Constraining PDFs and nPDFs with recent data

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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...

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

...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,

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

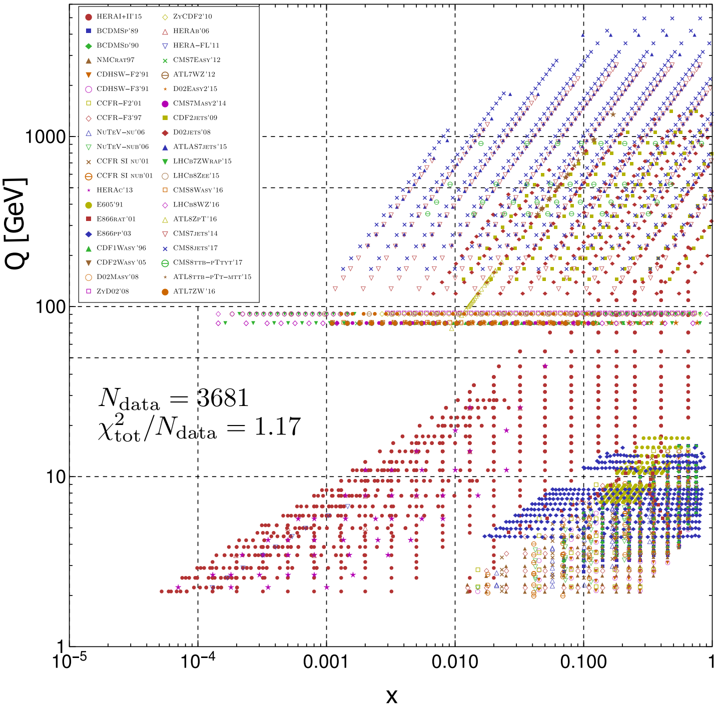
and obey the DGLAP equations $Q^2 \dfrac{\partial f_i^A}{\partial Q^2} = \sum_j P_{ij} \otimes f_j^A$

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

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

Global analysis – a multi-experiment–multi-observable fit

Experimental data in CT18 PDF analysis



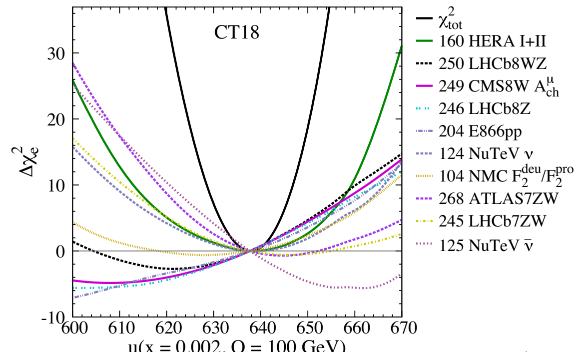
Multi-observable fit needed to constrain individual flavours, minimise:

Sum over data sets

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

Correlations important!

figs. from Hou et al., Phys. Rev. D 103 (2021) 014013



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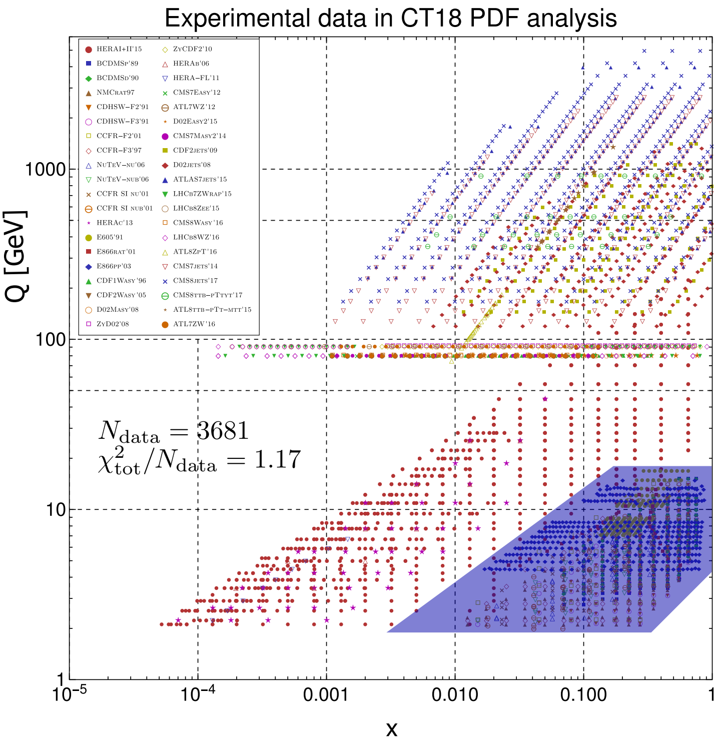
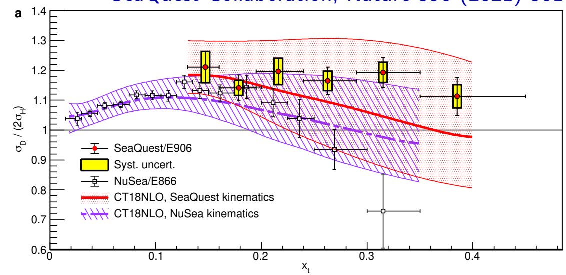


Fixed-target DIS and DY important in setting the large-x quark distributions (valence/sea and flavour separation)

New data still coming from Fermilab & JLab!

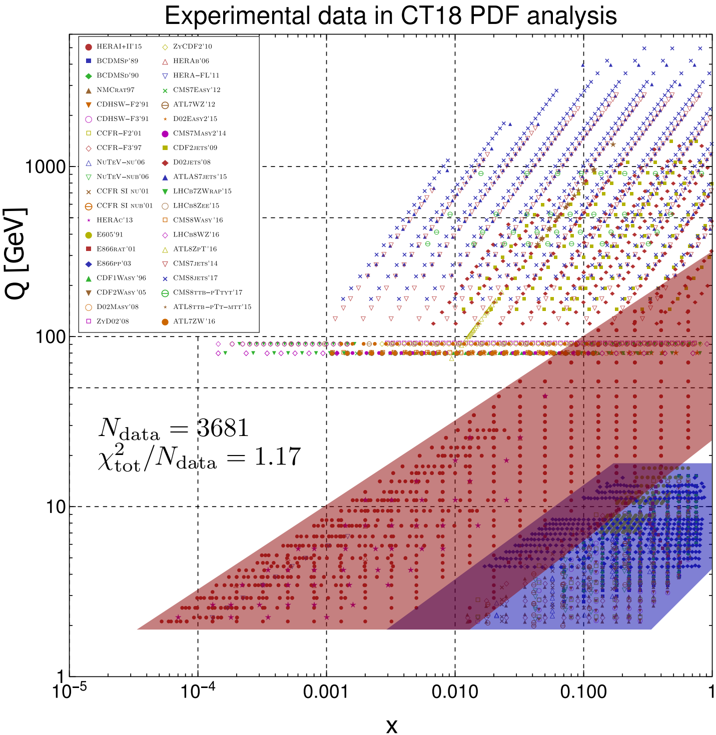
new!

SeaQuest Collaboration, Nature 590 (2021) 561



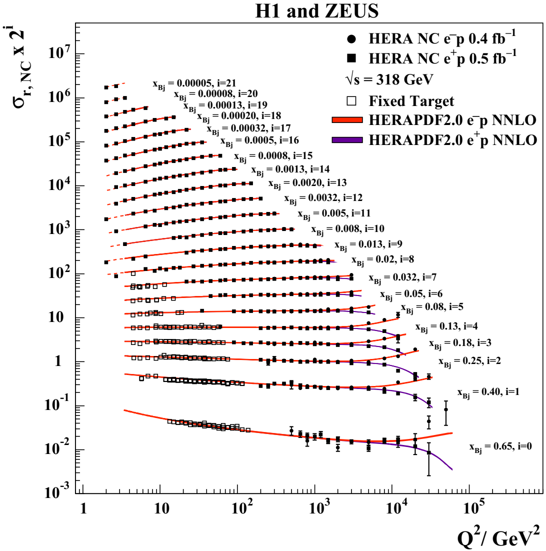
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_{\text{beam}} \gg x_{\text{target}}} \approx \frac{1}{2}\left[1 + \frac{\bar{d}\,(x_{\text{target}})}{\bar{u}\,(x_{\text{target}})}\right]$$

Global analysis – a multi-experiment–multi-observable fit



Collider DIS from HERA with large x, Q^2 lever arm ➔ gluons through DGLAP

H1 and ZEUS, Eur. Phys. J. C 75 (2015) 580



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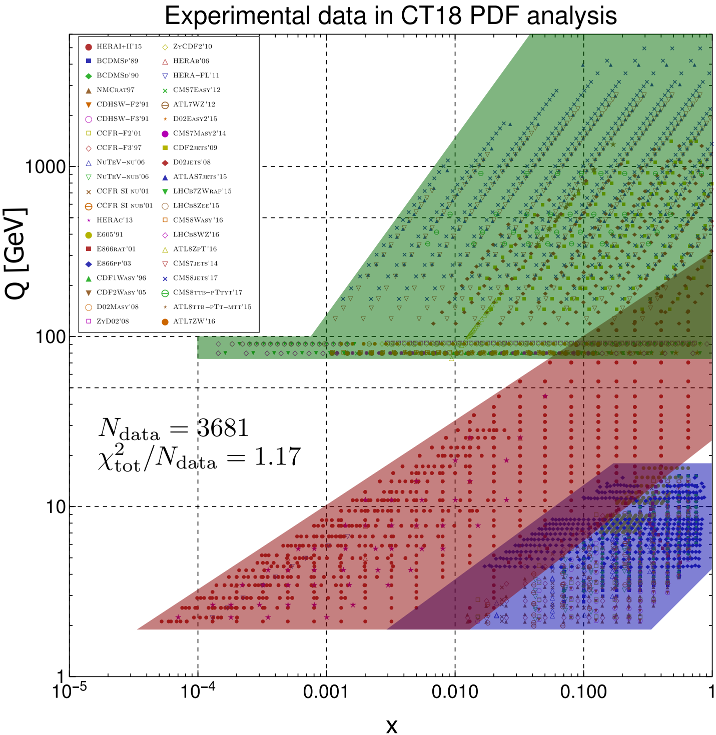
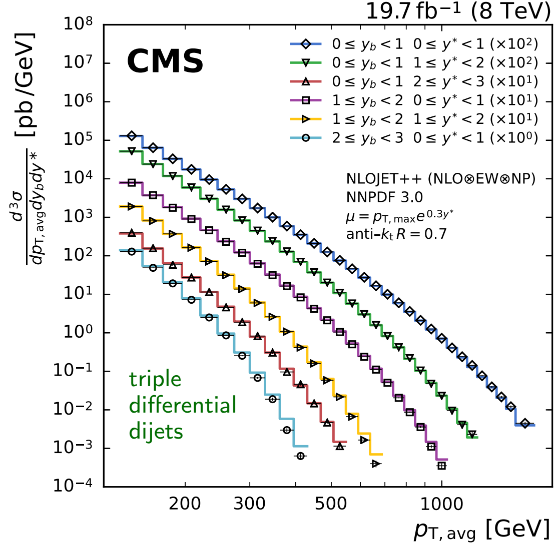


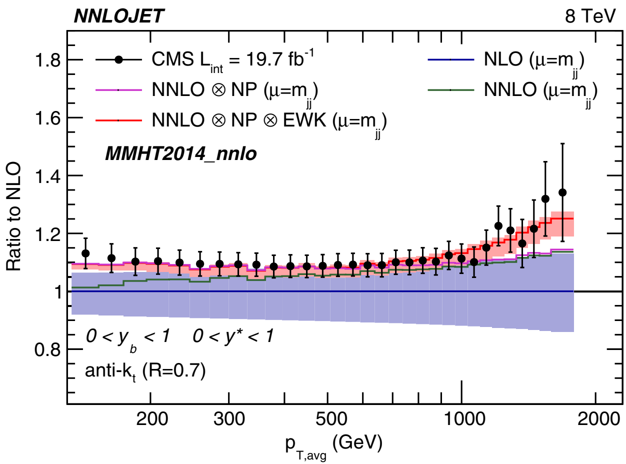
Hadron colliders give access to new processes → $W^\pm, Z$, jets, $t\bar{t}\ldots$

CMS Collaboration, Eur. Phys. J. C 77 (2017) 746

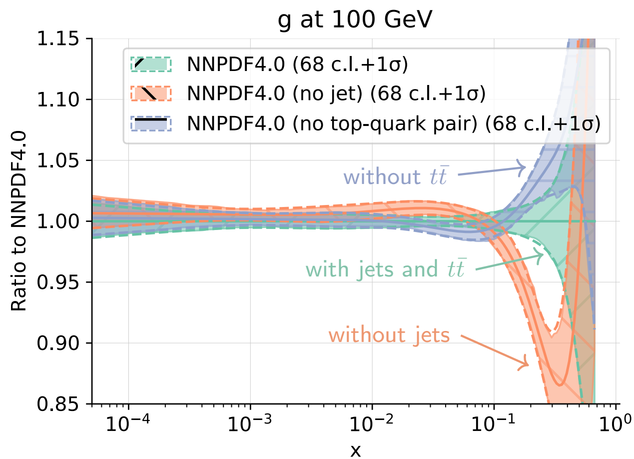


LHC jets at NNLO in proton-PDF fits

Gehrmann-De Ridder et al., Phys. Rev. Lett. 123 (2019) 102001



Ball et al., arXiv:2109.02653



Jets important for constraining large-x gluons

see e.g. Ball et al., arXiv:2109.02653

NNLO the new standard

Curie et al., Phys. Rev. Lett. 118 (2017) 072002
Phys. Rev. Lett. 119 (2017) 152001

Nonperturbative and electroweak corrections important at small and large p_{T}, respectively

NNLO improves fit quality particularly for LHC data

see e.g. Bailey et al., Eur. Phys. J. C 81 (2021) 341

$\chi^2_{\mathrm{tot}}/N_{\mathrm{data}}$	LO	NLO	NNLO
MSHT20	N/A	1.33	1.17
NNPDF4.0	3.35	1.24	1.16

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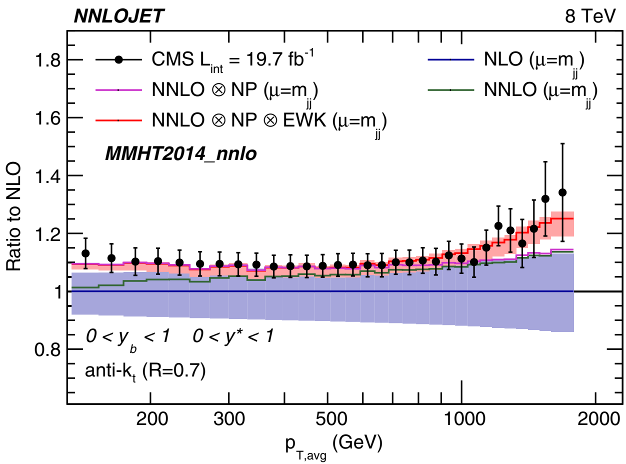
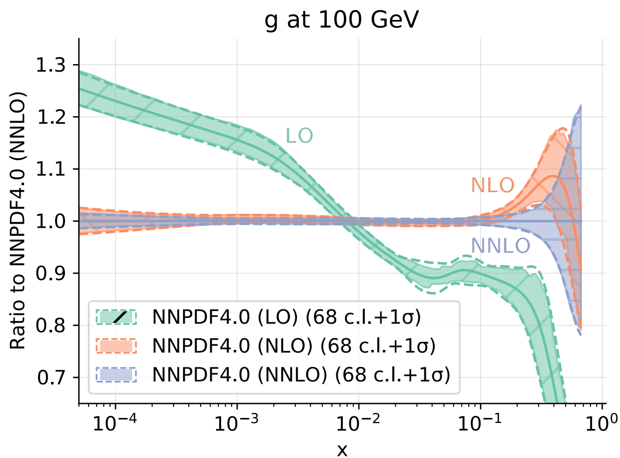


Ball et al., arXiv:2109.02653



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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]	✗	✗	✓	✗	✗	✗	✗	✗

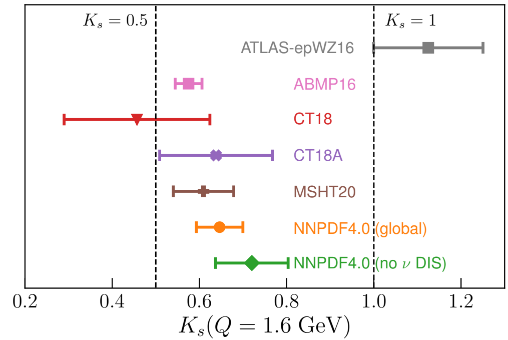
Proton-PDF fits traditionally include neutrino-*nucleus* DIS for improved strange-quark constraints ➔ suppressed strangeness

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

ATLAS Collaboration, Phys. Rev. Lett. 109 (2012) 012001
Eur. Phys. J. C 77 (2017) 367

Simultaneous fit feasible w/ NNLO c-quark mass corrections

Faura et al., Eur. Phys. J. C 80 (2020) 1168
Bailey et al., Eur. Phys. J. C 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!

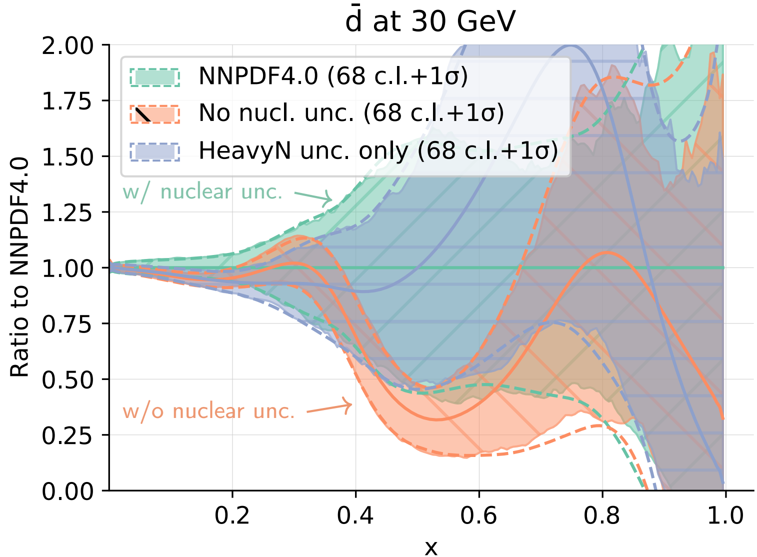
NNPDF4.0:

- 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., Eur. Phys. J. C 79 (2019) 282
Ball et al., arXiv:2109.02653

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

CT18: does not report on any use of nuclear corrections



Nuclear PDFs from global analyses with recent data

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

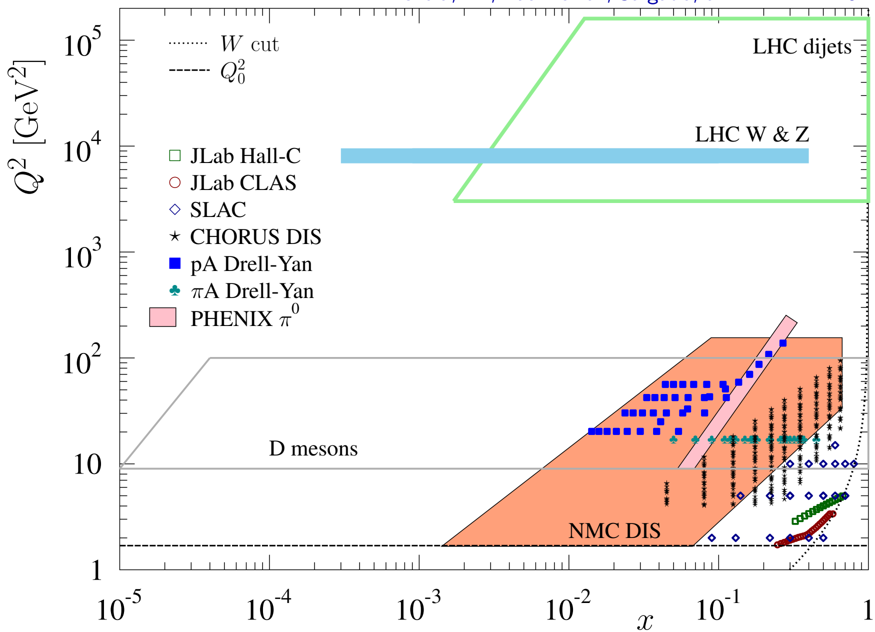
- → rely only to the QCD collinear factorisation
- → model-agnostic way to study the nuclear effects

LHC is extending the x, Q^2 reach by orders of magnitude

Highlights in this talk:

- → Run 1 dijets, D^0s
- → Run 2 $W^{\pm}, Z$

Eskola, PP, Paukkunen, Salgado, arXiv:2112.12462



Recent nPDF global fits – all new since QM2019!

	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	940	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	arXiv:2112.12462	arXiv:2201.12363

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πA DY				✓	
RHIC dAu π^0,$\pi^\pm$		✓		✓	
LHC pPb π^0,$\pi^\pm$,$K^\pm$		✓			
LHC pPb dijets				✓	✓
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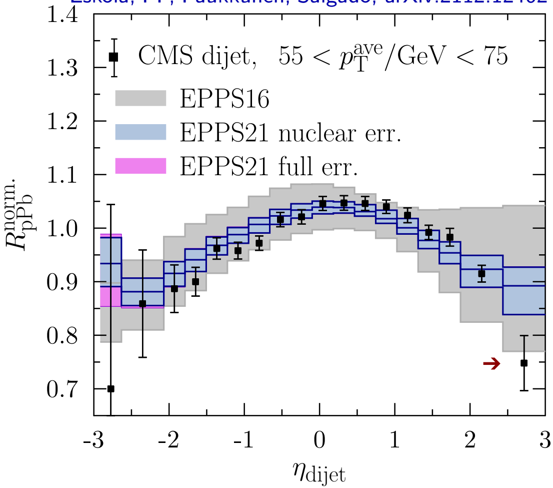
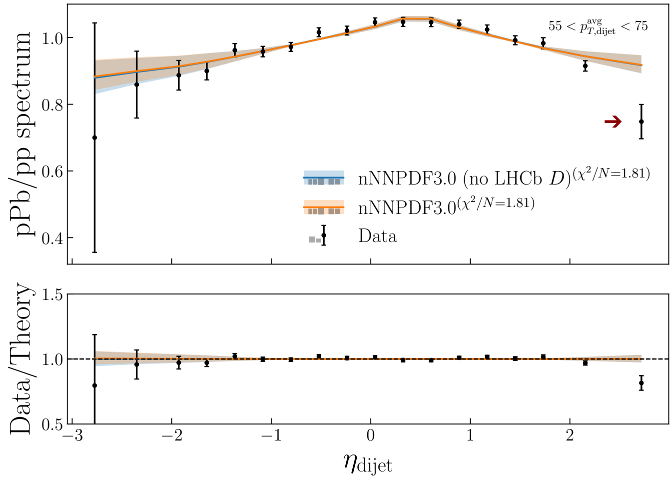
Dijets in EPPS21 and nNNPDF3.0

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

Eskola, PP, Paukkunen, Salgado, arXiv:2112.12462



Abdul Khalek et al., arXiv:2201.12363



Drastic reduction in the nPDF uncertainties!

→ Important constraints for the nuclear gluons!

Eskola, PP, Paukkunen, Eur. Phys. J. C 79 (2019) 511
Eskola, PP, Paukkunen, Salgado, arXiv:2112.12462
Abdul Khalek et al., arXiv:2201.12363

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

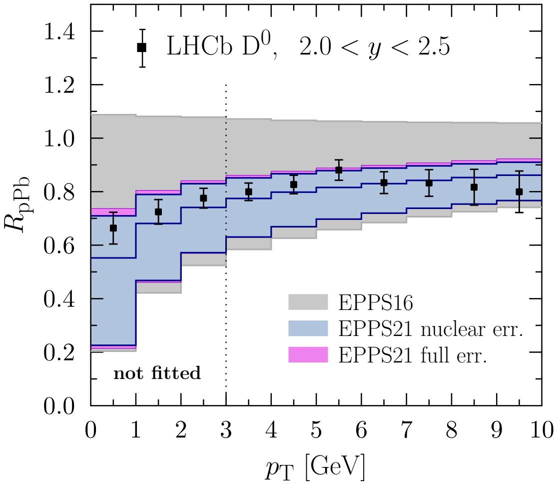
→ missing data correlations important?

→ NNLO? non-pert. effects?

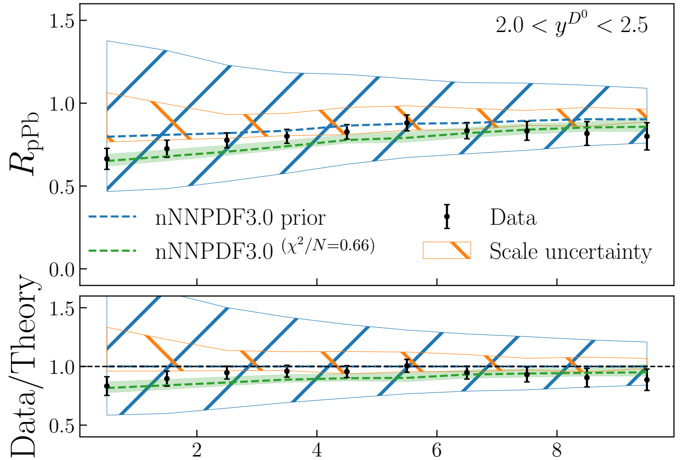
D^0s in EPPS21 and nNNPDF3.0

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

Eskola, PP, Paukkunen, Salgado, arXiv:2112.12462



Abdul Khalek et al., arXiv:2201.12363



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Kusina et al., Phys. Rev. Lett. 121 (2018) 052004
Eskola, Helenius, PP, Paukkunen, JHEP 05 (2020) 037
Eskola, PP, Paukkunen, Salgado, arXiv:2112.12462
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

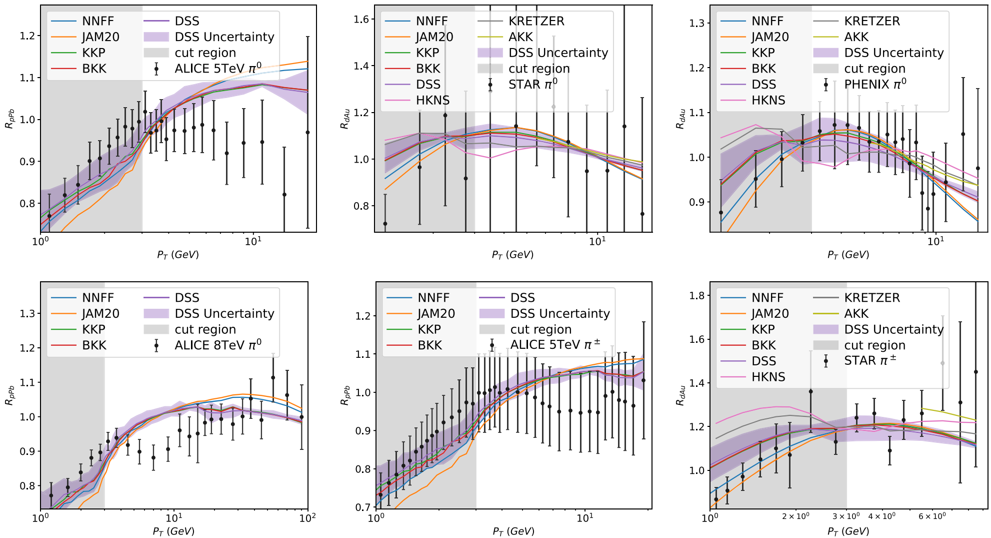
Single-inclusive hadrons – nCTEQ15WZSIH

Duwentäster et al., Phys. Rev. D 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

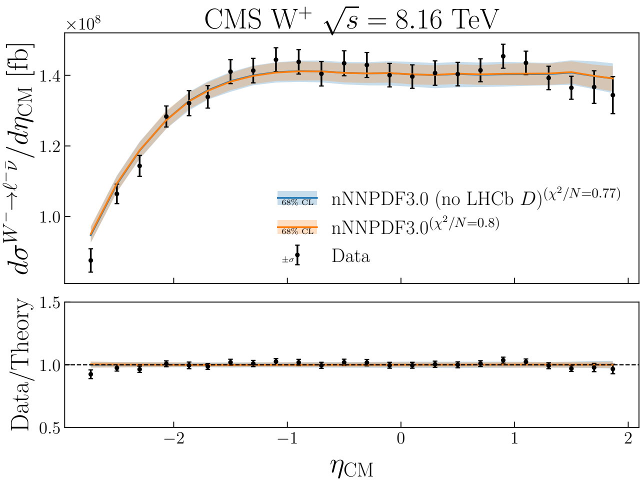


data from: PHENIX Collaboration, Phys. Rev. Lett. 98 (2007) 172302
STAR Collaboration, Phys. Lett. B 637 (2006) 161
Phys. Rev. C 81 (2010) 064904
ALICE Collaboration, Phys. Lett. B 760 (2016) 720
Eur. Phys. J. C 78 (2018) 624
Phys. Lett. B 827 (2022) 136943

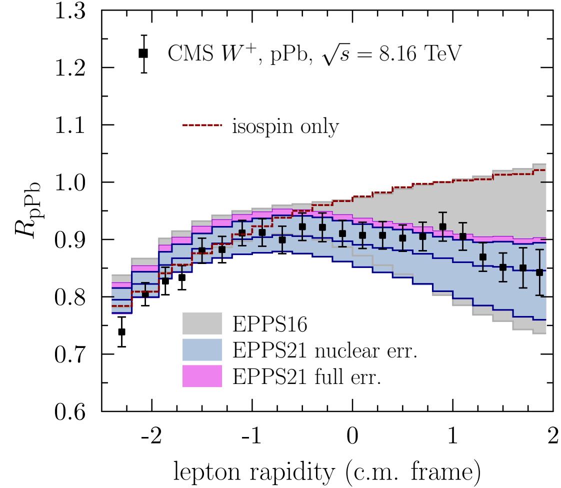
W bosons in pPb at 8.16 TeV

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

Abdul Khalek et al., arXiv:2201.12363



Eskola, PP, Paukkunen, Salgado, arXiv:2112.12462



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, Eur. Phys. J. C 82 (2022) 271

data from: CMS Collaboration, JHEP 05 (2021) 182
pp baseline: CMS Collaboration, Eur. Phys. J. C 75 (2015) 147

New Run 2 data from CMS

CMS Collaboration, JHEP 05 (2021) 182
➔ A. Baty, Thu 17:30

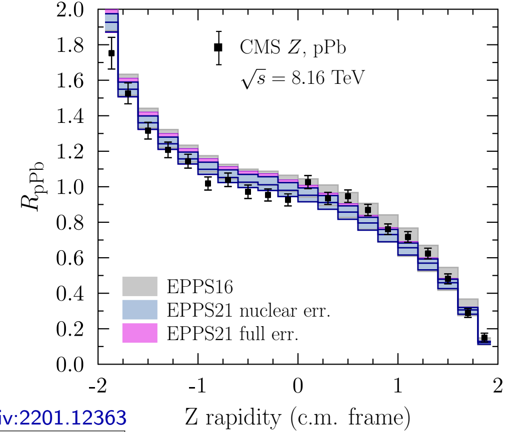
- nNNPDF3.0 include both low-mass and on-peak data
- R_{pPb} studied in EPPS21 ➔ not included in the final fit

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

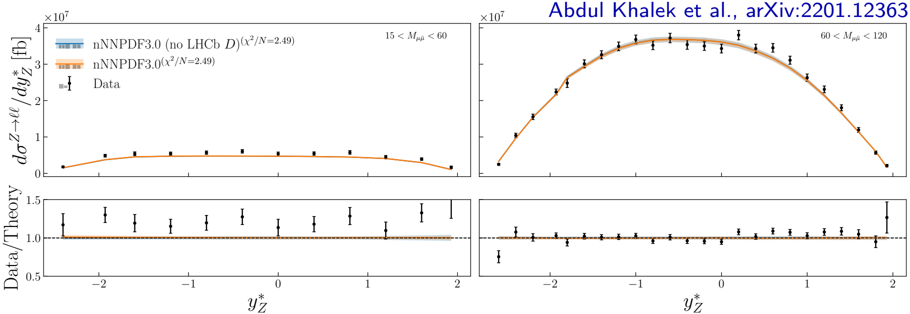
- abrupt change in the shape at midrapidity
- NNLO to cure for the low-mass data?

Abdul Khalek et al., arXiv:2201.12363

Eskola, PP, Paukkunen, Salgado, arXiv:2112.12462



Abdul Khalek et al., arXiv:2201.12363



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

High-x DIS – JLab Hall-C and CLAS

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

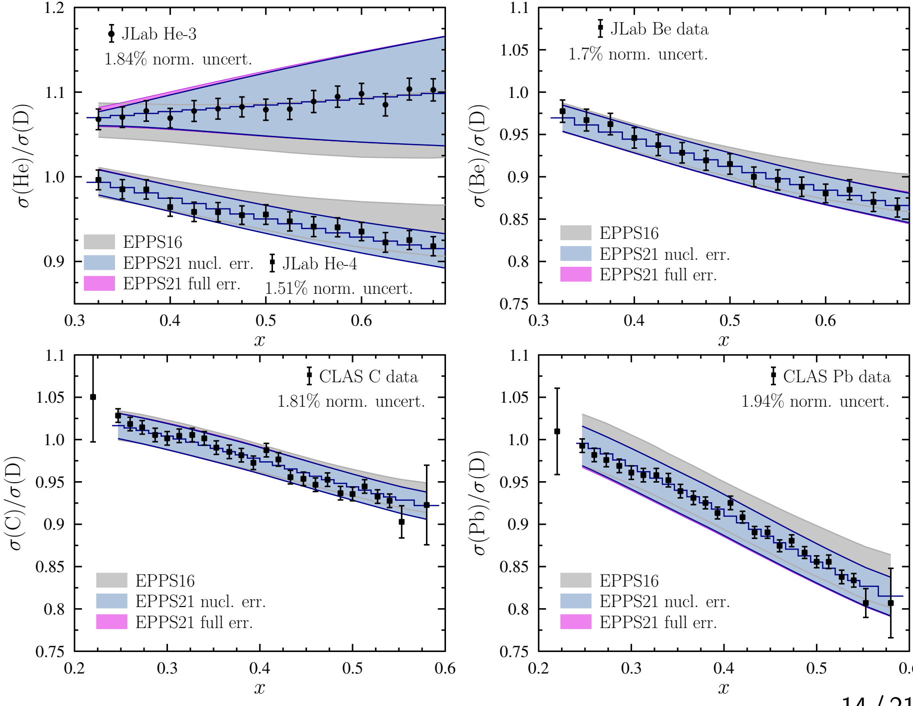
Eskola, PP, Paukkunen, Salgado, arXiv:2112.12462

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

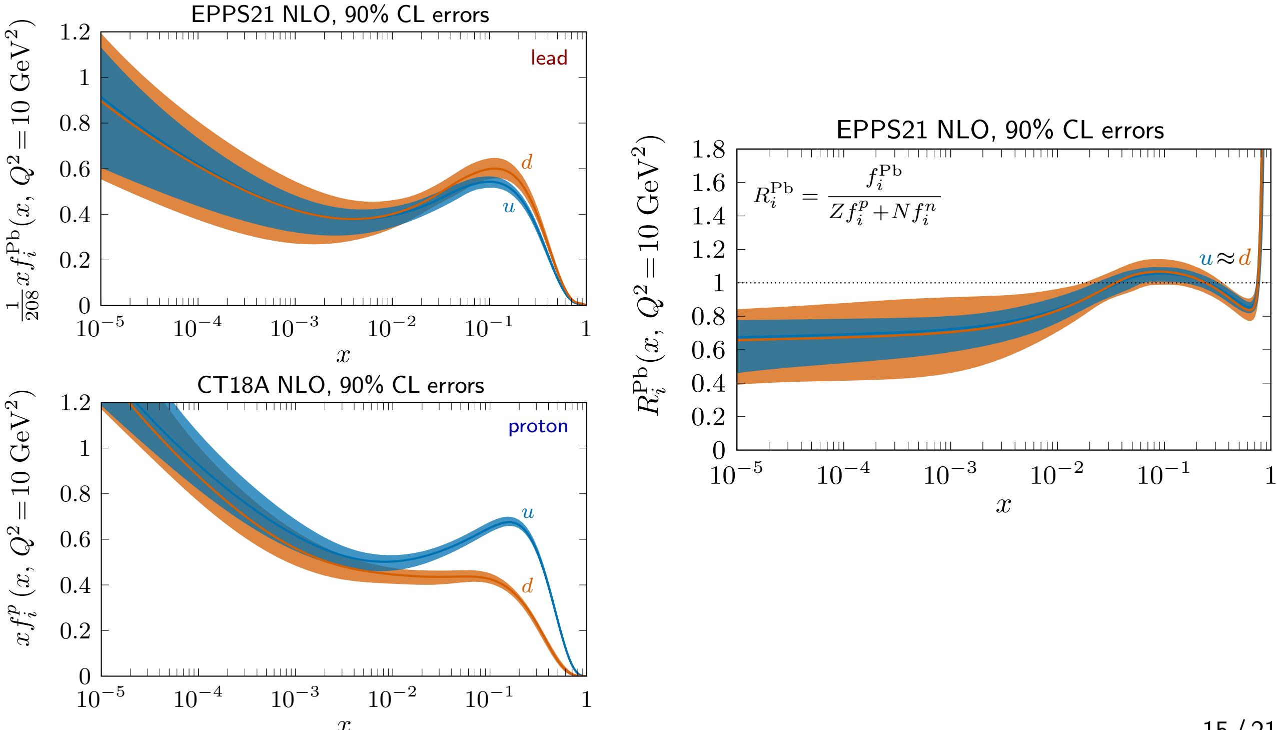
Target-mass corrections important!

Deuterium and higher-twist corrections can improve the fit
Segarra et al., Phys. Rev. D 103 (2021) 114015

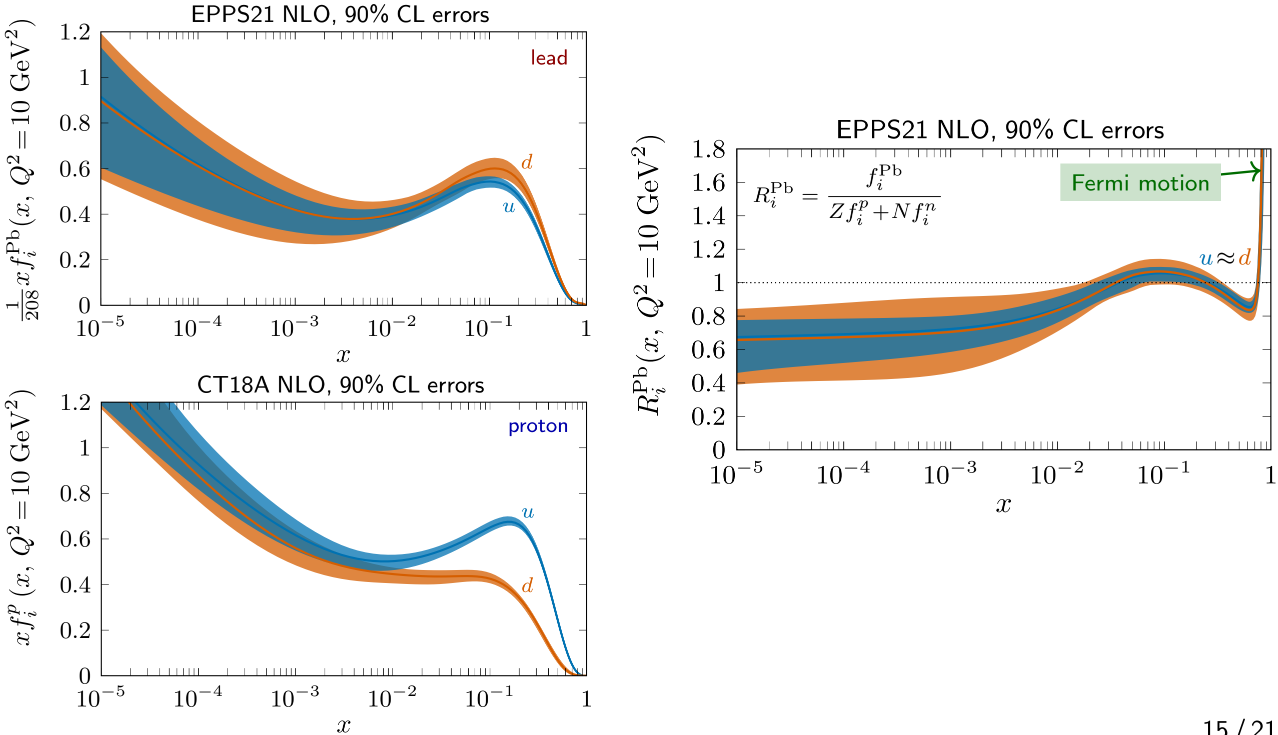
but are not necessary to describe the data
Paukkunen & Zurita, Eur. Phys. J. C 80 (2020) 381
Eskola, PP, Paukkunen, Salgado, arXiv:2112.12462



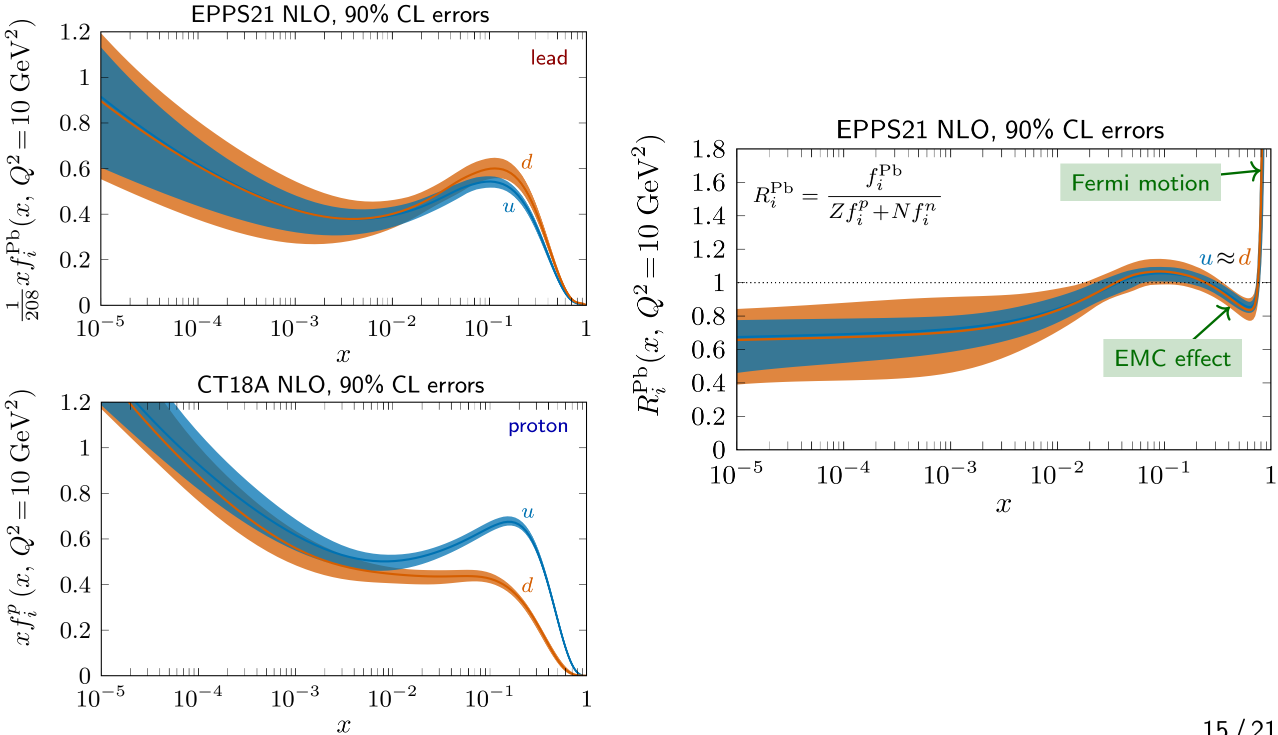
Comparing nuclear and proton PDFs – u and d



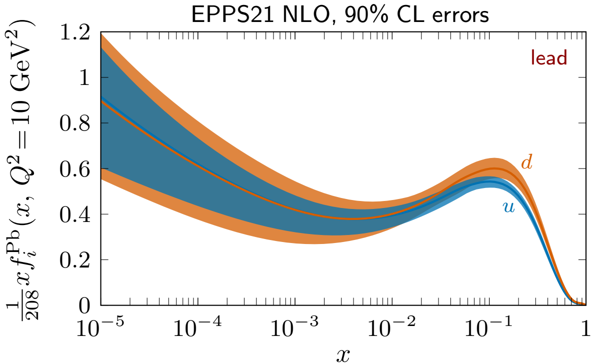
Comparing nuclear and proton PDFs – u and d

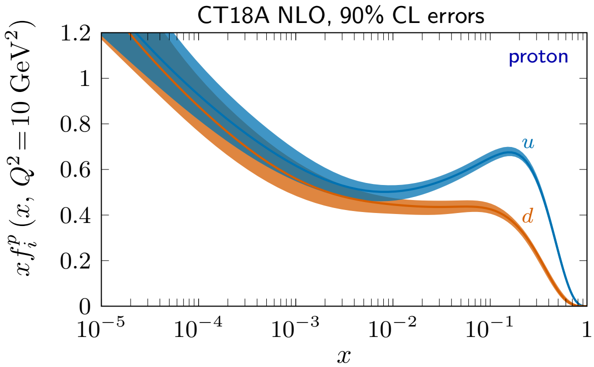


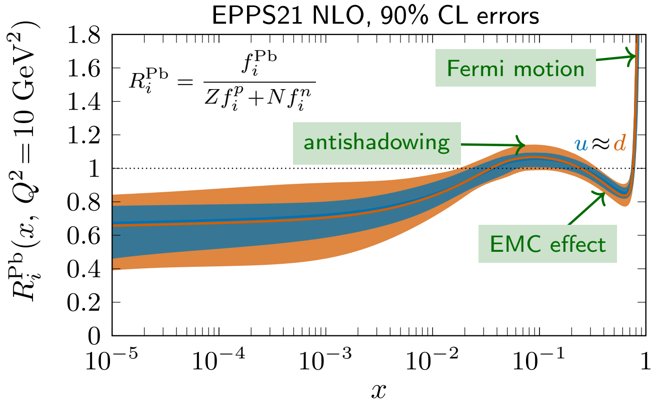
Comparing nuclear and proton PDFs – u and d



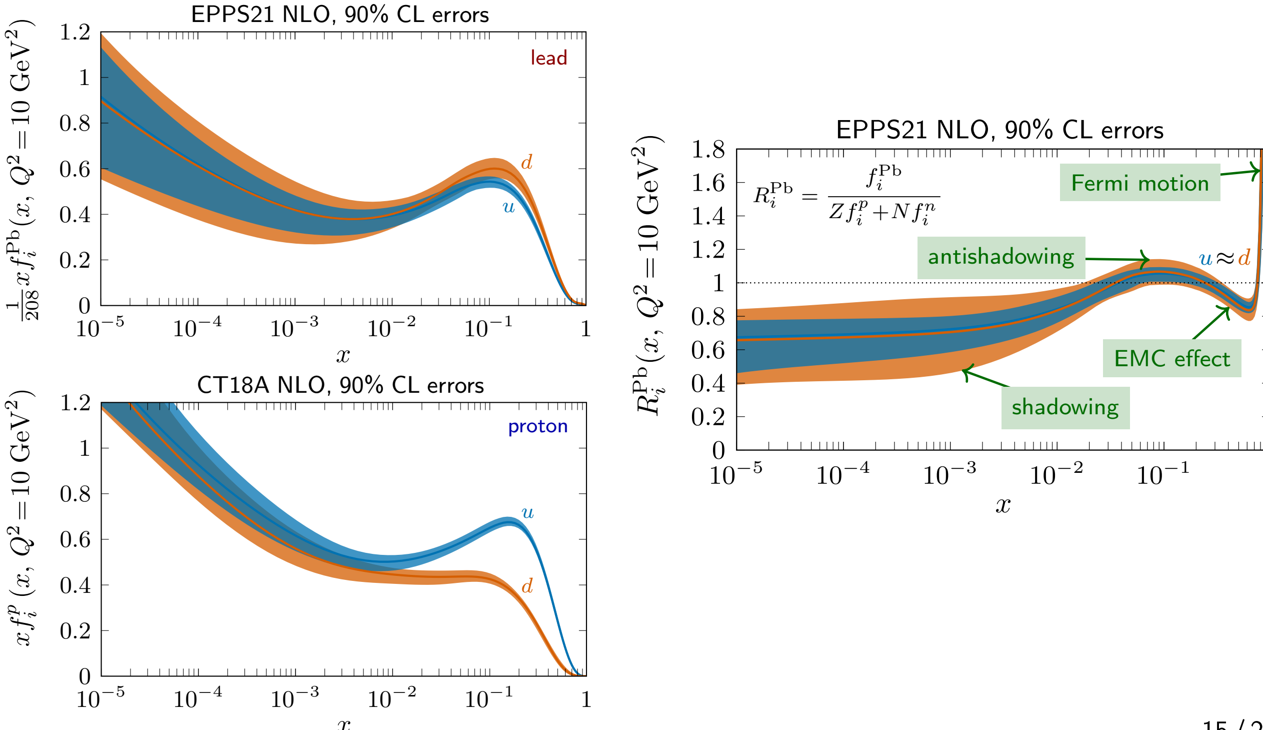
Comparing nuclear and proton PDFs – u and d



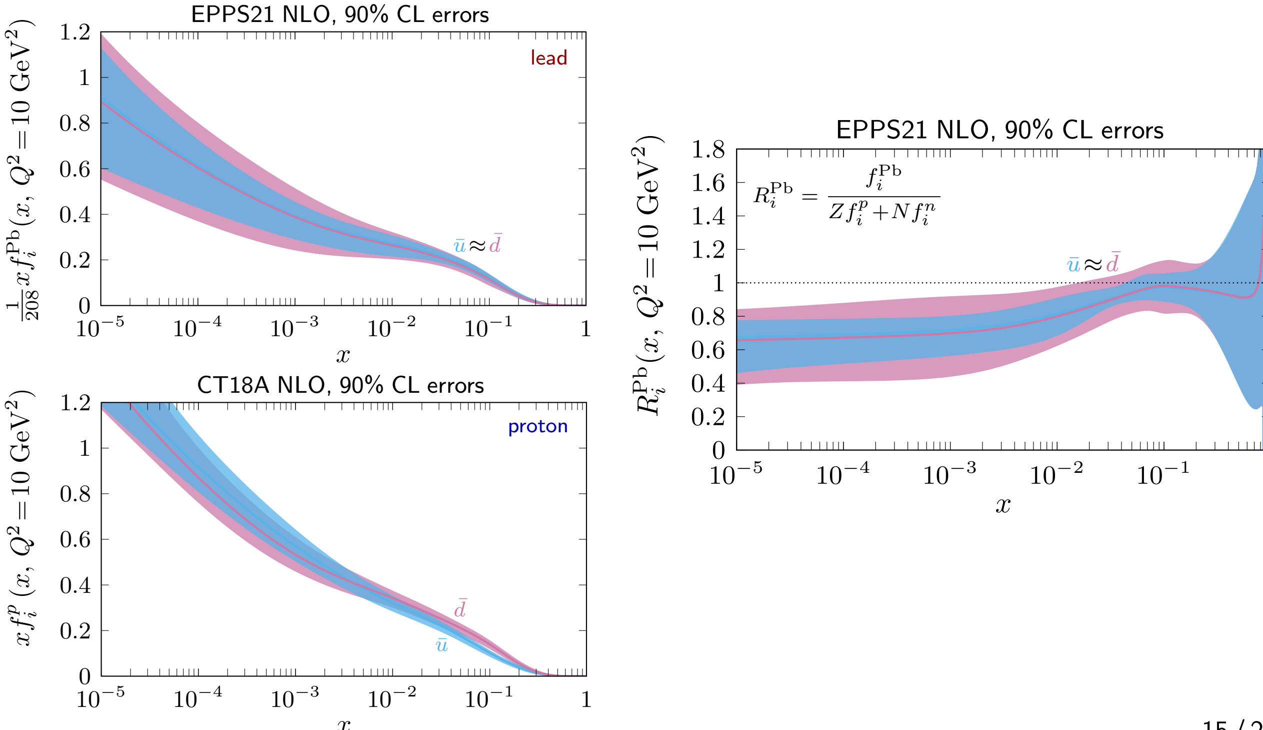




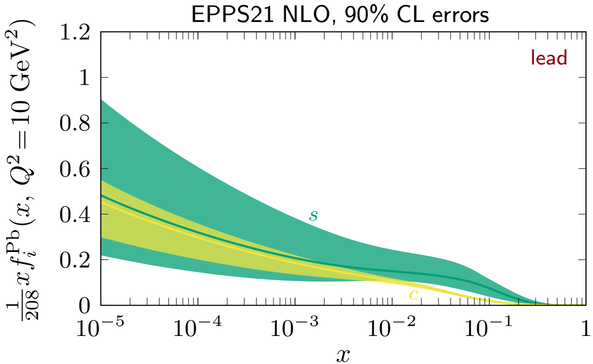
Comparing nuclear and proton PDFs – u and d

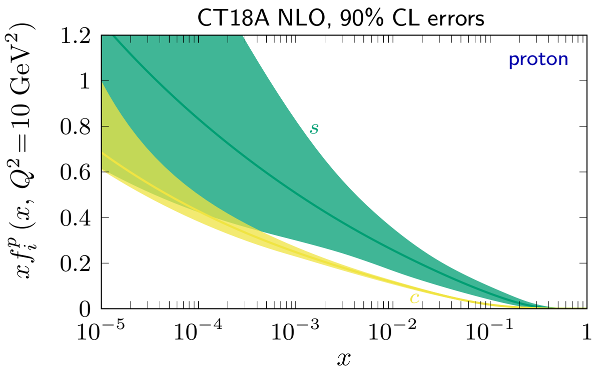


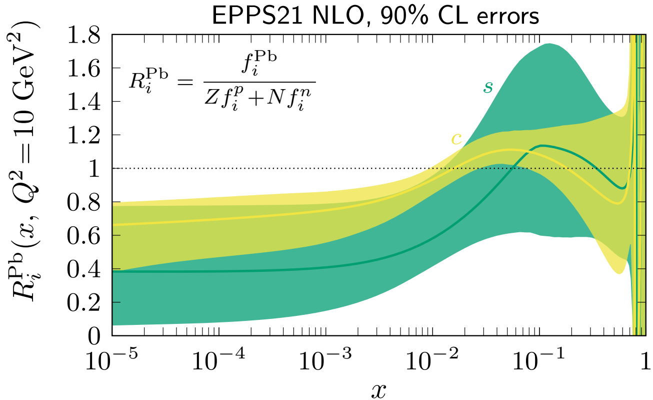
Comparing nuclear and proton PDFs – $\bar{u}$ and $\bar{d}$



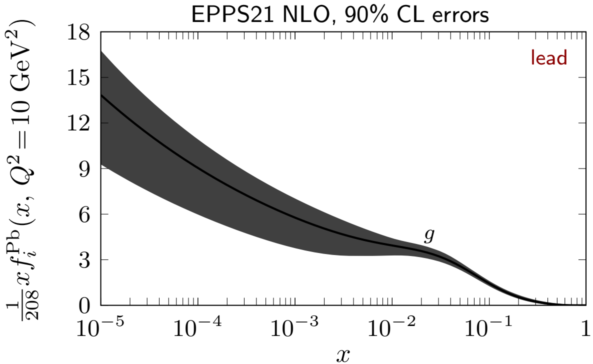
Comparing nuclear and proton PDFs – s and c

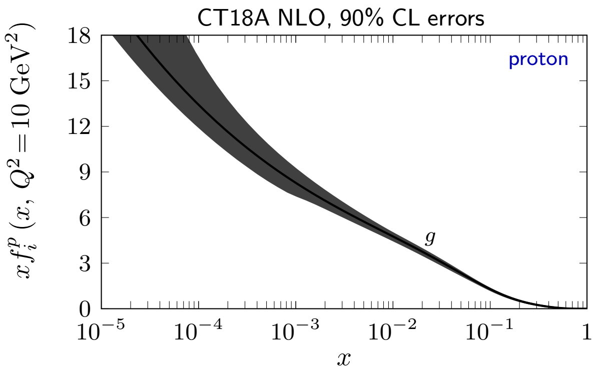


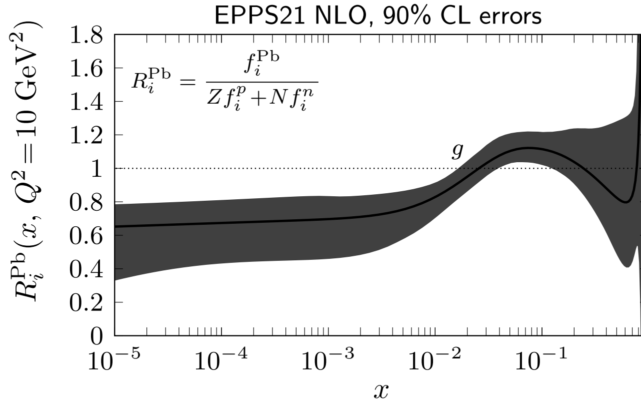




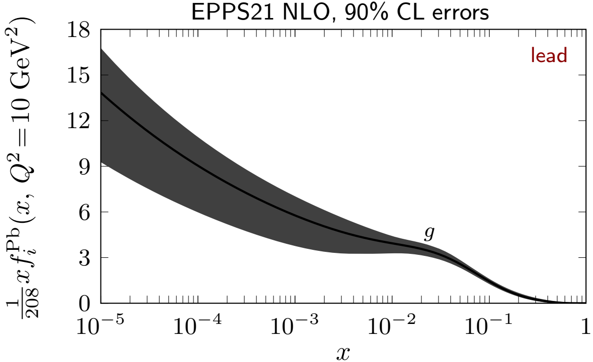
Comparing nuclear and proton PDFs – *glue*

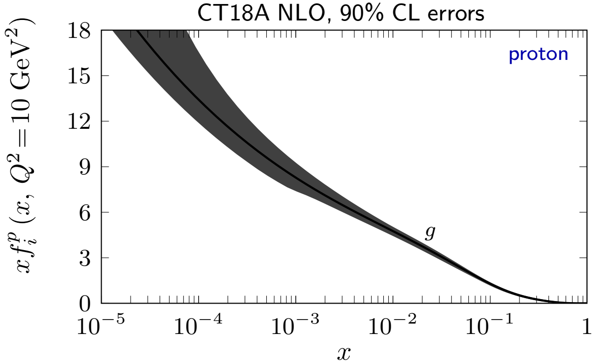


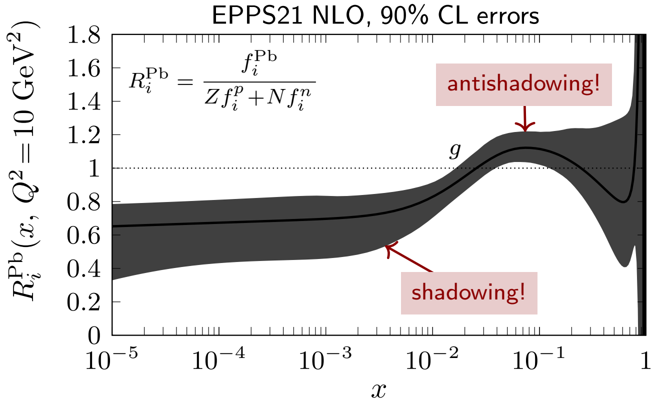




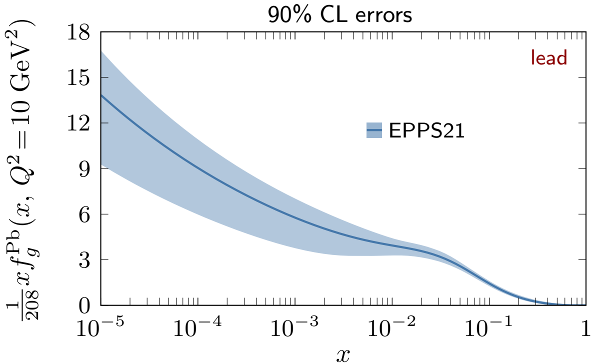
Comparing nuclear and proton PDFs – *glue*

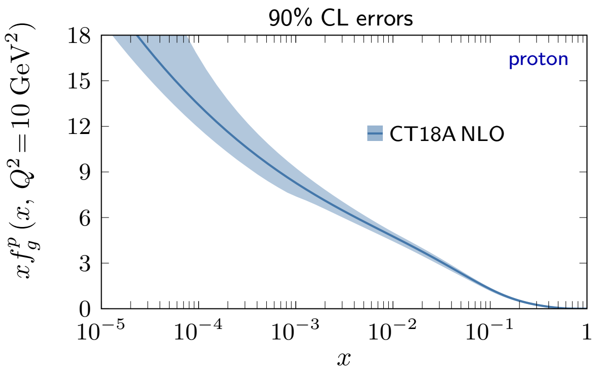


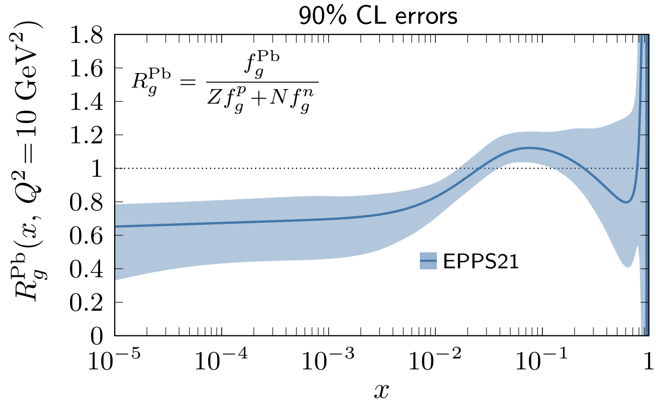




nPDF comparison – *glue*

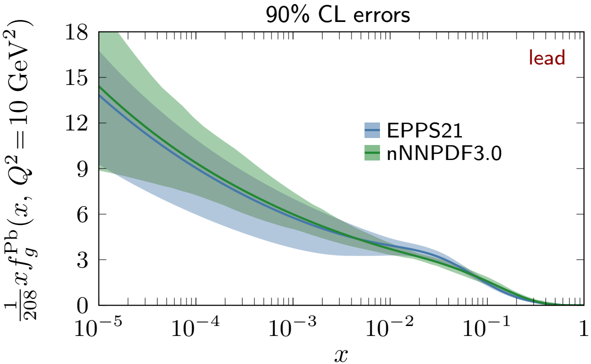


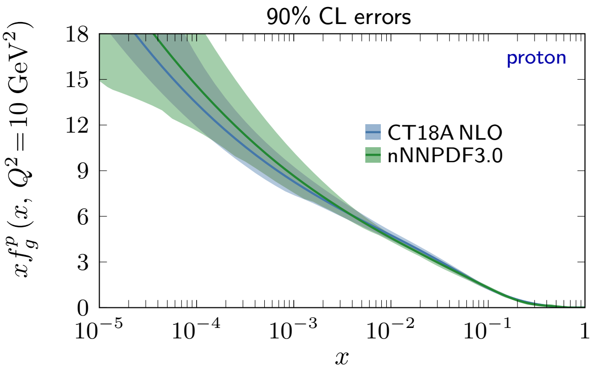


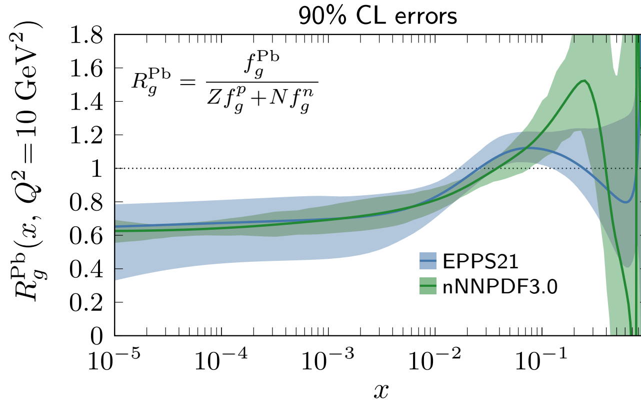


EPPS21: incl.-h^{RHIC} $\mathrm{D}^{0\,\mathrm{fwd}}_{\ \,\mathrm{bwd}}$ jets W,Z

nPDF comparison – *glue*

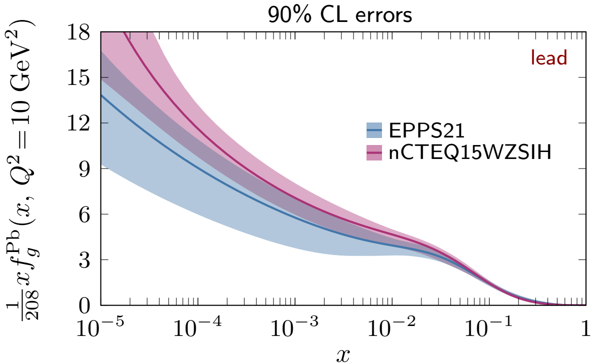


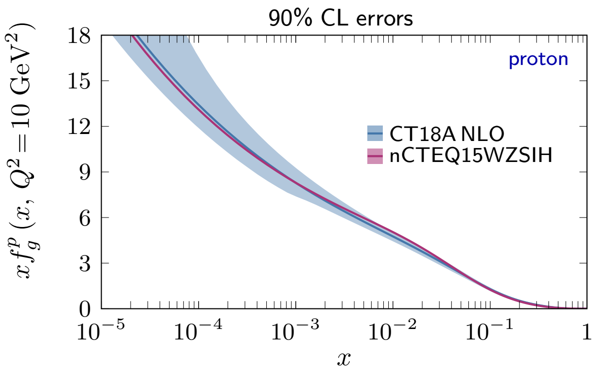


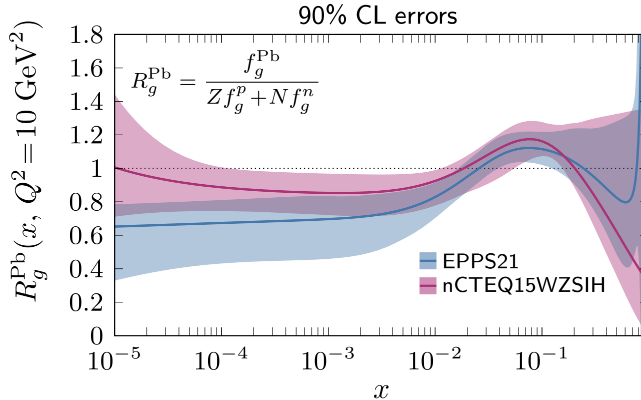


EPPS21:	incl.-h^{RHIC}	$\mathrm{D}^{0\,\mathrm{fwd}}_{\mathrm{bwd}}$	jets	W,Z
nNNPDF3.0:		$\mathrm{D}^{0\,\mathrm{fwd}}$	jets	W,Z

nPDF comparison – *glue*

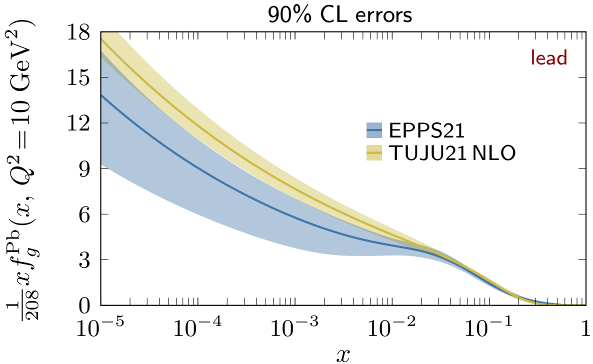


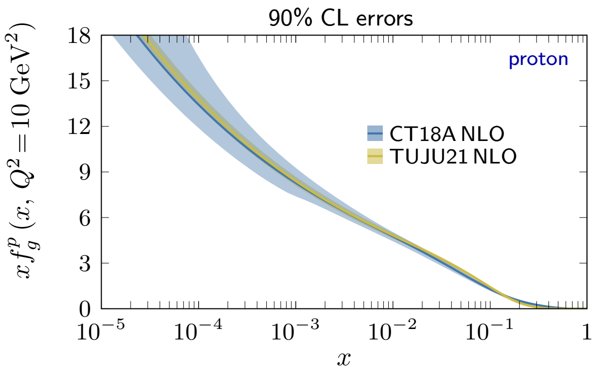


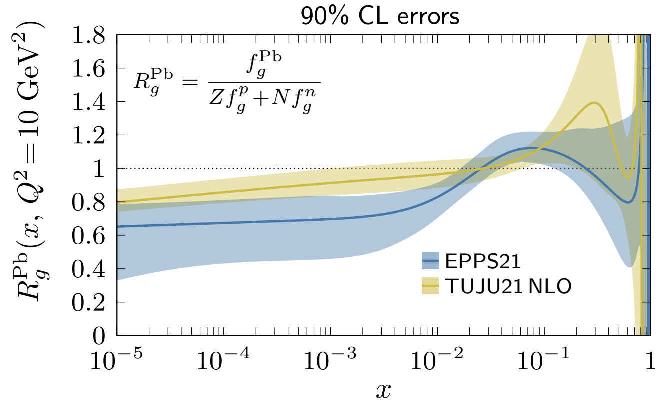


EPPS21:	incl.-h^{RHIC}	$\mathrm{D}^{0\,\mathrm{fwd}}_{\mathrm{bwd}}$	jets	W,Z
nNNPDF3.0:		$\mathrm{D}^{0\,\mathrm{fwd}}$	jets	W,Z
nCTEQ15WZSIH:	incl.-$h^{\mathrm{RHIC}}_{\mathrm{LHC}}$			W,Z

nPDF comparison – *glue*



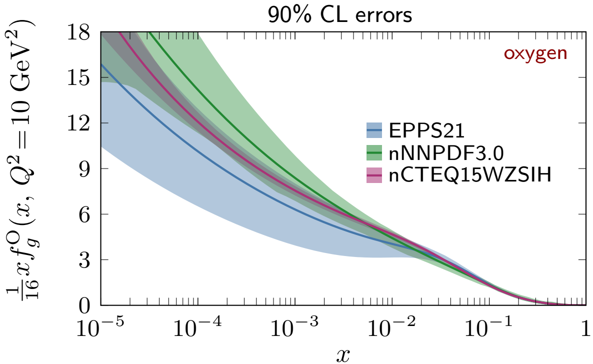


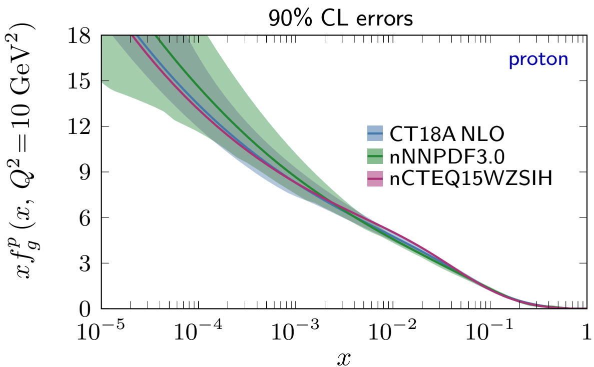


EPPS21:	incl.-$h^{\rm RHIC}$	$D^{0\,\rm fwd}_{\rm bwd}$	jets	W,Z
nNNPDF3.0:		$D^{0\,\rm fwd}$	jets	W,Z
nCTEQ15WZSIH:	incl.-$h^{\rm RHIC}_{\rm LHC}$			W,Z
TUJU21:				W,Z

nPDF comparison – *glue* in oxygen

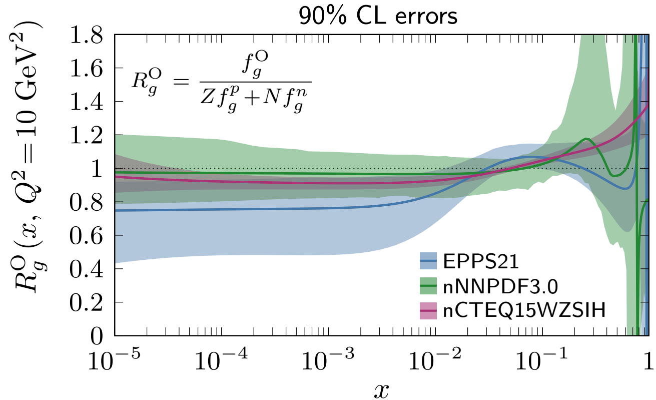
see also: PP, Phys. Rev. D 105 (2022) L031504





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

→ A. Mazeliauskas, Wed 9:40

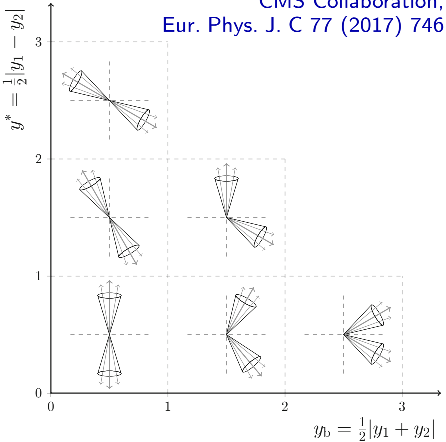


EPPS21:	incl.-h^{RHIC}	$\mathrm{D}^{0\,\mathrm{fwd}}_{\ \ \mathrm{bwd}}$	jets	W,Z
nNNPDF3.0:		$\mathrm{D}^{0\,\mathrm{fwd}}$	jets	W,Z
nCTEQ15WZSIH:	incl.-$h^{\mathrm{RHIC}}_{\mathrm{LHC}}$			W,Z

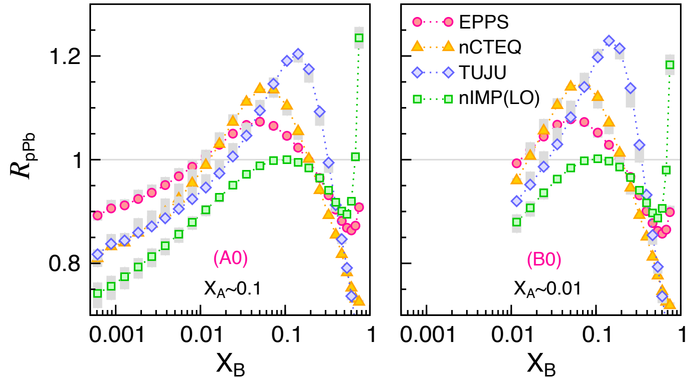
only dAu and pPb!

Triple-differential dijets in pPb?

CMS Collaboration,
Eur. Phys. J. C 77 (2017) 746



Shen et al., arXiv:2112.11819



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

measurable!

$$X_B = \sum_{n \in \text{dijet}} \frac{E_{Tn}}{\sqrt{s}} e^{-y_n} \overset{\text{LO}}{=} x_{\text{Pb}}$$

momentum fraction from the lead side

Triple-differential measurement fixes partonic kinematics at LO

→ powerful test of factorisation and PDFs

Measured in pp at 8 TeV
CMS Collaboration, Eur. Phys. J. C 77 (2017) 746

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

Ellis & Soper, Phys. Rev. Lett. 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?

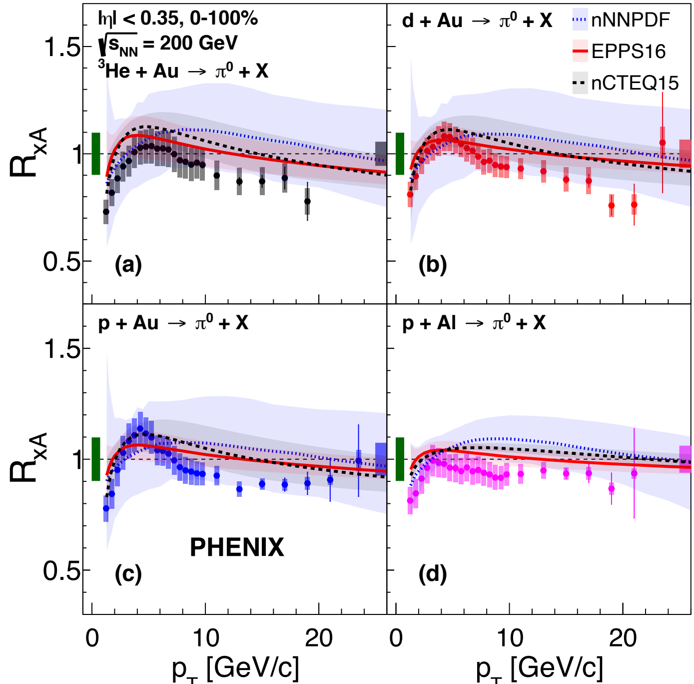
At high p_T the nPDF predictions overshoot the data, but mind the large normalisation uncertainties

Progress in QM2022

LHCb measurements of D^0s and π^0s at 8.16 TeV and charged hadrons at 5.02 TeV in pPb

➔ Ó. Boente García, Thu 11:10
➔ B. Audurier, Thu 15:00

PHENIX Collaboration, arXiv:2111.05756



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

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

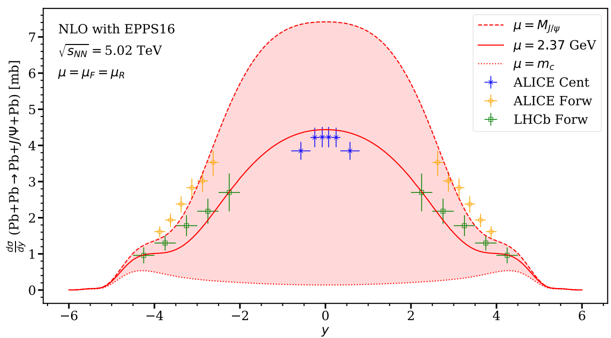
in ultrapheripheral Pb+Pb

➔ T. Löytäinen, Thu 12:50

Large scale uncertainty

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

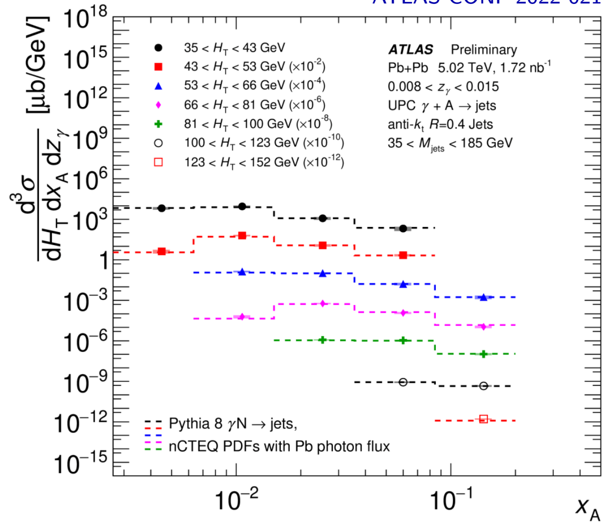
Eskola et al., arXiv:2203.11613



ATLAS inclusive dijet photoproduction measurement now fully unfolded

➔ B. J. Gilbert, Tue 16:50

ATLAS-CONF-2022-021



Summary

Ample progress in incorporating new data in global PDF fits:

- LHC pp data precision requires NNLO proton-PDF fit
- LHC pPb data put unprecedented constraints on the gluon nPDF
- Ongoing work to understand the (cross)correlations between proton and nuclear PDF analyses

The future is bright!

- Both collider and fixed-target experiments keep providing new data
- LHC Run 3 just around the corner
- High-lumi LHC and EIC in the "near" sight

Progress in QM2022

Many exiting experimental results:

Dijet photoproduction in 5 TeV PbPb at ATLAS
→ B. J. Gilbert, Tue 16:50

π^0 in 8 TeV pPb and $h^\pm$ in 5 TeV pPb at LHCb
→ Ó. Boente García, Thu 11:10

D^0 in 8 TeV pPb at LHCb
→ B. Audurier, Thu 15:00

Z in 8 TeV pPb and $Z+c$ in 13 TeV pp at LHCb
→ T. Li, Thu 16:50

$W^\pm$ in 13 TeV pp, 8 TeV pPb and 5 TeV PbPb at ALICE
→ S. Sakai, Thu 17:10

Z/γ^* in 8 TeV pPb and 5 TeV PbPb at CMS
→ A. Baty, Thu 17:30

Backup

Collider DIS – HERA I+II combined data

Completion of the H1+ZEUS inclusive and heavy-quark DIS combination work

H1 and ZEUS, Eur. Phys. J. C 75 (2015) 580
Eur. Phys. J. C 78 (2018) 473

➔ coherent data sets with reduced systematic uncertainties

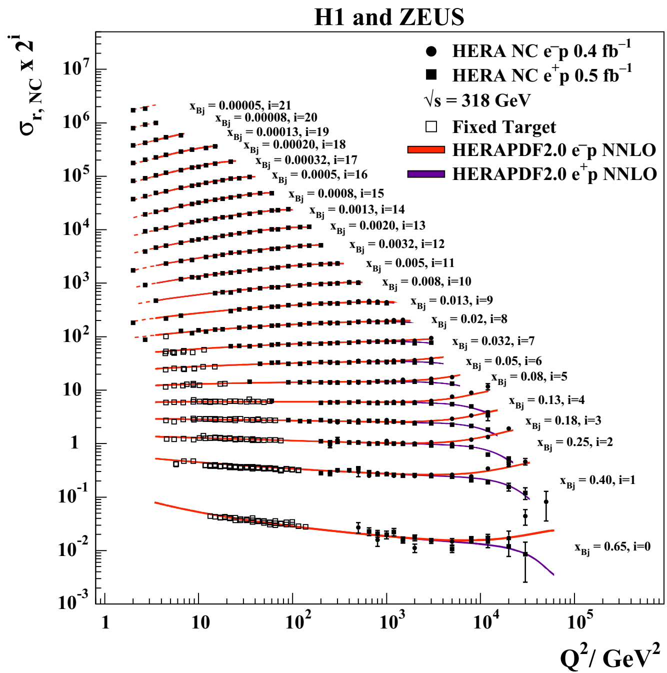
Backbone of any modern proton-PDF analysis

- Both neutral and charged current
  - ➔ quark flavour separation
- Large Q^2 lever arm
  - ➔ constrain glue through DGLAP
- Hints of small-x BFKL dynamics / need for resummation?

Ball et al., Eur. Phys. J. C 78 (2018) 321
Abdolmaleki et al., Eur. Phys. J. C 78 (2018) 621

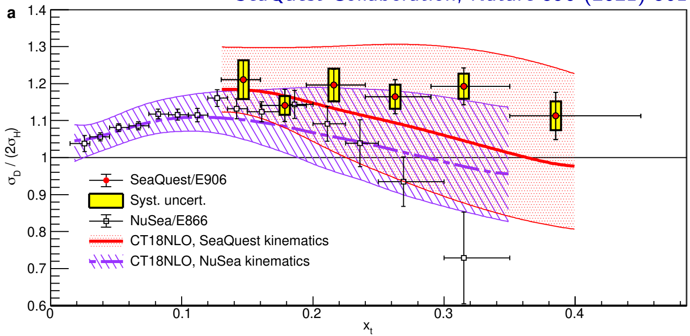
EIC will provide the same for nPDF fits!

H1 and ZEUS, Eur. Phys. J. C 75 (2015) 580



Fixed-target DY and DIS – Fermilab SeaQuest and JLab Marathon

SeaQuest Collaboration, Nature 590 (2021) 561

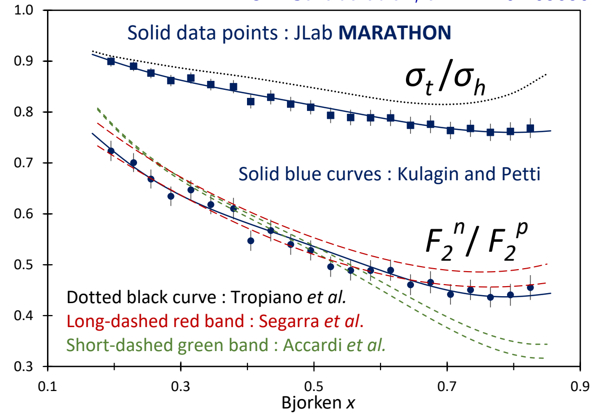


SeaQuest data favours proton $\bar{d} > \bar{u}$ without a large-x reversal

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_{\text{beam}} \gg x_{\text{target}}} \approx \frac{1}{2}\left[1 + \frac{f^p_{\bar{d}}(x_{\text{target}})}{f^p_{\bar{u}}(x_{\text{target}})}\right]$$

neglect deuteron corrections and assume isospin symmetry: $f^n_{\bar{u}} = f^p_{\bar{d}}$

MARATHON Collaboration, arXiv:2104.05850



First DIS data on mirror nuclei!

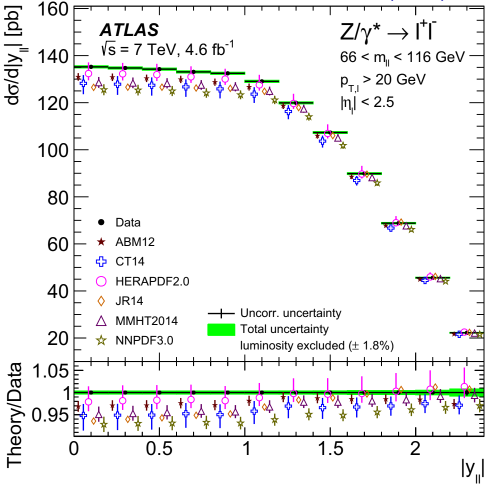
Idea: He-3, H-3

$$\frac{2\mathcal{R}_{ht} - \sigma_h/\sigma_t}{2\sigma_h/\sigma_t - \mathcal{R}_{ht}} \approx \frac{F_2^n}{F_2^p} \approx \frac{1}{4} + \frac{f^p_d(x)}{f^p_u(x)}$$

$$\mathcal{R}_{ht} = \frac{F_2^h/(2F_2^p + F_2^n)}{F_2^t/(F_2^p + 2F_2^n)} \approx 1 \text{ from models}$$

LHC EW data in proton-PDF fits

ATLAS Collaboration, Eur. Phys. J. C 77 (2017) 367



EW bosons give access to flavours that are otherwise poorly constrained ➔ strange and charm

Associated production with a heavy quark to enhance contribution from certain flavours

- $W^{\pm} + c$ ➔ strangeness
- $Z + c$ ➔ intrinsic charm

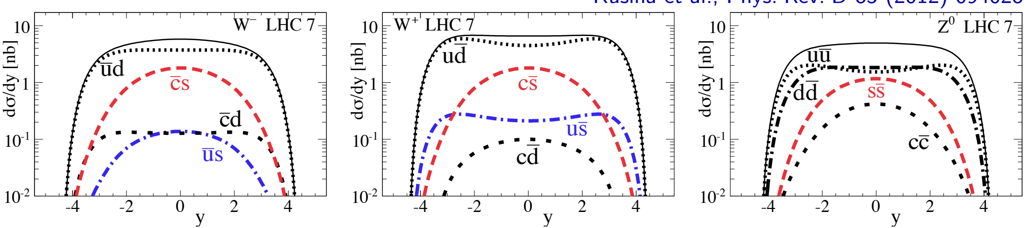
➔ T. Li, Thu 16:50

Differences in the resulting strange across recent global analyses

Perturbative vs. fitted charm makes a big difference

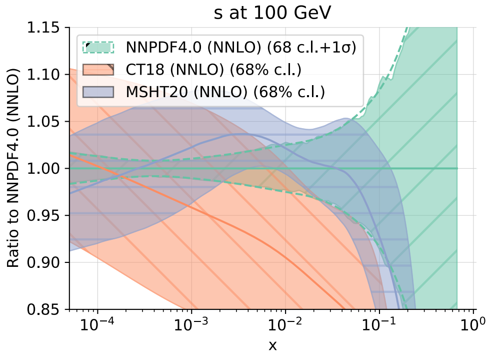
Ball et al., arXiv:2109.02653

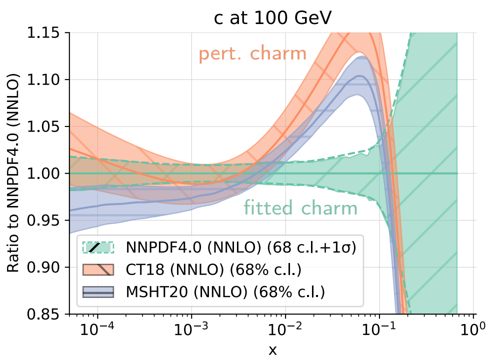
Kusina et al., Phys. Rev. D 85 (2012) 094028



LHC EW data in proton-PDF fits

Ball et al., arXiv:2109.02653





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➔ T. Li, Thu 16:50

Differences in the resulting strange across recent global analyses

Perturbative vs. fitted charm makes a big difference

Ball et al., arXiv:2109.02653

Perturbative stability and missing higher orders

Ball et al., arXiv:2109.02653

NNLO improves fit quality particularly for LHC data

see e.g. Bailey et al., Eur. Phys. J. C 81 (2021) 341

Ongoing work to include theoretical uncertainties from missing higher orders in the fits

- Use e.g. a *theory covariance matrix* evaluated from scale variations

  Abdul Khalek et al., Eur. Phys. J. C 79 (2019) 931

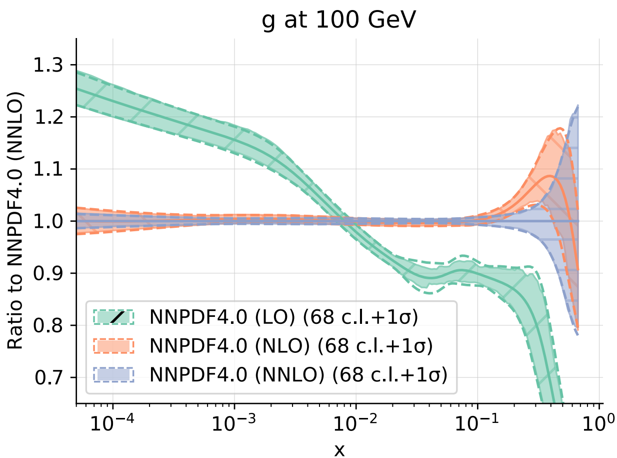
data uncertainties ↓

$$\chi^2 = (D-T)^T \, (C+S)^{-1} \, (D-T)$$

↑ theory uncertainties

→ Need a way to consistently propagate these into the predictions

Harland-Lang & Thorne, Eur. Phys. J. C 79 (2019) 225
Ball & Pearson, Eur. Phys. J. C 81 (2021) 830



$\chi^2_{\text{tot}}/N_{\text{data}}$	LO	NLO	NNLO
MSHT20	N/A	1.33	1.17
NNPDF4.0	3.35	1.24	1.16

Mitigating free-proton PDF uncertainty

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

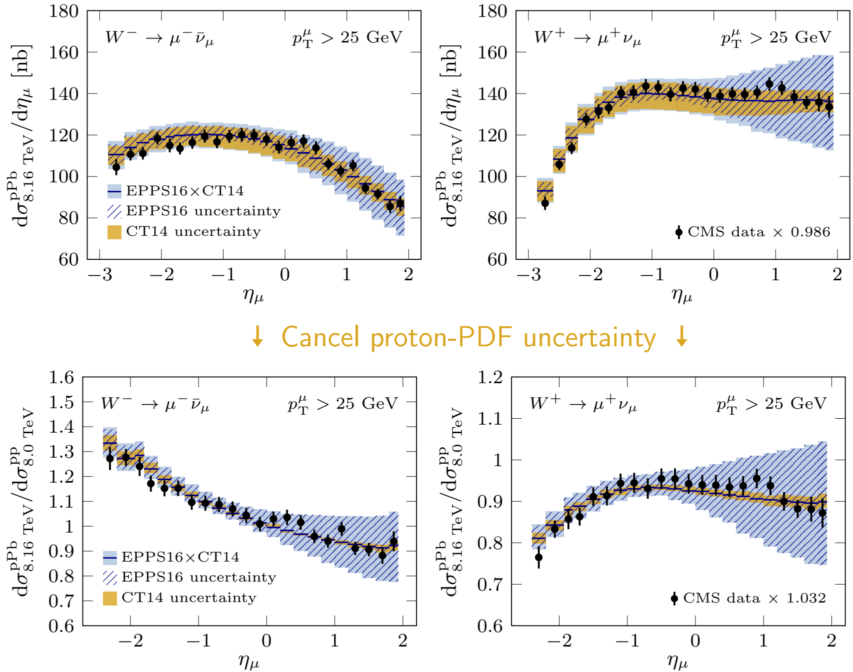
Eskola, PP, Paukkunen, Salgado, Eur. Phys. J. C 82 (2022) 271

Absolute pPb cross sections sensitive to proton-PDF uncertainties!

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

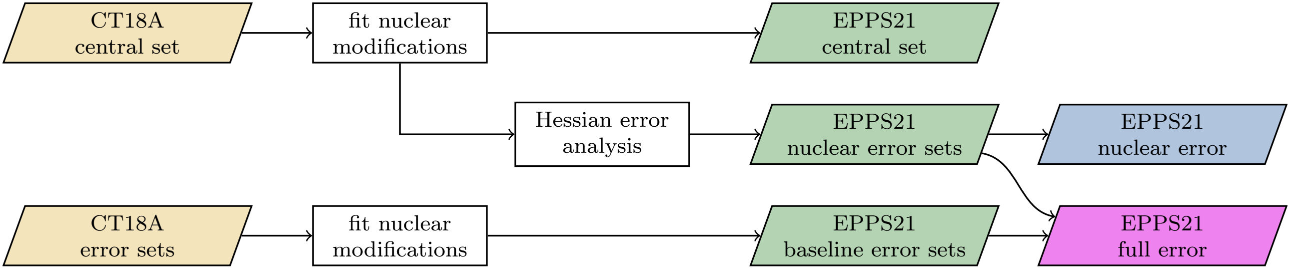
nCTEQ15WZSIH, TUJU21 and nNNPDF3.0 fit to absolute cross sections

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



Propagating free-proton PDF uncertainty

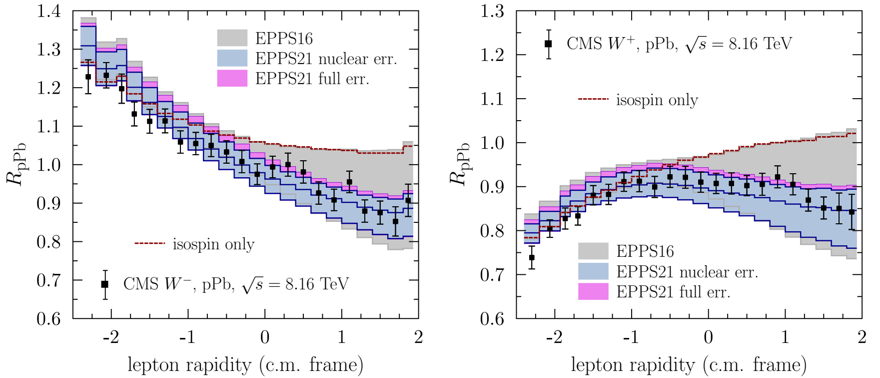
Eskola, PP, Paukkunen, Salgado, arXiv:2112.12462



EPPS21: fit nuclear modifications for each CT18A error set separately

- ➔ subleading effect

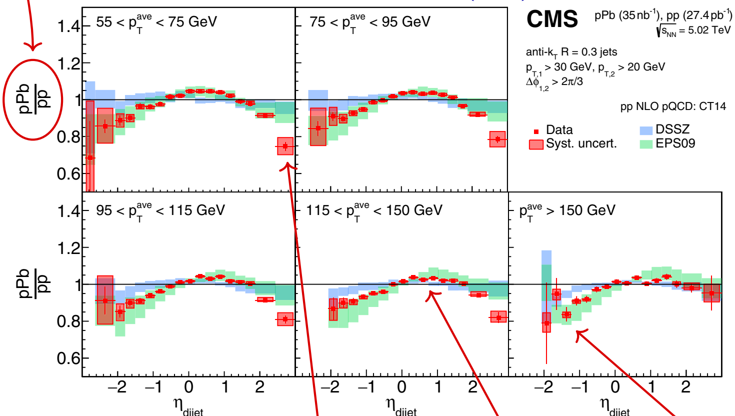
nNNPDF3.0 uses similar approach in Monte Carlo framework



Dijets in pPb at 5.02 TeV

Ratio of ratios: $R^{\rm norm.}_{\rm pPb} = \dfrac{{\rm d}^2\sigma^{\bf pPb}/{\rm d}p_{\rm T}^{\rm ave}{\rm d}\eta_{\rm dijet}}{{\rm d}\sigma^{\bf pPb}/{\rm d}p_{\rm T}^{\rm ave}} \Big/ \dfrac{{\rm d}^2\sigma^{\bf pp}/{\rm d}p_{\rm T}^{\rm ave}{\rm d}\eta_{\rm dijet}}{{\rm d}\sigma^{\bf pp}/{\rm d}p_{\rm T}^{\rm ave}}$

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

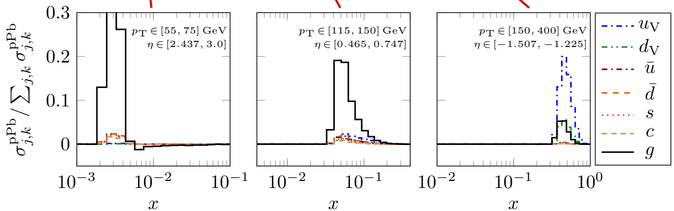


Double ratio convenient for:

- 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,
Eur. Phys. J. C 79 (2019) 511

NLO pQCD:



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

Heavy-flavour production mass schemes

FFNS

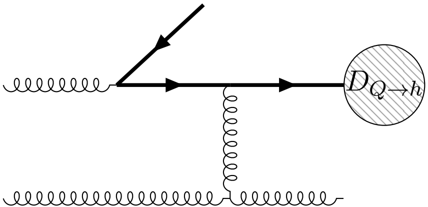
In *fixed flavour number scheme*, valid at small p_{T}, heavy quarks are produced only at the matrix element level

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

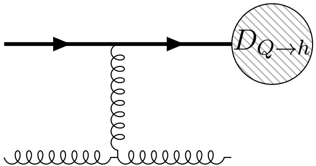
ZM-VFNS

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 m/p_{T} terms



$-$ subtraction term $+$



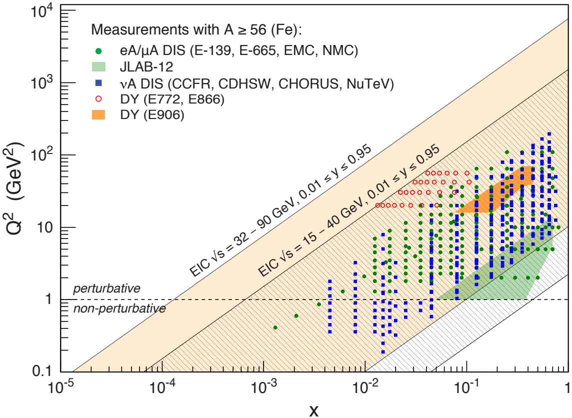
GM-VFNS

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}

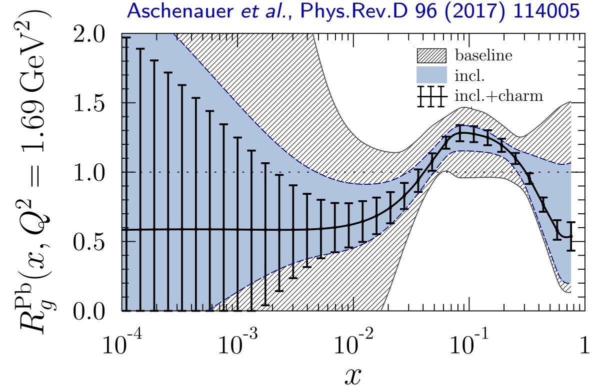
Resums $\log(p_{\mathrm{T}}/m)$ and includes m/p_{T} terms in the FFNS matrix elements

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

Gluon constraints from EIC



Aschenauer *et al.*, Phys.Rev.D 96 (2017) 114005



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 $F_{\rm L}$ 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