Nuclear PDFs at the beginning of LHC Run 3

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S@INT Seminar

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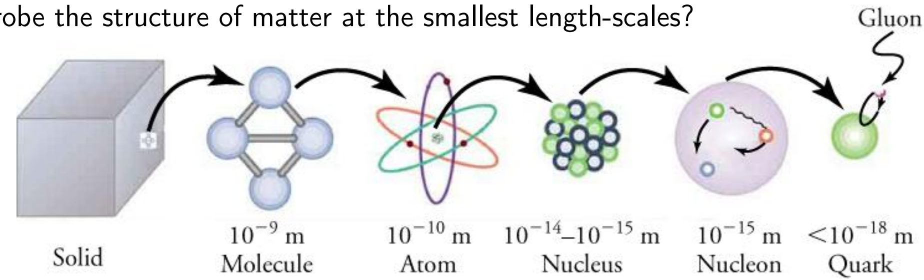
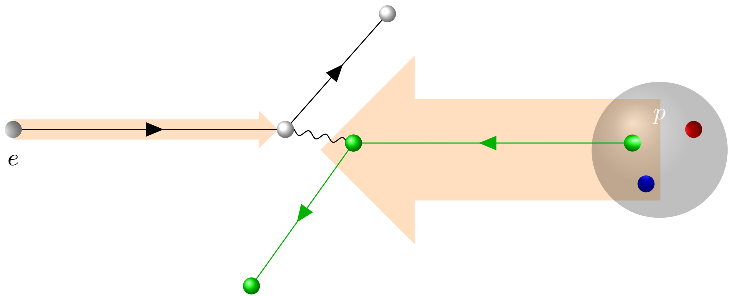
HELSINKI INSTITUTE OF PHYSICS
erc

Probing the nucleon structure

Q: How to probe the structure of matter at the smallest length-scales?



A: Hit it as hard as you can and see what comes out



But what is it that we are probing at sub-nucleon level? ➔ Need help from theory!

At the heart of it all: Collinear factorisation of 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...

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

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

parent hadron or nucleus

factorisation scale

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

parton flavour

fraction of momentum carried by the parton

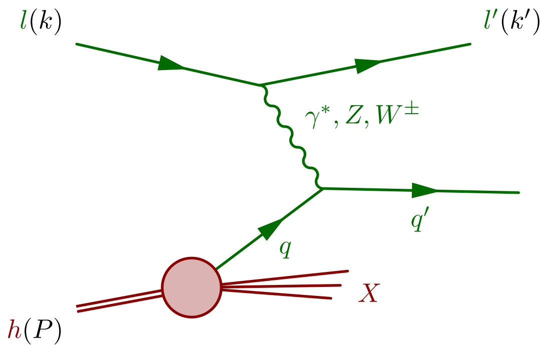
splitting functions

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.

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

Deep inelastic scattering (DIS)



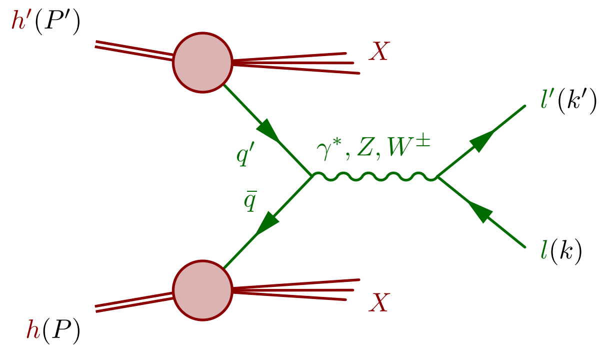
For the photon-mediated case:

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

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

access scale and momentum-fraction dependence through external kinematics

Drell-Yan (DY)



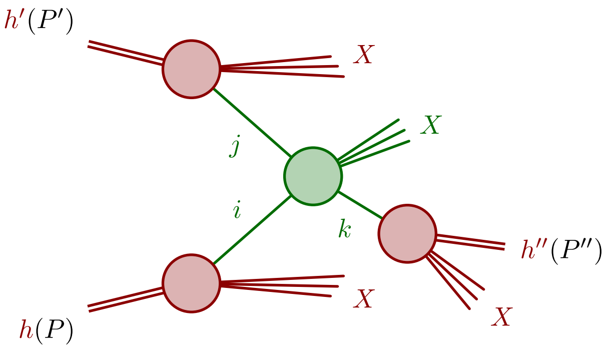
The photon-mediated case:

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

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

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

Hadron-production

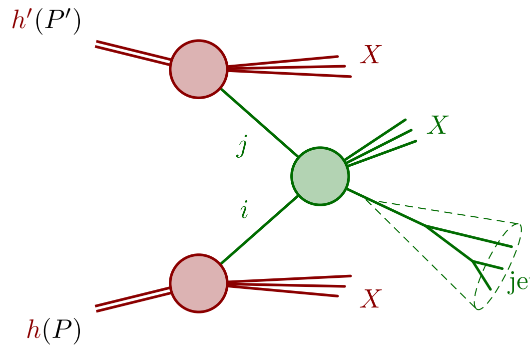


$$\sigma^{h+h'\to h''+X} = \sum_{i,j,k\in\{q,\bar{q},g\}} f_i^h \otimes f_j^{h'} \otimes \hat{\sigma}^{ij\to k+X} \otimes D_k^{h''}$$

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

➔ a source of uncertainty for PDF fits

Jet-production



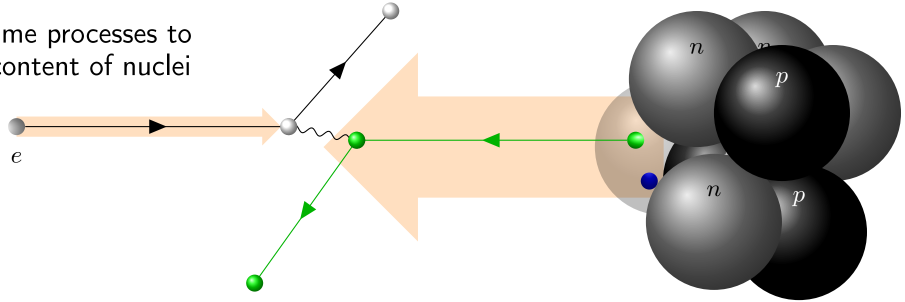
$$\sigma^{h+h'\to \text{jet}+X} = \sum_{i,j\in\{q,\bar{q},g\}} f_i^h \otimes f_j^{h'} \otimes \hat{\sigma}^{ij\to \text{jet}+X}$$

Additional complications:

- need an IR-safe definition of a jet
- non-perturbative corrections

Why *nuclear* PDFs?

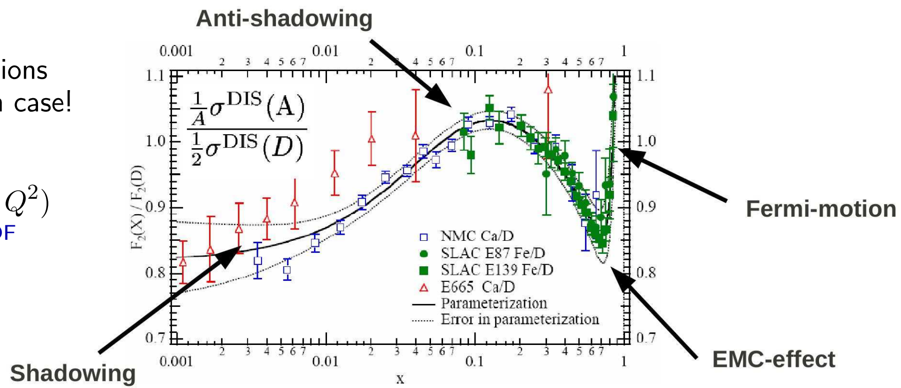
We can use the same processes to study the parton content of nuclei



Observe *significant* modifications compared to the free-nucleon case!

$$f_i^{p/A}(x, Q^2) \neq f_i^{p}(x, Q^2)$$

bound-proton PDF   free-proton PDF



Nuclear PDFs (nPDFs)
are fitted with similar global analyses as their free-proton counterparts

- ➔ rely only to the QCD collinear factorisation
- ➔ model-agnostic way to study the nuclear effects

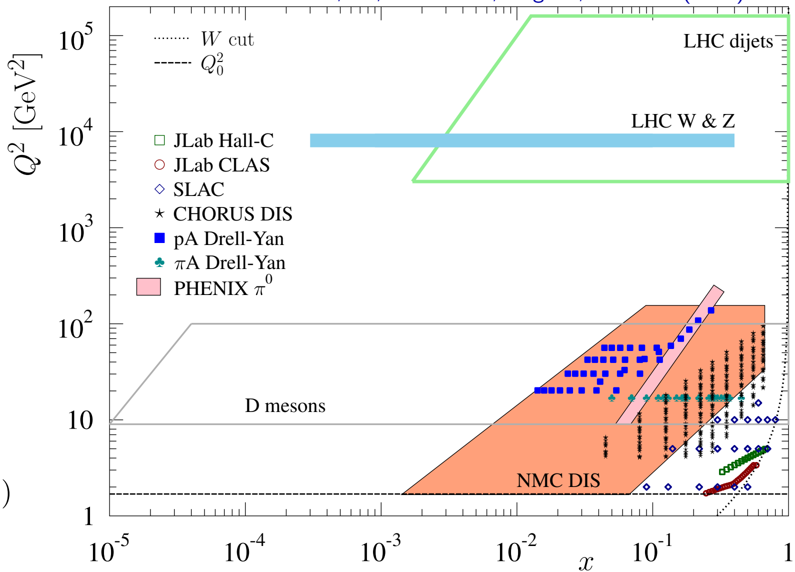
Multi-observable fit needed to constrain individual flavours, minimise:

Sum over data sets

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

Correlations important!

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



Example parametrization: EPPS21

- Define nuclear PDFs in terms of

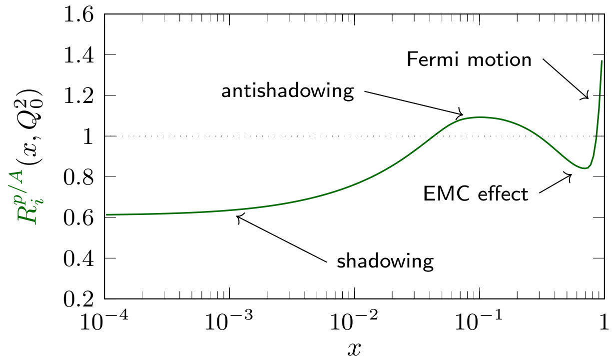
$$\underbrace{f_i^{p/A}}_{\text{bound-proton PDF}}(x,Q^2) = \overbrace{R_i^{p/A}}^{\text{nuclear modification}}(x,Q^2)\ \underbrace{f_i^{p}}_{\text{free-proton PDF}}(x,Q^2)$$

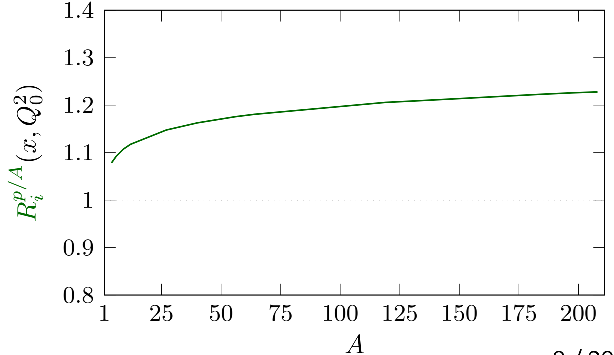
- PDFs of the full nucleus are then constructed with

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

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 $Q_0 = m_{\mathrm{charm}} = 1.3$ GeV
  - Use a phenomenologically motivated piecewise function in x
  - Use a power-law type function in A





Recent nPDF global fits

	KSASG20	nCTEQ15WZSIH*	TUJU21	EPPS21	nNNPDF3.0
Order in α_s	NLO & NNLO	NLO	NLO & NNLO	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 D^0				✓	✓
LHC pPb W,Z		✓	✓	✓	✓
LHC pPb γ					✓
Q, W cut in DIS	1.3, 0.0 GeV	2.0, 3.5 GeV	1.87, 3.5 GeV	1.3, 1.8 GeV	1.87, 3.5 GeV
p_T cut in D^0,h-prod.	N/A	3.0 GeV	N/A	3.0 GeV	0.0 GeV
Data points	4353	948	2410	2077	2188
Free parameters	9	19	16	24	256
Error analysis	Hessian	Hessian	Hessian	Hessian	Monte Carlo
Free-proton PDFs	CT18	∼CTEQ6M	own fit	CT18A	∼NNPDF4.0
Free-proton corr.	no	no	no	yes	yes
HQ treatment	FONLL	S-ACOT	FONLL	S-ACOT	FONLL
Indep. flavours	3	5	4	6	6
Reference	PRD 104, 034010	PRD 104, 094005	arXiv:2112.11904	EPJC 82, 413	arXiv:2201.12363

*see also arXiv:2204.09982, arXiv:2204.13157

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*see also arXiv:2204.09982, arXiv:2204.13157

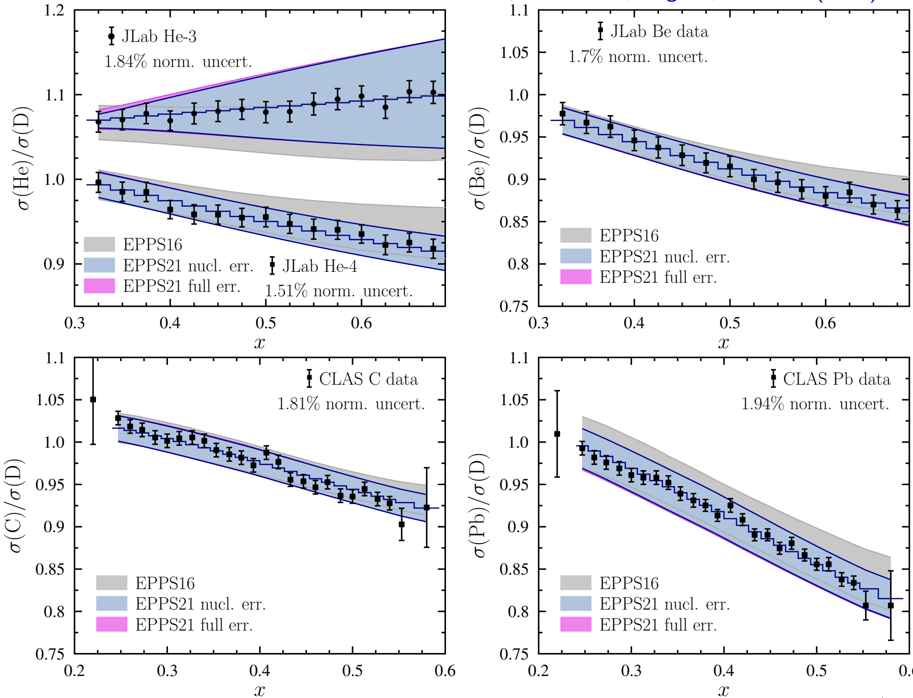
High-x DIS – JLab Hall-C and CLAS

data from: Seely et al., PRL 103 (2009) 202301
CLAS Collaboration, Nature 566 (2019) 354

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

DIS in the "transition region" $W \gtrsim 1.7$ GeV just above the resonance-dominated one

Target-mass corrections important!



Deuterium and higher-twist corrections can improve the fit

Segarra et al., PRD 103 (2021) 114015

but are not necessary to describe the data

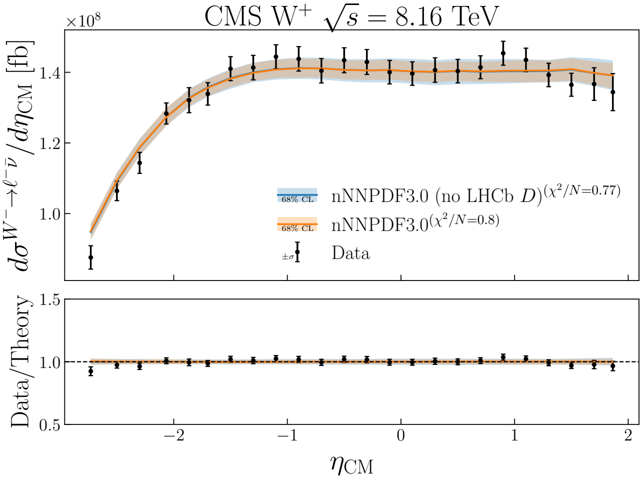
Paukkunen & Zurita, EPJC 80 (2020) 381

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

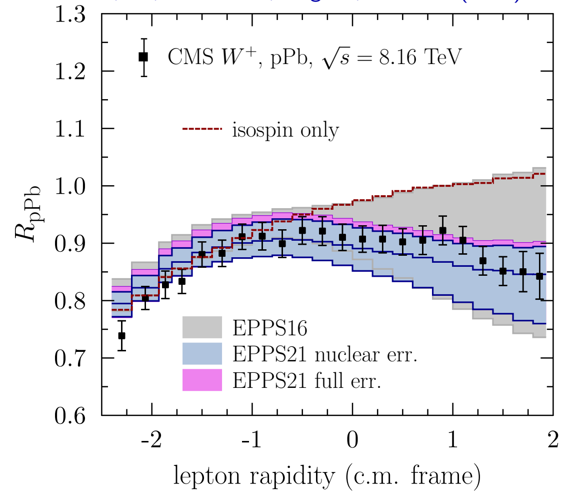
W bosons in pPb at 8.16 TeV

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

Abdul Khalek et al., arXiv:2201.12363



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



EW bosons important probes of flavour separation

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

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

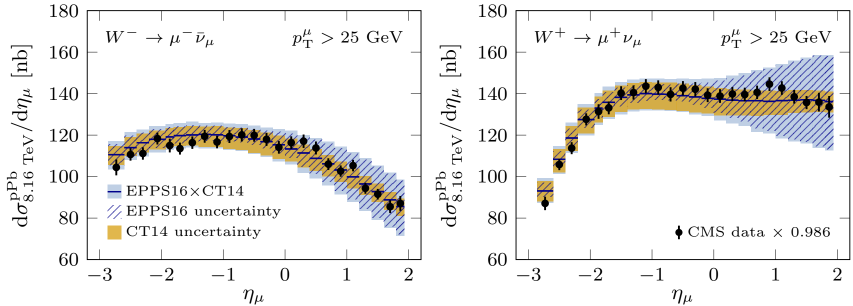
Absolute pPb cross sections sensitive to proton-PDF uncertainties!

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

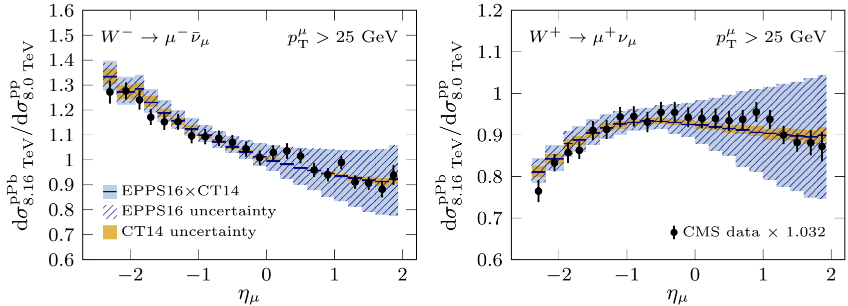
nCTEQ15WZSIH, TUJU21 and nNNPDF3.0 fit to absolute cross sections

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

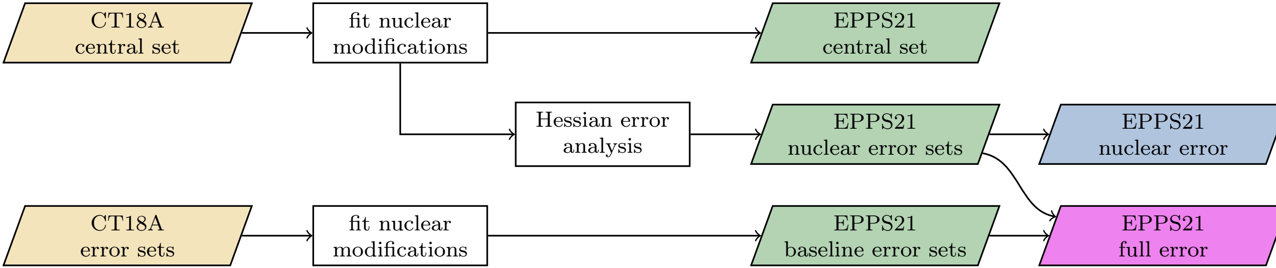


↓ Cancel proton-PDF uncertainty ↓



Propagating free-proton PDF uncertainty

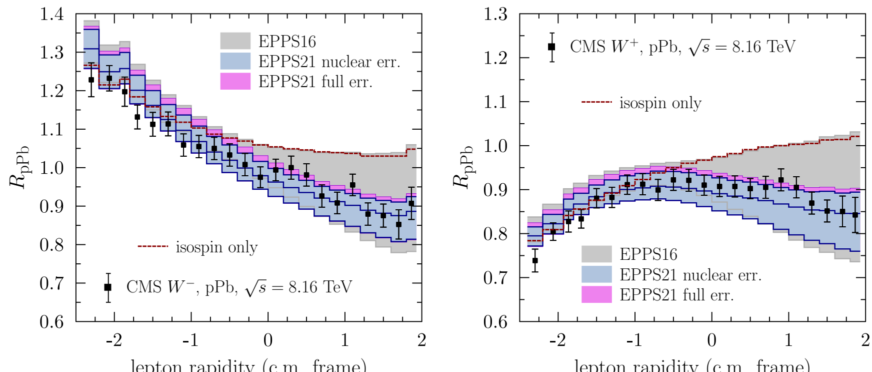
Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 413



EPPS21: fit nuclear modifications for each CT18A error set separately

→ subleading effect

nNNPDF3.0 uses similar approach in Monte Carlo framework



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

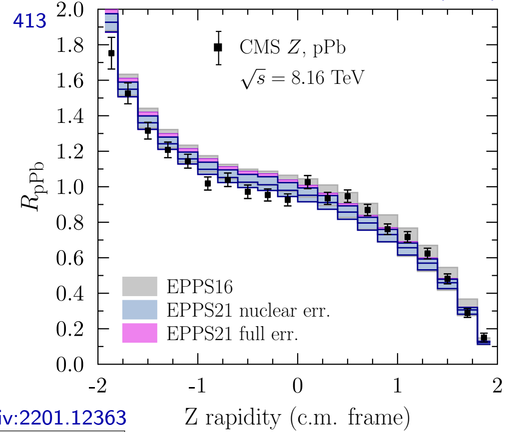
- nNNPDF3.0 include both low-mass and on-peak data
- R_{pPb} studied in EPPS21 ➔ not included in the final fit

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

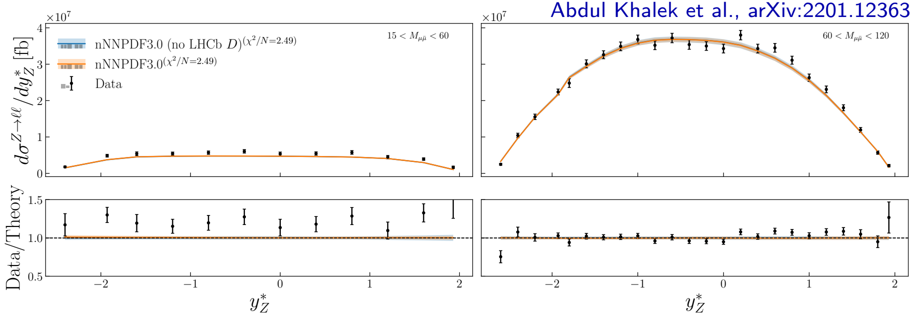
- abrupt change in the shape at midrapidity
- NNLO to cure for the low-mass data?

Abdul Khalek et al., arXiv:2201.12363

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



Abdul Khalek et al., arXiv:2201.12363

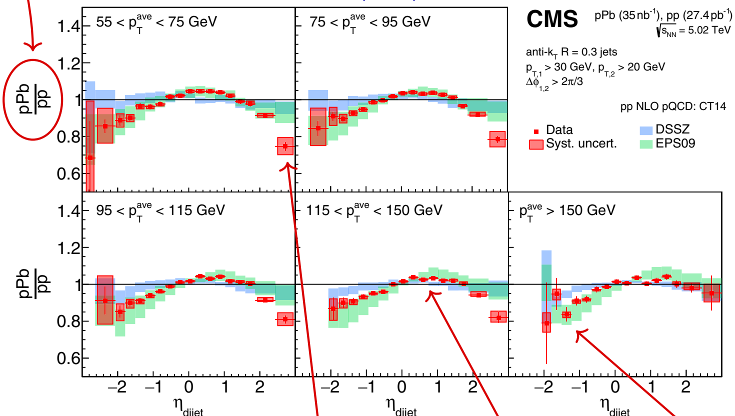


	χ^2/N_{data}
EPPS21	2.1
nNNPDF3.0	2.49

Dijets in pPb at 5.02 TeV

Ratio of ratios: $R_{\mathrm{pPb}}^{\mathrm{norm.}} = \dfrac{\mathrm{d}^2\sigma^{\mathbf{pPb}}/\mathrm{d}p_{\mathrm{T}}^{\mathrm{ave}}\mathrm{d}\eta_{\mathrm{dijet}}}{\mathrm{d}\sigma^{\mathbf{pPb}}/\mathrm{d}p_{\mathrm{T}}^{\mathrm{ave}}} \Big/ \dfrac{\mathrm{d}^2\sigma^{\mathbf{pp}}/\mathrm{d}p_{\mathrm{T}}^{\mathrm{ave}}\mathrm{d}\eta_{\mathrm{dijet}}}{\mathrm{d}\sigma^{\mathbf{pp}}/\mathrm{d}p_{\mathrm{T}}^{\mathrm{ave}}}$

CMS Collaboration, PRL 121 (2018) 062002

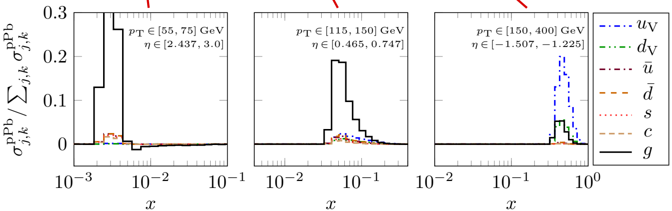


Double ratio convenient for:

- Cancellation of hadronization and luminosity uncertainties separately for pPb and pp
  - → do not expect strong final-state 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:

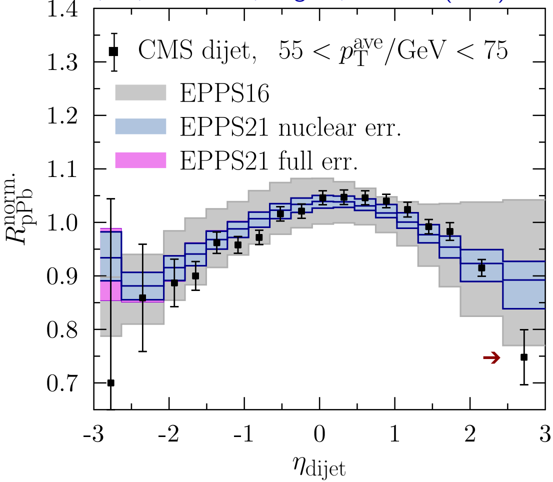


Good resolution to gluon nuclear modifications for $10^{-3} < x < 0.5$

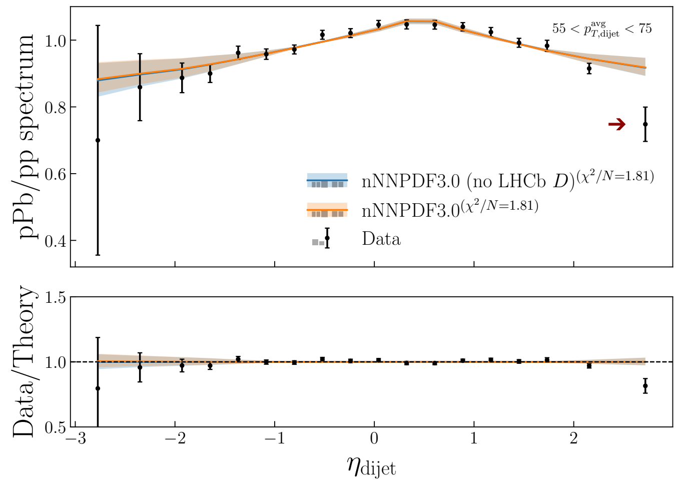
Dijets in EPPS21 and nNNPDF3.0

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

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



Abdul Khalek et al., arXiv:2201.12363



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., arXiv:2201.12363

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

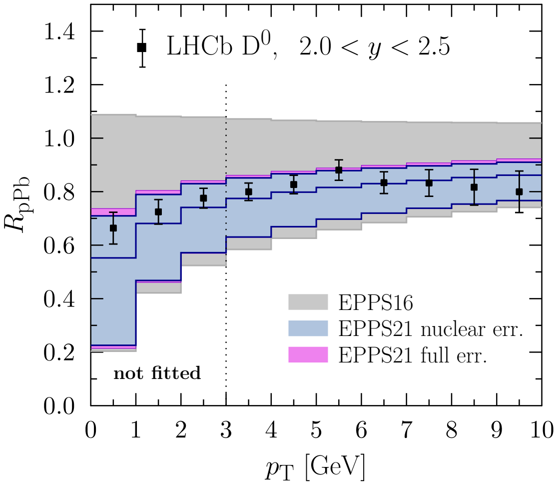
➔ missing data correlations important?

➔ NNLO? non-pert. effects?

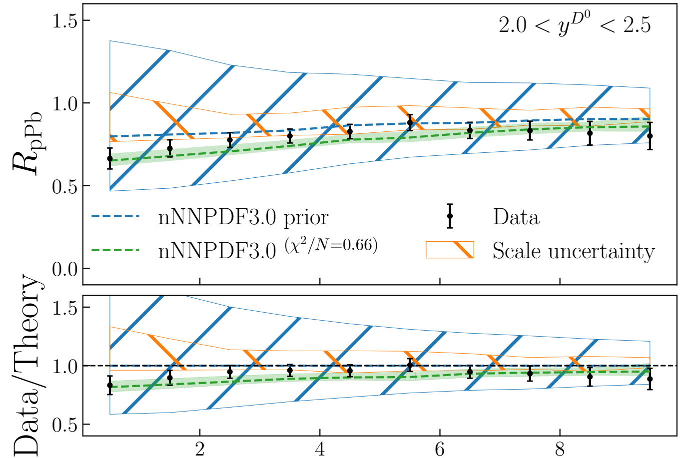
D^0s in EPPS21 and nNNPDF3.0

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

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



Abdul Khalek et al., arXiv:2201.12363



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., arXiv:2201.12363

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

Heavy-flavour production mass schemes

FFNS

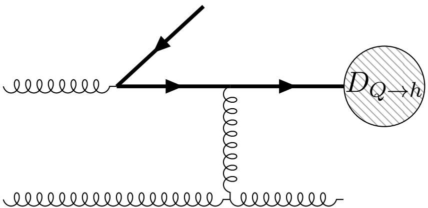
In *fixed flavour number scheme*, valid at small p_{T}, heavy quarks are produced only at the matrix element level

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

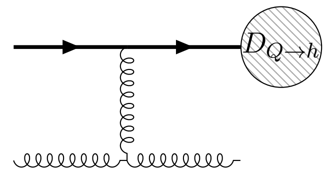
ZM-VFNS

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!

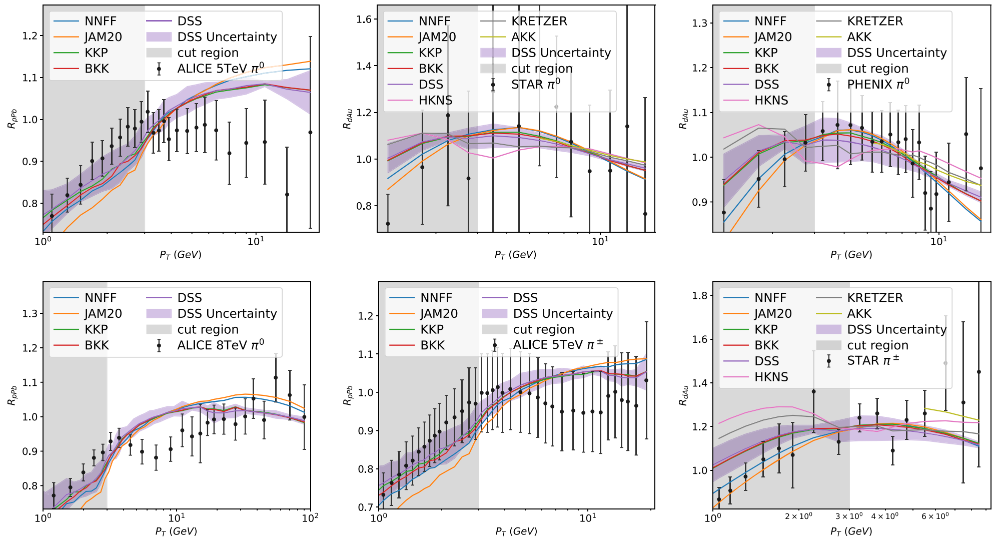
Single-inclusive hadrons – nCTEQ15WZSIH

Duwentäster et al., PRD 104 (2021) 094005

Complementary gluon constraints from $\pi^0, \pi^\pm, K^\pm$ production

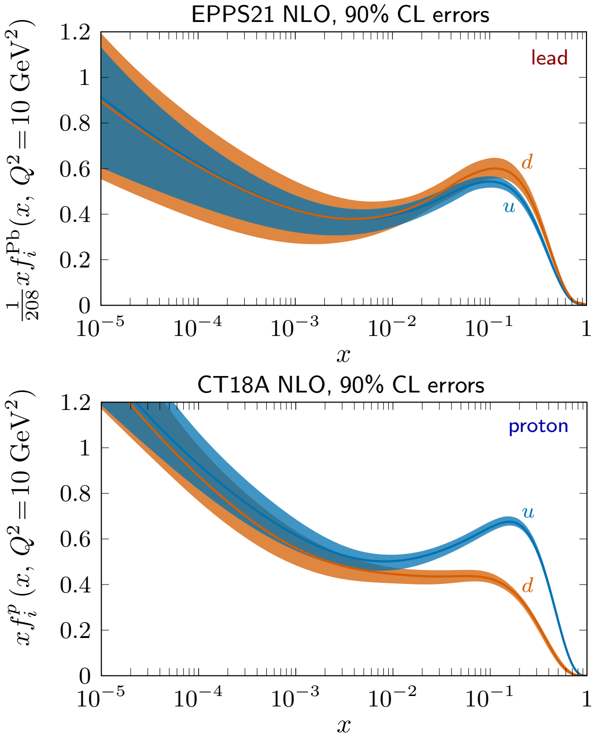
Fragmentation **F**unctions *partially* cancel in nuclear ratios

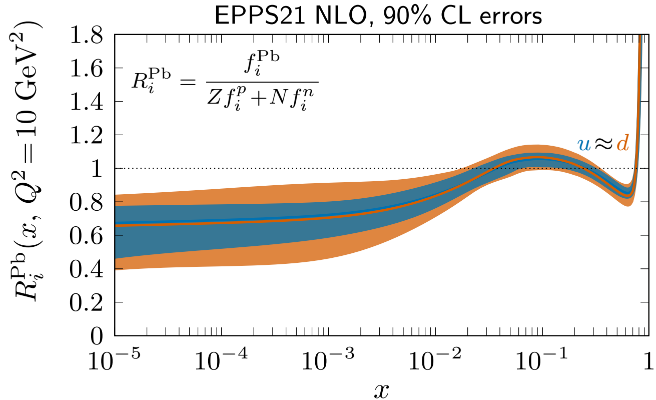
nCTEQ15WZSIH fits to the data from PHENIX, STAR and ALICE with a cut at $p_\mathrm{T} > 3$ GeV



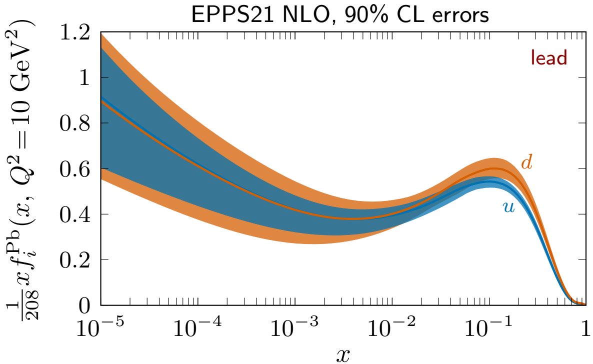
data from: PHENIX Collaboration, PRL 98 (2007) 172302
STAR Collaboration, PLB 637 (2006) 161
PRC 81 (2010) 064904
ALICE Collaboration, PLB 760 (2016) 720
EPJC 78 (2018) 624
PLB 827 (2022) 136943

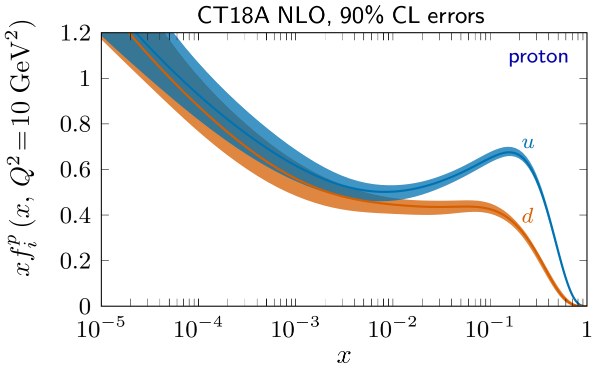
Comparing nuclear and proton PDFs – u and d

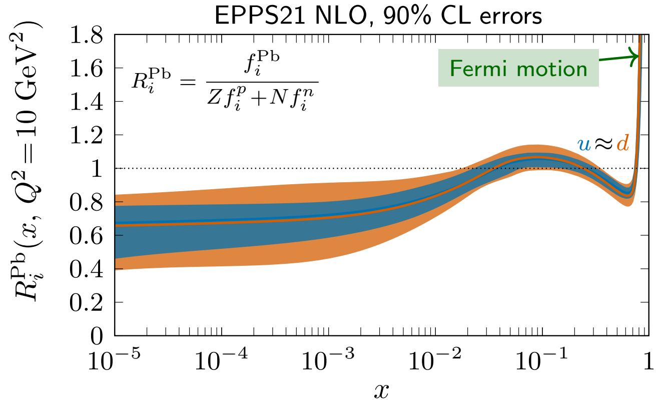




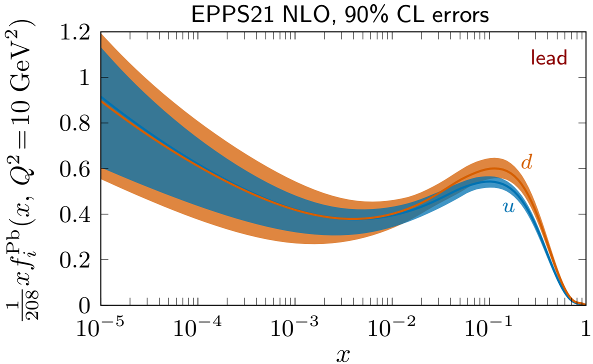
Comparing nuclear and proton PDFs – u and d

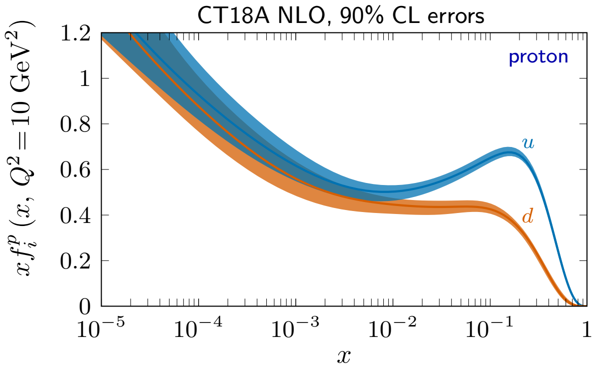


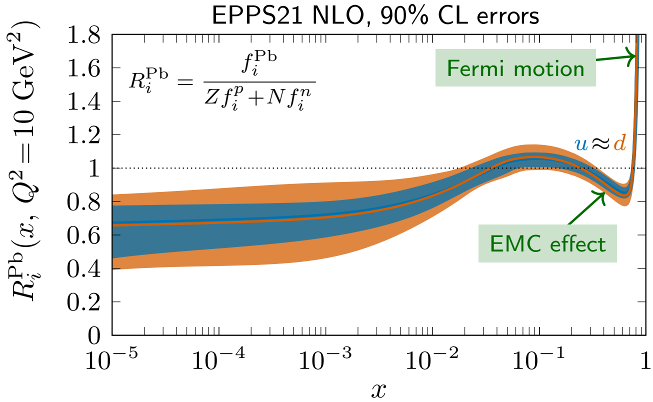




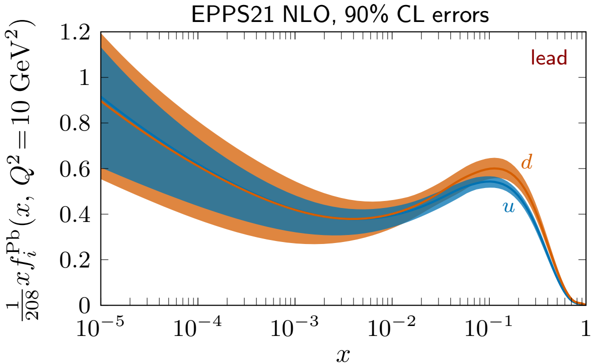
Comparing nuclear and proton PDFs – u and d

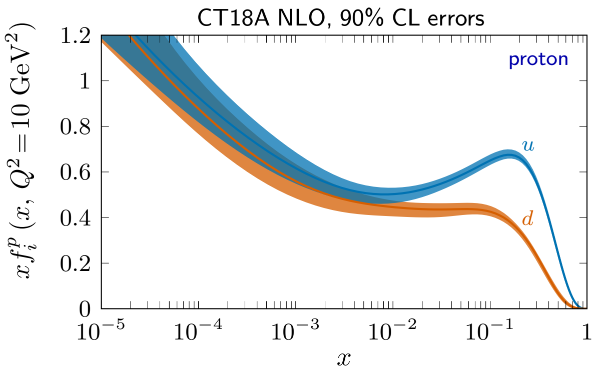


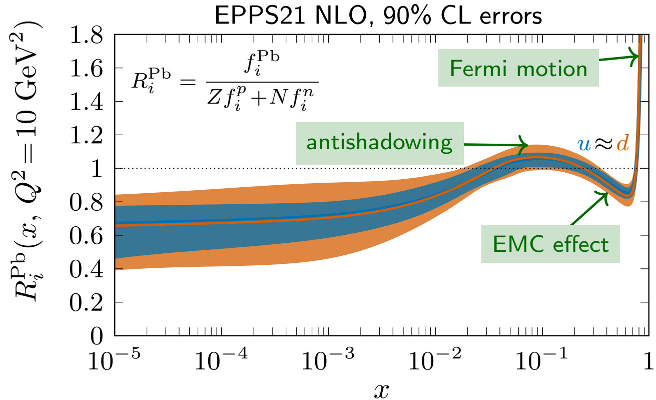




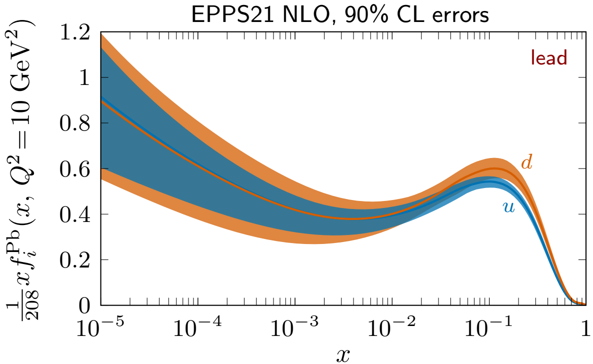
Comparing nuclear and proton PDFs – u and d

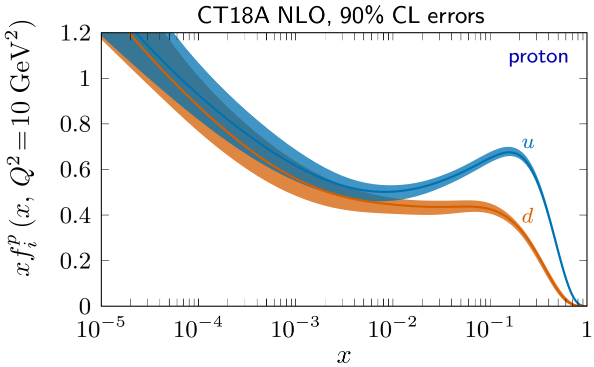


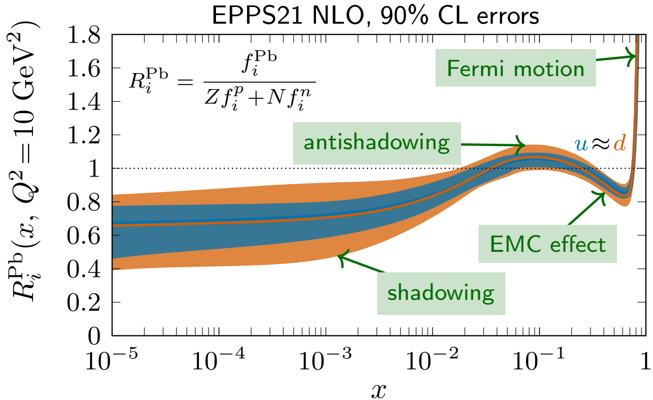




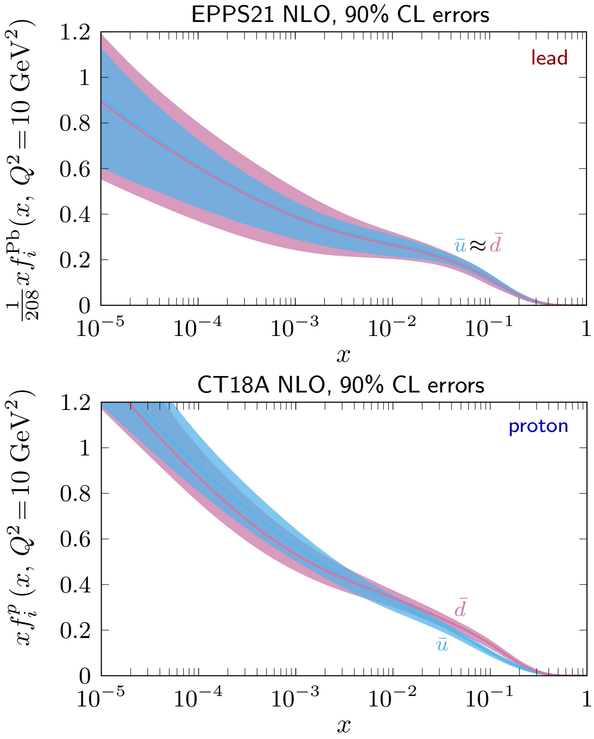
Comparing nuclear and proton PDFs – u and d

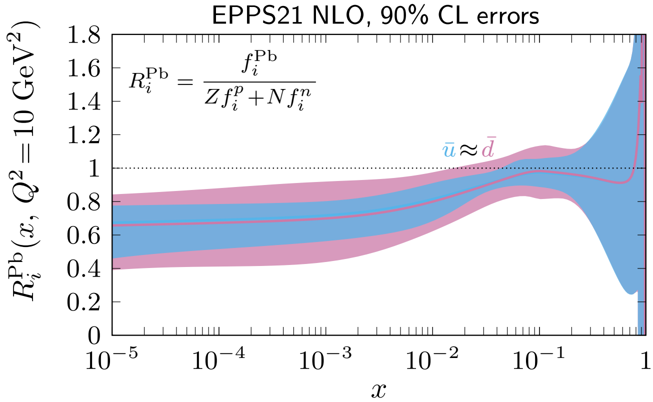




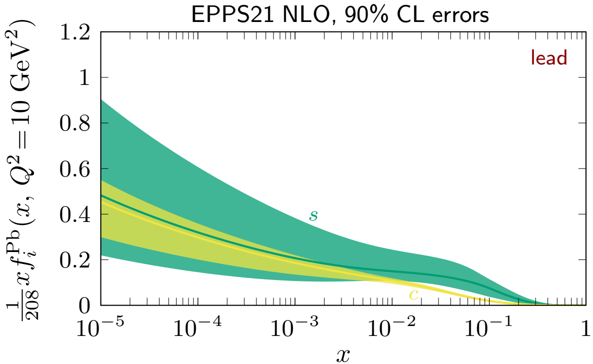


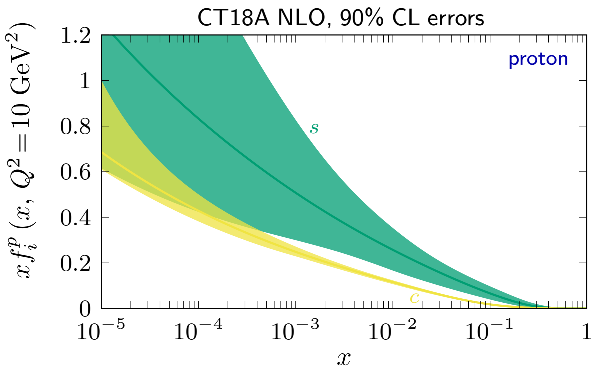
Comparing nuclear and proton PDFs – $\bar{u}$ and $\bar{d}$

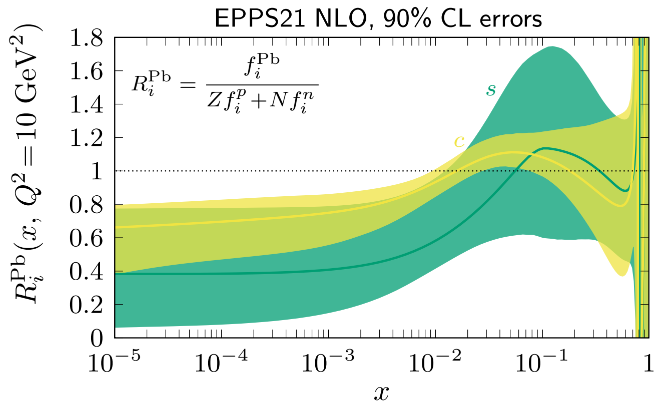




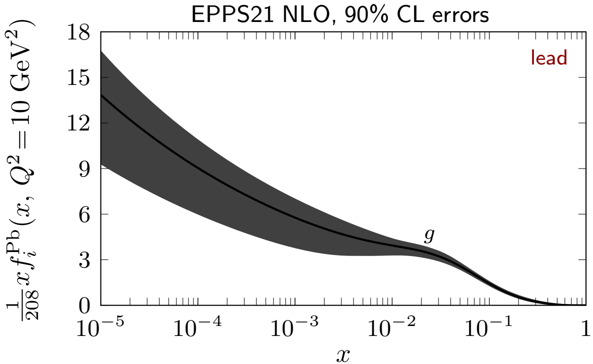
Comparing nuclear and proton PDFs – s and c

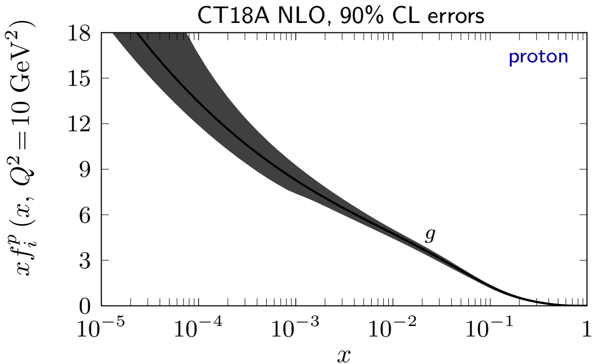


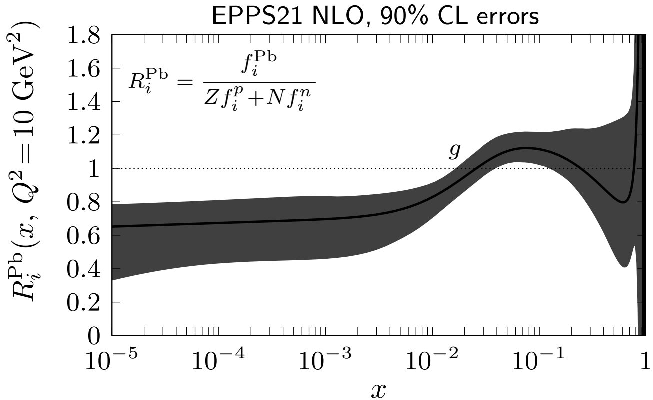




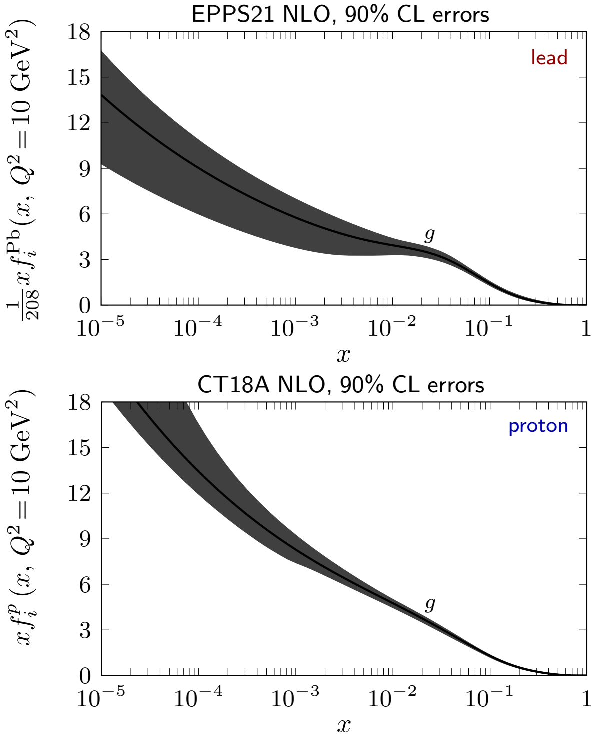
Comparing nuclear and proton PDFs – *glue*

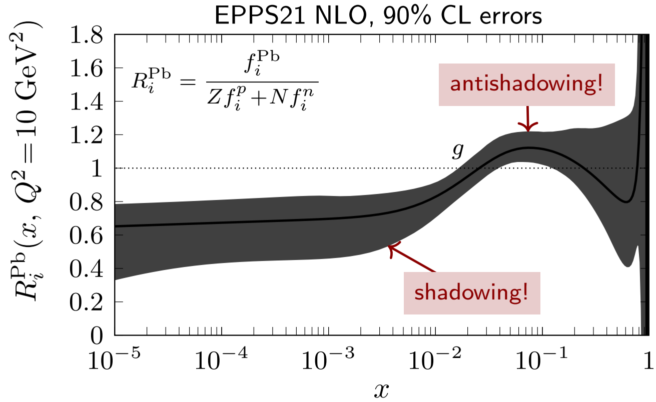




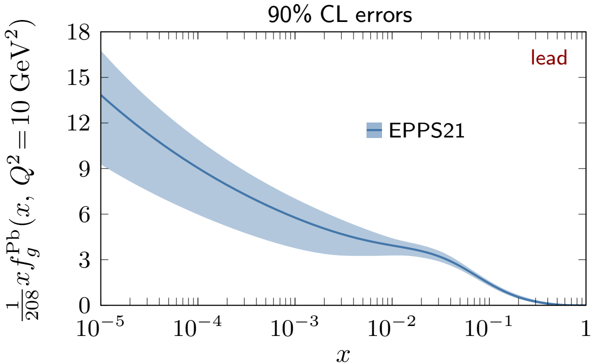


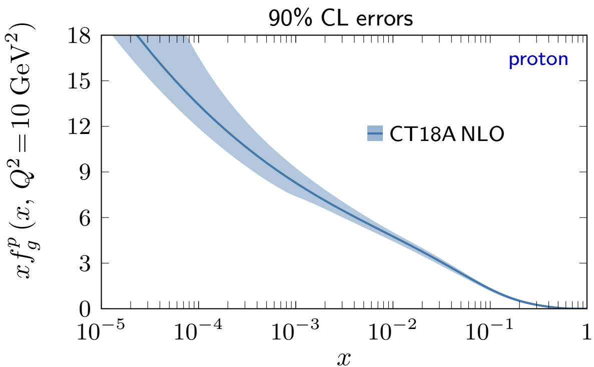
Comparing nuclear and proton PDFs – *glue*

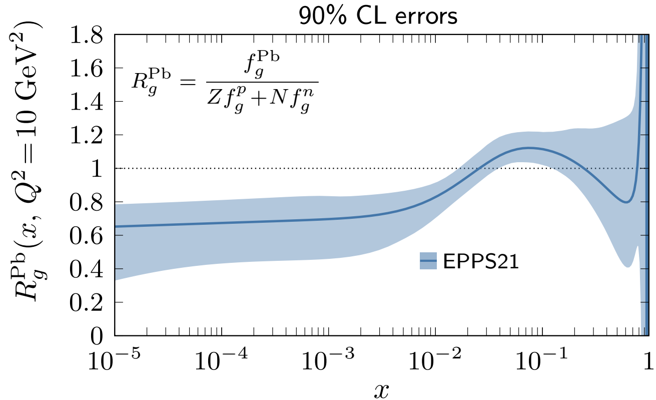




nPDF comparison – *glue*

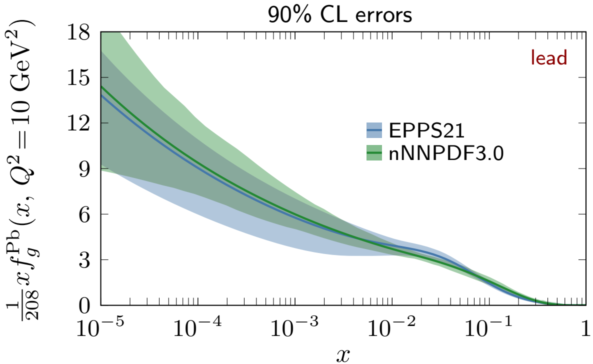


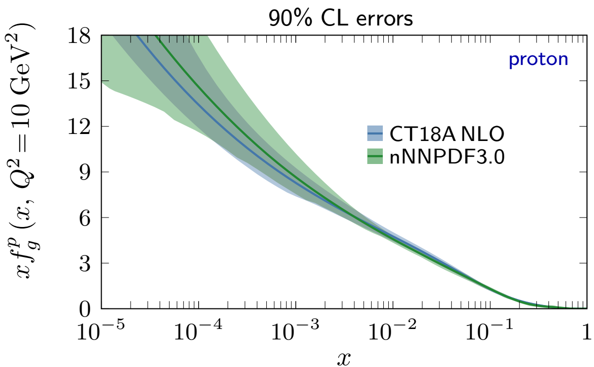


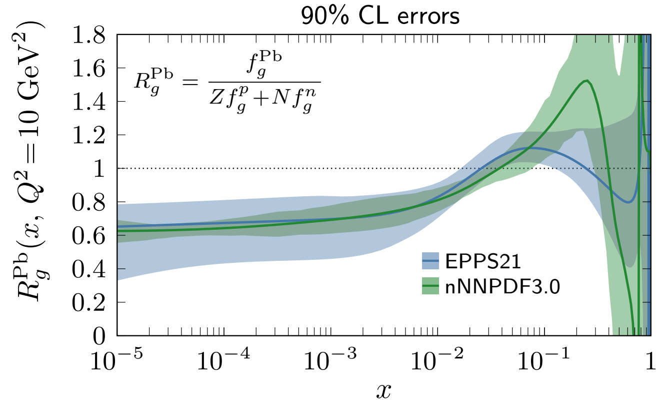


EPPS21: incl.-$h^{\rm RHIC}$ D$^{0\,\rm fwd}_{\rm bwd}$ jets W,Z

nPDF comparison – *glue*

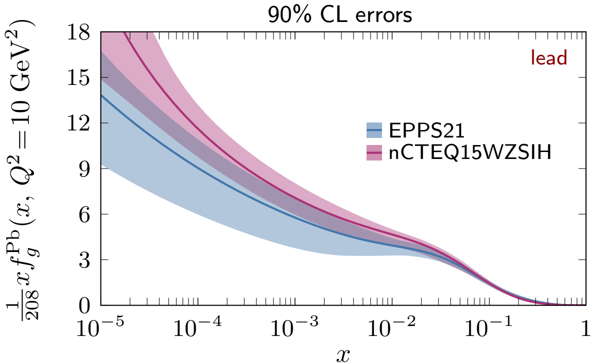


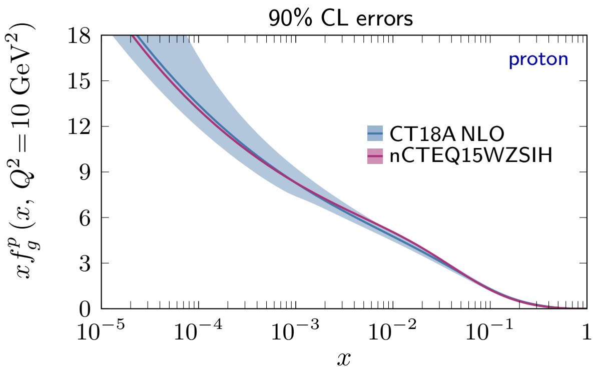


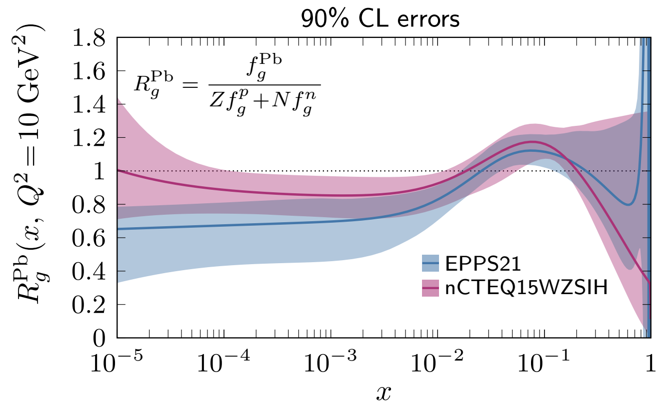


EPPS21:	incl.-$h^{\rm RHIC}$	$\mathrm{D}^{0\,\rm fwd}_{\rm bwd}$	jets	W,Z
nNNPDF3.0:		$\mathrm{D}^{0\,\rm fwd}$	jets	W,Z

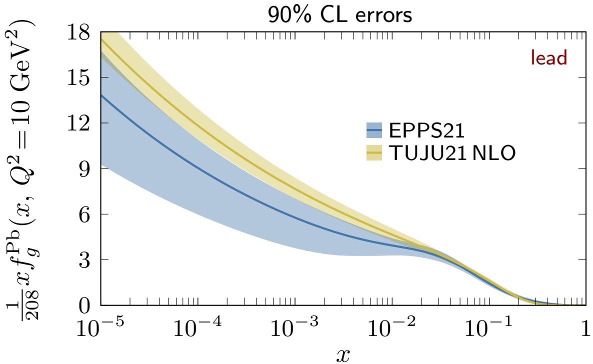
nPDF comparison – *glue*

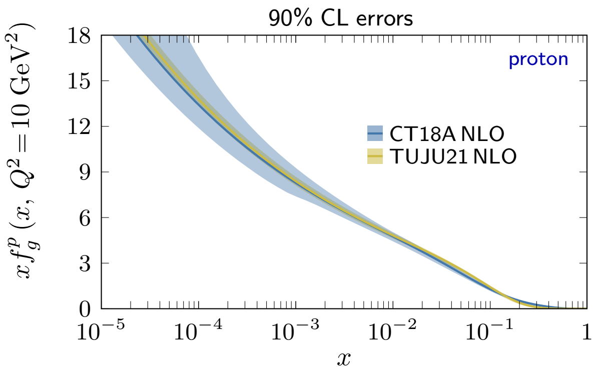


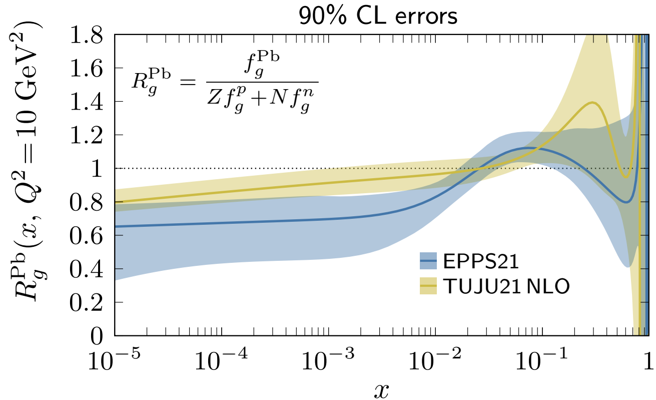




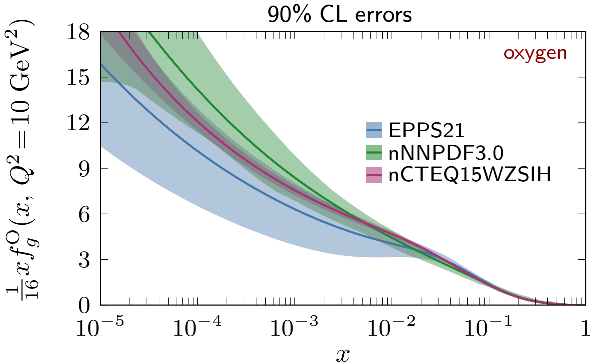
EPPS21:	incl.-h^{RHIC}	$\mathrm{D}^{0\,\mathrm{fwd}}_{\mathrm{bwd}}$	jets	W,Z
nNNPDF3.0:		$\mathrm{D}^{0\,\mathrm{fwd}}$	jets	W,Z
nCTEQ15WZSIH:	incl.-$h^{\mathrm{RHIC}}_{\mathrm{LHC}}$			W,Z

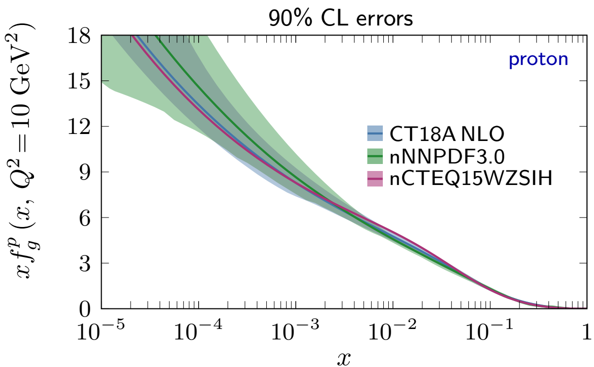






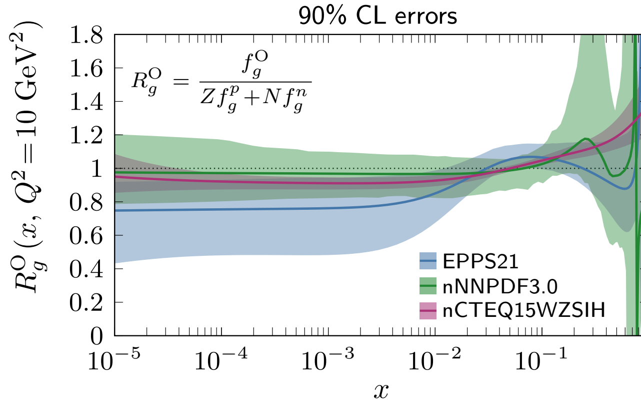
EPPS21:	incl.-h^{RHIC}	$\mathrm{D}^{0\,\mathrm{fwd}}_{\mathrm{bwd}}$	jets	W,Z
nNNPDF3.0:		$\mathrm{D}^{0\,\mathrm{fwd}}$	jets	W,Z
nCTEQ15WZSIH:	incl.-$h^{\mathrm{RHIC}}_{\mathrm{LHC}}$			W,Z
TUJU21:				W,Z





nPDFs a major source of uncertainty in testing small-system energy loss with OO

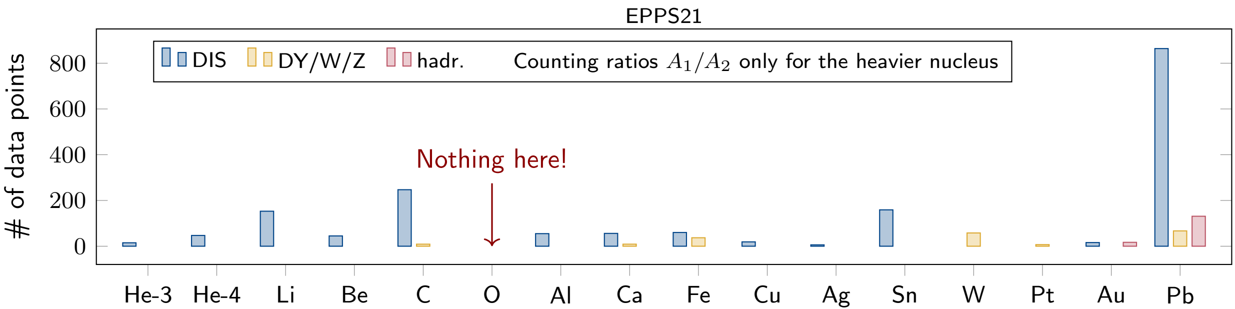
Brewer et al., PRD 105 (2022) 074040



EPPS21:	incl.-h^{RHIC}	$\mathrm{D}^{0\,\mathrm{fwd}}_{\mathrm{bwd}}$	jets	W,Z
nNNPDF3.0:		$\mathrm{D}^{0\,\mathrm{fwd}}$	jets	W,Z
nCTEQ15WZSIH:	incl.-$h^{\mathrm{RHIC}}_{\mathrm{LHC}}$			W,Z

only dAu and pPb!

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!

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

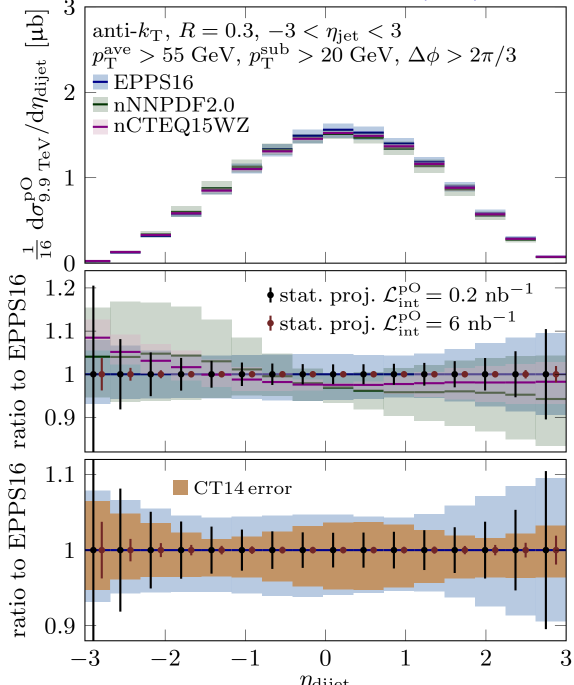
Problem: absolute cross sections very sensitive to the used free-proton PDFs

- 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



PP, PRD 105 (2022) L031504

Problem: We do not expect pp reference at 9.9 TeV

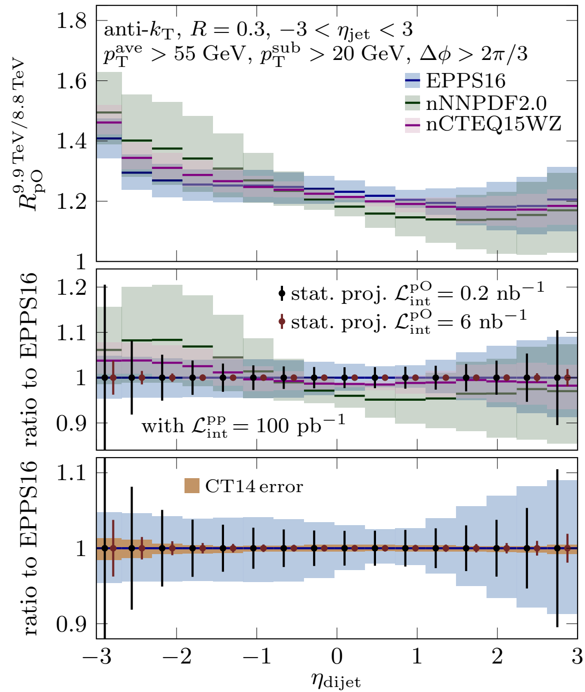
- Could we use a mixed energy ratio pO(9.9 TeV)/pp(8.8 TeV)? Yes!

Excellent cancellation of free-proton PDFs

→ Direct access to nuclear modifications

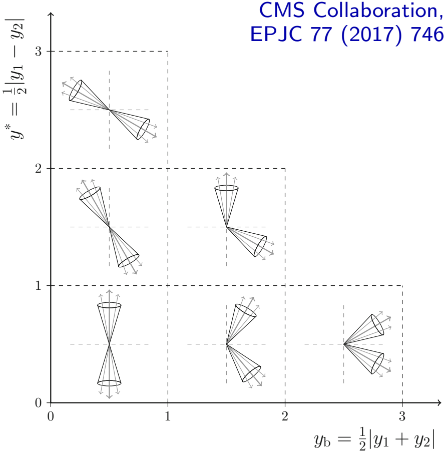
Already few nb^{-1} can be expected to be enough to put new constraints on nPDFs (if we have sufficient statistics for the pp reference)

→ Can resolve different nPDF parametrisations!

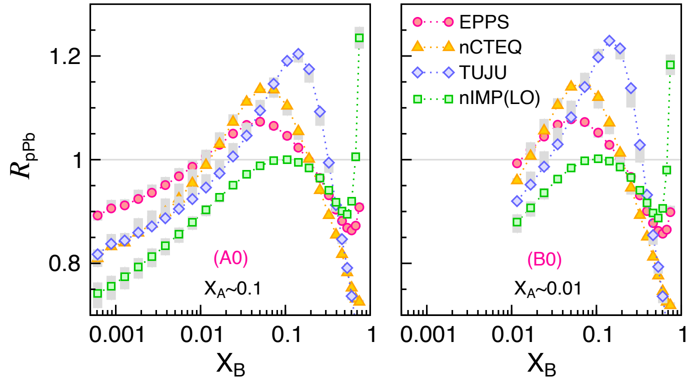


Triple-differential dijets in pPb?

CMS Collaboration, EPJC 77 (2017) 746



Shen et al., arXiv:2112.11819



Triple-differential measurement fixes partonic kinematics at LO

→ powerful test of factorisation and PDFs

Measured in pp at 8 TeV

CMS Collaboration, EPJC 77 (2017) 746

Should be feasible in pPb with Run 2/3 statistics?

Various observable choices possible, e.g. X_A, X_B, y^*

measurable!

$$X_B = \sum_{n \in \mathrm{dijet}} \frac{E_{\mathrm{T}n}}{\sqrt{s}} e^{-y_n} \stackrel{\mathrm{LO}}{=} x_{\mathrm{Pb}}$$

momentum fraction from the lead side

Ellis & Soper, PRL 74 (1995) 5182

PHENIX pion production small-system scan *new!*

New mid-rapidity π^0 data from PHENIX
PHENIX Collaboration, arXiv:2111.05756

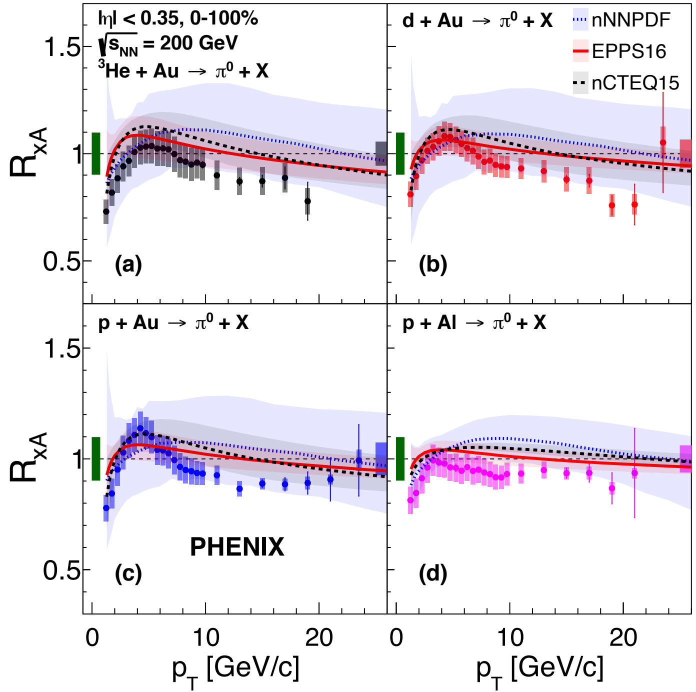
- improved precision
- higher p_T ➔ larger x

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

PHENIX Collaboration, arXiv:2111.05756



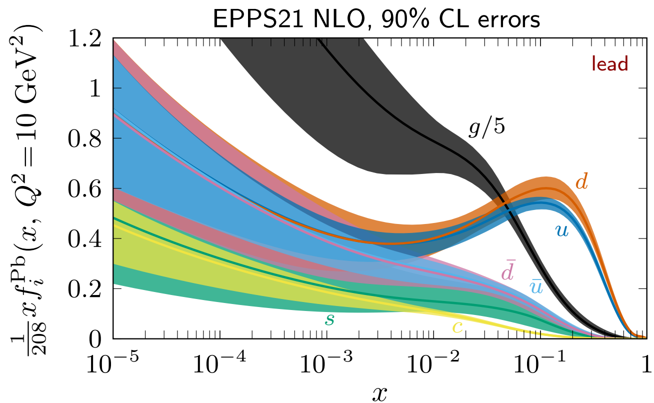
Summary

Ample progress in incorporating new data in global nPDF fits:

- Testing the high-x region with new JLab DIS data
- LHC pPb data put unprecedented constraints on the gluon nPDF
- Work towards more global NNLO fits
- Ongoing work to understand the (cross)correlations between proton and nuclear PDF analyses

The future is luminous!

- Both collider and fixed-target experiments keep providing new data
- LHC Run 3 just around the corner
- New experiments and upgrades to utilize: SMOG@LHCb, FoCal@ALICE, sPHENIX, EIC, LHeC, FPF. . .



Backup

Proton strangeness from νA DIS vs. LHC EW data

$$K_s = \frac{\int_0^1 \mathrm{d}x x[s(x,Q^2)+\bar{s}(x,Q^2)]}{\int_0^1 \mathrm{d}x x[\bar{u}(x,Q^2)+\bar{d}(x,Q^2)]}$$

table and fig. from Feng et al., "The Forward Physics Facility at the High-Luminosity LHC", arXiv:2203.05090

			Proton PDF sets				Nuclear PDF sets			
Data set		Ref.	ABMP16	CT18	MSHT20	NNPDF4.0	EPPS21	nCTEQ15	nNNPDF3.0	TUJU21
CHORUS $\sigma_{CC}^{\nu,\bar{\nu}}$	Pb	[1238]	✗	✗	✓	✓	✓	✗	✓	✓
CHORUS	Pb	[1239]	✓	✗	✗	✗	✗	✗	✗	✗
NOMAD $\mathcal{R}_{\mu\mu}$	Fe	[1195]	✓	✗	✗	(✓)	✗	✗	✗	✗
CCFR xF_3^p	Fe	[1240]	✗	✓	✗	✗	✗	✗	✗	✗
CCFR F_2^p	Fe	[1241]	✗	✓	✗	✗	✗	✗	✗	✗
CDSHW F_2^p, xF_3^p	Fe	[1242]	✗	✓	✗	✗	✗	✗	✗	✓
NuTeV $\sigma_{CC}^{\nu,\bar{\nu}}$	Fe	[1196]	✓	✓	✓	✓	✗	✗	✓	✗
NuTeV F_2, F_3	Fe	[1194]	✗	✗	✓	✗	✗	✗	✗	✗

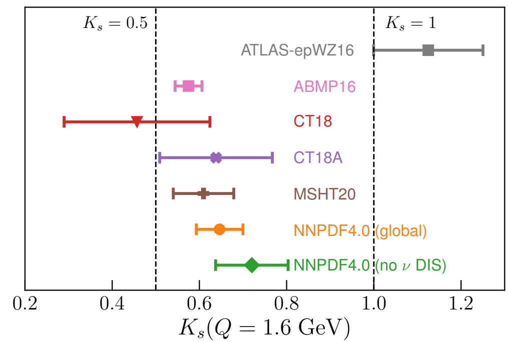
Proton-PDF fits traditionally include neutrino-*nucleus* DIS for improved strange-quark constraints → suppressed strangeness

Complementary data from ATLAS EW-boson production confronts this view with preference for unsuppressed strange

ATLAS Collaboration, PRL 109 (2012) 012001
EPJC 77 (2017) 367

Simultaneous fit feasible w/ NNLO c-quark mass corrections

Faura et al., EPJC 80 (2020) 1168
Bailey et al., EPJC 81 (2021) 341
Ball et al., arXiv:2109.02653



Nuclear uncertainties in proton-PDF fits

Ball et al., arXiv:2109.02653

Nuclear effects can impact the proton-PDF fits!

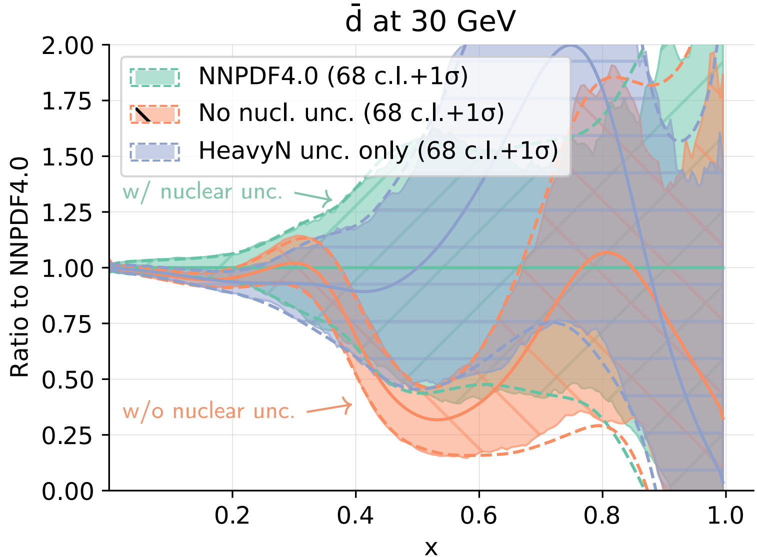
NNPDF4.0:

- Different large-x sea-quark behaviour depending on whether the uncertainties from nNNPDF2.0 nuclear PDFs were included or not
- Nuclear data found to constrain the proton PDFs even with nuclear uncertainties included

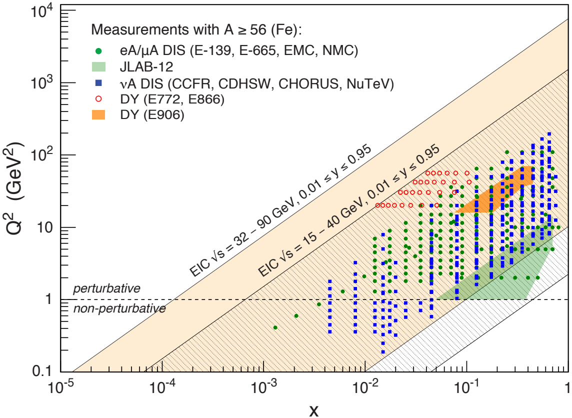
Ball et al., EPJC 79 (2019) 282
Ball et al., arXiv:2109.02653

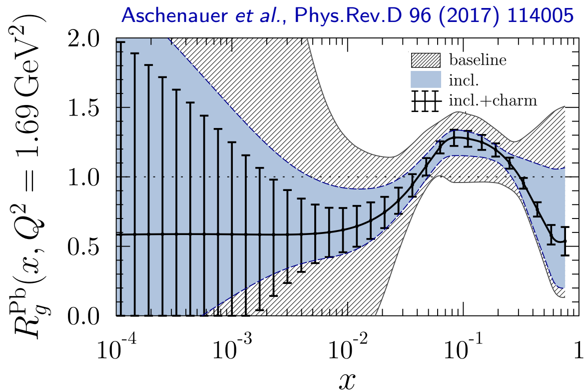
MSHT20: take nuclear corrections from DSSZ + additional 3-param. fit
Bailey et al., EPJC 81 (2021) 341

CT18: does not report on any use of nuclear corrections



Gluon constraints from EIC





EIC will significantly widen the kinematic range of DIS constraints for nPDFs

- Comparing with LHC measurements will put collinear factorization with nuclei to a stringent test

With the F_{L} extraction cabability, EIC provides a clean probe to study small-x gluons

- Good constraining power to well down to 10^{-2} in a high-energy scenario

Charm-tagged cross-section measurement can vastly reduce high-x gluon uncertainty

see also: Kelsey *et al.*, Phys.Rev.D 104 (2021) 054002

UPCs in collinear factorisation

First phenomenological implementation of the exclusive J/ψ photoproduction NLO corrections

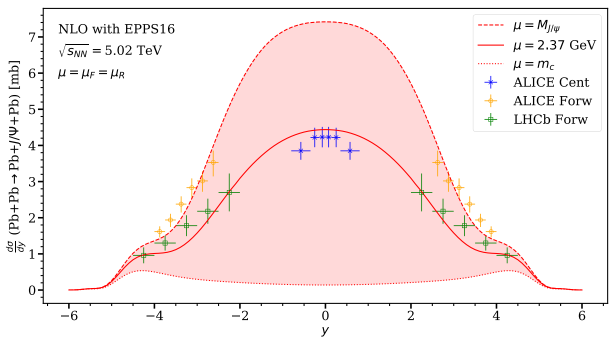
Ivanov et al., EPJC 34 (2004) 297
Jones et al., J. Phys. G 43 (2016) 035002

in ultrapheripheral Pb+Pb

Large scale uncertainty

- ➔ perturbative convergence?
- ➔ cancel with nuclear ratios?

Eskola et al., arXiv:2203.11613



ATLAS inclusive dijet photoproduction measurement now fully unfolded

ATLAS-CONF-2022-021