Status of nuclear-PDF analyses and prospects with light ions

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WS on tuning of hadronic interaction models

25 January 2024

Collinear factorization in perturbative QCD

The cross section for producing an inclusive final state $k+X$ can be described as a convolution of...

...**C**oefficient **F**unctions $\mathrm{d}\hat{\sigma}^{ij\to k+X'}$ which are calculable from perturbative QCD...

$$\mathrm{d}\sigma^{AB\to k+X}(Q^2) \stackrel{Q\gg\Lambda_{\mathrm{QCD}}}{=} \sum_{i,j,X'} f_i^A(Q^2)\otimes \mathrm{d}\hat{\sigma}^{ij\to k+X'}(Q^2)\otimes f_j^B(Q^2) + \mathcal{O}(1/Q^2)$$

...and **P**arton **D**istribution **F**unctions f_i^A, f_j^B which contain long-range physics and cannot be obtained by perturbative means...

...plus "**H**igher **T**wist" corrections which are suppressed at high enough momentum scale $Q \gg \Lambda_{\mathrm{QCD}}$

parent hadron or nucleus

factorization scale

The PDFs $f_i^A(x, Q^2)$ are *universal*, process independent,

parton flavour

fraction of momentum carried by the parton

splitting functions

and obey the DGLAP equations $Q^2\frac{\partial f_i^A}{\partial Q^2} = \sum_j P_{ij}\otimes f_j^A$

Mellin conv.

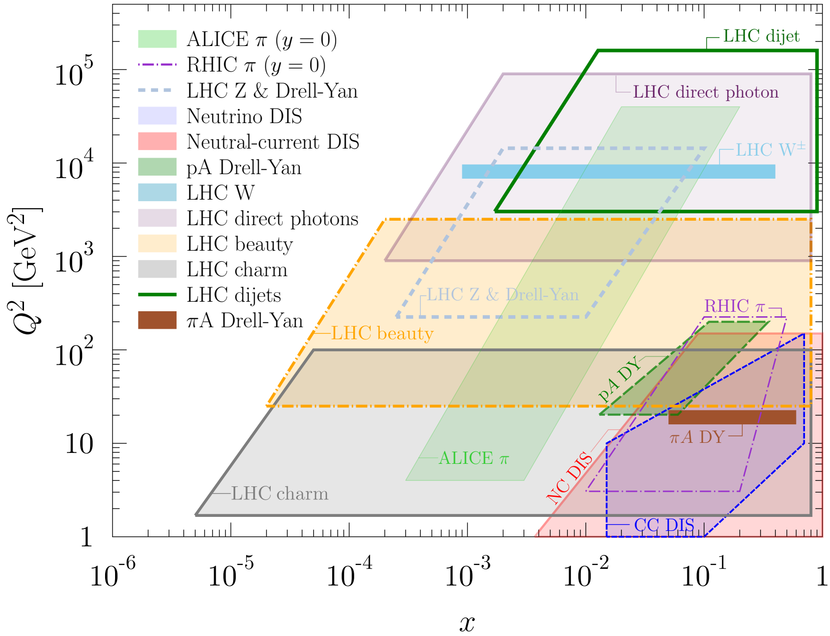
...this is the framework which every PDF analysis and application relies on and tests!

Nuclear PDFs (nPDFs) are fitted to inclusive hard cross section data

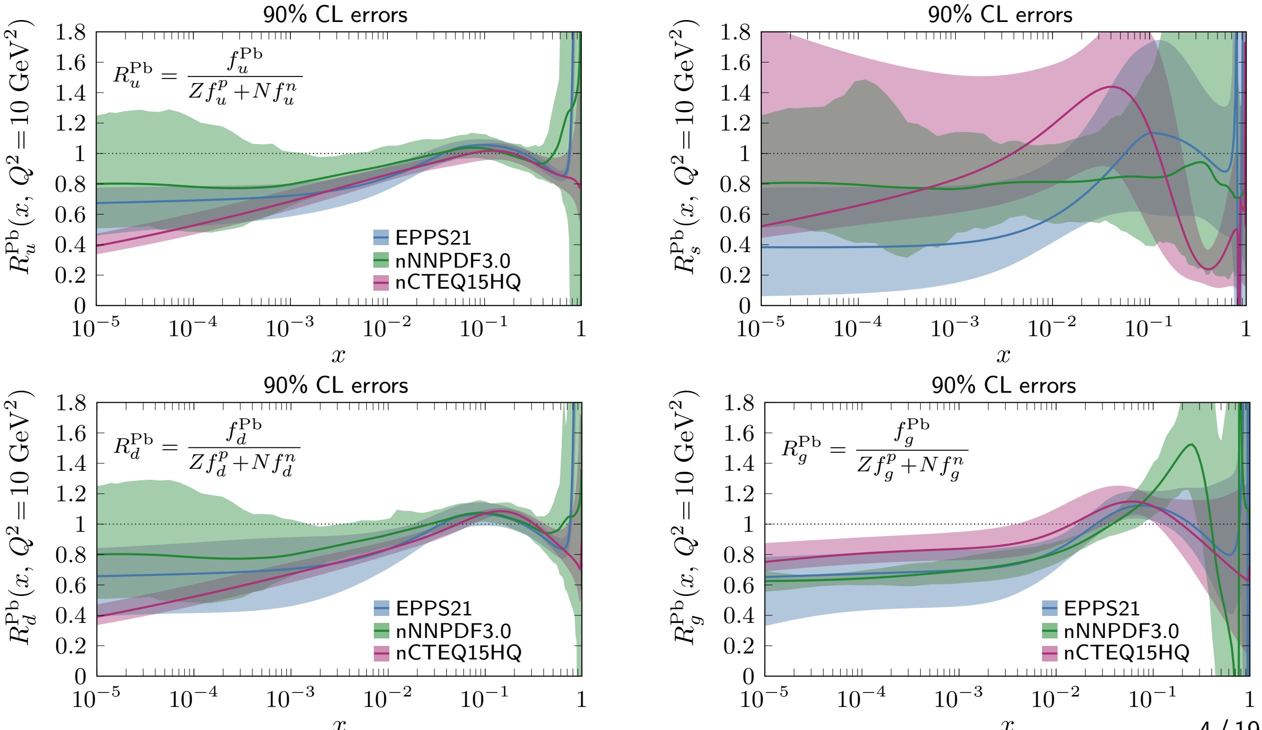
- ➔ rely only to the QCD collinear factorization
- ➔ Q^2 evolution governed by DGLAP equations
- ➔ use model-agnostic *parametrisations* of nuclear effects as a function of x

Vast improvement in available data and x, Q^2 reach from LHC!

New review: Klasen & Paukkunen, arXiv:2311.00450



Nuclear modifications



Recent nPDF global fits

	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

Recent nPDF global fits (and what I am able to cover in this talk)

	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15HQ
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πA DY			✓		
RHIC dAu π^0,$\pi^\pm$			✓		✓
LHC pPb π^0,$\pi^\pm$,$K^\pm$					✓
LHC pPb dijets			✓	✓	
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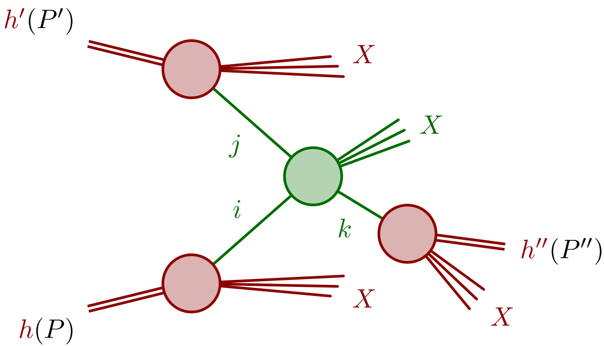
Hadron-production

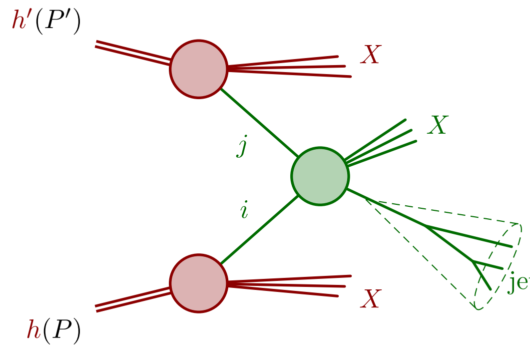


$$\sigma^{h+h'\to h''+X} = \sum_{i,j,k\in\{q,\bar{q},g\}} f_i^h \otimes f_j^{h'} \otimes \hat{\sigma}^{ij\to k+X} \otimes D_k^{h''}$$

Account for the hadronization effects with the *parton to hadron fragmentation functions* $D_k^{h''}$

→ a source of uncertainty for PDF fits

Jet-production



$$\sigma^{h+h'\to \text{jet}+X} = f_{\text{NP}} \sum_{i,j\in\{q,\bar{q},g\}} f_i^h \otimes f_j^{h'} \otimes \hat{\sigma}^{ij\to \text{jet}+X}$$

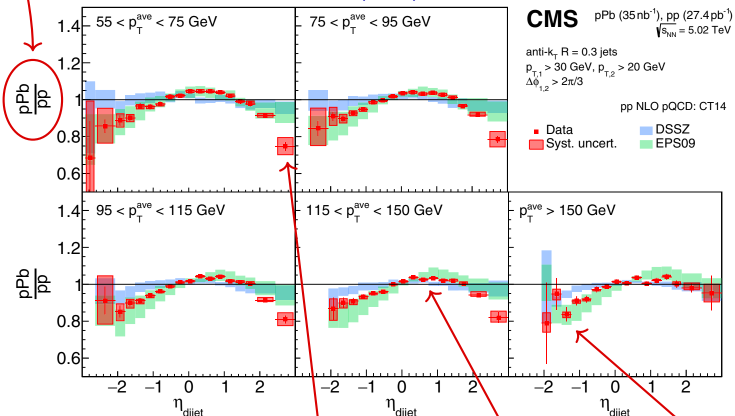
Instead of fragmentation functions:

- need an IR-safe definition of a jet
- non-perturbative corrections f_{NP}

Dijets in pPb at 5.02 TeV

Ratio of ratios: $R^{\text{norm.}}_{\text{pPb}} = \frac{d^2\sigma^{\mathbf{pPb}}/dp_T^{\text{ave}} d\eta_{\text{dijet}}}{d\sigma^{\mathbf{pPb}}/dp_T^{\text{ave}}} \bigg/ \frac{d^2\sigma^{\mathbf{pp}}/dp_T^{\text{ave}} d\eta_{\text{dijet}}}{d\sigma^{\mathbf{pp}}/dp_T^{\text{ave}}}$

CMS Collaboration, PRL 121 (2018) 062002

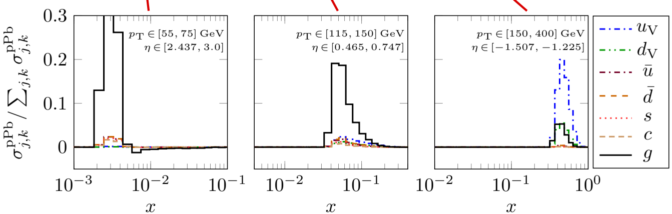


Double ratio convenient for:

- Cancellation of hadronization and luminosity uncertainties separately for pPb and pp
  - → do not expect strong non-pert. effects
- Cancellation of free-proton-PDF and scale uncertainties in pPb/pp
  - → direct access to nuclear modifications

Eskola, PP, Paukkunen, EPJC 79 (2019) 511

NLO pQCD:

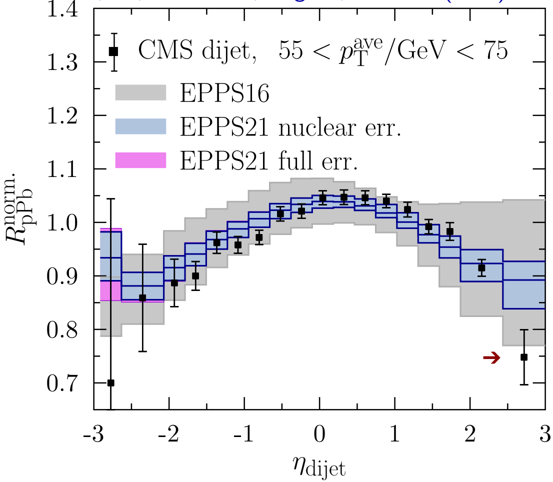


Good resolution to gluon nuclear modifications for $10^{-3} < x < 0.5$

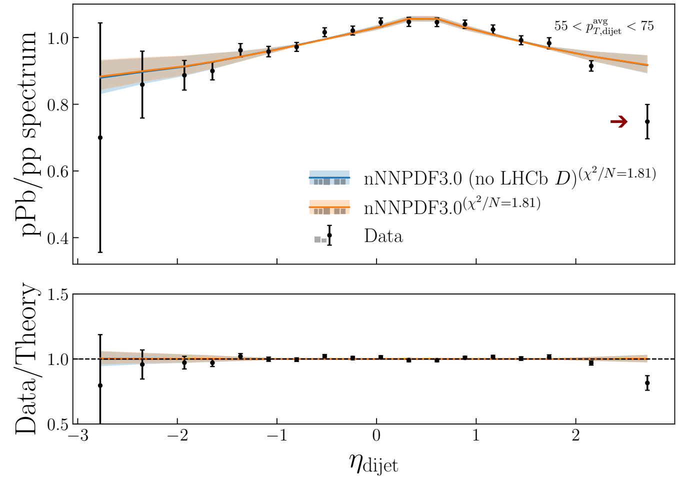
Dijet constraints in EPPS21 and nNNPDF3.0

data from: CMS Collaboration, PRL 121 (2018) 062002

Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 413



Abdul Khalek et al., EPJC 82 (2022) 507



Drastic reduction in the nPDF uncertainties!

➔ Important constraints for the nuclear gluons!

Eskola, PP, Paukkunen, EPJC 79 (2019) 511
Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 413
Abdul Khalek et al., EPJC 82 (2022) 507

Both EPPS21 and nNNPDF3.0 find difficulties in reproducing the most forward data points

➔ missing data correlations important?

➔ NNLO? non-pert. effects?

Heavy-flavour production mass schemes

FFNS

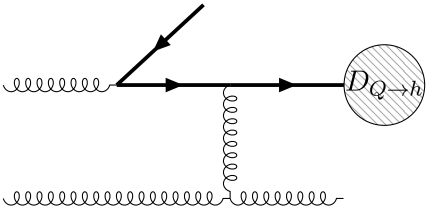
In *fixed flavour number scheme*, valid at small p_{T}, heavy quarks are produced only at the matrix element level

Contains $\log(p_{\mathrm{T}}/m)$ and $\mathcal{O}(m)$ terms

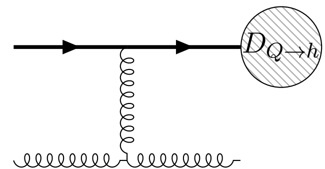
ZM-VFNS

In *zero-mass variable flavour number scheme*, valid at large p_{T}, heavy quarks are treated as massless particles produced also in ISR/FSR

Resums $\log(p_{\mathrm{T}}/m)$ but ignores $\mathcal{O}(m)$ terms



$-$ subtraction term $+$



GM-VFNS

A *general-mass variable flavour number scheme* combines the two by supplementing subtraction terms to prevent double counting of the resummed splittings, valid at all p_{T}

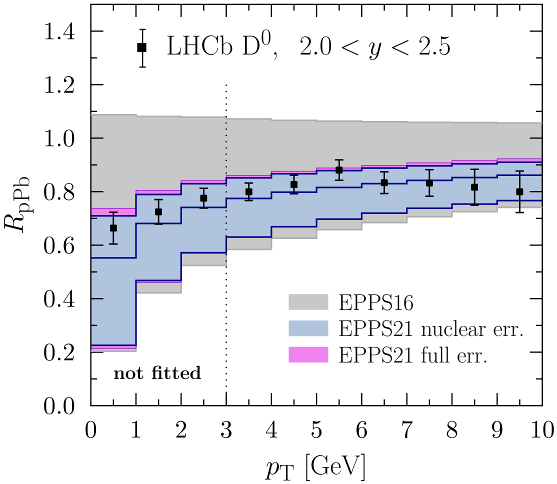
Resums $\log(p_{\mathrm{T}}/m)$ and includes $\mathcal{O}(m)$ terms in the FFNS matrix elements

Important: includes also gluon-to-HF fragmentation – large contribution to the cross section!

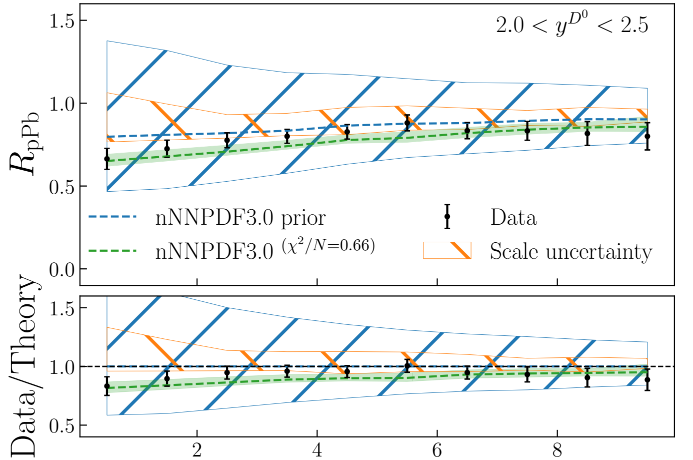
Helenius & Paukkunen, JHEP 05 (2018) 196

D^0s in pPb in EPPS21 and nNNPDF3.0

Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 413



Abdul Khalek et al., EPJC 82 (2022) 507



Drastic reduction in the nPDF uncertainties!

➔ Important constraints for the nuclear gluons!

Kusina et al., PRL 121 (2018) 052004
Eskola, Helenius, PP, Paukkunen, JHEP 05 (2020) 037
Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 413
Abdul Khalek et al., EPJC 82 (2022) 507

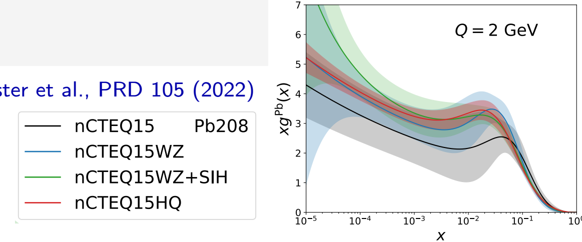
nNNPDF3.0 with POWHEG+PYTHIA finds a large scale uncertainty ➔ fit only forward data

not seen in the S-ACOT-m_T GM-VFNS used in EPPS21

Helenius & Paukkunen, JHEP 05 (2018) 196
Eskola, Helenius, PP, Paukkunen, JHEP 05 (2020) 037

A data-driven approach – nCTEQ15HQ

Duwentäster et al., PRD 105 (2022) 114043

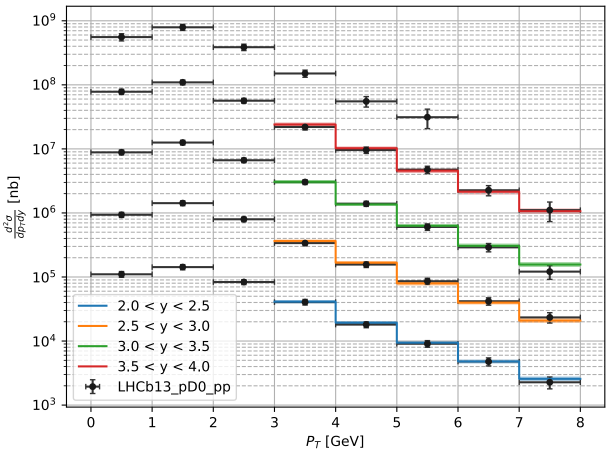


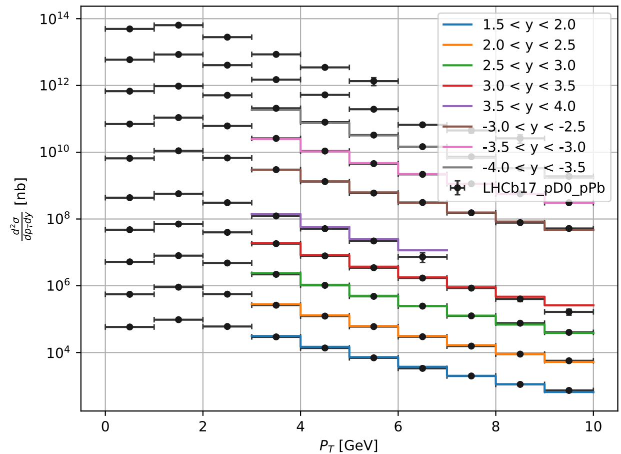
nCTEQ15HQ uses a data-driven approach

Lansberg & Shao, EPJC 77 (2017) 1
Kusina et al., PRL 121 (2018) 052004

to fit the D^0 and J/ψ data:

1. Fit the matrix elements to pp data...
(assume $2 \to 2$ kinematics, gg IS only)
2. ...use the fitted matrix elements to fit nuclear PDFs with pPb data



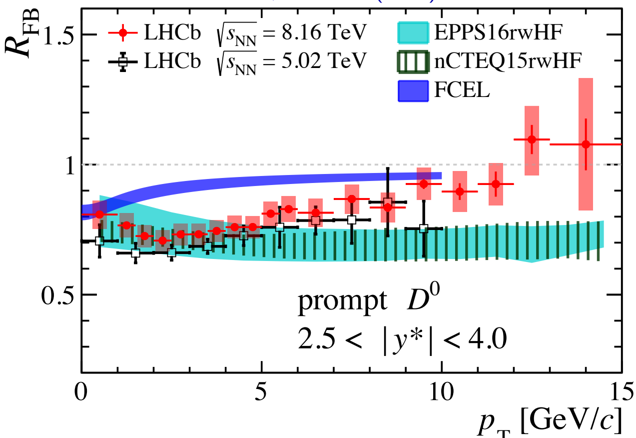


New LHCb measurement at 8.16 TeV initially claimed to be in tension with nPDFs
(not included in the nPDF analyses yet)

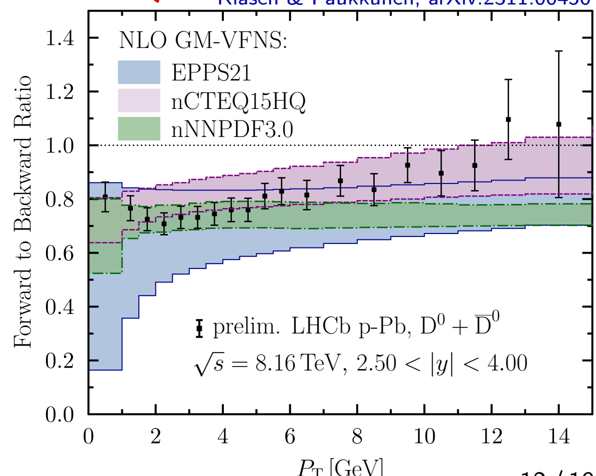
Not only probing nPDFs but also testing production mechanism!
(Here HELAC vs S-ACOT-m_T)

Rather different predictions!

LHCb Collaboration, PRL 131 (2023) 102301



Klasen & Paukkunen, arXiv:2311.00450



At forward rapidities, π^0 & $h^\pm$ agree with each other and nPDFs constrained with D^0s

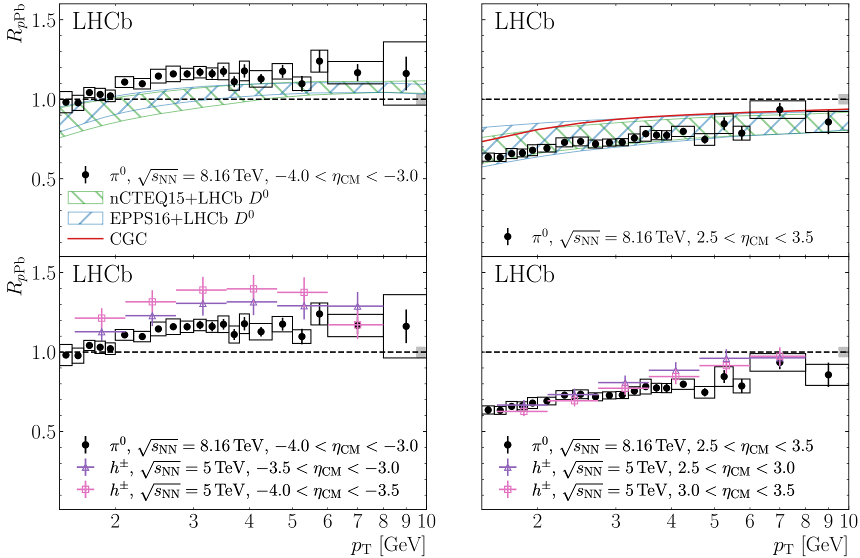
At backward rapidities, this agreement seems to break down!

Heavier mesons and baryons potential explanation to the $h^\pm$ excess in pPb, but do we see also a "Cronin effect" in pions?

How does this effect evolve with the system size? Does it persist in **pO/Op**?

How low can we go in p_T such that the collinear factorization is valid in pA without additional higher-twist corrections?

LHCb Collaboration, PRL 131 (2023) 042302



PHENIX pion production small-system scan

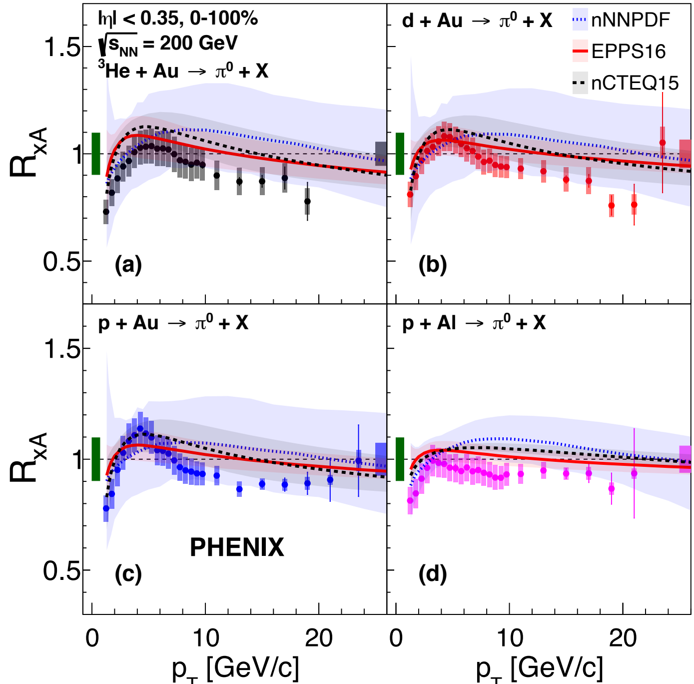
Contrary to nPDF expectations, measured "Cronin peak" size follows the ordering ${}^{3}\mathrm{He}+\mathrm{Au} < d+\mathrm{Au} < p+\mathrm{Au}$

- higher-twist (multiple-scattering)?
- flow-like component?

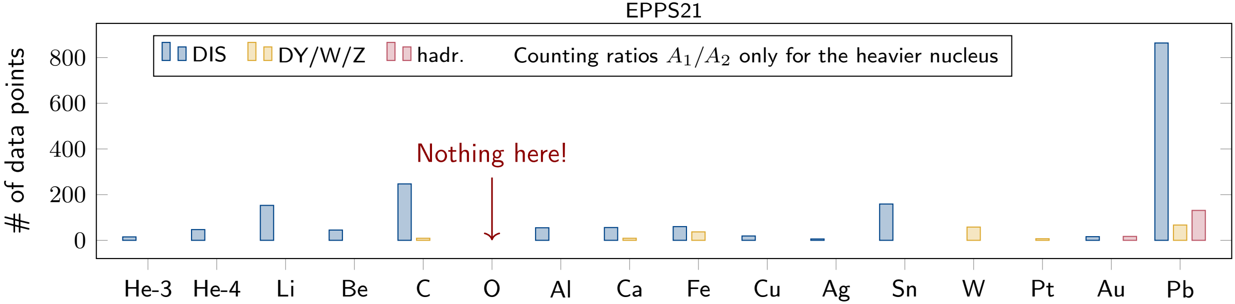
At high p_{T} the nPDF predictions overshoot the data, but mind the large normalisation uncertainties

How do the LHC pPb and **pO** data fit this picture?

PHENIX Collaboration, PRC 105 (2022) 064902



Data availability w.r.t. A

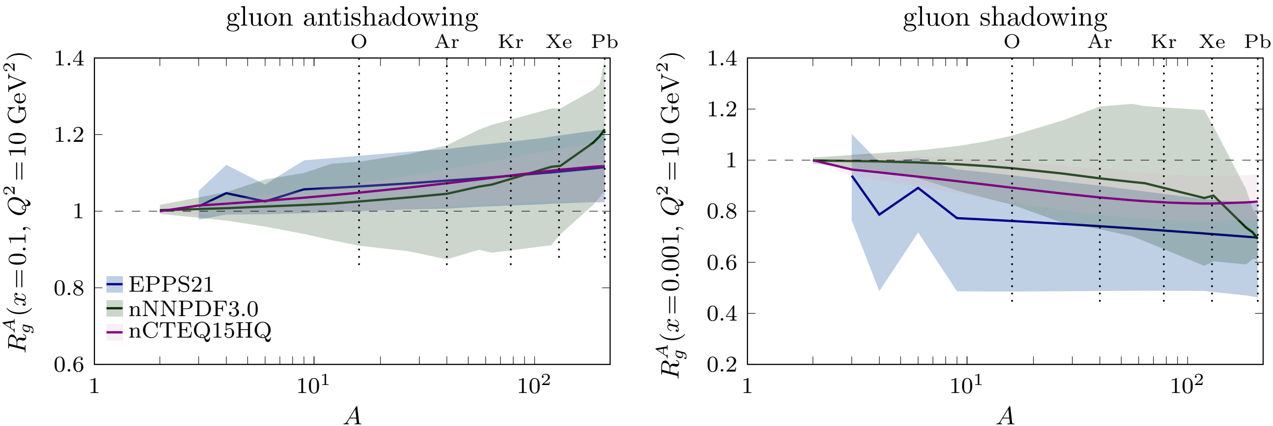


$\sim 50\%$ of the data points are for Pb!

- ☺ Good coverage of DIS measurements for different A (but only fixed target!)
- 😐 DY data more scarce, but OK A coverage
- ☹ Hadronic observables available only for heavy nuclei!

Light-ion runs at LHC could:

- Complement other light-nuclei DY data with W and Z production (strangeness!)
- Give first direct constraints (e.g. dijets, D-mesons) on light-nuclei small-x gluon distributions!



A-dependence of gluon PDFs not well constrained by data!

- Having data for even one additional nucleus would help interpolating the effect for others (but note that A-dependence is not necessarily smooth or even monotonous)
- nPDFs a major source of uncertainty for testing existence of QGP in small systems

Huss et al., PRL 126 (2021) 192301
Brewer et al., PRD 105 (2022) 074040

Similar setup as in CMS 5.02 TeV pPb measurement

Total integrated pO cross section of $81\ \mu\mathrm{b}$

- Compare with $\sim 330\ \mu\mathrm{b}$ in pPb at 5.02 TeV
- Sufficient to give reasonable statistics even at relatively low luminosities

  16000 events at $0.2\ \mathrm{nb}^{-1}$

  486000 events at $6\ \mathrm{nb}^{-1}$

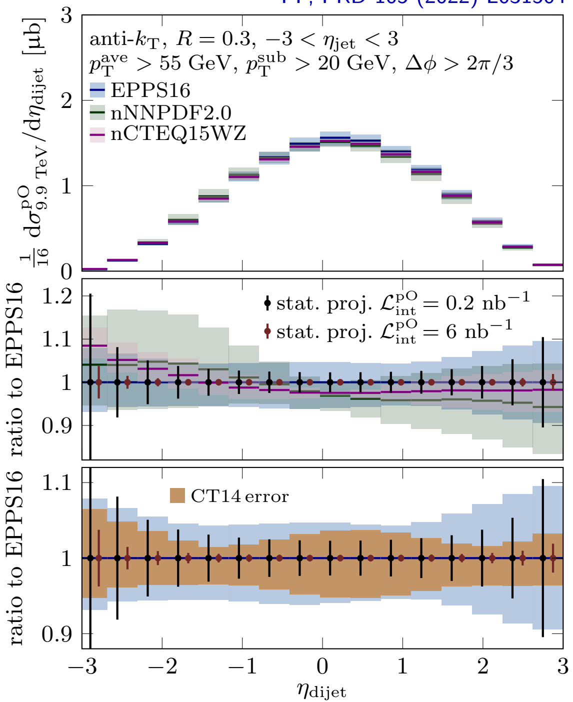
Problem: absolute cross sections very sensitive to the used free-proton PDFs

- Difficult to disentangle nuclear modifications from the free-proton d.o.f.s

Problem: We do not expect pp reference at 9.9 TeV

- Could we use a mixed energy ratio pO(9.9 TeV)/pp(8.8 TeV)?

PP, PRD 105 (2022) L031504



Dijet R_{pO} in pO at 9.9 TeV

PP, PRD 105 (2022) L031504

Problem: We do not expect pp reference at 9.9 TeV

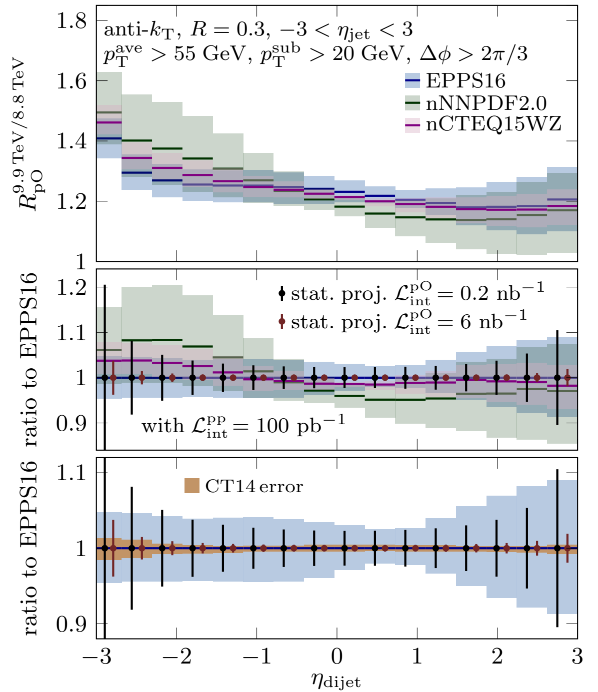
- Could we use a mixed energy ratio pO(9.9 TeV)/pp(8.8 TeV)? Yes!

Excellent cancellation of free-proton PDFs

→ Direct access to nuclear modifications

Already few nb^{-1} can be expected to be enough to put new constraints on nPDFs (if we have sufficient statistics for the pp reference)

→ Can resolve different nPDF parametrisations!



Summary

A new generation of nPDF analyses with strong constraints from LHC data have appeared in the past few years and are available for applications in high-energy physics

Still, the uncertainties in many places are large and new constrains are desperately needed

In particular, the A-dependence of gluon PDF nuclear modifications is currently practically unconstrained

Wishlist for pO (with the expected short-run luminosities):

- D-mesons, *identified* light hadrons, jets
- Cross sections and, if possible, nuclear modification ratios, even if with pp baseline at some different (but close by) energy (avoid interpolated baselines)

For discussion: What are the needs for astroparticle physics? Which nuclei, parton flavours and kinematical regions are needed? What is the precision that we should target?

→ Possible input for run plans at the LHC and EIC

Thank you!

Example parametrization: EPPS21

- Define nuclear PDFs in terms of

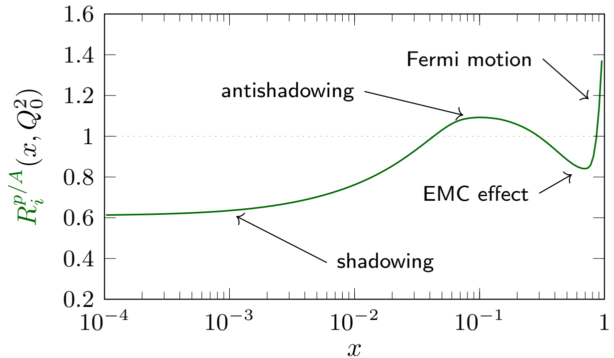
$$\underbrace{f_i^{p/A}(x,Q^2)}_{\text{bound-proton PDF}} = \overbrace{R_i^{p/A}(x,Q^2)}^{\text{nuclear modification}} \underbrace{f_i^{p}(x,Q^2)}_{\text{free-proton PDF}}$$

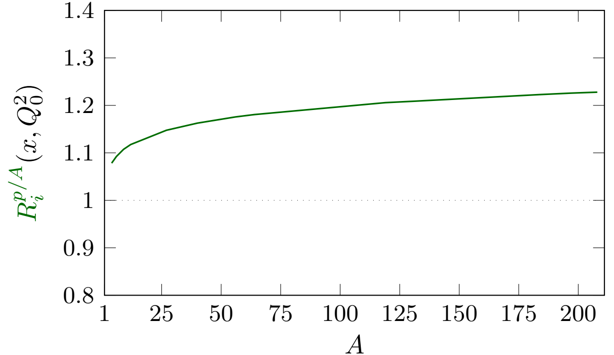
- PDFs of the full nucleus are then constructed with

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

and assuming $f_i^{p/A} \xleftrightarrow{\text{isospin}} f_j^{n/A}$

- Parametrize the x and A dependence of $R_i^{p/A}(x,Q_0^2)$ at $Q_0 = m_{\text{charm}} = 1.3\ \text{GeV}$
  - Use a phenomenologically motivated piecewise function in x
  - Use a power-law type function in A

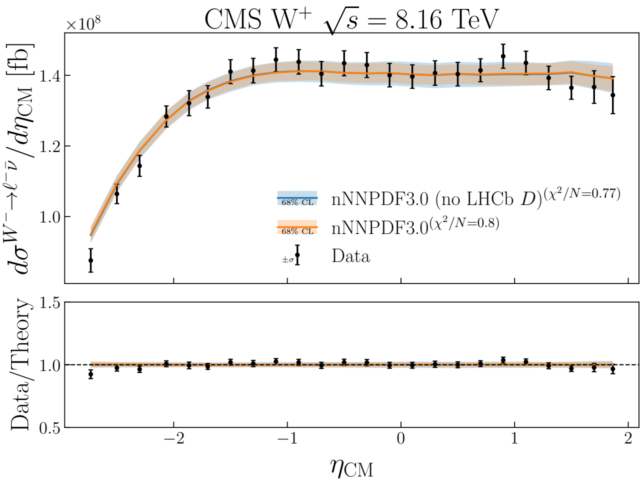




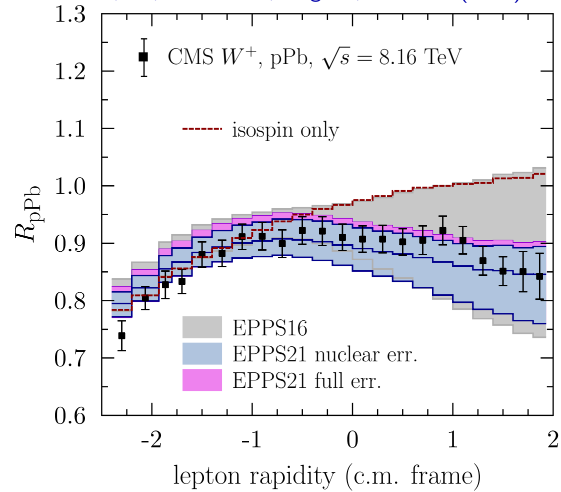
W bosons in pPb at 8.16 TeV

data from: CMS Collaboration, PLB 800 (2020) 135048
pp baseline: CMS Collaboration, EPJC 76 (2016) 469

Abdul Khalek et al., EPJC 82 (2022) 507



Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 413



EW bosons important probes of flavour separation

- $u\bar{d}$ ($c\bar{s}$) $\rightarrow W^+$
- $\bar{u}d$ ($\bar{c}s$) $\rightarrow W^-$

Small-x, high-Q^2 quarks and gluons correlated by DGLAP evolution ➔ sensitivity to gluons

nCTEQ15WZSIH, TUJU21 and nNNPDF3.0 fit to absolute cross sections

EPPS21 uses nuclear-modification ratios to cancel proton-PDF uncertainties

Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 271

Mitigating free-proton PDF uncertainty

data from: CMS Collaboration, PLB 800 (2020) 135048
pp baseline: CMS Collaboration, EPJC 76 (2016) 469

Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 271

Absolute pPb cross sections sensitive to proton-PDF uncertainties!

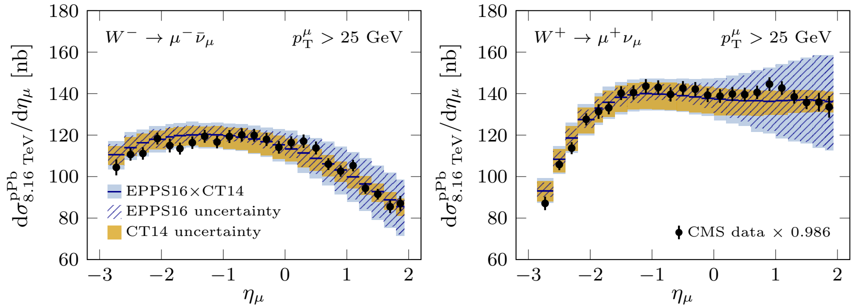
Difficult to disentangle nuclear modifications from free-proton d.o.f.s

nCTEQ15WZSIH, TUJU21 and nNNPDF3.0 fit to absolute cross sections

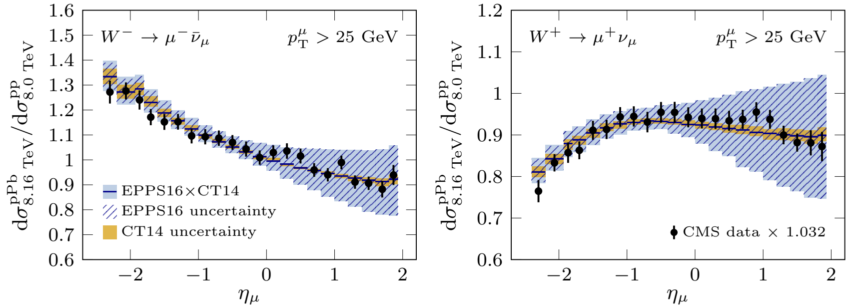
Wherever possible, EPPS21 uses nuclear modification ratios to cancel the free-proton-PDF uncertainties

- ➔ can still become relevant with LHC Run 3 statistics

Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 271

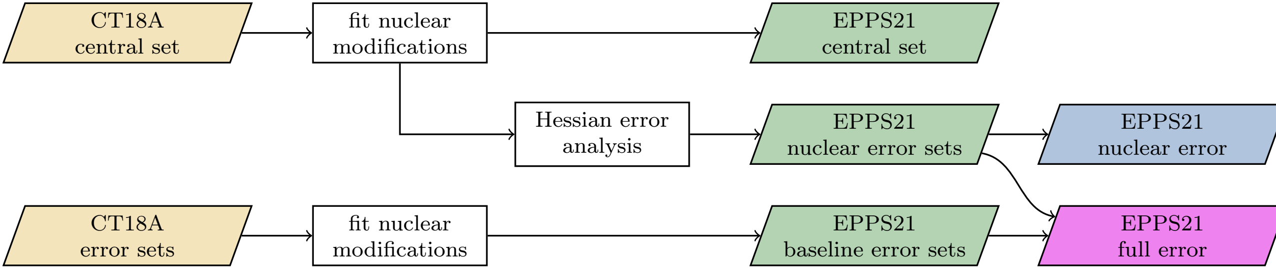


↓ Cancel proton-PDF uncertainty ↓



Propagating free-proton PDF uncertainty

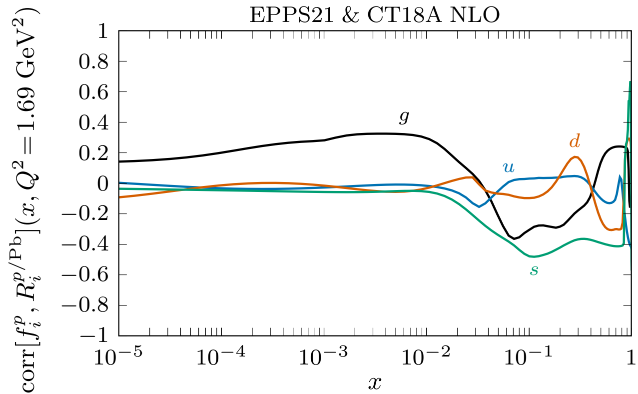
Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 413



EPPS21: fit nuclear modifications for each CT18A error set separately

nNNPDF3.0 uses similar approach in Monte Carlo framework

Note: nuclear modifications and proton PDFs become correlated!



Z bosons in pPb at 8.16 TeV

data from: CMS Collaboration, JHEP 05 (2021) 182
pp baseline: CMS Collaboration, EPJC 75 (2015) 147

New Run 2 data from CMS

CMS Collaboration, JHEP 05 (2021) 182

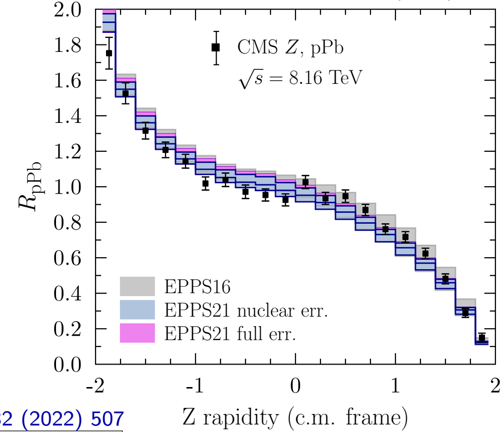
- nNNPDF3.0 include both low-mass and on-peak data
- R_{pPb} studied in EPPS21 ➔ not included in the final fit

Both EPPS21 and nNNPDF3.0 observe some tension between the data and fit

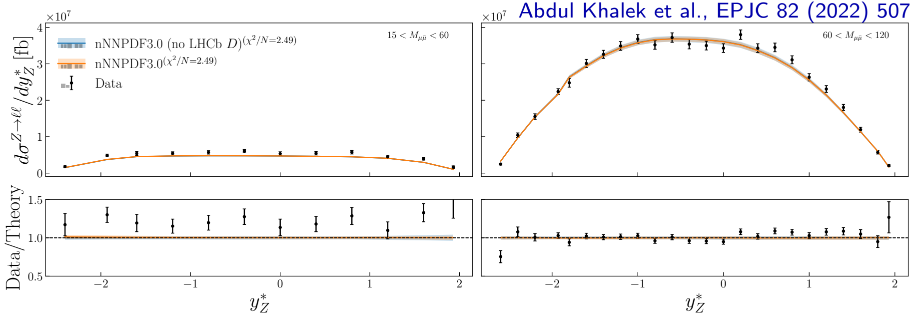
- abrupt change in the shape at midrapidity
- NNLO to cure for the low-mass data?

Abdul Khalek et al., EPJC 82 (2022) 507

Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 413



Abdul Khalek et al., EPJC 82 (2022) 507



	χ^2/N_{data}
EPPS21	2.1
nNNPDF3.0	2.49