

nNNPDF1.0: Nuclear Parton Distributions from lepton-nucleus scattering and the Impact of an Electron-Ion Collider

[arXiv:1904.00018](https://arxiv.org/abs/1904.00018)

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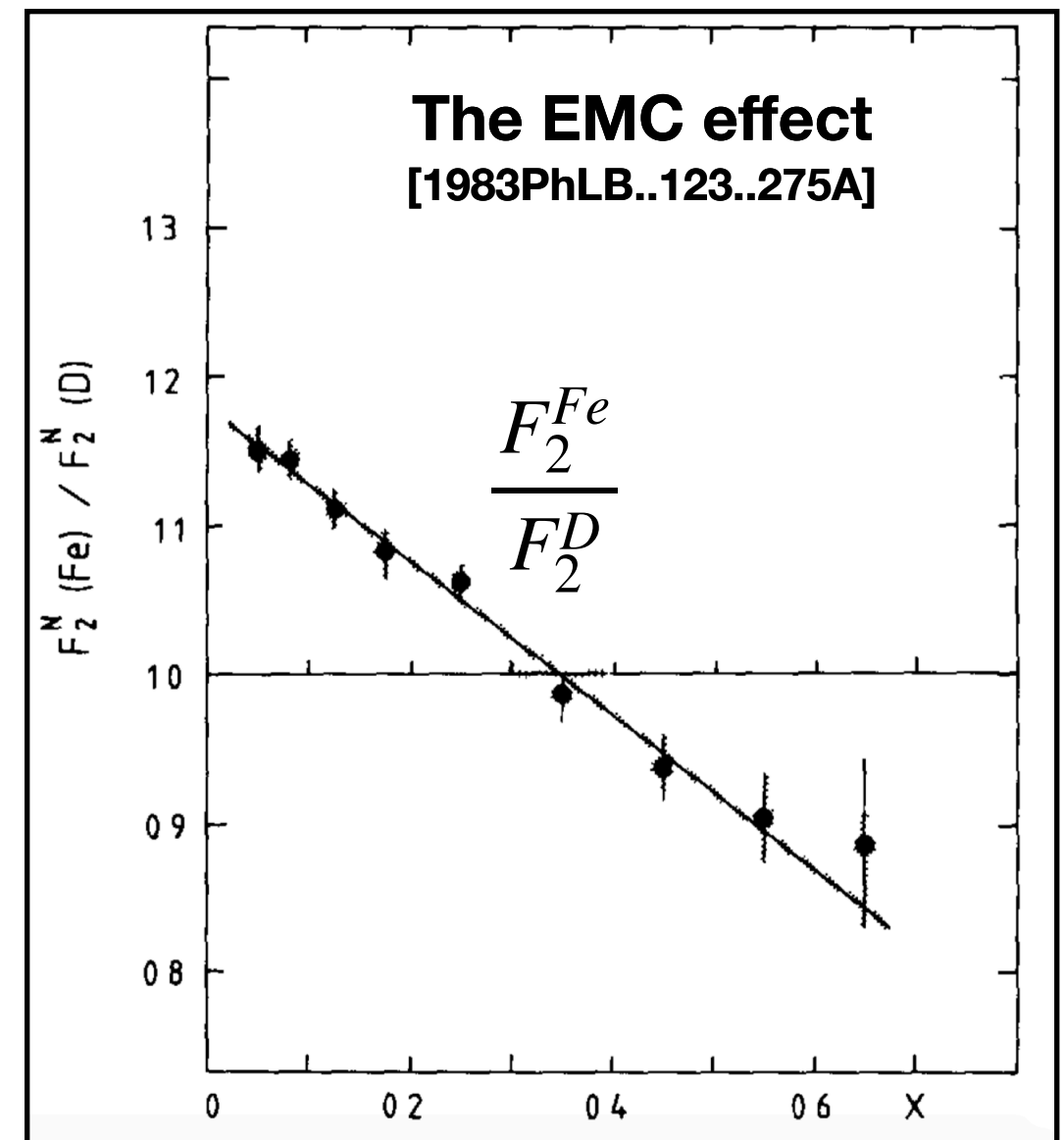


1 Introduction

- ◆ How it started
- ◆ Heavy-ion collisions
- ◆ Flavour separation
- ◆ Gluon saturation

Nuclear PDFs: How it started

Nuclear-binding effects ($\sim \text{MeV}$)
Momentum transfer ($\sim \text{GeV}$)

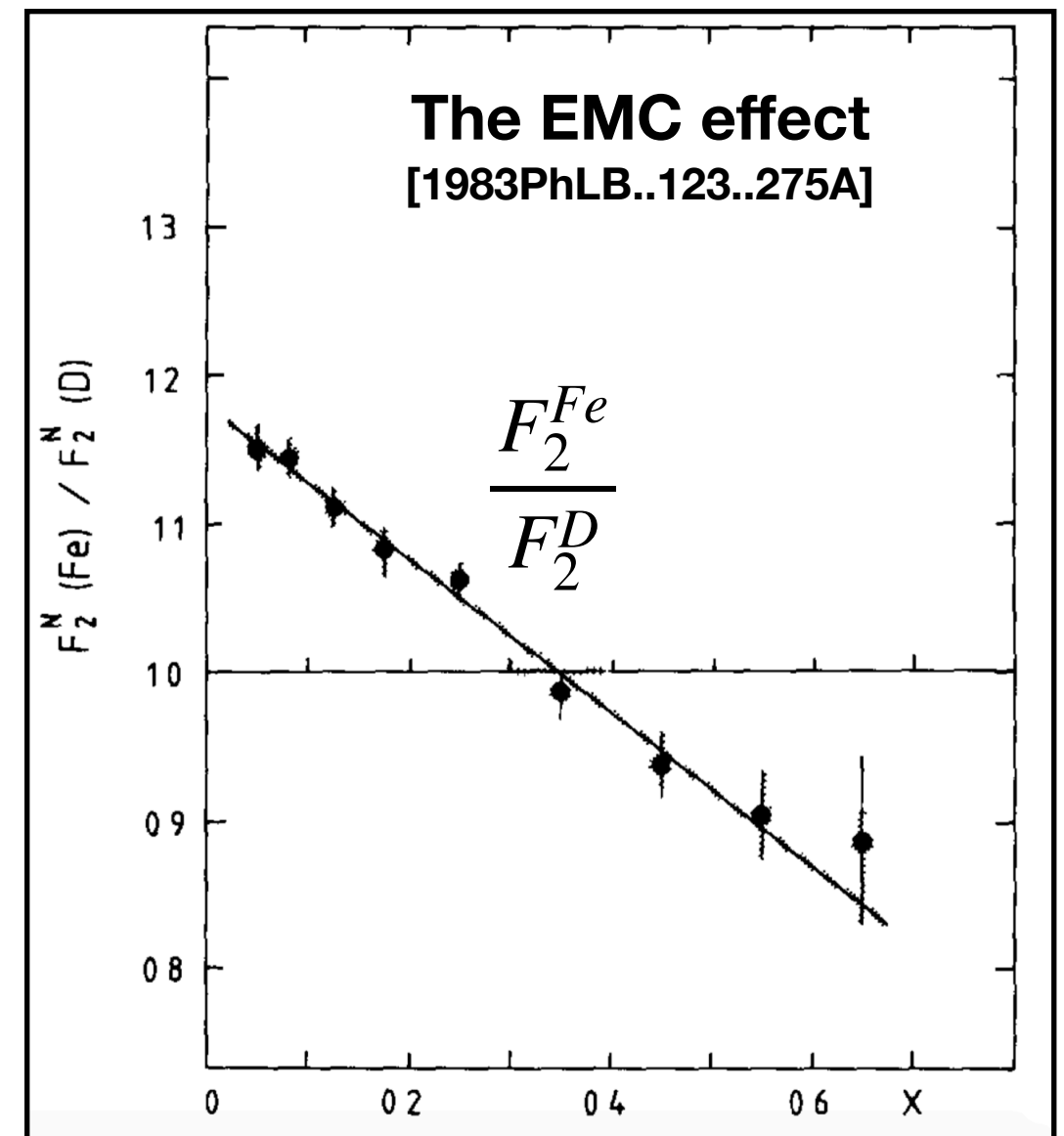


Nuclear PDFs: How it started

Nuclear-binding effects ($\sim \text{MeV}$)
Momentum transfer ($\sim \text{GeV}$)

Four equally possible scenarios:

- a) the fundamental interactions are the same but PDFs are different.
- b) The fundamental interactions are different in the medium but PDFs are the same.
- c) Both a) and b).
- d) The factorisation picture is no longer valid.



DIS Structure Function

$$F_2(x, Q^2, A) = \underbrace{\sum_i^{n_f} \sum_j^{n_f} C_i(x, Q^2)}_{\text{pQCD}} \otimes \underbrace{\Gamma_{ij}(x, Q^2)}_{\text{DGLAP}} \otimes \underbrace{q_j(x, Q_0^2, A)}_{\text{npQCD}}$$

Nuclear PDFs: How it started

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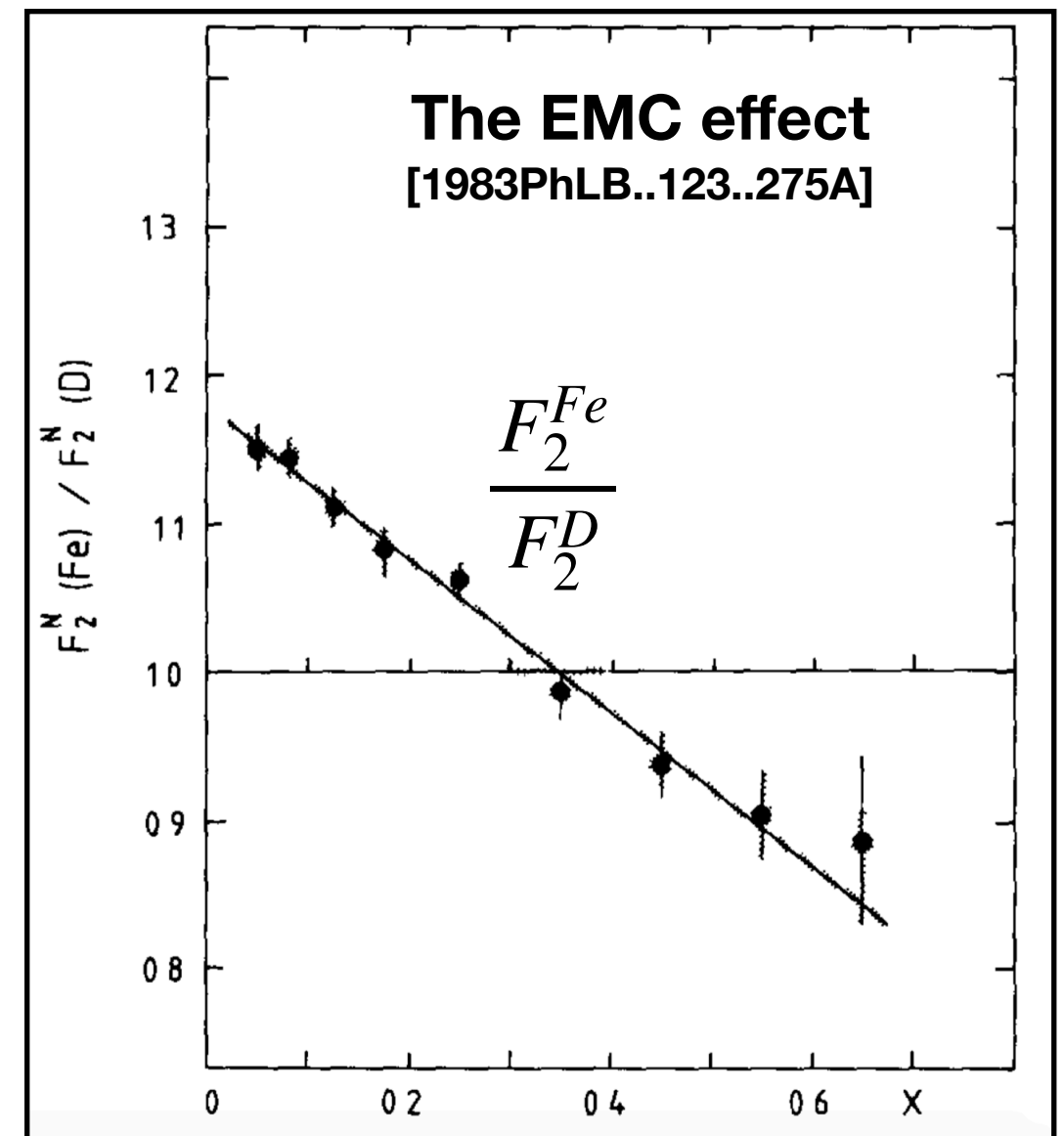
The simplest and most popular:

a) the fundamental interactions are the same but PDFs are different.

b) The fundamental interactions are different in the medium but PDFs are the same.

c) Both a) and b).

d) The factorisation picture is no longer valid.



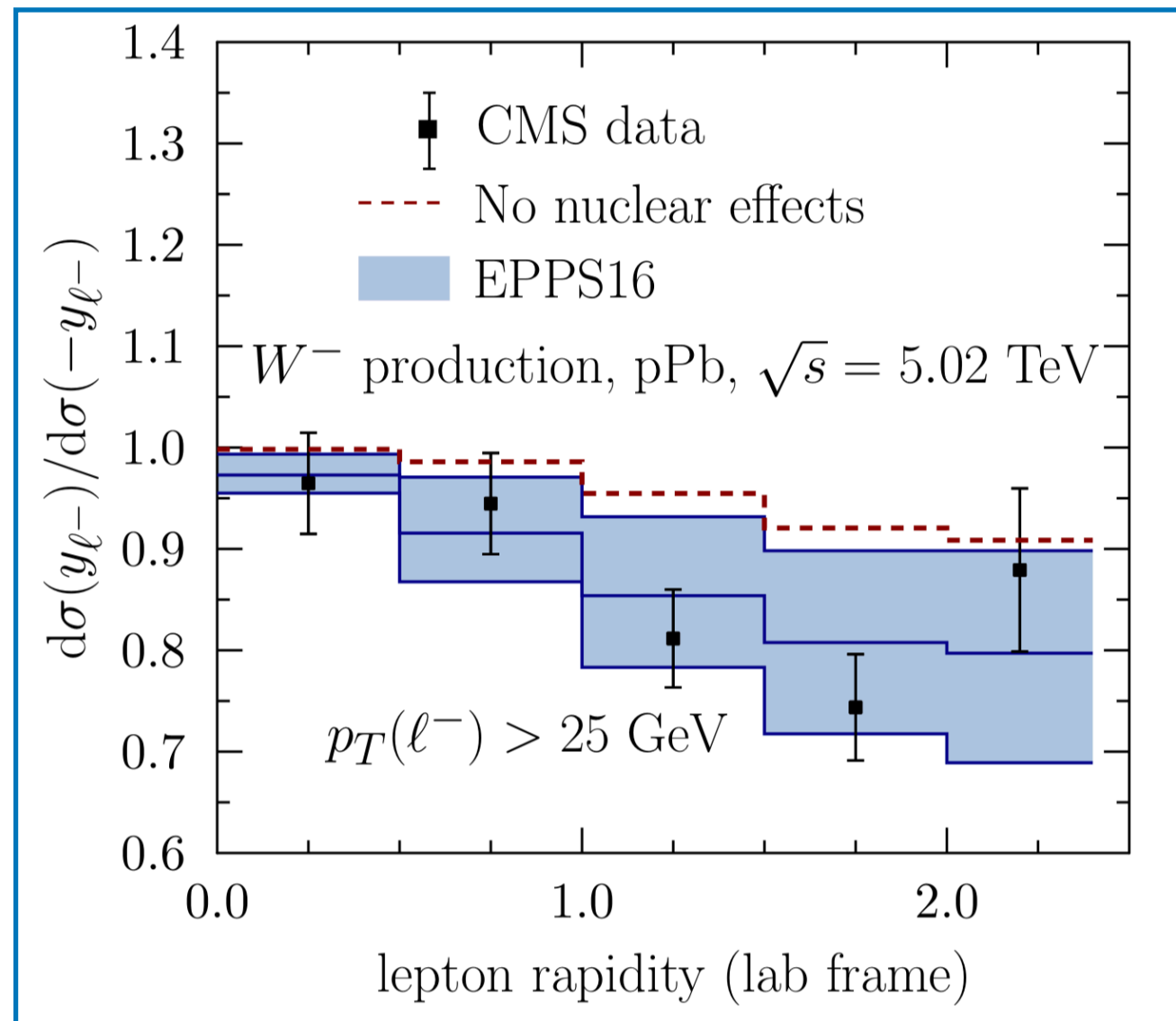
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Heavy-Ion Collisions

$W^\pm$ Production prediction with/without nuclear effects

EPPS16, Fig.19, [1612.05741]



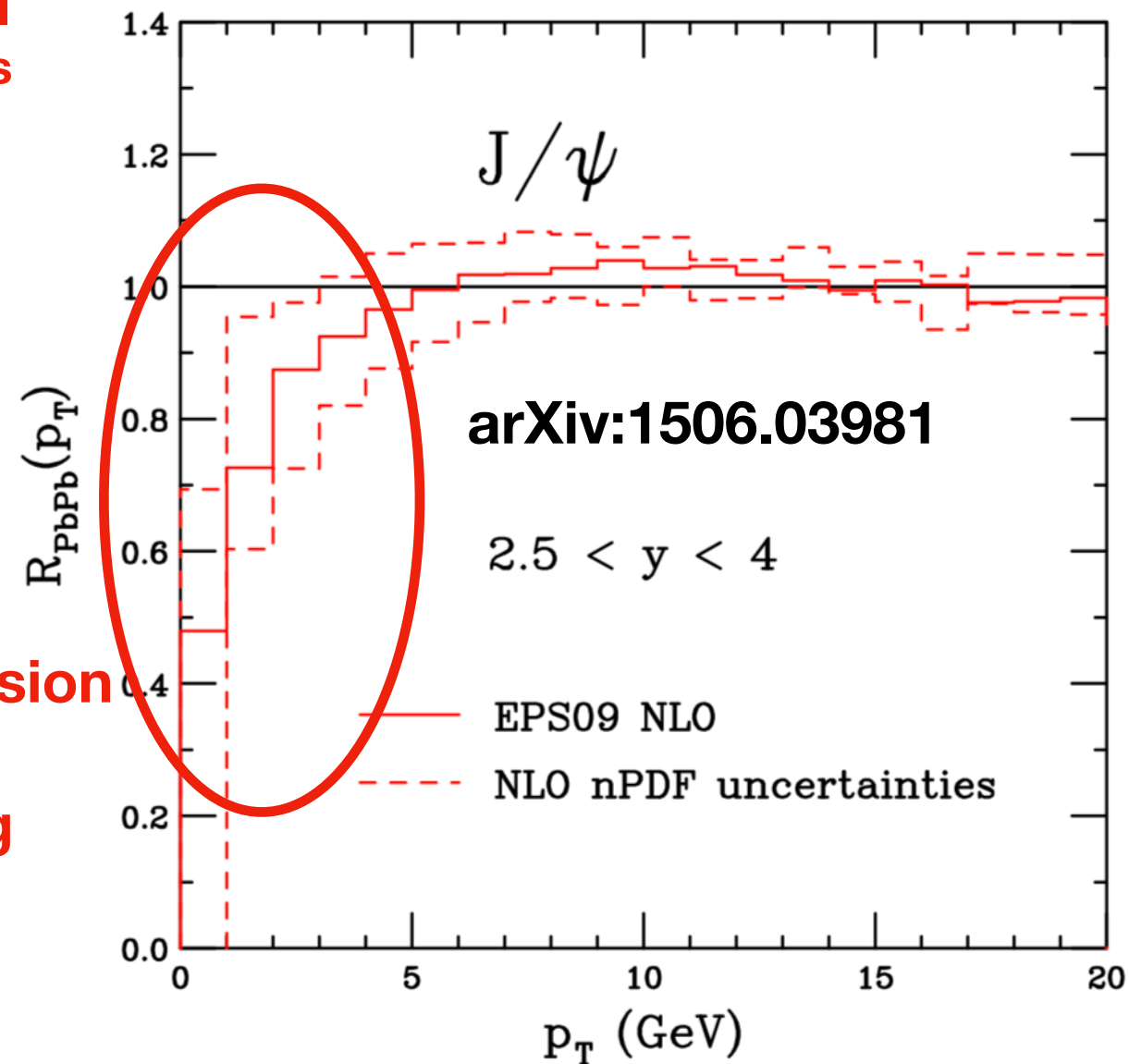
Better description of the data

Heavy-Ion Collisions

=1 in absence of initial
and final states effects

$$R_{AA}(p_T) \propto \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

Quarkonium suppression
in AA collisions
Due to shadowing

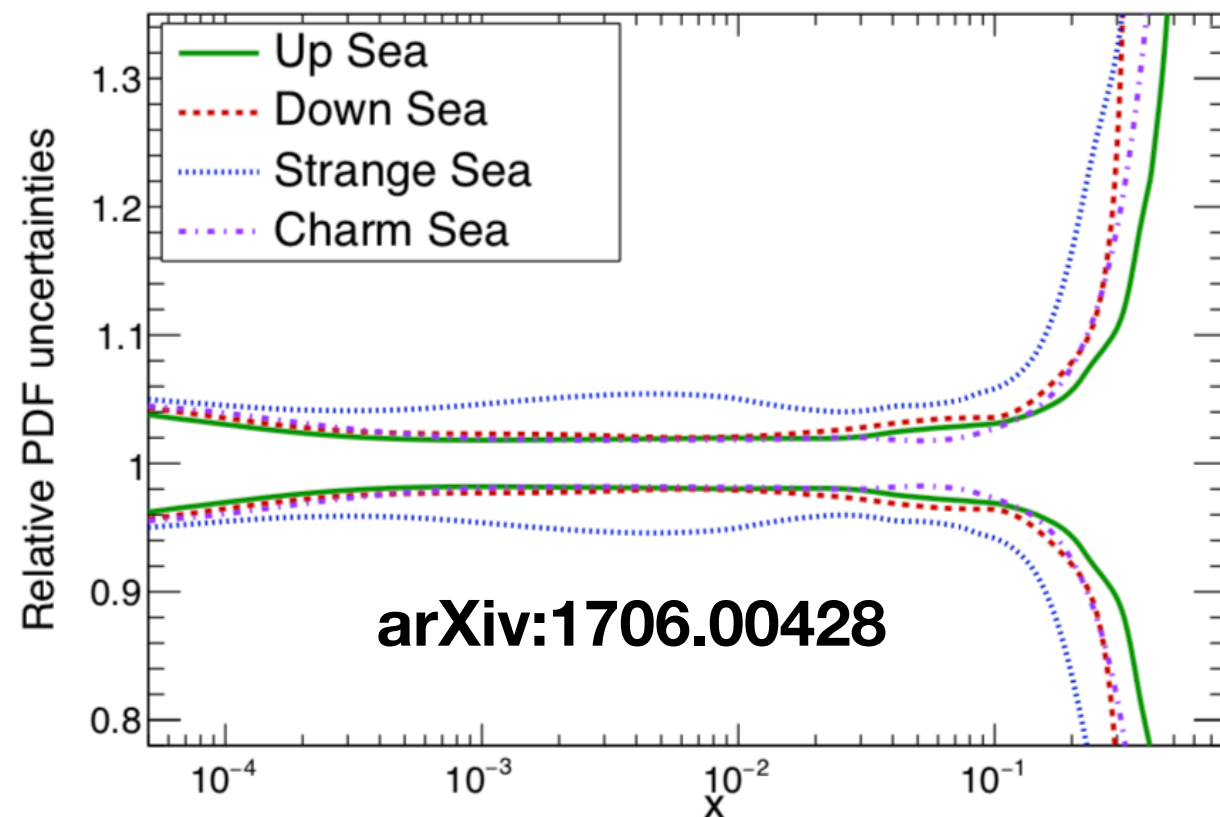


Proton Flavour Separation

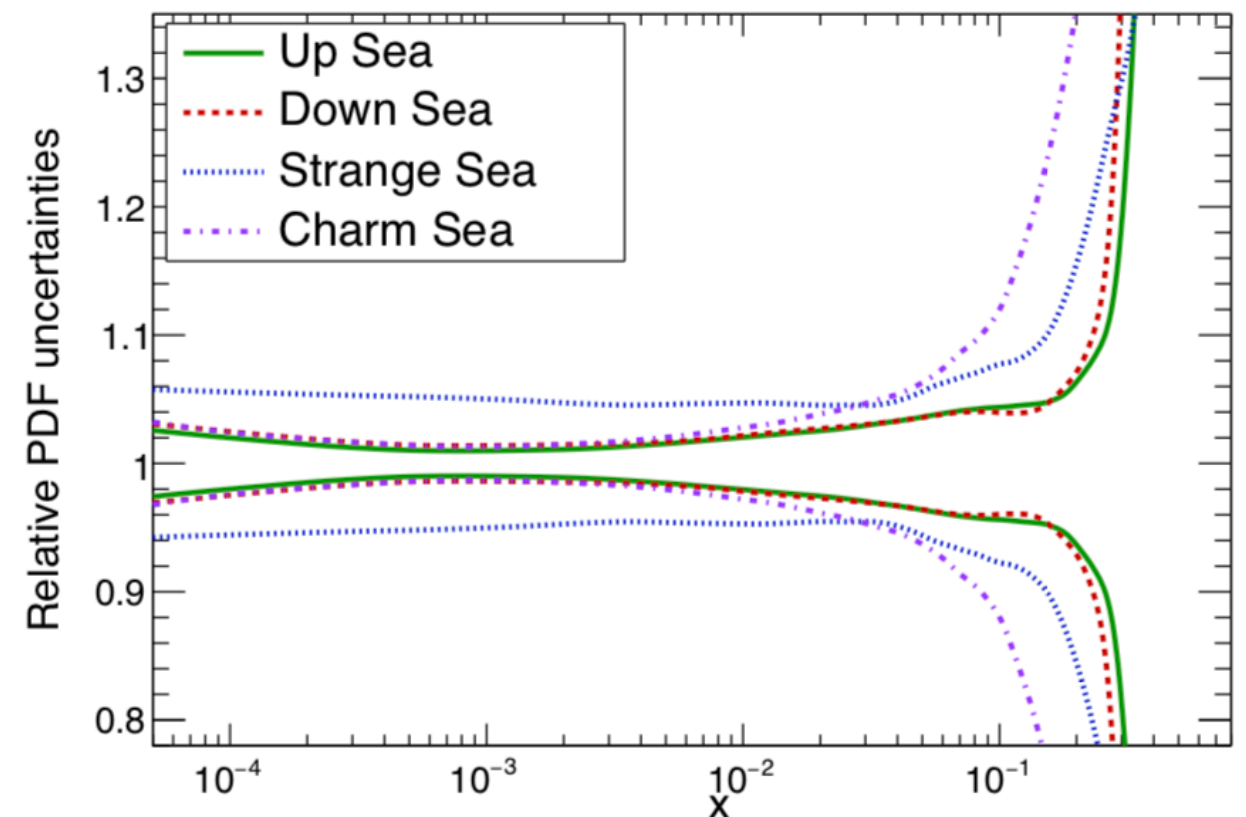
The $W^\pm$ mediated DIS access different combinations of quark and anti-quark flavours than photon-mediated DIS.

Additional constraint on the strange sea in the proton PDFs

NNPDF3.0 NNLO, $Q = 100$ GeV



NNPDF3.1 NNLO, $Q = 100$ GeV



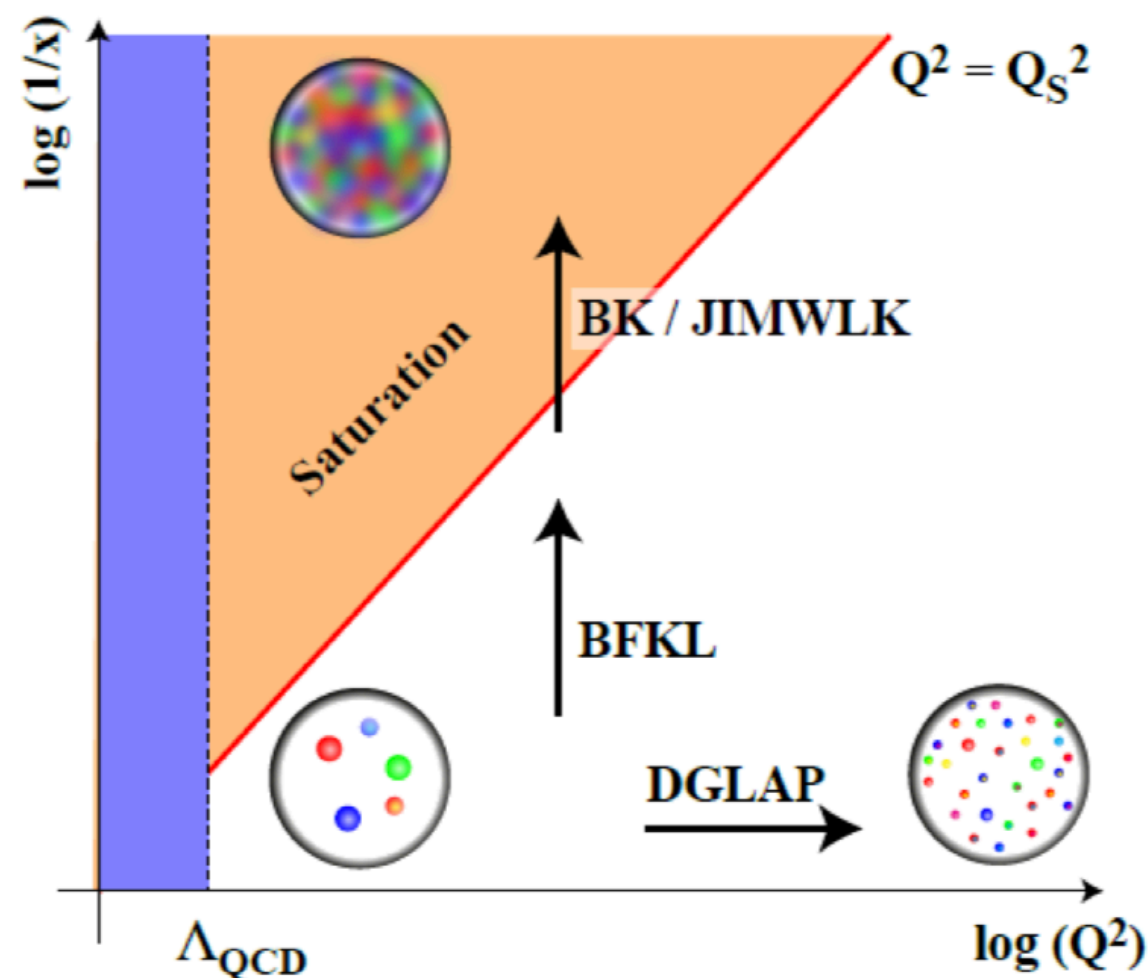
CC DIS provide access to flavour-dependent PDFs without the uncertainties from fragmentation functions (SIDIS)

Gluon Saturation in Nuclei

Saturation scale for gluon PDF can be estimated by:

$$Q_s^2 = \frac{\alpha_s}{\pi R^2} xG(x, Q^2) \propto \left(\frac{A}{x} \right)^{1/3}$$

For a given x ,
heavier the nucleus,
larger is Q_s^2 ,
hence, more accessible.



saturation can be more easily probed
in collisions of protons on heavy nuclei targets

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2 nNNPDF 1.0

- ◆ Data
- ◆ Kinematics
- ◆ Parametrisation
- ◆ Cost Function
- ◆ Data vs. Theory
- ◆ NLO fit
- ◆ Boundary Condition
- ◆ Comparisons

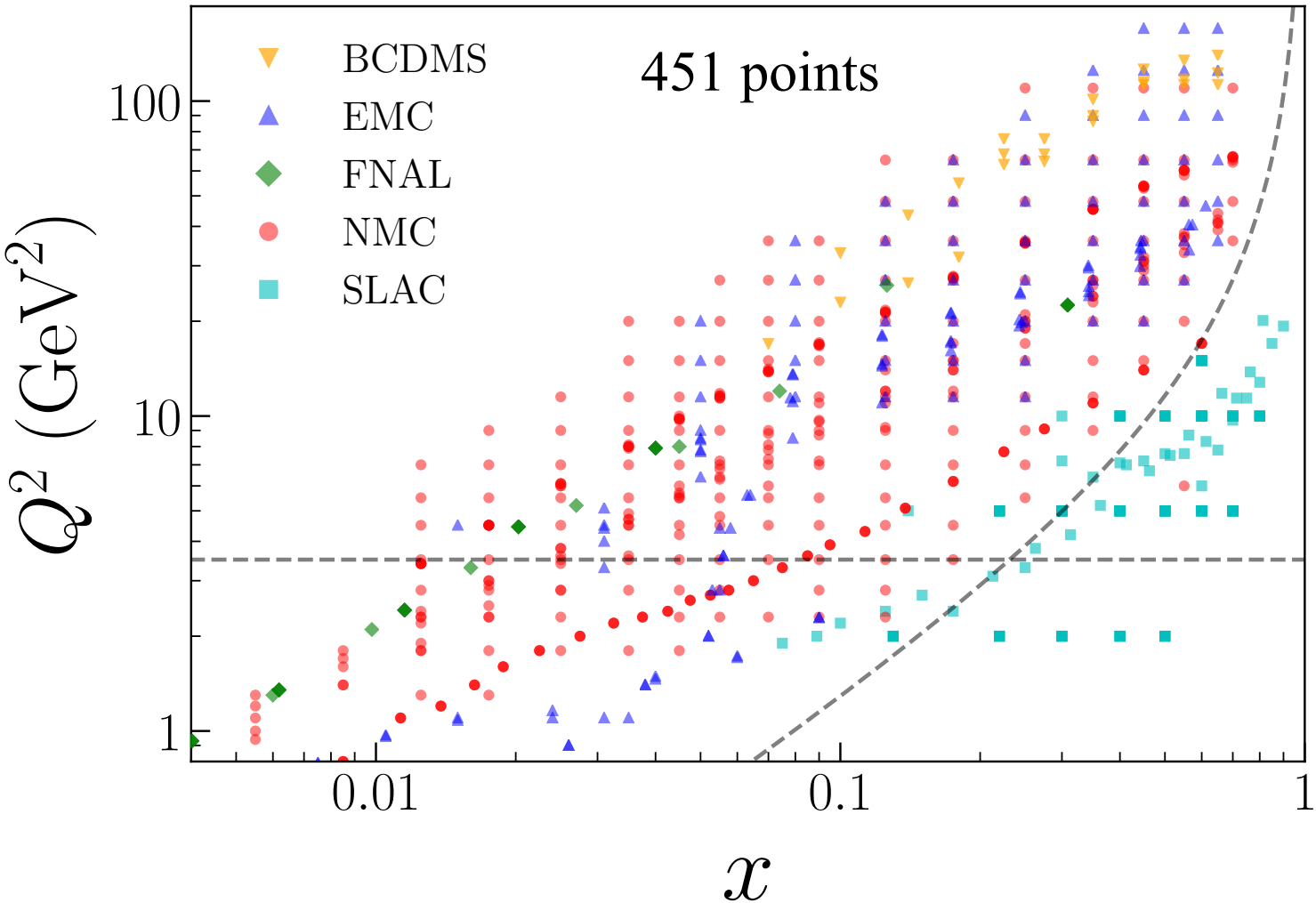
Data

	EPS09	DSSZ12	KA15	NCTEQ15	EPPS16	nNNPDF1.0
Order in α_s	LO & NLO	NLO	NNLO	NLO	NLO	NNLO
Neutral current DIS $\ell+A/\ell+d$	✓	✓	✓	✓	✓	✓
Drell-Yan dilepton $p+A/p+d$	✓	✓	✓	✓	✓	
RHIC pions $d+Au/p+p$	✓	✓		✓	✓	
Neutrino-nucleus DIS		✓			✓	In progress
Drell-Yan dilepton $\pi+A$					✓	
LHC p+Pb jet data					✓	
LHC p+Pb W, Z data					✓	In progress
Q cut in DIS	1.3 GeV	1 GeV	1 GeV	2 GeV	1.3 GeV	1.87 GeV
datapoints	929	1579	1479	708	1811	451
free parameters	15	25	16	17	20	183*
error analysis	Hessian	Hessian	Hessian	Hessian	Hessian	Monte
error tolerance $\Delta\chi^2$	50	30	not given	35	52	Carlo rep
Free proton baseline PDFs	CTEQ6.1	MSTW2008	JR09	CTEQ6M-like	CT14NLO	NNPDF3.1
Heavy-quark effects		✓		✓	✓	✓
Flavor separation				some	✓	
Reference	[JHEP 0904 065]	[PR D85 074028]	[PR D93, 014026]	[PR D93 085037]	[EPJ C77 163]	[arXiv:1904.00018]

Table 1, [1802.05927]

Kinematics

$^2\text{D}, ^4\text{He}, ^6\text{Li}, ^9\text{Be}, ^{12}\text{C}, ^{14}\text{N}, ^{27}\text{Al}, ^{40}\text{Ca}, ^{56}\text{Fe}, ^{64}\text{Cu}, ^{108}\text{Ag}, ^{119}\text{Sn}, ^{131}\text{Xe}, ^{197}\text{Au}, ^{208}\text{Pb}$



	nNNPDF1.0	nCTEQ15	EPPS16
$W_{\min}^2$	12.5 GeV ²	12.25 GeV ²	n/a
$Q_{\min}^2$	3.5 GeV ²	4 GeV ²	1.69 GeV ²

Kinematical cuts
Consistent with our
Proton PDF Boundary
NNPDF3.1

Parametrisation

Isoscalar nuclei F_2 as observable

$$xg(x, Q_0, A) = B_g(A)x^{-\alpha_g}(1-x)^{\beta_g}\xi_3^{(3)}(x, A),$$
$$x\Sigma(x, Q_0, A) = x^{-\alpha_\Sigma}(1-x)^{\beta_\Sigma}\xi_1^{(3)}(x, A),$$
$$xT_8(x, Q_0, A) = x^{-\alpha_{T_8}}(1-x)^{\beta_{T_8}}\xi_2^{(3)}(x, A)$$

Momentum Sum Rule

$$B_g(A) = \frac{1 - \int_0^1 dx\, x\Sigma(x, Q_0, A)}{\int_0^1 dx\, xg(x, Q_0, A)}.$$

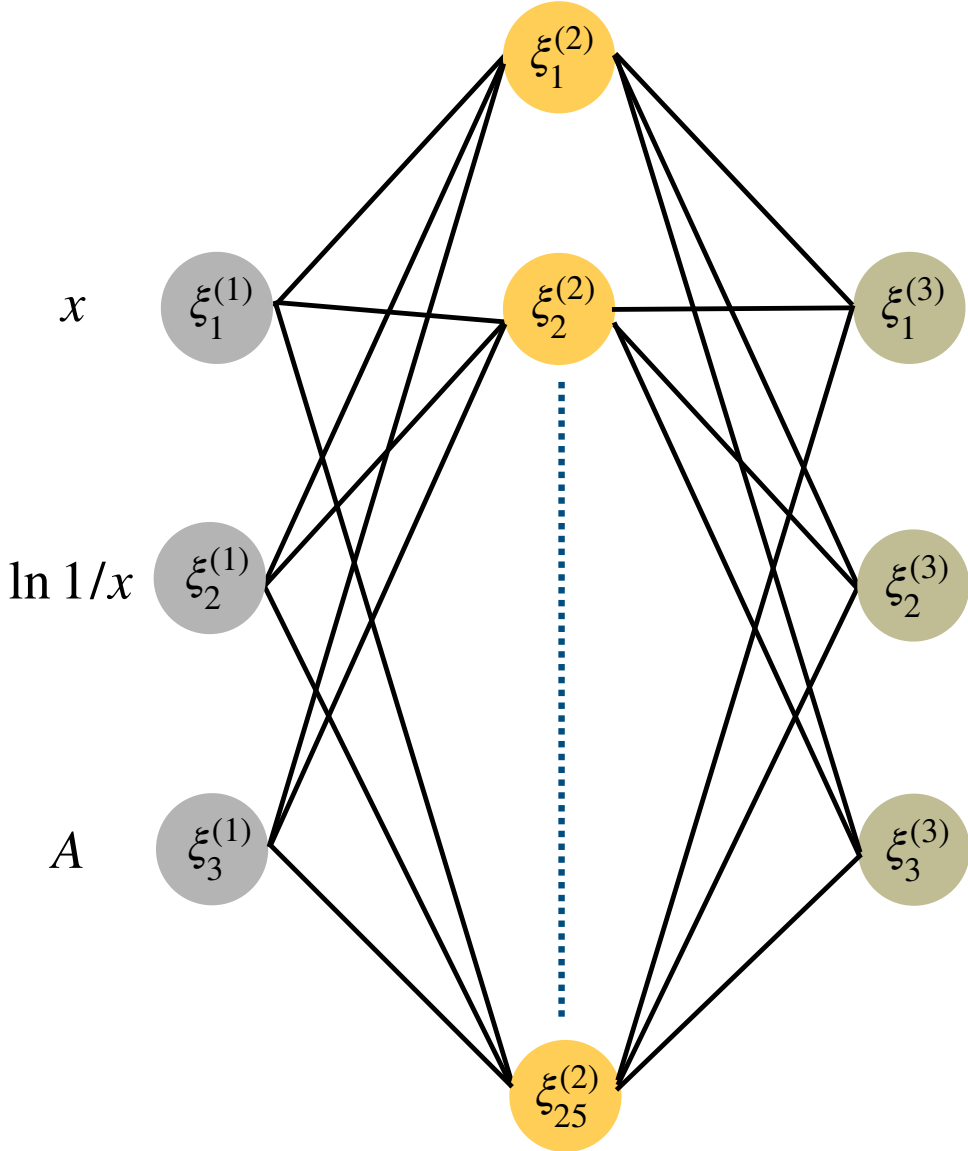
Evolution basis

$$\Sigma = \sum_{i=1}^{n_f} q_i^+ \quad \text{where: } q^\pm = q \pm \bar{q}$$

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

No contribution from T_3 in isoscalar observables

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



Cost Function

$$\chi^2 \equiv \sum_{i,j=1}^{N_{\text{dat}}} \left(R_i^{(\text{exp})} - R_i^{(\text{th})}(\{f_m\}) \right) \left(\text{cov}_{t_0} \right)^{-1}_{ij} \left(R_j^{(\text{exp})} - R_j^{(\text{th})}(\{f_m\}) \right) \\ + \lambda \sum_{m=g,\Sigma,T_8} \sum_{l=1}^{N_x} \left(f_m(x_l, Q_0, A) - f_m^{(p+n)/2}(x_l, Q_0) \right)^2 .$$

Cost Function

$$\chi^2 \equiv \sum_{i,j=1}^{N_{\text{dat}}} \left(R_i^{(\text{exp})} - R_i^{(\text{th})}(\{f_m\}) \right) \left(\text{cov}_{t_0} \right)_{ij}^{-1} \left(R_j^{(\text{exp})} - R_j^{(\text{th})}(\{f_m\}) \right) + \lambda \sum_{m=g,\Sigma,T_8} \sum_{l=1}^{N_x} \left(f_m(x_l, Q_0, A) - f_m^{(p+n)/2}(x_l, Q_0) \right)^2 .$$

Per replica boundary condition on the level of minimisation to reproduce NNPDF3.1 central value and uncertainties at $A=1$ with $x \in [10^{-3}, 0.7]$

Cost Function

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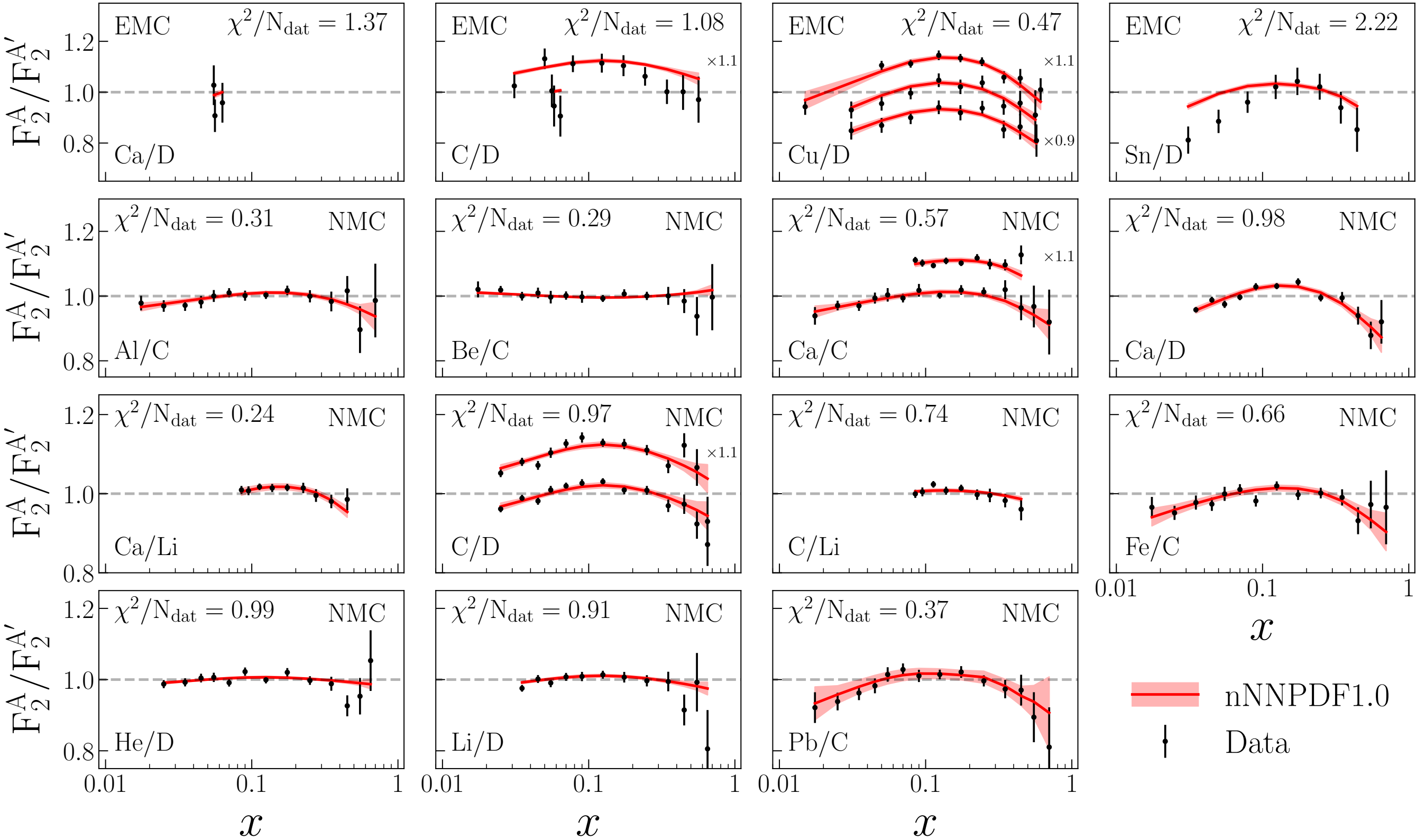
Fitting pdf in ratio

$$R = \frac{C \otimes \text{nNNPDF1.0}(A)}{C \otimes \text{nNNPDF1.0}(A')}$$

The Fit

Data vs. Theory

EMC - NMC



NLO fit

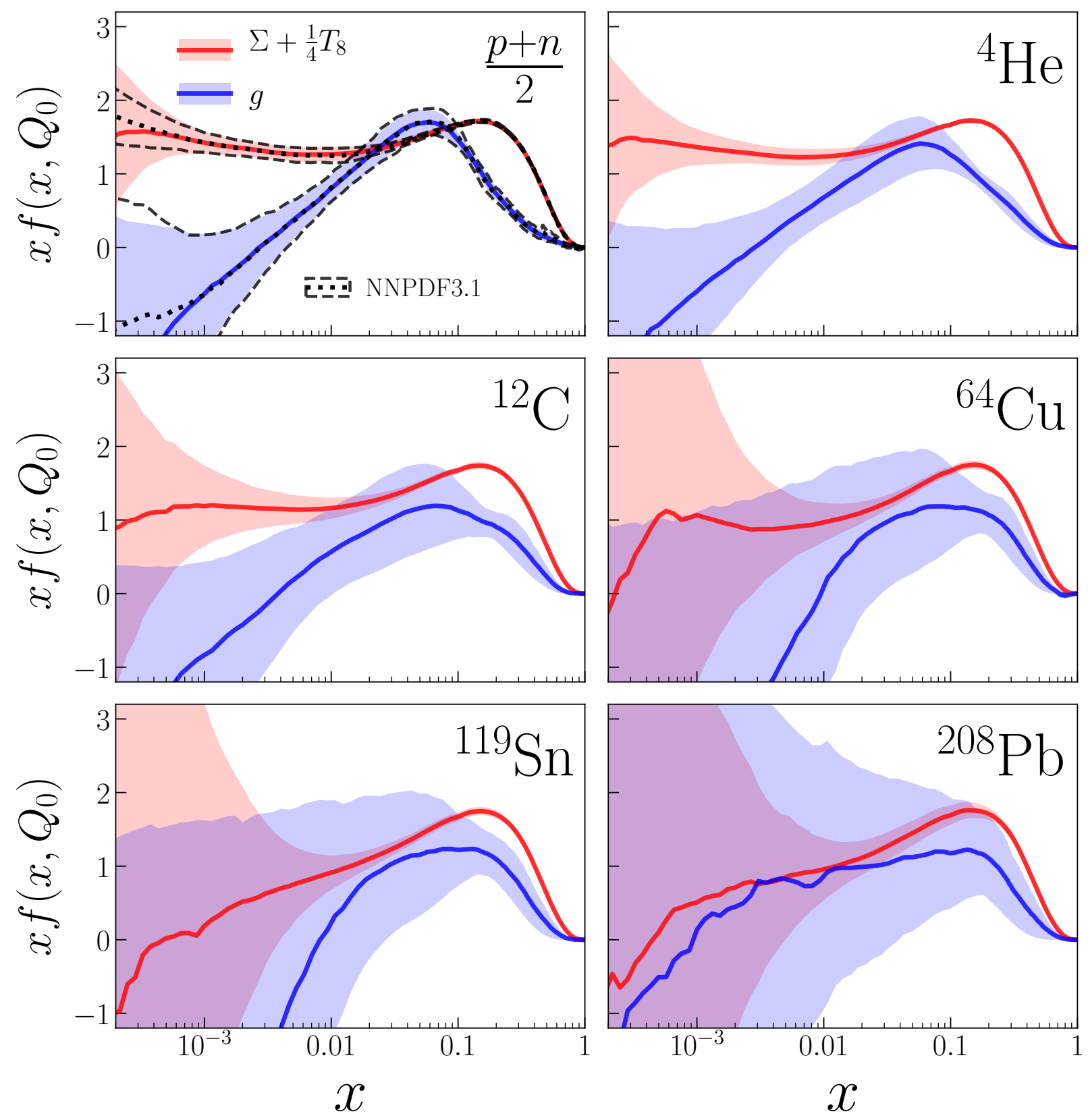
$\Sigma + \frac{1}{4} T_8$
 g

Errors computed
as 90% CL (1k replicas)

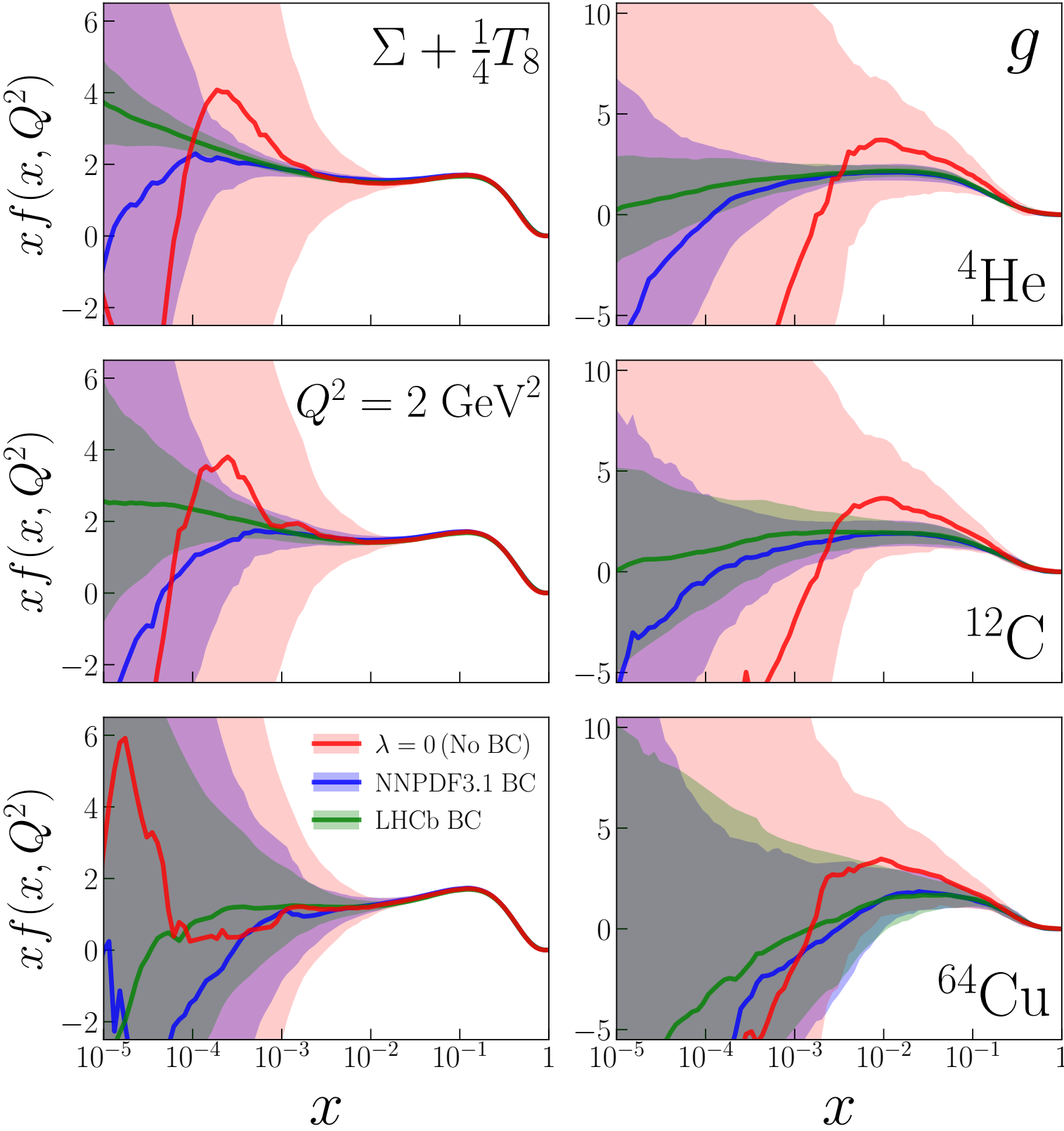
NNPDF3.1 central value
and uncertainties
reproduced

$$f(x, Q, A = 1) = \frac{1}{2} \left[f_p(x, Q^2) + f_n(x, Q^2) \right]$$

The boundary condition
constrain the nPDFs
for low-A nuclei



Boundary Condition



No BC
NNPDF3.1
NNPDF3.1+LHCb

Imposed for
 $x \in [10^{-3}, 0.7]$

In the χ^2 :

$$\lambda \sum_{m=g,\Sigma,T_8} \sum_{l=1}^{N_x} \left(f_m(x_l, Q_0, A) - f_m^{(p+n)/2}(x_l, Q_0) \right)^2$$

Important constraints on
nPDF central values and
uncertainties across A

Pronounced reduction
of uncertainty due to
the accurate determination
of the proton's quark sea
at small- x in
NNPDF3.1 + LHCb

Comparisons

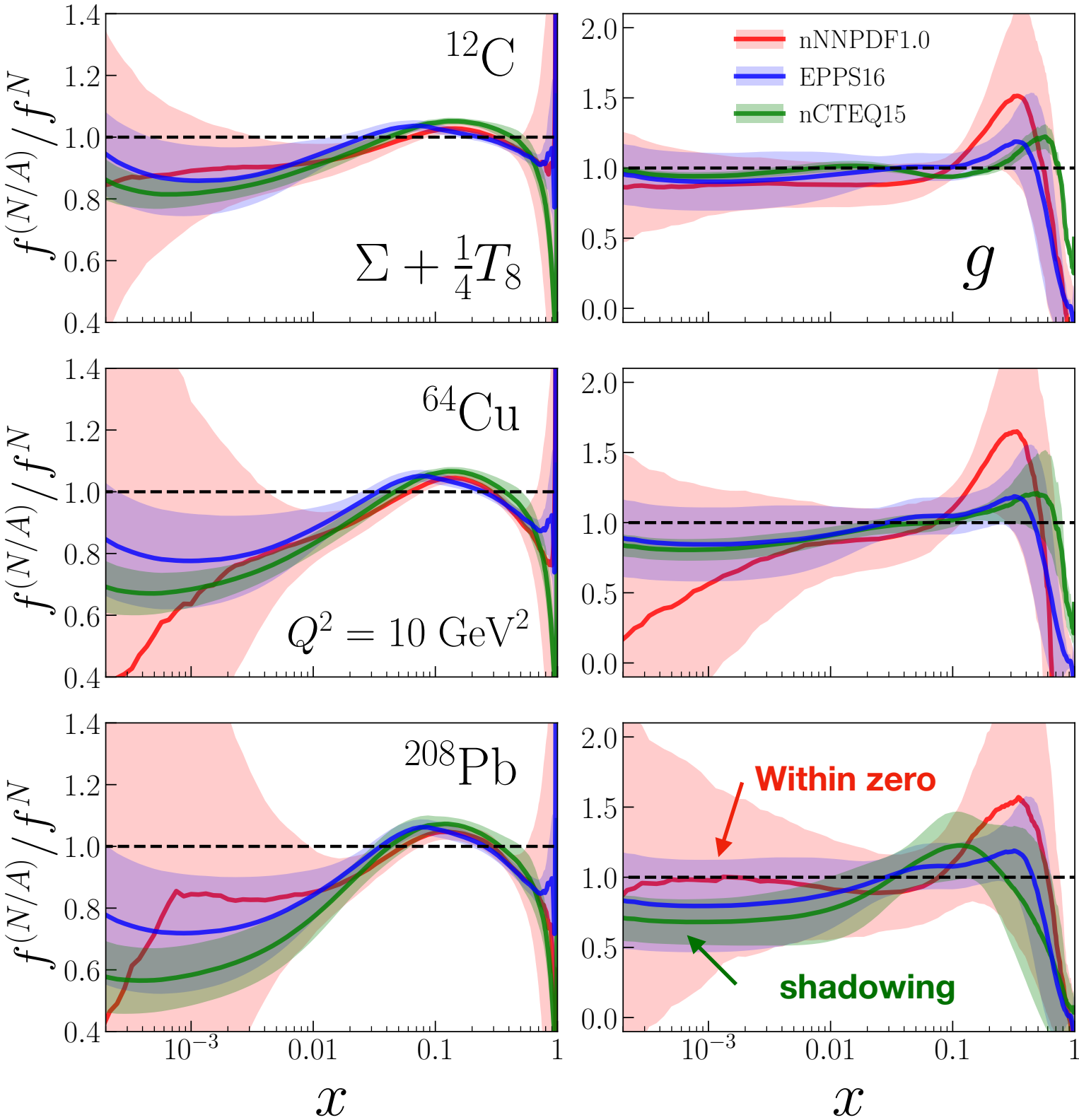
nNNPDF1.0
EPPS16
nCTEQ15

(parameterisations
in backup)

All nPDFs
are normalised to
nNNPDF1.0(A=1)
central value

- 90% CL for all nPDFs
- Hessian for
nCTEQ15 and EPPS16
 - Monte Carlo for
nNNPDF1.0

Significant differences
in uncertainties
in non-data region



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2 | nNNPDF1.0

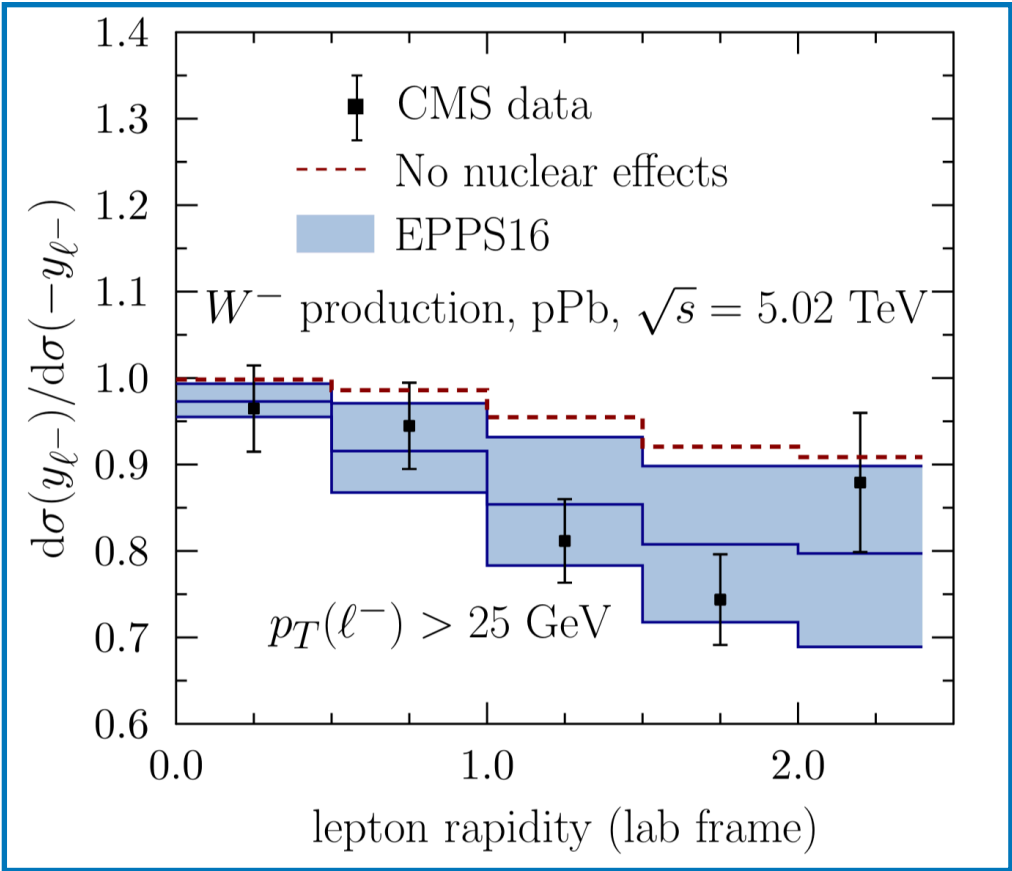
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- ◆ Cost Function
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- ◆ NLO fit
- ◆ Boundary Condition

3 | EIC

- ◆ Motivation
- ◆ Kinematics
- ◆ Impact

The need for EIC

Hera DIS data being the backbone of free-proton PDFs,
we need something similar for nPDFs



EPPS16, Fig.19, [1612.05741]

**EIC
impact**

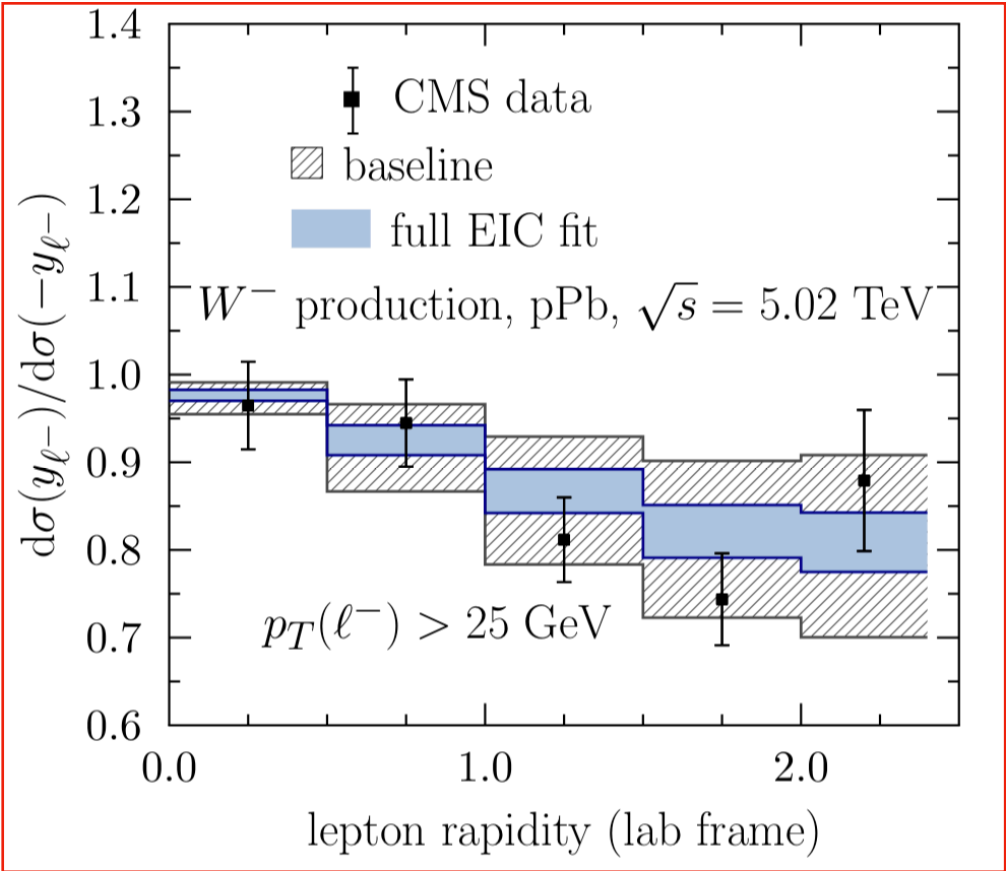


Fig.17, [1708.05654]

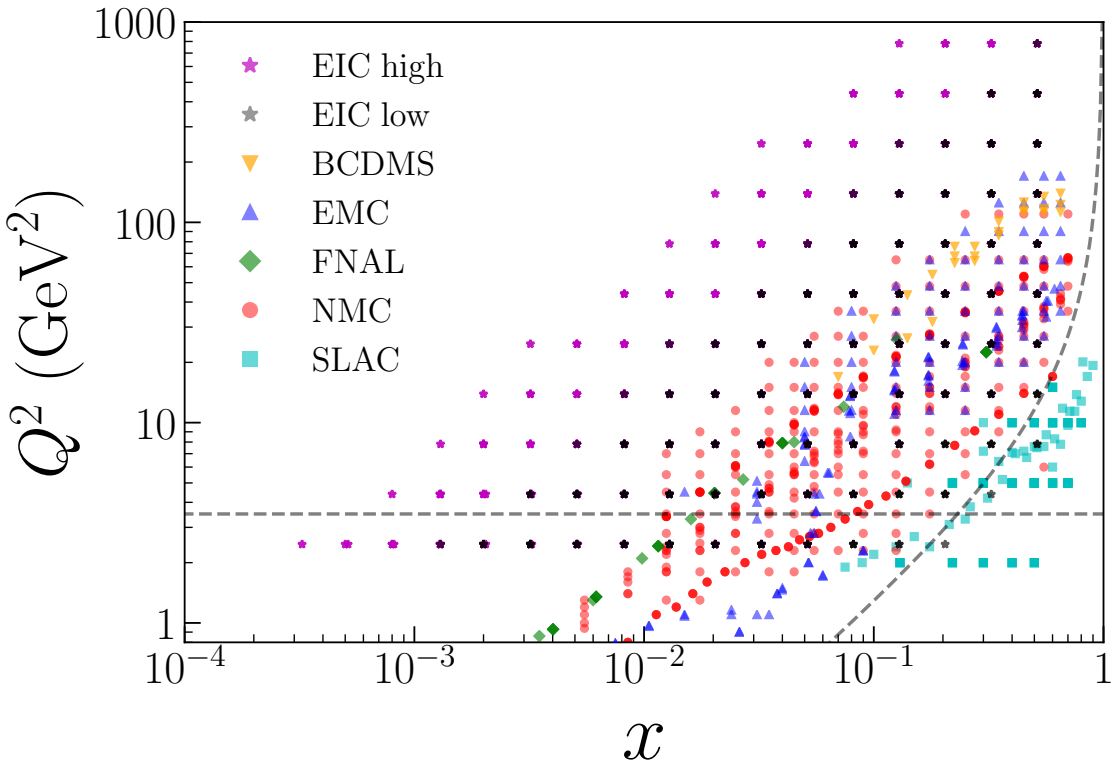
Reliable data to constrain the gluon at small-x and low-Q²

EIC kinematics

Scenario	A	E_e	E_A/A	Q^2_{max}	x_{min}	N_{dat}
eRHIC_5x50C	12	5 GeV	50 GeV	440 GeV ²	0.003	50
eRHIC_5x75C	12	5 GeV	75 GeV	440 GeV ²	0.002	57
eRHIC_5x100C	12	5 GeV	100 GeV	780 GeV ²	0.001	64
eRHIC_5x50Au	197	5 GeV	50 GeV	440 GeV ²	0.003	50
eRHIC_5x75Au	197	5 GeV	75 GeV	440 GeV ²	0.002	57
eRHIC_5x100Au	197	5 GeV	100 GeV	780 GeV ²	0.001	64
eRHIC_20x50C	12	20 GeV	50 GeV	780 GeV ²	0.0008	75
eRHIC_20x75C	12	20 GeV	75 GeV	780 GeV ²	0.0005	79
eRHIC_20x100C	12	20 GeV	100 GeV	780 GeV ²	0.0003	82
eRHIC_20x50Au	197	20 GeV	50 GeV	780 GeV ²	0.0008	75
eRHIC_20x75Au	197	20 GeV	75 GeV	780 GeV ²	0.0005	79
eRHIC_20x100Au	197	20 GeV	100 GeV	780 GeV ²	0.0003	82

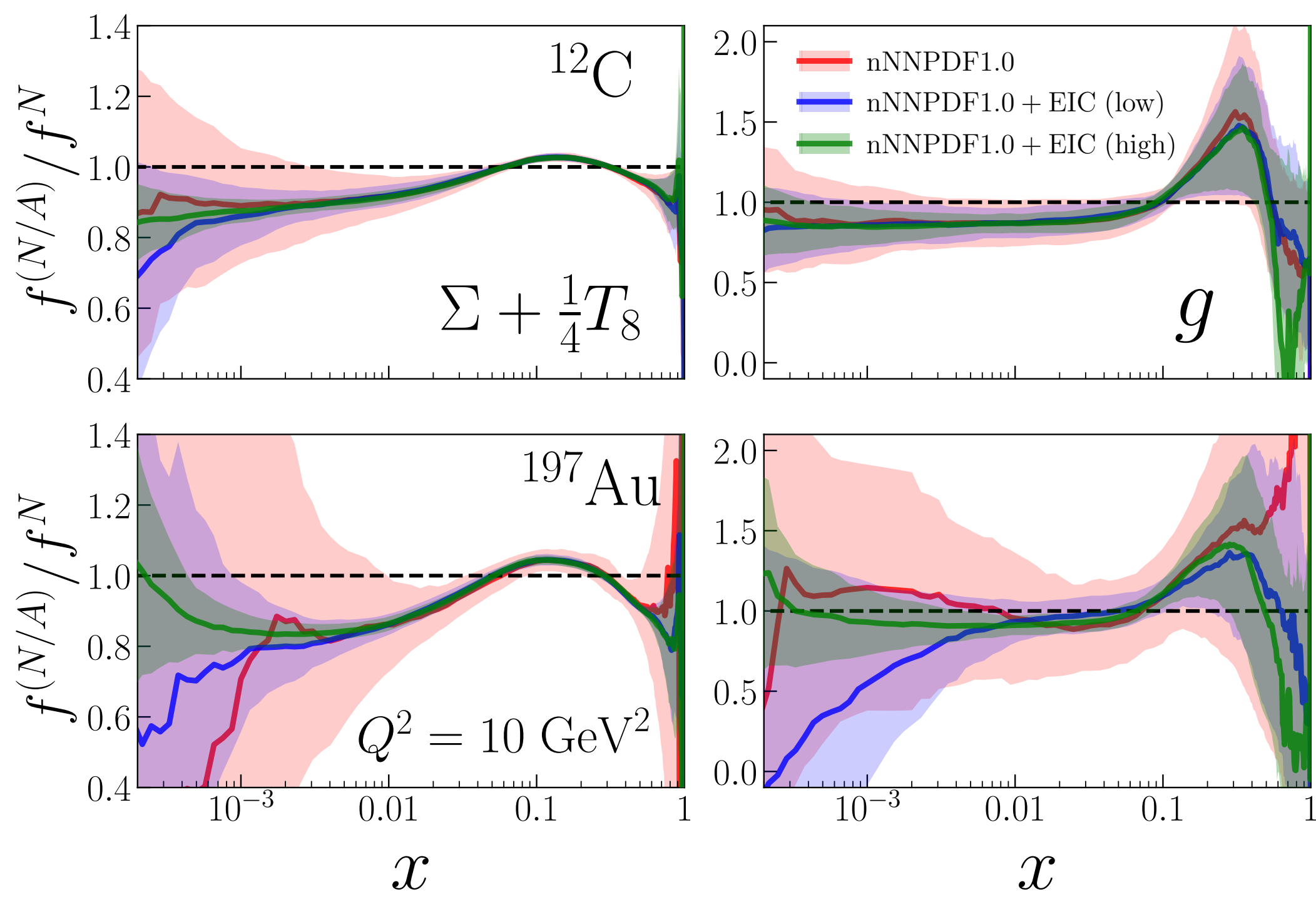
EIC projections, H. Paukkunen et al.
[arXiv:1708.05654]

- Two scenarios:
- Low energy (5 GeV)
 - High energy (20 GeV)



Pseudo-data constructed
With nNNPDF1.0 (Gold, Carbon)

EIC impact on nPDFs



Signification reduction of nPDF uncertainties at low-x for large A
Particularly for the higher energy scenario

Summary

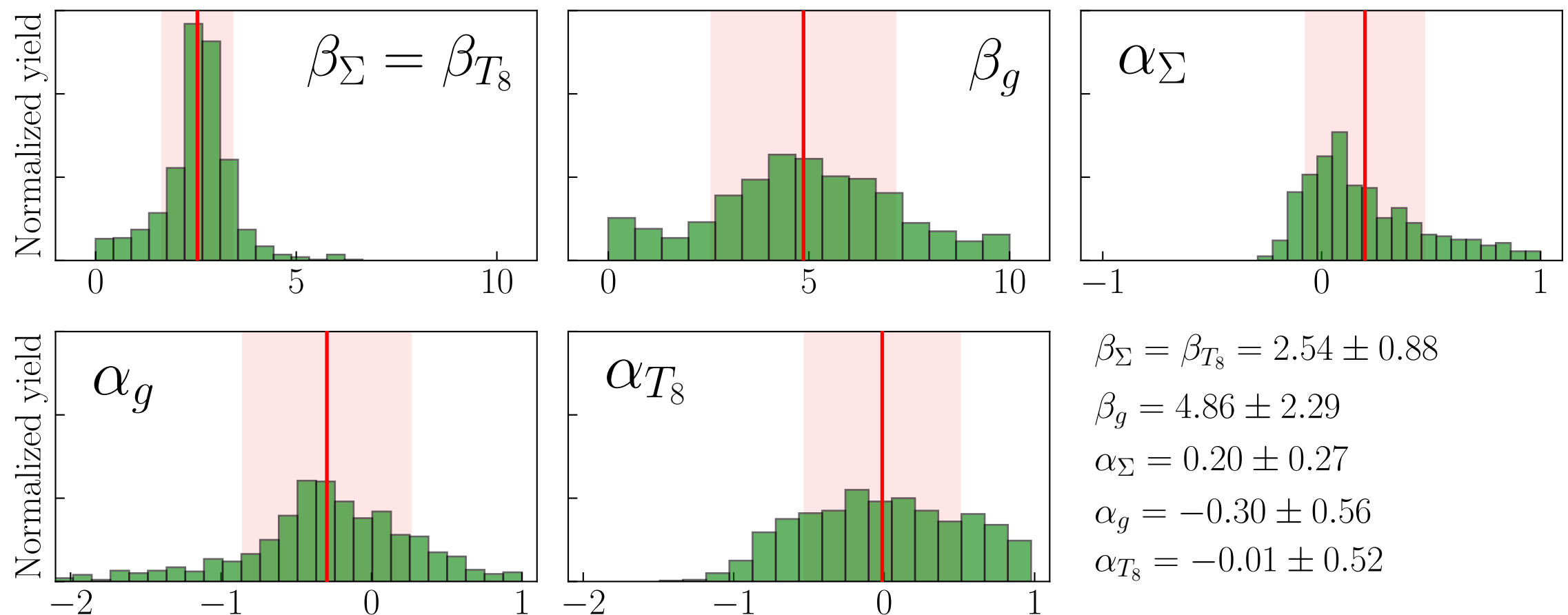
- First determination of nPDF using NNPDF methodology.
- Excellent agreement (NLO and NNLO)
with all available NC DIS data (A=2 to A=208).
- Quark distributions are reasonably constrained for $x \geq 10^{-2}$.
- Significant methodology improvement lead by use of TensorFlow and stochastic gradient descent for the first time in NNPDF.
- Vitality of the boundary condition (A=1 limit), reproducing NNPDF3.1 central values and uncertainties of using consistently the same theory settings.
- Quantification of the future impact of e+A measurements from an Electron-Ion Collider constraining the quark and gluon nPDFs down to $x \approx 5 \times 10^{-4}$.
- LHAPDF sets available on [NNPDF](#) website.
- In progress: Fitting ATLAS Z-W production and CHORUS, NuTeV DIS CC

Backup Slides

Effective Exponents

In previous NNPDF analyses, the preprocessing exponents α_f and β_f were fixed to a randomly chosen value from a range that was determined iteratively.

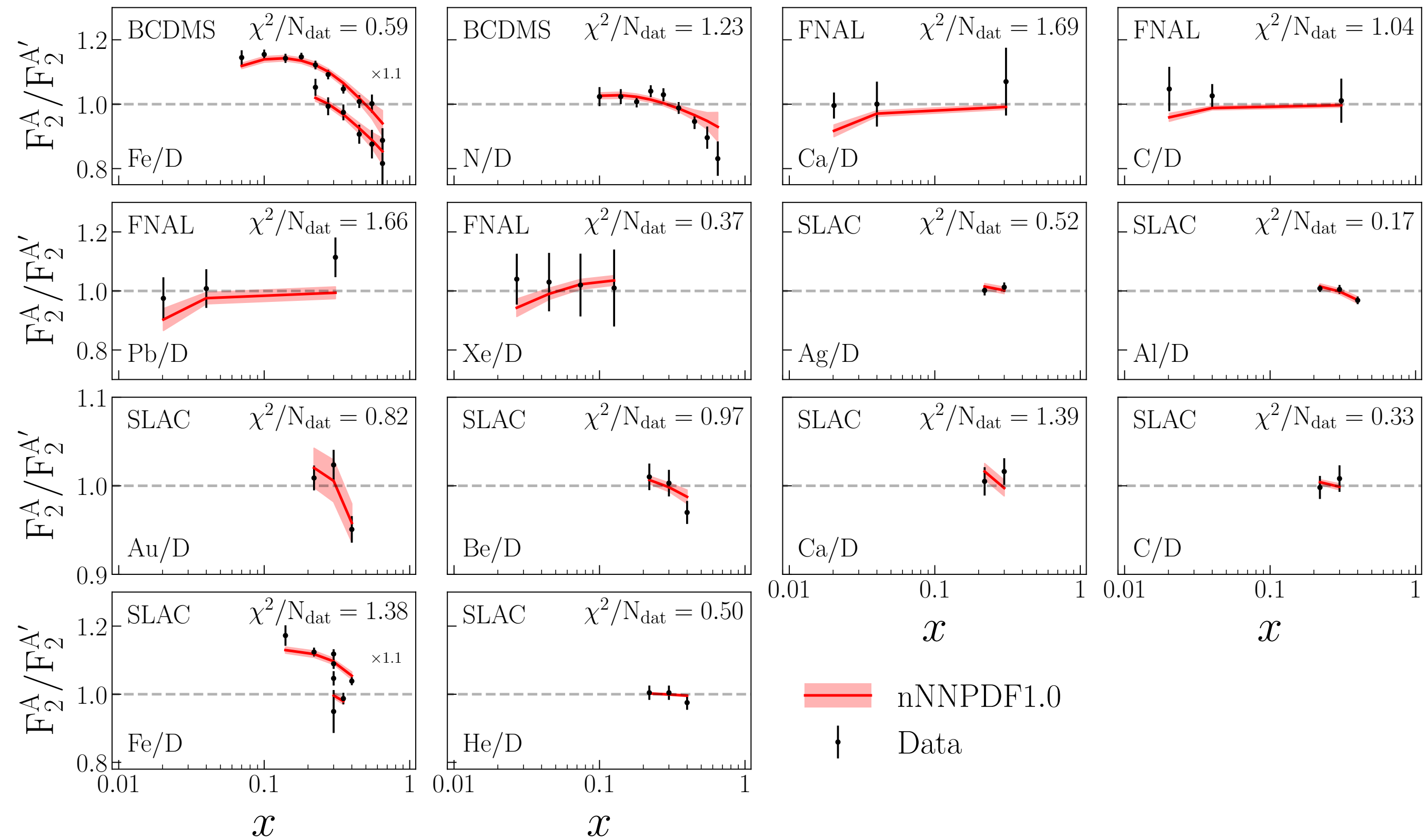
Here instead we will fit their values for each Monte Carlo replica, so that they are treated simultaneously with the weights and thresholds of the neural network.



$$\alpha_f \in [-5, 1], \quad \beta_f \in [0, 10], \quad f = \Sigma, T_8, g.$$

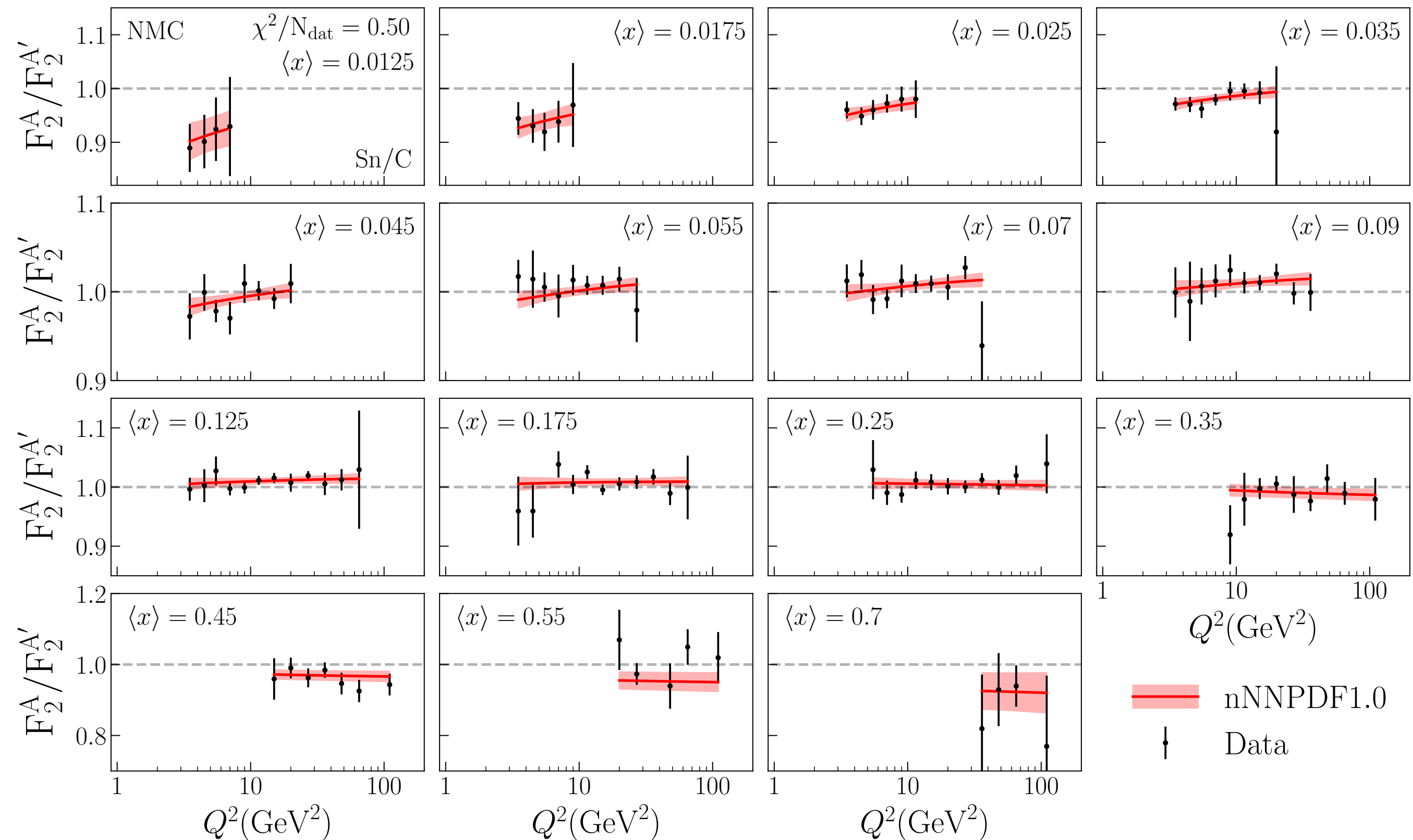
Data vs. Theory

BCDMS - FNAL - SLAC

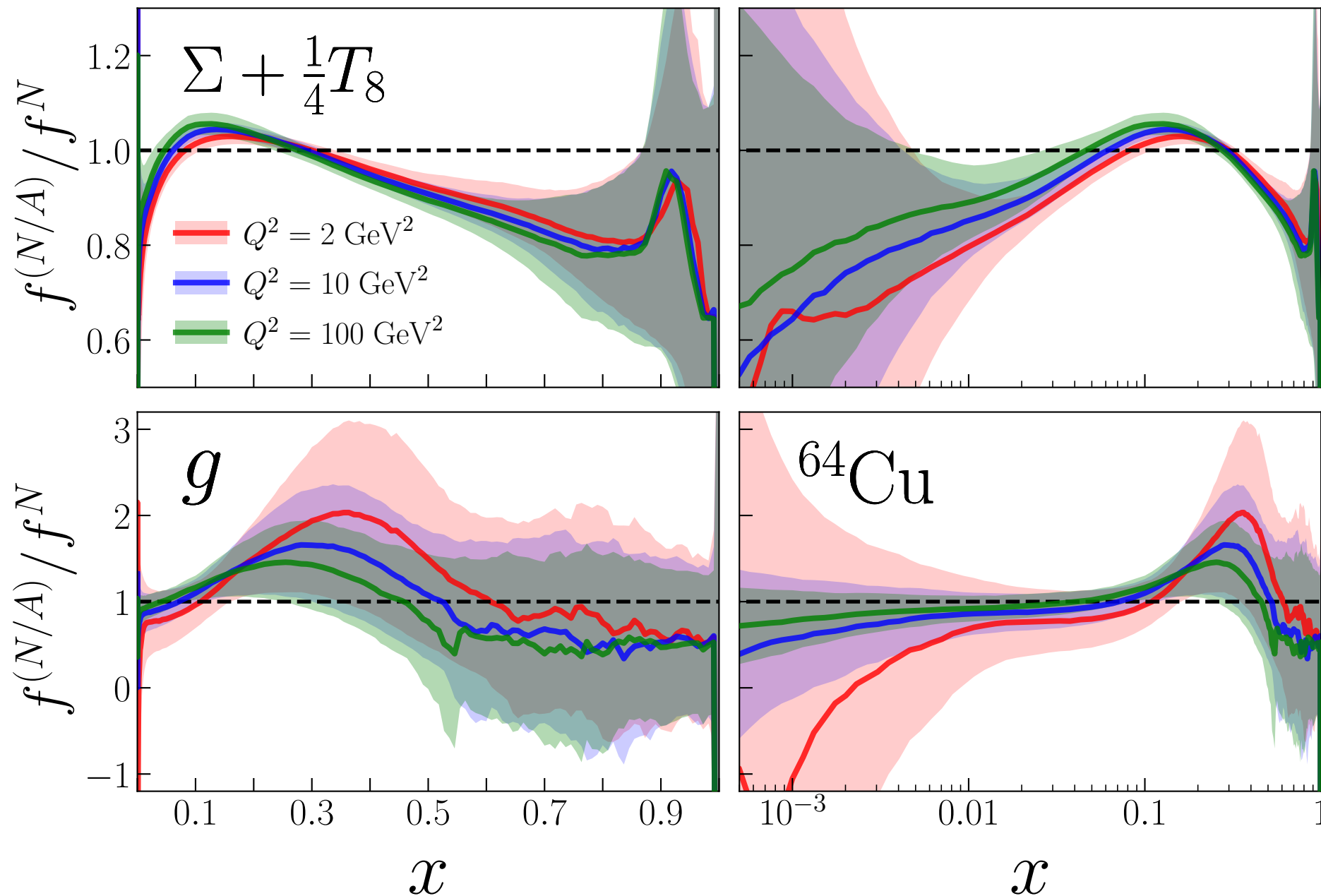


Data vs. Theory

NMC



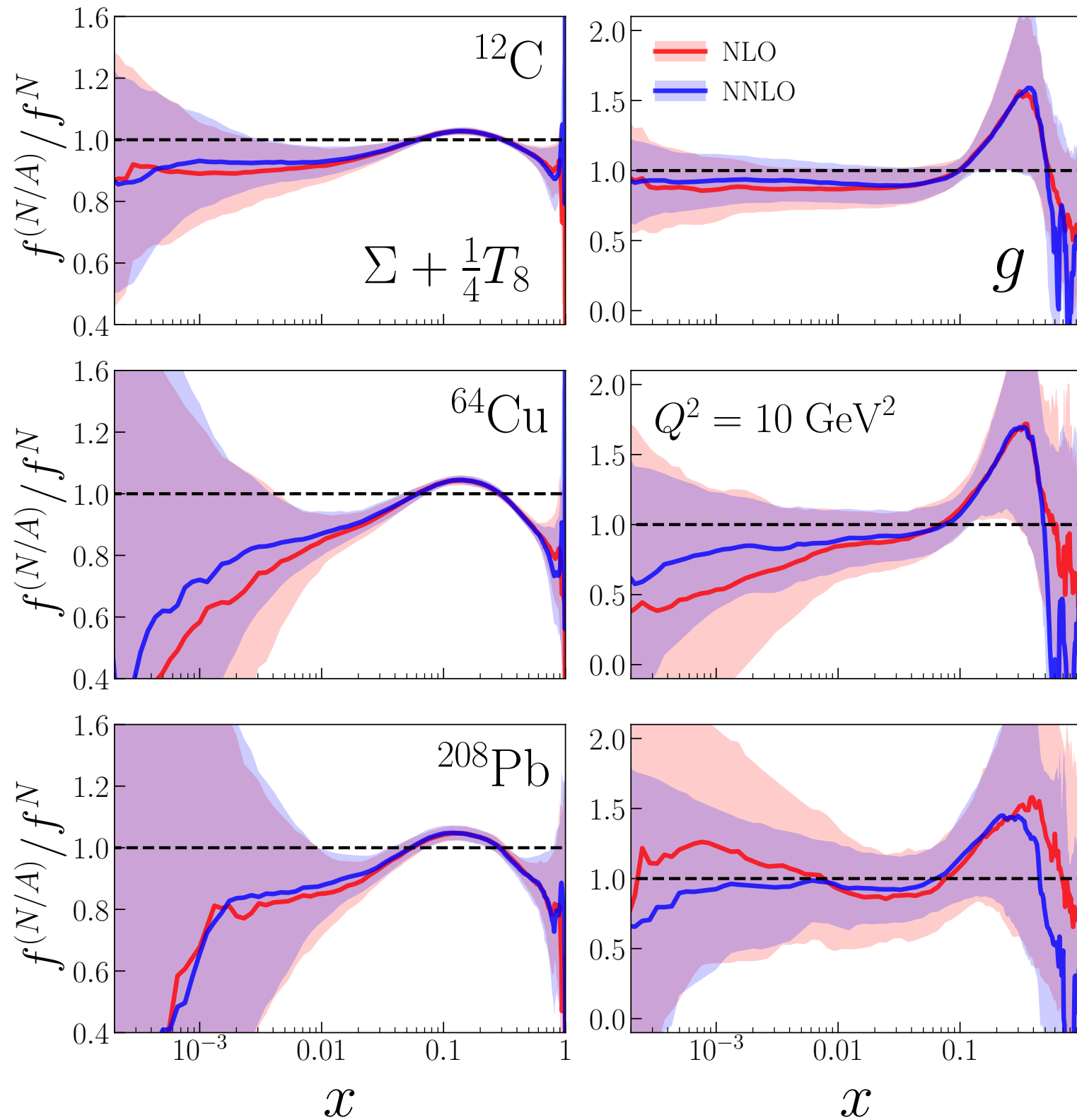
Q² dependence



The sensitivity to nuclear modifications is reduced when going from low to high Q^2 in the small- x region

Large reduction in the gluon uncertainty at small- x due to DGLAP

NLO vs NNLO



**Difference pronounced
at large- and small- x**

**Reduction in uncertainty
in NNLO**

Parametrisation

nCTEQ15 [1509.00792]

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4 x})^{c_5},$$

for $i = u_v, d_v, g, \bar{u} + \bar{d}, s + \bar{s}, s - \bar{s},$

$$\frac{\bar{d}(x, Q_0)}{\bar{u}(x, Q_0)} = c_0 x^{c_1} (1-x)^{c_2} + (1 + c_3 x)(1-x)^{c_4}.$$

$$c_k \rightarrow c_k(A) \equiv c_{k,0} + c_{k,1} (1 - A^{-c_{k,2}}),$$

$$k = \{1, \dots, 5\}.$$

EPPS16 [1612.05741]

$$f_i^{p/A}(x, Q^2) = \underline{R_i^A}(x, Q^2) f_i^p(x, Q^2)$$

$$R_i^A(x, Q_0^2) = \begin{cases} a_0 + a_1(x - x_a)^2 & x \leq x_a \\ b_0 + b_1 x^\alpha + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a \leq x \leq x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \leq x \leq 1, \end{cases}$$

nNNPDF1.0 [1904.00018]

$$xg(x, Q_0, A) = B_g x^{-\alpha_g} (1-x)^{\beta_g} \xi_3^{(3)}(x, A),$$

$$x\Sigma(x, Q_0, A) = x^{-\alpha_\Sigma} (1-x)^{\beta_\Sigma} \xi_1^{(3)}(x, A),$$

$$xT_8(x, Q_0, A) = x^{-\alpha_{T_8}} (1-x)^{\beta_{T_8}} \xi_2^{(3)}(x, A)$$