EPPS21 progress report and perspectives on light ions

Petja Paakkinen

University of Jyväskylä

AoF CoE in Quark Matter
partner in ERC AdG YoctoLHC

Light ion collisions at the LHC

12 November 2024

UNIVERSITY OF JYVÄSKYLÄ
Centre of Excellence in Quark Matter
Research Council of Finland
HELSINKI INSTITUTE OF PHYSICS
erc

Nuclear PDFs from global analyses

parent nucleus

factorization scale

Nuclear PDFs $f_i^A(x, Q^2)$ are fitted

parton flavour

fraction of momentum carried by the parton

to inclusive hard cross section data

- ➔ use $\{e, \nu, \pi, p\} + A$ collisions to avoid hot-QCD effects
- ➔ rely only to the QCD collinear factorization
- ➔ use model-agnostic *parametrisations* of nuclear effects as a function of x

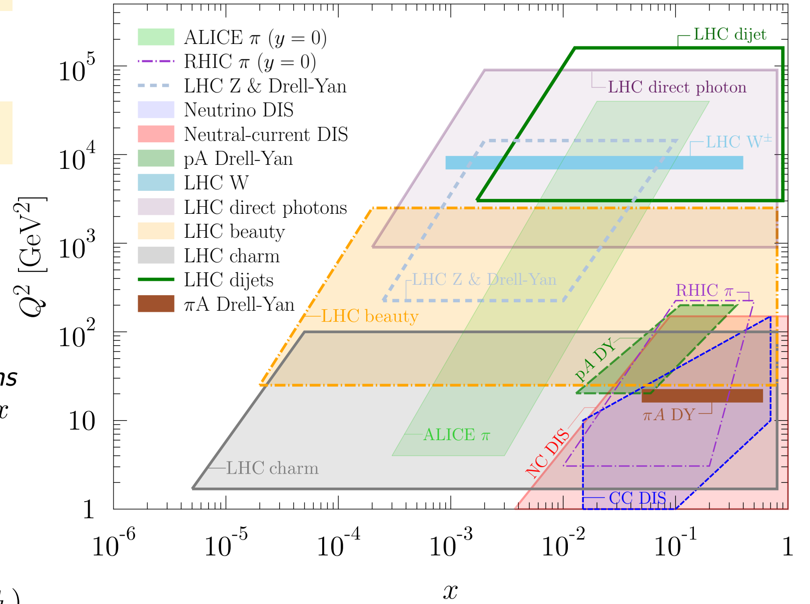
Use statistical inference, minimize:

Sum over data sets

$$\chi^2_{\text{tot}} = \sum_k (\underbrace{D_k}_{\text{data}} - \underbrace{T_k}_{\text{theory}})^T \underbrace{C_k^{-1}}_{\text{cov.}} (D_k - T_k)$$

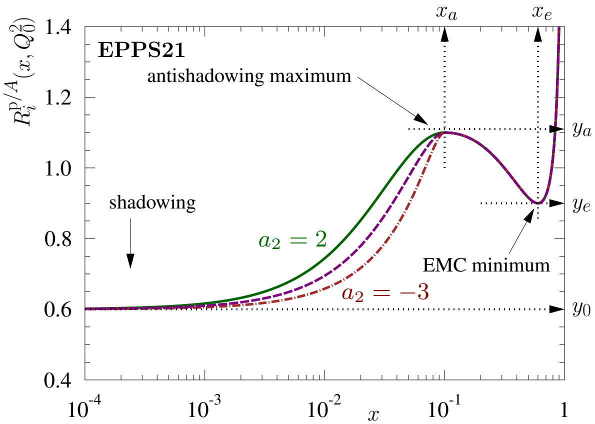
Data correlations important!

New review: Klasen & Paukkunen, Ann. Rev. Nucl. Part. Sci. 74 (2024) 1–41



Short intro to EPPS21 parametrization

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



- Define nuclear PDFs in terms of

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

- 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 $f_i^{p/A} \overset{\text{isospin}}{\longleftrightarrow} f_j^{n/A}$

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

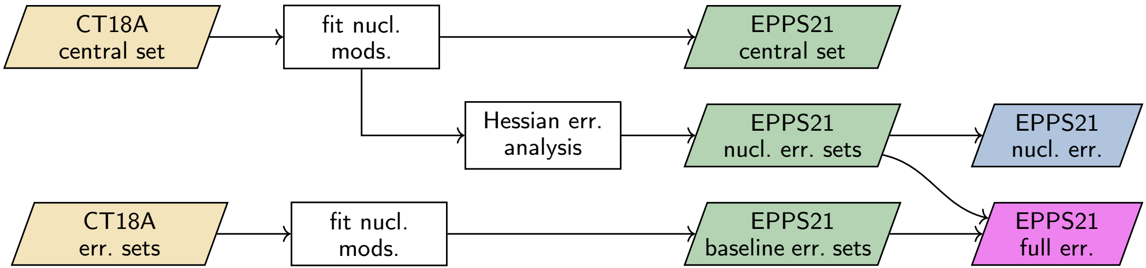
- More flexible fit with additional free parameters
  - $N_{\text{param}} = 24$ (20 in EPPS16)

- Improved small-x gluon parametrization (for $x < x_a$)

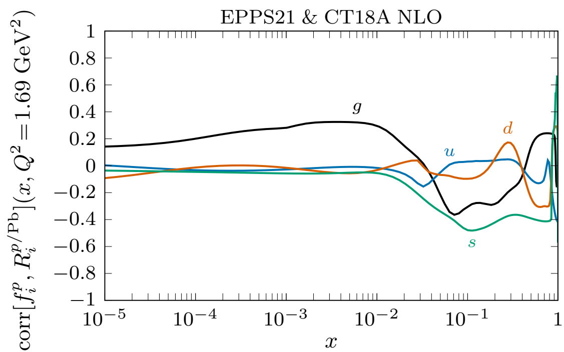
$$R_i^{p/A}(x, Q_0^2) = a_0 + a_1(x - x_a)\left[e^{-xa_2/x_a} - e^{-a_2}\right]$$

Propagating the baseline proton-PDF uncertainty in the EPPS21 fit

We study baseline-PDF sensitivity by fitting nuclear modifications separately for each CT18A error set



- Possible to propagate the baseline uncertainty consistently into any desired observable
  - See the paper for instructions
- Nuclear modification and free-proton baseline uncertainties become correlated
  - Information contained in error sets



JLab NC DIS

data from: Hall-C Experiment, Phys. Rev. Lett. 103 (2009) 202301
CLAS Collaboration, Nature 566 (2019) 354-358

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

Excellent fit!

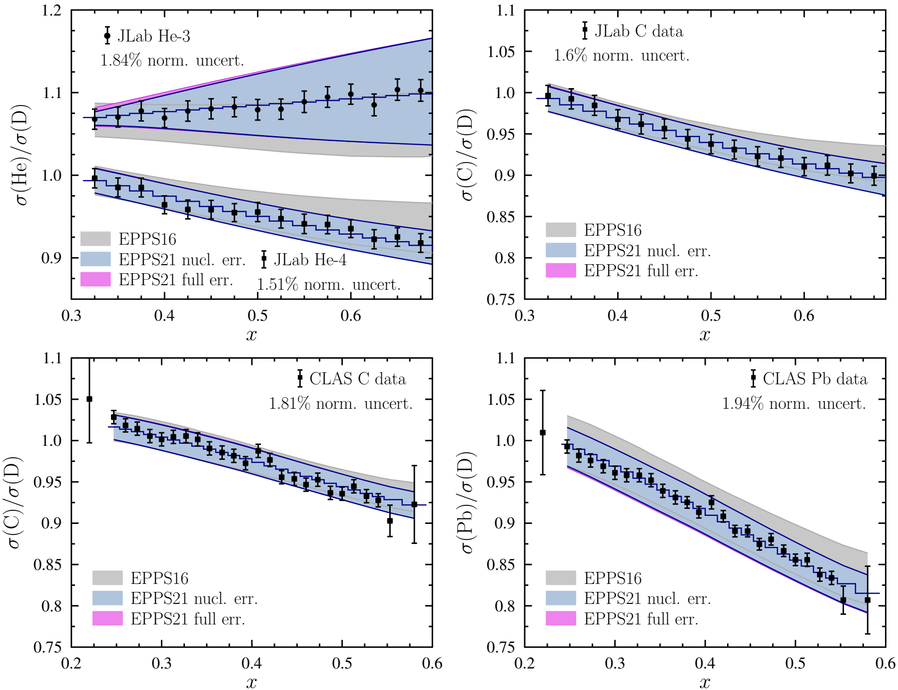
Results in line with the reweighting study
Paukkunen & Zurita, Eur.Phys.J.C 80 (2020) 381

We take into account the leading target-mass corrections

No sign of any strong A-dependent higher-twist contribution

N.B. A-dependence not necessarily smooth for light nuclei ➔ need to scale the nuclear modifications for He-3 and Li-6 by factors

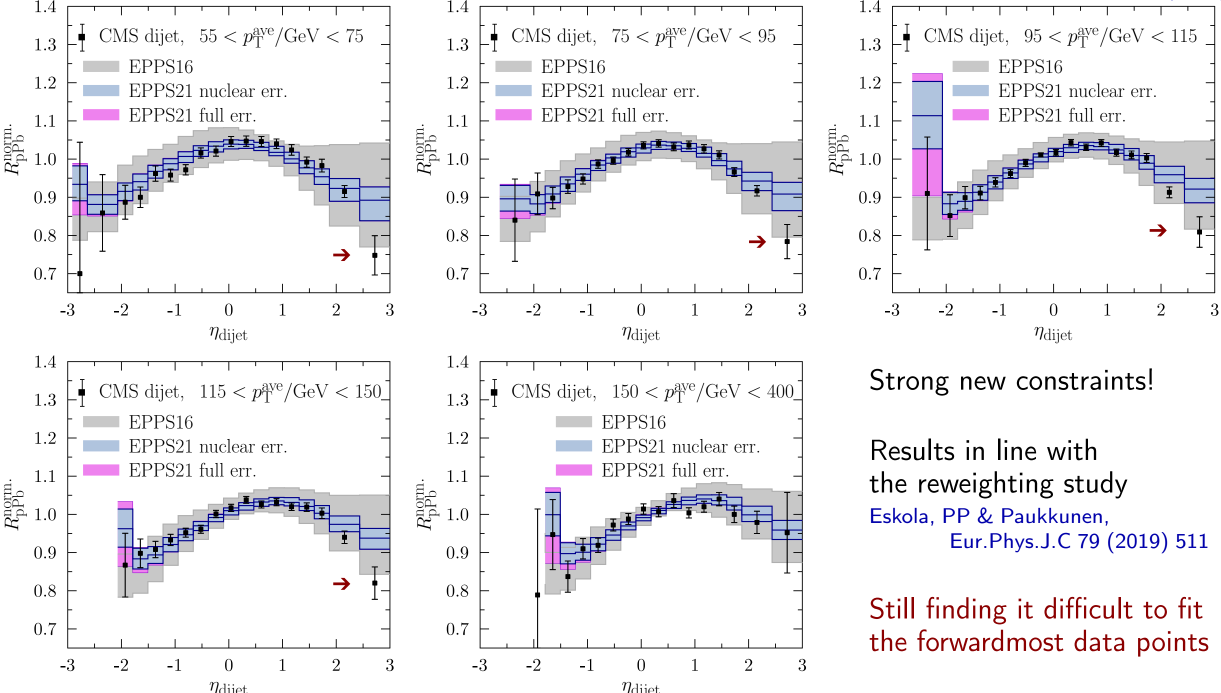
$$f_3 = 0.291, \quad f_6 = 0.495$$



Dijets at 5.02 TeV

data from: CMS Collaboration, Phys. Rev. Lett. 121 (2018) 062002

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



Strong new constraints!

Results in line with the reweighting study
Eskola, PP & Paukkunen, Eur.Phys.J.C 79 (2019) 511

Still finding it difficult to fit the forwardmost data points

D^0s at 5.02 TeV – backward

data from: LHCb Collaboration, JHEP 10 (2017) 090

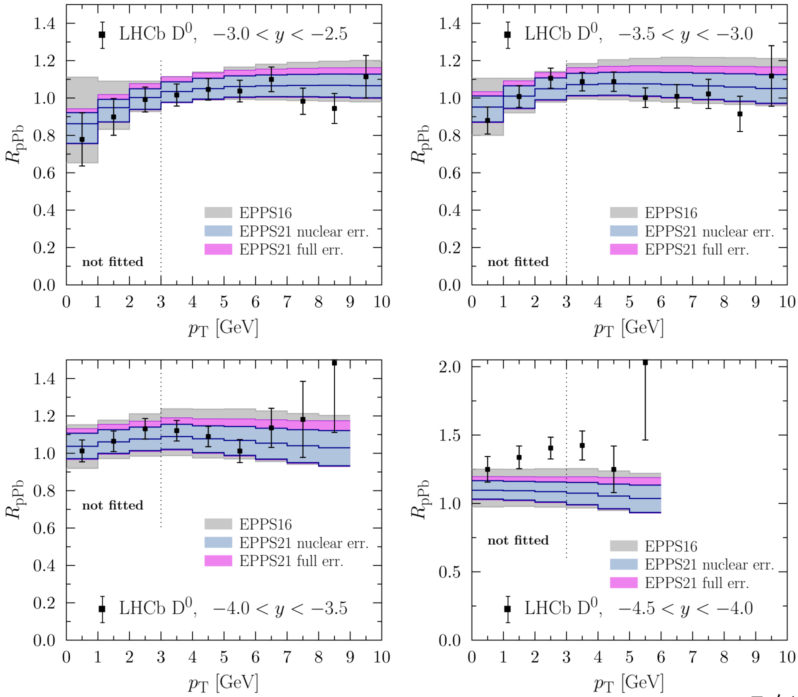
Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 413

Excellent fit!

Results in line with the reweighting study
Eskola, Helenius, PP & Paukkunen, JHEP 05 (2020) 037

Using the NLO pQCD S-ACOT-m_T GM-VFNS
Helenius & Paukkunen, JHEP 05 (2018) 196

Using a $p_T > 3$ GeV cut to reduce theoretical uncertainties



D^0s at 5.02 TeV – forward

data from: LHCb Collaboration, JHEP 10 (2017) 090

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

Excellent fit!

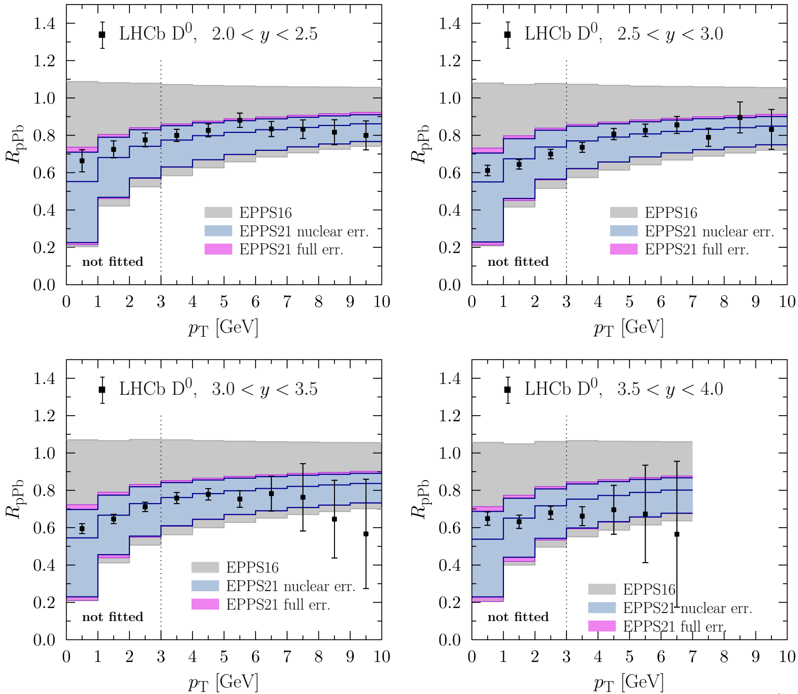
Results in line with the reweighting study

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

Using the NLO pQCD S-ACOT-m_{T} GM-VFNS

Helenius & Paukkunen, JHEP 05 (2018) 196

Using a $p_{\mathrm{T}} > 3$ GeV cut to reduce theoretical uncertainties



data from: CMS Collaboration, Phys.Lett.B 800 (2020) 135048
Eur.Phys.J.C 76 (2016) 469

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

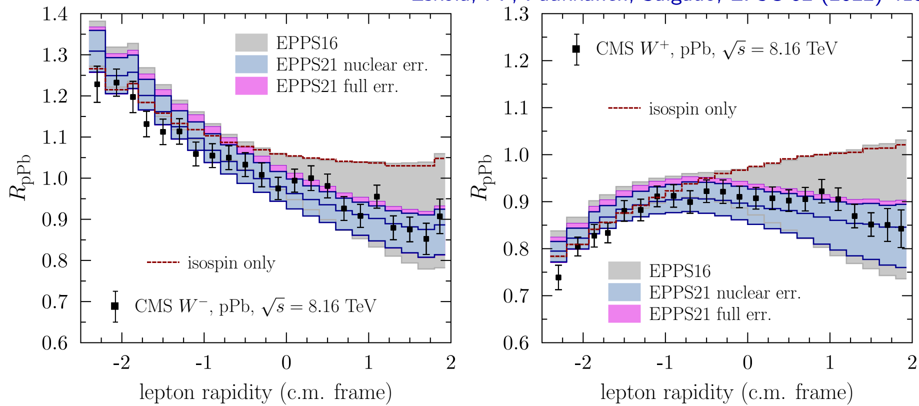
Excellent fit!

Using a mixed-energy nuclear modification ratio

$$R_{\rm pPb} = \frac{{\rm d}\sigma^{\rm pPb}_{\rm 8.16\,TeV}/{\rm d}\eta_\mu}{{\rm d}\sigma^{\rm pp}_{\rm 8.0\,TeV}/{\rm d}\eta_\mu}$$

to cancel the free-proton PDF uncertainty

Eskola, PP, Paukkunen, Salgado, Eur.Phys.J.C 82 (2022) 271

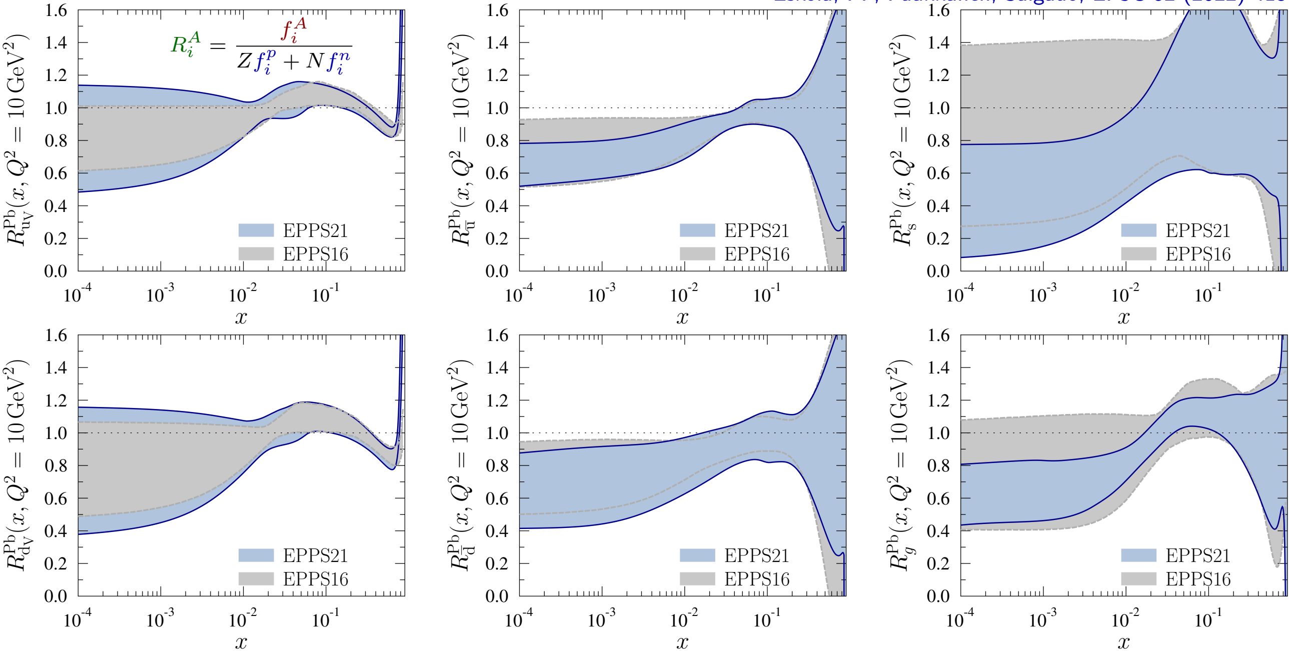


Fully consistent with the dijets and D^{0}s (but might prefer slightly smaller shadowing)

- Important check on the nuclear PDF universality & factorization

These data do not appear to give additional flavour-separation constraints on top of those we had already in EPPS16

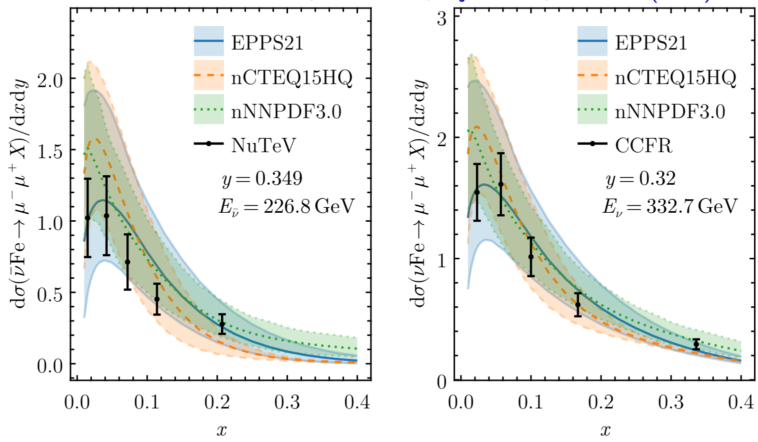
Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 413

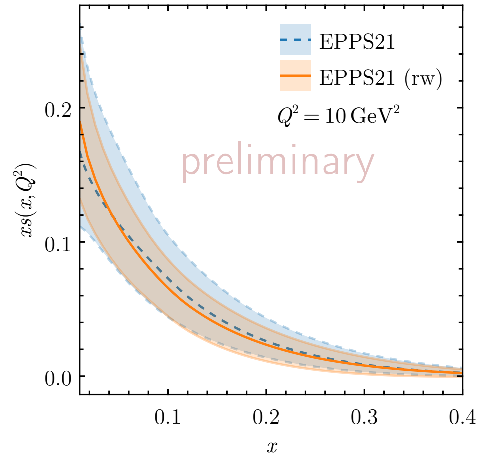


- Better control over gluon shadowing & antishadowing!

Ongoing work: Strangeness from dimuon DIS

Helenius, Paukkunen, Yrjänheikki, JHEP 09 (2024) 043

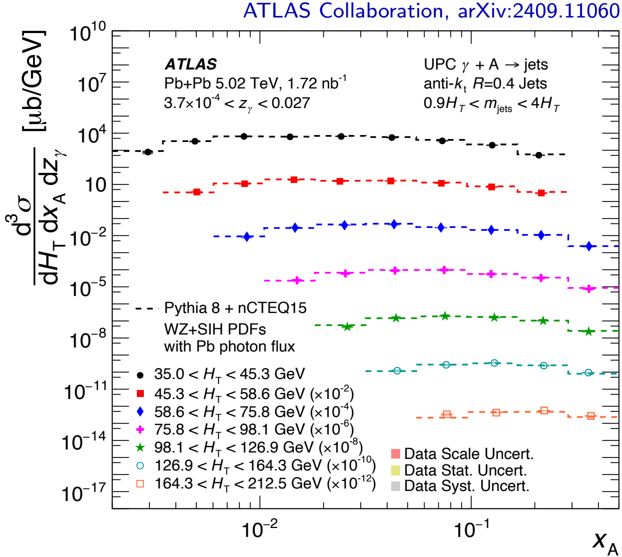


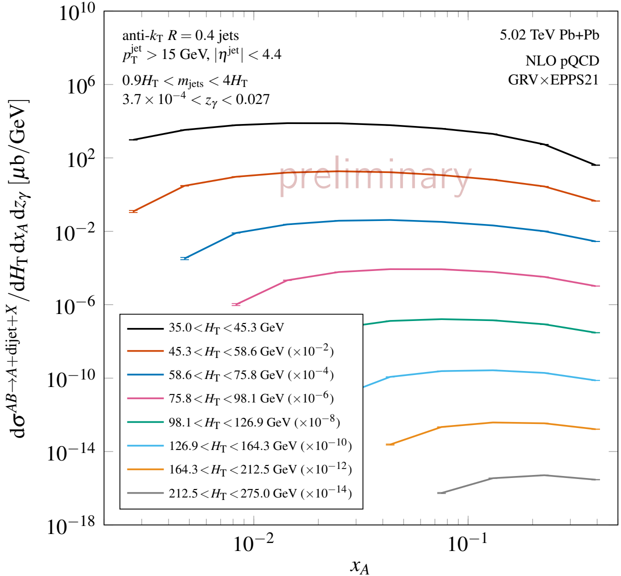


Ongoing study of constraining the nuclear strangeness with dimuon DIS data

- Using the new semi-inclusive DIS approach Helenius, Paukkunen, Yrjänheikki, JHEP 09 (2024) 043
- Same data already used in fitting the proton PDFs ➔ need to be careful with the correlations

Ongoing work: Impact of the UPC dijets

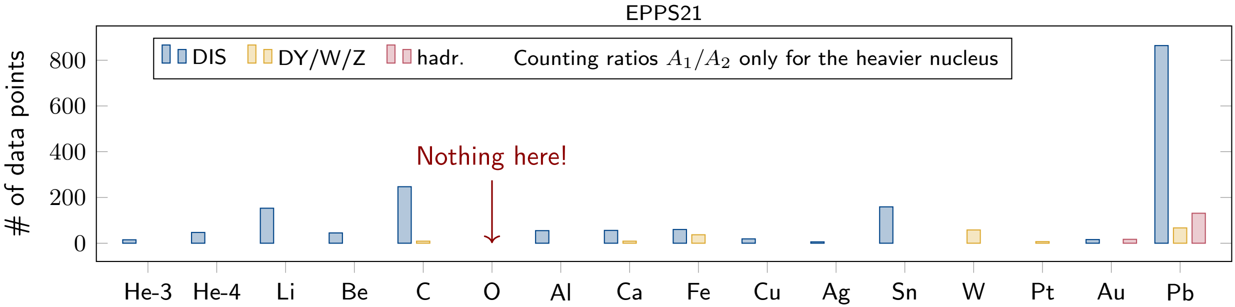




Preparing for direct comparisons with the ATLAS inclusive UPC dijet data

- Using the calculations with realistic effective photon flux and e.m. breakup probability
  Eskola, Guzey, Helenius, PP, Paukkunen, arXiv:2404.09731 [hep-ph]
- Need to include still hadronisation and no-diffraction corrections

Data availability w.r.t. A

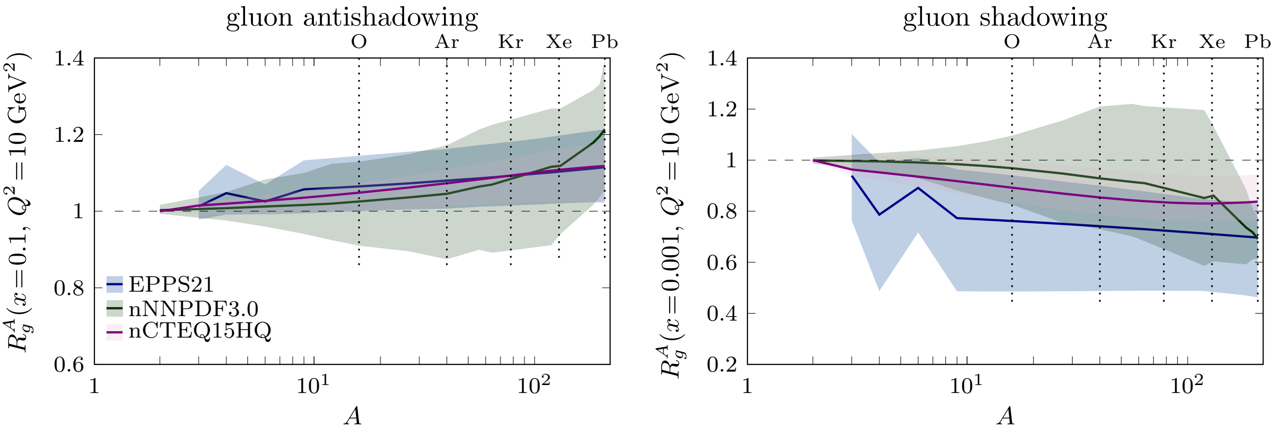


$\sim 50\%$ of the data points are for Pb!

- ☺ 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)
- Nuclear PDFs a major source of uncertainty for testing existence of QGP in small systems

Huss et al., PRL 126 (2021) 192301
Brewer, Huss, Mazeliauskas, van der Schee, PRD 105 (2022) 074040
Gebhard, Mazeliauskas, Takacs, arXiv:2410.22405 [hep-ph]

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 $6\ \mathrm{nb}^{-1}$

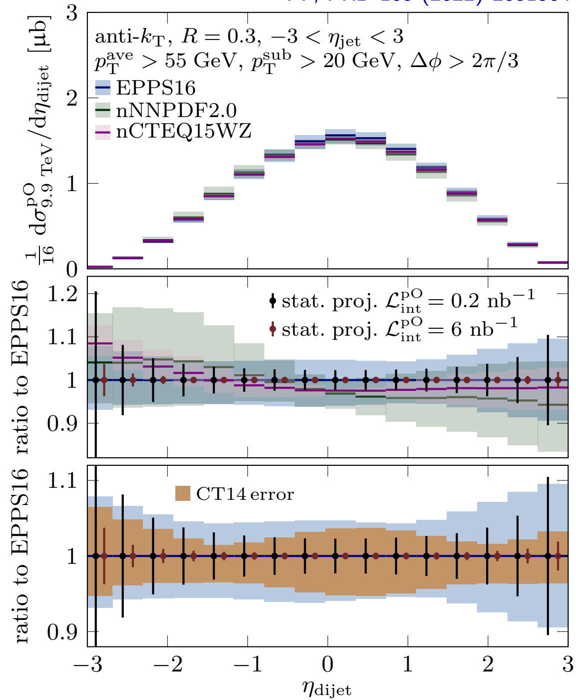
Problem: absolute cross sections very sensitive to the used free-proton PDFs

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

→ Better to study R_{pO}

Problem: We do not expect pp reference at 9.9 TeV

PP, PRD 105 (2022) L031504



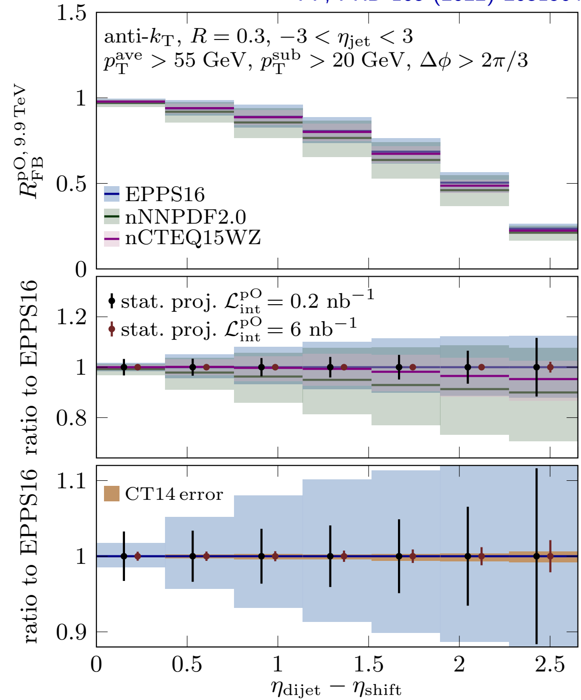
Dijet R_{pO} in pO at 9.9 TeV

PP, PRD 105 (2022) L031504

Problem: We do not expect pp reference at 9.9 TeV

Solution 1: Use a forward-to-backward ratio

- Excellent cancellation of free-proton PDFs
- Price to pay: mixing small and large x effects
- Even rather different nuclear modifications can yield similar shape



PP, PRD 105 (2022) L031504

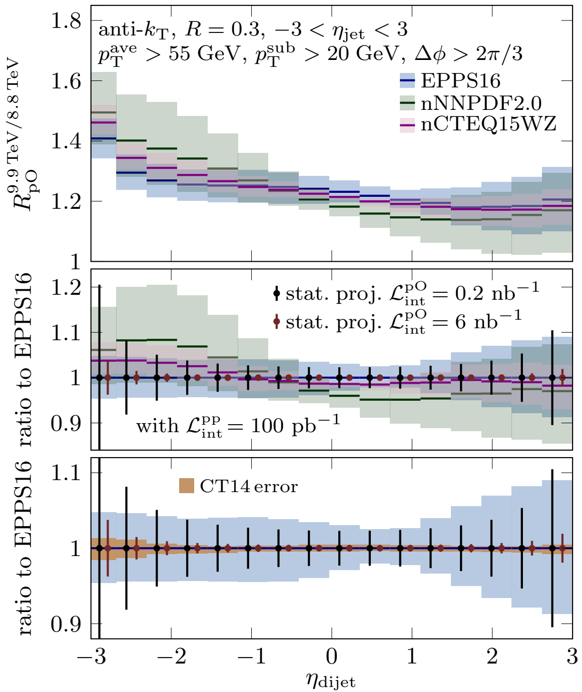
Problem: We do not expect pp reference at 9.9 TeV

Solution 1: Use a forward-to-backward ratio

- Excellent cancellation of free-proton PDFs
- Price to pay: mixing small and large x effects
- Even rather different nuclear modifications can yield similar shape

Solution 2: Use a mixed energy ratio pO(9.9 TeV)/pp(8.8 TeV)

- Excellent cancellation of free-proton PDFs
- Can resolve different nPDF parametrisations!
- Already $\sim 1\ \mathrm{nb}^{-1}$ can be expected to be enough to put new constraints on nPDFs (if we have sufficient statistics for the pp reference)



Forward π^0s agree with D^0-constrained nPDFs, but at backward rapidities this agreement seems to break down!

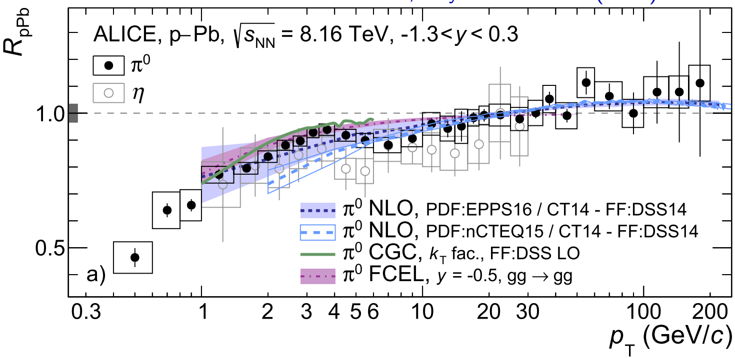
Do I see a bump also in midrapidity data at 3–4 GeV?

Similar/larger enhancements seen in charged hadrons

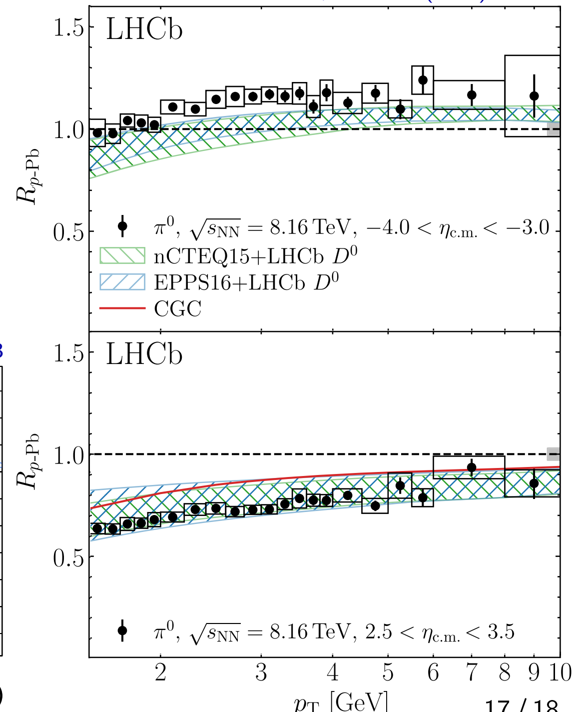
PHENIX Collaboration, PRC 101 (2020) 034910
PHENIX Collaboration, PRC 105 (2022) 064902
LHCb Collaboration, PRL 128 (2022) 142004

➔ How do these effects scale in A?

ALICE Collaboration, Phys. Lett. B 827 (2022) 136943



LHCb Collaboration, PRL 131 (2023) 042302



Summary

Nuclear PDFs are being constrained by an increasing amount of LHC data

- EPPS21 global fit includes few thousand data points on a variety of processes
  - ➔ Collinear factorization works in pA across a large phase space in x, Q^2
  - ➔ Nuclear gluon content in Pb better constrained than ever before

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

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

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

- Dijets, D-mesons, identified light hadrons
- Cross sections and, if possible, nuclear modification ratios
  - ➔ Can use mixed-energy ratios, if pp baseline available at some different (but close by) energy
  - ➔ Opinion: if measurement baseline is interpolated, then theory baseline must be too

For precision light-ion PDFs, probably need to go beyond short pilot runs

Backup

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...

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

...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 $Q \gg \Lambda_{\mathrm{QCD}}$

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

- parent hadron or nucleus (A)
- parton flavour (i)
- fraction of momentum carried by the parton (x)
- factorization scale (Q^2)

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

- splitting functions (P_{ij})
- Mellin conv. ($\otimes$)

Summary of 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 HF			✓ 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 inc.-h,HF	N/A	N/A	3.0, 3.0 GeV	N/A, 0.0 GeV	3.0, 3.0 GeV
Data points	4353	2410	2077	2188	1484
Free parameters	18	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
HF 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

Heavy-flavour production mass schemes

FFNS

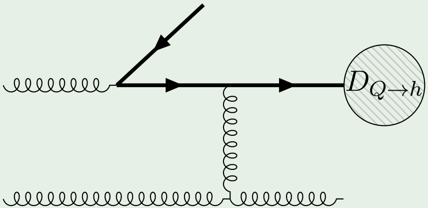
In *fixed flavour number scheme*, **valid at small** p_{T}, heavy quarks are produced only at the matrix element level

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

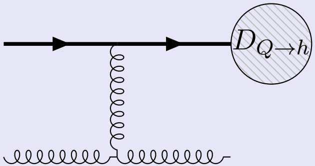
ZM-VFNS

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 at 8.16 TeV

New LHCb measurement at 8.16 TeV
initially claimed to be in tension with nPDFs

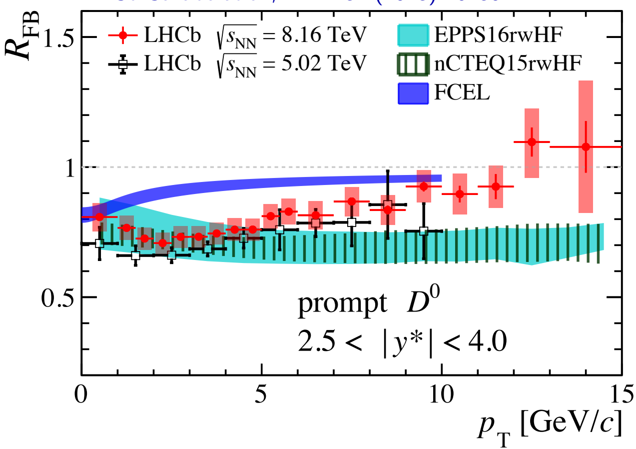
(not included in the nPDF analyses yet)

Not only probing nPDFs but also testing
production and interaction mechanism!

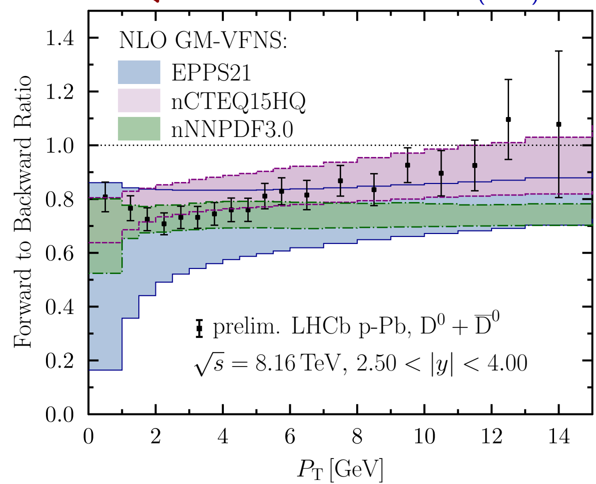
(Here HELAC vs. S-ACOT-m_T vs. FCEL)

Rather different predictions!

LHCb Collaboration, PRL 131 (2023) 102301



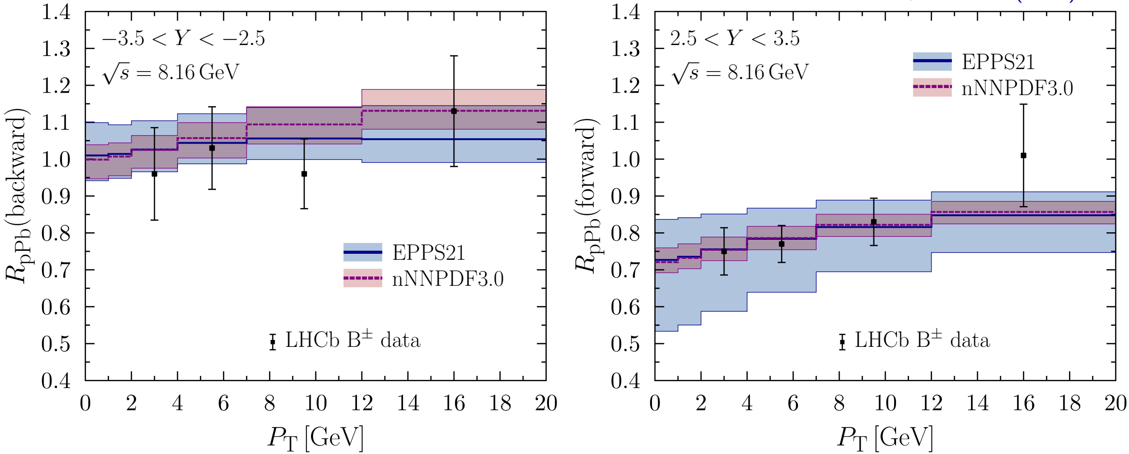
Klasen & Paukkunen,
Ann. Rev. Nucl. Part. Sci. 74 (2024) 1–41



B-mesons in pPb at 8.16 TeV

data from: LHCb Collaboration, Phys. Rev. D 99 (2019) 052011

Helenius & Paukkunen, JHEP 07 (2023) 054



B-meson production theoretically clean due to high b-quark mass, but scale-variation ($\sim$ higher order) uncertainties can still be relevant in GM-VFNS at NLO towards low-p_{T}

Helenius & Paukkunen, JHEP 07 (2023) 054

LHCb data in agreement with S-ACOT-m_{T} using EPPS21 and nNNPDF3.0 nPDFs

→ Need more statistics for strong constraints

PHENIX pion production small-system scan

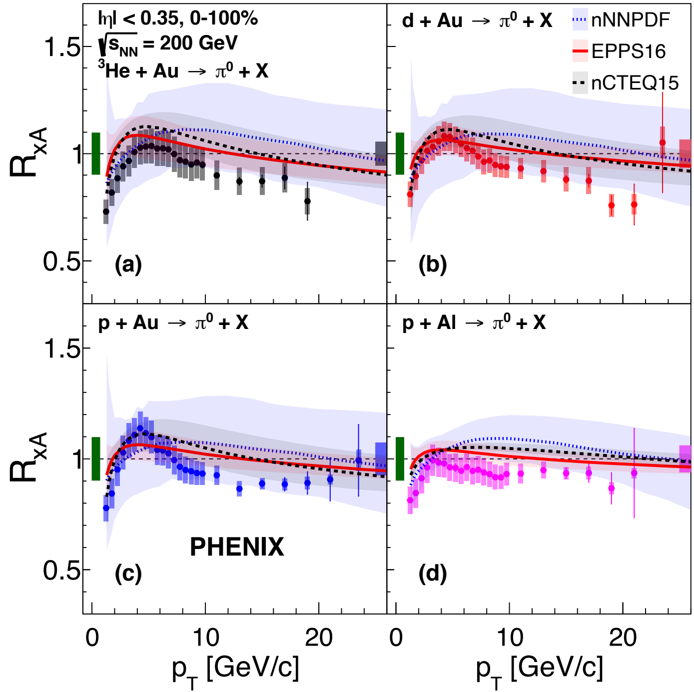
PHENIX Collaboration, PRC 105 (2022) 064902

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

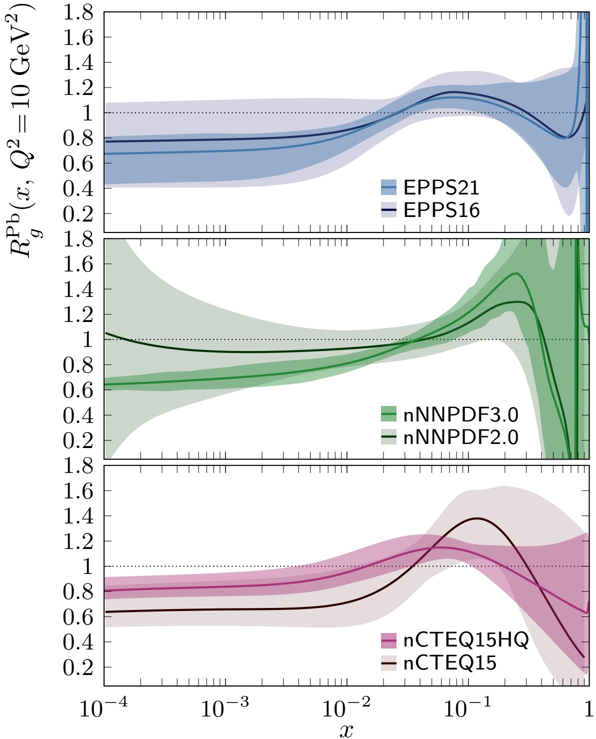
- higher-twist (multiple-scattering)?
- flow-like component?

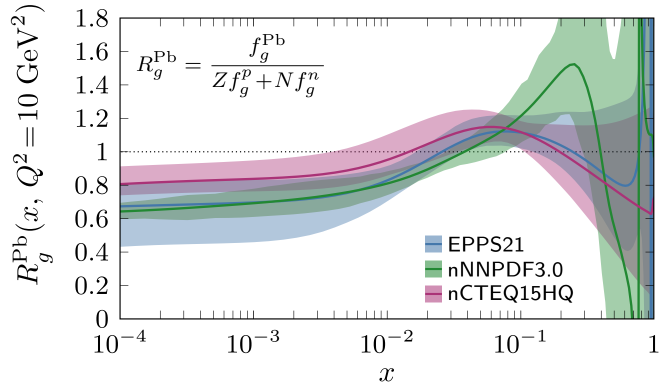
At high p_T the nPDF predictions overshoot the data, but mind the large normalisation uncertainties

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



Impact on nPDFs – *glue*



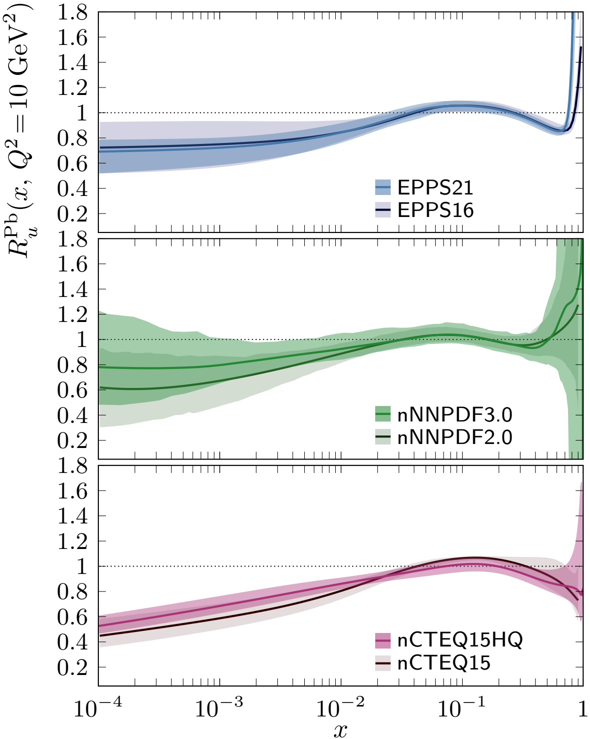


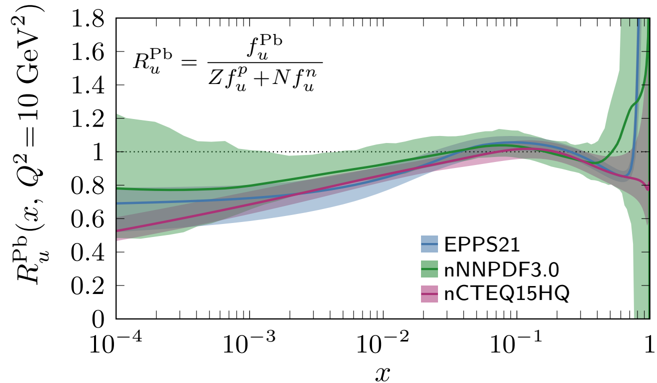
All major global nPDF fits find significant reduction in gluon uncertainties when including LHC data

Constraints driven by dijets & heavy-flavour, but also Ws and light mesons carry sensitivity

Differences between sets due to methodological and data-selection choices

Impact on nPDFs – *up*

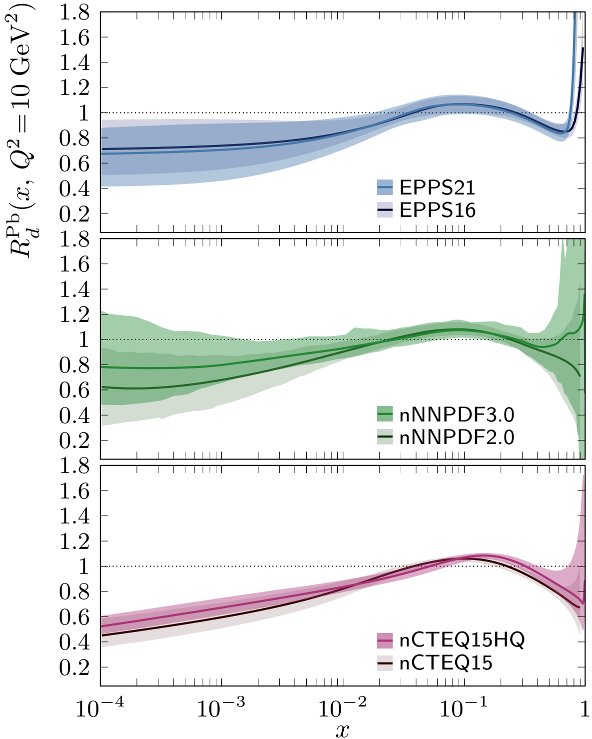


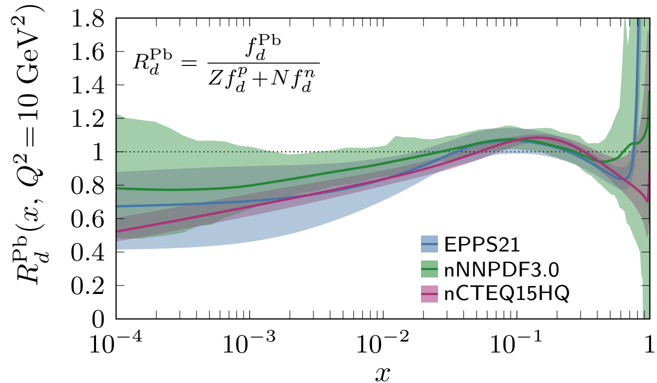


Valence region constrained by fixed-target DIS data

Uncerainties grow towards small x due to lack of collider DIS data

Impact on nPDFs – *down*

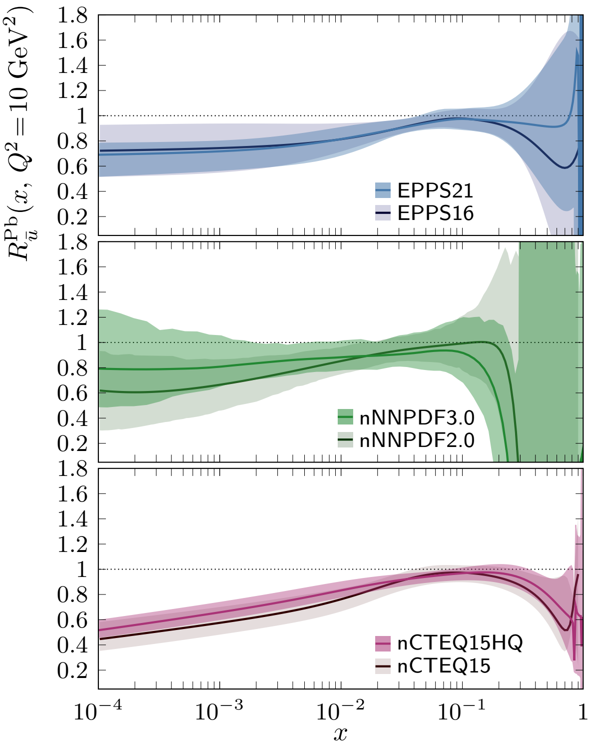


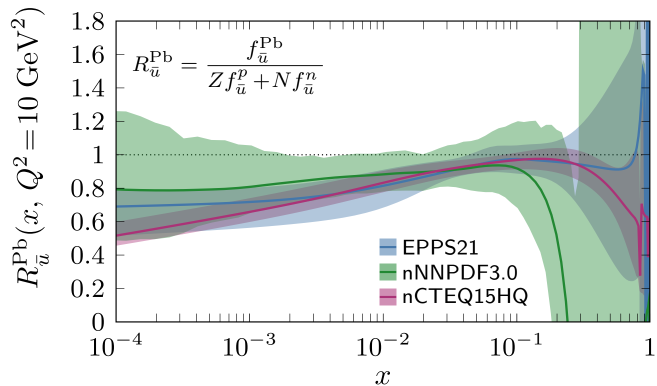


Valence region constrained by fixed-target DIS data

Uncerainties grow towards small x due to lack of collider DIS data

Impact on nPDFs – *anti-up*

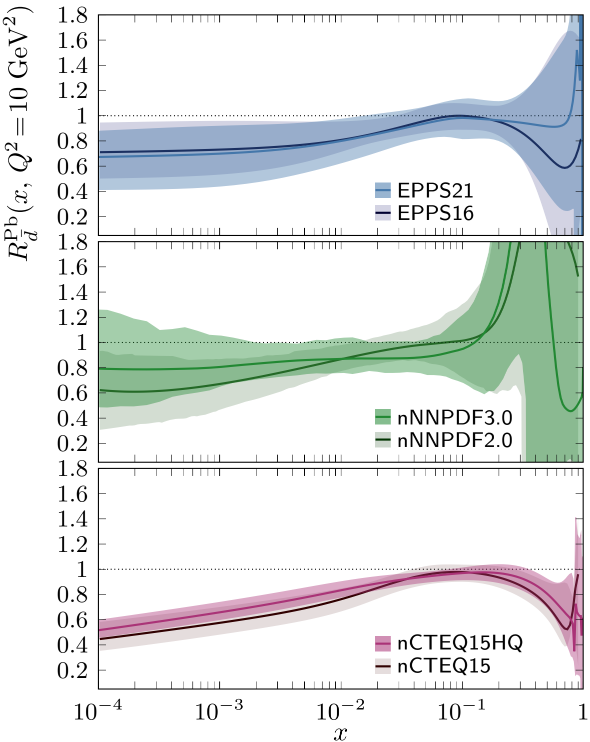


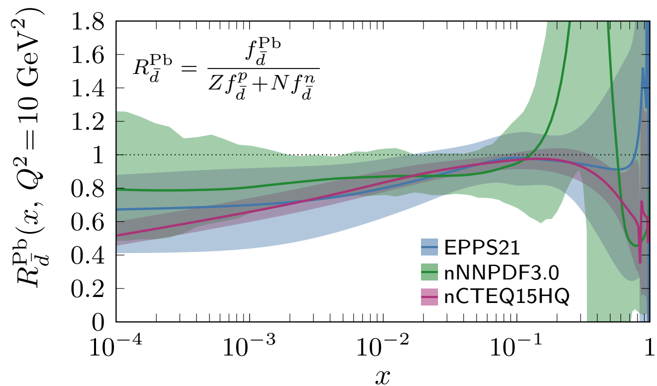


Valence / sea quark separation dominated by fixed-target DY data

nNNPDF3.0 has larger uncertainties due to not including these data

Impact on nPDFs – *anti-down*

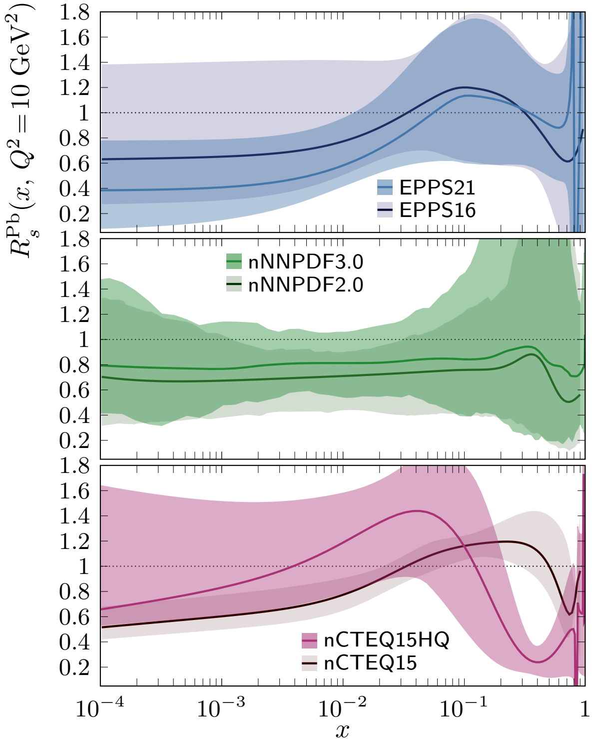


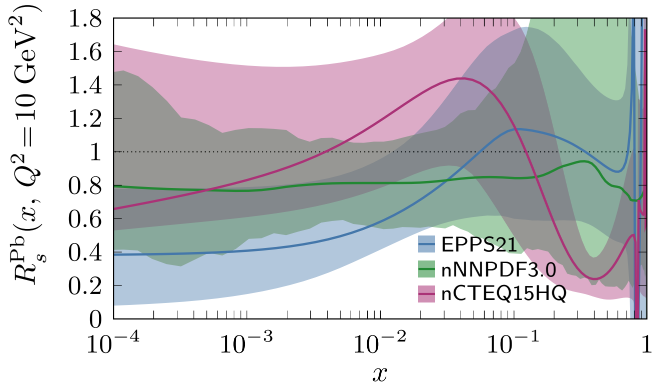


Valence / sea quark separation dominated by fixed-target DY data

nNNPDF3.0 has larger uncertainties due to not including these data

Impact on nPDFs – *strange*





Strangeness poorly known in lack of direct constraints

Dimuon process in neutrino-DIS could be used to improve

Helenius, Paukkunen, Yrjänheikki, JHEP 09 (2024) 043