Hard probes and nuclear PDFs

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Hard Probes 2024

26 September 2024

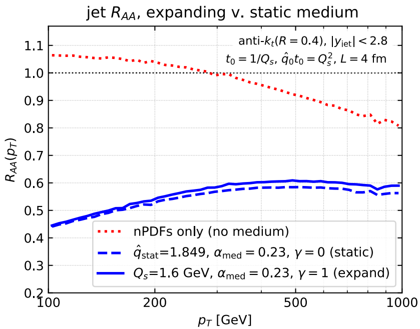
"Hard probes, e.g. high-pT hadrons and heavy quarks, are formed in the early stages of the collisions via initial **hard scattering** of high-energy **partons** (quarks and gluons). Their production mechanism is well understood by perturbative QCD. Thus they serve as "calibrated probes" injected in the QGP medium."

Akiba, Prog. Theor. Exp. Phys. (2015) 03A105

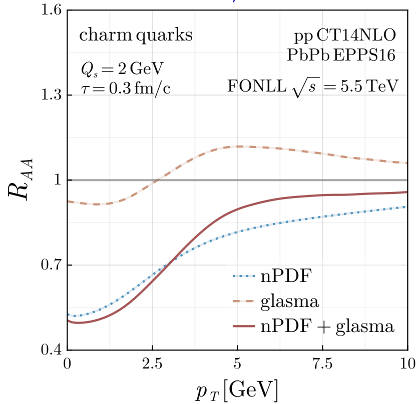
But in order to have these probes *well calibrated*, we need to know the distributions of the initial-state partons in the colliding nuclei precisely enough. I.e. need to study the **nuclear PDFs** (nPDFs).

cf. Apolinário et al., Prog. Part. Nucl. Phys. 127 (2022) 103990
Pablos, EPJ Web of Conferences 296 (2024) 01028

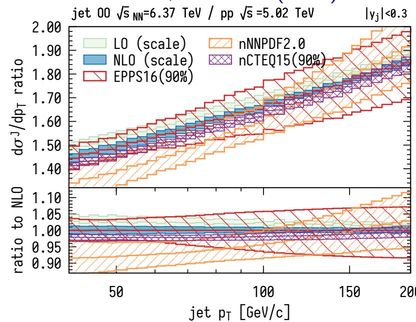
Caucal et al., JHEP 04 (2021) 209



Avramescu et al., arXiv:2409.10564



Brewer et al., PRD 105 (2022) 074040



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

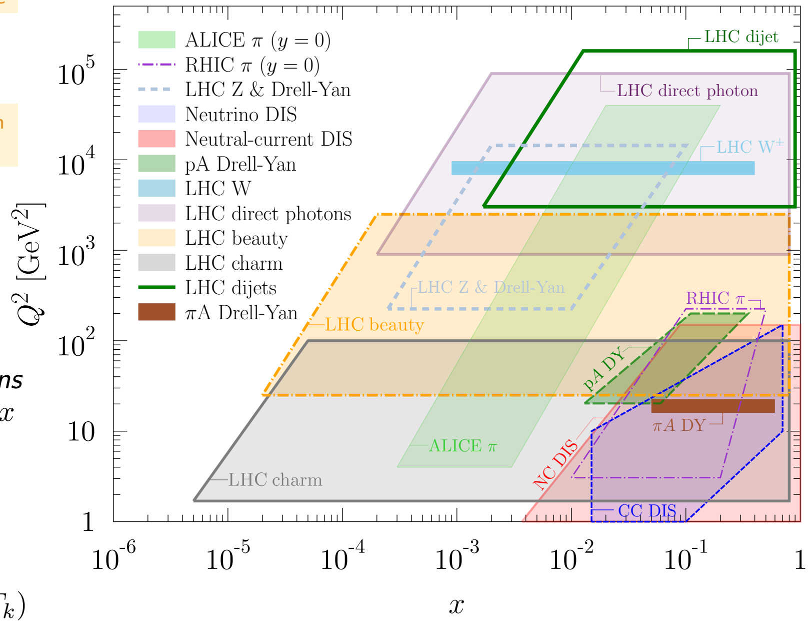
Use statistical inference, minimize:

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

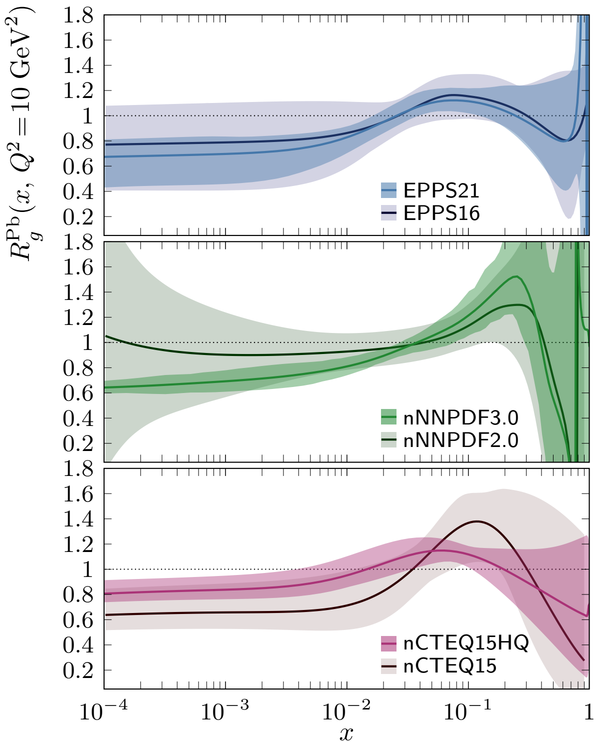


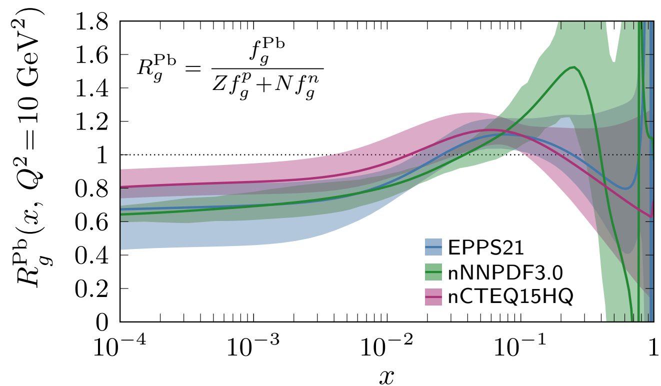
Summary of recent nPDF global fits

	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

*see also A. Kusina, Mon 3:00 PM for preliminary nCTEQ24/25 results

Impact on nPDFs – *glue*



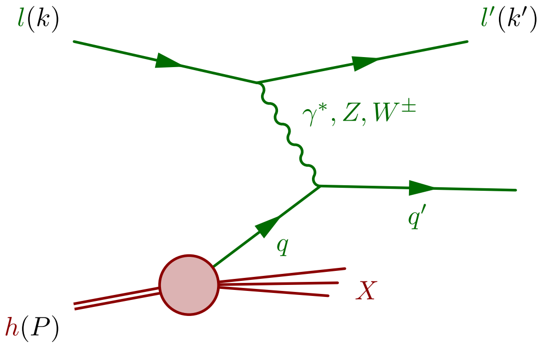


All major global nPDF fits find significant reduction in gluon uncertainties when including LHC data

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

Differences between sets due to methodological and data-selection choices

Deep inelastic scattering (DIS)

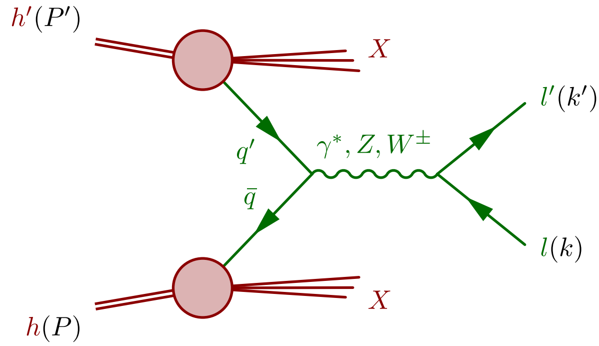


For the photon-mediated case:

$$\frac{\mathrm{d}^2\sigma^{\mathrm{DIS}}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{\mathrm{d}^2\hat{\sigma}}{\mathrm{d}x\mathrm{d}Q^2} \sum_{i\in\{q,\bar{q}\}} e_i^2 f_i^h(x, Q^2) + {}_{\text{corrections}}^{\text{NLO}}$$

$$\left.\begin{aligned} Q^2 &= -(k-k')^2 \\ x &= \frac{Q^2}{2P\cdot(k-k')} \end{aligned}\right\} \leftarrow$$ access scale and momentum-fraction dependence through external kinematics

Drell-Yan (DY)



The photon-mediated case:

$$\frac{\mathrm{d}^2\sigma^{\mathrm{DY}}}{\mathrm{d}y\mathrm{d}M^2} = \frac{4\pi\alpha_{\mathrm{e.m.}}^2}{9M^4} \sum_{i\in\{q,\bar{q}\}} e_i^2 x_1 x_2 f_i^h(x_1, M^2) f_{\bar{i}}^{h'}(x_2, M^2) + {}_{\text{corrections}}^{\text{NLO}}$$

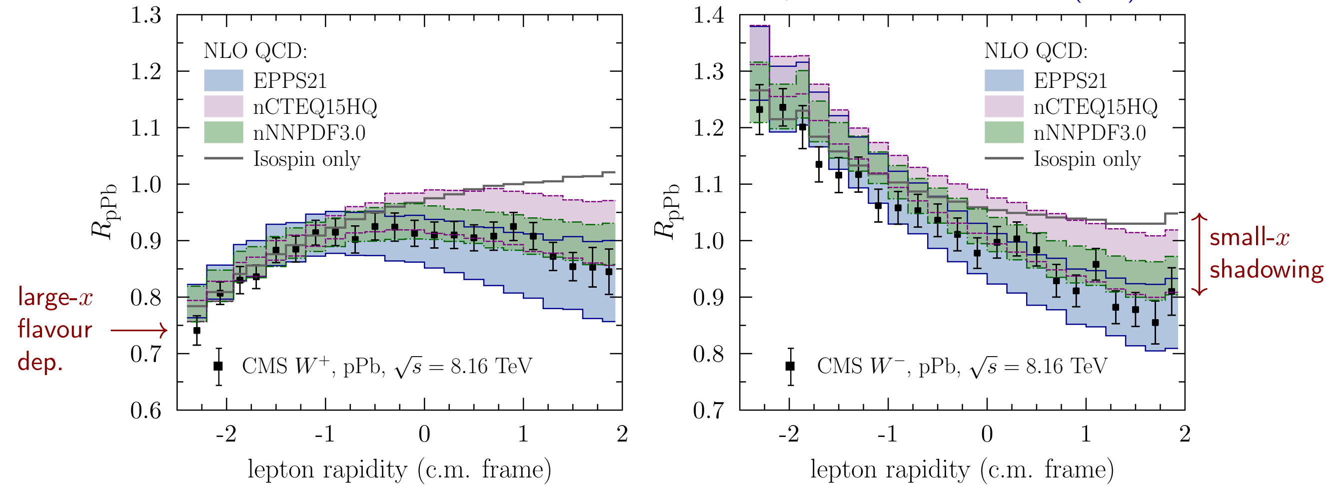
$$M^2 = (k+k')^2 = x_1 x_2 s$$

$$y = \frac{1}{2}\log\frac{(k_0+k_0')+(k_3+k_3')}{(k_0+k_0')-(k_3+k_3')} = \frac{1}{2}\log\frac{x_1}{x_2}$$

W bosons in pPb at 8.16 TeV

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

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



Run-2 W boson data included in practically all recent nPDF fits:

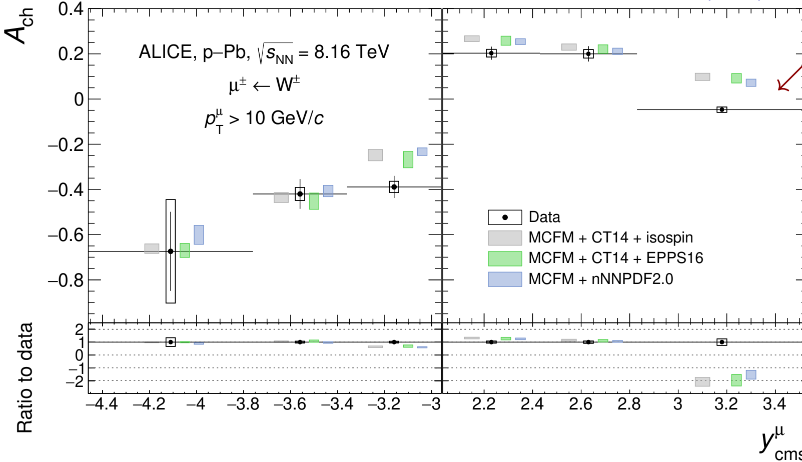
nCTEQ15HQ
nNNPDF3.0
TUJU21
} ← Use absolute pPb cross sections

EPPS21 ← Use R_{pPb} to cancel free-proton PDFs

$$R_{\mathrm{pPb}} = \frac{\sigma^{\mathbf{pPb}}(8.16\ \mathrm{TeV})}{\sigma^{\mathbf{pp}}(8.0\ \mathrm{TeV})}$$

W boson charge asymmetry in pPb at 8.16 TeV

ALICE Collaboration, JHEP 05 (2023) 036



large data-theory difference in a forward bin either due to:

strongly flavour dependent shadowing (not supported by CMS R_{pPb})

large-x *proton*-PDF flavour asymmetry (should be tested)

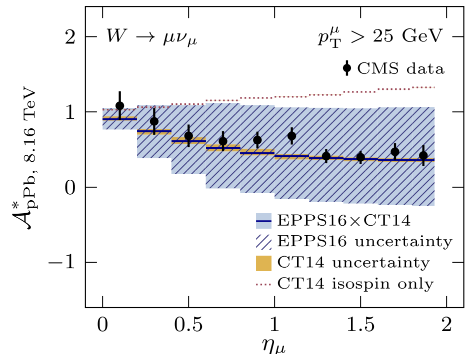
Charge asymmetry very sensitive to free-proton baseline

Paukkunen & Salgado, JHEP 03 (2011) 071

To probe nuclear modifications, use instead:

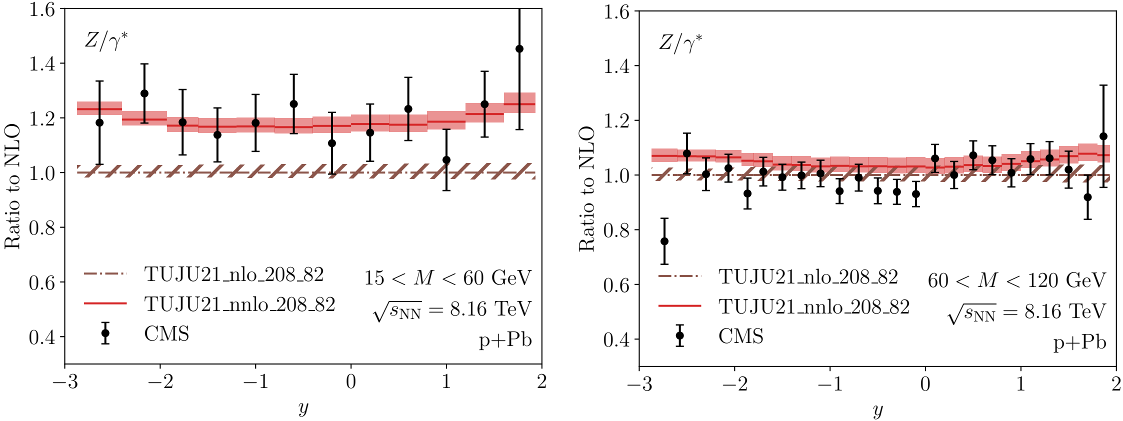
$$\mathcal{A}^*_{pPb} = \frac{d\sigma^{W^+}_{pPb}/d\eta_\mu|_{\eta_\mu} - d\sigma^{W^-}_{pPb}/d\eta_\mu|_{-\eta_\mu}}{d\sigma^{W^+}_{pPb}/d\eta_\mu|_{-\eta_\mu} - d\sigma^{W^-}_{pPb}/d\eta_\mu|_{\eta_\mu}}$$

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



Eskola, PP, Paukkunen, Salgado, Eur. Phys. J. C 82 (2022) 271 pPb data from: CMS Collaboration, JHEP 05 (2021) 182

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



Low-mass DY $(15 < M < 60 \text{ GeV})$: First clear evidence for the need of NNLO nPDFs

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

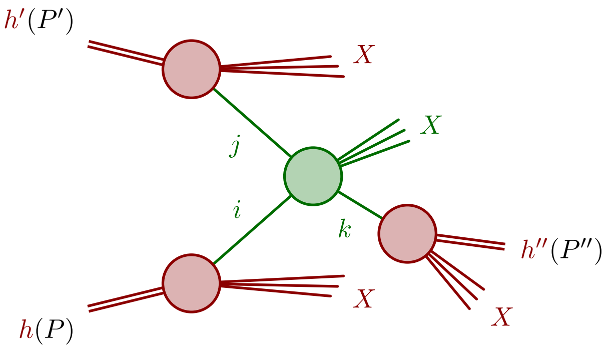
Z-peak region $(60 < M < 120 \text{ GeV})$: Poor χ^2 in all nPDF analyses due to data fluctuations

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

Also ALICE & LHCb 8.16 TeV data available

ALICE Collaboration, JHEP 09 (2020) 076
LHCb Collaboration, JHEP 06 (2023) 022

Hadron-production

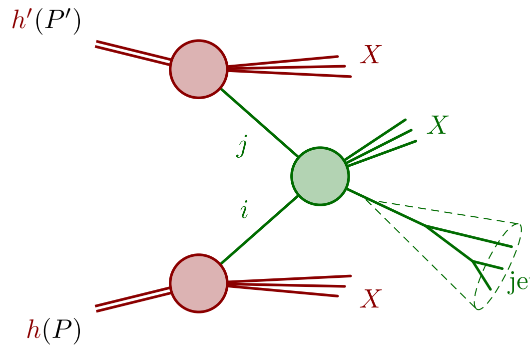


$$\sigma^{h+h'\to h''+X} = \sum_{i,j,k\in\{q,\bar{q},g\}} f_i^h \otimes f_j^{h'} \otimes \hat{\sigma}^{ij\to k+X} \otimes D_k^{h''}$$

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

→ a source of uncertainty for PDF fits

Jet-production



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

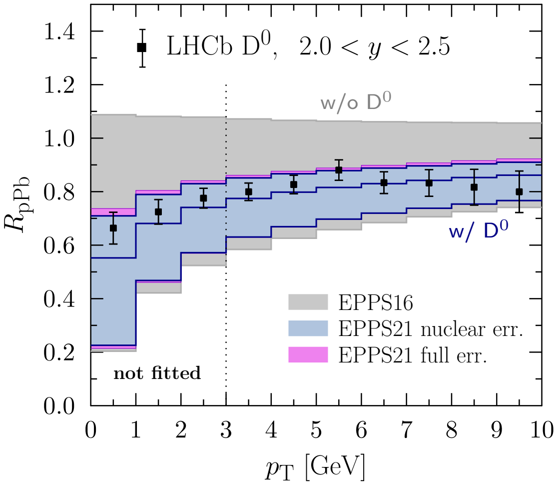
Instead of fragmentation functions:

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

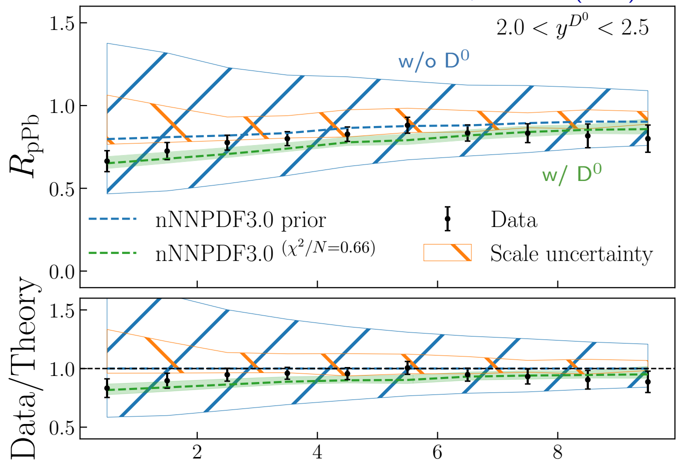
D^0s in EPPS21 and nNNPDF3.0

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

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 in R_{pPb} ➔ fit only forward data

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

EPPS21 uses S-ACOT-m_{T} GM-VFNS ➔ scale uncertainty small except at low p_{T}

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

FFNS

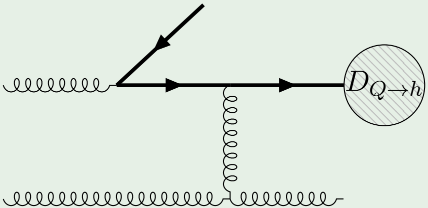
In *fixed flavour number scheme*, **valid at small** p_{T}, heavy quarks are produced only at the matrix element level

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

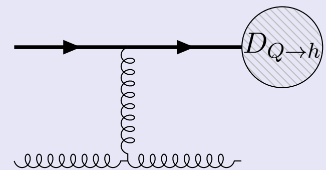
ZM-VFNS

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

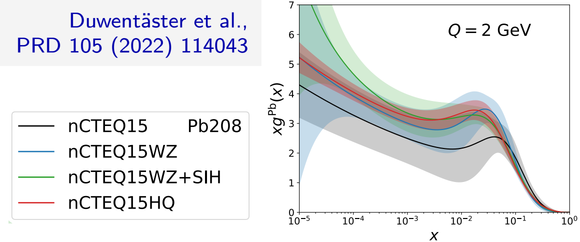
A *general-mass variable flavour number scheme* combines the two by supplementing subtraction terms to prevent double counting of the resummed splittings, **valid at all** p_{T}

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!

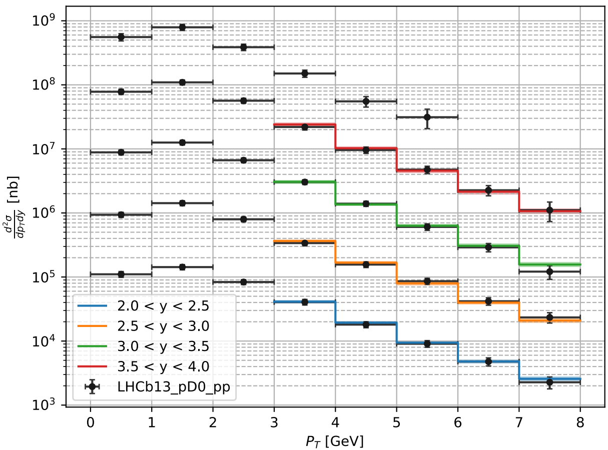
Helenius & Paukkunen, JHEP 05 (2018) 196

Duwentäster et al., PRD 105 (2022) 114043

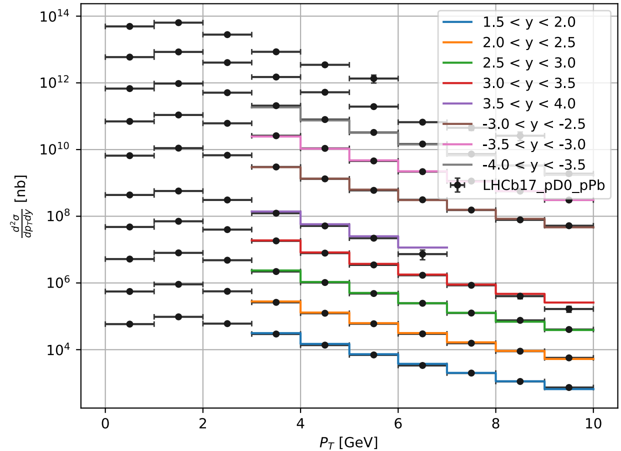


nCTEQ15HQ uses a data-driven approach
Lansberg & Shao, EPJC 77 (2017) 1
Kusina et al., PRL 121 (2018) 052004
to fit the D^0 and J/ψ data:

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

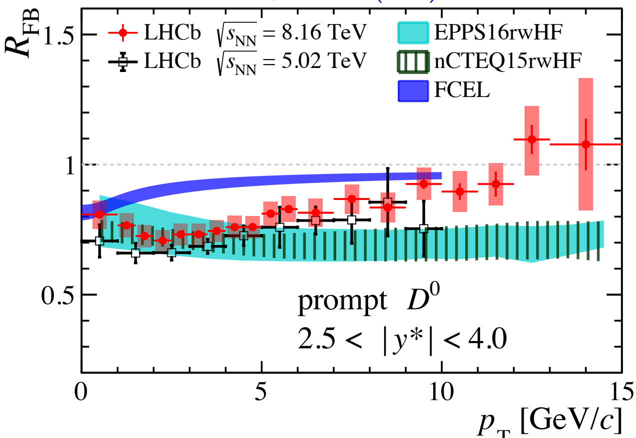
(not included in the nPDF analyses yet)

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

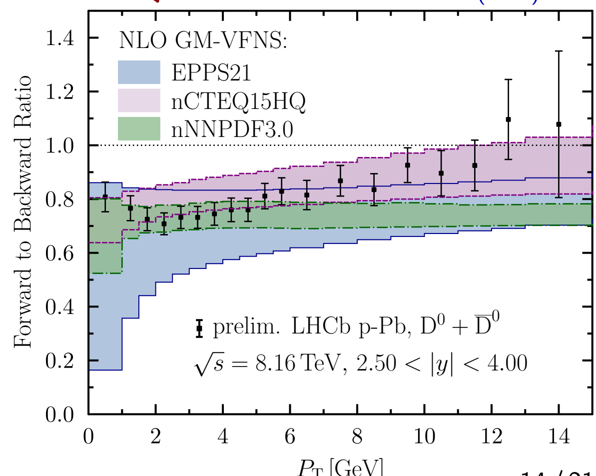
(Here HELAC vs. S-ACOT-m_T vs. FCEL)

Rather different predictions!

LHCb Collaboration, PRL 131 (2023) 102301

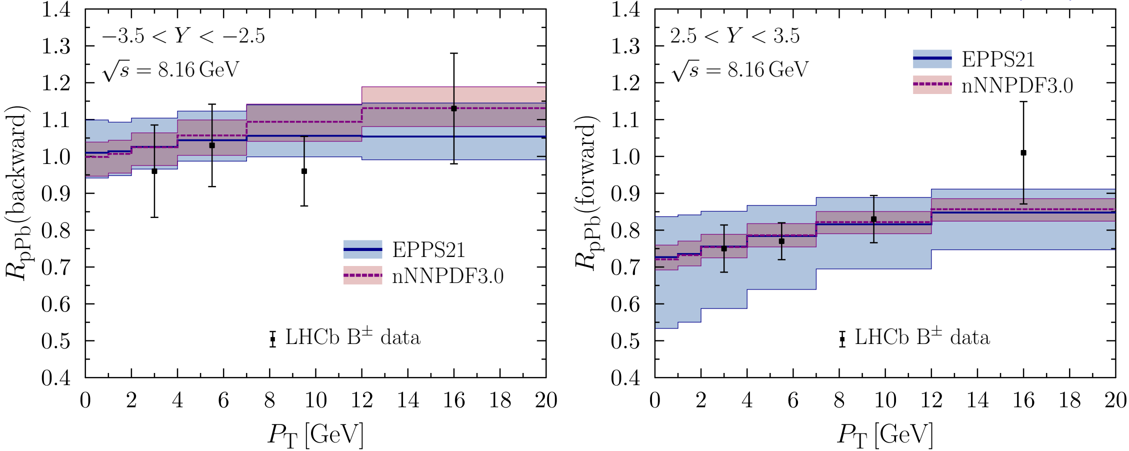


Klasen & Paukkunen, Ann. Rev. Nucl. Part. Sci. 74 (2024) 1–41



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

Neutral pions in pPb at 8.16 TeV

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

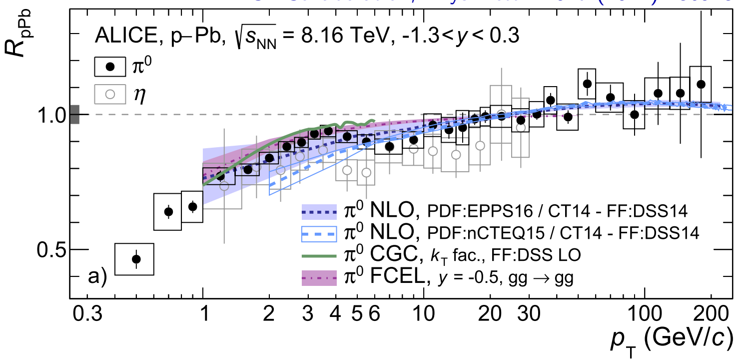
Do I see a bump also in midrapidity data at 3–4 GeV?

Similar/larger enhancements seen in charged hadrons

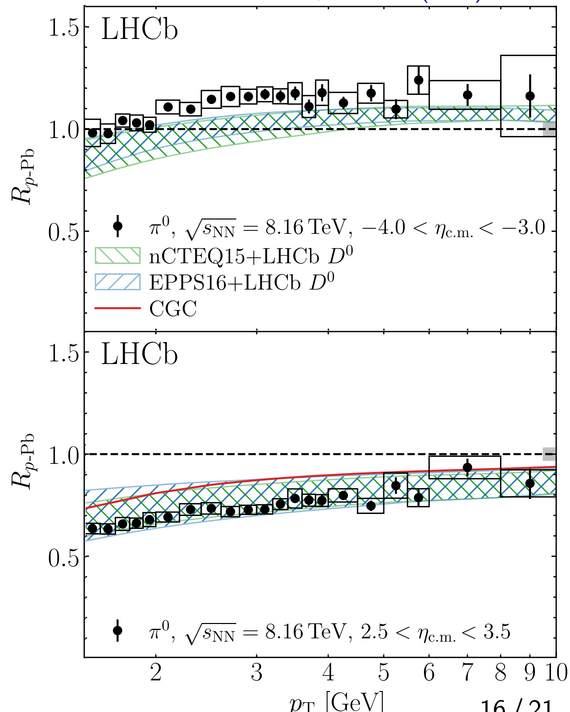
PHENIX Collaboration, PRC 101 (2020) 034910
PHENIX Collaboration, PRC 105 (2022) 064902
LHCb Collaboration, PRL 128 (2022) 142004

→ Traditional $p_{\mathrm{T}} > 3$ GeV cut probably too small

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



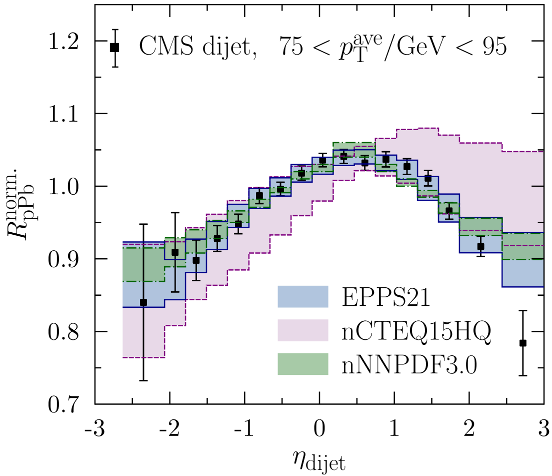
LHCb Collaboration, PRL 131 (2023) 042302

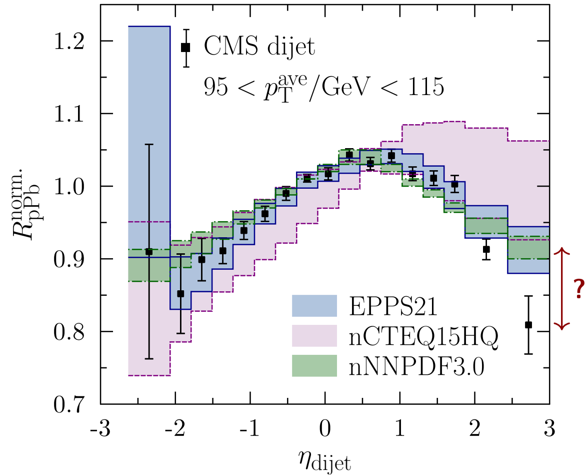


Dijets in pPb at 5.02 TeV

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

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





EPPS21 and nNNPDF3.0 include CMS dijets, given as self-normalized ratio to cancel hadronization effects:

$$R_{pPb}^{norm.} = \frac{d^2\sigma^{\mathbf{pPb}}/dp_T^{ave}d\eta_{dijet}}{d\sigma^{\mathbf{pPb}}/dp_T^{ave}} \Bigg/ \frac{d^2\sigma^{\mathbf{pp}}/dp_T^{ave}d\eta_{dijet}}{d\sigma^{\mathbf{pp}}/dp_T^{ave}}$$

Inability to fit forward data due to the missing (induced) data correlations? Or NNLO / NP effects?

Dijets in pPb at 8.16 TeV

G. Nigmatkulov, Mon 2:00 PM

New measurement of dijets at 8.16 TeV from CMS

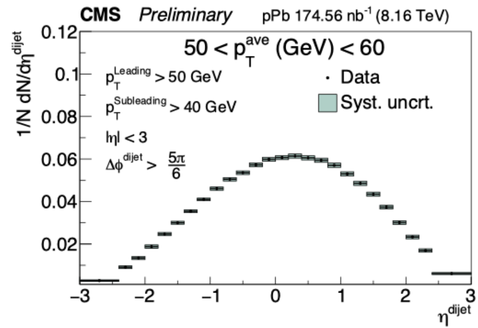
Preliminary results with rapidity spectra in 16 bins of $p_{\rm T}$ from 50 to 500 GeV

Note: the rapidity spectra carry non-vanishing proton-PDF dependence and scale uncertainty at NLO

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

- → Cure with forward-to-backward ratio?

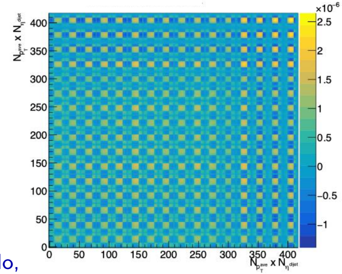
Eskola, Paukkunen, Salgado, JHEP 10 (2013) 213

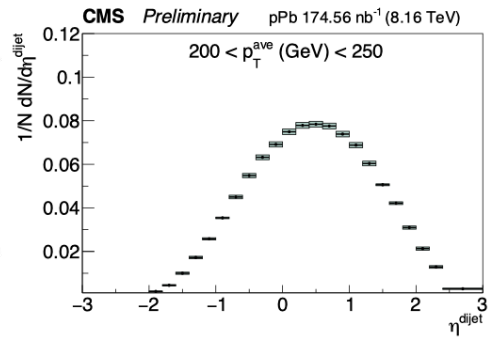


Systematic uncertainties important

- → Correlations significant
- ✓ Covariance matrix expected to be provided
- ■ N.B. For self-normalized quantities even statistical uncertainties become correlated

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



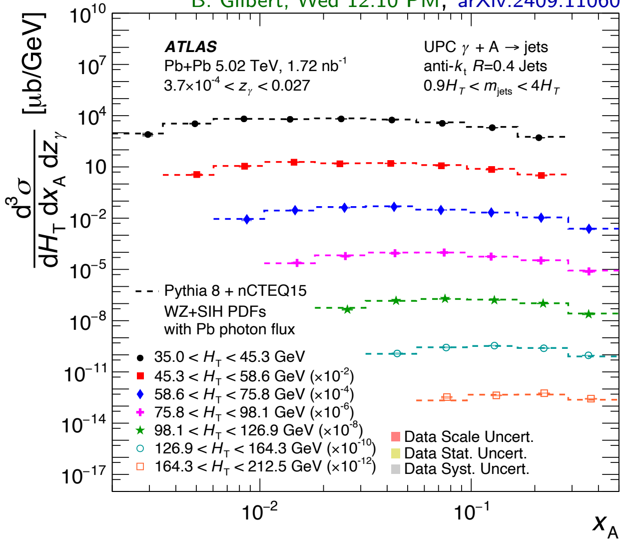


Dijet photoproduction in UPCs has been promoted as a probe of nuclear PDFs

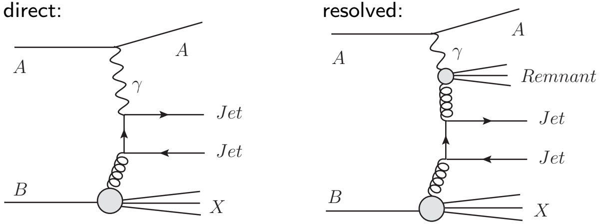
Strikman, Vogt & White, PRL 96 (2006) 082001

ATLAS measurement now final!

B. Gilbert, Wed 12:10 PM, arXiv:2409.11060



Guzey & Klasen, PRC 99 (2019) 065202



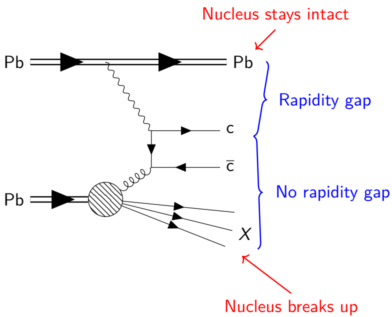
Triple differential in

$$H_{\rm T} = \sum_{i\in\text{jets}} p_{{\rm T},i}, \quad z_\gamma = \frac{M_{\text{jets}}}{\sqrt{s_{\rm NN}}}e^{+y_{\text{jets}}},$$

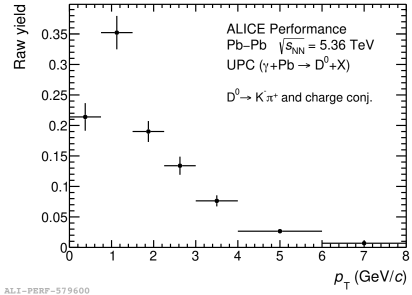
$$x_A = \frac{M_{\text{jets}}}{\sqrt{s_{\rm NN}}}e^{-y_{\text{jets}}}$$

Note: transverse-plane collision geometry gets resolved at large z_γ !

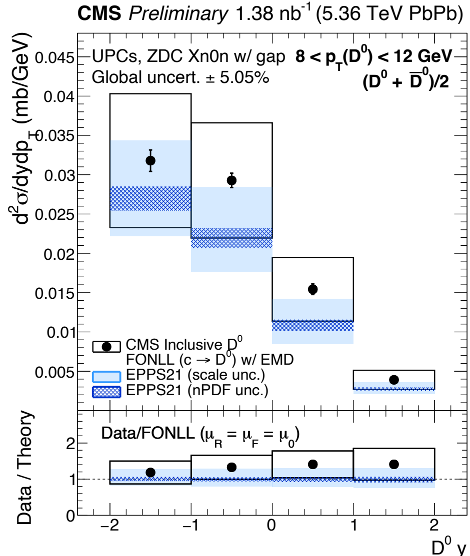
Eskola, Guzey, Helenius, PP, Paukkunen, arXiv:2404.09731



S. Nese, Wed 10:00 AM



C. Mc Ginn, Wed 10:50 AM



ALICE plans to measure inclusive D^0, $D^{\pm}$, D^* and J/ψ photoproduction

CMS preliminary UPC D^0 data in agreement with FONLL predictions within scale and systematic uncertainties

- ➔ Important cross check w.r.t. D^0 hadroproduction data

Inclusive UPC processes emerging as new nPDF probes!

Summary

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

- Recent global fits include 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 better constrained than ever before
- Data to theory agreement is starting to become sensitive to NNLO effects (low-mass DY), treatment of heavy-flavour production (D^0), imposed p_T cuts. . .
  - ➔ Can aim at over-constraining nuclear PDFs to find the limits where additional effects (saturation, cold nuclear matter energy loss, hadronization nonuniversality) become significant
  - ➔ Need both precision data and calculations
- *Inclusive* UPC processes emerging as new nPDF probes!

Thank you!

. . . and my apologies I could not cover every nPDF related analysis available

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

parent hadron or nucleus

factorization scale

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

parton flavour

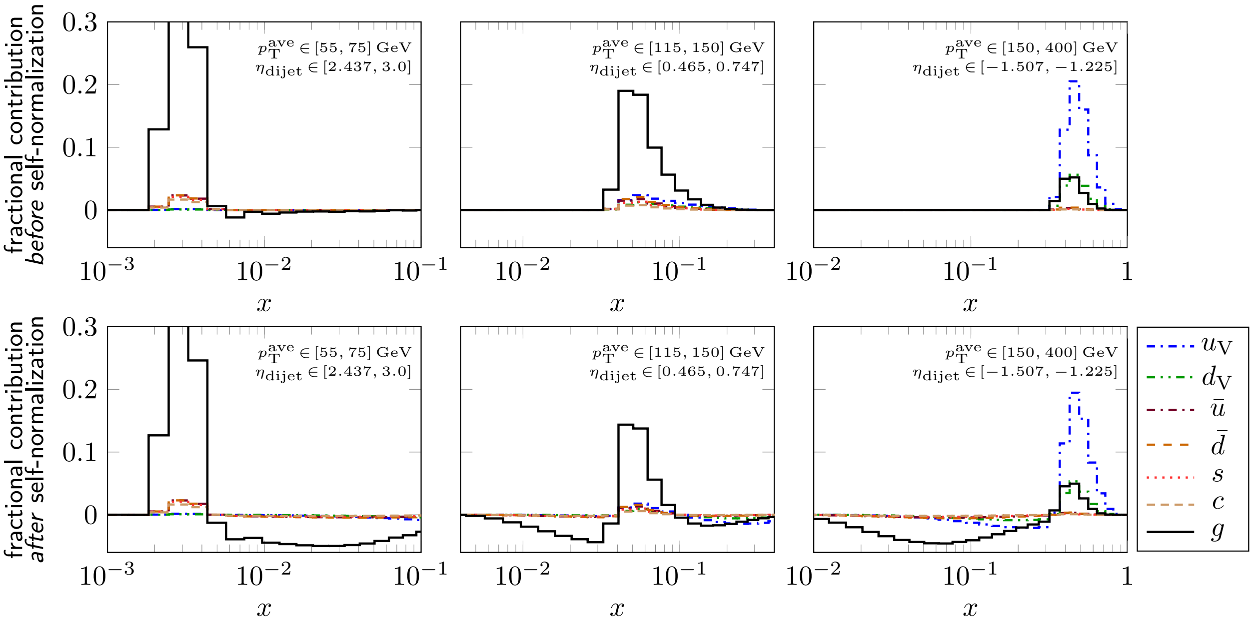
fraction of momentum carried by the parton

splitting functions

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

Mellin conv.

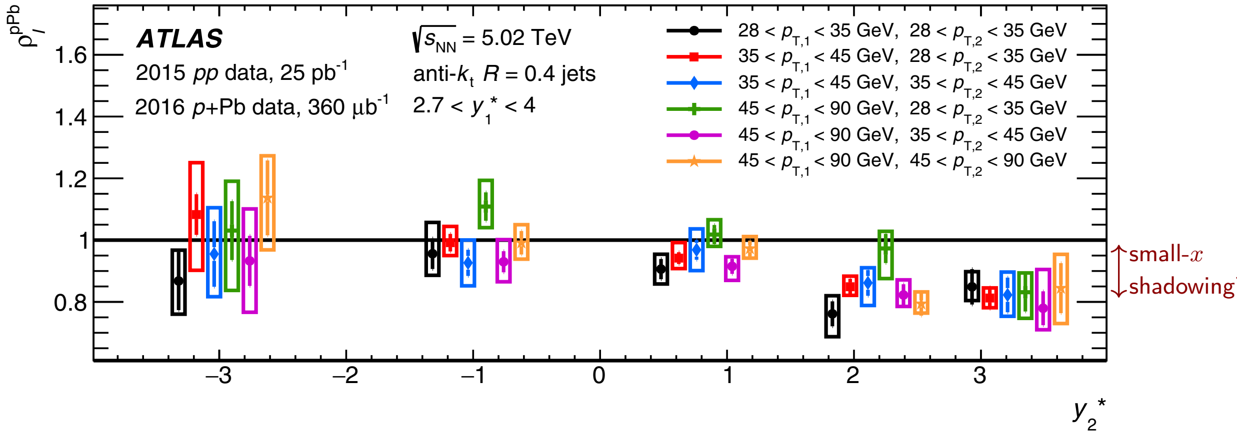
Dijets in pPb at 5.02 TeV – x-dependence at NLO pQCD



Self-normalization introduces additional (anti-)correlation between data points and across probed x!

Dijets in pPb at 5.02 TeV – per-trigger yields

ATLAS Collaboration, Phys. Rev. C 100 (2019) 034903



Nuclear modification of per-trigger yields, practically a ratio of 2-jet over 1-jet ratios:

$$\rho_I^{\mathrm{pPb}} = \frac{\mathrm{d}^4\sigma^{\mathbf{pPb}}{}_{2-\mathrm{jet}}/\mathrm{d}p_{\mathrm{T},1}\mathrm{d}y_1^*\mathrm{d}p_{\mathrm{T},2}\mathrm{d}y_2^*}{\sigma^{\mathbf{pPb}}{}_{1-\mathrm{jet}}} \Bigg/ \frac{\mathrm{d}^4\sigma^{\mathbf{pp}}{}_{2-\mathrm{jet}}/\mathrm{d}p_{\mathrm{T},1}\mathrm{d}y_1^*\mathrm{d}p_{\mathrm{T},2}\mathrm{d}y_2^*}{\sigma^{\mathbf{pp}}{}_{1-\mathrm{jet}}}$$

Forward suppression indicating small-x shadowing?

cf. D. Perepelitsa at "Heavy Ion Physics in the EIC Era" INT Program, August 22, 2024

Novel probes: Exclusive UPC J/ψ photoproduction in collinear factorization

First phenomenological implementation of the NLO corrections

Ivanov et al., EPJC 34 (2004) 297
Jones et al., J. Phys. G 43 (2016) 035002

in ultraperipheral Pb+Pb

Eskola et al., PRC 106 (2022) 035202

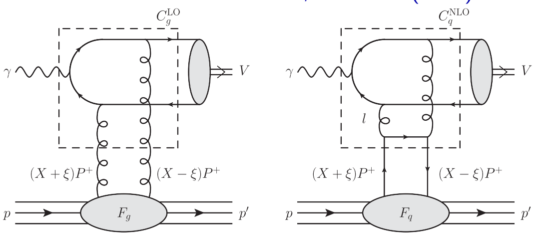
Exclusive process

- ➔ need a mapping between GPDs and traditional PDFs

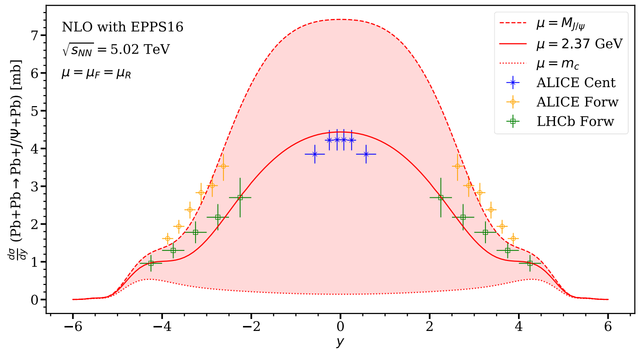
Large scale uncertainty

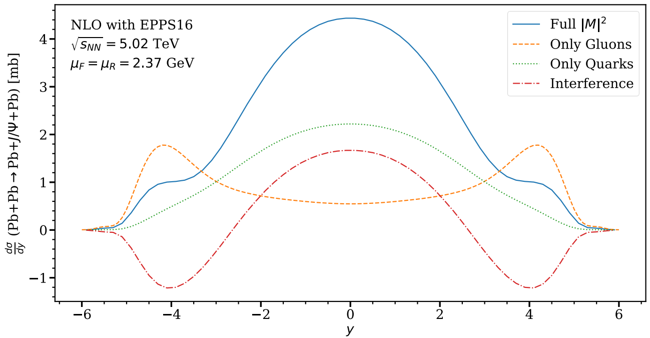
- ➔ perturbative convergence?

Flett et al., PRD 101 (2020) 094011

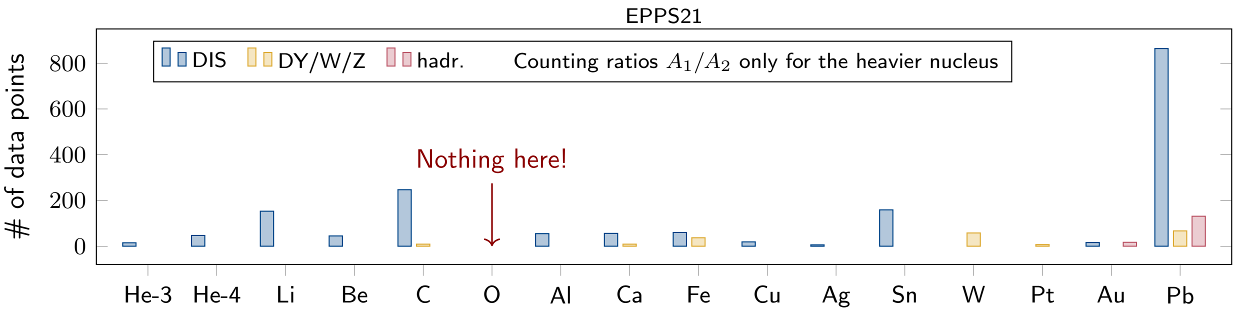


Eskola et al., PRC 106 (2022) 035202





Data availability w.r.t. A



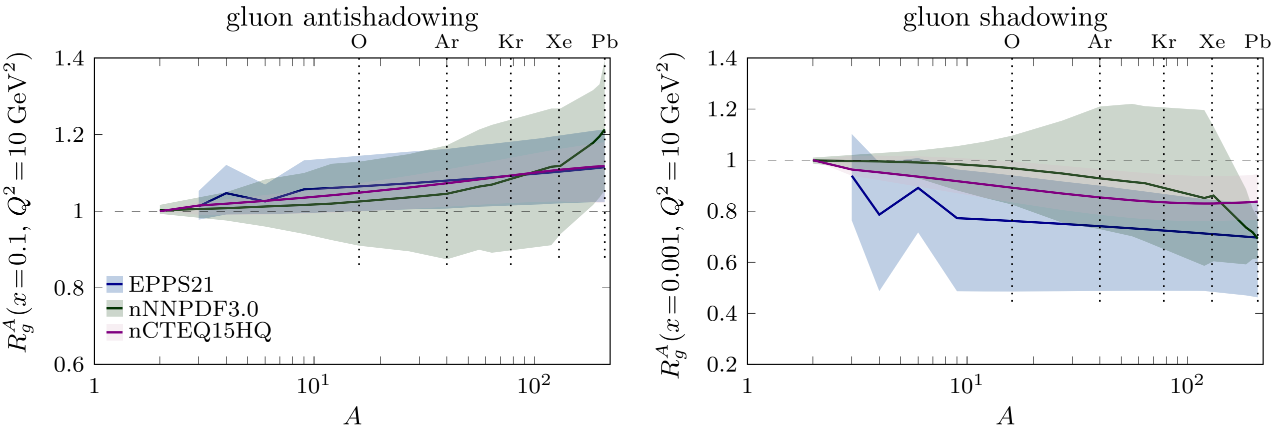
$\sim 50\%$ of the data points are for Pb!

- ☺ 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 nuclear modifications

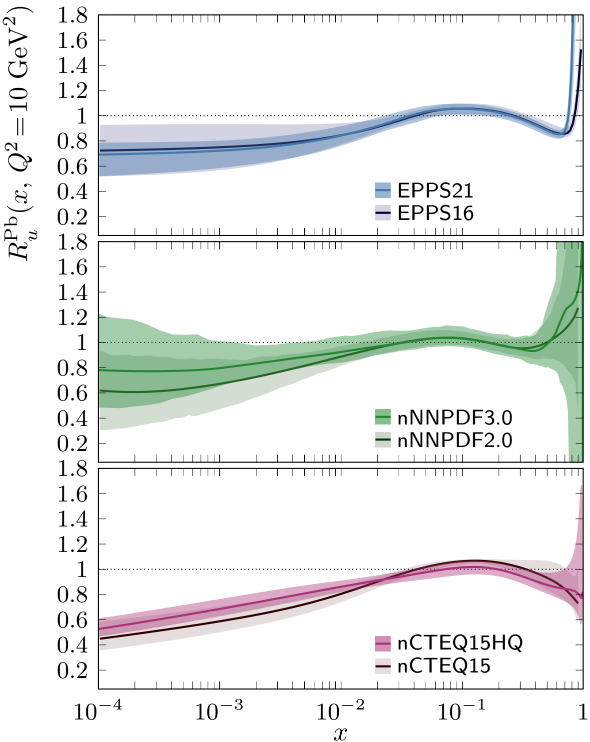


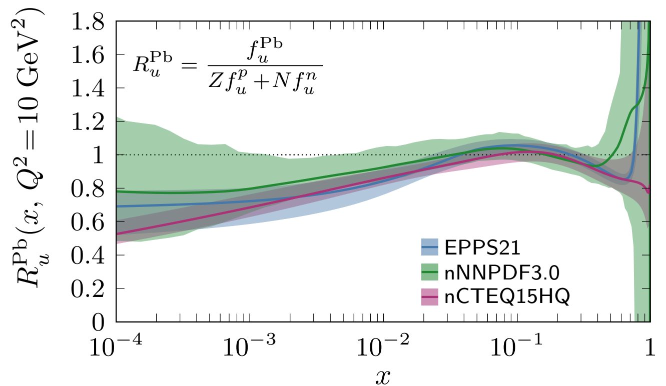
A-dependence of gluon PDFs not well constrained by data!

- 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

Impact on nPDFs – *up*

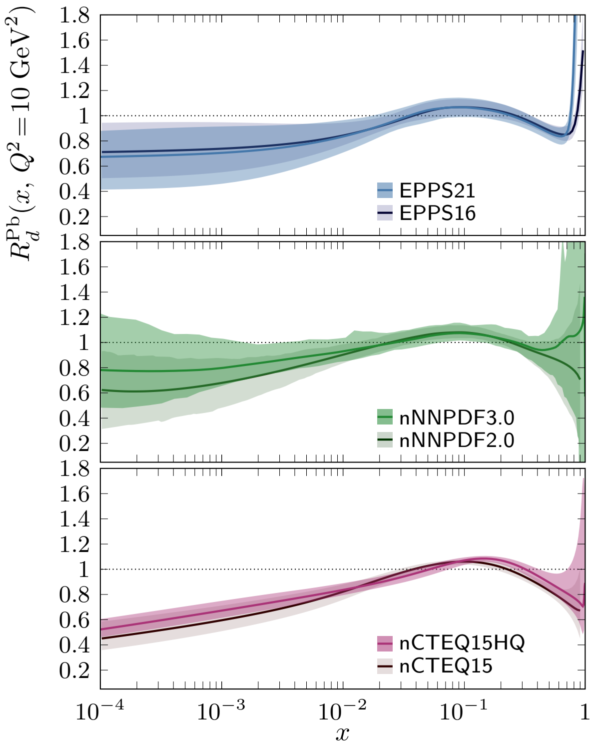


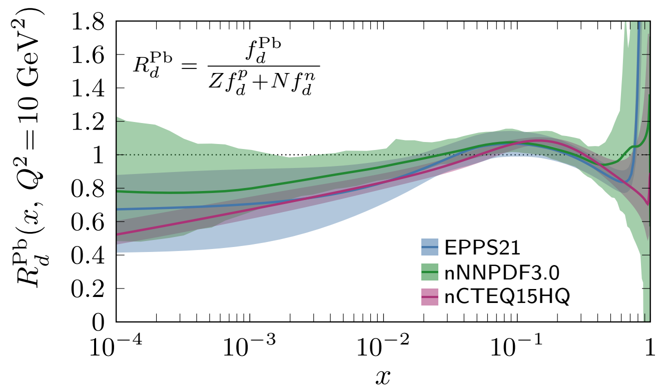


Valence region constrained by fixed-target DIS data

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

Impact on nPDFs – *down*

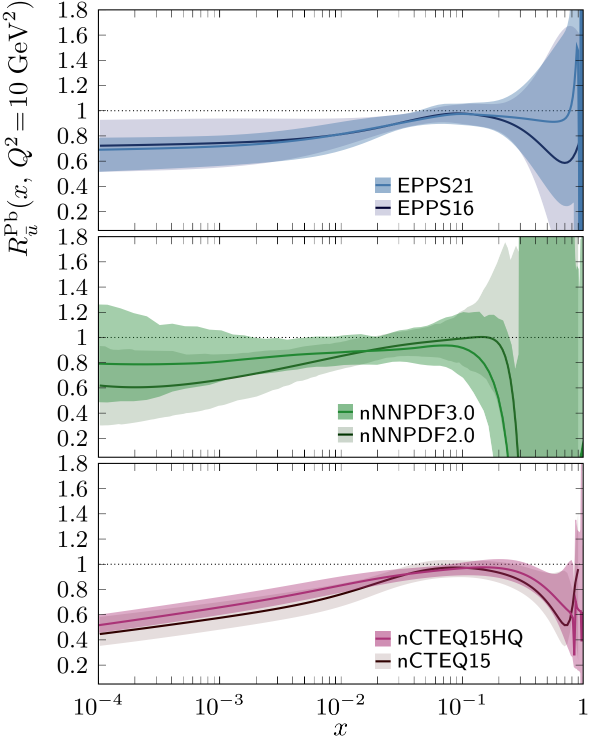


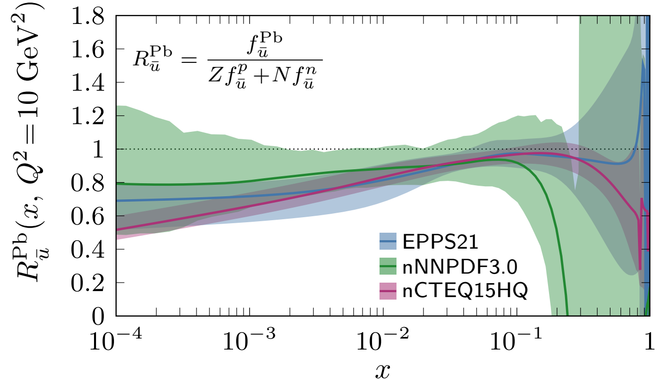


Valence region constrained by fixed-target DIS data

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

Impact on nPDFs – *anti-up*

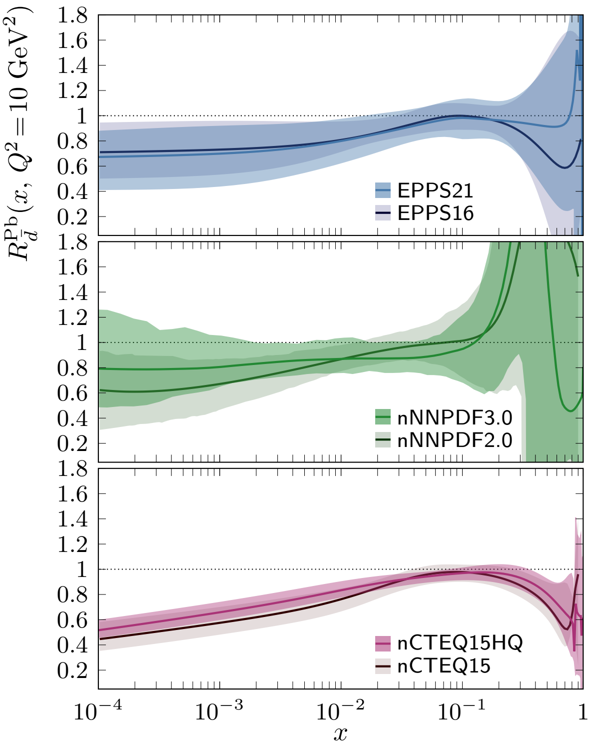


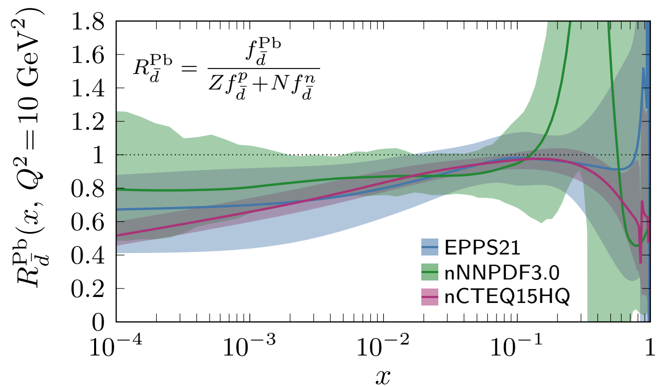


Valence / sea quark separation dominated by fixed-target DY data

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

Impact on nPDFs – *anti-down*

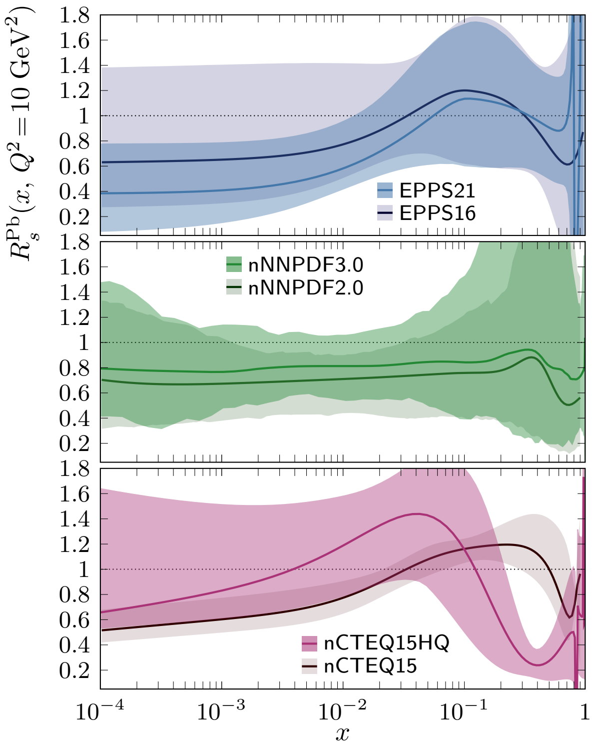


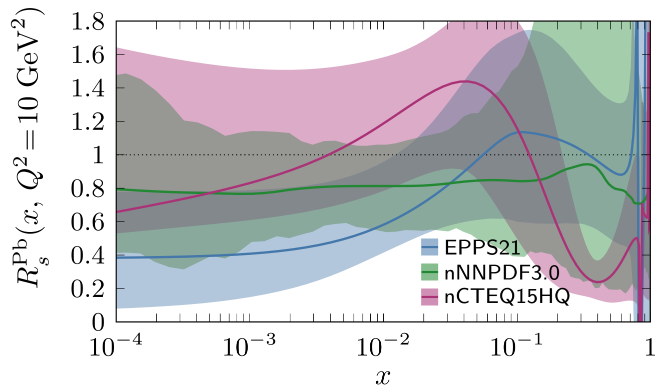


Valence / sea quark separation dominated by fixed-target DY data

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 for improved constraints

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