EPPS21 nuclear PDFs

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Reference: EPJC 82, 413 [arXiv:2112.12462]

Recent nuclear PDFs

		EPPS16	TUJU21	nNNPDF3.0	nCTEQ15WZSIH	EPPS21
	Order in α_s	NLO	NLO + NNLO	NLO	NLO	NLO
fixed target data	DIS ℓ^-+A	✓	✓	✓	✓	✓
fixed target data	DIS ν+A	✓	✓	✓		✓
fixed target data	Drell-Yan p+A	✓		✓	✓	✓
fixed target data	Drell-Yan in $\pi+A$	✓				✓
collider data	p+Pb dijets	✓		✓		✓
collider data	p+Pb W & Z	✓	✓	✓	✓	✓
collider data	p+Pb D-mesons			✓		✓ New!
collider data	p+Pb direct γ			✓		
collider data	p+Pb π^0, $\pi^\pm$, $\mathrm{K}^\pm$				✓	
collider data	d+Au π^0, $\pi^\pm$	✓			✓	✓
	datapoints	1811	2410	2188	940	2077
	free parameters	20	16	256	19	24
	error analysis	Hessian	Hessian	Monte-Carlo	Hessian	Hessian
	heavy-quark scheme	SACOT	FONLL	FONLL	SACOT	SACOT
	fitted flavours	6	4	6	5	6
	proton PDF correlations			✓		✓ New!
	reference	EPJC 77, 163	2112.11904	2201.12363	PRD 104, 094005	EPJC 82, 413

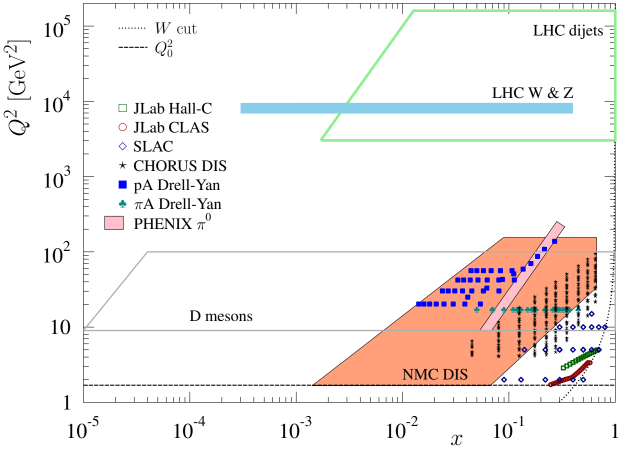
- The available x, Q^2 region is getting wider
- New data in EPPS21 vs. EPPS16:

- CMS 5TeV double-diff. dijets

- LHCb 5TeV double-diff. D mesons

- CMS 8.16TeV $W^{\pm}$

- JLab Hall-C and CLAS DIS



Parametrization

- Our definition of nuclear PDFs

Free proton baseline = **CT18A**

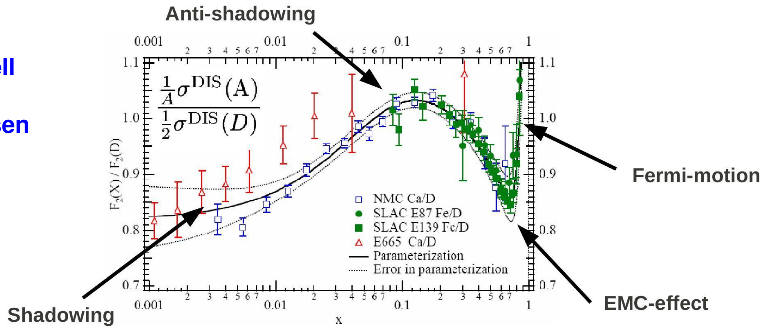
$$f_i^{p/A}(x,Q^2) \equiv R_i^{p/A}(x,Q^2) \, f_i^{p}(x,Q^2)$$

Nuclear modifications

- Fit ratios $\sigma^{\mathrm{DIS}}(\ell^- A)/\sigma^{\mathrm{DIS}}(\ell^- D)$

$\Longrightarrow$ **Need a free-proton PDF as well**

$\Longrightarrow$ **Nuclear PDFs tied to the chosen free-proton PDFs**



Parametrization

- Our definition of nuclear PDFs

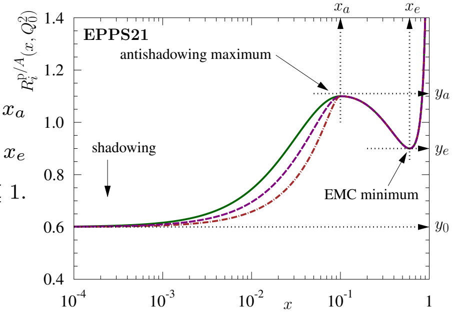
Free proton baseline = **CT18A**

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

Nuclear modifications

- Fit function x **dependence** at $Q_0^2 = m_{\rm charm}^2$

$$R_i^{p/A}(x,Q_0^2) = \begin{cases} a_0 + a_1(x-x_a)\left[e^{-xa_2/x_a} - e^{-a_2}\right], & x \le x_a \\ b_0 x^{b_1}(1-x)^{b_2} e^{x b_3}, & x_a \le x \le x_e \\ c_0 + c_1(c_2-x)(1-x)^{-\beta}, & x_e \le x \le 1. \end{cases}$$



- The A **dependence** parametrized at $x \to 0$, x_a, and x_e

$$y_i(A) = 1 + \left[y_i(A_{\rm ref}) - 1\right]\left(\frac{A}{A_{\rm ref}}\right)^{\gamma_i}, \quad A_{\rm ref} = 12$$

- For strange $\gamma_{y_0} \longrightarrow \gamma_{y_0} y_0 \theta(1-y_0)$ to keep away from overly negative strangeness

Parametrization

- Our definition of nuclear PDFs

Free proton baseline = **CT18A**

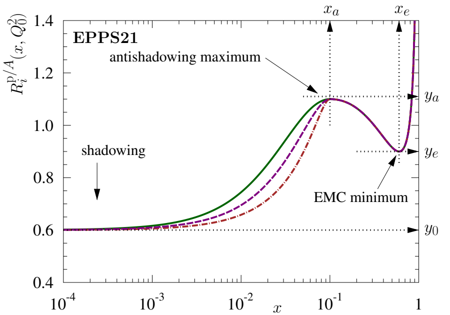
$$f_i^{\mathrm{p}/A}(x,Q^2) \equiv R_i^{\mathrm{p}/A}(x,Q^2)\, f_i^{\mathrm{p}}(x,Q^2)$$

Nuclear modifications

- For **small nuclei** the smooth A dependence appears to work less well. Introduce extra parameters,

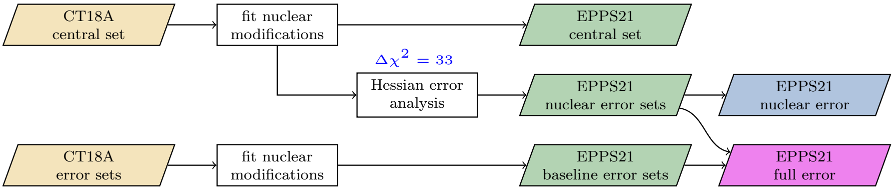
$$R_i^{\mathrm{p}/A}(x,Q_0^2) \longrightarrow 1 + f_A\left[R_i^{\mathrm{p}/A}(x,Q_0^2) - 1\right]$$

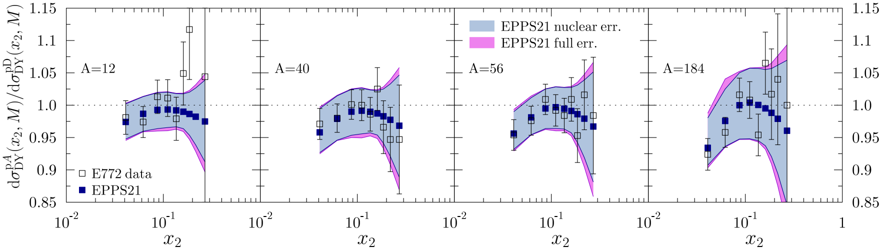
central fit results with $f_3 = 0.291$, $f_6 = 0.495$.



Analysis flow

- Dependence of proton PDFs estimated by repeating the fit with CT18A error sets



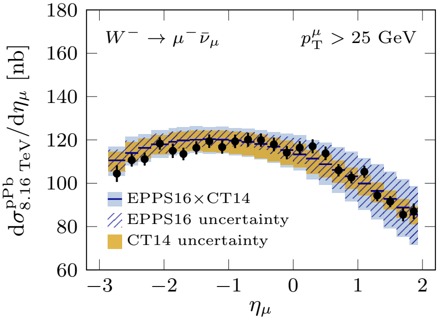


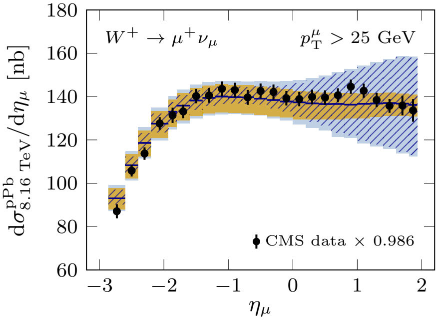
Free-proton errors in fitting CMS p-Pb 8.16TeV $W^{\pm}$ data [Phys.Lett.B 800 (2020) 135048]

- Absolute cross sections sensitive to both free-proton PDFs & nuclear modifications

$$d\sigma = \sum_{i,j} f_i^{\rm p}(Q_f^2) \otimes d\sigma_{ij}(Q_f^2, Q_r^2) \otimes f_j^{\rm Pb}(Q_f^2)$$

$$f_i^{\rm p/Pb}(x,Q^2) = R_i^{\rm p/Pb}(x,Q^2)\, f_i^{\rm p}(x,Q^2)$$



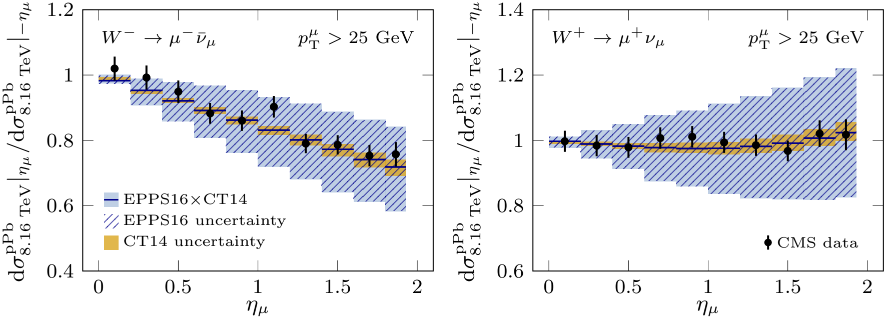


[Eur.Phys.J.C 82 (2022) 3, 271]

- Proton-PDF uncertainty can exceed the nuclear-PDF uncertainty

- Forward-to-backward ratios

$$\frac{d\sigma^{\rm pPb}(\eta)}{d\sigma^{\rm pPb}(-\eta)}$$



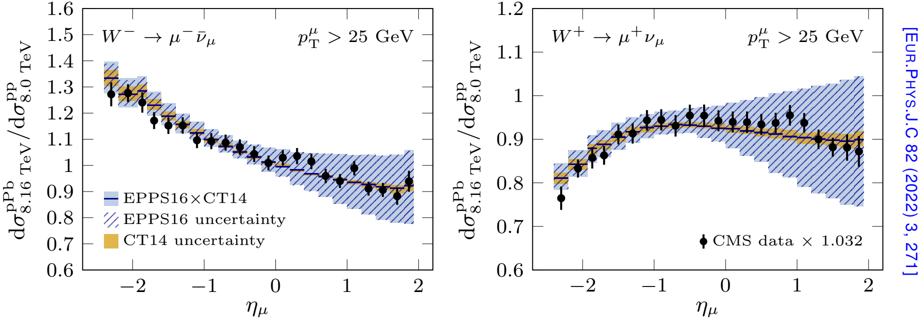
[EUR.PHYS.J.C 82 (2022) 3, 271]

- A good (but not perfect) cancellation of proton uncertainties

Free-proton errors in fitting CMS p-Pb 8.16TeV $W^{\pm}$ data [PHYS.LETT.B 800 (2020) 135048]

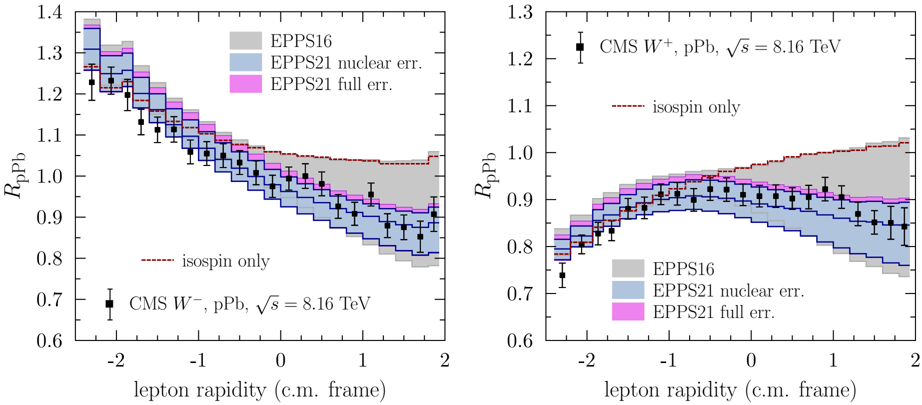
- Ratios of cross sections in p-Pb and p-p

$$\frac{d\sigma^{\mathrm{pPb}}(\eta)}{d\sigma^{\mathrm{pp}}(\eta)}$$



- A good (but not perfect) cancellation of proton uncertainties

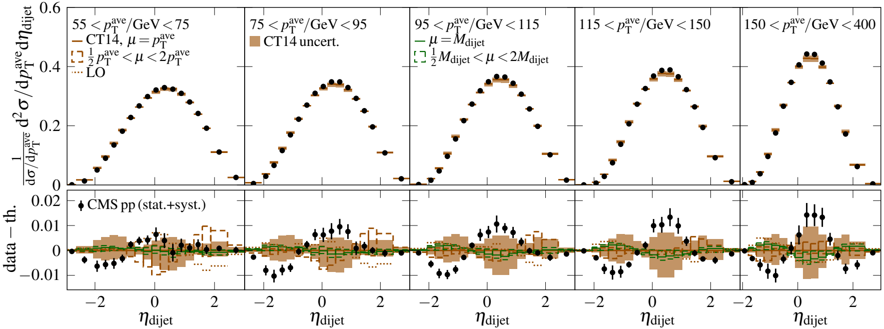
CMS p-Pb 8.16TeV $W^{\pm}$ data vs. EPPS21



- Central values appear to overshoot at backward but still $\chi^2/N_{\rm data} \approx 0.94$

- A precision jet observable

$$\frac{d^2\sigma^{\rm pp}}{dp_{\rm T}^{\rm ave}d\eta_{\rm dijet}}\left(\frac{d\sigma^{\rm pp}}{dp_{\rm T}^{\rm ave}}\right)^{-1}$$



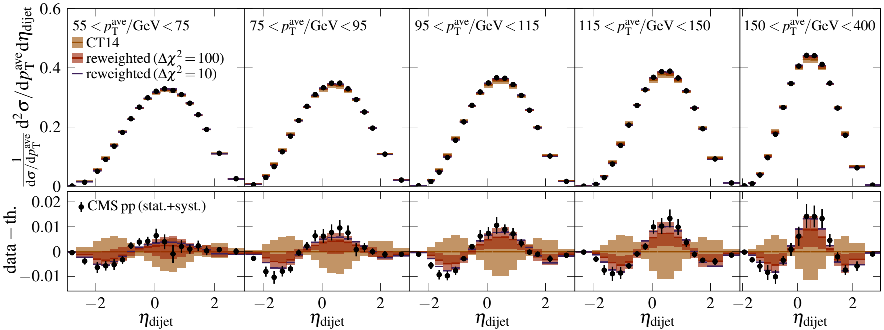
[EUR.PHYS.J.C 79 (2019) 6, 511]

- NLO QCD differs significantly from the data (note: smallish cone $R = 0.3$)

Double-differential CMS dijet data [Phys.Rev.Lett. 121 (2018) 6, 062002]

- A precision jet observable

$$\frac{d^2\sigma^{\rm pp}}{dp_{\rm T}^{\rm ave}\, d\eta_{\rm dijet}} \left(\frac{d\sigma^{\rm pp}}{dp_{\rm T}^{\rm ave}}\right)^{-1}$$

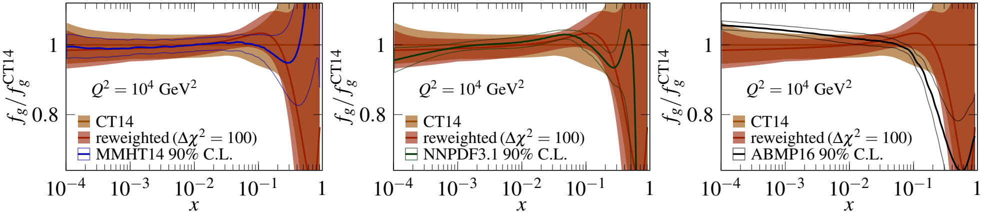


[Eur.Phys.J.C 79 (2019) 6, 511]

- Can improve the description by Hessian PDF reweighting/profiling

- A precision jet observable

$$\frac{d^2\sigma^{\rm pp}}{dp_{\rm T}^{\rm ave}d\eta_{\rm dijet}}\left(\frac{d\sigma^{\rm pp}}{dp_{\rm T}^{\rm ave}}\right)^{-1}$$



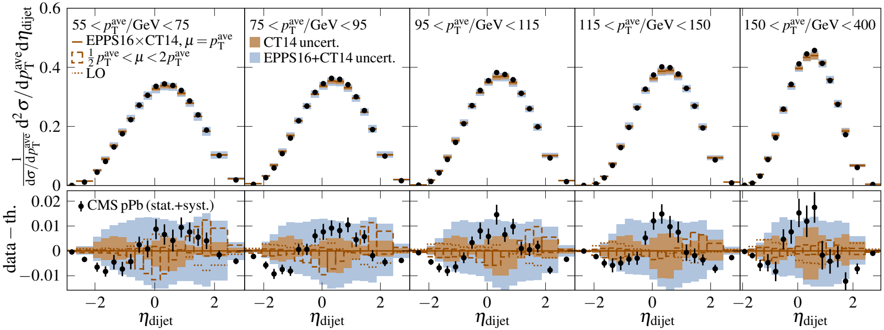
[Eur.Phys.J.C 79 (2019) 6, 511]

- Would require large changes in the CT14 PDFs

Double-differential CMS dijet data [Phys.Rev.Lett. 121 (2018) 6, 062002]

- A precision jet observable

$$\frac{d^2\sigma^{\rm pPb}}{dp_{\rm T}^{\rm ave}d\eta_{\rm dijet}}\left(\frac{d\sigma^{\rm pPb}}{dp_{\rm T}^{\rm ave}}\right)^{-1}$$

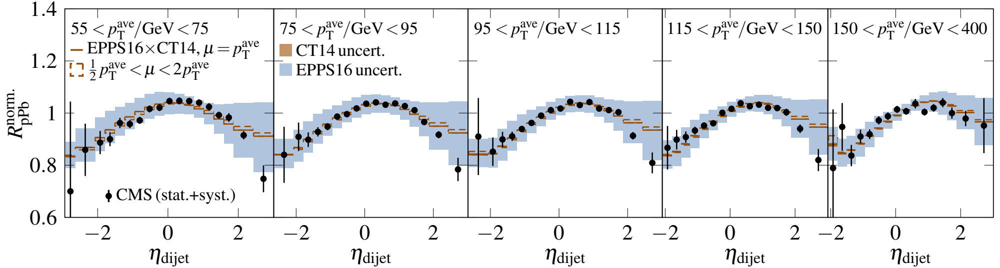


[Eur.Phys.J.C 79 (2019) 6, 511]

- The p-Pb data show similar differences w.r.t NLO calculation as p-p

- A precision jet observable

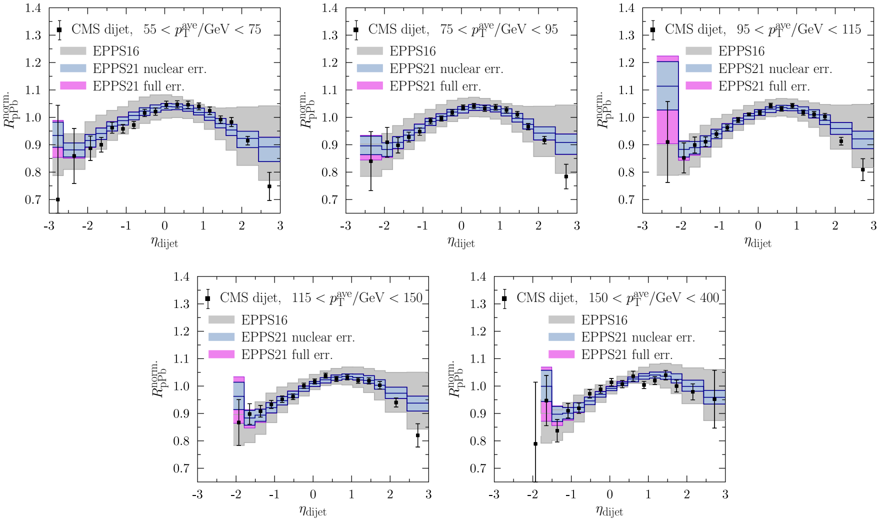
$$\frac{d^2\sigma^{\mathrm{pPb}}}{dp_{\mathrm{T}}^{\mathrm{ave}}d\eta_{\mathrm{dijet}}}\left(\frac{d\sigma^{\mathrm{pPb}}}{dp_{\mathrm{T}}^{\mathrm{ave}}}\right)^{-1} \Big/ \frac{d^2\sigma^{\mathrm{pp}}}{dp_{\mathrm{T}}^{\mathrm{ave}}d\eta_{\mathrm{dijet}}}\left(\frac{d\sigma^{\mathrm{pp}}}{dp_{\mathrm{T}}^{\mathrm{ave}}}\right)^{-1}$$



[EUR.PHYS.J.C 79 (2019) 6, 511]

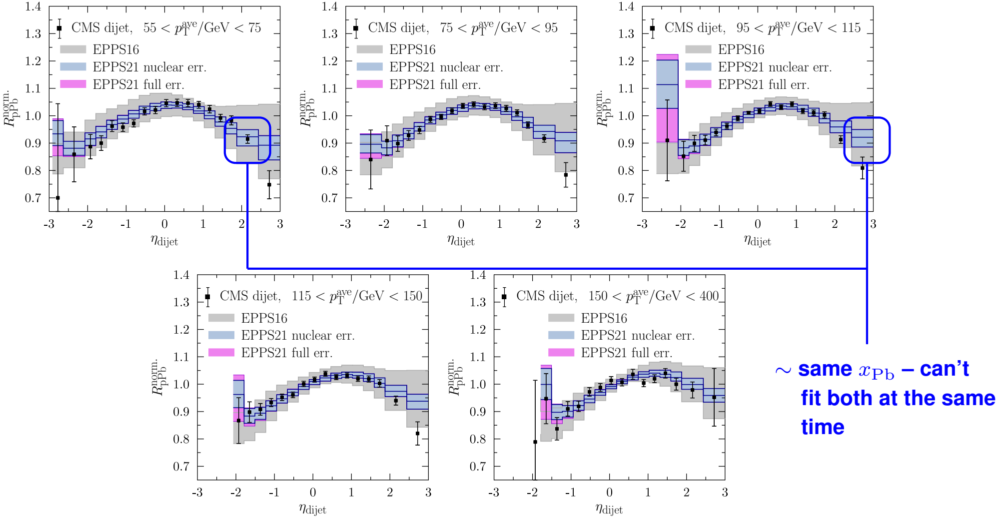
- The ratio p-Pb over p-p compatible with EPPS16

Double-differential dijet data [Phys.Rev.Lett. 121 (2018) 6, 062002]: Comparison with the EPPS21 fit



- Generally a very good agreement except the most forward data points

Double-differential dijet data [Phys.Rev.Lett. 121 (2018) 6, 062002]: Comparison with the EPPS21 fit

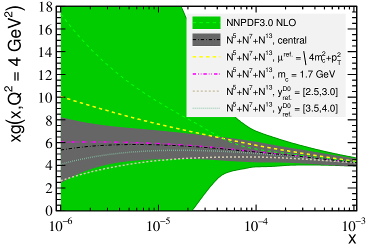


- Generally a very good agreement except the most forward data points

Open heavy-flavour measurements promising PDF constraints

- The potential of D (and B) meson production as a PDF constraint has been actively investigated [GAULD, ROJO, PRL 118, 072001 ; PROSA, EPJ C75, 396 ; KUSINA ET.AL. PRL 121,052004]

reduction of NNPD3.0 gluon uncertainty
upon including LHCb D-meson data



- Theoretical description typically based on fixed-order QCD [Mangano et.al. NP B373, 295], FONLL [CACCIARI ET.AL. JHEP 9805, 007], or Powheg+Pythia [Frixione et.al. JHEP 0709, 126]

- We use a **general-mass variable-flavour-number scheme (GM-VFNS)** approach
[KNIEHL ET.AL PRD71, 014018, HELENIUS, PAUKKUNEN, JHEP 1805 (2018) 196]

The GM-VFNS framework

- The master formula for D-meson production in GM-VFNS:

sum over all partonic subprocesses

$$\frac{d\sigma(h_1+h_2\to D+X)}{dP_{\rm T}dY} = \sum_{ijk}\int_{z^{\rm min}}^{1}\frac{dz}{z}\int_{x_1^{\rm min}}^{1}dx_1\int_{x_2^{\rm min}}^{1}dx_2$$

here $z \equiv E_D/E_k$, but generally not unique

$$f_i^{h_1}(x_1,\mu^2_{\rm fact})\ \frac{d\hat\sigma^{ij\to k+X}(x_1,x_2,m^2,\mu^2_{\rm ren},\mu^2_{\rm fact},\mu^2_{\rm frag})}{dp_{\rm T}dy}\ f_j^{h_2}(x_2,\mu^2_{\rm fact})\ D_{k\to D}(z,\mu^2_{\rm frag})$$

Coefficient functions behave as FFNS at low $p_{\rm T}$, but as zero-mass $\overline{\rm MS}$ matrix elements at high $p_{\rm T}$

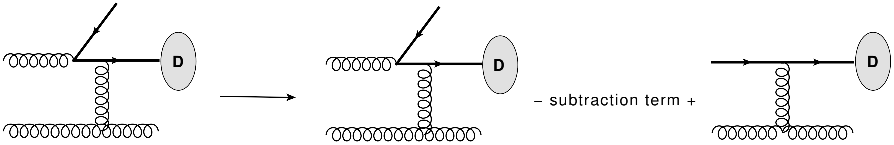
Scale-dependent, universal fragmentation functions (FFs)

- In comparison, fixed flavour-number scheme (FFNS) produces heavy quarks explicitly in three partonic processes

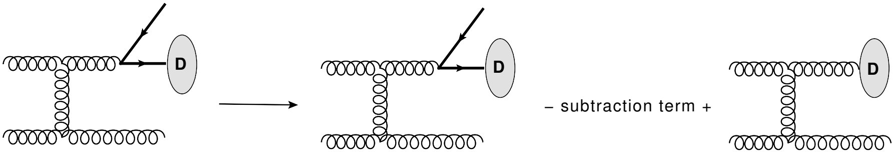
$$g+g\to Q+X,\quad q+\overline{q}\to Q+X,\quad q+g\to Q+X\,,$$

The GM-VFNS framework

- In GM-VFNS the contributions **initiated by heavy-quarks**...



...and those in which a **light quark/gluon fragments** into a D meson...

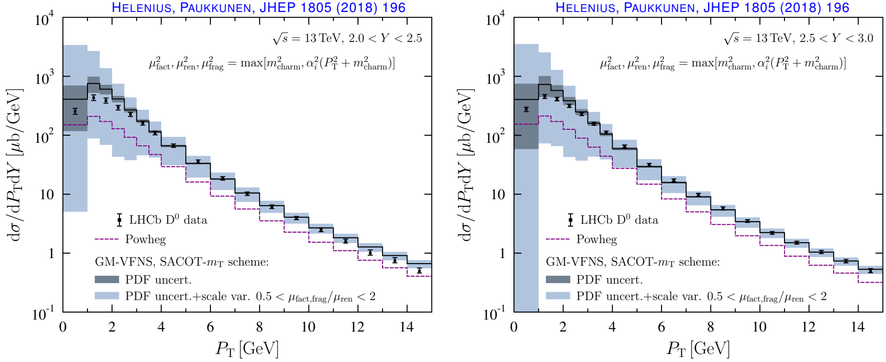


...are scheme dependent

- We adopt the **SACOT-m_{T}** scheme [HELENIUS, PAUKKUNEN, JHEP 1805 (2018) 196]

Comparison with the LHCb 13 TeV p-p data

- LHCb p-p cross sections well reproduced by the SACOT-m_{T} approach

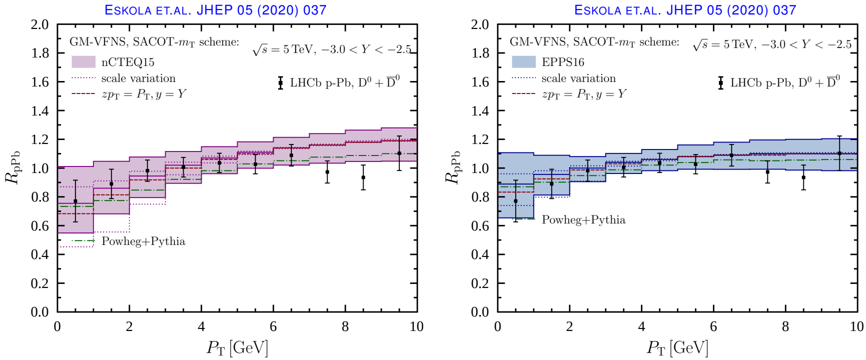


PDF = NNPDF3.1NLO (pch)
FF = KKKS08

- Sizable theory uncertainties at low p_{T}: scale-choice and proton-PDF uncertainties shown, but there are others too (scheme dependence, fragmentation,...)

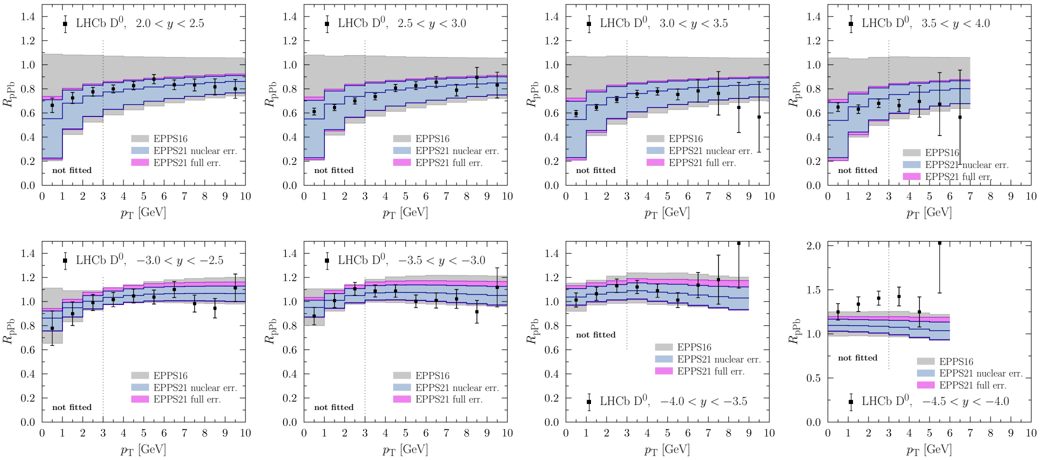
Theory uncertainties in nuclear modifications $\sigma_{\mathrm{pPb}}/\sigma_{\mathrm{pp}}$

- As an example, LHCb data w.r.t. nCTEQ15 and EPPS16



- Uncertainties due to scale choices and fragmentation variable z in $D_{k\to D}(z, \mu^2_{\mathrm{frag}})$ and proton-PDF uncertainties grow towards low p_T

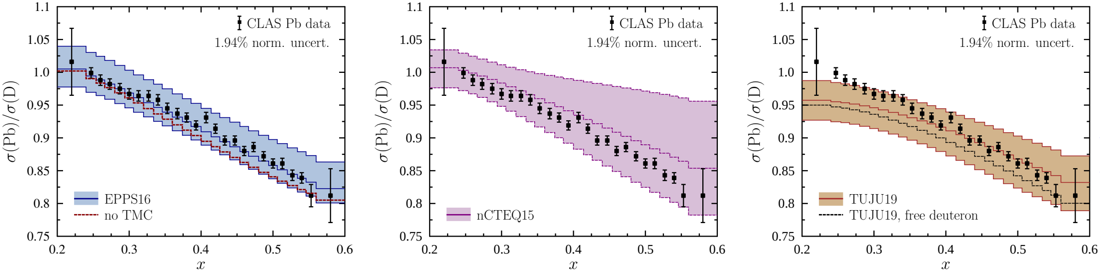
The LHCb data [JHEP 10 (2017) 090] $\sigma_{\rm pPb}/\sigma_{\rm pp}$ vs. EPPS21



- Good fit across a wide range of rapidity – no sign of e.g. non-linear effects at small-x

New JLab/CLAS DIS data at high x, low Q^2

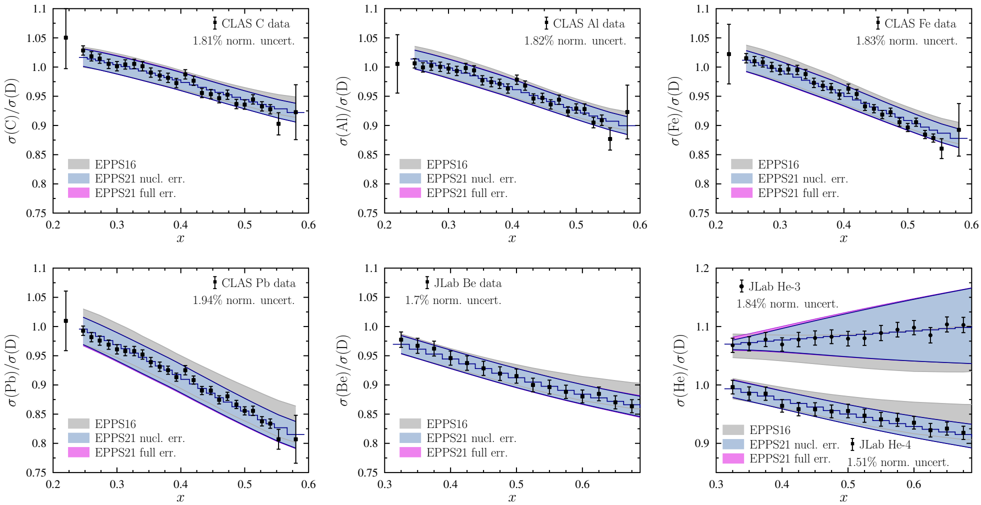
- Probe kinematic region often left out from PDF fits, $1.62 < Q^2/\mathrm{GeV}^2 < 3.37, W \geq 1.8\mathrm{GeV}$



NATURE 566 (2019) 7744, 354
EUR.PHYS.J.C 80 (2020) 5, 381

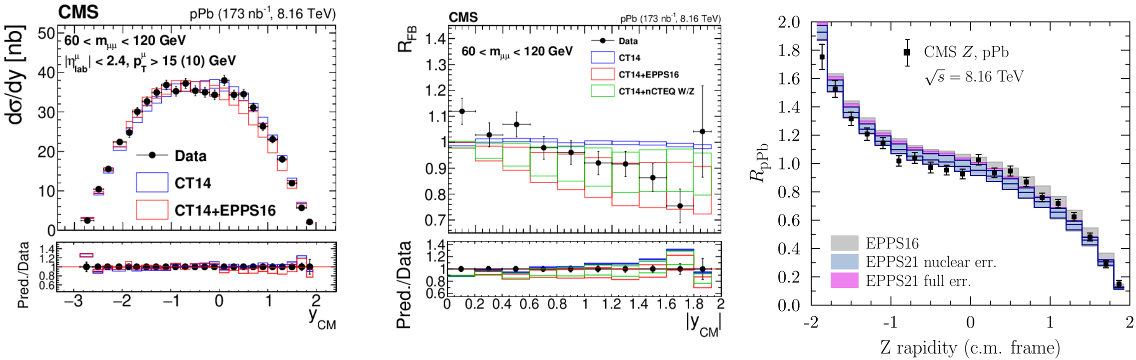
- The **target-mass corrections** matter, essentially $x \longrightarrow \xi = \dfrac{2x}{1+\sqrt{1+4x^2M^2_{\mathrm{nucleon}}/Q^2}}$
- No visible A-dependent higher-twist effects = reproduce also data at same x but higher Q^2

JLab CLAS & Hall-C data vs. the EPPS21 fit



- Good description of the A-systematics from He-3 to Pb-208

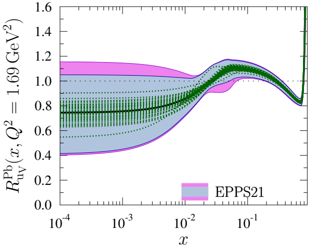
- Precise CMS Z data [JHEP 05 (2021) 182] broadly consistent with nuclear-PDF predictions



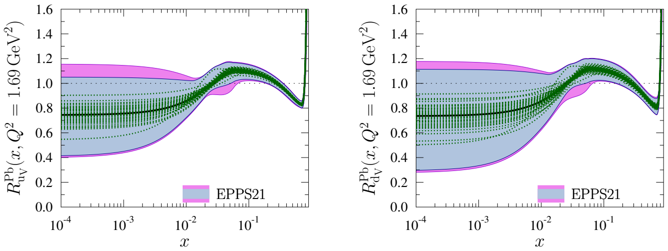
- However, $\chi^2/N_{\rm data} \sim 2$ – fitting nor NNLO corrections helps here

$\Longrightarrow$ **Not included in EPPS21**

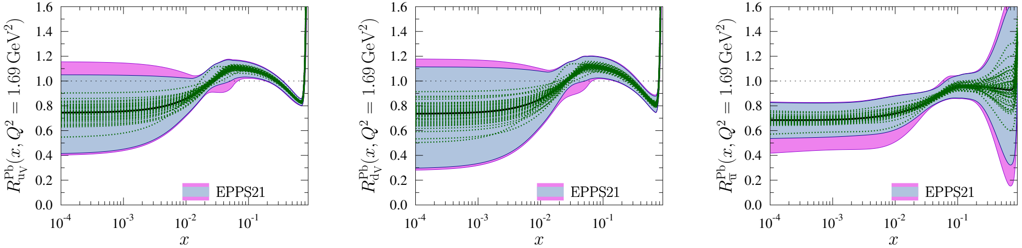
Nuclear modifications $(Zf_i^{p/A} + Nf_i^{n/A})/(Zf_i^{p} + Nf_i^{n})$ for Pb at $Q^2 = m^2_{\rm charm}$



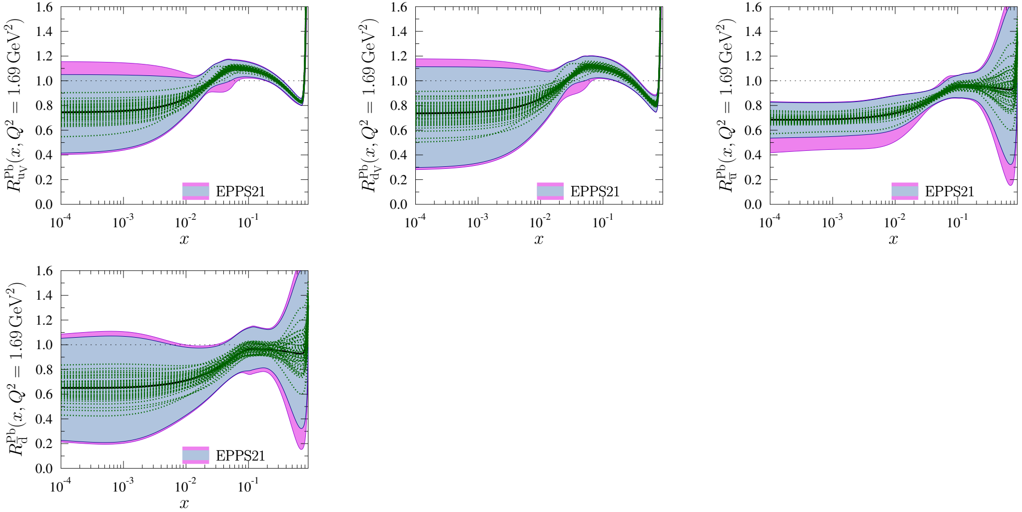
Nuclear modifications $(Zf_i^{\mathrm{p/A}} + Nf_i^{\mathrm{n/A}})/(Zf_i^{\mathrm{p}} + Nf_i^{\mathrm{n}})$ for Pb at $Q^2 = m^2_{\mathrm{charm}}$



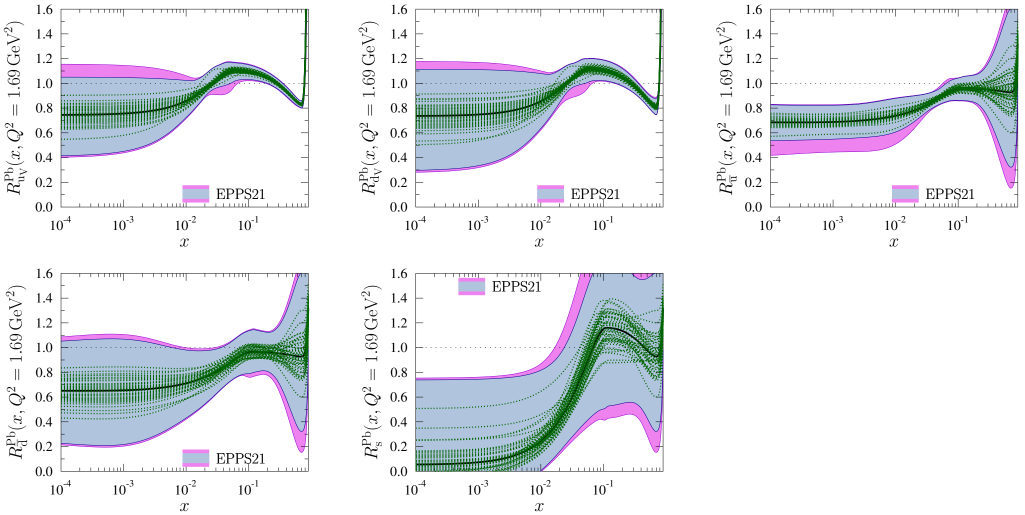
Nuclear modifications $(Zf_i^{\mathrm{p/A}} + Nf_i^{\mathrm{n/A}})/(Zf_i^{\mathrm{p}} + Nf_i^{\mathrm{n}})$ for Pb at $Q^2 = m^2_{\mathrm{charm}}$



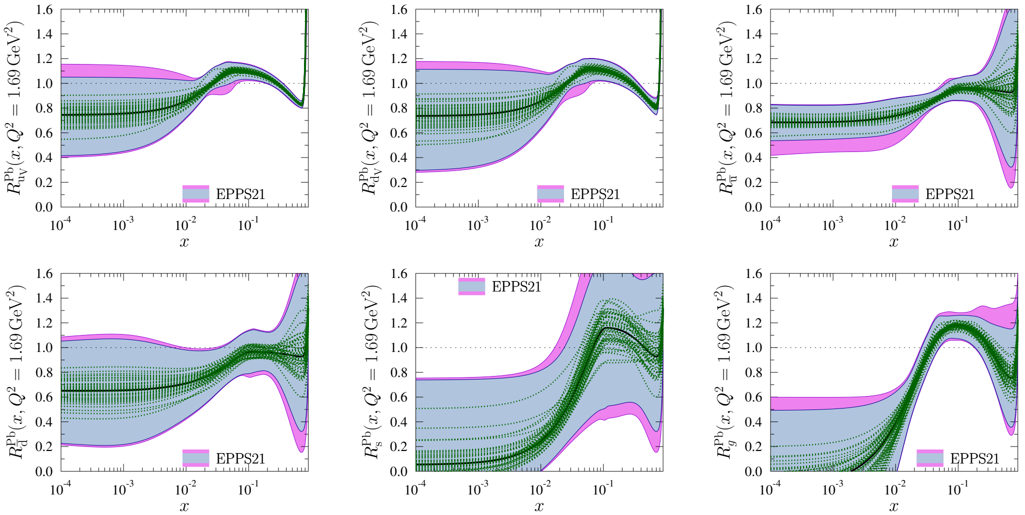
Nuclear modifications $(Zf_i^{p/A} + Nf_i^{n/A})/(Zf_i^p + Nf_i^n)$ for Pb at $Q^2 = m^2_{\rm charm}$



Nuclear modifications $(Zf_i^{p/A} + Nf_i^{n/A})/(Zf_i^p + Nf_i^n)$ for Pb at $Q^2 = m^2_{\rm charm}$

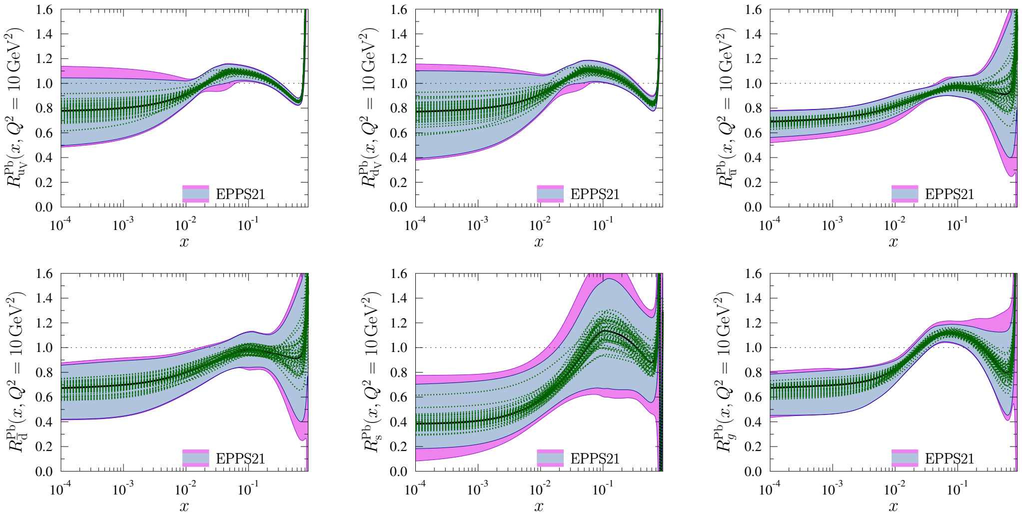


Nuclear modifications $(Zf_i^{p/A} + Nf_i^{n/A})/(Zf_i^p + Nf_i^n)$ for Pb at $Q^2 = m_{charm}^2$



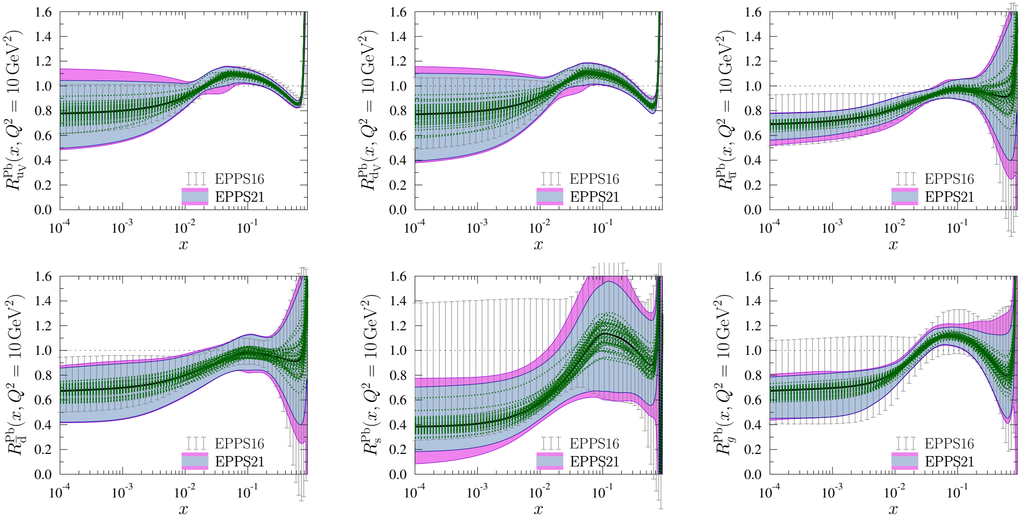
- The free-proton PDF uncertainties typically subdominant in nuclear effects – largest in strangeness

Nuclear modifications $(Zf_i^{p/A} + Nf_i^{n/A})/(Zf_i^{p} + Nf_i^{n})$ for Pb at $Q^2 = 10\,\mathrm{GeV}^2$



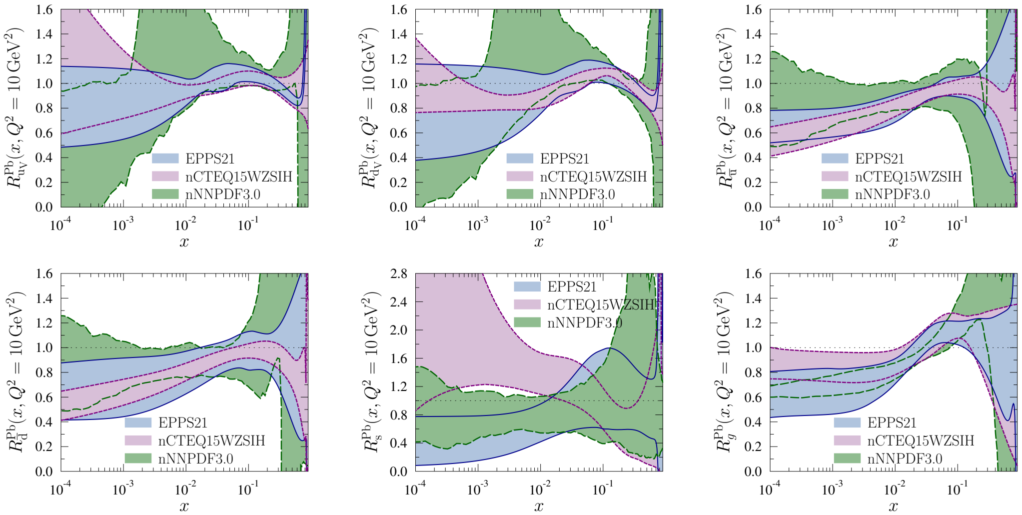
- The free-proton PDF uncertainties typically subdominant in nuclear effects – largest in strangeness

Nuclear modifications Pb at $Q^2 = 10\,\mathrm{GeV}^2$, EPPS16 vs. EPPS21



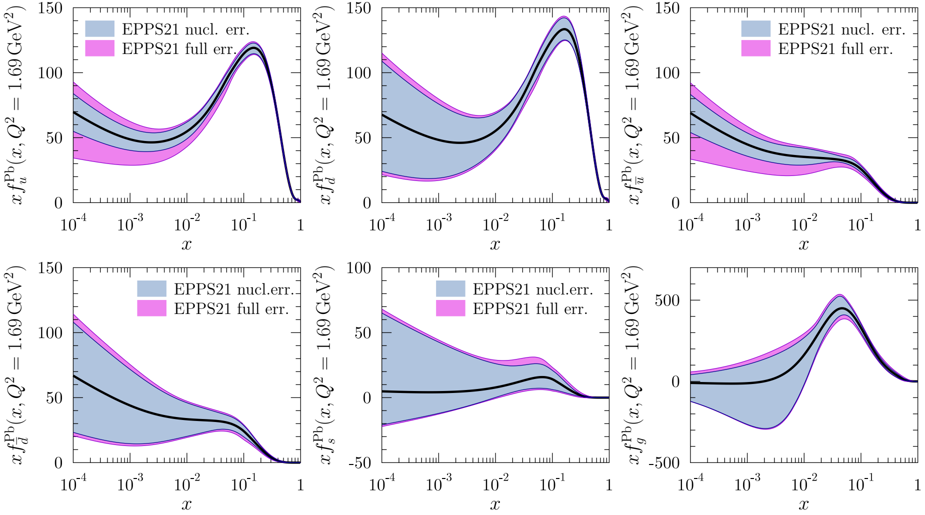
- Largest impact vs. EPPS16 seen in the gluon – strangeness also affected by fit function

Nuclear modifications $(Zf_i^{p/A}+Nf_i^{n/A})/(Zf_i^{p}+Nf_i^{n})$ for Pb at $Q^2 = 10\,\mathrm{GeV}^2$

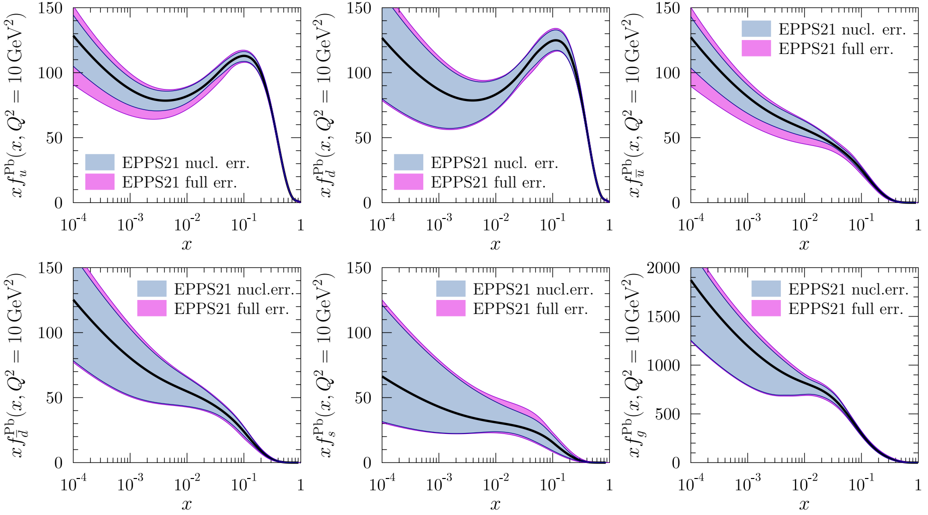


- Broadly mutually consistent – shapes and uncertainties still very different between fits

Absolute nuclear PDFs for Pb at $Q^2 = m^2_{\rm charm}$

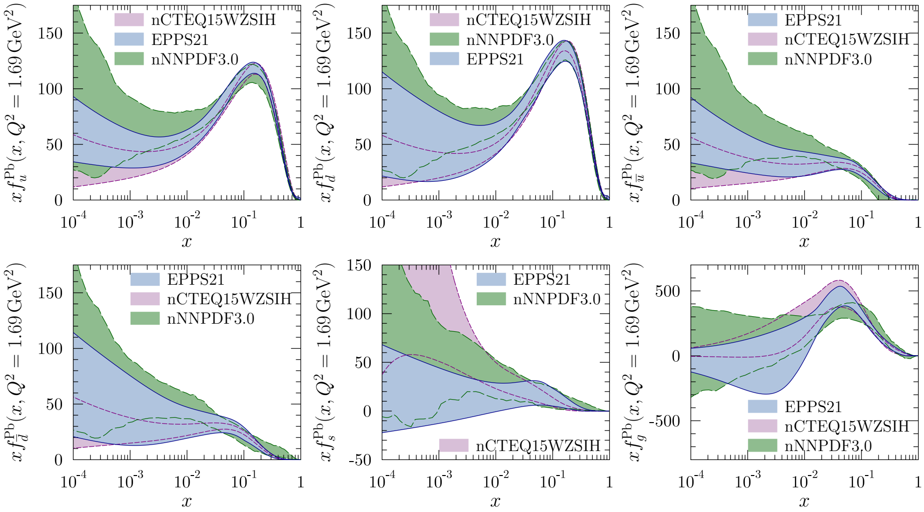


- Free-proton uncertainties visible e.g. in up quarks



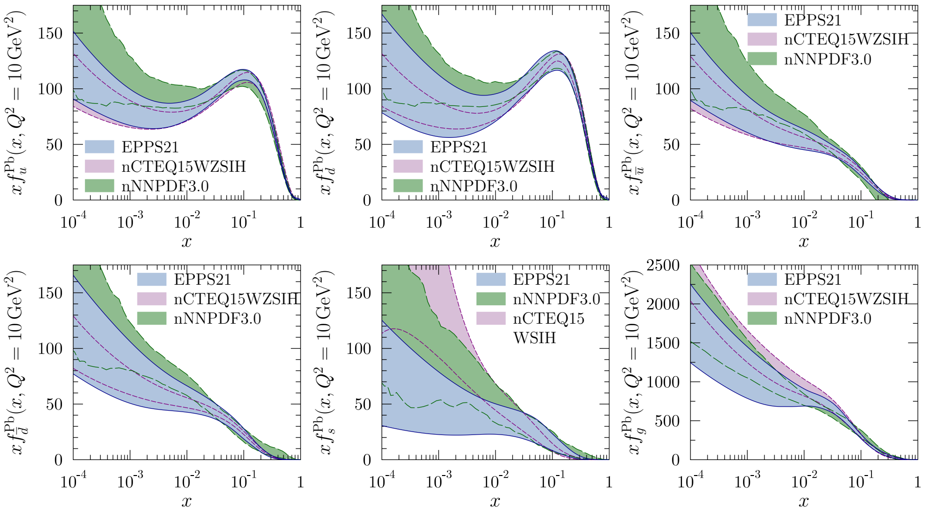
- Free-proton uncertainties visible e.g. in up quarks

Absolute nuclear PDFs at $Q^2 = m^2_{\rm charm}$, EPPS21 vs. nNNPDF3.0 vs. nCTEQ15WZSIH



- Broadly consistent but “all don’t overlap with all“

Absolute nuclear PDFs at $Q^2 = 10\,\mathrm{GeV}^2$, EPPS21 vs. nNNPDF3.0 vs. nCTEQ15WZSIH



- Broadly consistent but “all don’t overlap with all“

Summary

- Outlined the EPPS21 analysis of nuclear PDFs
- The most important developments vs. EPPS16:
  - CMS double diff. dijets
  - LHCb double diff. D mesons $\rightsquigarrow$ constrains for gluons through wide range in x
  - CMS 8 TeV $W^{\pm}$
  - JLab large-x DIS data $\rightsquigarrow$ improve the A systematics at large x
  - map correlations with proton PDF $\rightsquigarrow$ more consistent propagation of uncertainties
- More data on the way – NNLO accuracy becoming relevant?
- The LHC p-Pb data begins to be precise enough to seriously test the factorization outside p-p