Nuclear PDFs after 10 years of LHC data[1]

Michael Klasen

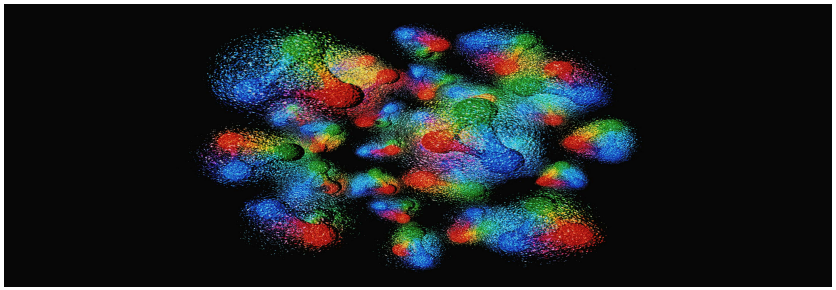
ITP, University of Münster

DIS 2024 Grenoble, April 8, 2024

GEFÖRDERT VOM

[1] MK, H. Paukkunen, Ann. Rev. Nucl. Part. Sci. (2024) [2311.00450]

Nuclear structure at high energies



Important current research topic:

- Understand fundamental q, g dynamics of p, n bound in nuclei
- Determine initial conditions in creation of new state of matter: Color-glass condensate (CGC) $\rightarrow$ quark-gluon plasma (QGP)

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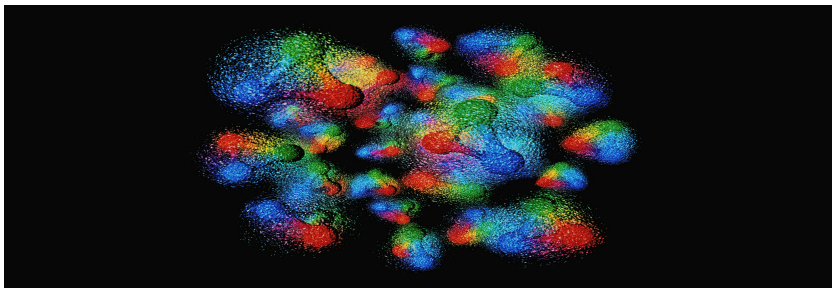

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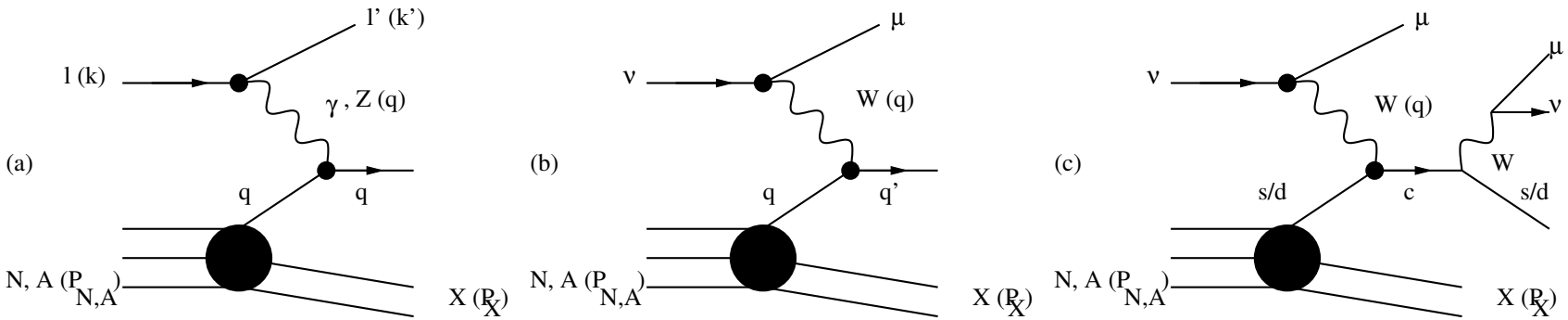
Knowns and (known) unknowns:

- Evolution of PDFs $f_{q,g}(x, Q^2)$ with squared energy Q^2: Calculable at NLO and beyond through DGLAP equations
- Dependence on longitudinal momentum fraction x: QCD factorization theorem $\rightarrow$ global fits to experimental data
- Fundamental dynamics of nuclear modifications: Parameterized, but remain to be fully understood

Key processes and open questions

Deep-inelastic scattering (NC, CC, dimuon production):



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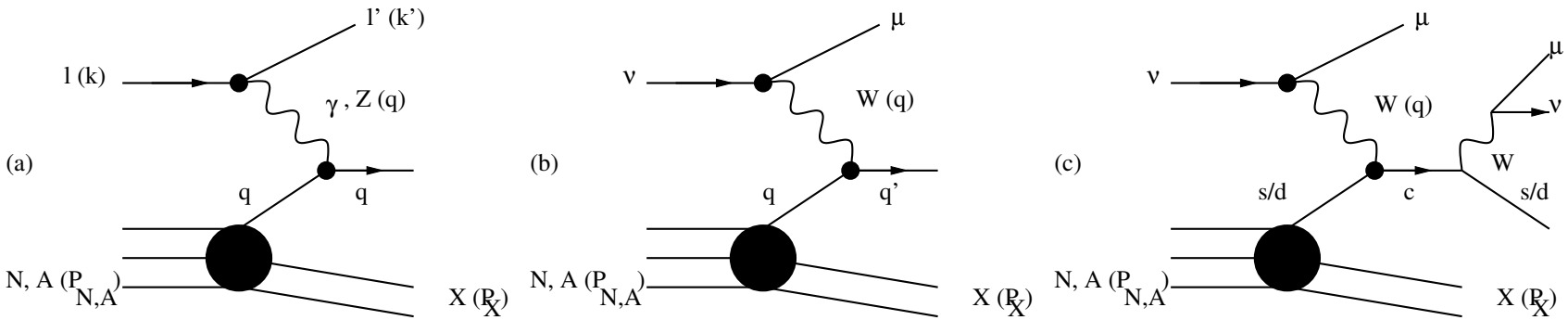
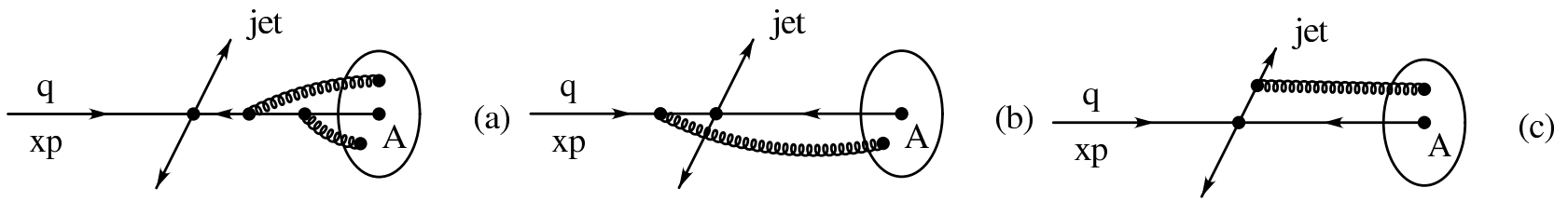


Hadronic collisions: Leading twist, higher-twist [J.w. Qiu, 0305161]

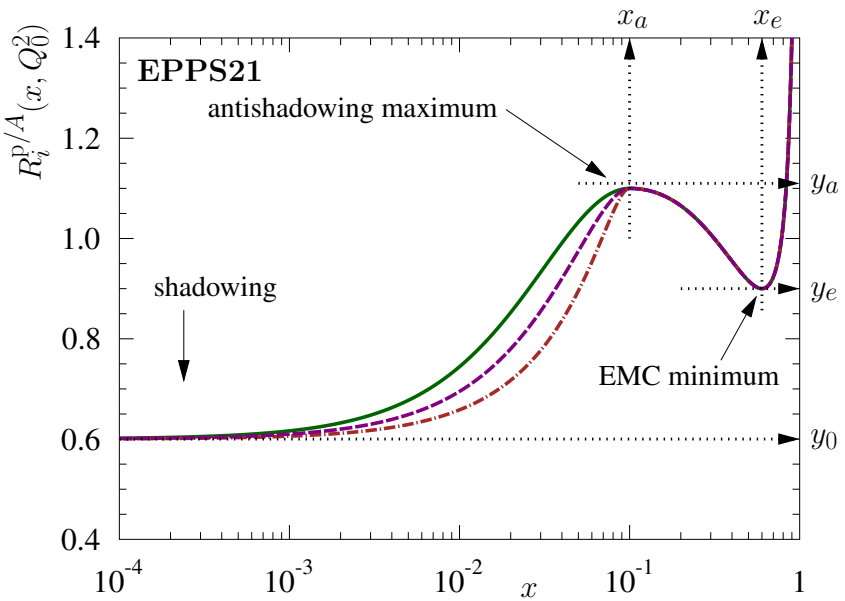


- Transv. size, jet mass, rescattering: $\mathcal{O}\left(r_T^2 \sim \frac{1}{p_T^2}, \frac{m_J^2}{p_T^2}, \frac{\alpha_s(Q^2)\Lambda^2}{Q^2}\right)$
- Enhanced in nuclear collisions by $A^{1/3}$ due to many soft partons

Nuclear modification factor

Definition:

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



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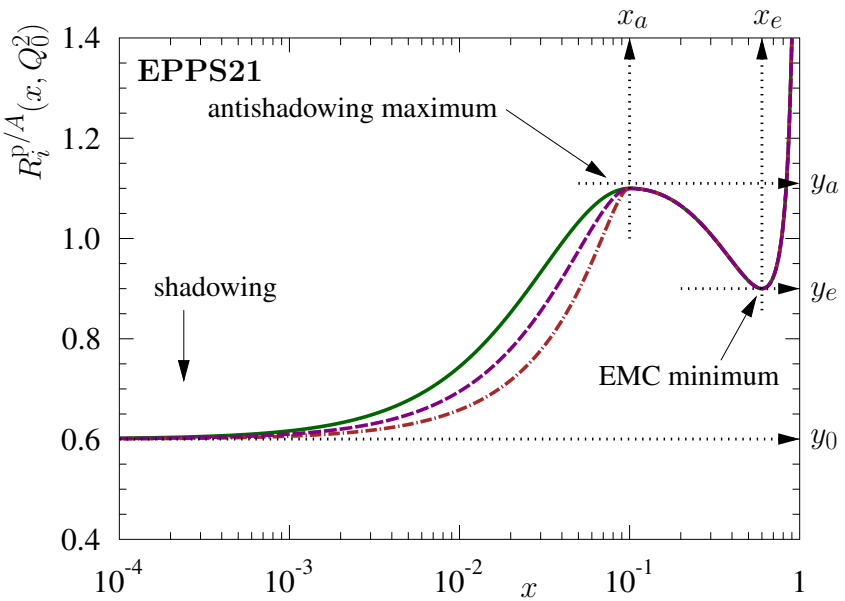

Regions:

- Shadowing: Surface nucleons absorb $q\bar{q}$ dipole, cast shadow
- Antishadowing: Imposed by momentum sum rule
- EMC effect: q_v suppression due to nuclear binding, pions, quark clusters, Nachtmann scaling, short-range correlations, ...
- Fermi motion: Nucleons move, $F_2^A = \int_x^A dz\ f_N(z)\ F_2^N(\frac{x}{z})$

(Perturbative) Quantum Chromodynamics

Nuclear structure function(s) in deep-inelastic scattering (DIS):

$$F_2^A(x, Q^2) = \sum_i f_i^{(A,Z)}(x, Q^2) \otimes C_{2,i}(x, Q^2)$$

QCD factorization theorem, Wilson coefficients $C_{2,i}$ at (N)NLO

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DGLAP evolution equations:

$$\frac{\partial f_i(x, Q^2)}{\partial \log Q^2} = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(Q^2)\right) f_j(z, Q^2)$$

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Sum rules, but also isospin symmetry:

$$f_{d,u}^{n/A}(x,Q^2) \;=\; f_{u,d}^{p/A}(x,Q^2)$$

Theoretical input and experimental data

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	$\sim$CTEQ6.1	CT18A	$\sim$NNPDF4.0	$\sim$HERAPDF2.0	CT18
Deuteron corrections	$(\checkmark)^{a,b}$	$\checkmark^{c}$	✓	✓	✓
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
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JLab NC DIS	$(\checkmark)^{a}$	✓			✓
CHORUS/CDHSW CC DIS	$(\checkmark/\text{-})^{b}$	✓/-	✓/-	✓/✓	✓/✓
NuTeV/CCFR 2μ CC DIS	$(\checkmark/\checkmark)^{b}$		✓/-		
pA DY	✓	✓	✓		✓
Collider data:					
Z bosons	✓	✓	✓	✓	
$W^{\pm}$ bosons	✓	✓	✓	✓	
Light hadrons	✓	$\checkmark^{d}$			
Jets		✓	✓		
Prompt photons			✓		
Prompt D^0	✓	✓	$\checkmark^{e}$		
Quarkonia (J/ψ, ψ', Υ)	✓				

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WED 09:10 M. Costantini (U Cambridge) MCMC for PDFs
WED 09:50 T. Giani (NIKHEF) Bayesian inference for PDFs
WED 10:10 P. Risse (U Münster) MCMC for PDFs
WED 11:20 N. Derakhshanian (IFJ PAN) MCMC for nPDFs

Perturbative order

Required precision:

- Protons: Wealth of HERA, LHC pp data $\rightarrow$ 1% accuracy, NNLO
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- Slow NNLO for pA: V (FEWZ, MCFM, Vrap, DYNNLO$\rightarrow$Matrix), jets (NNLOjet), t (top++, Matrix) [, b (top++, Matrix)]
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Open heavy quarks (important for pA):

- FFNS $\rightarrow$ FONLL
- VFNS ZM $\rightarrow$ GM (ACOT, RT)

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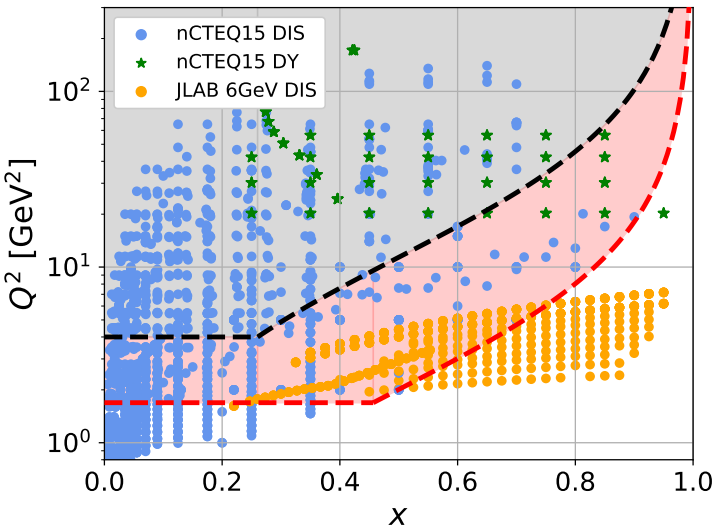
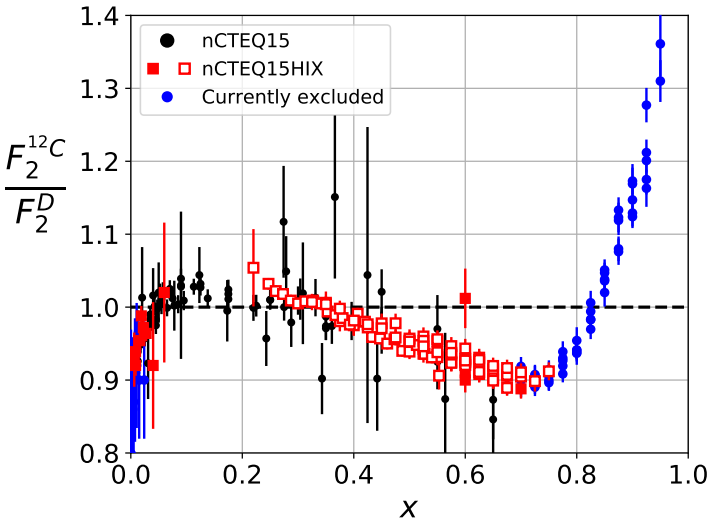
Heavy quarkonia (important for pA):

- CEM [R. Vogt et al., PRC 105 (2022) 055202: J.P. Lansberg et al., PLB 807 (2020) 135559]
- NRQCD [K.T. Chao et al., JHEP 08 (2021) 111; M. Butenschön, B. Kniehl, PRL 130 (2023) 041901]

High-x JLab data: Deuteron, TMCs and HT

A. Accardi et al., Phys. Rev. D 93 (2016) 114017 [1602.03154]; E.P. Segarra et al., Phys. Rev. D 103 (2021) 114015 [2012.11566]





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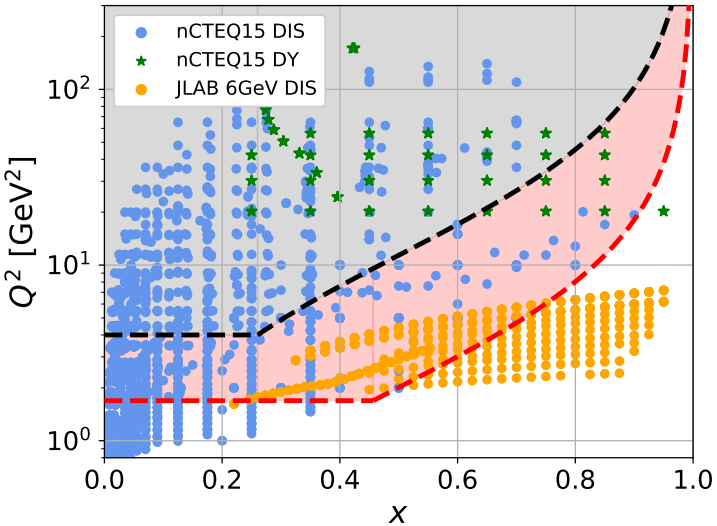

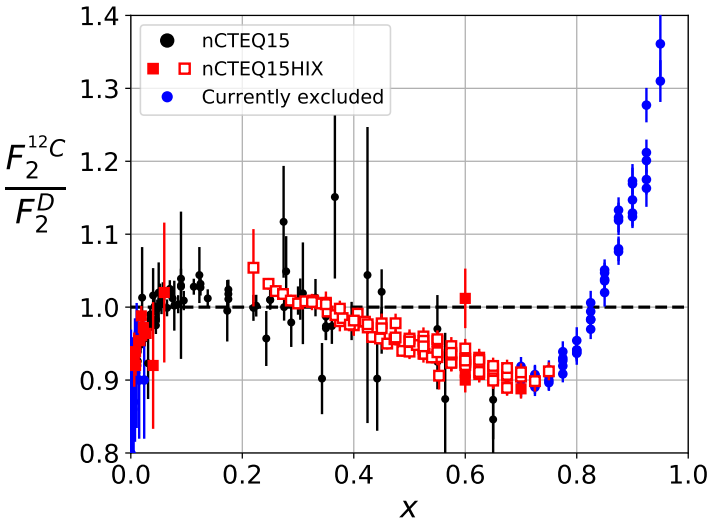

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- Loosely bound $\rightarrow$ often isoscalar (pn) assumed, fitted with p
- Fermi motion, nucl. binding, off-shell effects (few %) [CJ15,CJ22]

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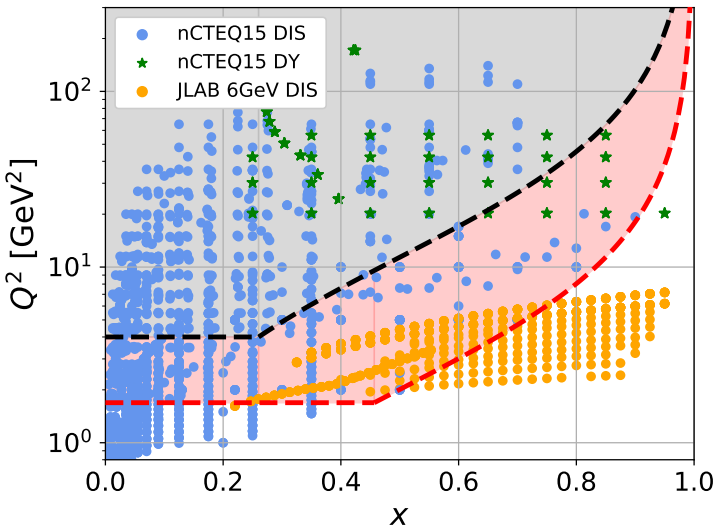

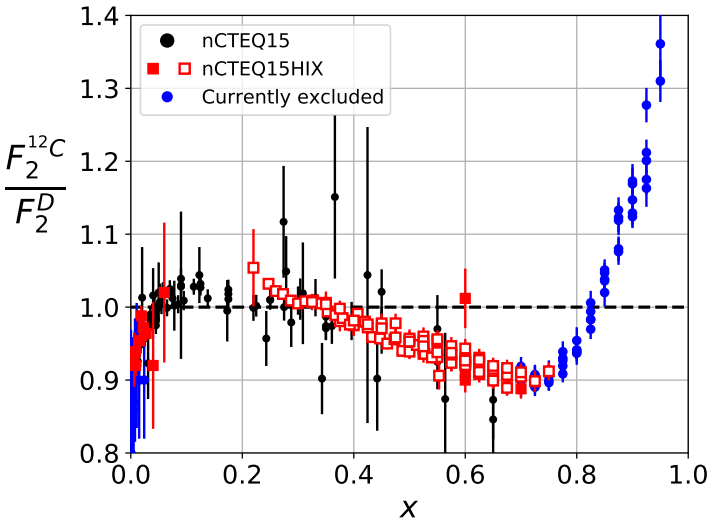

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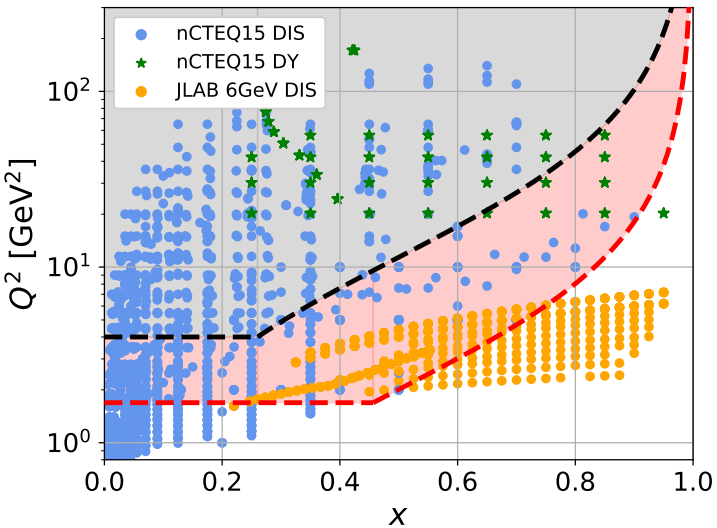

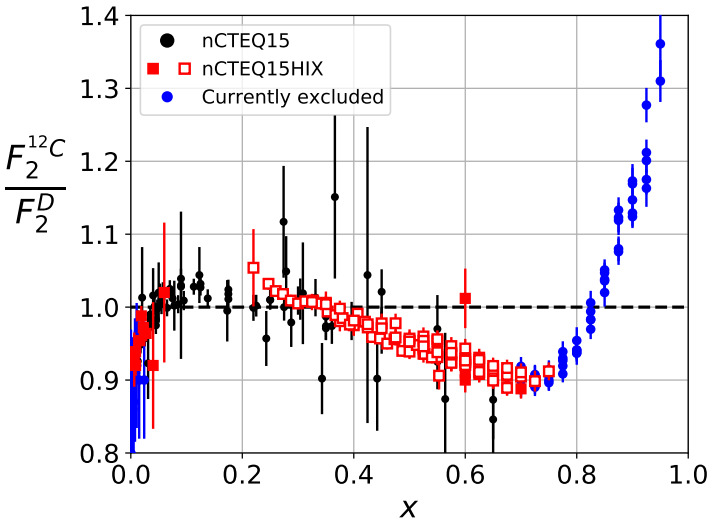

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Higher twist (HT) corrections: [CJ15,CJ22]

- $F_2^A(x,Q) \rightarrow F_2^A(x,Q)\left[1+\frac{A^{1/3}h_0 x^{h_1}(1+h_2 x)}{Q^2}\right]$

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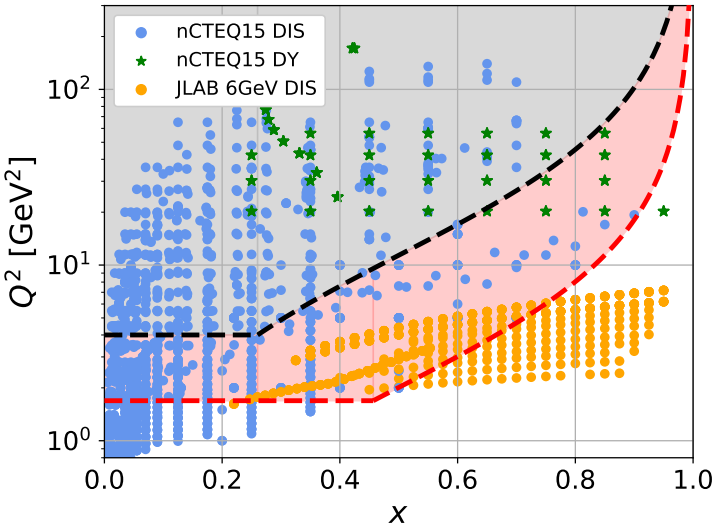

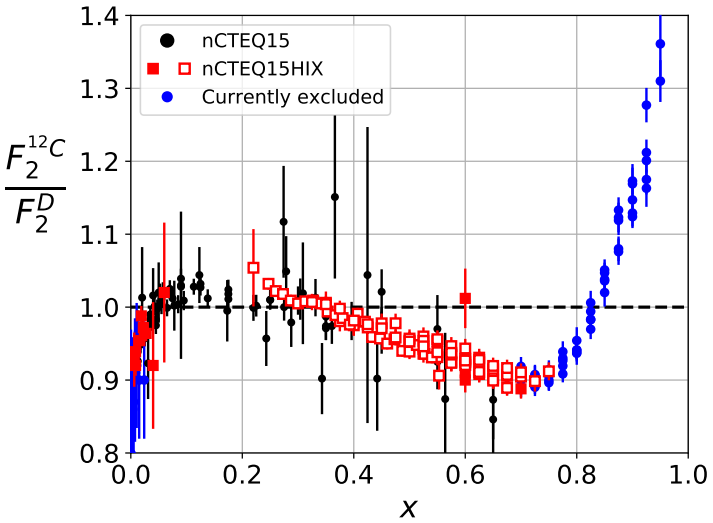

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TUE 12:20 C. Keppel (JLab) F_2^n
WED 11:40 R. Ruiz (IFJ PAN Cracow) TMCs
WED 12:00 M. Cerutti (Hampton U) D and HT at large x
WED 12:20 R. Petti (S Carolina U) nDIS and HT at large x
WED 14:10 C. Cotton (U Virginia) nDIS and EMC at Hall C
```

Compatibility of neutrino DIS data

MK, H. Paukkunen, Ann. Rev. Nucl. Part. Sci. (2024) [2311.00450]

Are CC DIS data compatible with NC DIS and DY data?

- No (in particular high-precision NuTeV data)

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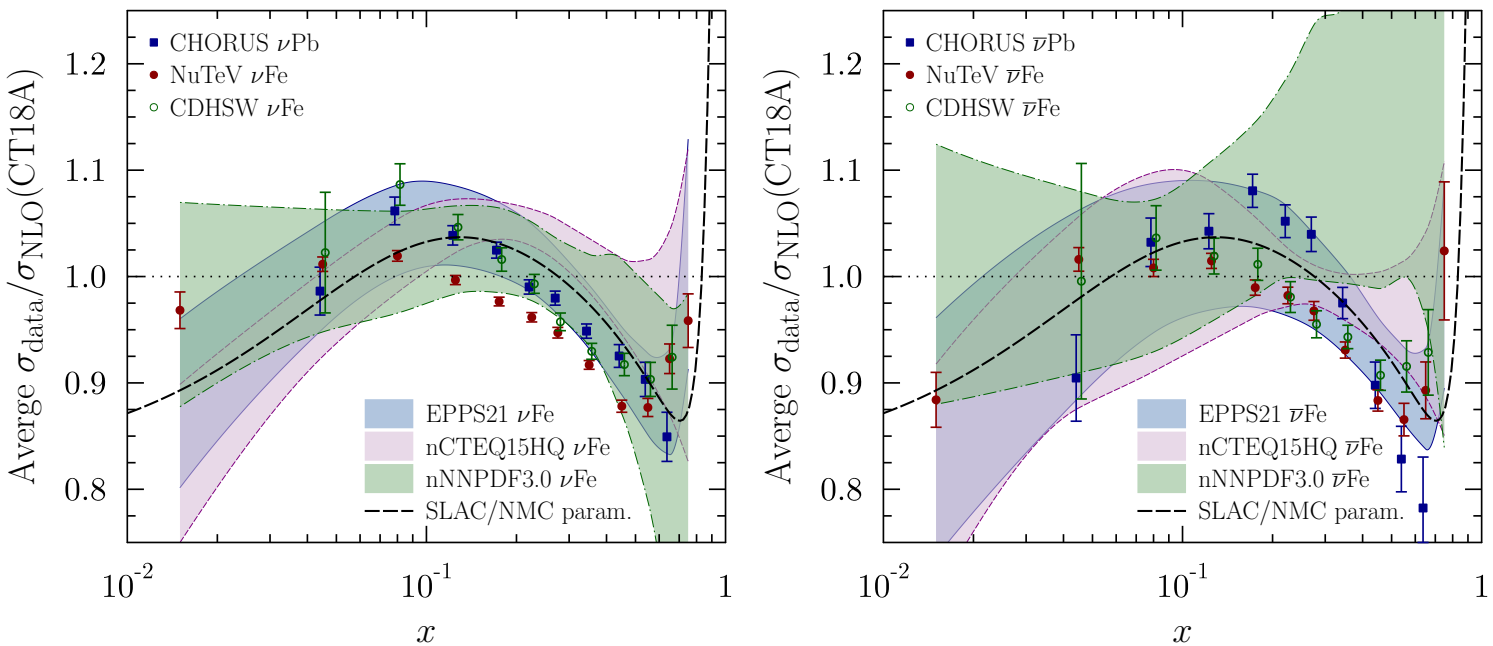
Consolidated perspective:



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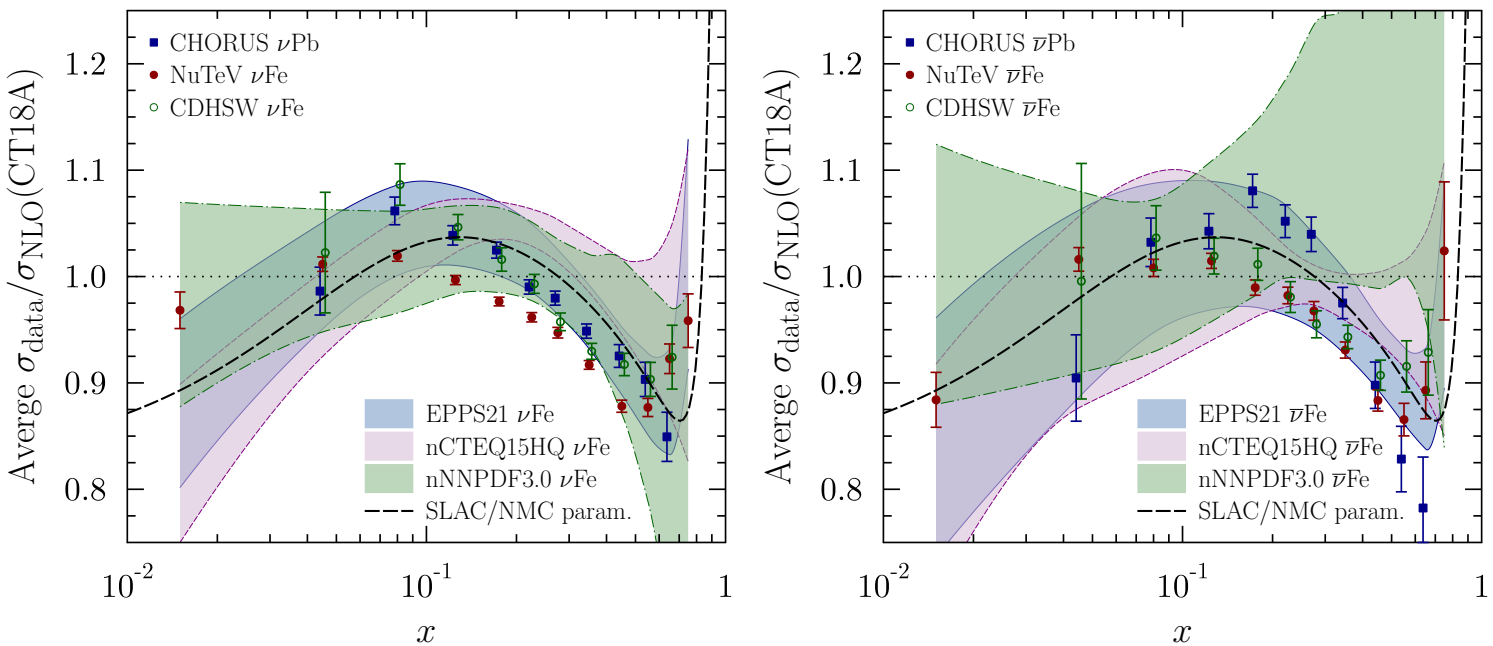

NB: Proton is CT18A, EW corr. in CDHSW. Impact on s quark!

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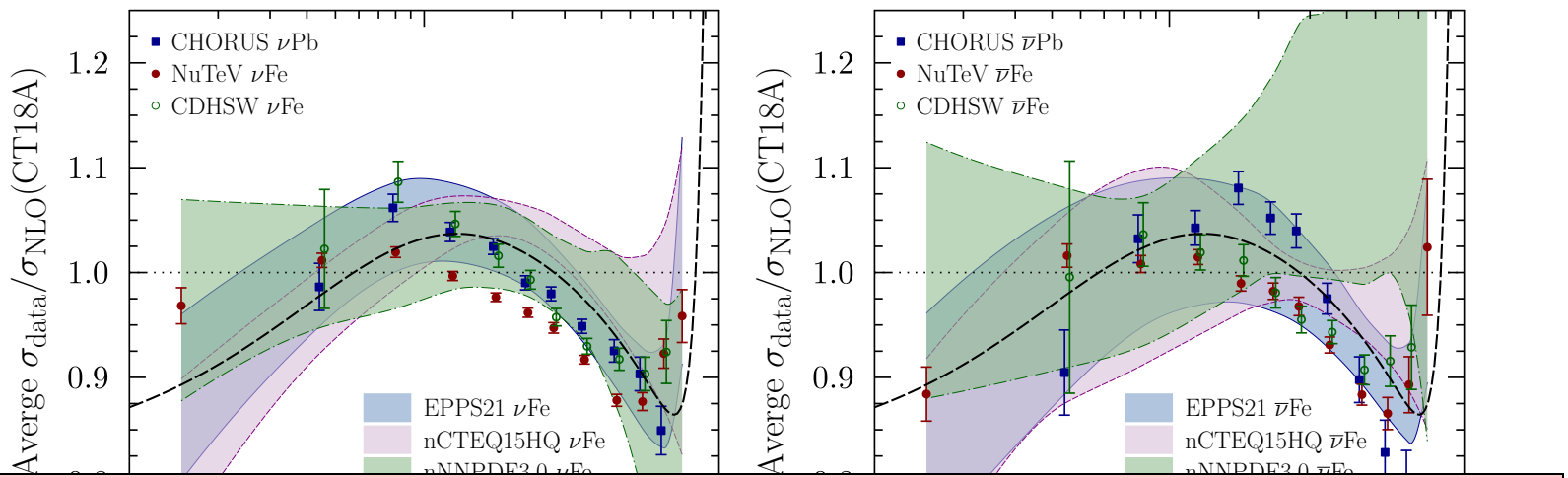
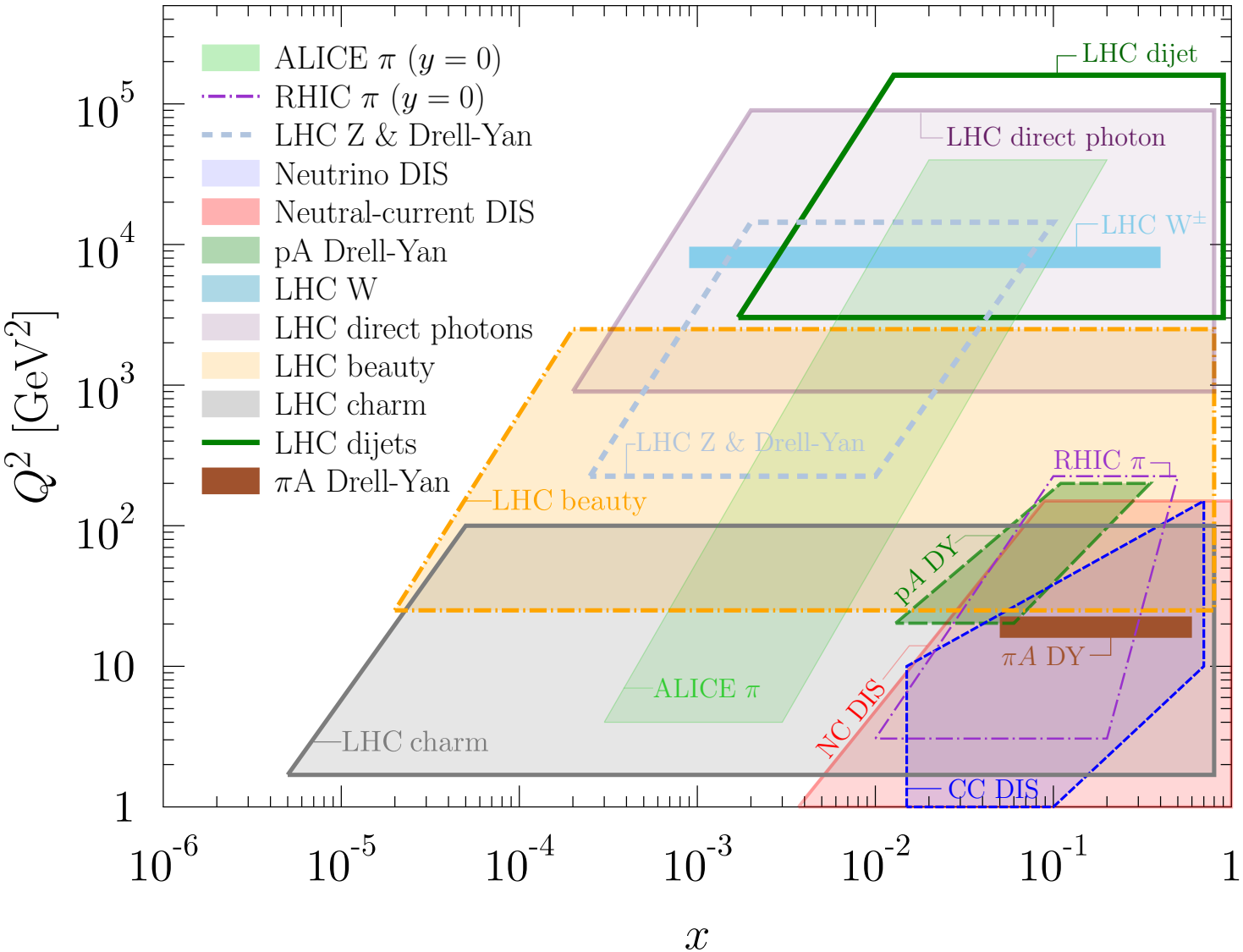


TUE 14:10 J. Rojo (VU Amsterdam, NIKHEF) \nu DIS at LHC
TUE 14:30 S. Yrjänheikki (U Jyväskylä) Dimuon SIDIS
TUE 14:50 J. Atkinson (U Bern) FASER\nu
TUE 15:10 O. Durhan (METU) SND@LHC

Kinematic coverage in x and Q^2



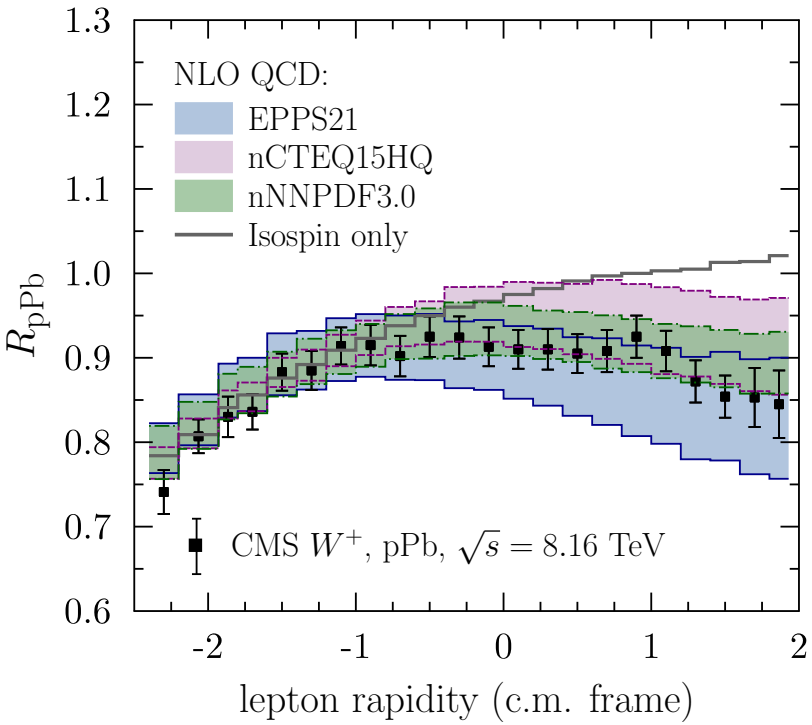
Experimental data on W/Z bosons

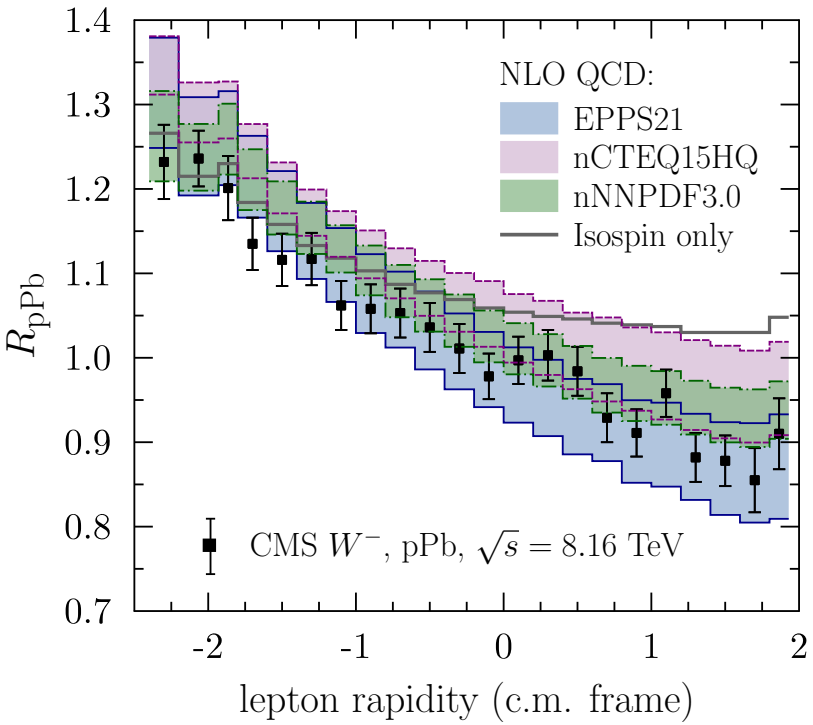
Analysis	nCTEQ15HQ	EPPS21	nNNPDF3.0	TUJU21	KP16
Run-I:					
ATLAS Z	✓	✓	✓	✓	✓
CMS Z	✓	✓	✓	✓	✓
ALICE Z			✓[b]		
LHCb Z	✓		✓[b]		
ATLAS $W^{\pm}$	✓				✓
CMS $W^{\pm}$	✓	✓	✓		
ALICE $W^{\pm}$	✓		✓[b]		
Run-II:					
CMS Z			✓[b]		
ALICE Z			✓[b]		
LHCb Z					
CMS $W^{\pm}$	✓	✓[a]	✓	✓	
ALICE $W^{\pm}$					

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

Run-II $W^{\pm}$ boson production in pPb from CMS

MK, H. Paukkunen, Ann. Rev. Nucl. Part. Sci. (2024) [2311.00450]





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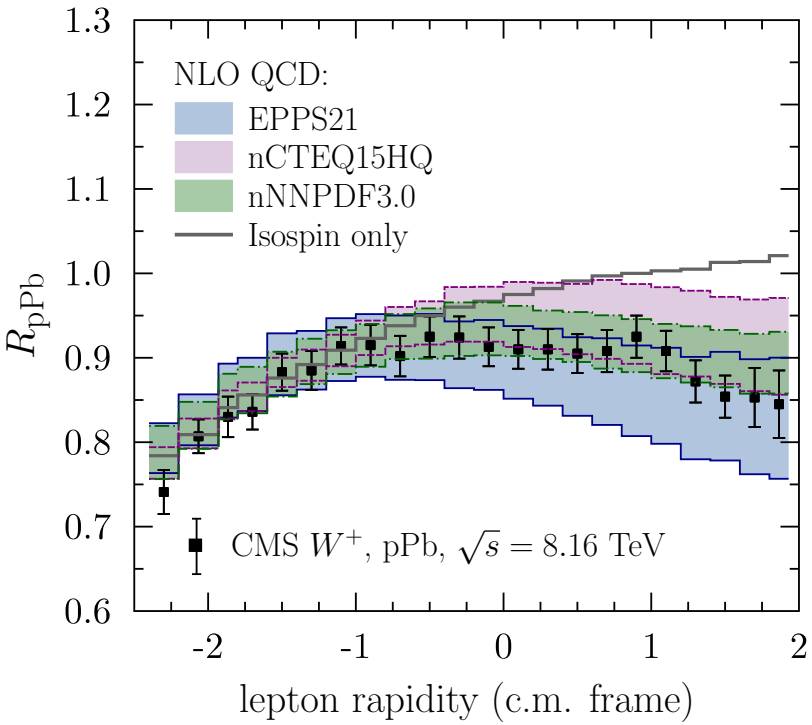
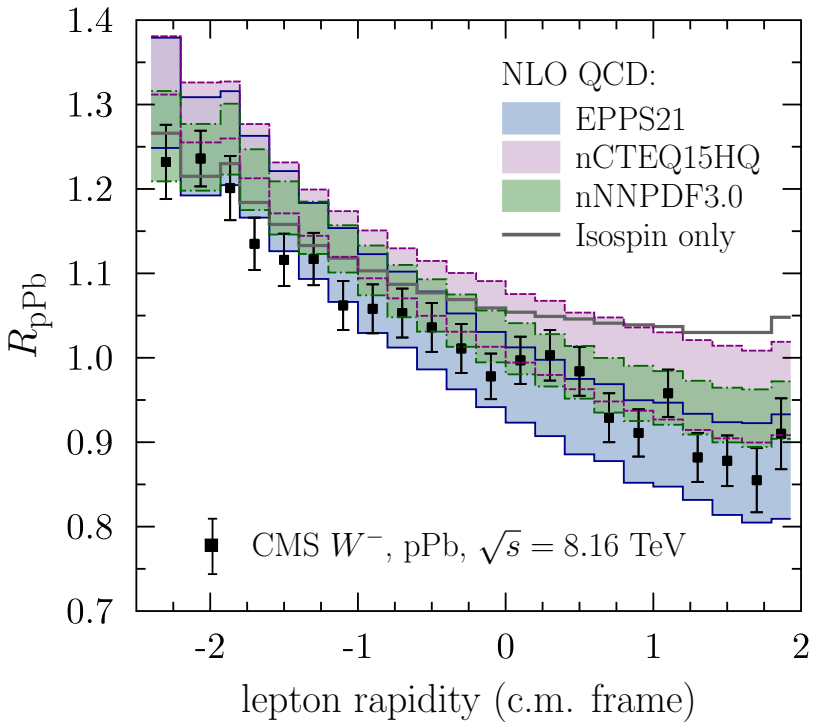
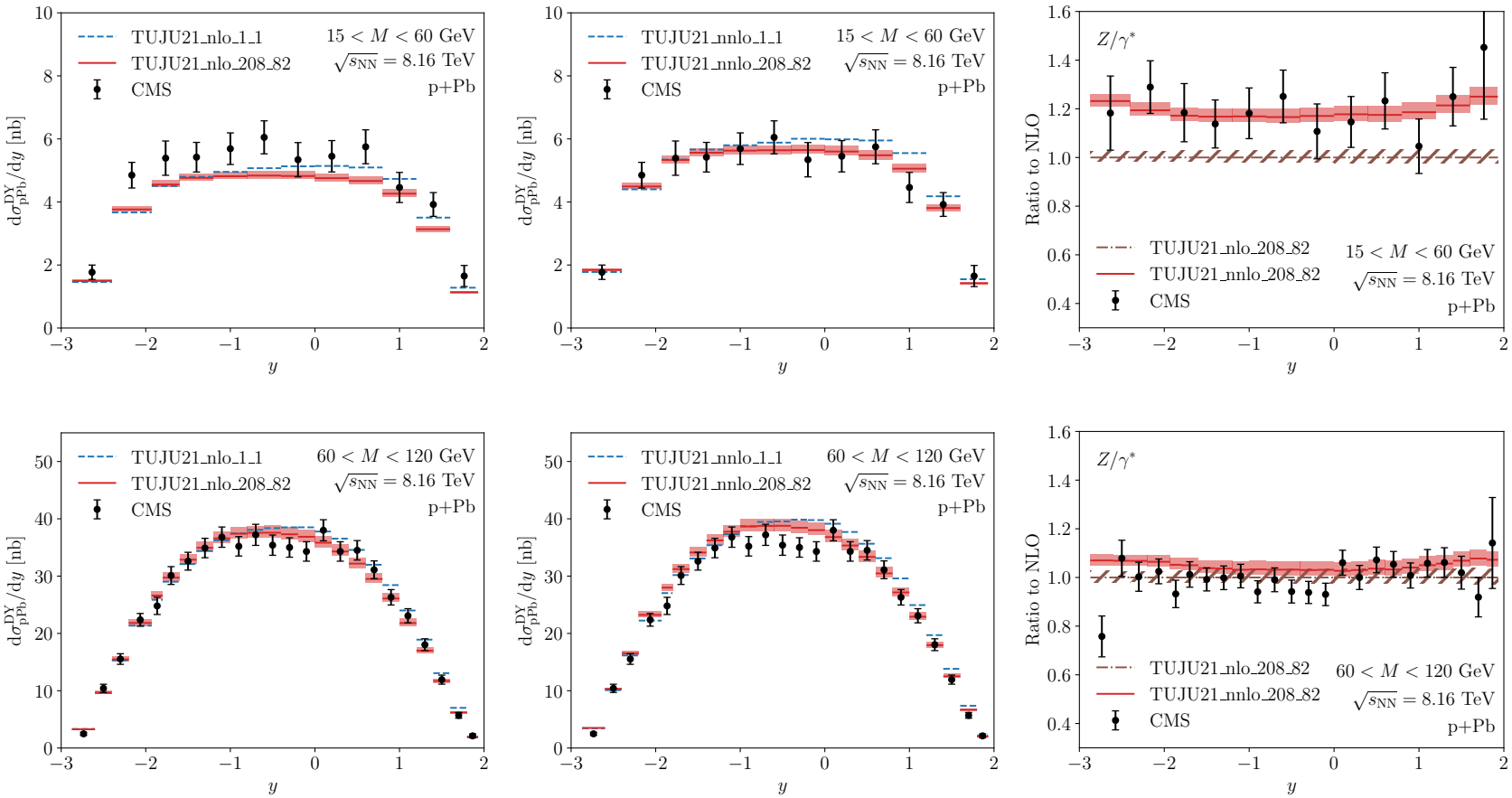




- nCTEQ/nNNPDF fit absolute cross sections, EPPS ratios
- Limited impact on s quark, since mostly evolved from gluon

Run-II Z boson production in pPb from CMS

I. Helenius, W. Vogelsang, M. Walt, Phys. Rev. D 105 (2022) 094031



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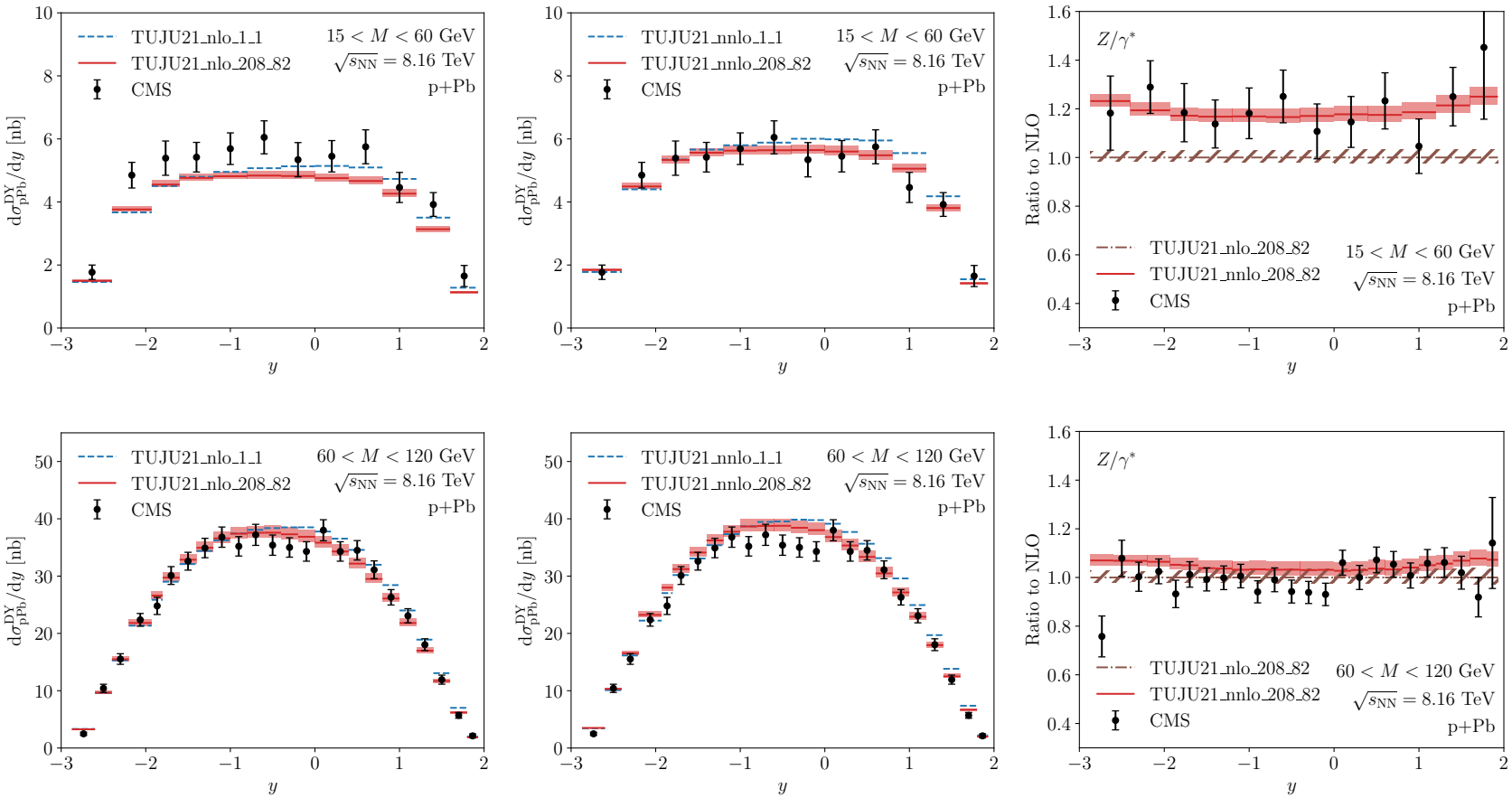

- Low-mass data in tension w/ NLO (also nNNPDF) $\rightarrow$ NNLO?

Run-II isolated photon production in pPb from ATLAS

ATLAS Coll., PLB 796 (2019) 230; nNNPDF Coll., EPJC 82 (2022) 507

Pre-LHC data: E706 (pBe); PHENIX, STAR (DAu)

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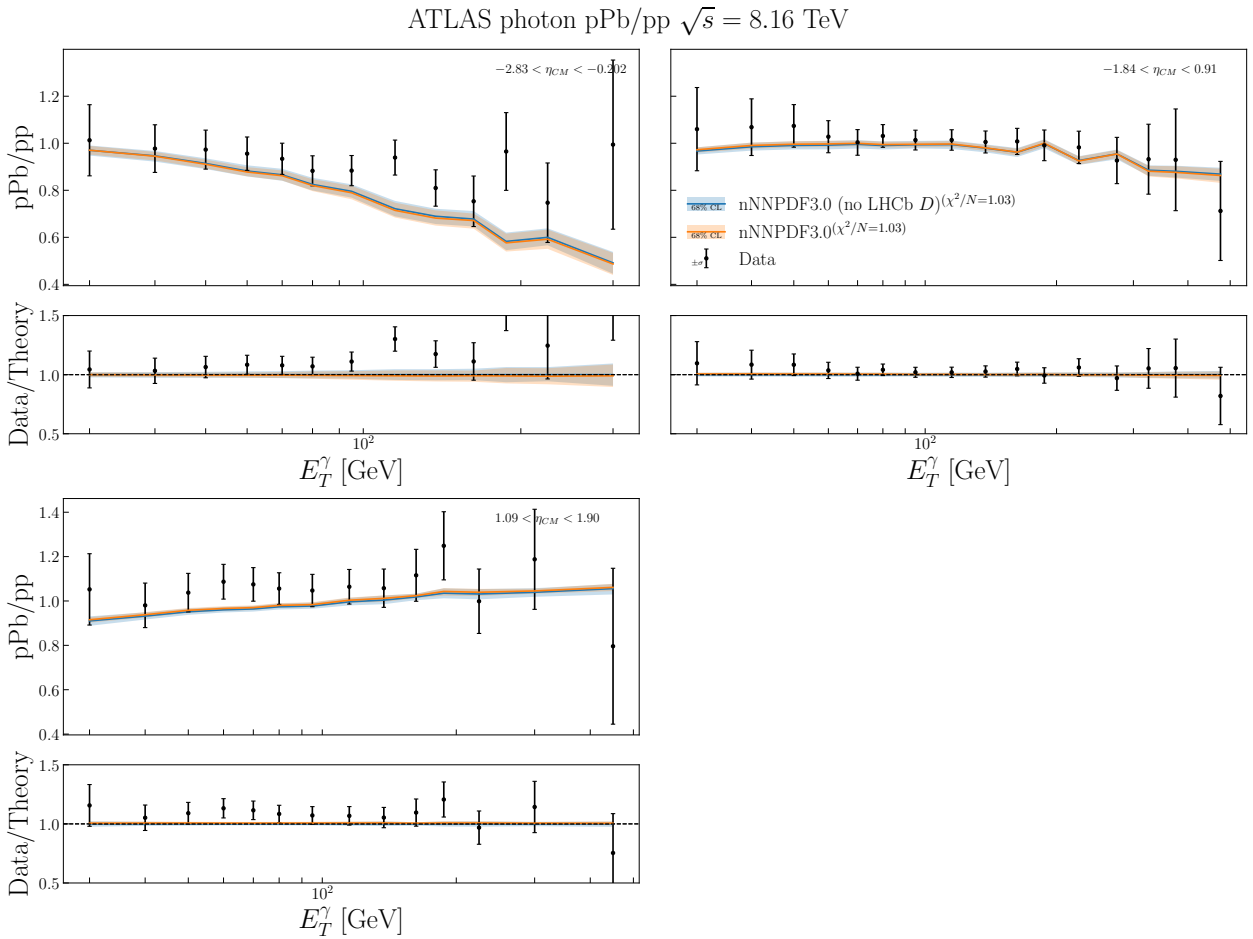

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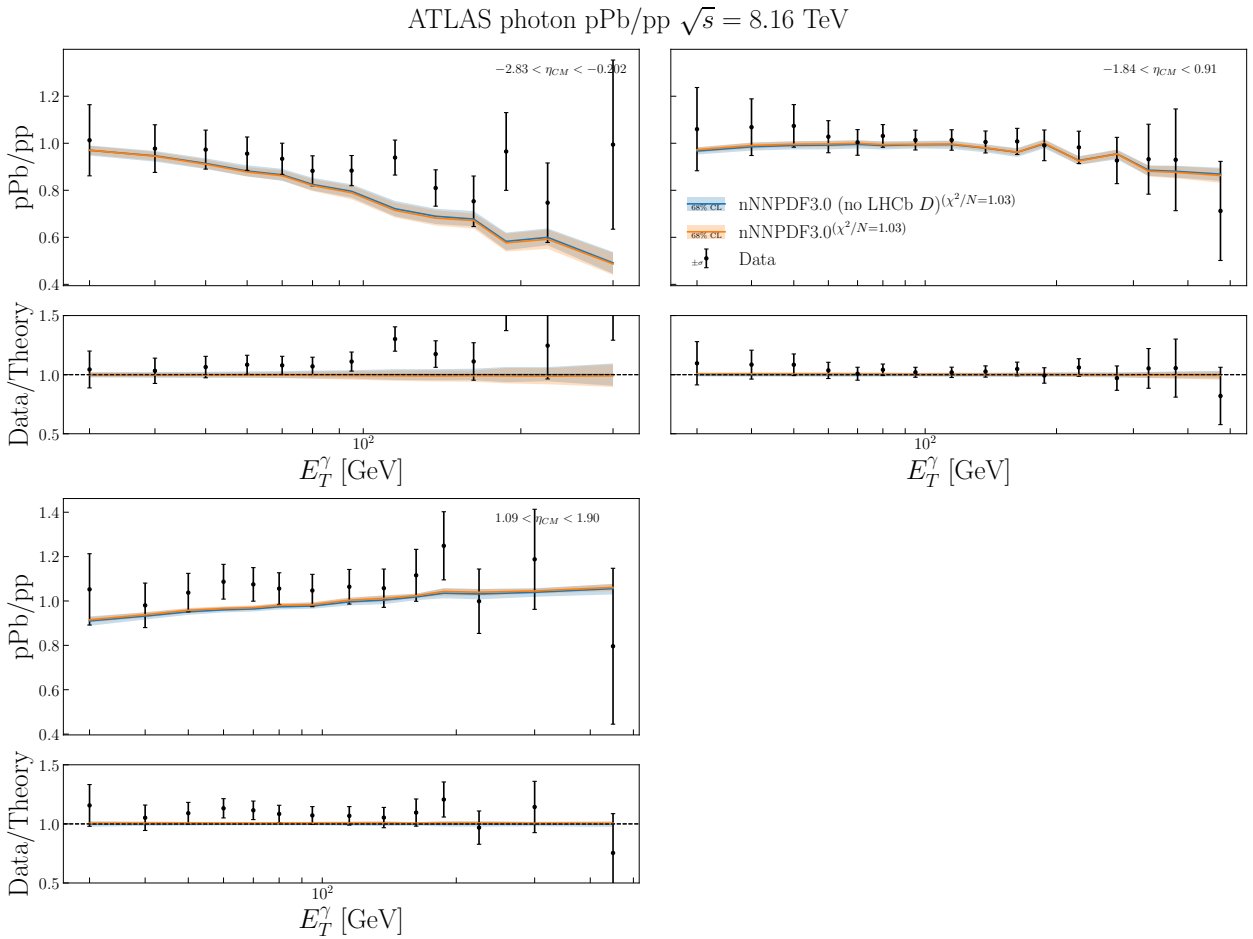
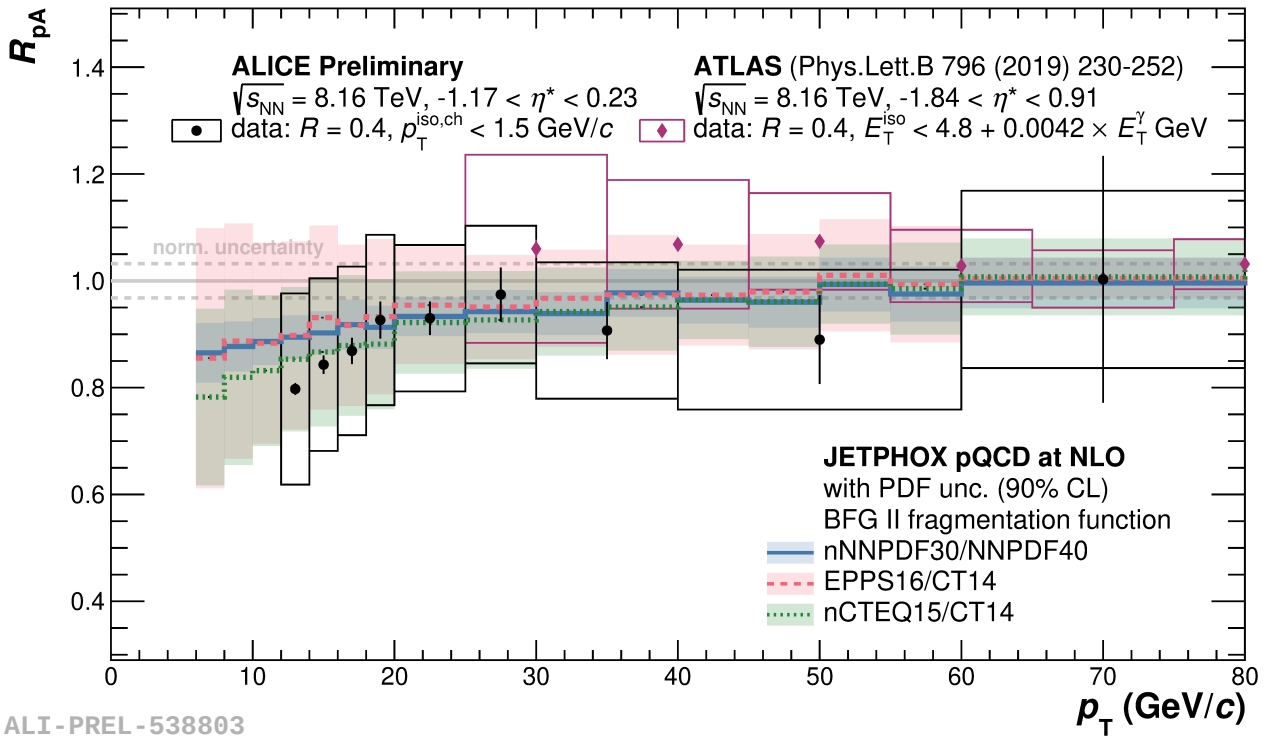


NB: Absolute cross sections underestimated at NLO $\rightarrow$ NNLO?

Run-II isolated photon production in pPb from ALICE

F. Jonas, talk at "Hard Probes 2023" and PhD thesis, U Münster (2023)



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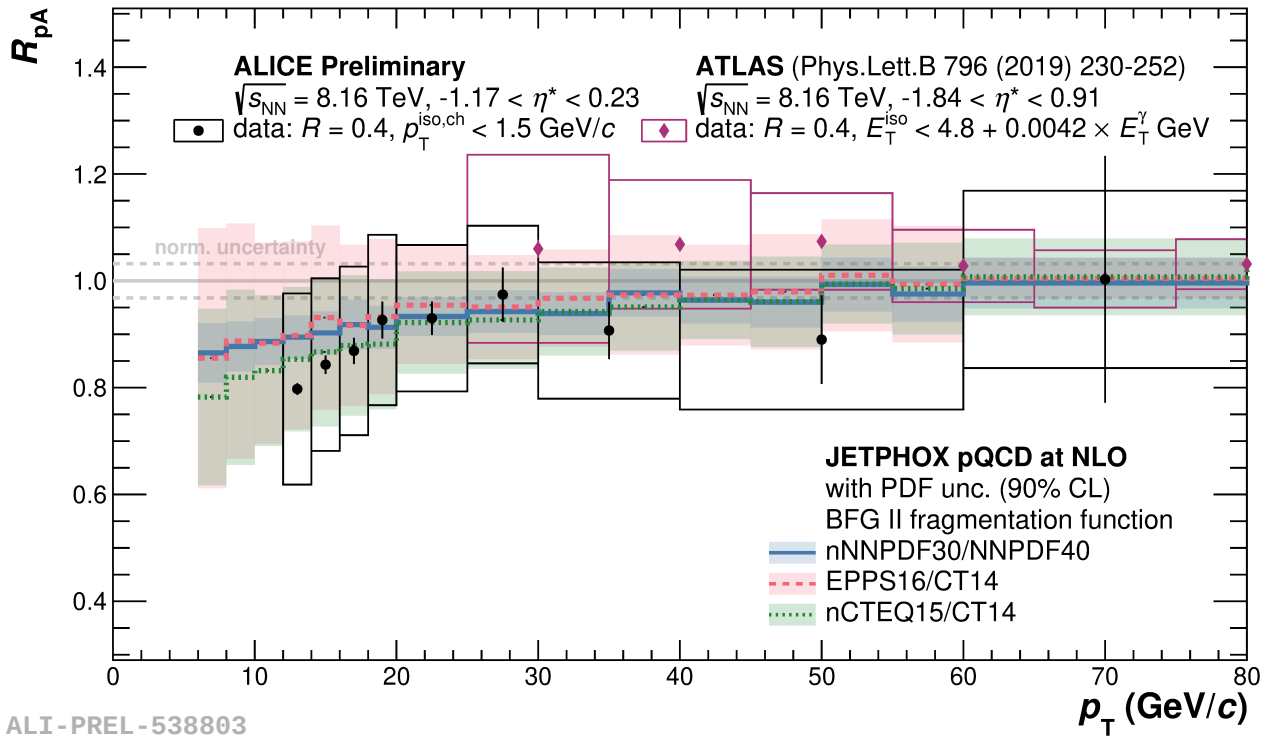

- High-p_T ALICE data $\sim$ ATLAS data w/in uncertainties
- New low-p_T ALICE data has sensitivity $\rightarrow$ publish!
- Gluons: nCTEQ15HQ $>$ nCTEQ15, EPPS21 $\sim$ EPPS16
- New ALICE FoCal will cover $3.2 < \eta < 5.8$ in Run-IV

Single inclusive hadrons

P. Duwentäster, MK et al. [nCTEQ Coll.], PRD 104 (2021) 094005

(In-)sensitivity to fragmentation functions:

DSS unmodified data	DSS modified data	KKP	BKK	NNFF	JAM20
0.461	0.412	0.401	0.420	0.456	0.553

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Impact of (RHIC+) LHC (ALICE) data:

χ^2/N_{dof} for selected experiments and processes												
	STAR		PHENIX	ALICE				DIS	DY	WZ	SIH	**Total**
	π^0	$\pi^\pm$	π^0	5 TeV π^0	5 TeV $\pi^\pm$	5 TeV $K^\pm$	8 TeV π^0					
nCTEQ15	0.13	2.68	0.30	2.53	0.62	0.71	1.96	0.86	0.78	(3.74)	(1.23)	**1.28**
nCTEQ15SIH	0.16	0.69	0.41	0.48	0.13	0.29	0.58	0.87	0.72	(2.32)	0.38	**1.00**
nCTEQ15WZ	0.17	3.24	0.23	0.67	0.21	0.41	1.58	0.90	0.78	0.90	(0.81)	**0.90**
nCTEQ15WZ+SIH	0.14	0.75	0.30	0.47	0.13	0.26	0.79	0.91	0.77	1.02	0.41	**0.85**

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Little impact of η data, also no FF uncertainty available.

Run-I dijet production from CMS

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

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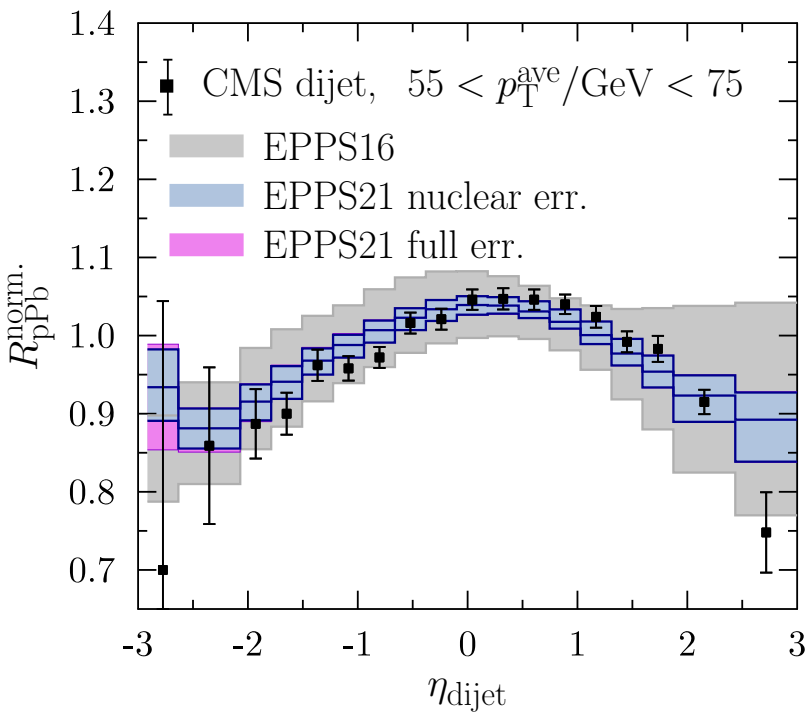

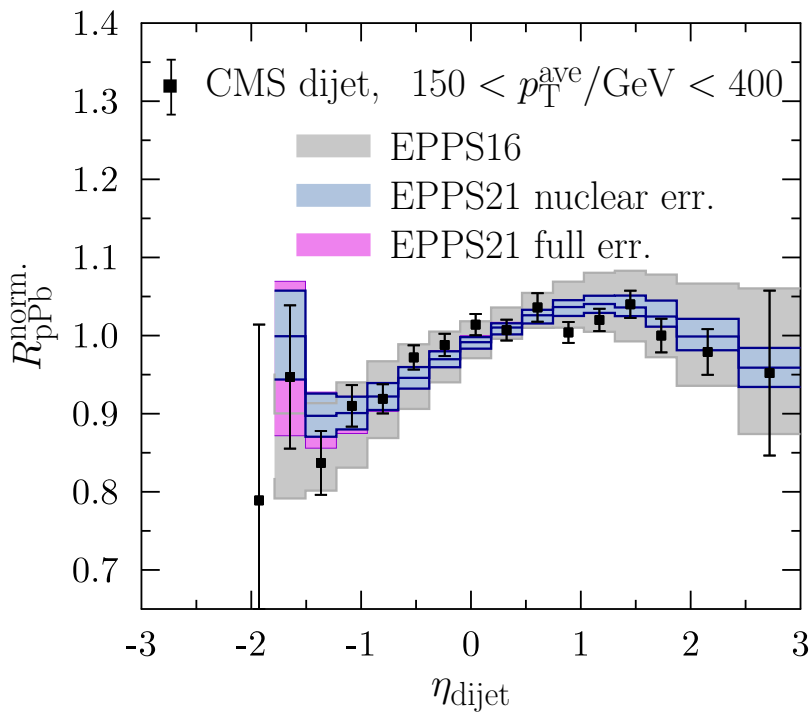

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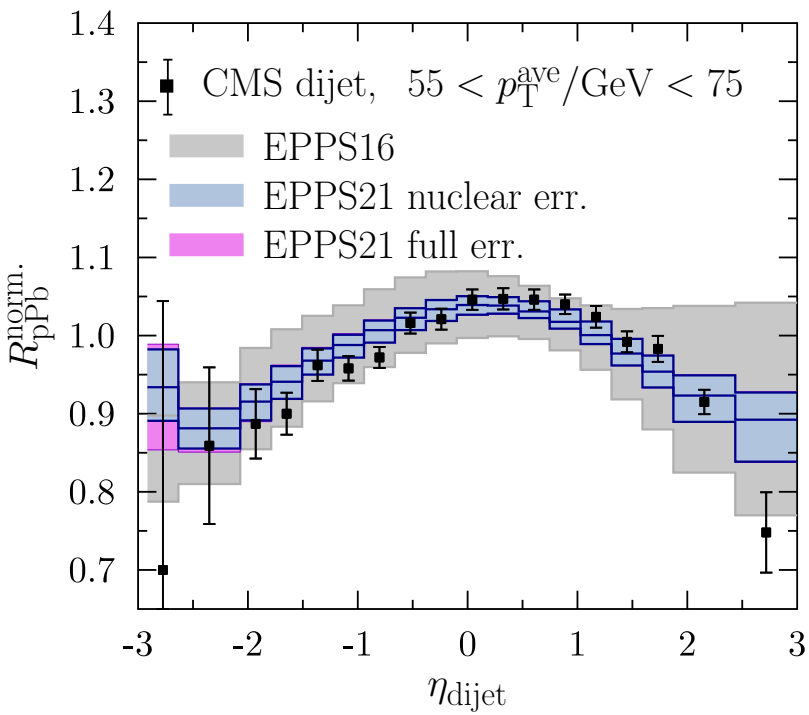

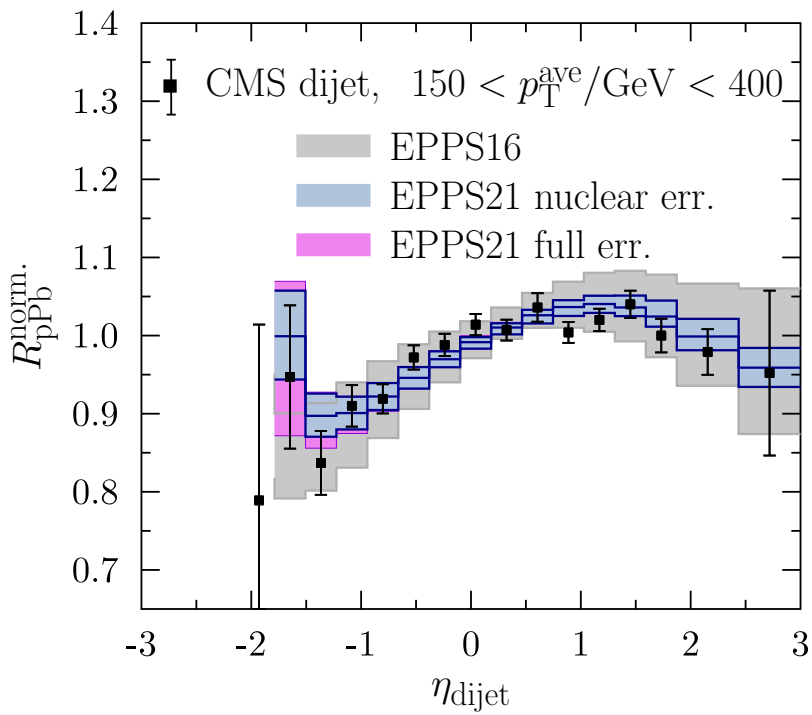

NB: CMS Run-I *pp* rapidity ratios in tension with NLO $\rightarrow$ NNLO?

Methodology for heavy quark/quarkonium production

P. Duwentäster, MK et al. [nCTEQ Coll.], Phys. Rev. D 105 (2022) 114043 [2204.09982]

Data-driven approach (Crystal Ball function):

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

- Originally proposed for J/Ψ pairs and double parton scattering

  [C.H. Kom, A. Kulesza, J. Stirling, PRL 107 (2011) 082002]

- Impact on nPDFs demonstrated with reweighting studies

  [A. Kusina, J.P. Lansberg, I. Schienbein, H.S. Shao, PRL 121 (2018) 052004 and PRD 104 (2021) 014010]

- New rapidity dependence allows to cover also LHCb data

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Choice of proton PDF (nCTEQ15) and factorization scales:

	D^0	J/ψ	$B\to J/\psi$	$\Upsilon(1S)$	$\psi(2S)$	$B\to\psi(2S)$
μ_0^2	$4M_D^2+p_{T,D}^2$	$M_{J/\psi}^2+p_{T,J/\psi}^2$	$4M_B^2+\frac{M_B^2}{M_{J/\psi}^2}p_{T,J/\psi}^2$	$M_{\Upsilon(1S)}^2+p_{T,\Upsilon(1S)}^2$	$M_{\psi(2S)}^2+p_{T,\psi(2S)}^2$	$4M_B^2+\frac{M_B^2}{M_{\psi(2S)}^2}p_{T,\psi(2S)}^2$

Fit to pp data and validation with NLO predictions

P. Duwentäster, MK et al. [nCTEQ Coll.], Phys. Rev. D 105 (2022) 114043 [2204.09982]

Crystal Ball fit parameters: Cut data with $p_T < 3$ GeV and $|y| > 4$

	D^0	J/ψ	$B \to J/\psi$	$\Upsilon(1S)$	$\psi(2S)$	$B \to \psi(2S)$
κ	0.33457	0.47892	0.15488	0.94524	0.21589	0.45273
λ	1.82596	0.30379	0.12137	0.06562	0.07528	0.13852
$\langle p_T \rangle$	2.40097	5.29310	-7.65026	8.63780	8.98819	7.80526
n	2.00076	2.17366	1.55538	1.93239	1.07203	1.64797
a	-0.03295	0.02816	-0.08083	0.22389	-0.10614	0.06179
N_{points}	34	501		375	55	
χ^2/N_{dof}	0.25	0.88		0.92	0.77	

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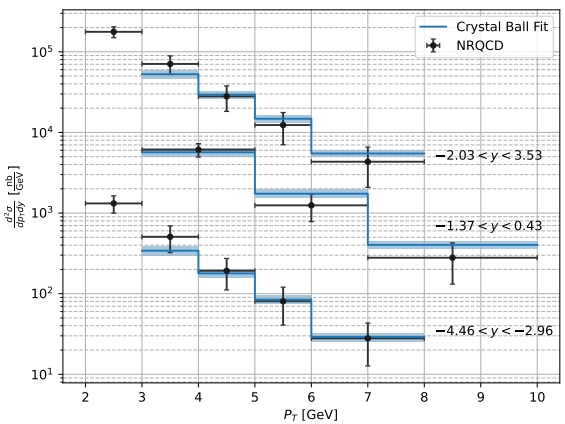
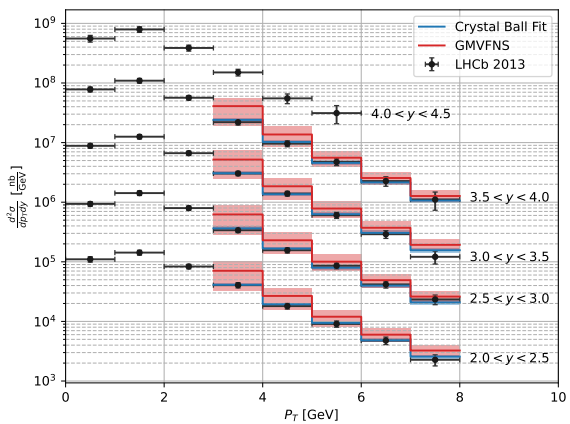
Heavy quarkonia in NRQCD:

[M. Butenschön, B. Kniehl, PRL 106 (2011) 022003]



Open heavy quarks in GM-VFNS:

[B. Kniehl et al., PRD 71 (2005) 014018]



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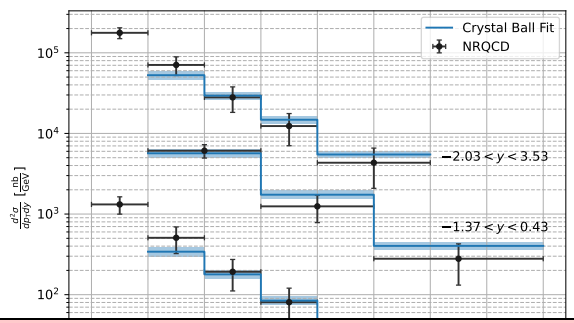

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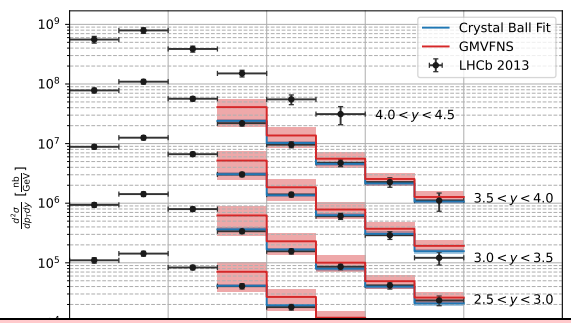
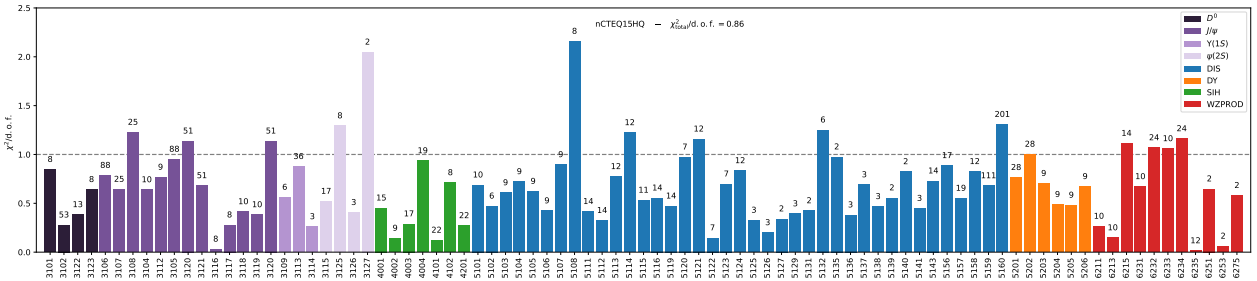


TUE 12:20 J. Wissmann (U Münster) HQs in GM-VFNS in nCTEQ
WED 11:00 T. Jezo (U Münster) nCTEQ24

Impact of heavy quark and quarkonium data

P. Duwentäster, MK et al. [nCTEQ Coll.], Phys. Rev. D 105 (2022) 114043 [2204.09982]

Cut D^0 data with $p_T > 15$ GeV (no p), 2 high-p_T LHCb Υ points



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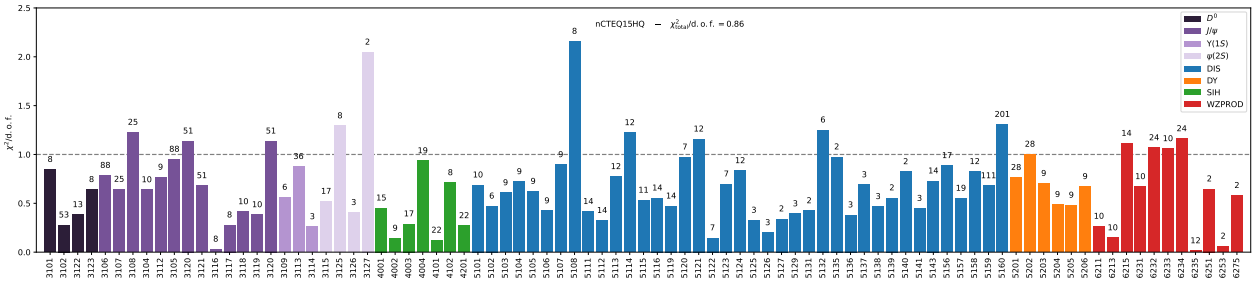
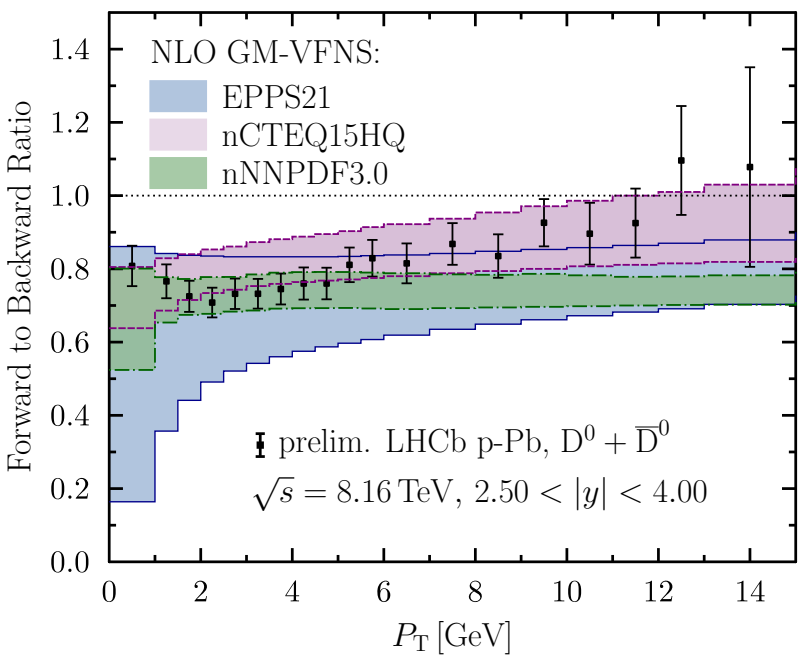
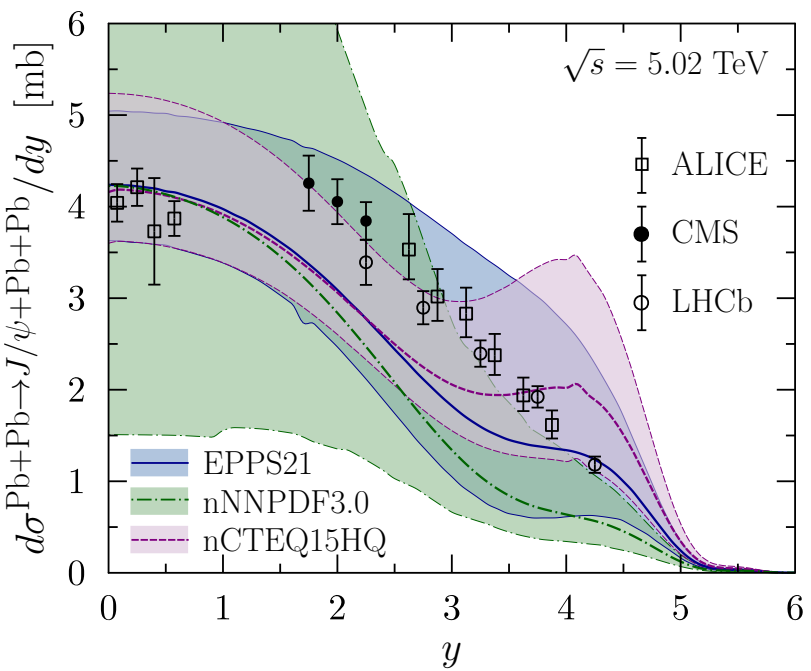


Comparison with incl. D^0 (LHCb Run-II) and excl. J/ψ data:





Heavy-quark and quarkonium data

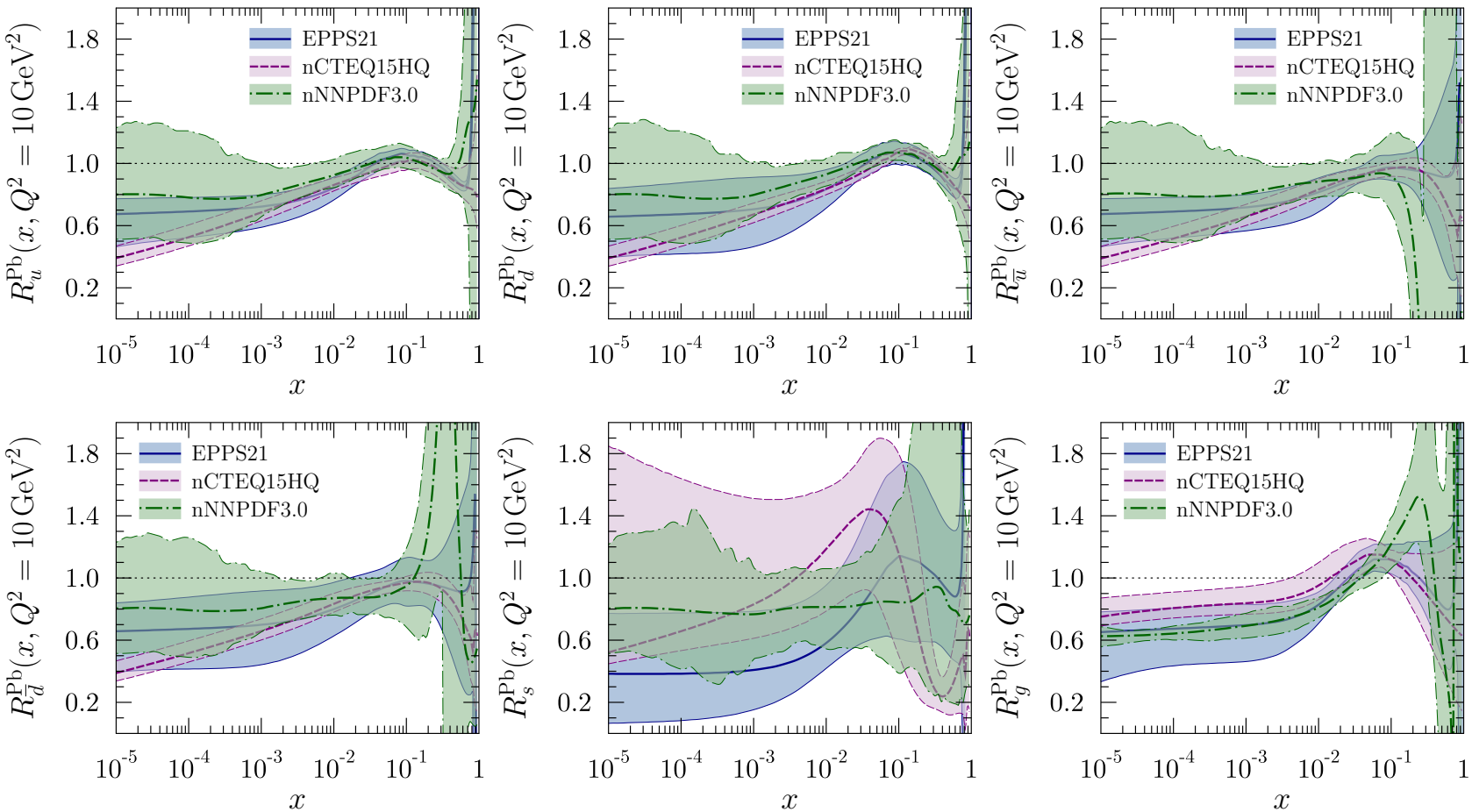
MK, H. Paukkunen, Ann. Rev. Nucl. Part. Sci. (2024) [2311.00450]

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).

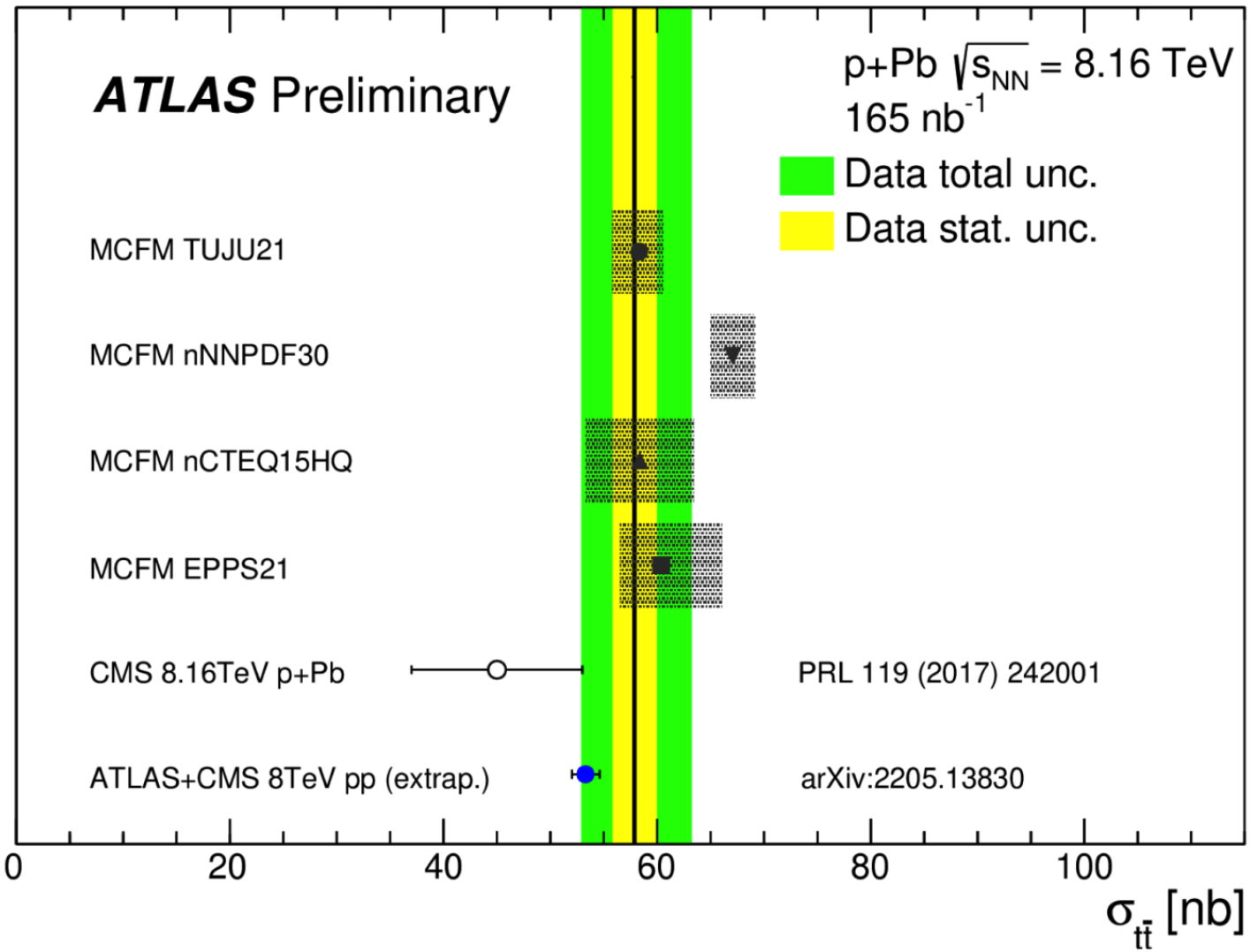
Nuclear PDFs after 10 years of LHC data

MK, H. Paukkunen, Ann. Rev. Nucl. Part. Sci. (2024) [2311.00450]



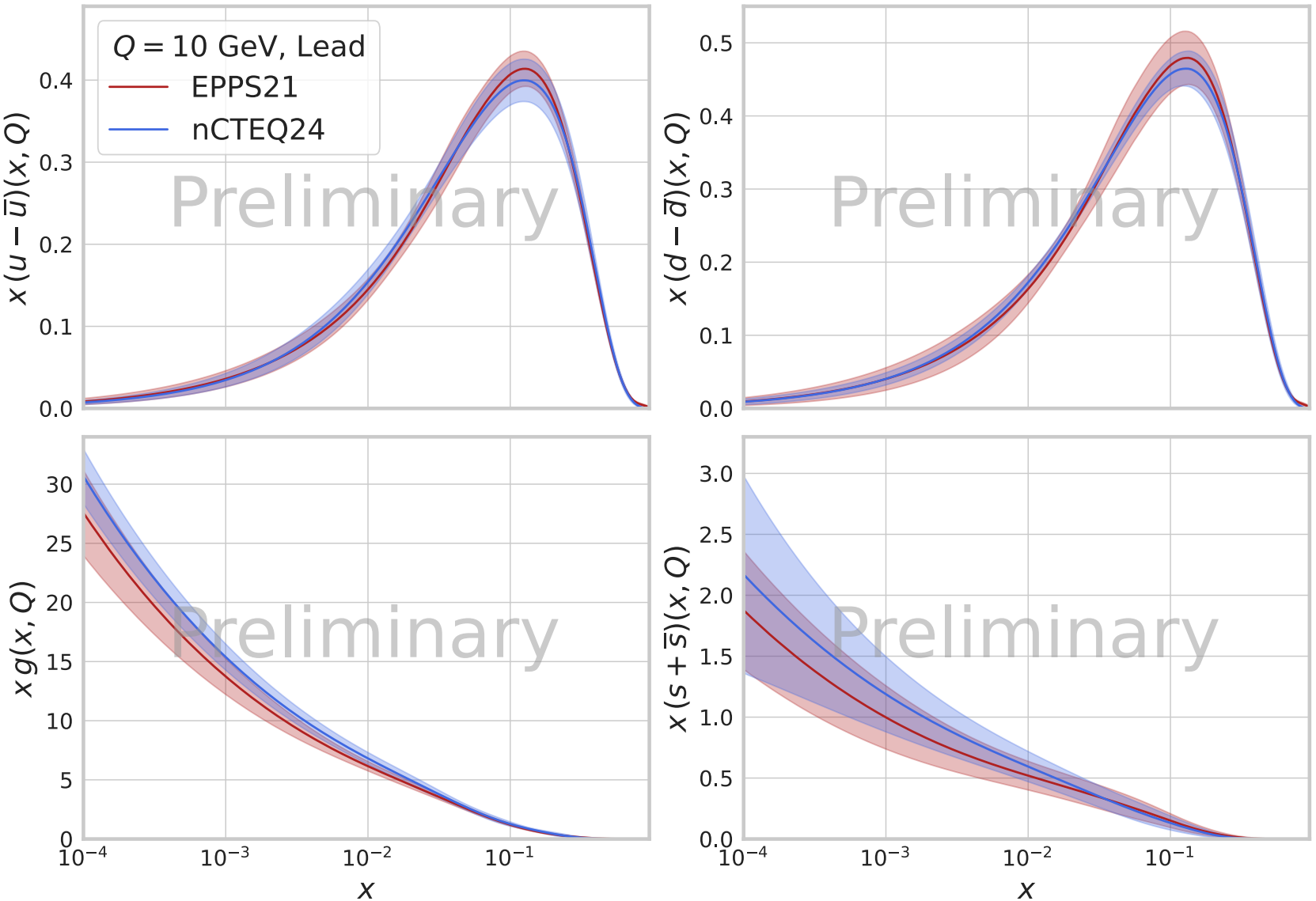
Top pair production in pPb with ATLAS

ATLAS-CONF-2023-063



nCTEQ24 (prel.) vs. EPPS21

T. Jezo, talk at DIS24 (WED 11:00)



Conclusion

Nuclear PDFs:

- QCD factorization, DGLAP evolution, HT enhancement
- Shadowing (LTA?), antishadowing, EMC effect, Fermi motion
- Dynamics: Partonic, hadronic, duality?
- Non-linear effects, initial-state phase transition to QGP

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Recent developments in fixed-target experiments:

- NC DIS: JLab at high $x \rightarrow$ TMC, HT, deuteron
- CC DIS: CHORUS (CDHSW, dimuon) ((CCFR/NuTeV))
- Neutrino data constrain in particular the strange quark

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10 years of LHC data:

- Electroweak bosons $\rightarrow$ nCTEQ, EPPS, nNNPDF, TUJU, KP
- Heavy quarks/quarkonia $\rightarrow$ Gluon down to $x = 10^{-5}$
- Photons/light hadrons/jets $\rightarrow$ Need for NNLO?

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Lattice QCD: [LP3 Coll., NPLQCD Coll.]

- Large x, low A, m_π, quasi-/pseudo-PDFs etc., R_{u-d}, p_g/p_A

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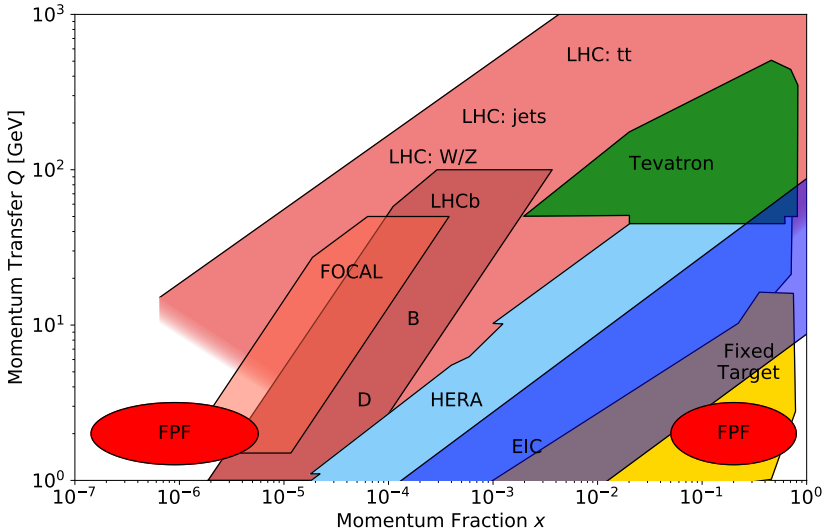
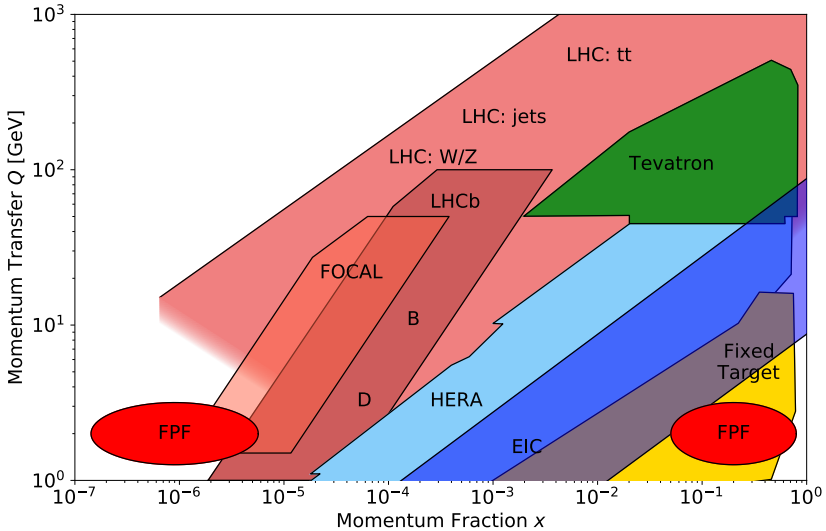
Lattice QCD: [LP3 Coll., NPLQCD Coll.]

FRI 09:00 H.W. Lin (MSU) PDFs in LQCD

Outlook


LHC: tt
LHC: jets
LHC: W/Z
Tevatron
LHCb
FOCAL
B
D
HERA
EIC
Fixed Target
FPF
FPF
Momentum Transfer Q [GeV]
Momentum Fraction x

Outlook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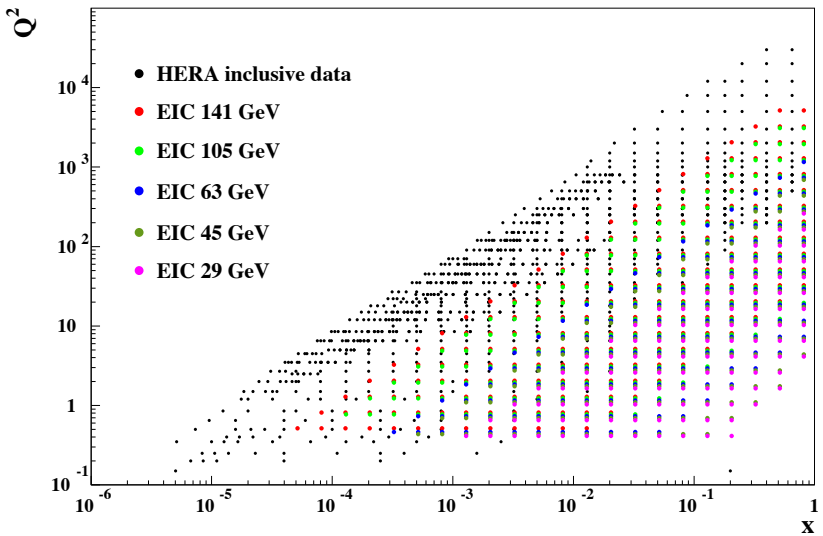
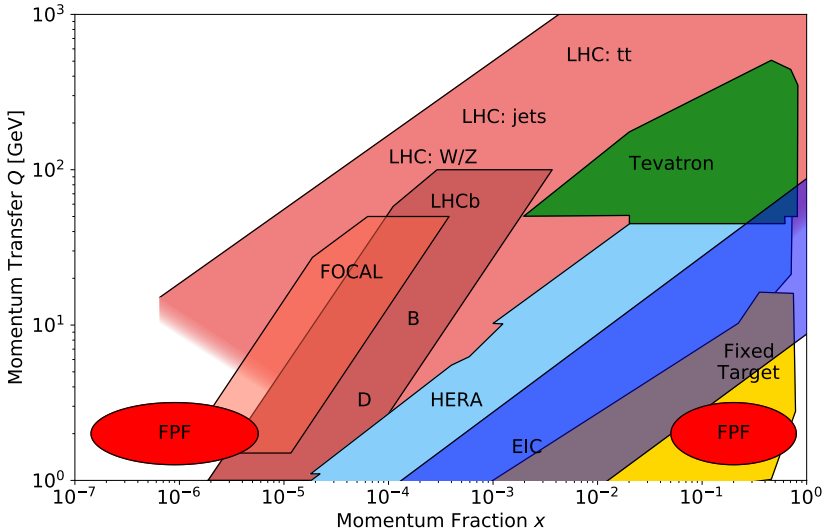

HERA inclusive data
EIC 141 GeV
EIC 105 GeV
EIC 63 GeV
EIC 45 GeV
EIC 29 GeV
Q²
x

Outlook


LHC: tt
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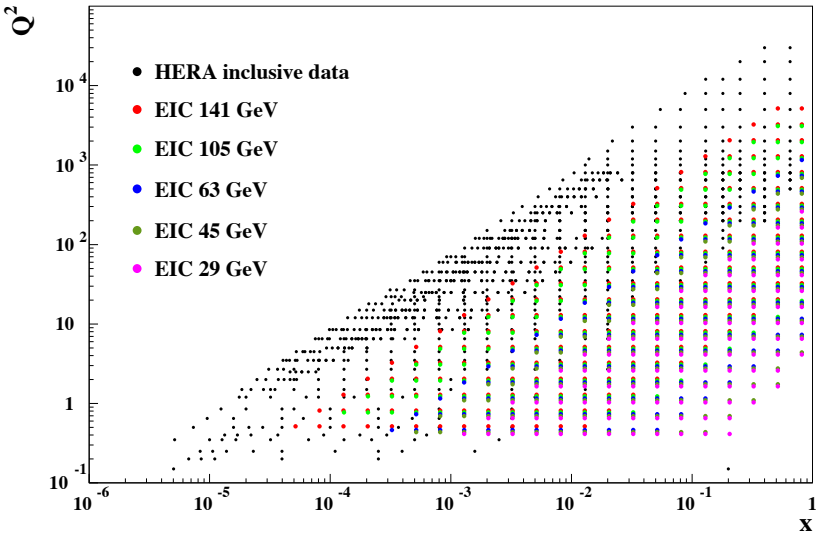
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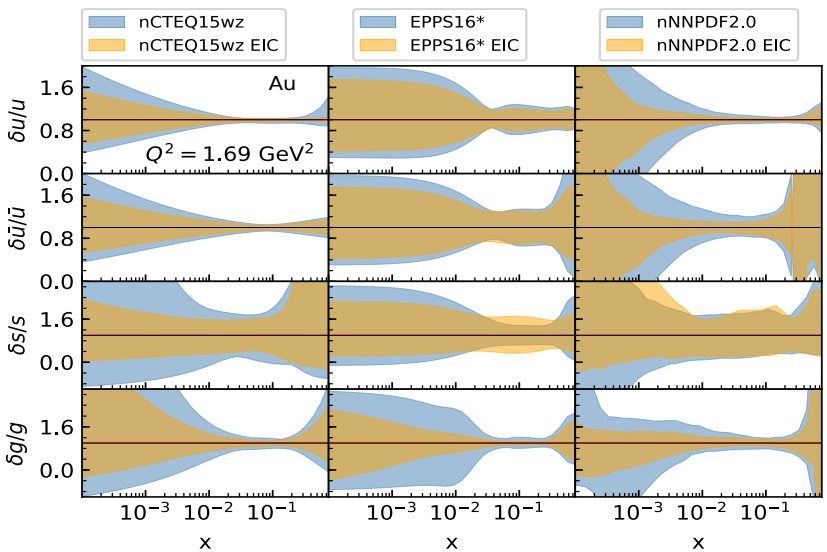
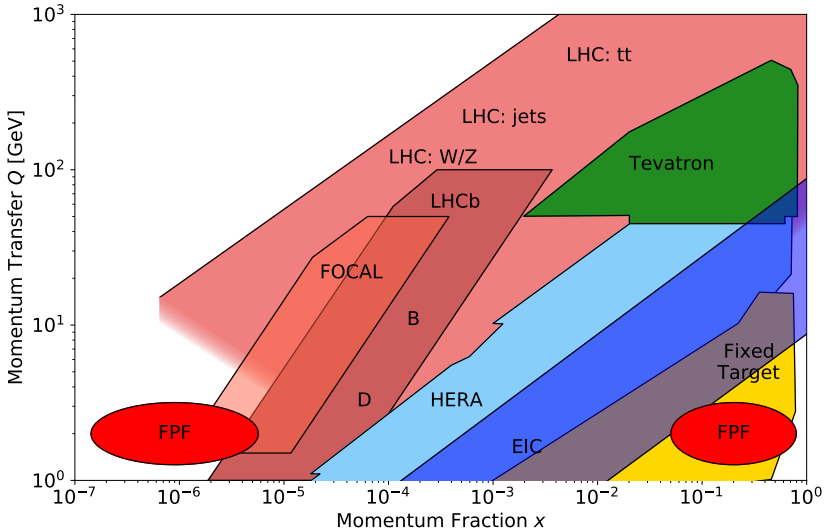

nCTEQ15wz
nCTEQ15wz EIC
EPPS16*
EPPS16* EIC
nNNPDF2.0
nNNPDF2.0 EIC
Au
$Q^2 = 1.69$ GeV^2
δu/u
δū/ū
δs/s
δg/g
x

Outlook


LHC: tt
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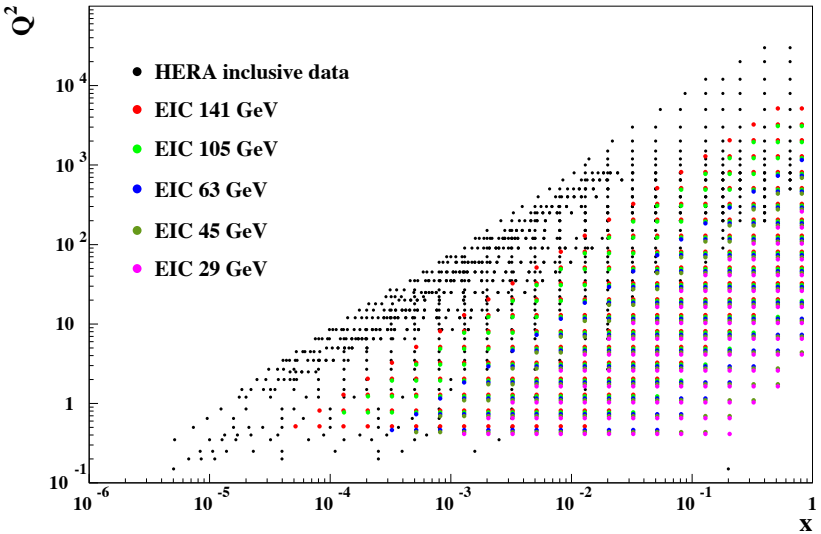
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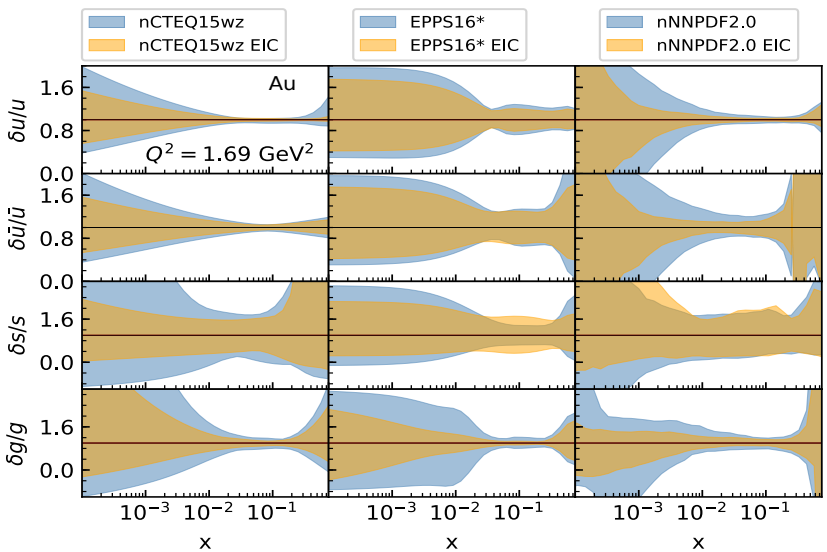
nCTEQ15wz
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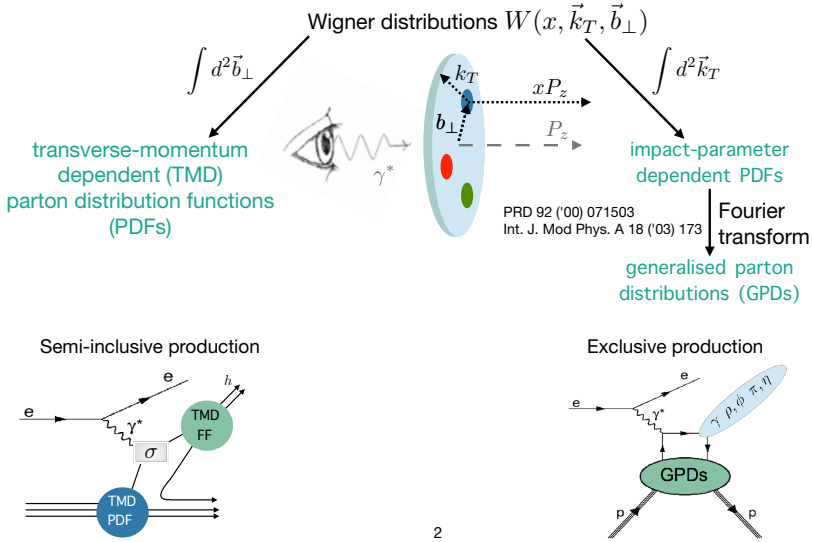
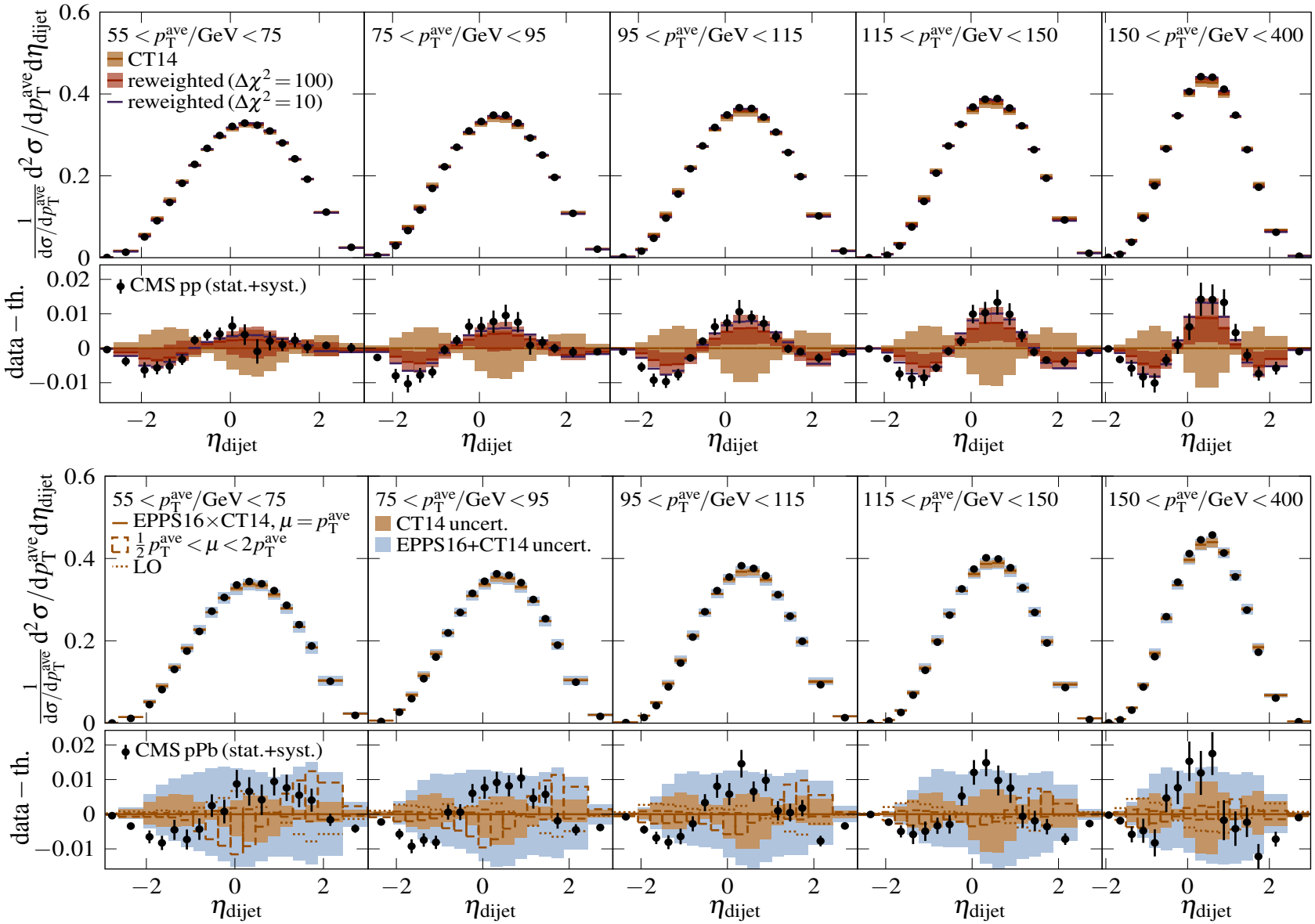
Au
$Q^2 = 1.69$ GeV²
δu/u
δū/d̄
δs/s
δg/g
x


Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$
$\int d^2\vec{b}_\perp$
$\int d^2\vec{k}_T$
transverse-momentum dependent (TMD) parton distribution functions (PDFs)
impact-parameter dependent PDFs
Fourier transform
generalised parton distributions (GPDs)
PRD 92 ('00) 071503
Int. J. Mod Phys. A 18 ('03) 173
Semi-inclusive production
Exclusive production
TMD FF
TMD PDF
GPDs

Backup

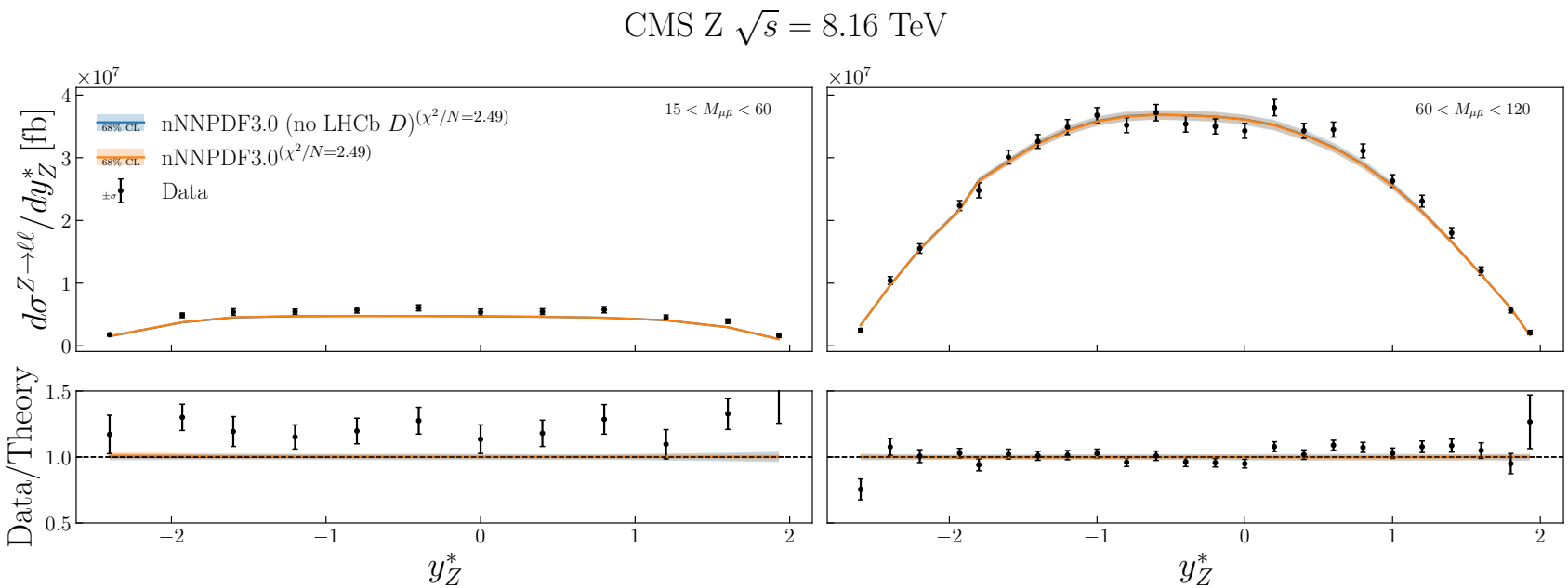
EPPS16 vs. Run-I CMS dijet data

K. Eskola, P. Paakinen, H. Paukkunen, Eur. Phys. J. C 79 (2019) 511



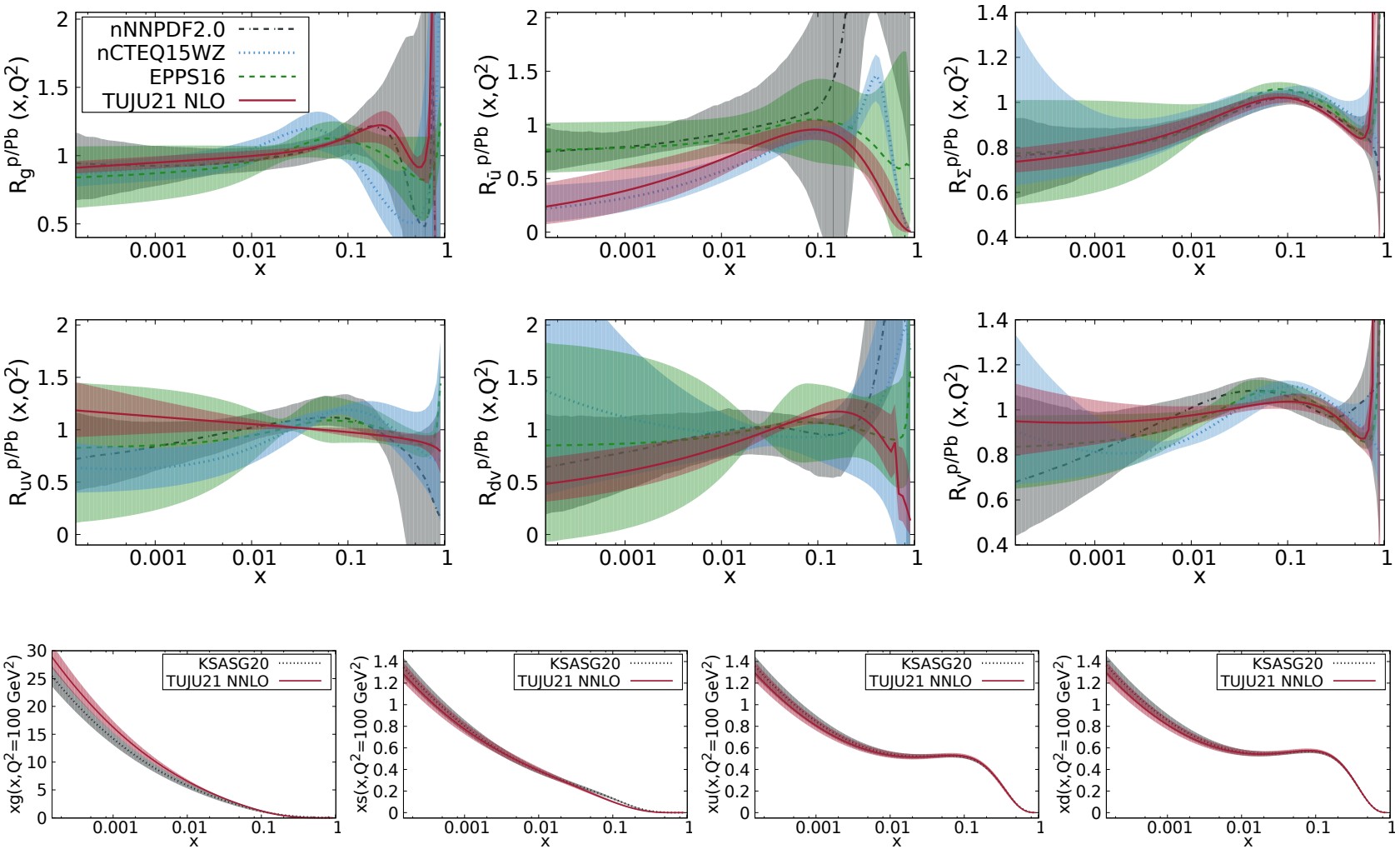
nNNPDF3.0 vs. Run-II CMS low- and high-mass Z data

R. Abdul Khalek et al. [nNNPDF Coll.], Eur. Phys. J. C 82 (2022) 507



TUJU21 NNLO vs. KSASG20 NNLO

I. Helenius, W. Vogelsang, M. Walt, Phys. Rev. D 105 (2022) 094031; H. Khanpour et al., Phys. Rev. D 104 (2021) 034010



KP16 model components

P. Ru, S.A. Kulagin, R. Petti, B.W. Zhang, Phys. Rev. D 94 (2016) 113013