Overview of nPDF progress and issues / problems

Petja Paakkinen

University of Jyväskylä

AoF CoE in Quark Matter
partner in ERC AdG YoctoLHC

QCD challenges from pp to AA collisions

3 September 2024

University of Jyväskylä · Centre of Excellence in Quark Matter · Research Council of Finland · Helsinki Institute of Physics · erc

Nuclear PDFs from global analyses

Nuclear PDFs (nPDFs) are fitted 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 on fit parameters, minimize:

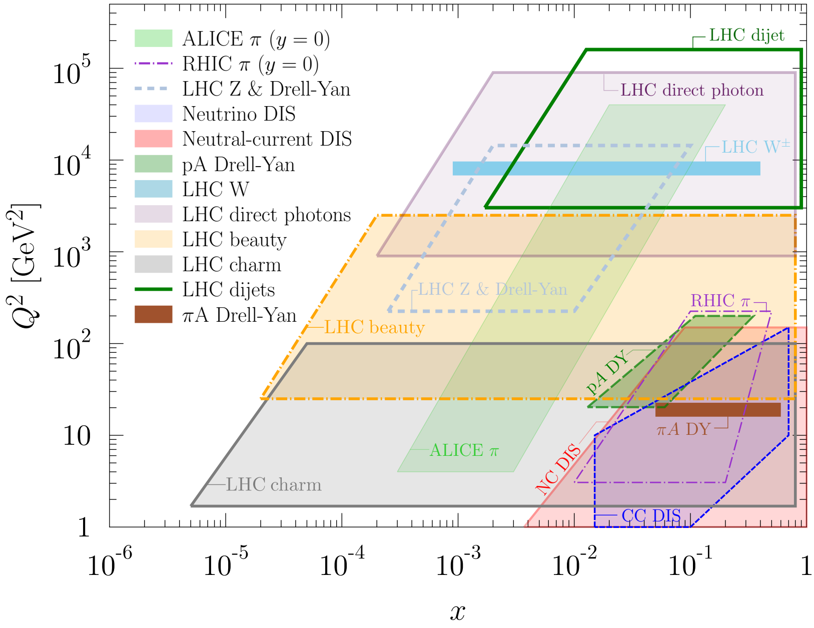
Sum over data sets

$$\chi^2_{\text{tot}} = \sum_k (D_k - T_k)^T \, C_k^{-1} \, (D_k - T_k)$$

(data, theory, cov.)

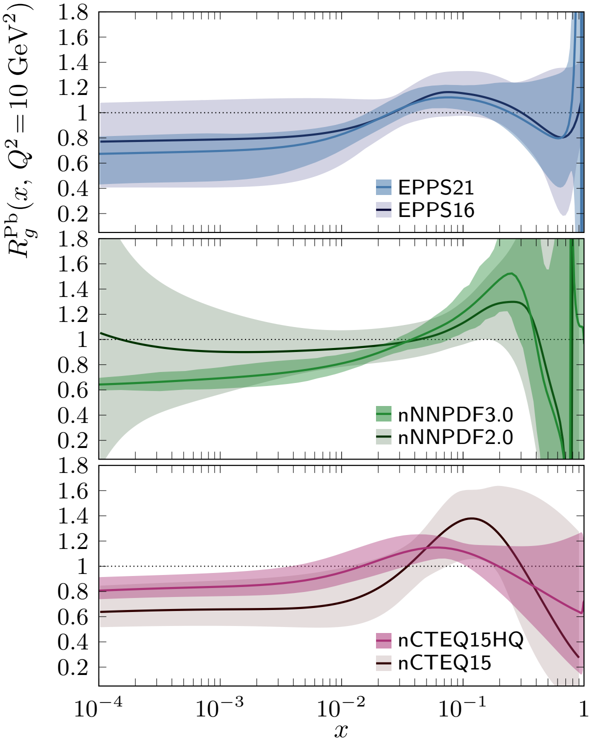
Data correlations important!

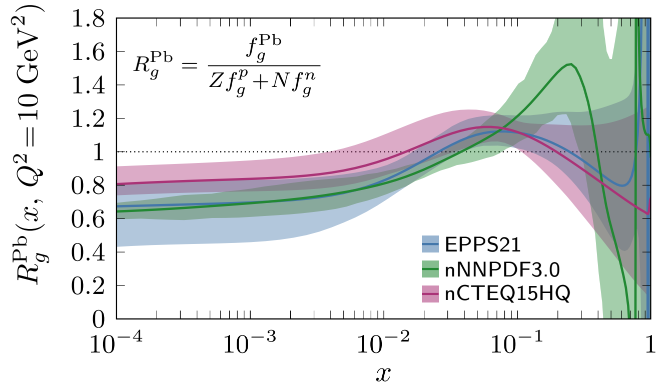
New review: Klasen & Paukkunen, Ann. Rev. Nucl. Part. Sci. 74 (2024) 1–41



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



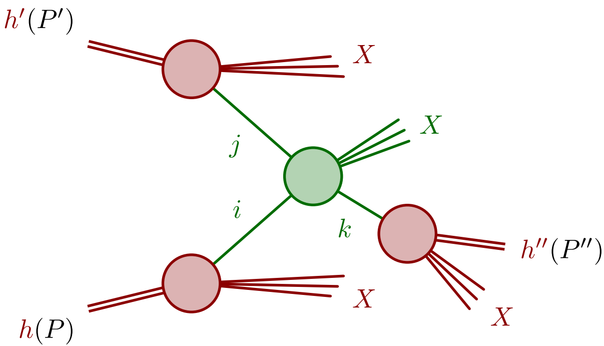


All major global nPDF fits find significant reduction in gluon uncertainties when including LHC data

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

Differences between sets due to methodological and data-selection choices

Hadron-production

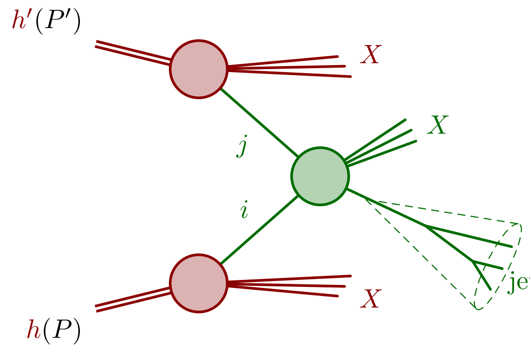


$$\sigma^{h+h'\to h''+X} = \sum_{i,j,k\in\{q,\bar{q},g\}} f_i^h \otimes f_j^{h'} \otimes \hat{\sigma}^{ij\to k+X} \otimes D_k^{h''}$$

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

➔ a source of uncertainty for PDF fits

Jet-production



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

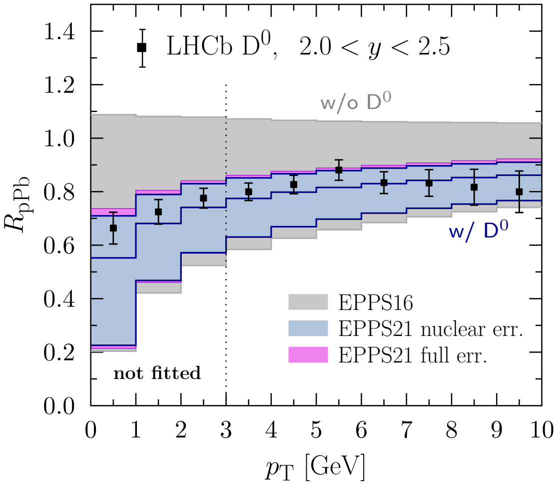
Instead of fragmentation functions:

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

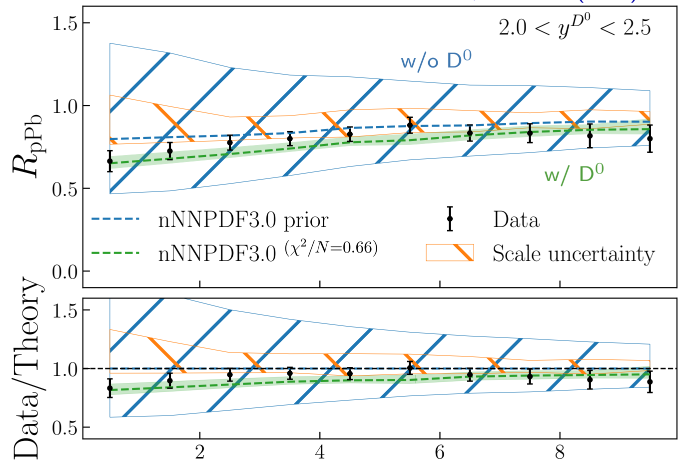
D^0s in EPPS21 and nNNPDF3.0

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

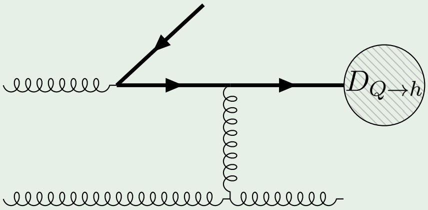
In *fixed flavour number scheme*, **valid at small** p_{T}, heavy quarks are produced only at the matrix element level

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

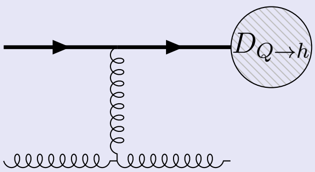
ZM-VFNS

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

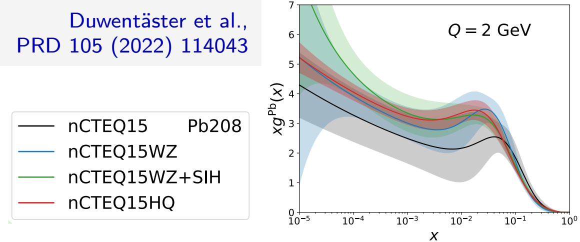
A *general-mass variable flavour number scheme* combines the two by supplementing subtraction terms to prevent double counting of the resummed splittings, **valid at all** p_{T}

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

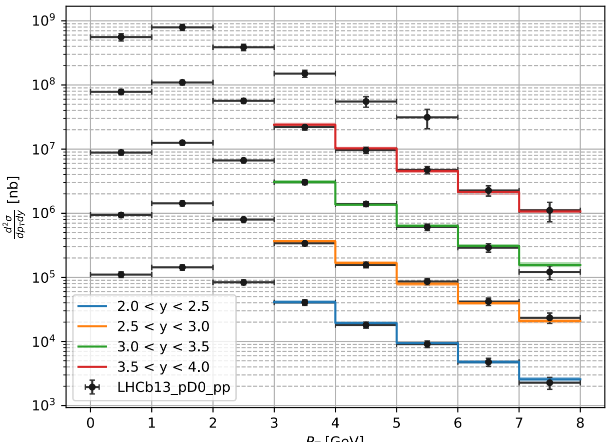


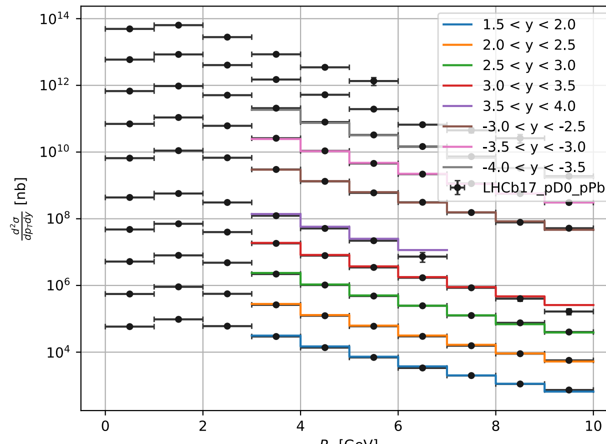
nCTEQ15HQ uses a data-driven approach

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





D^0s in pPb at 8.16 TeV

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

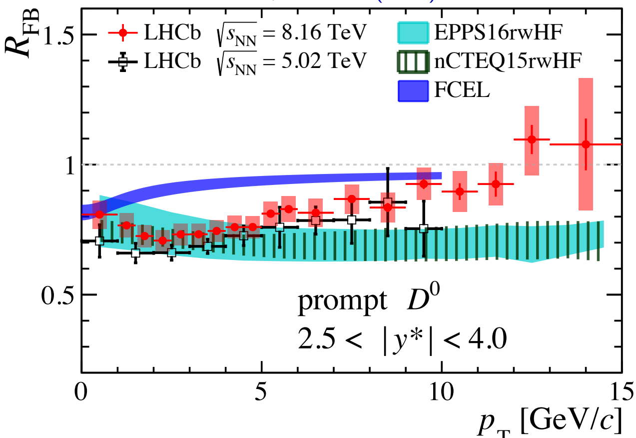
(not included in the nPDF analyses yet)

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

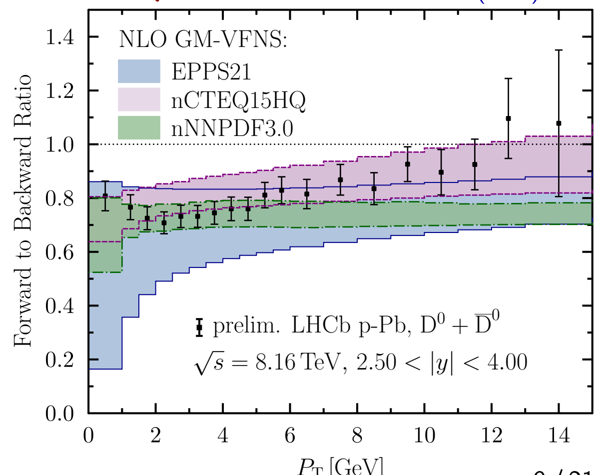
(Here HELAC vs. S-ACOT-m_T vs. FCEL)

Rather different predictions!

LHCb Collaboration, PRL 131 (2023) 102301



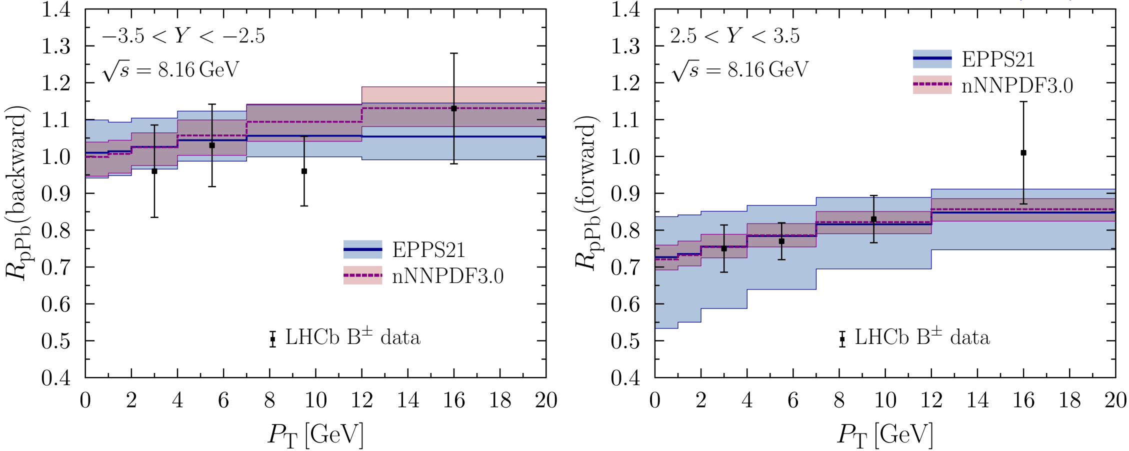
Klasen & Paukkunen, Ann. Rev. Nucl. Part. Sci. 74 (2024) 1–41



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}

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

→ Need more statistics for strong constraints

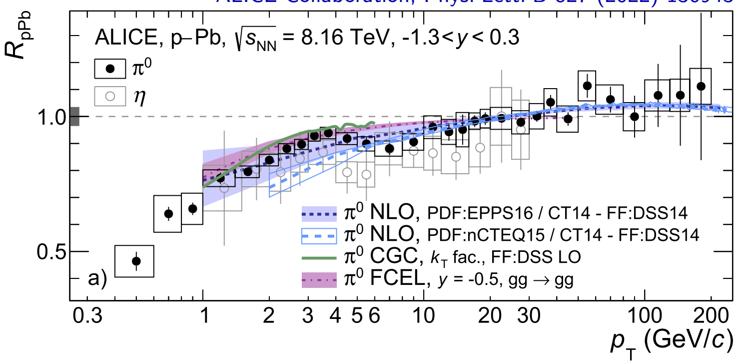
Neutral pions in pPb at 8.16 TeV

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

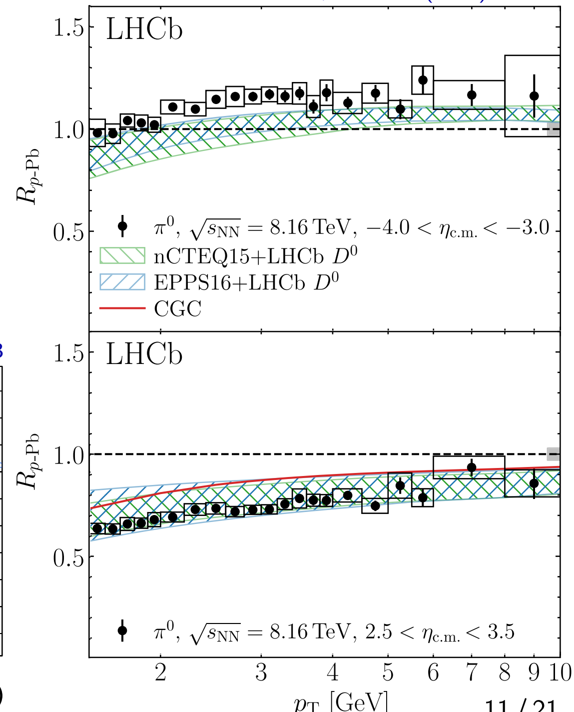
Do I see a bump also in midrapidity data at 3–4 GeV?

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

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



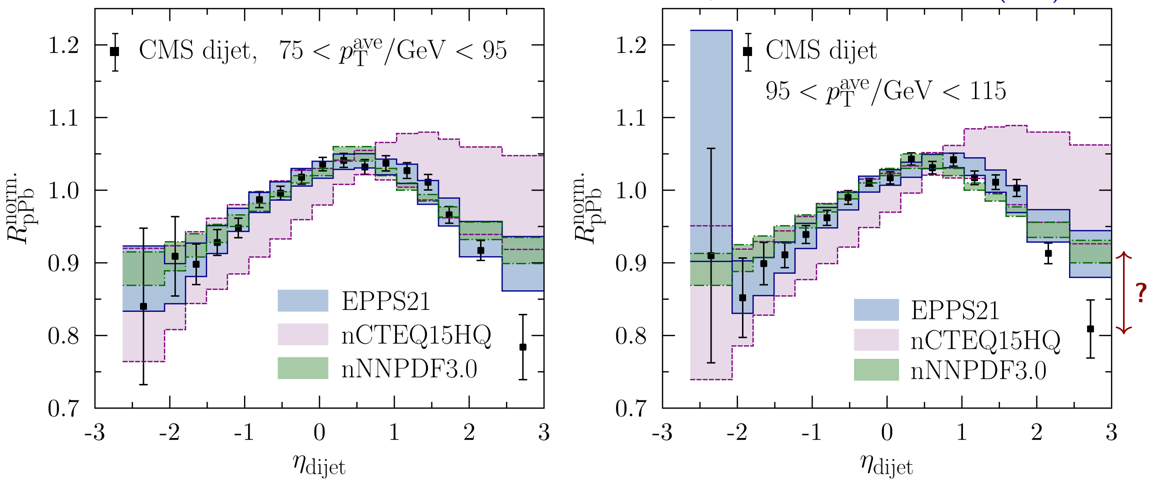
LHCb Collaboration, PRL 131 (2023) 042302



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

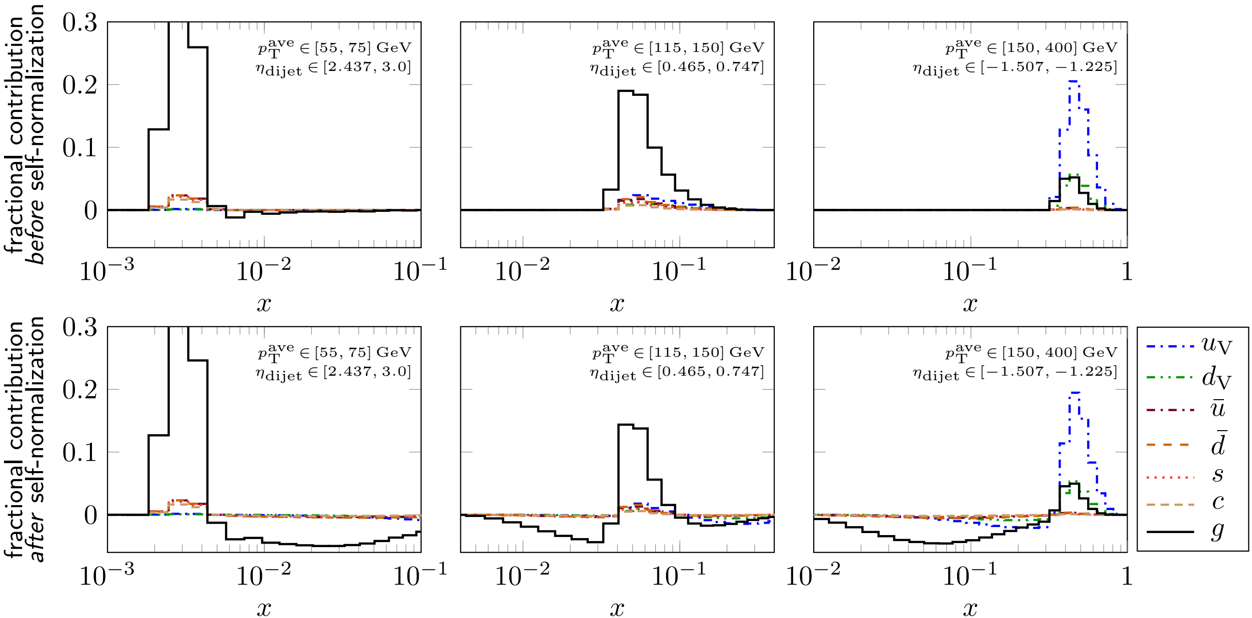


Data provided as self-normalized ratio to cancel hadronization effects:

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

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

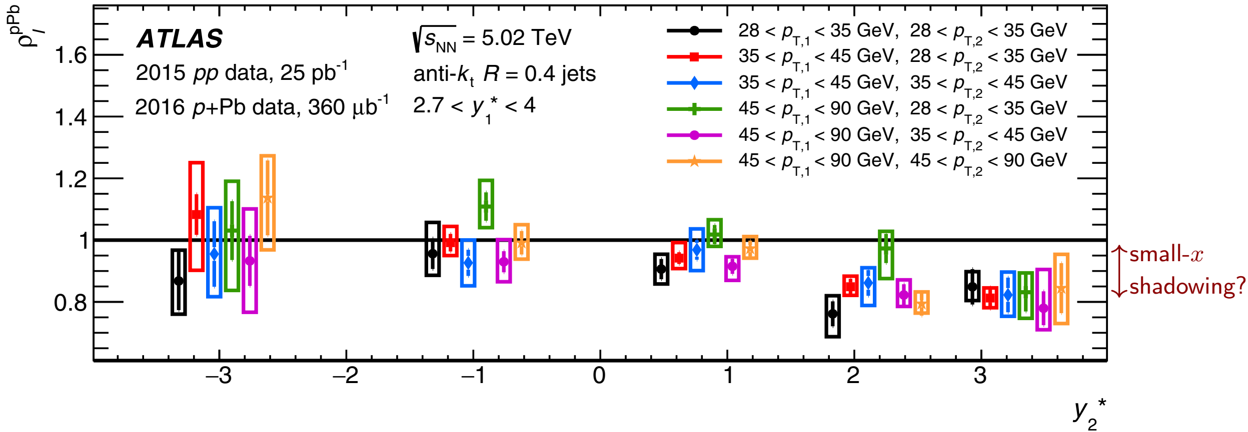
Dijets in pPb at 5.02 TeV – x-dependence at NLO pQCD



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:

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

We are missing a very basic measurement: pPb dijet *cross section* (min. bias, not normalized by any trigger) !

→ Would test our understanding of jet hadronization / UE corrections in pPb

'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

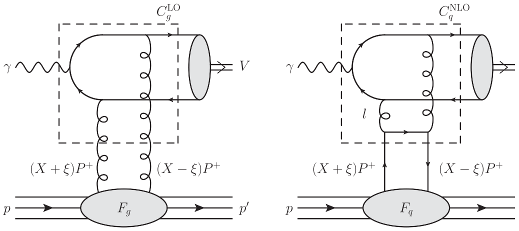
Exclusive process

- ➔ need a mapping between GPDs and traditional PDFs

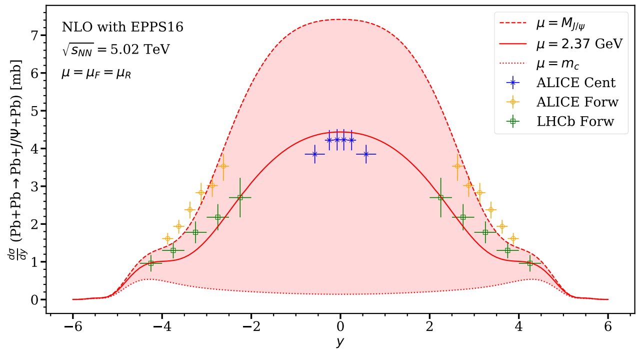
Large scale uncertainty

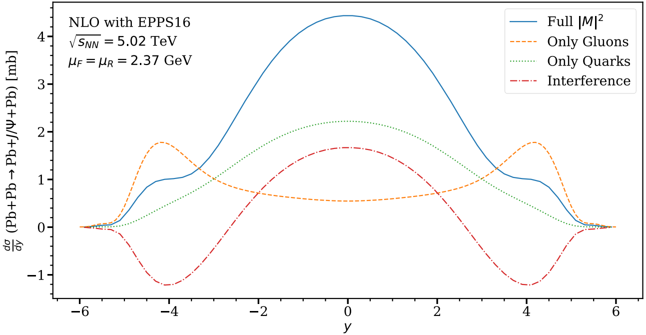
- ➔ perturbative convergence?

Flett et al., PRD 101 (2020) 094011



Eskola et al., PRC 106 (2022) 035202

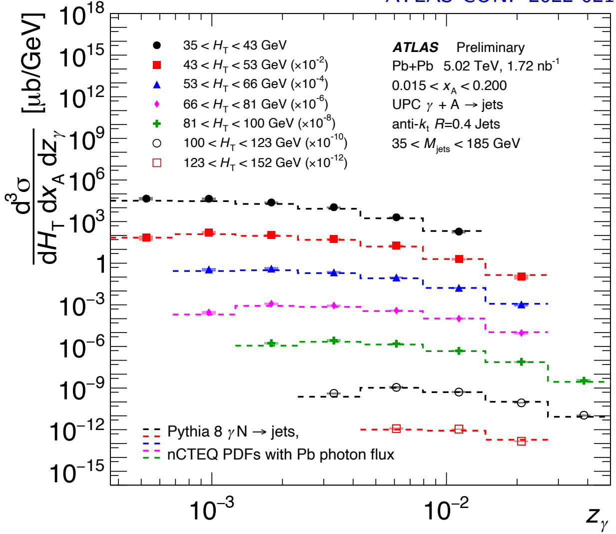




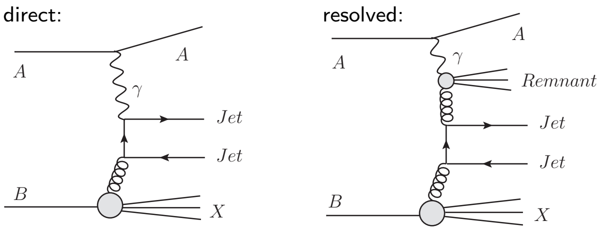
Dijet photoproduction in UPCs has been promoted as a probe of nuclear PDFs

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

ATLAS-CONF-2022-021



Guzey & Klasen, PRC 99 (2019) 065202



ATLAS measurement triple differential in

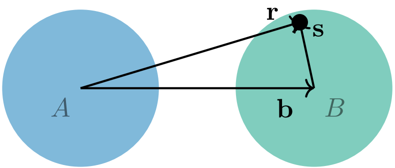
$$H_\mathrm{T} = \sum_{i\in\mathrm{jets}} p_{\mathrm{T},i}, \quad z_\gamma = \frac{M_\mathrm{jets}}{\sqrt{s_\mathrm{NN}}} e^{+y_\mathrm{jets}},$$

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

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

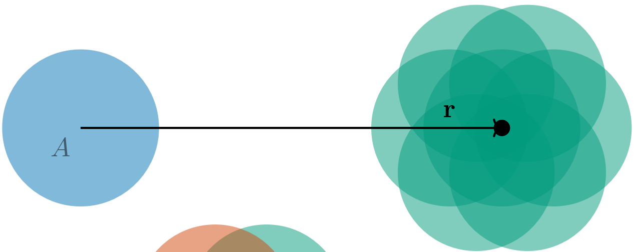
Eskola, Guzey, Helenius, PP, Paukkunen, arXiv:2404.09731

Impact-parameter dependence of UPC dijet production



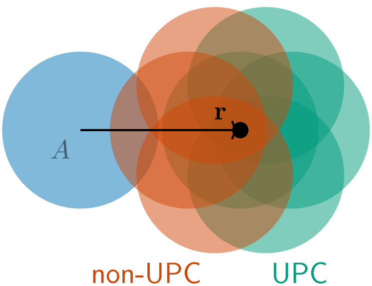
Using an impact-parameter dependent factorization similar to

Baron & Baur, PRC 48 (1993) 1999
Greiner et al., PRC 51 (1995) 911



$|\mathbf{r}| \sim |\mathbf{b}| \gg |\mathbf{s}| \sim R_B$ ‘far-passing’

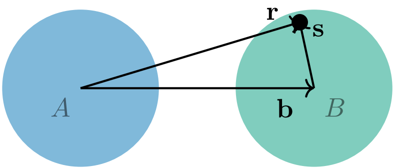
➔ any $\mathbf{s}$ equally allowed



$|\mathbf{r}| \sim |\mathbf{b}| \sim |\mathbf{s}| \sim R_B$ ‘close-encounter’

➔ restricted $\mathbf{s}$ phase space for UPC events

Impact-parameter dependence of UPC dijet production



Using an impact-parameter dependent factorization similar to

Baron & Baur, PRC 48 (1993) 1999
Greiner et al., PRC 51 (1995) 911

$$d\sigma^{AB\to A+\mathrm{dijet}+X} = \sum_{i,j,X'} \int d^2\mathbf{b}\, \Gamma_{AB}(\mathbf{b}) \int d^2\mathbf{r}\, f_{\gamma/A}(y,\mathbf{r}) \otimes f_{i/\gamma}(x_\gamma, Q^2) \otimes \int d^2\mathbf{s}\, f_{j/B}(x, Q^2, \mathbf{s}) \otimes d\hat{\sigma}^{ij\to \mathrm{dijet}+X'} \delta(\mathbf{r}-\mathbf{s}-\mathbf{b})$$

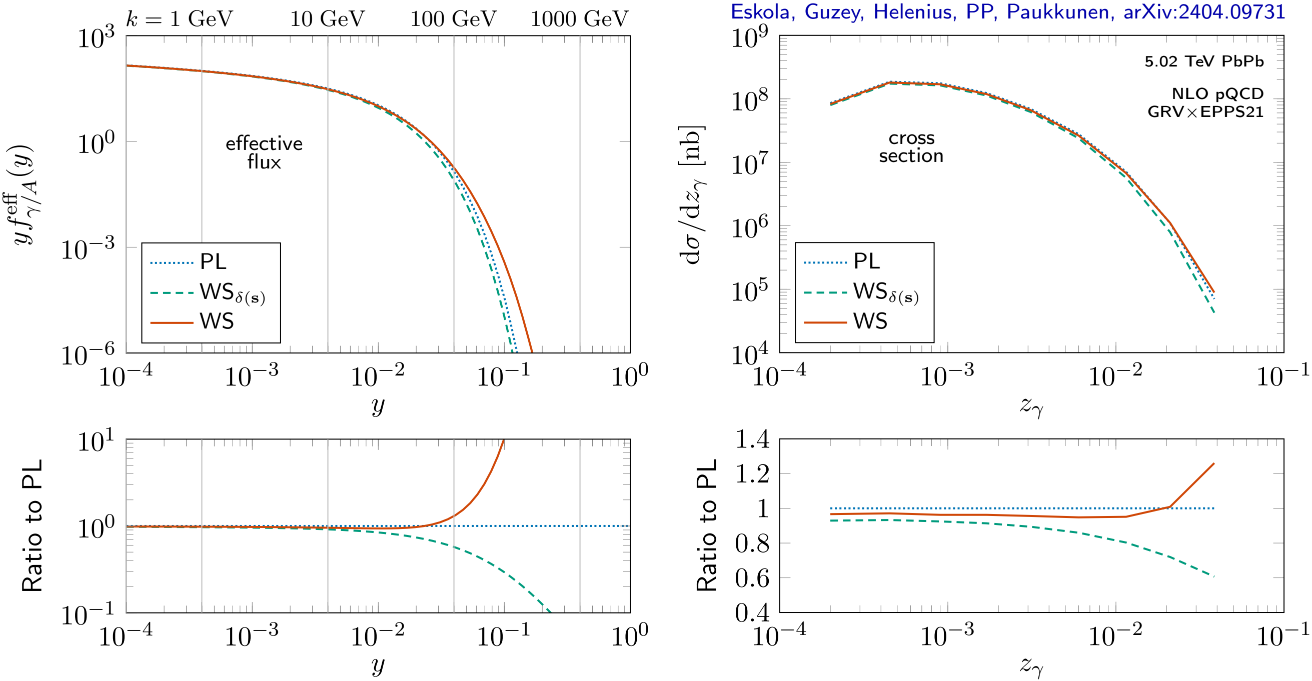
Now, <u>if</u> $f_{j/B}(x, Q^2, \mathbf{s}) = \frac{1}{B} T_B(\mathbf{s}) \cdot f_{j/B}(x, Q^2)$, we can write

$$d\sigma^{AB\to A+\mathrm{dijet}+X} = \sum_{i,j,X'} f^{\mathrm{eff}}_{\gamma/A}(y) \otimes f_{i/\gamma}(x_\gamma, Q^2) \otimes f_{j/B}(x, Q^2) \otimes d\hat{\sigma}^{ij\to \mathrm{dijet}+X'}$$

where the <u>effective</u> photon flux reads

$$f^{\mathrm{eff}}_{\gamma/A}(y) = \frac{1}{B} \int d^2\mathbf{r} \int d^2\mathbf{s}\, f_{\gamma/A}(y,\mathbf{r})\, T_B(\mathbf{s})\, \Gamma_{AB}(\mathbf{r}-\mathbf{s})$$

cf. ATLAS-CONF-2022-021 (Appendix A)

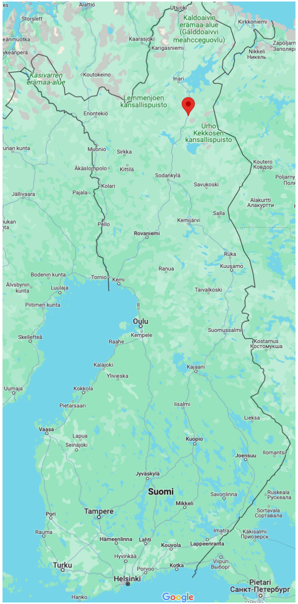


➔ Different approximations of the effective flux diverge at large photon energies

Summary

The main points I wanted to make:

- Heavy-flavour production is *scheme dependent* in the *perturbative expansion* of QCD
  - → Drawing strong conclusions based on predictions in just one scheme is potentially misleading
- Some excess in low-p_{T} light-hadron production observed over nPDF predictions
  - → Room for higher-twist effects? Hadronization non-universality?
- Per-trigger yields / self-normalization induce correlations between data points
  - → We are missing a measurement of pPb dijet cross section
- *Inclusive* UPC processes emerging as new nPDF probes!
  - → For processes sensitive to high photon energies it becomes necessary to treat the full transverse-plane collision geometry



When?

- June 9-13 2025, 24 hours of daylight

Where?

- Saariselkä, finnish Lapland
- Booking made to hotel Riekonlinna

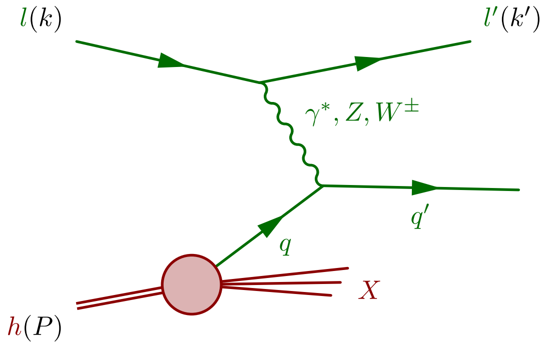
How to get there?

- Daily flights from Helsinki to Ivalo, eg.
  - Sunday June 8, HEL→IVL: 6:45 - 8:55, 21:45 - 23:15
  - Friday June 13, IVL→HEL: 22:00 - 23:30
  - Saturday June 14, IVL→HEL: 12:45 - 14:55
- Also train/bus options available
- Helsinki, many direct flights from Europe/Asia/US

Thank you!

Probes with leptonic final states

Deep inelastic scattering (DIS)



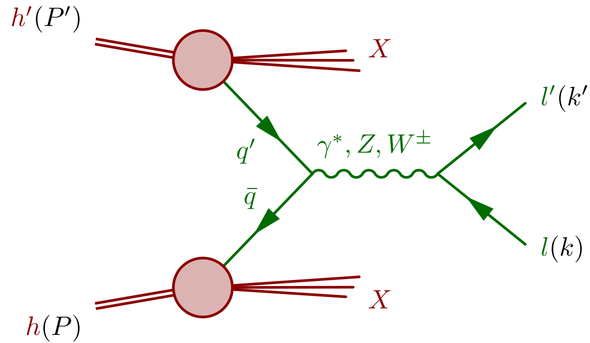
For the photon-mediated case:

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

$$\left.\begin{aligned} Q^2 &= -(k-k')^2 \\ x &= \frac{Q^2}{2P\cdot(k-k')} \end{aligned}\right\}$$

← access scale and momentum-fraction dependence through external kinematics

Drell-Yan (DY)



The photon-mediated case:

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

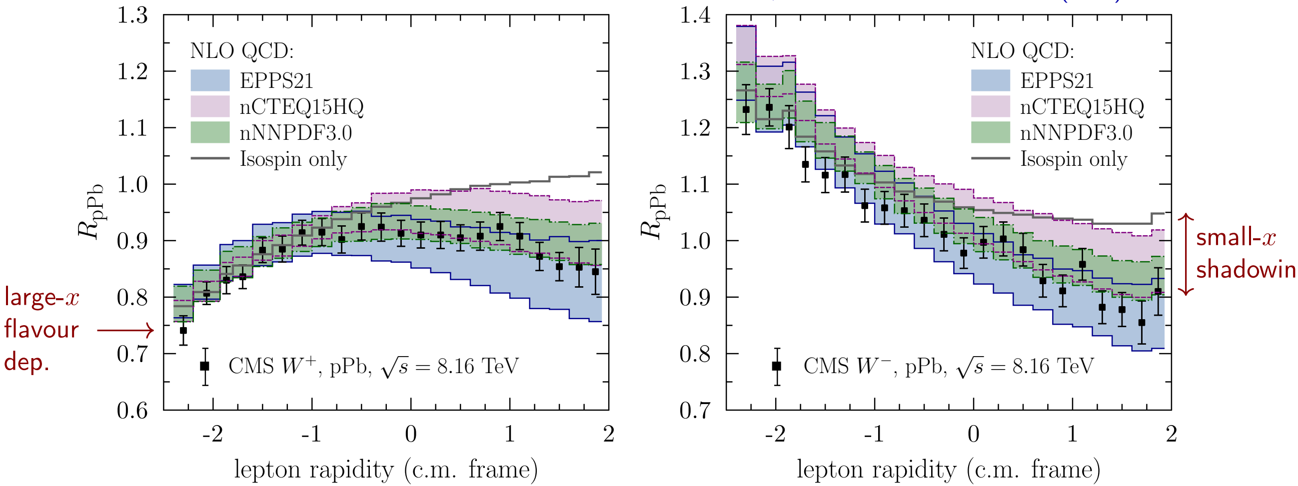
$$M^2 = (k+k')^2 = x_1 x_2 s$$

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

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:

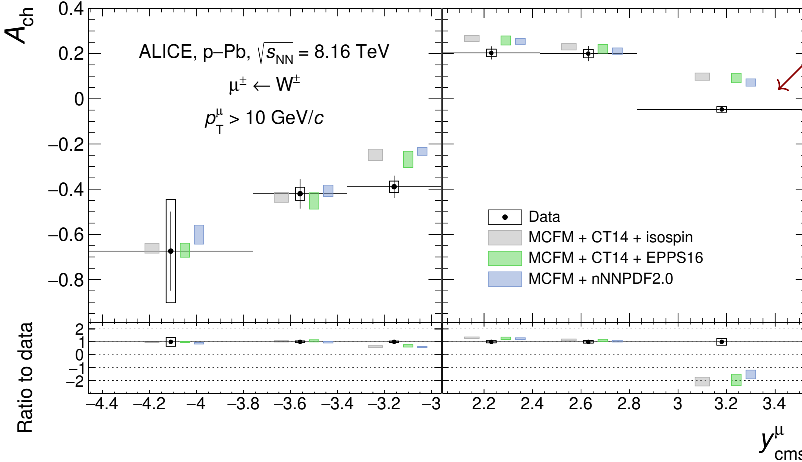
nCTEQ15HQ, nNNPDF3.0, TUJU21 ← Use absolute pPb cross sections

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

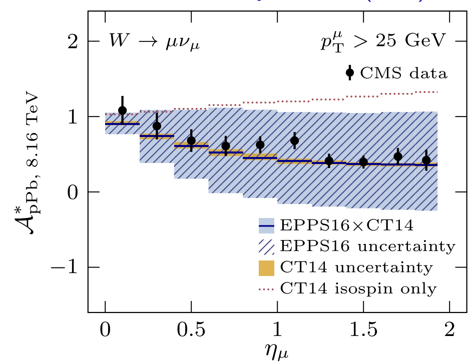
Paukkunen & Salgado, JHEP 03 (2011) 071

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

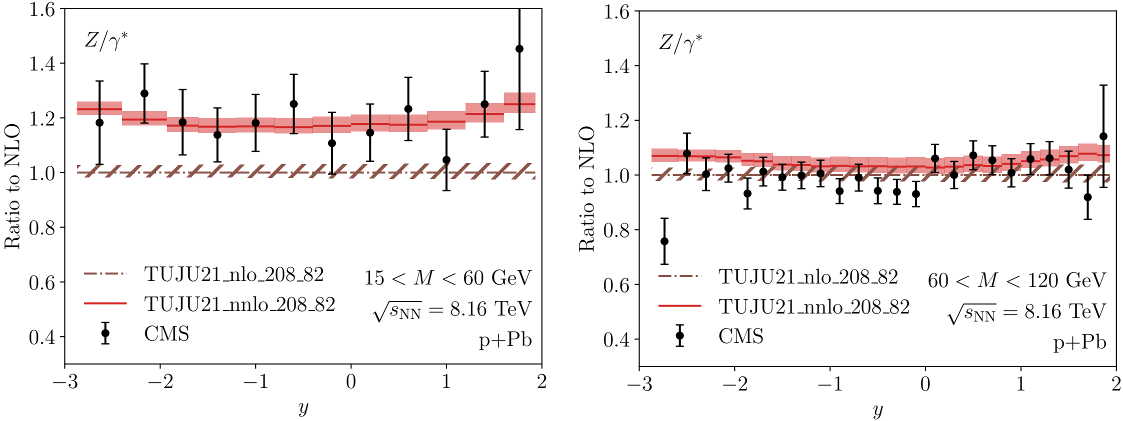
Eskola, PP, Paukkunen, Salgado, Eur. Phys. J. C 82 (2022) 271



Z bosons in pPb at 8.16 TeV

pPb data from: CMS Collaboration, JHEP 05 (2021) 182

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



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

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

Z-peak region ($60 < M < 120$ 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

➔ Need a treatment of outlier/inconsistent data in the fit?