Recent progress on proton and nuclear PDFs at the LHC

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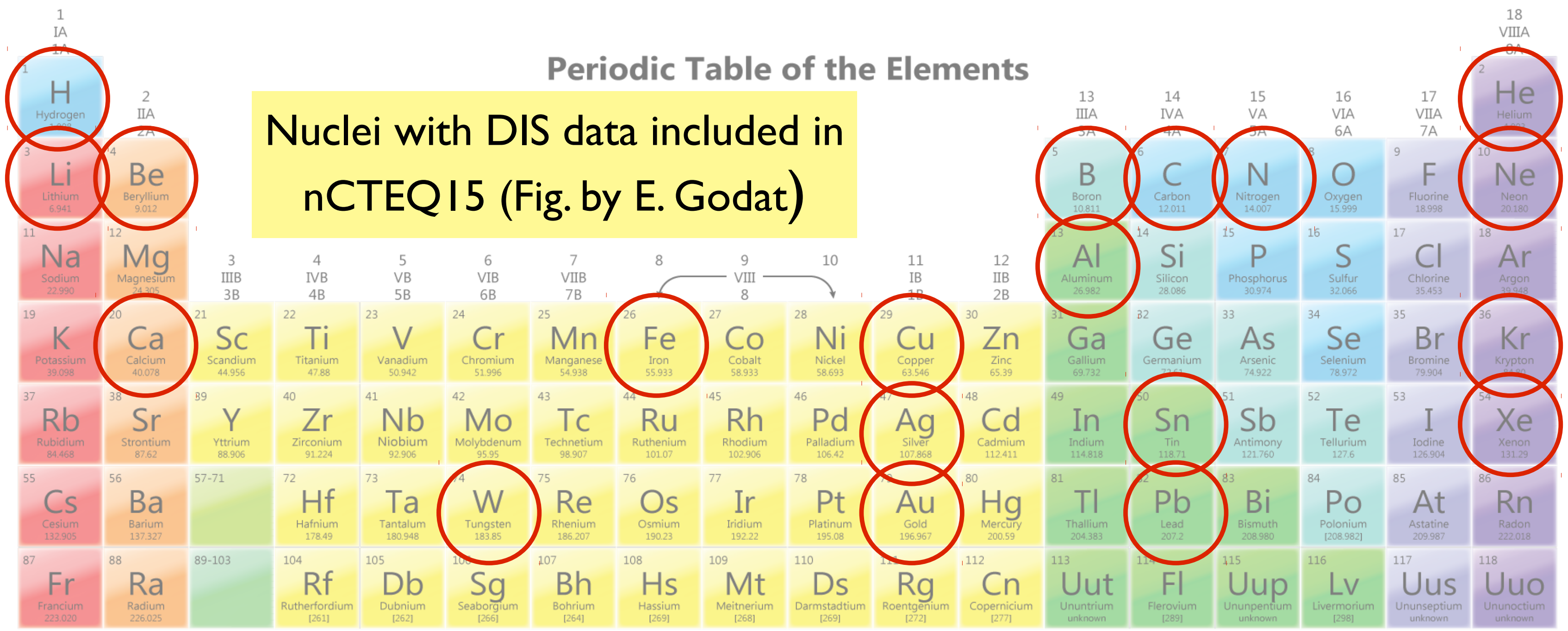
Plan

- Proton and nuclear PDFs: Common framework
- Proton PDFs
  - PDFs replicas with scale variations
  - Tools for theory calculations
  - Intrinsic charm
- Recent progress on nuclear PDFs
  - Updates from EPPS
  - Updates from nCTEQ
  - Updates from nNNPDF

Proton and nuclear PDFs:
Common framework

Nuclear PDFs

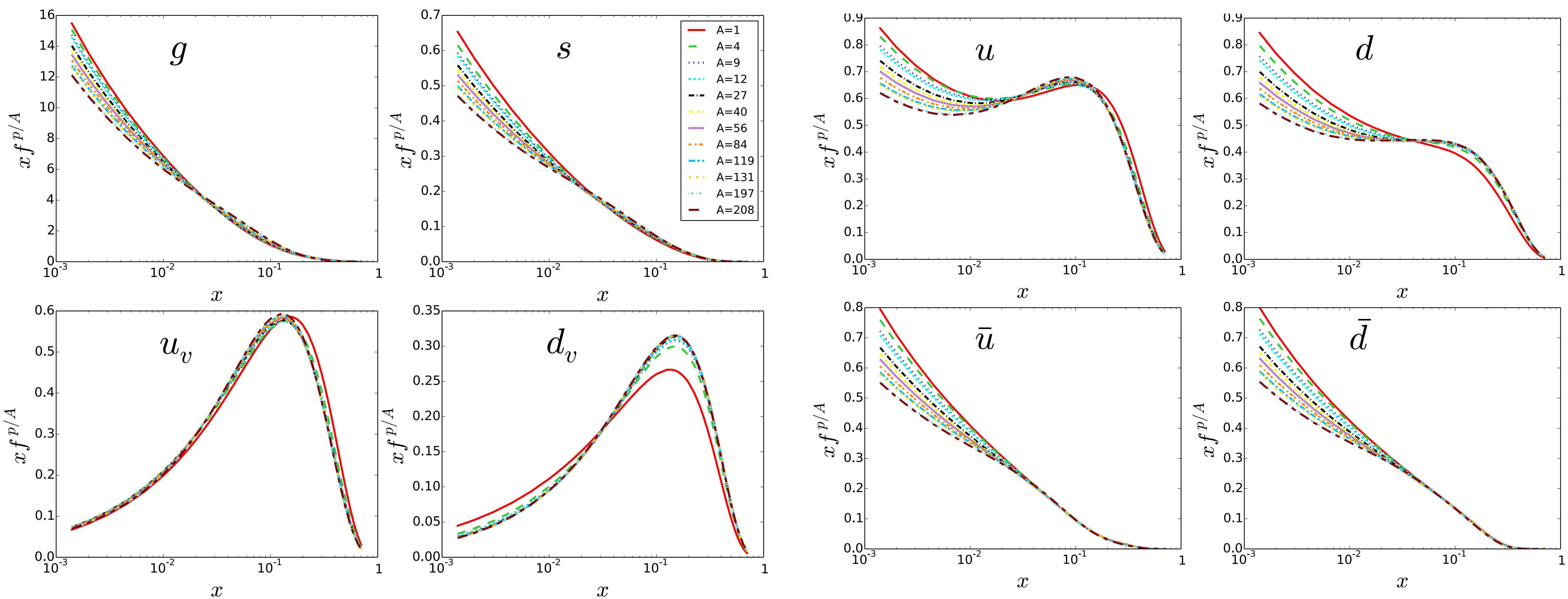


Nuclei with DIS data included in nCTEQ15 (Fig. by E. Godat)

- 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

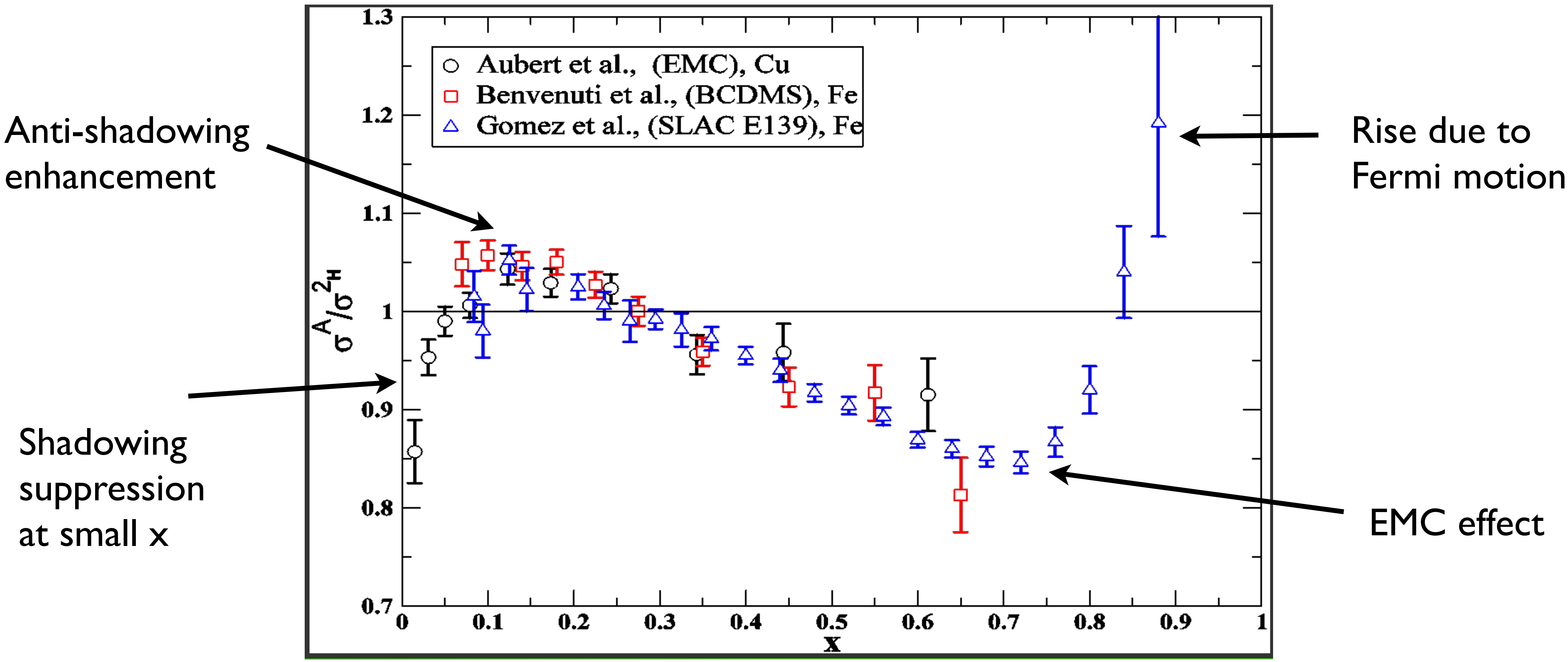
nCTEQ15, arXiv:1509.00792

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



Nuclear modifications

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



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

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 are **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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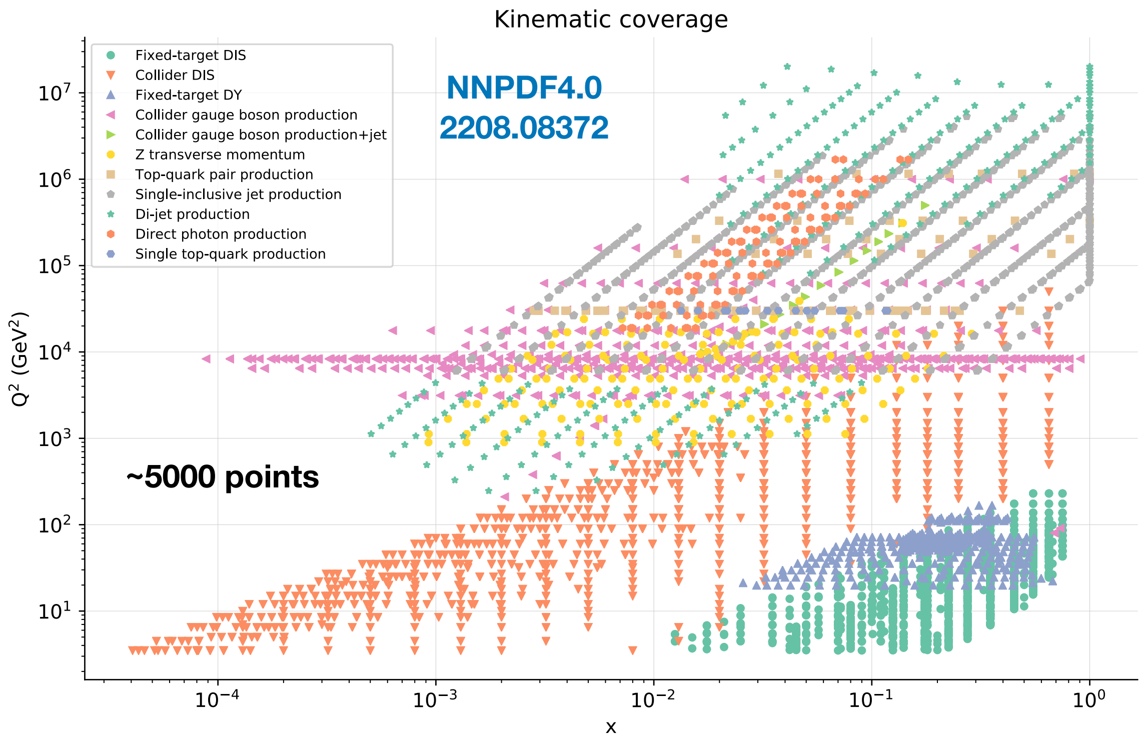
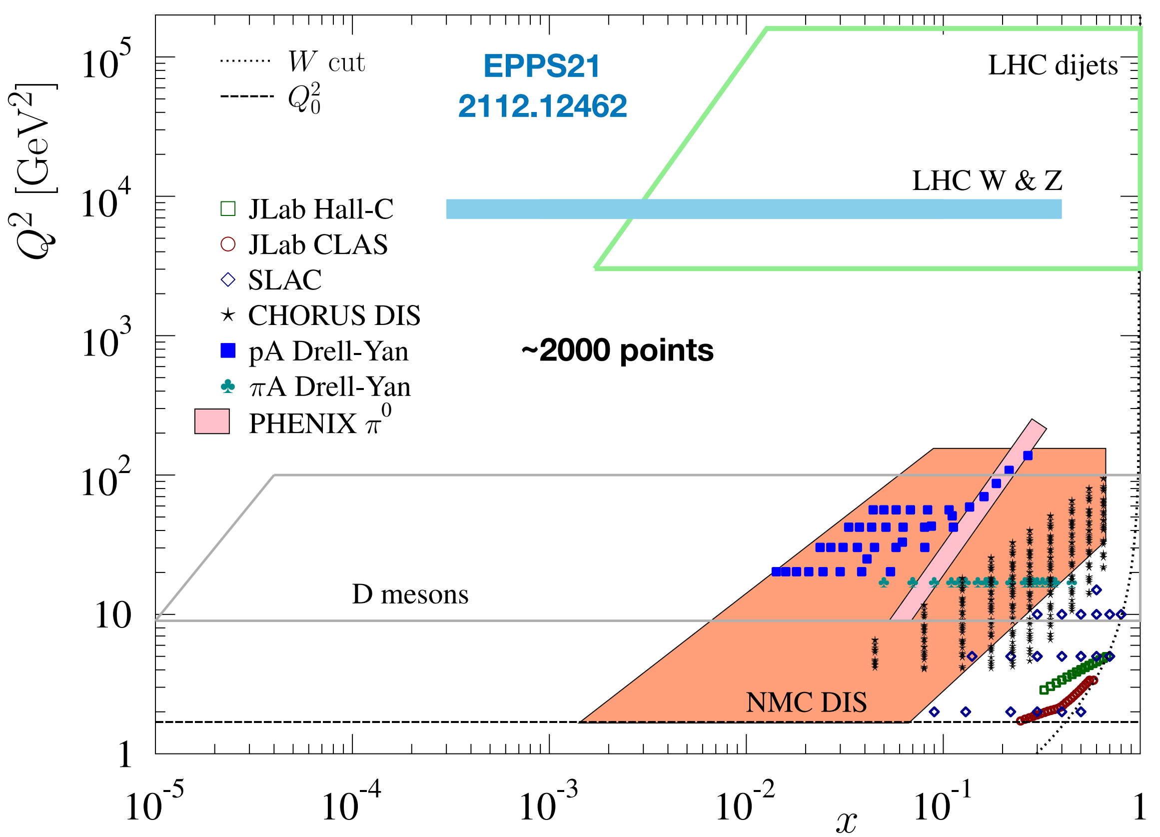
Similarities between proton and nuclear PDFs

- **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: [Talk by Paul Newman]

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: [Talk by Oscar Bento Garcia]

ALICE, ATLAS,CMS, LHCb

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

Proton PDFs

Some recent developments

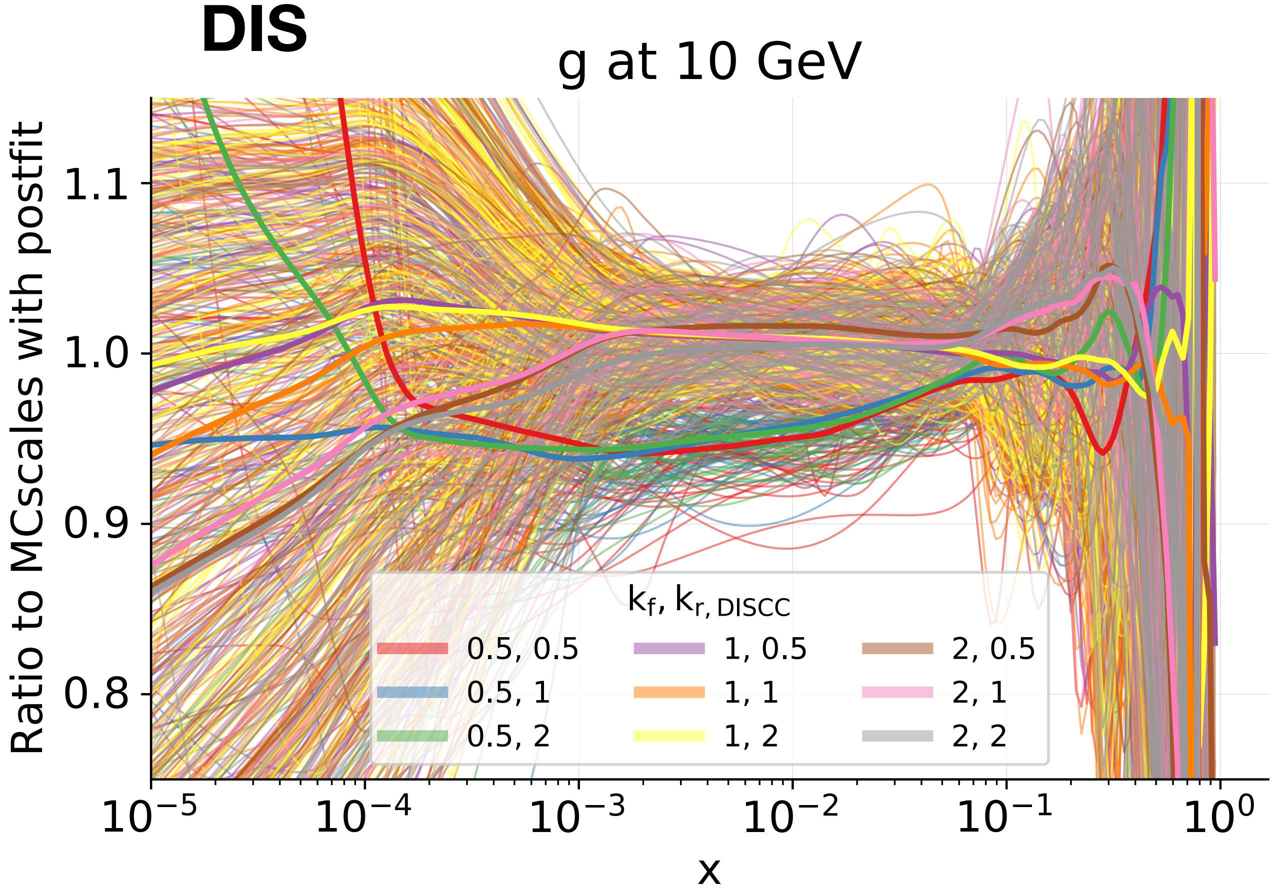
- **Charm PDF**
  - NNPDF: Evidence for IC in the proton [2208.08372, Nature 2022, Talk by Giacomo Magni]
  - CT18FC: The persistent non-perturbative charm enigma [2211.01387]
  - Predictions involving IC effects in kT-factorization approach [Talk Rafal Maciula]
- **PDFs with theory uncertainties:**
  - Incorporating scale uncertainties in PDFs using a MC sampling approach [2207.07616, Talk by Zaida Kassabov]
- **PDF fits using HERA+LHC data** [Talk by Paul Newman]
- **Pineline: Tools for theory predictions for PDF fits:** [Talk by Juan Martinez]
- **PDFs and new physics searches** [2209.08115, Talk by Felix Hekhorn]

PDFs with theory uncertainties

PDF replicas for each scale choice

Talk by Zaida Kassabov

DIS



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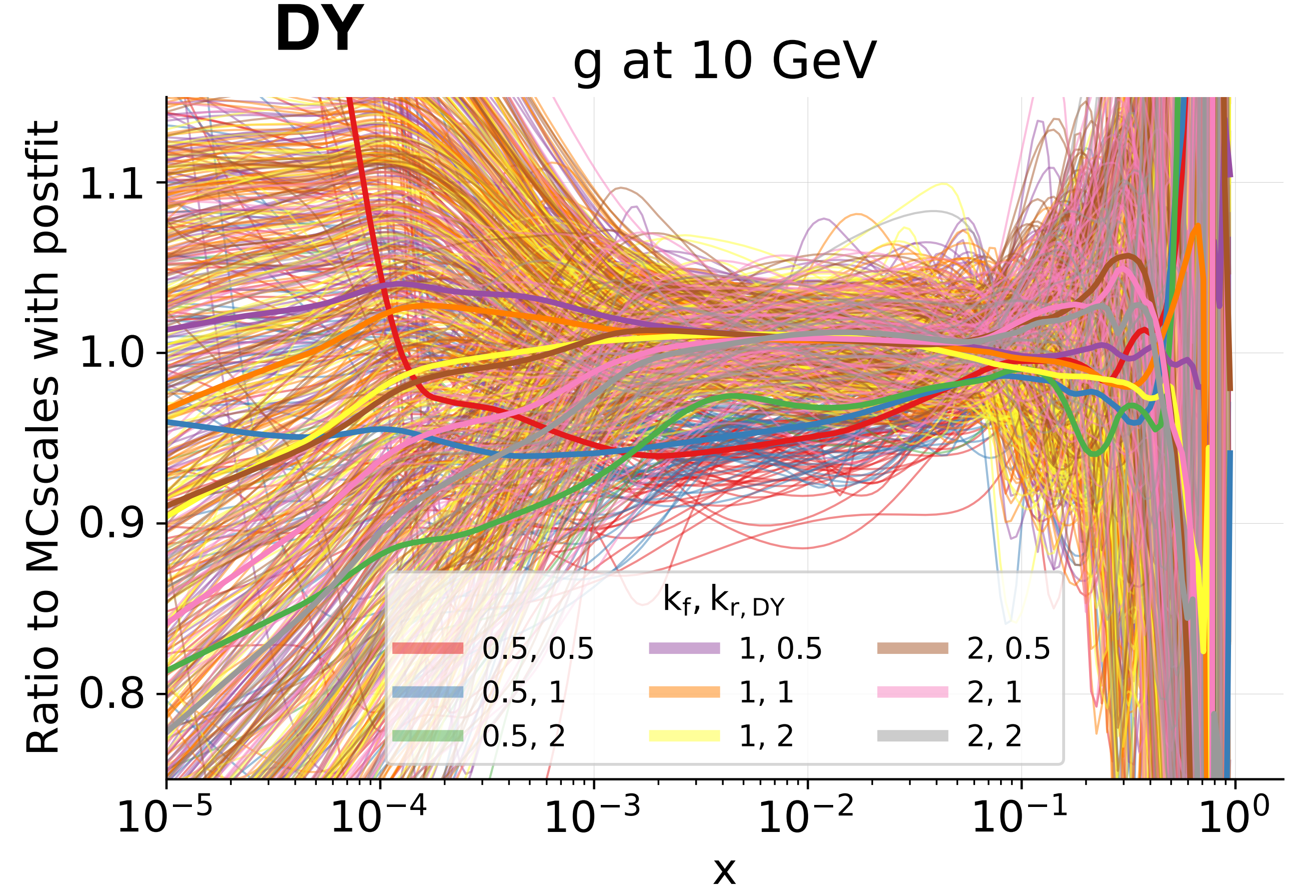
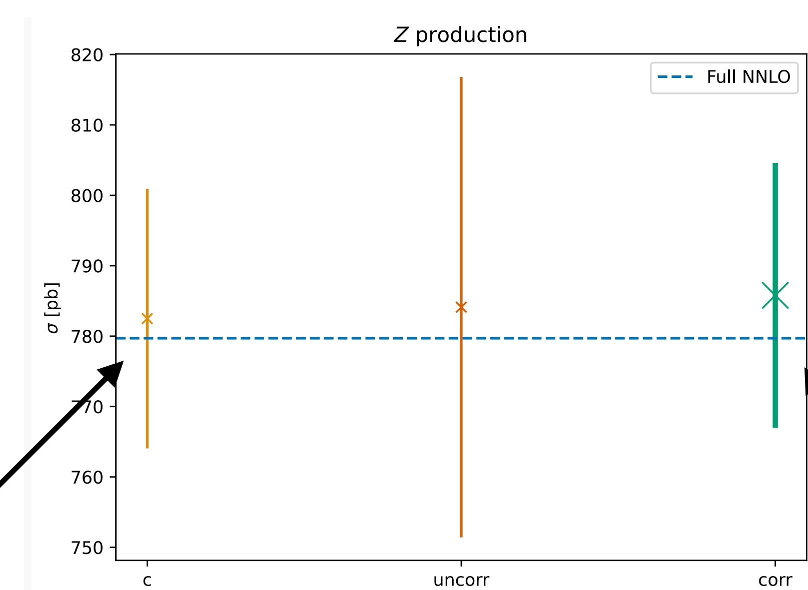


Parton distributions with scale uncertainties: a MonteCarlo sampling approach (ZK, Ubiali, Voisey, arxiv:2207.07616)

- Assign different scale multipliers, for each process being fitted, to each NNPDF replica.
- Record the information so scales can be matched between the PDF and the partonic cross section.



Scale variation only in $\hat{\sigma}$

Uncorr scale variation in PDF and $\hat{\sigma}$

Corr scale variation in PDF and $\hat{\sigma}$

Tools for theory predictions

Towards a smartphone app for PDF fitting

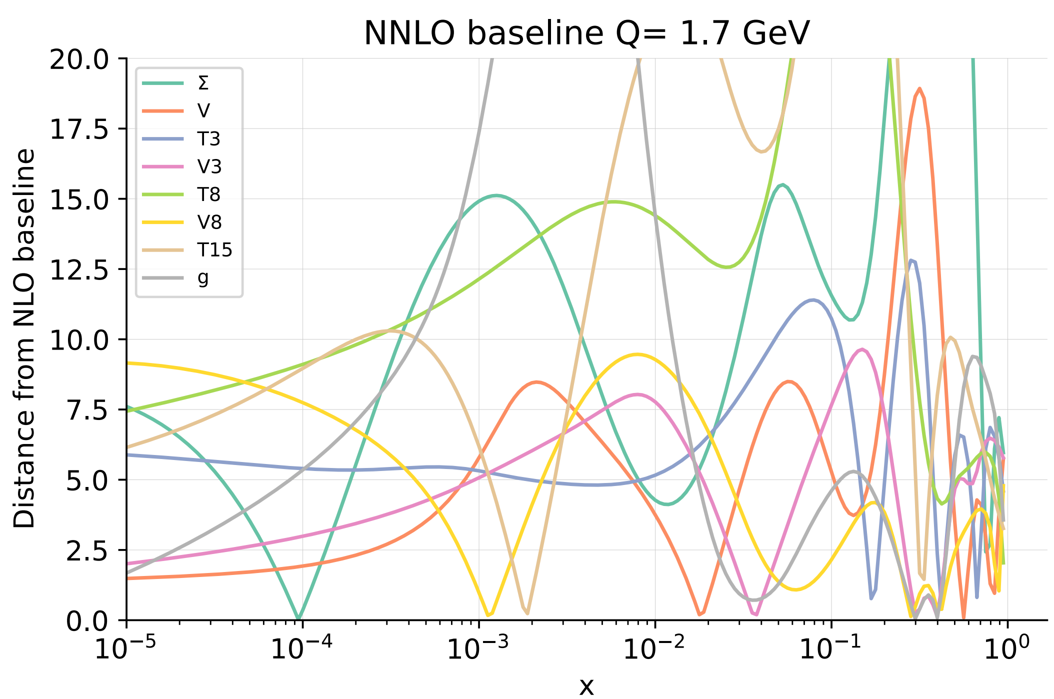
Talk by Juan Martinez

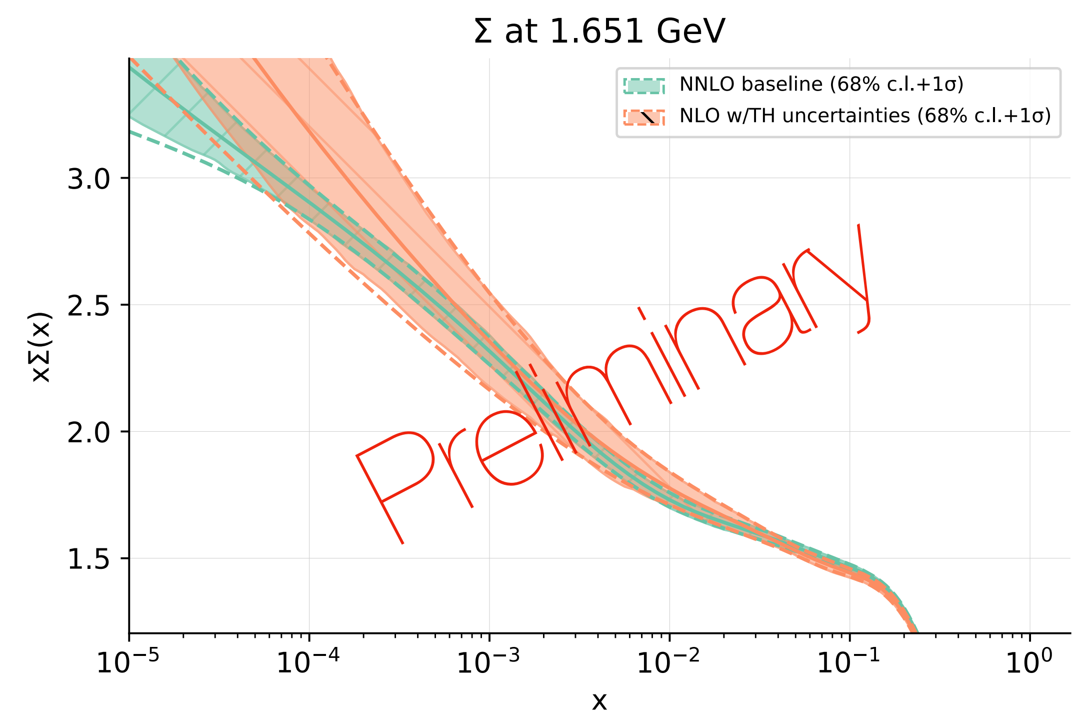
The future of PDF fitting

- N3LO evolution
- NNLO predictions
- Mixed QCD-EW corrections
- Missing High Order Uncertainties
- Beyond proton PDFs
- Different theory settings

Most future plans for PDF require the generation of new interpolation grids, and generating them can take great amounts of time.

Highly desirable: some framework in which I can run the appropriate settings, let it run in the background and get the necessary interpolation grids maybe a month later.



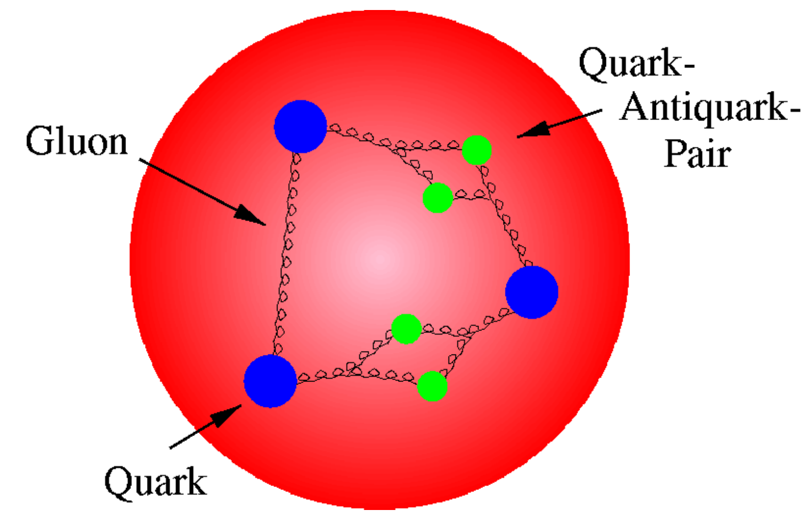


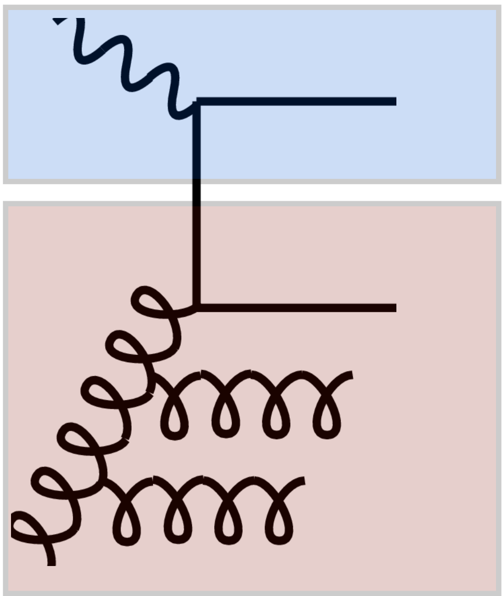
Pineline: https://nnpdf.github.io/pineline

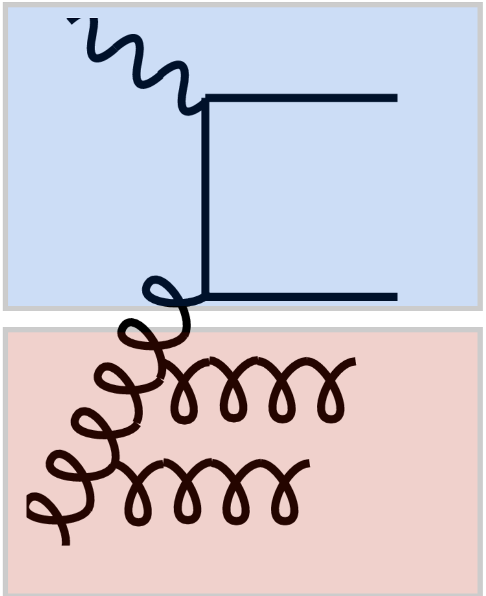
Charm PDF

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

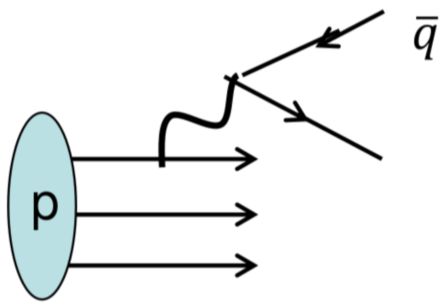
  - lattice calculations: even one or two moments would help

How to define "intrinsic"?

- So far, we only talked about "the charm PDF"
- The question was whether a perturbatively generated charm PDF is sufficient or whether one needs to determine a non-perturbative charm PDF from data (Fitted Charm)
- No need to split up the charm PDF into something "extrinsic" and "intrinsic". At the end it's the entire charm PDF which is needed for collider pheno
- However, for comparing with models in the literature, we need to say precisely what we understand under "intrinsic" and "extrinsic".
- IC from nucleon WF models based on this picture. Mapping IC models on twist-2 PDFs unclear!

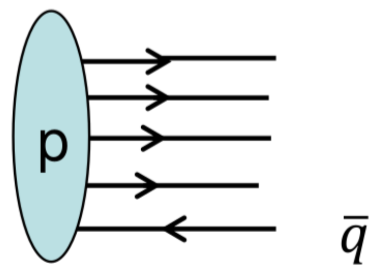
"Extrinsic" sea

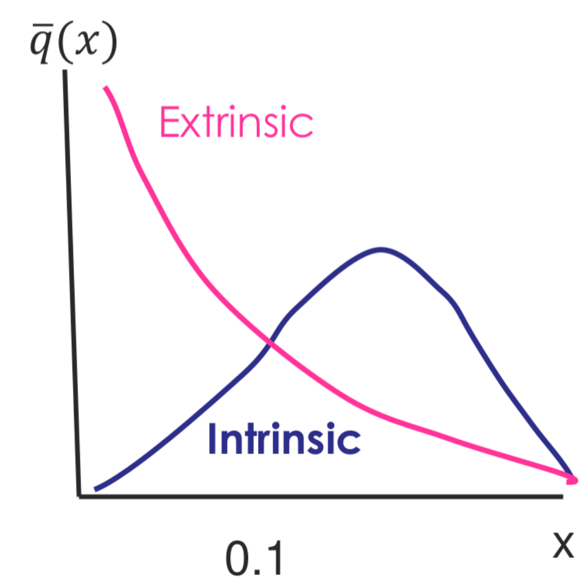
[maps on leading power sea production; generated radiatively, calculable in pQCD]



"Intrinsic" sea

[Excited Fock non-perturbative state. Beyond leading power production]





Models

- For a review see arXiv:1504.06287
- Most models are concentrated at large x and have a precise x-shape but <u>do not predict the scale</u> (BHPS, Meson-Baryon models)
- In some models $c(x) = \bar{c}(x)$ in others <u>not</u>
- 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

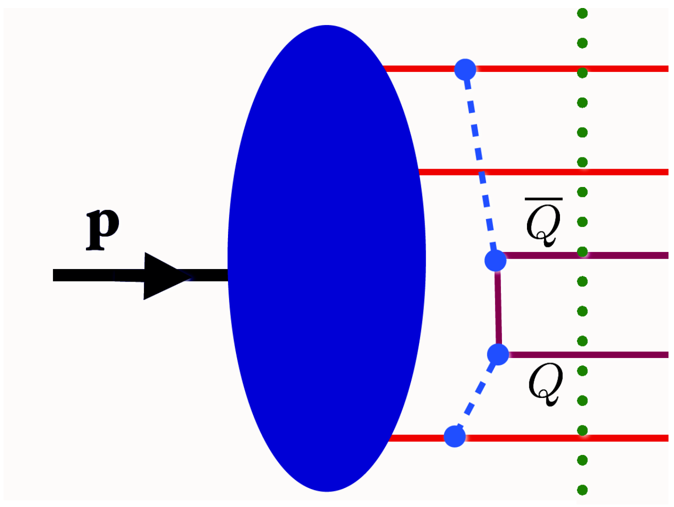


Figure 1: Five-quark Fock state $|uudQ\overline{Q}\rangle$ of the proton and the origin of the intrinsic sea.

- 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 $|p\rangle \rightarrow |uudc\bar{c}\rangle$ calculable in old-fashioned perturbation theory:

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

- 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:

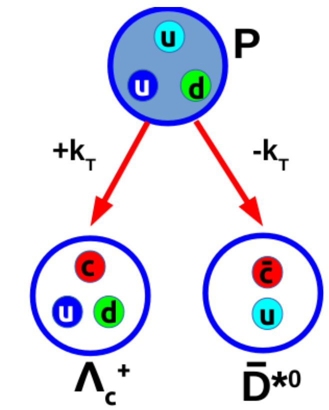
$$c_1(x) = \bar{c}_1(x) \propto x^2[6x(1+x)\ln x + (1-x)(1+10x+x^2)]$$

Typical moments;

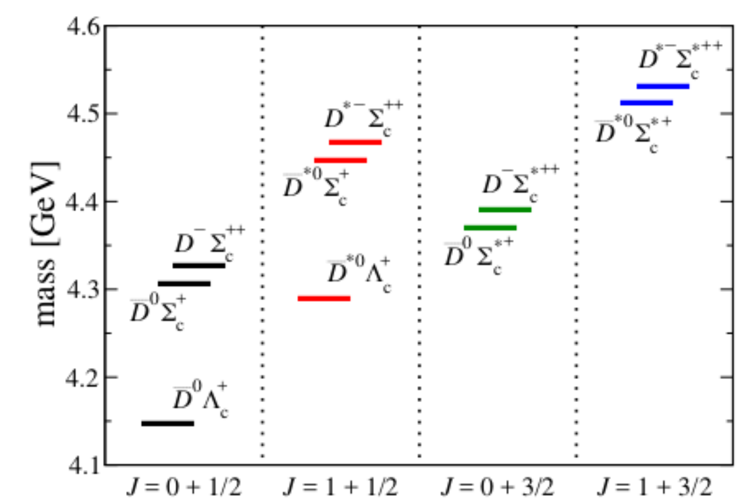
	$\int_0^1 dx\ c(x)$	$\int_0^1 dx\ x\,[c(x) + \bar{c}(x)] \equiv < x >_{c+\bar{c}}$
CTEQ6.6	0	0
CTEQ6.6c0	0.01	0.0057
CTEQ6.6c1	0.035	0.0200

Meson-Baryon models

Hobbs,Londergan,Melnitchouk,PRD89(2014)074008



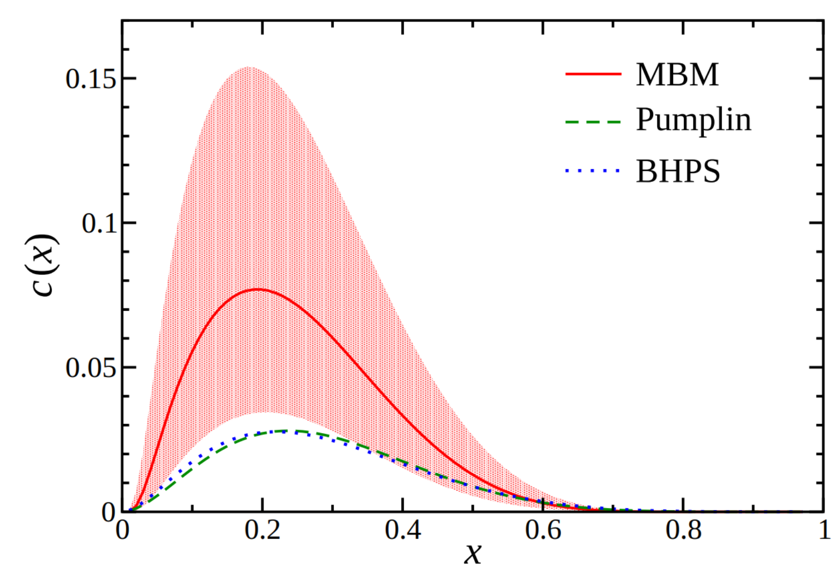
- 5-quark states from hadronic interactions
- Framework conserving spin/parity
- Non-perturbative mechanisms needed to break
  $c(x, Q^2 \leq m_c^2) = \bar{c}(x, Q^2 \leq m_c^2) = 0$
- EFT which connects IC to properties of the hadronic spectrum
  $$|N\rangle = \sqrt{Z_2}\,|N\rangle_0 + \sum_{M,B} \int dy\, f_{MB}(y)\,|M(y); B(1-y)\rangle$$
  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**:

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

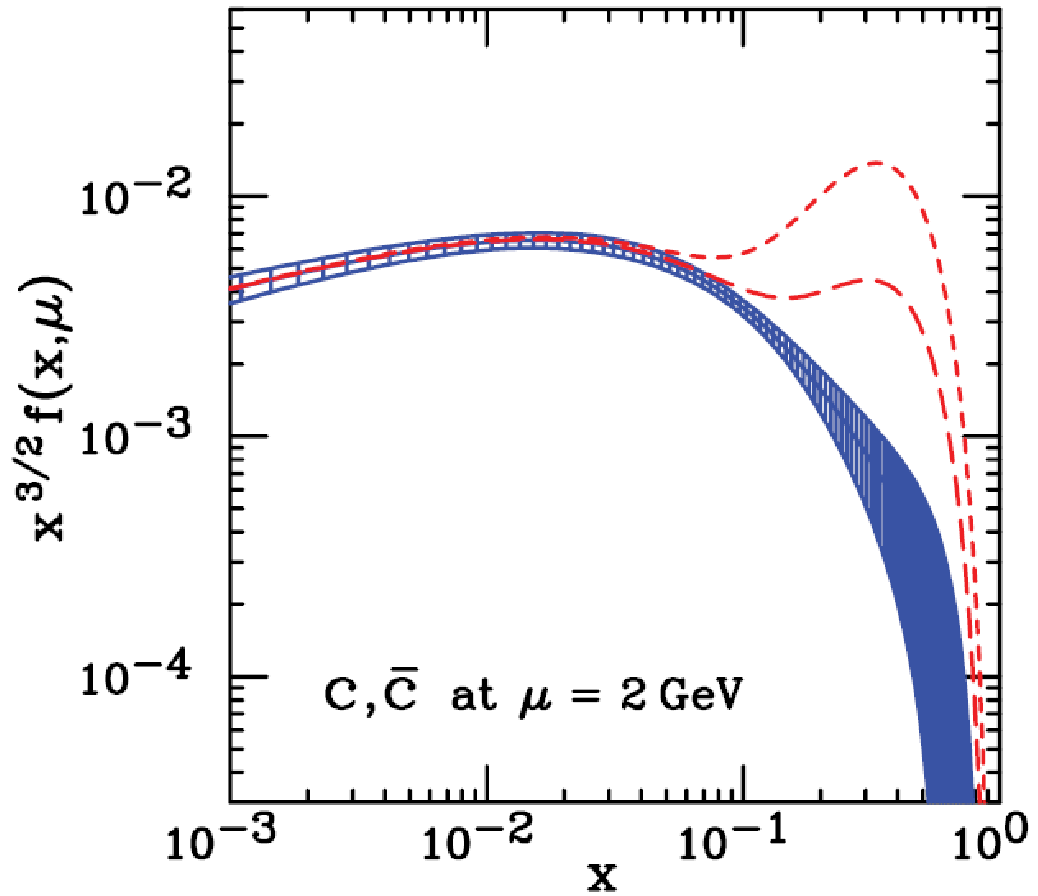


A global fit by CTEQ to extract IC

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)

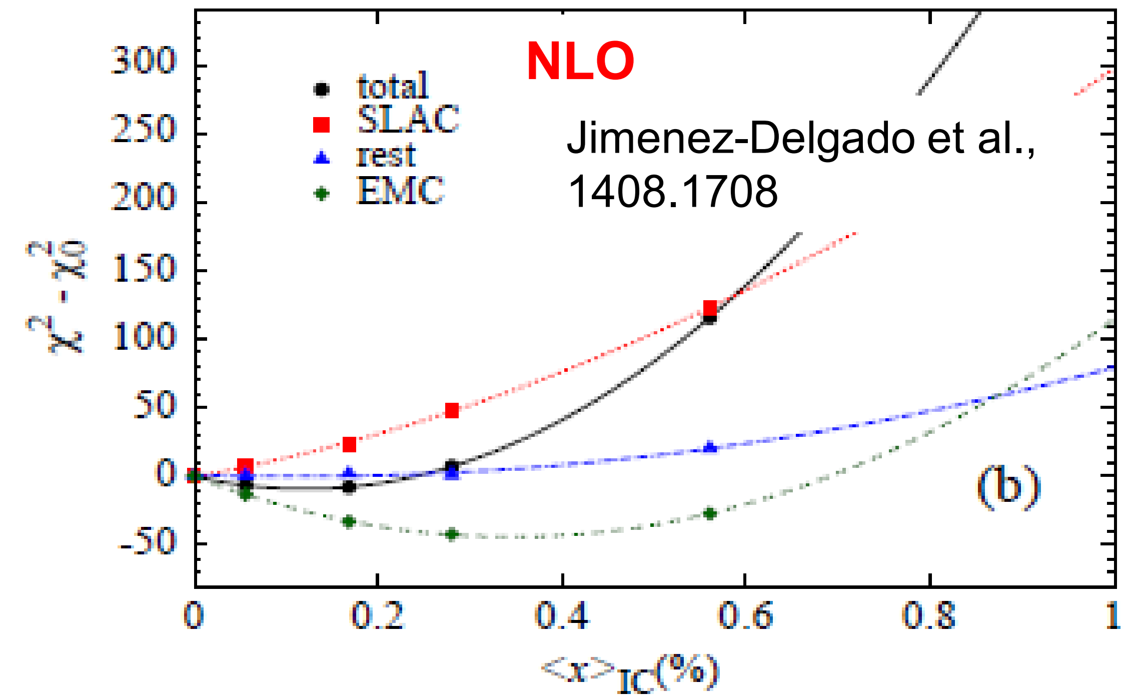
We find that the range of IC is constrained to be from zero (no IC) to a level 2–3 times larger than previous model estimates. The behaviors of typical charm distributions within this range are described, and their implications for hadron collider phenomenology are briefly discussed.

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)



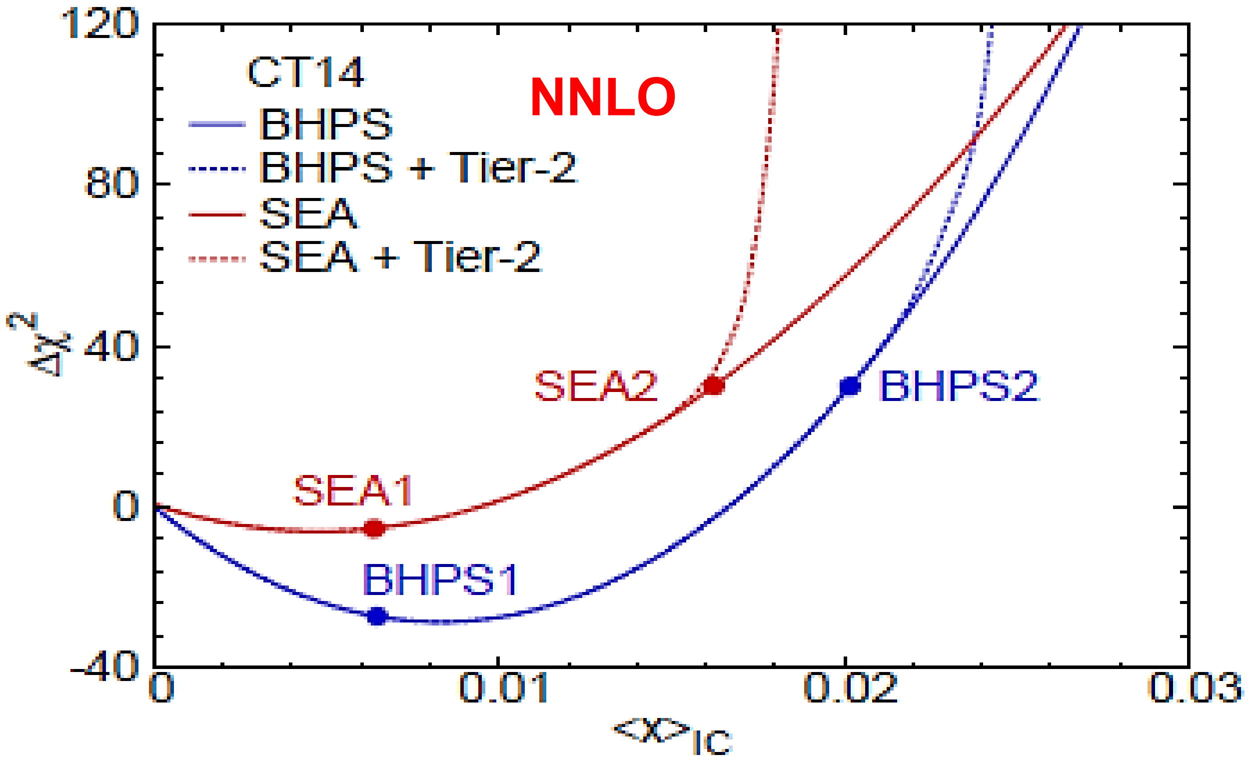
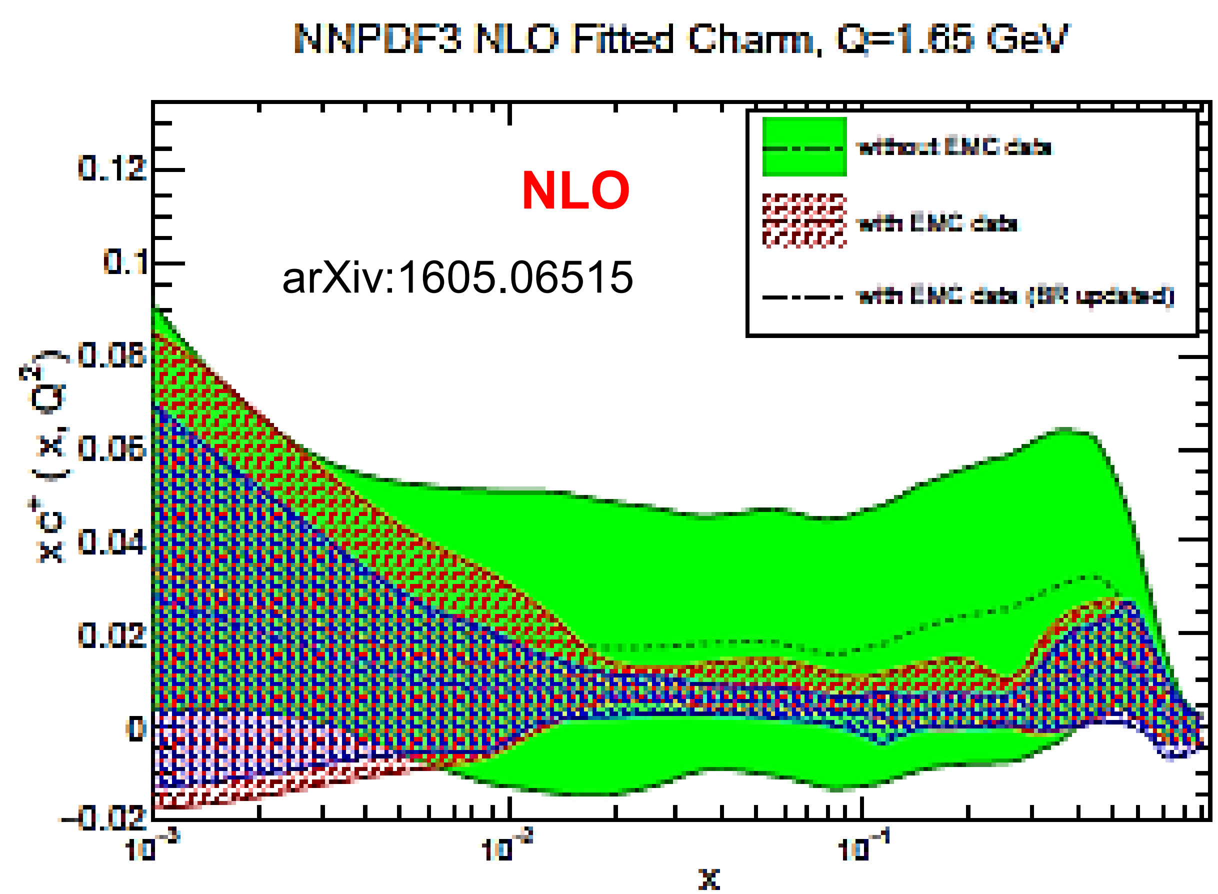
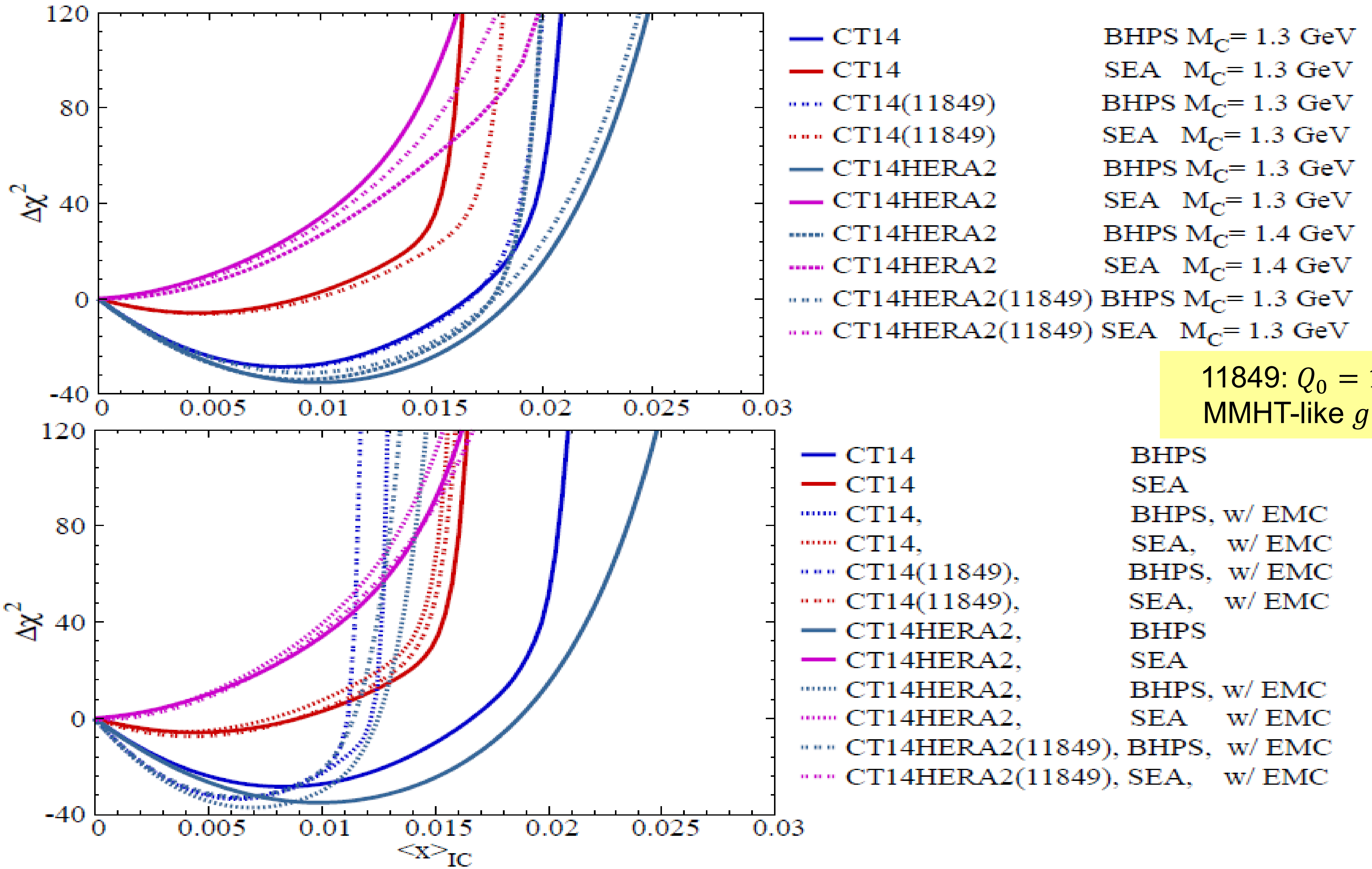


Figure 1: The $\Delta\chi^2$ versus the momentum fraction of charm $\langle x \rangle_{IC}$. **PoS DIS2015 (2015) 166**



CT14 IC fits



11849: $Q_0 = 1$ GeV, MMHT-like $g(x, Q_0)$

For the Brodsky-Hoyer-Peterson-Sakai (BHPS) parametrization, a **marginally** better χ^2 for IC with $\langle x \rangle_{IC} \approx 1\%$

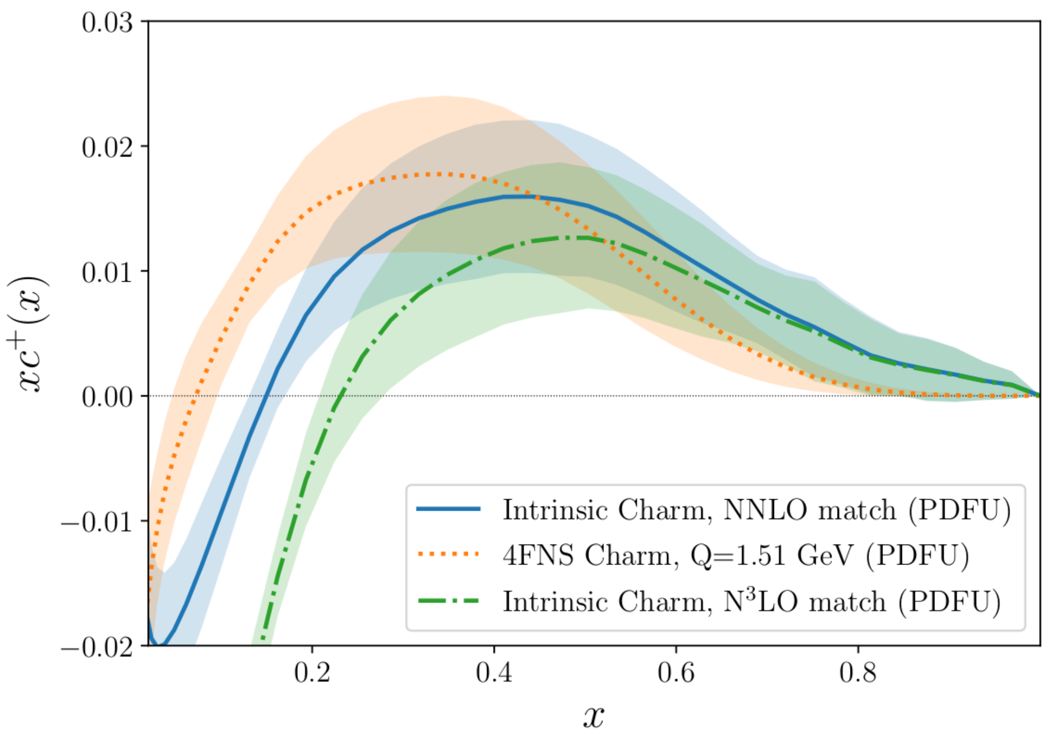
For SEA parametrization, IC with $\langle x \rangle_{IC} \approx 1.5\%$ is allowed within uncertainty

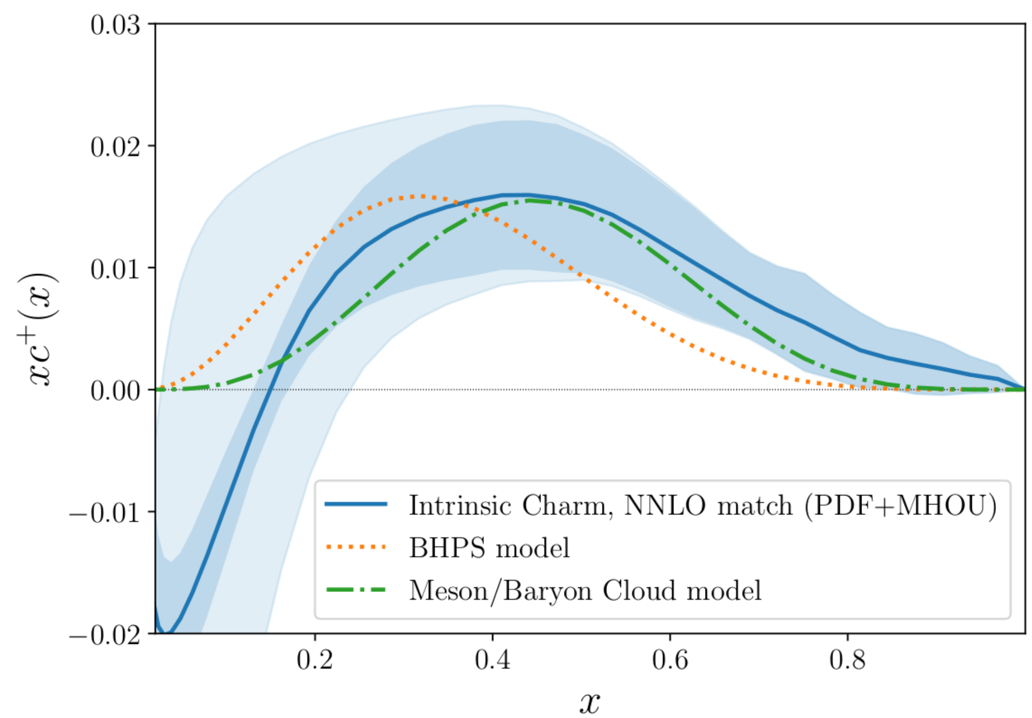
The latest IC results from NNPDF

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





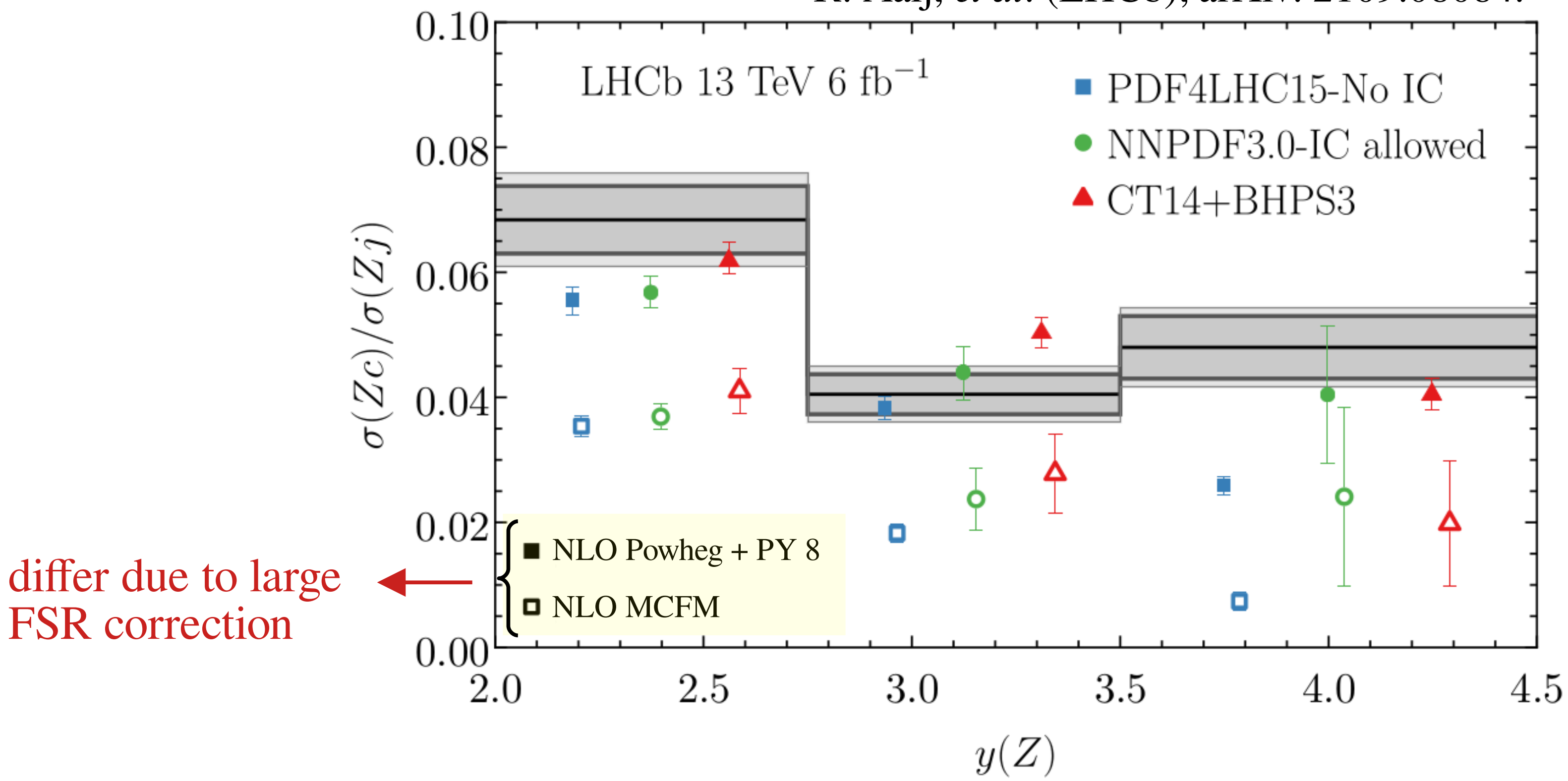
- IC PDF quite hard, peaking at $x \gtrsim 0.4$
- Low-x behaviour:
  - rather big differences between NNLO and N3LO matching (perturbative stability?)
  - Negative IC at small-x unlike models
  - MHOU persists to quite high $x \gtrsim 0.2$

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.



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

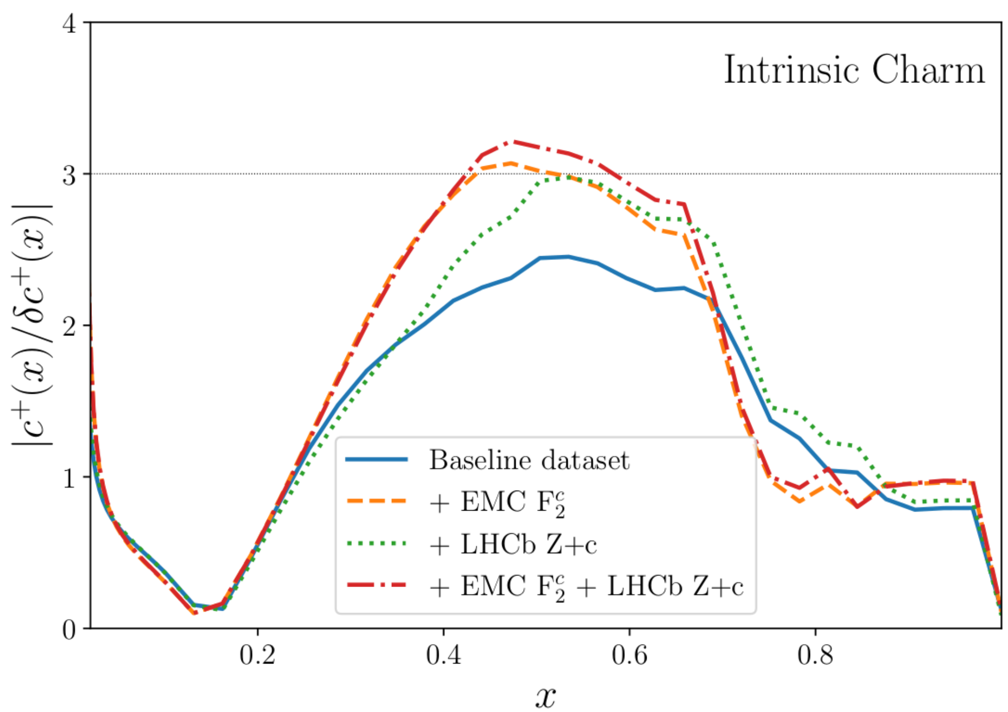
- NNLO calculations recently available: R. Gauld et al: 2005.03016; M. Czakon et al: 2011.01011
  Not yet implemented in PDF fits
- Need NNLO; control over showering, final state effects

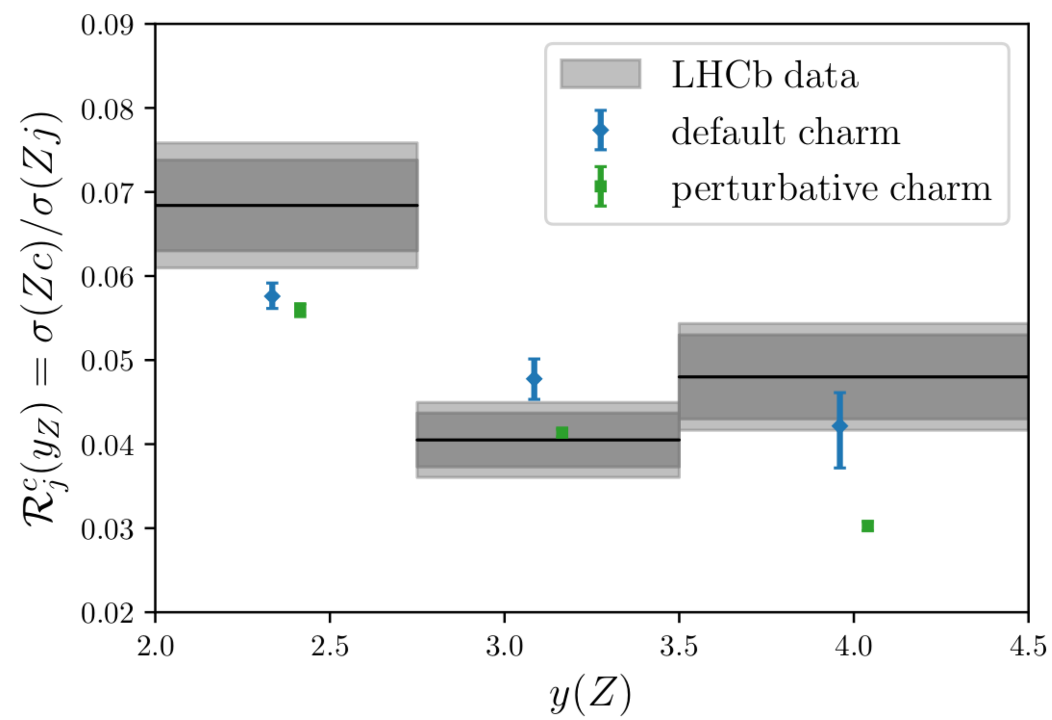
The latest IC results from NNPDF

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

Nuclear PDFs

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

Talk by Petja Paakkinen

- 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

Comparison of recent nPDF fits

Talk by P. Paakkinen

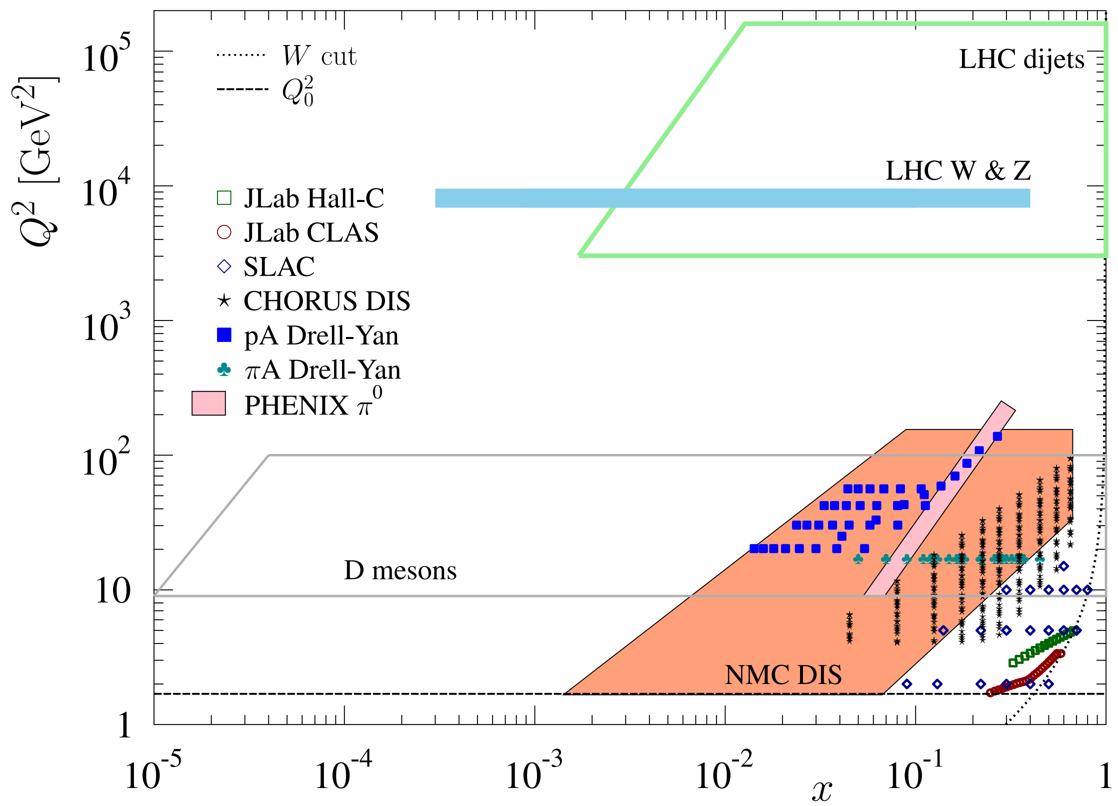
	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15HQ
Order in α_s	NLO & NNLO	NLO & NNLO	NLO	NLO	NLO
lA NC DIS	✓	✓	✓	✓	✓
νA CC DIS	✓	✓	✓	✓	
pA DY	✓		✓	✓	✓
πA DY			✓		
RHIC dAu π^0,$\pi^\pm$			✓		✓
LHC pPb π^0,$\pi^\pm$,$K^\pm$					✓
LHC pPb dijets			✓	✓	
LHC pPb HQ			✓ **GMVFN**	✓ **FO+PS**	✓ **ME fitting**
LHC 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 EPPS

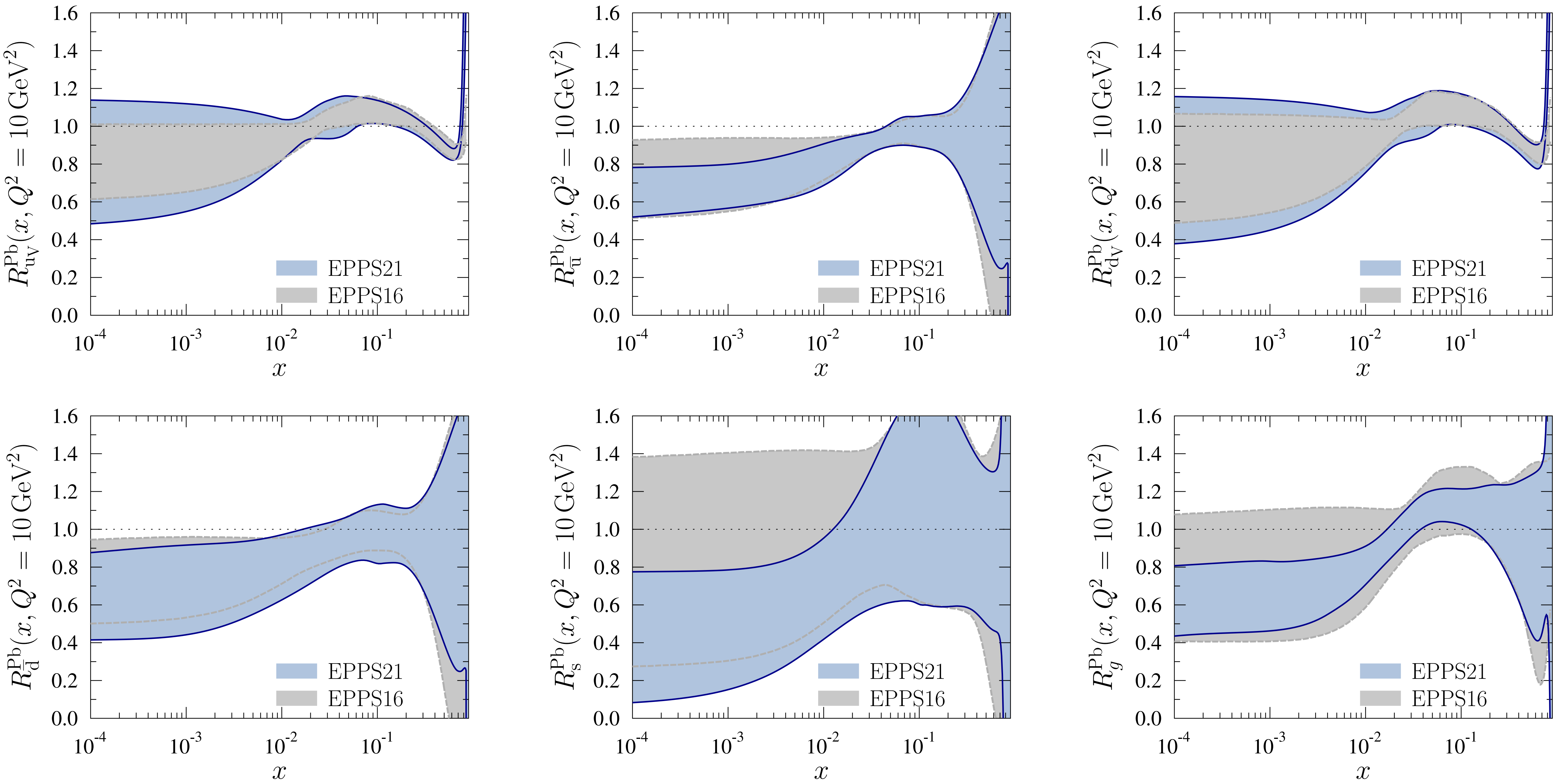
EPPS21 vs EPPS16

- 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.

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 [2204.13157]
    Next global analysis use (CHORUS+Dimuon data)
  - 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 [Dec 2022]

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

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

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

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

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**

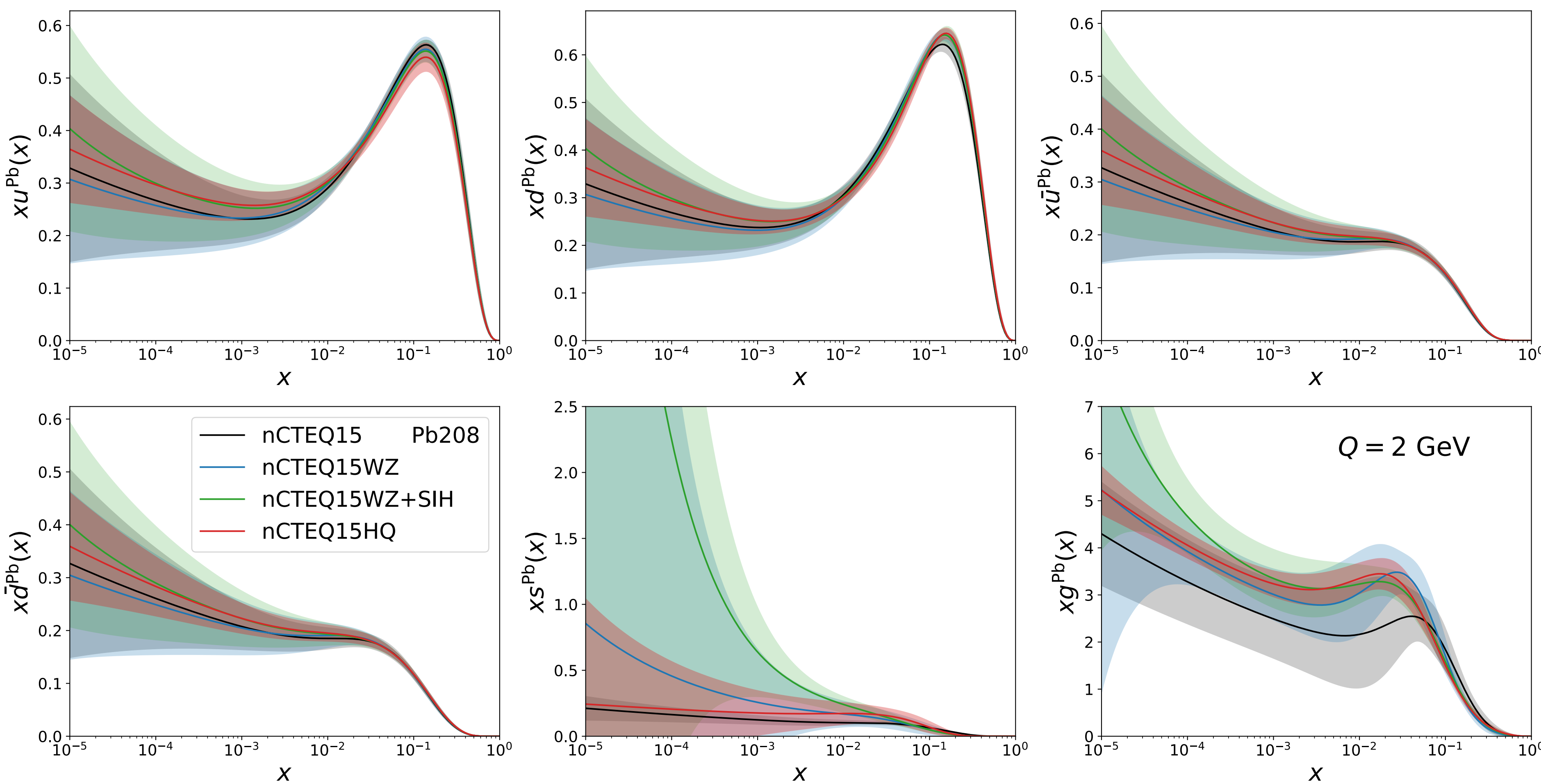


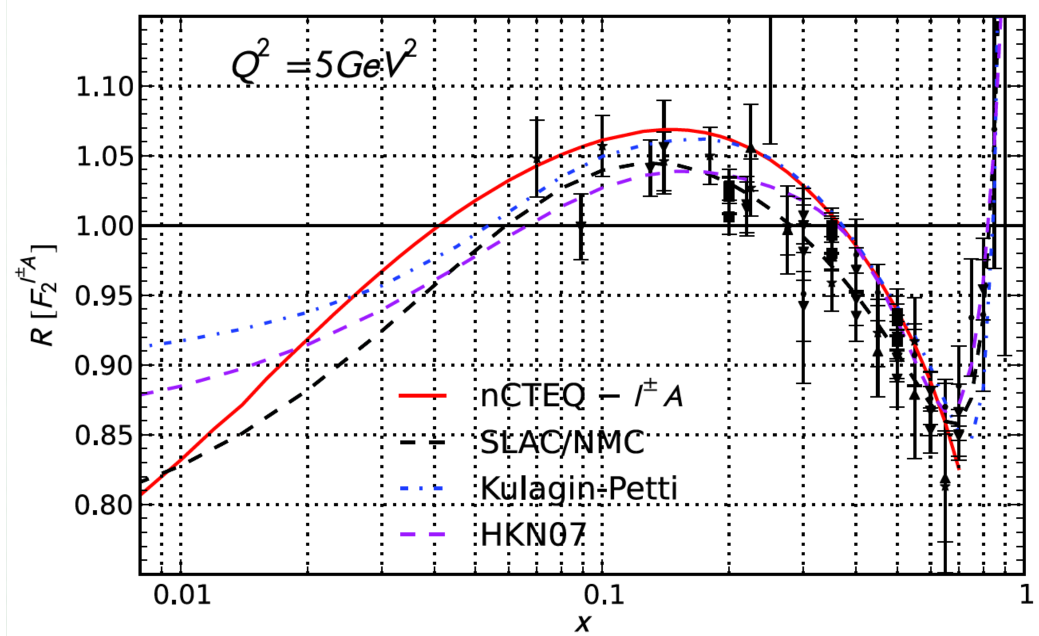
FIG. 4: Lead PDFs from different nCTEQ15 versions. The baseline nCTEQ15 fit is shown in black, nCTEQ15WZ in blue, nCTEQ15WZSIH in green, and the new fit in red.

nCTEQ and neutrino data

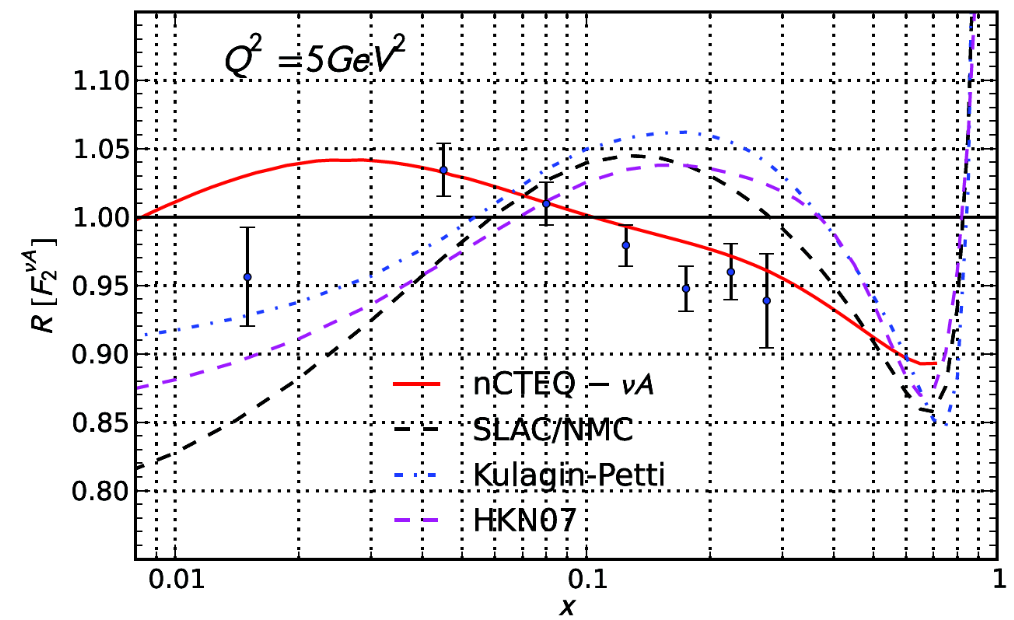
Neutrino deep inelastic scattering:

- 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

Fit to $l^{\pm}A$ DIS and DY data
$\chi^2/\mathrm{dof} = 0.89$



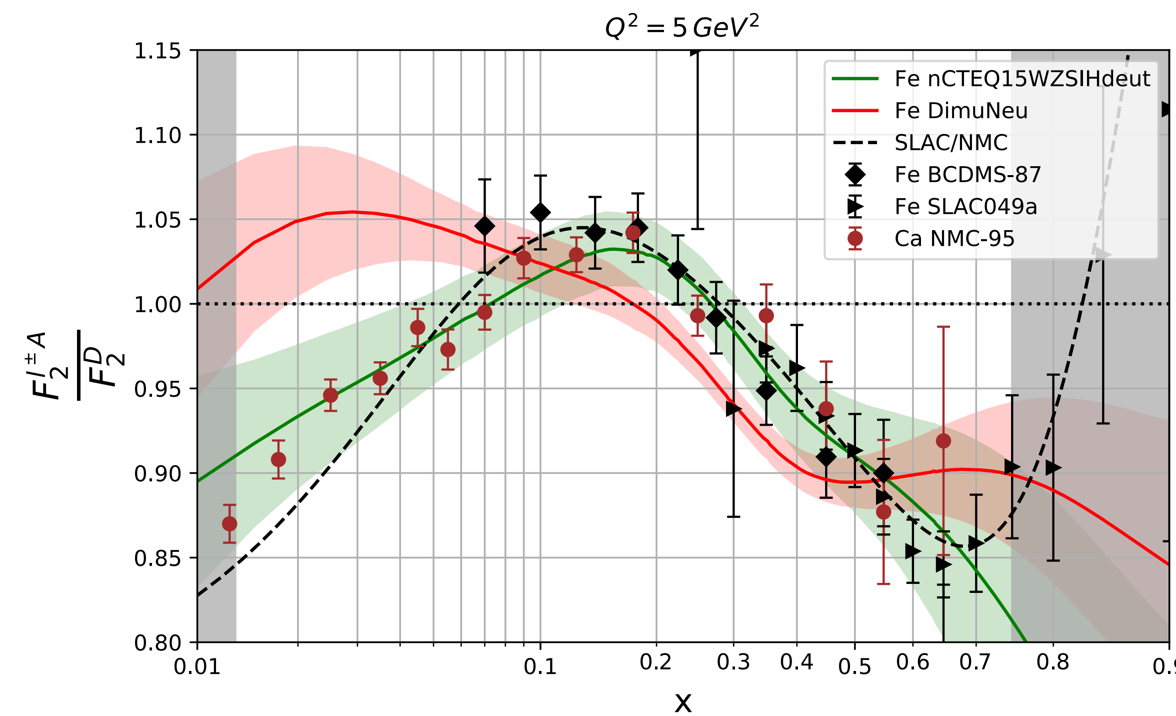
Fit to νA DIS data only
$\chi^2/\mathrm{dof} = 1.33$

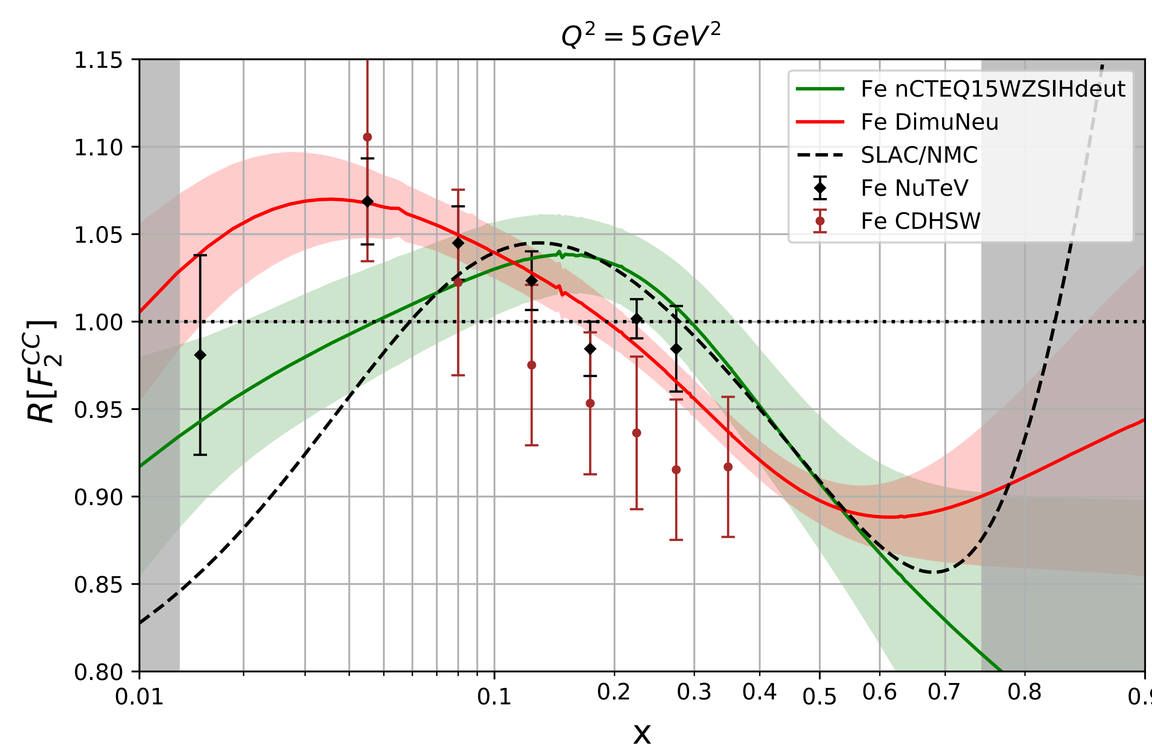


Neutrino DIS vs Charged lepton DIS

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	Fe	23 - 188	465	No	[48]
CDHSW $\bar{\nu}$			464		
CCFR ν	Fe	35 - 340	1109	No	[50]
CCFR $\bar{\nu}$			1098		
NuTeV ν	Fe	35 - 340	1170	Yes	[23]
NuTeV $\bar{\nu}$			966		
Chorus ν	Pb	25 - 170	412	Yes	[27]
Chorus $\bar{\nu}$			412		
CCFR dimuon ν	Fe	110 - 333	40	No	[19]
CCFR dimuon $\bar{\nu}$		87 - 266	38		
NuTeV dimuon ν	Fe	90 - 245	38	No	[19]
NuTeV dimuon $\bar{\nu}$		79 - 222	34		





- 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

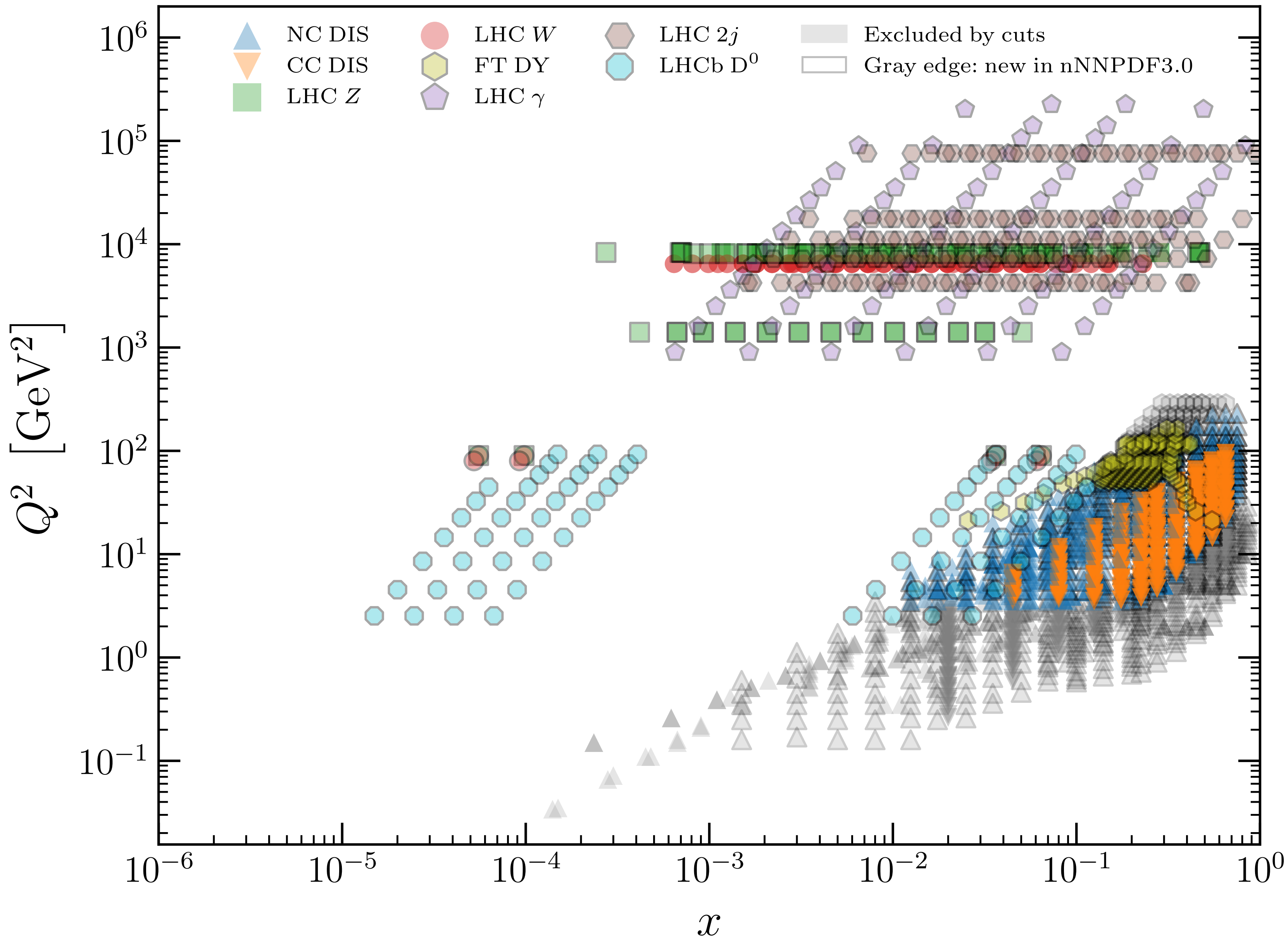


Figure 2.1. The kinematic coverage in the (x, Q^2) plane of the nNNPDF3.0 dataset. The evaluation of x and Q^2 for the hadronic processes assumes LO kinematics. Data points are classified by process. Data points new in nNNPDF3.0 in comparison to nNNPDF2.0 are marked with a grey edge. Data points excluded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

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

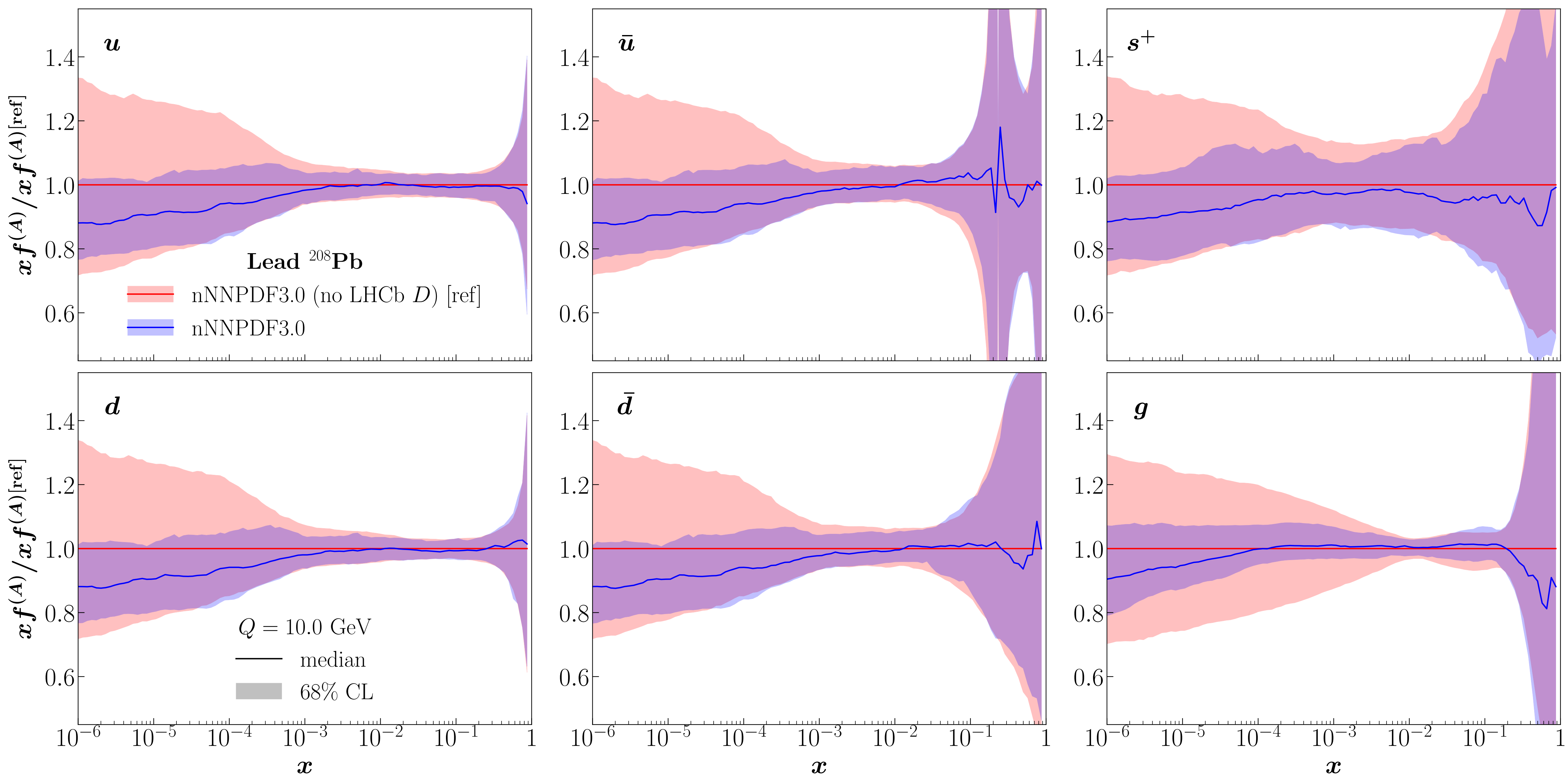


Figure 4.5. Comparison of the nPDFs of lead nuclei at $Q = 10$ GeV between nNNPDF3.0 (no LHCb D) and nNNPDF3.0, normalised to the central value of the former.

nNNPDF3.0 [2201.123623]

Comparison with EPPS16 and nCTEQ15WZSIH

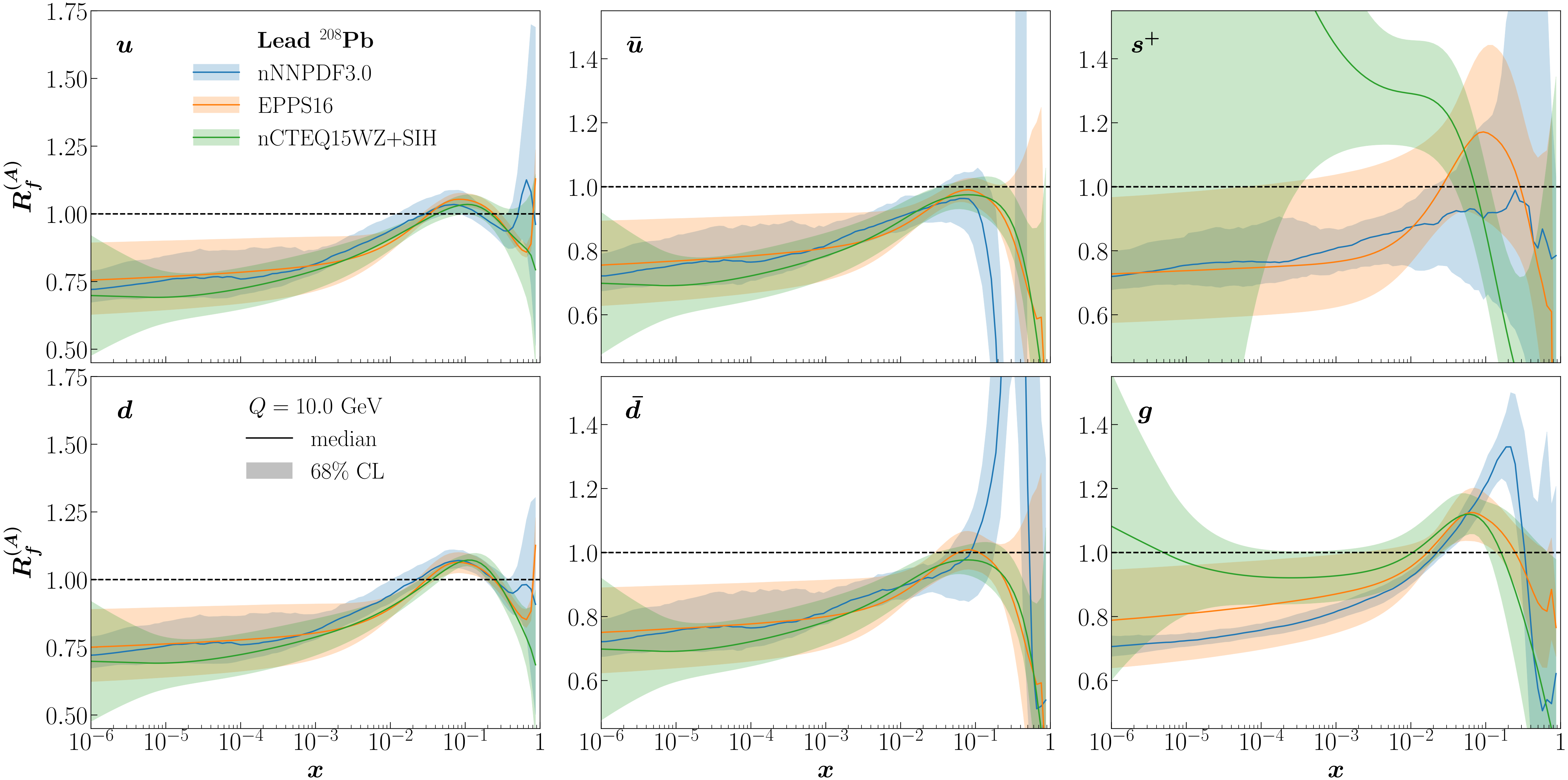


Figure 4.13. The nNNPDF3.0 predictions for the nuclear modification ratios in lead at $Q = 10$ GeV, compared to the corresponding results from the EPPS16 and nCTEQWZ+SIH global analyses. The PDF uncertainty bands correspond in all cases to 68% CL intervals.

nNNPDF3.0 [2201.123623]

Methodological improvements

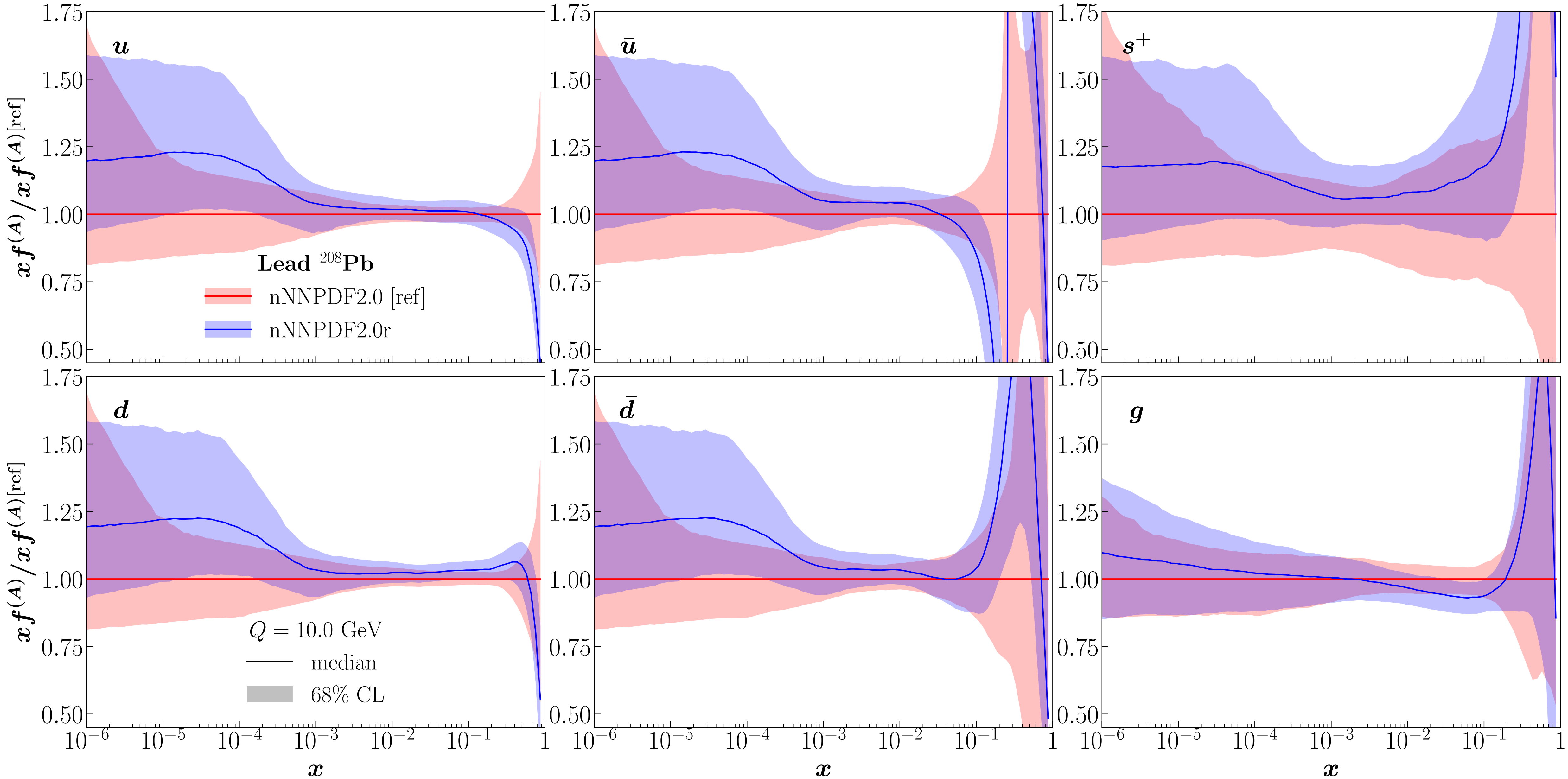


Figure 5.1. Comparison of nNNPDF2.0 with the nNNPDF2.0r variant. Results are shown for the lead PDFs at $Q = 10$ GeV normalised to the central value of nNNPDF2.0, and the uncertainty bands represent the 68% CL intervals.

Backup

Thank you!

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

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

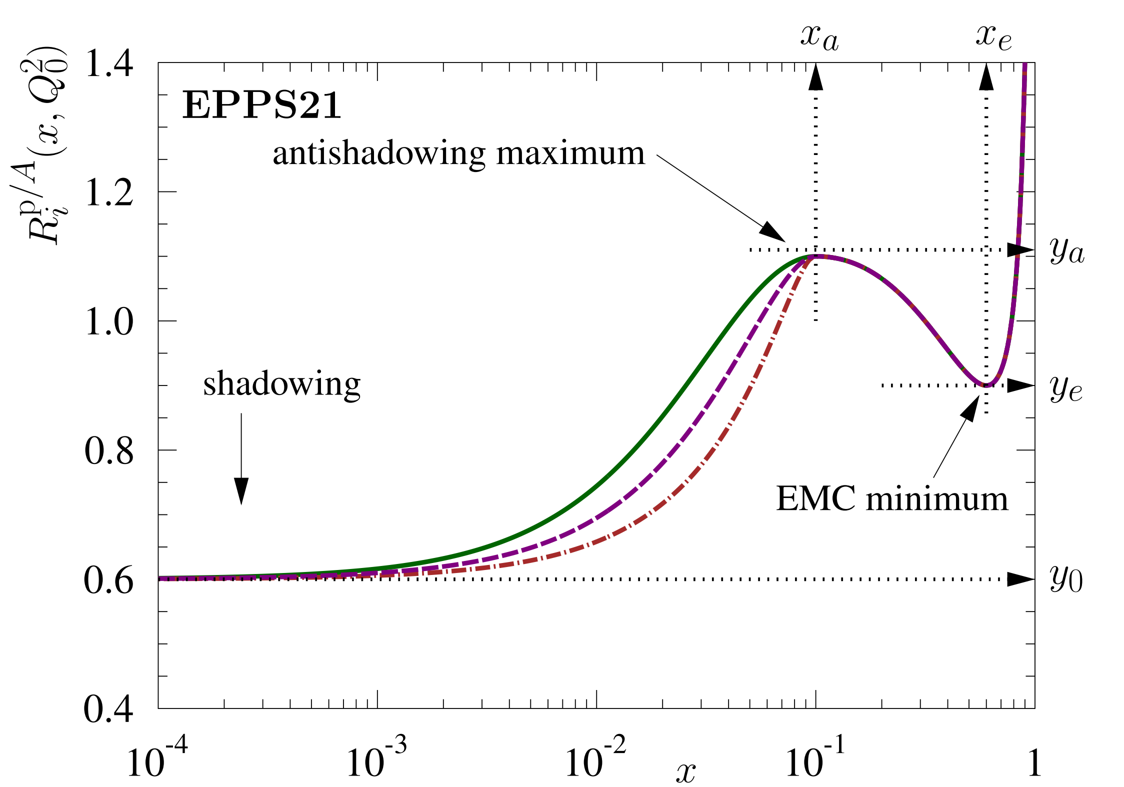
- $Q_0 = m_c = 1.3$ GeV
- Proton baseline: CT18ANLO
- $m_c = 1.3, m_b = 4.75, \alpha_s(Q)$ as in CT18ANLO
- Isospin symmetry

- 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

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



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

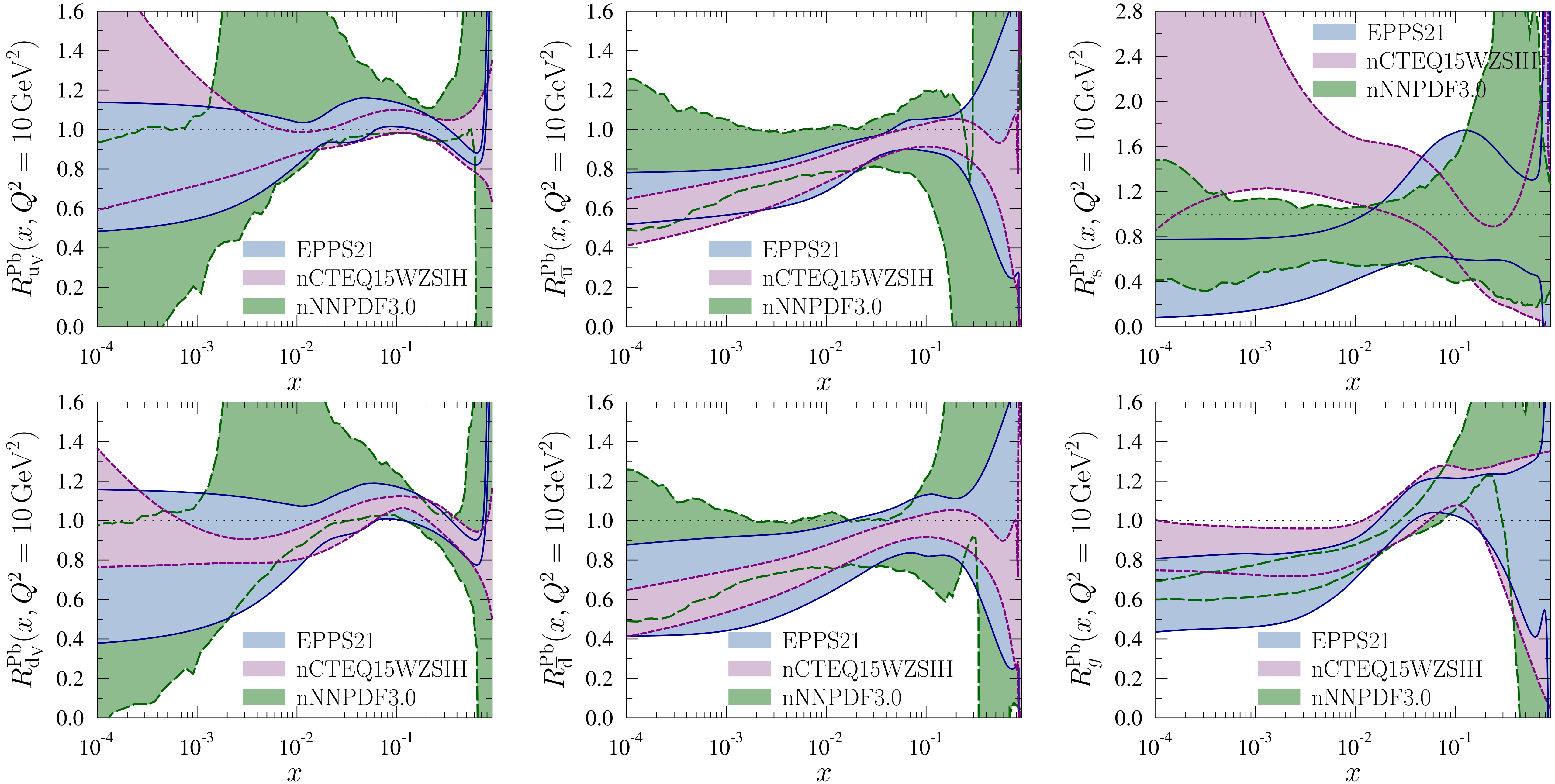
- Parametrization is a piecewise defined function
- Some changes w.r.t. EPPS16

$$R_i^A(x, Q_0^2) =$$

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

- 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 nCTEQ15WZ and nNNPDF3.0



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

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

nCTEQHQ nPDFs

arXiv:2204.09982

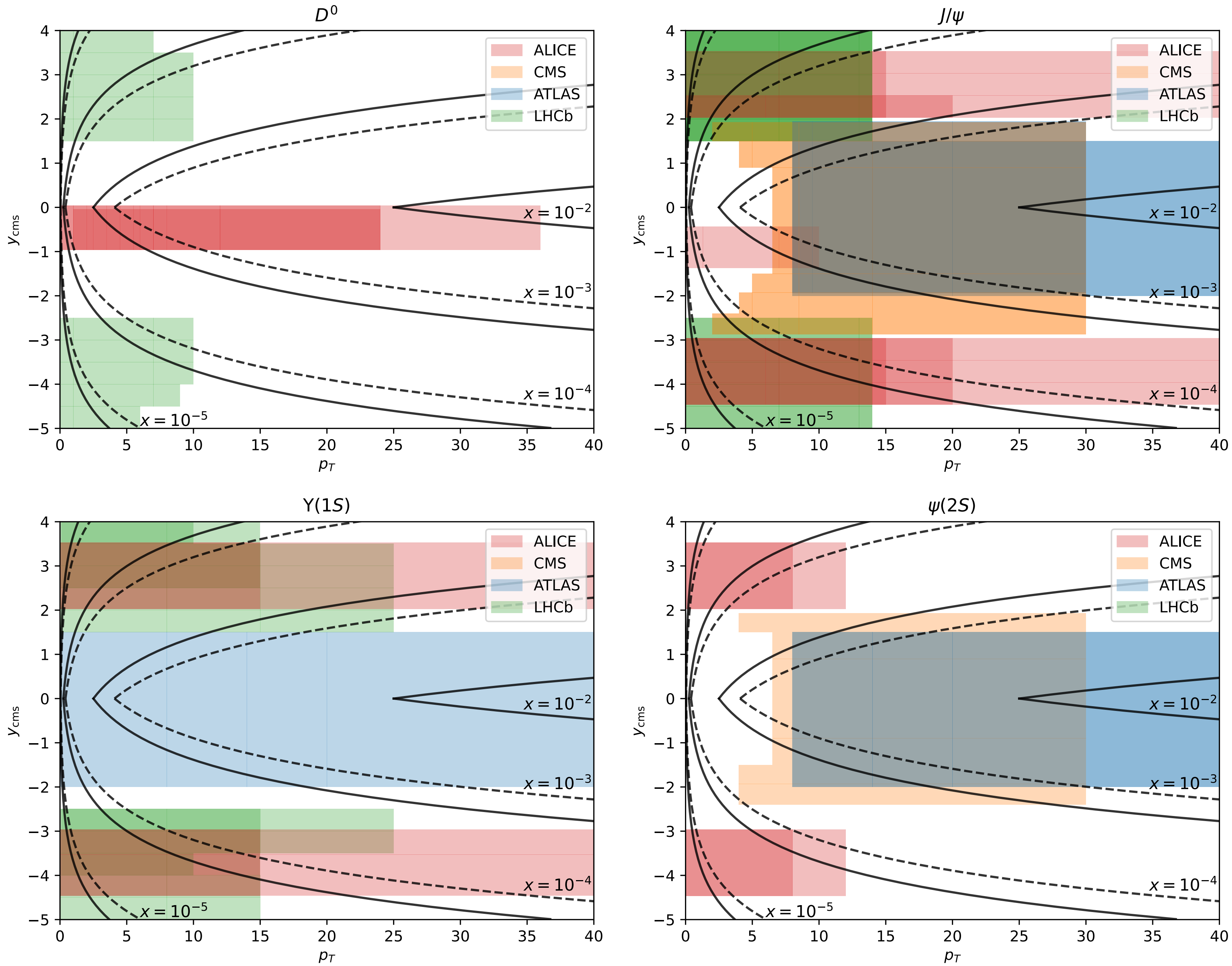


FIG. 1: Coverage of the kinematic (p_T, y_{cms})-plane of the quarkonium and open heavy quark production data sets from proton-lead collisions. ALICE data is shown in red, ATLAS in blue, CMS in orange and LHCb in green. The dashed and solid contours show the estimated x-dependence for $\sqrt{s} = 5$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

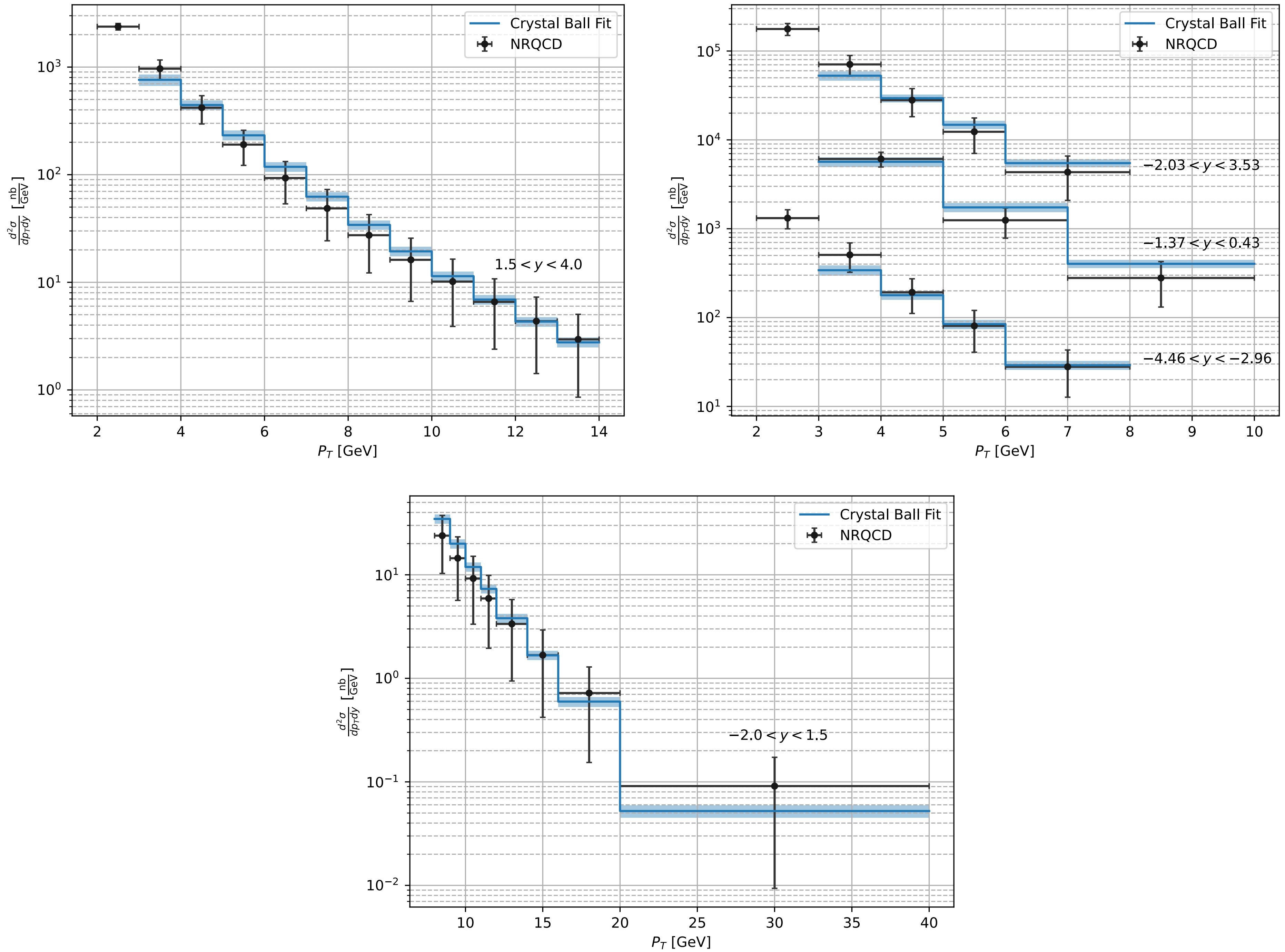


FIG. 2: Comparison between prompt J/ψ production in pp collisions for LHCb[87], ALICE[88] and ATLAS[89] kinematics as predicted by NRQCD and with the data-driven approach. The uncertainties of the NRQCD predictions come from scale variation $1/2 < \mu_r/\mu_{r,0} = \mu_f/\mu_{f,0} = \mu_{\text{NRQCD}}/\mu_{\text{NRQCD},0}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

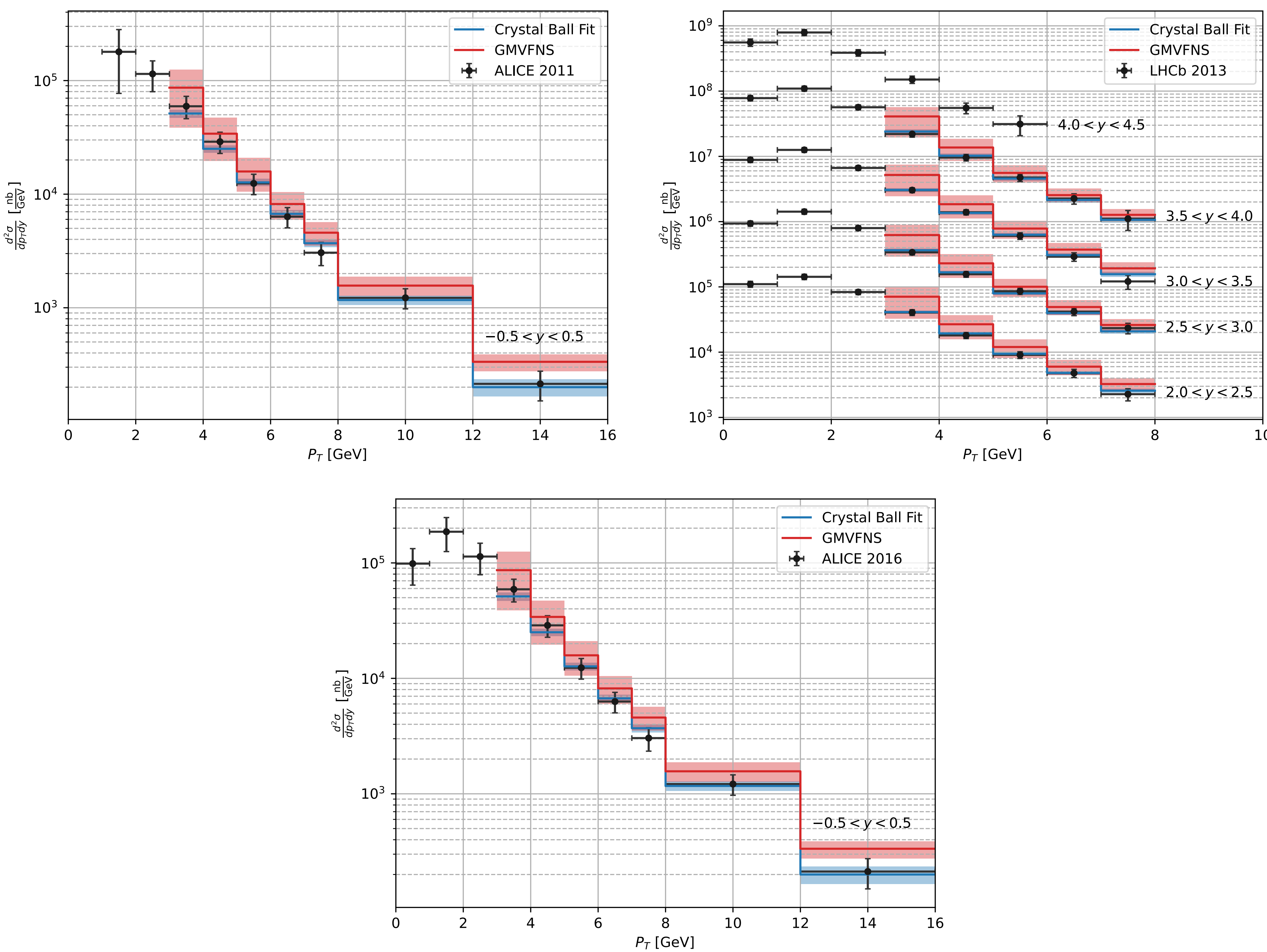
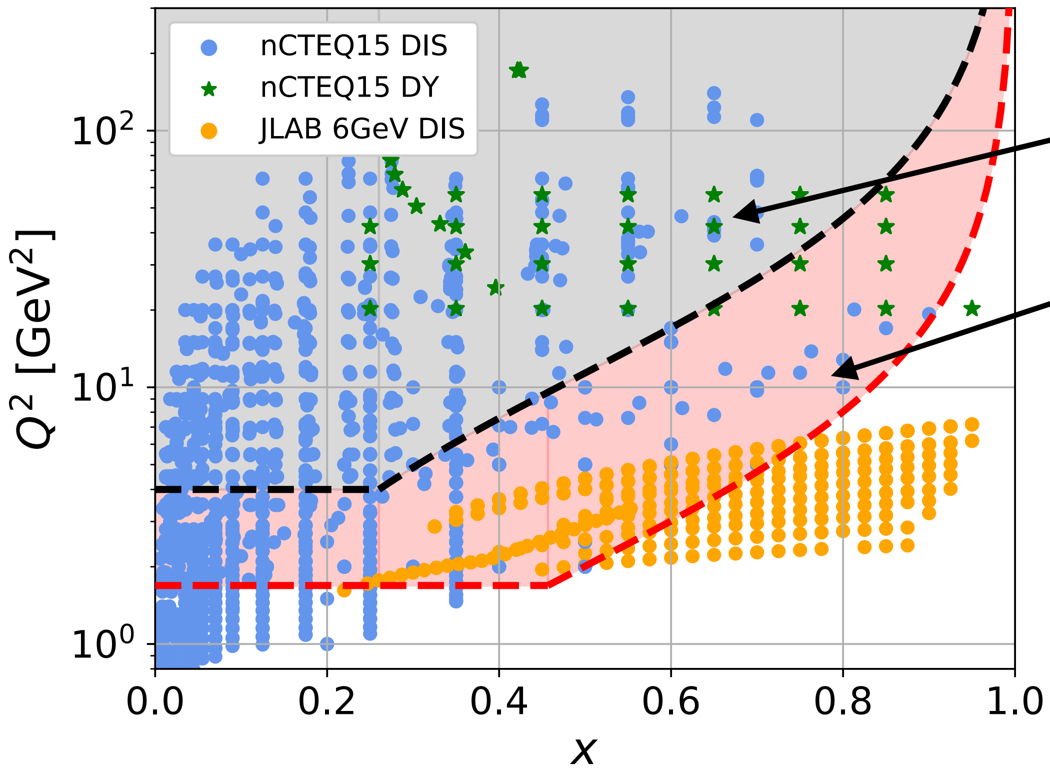


FIG. 3: Comparison between prompt D^0 production as predicted in the GMVFNS (red) and with the data-driven approach (blue). The uncertainties of the GMVFNS predictions come from varying the scales individually by a factor of 2, such that there is never a factor 4 between two scales. Different rapidity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

nCTEQHiX nPDFs with lower W-cut and JLAB data

arXiv:2012.11566

DIS and DY data entering the analysis



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

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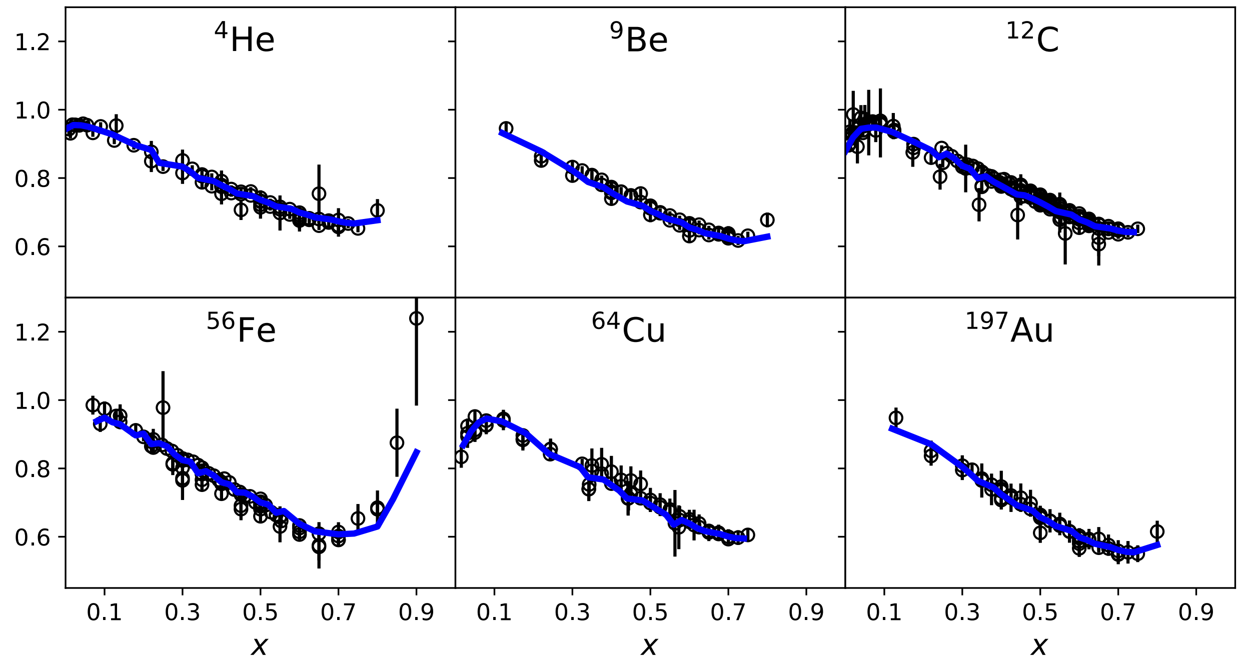
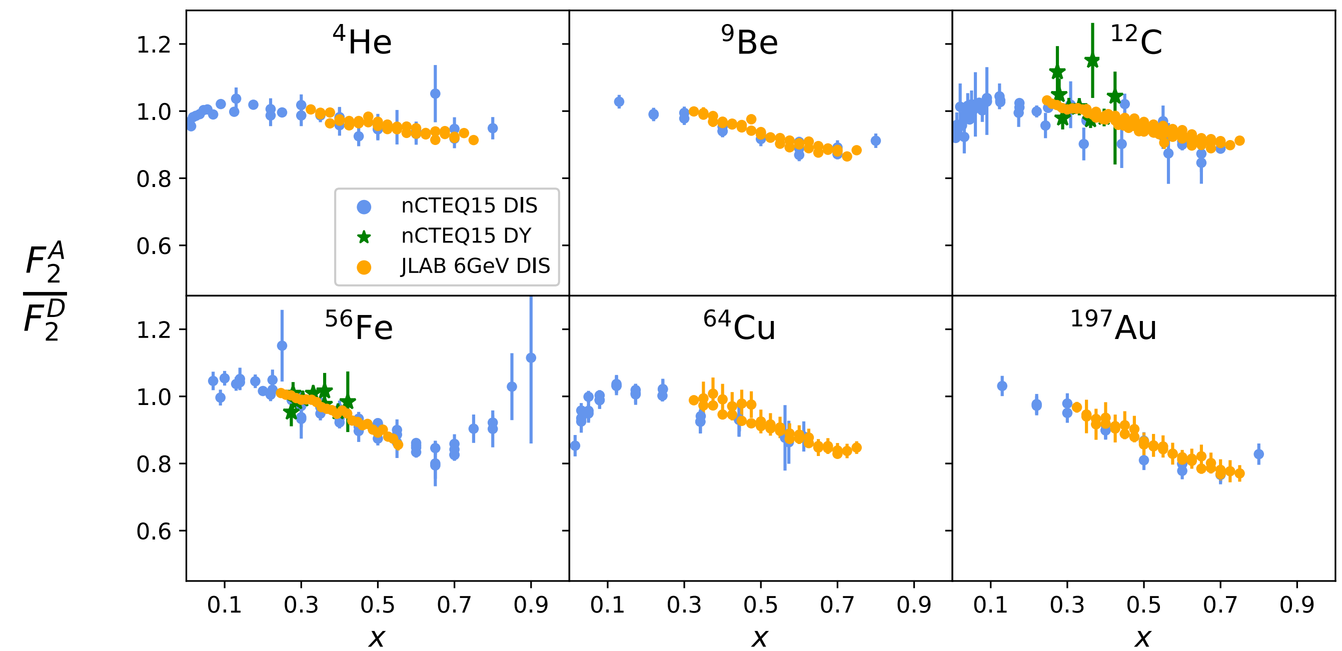
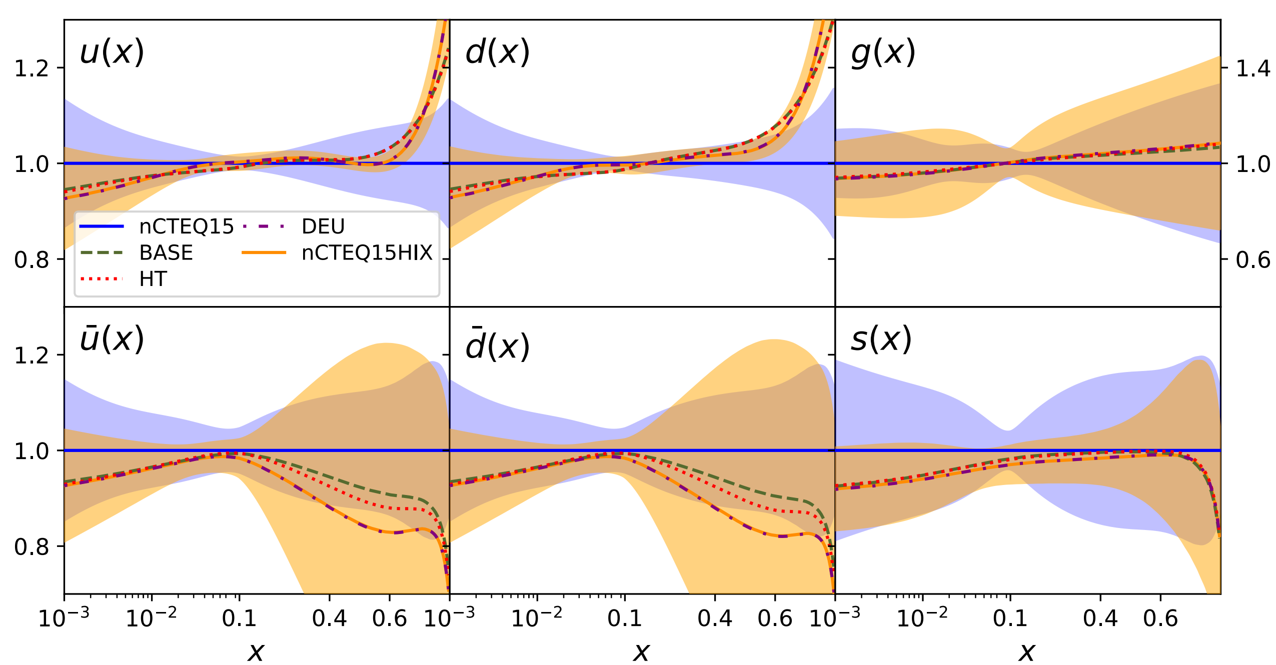
$(F_2^A/F_2^D) \times (F_2^D/F_2^p)_{CJ}$ **vs data**



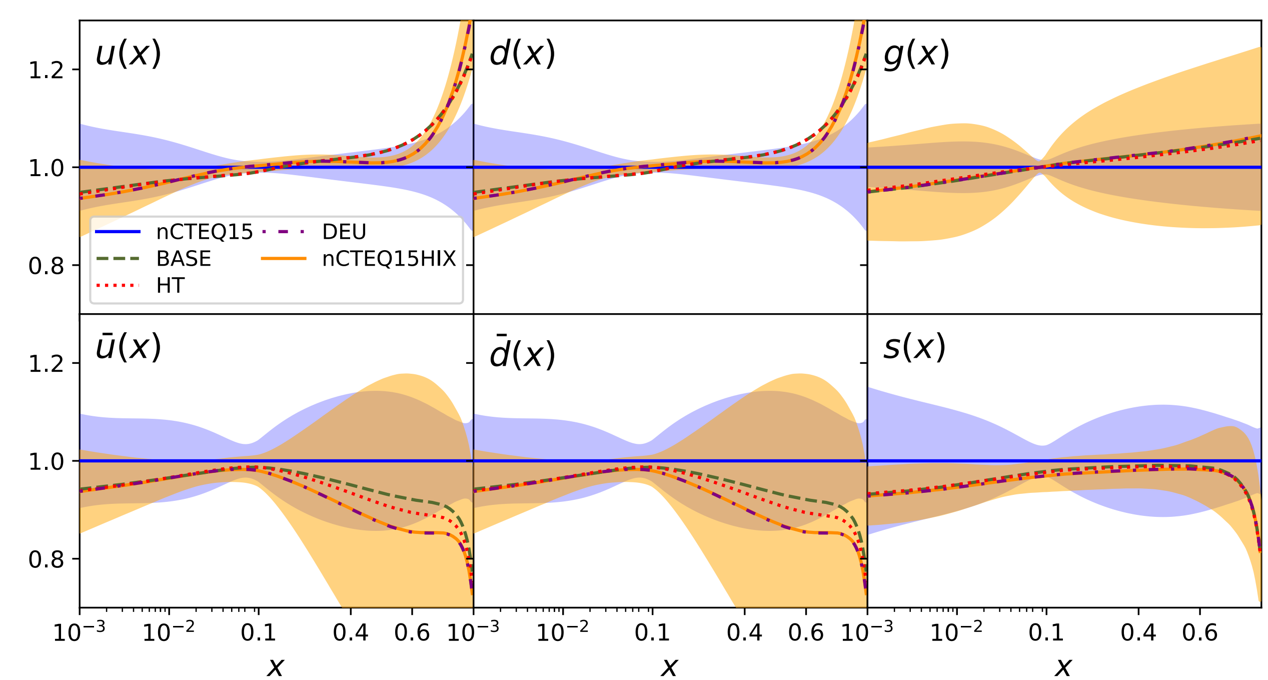
Selected data



Iron PDF Ratios to nCTEQ15 ($Q = 2$ GeV)



Carbon PDF Ratios to nCTEQ15 ($Q = 2$ GeV)



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

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