



**DIS2022**

XXIX International Workshop on Deep-  
Inelastic Scattering and Related Subjects  
Santiago de Compostela, 2-6 May 2022

# EPPS21: Nuclear PDFs with LHC data and proton-PDF errors

based on arXiv:2112.12462 and Eur.Phys.J.C 82 (2022) 271

Petja Paakkinen<sup>1,2</sup>

in collaboration with K. J. Eskola<sup>1</sup>, H. Paukkunen<sup>1</sup> and C. A. Salgado<sup>2</sup>

<sup>1</sup>University of Jyväskylä – AoF CoE in Quark Matter

<sup>2</sup>IGFAE – Universidade de Santiago de Compostela – ERC AdG YoctoLHC

DIS2022

3 May 2022



UNIVERSITY OF JYVÄSKYLÄ



HELSINKI INSTITUTE OF PHYSICS



Instituto Galego de Física de Altas Enerxías

UNIVERSIDADE  
DE SANTIAGO  
DE COMPOSTELA

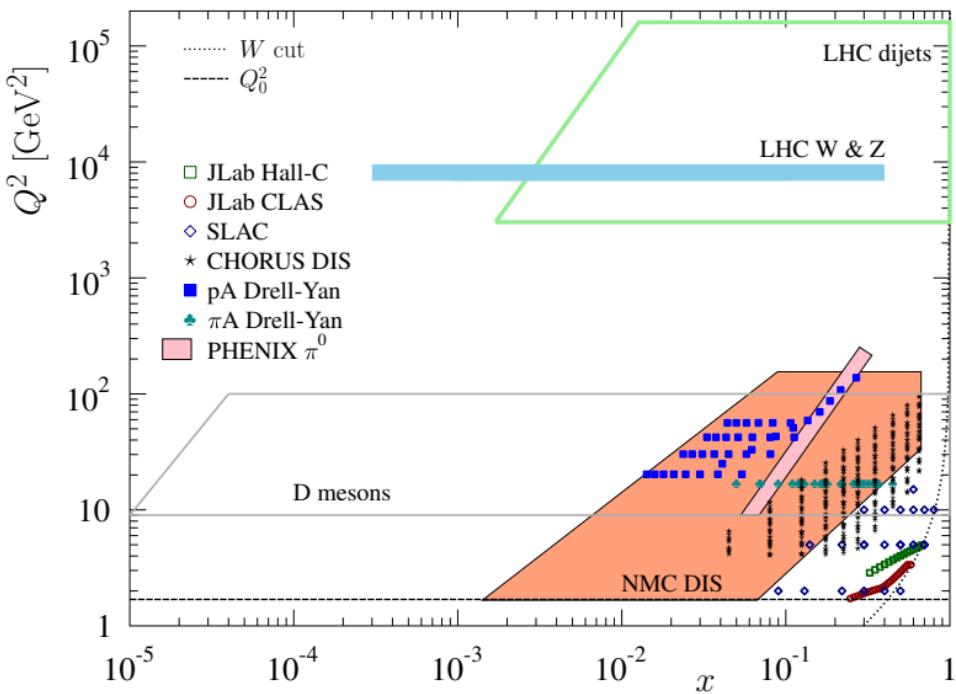
# New global fit with extended data set

New data in EPPS21:

- LHC 5 TeV dijets,  $D^0$ s
- LHC 8 TeV  $W^\pm$
- JLab Hall-C & CLAS DIS

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

JLab data in the “transition region”  $W \gtrsim 1.8$  GeV just above the resonance-dominated one



# Short intro to EPPS21 parametrization

- Define nuclear PDFs in terms of

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

nuclear modification  
bound-proton PDF                                  free-proton PDF

- PDFs of the full nucleus are then constructed with

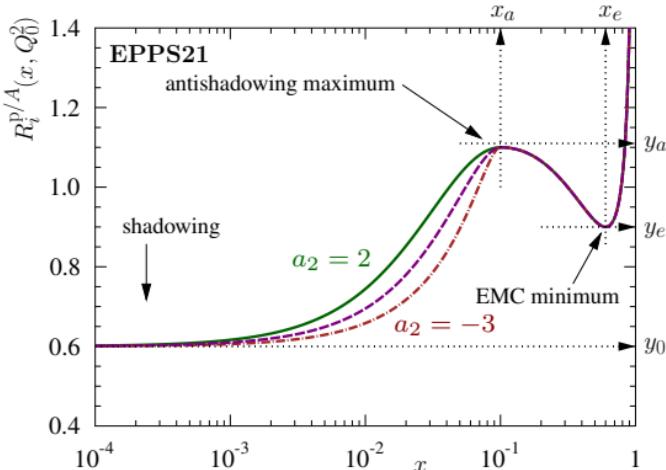
$$f_i^A(x, Q^2) = Z f_i^{p/A}(x, Q^2) + N f_i^{n/A}(x, Q^2),$$

and assuming  $f_i^{p/A} \rightleftarrows f_j^{n/A}$

- Parametrize the  $x$  and  $A$  dependence of

$$R_i^{p/A}(x, Q_0^2)$$
 at  $Q_0 = m_{\text{charm}} = 1.3 \text{ GeV}$

- ▶ Use a phenomenologically motivated piecewise function in  $x$
- ▶ Use a power-law type function in  $A$



- More flexible fit with additional free parameters

- ▶  $N_{\text{param}} = 24$  (20 in EPPS16)

- Improved small- $x$  gluon parametrization

$$R_i^{p/A}(x, Q_0^2) = a_0 + a_1(x - x_a) [e^{-xa_2/x_a} - e^{-a_2}]$$

for  $x < x_a$

# Comparison with other recent nPDF fits

	KSASG20	nCTEQ15WZSIH	TUJU21	EPPS21	nNNPDF3.0
Order in $\alpha_s$	NLO & NNLO	NLO	NLO & NNLO	NLO	NLO
$l\Lambda$ NC DIS	✓	✓	✓	✓	✓
$\nu A$ CC DIS	✓		✓	✓	✓
pA DY	✓	✓		✓	✓
$\pi A$ DY				✓	
RHIC dAu $\pi^0, \pi^\pm$		✓		✓	
LHC pPb $\pi^0, \pi^\pm, K^\pm$		✓			
LHC pPb dijets				✓	✓
LHC pPb D <sup>0</sup>				✓	✓ reweight
LHC pPb W,Z		✓	✓	✓	✓
LHC pPb $\gamma$					✓
$Q, W$ 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 <sup>0</sup> , 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	arXiv:2112.12462	arXiv:2201.12363

# Need to mitigate free-proton PDF uncertainty

Absolute cross sections carry large proton-PDF uncertainty!

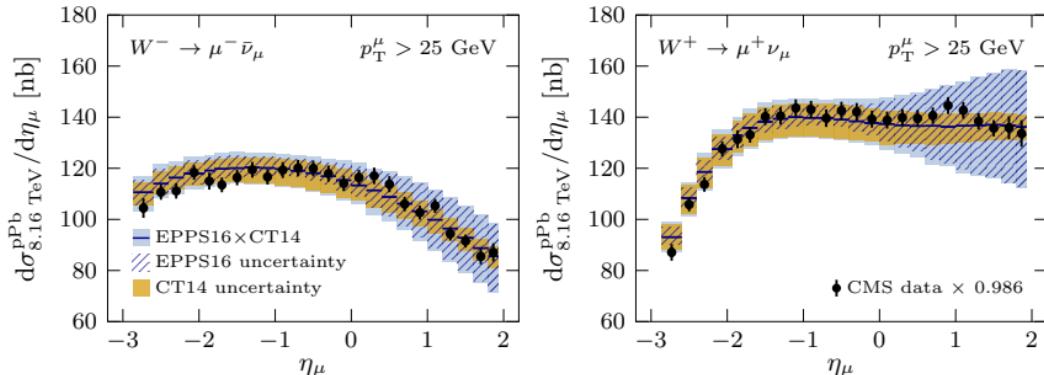
Difficult to disentangle nuclear modifications from free-proton d.o.f.s

Wherever possible, we use nuclear modification ratios to cancel the free-proton PDF uncertainty

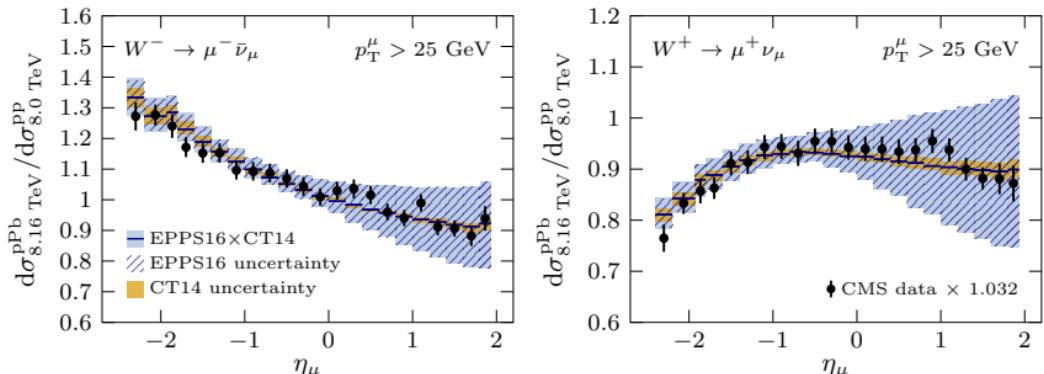
For Ws at 8.16 TeV, we formulate a mixed-energy nuclear modification ratio

$$R_{\text{pPb}} = \frac{d\sigma_{8.16 \text{ TeV}}^{\text{pPb}} / d\eta_\mu}{d\sigma_{8.0 \text{ TeV}}^{\text{pp}} / d\eta_\mu}$$

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



↓ Cancel proton-PDF uncertainty ↓



# How to propagate proton-PDF uncertainties into nPDF fit?

We have tested the impact of proton-PDF uncertainties with the theoretical covariance matrix method

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

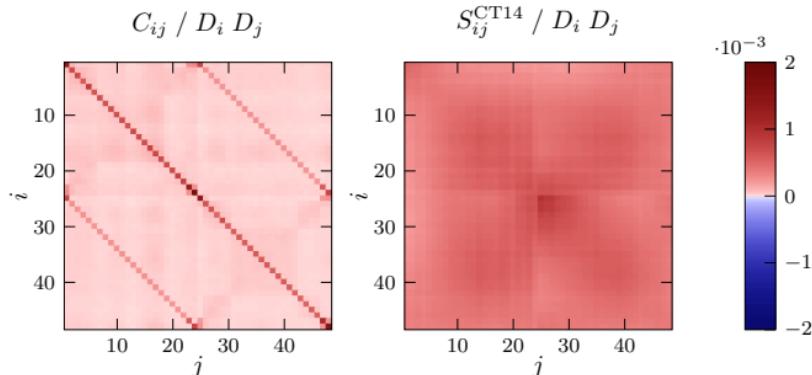
$$\chi^2 = (D - f_N T)^T (C + S^{\text{CT14}})^{-1} (D - f_N T) \\ + \left( \frac{f_N - 1}{\sigma_N} \right)^2$$

We can also propagate the data covariances into any desired observable via

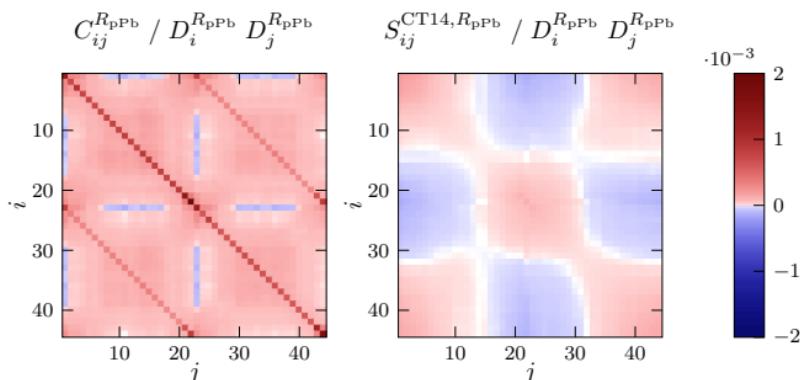
$$C^{\text{new}} = J C J^T,$$

where  $J$  is the Jacobian of the transformation

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



↓ Cancel proton-PDF uncertainty ↓



# Reweighting results – absolute cross sections

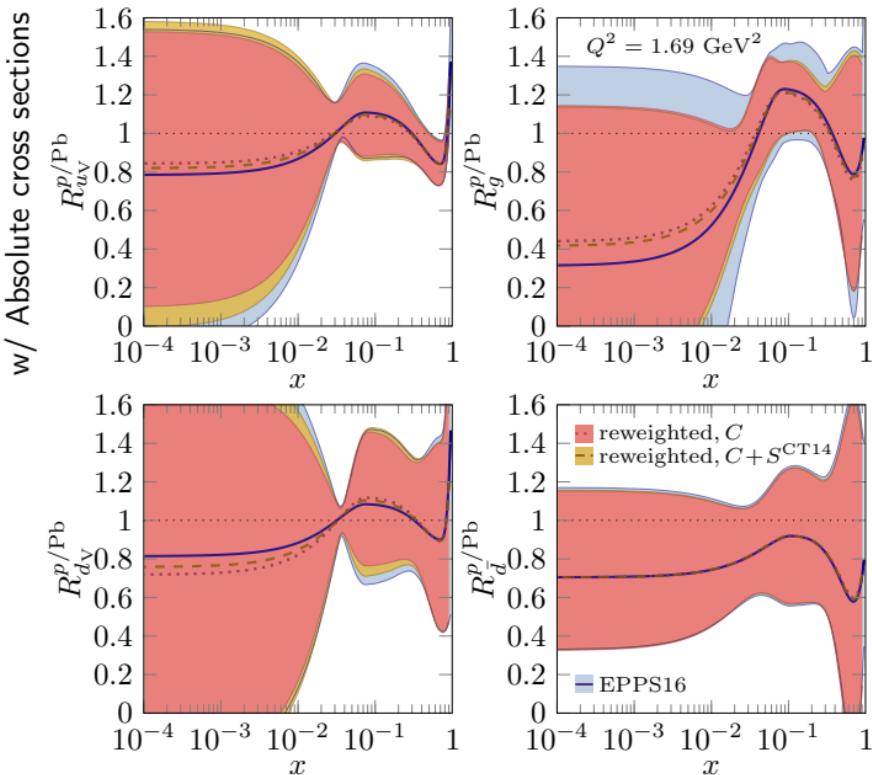
Study the impact on nuclear PDFs  
with the Hessian reweighting method  
[Paukkunen & Zurita, JHEP 12 (2014) 100]

Largest impact at the parametrization  
scale on gluons (probed through  
 $g \rightarrow q\bar{q}$  splittings)

Proton-PDF uncertainties appear to  
be important only for the valence  
flavour separation

- can be reduced by using the ratio observables
- may still become relevant with the increased data precision at LHC Run 3
- possible consequences for the attempts to constrain EMC-effect models

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



# Reweighting results – nuclear modification ratios

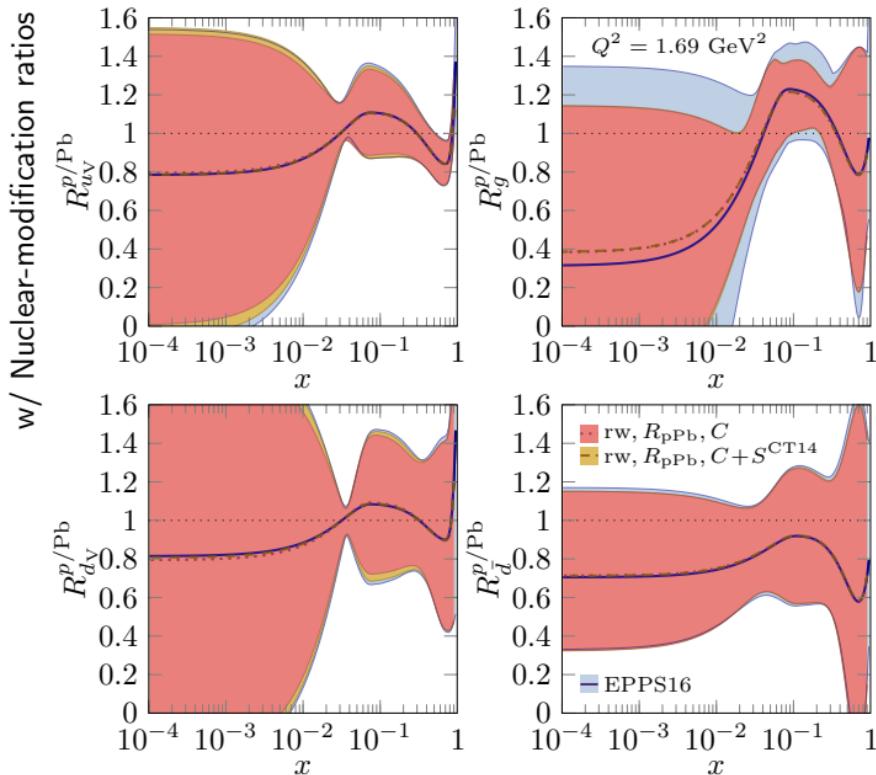
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[Eskola, PP, Paukkunen & Salgado, Eur.Phys.J.C 82 (2022) 271]



# Reweighting results – with approx. Run 3 statistics

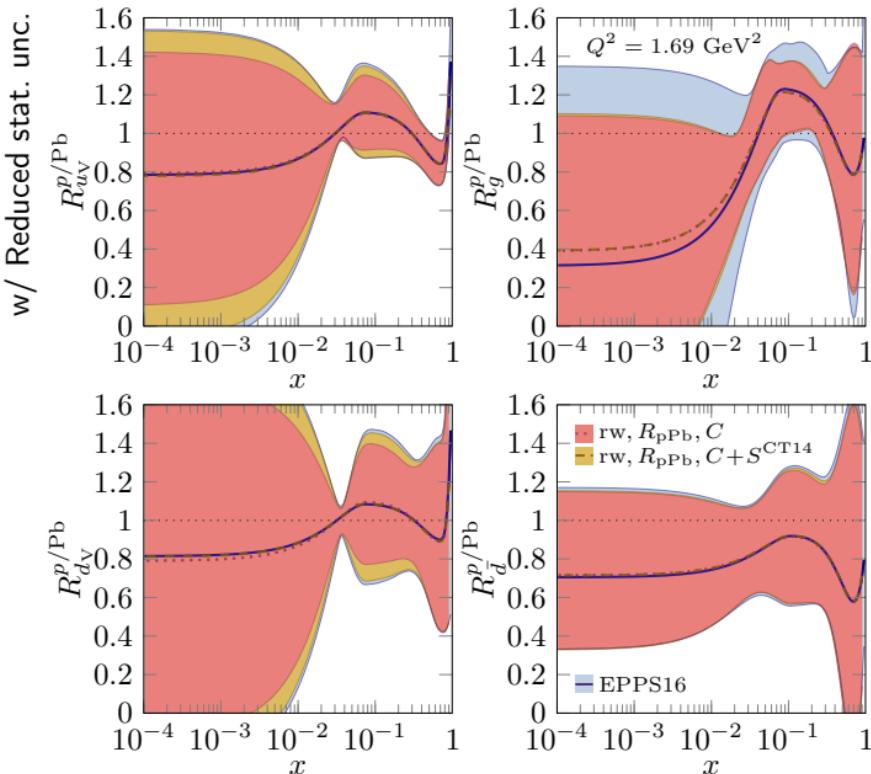
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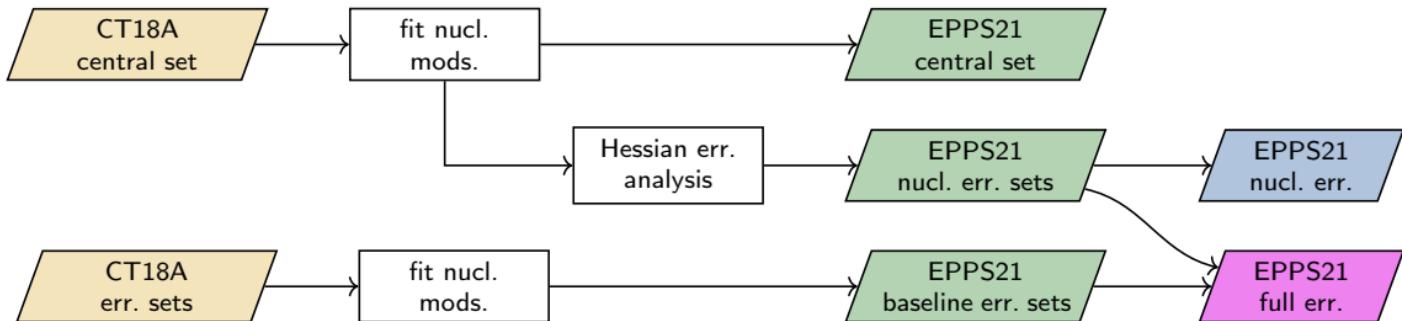
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[Eskola, PP, Paukkunen & Salgado, Eur.Phys.J.C 82 (2022) 271]

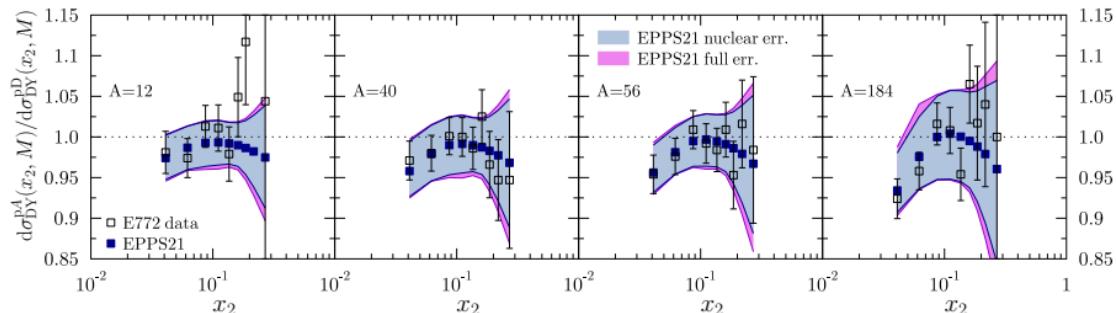


# Propagating the baseline proton-PDF uncertainty in the EPPS21 fit

We study baseline-PDF sensitivity by fitting nuclear modifications separately for each CT18A error set



- Possible to propagate the baseline uncertainty consistently into any desired observable
- Subdominant effect in the fitted ratio observables



Excellent fit!

Results in line with  
the reweighting study

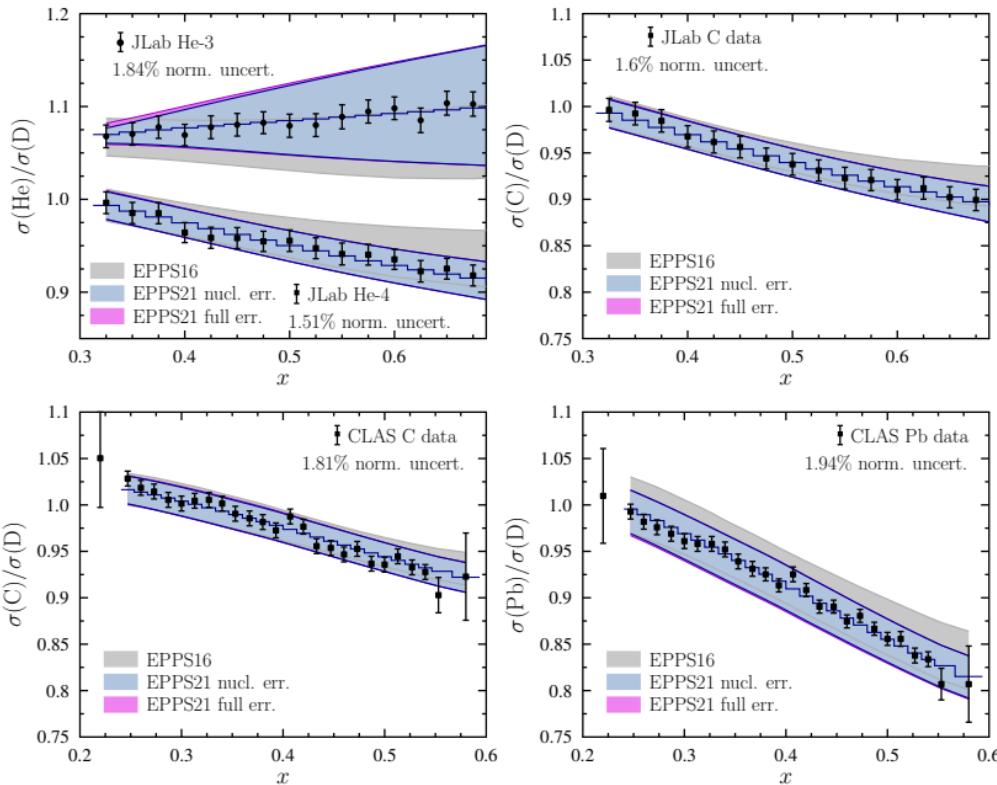
[Paukkunen & Zurita,  
Eur.Phys.J.C 80 (2020) 381]

We take into account  
the leading target-mass  
corrections

No sign of any strong  
 $A$ -dependent higher-twist  
contribution

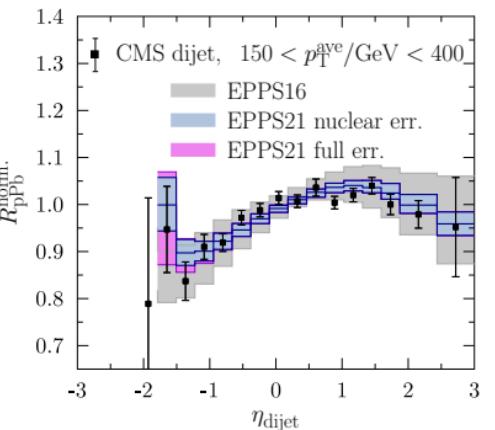
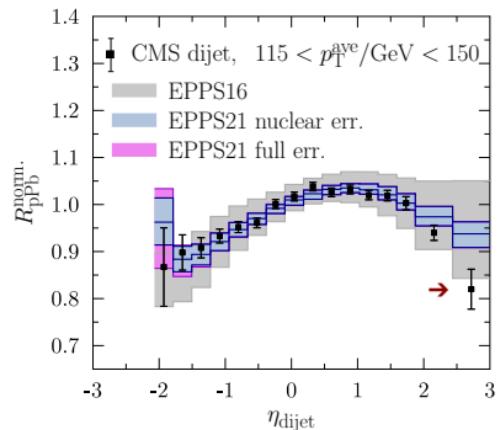
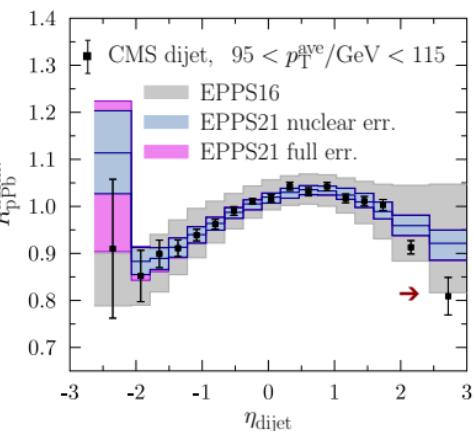
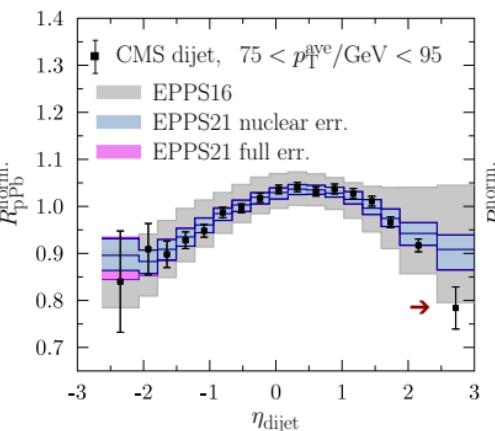
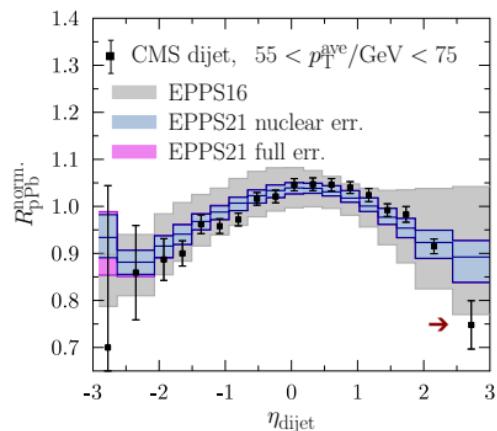
N.B.  $A$ -dependence not  
necessarily smooth for light  
nuclei → need to scale the  
nuclear modifications for  
He-3 and Li-6 by factors

$$f_3 = 0.291, \quad f_6 = 0.495$$



# Dijets at 5.02 TeV

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



Strong new constraints!

Results in line with  
the reweighting study

[Eskola, PP & Paukkunen,  
Eur.Phys.J.C 79 (2019) 511]

Still finding it difficult to fit  
the forwardmost data points

# $D^0$ s at 5.02 TeV – backward

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

Excellent fit!

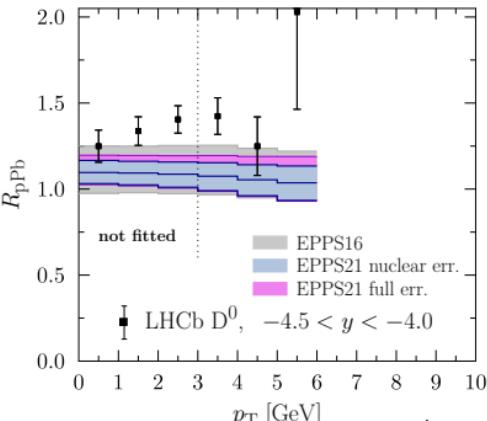
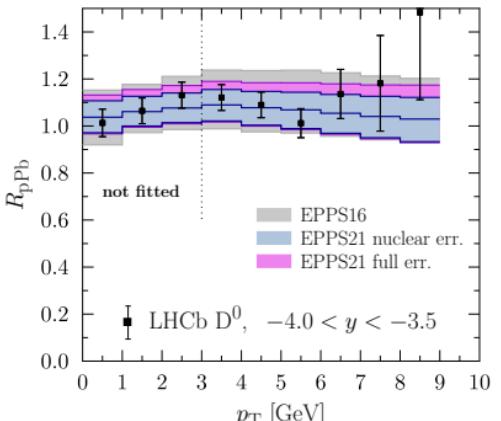
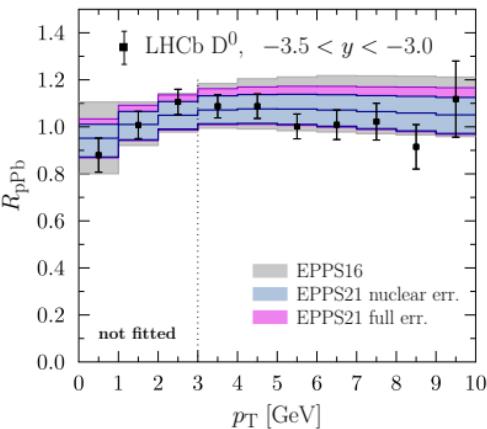
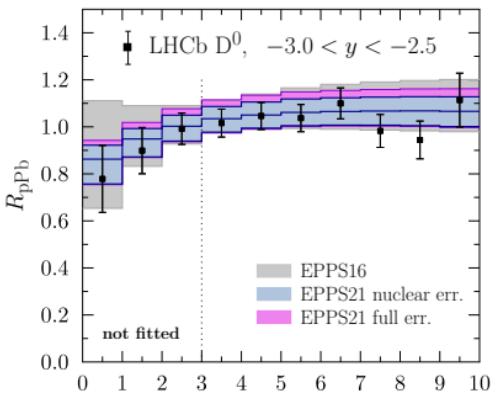
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[Eskola, Helenius, PP & Paukkunen,  
JHEP 05 (2020) 037]

Using the NLO pQCD  
S-ACOT- $m_T$  GM-VFNS

[Helenius & Paukkunen,  
JHEP 05 (2018) 196]

Using a  $p_T > 3$  GeV cut  
to reduce theoretical  
uncertainties



# $D^0$ s at 5.02 TeV – forward

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

Excellent fit!

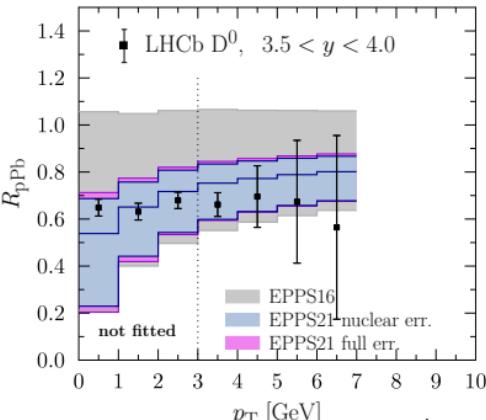
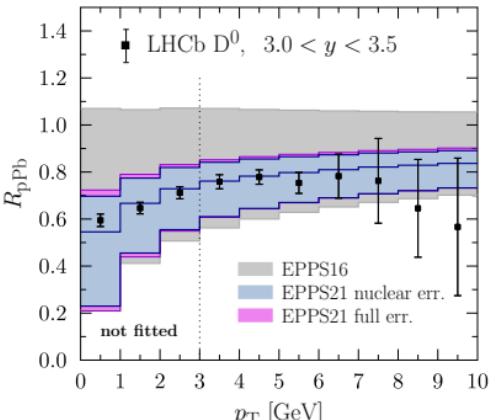
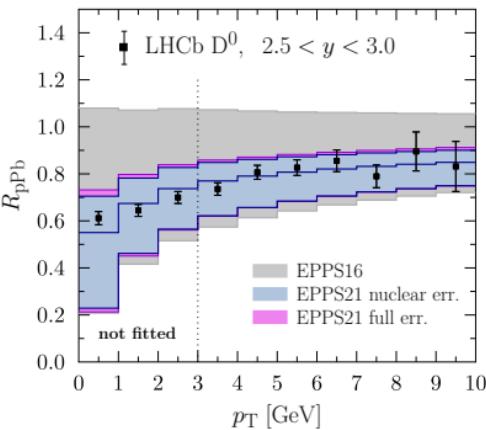
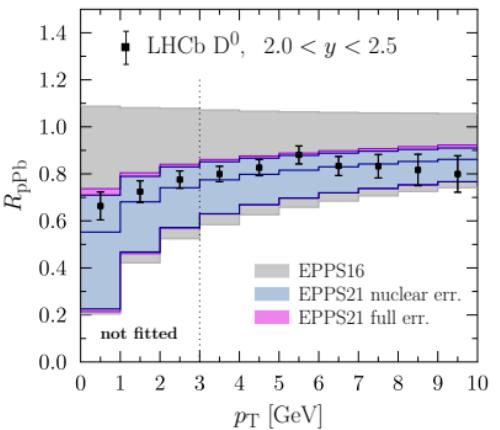
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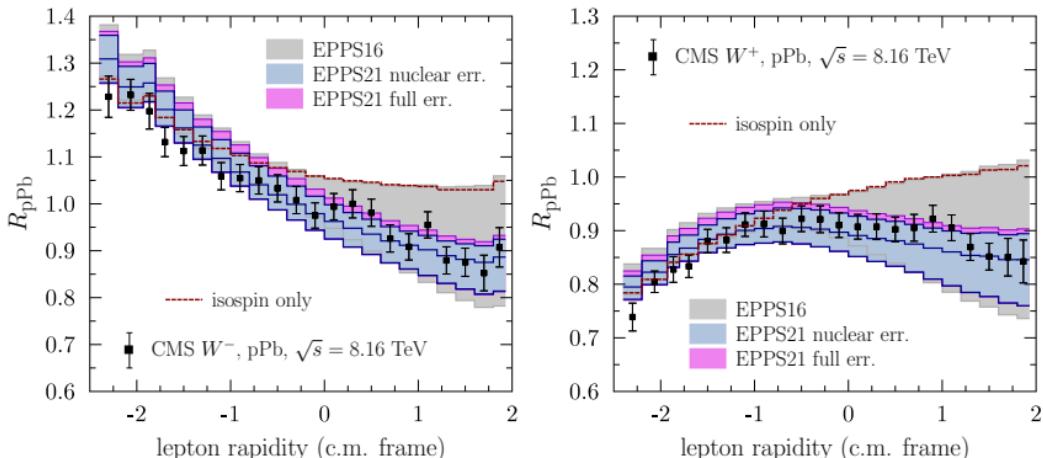


Excellent fit!

Using the mixed-energy nuclear modification ratio

$$R_{\text{pPb}} = \frac{d\sigma_{8.16 \text{ TeV}}^{\text{pPb}} / d\eta_\mu}{d\sigma_{8.0 \text{ TeV}}^{\text{pp}} / d\eta_\mu}$$

to cancel the free-proton PDF uncertainty



Fully consistent with the dijets and D<sup>0</sup>s

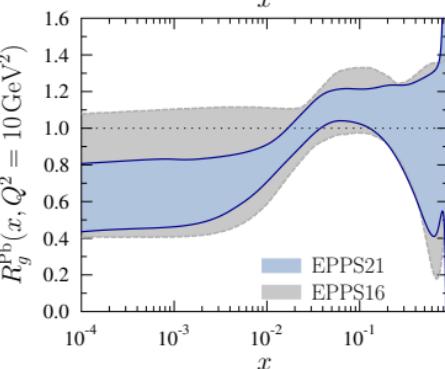
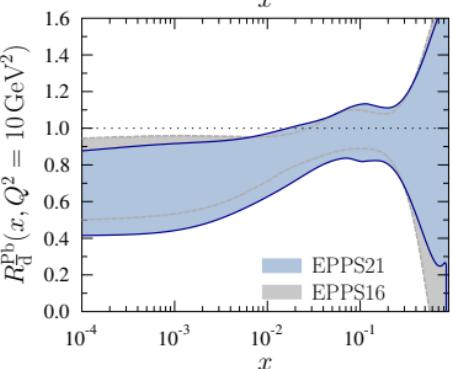
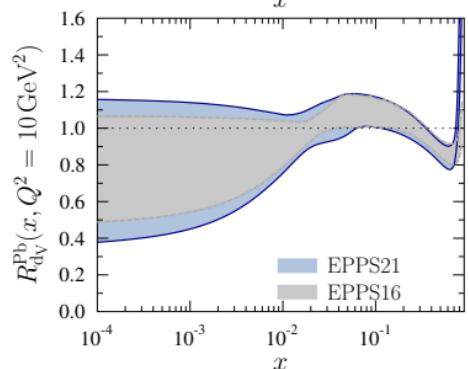
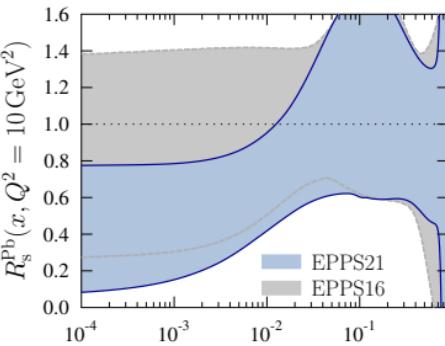
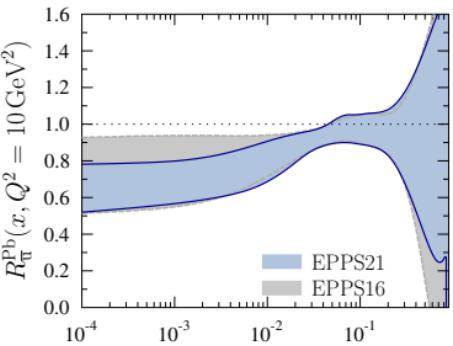
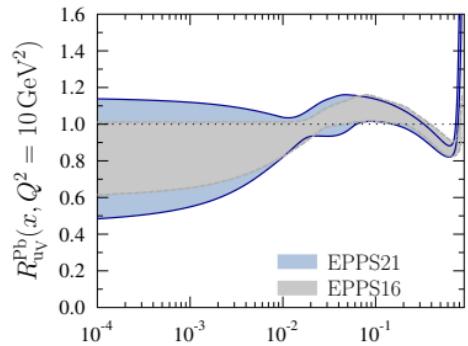
- Important check on the nuclear PDF universality & factorization

These data do not appear to give additional flavour-separation constraints on top of those we had already in EPPS16

- Looking forward to increased precision at LHC Run 3

# Comparison with EPPS16

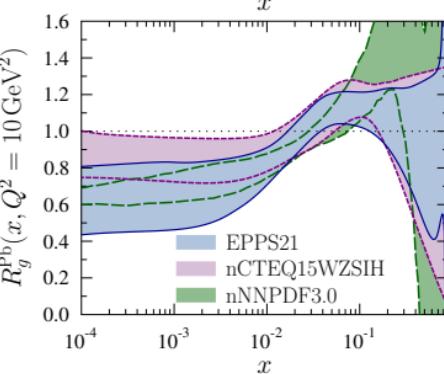
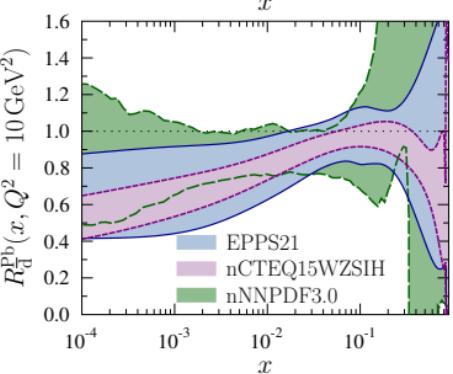
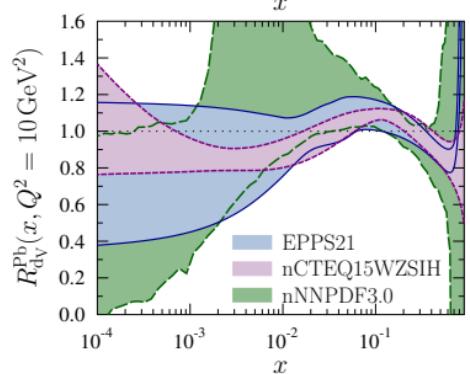
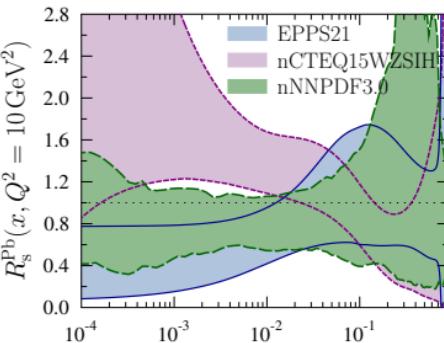
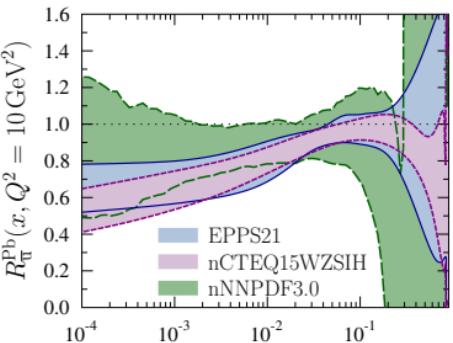
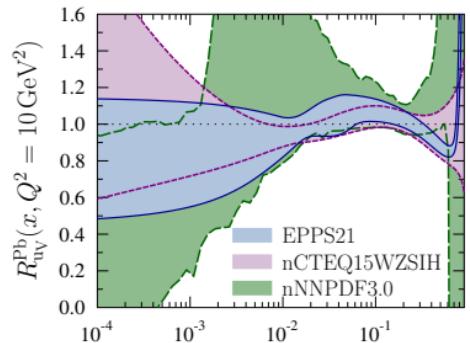
$$R_i^A = \frac{Z f_i^{p/A} + N f_i^{n/A}}{Z f_i^p + N f_i^n}$$



- Shadowing in all sea-quark flavours
- Better control over gluon shadowing & antishadowing!

# Comparison with nNNPDF3.0 and nCTEQ15WZSIH

$$R_i^A = \frac{Z f_i^{p/A} + N f_i^{n/A}}{Z f_i^p + N f_i^n}$$



- All three mostly consistent within uncertainties, but significant differences flavour by flavour
- Gluon shadowing+antishadowing established!

# Summary

## A new EPPS21 parametrization of nuclear PDFs available for perturbative-QCD applications

- Obtained a good fit for multiple new nuclear data from LHC ( $W_s$ ,  $D^0$ s and dijets) and JLab
- Strong new constraints on gluon modifications in lead
- Flavour separation uncertainties remain significant

## Study the baseline free-proton PDF sensitivity / error

- We use data as nuclear modification ratios to decorrelate nuclear-modification and free-proton d.o.f.s to best possible extent
  - Subleading effect with the present data precision, but this can change with the LHC Run 3

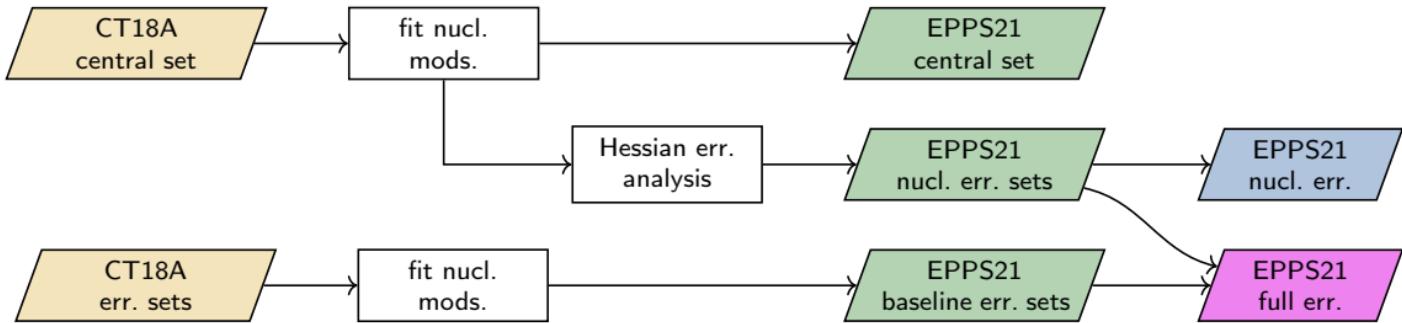
## PDF grids available from:

- <https://www.jyu.fi/science/en/physics/research/highenergy/urhic/npdfs/epps21-nuclear-pdfs>
- to appear in the LHAPDF website

Backup

# Charting the baseline proton-PDF uncertainty

We study baseline-PDF sensitivity by fitting nuclear modifications separately for each CT18A error set



The full error is calculated with:

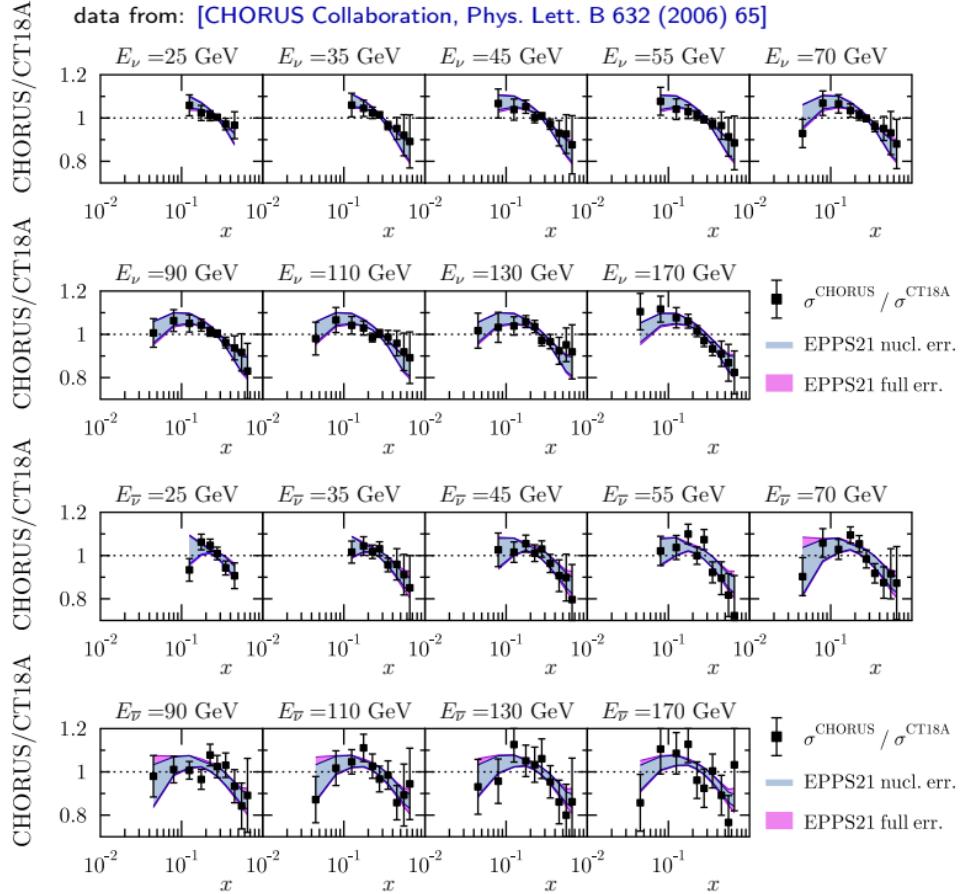
$$\begin{aligned} (\delta X_{\text{full}}^{\pm})^2 &= (\delta X_{\text{nucl.}}^{\pm})^2 + \underbrace{(\delta X_{\text{baseline}}^{\pm})^2}_{N_{\text{baseline param.}}} \\ &= \sum_k \left( \min \left\{ \underbrace{X[S_k^+]}_{\text{calculate with } f_i^{p/A}[S_k^+]} - X[S_0], X[S_k^-] - X[S_0], 0 \right\} \right)^2 \end{aligned}$$

fitted using the  $f_i^p[S_k^+]$  proton PDFs

calculate with  $f_i^{p/A}[S_k^+] = \underbrace{R_i^{p/A}[S_k^+]}_{\text{fitted using the } f_i^p[S_k^+]} f_i^p[S_k^+]$

# CHORUS $\nu A$ CC DIS

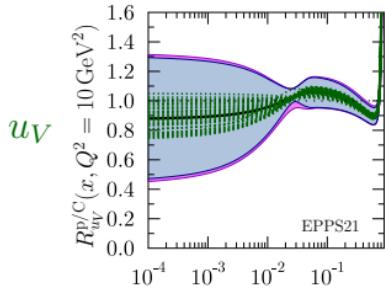
data from: [CHORUS Collaboration, Phys. Lett. B 632 (2006) 65]



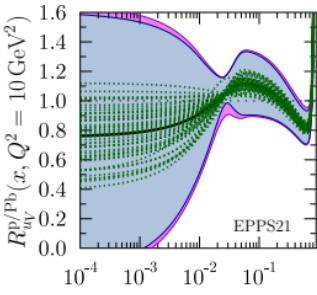
# Fit results – valence

## Bound-proton modifications

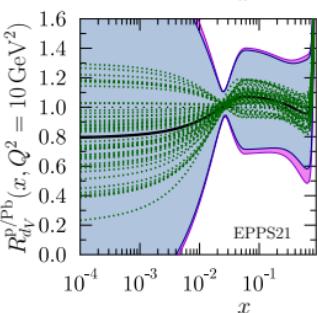
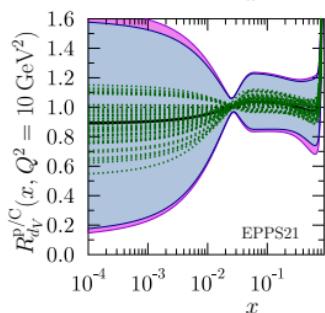
Carbon



Lead



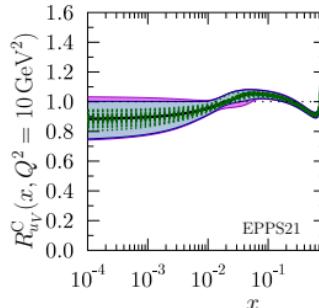
*d*<sub>V</sub>



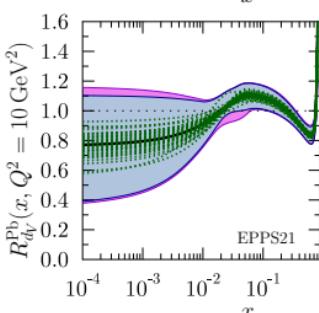
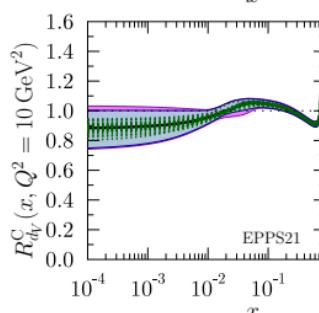
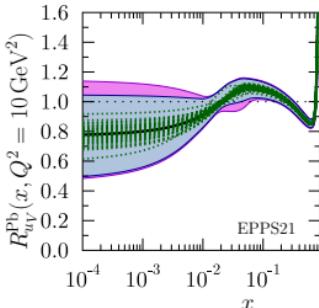
$$R_i^{p/A} = \frac{f_i^{p/A}}{f_i^p}$$

## Full-nucleus modifications

Carbon



Lead

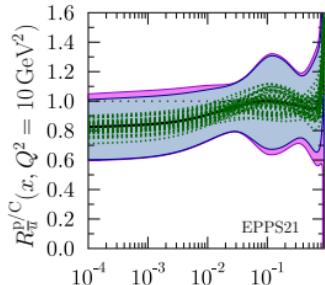


$$R_i^A = \frac{Z f_i^{p/A} + N f_i^{n/A}}{Z f_i^p + N f_i^n}$$

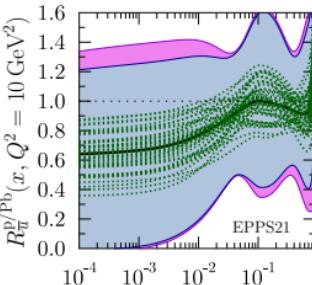
# Fit results – sea

## Bound-proton modifications

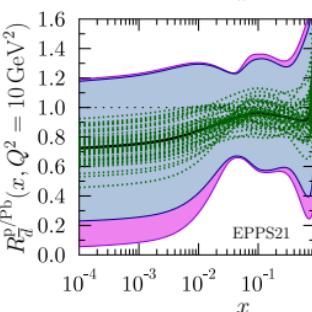
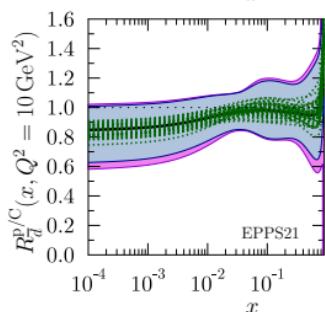
Carbon



Lead



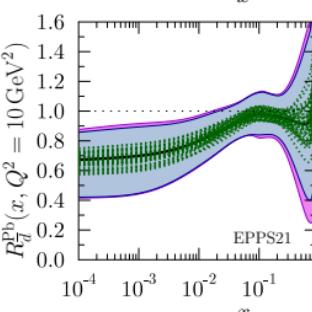
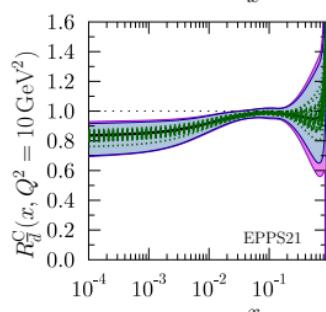
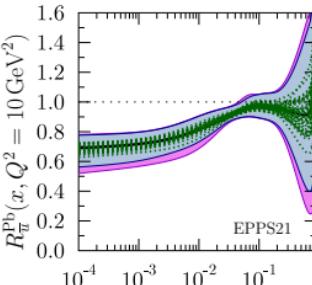
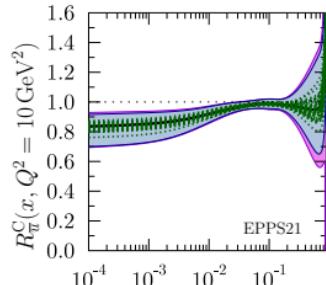
$\bar{d}$



$$R_i^{p/A} = \frac{f_i^{p/A}}{f_i^p}$$

## Full-nucleus modifications

Carbon

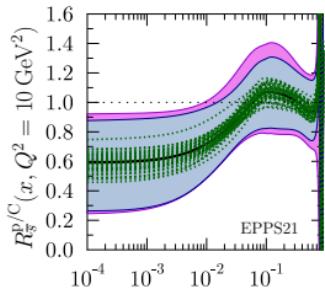


$$R_i^A = \frac{Z f_i^{p/A} + N f_i^{n/A}}{Z f_i^p + N f_i^n}$$

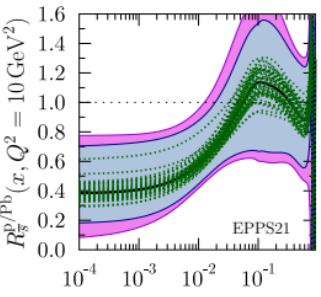
# Fit results – strange and glue

## Bound-proton modifications

Carbon

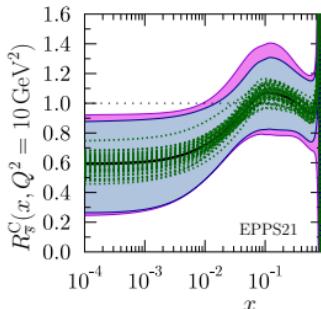


Lead

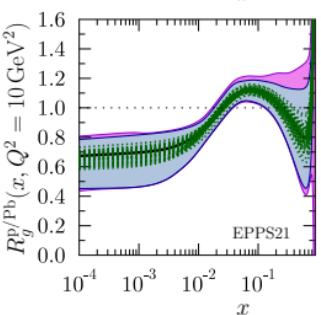
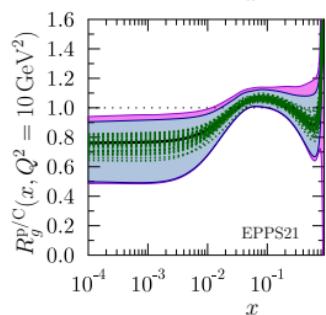
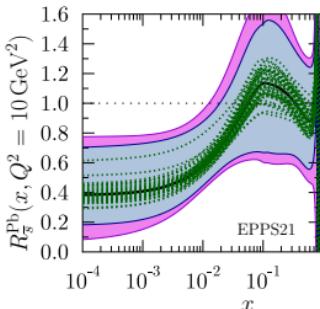


## Full-nucleus modifications

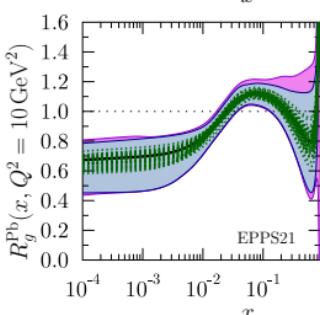
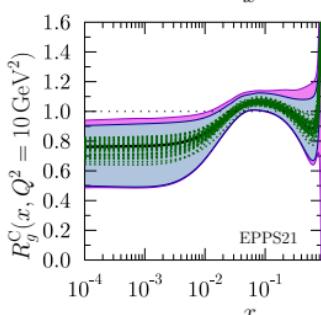
Carbon



Lead



$$R_i^{p/A} = \frac{f_i^{p/A}}{f_i^p}$$

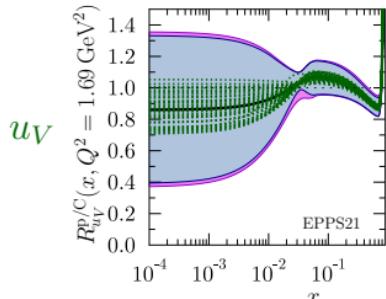


$$R_i^A = \frac{Z f_i^{p/A} + N f_i^{n/A}}{Z f_i^p + N f_i^n}$$

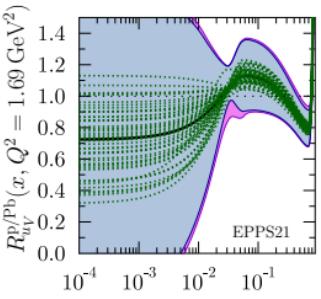
# Fit results at parametrization scale – valence

## Bound-proton modifications

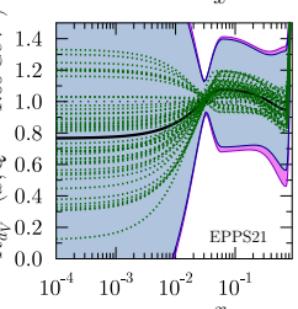
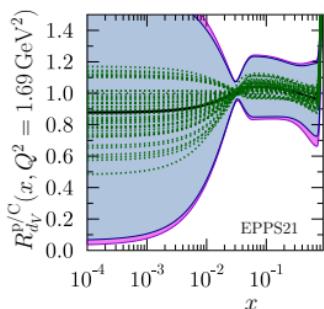
### Carbon



### Lead

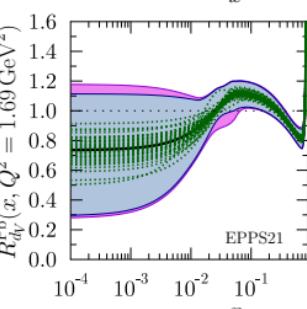
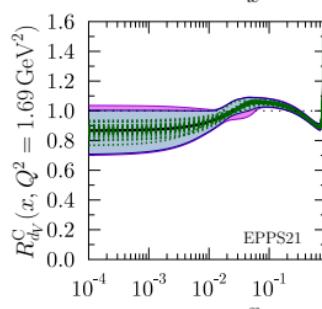
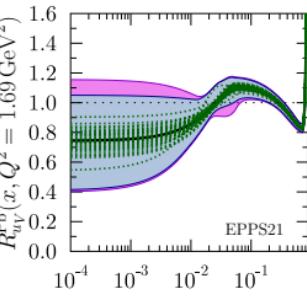
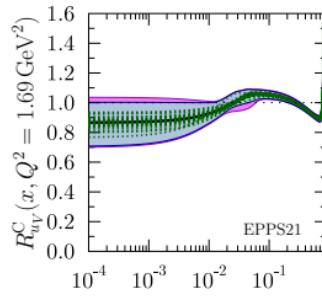


### $d_V$



## Full-nucleus modifications

### Carbon



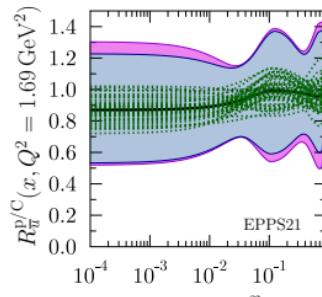
$$R_i^{p/A} = \frac{f_i^{p/A}}{f_i^p}$$

$$R_i^A = \frac{Z f_i^{p/A} + N f_i^{n/A}}{Z f_i^p + N f_i^n}$$

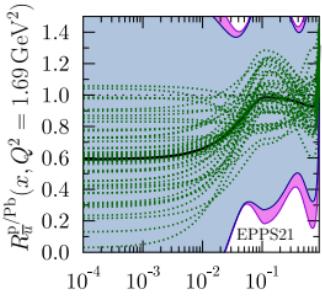
# Fit results at parametrization scale – sea

## Bound-proton modifications

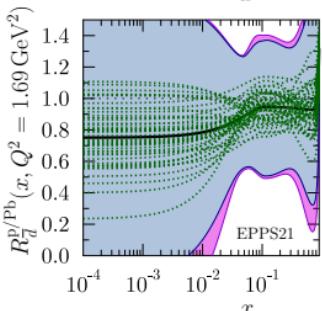
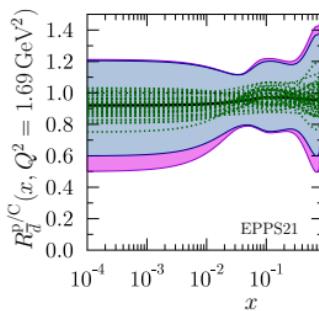
### Carbon



### Lead



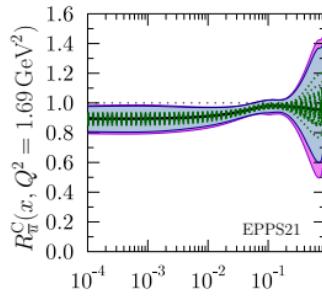
### $\bar{d}$



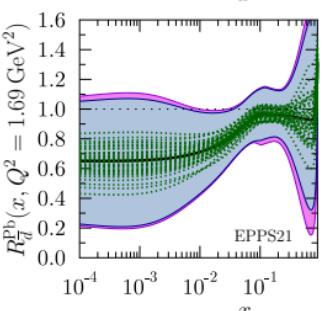
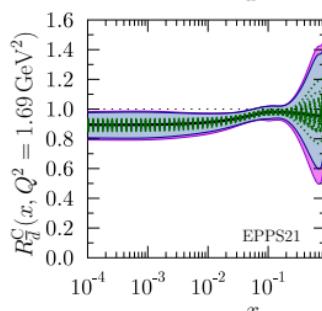
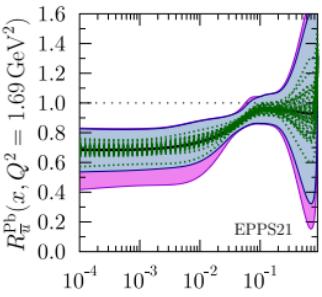
$$R_i^{p/A} = \frac{f_i^{p/A}}{f_i^p}$$

## Full-nucleus modifications

### Carbon



### Lead

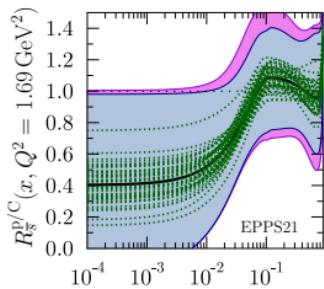


$$R_i^A = \frac{Z f_i^{p/A} + N f_i^{n/A}}{Z f_i^p + N f_i^n}$$

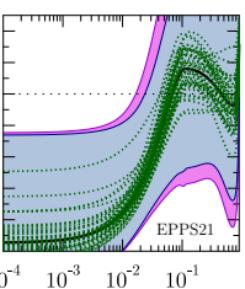
# Fit results at parametrization scale – strange and glue

## Bound-proton modifications

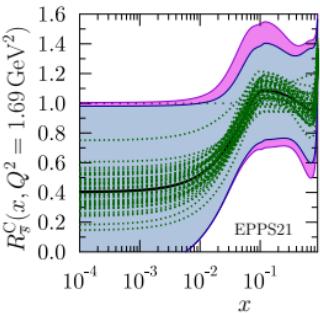
Carbon



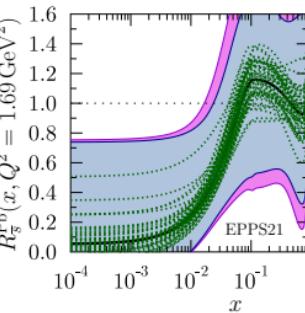
Lead



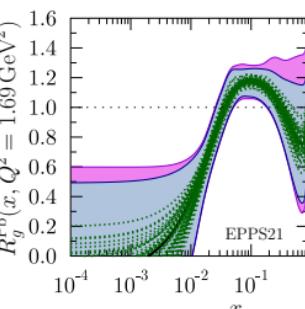
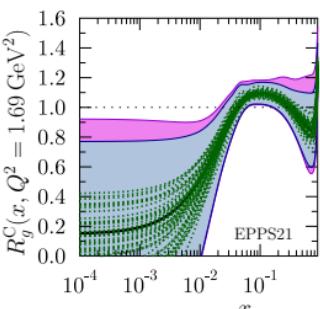
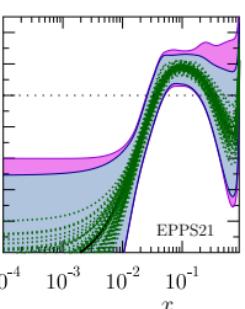
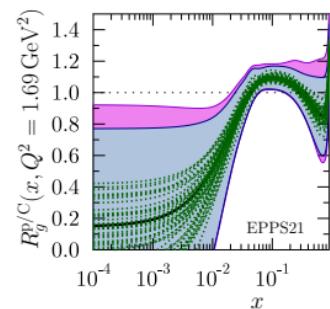
Carbon



Lead



*s*



*g*

$$R_i^{p/A} = \frac{f_i^{p/A}}{f_i^p}$$

$$R_i^A = \frac{Z f_i^{p/A} + N f_i^{n/A}}{Z f_i^p + N f_i^n}$$