Nuclear PDFs

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Workshop on "Implications of LHCb measurements and future prospects"
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Plan

- Proton and nuclear PDFs: Common framework
- Global analyses of nuclear PDFs
  - Updates from nCTEQ
  - Updates from nNNPDF
  - Updates from EPPS
- Conclusions

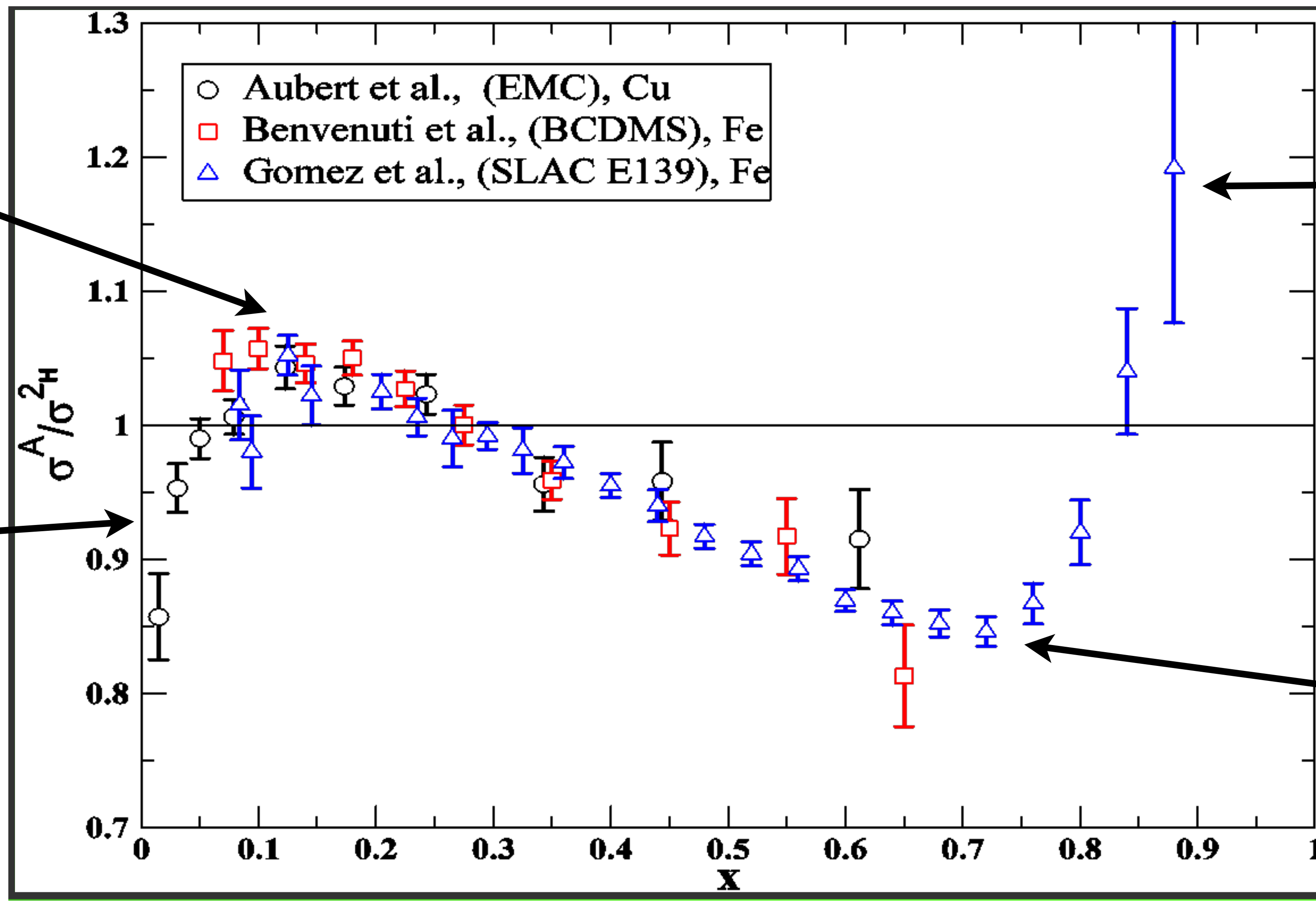
Proton and nuclear PDFs: Common framework

Nuclear modifications

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

Anti-shadowing enhancement

Shadowing suppression at small x

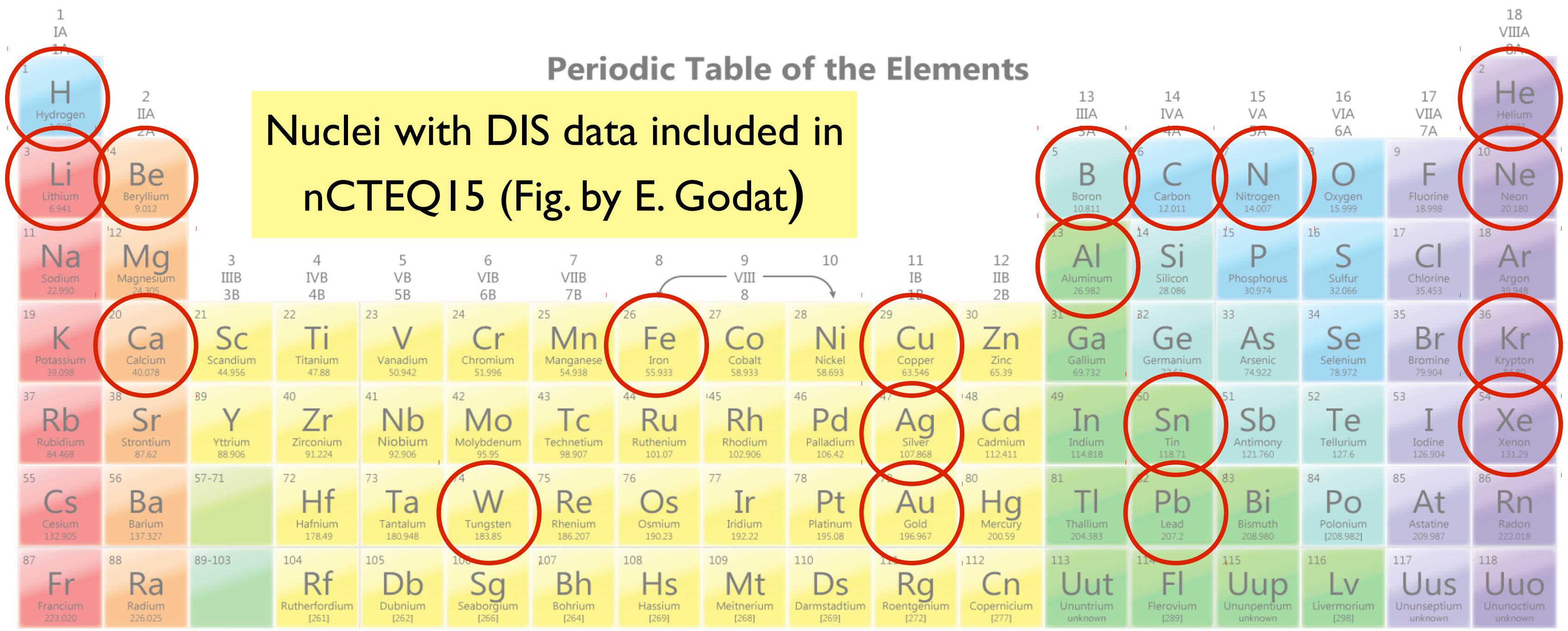


Rise due to Fermi motion

EMC effect

- Nuclear modifications can be incorporated inside **nuclear PDFs** but underlying dynamics remains to be fully theoretically understood

Nuclear PDFs

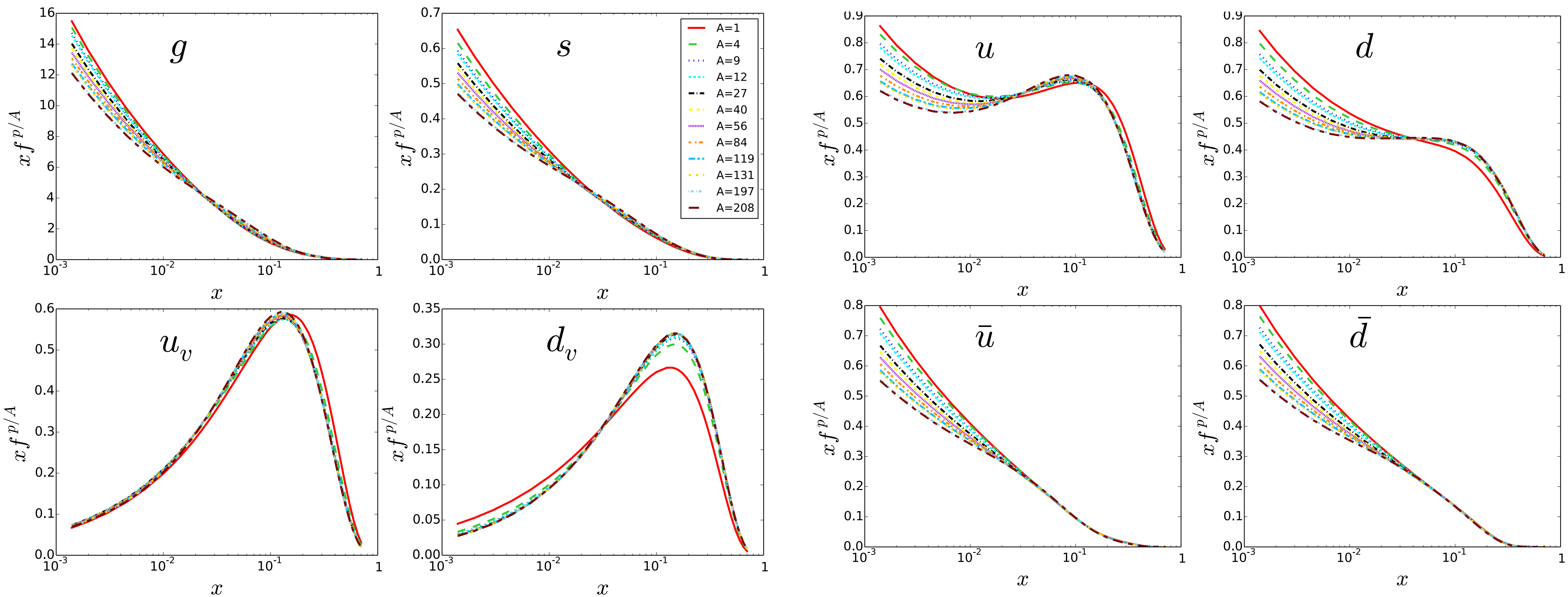


Nuclei with DIS data included in nCTEQ15 (Fig. by E. Godat)

- 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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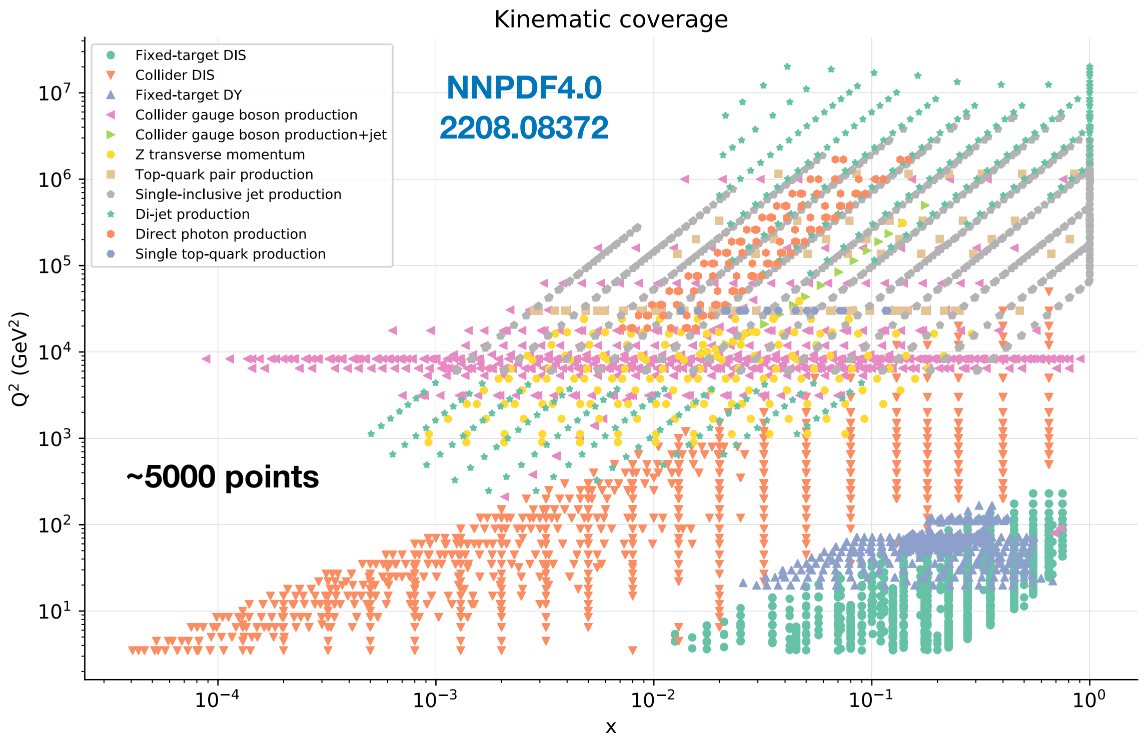
Similarities between proton and nuclear PDFs

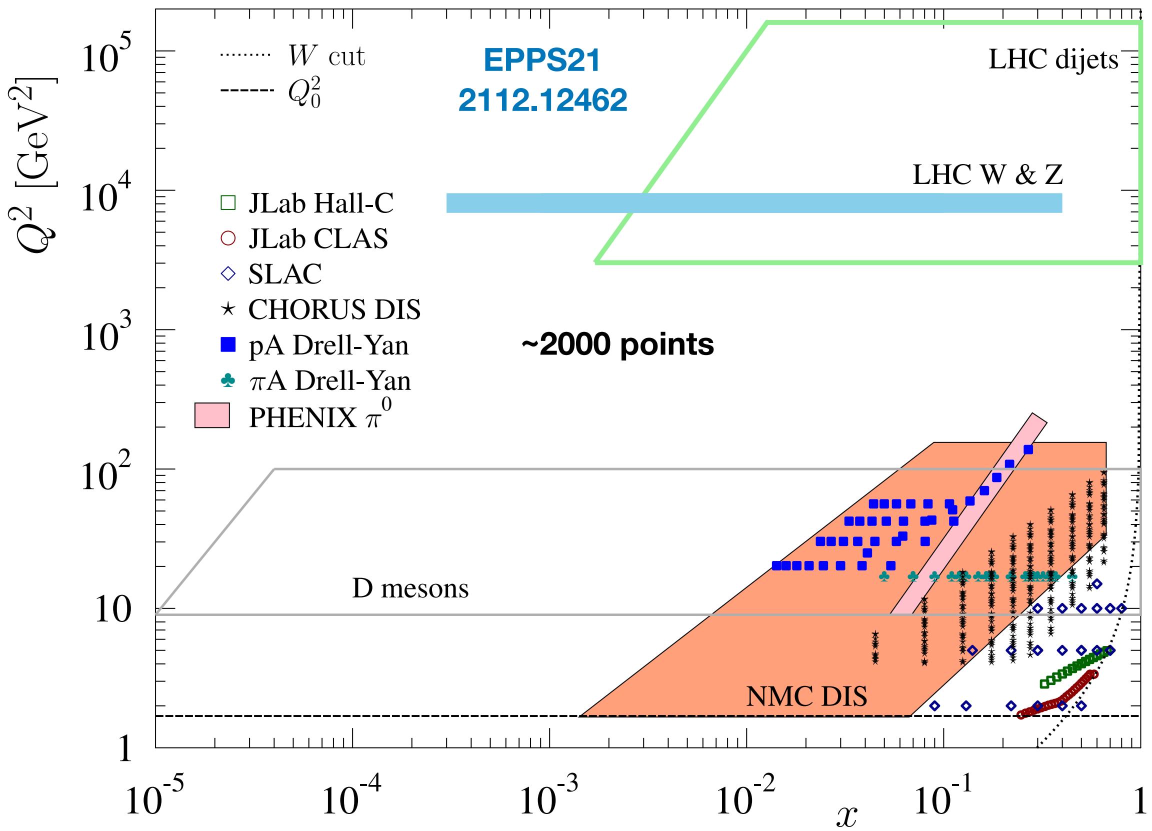
- **Same formalism** if nuclear PDFs are restricted to $0 \leq x \leq 1$ (reasonable!):
  - Same **DGLAP** evolution equations
  - Same **sum rules**
  - Same **hard scattering cross sections**
- **Same approaches:**
  - Global analyses (uncertainties, grids, automation)
  - Lattice calculations (more complex for nuclei)
- **Partly intertwined:**
  - proton PDF fits use also nuclear data
  - nuclear PDF fits use a proton baseline
  - Try simultaneous fits. Or self-consistent iterative procedures.

Differences between proton and nuclear PDFs

- **Proton PDFs:**
  - Data for many processes, covering a wide kinematic range. LHC important but also HERA data
  - Aiming at 1% precision! Requires high level of sophistication!
  - Many global analyses available



- **Nuclear PDFs:**
  - Fewer data, more restricted kinematic range. LHC data crucial. No analogue of HERA
  - Much larger nPDF uncertainties. Nuclear A-dependence quite rough so far. In the future dedicated fits for lead only and for other nuclei
  - Higher twist effects potentially nuclear-enhanced



LHC data important for proton and nuclear PDFs

pp:

ATLAS, CMS, LHCb

- W/Z production
- DY lepton pairs
- High pT jets
- Heavy quarks (c, b)
- Top quarks
- Prompt photons
- W+c, Z+c

pPb, γPb:

ALICE, ATLAS, CMS, LHCb

- W/Z production
- DY lepton pairs
- Dijets
- Heavy quarks (c, b): Charm hadrons
- Light hadrons inclusive pions, kaons
- Prompt photons

Global analyses of nuclear PDFs

Global analyses of nPDFs: 2022

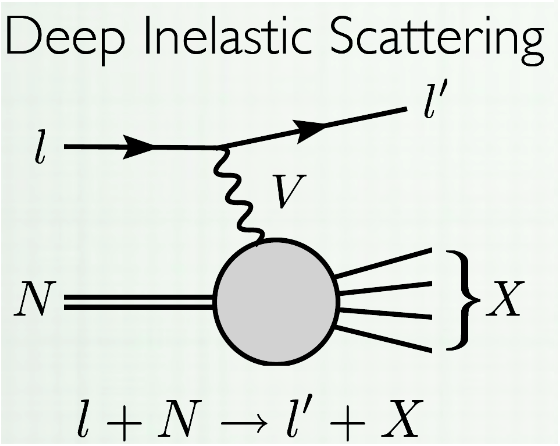
- **EPPS**
  - **EKS98:** hep-ph/9807297
  - **EKPS07:** hep-ph/0703104
  - **EPS08:** 0802.0139
  - **EPS09:** 0902.4154
  - **EPPS16:** 1612.05741
  - **EPPS21:** 2112.12462
- **nCTEQ**
  - **nCTEQ09:** 0907.2357
  - **nCTEQ15:** 1509.00792
  - **nCTEQ15WZ:** 2007.09100
  - **nCTEQ15HiX:** 2012.11566
  - **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

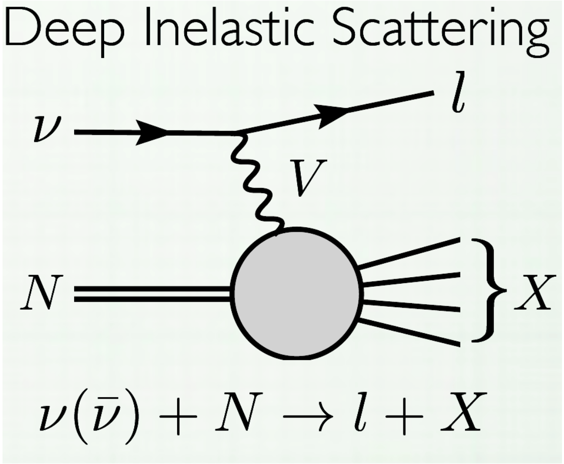
- **Similarities**
  - All use the **same twist-2 pQCD formalism based on collinear factorisation**: DGLAP evolution, sum rules, pQCD observables, χ^2 minimisation
  - Isospin symmetry, region x>1 is neglected in all analyses
- **Main differences**
  - **Parametrisation** of the boundary conditions at 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

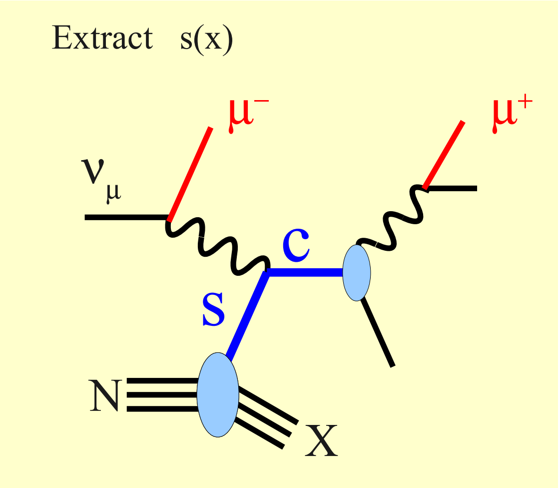
- **lA DIS:** backbone of all global analyses
  - Data from SLAC, NMC, EMC, BCDMS, FNAL: all groups (**but different cuts**)
  - Data from JLAB (CLAS, Hall-C): nCTEQ15HiX, EPPS21, KSASG20



- **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

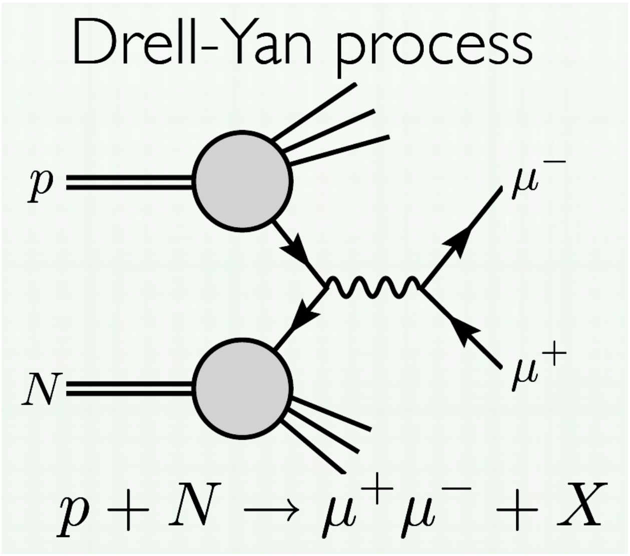


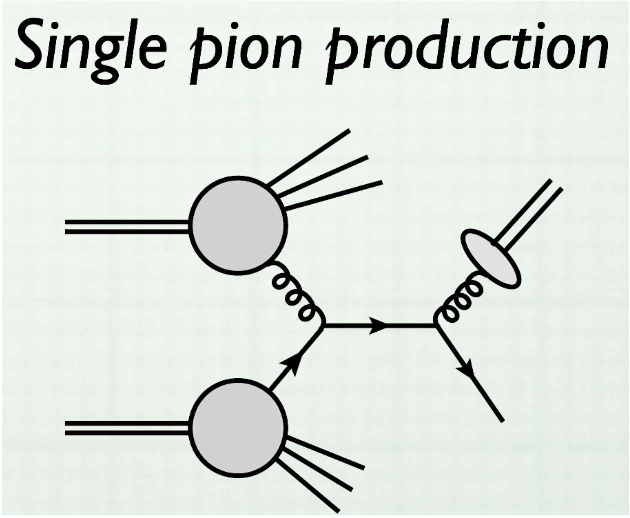
- **nuA SIDIS charm production** (dimuon data): strange PDF
  - NuTeV, CCFR nu-Fe: nNNPDF2.0, BaseDimuCHORUS



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

Comparison of recent nPDF fits

P. Paakkinen

	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15HQ
Order in α_s	NLO & NNLO	NLO & NNLO	NLO	NLO	NLO
lA NC DIS	✓	✓	✓	✓	✓
νA CC DIS	✓	✓	✓	✓	
pA DY	✓		✓	✓	✓
πA DY			✓		
RHIC dAu π^0,$\pi^\pm$			✓		✓
LHC pPb π^0,$\pi^\pm$,$K^\pm$					✓
LHC pPb dijets			✓	✓	
LHC pPb HQ			✓ GMVFN	✓ FO+PS	✓ ME fitting
LHC pPb W,Z		✓	✓	✓	✓
LHC pPb γ				✓	
Q, W cut in DIS	1.3, 0.0 GeV	1.87, 3.5 GeV	1.3, 1.8 GeV	1.87, 3.5 GeV	2.0, 3.5 GeV
p_T cut in HQ,inc.-h	N/A	N/A	3.0 GeV	0.0 GeV	3.0 GeV
Data points	4353	2410	2077	2188	1496
Free parameters	9	16	24	256	19
Error analysis	Hessian	Hessian	Hessian	Monte Carlo	Hessian
Free-proton PDFs	CT18	own fit	CT18A	~NNPDF4.0	~CTEQ6M
Free-proton corr.	no	no	yes	yes	no
HQ treatment	FONLL	FONLL	S-ACOT	FONLL	S-ACOT
Indep. flavours	3	4	6	6	5
Reference	PRD 104, 034010	PRD 105, 094031	EPJC 82, 413	EPJC 82, 507	PRD 105, 114043

Updates from nCTEQ

Towards the next nCTEQ global analysis

nCTEQ nuclear PDFs:

- **Preparation of next global release** (**nCTEQ2024**)
  - 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 **[2301.07715]**

nCTEQHQ nPDFs

arXiv:2204.09982

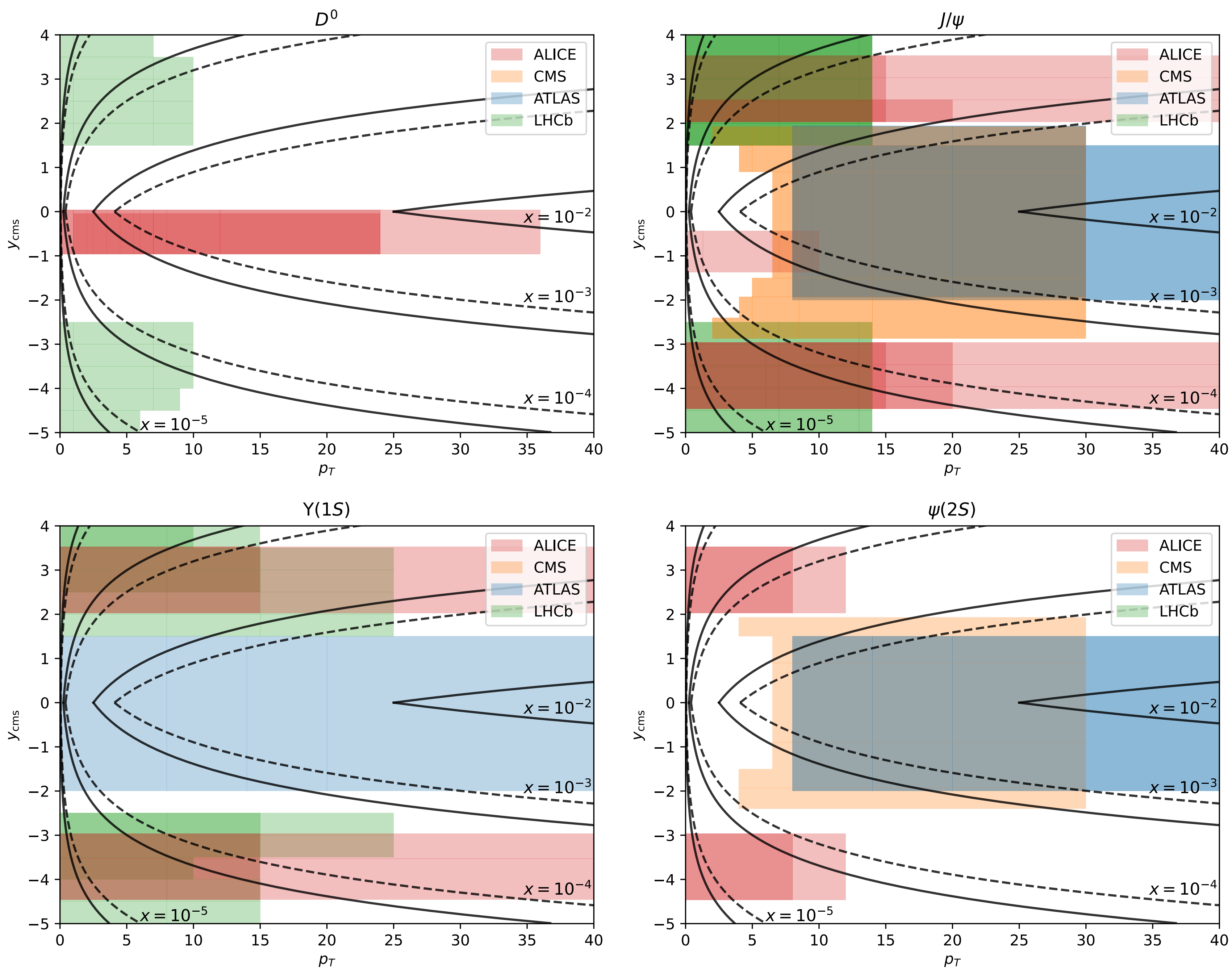


FIG. 1: Coverage of the kinematic $(p_T, y_{\rm cms})$-plane of the quarkonium and open heavy quark production data sets from proton-lead collisions. ALICE data is shown in red, ATLAS in blue, CMS in orange and LHCb in green. The dashed and solid contours show the estimated x-dependence for $\sqrt{s}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

Implementation of the data-driven approach in 1712.07024, 2012.11462 for heavy quarkonium data into the nCTEQ global analysis

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

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

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

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**

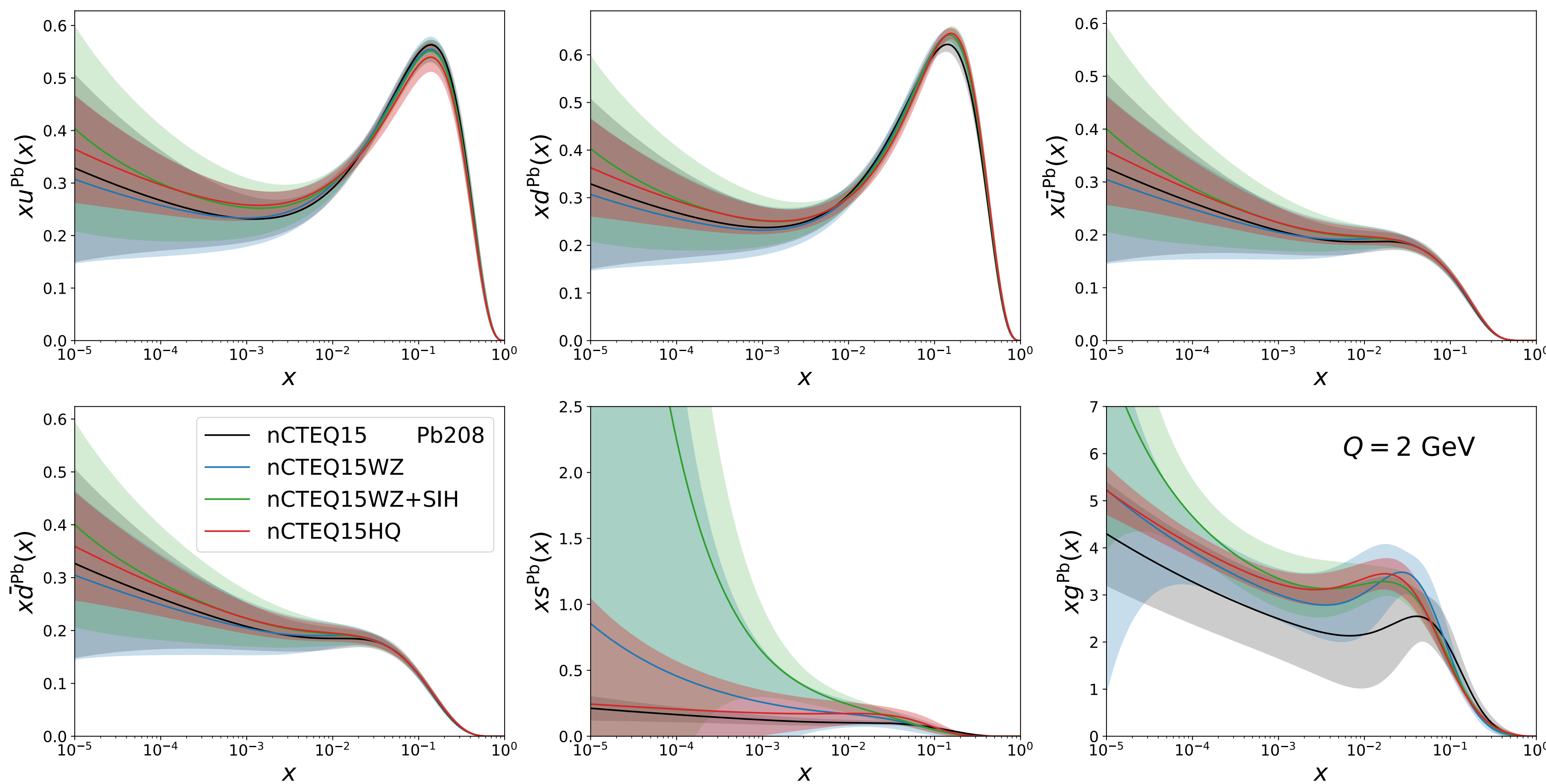


FIG. 4: Lead PDFs from different nCTEQ15 versions. The baseline nCTEQ15 fit is shown in black, nCTEQ15WZ in blue, nCTEQ15WZSIH in green, and the new fit in red.

nCTEQ15HQ nPDFs

arXiv:2204.09982

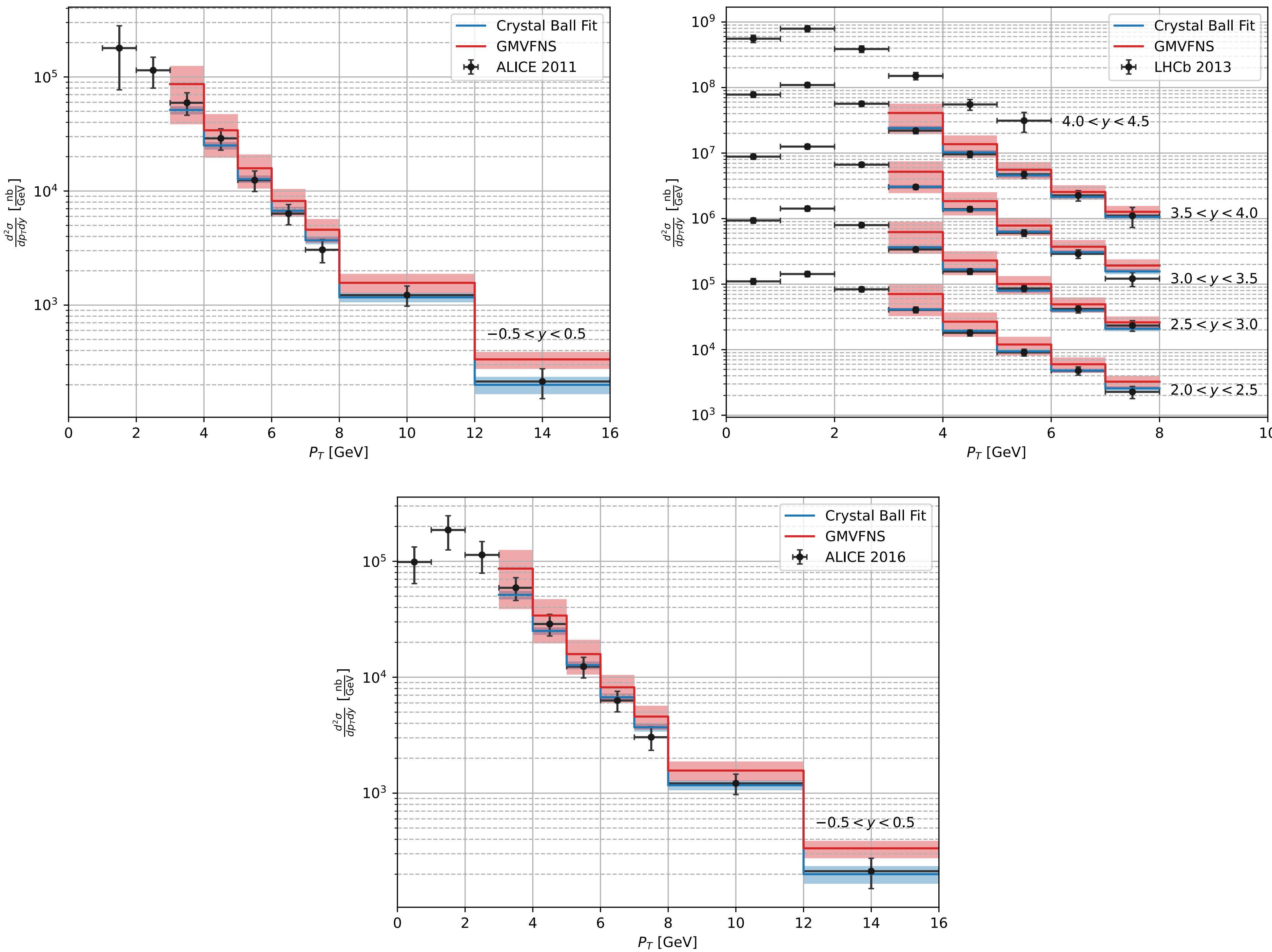


FIG. 3: Comparison between prompt D^0 production as predicted in the GMVFNS (red) and with the data-driven approach (blue). The uncertainties of the GMVFNS predictions come from varying the scales individually by a factor of 2, such that there is never a factor 4 between two scales. Different rapidity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

nCTEQ15HQ nPDFs

arXiv:2204.09982

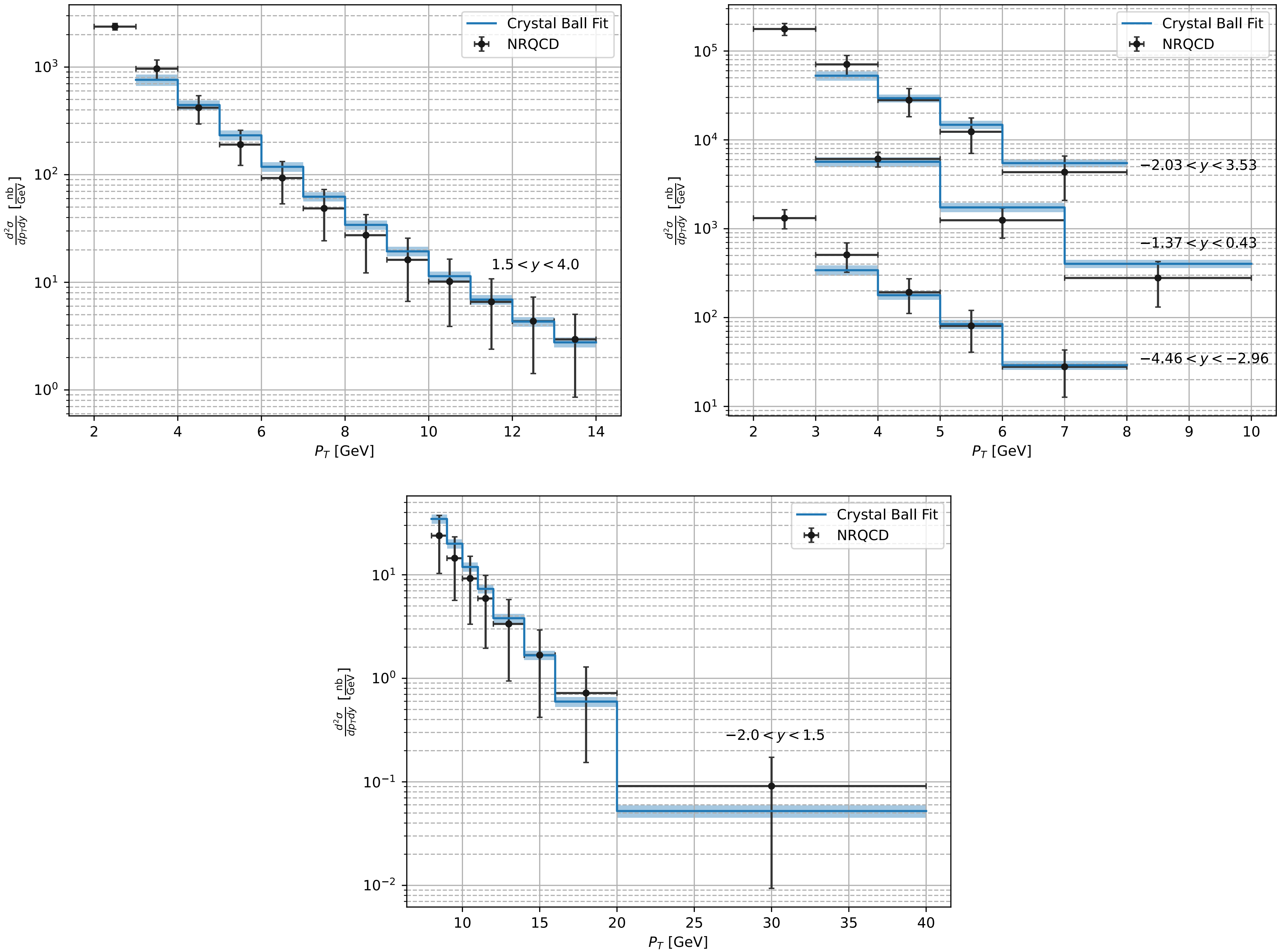


FIG. 2: Comparison between prompt J/ψ production in pp collisions for LHCb[87], ALICE[88] and ATLAS[89] kinematics as predicted by NRQCD and with the data-driven approach. The uncertainties of the NRQCD predictions come from scale variation $1/2 < \mu_r/\mu_{r,0} = \mu_f/\mu_{f,0} = \mu_{\text{NRQCD}}/\mu_{\text{NRQCD},0} < 2$ 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.

Updates from nNNPDF

nNNPDF3.0 [2201.123623]

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

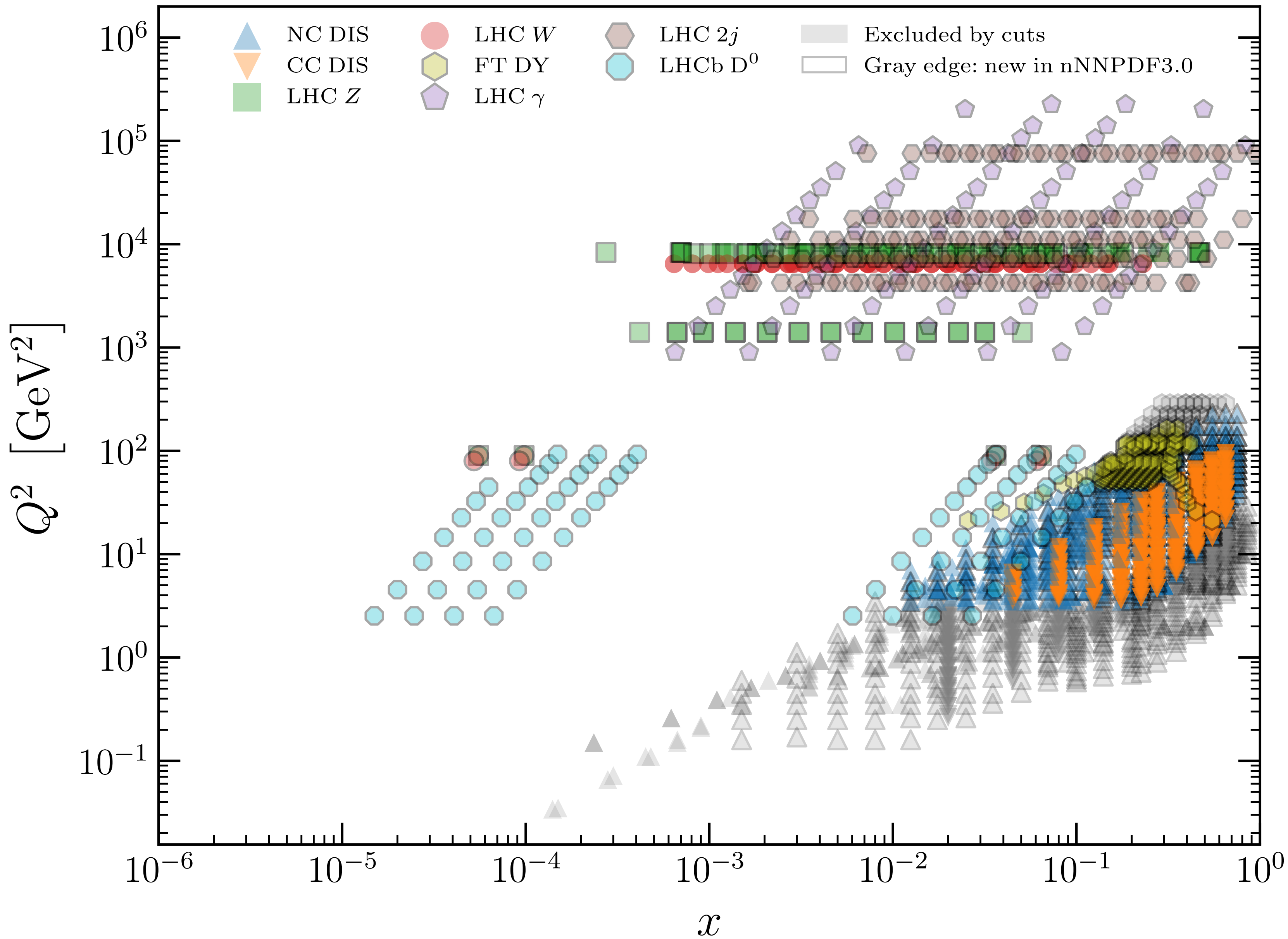
Process	Dataset	Ref.	$n_{\rm dat}$	Nucl. spec.	Theory
NC DIS	NMC 96	[53]	123/260	^{2}D/p	APFEL
	SLAC 91	[54]	38/211	^{2}D	APFEL
	BCDMS 89	[55]	250/254	^{2}D	APFEL
Fixed-target DY	FNAL E866	[56]	15/15	^{2}D/p	APFEL
	FNAL E605	[57]	85/119	^{64}Cu	APFEL
Collider DY	ALICE $W^\pm$, Z (5.02 TeV)	[58]	6/6	^{208}Pb	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



DIS-Cuts:
- $Q^2 > 3.5$ GeV^2
- $W^2 > 12.5$ 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)

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.

nNNPDF3.0 [2201.123623]

Comparison with EPPS16 and nCTEQ15WZSIH

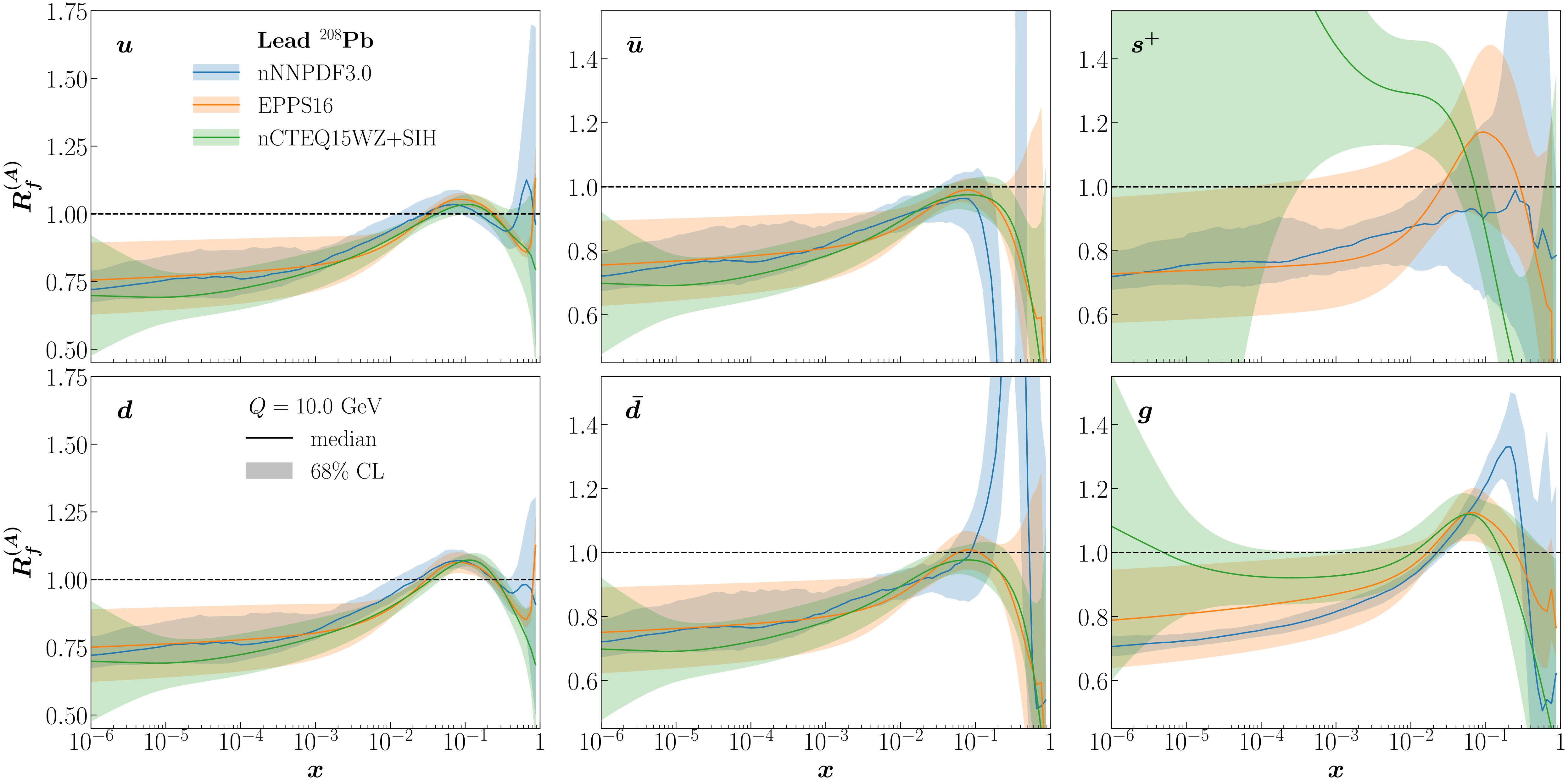


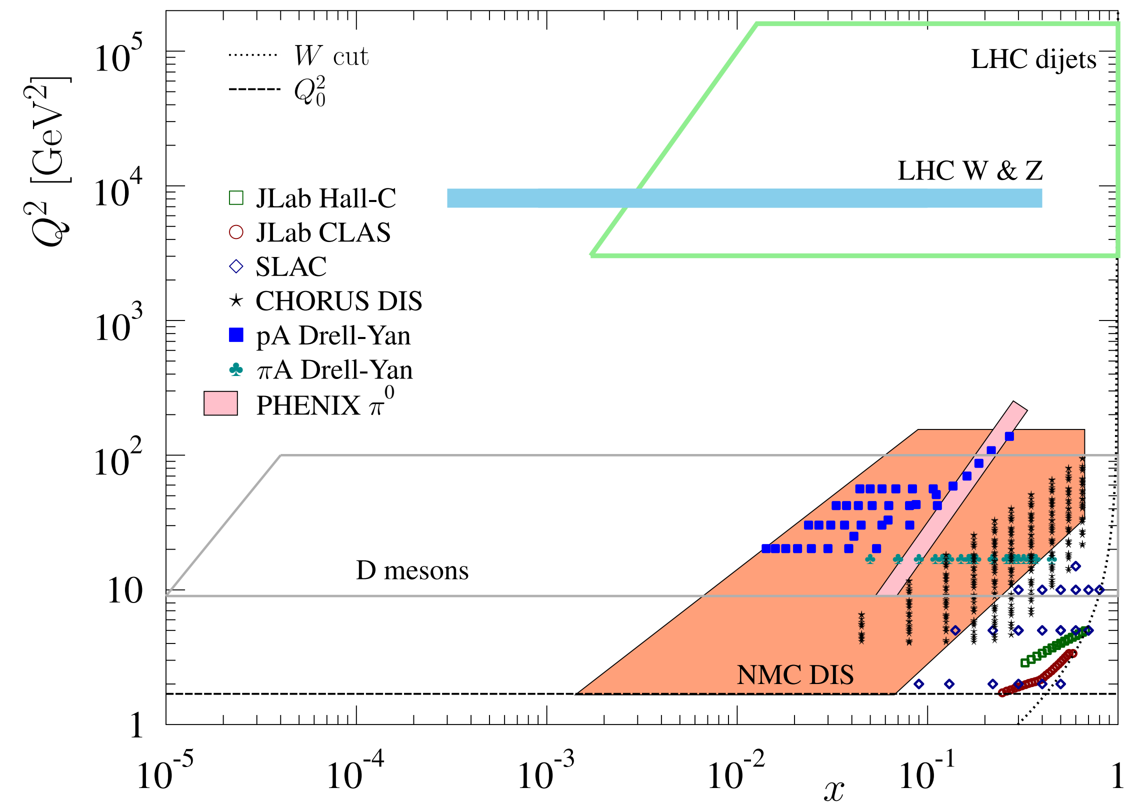
Figure 4.13. The nNNPDF3.0 predictions for the nuclear modification ratios in lead at $Q = 10$ GeV, compared to the corresponding results from the EPPS16 and nCTEQWZ+SIH global analyses. The PDF uncertainty bands correspond in all cases to 68% CL intervals.

Updates from EPPS

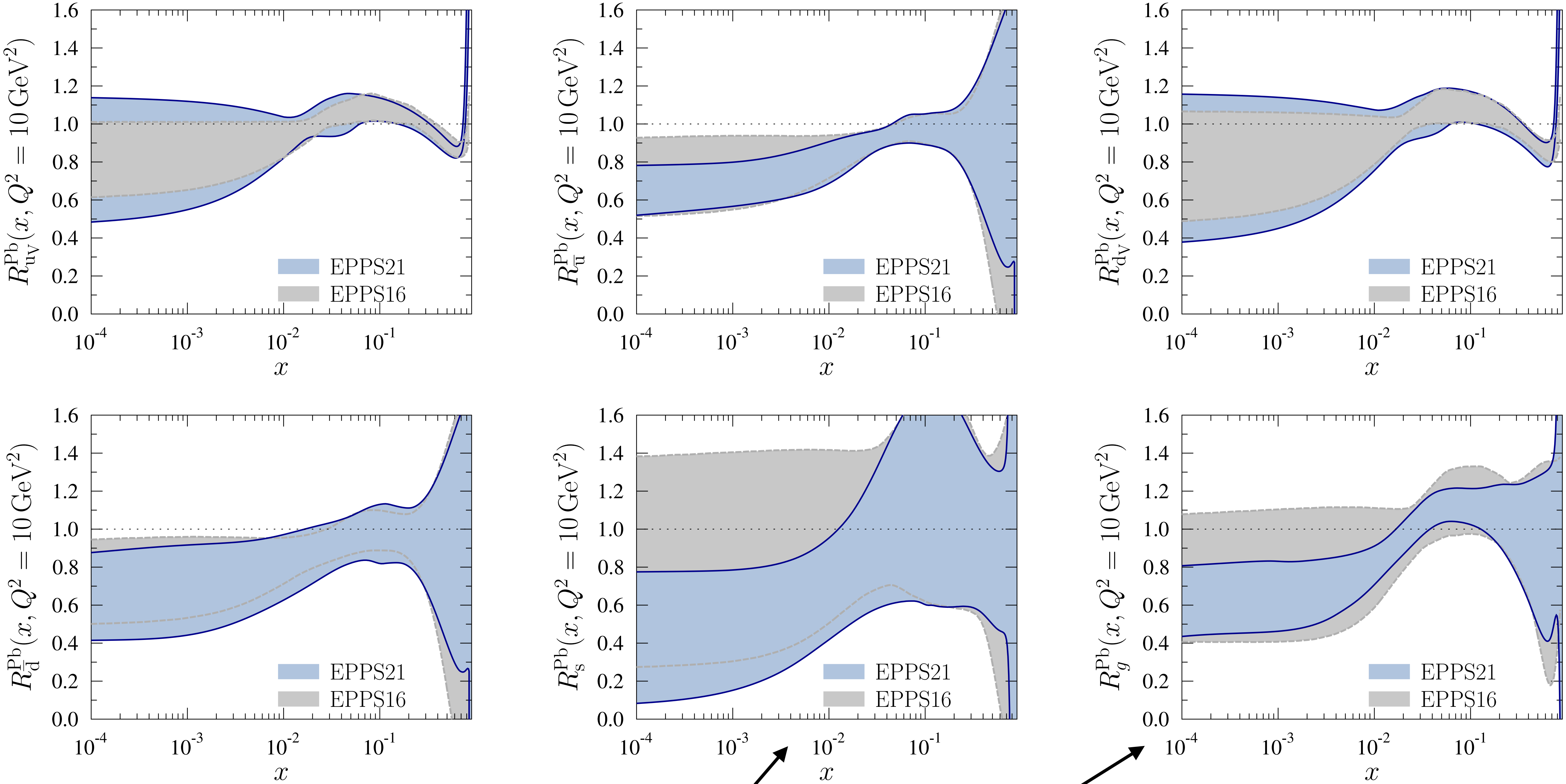
EPPS21 [2121.12462] vs EPPS16

- 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

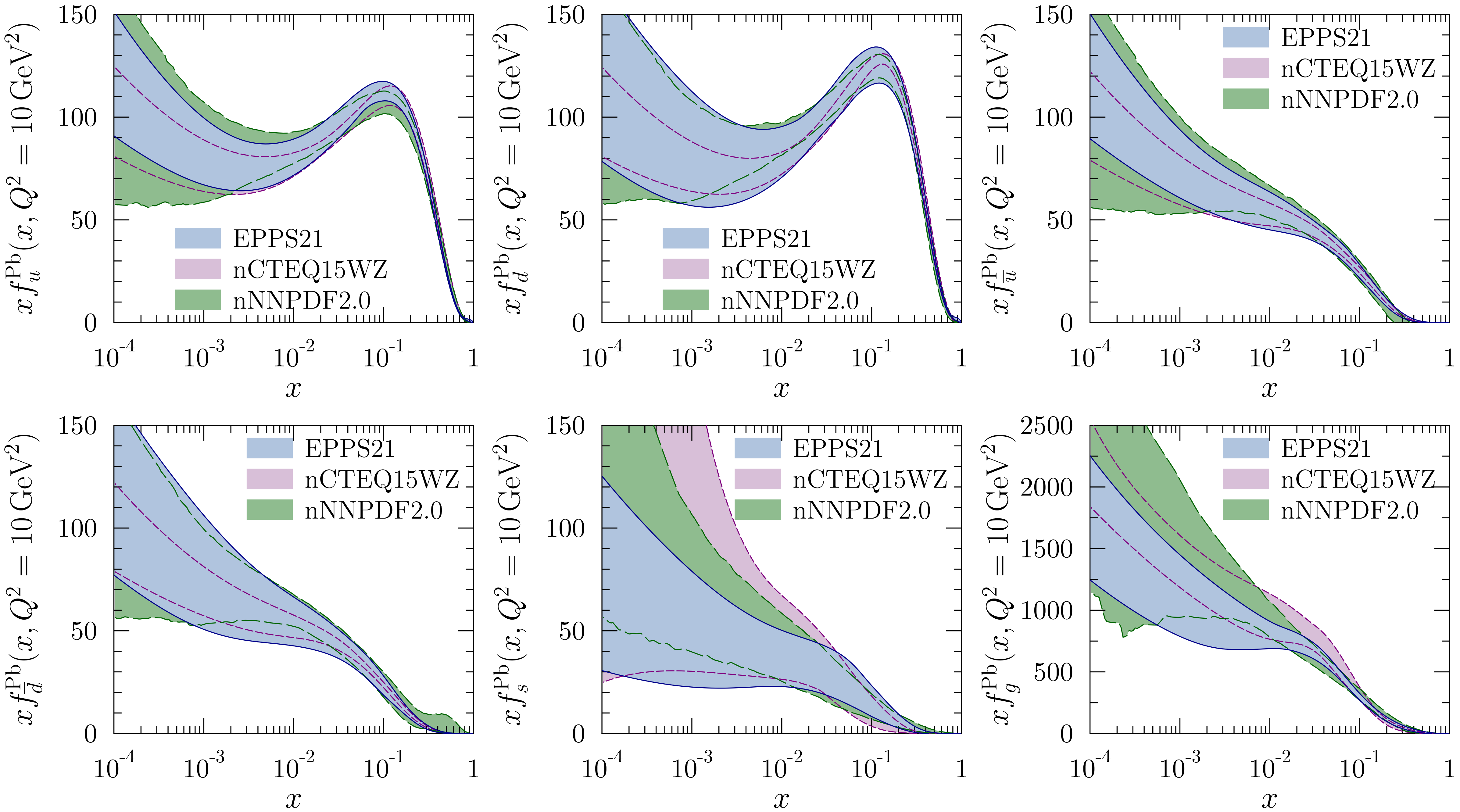


EPPS21 vs EPPS16



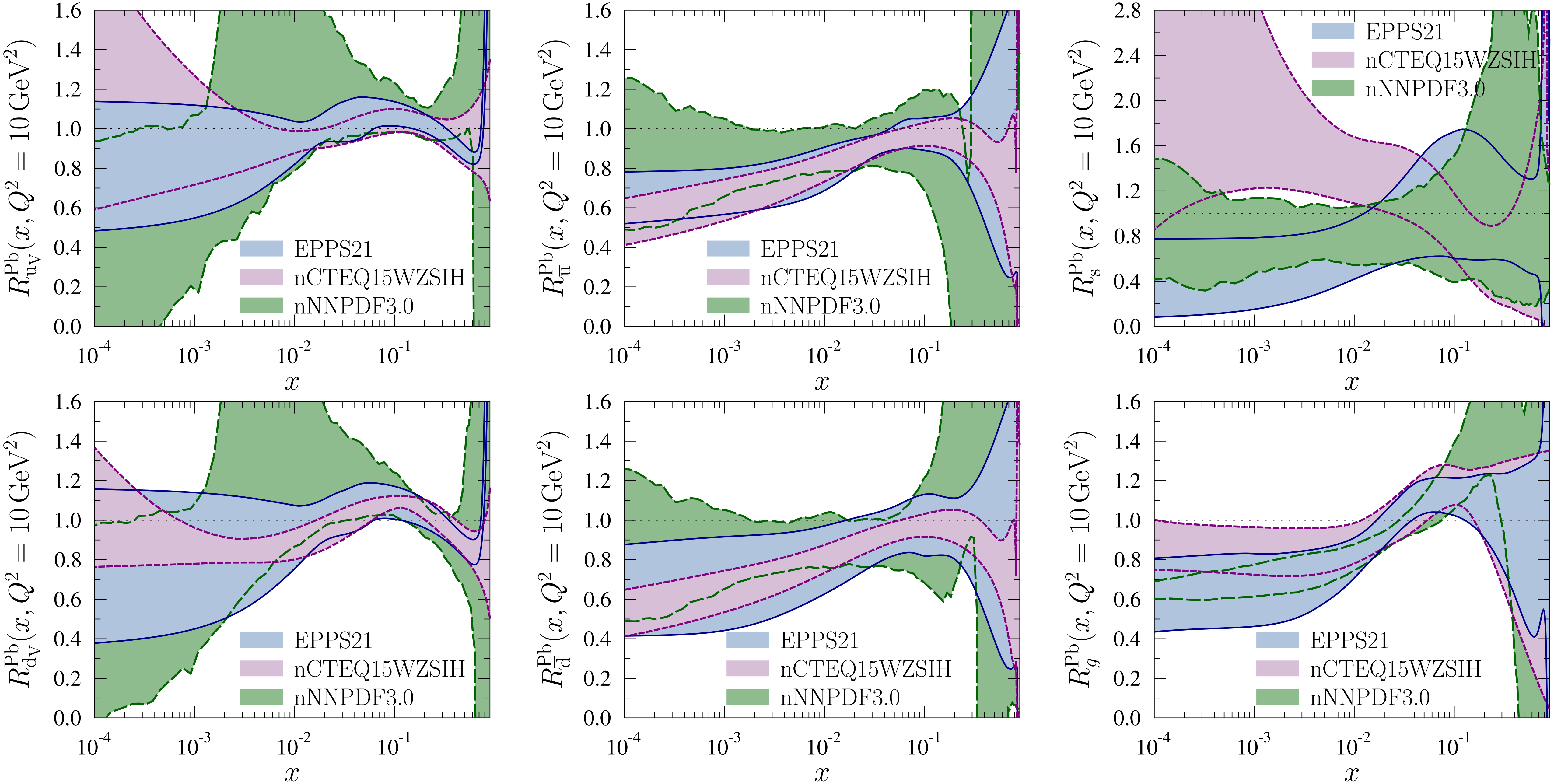
- Largest difference for strange quarks and gluons: much better constrained in EPPS21. Gluon due to D-meson and dijet data. Strange quark due to W, Z data and the more precise gluon.

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

EPPS21 vs nCTEQ15WZ and nNNPDF3.0



- All three mostly consistent within uncertainties, but significant differences flavour by flavour
- Gluon shadowing+antishadowing established!

Conclusions

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

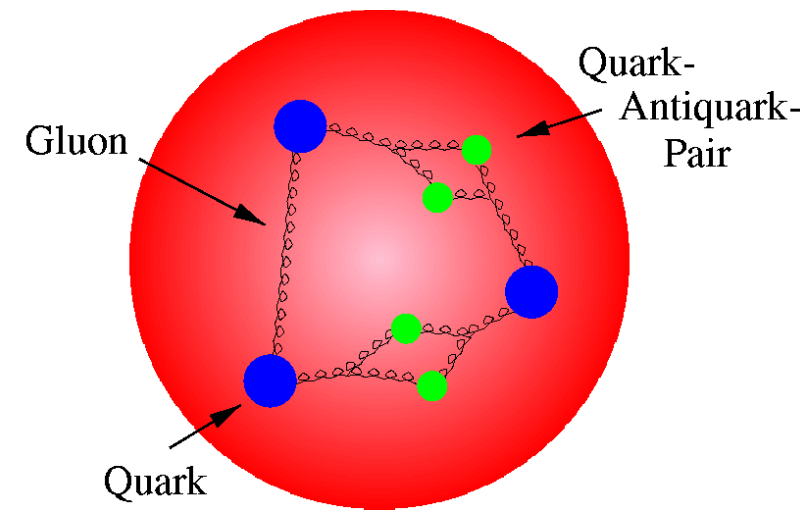
- **Future:**
  - More data, more **truly global fits**, improved precision
  - **Combined** proton PDF and nPDF fits ↔ **Lead-only fits**
  - nPDF fits with photon content
  - Fitted charm nPDFs ('intrinsic nuclear charm'?)
  - Better understanding of nuclear (A,Z)-dependence, x-dependence:
    - **Test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

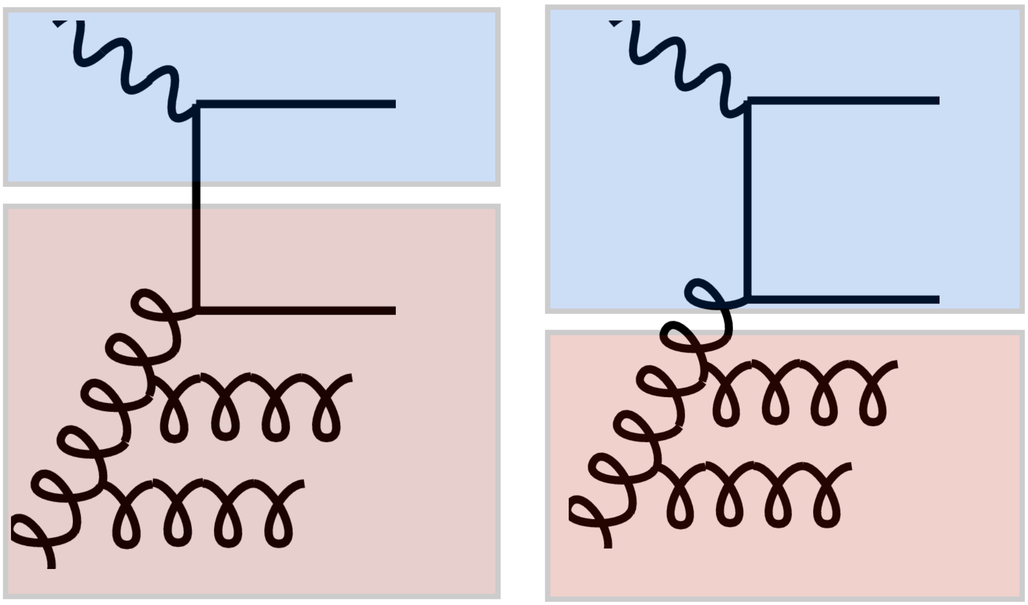
Thank you!

Backup

Is there charm in the nucleon wave function?

- Standard approach: **Charm entirely perturbative**
- <u>Heavy Flavour Schemes</u>
  - FFNS: charm not in the proton
    keep logs(Q/m) in fixed order
  - VFNS: charm PDF in the proton
    resum logs(Q/m)
- Different Heavy Flavour Schemes = different ways to organize the perturbation series
- What is structure? What is interaction?
  - Scheme dependence of PDF and of Wilson coefficient
  - Freedom to choose the factorization scale
- However, charm not so much heavier than Λ_{QCD}
  There could be a sizeable **non-perturbative** charm component
- Important to test the charm PDF experimentally





Charm PDFs

- Large majority of global analyses:

  Charm PDF is **calculated**, there is no fit parameter!

- Boundary condition for DGLAP evolution calculated perturbatively:

  (matching condition when switching from n_f=3 to n_f=4 flavours)

  $c(x,Q=m_c) = 0$ @NLO, MSbar

- Is there a (sizable) non-perturbative contribution to the twist-2 charm PDF?

  After all, we cannot calculate the strange PDF in perturbation theory and charm is not so heavy. So we may fit the charm PDF boundary condition (**Fitted Charm**)

- **Answers** can come from:

  - global analysis: **need data sensitive to charm**
    Fitted Charm vs Perturbatively Generated Charm

  - lattice calculations: even one or two moments would help

Models

- For a review see arXiv:1504.06287
- Most models are concentrated at large x and have a precise x-shape but do not predict the scale (BHPS, Meson-Baryon models)
- In some models $c(x) = \bar{c}(x)$ in others not
- In global analyses also phenomenological models with a sea-like charm (broad range in x) are analyzed

Brodsky-Hoyer-Peterson-Sakai (BHPS) model

PLB93(1980)451

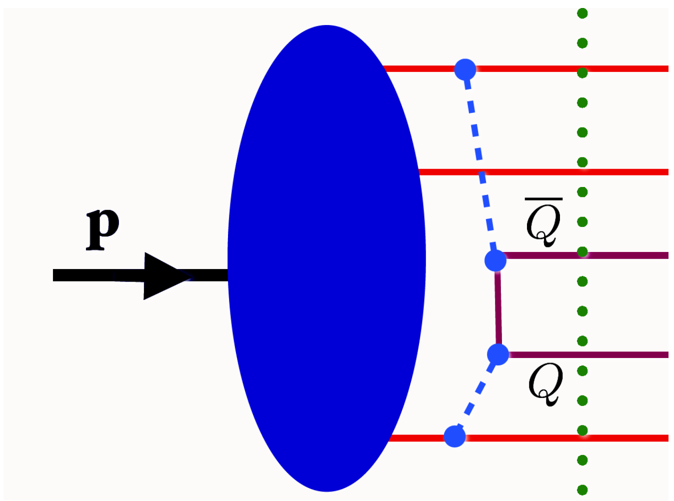


Figure 1: Five-quark Fock state $|uudQ\overline{Q}\rangle$ of the proton and the origin of the intrinsic sea.

- Light cone Fock space picture: $|p\rangle = |uud\rangle + |uudg\rangle + | + uudc\bar{c}\rangle + \ldots$
- |uudQQbar> state with heavy quarks connected to valence quarks, fundamental property of wave function
- IC PDF: transition matrix element $|p\rangle \to |uudc\bar{c}\rangle$ calculable in old-fashioned perturbation theory:

$$P(p \to uudc\bar{c}) \sim \left[M^2 - \sum_{i=1}^{5} \frac{k_{\perp i}^2 + m_i^2}{x_i}\right]^{-2}$$

- Intrinsic contribution dominant at large x and on the order $O(\Lambda^2/m_Q^2)$

The x-dependence predicted by the BHPS model, unknown at which scale:

$$c_1(x) = \bar{c}_1(x) \propto x^2[6x(1+x)\ln x + (1-x)(1+10x+x^2)]$$

Typical moments;

	$\int_0^1 dx\ c(x)$	$\int_0^1 dx\ x\,[c(x)+\bar{c}(x)] \equiv < x >_{c+\bar{c}}$
CTEQ6.6	0	0
CTEQ6.6c0	0.01	0.0057
CTEQ6.6c1	0.035	0.0200

Meson-Baryon models

Hobbs,Londergan,Melnitchouk,PRD89(2014)074008

- 5-quark states from hadronic interactions

- Framework conserving spin/parity

- Non-perturbative mechanisms needed to break
  $c(x, Q^2 \leq m_c^2) = \bar{c}(x, Q^2 \leq m_c^2) = 0$

- EFT which connects IC to properties of the hadronic spectrum
  $$|N\rangle = \sqrt{Z_2}\,|N\rangle_0 + \sum_{M,B} \int dy\, f_{MB}(y)\,|M(y); B(1-y)\rangle$$
  with $y = k^+/P^+$ where k is meson and P nucleon momentum

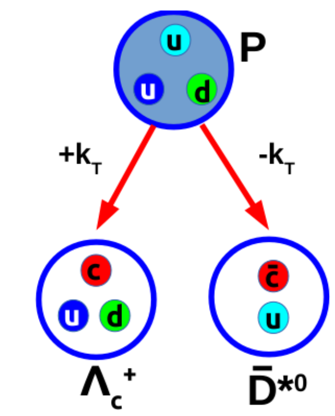
- $c(x) = \sum_{M,B} \left[\int_x^1 \frac{d\bar{y}}{\bar{y}} f_{MB}(\bar{y}) c_B\left(\frac{x}{\bar{y}}\right) \right]$, similar for $\bar{c}(x)$

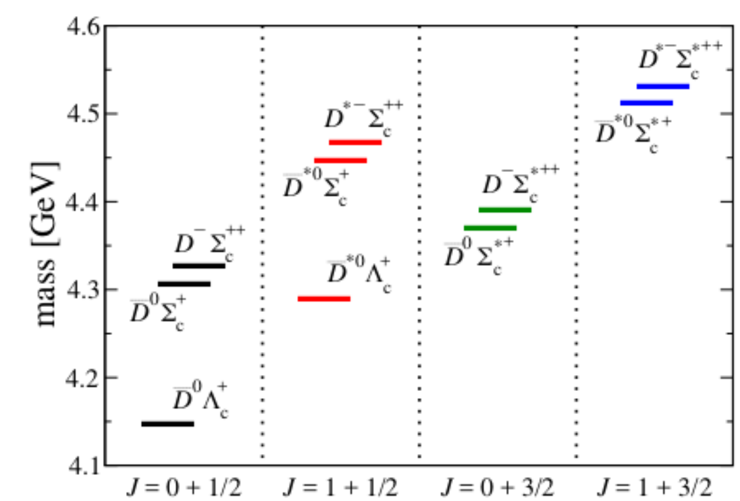
- MB-Model depends on UV cutoff Λ, predicts high-x excess

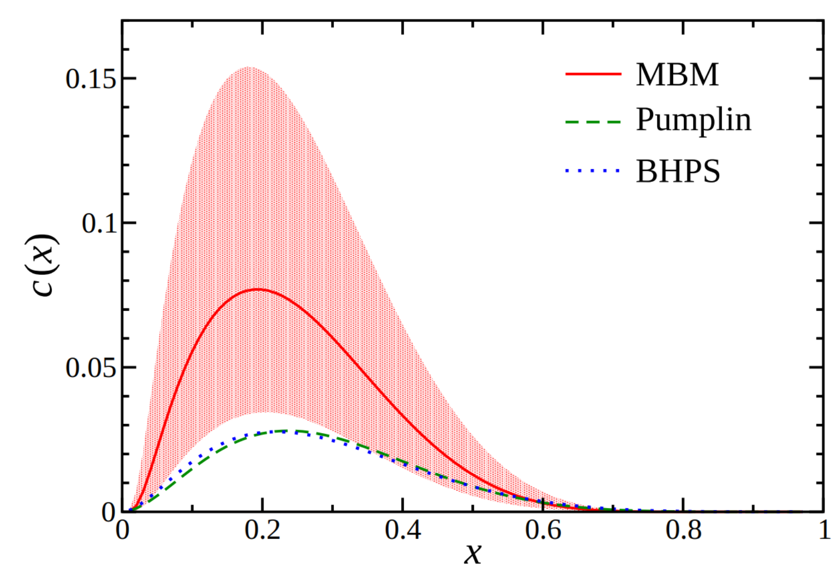
- Universal cutoff Λ tuned to ISR $pp \to \Lambda_c + X$ data

multiplicities, **momentum sum**:

$$\langle n\rangle_{MB}^{(\mathrm{charm})} = 2.40\%\,{}^{+2.47}_{-1.36}; \qquad P_c := \langle x\rangle_{\mathrm{IC}} = 1.34\%\,{}^{+1.35}_{-0.75}$$





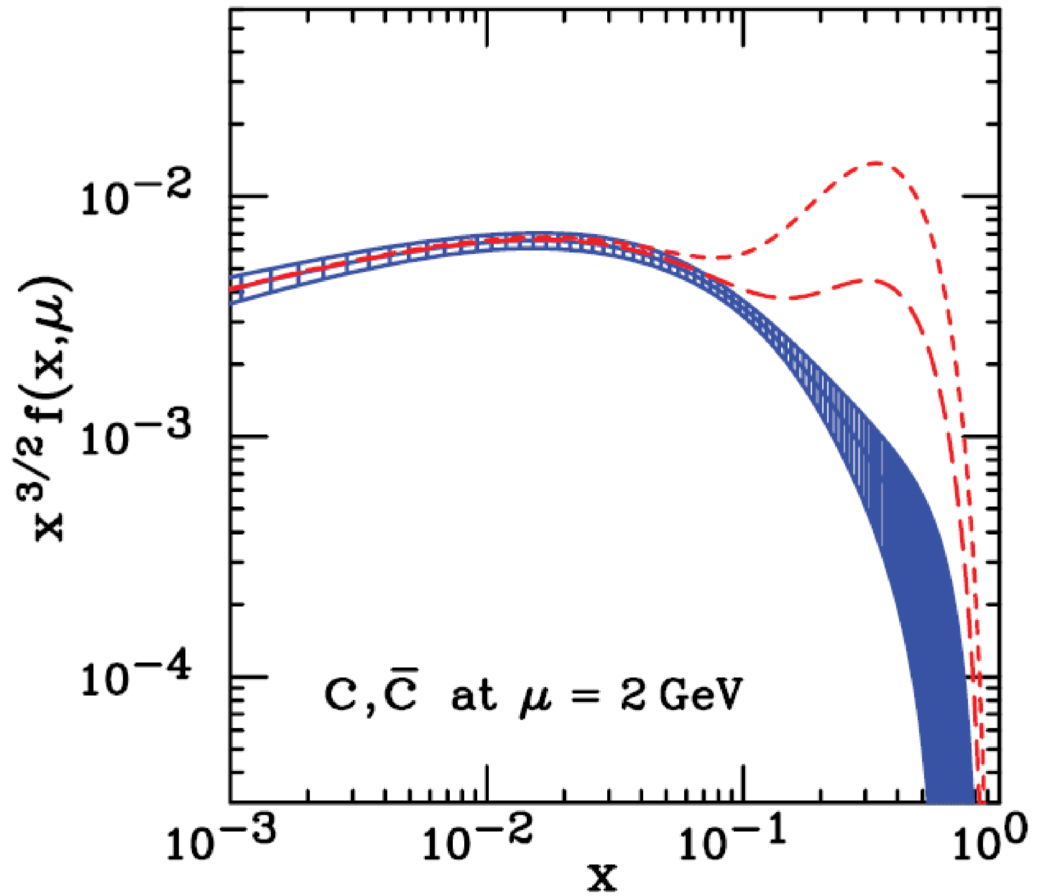


A global fit by CTEQ to extract IC

PHYSICAL REVIEW D 75, 054029 (2007)

Charm parton content of the nucleon

J. Pumplin,[1,*] H. L. Lai,[1,2,3] and W. K. Tung[1,2]



Blue band corresponds to CTEQ6 best fit, including uncertainty

Red curves include intrinsic charm of 1% and 3% (χ^2 changes only slightly)

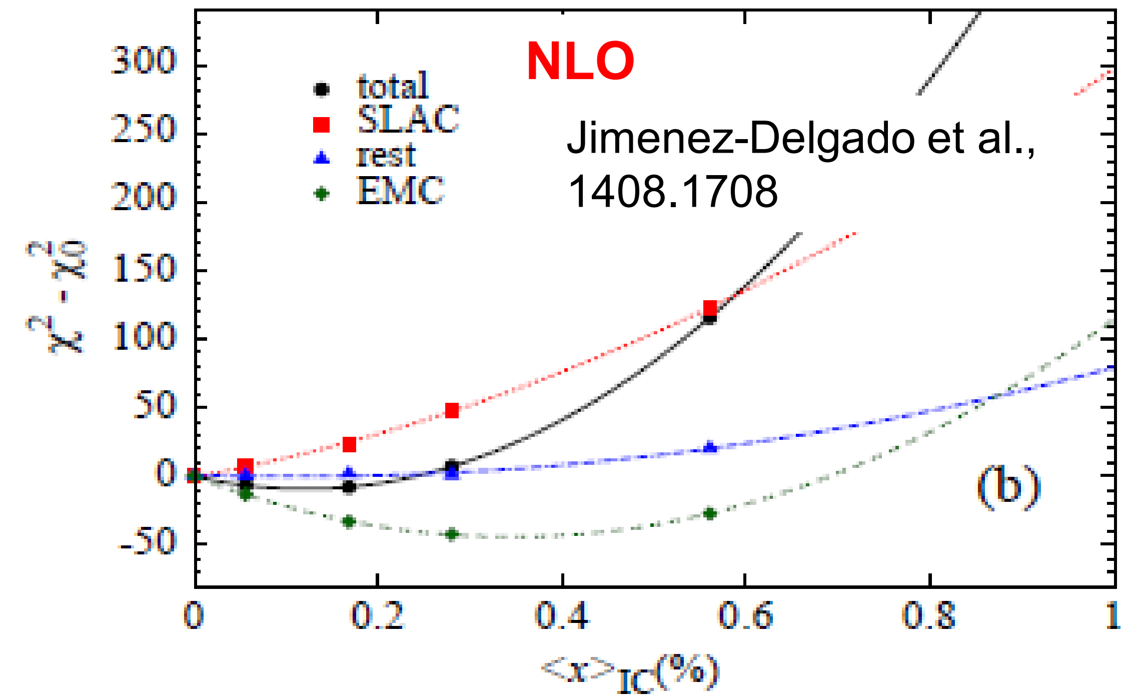
We find that the range of IC is constrained to be from zero (no IC) to a level 2–3 times larger than previous model estimates. The behaviors of typical charm distributions within this range are described, and their implications for hadron collider phenomenology are briefly discussed.

No conclusive evidence for intrinsic-charm

PDFs with fitted charm ca. 2016

Several studies conclude that IC may carry no more than 1% of the proton's momentum

Constraints depend on data selection (e.g., on whether the EMC F_2^c data are included) and methodology (CTEQ vs. NNPDF)



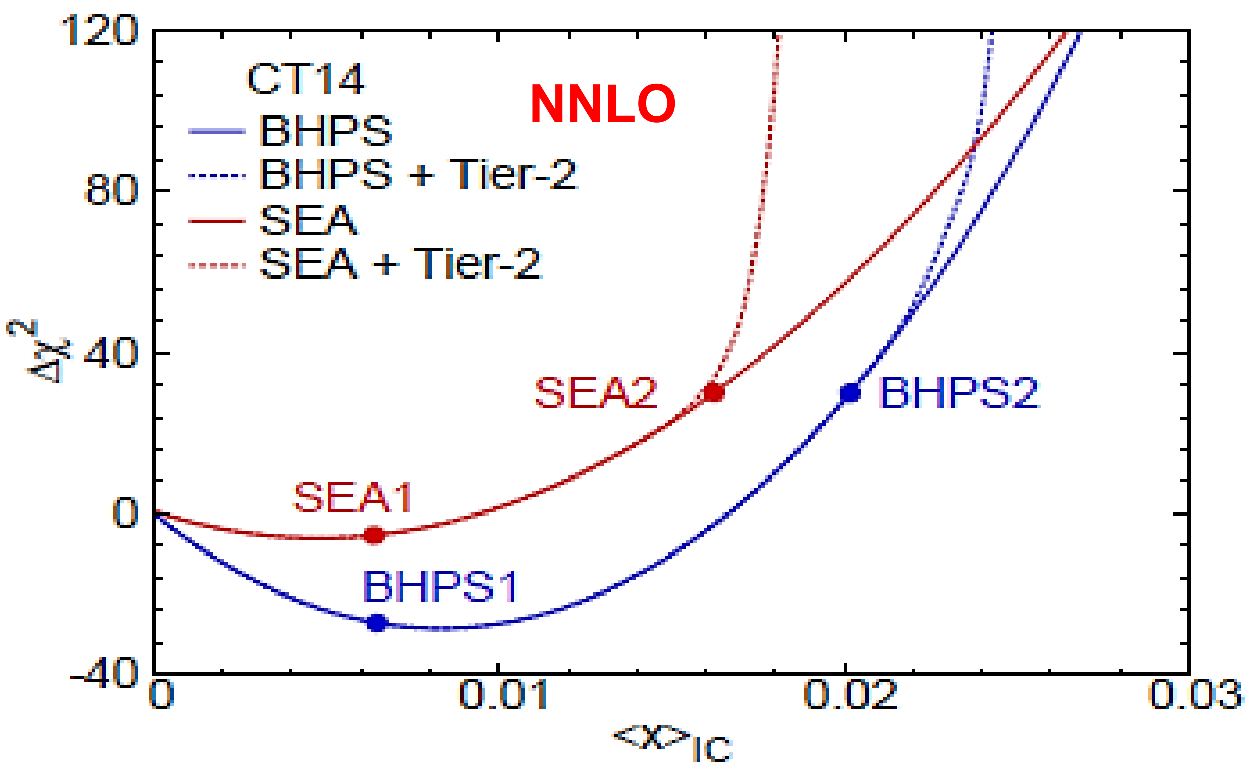
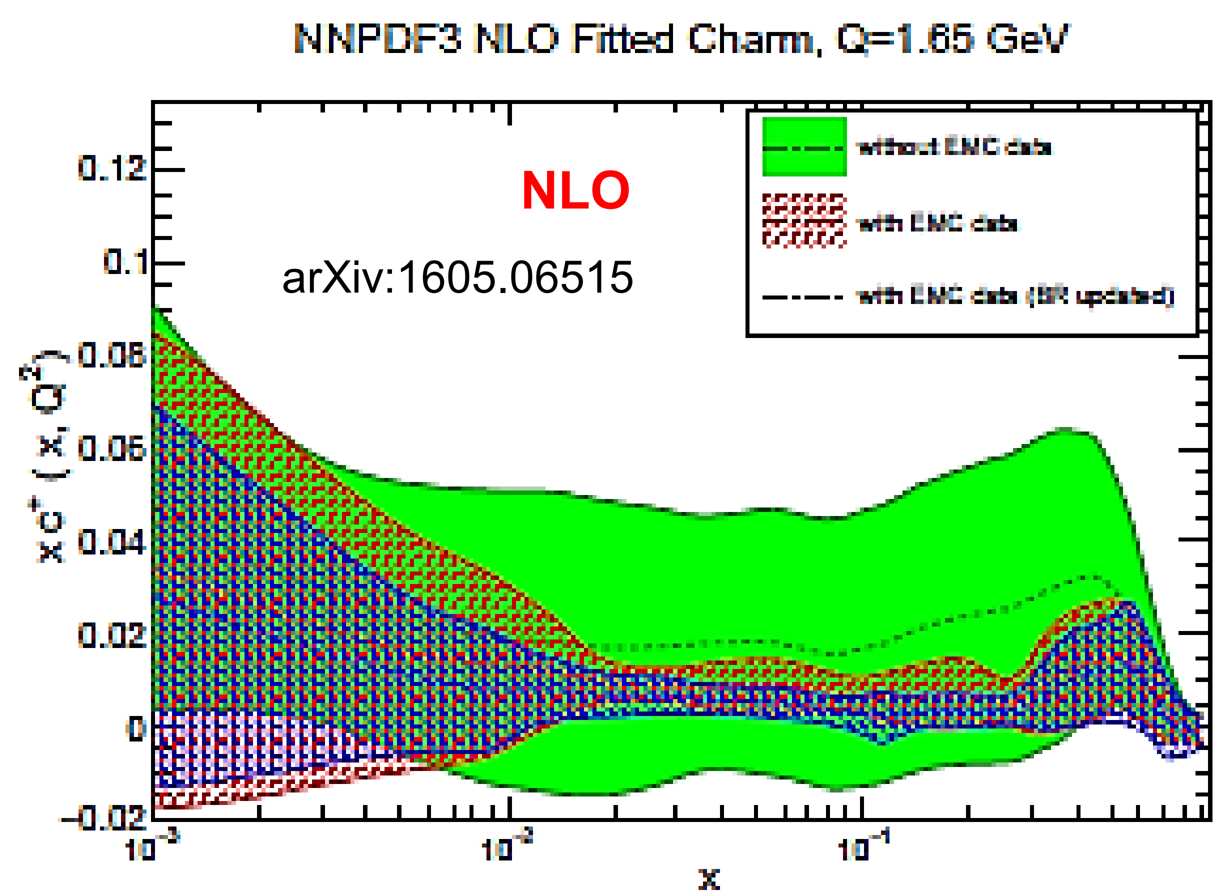


Figure 1: The $\Delta\chi^2$ versus the momentum fraction of charm $\langle x \rangle_{IC}$. **PoS DIS2015 (2015) 166**

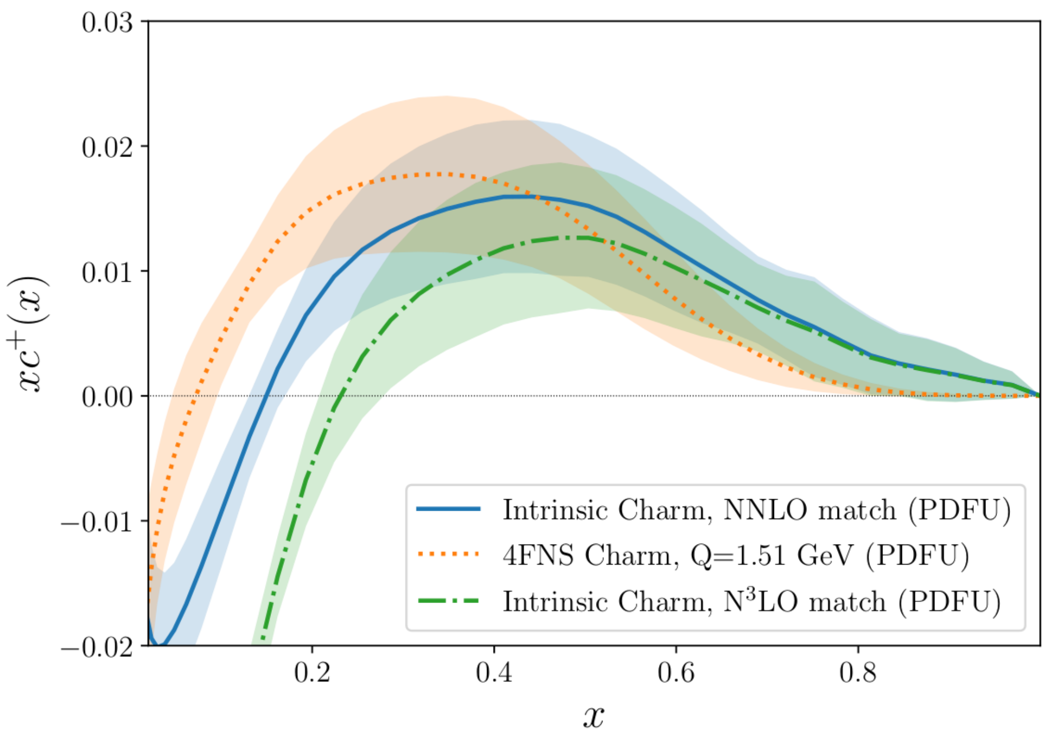


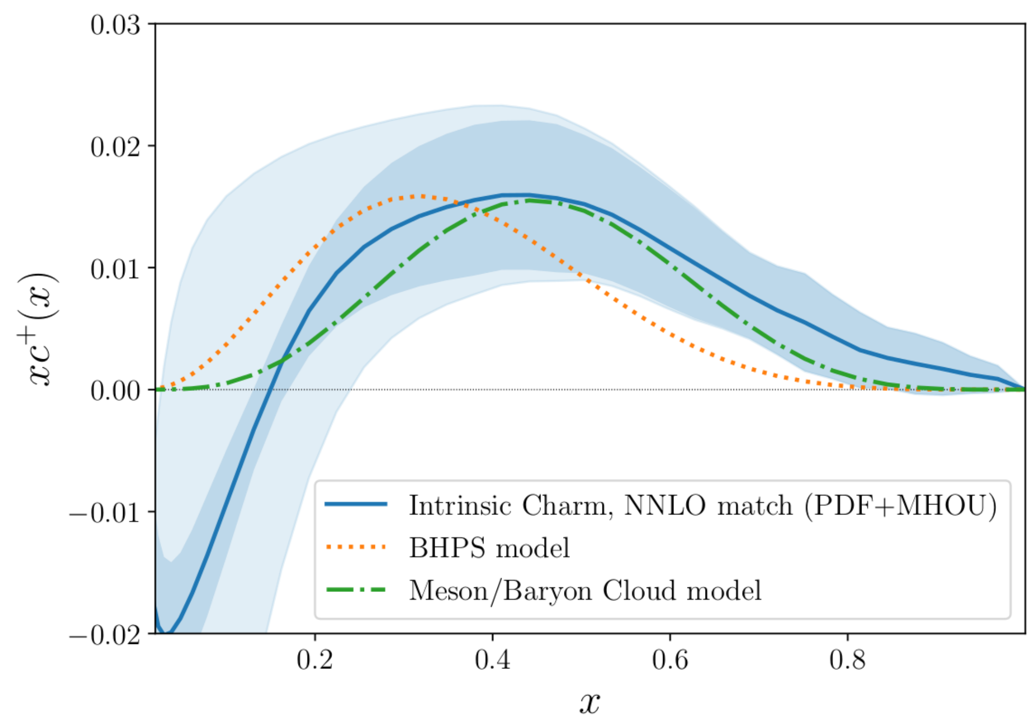
The latest IC results from NNPDF

Talk by Giacomo Magni

NNPDF, Nature 608 (2022) 7923, 483; 2208.08372

- NNPDF claims 3-sigma evidence for 'IC' (or safer: 3-sigma evidence for non-pert charm)
- Based on local (x-dependent) deviation of FC PDF from perturbative scenario
- Depends crucially on size and shape of PDF uncertainty





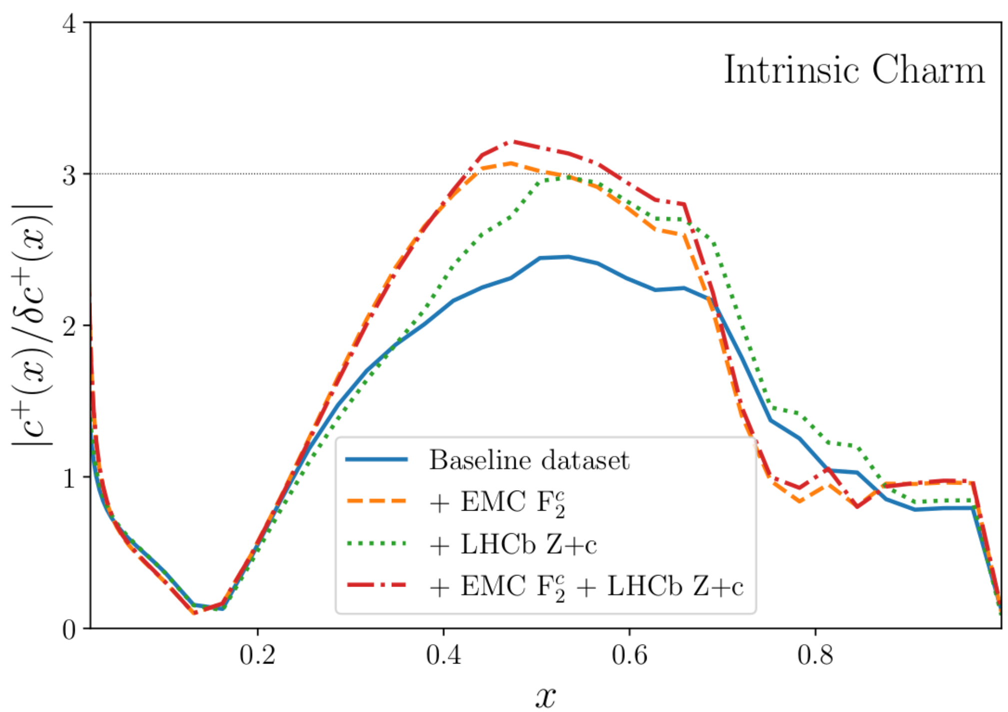
- IC PDF quite hard, peaking at $x \gtrsim 0.4$
- Low-x behaviour:
  - rather big differences between NNLO and N3LO matching (perturbative stability?)
  - Negative IC at small-x unlike models
  - MHOU persists to quite high $x \gtrsim 0.2$

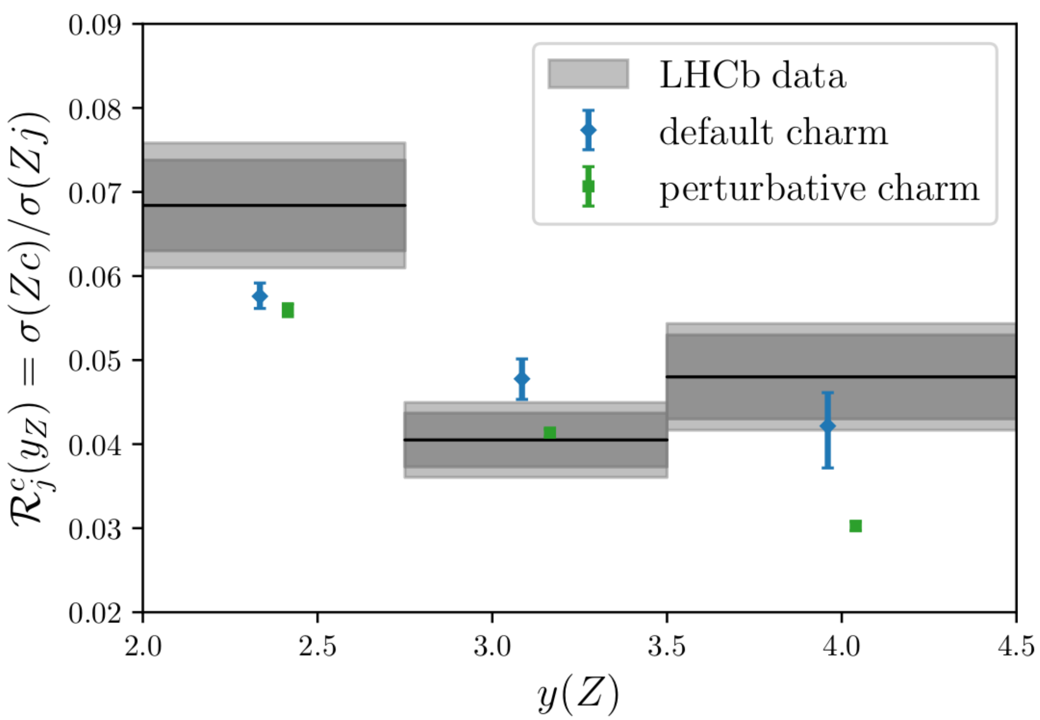
The latest IC results from NNPDF

Talk by Giacomo Magni

NNPDF, Nature 608 (2022) 7923, 483; 2208.08372

- 3-sigma evidence for 'IC' reached with LHCb Z+c data
- Theory uncertainties for these data remain large (showering, final state effects)





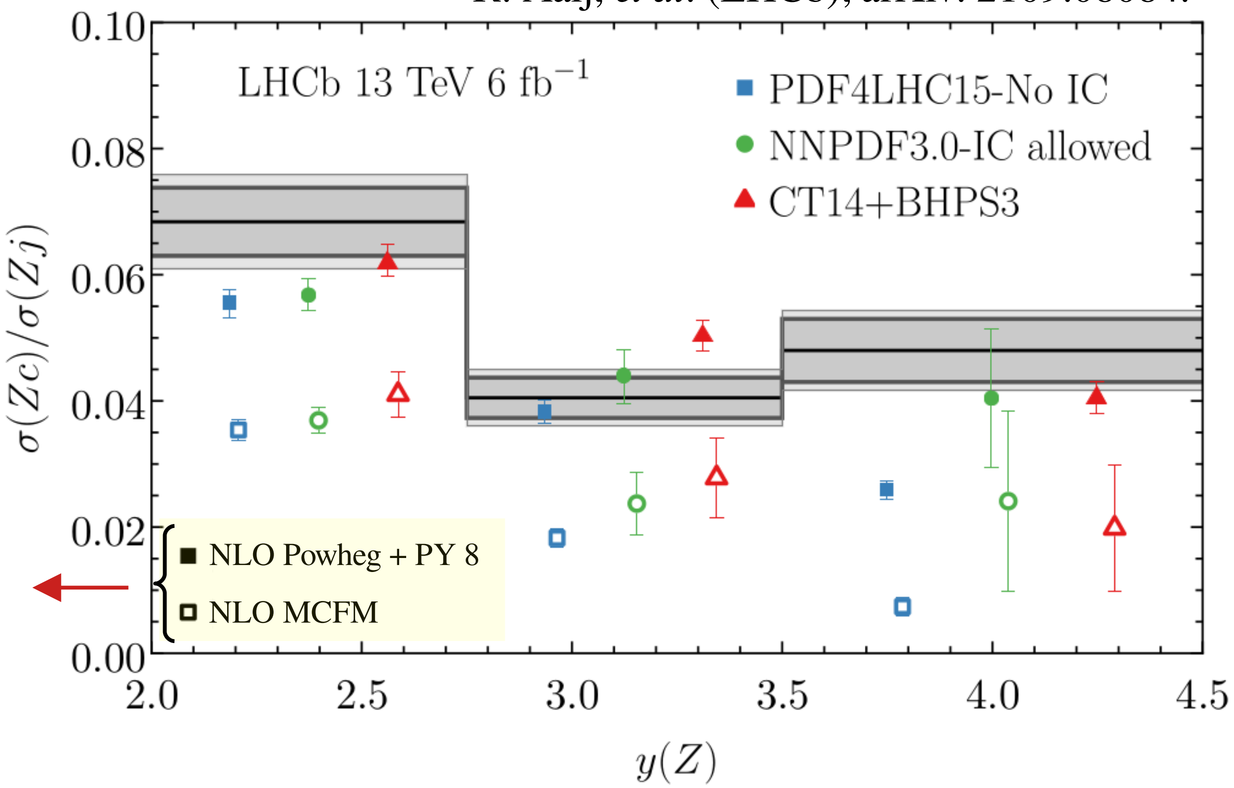
- 2.5-sigma significance with baseline data set
- Similar group of experiments in CT18 FC does not yield strong signal (larger uncertainties): see 2211.01387
- Future improvements due to data from: LHC, EIC, CERN FPF, Fixed target experiments

Z+c production at LHC

Boetcher,Ilten,Williams, 1512.06666

- Z+c potentially sensitive to IC
- Sizable theory uncertainties: calculated NLO cross section ratio depends on showering, hadronization
- 2022 LHCb 13 TeV data: (Z+c)/(Z+jet) ratios; 3 rapidity bins; most forward bins probes large-x

R. Aaij, *et al.* (LHCb); arXiv: 2109.08084.



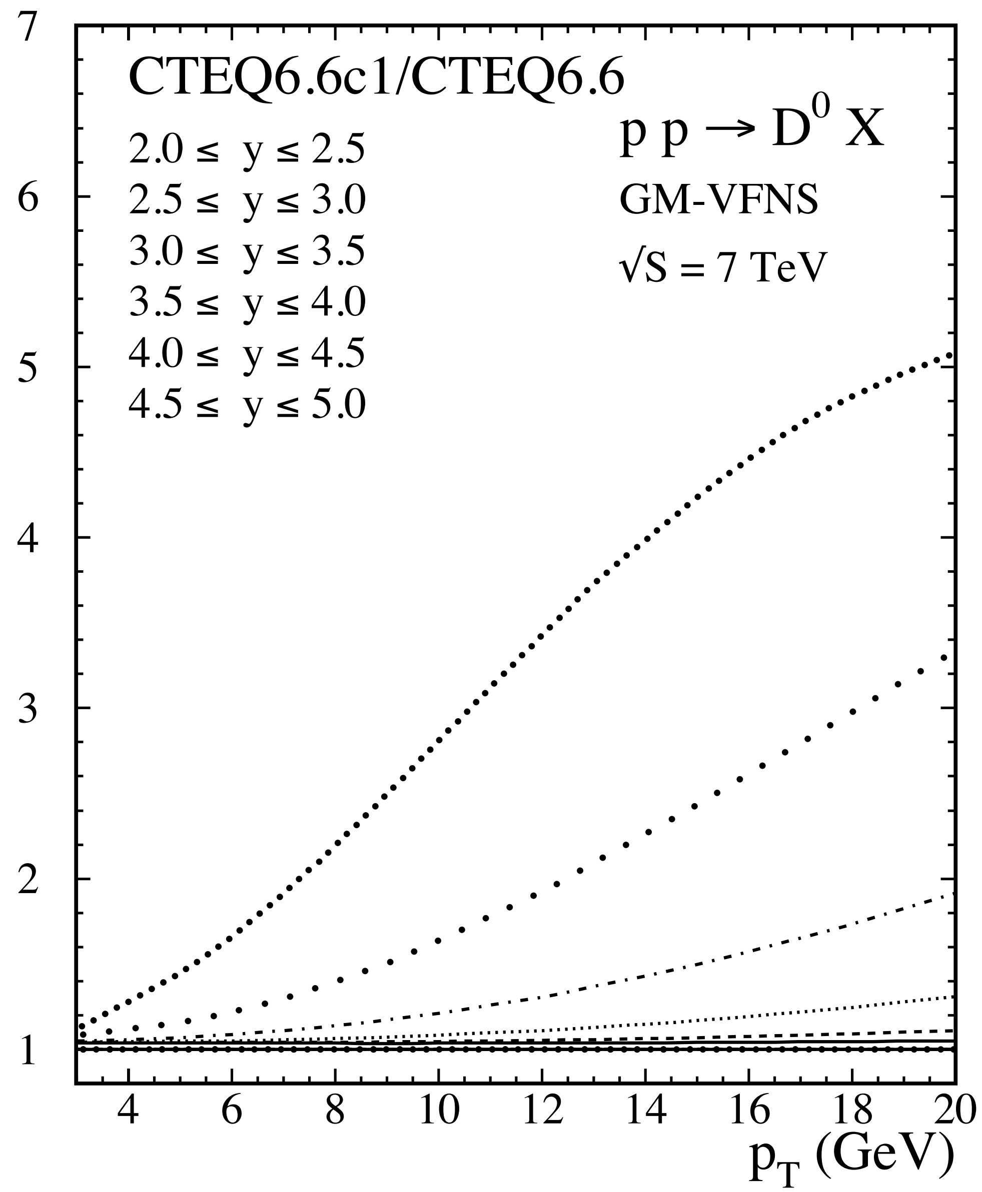
differ due to large FSR correction

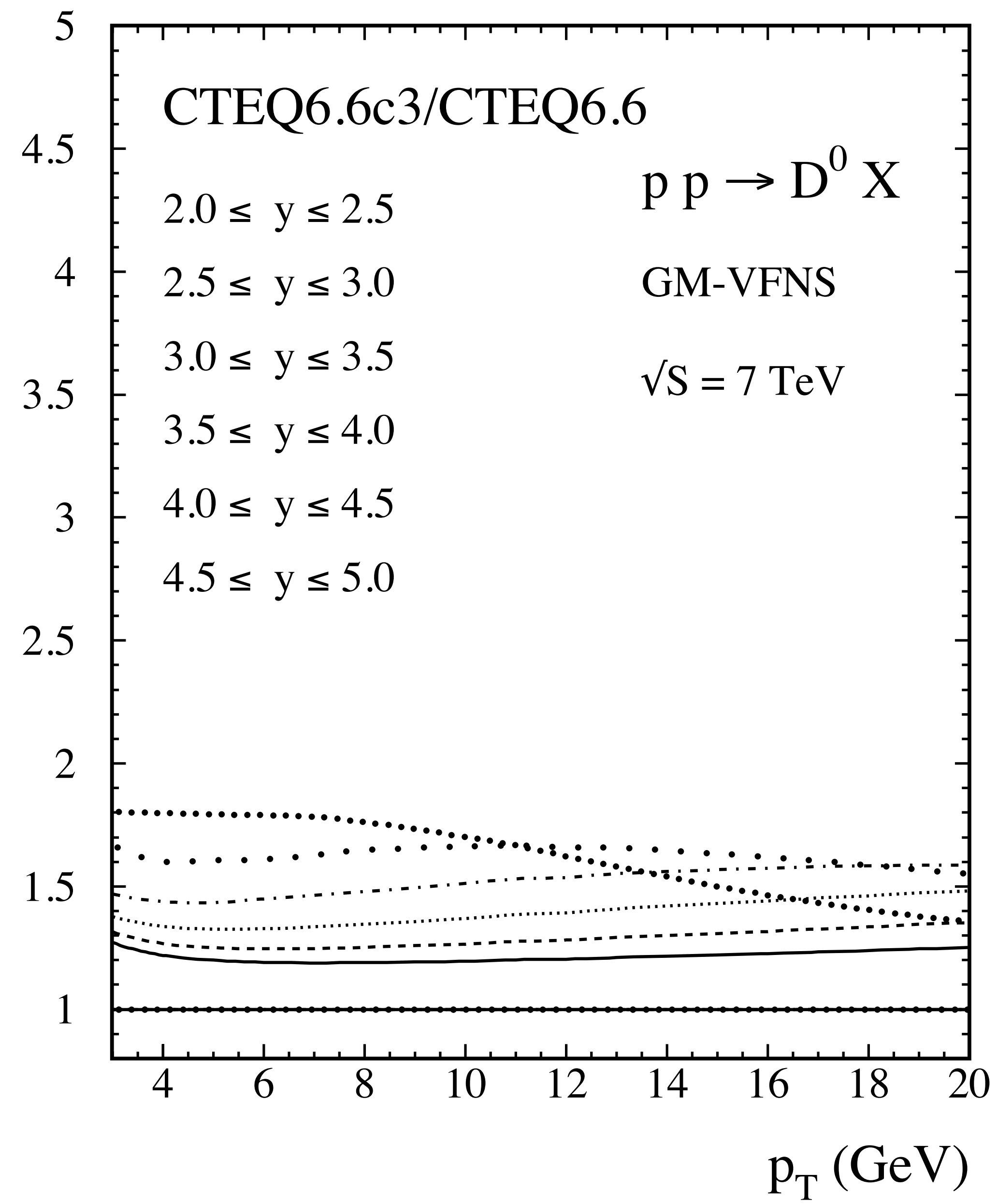
$$x \sim \frac{Q}{\sqrt{s}} \exp y$$

- NNLO calculations recently available: R. Gauld et al: 2005.03016; M. Czakon et al: 2011.01011
Not yet implemented in PDF fits
- Need NNLO; control over showering, final state effects

Inclusive D meson production at LHCb

arXiv:1202.0439,arXiv:0901.4130





CTEQ6.6 updated:

BHPS, 3.5 % $(c + \bar{c})$ at $\mu = 1.3$ GeV

high-strength sea-like charm

➜ large effects expected at large rapidities

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 $\rightarrow$ require numerical precision
- use noise reducing derivatives

N = Au

N = Pb N = Fe