

# 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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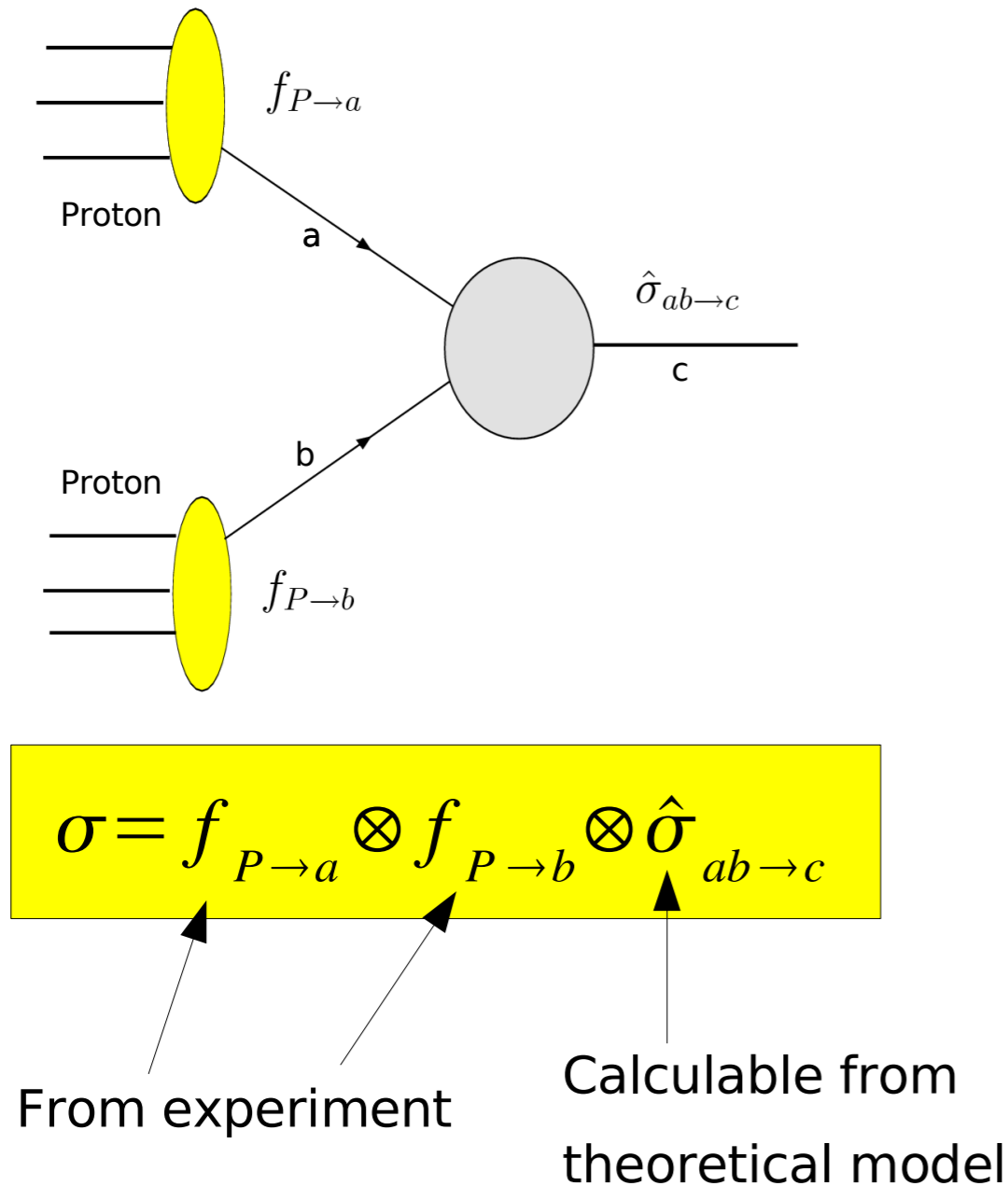
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# Example: Factorization for pp collisions



## Parton Distribution Functions (PDFs)

$$f_{P \rightarrow a, b}(x, \mu^2)$$

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

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

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

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

# Predictive Power

**Universality:** same PDFs/FFs enter different processes:

- DIS: 
$$F_2^A(x, Q^2) = \sum_i [f_i^A \otimes C_{2,i}] (x, Q^2)$$

- DY: 
$$\sigma_{A+B \rightarrow \ell^+ + \ell^- + X} = \sum_{i,j} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j \rightarrow \ell^+ + \ell^- + X}$$

- $A+B \rightarrow H + X$ : 
$$\sigma_{A+B \rightarrow H+X} = \sum_{i,j,k} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j \rightarrow k+X} \otimes D_k^H$$

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



# Flavor separation of PDFs

NC charged lepton DIS: 2 structure functions ( $\gamma$ -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

**Periodic Table of the Elements**

1 IA 1A 1 H Hydrogen 1.008	2 IIA 2A 4 Be Beryllium 9.012																18 VIIIA 8A 2 He Helium 4.002	
3 3A 3 Li Lithium 6.941	4 4A 4 B Boron 10.811	5 5A 5 C Carbon 12.011	6 6A 6 N Nitrogen 14.007	7 7A 7 O Oxygen 15.999	8 8A 8 F Fluorine 18.998	9 9A 9 Ne Neon 20.180												10 10A 10 Ar Argon 39.948
11 11A 11 Na Sodium 22.990	12 12A 12 Mg Magnesium 24.305	13 IIIB 3B 13 Al Aluminum 26.982	14 IVB 4B 14 Si Silicon 28.086	15 VB 5B 15 P Phosphorus 30.974	16 VIB 6B 16 S Sulfur 32.066	17 VIIB 7B 17 Cl Chlorine 35.453	18 VIIIB 8 18 Ar Argon 39.948											18 VIIIA 8A 18 Kr Krypton 83.80
19 19A 19 K Potassium 39.098	20 20A 20 Ca Calcium 40.078	21 IIIB 3B 21 Sc Scandium 44.956	22 IVB 4B 22 Ti Titanium 47.88	23 VB 5B 23 V Vanadium 50.942	24 VIB 6B 24 Cr Chromium 51.996	25 VIIB 7B 25 Mn Manganese 54.938	26 VIIIB 8 26 Fe Iron 55.933	27 VIIIB 8 27 Co Cobalt 58.933	28 VIIIB 8 28 Ni Nickel 58.693	29 IB 1B 29 Cu Copper 63.546	30 IIB 2B 30 Zn Zinc 65.39	31 IIIB 3B 31 Ga Gallium 69.723	32 IVB 4B 32 Ge Germanium 72.64	33 VB 5B 33 As Arsenic 74.922	34 VIB 6B 34 Se Selenium 78.972	35 VIIB 7B 35 Br Bromine 79.904	36 VIIIB 8 36 Kr Krypton 83.80	
37 19A 37 Rb Rubidium 84.468	38 20A 38 Sr Strontium 87.62	39 IIIB 3B 39 Y Yttrium 88.906	40 IVB 4B 40 Zr Zirconium 91.224	41 VB 5B 41 Nb Niobium 92.906	42 VIB 6B 42 Mo Molybdenum 95.95	43 VIIB 7B 43 Tc Technetium 98.907	44 VIIIB 8 44 Ru Ruthenium 101.07	45 VIIIB 8 45 Rh Rhodium 102.906	46 VIIIB 8 46 Pd Palladium 106.42	47 IB 1B 47 Ag Silver 107.868	48 IIB 2B 48 Cd Cadmium 112.411	49 IIIB 3B 49 In Indium 114.818	50 IVB 4B 50 Sn Tin 118.71	51 VB 5B 51 Sb Antimony 121.760	52 VIB 6B 52 Te Tellurium 127.6	53 VIIB 7B 53 I Iodine 126.904	54 VIIIB 8 54 Xe Xenon 131.29	
55 19A 55 Cs Cesium 132.905	56 20A 56 Ba Barium 137.327	57-71 IIIB 3B 57-71 Lanthanides	72 IVB 4B 72 Hf Hafnium 178.49	73 VB 5B 73 Ta Tantalum 180.948	74 VIB 6B 74 W Tungsten 183.85	75 VIIB 7B 75 Re Rhenium 186.207	76 VIIIB 8 76 Os Osmium 190.23	77 VIIIB 8 77 Ir Iridium 192.22	78 VIIIB 8 78 Pt Platinum 195.08	79 IB 1B 79 Au Gold 196.967	80 IIB 2B 80 Hg Mercury 200.59	81 IIIB 3B 81 Tl Thallium 204.383	82 IVB 4B 82 Pb Lead 207.2	83 VB 5B 83 Bi Bismuth 208.980	84 VIB 6B 84 Po Polonium [208.982]	85 VIIB 7B 85 At Astatine 209.987	86 VIIIB 8 86 Rn Radon 222.018	
87 19A 87 Fr Francium 223.020	88 20A 88 Ra Radium 226.025	89-103 IIIB 3B 89-103 Actinides	104 IVB 4B 104 Rf Rutherfordium [261]	105 VB 5B 105 Db Dubnium [262]	106 VIB 6B 106 Sg Seaborgium [266]	107 VIIB 7B 107 Bh Bohrium [264]	108 VIIIB 8 108 Hs Hassium [269]	109 VIIIB 8 109 Mt Meitnerium [268]	110 VIIIB 8 110 Ds Darmstadtium [269]	111 IB 1B 111 Rg Roentgenium [272]	112 IIB 2B 112 Cn Copernicium [277]	113 IIIB 3B 113 Uut Ununtrium unknown	114 IVB 4B 114 Fl Flerovium [289]	115 VB 5B 115 Uup Ununpentium unknown	116 VIB 6B 116 Lv Livermorium [298]	117 VIIB 7B 117 Uus Ununseptium unknown	118 VIIIB 8 118 Uuo Ununoctium unknown	

- ▶ **Fundamental quest:** understand **structure of nuclei** in terms of **quarks** and **gluons**
- ▶ **Necessary tool:** describe a **wealth of hard process reactions** in **lepton-nucleus (IA, vA,)**, **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**

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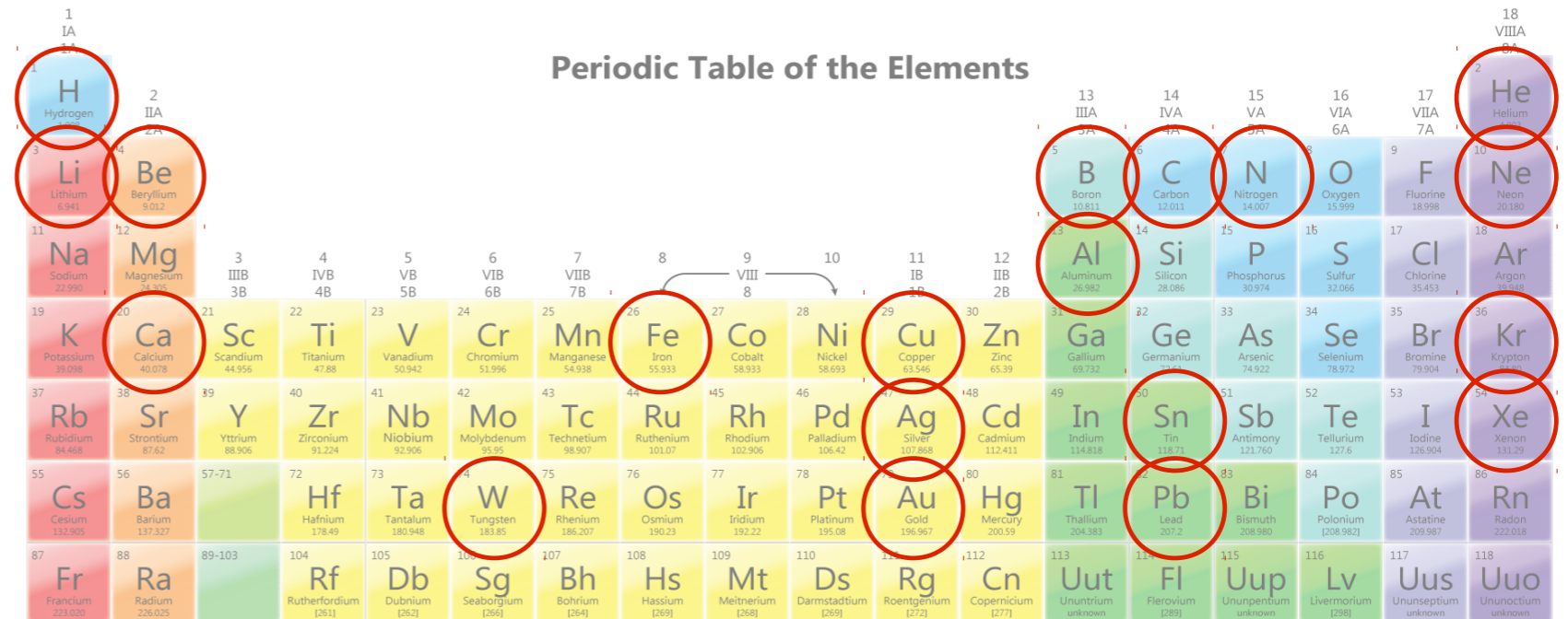
# Nuclei used in global analyses of PDFs

▶ **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 Target CC neutrino DIS:**

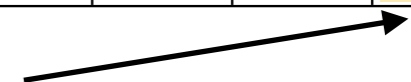
▶ Inclusive DIS: Fe (not included), **Pb: 824**

▶ Dimuon SIDIS: **Fe: 150**

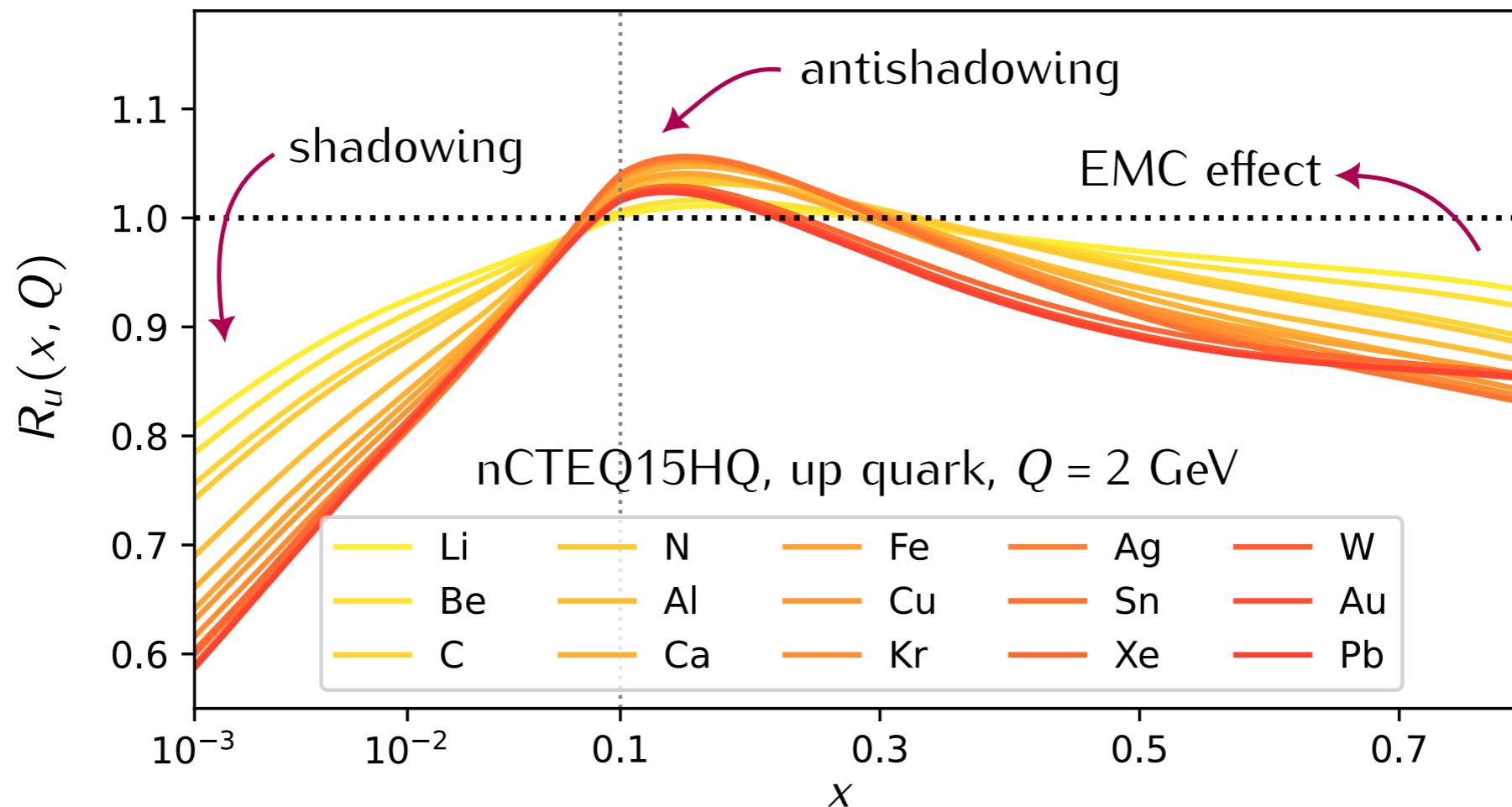
**FT NC DIS data depending on cuts**

$Q_{cut}^2$	$Q_{cut}$	$W_{cut}$ 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

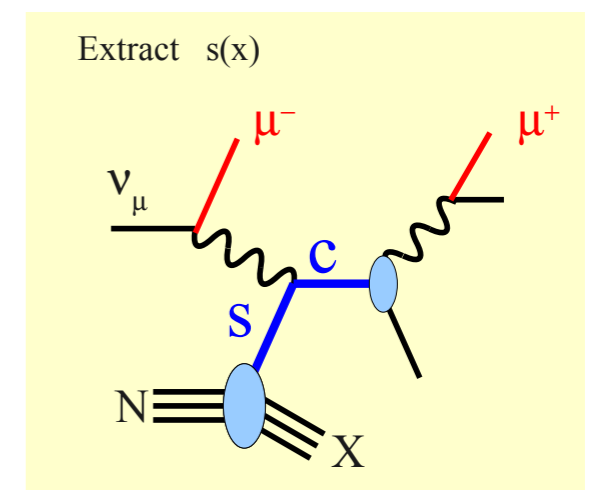
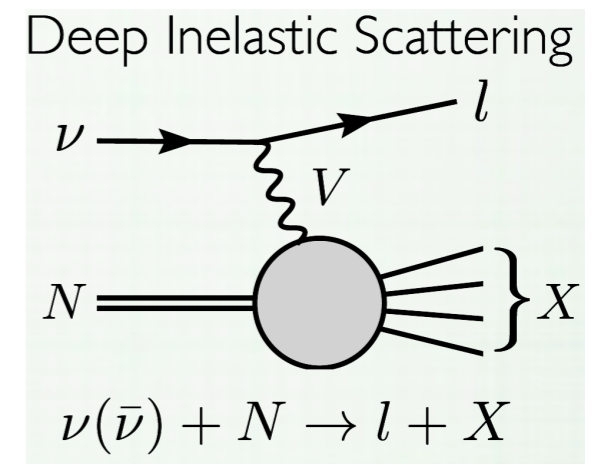
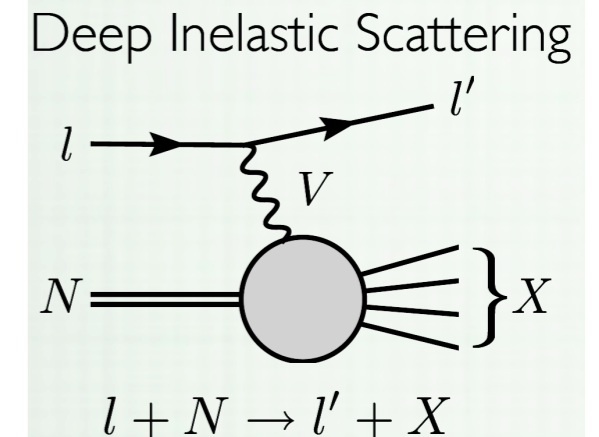


- Different nuclei are combined in a global analysis by modelling the A-dependence of the fit parameters:  $c_j(A) = p_j + a_j \ln A + b_j \ln^2 A$
- This modelling is quite rough so far. Room for progress
- Lead-only analysis conceivable. Additional HL-LHC data will help

**Which Data?**

# Used data sets I

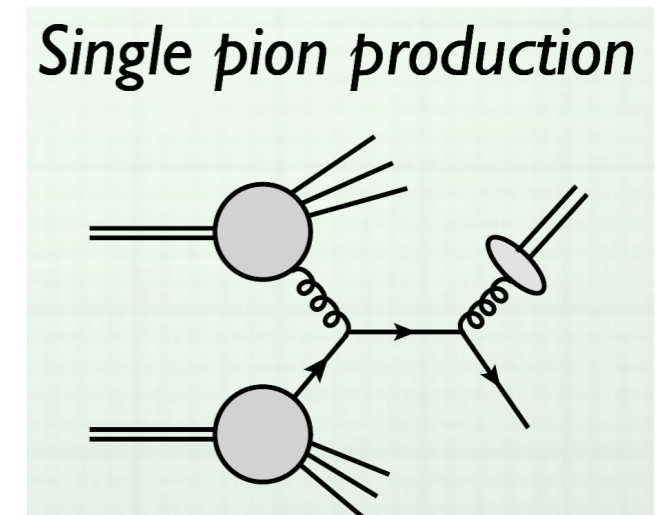
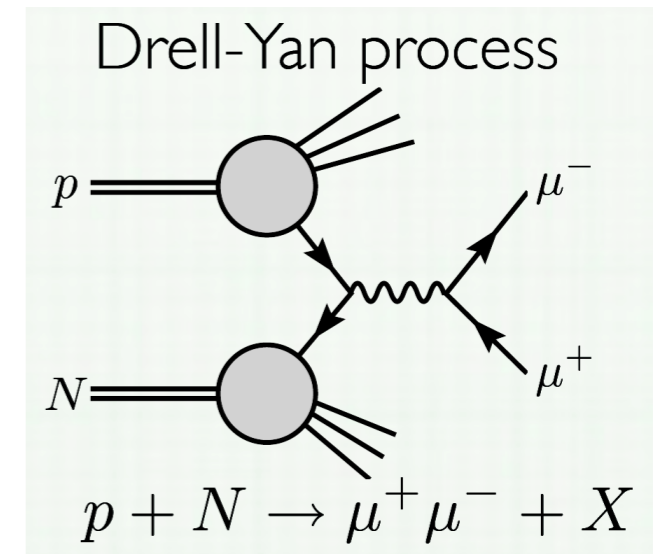
- **IA DIS:** backbone of all global analyses
  - Data from SLAC, NMC, EMC, BCDMS, FNAL: **all groups (but different cuts)**
  - Data from JLAB (CLAS, Hall-C): **nCTEQ15HiX, EPPS21, KSASG20**
- **nuA DIS:** quark flavour separation, strange PDF
  - CHORUS nu-Pb data: **DSSZ12, EPPS16, EPPS21, nNNPDF2.0, 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, KAI5, KSASG20, DSSZ12, nNNPDF3.0
  - $\pi$ -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

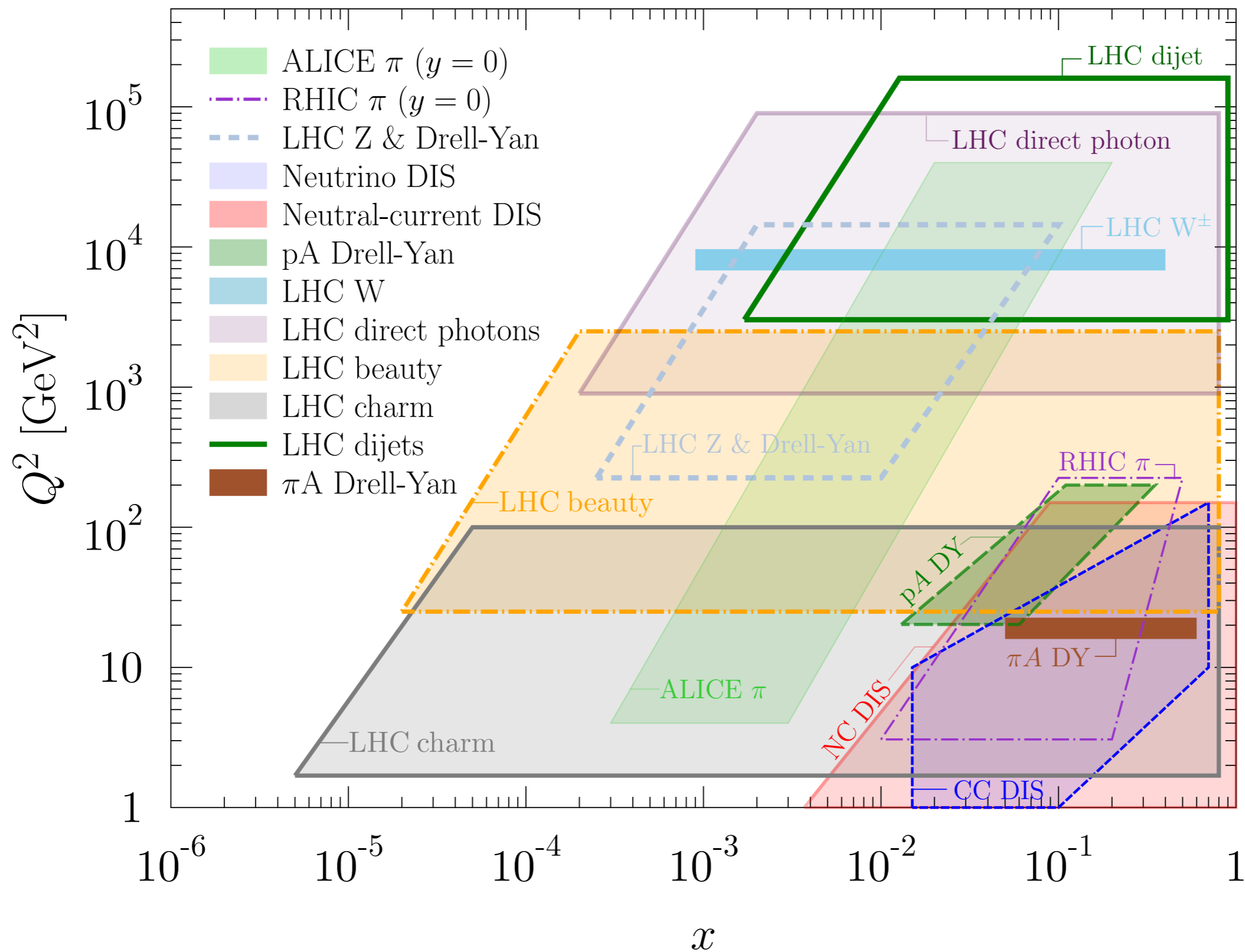


# Used data sets III

- **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

# 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  $p_T$  jets
- Heavy quarks (c, b)
- Top quarks
- Prompt photons
- W+c, Z+c

pPb,  $\gamma$ Pb:

**ALICE, ATLAS, CMS, LHCb**

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

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- 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

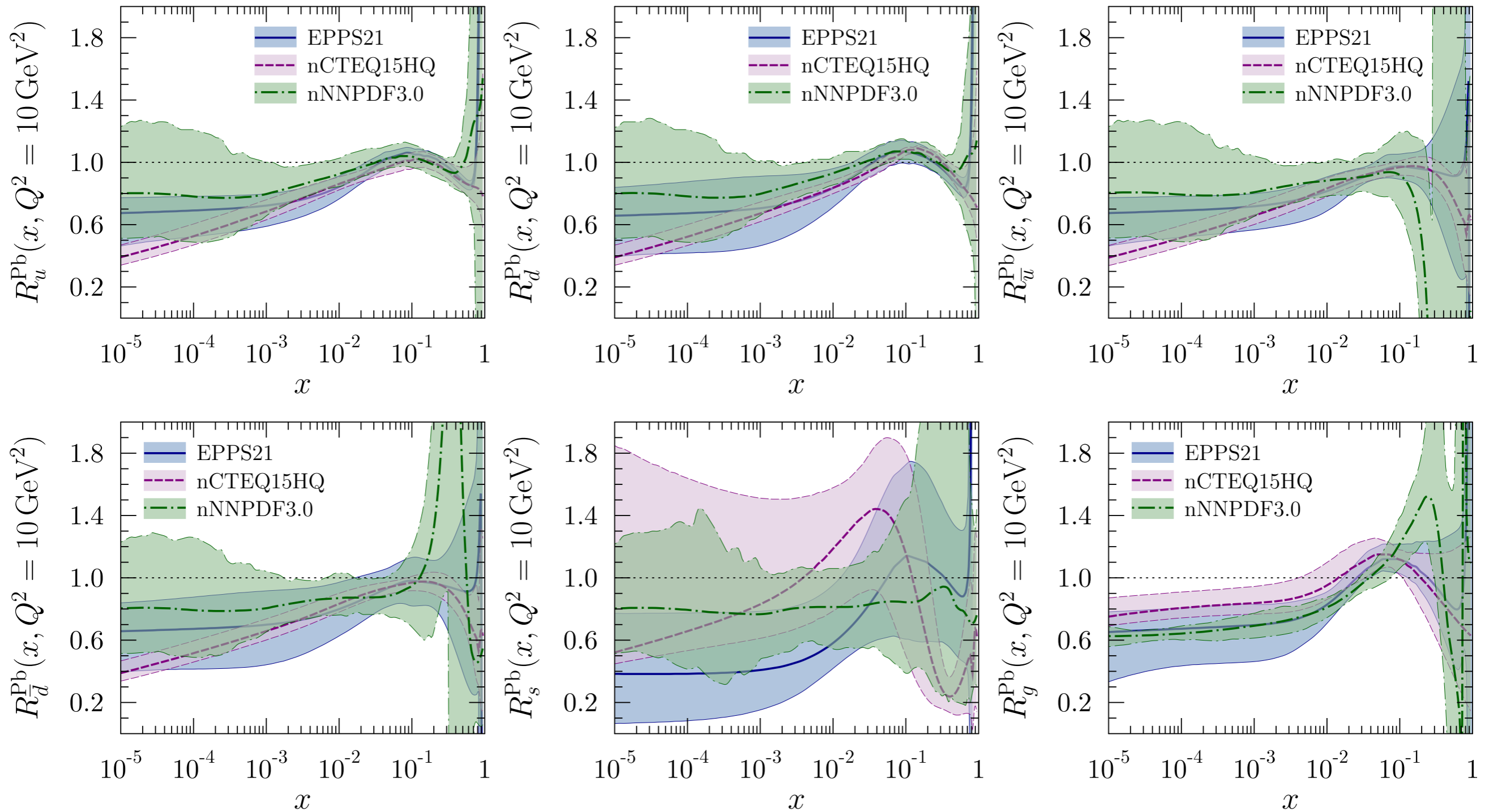
# Comparison of recent nPDF fits

M. Klasen, DIS24

ANALYSIS	nCTEQ15HQ	EPPS21	nNNPDF3.0	TUJU21	KSASG20
<b>THEORETICAL INPUT:</b>					
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	$\sim$ CTEQ6.1	CT18A	$\sim$ NNPDF4.0	$\sim$ HERAPDF2.0	CT18
Deuteron corrections	( $\checkmark$ ) <sup>a,b</sup>	$\checkmark$ <sup>c</sup>	$\checkmark$	$\checkmark$	$\checkmark$
<b>FIXED-TARGET DATA:</b>					
SLAC/EMC/NMC NC DIS	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
– Cut on $Q^2$	4 GeV <sup>2</sup>	1.69 GeV <sup>2</sup>	3.5 GeV <sup>2</sup>	3.5 GeV <sup>2</sup>	1.2 GeV <sup>2</sup>
– Cut on $W^2$	12.25 GeV <sup>2</sup>	3.24 GeV <sup>2</sup>	12.5 GeV <sup>2</sup>	12.0 GeV <sup>2</sup>	
JLab NC DIS	( $\checkmark$ ) <sup>a</sup>	$\checkmark$			$\checkmark$
CHORUS/CDHSW CC DIS	( $\checkmark$ / -) <sup>b</sup>	$\checkmark$ / -	$\checkmark$ / -	$\checkmark$ / $\checkmark$	$\checkmark$ / $\checkmark$
NuTeV/CCFR 2 $\mu$ CC DIS	( $\checkmark$ / $\checkmark$ ) <sup>b</sup>		$\checkmark$ / -		
$pA$ DY	$\checkmark$	$\checkmark$	$\checkmark$		$\checkmark$
<b>COLLIDER DATA:</b>					
Z bosons	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	
$W^\pm$ bosons	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	
Light hadrons	$\checkmark$	$\checkmark$ <sup>d</sup>			
Jets		$\checkmark$	$\checkmark$		
Prompt photons			$\checkmark$		
Prompt D <sup>0</sup>	$\checkmark$	$\checkmark$	$\checkmark$ <sup>e</sup>		
Quarkonia ( $J/\psi$ , $\psi'$ , $\Upsilon$ )	$\checkmark$				

# 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
<b>RUN-I:</b>					
ATLAS Z	✓	✓	✓	✓	✓
CMS Z	✓	✓	✓	✓	✓
ALICE Z			✓ <sup>b</sup>		
LHCb Z	✓		✓ <sup>b</sup>		
ATLAS $W^\pm$	✓				✓
CMS $W^\pm$	✓	✓	✓		
ALICE $W^\pm$	✓		✓ <sup>b</sup>		
<b>RUN-II:</b>					
CMS Z			✓ <sup>b</sup>		
ALICE Z			✓ <sup>b</sup>		
LHCb Z					
CMS $W^\pm$	✓	✓ <sup>a</sup>	✓	✓	
ALICE $W^\pm$					

<sup>a</sup> added in EPPS21; <sup>b</sup> added in nNNPDF3.0.

# Run-II W boson production in pPb from CMS

[Klasen, Paukkunen, 2311.00450]

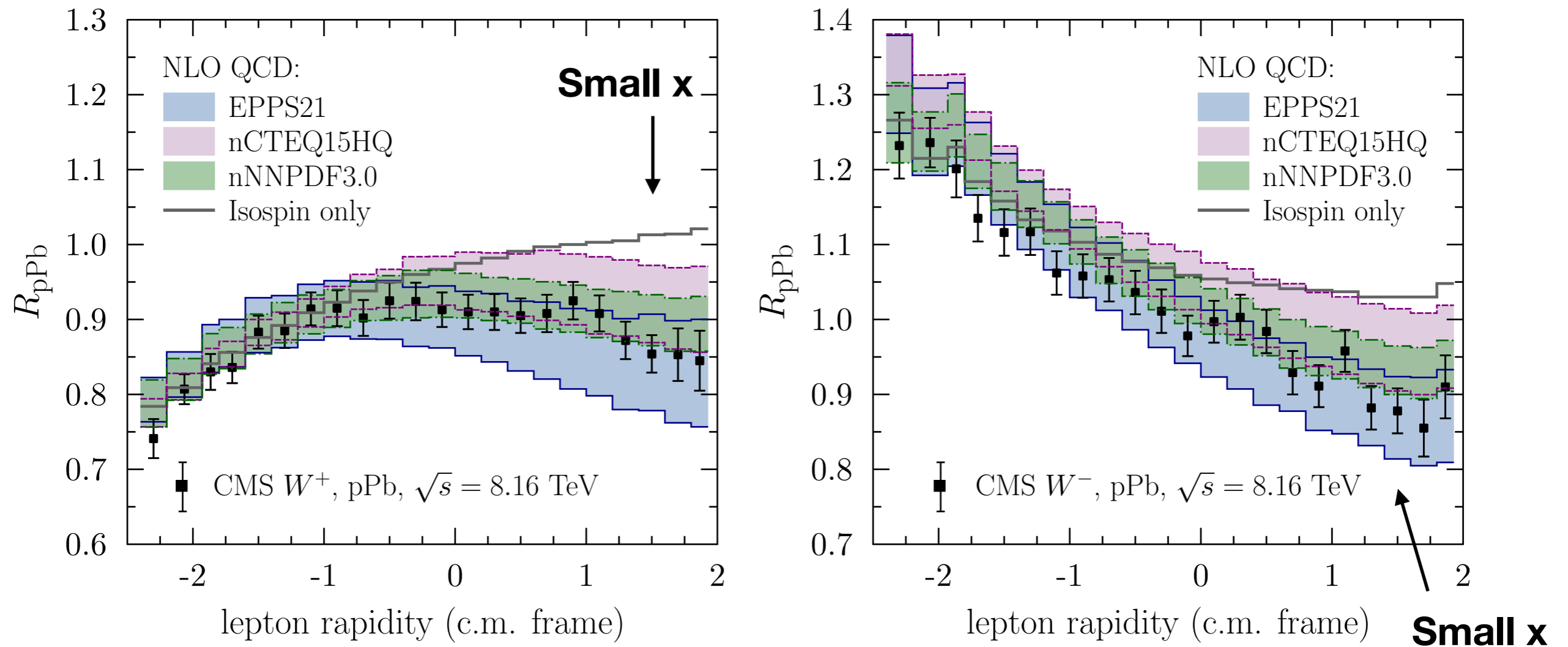


Figure 6: Nuclear modification ratios for  $W^+$  (left) and  $W^-$  bosons (right) at CMS Run-II (172, 173) compared with EPPS21 (51), nCTEQ15HQ (50), nNNPDF3.0 (52) and a calculation with 82 free protons and 126 free neutrons.

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

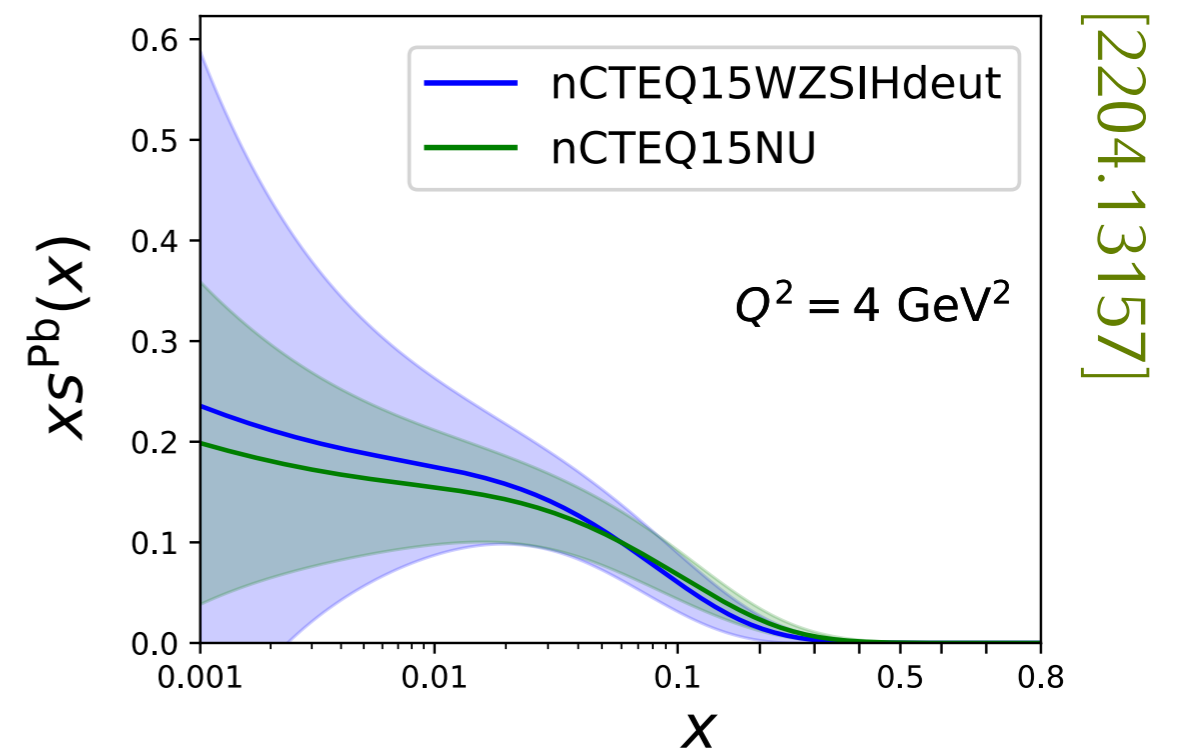
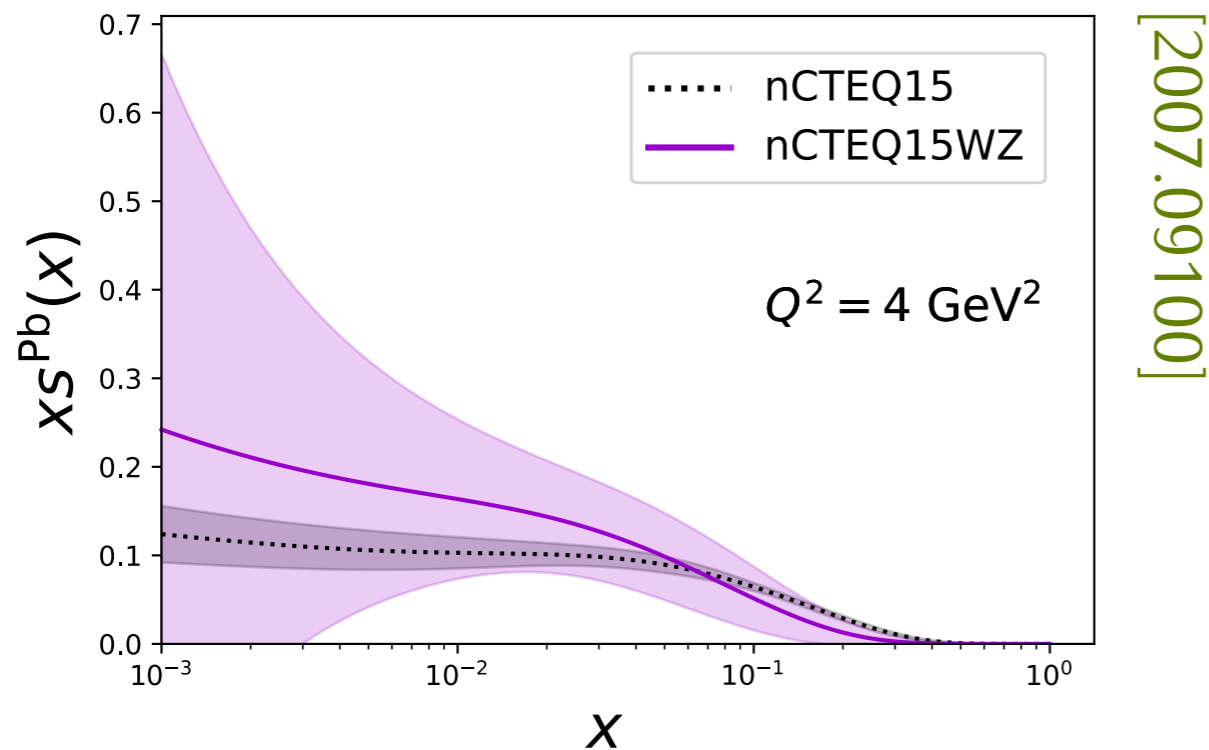
# Impact on the strange nPDF

- **nCTEQ15WZ** includes **LHC W/Z data**

✓ First realistic uncertainties

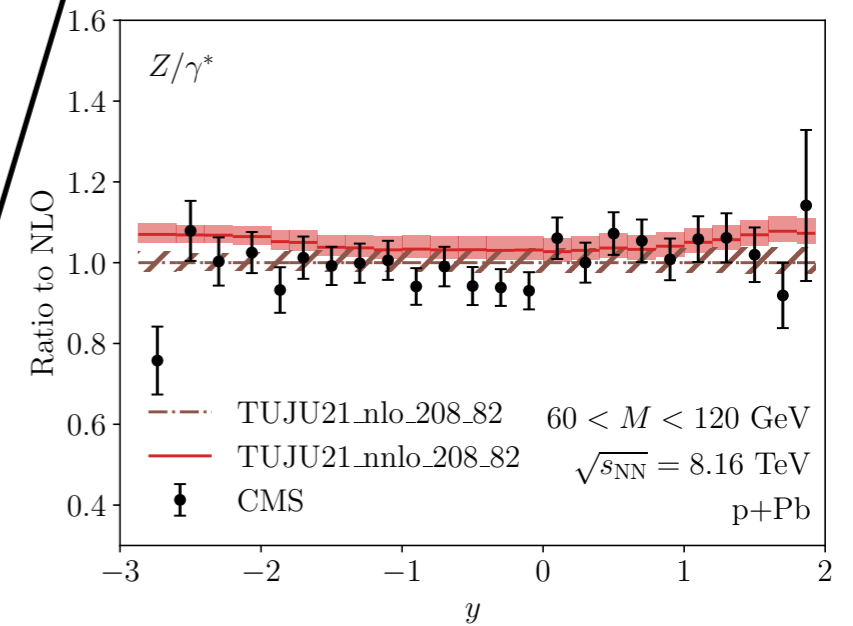
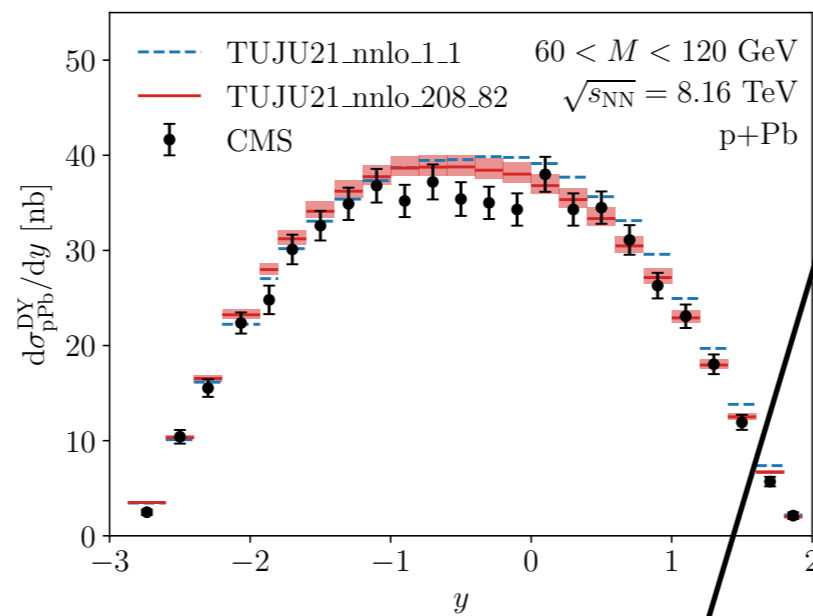
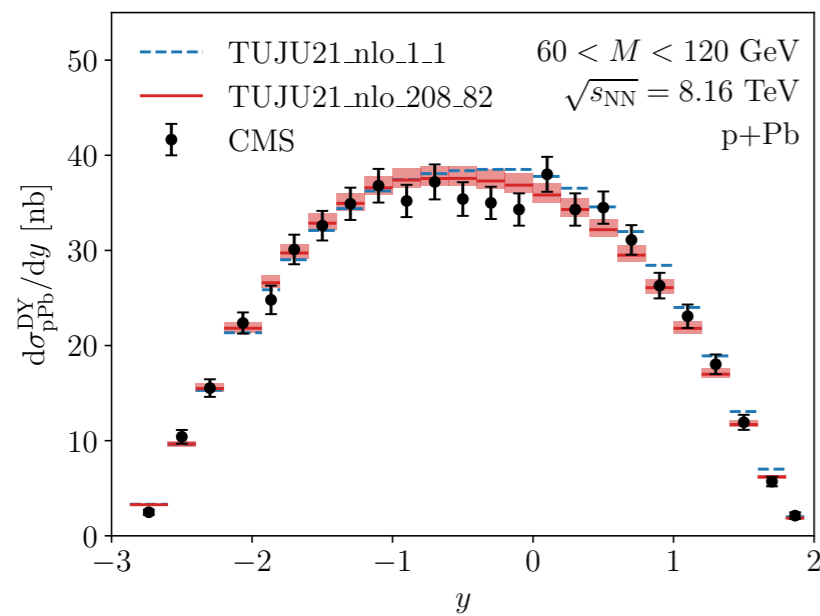
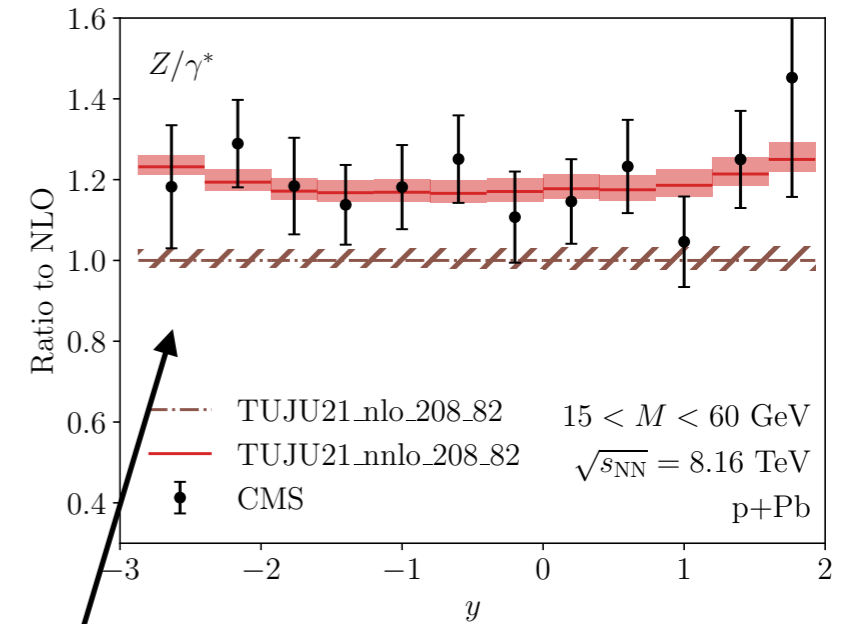
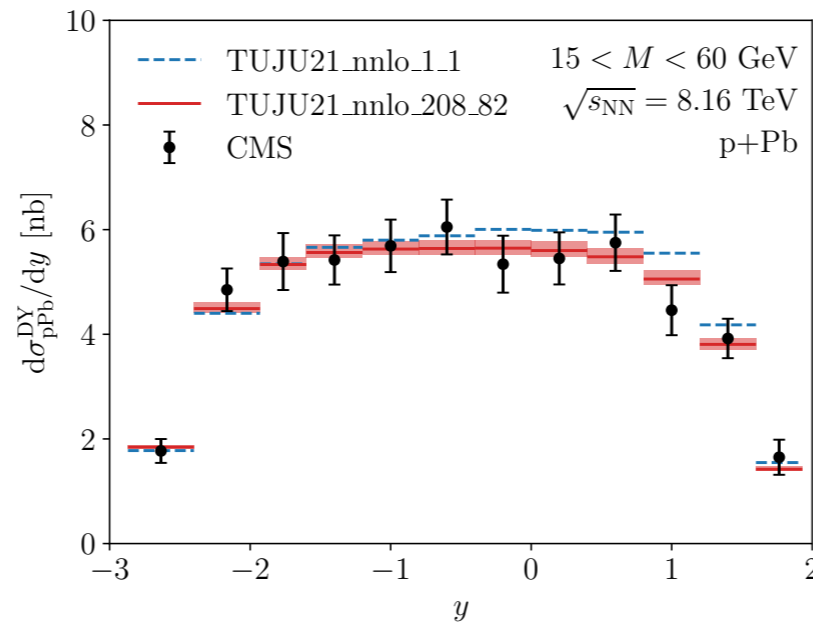
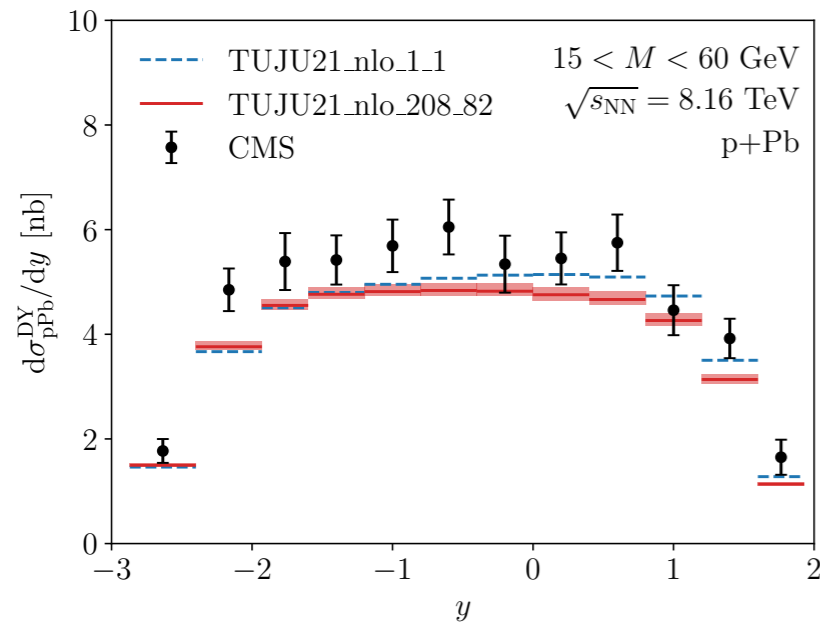
- **nCTEQ15NU** also adds **CC neutrino data** (including dimuon data)

✓ Neutrino data provides further constraints down to low- $x$



# Run-II Z boson production in pPb from CMS

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

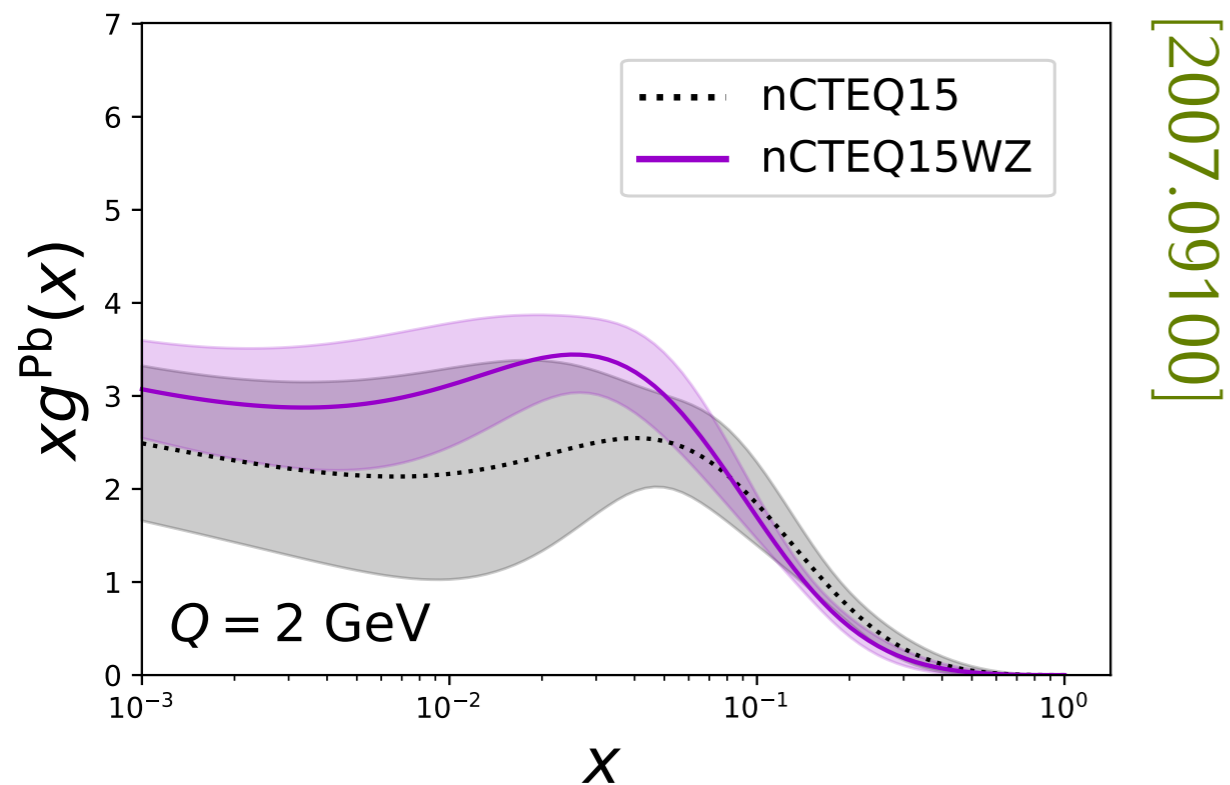


Low mass data in tension with NLO (also nNNPDF) → NNLO?

# LHC W/Z and the gluon nPDF

- **nCTEQ15WZ** includes **LHC W/Z** data

- ✓ Also constrains gluon



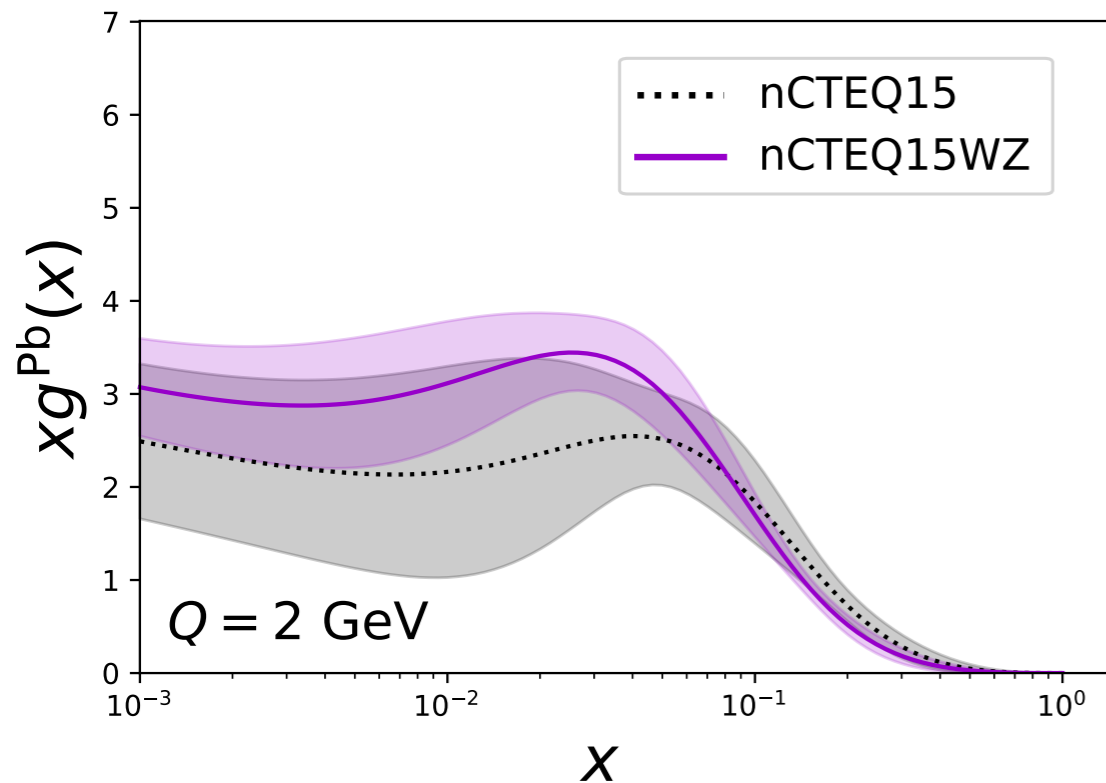
# LHC HQ data and the gluon nPDF

- **nCTEQ15WZ** includes **LHC W/Z** data

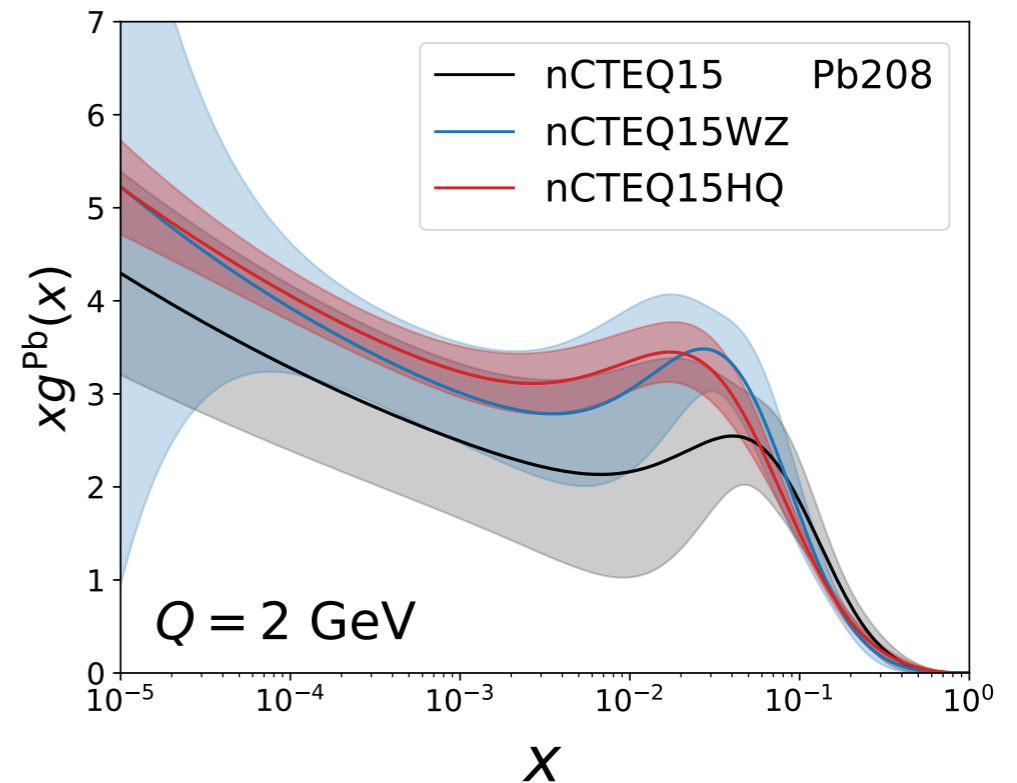
✓ Also constrains gluon

- **nCTEQ15HQ** also adds **quarkonium and open HQ data**

✓ Unprecedented low-x reach



[2007.09100]



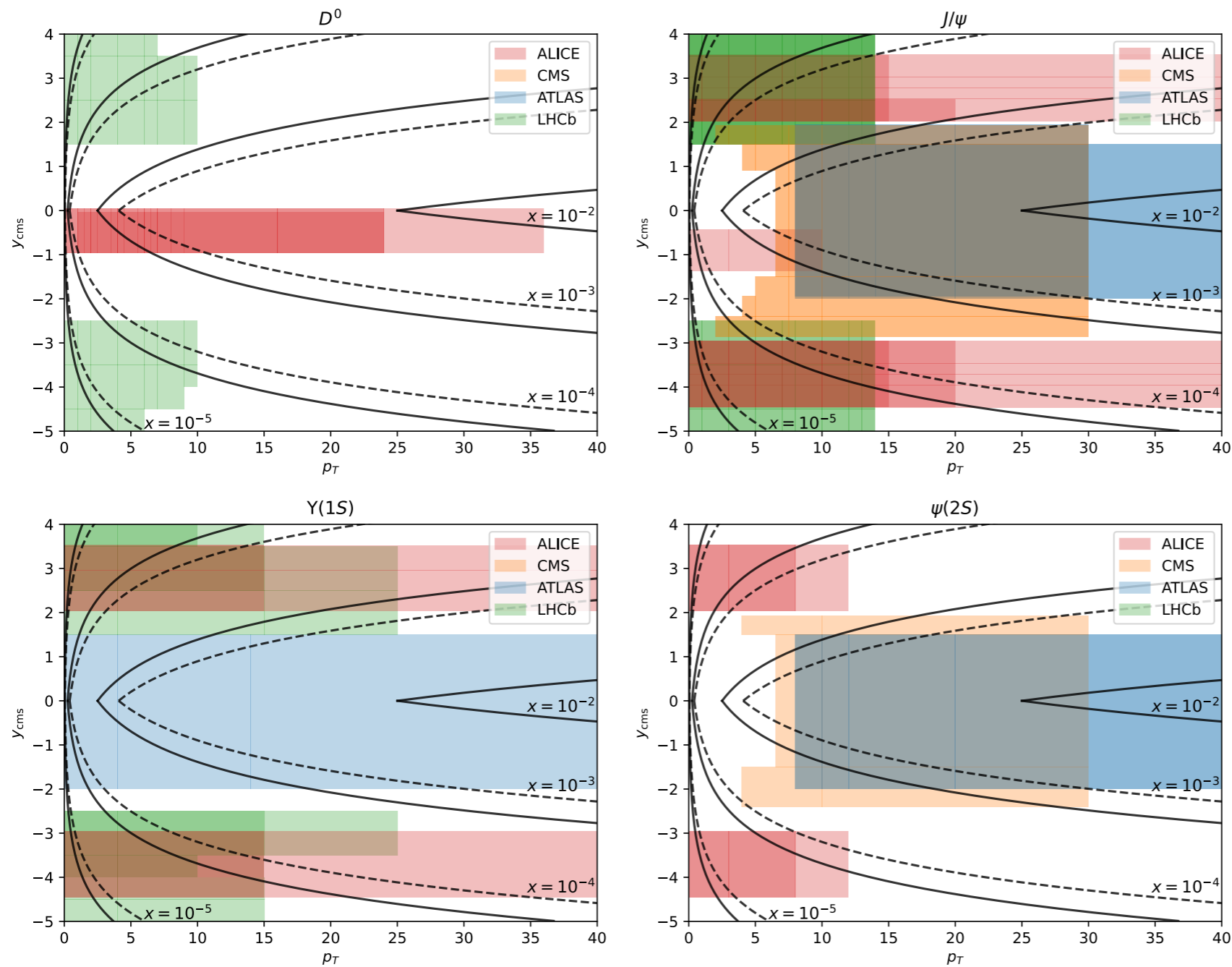
[2204.09982]

# Heavy quark and quarkonium data

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

<sup>a</sup> included in nCTEQ15HQ (50); <sup>b</sup> included in EPPS21 (51); <sup>c</sup> included in nNNPDF3.0 (52).





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

puts strong constraints on gluon distribution

FIG. 1: Coverage of the kinematic  $(p_T, y_{\text{cms}})$ -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.

See also [2012.11462](#) and [1712.07024](#)

- Data:
  - IA 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**

$$\sigma(AB \rightarrow Q + X) = \int dx_1 dx_2 f_{1,g}(x_1, \mu) f_{2,g}(x_2, \mu) \frac{1}{2\hat{s}} \overline{|\mathcal{A}_{gg \rightarrow Q+X}|^2} dPS.$$

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

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

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

	$D^0$	$J/\psi$	$\Upsilon(1S)$	$\psi(2S)$	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)	<b>1.23</b>
nCTEQ15WZ	(0.32)	(1.04)	(0.76)	(1.02)	0.91	0.77	0.63	(0.47)	(0.92)	<b>0.90</b>
nCTEQ15WZ+SIH	(0.46)	(0.84)	(0.90)	(1.07)	0.91	0.77	0.72	0.40	(0.93)	<b>0.92</b>
nCTEQ15HQ	0.35	0.79	0.79	1.06	0.93	0.77	0.78	0.40	0.77	<b>0.86</b>

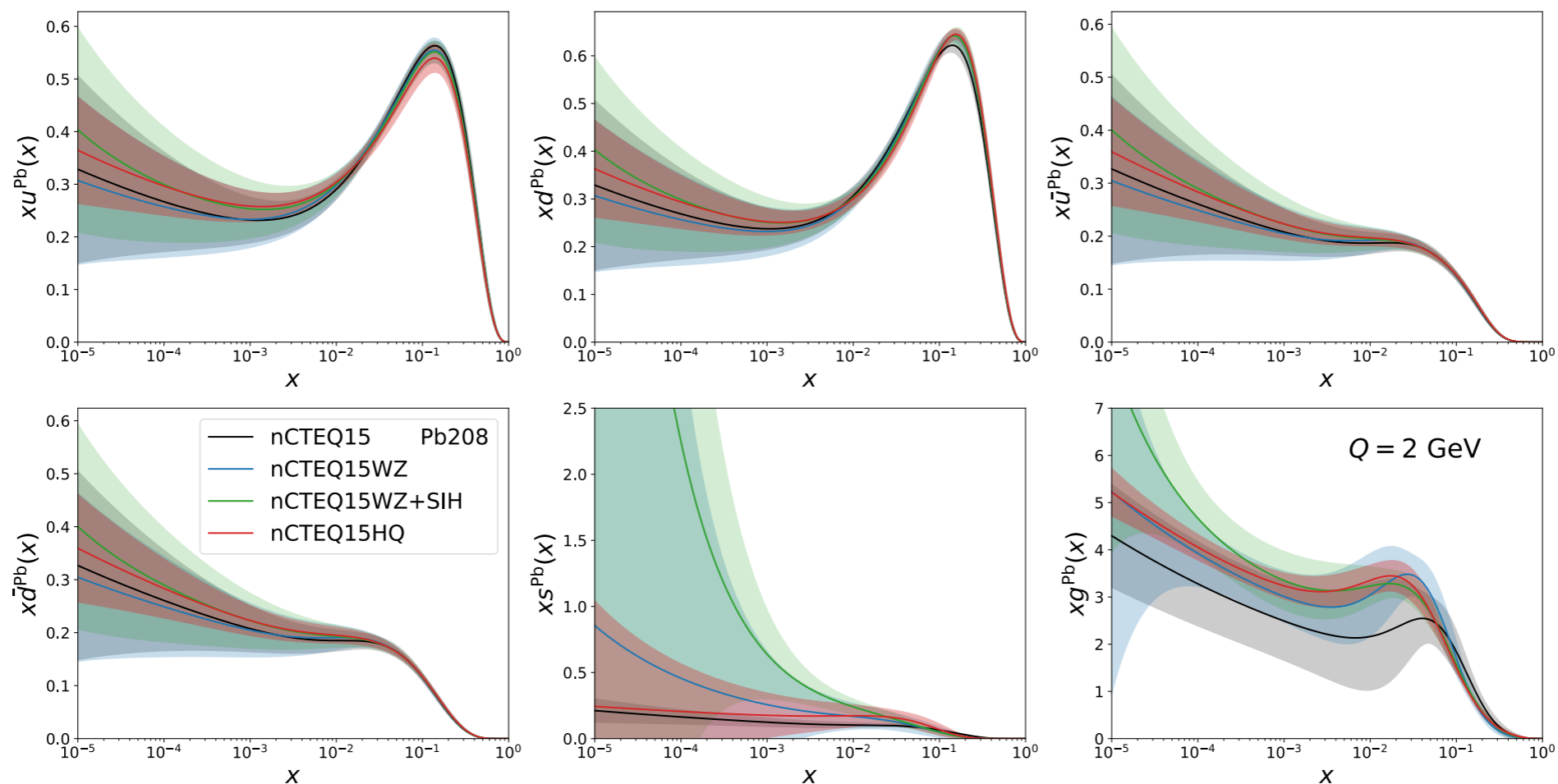


FIG. 4: Lead PDFs from different nCTEQ15 versions. The baseline nCTEQ15 fit is shown in black, nCTEQ15WZ in blue, nCTEQ15WZSIH in green, and the new fit in red.

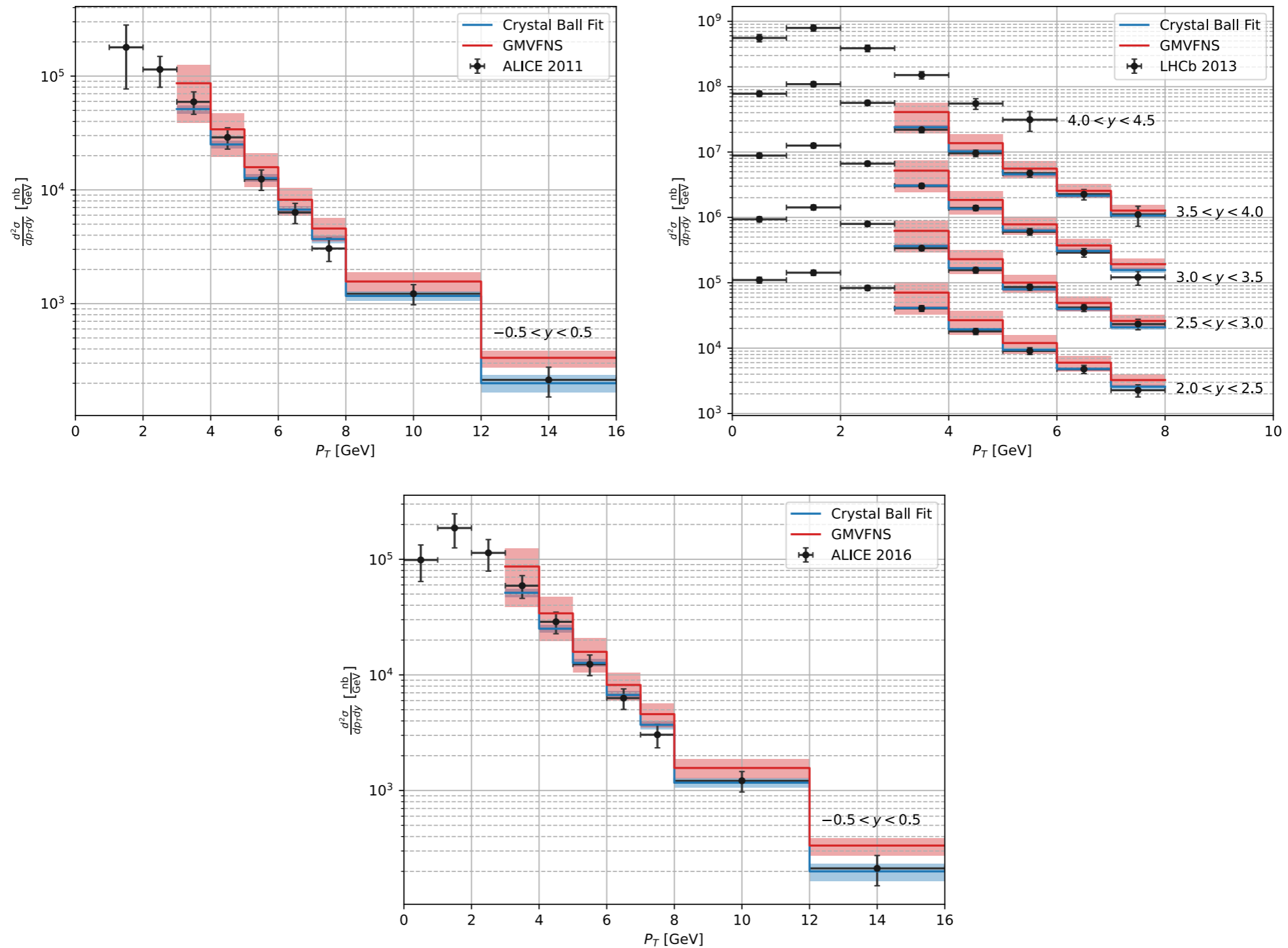


FIG. 3: Comparison between prompt  $D^0$  production as predicted in the GMVFNS (red) and with the data-driven approach (blue). The uncertainties of the GMVFNS predictions come from varying the scales individually by a factor of 2, such that there is never a factor 4 between two scales. Different rapidity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

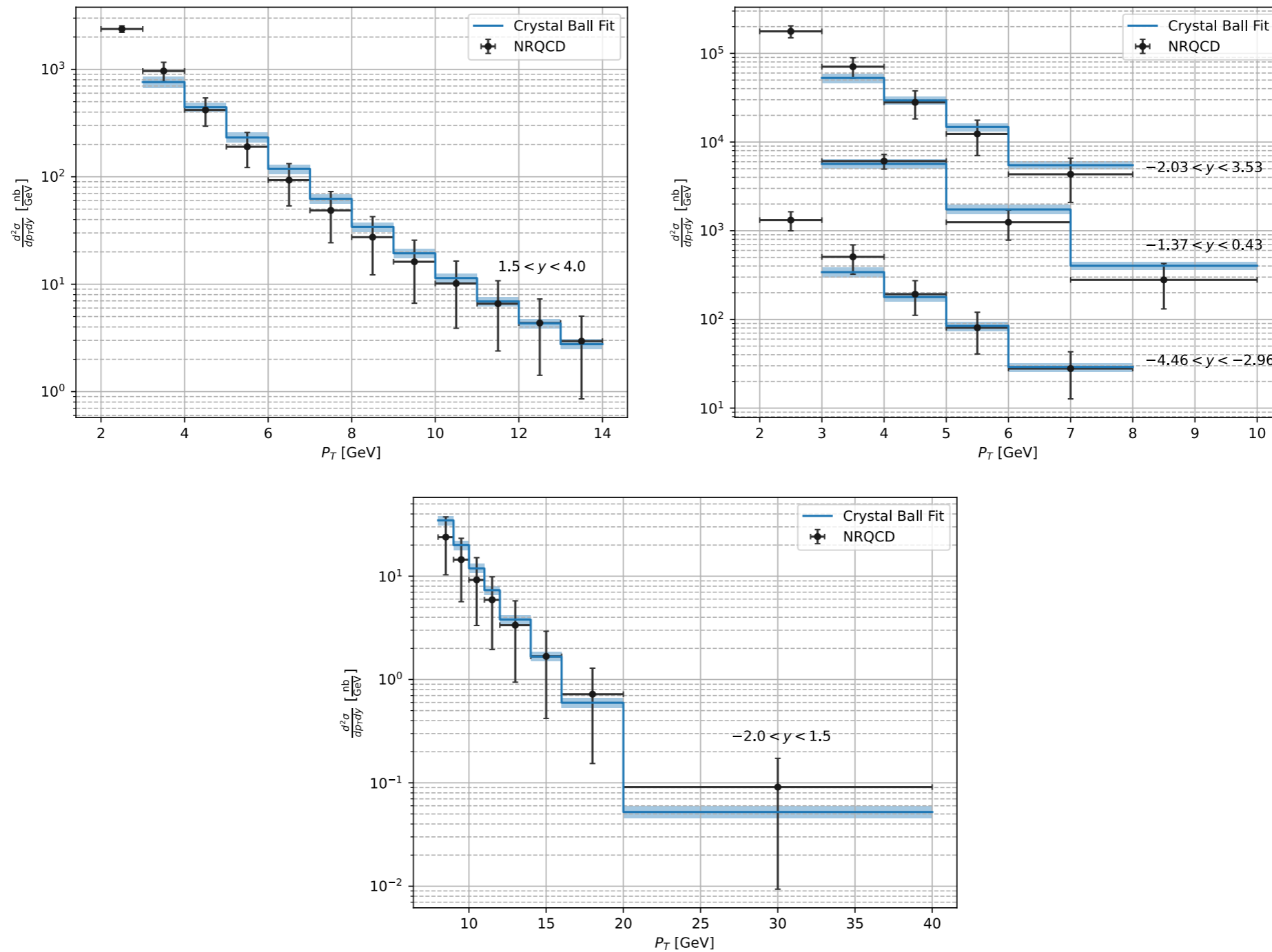
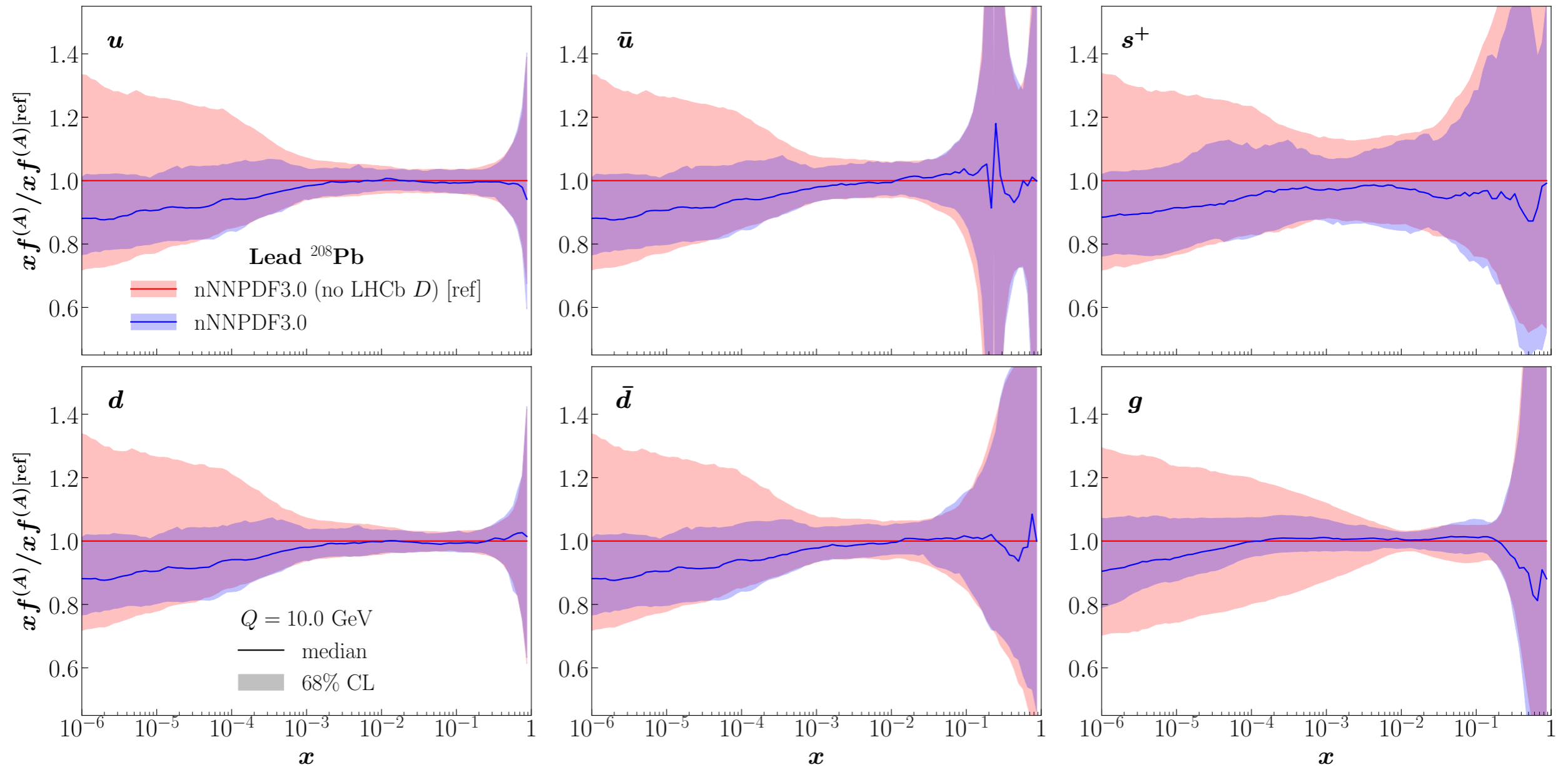


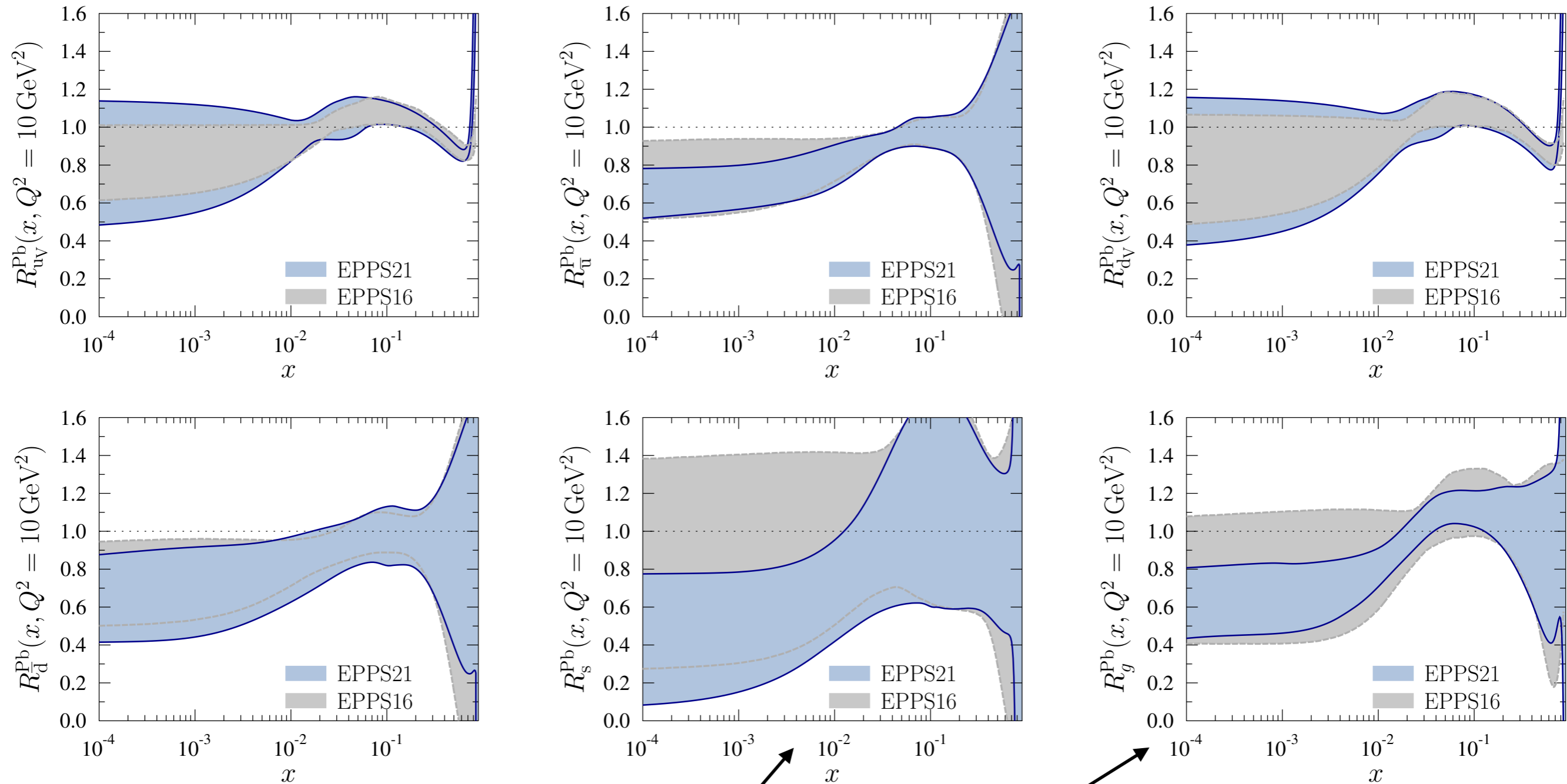
FIG. 2: Comparison between prompt  $J/\psi$  production in  $pp$  collisions for LHCb[87], ALICE[88] and ATLAS[89] kinematics as predicted by NRQCD and with the data-driven approach. The uncertainties of the NRQCD predictions come from scale variation  $1/2 < \mu_r/\mu_{r,0} = \mu_f/\mu_{f,0} = \mu_{\text{NRQCD}}/\mu_{\text{NRQCD},0}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

## 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.

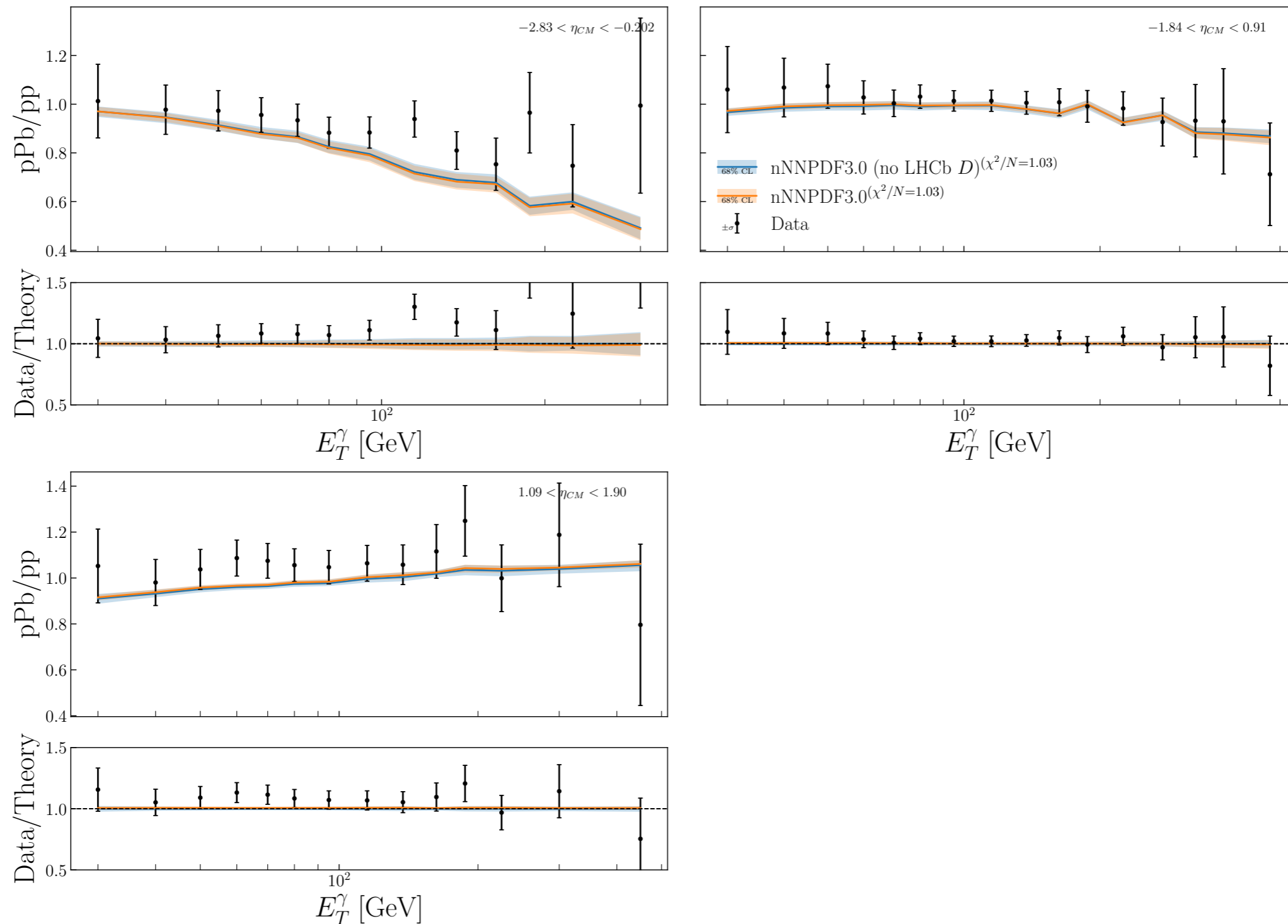
# EPPS21 vs EPPS16



- 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

ATLAS photon pPb/pp  $\sqrt{s} = 8.16$  TeV

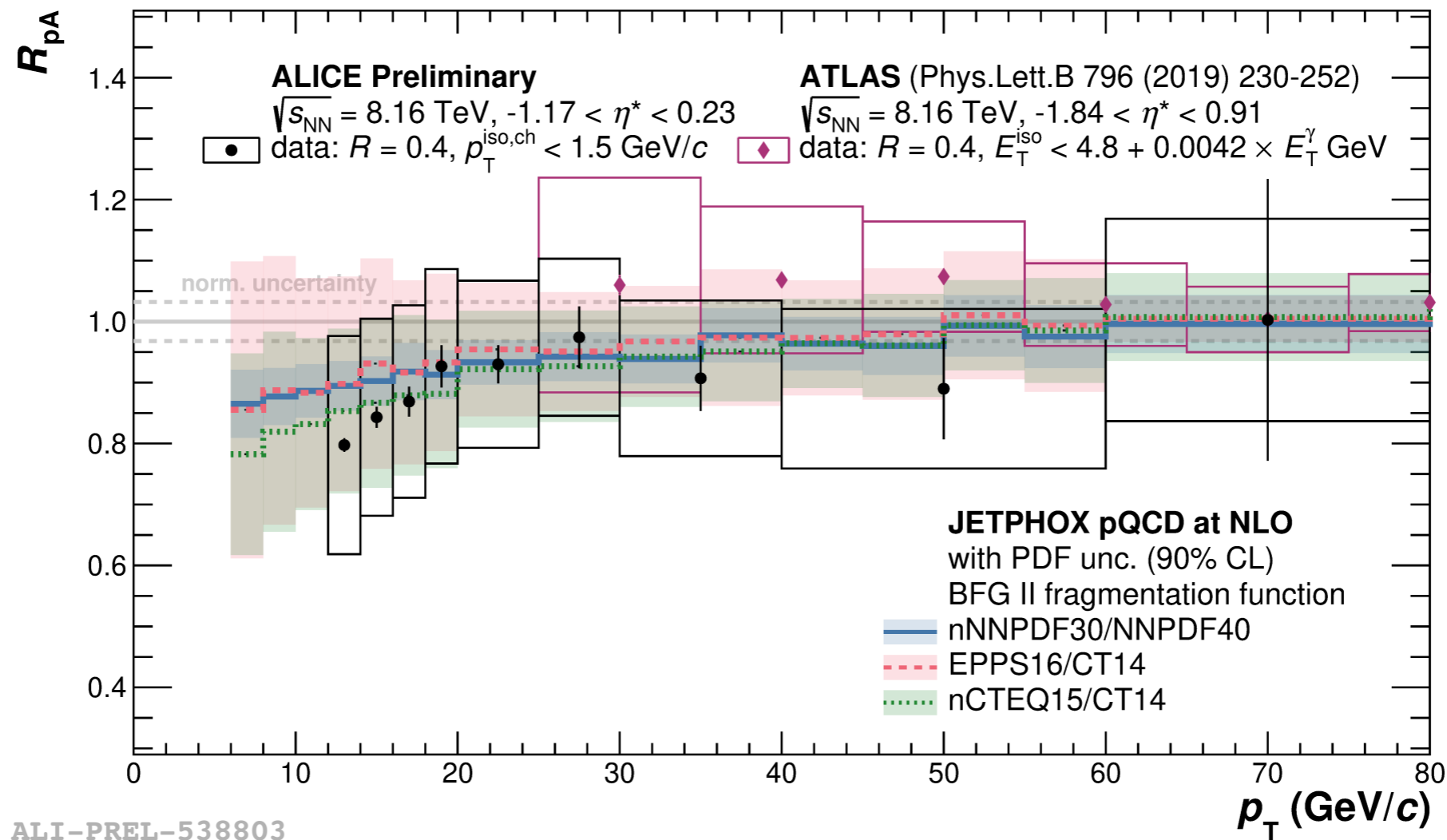


**Note: Absolute cross sections underestimated at NLO up to 30% at low pT  $\rightarrow$  NNLO?**



# Run-II isolated photons in pPb from ALICE

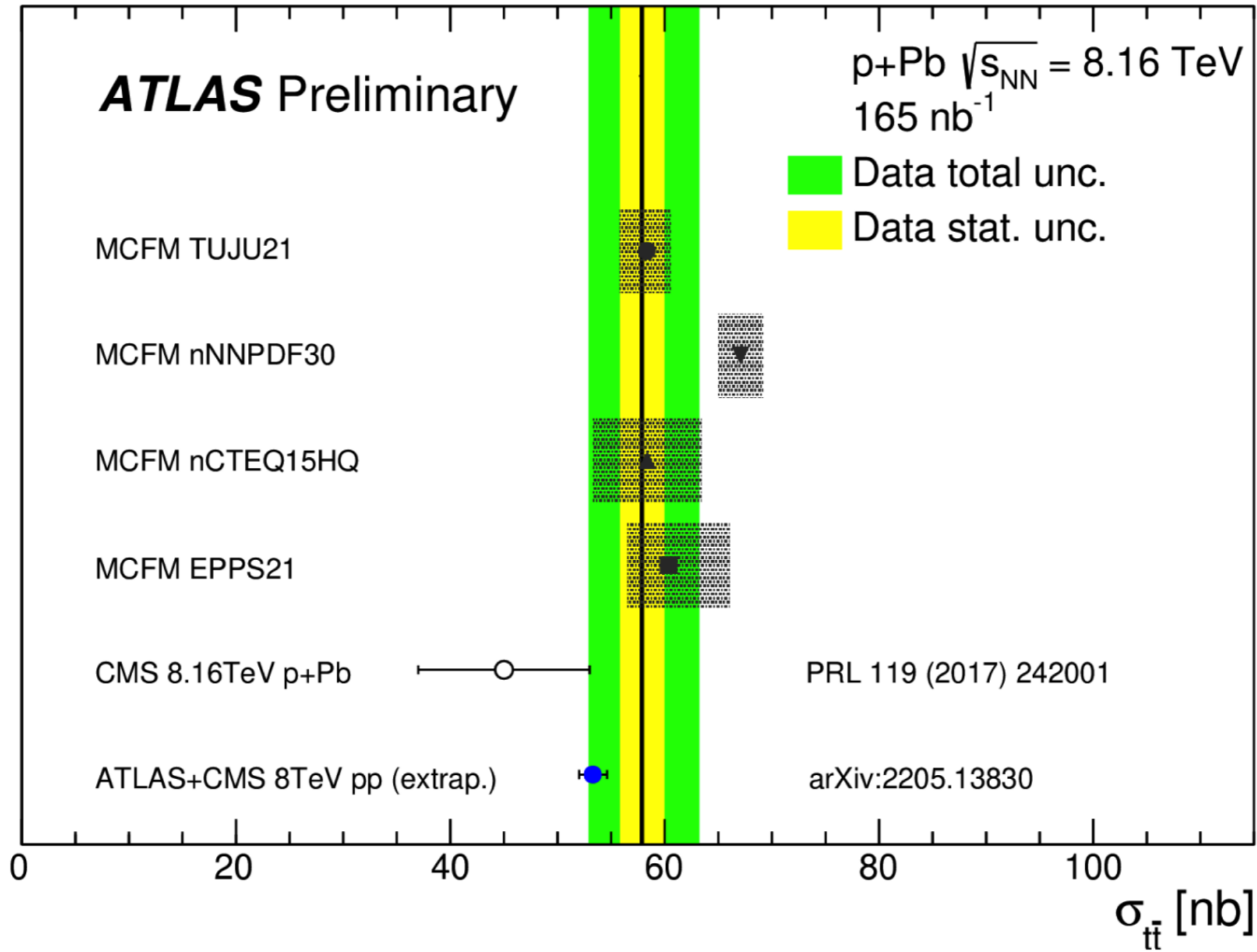
[Talk M. Klasen, DIS24]



- 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]



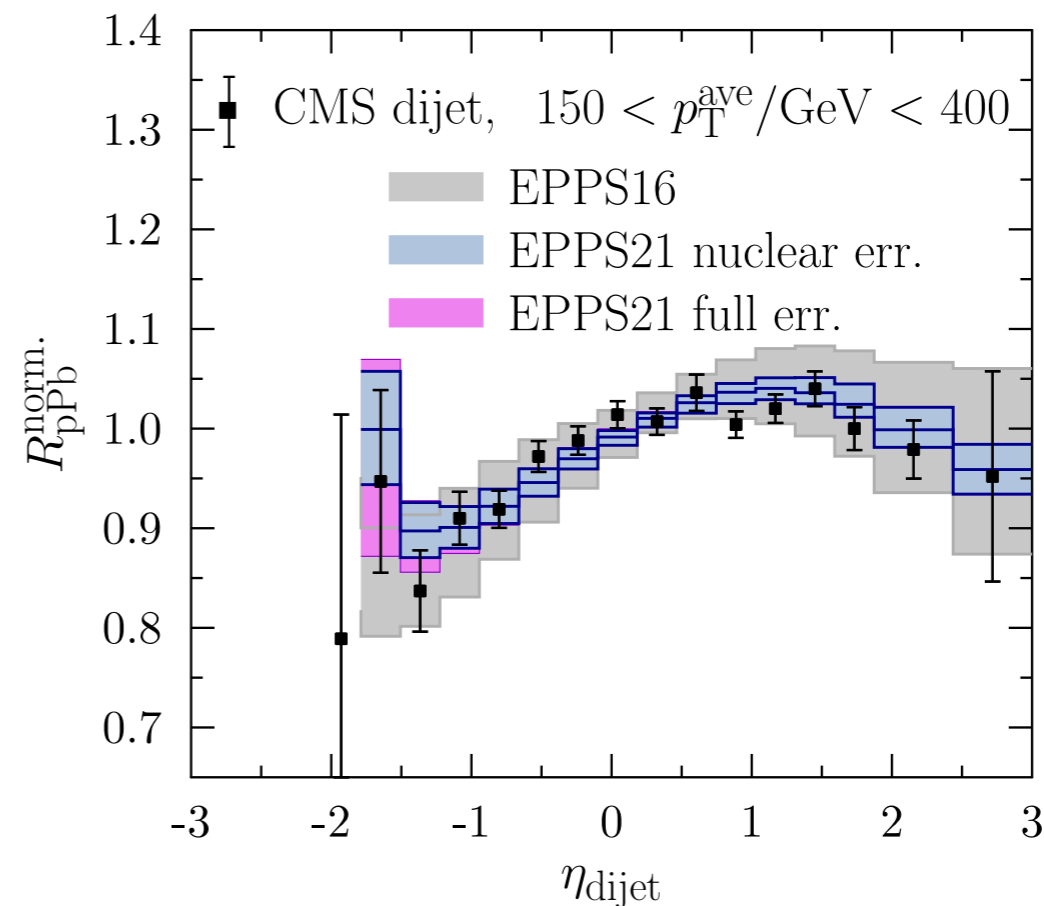
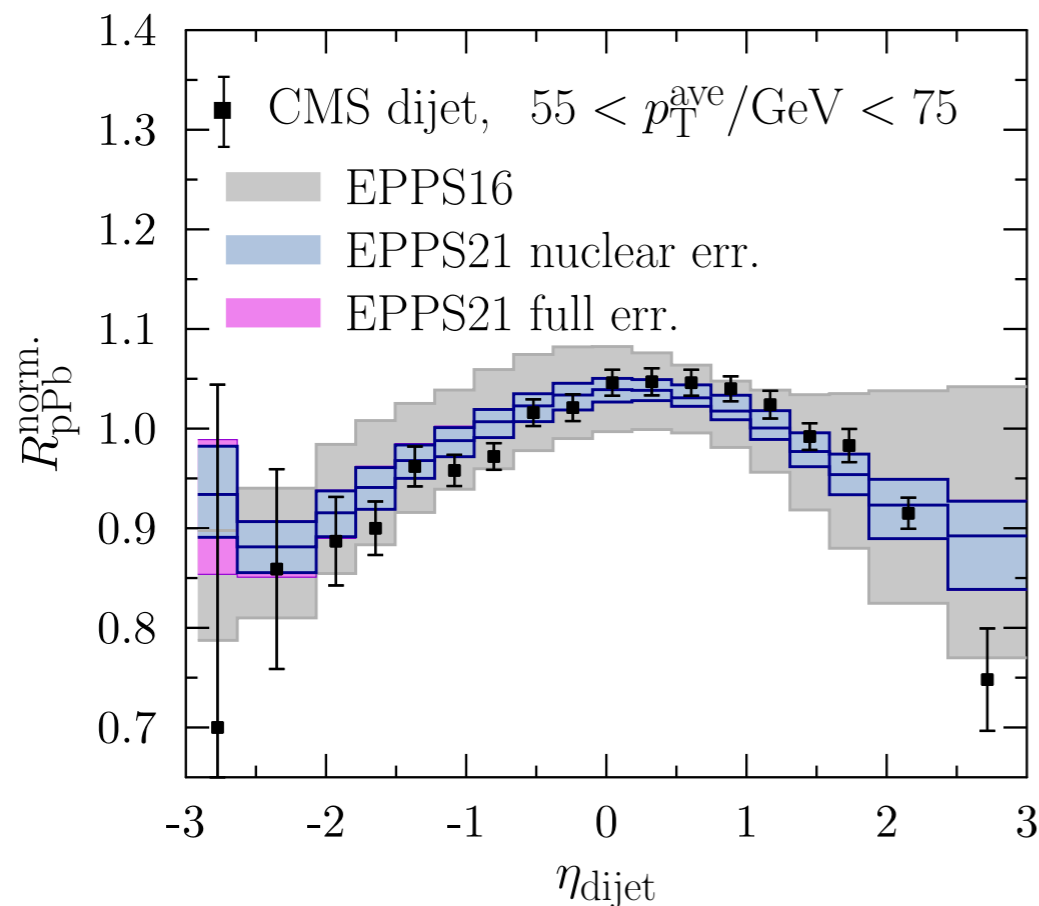
# Run-I dijet production from CMS

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

[Talk M. Klasen, DIS'24]

Specific to nuclear collisions:

- Large background from Underlying Event
- $7 \pm 5$  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  $\rightarrow$  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](#)