HADRON 2021

19TH INTERNATIONAL CONFERENCE ON HADRON SPECTROSCOPY AND STRUCTURE

Next generation nuclear PDFs and their relevance to hadron structure

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XUNTA DE GALICIA

What the nuclear PDFs are?

Based on the collinear factorization of QCD:

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

The coefficient functions $d\hat{\sigma}^{ij\to k+X'}$ are calculable from perturbative QCD...

...but the parton distribution functions f_i^A, f_j^B contain long-range physics and cannot be obtained by perturbative means

PDFs are *universal*, process independent, and obey the DGLAP equations

$$Q^2 \frac{\partial f_i^A}{\partial Q^2} = \sum_j P_{ij} \otimes f_j^A$$

For a nucleus A, one can decompose

$$f_i^A(x,Q^2) = Z\, \underbrace{f_i^{p/A}}_{\text{bound-proton PDF}}(x,Q^2) + (A-Z)\, \underbrace{f_i^{n/A}}_{\text{bound-neutron PDF}}(x,Q^2),$$

and assume $f_i^{p/A} \overset{\text{isospin}}{\longleftrightarrow} f_j^{n/A}$

How do we get the $f_i^{p/A}$?

- **Physical models**: too numerous to describe here – 'Everybody's Model is Cool'
- **Extract from lattice**: problematic due to the PDF definition on the light cone
- **Fit to data**: parametrize the x- and A-dependence – the global analysis approach

Nuclear modification factors

Nuclear PDFs (nPDFs) often described in terms of

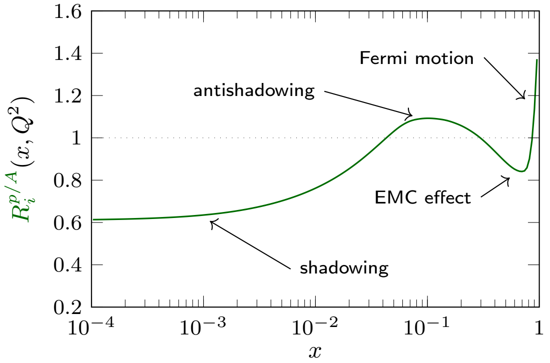
$$\underbrace{f_i^{p/A}(x,Q^2)}_{\text{bound-proton PDF}} = \overbrace{R_i^{p/A}(x,Q^2)}^{\text{nuclear modification}} \underbrace{f_i^{p}(x,Q^2)}_{\text{free-proton PDF}}$$

where $R_i^{p/A}$ exhibits the typical shape of

- Fermi motion at $x > 0.7$
- EMC (European Muon Collaboration) effect at $0.3 < x < 0.7$
- Antishadowing at $0.03 < x < 0.3$
- Shadowing at $x < 0.03$

where x is the fraction of nucleon momentum carried by the parton

These effects were originally discovered in deep-inelastic scattering (DIS) experiments, but have since been verified also in other perturbative processes (nPDF universality)

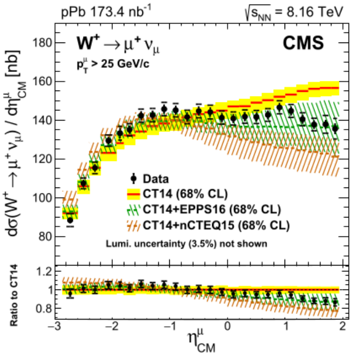


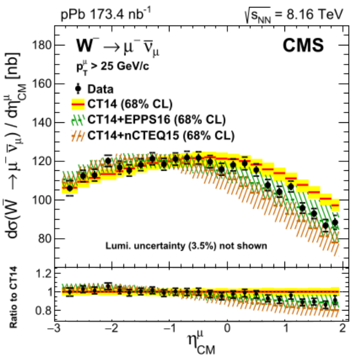
Latest and next generation NLO nPDF global fits

	EPPS16	nNNPDF2.0	nCTEQ15WZ	nCTEQ15HIX	EPPS21 prelim.
lA NC DIS	✓	✓	✓	✓	✓
+ JLab NC DIS				✓	✓ new!
νA CC DIS	✓	✓			✓
pA DY	✓		✓	✓	✓
πA DY	✓				✓
RHIC dAu/pp π^0	✓		✓		✓
LHC pPb dijet R_{FB}	✓				
→ dijet R_{pPb}					✓ new!
LHC pPb D^0					✓ new!
LHC pPb W,Z Run 1	✓	✓	✓		✓
+ Run 2 pPb W		✓	✓		✓ new!
Q cut in DIS	1.3 GeV	1.87 GeV	2 GeV	1.3 GeV	1.3 GeV
Data points	1811	1467	828	1564	2023 prelim.
Free parameters	20	256	19	19	24 prelim.
Error analysis	Hessian	Monte Carlo	Hessian	Hessian	Hessian
Error tolerance $\Delta\chi^2$	52	N/A	35	35	35 prelim.
Free-proton PDFs	CT14	NNPDF3.1	∼CTEQ6M	∼CTEQ6M	CT18A prelim.
HQ treatment	S-ACOT	FONLL	S-ACOT	S-ACOT	S-ACOT
Indep. flavours	6	6	5	4	6
Reference	EPJC 77, 163	JHEP 09, 183	EPJC 80, 968	PRD 103, 114015	TBA

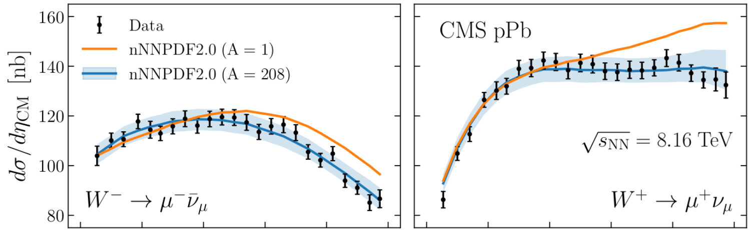
W bosons in pPb at 8.16 TeV

[CMS, Phys.Lett.B 800 (2020) 135048]





[Abdul Khalek, Ethier, Rojo & van Weelden, JHEP 09 (2020) 183]



Potential probes of the flavour separation (and strangeness):

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

Remember: small-x, high-Q^2 quarks and gluons correlated by DGLAP evolution ➔ constraints for gluons

Increased statistics for W bosons in the 8.16 TeV data set

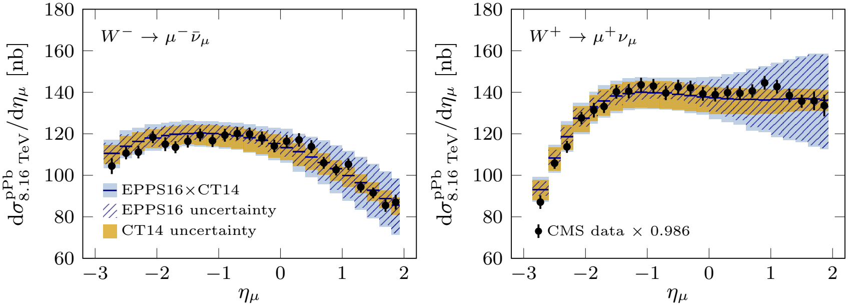
➔ Included in nNNPDF2.0 and nCTEQ15WZ

Need to mitigate free-proton PDF uncertainty

Absolute cross sections carry large proton-PDF uncertainty!

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

We could use the data as:



- **Absolute cross sections** — **as in nNNPDF2.0, nCTEQ15WZ**
  - ➔ susceptible to the proton-PDF uncertainties, should be accounted in the fit
- **Self-normalized cross sections**
  - ➔ cancel overall-normalization uncertainty, some proton-PDF uncertainties bound to remain
- **Forward-to-backward ratios** — **as in EPPS16**
  - ➔ more direct cancellation of the proton-PDF uncertainties, lose some data points
- **Nuclear modification ratios (with 8.0 TeV pp)** — **the current plan for EPPS21**
  - ➔ expect good cancellation of the proton-PDF uncertainties, additional experimental uncertainties from the proton–proton measurement

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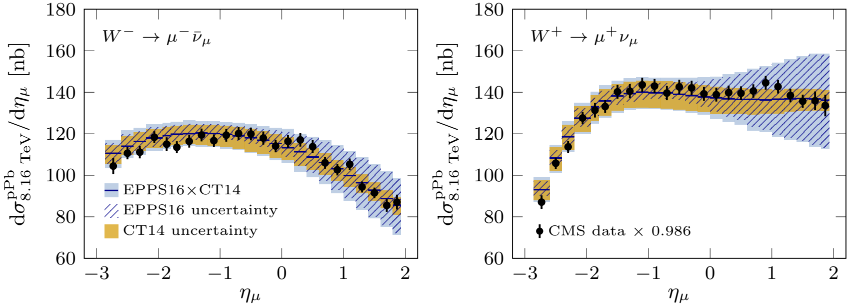

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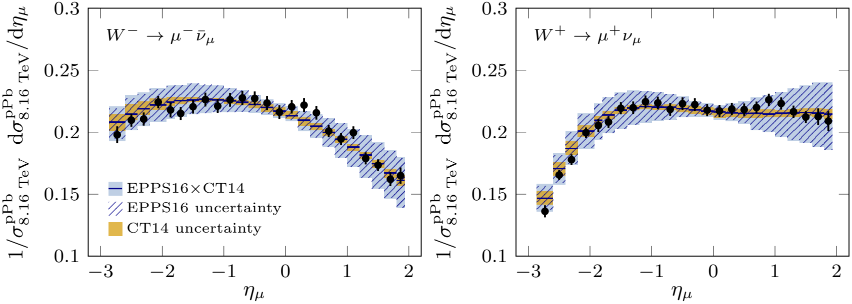

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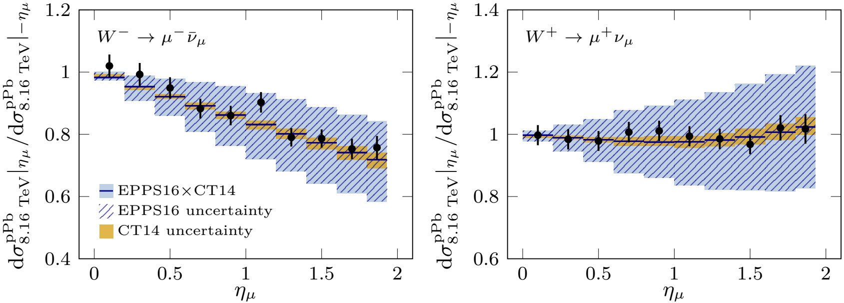

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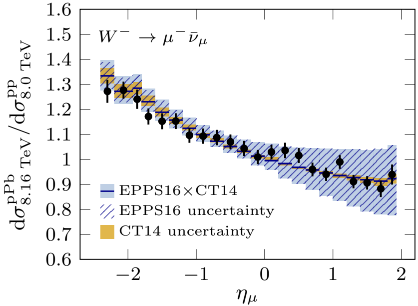

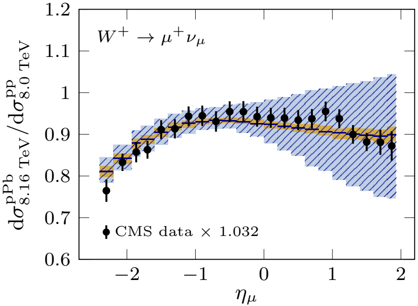

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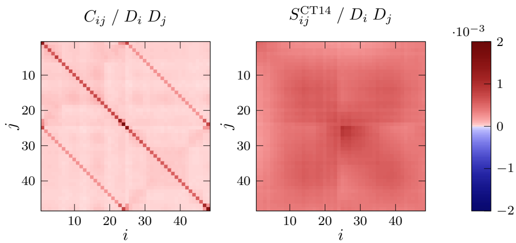
How to propagate proton-PDF uncertainties into nPDF fit?

Use a theoretical covariance matrix method

see [Abdul Khalek *et al.*, Eur.Phys.J. C79 (2019) 931]



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

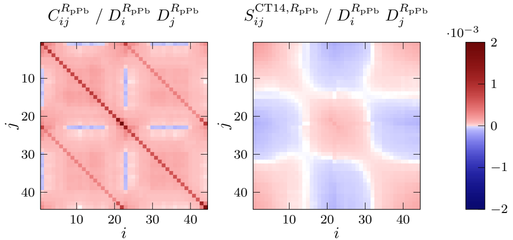
where the CT14 covariances are calculated with

$$S_{ij}^{\mathrm{CT14}} = \sum_k \frac{y_i[S^+_{\mathrm{CT14},k}] - y_i[S^-_{\mathrm{CT14},k}]}{2 \times \underbrace{1.645}_{90\% \to 68\% \text{ conf. level}}} \, \frac{y_j[S^+_{\mathrm{CT14},k}] - y_j[S^-_{\mathrm{CT14},k}]}{2 \times 1.645}$$

We can also propagate the covariances into those of other observables via

$$C^{\mathsf{new}} = J\, C\, J^{\mathrm{T}},$$

where J is the Jacobian of the transformation



Note: It is the strong *positive* correlations which make the uncertainty reduction with ratios possible!

Reweighting results

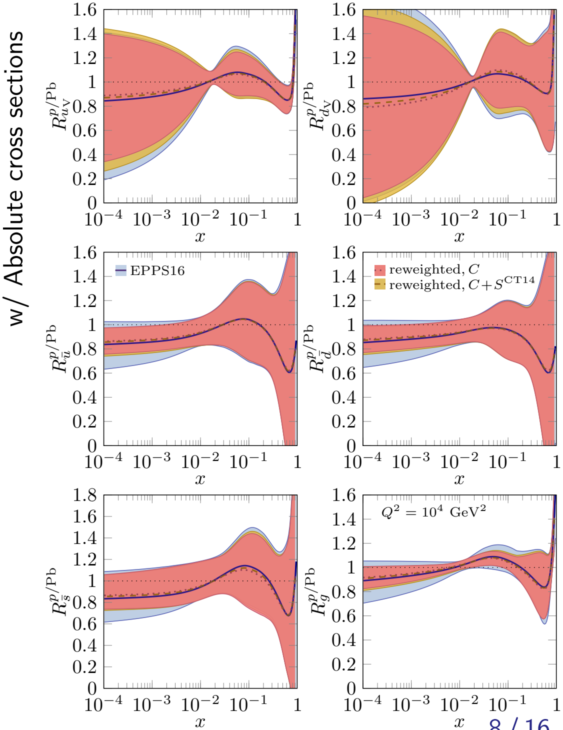
Study the impact on nuclear PDFs with the Hessian reweighting method
see [Paukkunen & Zurita, JHEP 12 (2014) 100]

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



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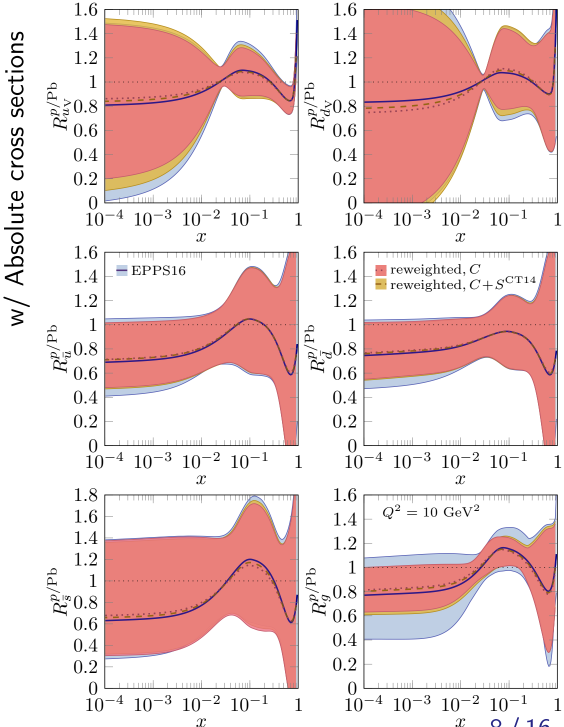

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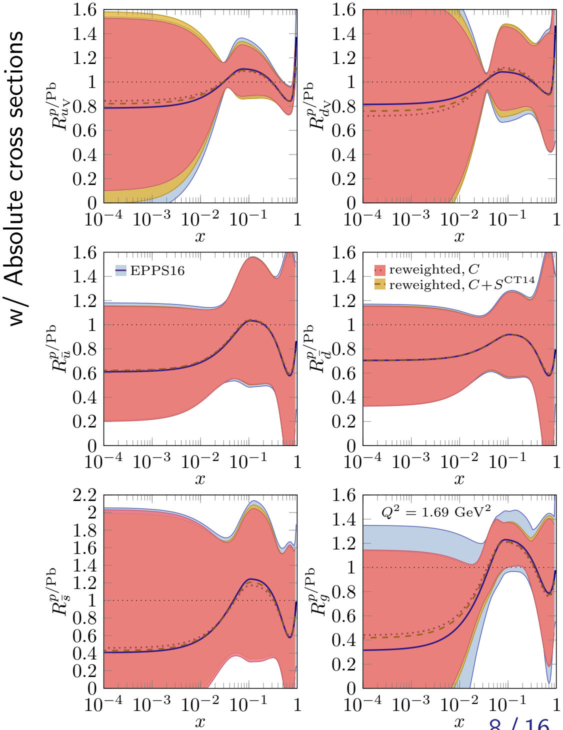

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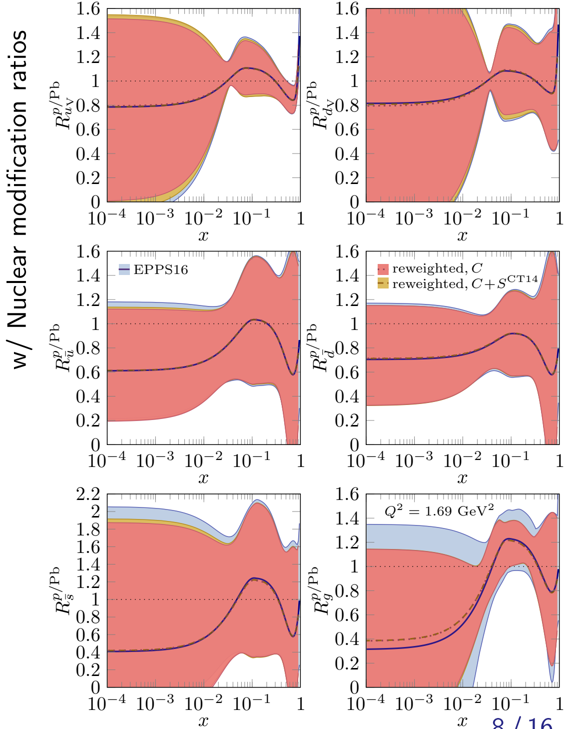

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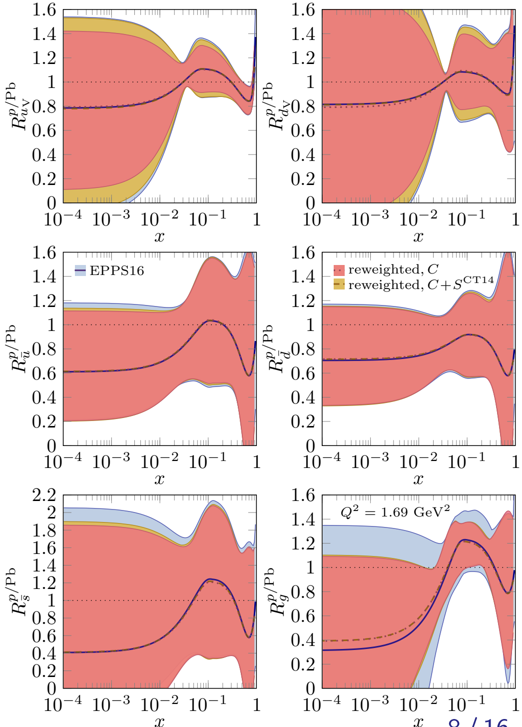
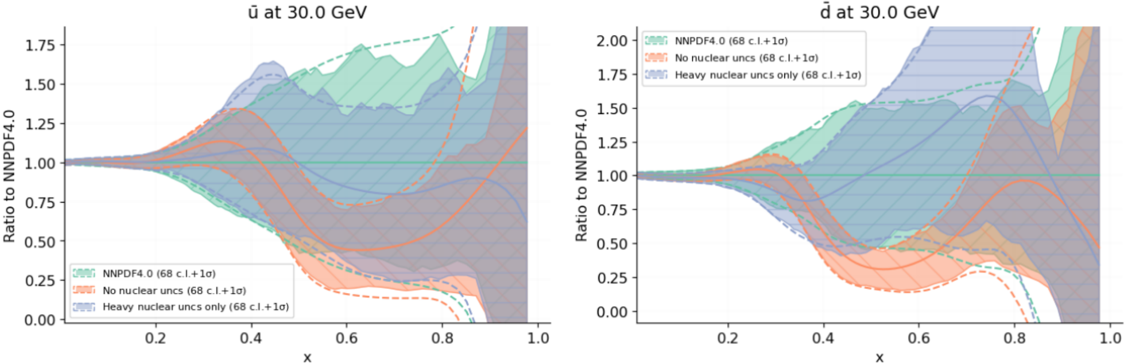
w/ Mock data with reduced stat. uncertainties



Detour: Nuclear uncertainties in proton-PDF analyses

[Pearson, Ball & Nocera, arXiv:2106.12349,
see also Eur.Phys.J.C 79 (2019) 282]



Also proton-PDF analyses rely on heavy nuclear data (fixed-target DIS and DY)

→ Large-x flavour separation depends on (assumed/fitted) nuclear corrections and uncertainties

- Might find a need for a proton+nPDF master analysis, or an iterative procedure

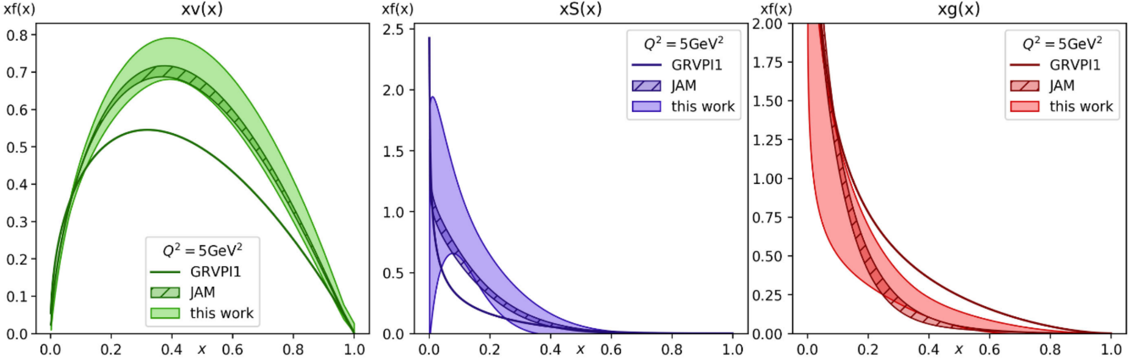
  see [Ball, Nocera & Pearson, Eur.Phys.J.C 81 (2021) 37]

- New data from non-heavy targets and understanding deuterium corrections extremely important

  see plenary talks by Paul E. Reimer and Timothy Hobbs

Detour: Nuclear uncertainties in pion-PDF analyses

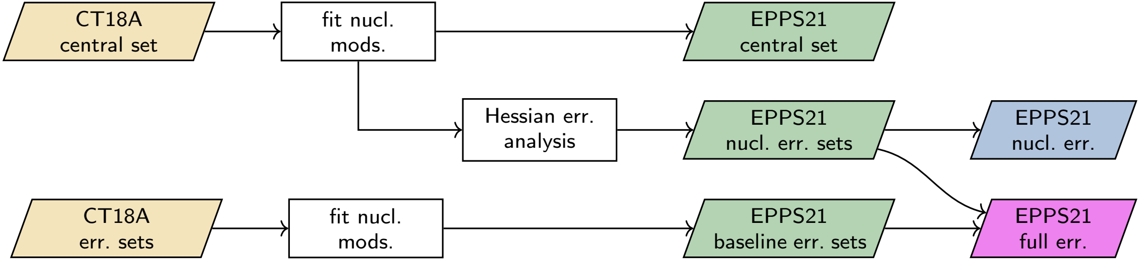
[Notikov *et al.*, Phys.Rev.D 102 (2020) 014040]



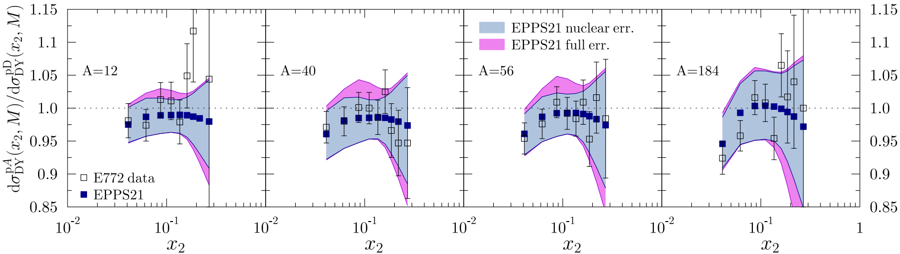
PDFs of charged pions are obtained from pion–nucleus DY and direct photon data

- → Much larger errors when nuclear uncertainties are accounted for
  . . . but note that different data are used in the fits
- → Pion-PDF uncertainties become correlated with the nuclear ones
- ! Need for a way to consistently propagate the cross-correlated uncertainties to observables

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



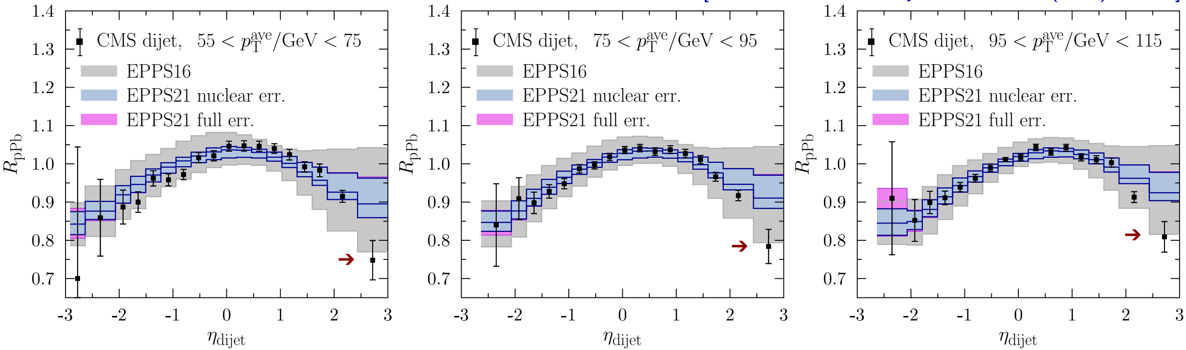
Baseline error mostly subdominant in the observables we fit, but shows up e.g. in the fixed-target DY

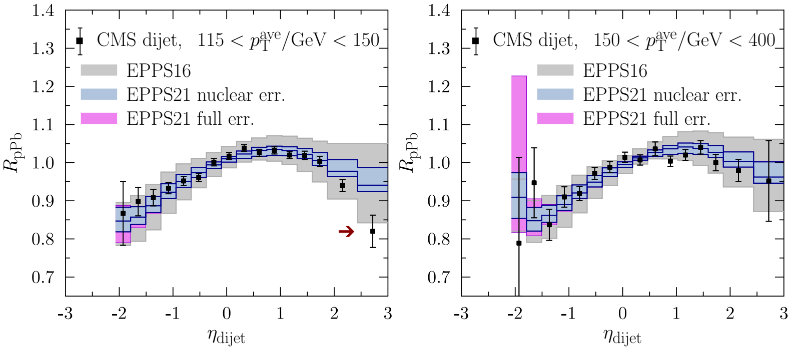


Dijets at 5.02 TeV *new!*

preliminary results,
Ref: [Eskola, PP, Paukkunen & Salgado, arXiv:2106.13661]

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





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

➔ currently excluded from the fit

preliminary results,
Ref: [Eskola, PP, Paukkunen & Salgado, arXiv:2106.13661]

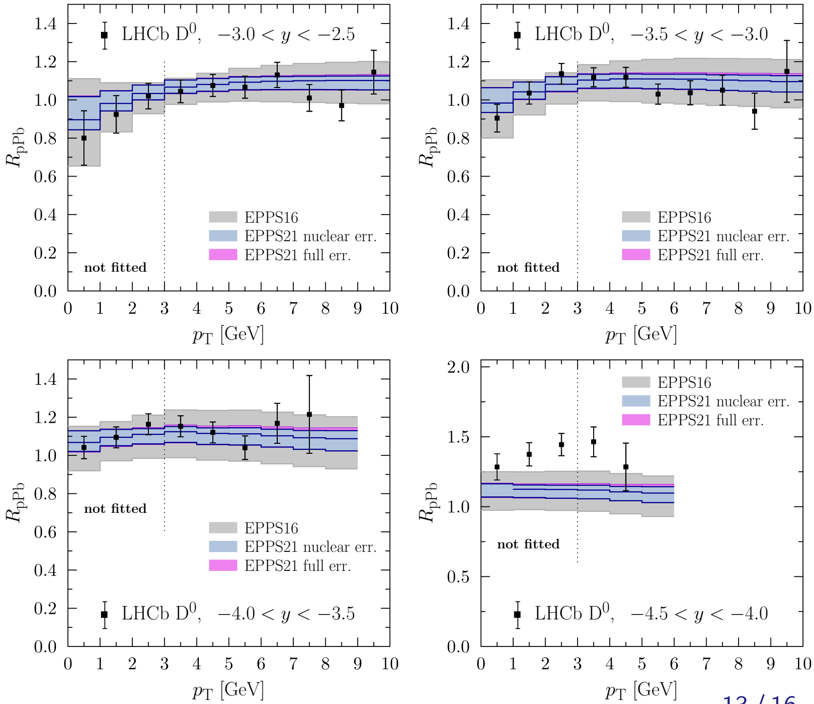
data from: [LHCb Collaboration, JHEP 10 (2017) 090]

Excellent fit!

Results in line with the reweighting study
[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^0s at 5.02 TeV – forward *new!*

preliminary results,
Ref: [Eskola, PP, Paukkunen & Salgado, arXiv:2106.13661]

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

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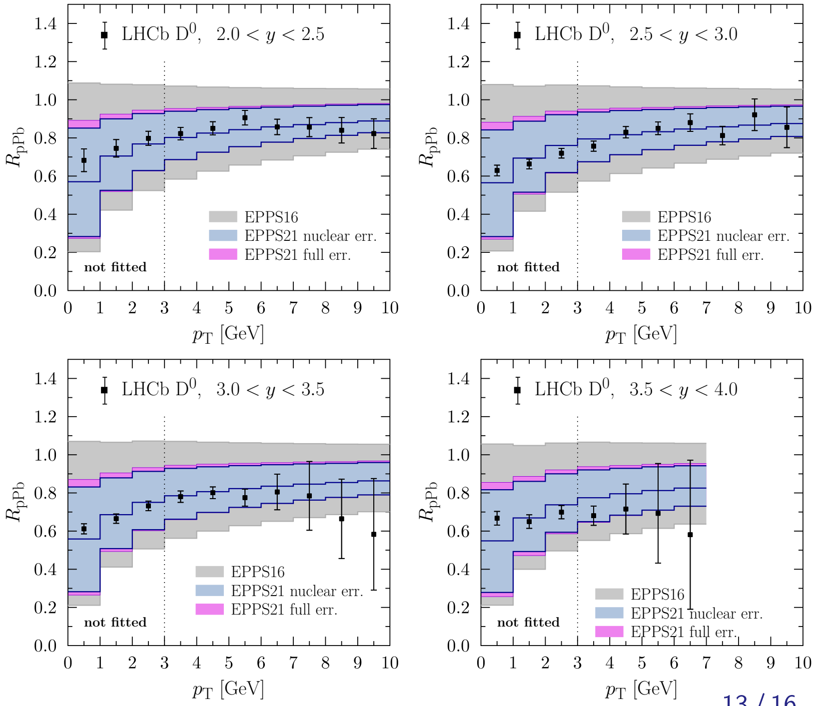


Ws at 8.16 TeV *new!*

preliminary results,
Ref: [Eskola, PP, Paukkunen & Salgado, arXiv:2106.13661]

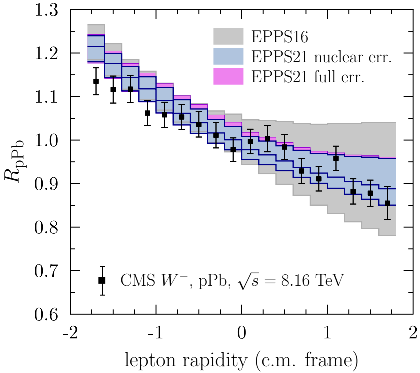
data from: [CMS Collaboration, Phys.Lett.B 800 (2020) 135048, Eur.Phys.J.C 76 (2016) 469]

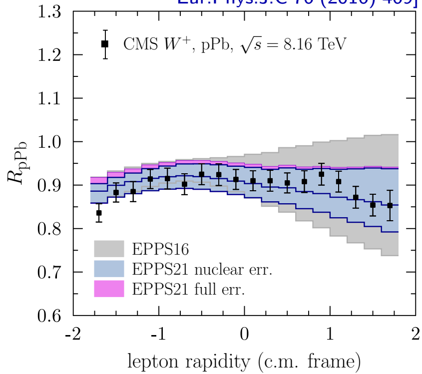
Excellent fit!

Using the mixed-energy nuclear modification ratio

$$R_{\mathrm{pPb}} = \frac{\mathrm{d}\sigma^{\mathrm{pPb}}_{8.16\ \mathrm{TeV}}/\mathrm{d}\eta_\mu}{\mathrm{d}\sigma^{\mathrm{pp}}_{8.0\ \mathrm{TeV}}/\mathrm{d}\eta_\mu}$$

to cancel the free-proton PDF uncertainty





Fully consistent with the dijets and D^0s

- Important check on the nPDF 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 to EPPS16

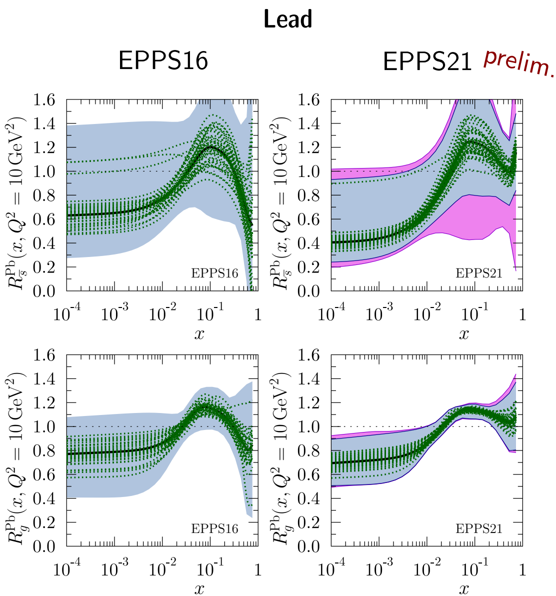
preliminary results,
Ref: [Eskola, PP, Paukkunen & Salgado, arXiv:2106.13661]

Flavour separation (esp. strangeness) remains a difficult beast to tame

- Not enough data to put stringent constraints on a flavour by flavour basis
- Some sensitivity to proton-PDF uncertainties

Significant reduction in the gluon uncertainties!

- Driven by dijet and D^0 data, but consistent with Ws
- Strong evidence for mid-x antishadowing and small-x shadowing



Summary

Next generation nuclear PDFs will include a large set of data from the LHC pPb collisions

- A new EPPS nPDF fit on its way...
- New constraints on gluon modifications in lead ➔ strong evidence for (anti)shadowing!
- Flavour separation uncertainties still remain large

With increasing precision the free-proton PDF uncertainties become more important

- Can use data as suitable ratios to reduce the uncertainty and decorrelate nuclear-modification and free-proton d.o.f.s
- Residual free-proton PDF uncertainty can still be relevant e.g. for the flavour separation

Nuclear data also used in proton and pion PDF analyses

- Nuclear uncertainties can be large and are taken into account in some analyses but not all
- For accurate predictions it would be needed to provide the correlations to the general user

Backup

JLab NC DIS *new!*

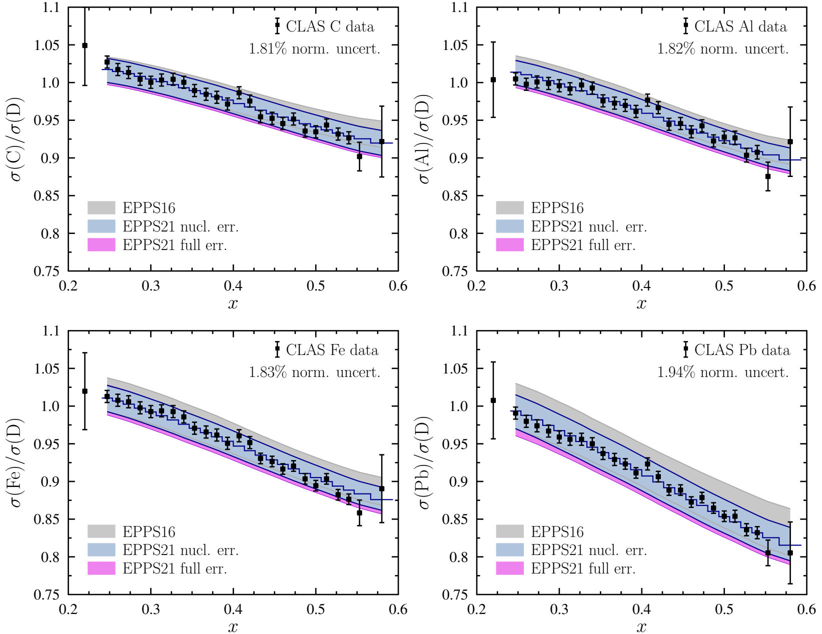
data from: [CLAS Collaboration, Nature 566 (2019) 354-358]

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 isospin-dependence in the bound-proton nuclear modifications $R_i^{p/A}$



Fit results – valence

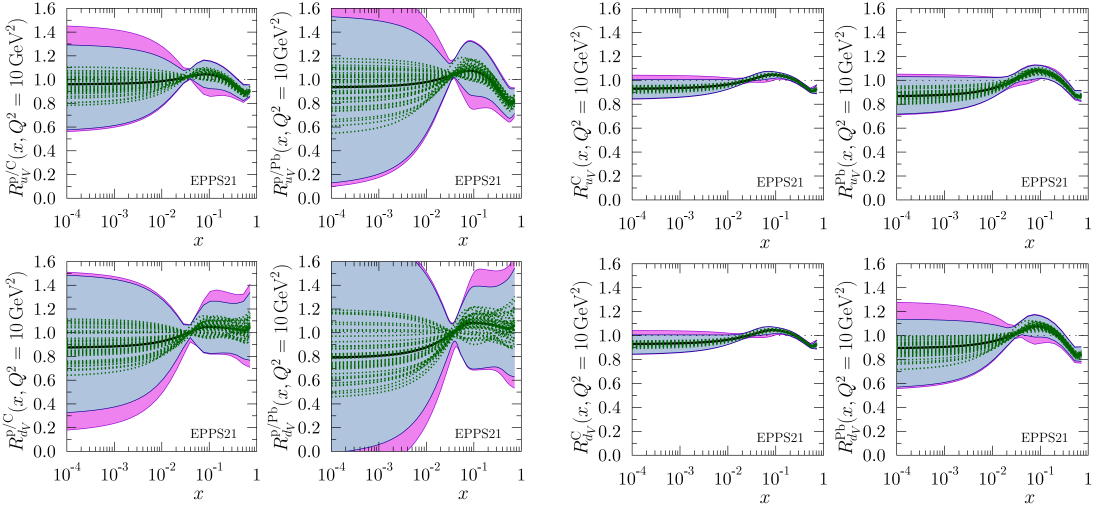
preliminary results,
Ref: [Eskola, PP, Paukkunen & Salgado, arXiv:2106.13661]

Bound-proton modifications *prelim.*   **Full-nucleus modifications** *prelim.*

Carbon   Lead   Carbon   Lead

u_V

d_V



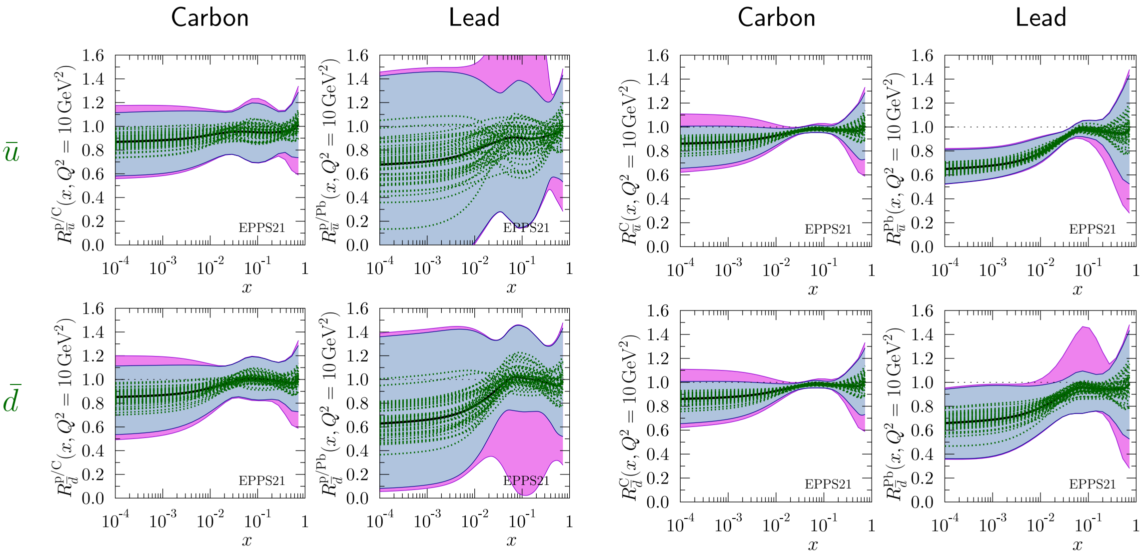
$$R_i^{p/A} = \frac{f_i^{p/A}}{f_i^p}$$

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

Fit results – sea

preliminary results,
Ref: [Eskola, PP, Paukkunen & Salgado, arXiv:2106.13661]

Bound-proton modifications *prelim.* **Full-nucleus modifications** *prelim.*

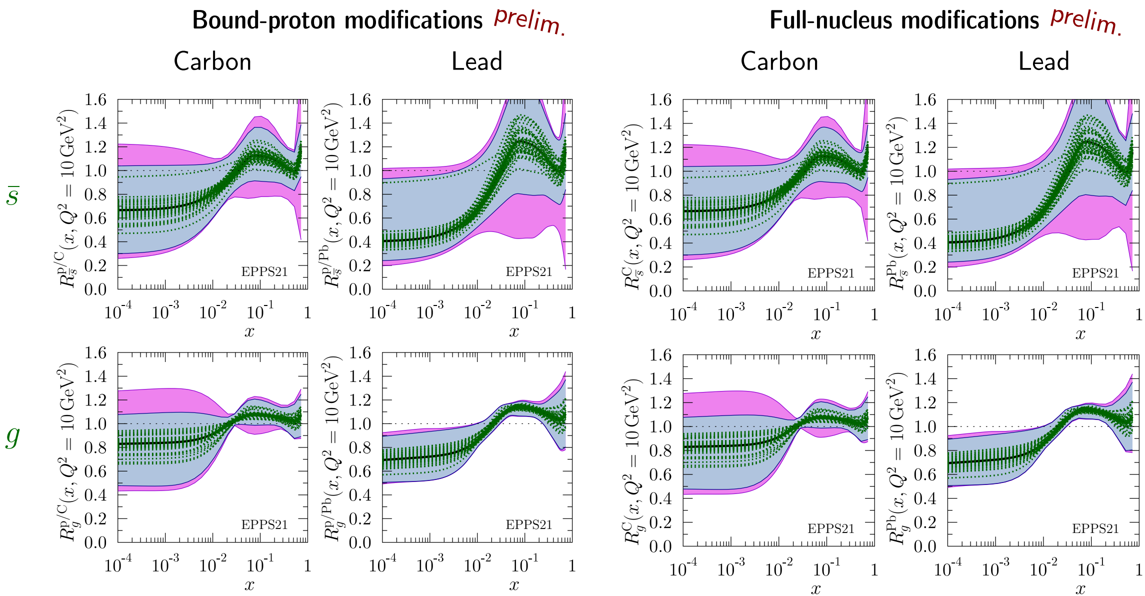


$$R_i^{p/A} = \frac{f_i^{p/A}}{f_i^p}$$

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

Fit results – strange and glue

preliminary results,
Ref: [Eskola, PP, Paukkunen & Salgado, arXiv:2106.13661]

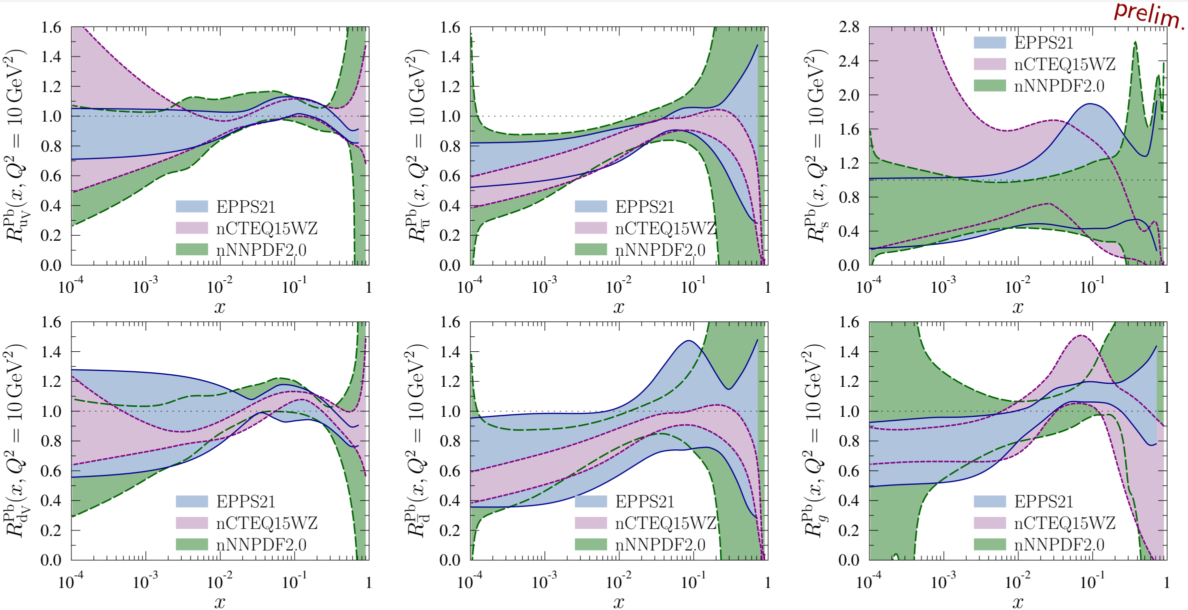


$$R_i^{p/A} = \frac{f_i^{p/A}}{f_i^p}$$

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

Comparison to nNNPDF2.0, nCTEQ15WZ

preliminary results, Ref: [Eskola, PP, Paukkunen & Salgado, arXiv:2106.13661]



- All three consistent within uncertainties, but significant differences in the uncertainty estimates
- Best constrained gluons in the (prelim.) EPPS21 fit!

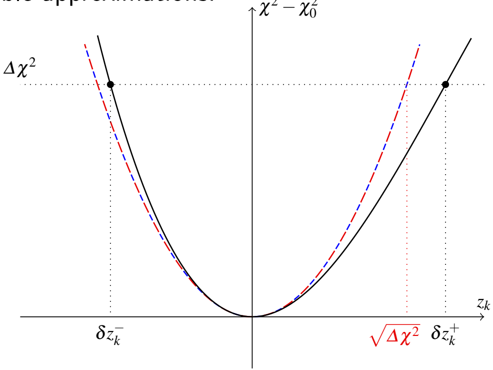
PDF reweighting: different approximations

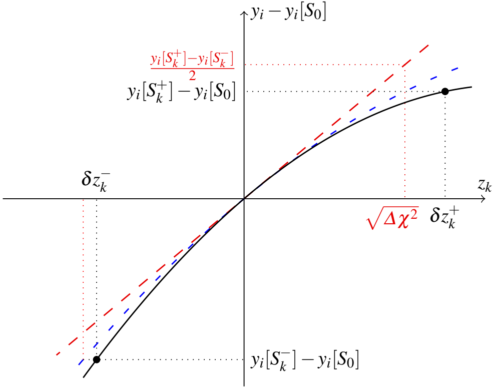
[Eskola, PP & Paukkunen, Eur.Phys.J.C 79 (2019) 511]

The Hessian reweighting is a method to study the impact of a new set of data on the PDFs without performing a full global fit

$$\chi^2_{\text{new}}(\mathbf{z}) = \chi^2_{\text{old}}(\mathbf{z}) + \sum_{ij} (y_i(\mathbf{z}) - y_i^{\text{data}})\, C_{ij}^{-1}\, (y_j(\mathbf{z}) - y_j^{\text{data}})$$

Possible approximations:





quadratic–linear: $\chi^2_{\text{old}} \approx \chi^2_0 + \sum_k z_k^2,$ $\quad y_i \approx y_i[S_0] + \sum_k d_{ik} z_k$

quadratic–quadratic: $\chi^2_{\text{old}} \approx \chi^2_0 + \sum_k z_k^2,$ $\quad y_i \approx y_i[S_0] + \sum_k (d_{ik} z_k + e_{ik} z_k^2)$

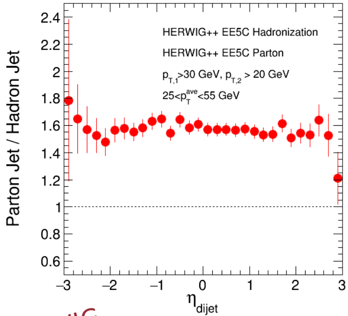
cubic–quadratic: $\chi^2_{\text{old}} \approx \chi^2_0 + \sum_k (a_k z_k^2 + b_k z_k^3),$ $\quad y_i \approx y_i[S_0] + \sum_k (d_{ik} z_k + e_{ik} z_k^2)$

Cancellation of hadronization effects

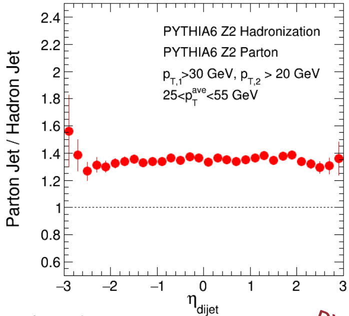
slide from: Doga Gulhan, HI Jet Workshop, July 2016

Cross-section ratios

HERWIG

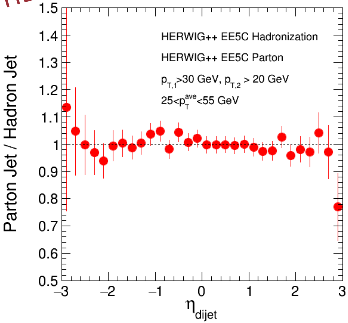


PYTHIA

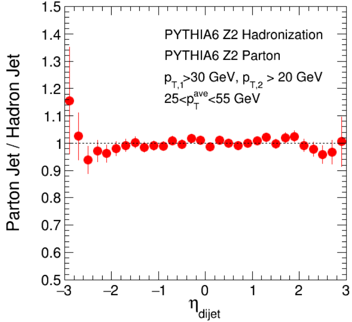


Area normalized ratios

HERWIG



PYTHIA



Hadronization uncertainty

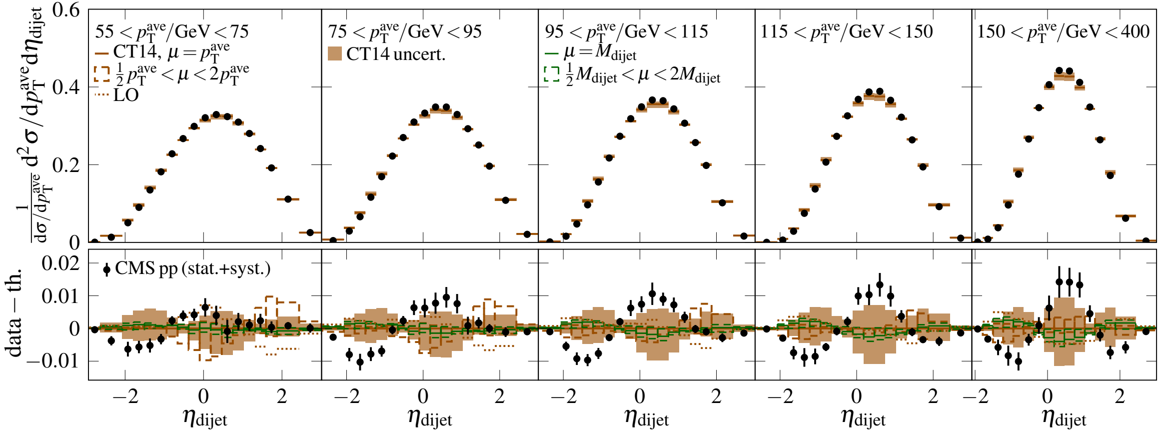
Parton jets have higher cross section for R = 0.3 jets with same kinematic selections compared to hadron jets

Parton jets are harder fragmenting

After self normalization effect of hadronization is negligible

CMS dijets at pp

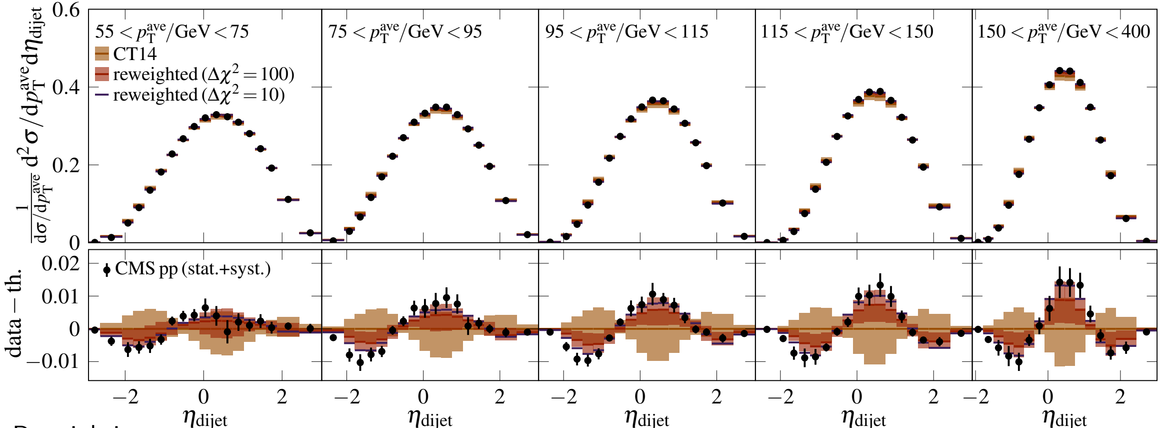
[Eskola, PP & Paukkunen, Eur.Phys.J.C 79 (2019) 511]



- Predicted NLO distributions somewhat wider than the measured spectra
- High-p_T^{ave} midrapidity robust against scale variations and LO-to-NLO effects
  - → can expect NNLO corrections to be small in this region
  - → observed discrepancy seems to be a PDF related issue
- Refitting might be needed to improve agreement with data
  - → study the impact with the reweighting method

CMS dijets at **pp** – CT14 reweighted

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

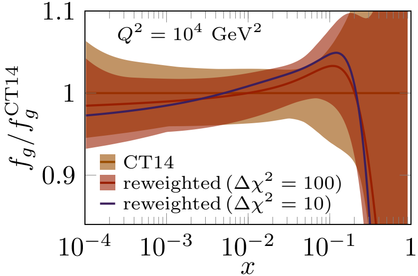


Reweighting:

- improves midrapidity description
- is not able to fully reproduce data at large rapidities even when applied with additional weight ($\Delta\chi^2 = 10$) (high-x parametrization issue? NNLO? data systematics?)

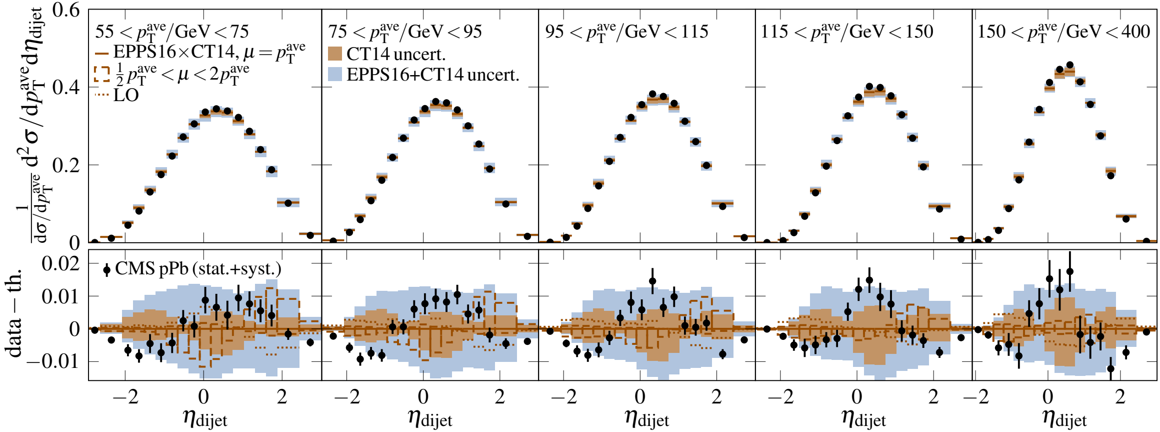
Significant gluon modifications needed especially at large x

- also valence quarks get modified



CMS dijets at pPb

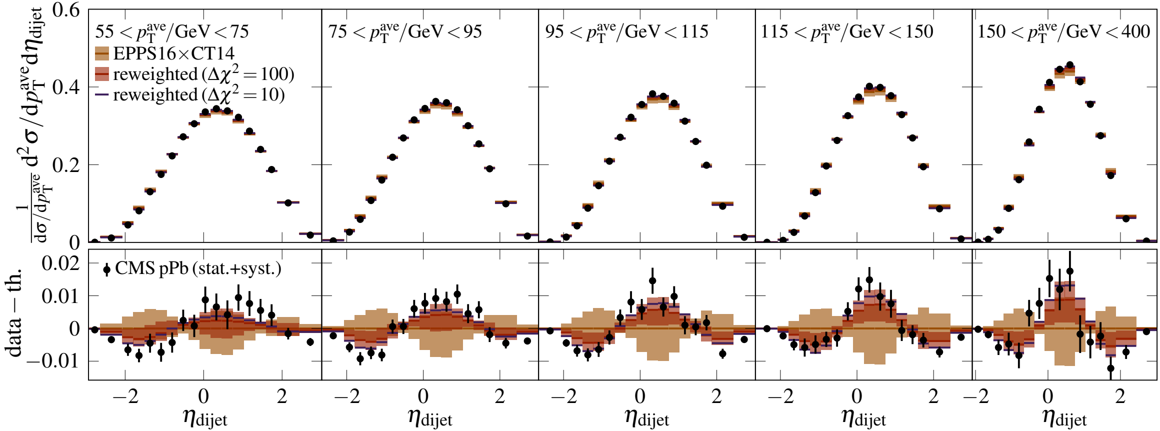
[Eskola, PP & Paukkunen, Eur.Phys.J.C 79 (2019) 511]



- pPb data deviates from NLO calculations *almost the same way* as the pp data
  - → had we not seen the same deviations in pp, we might have interpreted this as a fault in our nuclear PDFs
- Compared to pp case we have additional suppression in data compared to theory at forward rapidities
  - → implication of deeper gluon shadowing

CMS dijets at pPb after CT14 reweighting

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



- Modifications needed in CT14 to describe pp data have large impact on pPb predictions
  - → it is imperative to understand the pp baseline before making far-reaching conclusions from pPb data
- Using these data directly in nuclear PDF analysis with CT14 proton PDFs would lead to
  - overestimating nuclear effects
  - large scale-choice bias

→ Consider nuclear modification factor instead

Heavy-flavour production mass schemes

FFNS

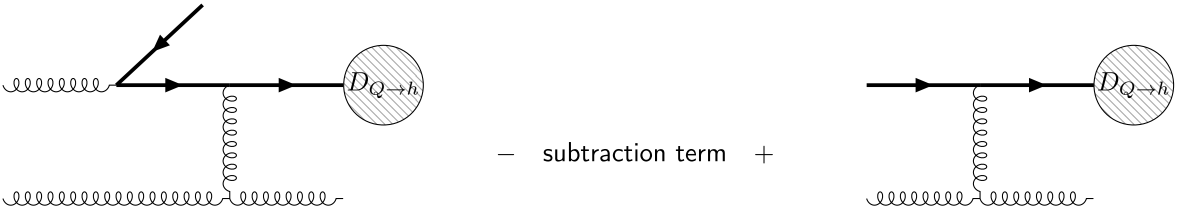
In *fixed flavour number scheme*, valid at small p_{T}, heavy quarks are produced only at the matrix element level

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



GM-VFNS

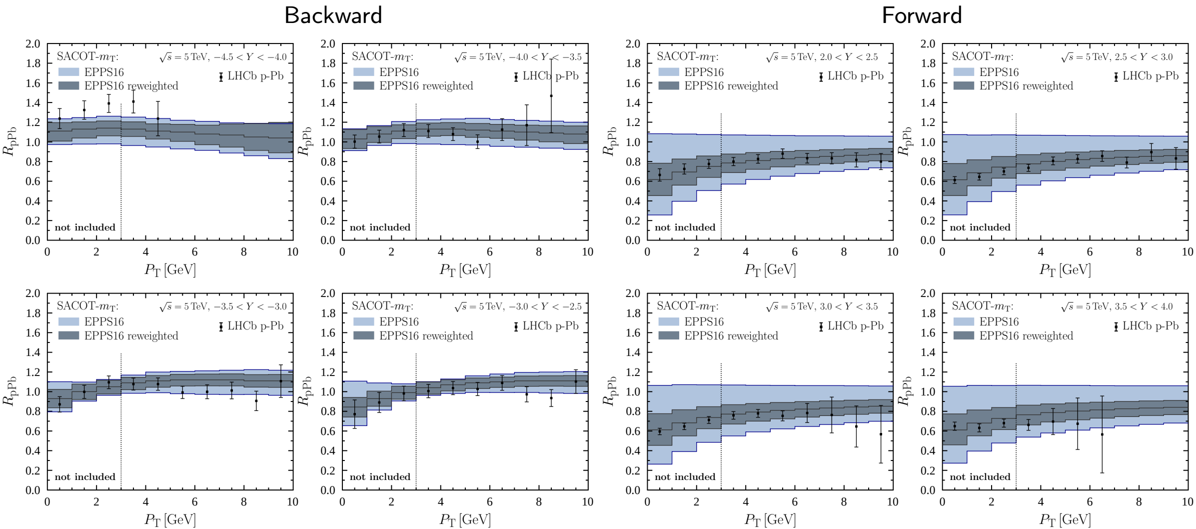
A *general-mass variable flavour number scheme* combines the two by supplementing subtraction terms to prevent double counting of the resummed splittings, valid at all p_{T}

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!

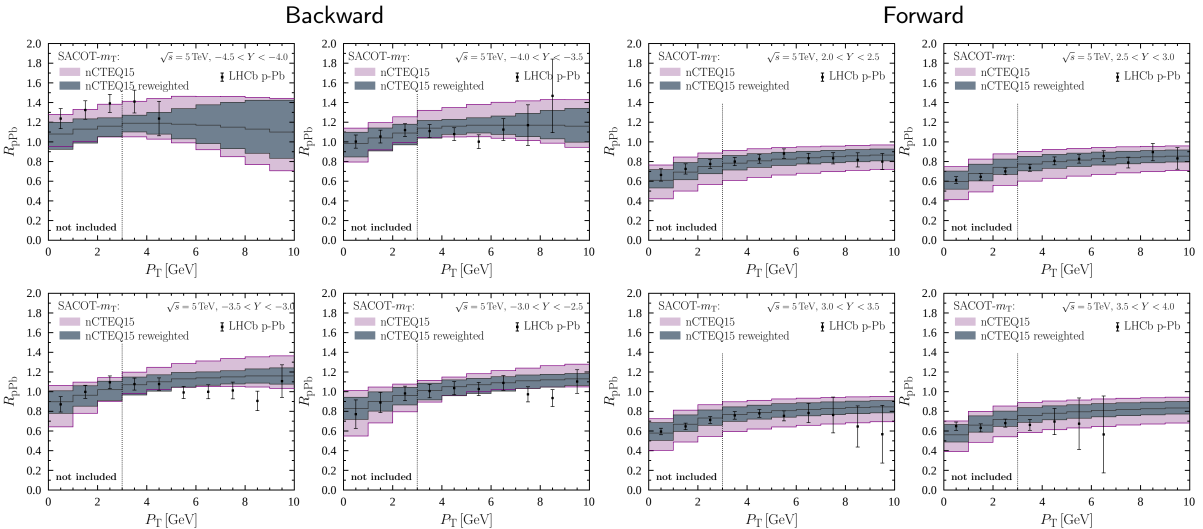
EPPS16 reweighted LHCb D-meson R_{pPb}

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



- Data well reproduced with the reweighted results
- Significant reduction in EPPS16 uncertainties especially in forward bins
- Good agreement with data below cut – no physics beyond collinear factorization needed

nCTEQ15 reweighted LHCb D-meson R_{pPb} [Eskola, Helenius, PP & Paukkunen, JHEP 05 (2020) 037]



- Uncertainties smaller to begin with in the forward direction (less flexible small-x parametrization) while larger in backward – almost identical results
- Data well reproduced