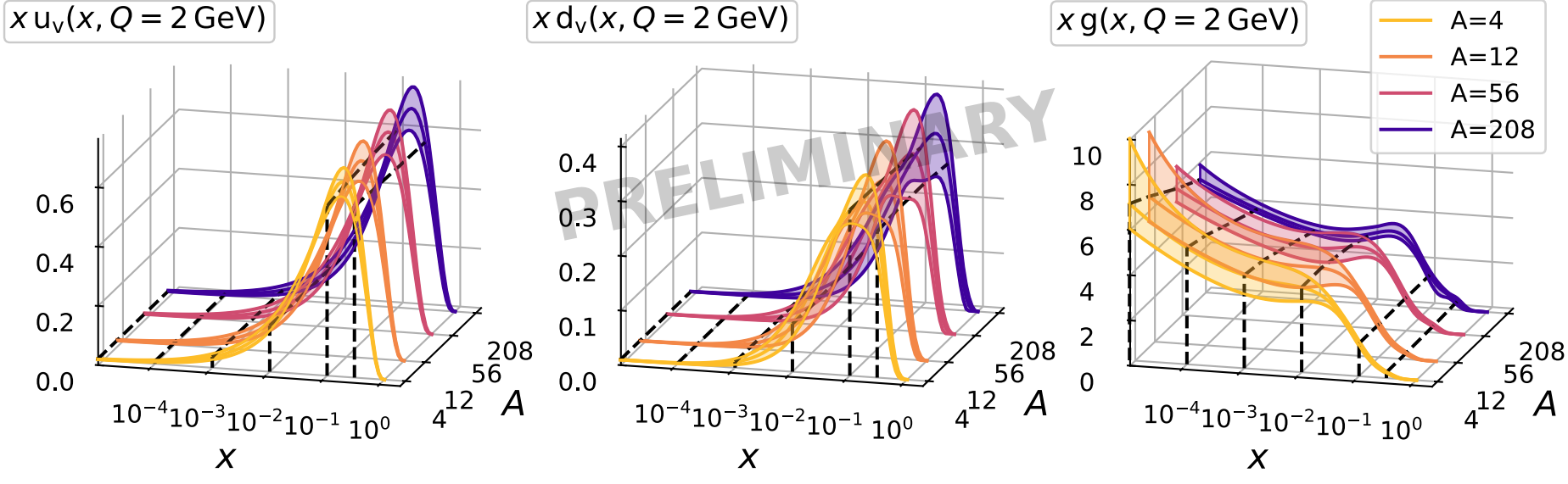


$$xf(x, Q_0) = c_{sum} x^{c_1} (1 - x)^{c_2} (1 + c_3\sqrt{x} + c_4 x) e^{c_5\sqrt{x}}$$

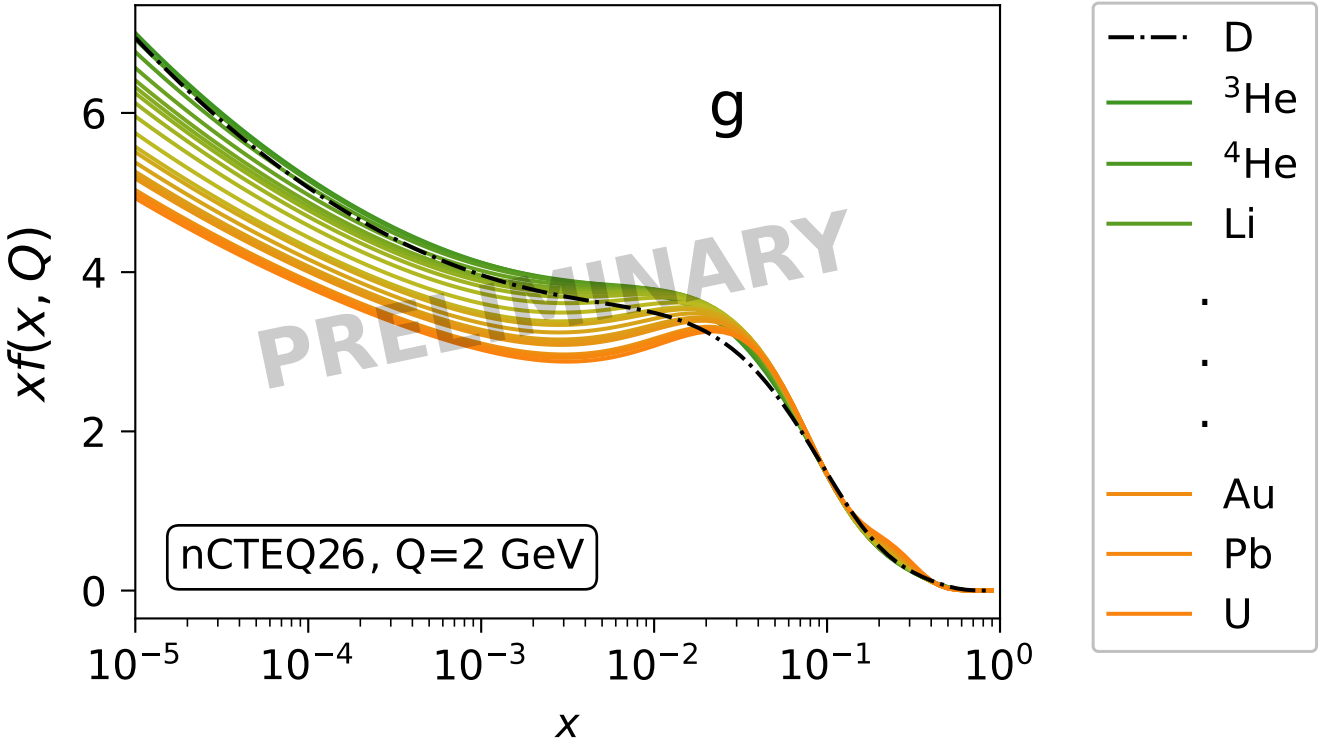
Results: A dependence

- Valence and gluon PDFs for a few selected nuclei
  - Mild A dependence, shadowing gets more pronounced with A



Results: A dependence

- To capture A dependence in more detail we introduce slices in x (Q fixed)



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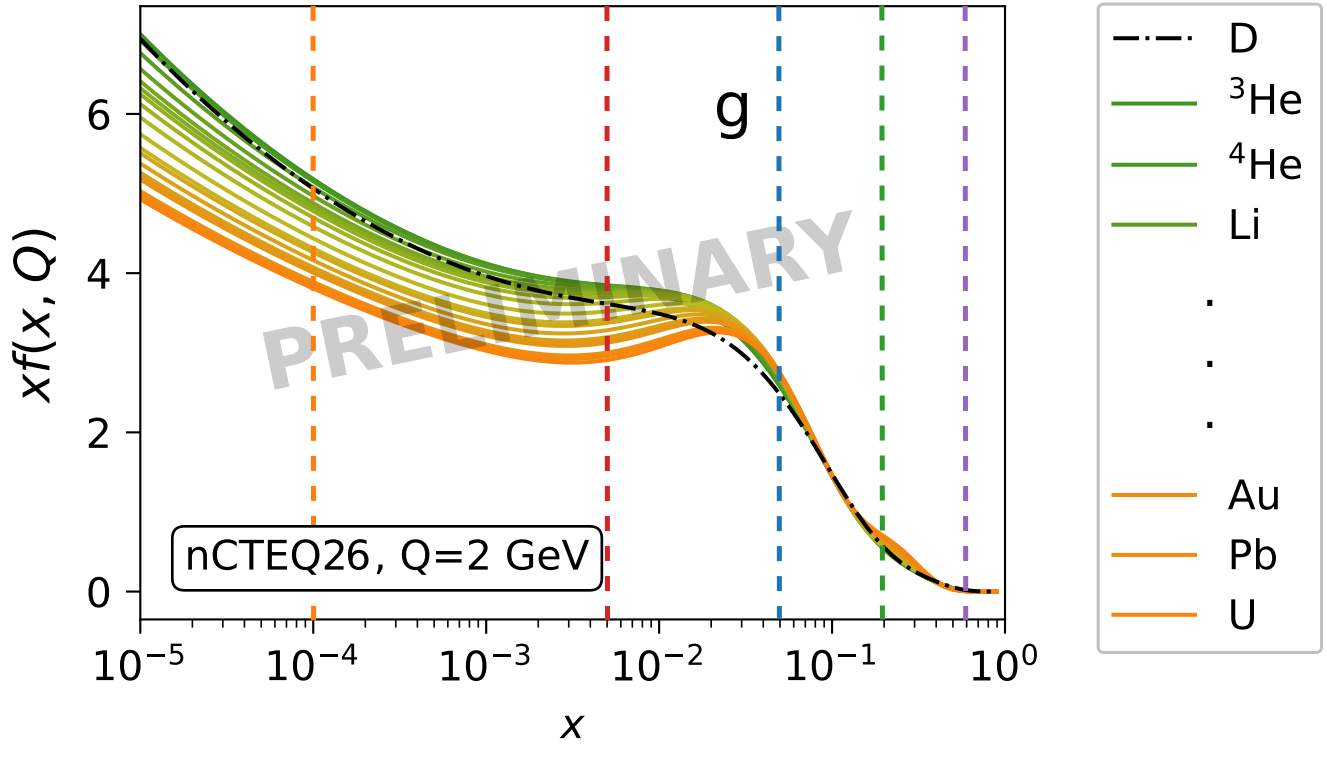

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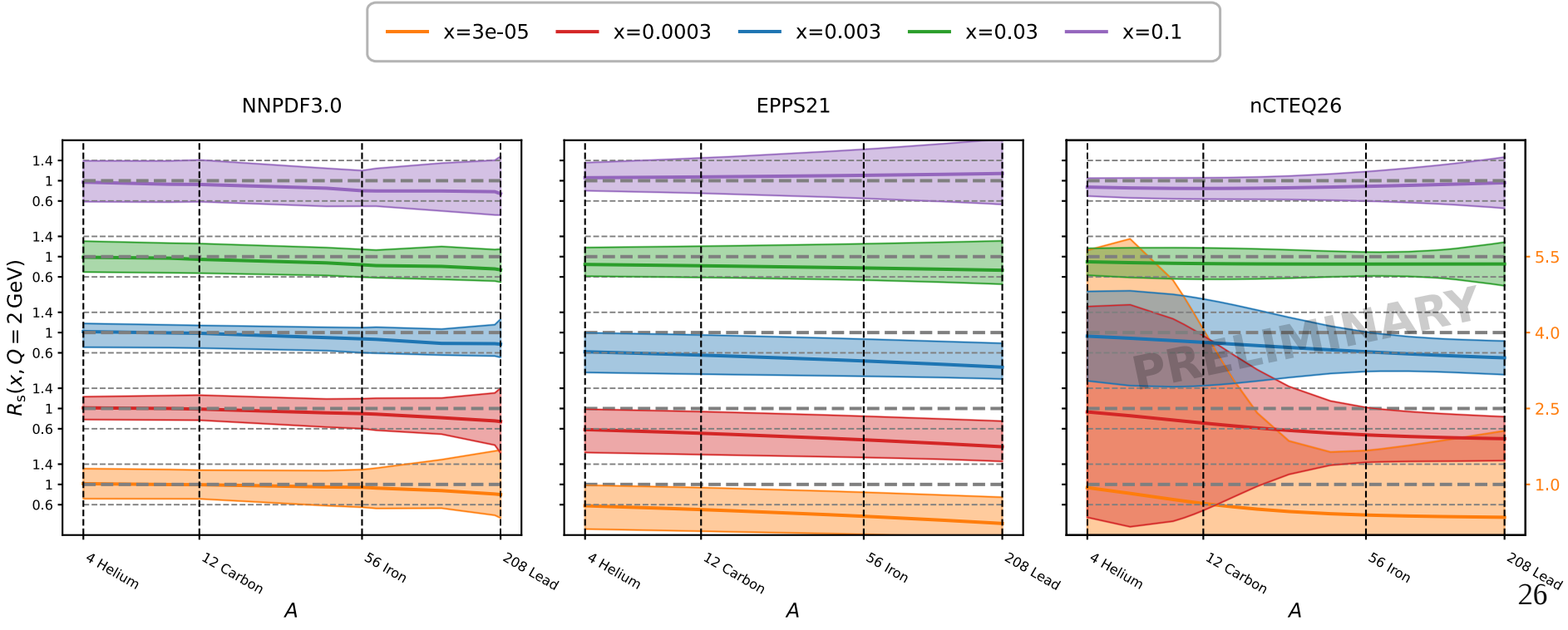
  - Strange:



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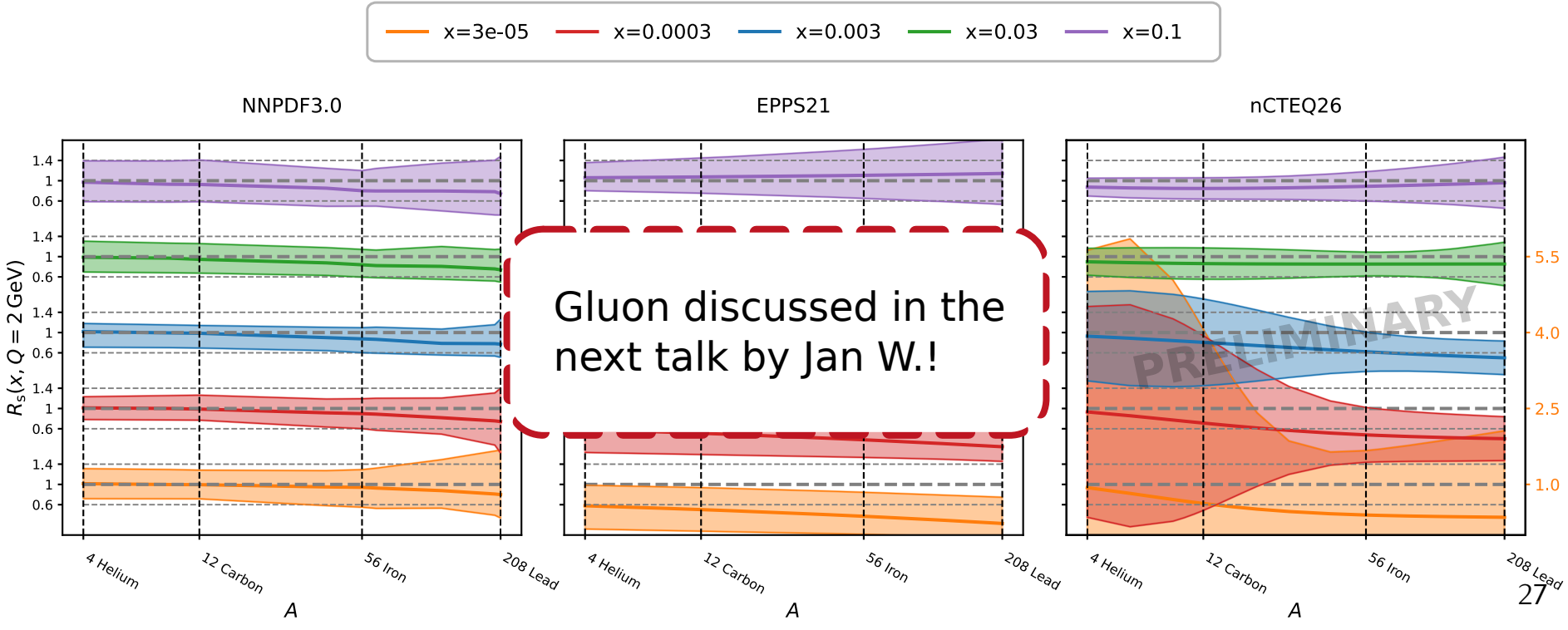
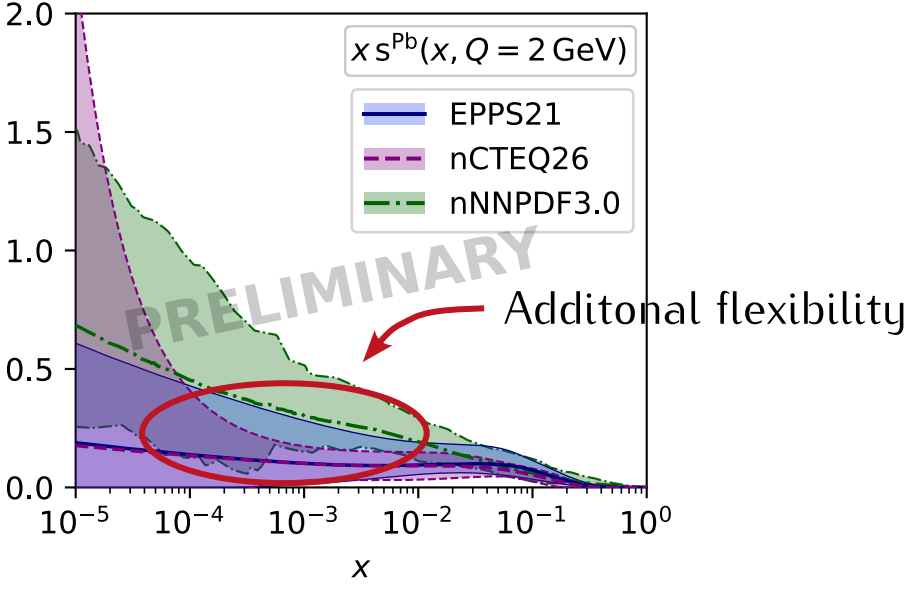
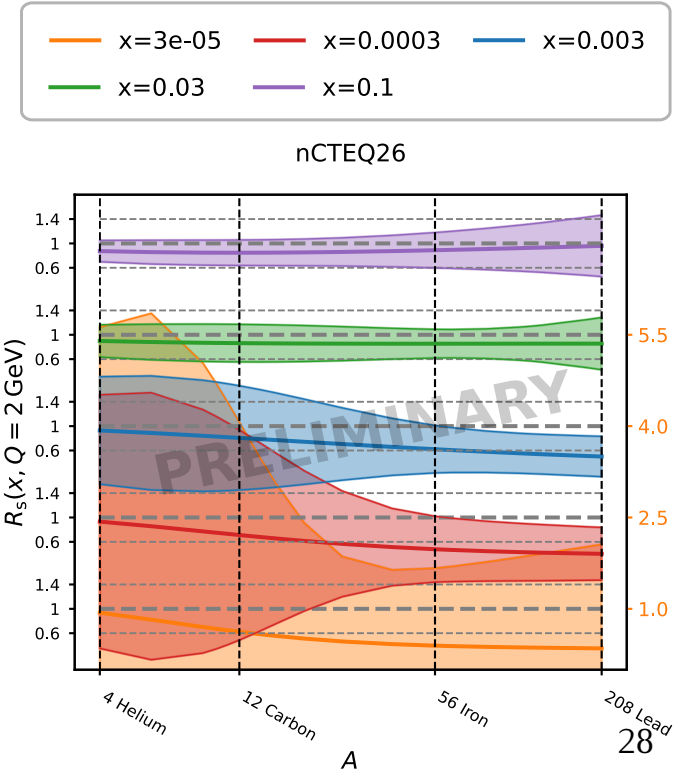


Results: strange uncertainty

- Strange uncertainty is substantial in low x
  - Imporant role by an extra parameter:

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





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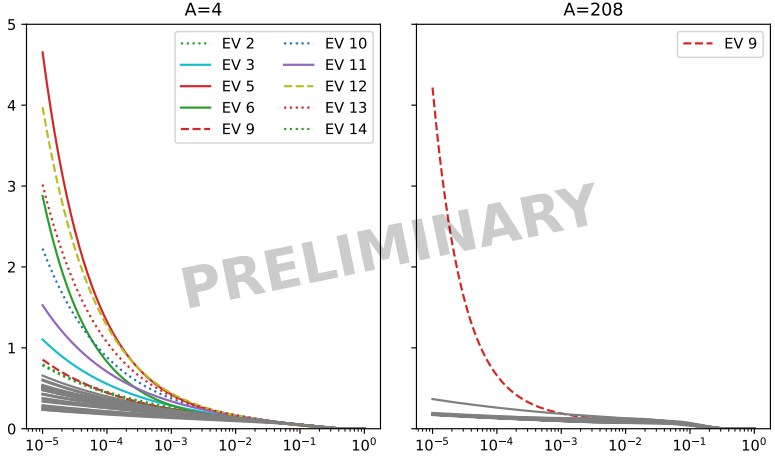
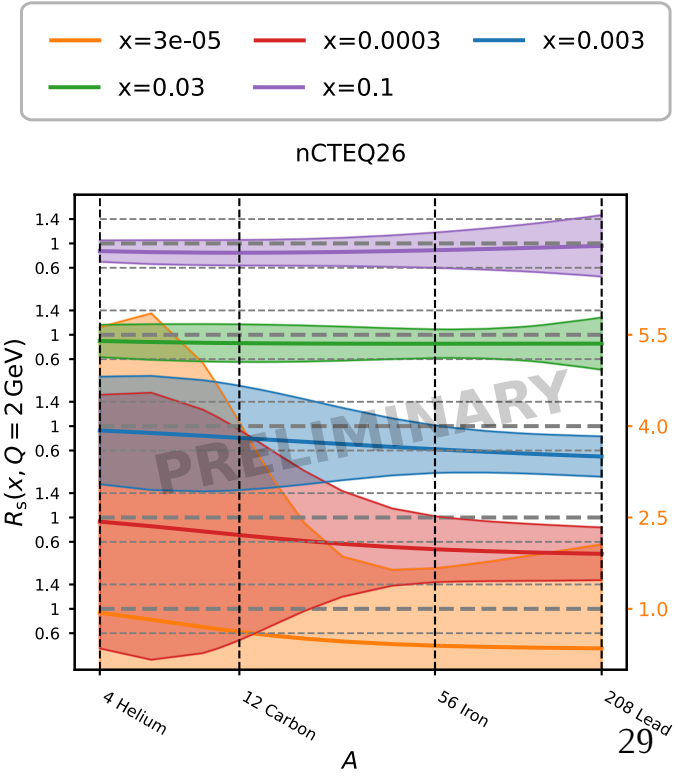
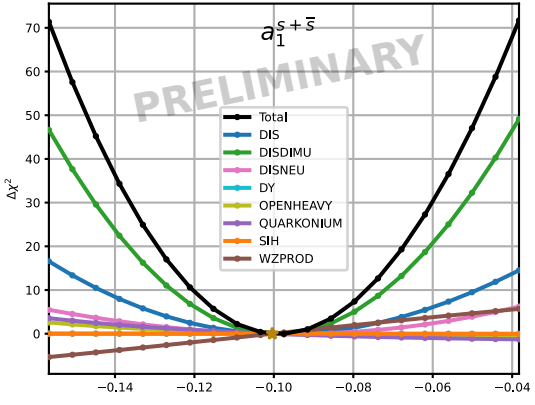
    $$xs(x,Q_0) = c_0 x^{c_1}(1-x)^{c_2}(1+c_3\sqrt{x}+c_4 x)e^{c_5\sqrt{x}}$$
  - Careful: in heavy nuclei error dominated by a single eigenvector

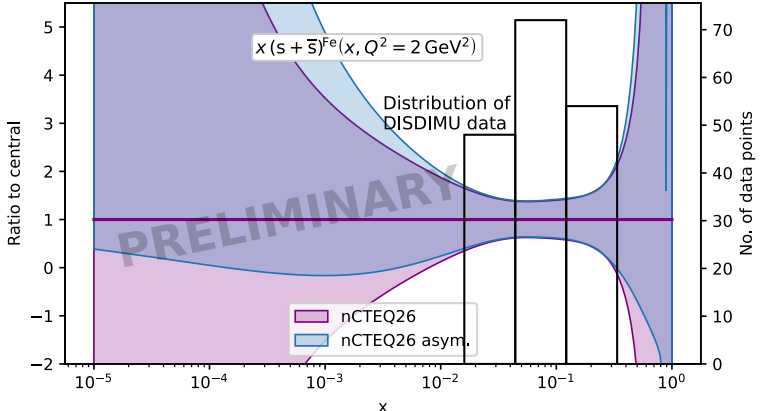




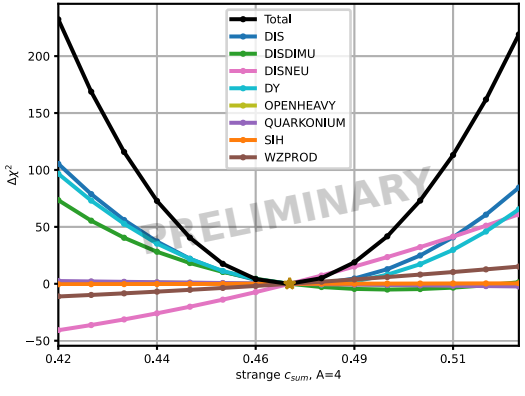
Results: strange uncertainty

- Strongest constraint from charm dimuon data





  - νDIS and dimuon data prefer different total strange momentum fraction



Summary

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- Our efforts now culminating in a new global analysis: nCTEQ26
  - Updated proton baseline and x parametrization
  - New A dependence
  - Wealth of new data
  - Theory and methodology updates on several fronts
- I showed preliminary results
  - Good data description overall
  - Paticular focus on A dependence
  - and strange and gluon uncertainties

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Next talk!

Backup