An update on nuclear PDFs

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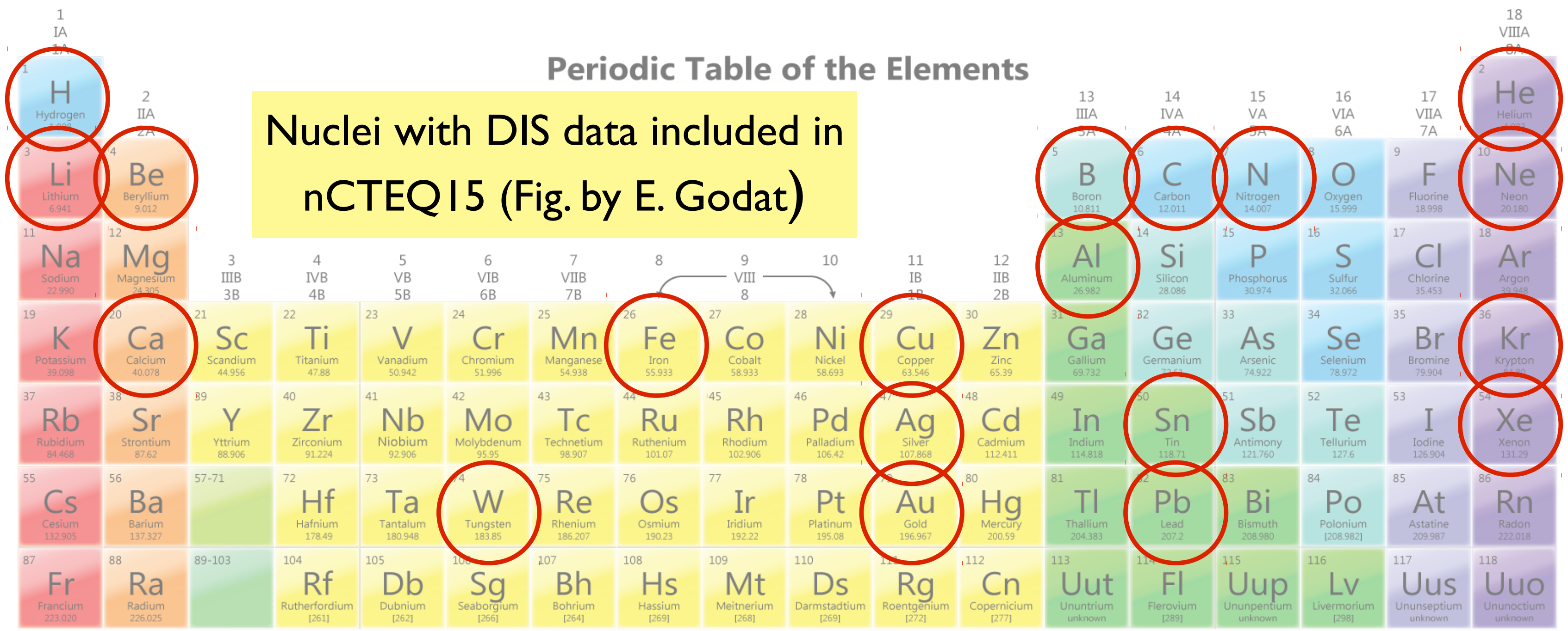
Plan

- Introduction/Motivation
- Global analyses of nuclear PDFs
  - Updates from EPPS
  - Updates from nCTEQ
  - Updates from nNNPDF
- Conclusions

Introduction/Motivation

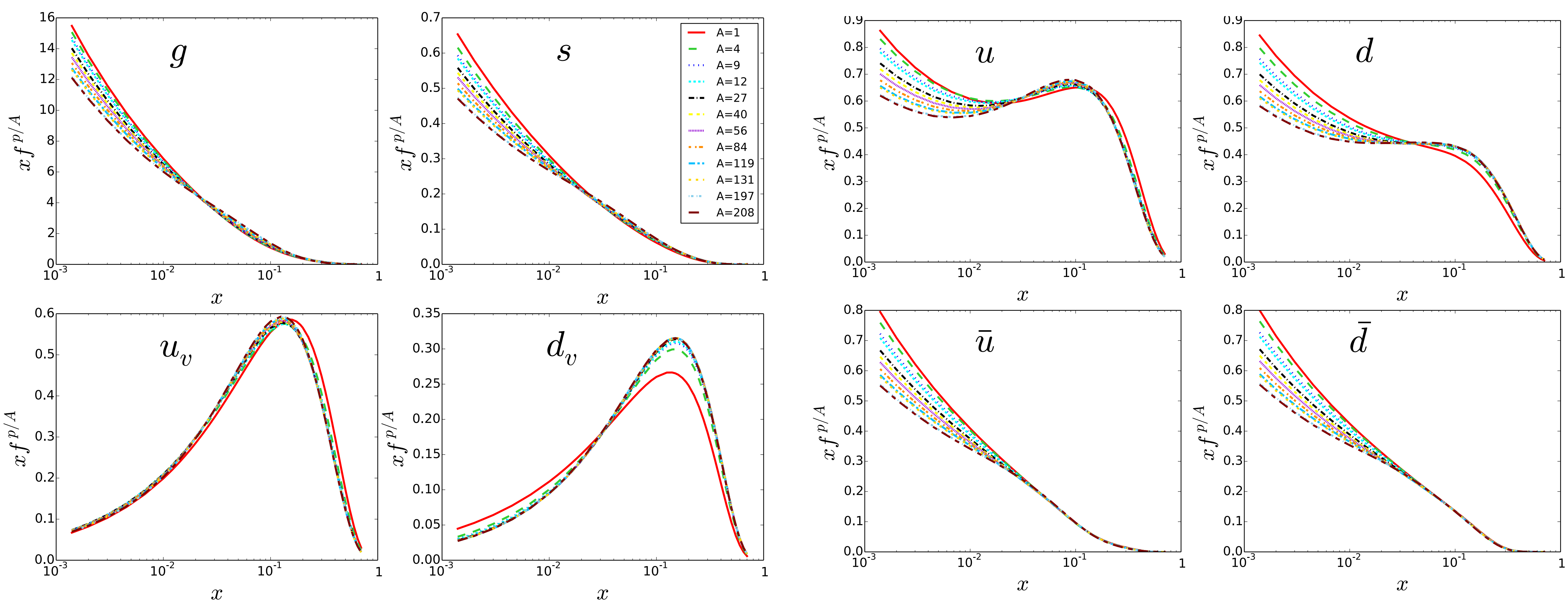
Nuclear PDFs



- Fundamental quest:
  - Hadron Structure: x,Q,A dependence
  - Nuclear modifications
- Necessary tool:
  - Cross sections for hard processes in lA, νA, pA, AA
  - Fixed target, colliders, atmosphere

nCTEQ15, arXiv:1509.00792

$$x f_i^{p/A}(x, Q_0) = x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5} \qquad c_k(A) = c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right)$$



Theoretical Framework (pQCD formalism)

Collinear Factorization Theorems:

- Provide (field theoretical) **definitions** of the **universal** PDFs
- Make the formalism **predictive**!
- Make a statement about the **error** of the factorization formula

PDFs and predictions for **observables+uncertainties** **refer to this standard pQCD framework**

Need a solid understanding of the standard framework!

- For pp and ep collisions there a **rigorous factorization proofs**
- For pA and AA factorization is a **working assumption** to be tested phenomenologically

  There might be breaking of collinear factorization, deviations from DGLAP evolution, other nuclear matter effects to be included (higher twist)

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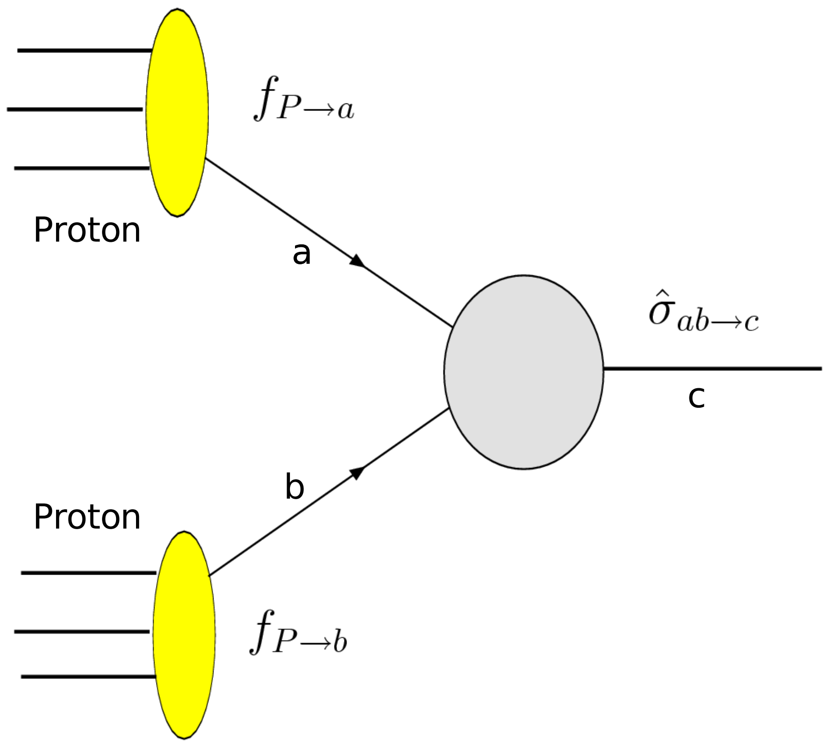
Example: Factorization for pp collisions



$$\sigma = f_{P\to a} \otimes f_{P\to b} \otimes \hat{\sigma}_{ab\to c}$$

From experiment

Calculable from theoretical model

Parton Distribution Functions (PDFs) $f_{P\to a,b}(x,\mu^2)$

- Universal
- Describe the structure of hadrons
- Obey DGLAP evolution equations

The hard part $\hat{\sigma}_{ab\to c}(\mu^2)$

- Free of short distance scales
- Calculable in perturbation theory
- Depends on the process

- Similar factorisation formulae for **inclusive lA, nuA** processes and **one-particle inclusive processes** (involving also fragmentation functions)

Predictive Power

Universality: same PDFs/FFs enter different processes:

- DIS: $$F_2^A(x,Q^2) = \sum_i \left[f_i^A \otimes C_{2,i}\right](x,Q^2)$$
- DY: $$\sigma_{A+B\to\ell^+ +\ell^- +X} = \sum_{i,j} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j\to\ell^+ +\ell^- +X}$$
- A+B -> H + X: $$\sigma_{A+B\to H+X} = \sum_{i,j,k} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j\to k+X} \otimes D_k^H$$

- Predictions for unexplored kinematic regions and for your favorite new physics process

Flavor separation of PDFs

NC charged lepton DIS: 2 structure functions (γ-exchange)

$$F_2^\gamma(x) \sim \frac{1}{9}[4(u+\bar{u}+c+\bar{c})+d+\bar{d}+s+\bar{s}](x)$$

$$F_2^\gamma(x) = 2xF_1^\gamma(x)$$

CC Neutrino DIS: 6 additional structure functions $F_{1,2,3}^{W+}$, $F_{1,2,3}^{W-}$

$$F_2^{W^+} \sim [d+s+\bar{u}+\bar{c}] \qquad F_3^{W^+} \sim 2[d+s-\bar{u}-\bar{c}]$$

$$F_2^{W^-} \sim [\bar{d}+\bar{s}+u+c] \qquad F_3^{W^-} \sim 2[u+c-\bar{d}-\bar{s}]$$

Useful/needed to disentangle different quark parton flavors in a **global analysis** of proton or nuclear PDFs

Scale dependence predicted by QCD

- x-**dependence** of PDFs is NOT calculable in pQCD
- μ^2-**dependence** is calculable in pQCD – given by **DGLAP** (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) evolution equations

DGLAP evolution equations

$$\frac{df_q(x,\mu^2)}{d\log\mu^2} = \frac{\alpha_S(\mu^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qq}\left(\frac{x}{y}\right)f_q(y,\mu^2) + P_{qg}\left(\frac{x}{y}\right)f_g(y,\mu^2)\right]$$

$$\frac{df_g(x,\mu^2)}{d\log\mu^2} = \frac{\alpha_S(\mu^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{gg}\left(\frac{x}{y}\right)f_g(y,\mu^2) + P_{gq}\left(\frac{x}{y}\right)f_q(y,\mu^2)\right]$$

- Different PDFs mix – set of $(2n_f + 1)$ coupled integro-differential equations.

- Need boundary conditions $\mathbf{f_i(x,Q_0)}$ at some perturbative initial scale $\mathbf{Q_0 \gtrsim 1}$ **GeV**
- The **x-dependence** is not calculable in pQCD, perform **global analysis** of **experimental data** **[EPPS, nCTEQ, nNNPDF, ...]**
- Progress on the **lattice**: see **arXiv:1711.07916, 2006.08636**

Sum rules provide constraints

- **Number sum rules** – connect partons to quarks from SU(3) flavour symmetry of hadrons; proton (uud), neutron (udd). For protons:

For all scales:

$$\int_0^1 dx \underbrace{[f_u(x) - f_{\bar{u}}(x)]}_{u-\text{valence distr.}} = 2 \qquad \int_0^1 dx \underbrace{[f_d(x) - f_{\bar{d}}(x)]}_{d-\text{valence distr.}} = 1$$

$$\int_0^1 dx [f_s(x) - f_{\bar{s}}(x)] = \int_0^1 dx [f_c(x) - f_{\bar{c}}(x)] = 0$$

- **Momentum sum rule** – momentum conservation connecting all flavours

For all scales:

$$\sum_{i=q,\bar{q},g} \int_0^1 dx \, x f_i(x) = 1$$

Momentum carried by up and down quarks is only around half of the total proton momentum the rest of the momentum is carried by gluons and small amount by sea quarks. In case of CT14NLO PDFs ($\mu = 1.3$ GeV):

At 1.3 GeV:

$$\int_0^1 dx \, x [f_u(x) + f_d(x)] \simeq 0.51$$

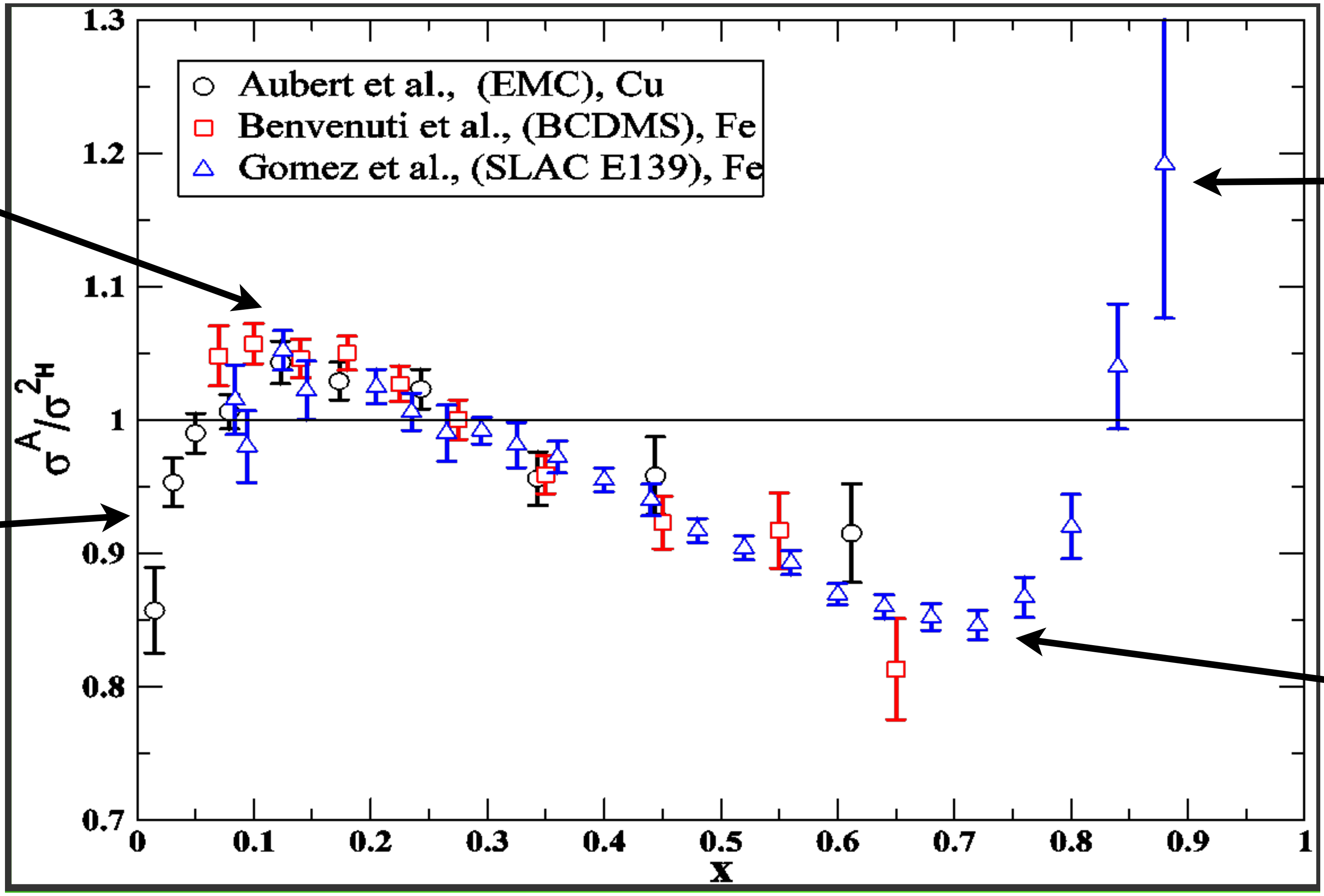
$$\int_0^1 dx \, x f_g(x) \simeq 0.40$$

Nuclear modifications

$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$

Anti-shadowing enhancement

Shadowing suppression at small x



Rise due to Fermi motion

EMC effect

- Nuclear modifications can be incorporated/parameterized inside nPDFs but underlying dynamics remains to be fully theoretically understood

Global analyses of nuclear PDFs

Global analysis of nuclear PDFs

Same approach as for proton PDF determinations

1. Boundary conditions:
   Parameterize x-dependence of PDFs at initial scale Q_0

$$f(x,Q_0)=A_0 x^{A_1}(1-x)^{A_2} P(x;A_3,\ldots);\ f=u_v, d_v, g, \bar{u}, \bar{d}, s, \bar{s}$$

2. Evolve from Q_0 to Q solving the DGLAP evolution equations: $f(x,Q)$

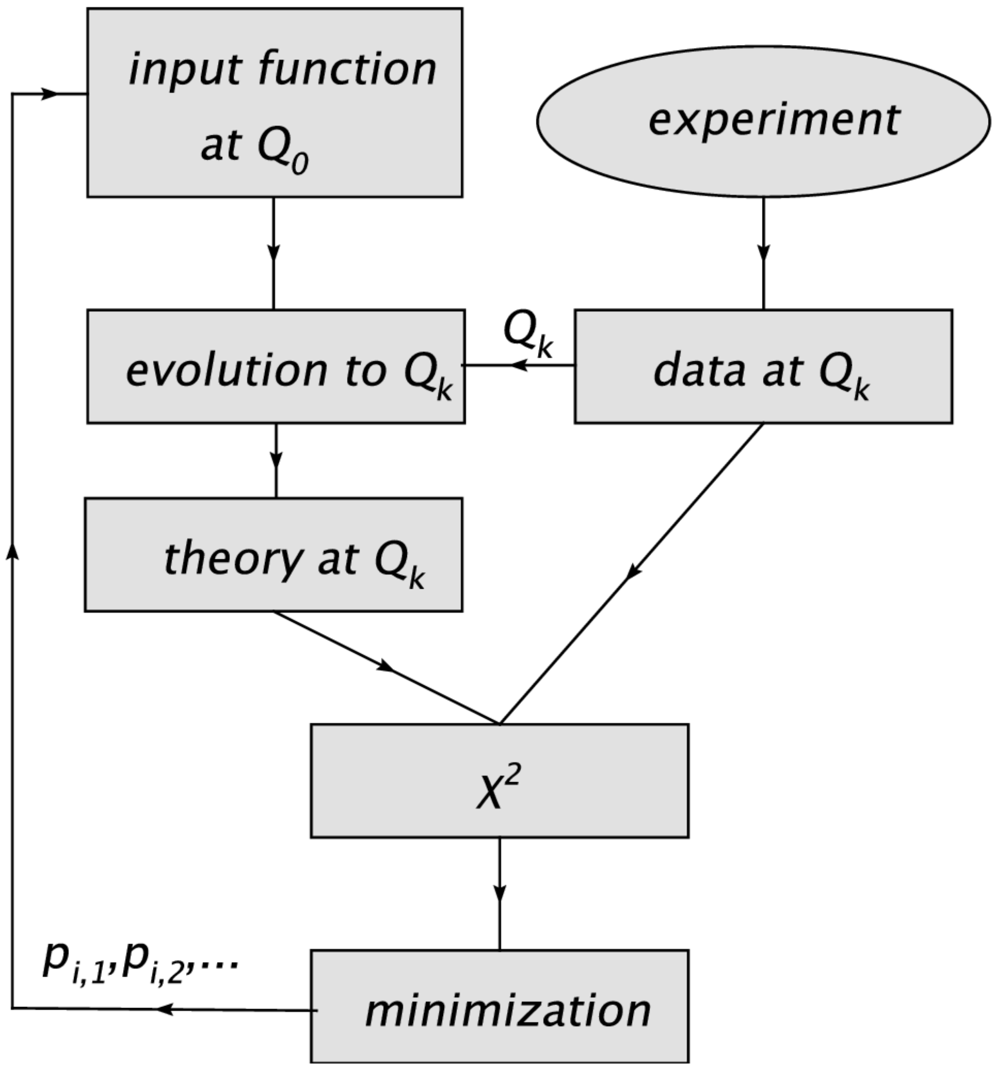
3. Define suitable χ^2 function and minimize w.r.t. fit parameters

$$\chi^2_{global}[A_i]=\sum_n w_n \chi^2_n;\ \chi^2_n=\sum_I \left(\frac{D_{nI}-T_{nI}}{\sigma_{nI}}\right)^2$$

Sum over experiments

Sum over data points

weights: default=1, allows to emphasize certain data sets



nPDFs ca. 2017

	nNNPDF1.0 EPJC79(2019471	EPPS16 EPJC77(2017)163	nCTEQ15 PRD93(2016)085037	KA15 PRD93(2016)014036	DSSZ12 PRD85(2012)074028	EPS09 JHEP0904(2009)065
lA DIS	✔	✔	✔	✔	✔	✔
DY in p+A	✘	✔	✔	✔	✔	✔
RHIC π d+Au	✘	✔	✔	✘	✔	✔
νA DIS	✘	✔	✘	✘	✔	✘
DY in π+A	✘	✔	✘	✘	✘	✘
LHC p+Pb dijets	✘	✔	✘	✘	✘	✘
LHC p+Pb W,Z	✘	✔	✘	✘	✘	✘

Order in α_s	NNLO	NLO	NLO	NNLO	NLO	NLO
Q-cut in DIS	**1.87 GeV**	1.3 GeV	**2 GeV**	1 GeV	1 GeV	1.3 GeV
W-cut	**3.53 GeV**	-	**3.5 GeV**	-	-	-
Data points	451	1811	708	1479	1579	929
Free parameters	Neural Net	20	16	16	25	15
Error tolerance	MC replica	52	35	N.N.	30	50
Proton baseline	NNPDF3.1	CT14NLO	~CTEQ6.1	JR09	MSTW08	CTEQ6.1
Mass scheme	FONLL-B	GM-VFNS	GM-VFNS	ZM-VFNS	GM-VFNS	ZM-VFNS
Flavour sep.	-	val.+sea	valence	-	-	-

Global analyses of nPDFs: 2022

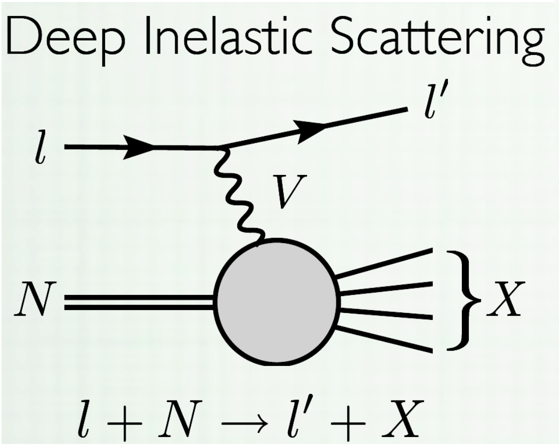
- **EPPS**
  - **EKS98:** hep-ph/9807297
  - **EKPS07:** hep-ph/0703104
  - **EPS08:** 0802.0139
  - **EPS09:** 0902.4154
  - **EPPS16:** 1612.05741
  - **EPPS21:** 2112.12462
- **nCTEQ**
  - **nCTEQ09:** 0907.2357
  - **nCTEQ15:** 1509.00792
  - **nCTEQ15WZ:** 2007.09100
  - **nCTEQ15HiX:** 2012.11566
  - **nCTEQ15WZSIH:** 2105.09873
  - **nCTEQ15HQ:** 2204.09982
  - **nCTEQ15WZSIHdeut:** 2204.13157
  - **BaseDimuChorus:** 2204.13157
- **nNNPDF**
  - **nNNPDF1.0:** 1904.00018
  - **nNNPDF2.0:** 2006.14629
  - **nNNPDF3.0:** 2201.12363
- **TUJU (open source XFitter, fit of proton baseline)**
  - **TUJU19:** 1908.03355
  - **TUJU21:** 2112.11904
- **KA**
  - **KA15:** 1601.00939
  - **KSASG20:** 2010.00555
- **nDS**
  - **nDS03:** hep-ph/0311227
  - **DSSZ12:** 1112.6324
- **HKM/HKN**
  - **HKM01:** hep-ph/0103208
  - **HKN04:** hep-ph/0404093
  - **HKN07:** 0709.3038

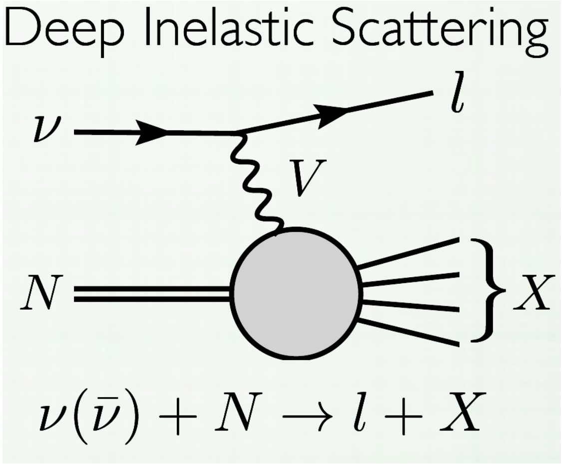
Similarities and Differences

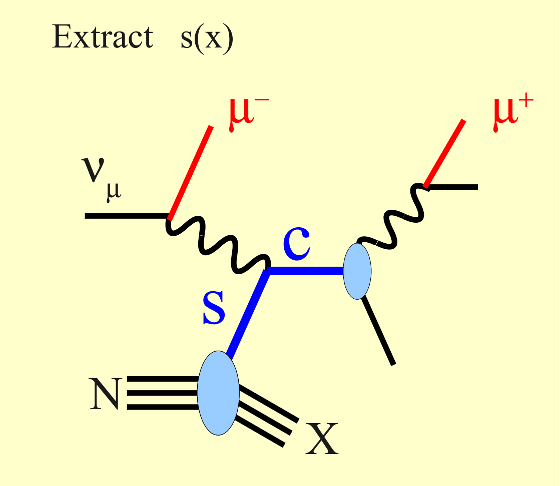
- **Similarities**
  - All use the **same twist-2 pQCD formalism based on collinear factorisation**: DGLAP evolution, sum rules, pQCD observables, χ^2 minimisation
  - Isospin symmetry, region x>1 is neglected in all analyses
- **Main differences**
  - **Parametrisation** of the boundary conditions at the initial scale Q_0: different functional forms or neural network
  - **Choice of analysed data**: which processes, kinematic cuts, treatment of correlations, normalisation uncertainties
  - **Analysis of PDF errors**: MC replica, Hessian error analysis, Tolerance criterion for 90% CL
- **Other differences**
  - parameters $Q_0, m_c, m_b, \alpha_s(M_Z)$, heavy flavour scheme, perturbative order (NLO, NNLO)
  - Deuteron corrections, Target mass corrections, Higher twist contributions

Used data sets I

- **IA DIS:** backbone of all global analyses
  - Data from SLAC, NMC, EMC, BCDMS, FNAL: all groups (**but different cuts**)
  - Data from JLAB (CLAS, Hall-C): nCTEQ15HiX, EPPS2, KSASG20
- **nuA DIS:** quark flavour separation, strange PDF
  - CHORUS nu-Pb data: DSSZ12, EPPS16, EPPS21, nNNPDF2.0, nNNPDF3.0, BaseDimuCHORUS, KSASG20, TUJU19, TUJU21
  - NuTeV, CCFR, CDHSW nu-Fe data: Tensions (see 2204.13157), used by KSASG20, TUJU19, TUJU21
- **nuA SIDIS charm production** (dimuon data): strange PDF
  - NuTeV, CCFR nu-Fe: nNNPDF2.0, BaseDimuCHORUS

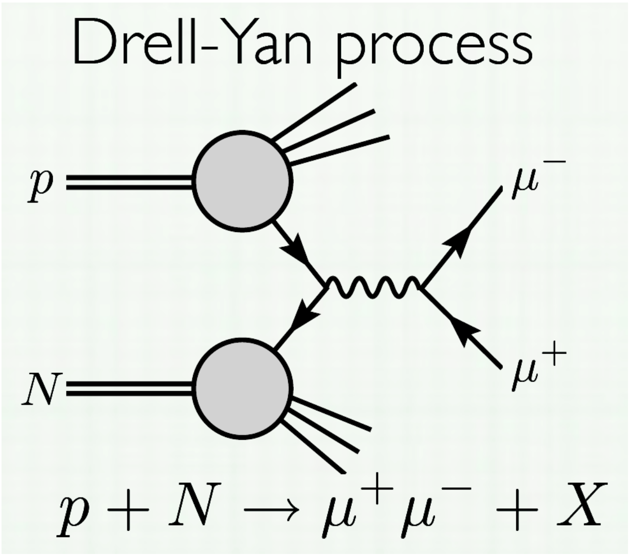


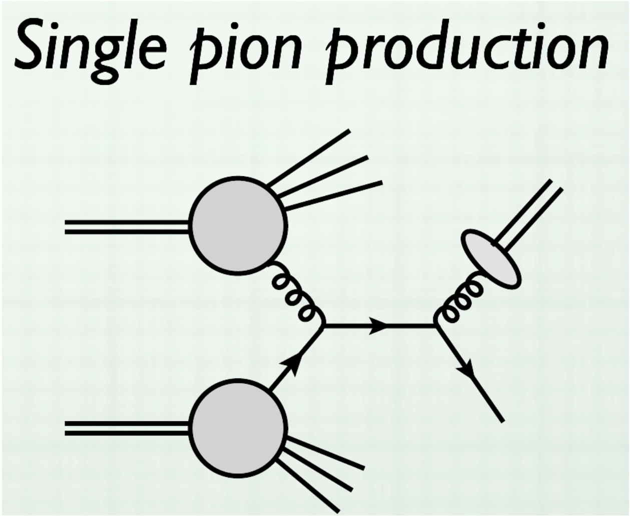




Used data sets II

- **pA DY:** disentangle valence and sea quarks
  - E772, E866 data: EPPS16, EPPS21,, nCTEQ15X, KA15, KSASG20, DSSZ12, nNNPDF3.0
  - π-A DY data: EPPS16, EPPS21
- **SIH data**: gluon distribution (weaker impact compared to HQ and dijet data)
  - RHIC single hadron production: EPPS16, EPPS21, nCTEQ15X (but nCTEQ15HIX)
  - LHC single hadron production: nCTEQ15SIH, nCTEQ16WZSIH, nCTEQ15HQ,nCETQ15SIHdeut
- **LHC W, Z production:** gluon, strange distribution
  - CMS, ATLAS (ALICE, LHCb) Run I (5 TeV), CMS Run II (8 TeV): EPPS16, EPPS21, nCTEQ15WZ, nCTEQ15WZSIH, nCTEQ15WZSIHdeut, nNNPDF2.0, nNNPDF3.0, TUJU21





Used data sets III

- **LHC Heavy Quark data:** strong constraints on gluon at small-x
  - EPPS21 (D-mesons), nCTEQ15HQ (Heavy quarks and quarkonia, Crystal Ball fit), nNNPDF3.0 (D-mesons), Bayesian reweighting)
- **LHC dijet data**: strong constraint on gluon distribution in shadowing and anti-shadowing region (medium x, medium-small x)
  - CMS 5 TeV dijet p-Pb data: EPPS16, EPPS21, nNNPDF3.0
- **LHC prompt photon data:** gluon distribution (medium x, medium-small x) nNNPDF3.0

Updates from EPPS

EPPS21 [2121.12462]

- Bound proton PDF:

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

- Full nuclear PDF

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

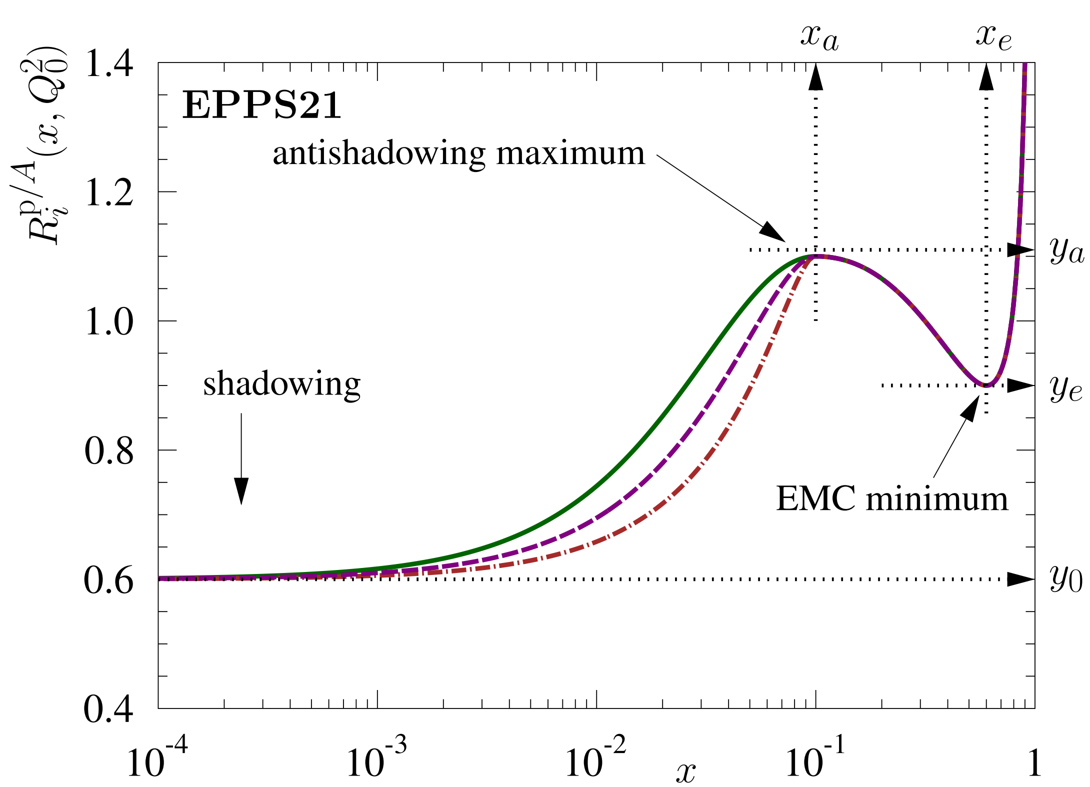
- $Q_0 = m_c = 1.3$ GeV
- Proton baseline: CT18ANLO
- $m_c = 1.3, m_b = 4.75, \alpha_s(Q)$ as in CT18ANLO
- Isospin symmetry

- Nuclear modification

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

- Parametrization is a piecewise defined function
- Some changes w.r.t. EPPS16
- Deuteron taken to be free
- 24 free parameters

$$R_i^A(x,Q_0^2) =$$
$$\begin{cases} a_0 + a_1 (x - x_a)\left[e^{-xa_2/x_a} - e^{-a_2}\right], & x \le x_a \\ b_0 x^{b_1} (1-x)^{b_2} e^{x b_3}, & x_a \le x \le x_e \\ c_0 + c_1 (c_2 - x)(1-x)^{-\beta}, & x_e \le x \le 1. \end{cases}$$



EPPS21: Details on Parametrization [2121.12462]

Table 1 Values of parameters that define the central EPPS21 nuclear PDFs at $Q_0^2 = 1.69\,\mathrm{GeV}^2$. The 24 parameters that were kept free in the fit are indicated in bold.

Parameter	u_V	d_V	$\bar{u}$
$y_0(A_{\mathrm{ref}})$	sum rule	sum rule	**0.870**
γ_{y_0}	sum rule	sum rule	**0.401**
a_2	0, fixed	0, fixed	0, fixed
x_a	**0.0577**	as u_V	**0.110**
x_e	**0.700**	as u_V	as u_V
$y_a(A_{\mathrm{ref}})$	**1.07**	**1.04**	**0.992**
γ_{y_a}	**0.221**	as u_V	0, as u_V
$y_e(A_{\mathrm{ref}})$	**0.877**	**0.968**	**0.956**
γ_{y_e}	**0.176**	as u_V	as u_V
c_0	1.8, fixed	1.8, fixed	1.8, fixed
β	**2.20**	as u_V	1.3, fixed
f_3	**0.291**	as u_V	as u_V
f_6	**0.495**	as u_V	as u_V

Parameter	$\bar{d}$	s	g
$y_0(A_{\mathrm{ref}})$	**0.921**	**0.403**	sum rule
γ_{y_0}	as $\bar{u}$	as $\bar{u}$	sum rule
a_2	0, fixed	0, fixed	**3.66**
x_a	as $\bar{u}$	as $\bar{u}$	**0.0975**
x_e	as u_V	as u_V	as u_V
$y_a(A_{\mathrm{ref}})$	**0.971**	**1.09**	**1.10**
γ_{y_a}	u_V	u_V	as u_V
$y_e(A_{\mathrm{ref}})$	as $\bar{u}$	as $\bar{u}$	**0.852**
γ_{y_e}	as u_V	as u_V	as u_V
c_0	1.8, fixed	1.8, fixed	1.8, fixed
β	1.3, fixed	1.3, fixed	1.3, fixed
f_3	as u_V	as u_V	as u_V
f_6	as u_V	as u_V	as u_V

- Parametrization is a piecewise defined function
- Some changes w.r.t. EPPS16

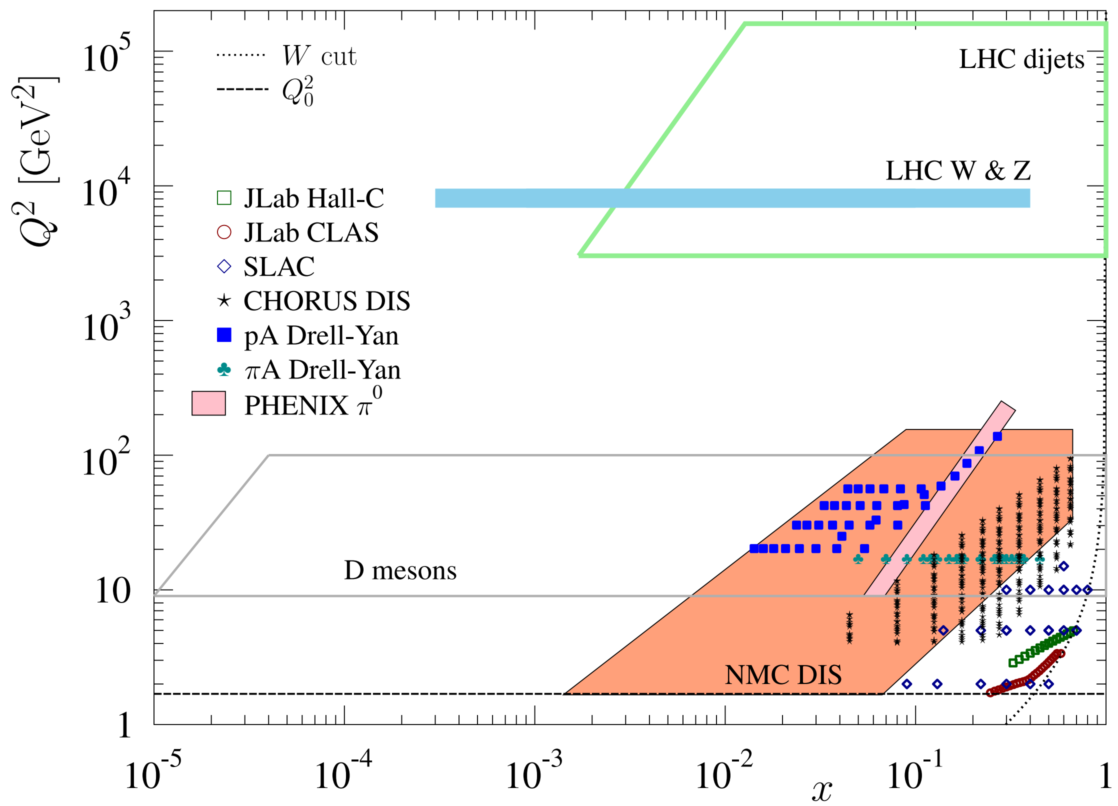
$$R_i^A(x, Q_0^2) = \begin{cases} a_0 + a_1 (x - x_a) \left[e^{-x a_2/x_a} - e^{-a_2} \right], & x \le x_a \\ b_0 x^{b_1} (1-x)^{b_2} e^{x b_3}, & x_a \le x \le x_e \\ c_0 + c_1 (c_2 - x)(1-x)^{-\beta}, & x_e \le x \le 1. \end{cases}$$

- Params: $a_0, a_1, a_2, b_0, b_1, b_2, c_0, c_1, c_2, x_a, x_e, \beta$ (first derivatives zero at x_a, x_e: fixes 4 para)
- $a_i, b_, c_i = a_i, b_i, c_i[y_a, y_e, y_0]$;
- sum rules: $y_0^g, y_0^{u_v}, y_0^{d_v}$ fixed for each A
- A-dep: $y_i(A) = 1 + [y_i(A_{ref}) - 1](A/A_{ref})^{\gamma_i}$ with $A_{ref} = 12$
- Strange quarks: $\gamma_{y_0} \to \gamma_{y_0} y_0 \theta(1 - y_0)$
- Extra modification for Li-6 and He-3: parameters f_3, f_6; deuteron taken to be free

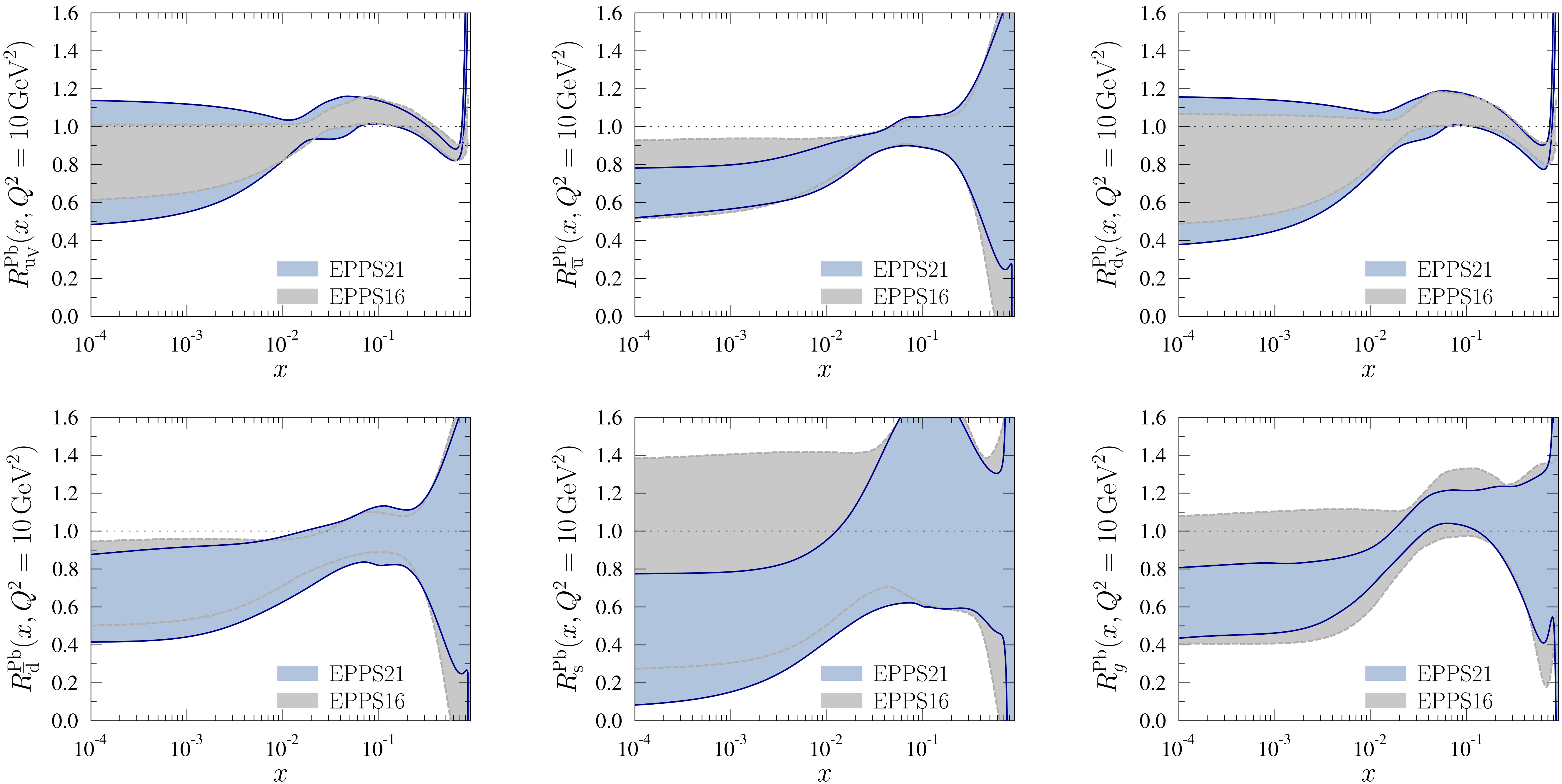
EPPS21 vs EPPS16

- more LHC p-Pb data
  - 5 TeV CMS dijet data from (run I)
  - 5 TeV LHCb D-meson data from (run I)
  - 8 TeV CMS $W^{\pm}$ data (run II)
- JLAB DIS data
- Uncertainties due to baseline proton PDF uncertainties
- EPPS16: no W-cut, EPPS21: W>1.8 GeV
- EPPS16: $\Delta\chi^2 \sim 50$, EPPS21: $\Delta\chi^2 \sim 33$
- EPPS16: 20 free parameters, EPPS21: 24 free parameters

EPPS21 data

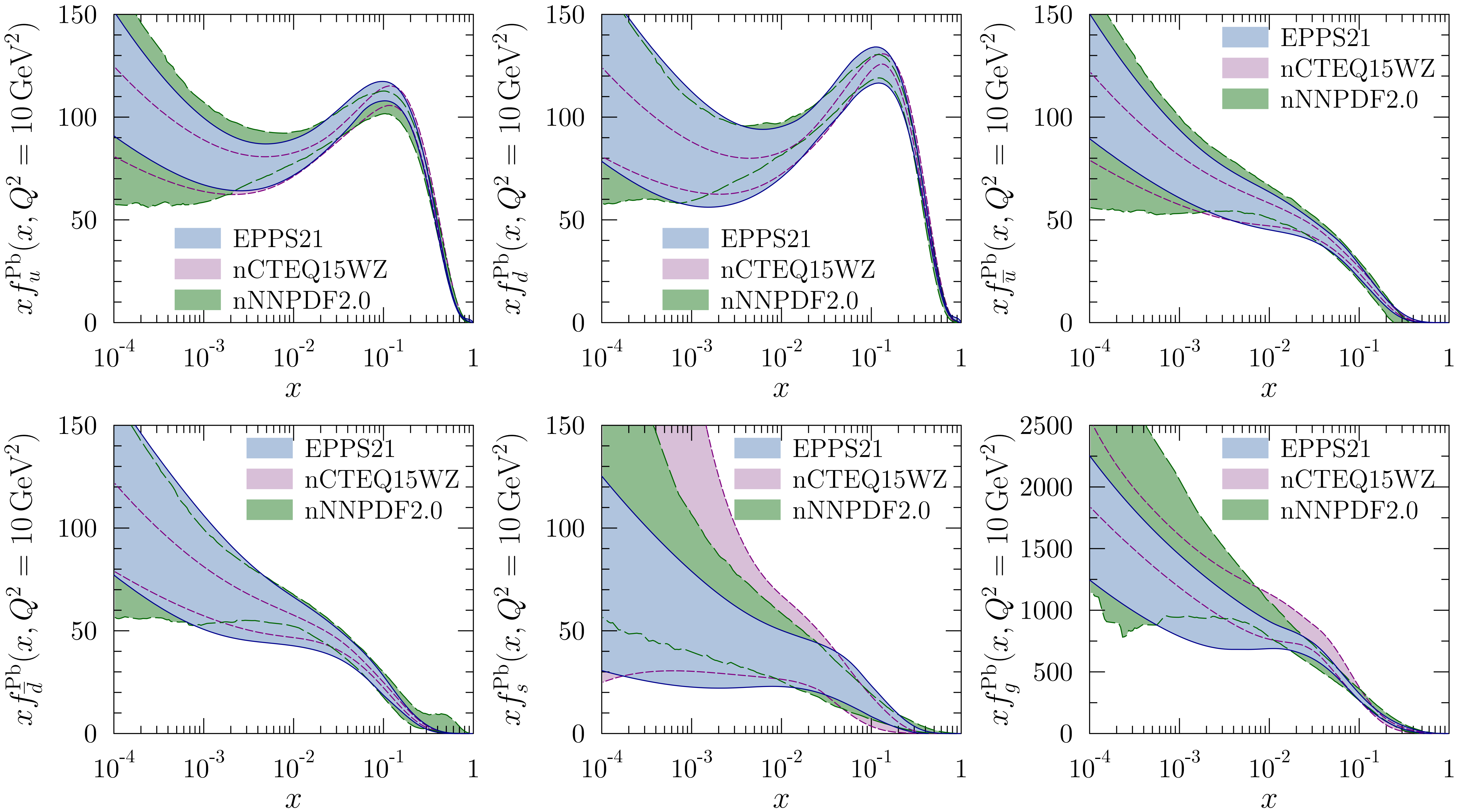


EPPS21 vs EPPS16



- Largest difference for strange quarks and gluons: much better constrained in EPPS21. Gluon due to D-meson and dijet data (gluon). Strange quark due to W,Z data and the more precise gluon.

EPPS21 vs nCTEQ15WZ and nNNPDF2.0



- General agreement within the shown 90% CL uncertainties
- $\bar{u}, \bar{d}$: nCTEQ no flavour separation; nNNPDF no DY fixed target data
- Strange quark uncertainty large in nCTEQ15WZ: no neutrino DIS data

Updates from nCTEQ

Towards the next nCTEQ global analysis

nCTEQ nuclear PDFs:

- **Preparation of next global release** (**nCTEQ2023**)
  - Performed detailed analysis of neutrino DIS data Next global analysis use (CHORUS+Dimuon data) **[2204.13157]**
  - LHC heavy quark data (gluon) **[2204.09982]**
  - Inclusive hadron production data (gluon) **[2105.09873]**
  - Explored lower W and Q-cuts using JLAB data **[2012.11566]**
  - LHC W/Z production data **[2007.09100]**
  - New review of Target Mass Corrections **[Nov/Dec 2022]**

nCTEQ15 framework

PRD93(2016)085037

- Functional form of the bound proton PDF same as for the free proton (CTEQ6M, x restricted to $0 < x < 1$)

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5}, \qquad i = u_v, d_v, g, \ldots$$
$$\bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} + (1 + c_3 x)(1-x)^{c_4}$$

- A-dependent fit parameters (reduces to free proton for $A = 1$)

$$c_k \to c_k(A) \equiv c_{k,0} + c_{k,1} \left(1 - A^{-c_{k,2}}\right), \quad k = \{1, \ldots, 5\}$$

- PDFs for nucleus (A, Z)

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

(bound neutron PDF $f_i^{n/A}$ by isospin symmetry)

nCTEQ15 data sets

PRD93(2016)085037

Fit properties:

- fit @NLO
- $Q_0 = 1.3\text{GeV}$
- using ACOT heavy quark scheme
- kinematic cuts:
  $Q > 2\text{GeV}$, $W > 3.5\text{GeV}$
  $p_T > 1.7$ GeV
- 708 (DIS & DY) + 32 (single π^0)
  = 740 data points after cuts
- 16+2 free parameters
  - 7 gluon
  - 7 valence
  - 2 sea
  - 2 pion data normalizations
- $\chi^2 = 587$, giving $\chi^2/\text{dof} = 0.81$

Error analysis:

- use Hessian method

$$\chi^2 = \chi_0^2 + \frac{1}{2} H_{ij}(a_i - a_i^0)(a_j - a_j^0)$$

$$H_{ij} = \frac{\partial^2 \chi^2}{\partial a_i \partial a_j}$$

- tolerance $\Delta\chi^2 = 35$ (every nuclear target within 90% C.L.)
- eigenvalues span 10 orders of magnitude → require numerical precision
- use noise reducing derivatives

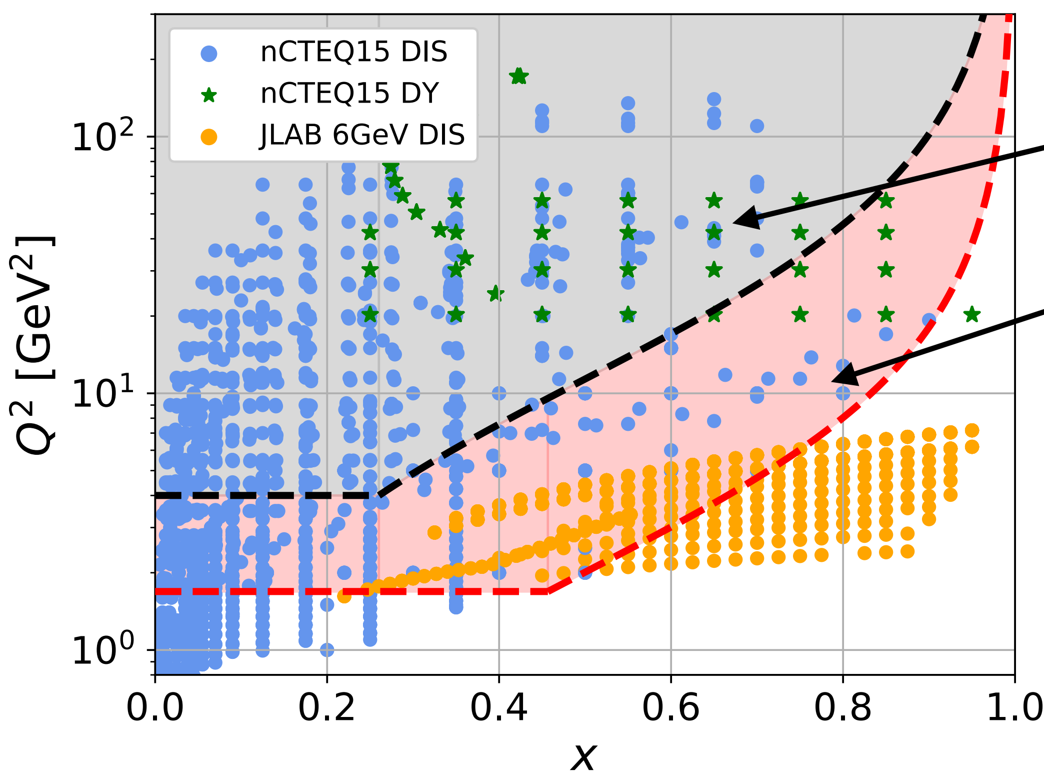
N = Au

N = Pb N = Fe

nCTEQHiX nPDFs with lower W-cut and JLAB data

DIS and DY data entering the analysis

arXiv:2012.11566



Standard cuts: Q>2 GeV, W>3.5 GeV

This analysis: Q>1.3 GeV, W> 1.7 GeV

Good fit $\chi^2/dof \sim 0.84$
Extension to even smaller W possible

Number of data depending on cuts

Q^2_{cut}	Q_{cut}	W_{cut} No Cut	W_{cut} 1.3	W_{cut} 1.7	W_{cut} 2.2	W_{cut} 3.5
1.3	$\sqrt{1.3}$	1906	1839	1697	1430	1109
1.69	1.3	1773	1706	1564	1307	1024
2	$\sqrt{2}$	1606	1539	1402	1161	943
4	2	1088	1042	952	817	708

Several effects included

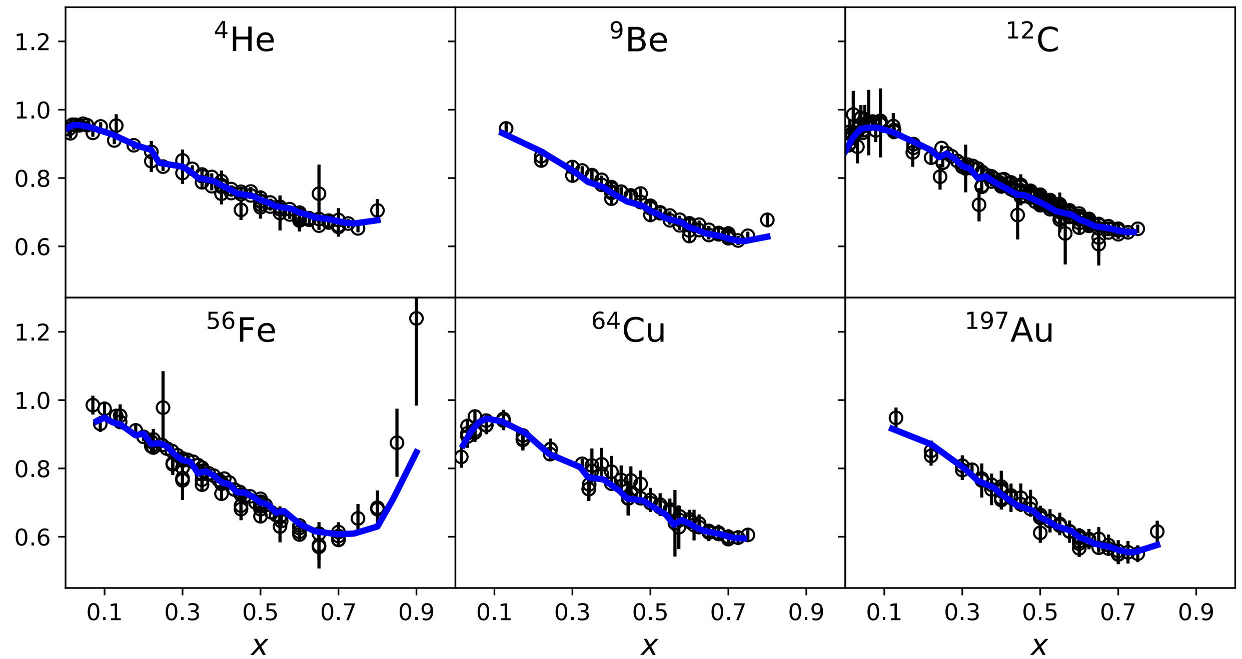
- **Higher Twist**
- **TMC**
- **Deuteron corrections**
- **Shape of the parametrisation at large x**

See also the reweighing analysis arXiv:2003.02195

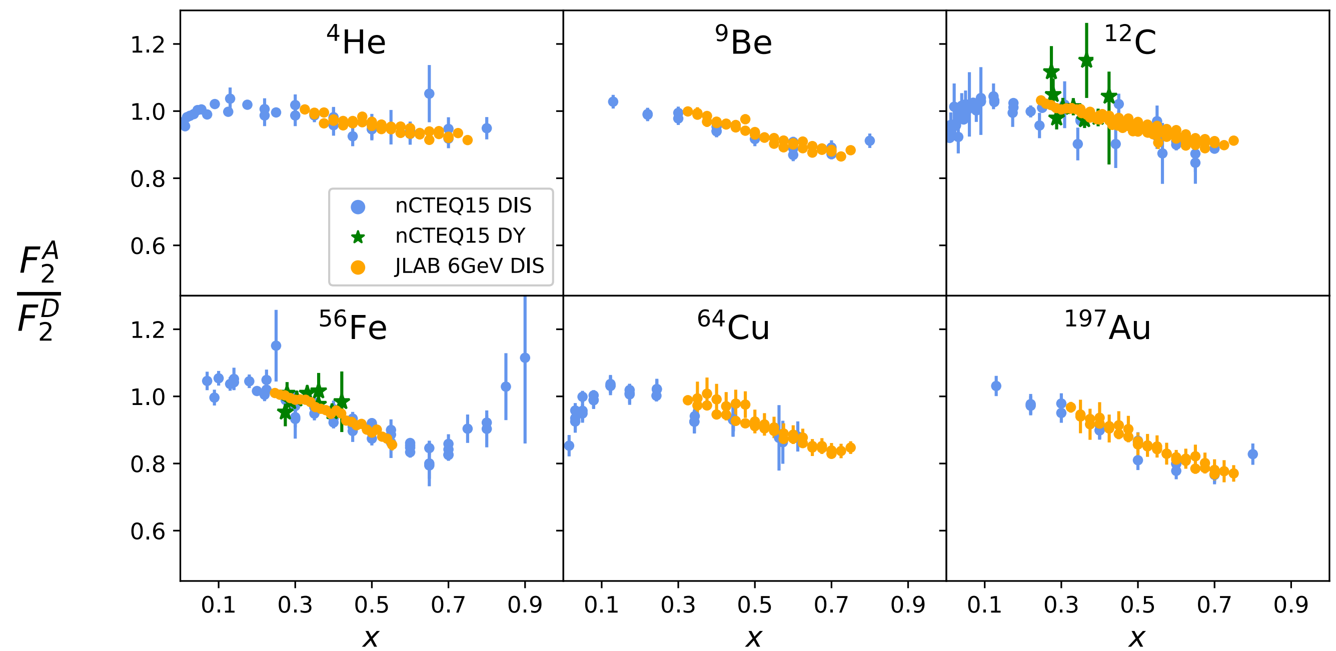
nCTEQHiX nPDFs with lower W-cut and JLAB data

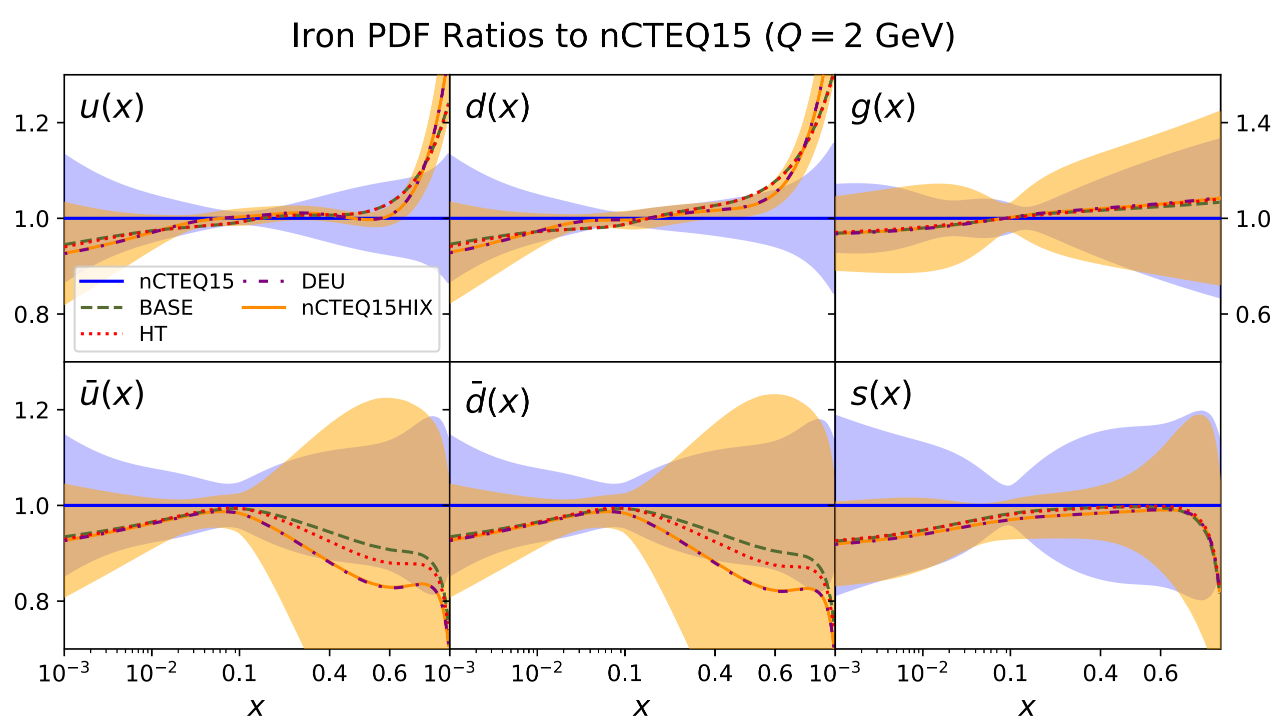
arXiv:2012.11566

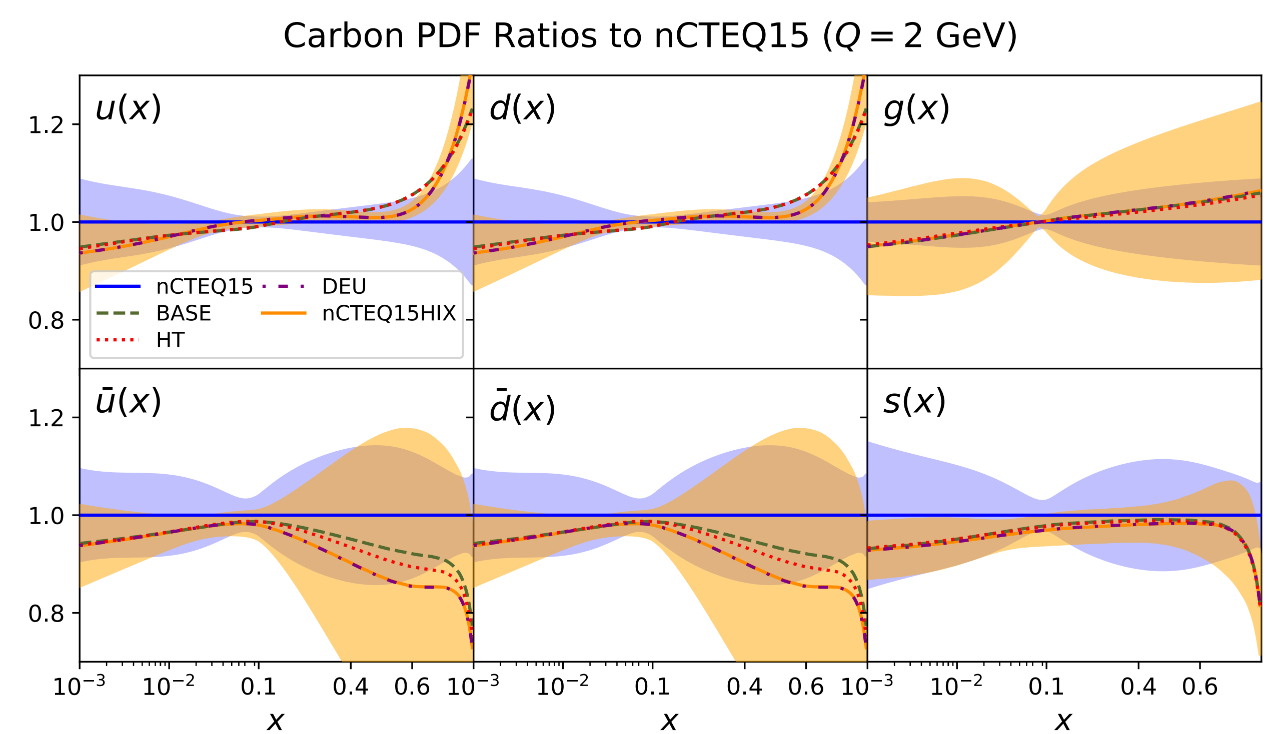
$(F_2^A/F_2^D)\times(F_2^D/F_2^p)_{CJ}$ vs data



Selected data







- u, d, g increased at large x; sea quarks $\bar{u}, \bar{d}, s = \bar{s}$ are suppressed at large x

nCTEQHQ nPDFs

arXiv:2204.09982

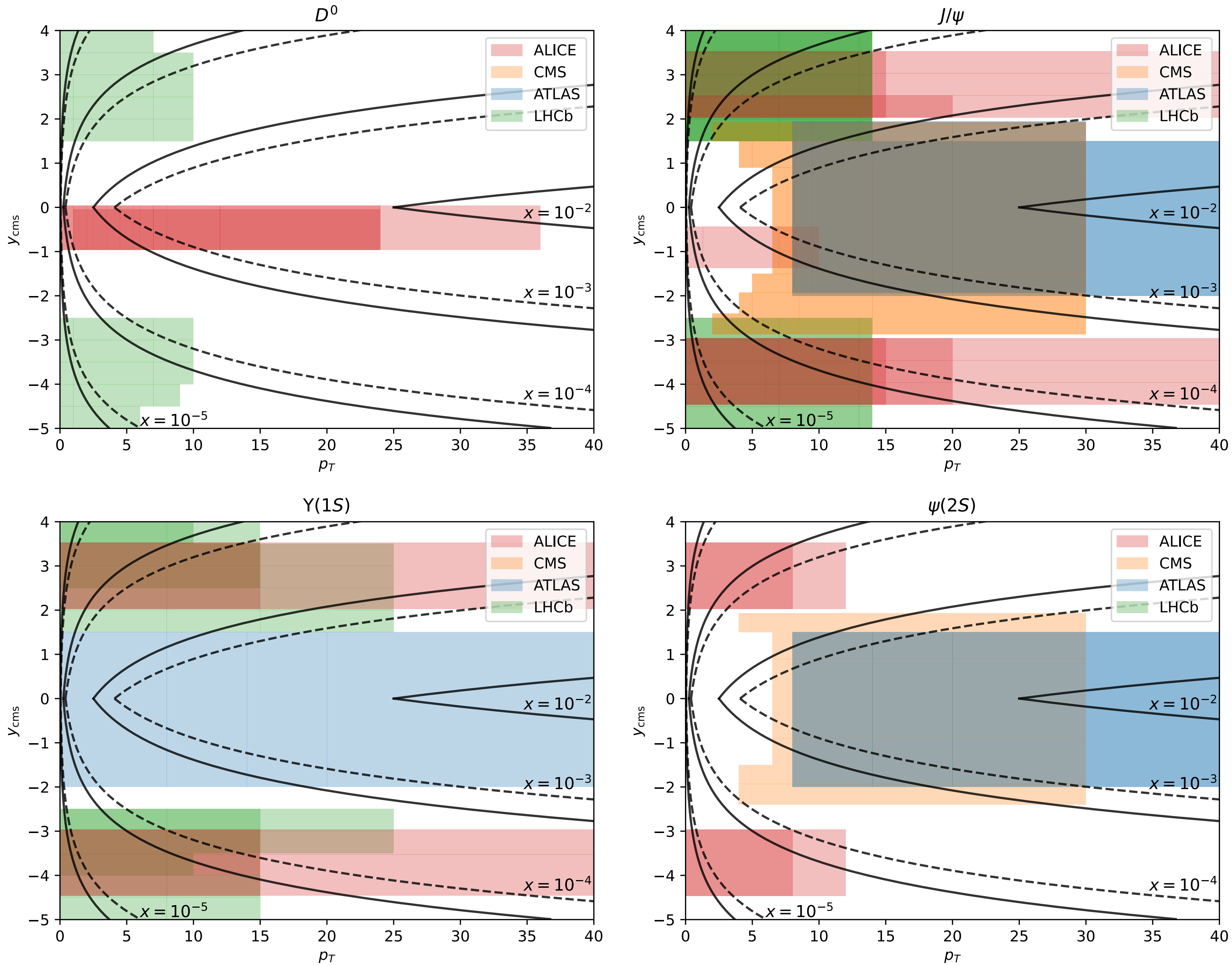


FIG. 1: Coverage of the kinematic $(p_T, y_{\rm cms})$-plane of the quarkonium and open heavy quark production data sets from proton-lead collisions. ALICE data is shown in red, ATLAS in blue, CMS in orange and LHCb in green. The dashed and solid contours show the estimated x-dependence for $\sqrt{s} = 5$ and 8 TeV, respectively.

Heavy quark(-onium) data cover a wide kinematic range down to $x \lesssim 10^{-5}$

puts strong constraints on gluon distribution

See also **2012.11462** and **1712.07024**

nCTEQ15HQ nPDFs

arXiv:2204.09982

- Data:
  - lA DIS + pA DY
  - LHC W,Z
  - RHIC/LHC SIH
  - LHC Heavy quark(-onium)
- 19 fit parameters (3 strange parameters open)
- Heavy quark(-onium) data:
  Data-driven approach relying on the following assumptions
  - gg-channel dominates
  - 2->2 kinematics

$$\sigma(AB \to \mathcal{Q} + X) = \int \mathrm{d}x_1 \; \mathrm{d}x_2 f_{1,g}(x_1, \mu) \, f_{2,g}(x_2, \mu) \, \frac{1}{2\hat{s}} \overline{\left|\mathcal{A}_{gg \to \mathcal{Q}+X}\right|^2} \mathrm{dPS}.$$

The effective scattering ME is parameterised with the Crystal Ball function:

$$\overline{\left|\mathcal{A}_{gg \to \mathcal{Q}+X}\right|^2} = \frac{\lambda^2 \kappa \hat{s}}{M_{\mathcal{Q}}^2} e^{a|y|} \times \begin{cases} e^{-\kappa \frac{p_T^2}{M_{\mathcal{Q}}^2}} & \text{if } p_T \leq \langle p_T \rangle \\ e^{-\kappa \frac{\langle p_T \rangle^2}{M_{\mathcal{Q}}^2}} \left(1 + \frac{\kappa}{n} \frac{p_T^2 - \langle p_T \rangle^2}{M_{\mathcal{Q}}^2}\right)^{-n} & \text{if } p_T > \langle p_T \rangle \end{cases}$$

nCTEQ15HQ nPDFs

arXiv:2204.09982

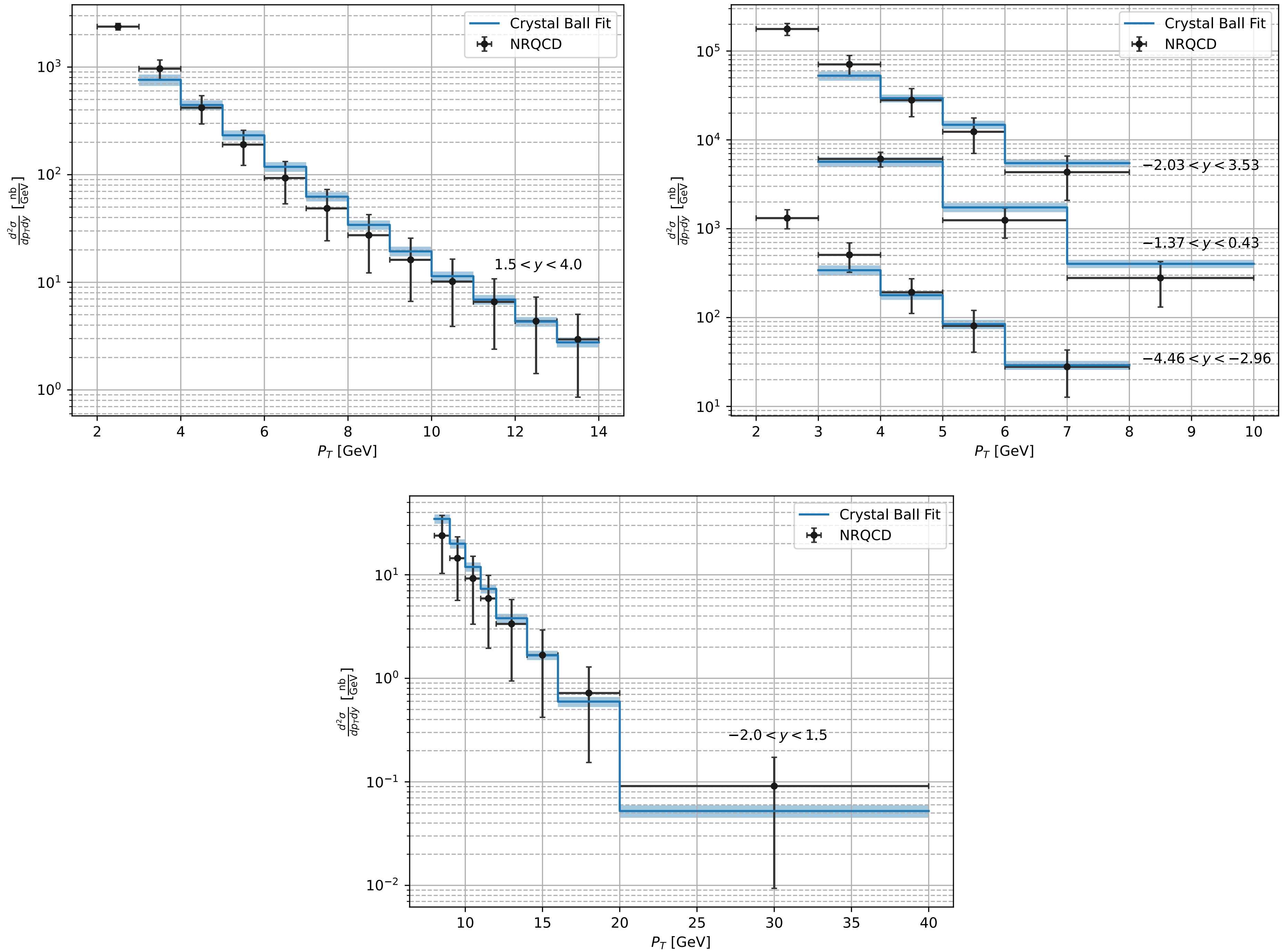


FIG. 2: Comparison between prompt J/ψ production in pp collisions for LHCb[87], ALICE[88] and ATLAS[89] kinematics as predicted by NRQCD and with the data-driven approach. The uncertainties of the NRQCD predictions come from scale variation $1/2 < \mu_r/\mu_{r,0} = \mu_f/\mu_{f,0} = \mu_{\text{NRQCD}}/\mu_{\text{NRQCD},0} < 2$ around the base scale $\mu_{r,0} = \mu_{f,0} = \sqrt{p_T^2 + 4m_c^2}$ and $m_{\text{NRQCD},0} = m_c$. Different rapidity bins are separated by multiplying the cross sections by powers of ten for visual clarity.

nCTEQ15HQ nPDFs

arXiv:2204.09982

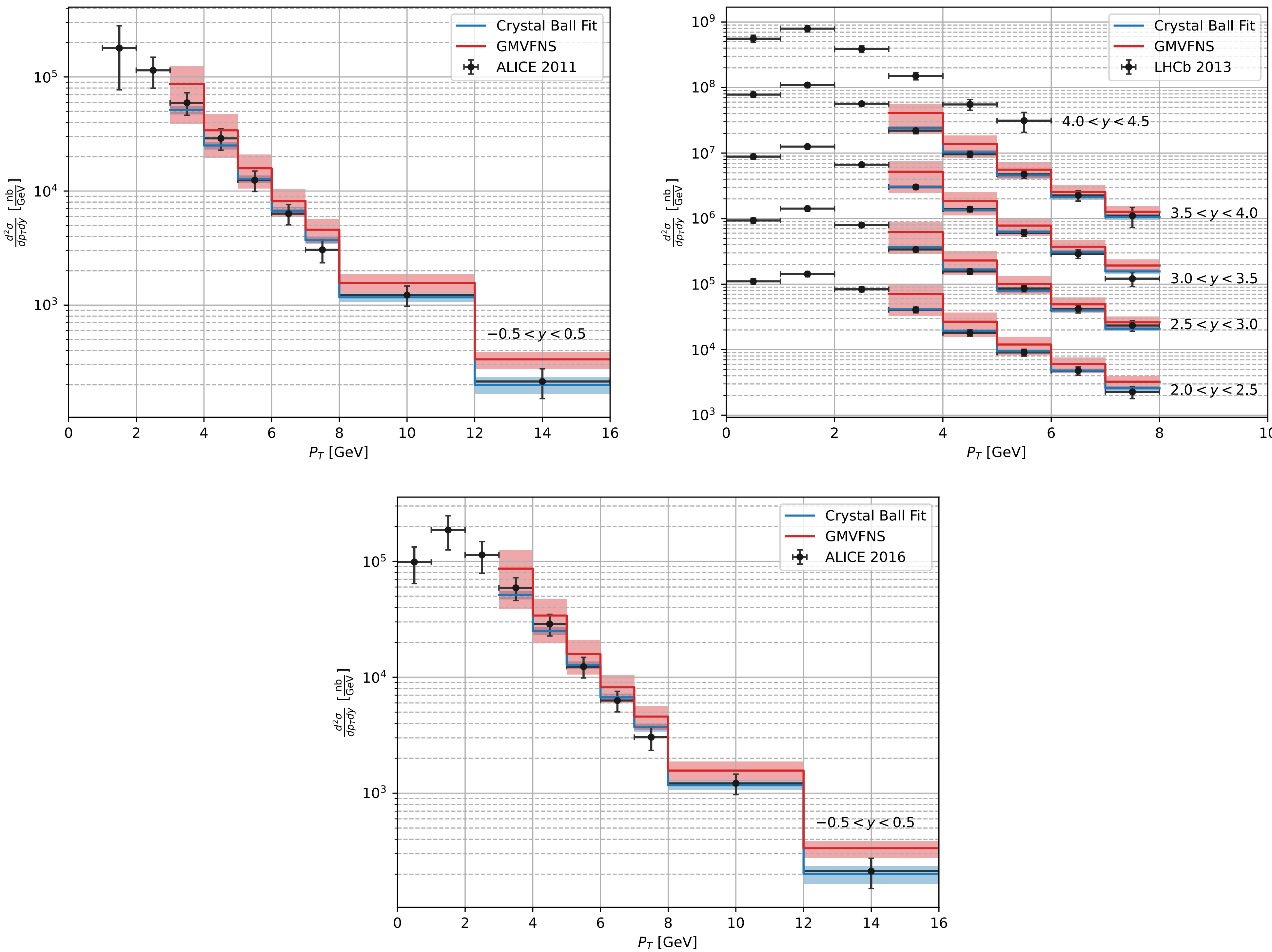


FIG. 3: Comparison between prompt D^0 production as predicted in the GMVFNS (red) and with the data-driven approach (blue). The uncertainties of the GMVFNS predictions come from varying the scales individually by a factor of 2, such that there is never a factor 4 between two scales. Different rapidity bins are separated by multiplying the cross sections by powers of ten for visual clarity.

nCTEQ15HQ nPDFs

arXiv:2204.09982

TABLE XI: χ^2/N_{dof} values for the individual heavy-quark final states, the individual processes DIS, DY, WZ, SIH, HQ, and the total. The shown χ^2 is the sum of regular χ^2 and normalization penalty. Excluded processes are shown in parentheses. Note that both nCTEQ15 AND nCTEQ15WZ included the neutral pions from STAR and PHENIX.

	D^0	J/ψ	$\Upsilon(1S)$	$\psi(2S)$	DIS	DY	WZ	SIH	HQ	**Total**
nCTEQ15	(0.56)	(2.50)	(0.82)	(1.06)	0.86	0.78	(2.19)	(0.78)	(1.96)	**1.23**
nCTEQ15WZ	(0.32)	(1.04)	(0.76)	(1.02)	0.91	0.77	0.63	(0.47)	(0.92)	**0.90**
nCTEQ15WZ+SIH	(0.46)	(0.84)	(0.90)	(1.07)	0.91	0.77	0.72	0.40	(0.93)	**0.92**
nCTEQ15HQ	0.35	0.79	0.79	1.06	0.93	0.77	0.78	0.40	0.77	**0.86**

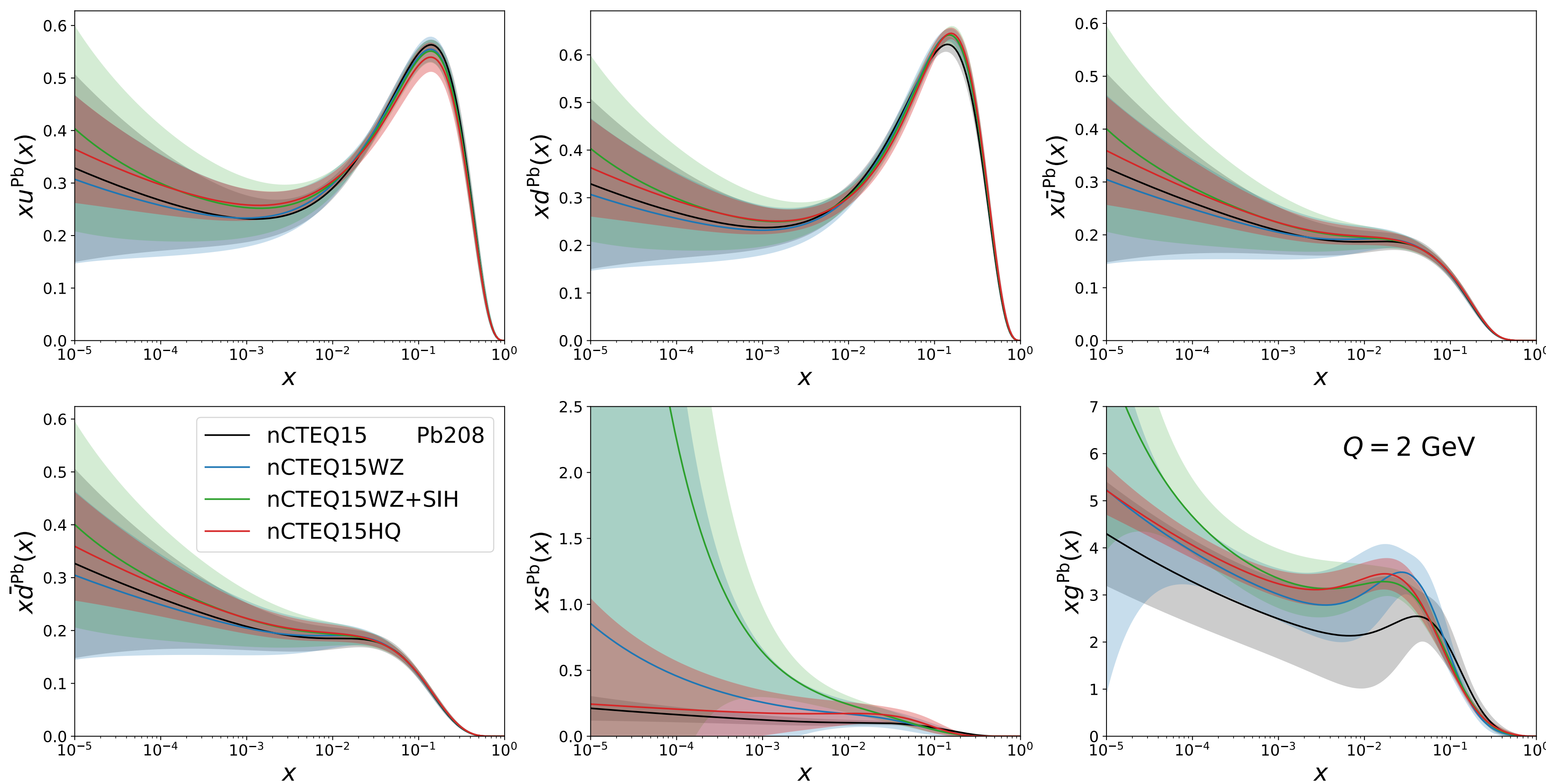
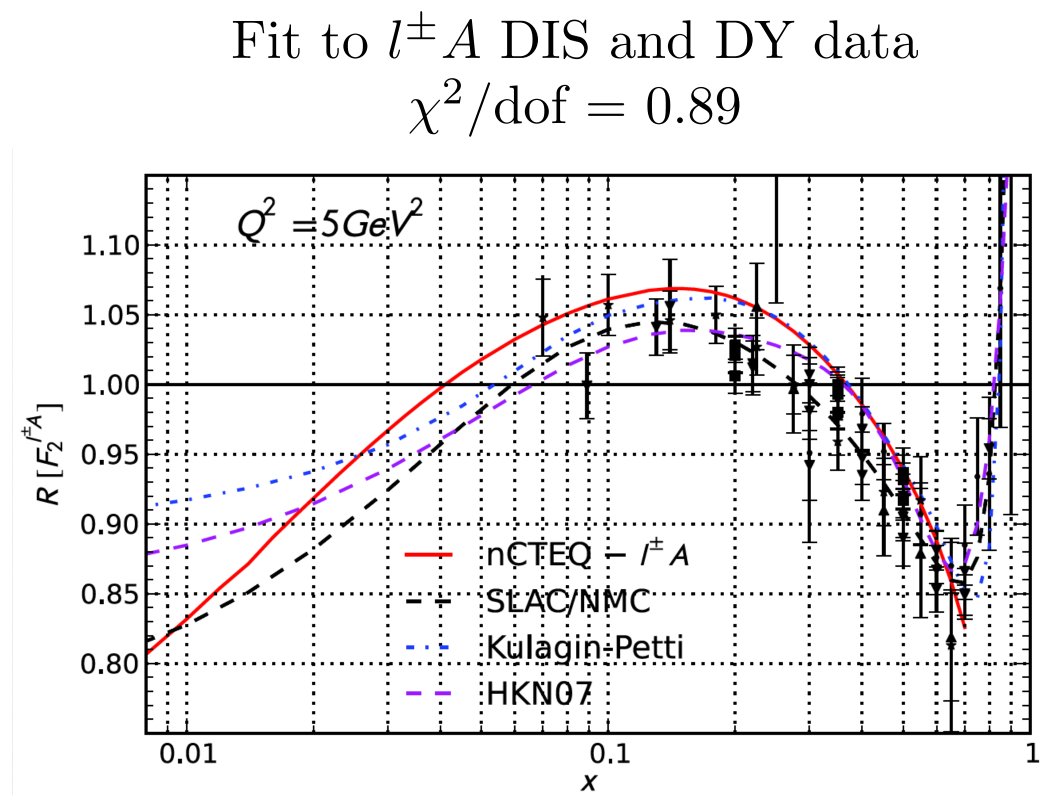


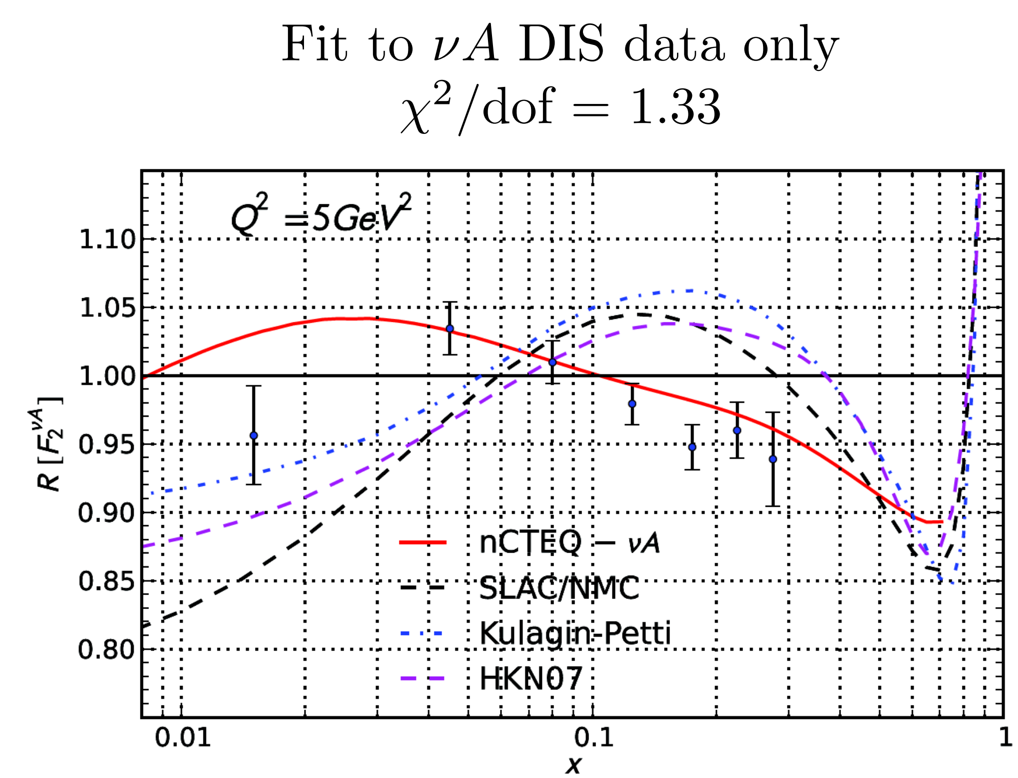
FIG. 4: Lead PDFs from different nCTEQ15 versions. The baseline nCTEQ15 fit is shown in black, nCTEQ15WZ in blue, nCTEQ15WZSIH in green, and the new fit in red.

nCTEQ and neutrino data

Neutrino deep inelastic scattering:

- Neutrino data important for many reasons: flavour separation of PDFs, ew precision physics, …
- Are nuclear corrections in neutrino DIS the same as in charged lepton DIS?
- Several studies have been performed:
  - "iron PDFs: PRD77(2008)054013
  - nCTEQ analysis of nuA+lA+DY data: PRL106(2011)122301
  - Differences independent of the proton baseline: Kalantarians, Keppel, PRC96(2017)032201

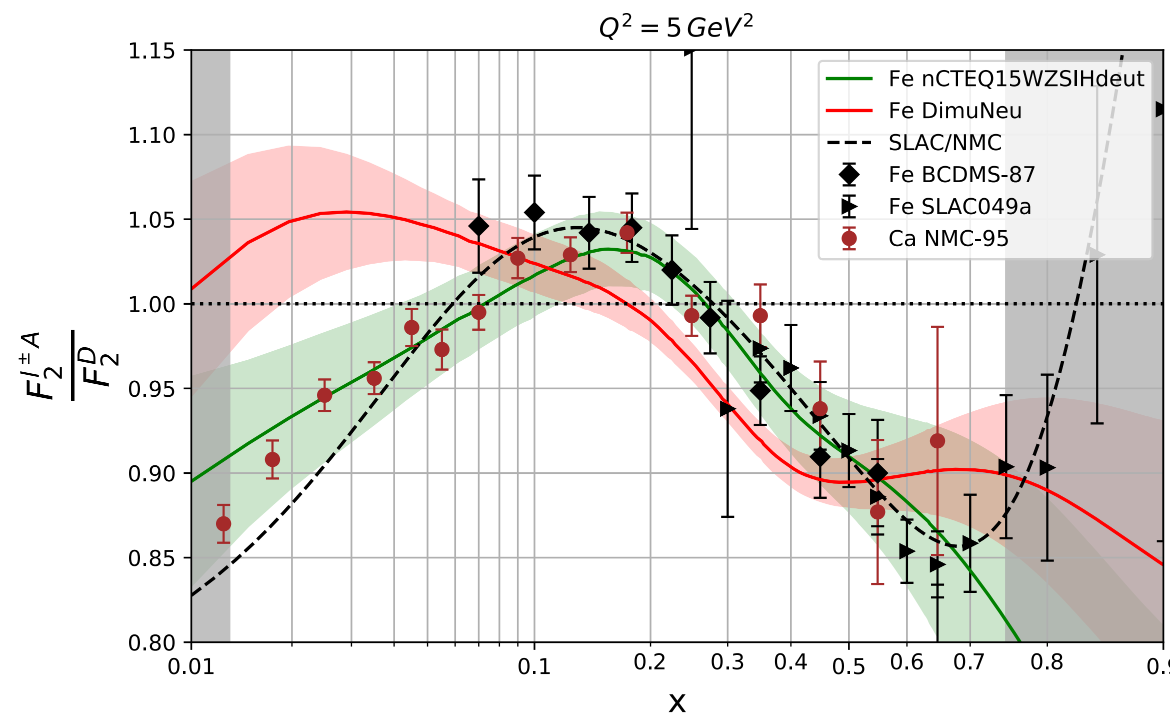




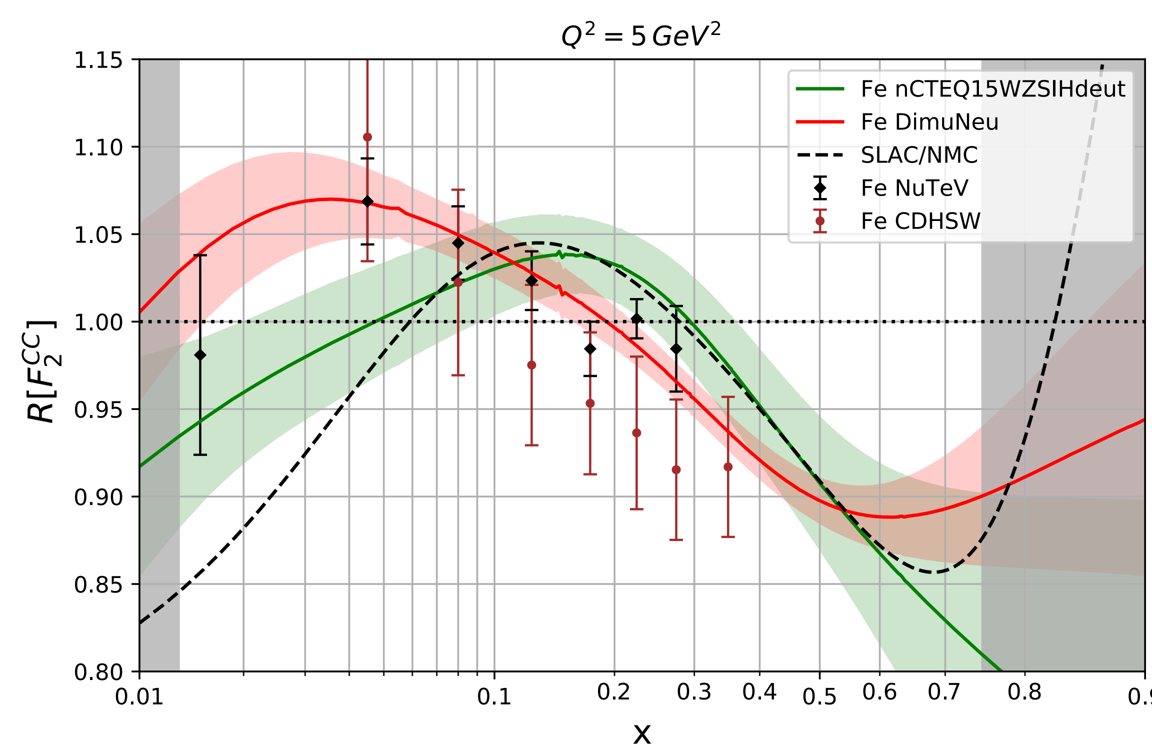
Neutrino DIS vs Charged lepton DIS

Ultimate analysis: " Compatibility of Neutrino DIS data and Its Impact on Nuclear Parton Distribution Functions", arXiv:2204.13157

Data set	Nucleus	$E_{\nu/\bar{\nu}}$(GeV)	#pts	Corr.sys.	Ref.
CDHSW ν CDHSW $\bar{\nu}$	Fe	23 - 188	465 464	No	[48]
CCFR ν CCFR $\bar{\nu}$	Fe	35 - 340	1109 1098	No	[50]
NuTeV ν NuTeV $\bar{\nu}$	Fe	35 - 340	1170 966	Yes	[23]
Chorus ν Chorus $\bar{\nu}$	Pb	25 - 170	412 412	Yes	[27]
CCFR dimuon ν CCFR dimuon $\bar{\nu}$	Fe	110 - 333 87 - 266	40 38	No	[19]
NuTeV dimuon ν NuTeV dimuon $\bar{\nu}$	Fe	90 - 245 79 - 222	38 34	No	[19]



- Most thorough analysis so far (thesis K. F. Muzak, U Münster): different tools to analyse compatibility of data
- Neutrino data creates significant tensions between key data sets: neutrino vs charged lepton+DY+LHC
- Tensions among different neutrino data sets: iron (CDHSW, NuTeV, CCFR) vs lead (CHORUS)?
- Next global analysis will include CHORUS and Di-muon data but not NuTeV, CCFR, CDHSW data



Updates from nNNPDF

nNNPDF3.0 [2201.123623]

New data in nNNPDF3.0 w.r.t. nNNPDF2.0

Process	Dataset	Ref.	$n_{\rm dat}$	Nucl. spec.	Theory
NC DIS	NMC 96	[53]	123/260	^{2}D/p	APFEL
	SLAC 91	[54]	38/211	^{2}D	APFEL
	BCDMS 89	[55]	250/254	^{2}D	APFEL
Fixed-target DY	FNAL E866	[56]	15/15	^{2}D/p	APFEL
	FNAL E605	[57]	85/119	^{64}Cu	APFEL
Collider DY	ALICE $W^\pm$, Z (5.02 TeV)	[58]	6/6	^{208}Pb	MCFM
	LHCb Z (5.02 TeV)	[28]	2/2	^{208}Pb	MCFM
	ALICE Z (8.16 TeV)	[60]	2/2	^{208}Pb	MCFM
	CMS Z (8.16 TeV)	[61]	36/36	^{208}Pb	MCFM
Dijet production	CMS p–Pb/pp (5.02 TeV)	[27]	84/84	^{208}Pb	NLOjet++
Prompt photon production	ATLAS p–Pb/pp (8.16 TeV)	[62]	43/43	^{208}Pb	MCFM
Prompt D^0 production	LHCb p–Pb/pp (5.02 TeV)	[28]	37/37	^{208}Pb	POWHEG

Table 2.1. The new measurements included in nNNPDF3.0 with respect to nNNPDF2.0. For each dataset, we indicate the name used throughout the paper, the reference, the number of data points $n_{\rm dat}$ after/before kinematic cuts, the nuclear species involved, and the codes used to compute the corresponding theoretical predictions. The datasets in the upper (lower) part of the table correspond to the first (second) group described in the text.

LHCb prompt D-meson production data included via Bayesian reweighting (no fit)

nNNPDF3.0 [2201.123623]

Kinematic coverage significantly expanded

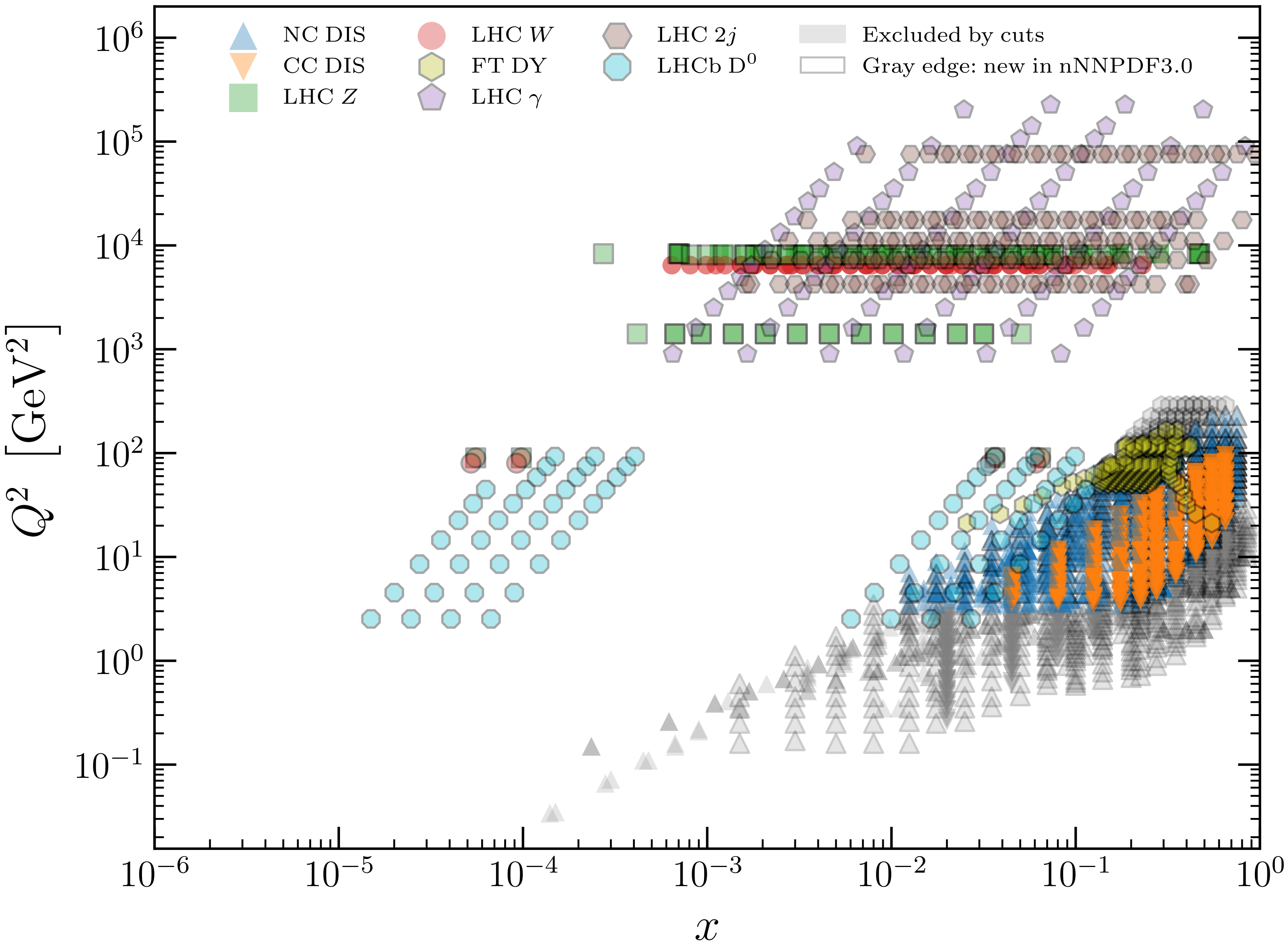


Figure 2.1. The kinematic coverage in the (x, Q^2) plane of the nNNPDF3.0 dataset. The evaluation of x and Q^2 for the hadronic processes assumes LO kinematics. Data points are classified by process. Data points new in nNNPDF3.0 in comparison to nNNPDF2.0 are marked with a grey edge. Data points excluded by kinematic cuts are filled grey.

DIS-Cuts:
- $Q^2 > 3.5\ \mathrm{GeV}^2$
- $W^2 > 12.5\ \mathrm{GeV}^2$

Cuts to FNAL-E605 p-Cu DY to remove points close to the production threshold

After cuts:
- 2188 points (3.0)
- 1467 points (2.0)

nNNPDF3.0 [2201.123623]

- General settings
  - $m_c = 1.51\ \text{GeV}, m_b = 4.92\ \text{GeV}, \alpha_s(M_Z) = 0.118$
  - Input scale $Q_0 = 1\ \text{GeV}$
  - PDFs at NLO MSbar
  - Isospin symmetry
  - Heavy quarks in DIS: FONLL GM-VFNS
  - pA collisions: ZM-VFNS
  - Various methodological improvements w.r.t. nNNPDF2.0

nNNPDF3.0 [2201.123623]

Impact of LHCb D-meson data: large uncertainty reduction at small-x, more shadowing

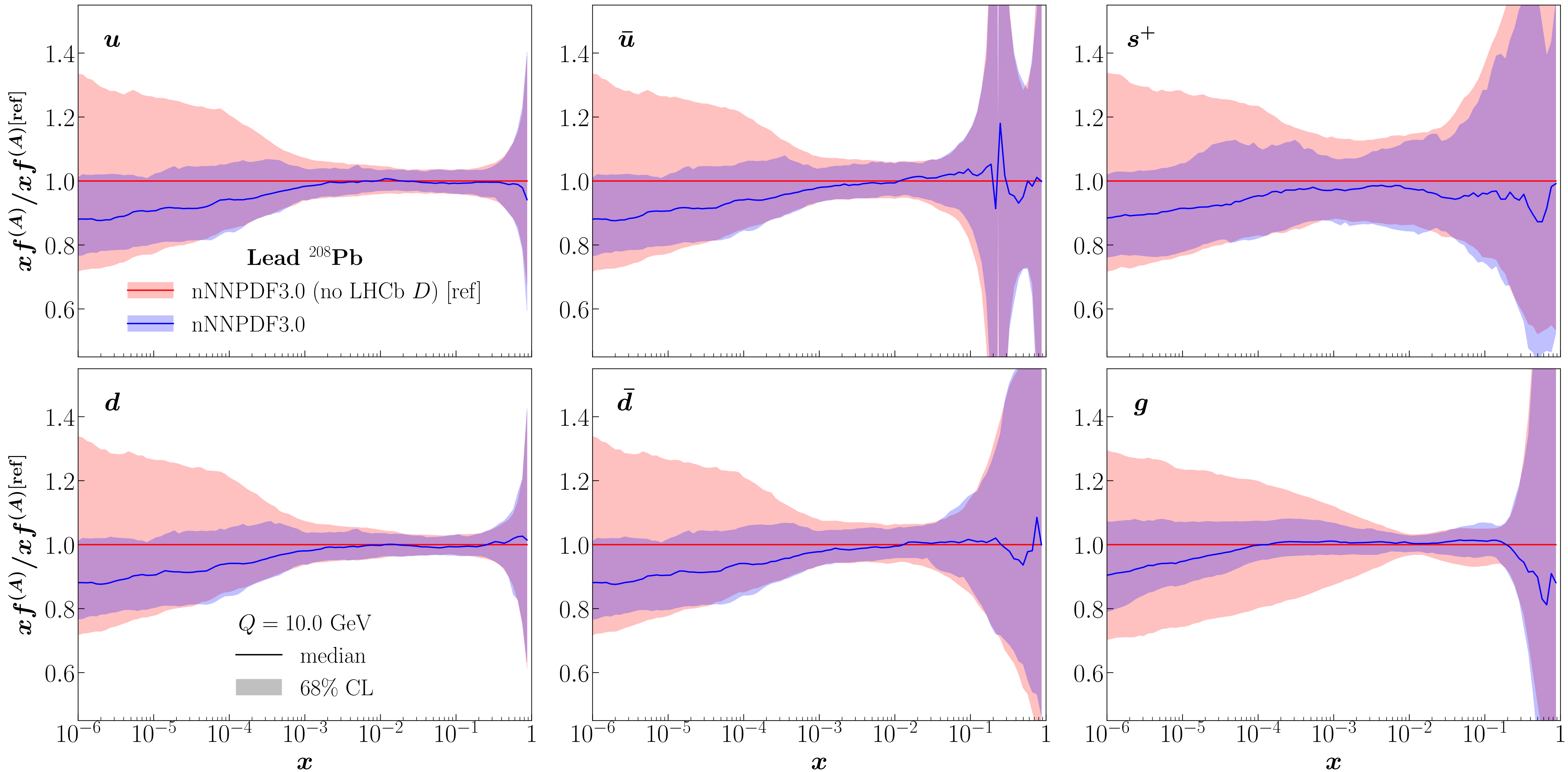


Figure 4.5. Comparison of the nPDFs of lead nuclei at $Q = 10$ GeV between nNNPDF3.0 (no LHCb D) and nNNPDF3.0, normalised to the central value of the former.

nNNPDF3.0 [2201.123623]

Comparison with EPPS16 and nCTEQ15WZSIH

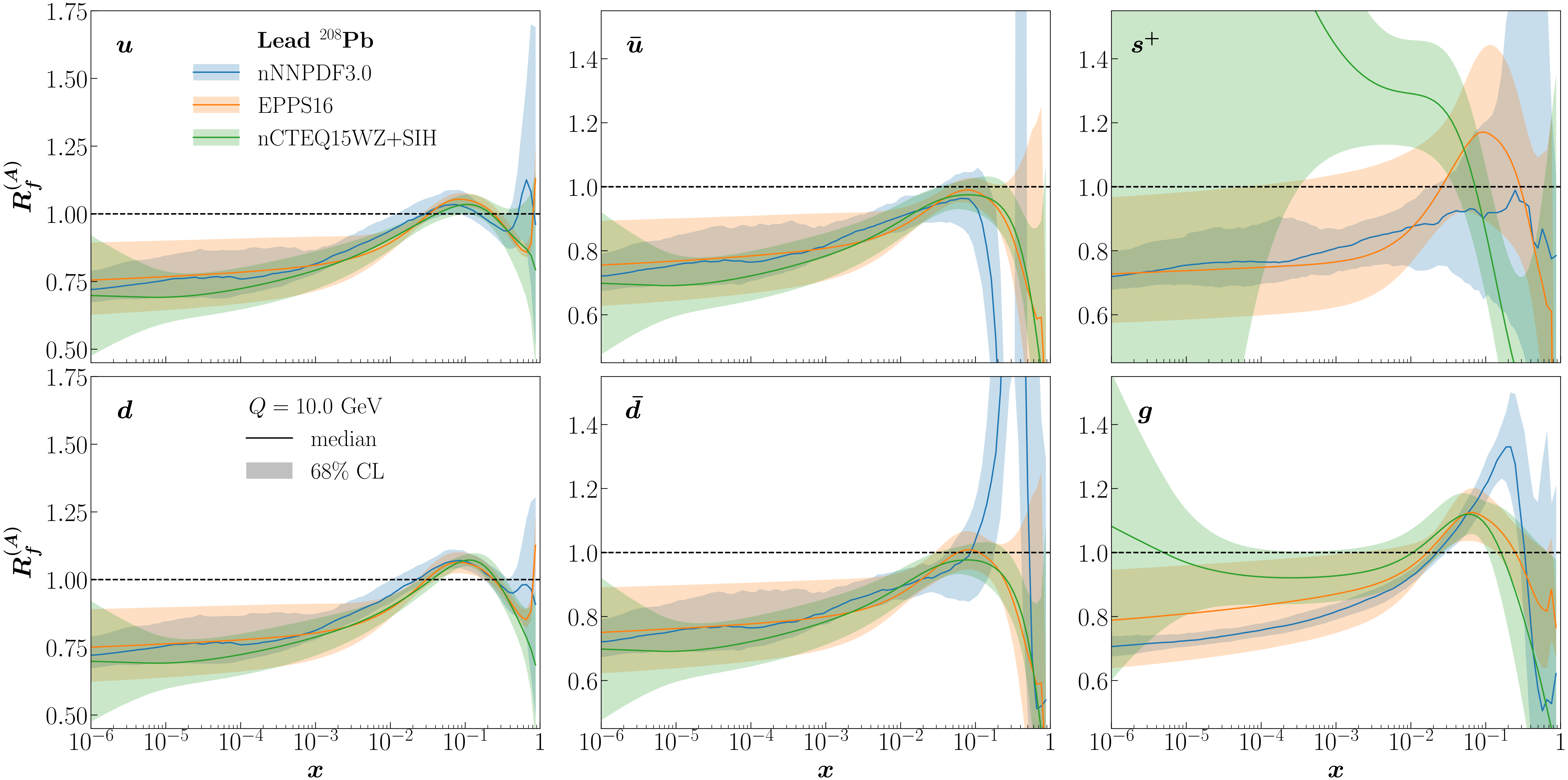


Figure 4.13. The nNNPDF3.0 predictions for the nuclear modification ratios in lead at $Q = 10$ GeV, compared to the corresponding results from the EPPS16 and nCTEQWZ+SIH global analyses. The PDF uncertainty bands correspond in all cases to 68% CL intervals.

nNNPDF3.0 [2201.123623]

Methodological improvements

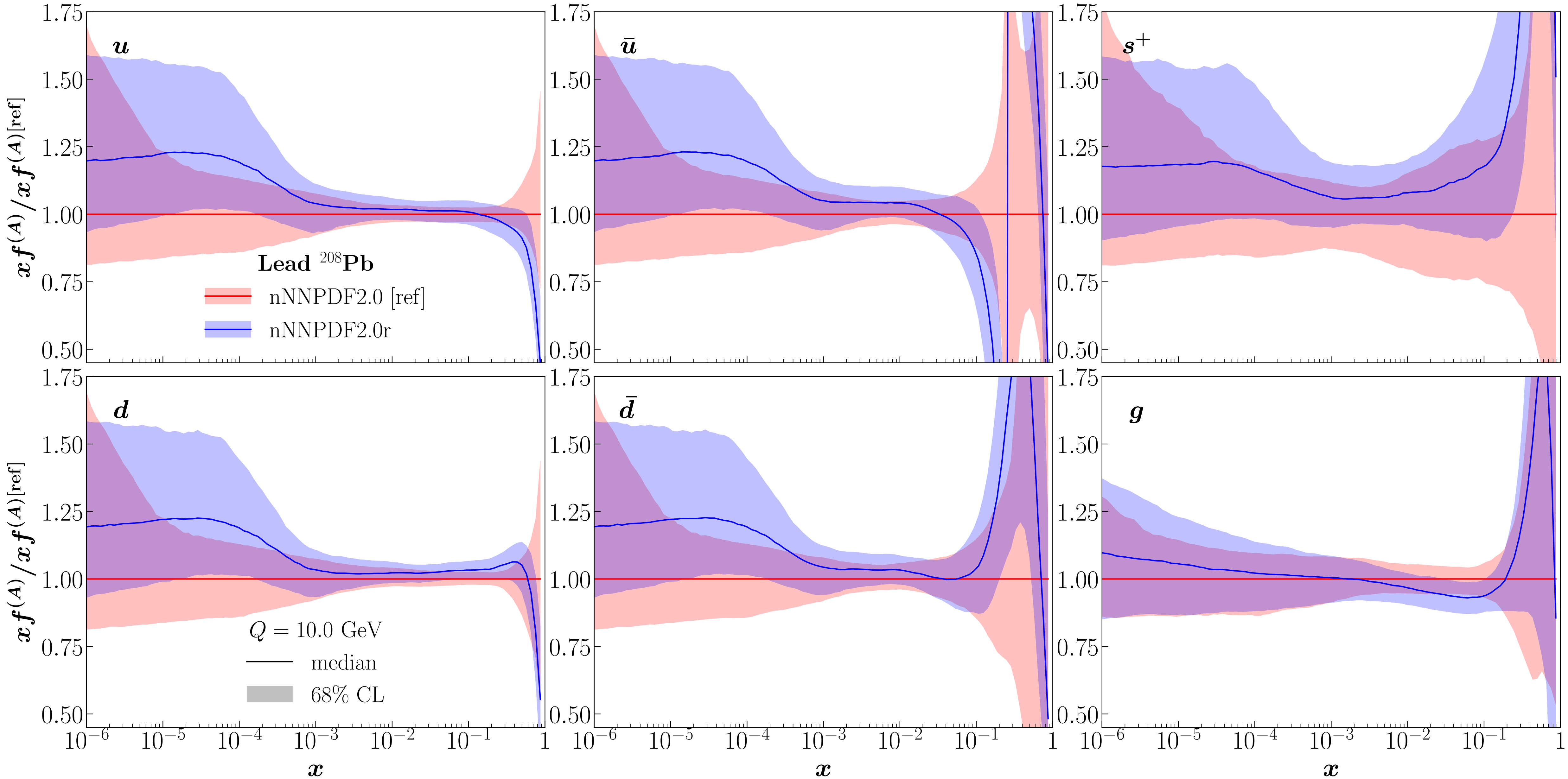


Figure 5.1. Comparison of nNNPDF2.0 with the nNNPDF2.0r variant. Results are shown for the lead PDFs at $Q = 10$ GeV normalised to the central value of nNNPDF2.0, and the uncertainty bands represent the 68% CL intervals.

Summary/Conclusions/Outlook

Conclusions

- A lot of progress in recent years, more to come!
  - HQ-data, di-jet data: much improved gluon
  - LHC W,Z data: gluon, strange PDF
  - JLAB data: improved determination of valence distributions
  - Neutrino data:
    - quark flavour separation
    - But tensions with neutrino-iron data, not with neutrino-lead data
- Different groups: EPPS, nCTEQ, nNNPDF, TUJU, KA, …
  Important to test systematics, new ideas, driving improvements!

Conclusions

- Future:
  - More data, more truly global fits, improved precision
  - Combined proton PDF and nPDF fits ↔ Lead-only fits
  - Better understanding of nuclear (A,Z)-dependence, x-dependence:
    - Test of nuclear models
    - Test of collinear factorisation
  - Competitive lattice calculations (also for nuclei)

Backup

Nuclear modifications

- Neutrino experiments use heavy nuclear targets:
  Pb, Fe, Ar, H_2O, C

- As discovered more than 30 years ago by the European Muon Collaboration, nucleon structure functions are modified by the nuclear medium (EMC effect)

- Studies of nucleon structure: need to correct for nuclear effects

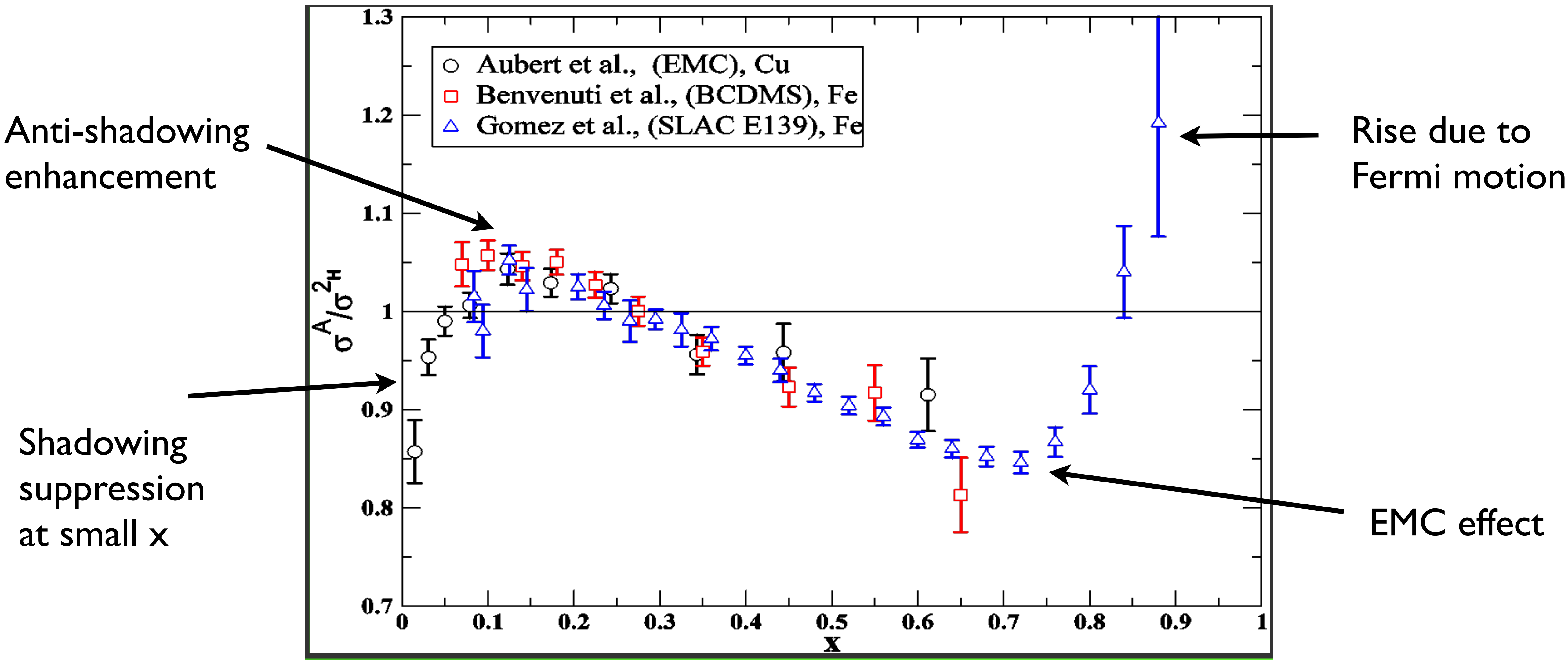
- Nuclear effects interesting in its own right!

  - Many models exist.

  - However, charged lepton nuclear effects still not fully explained, in particular the EMC effect ($0.3 < x < 0.7$)

The EMC effect

$$F_2^A(x) \neq Z F_2^p(x) + N F_2^n(x)$$



DIS on a nuclear target

Consider deep inelastic lepton–nucleon collisions: $l(k) + A(p_A) \to l'(k') + X$

Introduce the usual DIS variables: $q \equiv k - k'$, $\quad Q^2 \equiv -q^2$, $\quad x_A \equiv \frac{Q^2}{2p_A \cdot q}$

Hadronic tensor: $W^A_{\mu\nu} \propto \langle A(p_A)| \, J_\mu J^\dagger_\nu \, |A(p_A)\rangle = \sum_i \, a^{(i)}_{\mu\nu} \, \tilde{F}^A_i(x_A, Q^2)$,
where $a^{(i)}_{\mu\nu}$ are Lorentz-tensors composed out of the 4-vectors q and p_A and the metric $g_{\mu\nu}$

Express structure functions in the QCD improved parton model in terms of NPDFs

$$\tilde{\mathcal{F}}^A_k(x_A, Q^2) = \int_{x_A}^1 \frac{\mathrm{d}y_A}{y_A} \, \tilde{f}^A_i(y_A, Q^2) C_{k,i}(x_A/y_A) + \tilde{\mathcal{F}}^{A,\tau\geq 4}_k(x_A, Q^2)$$

NPDFs: Fourier transforms of matrix elements of twist-two operators composed out of the quark and gluon fields:

$$\tilde{f}^A_i(x_A, Q^2) \propto \langle A(p_A)| \, O_i \, |A(p_A)\rangle$$

Definitions of $\tilde{F}^A_i(x_A, Q^2)$, $\tilde{f}^A_i(x_A, Q^2)$, and the varibale $0 < x_A < 1$ carry over one-to-one from the well-known free nucleon case

Evolution Equations and Sum Rules

DGLAP as usual:

$$\begin{aligned}
\frac{d\tilde{f}_i^A(x_A, Q^2)}{d\ln Q^2} &= \frac{\alpha_s(Q^2)}{2\pi} \int_{x_A}^1 \frac{dy_A}{y_A} P_{ij}(y_A)\, \tilde{f}_j^A(x_A/y_A, Q^2) \,, \\
&= \frac{\alpha_s(Q^2)}{2\pi} \int_{x_A}^1 \frac{dy_A}{y_A} P_{ij}(x_A/y_A)\, \tilde{f}_j^A(y_A, Q^2) \,,
\end{aligned}$$

Sum rules:

$$\begin{aligned}
\int_0^1 dx_A\, \tilde{u}_v^A(x_A, Q^2) &= 2Z + N \,, \\
\int_0^1 dx_A\, \tilde{d}_v^A(x_A, Q^2) &= Z + 2N \,,
\end{aligned}$$

B cons.: 1/3 $<u_v>$ + $<d_v>$ = A

C cons.: 2/3 $<u_v>$ - 1/3 $<d_v>$ = Z

and the momentum sum rule

$$\int_0^1 dx_A\, x_A \left[\tilde{\Sigma}^A(x_A, Q^2) + \tilde{g}^A(x_A, Q^2)\right] = 1 \,,$$

where $N = A - Z$ and $\tilde{\Sigma}^A(x_A) = \sum_i (\tilde{q}_i^A(x_A) + \tilde{\bar{q}}_i^A(x_A))$ is the quark singlet combination

Rescaled definitions!

Problem: average momentum fraction carried by a parton $\propto A^{-1}$
since there are 'A-times more partons' which have to share the momentum

- Different nuclei (A, Z) not directly comparable
- Functional form for x-shape would change drastically with A
- Need to rescale!

PDFs are number densities: $\tilde{f}_i^A(x_A)\,\mathrm{d}x_A$ is the number of partons carrying a momentum fraction in the interval $[x_A, x_A + \mathrm{d}x_A]$

Define rescaled NPDFs $f_i^A(x_N)$ with $0 < x_N := A x_A < A$:

$$\boxed{f_i^A(x_N)\,\mathrm{d}x_N := \tilde{f}_i^A(x_A)\,\mathrm{d}x_A}$$

The variable x_N can be interpreted as parton momentum fraction w.r.t. the **average** nucleon momentum $\bar{p}_N := p_A/A$

Rescaled evolution equations and sum rules

Evolution:

$$\frac{\mathrm{d}f_i^A(x_N,Q^2)}{\mathrm{d}\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_{x_N/A}^{1}\frac{\mathrm{d}y_A}{y_A}\,P(y_A)\,f_i^A(x_N/y_A,Q^2)\,,$$
$$= \frac{\alpha_s(Q^2)}{2\pi}\int_{x_N}^{A}\frac{\mathrm{d}y_N}{y_N}\,P(x_N/y_N)\,f_i^A(y_N,Q^2)\,.$$

Assume that $f_i^A(x_N)=0$ for $x_N>1$, then **original, symmetrical** form recovered:

$$\frac{\mathrm{d}f_i^A(x_N,Q^2)}{\mathrm{d}\ln Q^2} = \begin{cases} \frac{\alpha_s(Q^2)}{2\pi}\int_{x_N}^{1}\frac{\mathrm{d}y_N}{y_N}\,P(y_N)\,f_i^A(x_N/y_N,Q^2) & : 0<x_N\le 1 \\ 0 & : 1<x_N<A, \end{cases}$$

Sum rules for the rescaled PDFs:

$$\int_0^A \mathrm{d}x_N\,u_v^A(x_N) = 2Z+N\,,$$
$$\int_0^A \mathrm{d}x_N\,d_v^A(x_N) = Z+2N\,,$$

and

$$\int_0^A \mathrm{d}x_N\,x_N\,\left[\Sigma^A(x_N)+g^A(x_N)\right] = A\,,$$

Rescaled structure functions

The rescaled structure functions can be defi ned as

$$x_N \mathcal{F}_i^A(x_N) := x_A \tilde{\mathcal{F}}_i^A(x_A) \; ,$$

with $\mathcal{F}_{1,2,3}(x) = \{F_1(x), F_2(x)/x, F_3(x)\}$.

More explicitly:

$$\begin{aligned} F_2^A(x_N) &:= \tilde{F}_2^A(x_A) \; , \\ x_N F_1^A(x_N) &:= x_A \tilde{F}_1^A(x_A) \; , \\ x_N F_3^A(x_N) &:= x_A \tilde{F}_3^A(x_A) \; . \end{aligned}$$

This leads to consistent results in the parton model using the rescaled PDFs.

Consistent also for the target mass corrected structure functions!

Effective PDFs of bound nucleons

Further decompose the NPDFs $f_i^A(x_N)$ in terms of effective parton densities for **bound** protons, $f_i^{p/A}(x_N)$, and neutrons, $f_i^{n/A}(x_N)$, inside a nucleus A:

$$f_i^A(x_N, Q^2) = Z\, f_i^{p/A}(x_N, Q^2) + N\, f_i^{n/A}(x_N, Q^2)$$

- The bound proton PDFs have the **same** evolution equations and sum rules as the free proton PDFs **provided** we neglect any contributions from the region $x_N > 1$
- Neglecting the region $x_N > 1$, is consistent with the DGLAP evolution
- The region $x_N > 1$ is expected to have a minor influence on the sum rules of less than one or two percent (see also [PRC73(2006)045206])
- Isospin symmetry: $u^{n/A}(x_N) = d^{p/A}(x_N)$, $d^{n/A}(x_N) = u^{p/A}(x_N)$

An observable $\mathcal{O}^A$ is then given by:

$$\mathcal{O}^A = Z\, \mathcal{O}^{p/A} + N\, \mathcal{O}^{n/A}$$

In conclusion: the free proton framework can be used to analyse nuclear data