Importance of pPb HL-LHC data for nPDF fits

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Workshop on “Physics with high-luminosity
proton-nucleus collisions at the LHC”
CERN, July 4-5, 2024

Plan (20’+5’)

- [Proton and nuclear PDFs: Common framework]
- Which nuclei?
- Which data?
- Global analyses of nuclear PDFs
- Impactt of LHC data
- Conclusions

Proton and nuclear PDFs:
Common theoretical framework

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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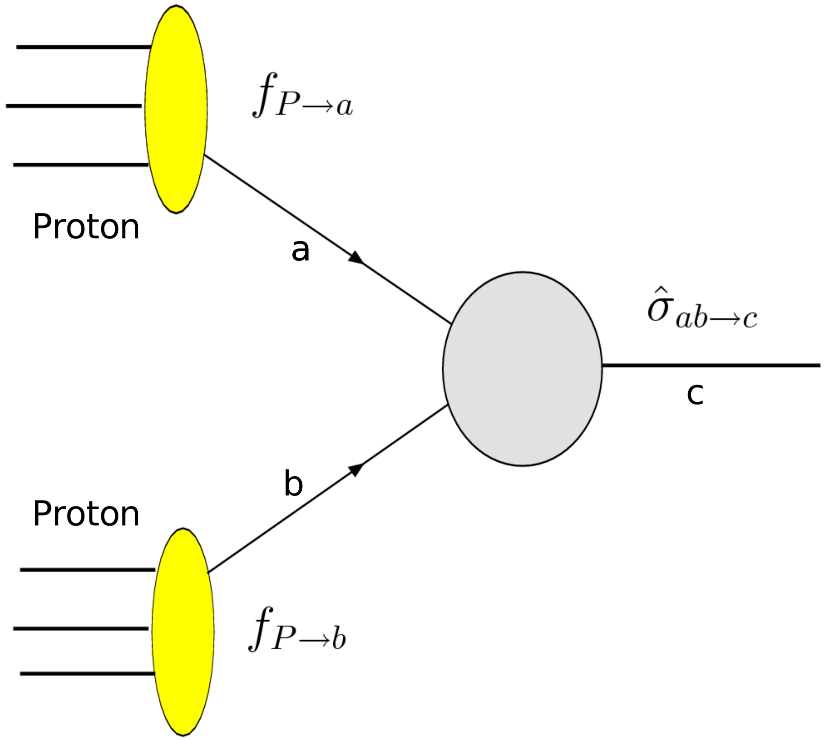
Example: Factorization for pp collisions



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

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 $F_{1,2,3}^{W+}$, $F_{1,2,3}^{W-}$

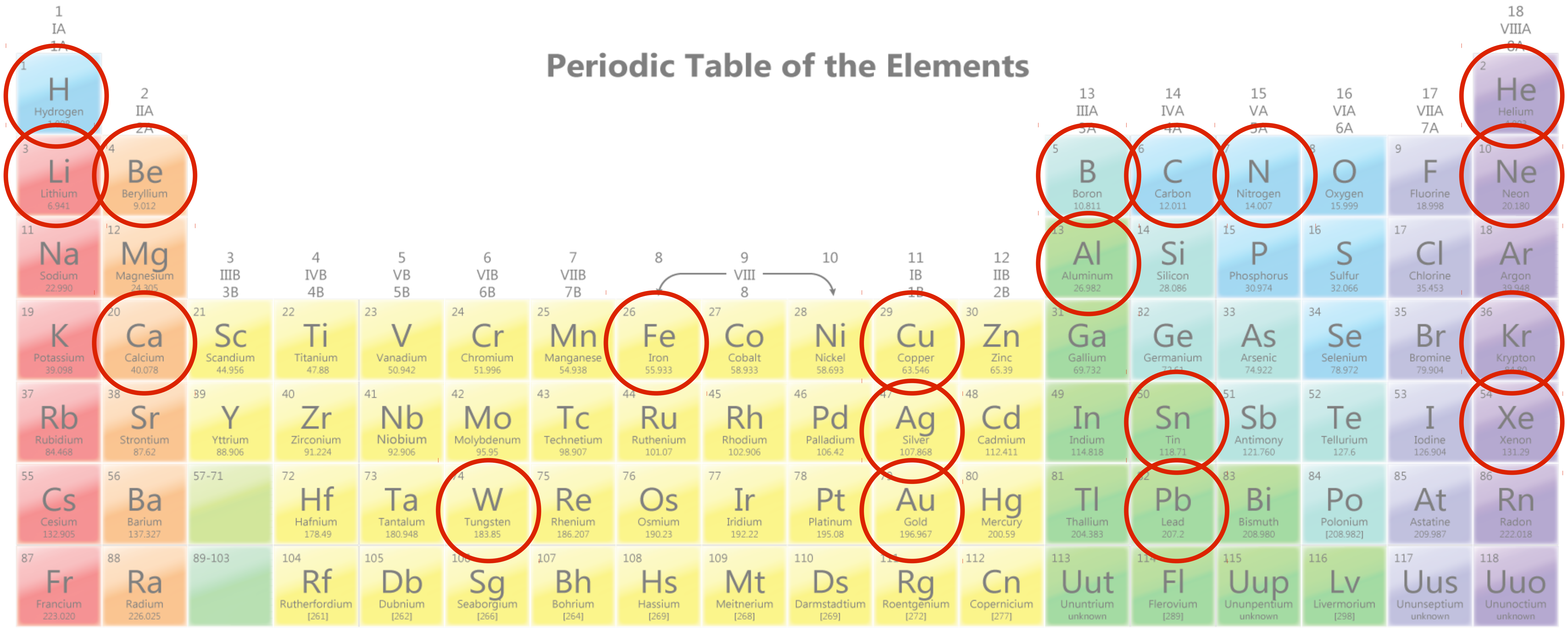
$$F_2^{W^+} \sim [d+s+\bar{u}+\bar{c}] \qquad F_3^{W^+} \sim 2[d+s-\bar{u}-\bar{c}]$$

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

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

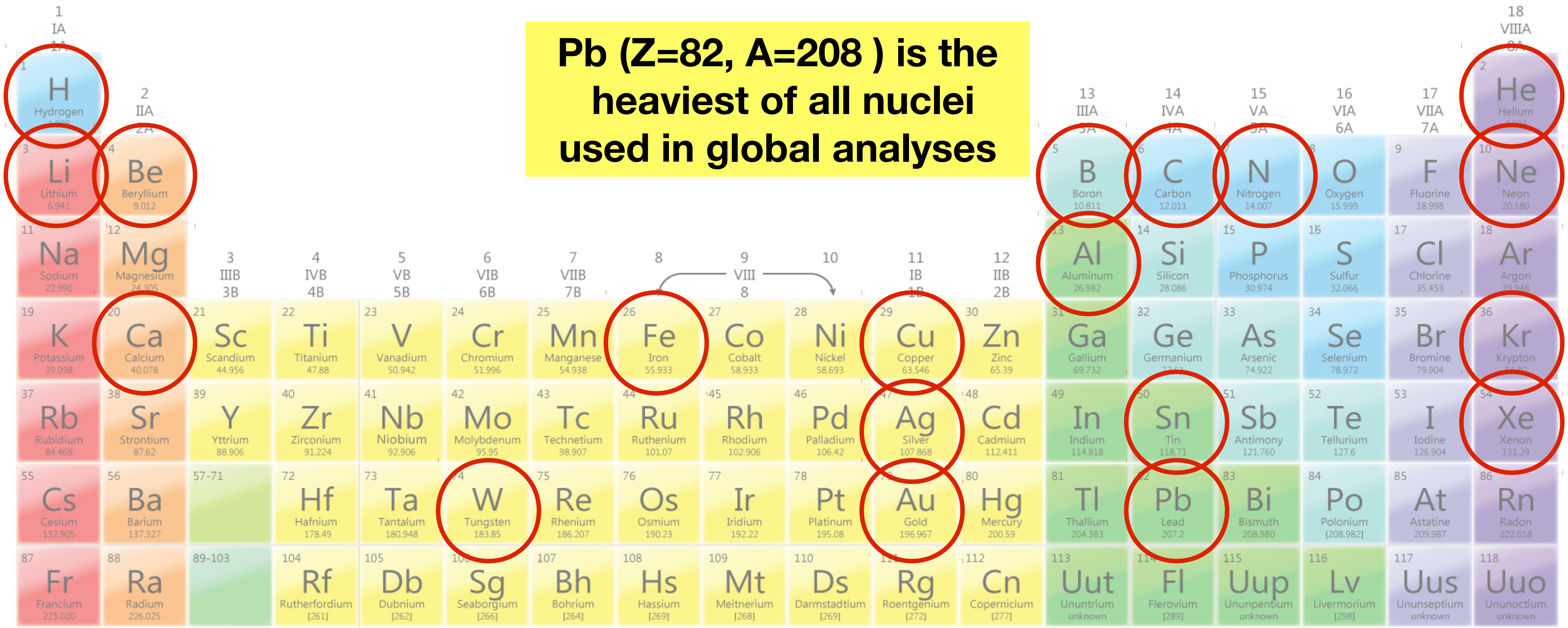
Which Nuclei?

Nuclei used in global analyses of PDFs



- **Fundamental quest**: understand structure of nuclei in terms of quarks and gluons
- **Necessary tool**: describe a wealth of hard process reactions in lepton-nucleus (lA, νA,), proton-nucleus (pA) and nucleus-nucleus (AA) collisions at colliders, fixed target experiments, in the atmosphere

Nuclei used in global analyses of PDFs

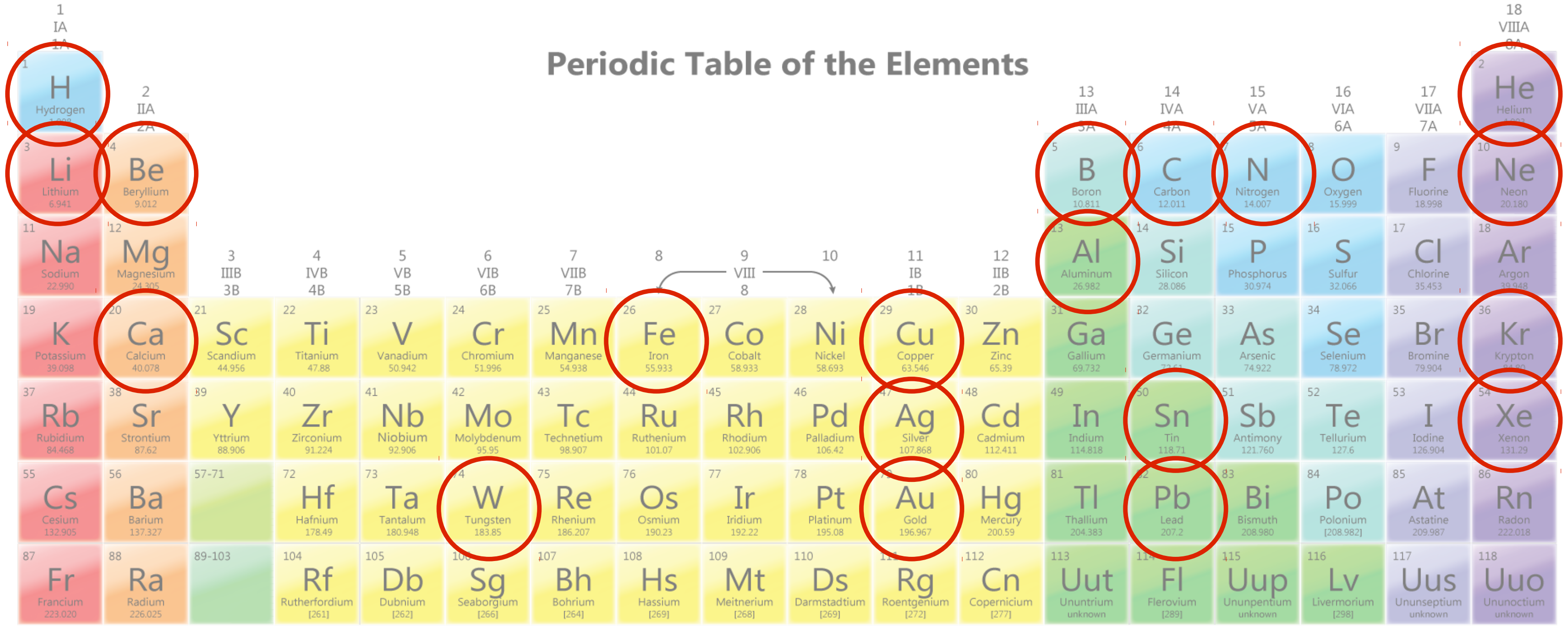


Pb (Z=82, A=208) is the heaviest of all nuclei used in global analyses

- **Fundamental quest**: understand structure of nuclei in terms of quarks and gluons
- **Necessary tool**: describe a wealth of hard process reactions in lepton-nucleus (lA, νA,), proton-nucleus (pA) and nucleus-nucleus (AA) collisions at colliders, fixed target experiments, in the atmosphere

Nuclei used in global analyses of PDFs

- **RHIC SIH**: **Au: 111**
- **LHC SIH**: **Pb: 193**
- **LHC W/Z**: **Pb: 120**
- **LHC HQ**: **Pb: 548**



- **Fixed Target NC DIS** (after ‘standard DIS’ cuts Q>2 GeV, W>3.5 GeV):
  - He: 32, Li: 11+14, Be: 3+14, C: 40+188, N: 29, Al:3+14, Ca: 17+28, **Fe: 22+14**, Cu: 18, Kr:12, Ag: 2, Sn: 8+111, Xe: 2, **Au: 3**, **Pb: 3+14**
  - JLAB 6 GeV DIS data: He, Be, C, Al, Fe, Cu, Pb (not passing standard DIS cuts)

- **Fixed Target DY**:
  - Be: 0+56, C: 9, Ca: 9, **Fe: 9+28**, W: 9+28

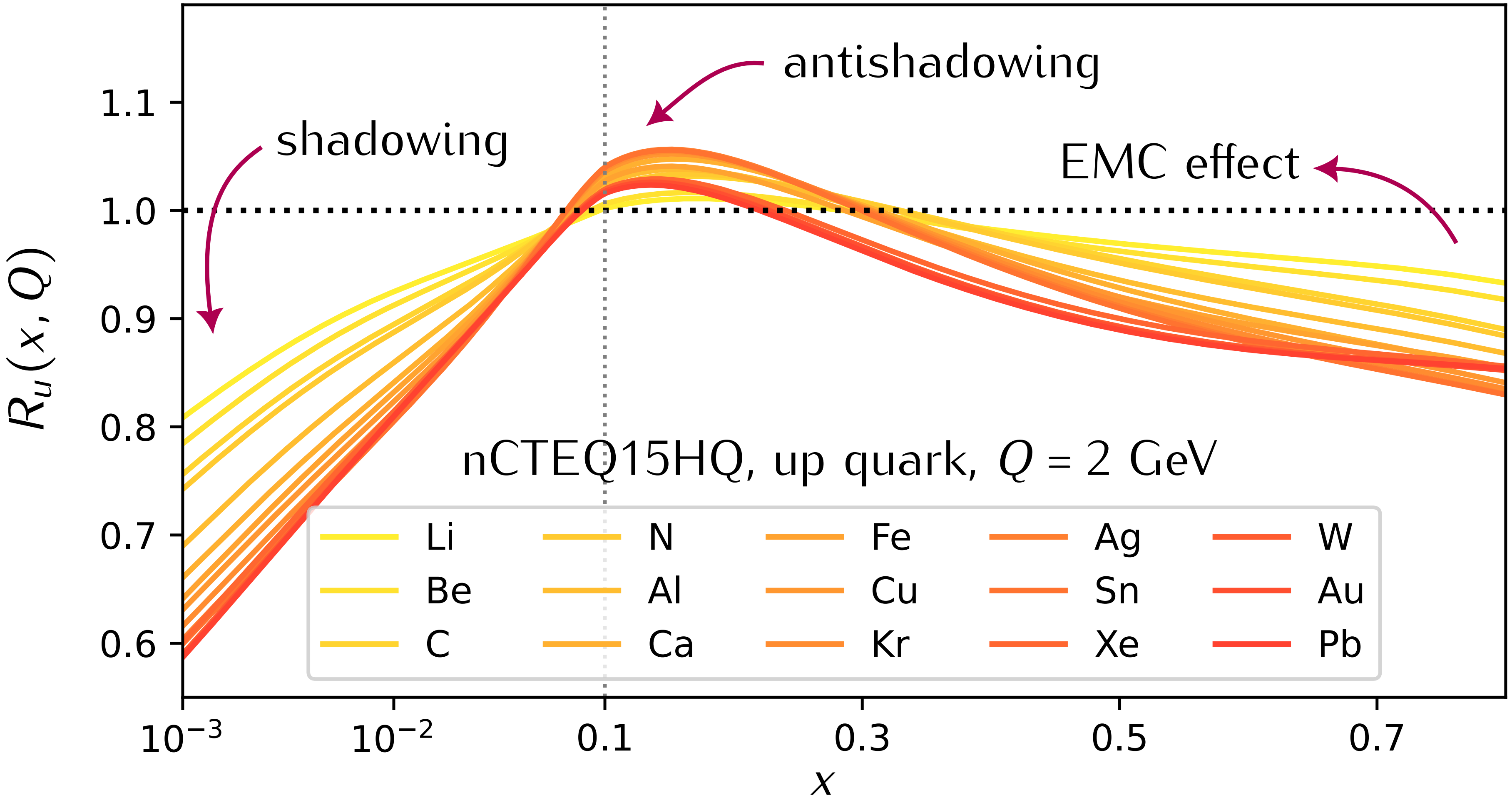
- **Fixed Traget CC neutrino DIS**:
  - Inclusive DIS: Fe (not included), **Pb: 824**
  - Dimuon SIDIS: **Fe: 150**

FT NC DIS 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

Standard DIS cuts

Dependence on A



- Different nuclei are combined in a global analysis by modelling the A-dependence of the fit parameters: $c_j(A) = p_j + a_j \ln A + b_j \ln^2 A$

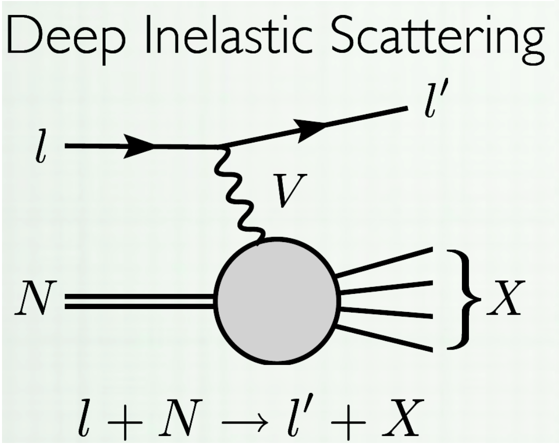
- This modelling is quite rough so far. Room for progress

- Lead-only analysis conceivable. Additional HL-LHC data will help

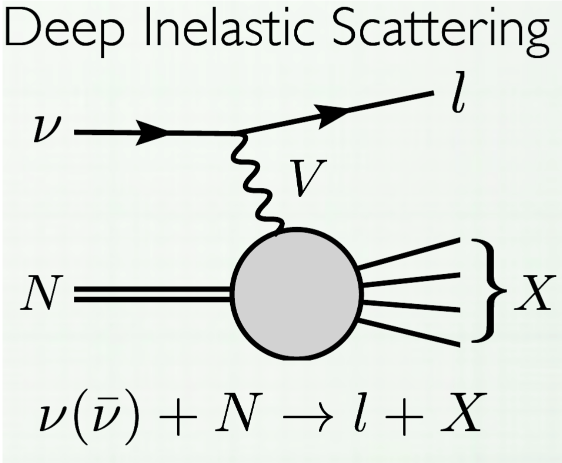
Which Data?

Used data sets I

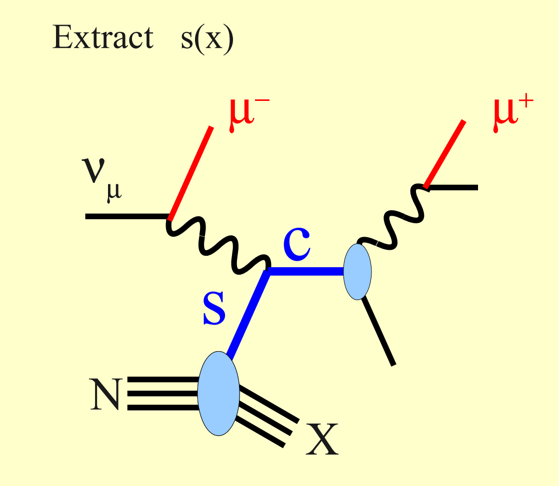
- **IA DIS:** backbone of all global analyses
  - Data from SLAC, NMC, EMC, BCDMS, FNAL: all groups (**but different cuts**)
  - Data from JLAB (CLAS, Hall-C): nCTEQ15HiX, EPPS21, KSASG20



- **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



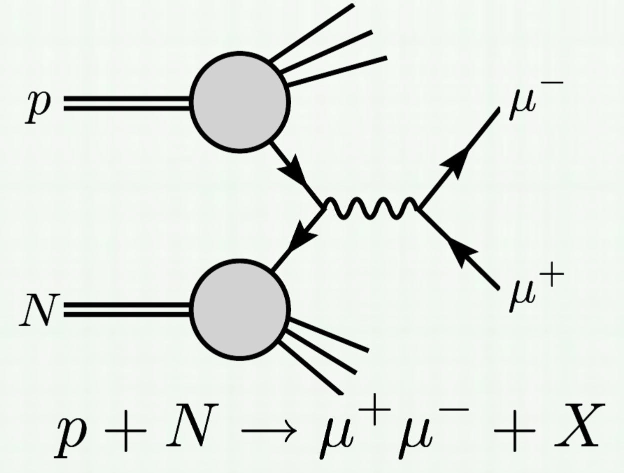
- **nuA SIDIS charm production** (dimuon data): strange PDF
  - NuTeV, CCFR nu-Fe: nNNPDF2.0, BaseDimuCHORUS



Used data sets II

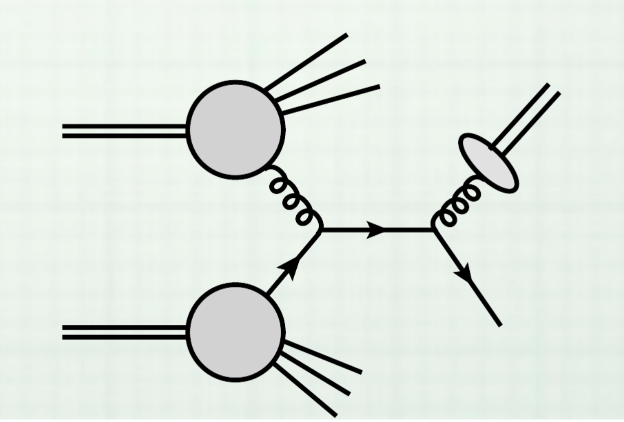
- **pA DY:** disentangle valence and sea quarks
  - E772, E866 data: EPPS16, EPPS21,, nCTEQ15X, KA15, KSASG20, DSSZ12, nNNPDF3.0
  - π-A DY data: EPPS16, EPPS21
- **SIH data**: gluon distribution (weaker impact compared to HQ and dijet data)
  - RHIC single hadron production: EPPS16, EPPS21, nCTEQ15X (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

Drell-Yan process



$p + N \to \mu^+\mu^- + X$

Single pion production

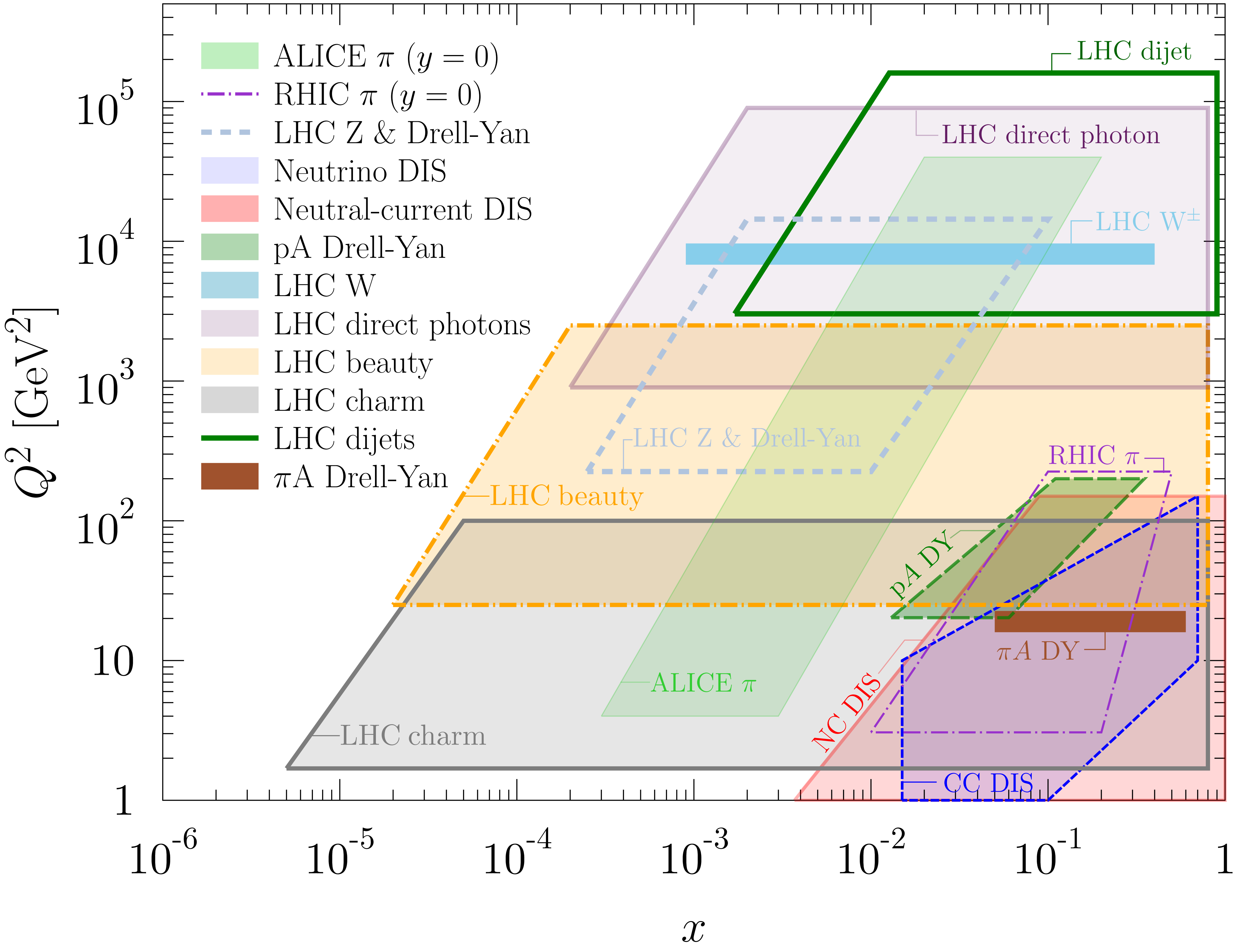


Used data sets III

- **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

Kinematic coverage of data used in global analyses

[Klasen, Paukkunen, 2311.00450]



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

LHC data important

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

- Enormously enhance kinematic coverage in (x,Q^2)
- Important for flavour separation over wide kinematic range
- **Higher scales require more precision** to constrain boundary conditions for PDFs at low scales: **HL-LHC!**
- Eventually lead-only global analysis
- Add collider data for other nuclei: Oxygen, …
- FOCAL

Global Analyses of nuclear PDFs

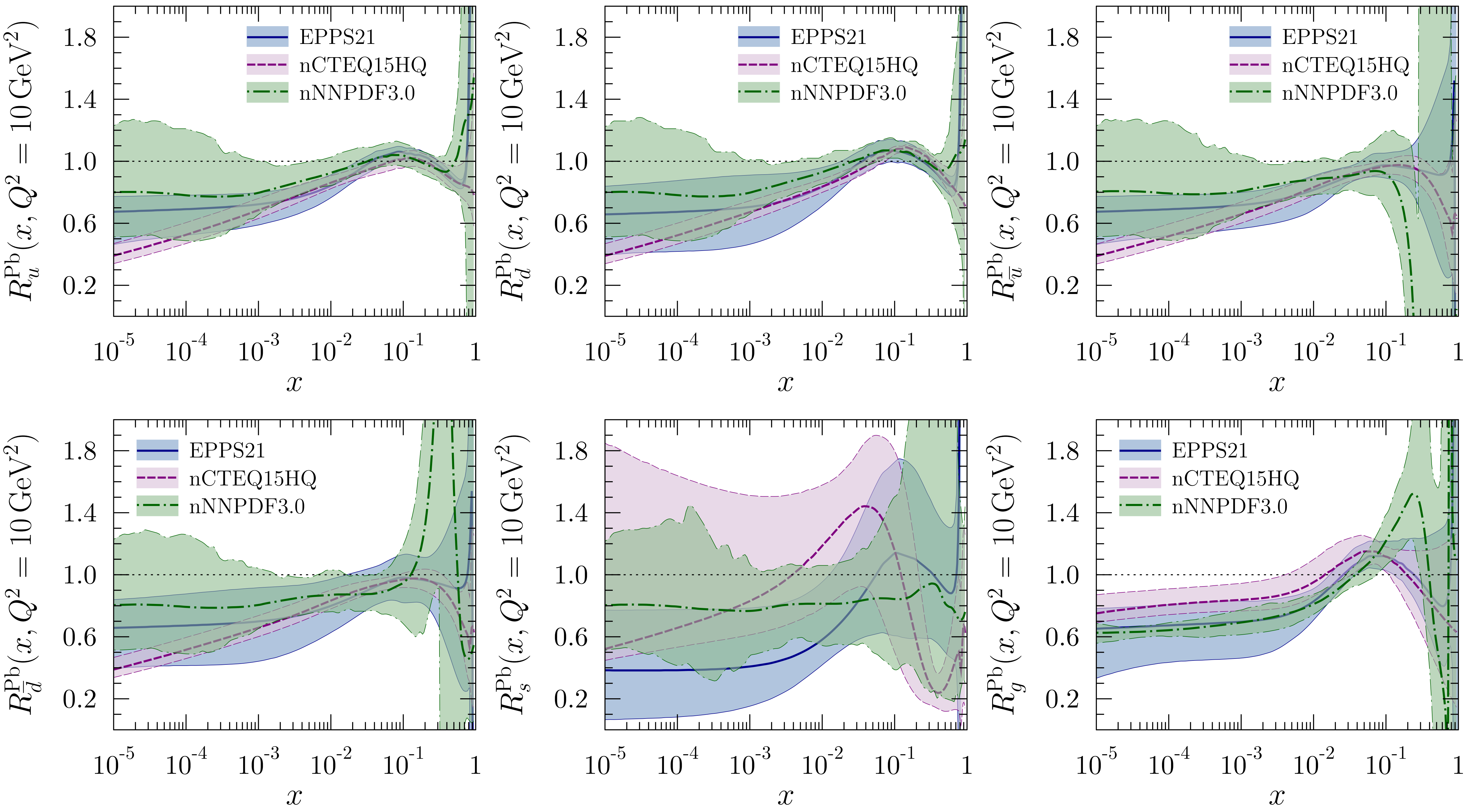
Comparison of recent nPDF fits

M. Klasen, DIS24

Analysis	nCTEQ15HQ	EPPS21	nNNPDF3.0	TUJU21	KSASG20
Theoretical input:					
Perturbative order	NLO	NLO	NLO	NNLO	NNLO
Heavy-quark scheme	SACOT$-\chi$	SACOT$-\chi$	FONLL	FONLL	FONLL
Data points	1484	2077	2188	2410	4353
Independent flavors	5	6	6	4	3
Free parameters	19	24	256	16	18
Error analysis	Hessian	Hessian	Monte Carlo	Hessian	Hessian
Tolerance	$\Delta\chi^2 = 35$	$\Delta\chi^2 = 33$	N/A	$\Delta\chi^2 = 50$	$\Delta\chi^2 = 20$
Proton PDF	∼CTEQ6.1	CT18A	∼NNPDF4.0	∼HERAPDF2.0	CT18
Deuteron corrections	(✓)[a,b]	✓[c]	✓	✓	✓
Fixed-target data:					
SLAC/EMC/NMC NC DIS	✓	✓	✓	✓	✓
– Cut on Q^2	4 GeV^2	1.69 GeV^2	3.5 GeV^2	3.5 GeV^2	1.2 GeV^2
– Cut on W^2	12.25 GeV^2	3.24 GeV^2	12.5 GeV^2	12.0 GeV^2	
JLab NC DIS	(✓)[a]	✓			✓
CHORUS/CDHSW CC DIS	(✓/-)[b]	✓/-	✓/-	✓/✓	✓/✓
NuTeV/CCFR 2μ CC DIS	(✓/✓)[b]		✓/-		
pA DY	✓	✓	✓		✓
Collider data:					
Z bosons	✓	✓	✓	✓	
$W^\pm$ bosons	✓	✓	✓	✓	
Light hadrons	✓	✓[d]			
Jets		✓	✓		
Prompt photons			✓		
Prompt D^0	✓	✓	✓[e]		
Quarkonia (J/ψ, ψ', Υ)	✓				

Nuclear PDFs after 10 years of LHC data

[Klasen, Paukkunen, 2311.00450]



Impact of LHC data

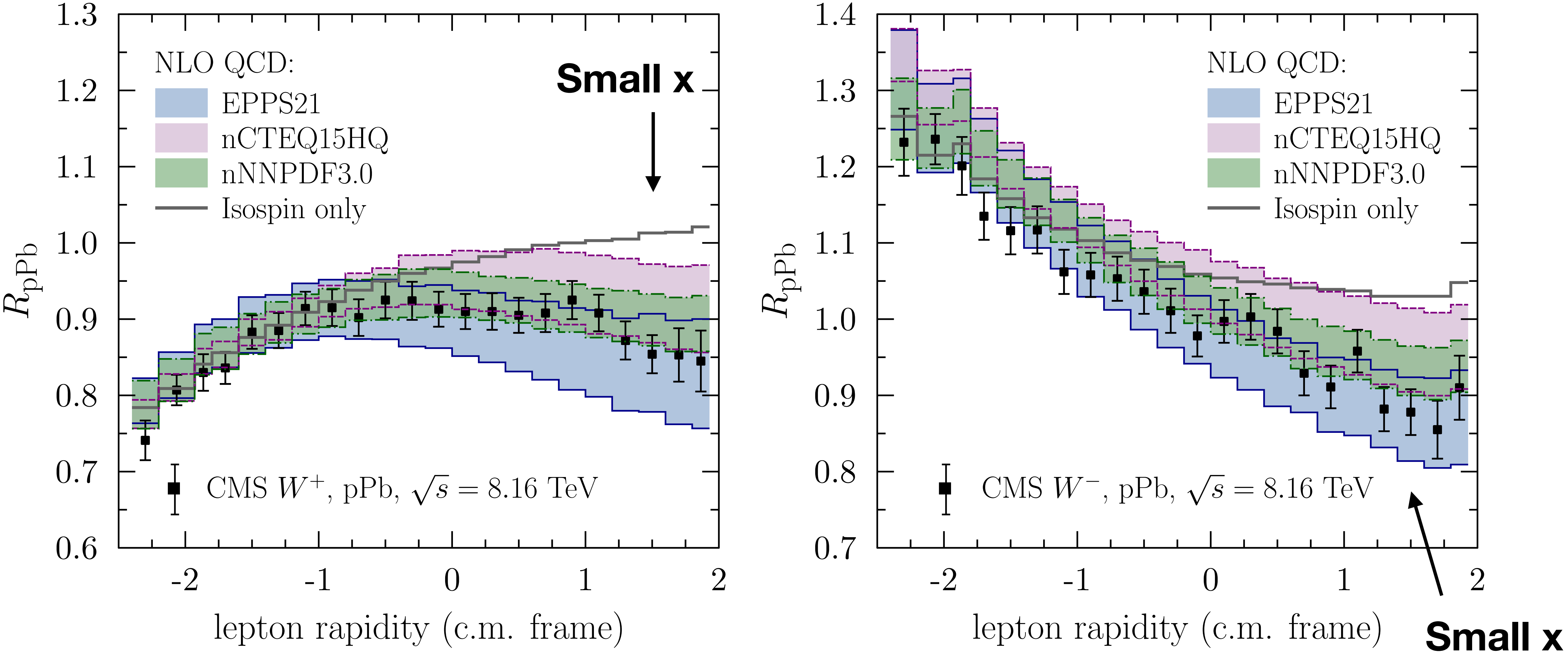
Experimental data on W/Z bosons

Analysis	nCTEQ15HQ	EPPS21	nNNPDF3.0	TUJU21	KP16
Run-I:					
ATLAS Z	✓	✓	✓	✓	✓
CMS Z	✓	✓	✓	✓	✓
ALICE Z			✓[b]		
LHCb Z	✓		✓[b]		
ATLAS $W^{\pm}$	✓				✓
CMS $W^{\pm}$	✓	✓	✓		
ALICE $W^{\pm}$	✓		✓[b]		
Run-II:					
CMS Z			✓[b]		
ALICE Z			✓[b]		
LHCb Z					
CMS $W^{\pm}$	✓	✓[a]	✓	✓	
ALICE $W^{\pm}$					

[a] added in EPPS21; [b] added in nNNPDF3.0.

Run-II W boson production in pPb from CMS

[Klasen, Paukkunen, 2311.00450]



Small x

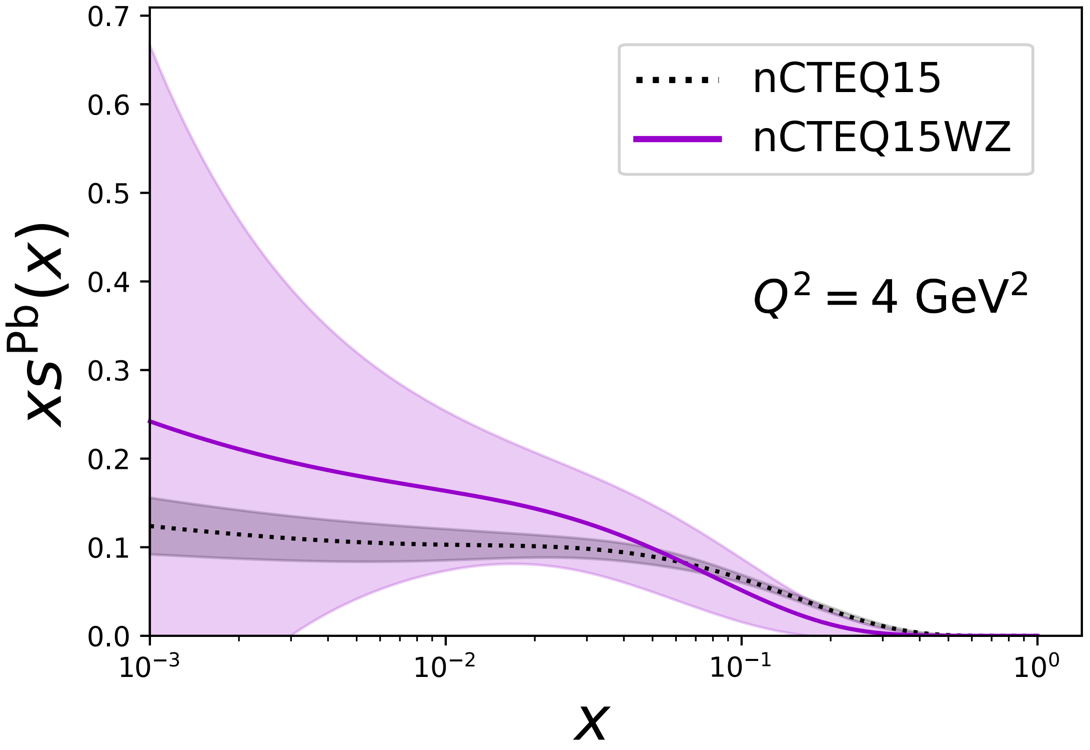
Small x

Figure 6: Nuclear modification ratios for W^+ (left) and W^- bosons (right) at CMS Run-II (172, 173) compared with EPPS21 (51), nCTEQ15HQ (50), nNNPDF3.0 (52) and a calculation with 82 free protons and 126 free neutrons.

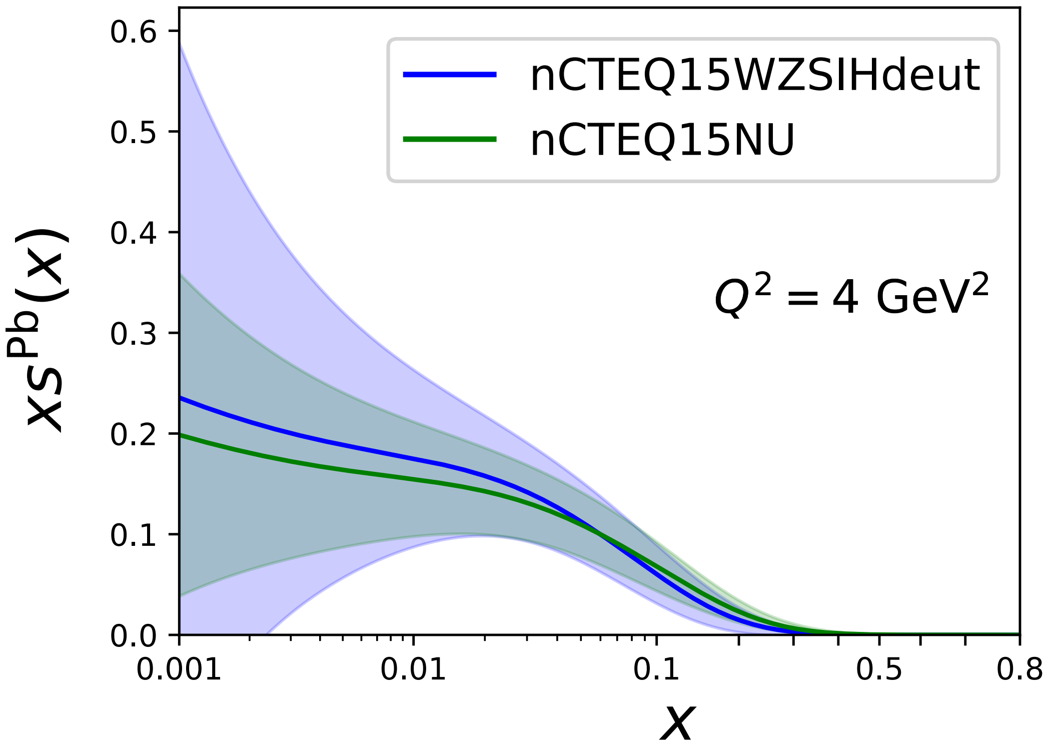
EPPS21 fitted shown R_{pPb} while nCTEQ15HQ and nNNPDF3.0 fitted pPb cross sections

Impact on the strange nPDF

- **nCTEQ15WZ** includes **LHC W/Z data**
  - ✓ First realistic uncertainties
- **nCTEQ15NU** also adds **CC neutrino data** (including dimuon data)
  - ✓ Neutrino data provides further constraints down to low-x



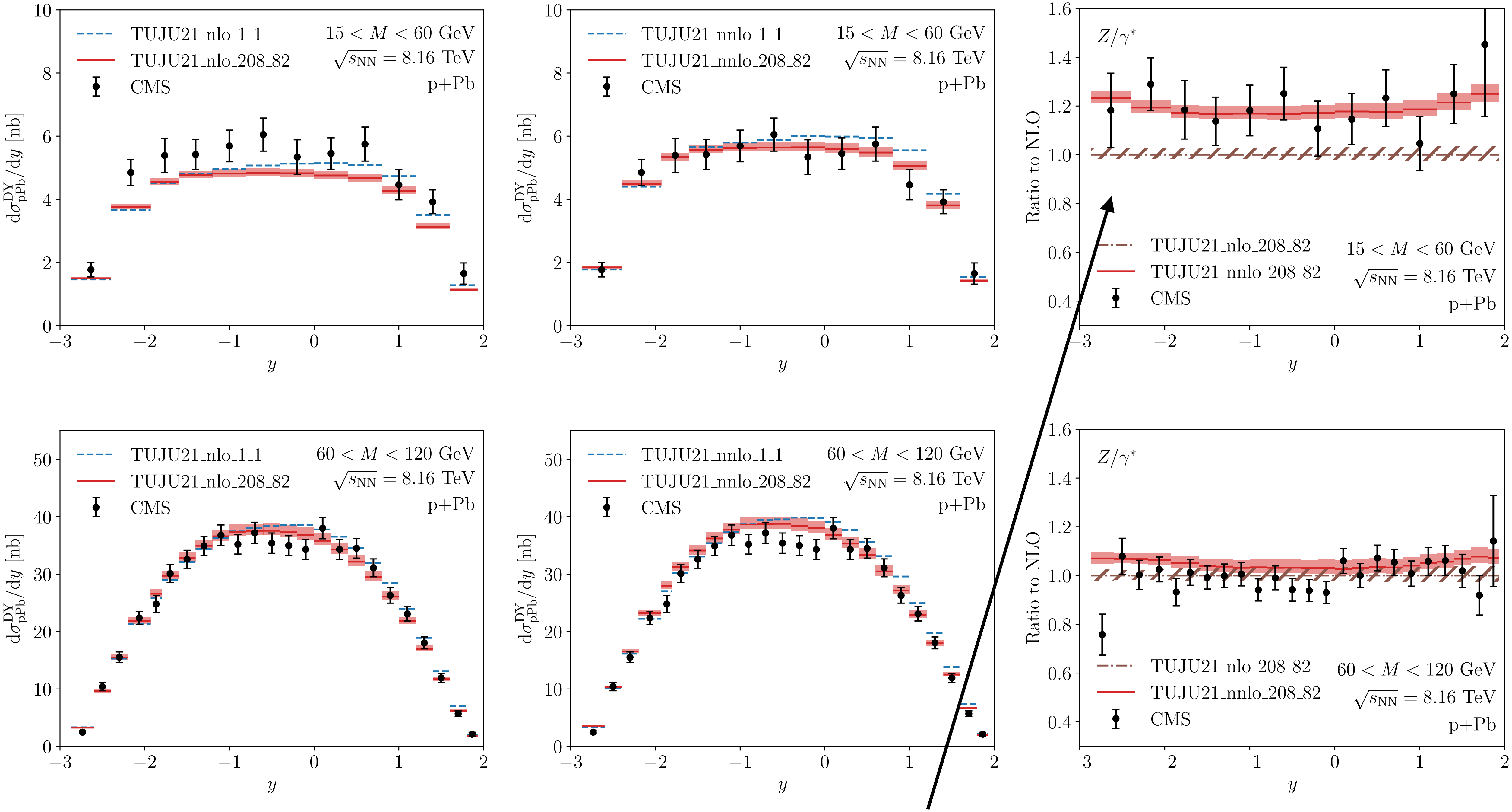
[2007.09100]



[2204.13157]

Run-II Z boson production in pPb from CMS

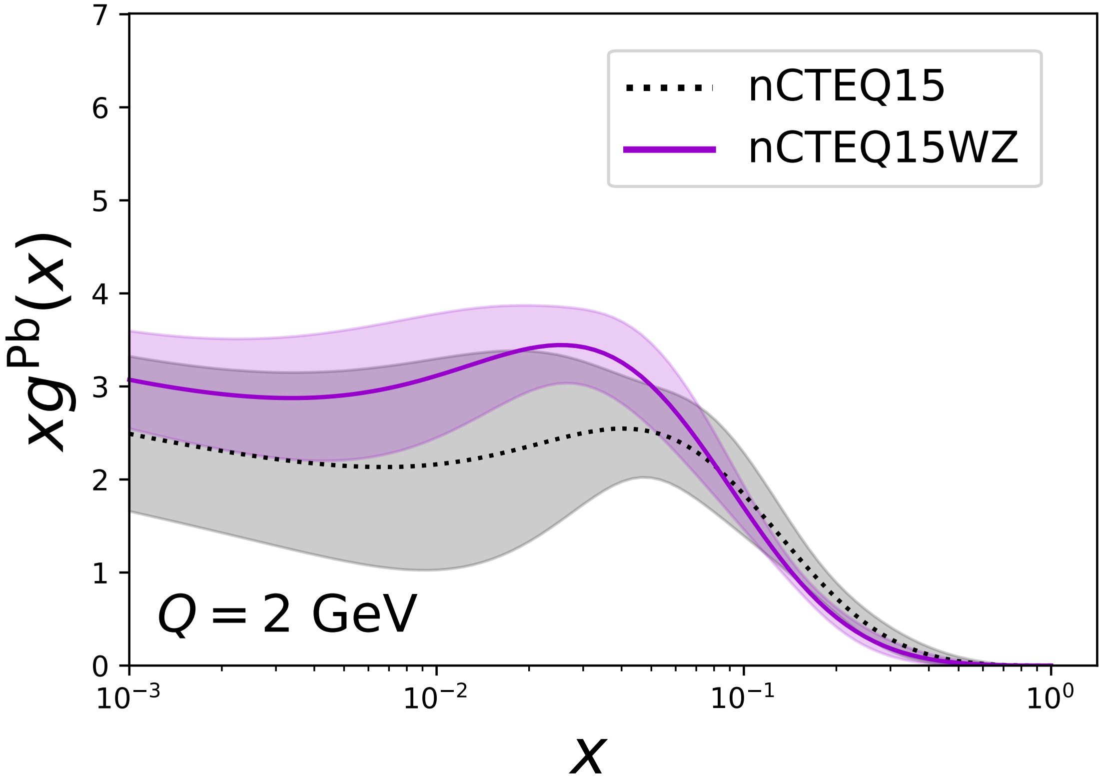
[Helenius, Vogelsang, Walt, PRD105(2022)094031]



Low mass data in tension with NLO (also nNNPDF) → NNLO?

LHC W/Z and the gluon nPDF

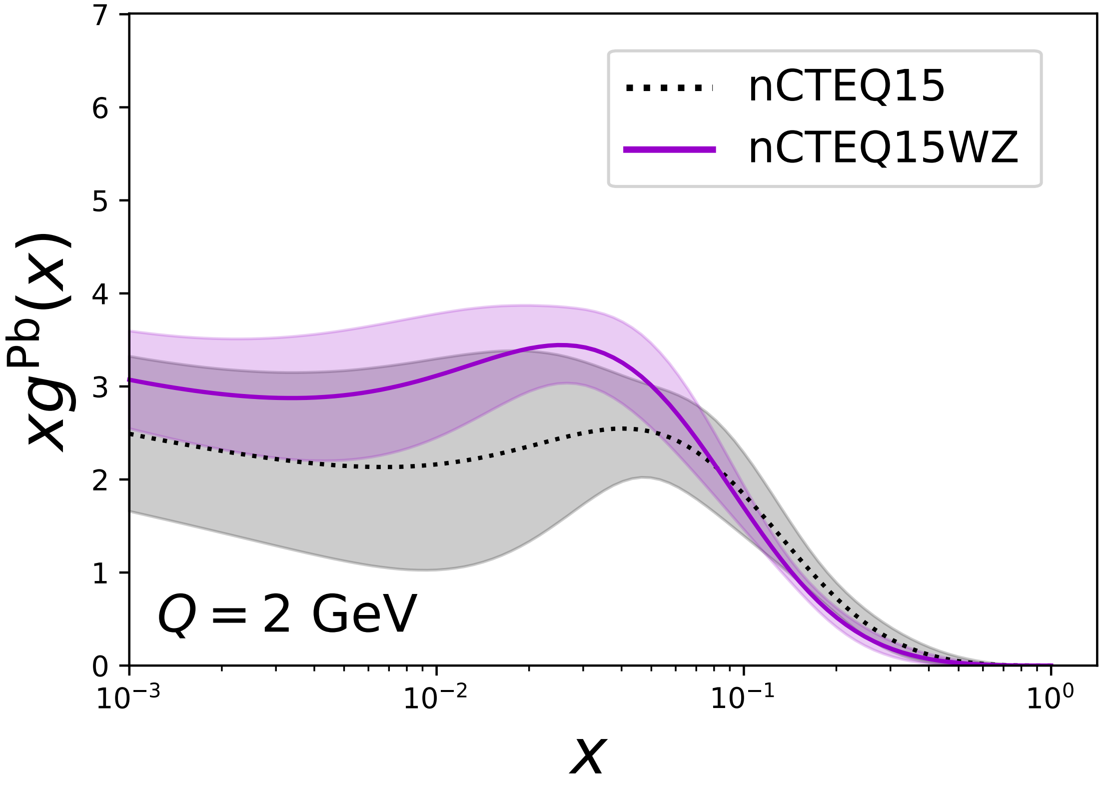
- **nCTEQ15WZ** includes **LHC W/Z** data
  - ✓ Also constrains gluon



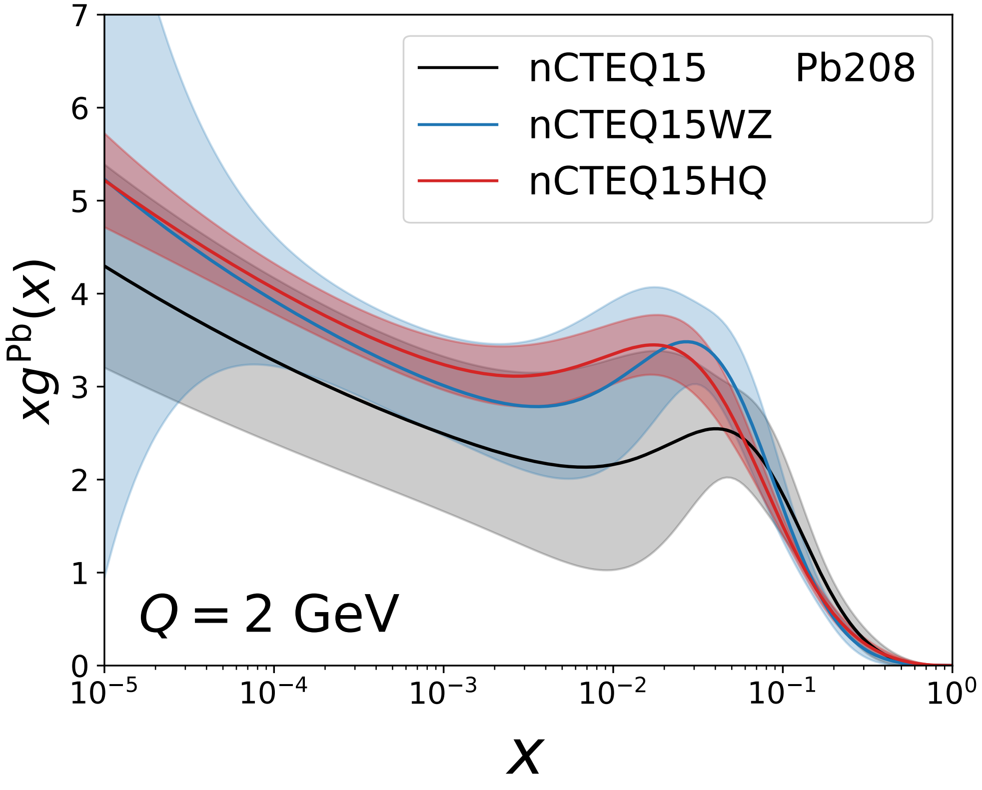
[2007.09100]

LHC HQ data and the gluon nPDF

- **nCTEQ15WZ** includes **LHC W/Z** data
  - ✓ Also constrains gluon
- **nCTEQ15HQ** also adds **quarkonium and open HQ data**
  - ✓ Unprecedented low-x reach



[2007.09100]



[2204.09982]

Heavy quark and quarkonium data

OBSERVABLE $\mathcal{O}$	D^0	J/ψ	$\Upsilon(1S)$	$\psi(2S)$	B^0, $B^\pm$	c jet	b jet
RUN-I:							
ATLAS		(240, 241)[a]	(241)[a]	(241)[a]			
CMS		(242)[a]	(243)	(244)[a]		(245)	(246)
ALICE	(247, 248, 249)[a]	(250, 251)[a], (252)	(253)	(254)[a]			(255)
LHCb	(256)[a,b,c]	(257)[a]	(258)				
RUN-II:							
ALICE		(259)[a], (260)	(261)[a]	(262)[a]			
LHCb	(263)	(264)[a]	(265)[a]		(266)		
FIXED TARGET:							
LHCb	(267, 268)	(267, 269)		(269)			

[a] included in nCTEQ15HQ (50); [b] included in EPPS21 (51); [c] included in nNNPDF3.0 (52).

nCTEQHQ nPDFs

arXiv:2204.09982

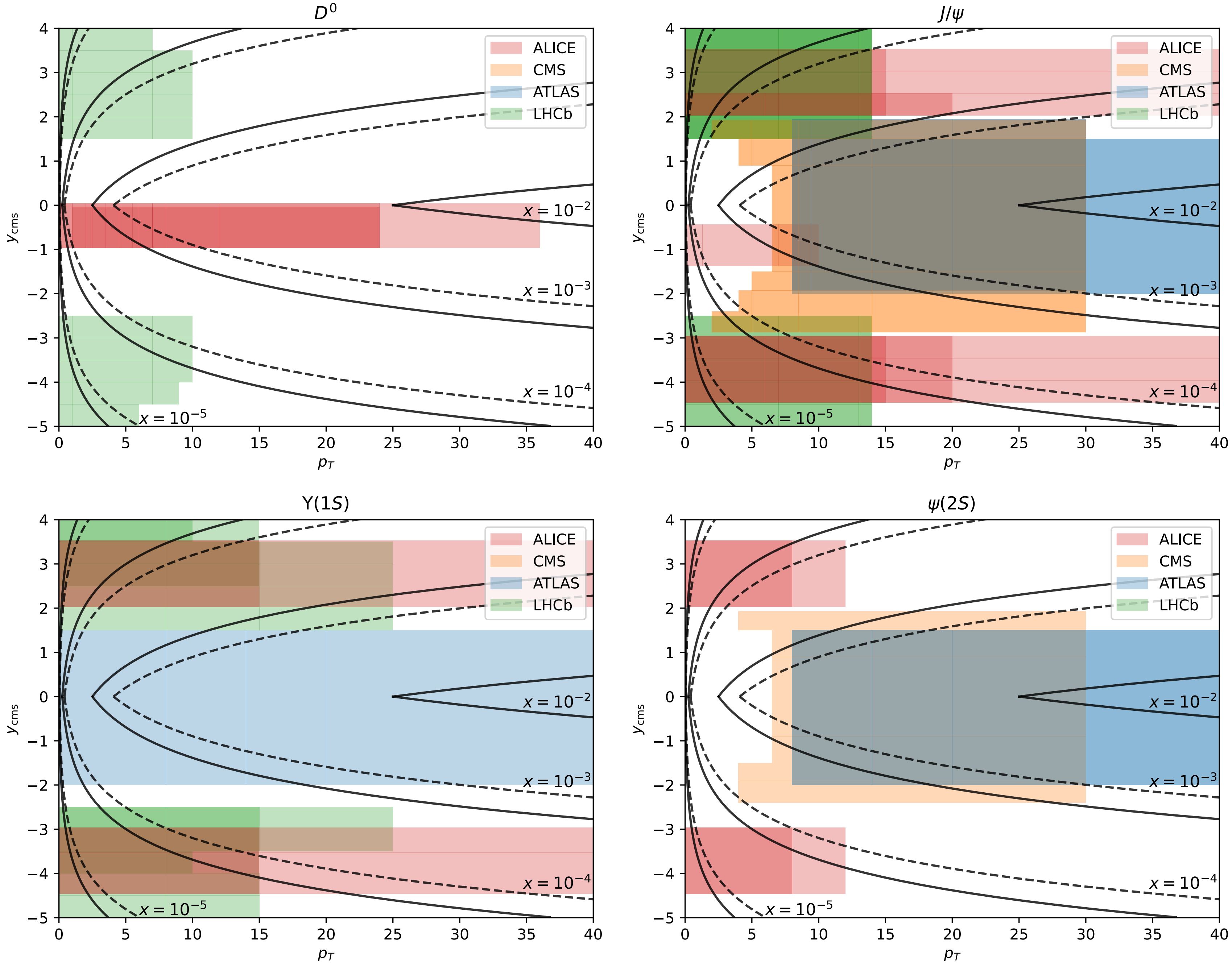


FIG. 1: Coverage of the kinematic (p_T, y_{cms})-plane of the quarkonium and open heavy quark production data sets from proton-lead collisions. ALICE data is shown in red, ATLAS in blue, CMS in orange and LHCb in green. The dashed and solid contours show the estimated x-dependence for $\sqrt{s} = 5$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

- 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

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

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**

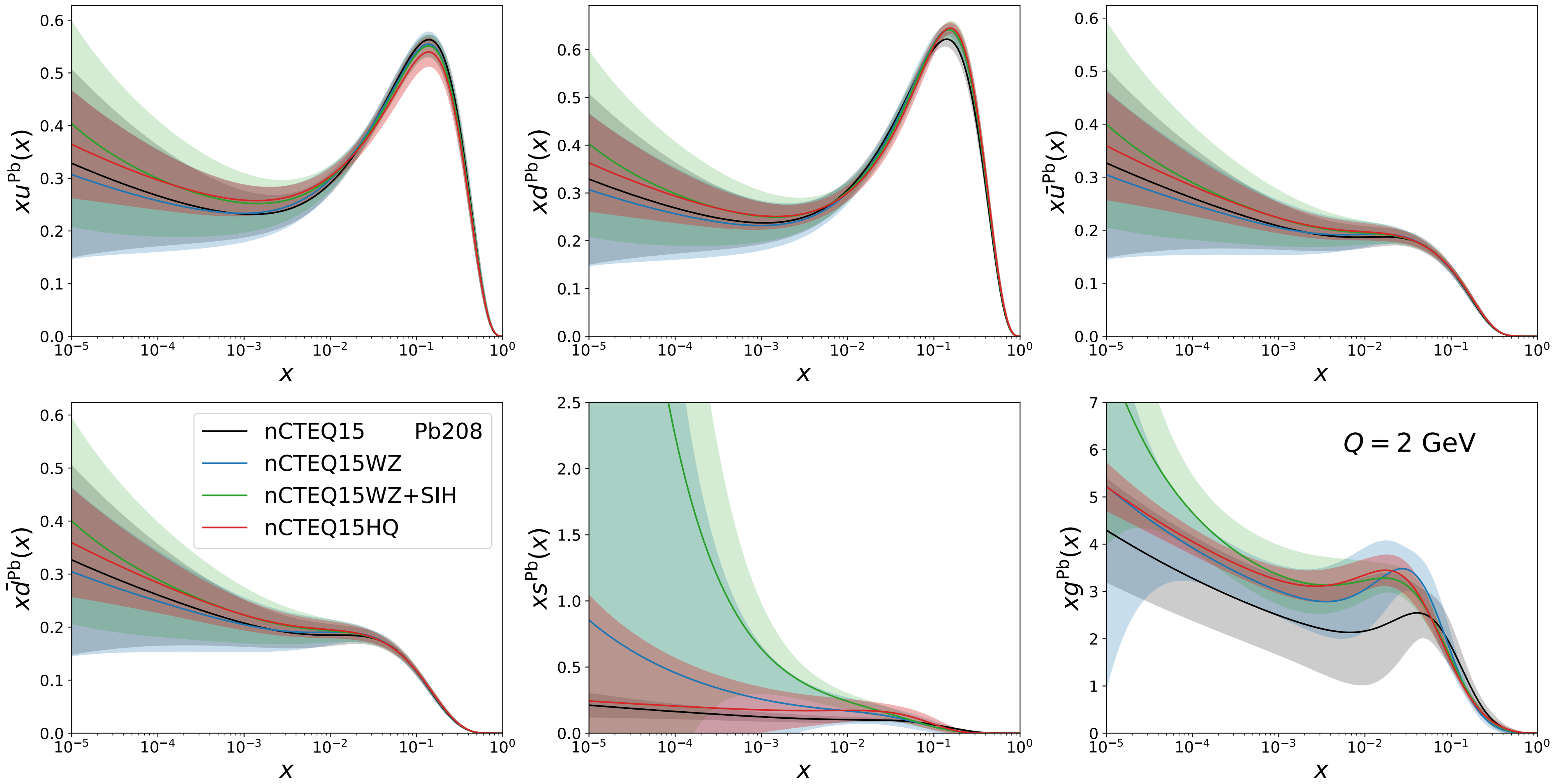


FIG. 4: Lead PDFs from different nCTEQ15 versions. The baseline nCTEQ15 fit is shown in black, nCTEQ15WZ in blue, nCTEQ15WZSIH in green, and the new fit in red.

nCTEQ15HQ nPDFs

arXiv:2204.09982

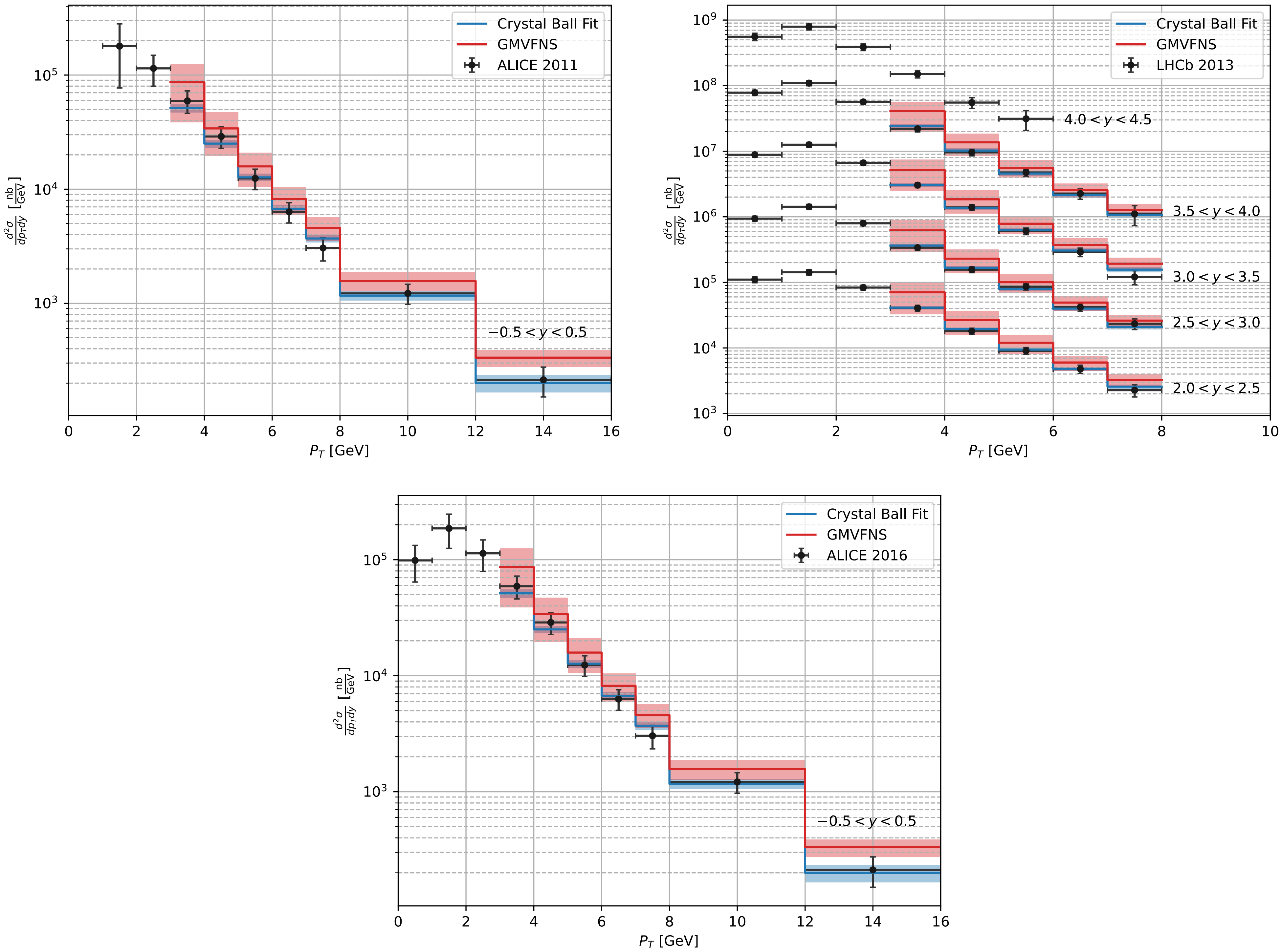


FIG. 3: Comparison between prompt D^0 production as predicted in the GMVFNS (red) and with the data-driven approach (blue). The uncertainties of the GMVFNS predictions come from varying the scales individually by a factor of 2, such that there is never a factor 4 between two scales. Different rapidity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

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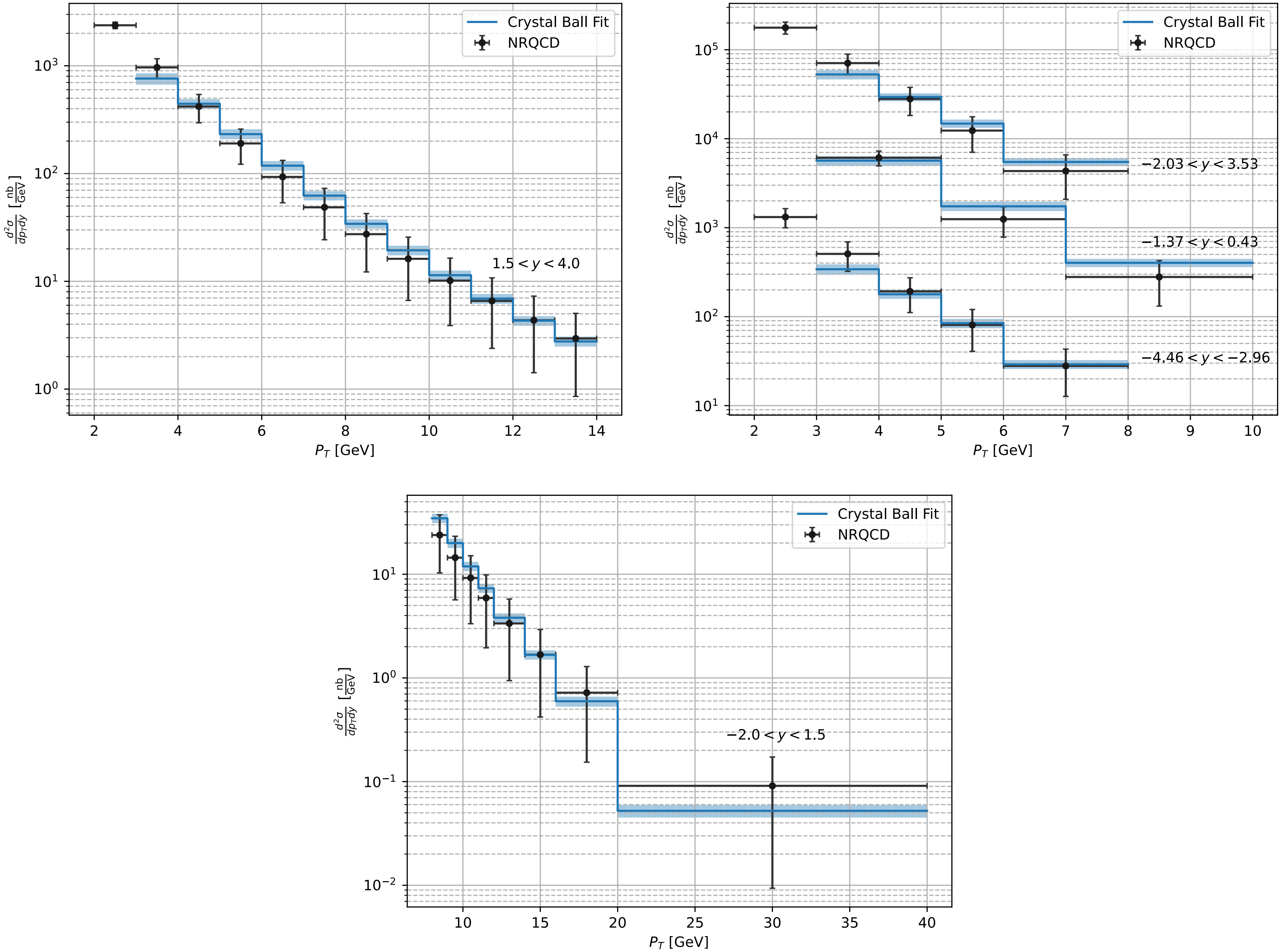


FIG. 2: Comparison between prompt J/ψ production in pp collisions for LHCb[87], ALICE[88] and ATLAS[89] kinematics as predicted by NRQCD and with the data-driven approach. The uncertainties of the NRQCD predictions come from scale variation $1/2 < \mu_r/\mu_{r,0} = \mu_f/\mu_{f,0} = \mu_{\text{NRQCD}}/\mu_{\text{NRQCD},0}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

nNNPDF3.0 [2201.123623]

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

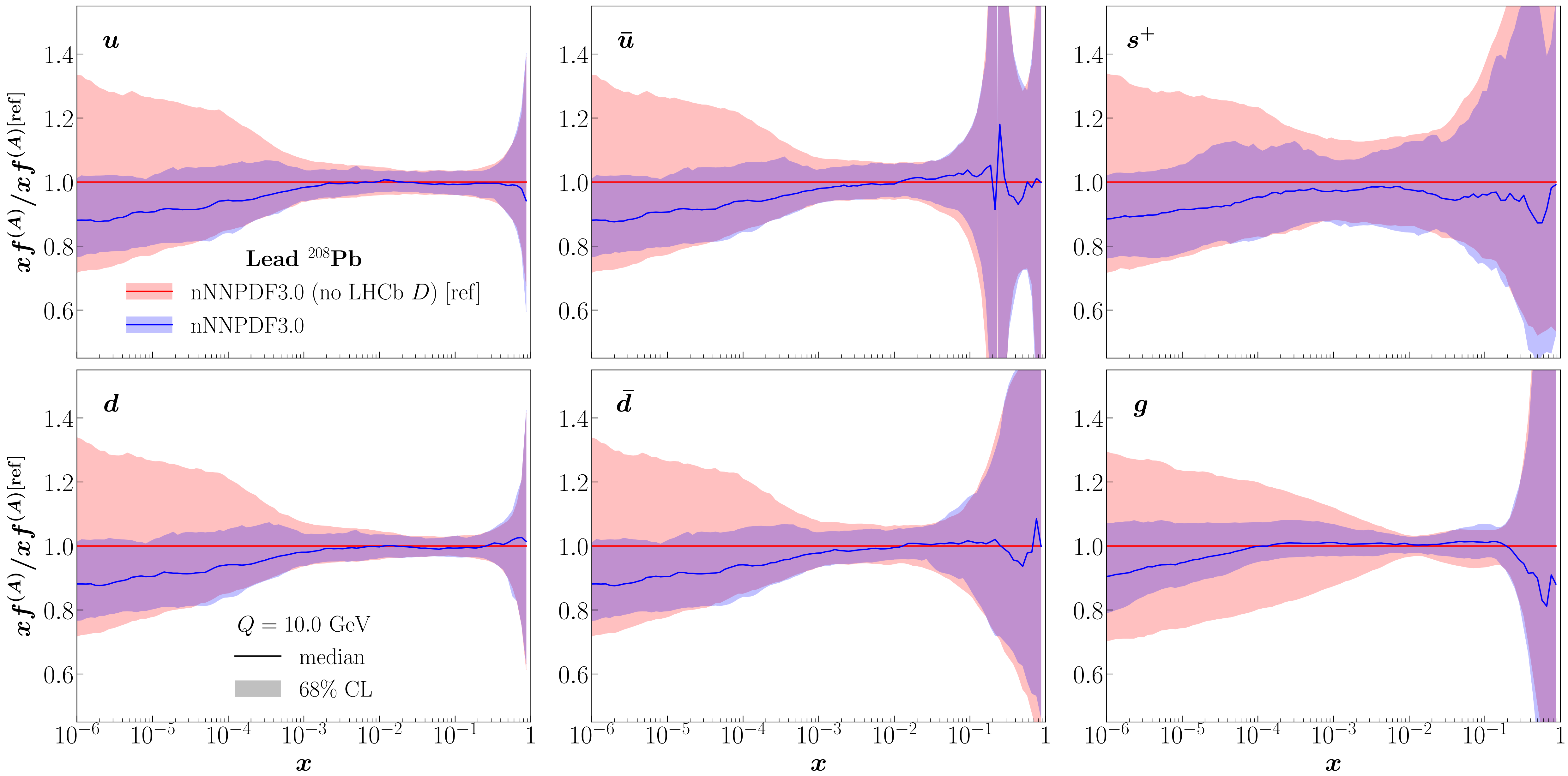
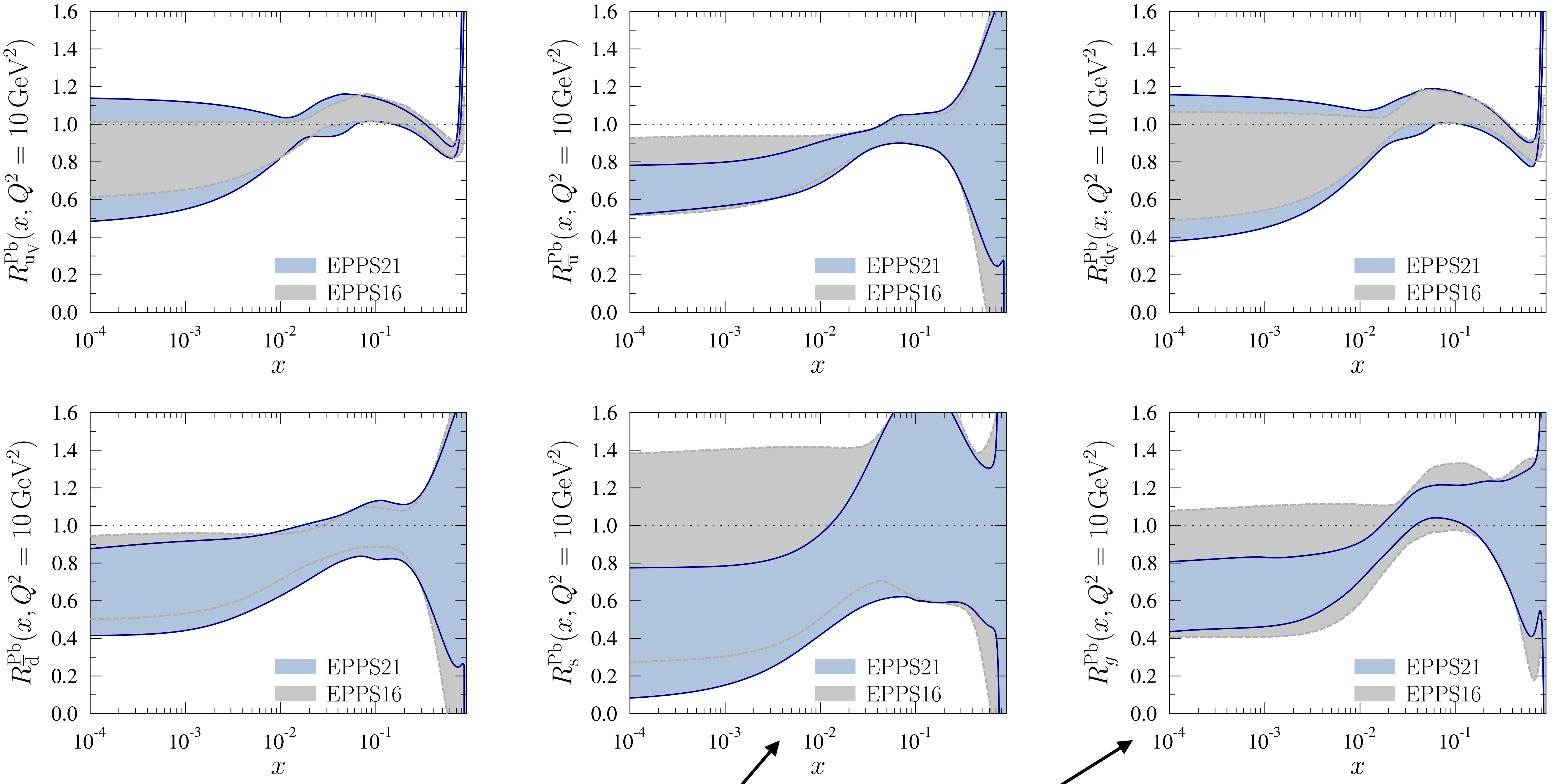


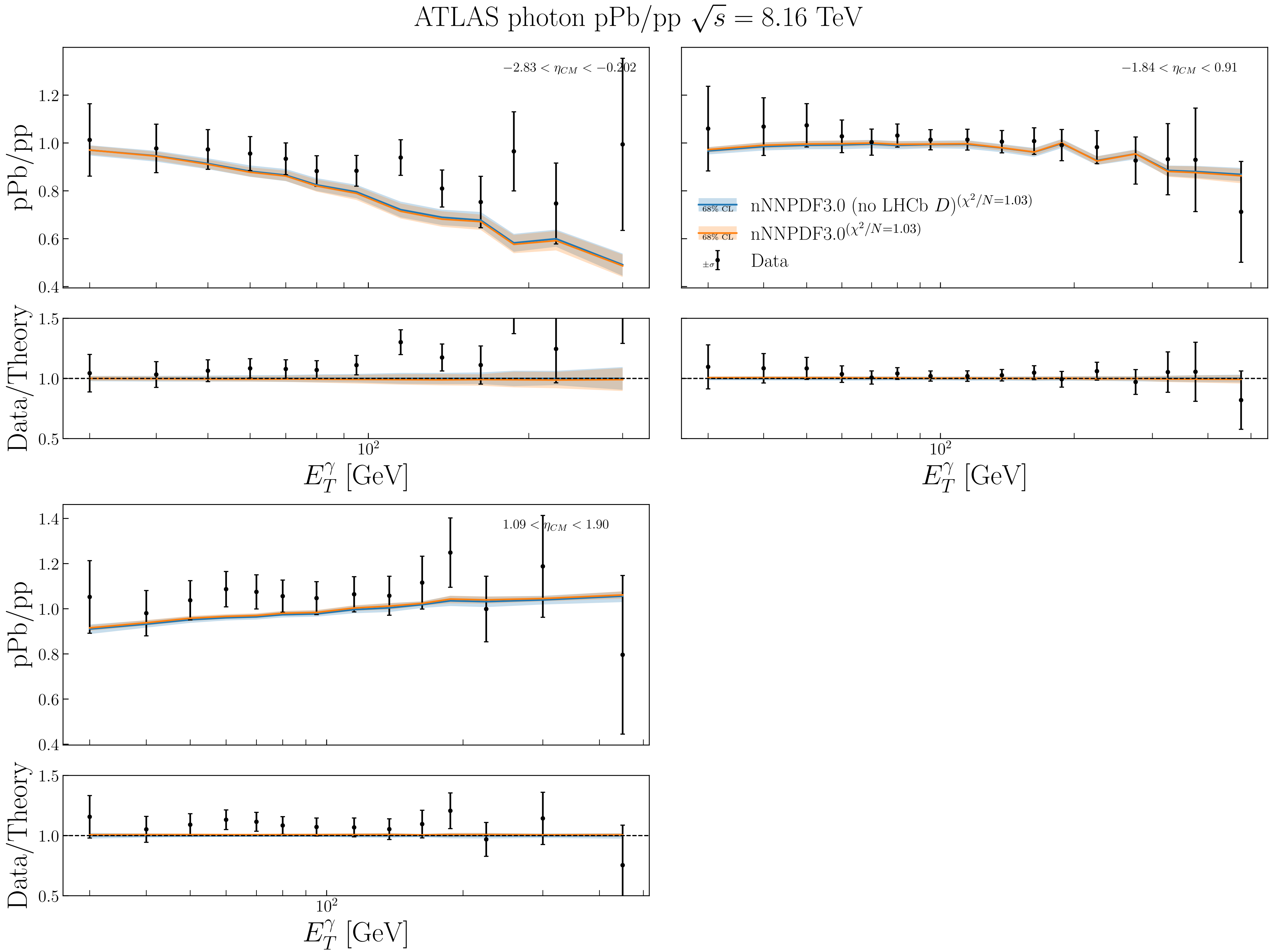
Figure 4.5. Comparison of the nPDFs of lead nuclei at $Q = 10$ GeV between nNNPDF3.0 (no LHCb D) and nNNPDF3.0, normalised to the central value of the former.

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.

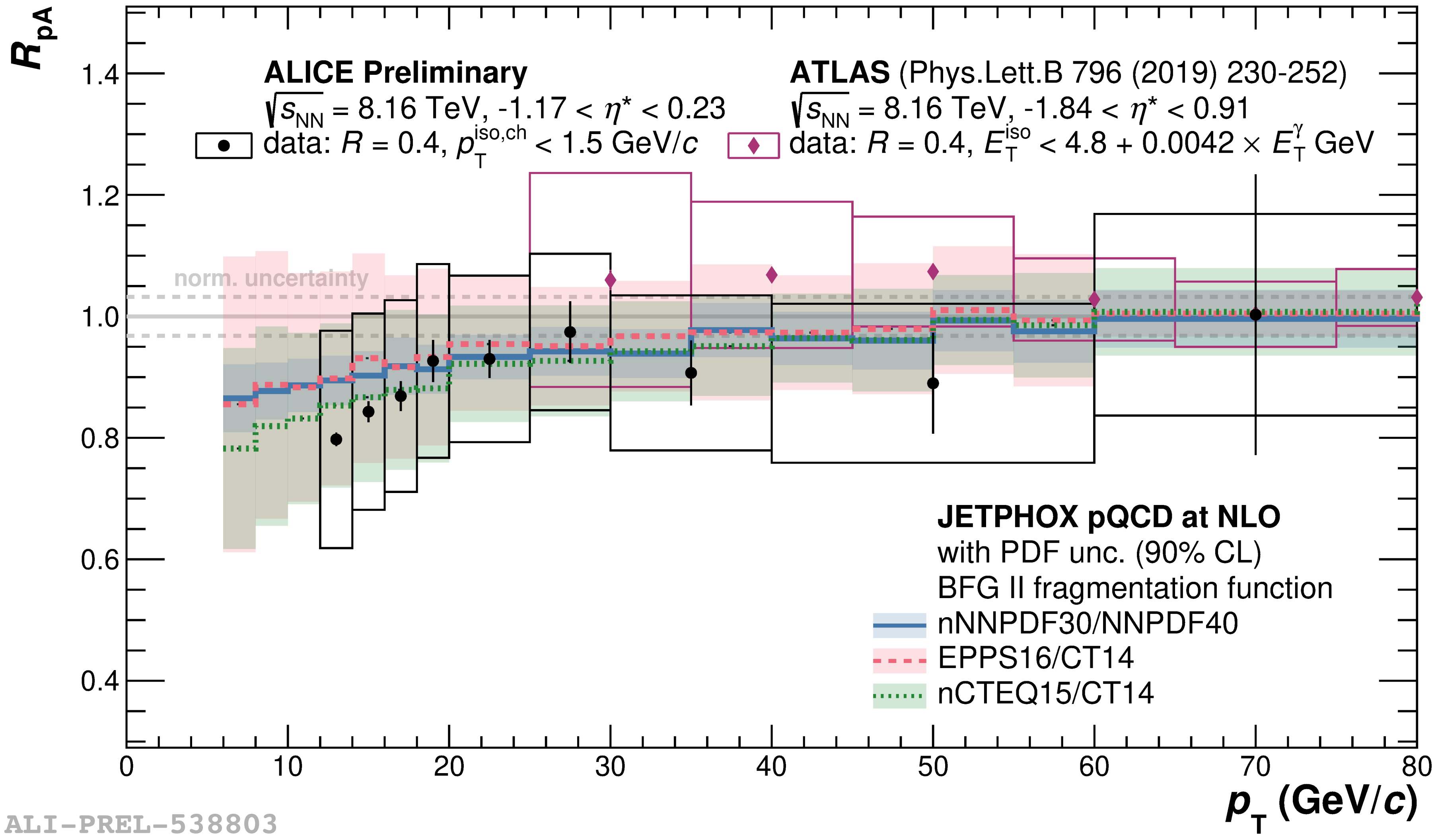
Run-II isolated photons in pPb from ATLAS



Note: Absolute cross sections underestimated at NLO up to 30% at low pT → NNLO?

Run-II isolated photons in pPb from ALICE

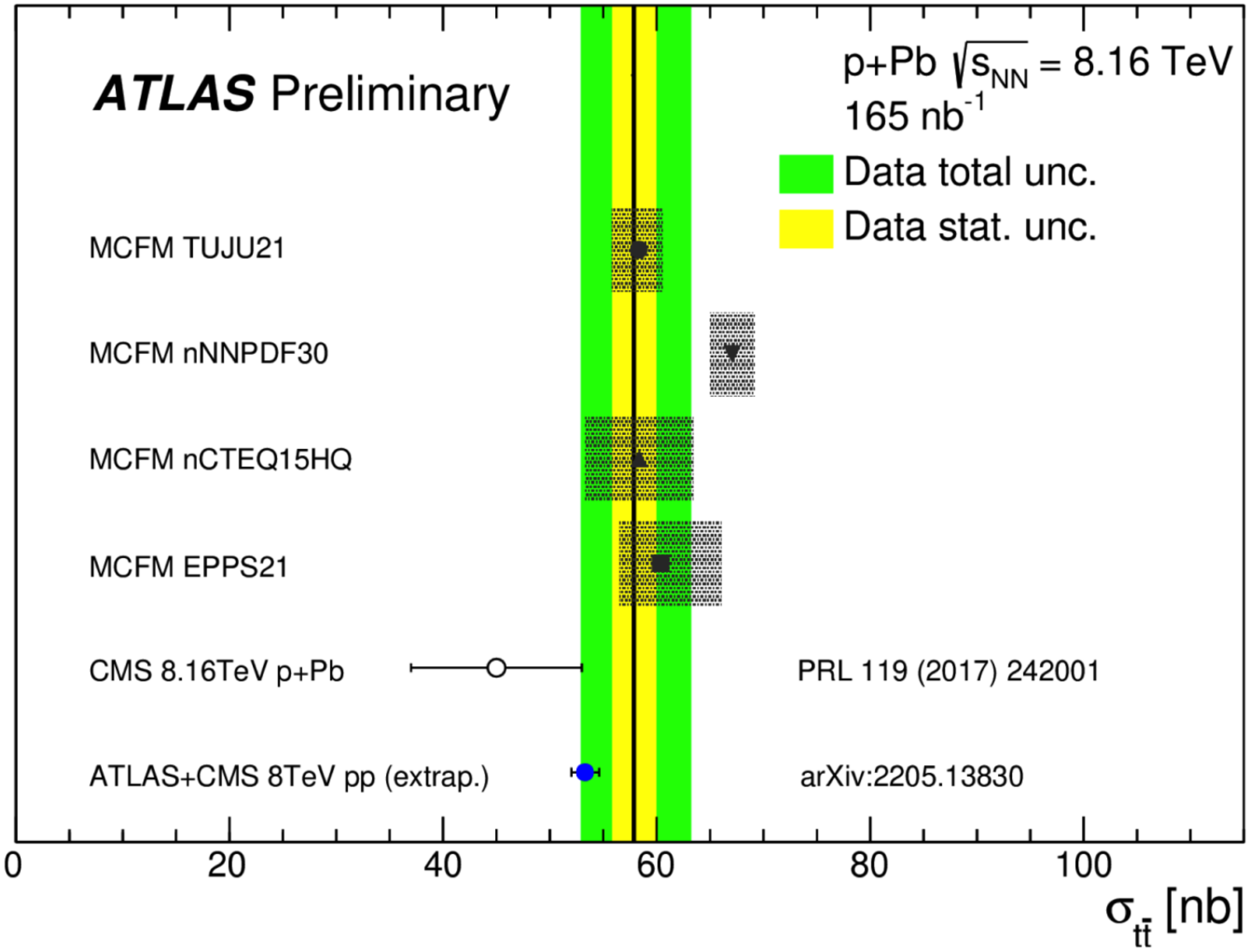
[Talk M. Klasen, DIS24]



- High-p_T ALICE data $\sim$ ATLAS data w/in uncertainties
- New low-p_T ALICE data has sensitivity $\rightarrow$ publish!
- Gluons: nCTEQ15HQ $>$ nCTEQ15, EPPS21 $\sim$ EPPS16
- New ALICE FoCal will cover $3.2 < \eta < 5.8$ in Run-IV

Top pair production in pPb with ATLAS

[ATLAS-CONF-2023-063]



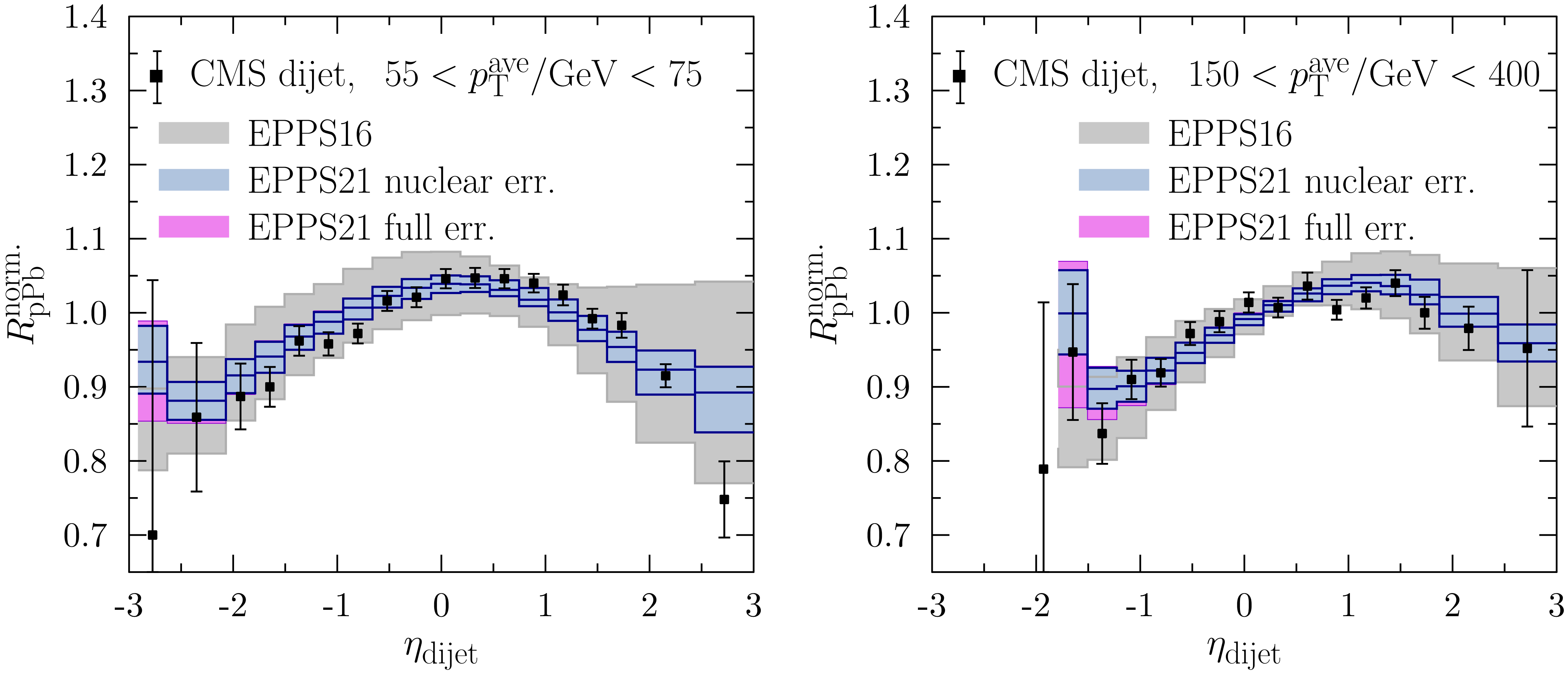
Run-I dijet production from CMS

[Talk M. Klasen, DIS'24]

CMS Coll., PRL 21 (2018) 062002; K. Eskola et al., EPJC 82 (2022) 413

Specific to nuclear collisions:

- Large background from Underlying Event
- 7 ± 5 pN interactions (Glauber) [Loizides, Kamin, d'Enterria, PRC 97 (2018) 054910]
- Requires subtraction of MPIs and sufficiently large p_T/small R



NB: CMS Run-I *pp* rapidity ratios in tension with NLO → NNLO?

Conclusions

Conclusions

- **A lot of progress in recent years**, more to come!
  - HQ-data, di-jet data: much improved gluon
    Important to test small-x gluon from HQ data against small-x gluons from prompt photon data (FOCAL)
  - LHC W,Z data: gluon, strange PDF
    More data to come, in particular for low invariant masses of lepton pairs
  - SIH data: small impact on gluon
  - Inclusive jets: gluon
  - Top quarks
  - Z+c, W+c?
- Different groups: EPPS, nCTEQ, nNNPDF, TUJU, KA, …
  Important to test systematics, new ideas, driving improvements!

Thank you!

From nCTEQ15 onwards

- **nCTEQ15**
  - ✓ Mostly NC DIS, some FT DY, a handful of SIH (740 pts)
- **nCTEQ15 upgrades**
  - ✓ nCTEQ15WZ ('20): + LHC W/Z data (+120 pts) **[2007.09100]**
  - ✓ nCTEQ15HIX ('20): + JLAB NC DIS data (+336 pts) + relaxed cuts **[2012.11566]**
  - ✓ nCTEQ15WZSIH ('21): + LHC W/Z + SIH data (+120 +112 pts) **[2105.09873]**
  - ✓ nCTEQ15HQ ('22): + LHC W/Z + HQ data (+120 +548 pts) **[2204.09982]**
  - ✓ nCTEQ15NU ('22): +LHC W/Z + SIH + CC DIS (+120 +112 +974 pts) (BaseDimuChorus fit) **[2204.13157]**
- **Upcoming nCTEQ global analysis**
  - ✓ Combines upgrades above
  - ✓ LHC W/Z, JLAB NC DIS, SIH, HQ, CC neutrino DIS (over 3000 pts)
  - ✓ TMC's ('23) **[2301.07715]**
  - ✓ New proton baseline CJ22, relaxed kinematic cuts, deuteron corrections, …

Global analyses of nPDFs: 2023

- **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