Constraining nPDFs with LHC data – now and in the future

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Section 1

nPDF overview

What the nPDFs are?

Based on the collinear factorization of QCD:

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

The coefficient functions $\mathrm{d}\hat{\sigma}^{ij\to k+X'}$ 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

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

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

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

- Physical models: too numerous to cite here – 'Everybody's Model is Cool'
- Extract from lattice: not an easy task
- Fit to data: parametrize the x- and A-dependence – *the global analysis approach*

Latest nPDF global analyses

	EPPS16	nNNPDF2.0	nCTEQ15WZ	nNNPDF1.0	TuJu19	KSASG20
Order in α_s	NLO	NLO	NLO	NNLO	NNLO	NNLO
lA NC DIS	✓	✓	✓	✓	✓	✓
νA CC DIS	✓	✓			✓	✓
pA DY	✓		✓			
πA DY	✓					
RHIC dAu/pp π	✓		✓			
LHC pPb jets	✓					
LHC pPb W,Z Run 1	✓	✓	✓			
LHC pPb W,Z Run 2		✓	✓			
Q cut in DIS	1.3 GeV	1.87 GeV	2 GeV	1.87 GeV	1.87 GeV	1.3 GeV
Data points	1811	1467	828	451	2336	4525
Free parameters	20	256	19	183	16	9
Error analysis	Hessian	Monte Carlo	Hessian	Monte Carlo	Hessian	Hessian
Error tolerance $\Delta\chi^2$	52	N/A	35	N/A	50	10
Free-proton PDFs	CT14	NNPDF3.1	$\sim$CTEQ6M	NNPDF3.1	own fit	CT18
HQ treatment	GM-VFNS	GM-VFNS	GM-VFNS	GM-VFNS	GM-VFNS	GM-VFNS
Indep. flavours	6	6	5	3	4	3
Year	2016	2020	2020	2019	2019	2020
Reference	EPJC 77, 163	JHEP 09, 183	EPJC 80, 968	EPJC 79, 471	PRD 100, 096015	arXiv:2010.00555

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State of the art

Average u and d quark modifications (in lead)

The average u and d valence and sea modifications

$$R^{A}_{u_V+d_V} = \frac{f^{p/A}_{u_V} + f^{p/A}_{d_V}}{f^{p}_{u_V} + f^{p}_{d_V}} \qquad R^{A}_{\bar{u}+\bar{d}} = \frac{f^{p/A}_{\bar{u}} + f^{p/A}_{\bar{d}}}{f^{p}_{\bar{u}} + f^{p}_{\bar{d}}}$$

are under control

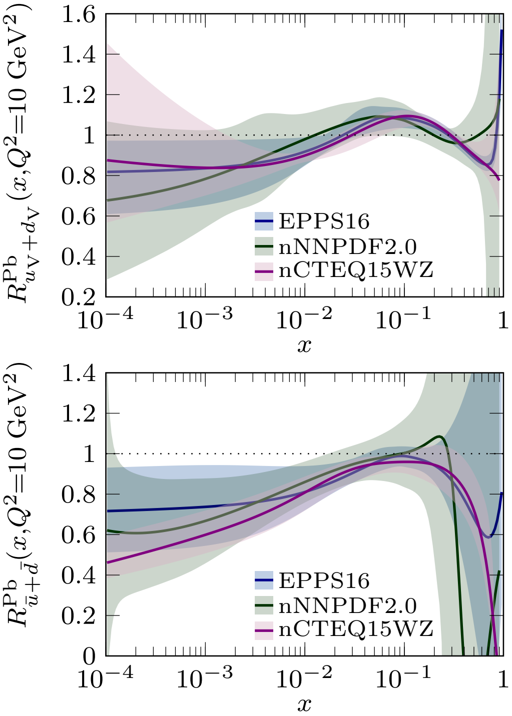
Since most nuclei are close to isoscalar, these are the dominant flavour combinations probed in nuclear DIS and DY

nNNPDF2.0 does not use fixed-target DY data

- → less constraints for valence/sea separation compared to EPPS16 & nCTEQ15WZ

$f^{p/A}_i$ = bound proton PDF

f^{p}_i = free-proton PDF



u versus d quark asymmetries (in lead)

The u/d flavour asymmetries

$$\mathcal{A}^{A}_{u_\mathrm{V}-d_\mathrm{V}} = \frac{f^{p/A}_{u_\mathrm{V}} - f^{p/A}_{d_\mathrm{V}}}{f^{p/A}_{u_\mathrm{V}} + f^{p/A}_{d_\mathrm{V}}} \qquad \mathcal{A}^{A}_{\bar{u}-\bar{d}} = \frac{f^{p/A}_{\bar{u}} - f^{p/A}_{\bar{d}}}{f^{p/A}_{\bar{u}} + f^{p/A}_{\bar{d}}}$$

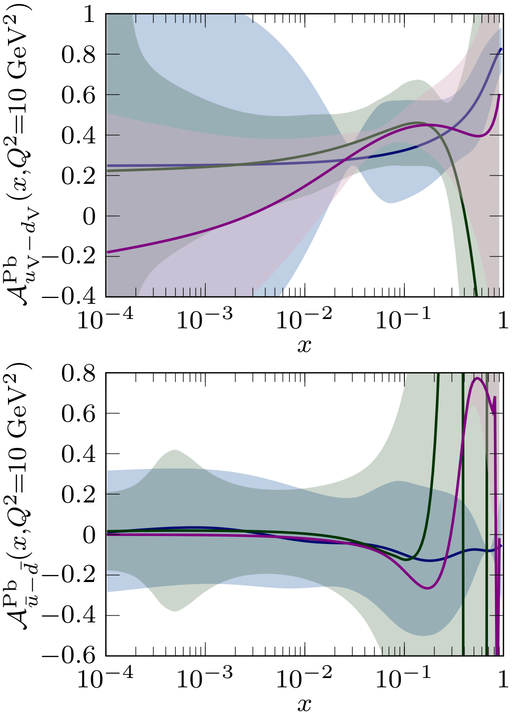
are difficult to constrain

The $u - d$ flavour differences enter the cross sections only through a non-isoscalarity correction

- ➔ factor of $\dfrac{A - 2Z}{A}$ suppression w.r.t. the average
- ➔ most HIC observables insensitive to these

Potential probes:

- νA CC DIS
- πA DY
- W$^\pm$ bosons



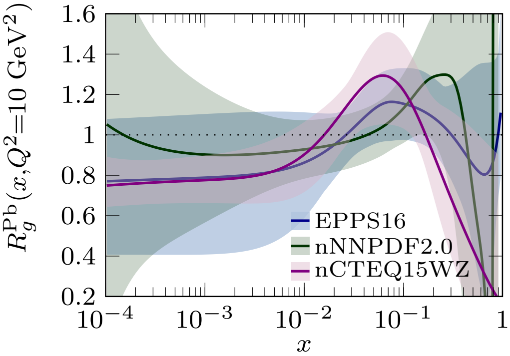
Gluon and strange modifications (in lead)

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

bound-proton PDF free-proton PDF

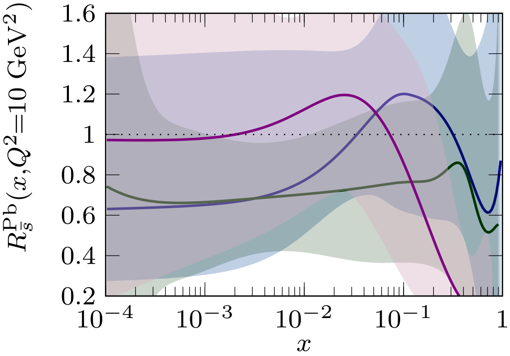
The gluon and strange modifications are poorly constrained in the current nPDF releases

- Better gluon constraints are available from LHC pPb dijets and D-mesons, but these need to be included in the global analyses (in progress)



Present data not able to put strong constraints for the strangeness

- W+charm measured in pp, doable in pPb?



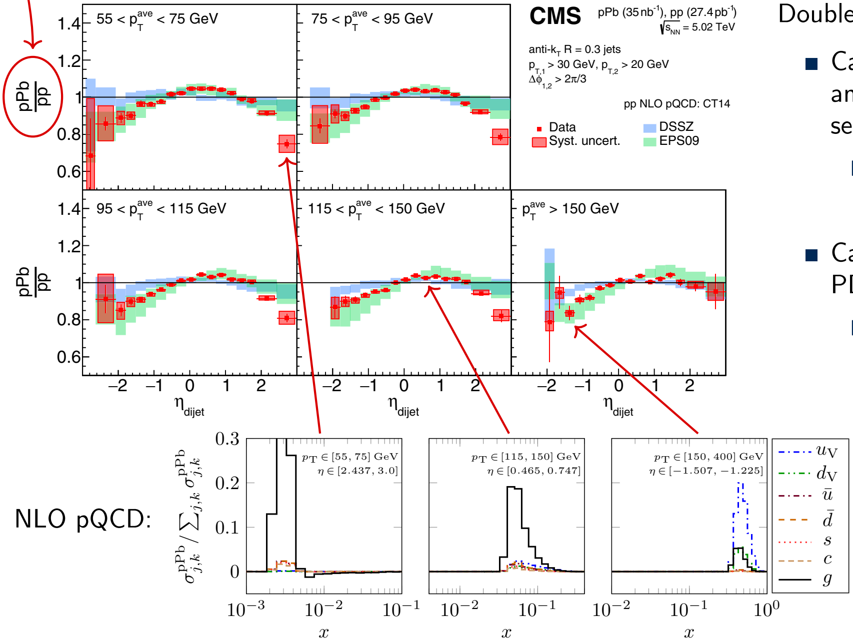
Section 2

Dijets and D^0s at 5.02 TeV – Better gluon constraints

Dijets in pPb at 5.02 TeV

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

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



Double ratio convenient for:

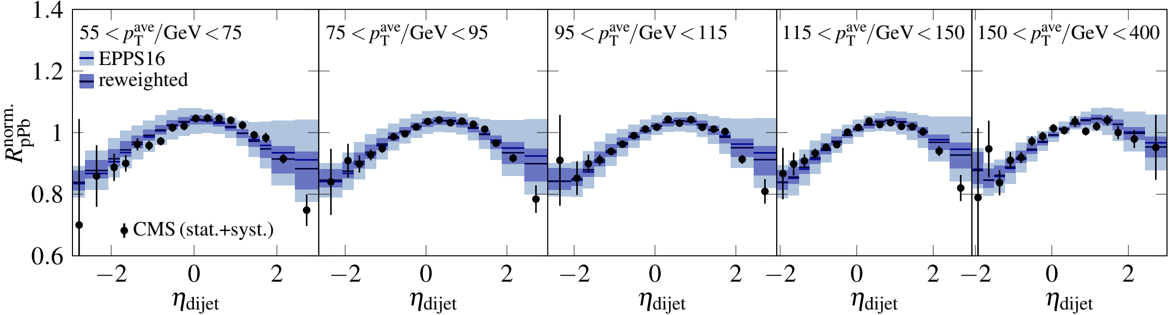
- Cancellation of hadronization and luminosity uncertainties separately for pPb and pp
  - do not expect strong final-state effects
- Cancellation of free-proton PDF uncertainties in pPb/pp
  - direct access to nuclear modifications

NLO pQCD:

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

Dijets in pPb at 5.02 TeV – EPPS16 reweighted

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

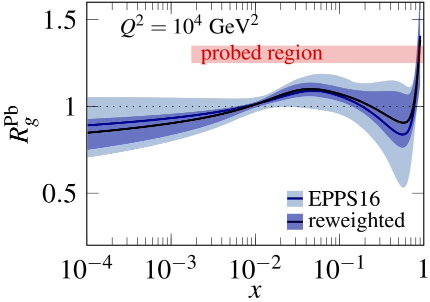


A Hessian PDF reweighting study shows that these data can put stringent constraints on the gluon modifications

- Drastic reduction in EPPS16 gluon uncertainties
- Support for mid-x antishadowing and small-x shadowing
- Probes the onset of shadowing down to $x > 10^{-3}$

Remaining questions:

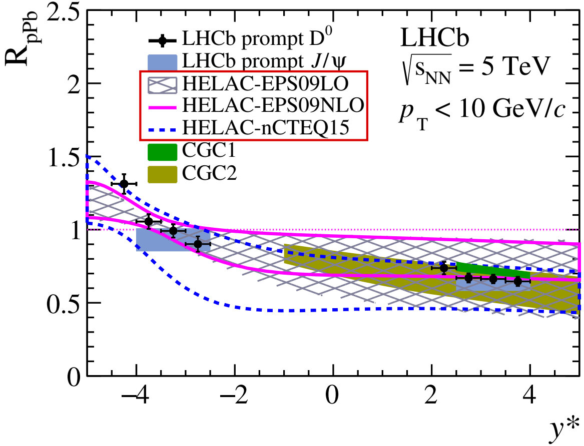
- Is there EMC suppression for gluons?
- What happens at $x < 10^{-3}$?



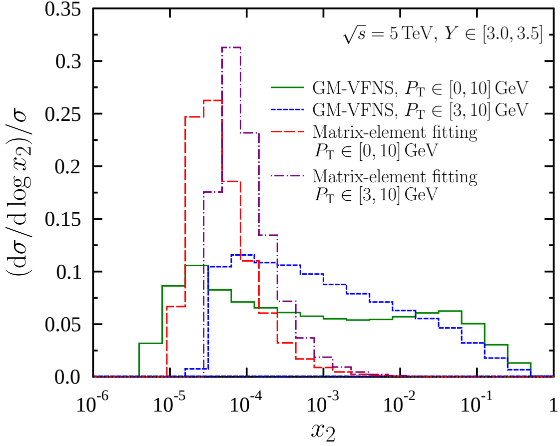
$$R_i^A(x,Q^2) = \underbrace{f_i^{\mathrm{p}/A}}_{\text{bound-proton PDF}}(x,Q^2) \,/\, \underbrace{f_i^{\mathrm{p}}}_{\text{free-proton PDF}}(x,Q^2)$$

D-mesons in pPb at 5.02 TeV – differences in theoretical descriptions

[LHCb Collaboration, JHEP 10 (2017) 090]



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



Data can probe nPDFs down to $x \sim 10^{-5}$, but x sensitivity differs between theoretical approaches:

- The HELAC framework [Lansberg & Shao, EPJ C77 (2017) 1] uses a matrix-element fitting method with $2 \to 2$ kinematics producing a narrow distribution in x (can be used also for quarkonia)
- The SACOT-m_T scheme [Helenius & Paukkunen, JHEP 1805 (2018) 196] of GM-VFNS NLO pQCD gives a much wider x-distribution due to taking into account the gluon-to-HQ fragmentation

D-mesons in pPb at 5.02 TeV – nPDFs reweighted

R_{pPb} mostly insensitive to the differences

- ➔ Reweighting with the two methods give compatible results for R_g^{Pb}

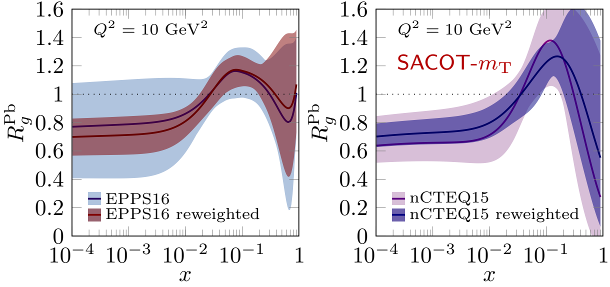
  see the refs. for comparison with POWHEG+PYTHIA, FONLL

- ■ Large reduction in small-x uncertainties, probed down to $x \sim 10^{-5}$
- ■ EPPS16 and nCTEQ15 brought to a closer mutual agreement

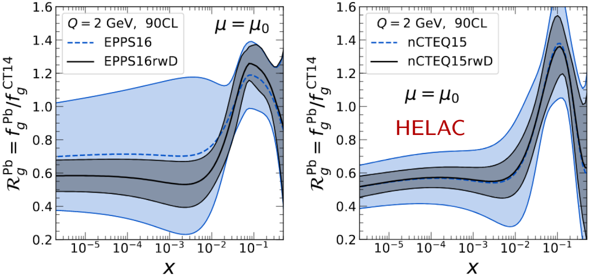
Striking similarity with the results with dijets

- ➔ Supports the validity of collinear factorization in pPb and the universality of nPDFs

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



[Kusina, Lansberg, Schienbein & Shao, PRL 121 (2018) 052004, fig. from arXiv:2012.11462]

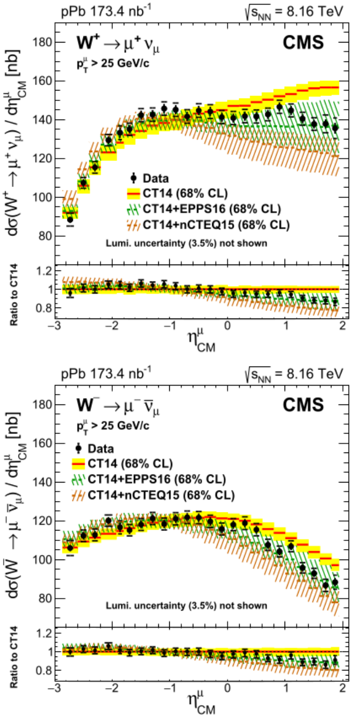


Section 3

W bosons at 8.16 TeV – Flavour separation?

W bosons in pPb at 8.16 TeV

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



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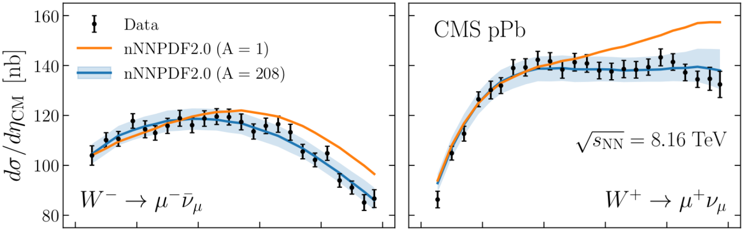
[Abdul Khalek, Ethier, Rojo & van Weelden, JHEP 09 (2020) 183]



Increased statistics compared to the Run 1 5.02 TeV data set

- Included in nNNPDF2.0 and nCTEQ15WZ

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

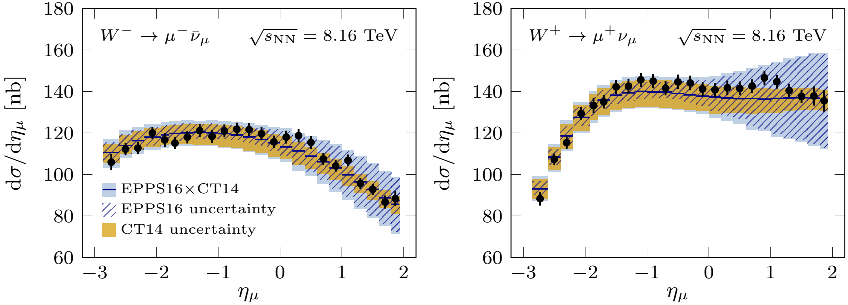
Need to mitigate free-proton PDF uncertainty

Work in progress

Absolute cross sections carry large proton-PDF uncertainty!

Cannot be neglected when fitting the nPDFs

No *obvious* best way to use these data, but we should test different options:



- **Use the absolute cross sections** **as in nNNPDF2.0, nCTEQ15WZ**
  - ➔ susceptible to the proton-PDF uncertainties, need to be accounted in the fit
- **Use self-normalized cross sections**
  - ➔ cancel overall-normalization uncertainty, some proton-PDF uncertainties bound to remain
- **Use forward-to-backward ratios** **as in EPPS16**
  - ➔ more direct cancellation of the proton-PDF uncertainties, lose some data points
- **Use nuclear modification ratios (with 8.0 TeV pp)** **the current plan for EPPS2x**
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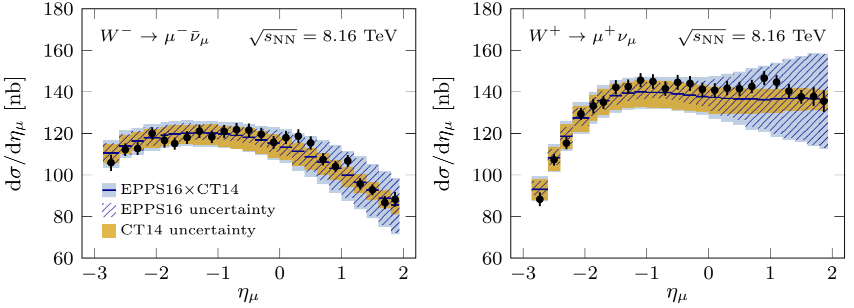

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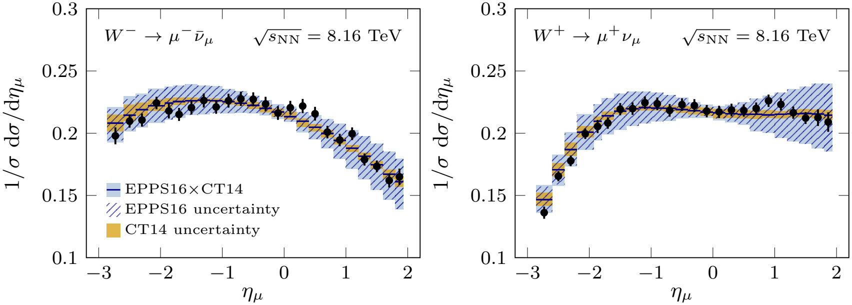

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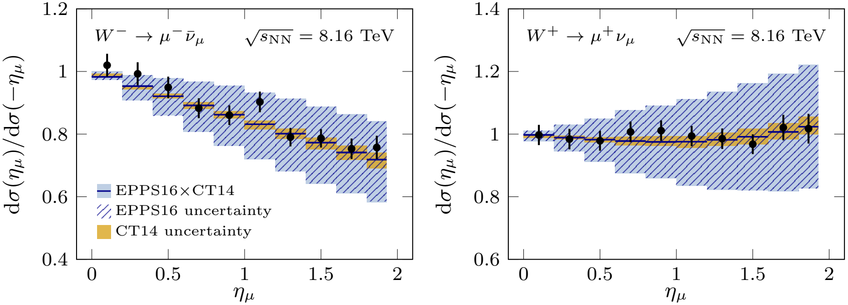

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How to propagate proton-PDF uncertainties into nPDF fit?

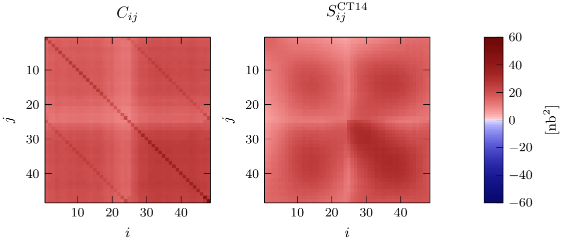
Work in progress

Use a theoretical covariance matrix method

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

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

where the CT14 covariances are calculated with

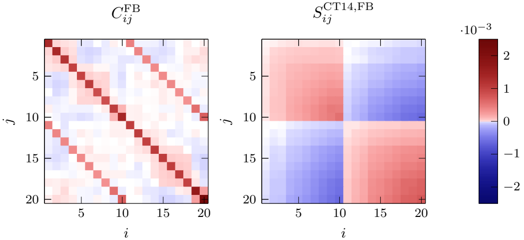


$$S_{ij}^{\mathsf{CT14}} = \sum_k \frac{y_i[S^+_{\mathsf{CT14},k}] - y_i[S^-_{\mathsf{CT14},k}]}{2} \, \frac{y_j[S^+_{\mathsf{CT14},k}] - y_j[S^-_{\mathsf{CT14},k}]}{2}$$

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

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

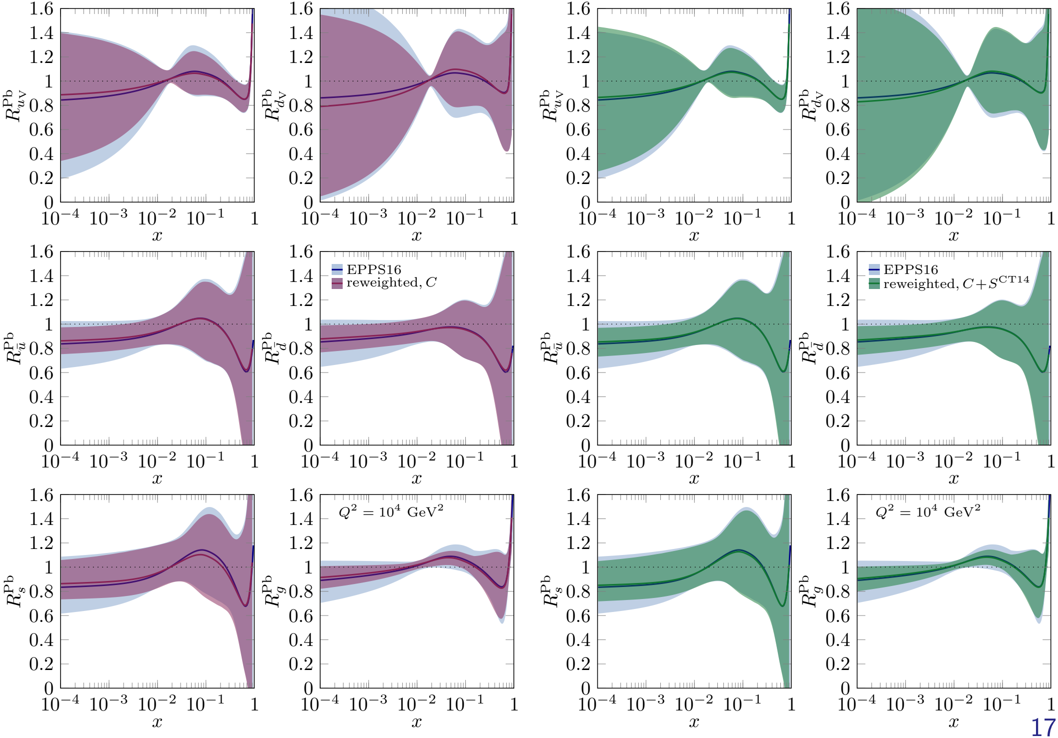
where J is the Jacobian of the transformation



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

Reweighting results with absolute cross sections

Work in progress



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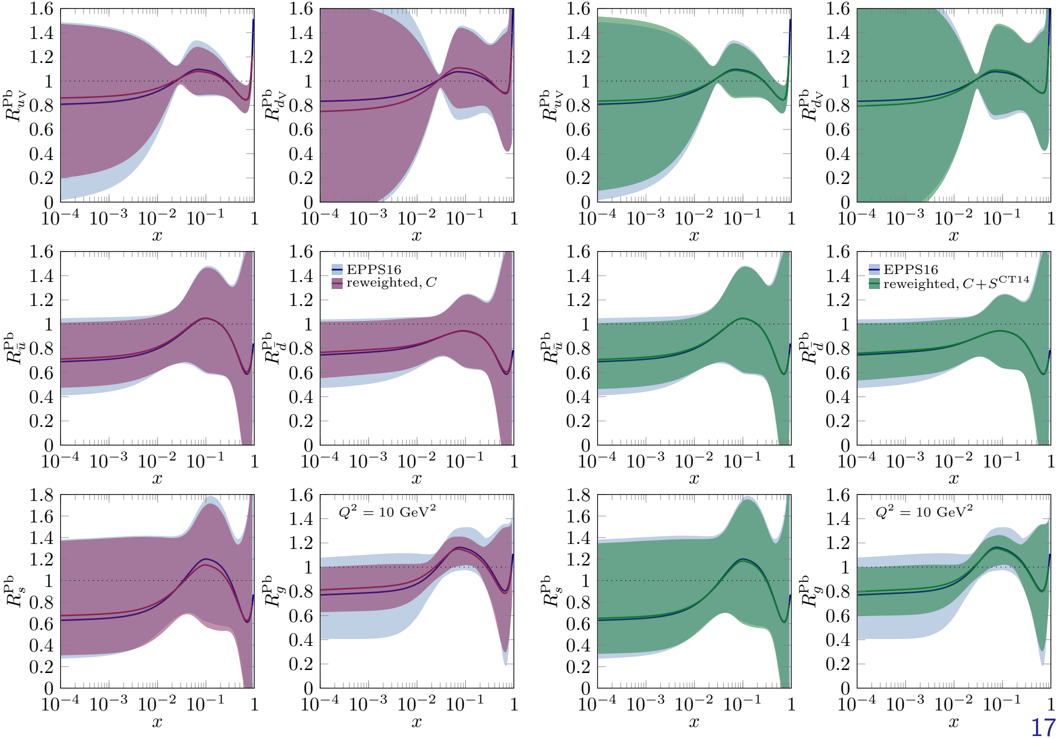

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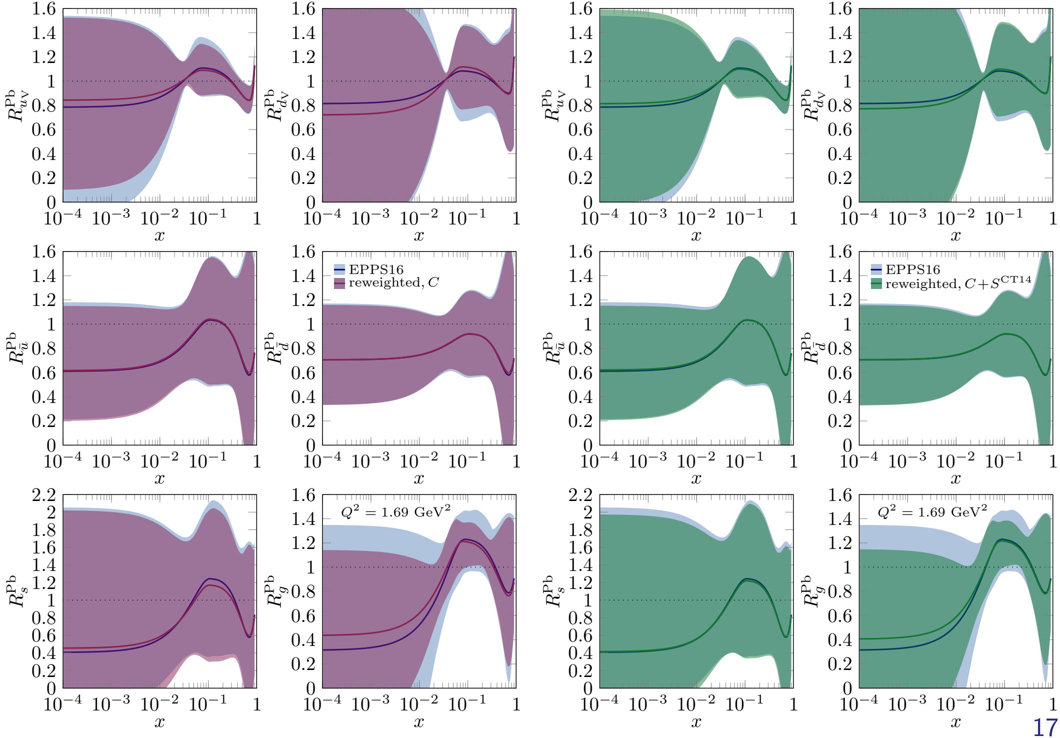
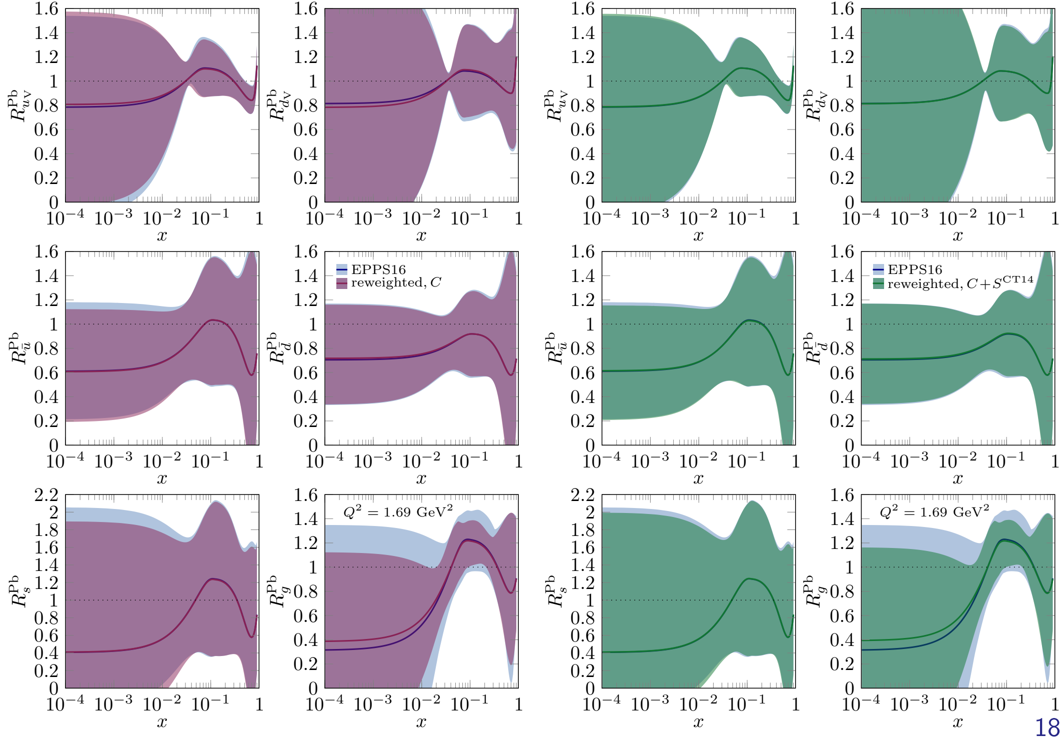


Reweighting results with FB ratios

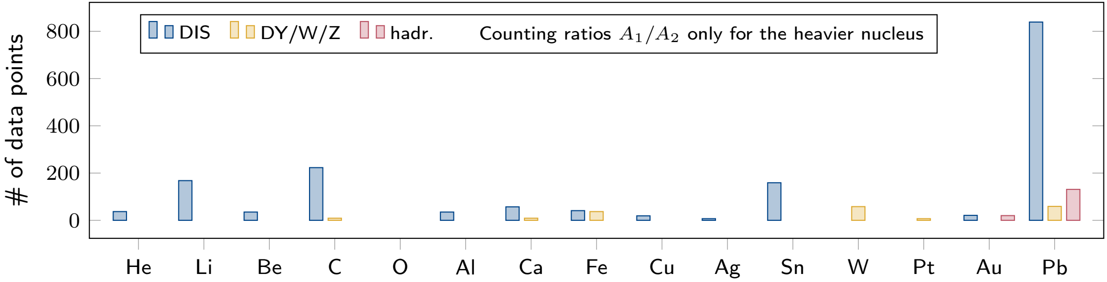
Work in progress



Section 4

Future opportunities with LHC – Lighter ions

Data availability w.r.t. A



EPPS16 + LHC pPb dijets, D-mesons & 8.16 TeV Ws + JLab CLAS NC DIS

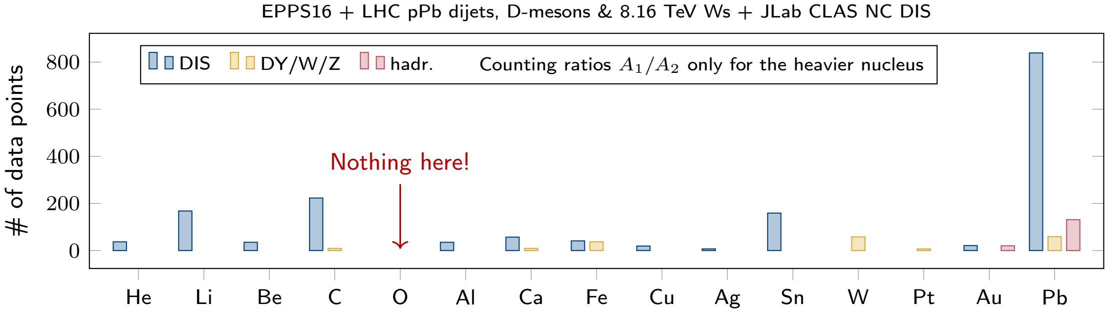
$\sim 50\%$ of the data points are for Pb!

- ☺ Good coverage of DIS measurements for different A
- 😐 DY data more scarce, but OK A coverage
- ☹ Hadronic observables available only for heavy nuclei!

Light-ion runs at LHC could:

- Complement other light-nuclei DY data with W and Z production (strangeness!)
- Give first direct constraints (e.g. dijets, D-mesons) on light-nuclei gluon distributions!

Data availability w.r.t. A



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Average u and d quark modifications (in oxygen)

The average u and d valence and sea modifications

$$R^{A}_{u_\mathrm{V}+d_\mathrm{V}} = \frac{f^{p/A}_{u_\mathrm{V}} + f^{p/A}_{d_\mathrm{V}}}{f^{p}_{u_\mathrm{V}} + f^{p}_{d_\mathrm{V}}} \qquad R^{A}_{\bar{u}+\bar{d}} = \frac{f^{p/A}_{\bar{u}} + f^{p/A}_{\bar{d}}}{f^{p}_{\bar{u}} + f^{p}_{\bar{d}}}$$

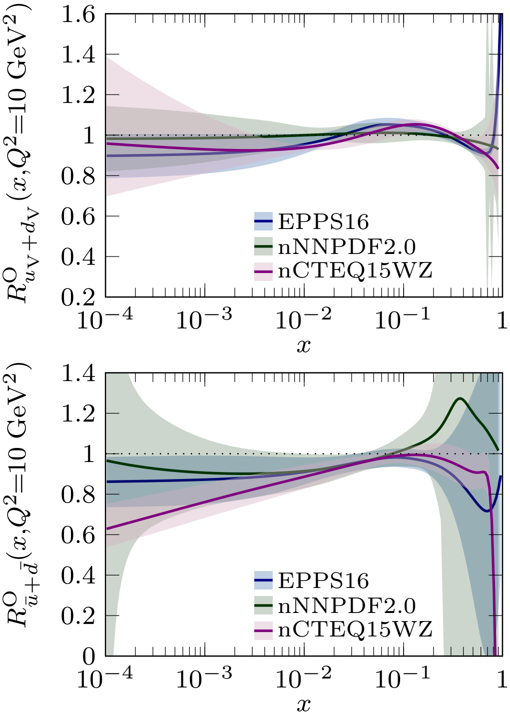
are under control (from interpolation)

Oxygen fully isoscalar

- → No contribution from flavour asymmetry!
- From nPDF point of view, oxygen is “simpler” than lead

nNNPDF2.0 differs (again) from EPPS16 and nCTEQ15WZ due to not having fixed-target DY data

- Data from E772 indicate that there should be antishadowing for valence, but not for sea quarks

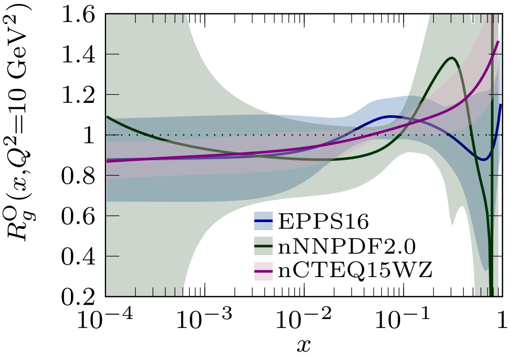


Gluon and strange modifications (in oxygen)

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

No agreement for the shape of gluon modifications!

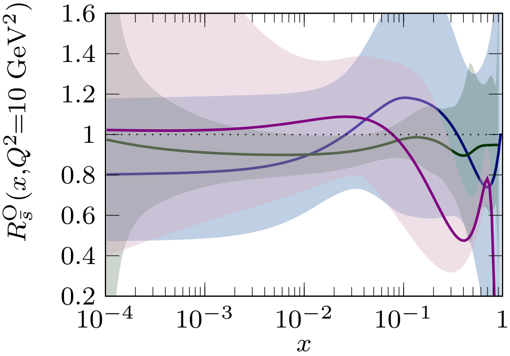
- ➔ Can cause significant uncertainties e.g. for jet R_{OO}
- ! No direct data constraints available
- ➔ We could expect major improvement from a LHC pO run



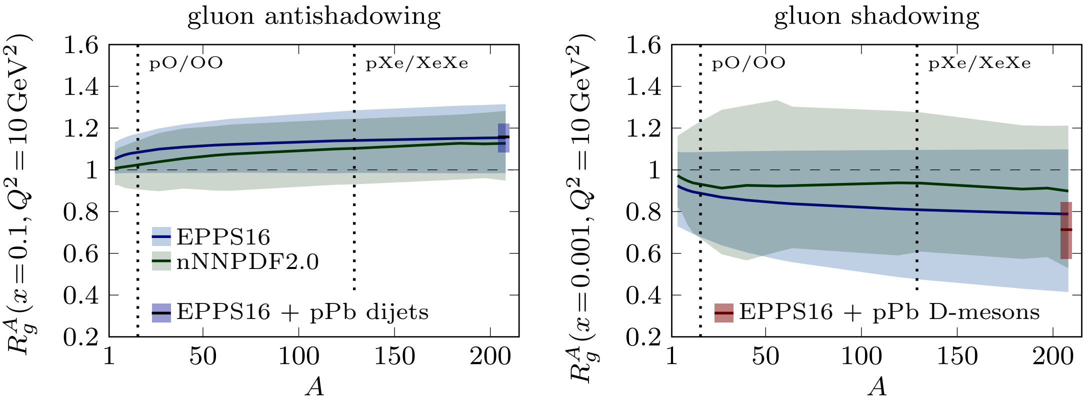
Large uncertainties also for the strange quark

- nNNPDF2.0 has smaller uncertainties here likely due to including NuTeV νFe CC DIS data

  (interpolation, again)
- Measuring EW bosons in pO/OO might be able to test these



A-dependence of gluon modifications



Direct gluon constraints available only for heavy nuclei (most constraining: pPb dijets & D-mesons)

- ➔ Gluons and small-x quarks poorly constrained for lighter nuclei
- ➔ Significant parametrization dependence

How confidently can we interpolate the light-nuclei gluons from measurements at large A?

- ■ SMOG@LHCb can help for the large x
- ➔ Need for lighter-ion pA runs!

A case study: Dijet production in pO at 9.9 TeV

Similar setup as in the CMS 5.02 TeV pPb measurement

Total integrated pO cross section of $\sim 80\ \mu\mathrm{b}$

- Grows with larger $\sqrt{s_{\mathrm{NN}}}$, decreases with smaller A
- Compare with $\sim 330\ \mu\mathrm{b}$ in pPb at 5.02 TeV
- Sufficient to give reasonable statistics even at relatively low luminosities

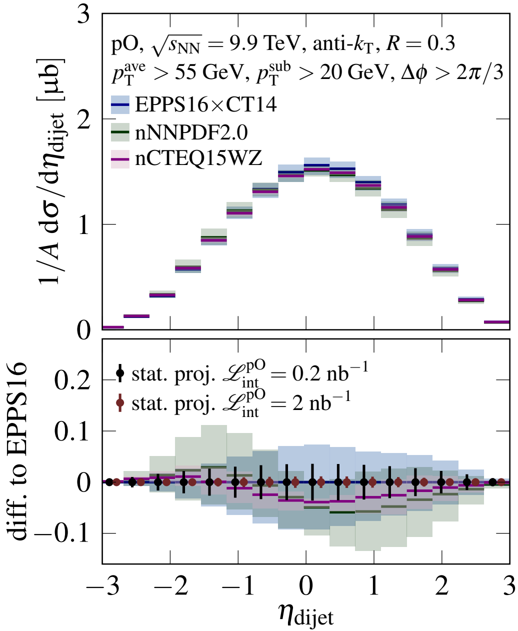
Here only single-differential

- Going multi-differential would improve locality in x and Q^2 (requires more luminosity)

Question: Systematic uncertainties?

N.B. For each nPDF, I am using the corresponding baseline free-proton PDF

→ Calculations with nCTEQ15WZ do not include free-proton PDF uncertainties



*not corrected for hadronization effects
*not corrected for efficiency

Dijet production in pO at 9.9 TeV – free-proton uncertainties

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

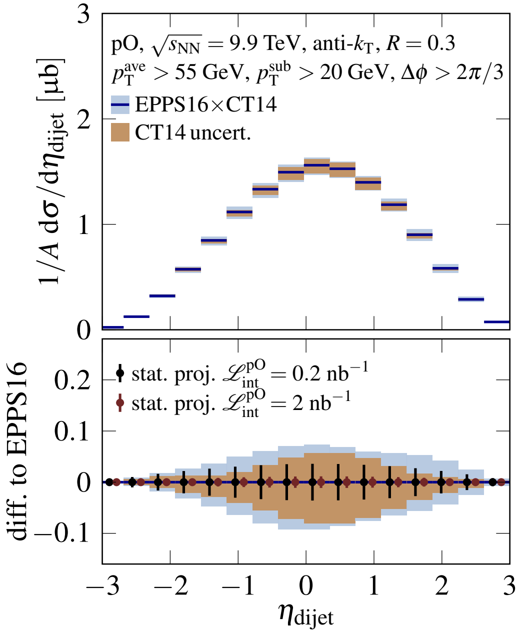
- Difficult to disentangle nuclear modifications from the free-proton d.o.f.s

N.B. In the EPPS framework, free-proton uncertainties enter both from the

- incoming proton PDFs: f_i^p
- incoming bound-nucleon PDFs: $f_i^{p/A} = R_i^A f_i^p$

Possible ways to mitigate the problem:

- Take forward-to-backward ratio (R_{FB})
- Take nuclear modification ratio ($R_{\mathrm{pPb}}^{(\mathrm{norm.})}$)
  - requires a pp reference measurement at the same collision energy



*not corrected for hadronization effects
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Dijet R_{FB} in pO at 9.9 TeV

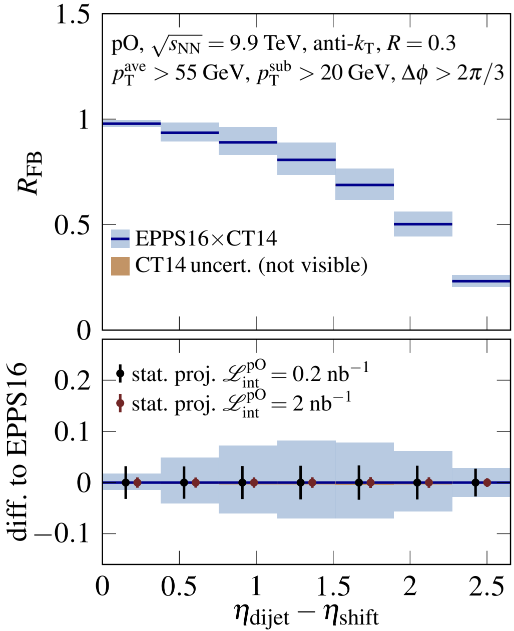
Excellent cancellation of free-proton PDFs

Luminosity (and hadronization) uncertainties also (expected to) cancel!

Already $\sim 1\ \mathrm{nb}^{-1}$ can be expected to be enough to put new constraints on nPDFs

Problem: access only to nPDF small v.s. large x correlations – mixing different effects

- Forward shadowing and backward antishadowing pull to the same direction
- Even rather different nuclear modifications can yield similar shape for R_{FB}



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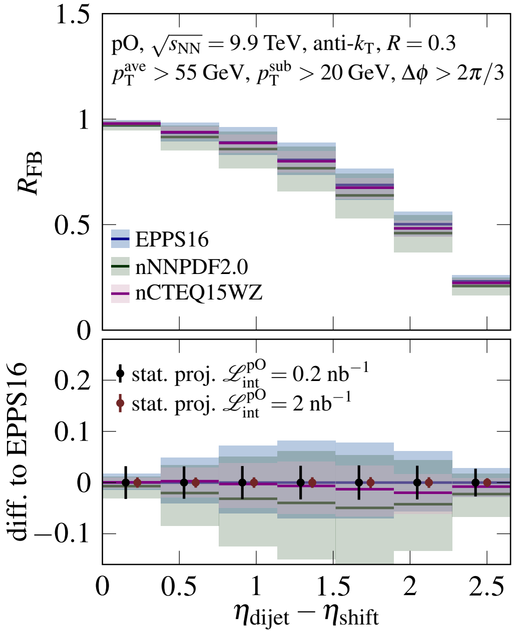


Dijet $R_{\mathrm{pO}}^{\mathrm{norm.}}$ in pO at 9.9 TeV

Excellent cancellation of free-proton PDFs

- ➔ Direct access to nuclear modifications

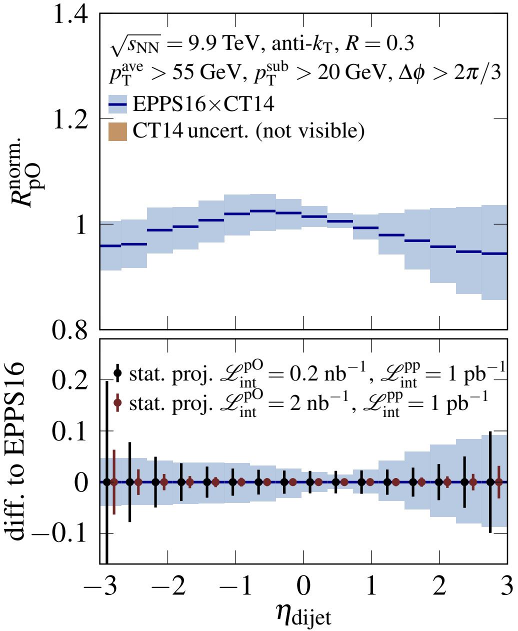
Luminosity (and hadronization) uncertainties also (expected to) cancel!

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

- ➔ Can resolve different nPDF parametrisations!

Problem: We might not expect to have the pp reference at 9.9 TeV

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



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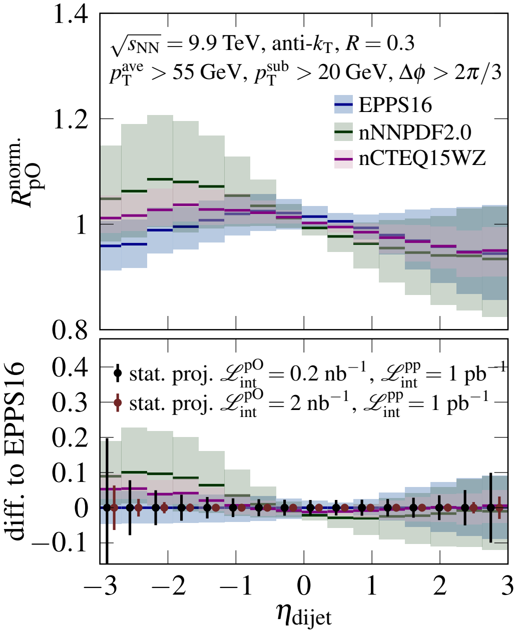


Thank you!

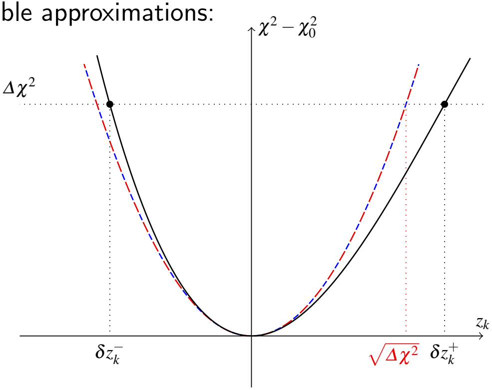
PDF reweighting: different approximations

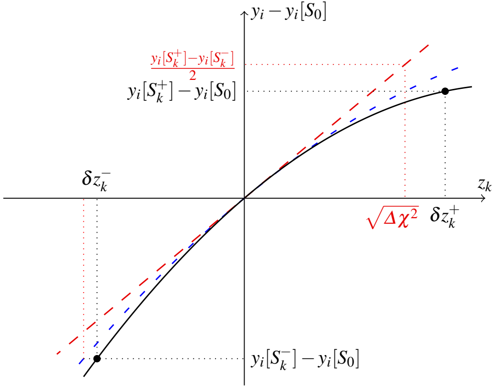
[Eskola, PP & Paukkunen, Eur.Phys.J.C 79 (2019) 511]

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

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

Possible approximations:





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

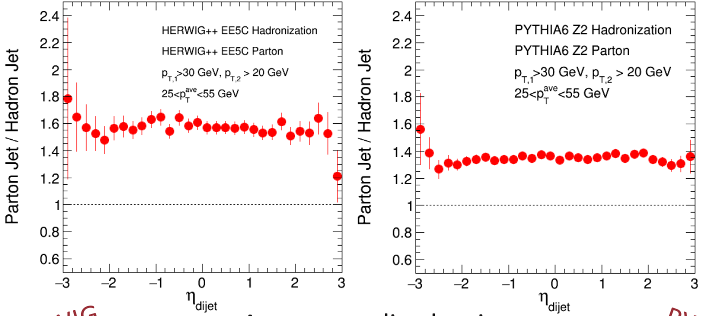
Cancellation of hadronization effects

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

HERWIG

Cross-section ratios

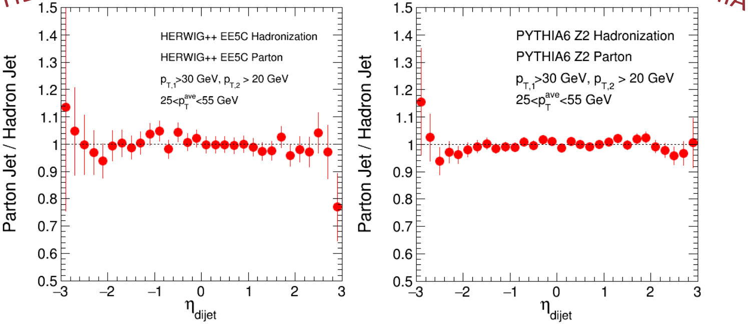
PYTHIA



HERWIG

Area normalized ratios

PYTHIA



Hadronization uncertainty

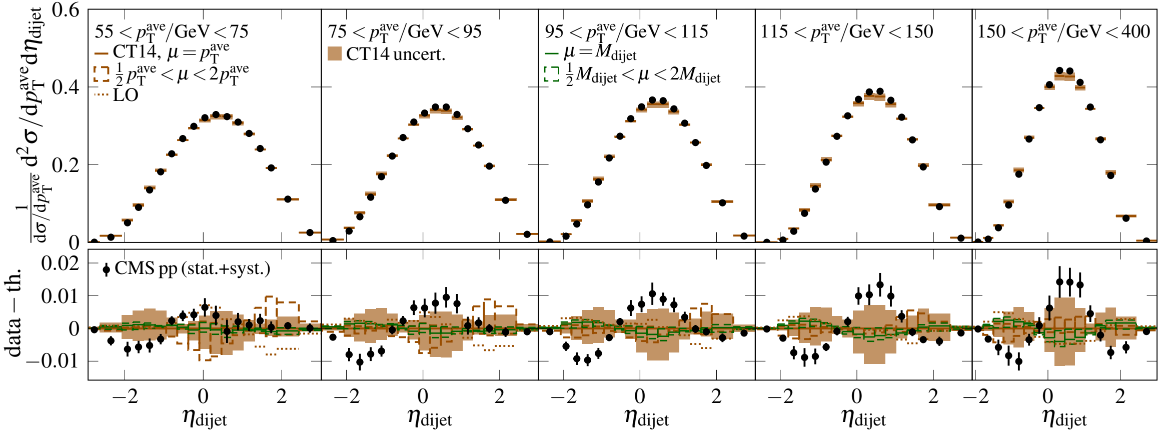
Parton jets have higher cross section for R = 0.3 jets with same kinematic selections compared to hadron jets

Parton jets are harder fragmenting

After self normalization effect of hadronization is negligible

CMS dijets at **pp**

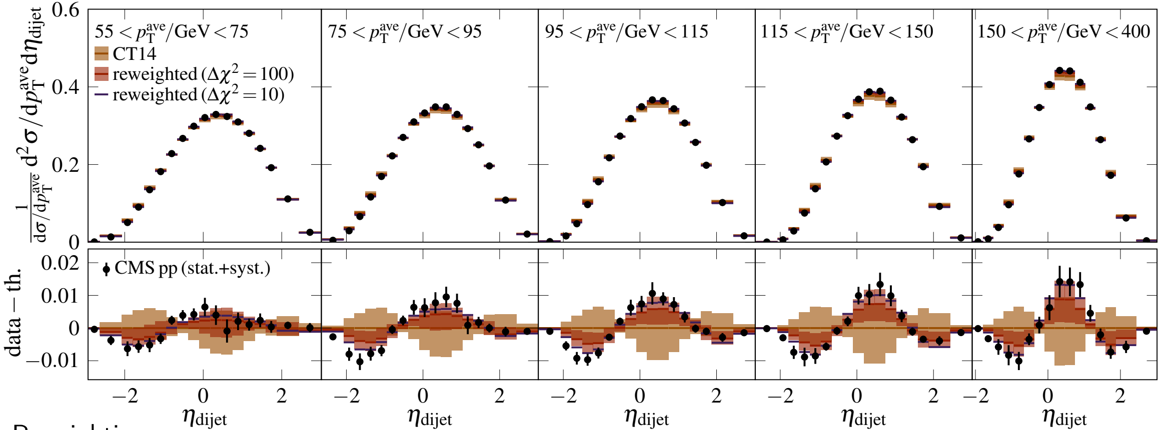
[Eskola, PP & Paukkunen, Eur.Phys.J.C 79 (2019) 511]



- 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]

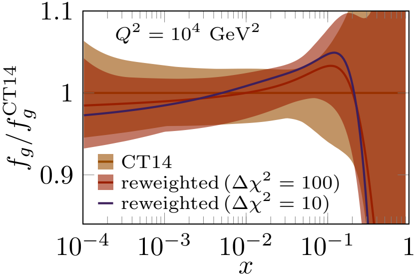


Reweighting:

- 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?)

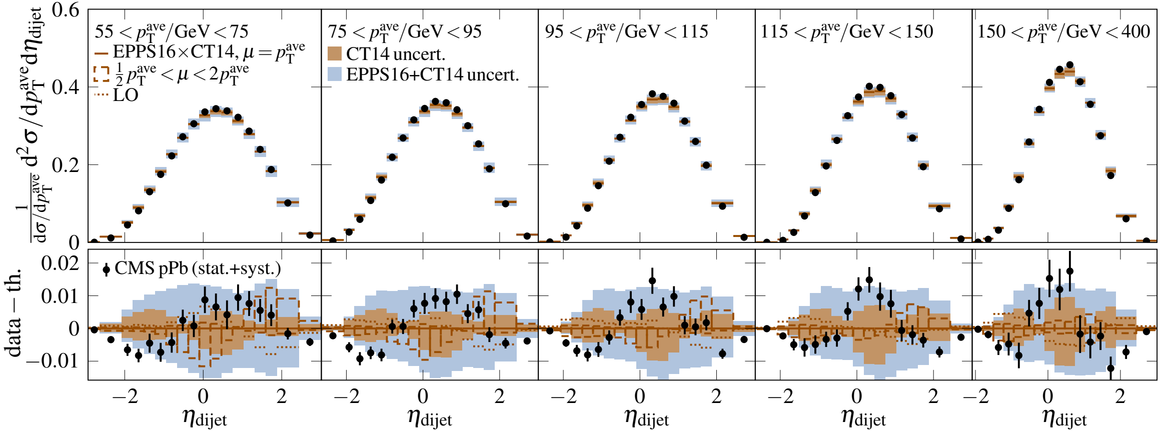
Significant gluon modifications needed especially at large x

- also valence quarks get modified



CMS dijets at **pPb**

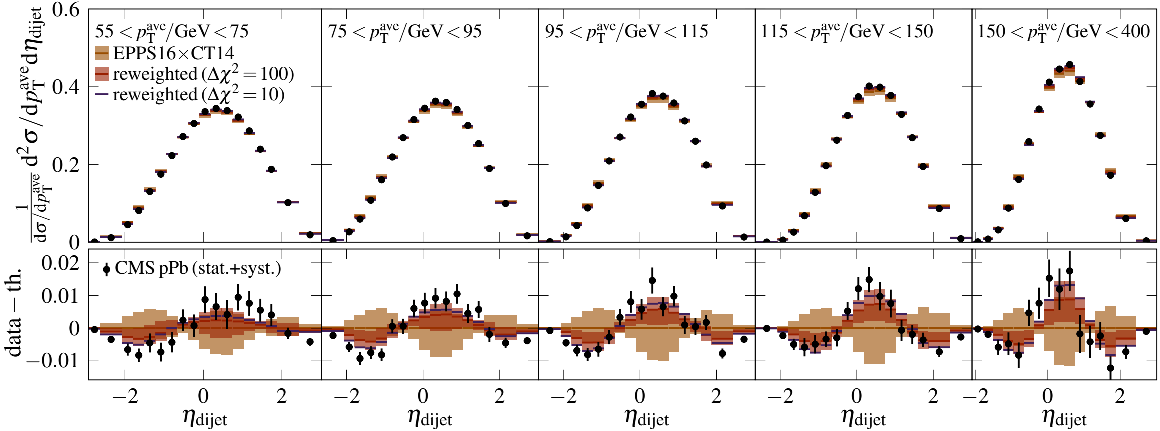
[Eskola, PP & Paukkunen, Eur.Phys.J.C 79 (2019) 511]



- 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

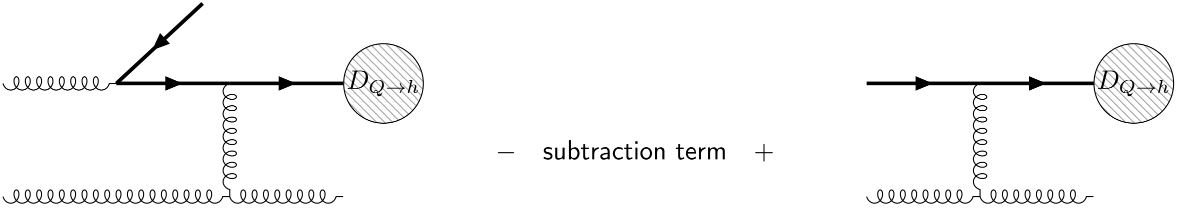
In *fixed flavour number scheme*, valid at small p_{T}, heavy quarks are produced only at the matrix element level

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

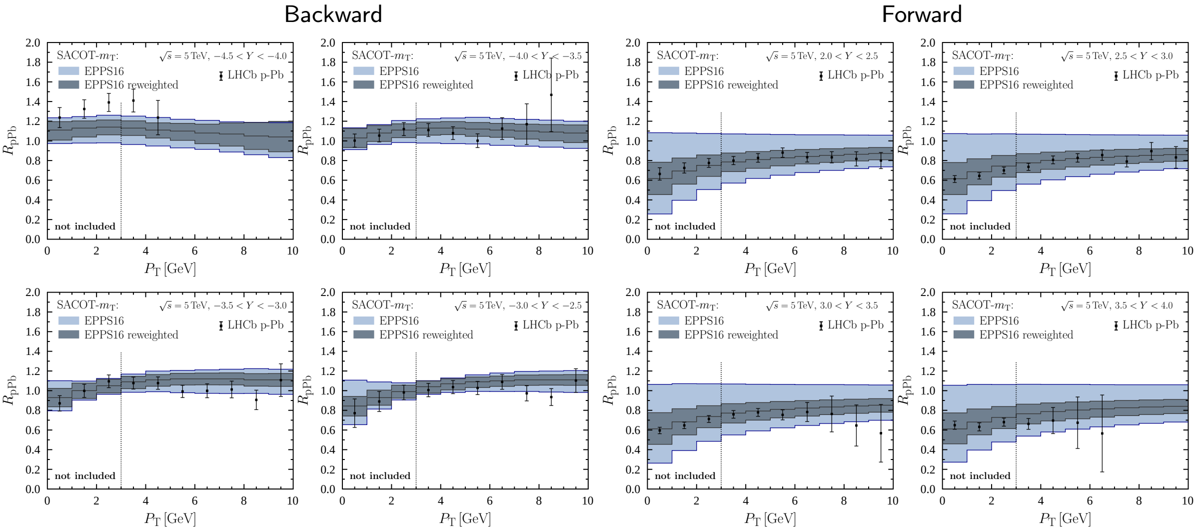
A *general-mass variable flavour number scheme* combines the two by supplementing subtraction terms to prevent double counting of the resummed splittings, valid at all p_{T}

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!

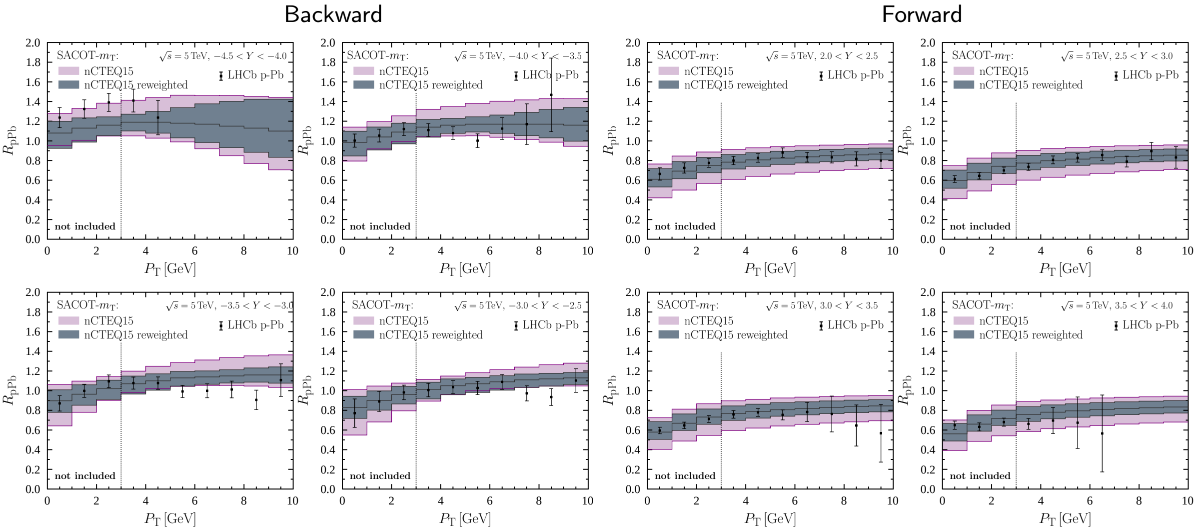
EPPS16 reweighted LHCb D-meson R_{pPb}

[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

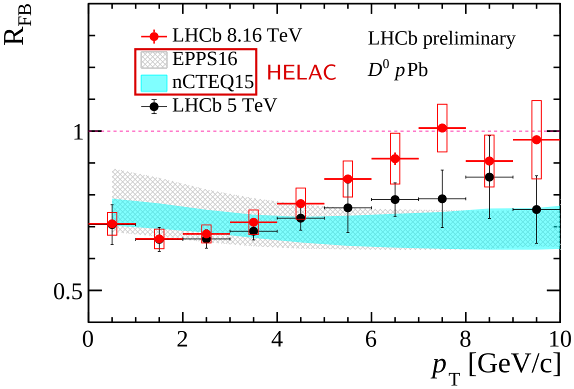
nCTEQ15 reweighted LHCb D-meson R_{pPb} [Eskola, Helenius, PP & Paukkunen, JHEP 05 (2020) 037]



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

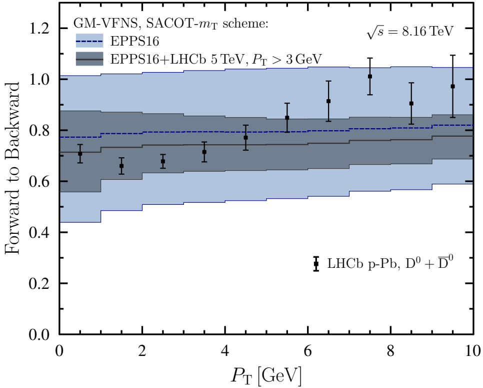
D-mesons at 8.16 TeV – do we have tension?

[LHCb Collaboration, LHCb-CONF-2019-004]



➔

[Eskola, Helenius, PP & Paukkunen, unpublished]



QM2019 LHCb summary talk:

~~*“Tension between data and nPDFs predictions. Additional effects required.”*~~

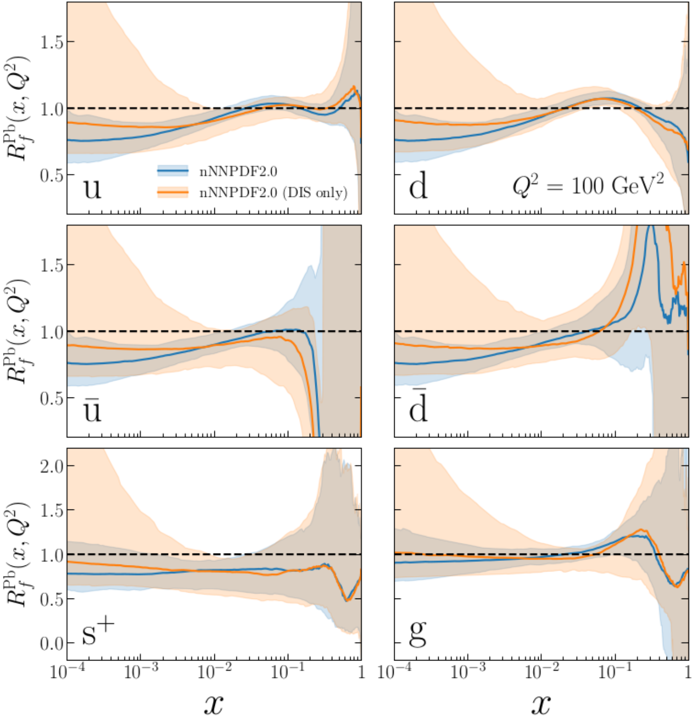
➔ *Theoretical description matters, HELAC predicts much smaller nPDF uncertainties for R_{FB} than SACOT-m_T!*

The slope of the 8.16 TeV data still differs from that in nPDF predictions and in 5.02 TeV data

➔ How can we explain the difference?

W/Z bosons in pPb at 5.02 TeV and 8.16 TeV – impact in nNNPDF2.0

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



Flexible neural-network parametrization (256 free parameters)

Includes CMS and ATLAS W/Z data

Compared to DIS-only fit:

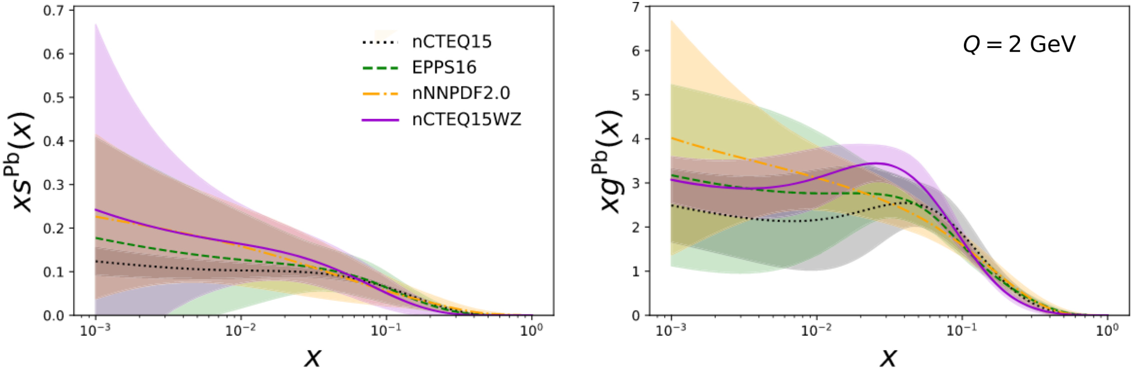
- Preference for EMC effect both in u and d
- Enhanced shadowing for all quarks
- Some preference for gluon shadowing & antishadowing

Here:

$$R_f^A(x, Q^2) = \frac{Z f_f^{\mathrm{p}/A}(x,Q^2) + (A-Z) f_f^{\mathrm{n}/A}(x,Q^2)}{Z f_f^{\mathrm{p}}(x,Q^2) + (A-Z) f_f^{\mathrm{n}}(x,Q^2)}$$

W/Z bosons in pPb at 5.02 TeV and 8.16 TeV – impact in nCTEQ15WZ

[Kusina *et al.*, Eur.Phys.J.C 80 (2020) 968]

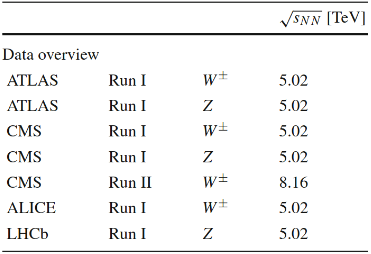


Includes also ALICE & LHCb W/Z data

→ Most extensive EW-boson data set to date

Compared to nCTEQ15:

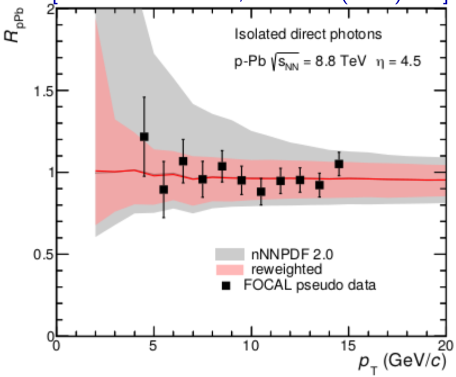
- Additional freedom for s needed to describe the data
  - much larger uncertainty
- Less gluon shadowing



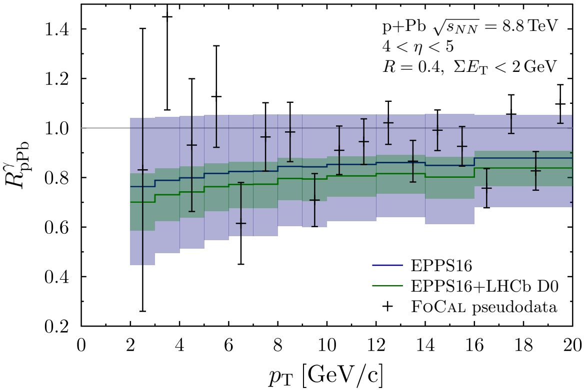
			$\sqrt{s_{NN}}$ [TeV]
Data overview			
ATLAS	Run I	$W^{\pm}$	5.02
ATLAS	Run I	Z	5.02
CMS	Run I	$W^{\pm}$	5.02
CMS	Run I	Z	5.02
CMS	Run II	$W^{\pm}$	8.16
ALICE	Run I	$W^{\pm}$	5.02
LHCb	Run I	Z	5.02

Future prospects: Forward photons with FoCal

[Abdul Khalek *et al.*, JHEP 09 (2020) 183]



[collab. with Eskola, Helenius & Paukkunen]



Isolated photons at forward rapidities are a good probe of the nuclear small-x gluons

- Isolation cut reduces the fragmentation component
  - ➔ enhanced small-x sensitivity [Helenius *et al.*, JHEP 09 (2014) 138]
- Test for the possible onset of non-linear QCD effects
- Test for the factorization & process independence (universality) of nPDFs

Constraints from D^0s already more stringent than what we can expect from FoCal

EW bosons in pO and OO?

EW probes are more luminosity hungry

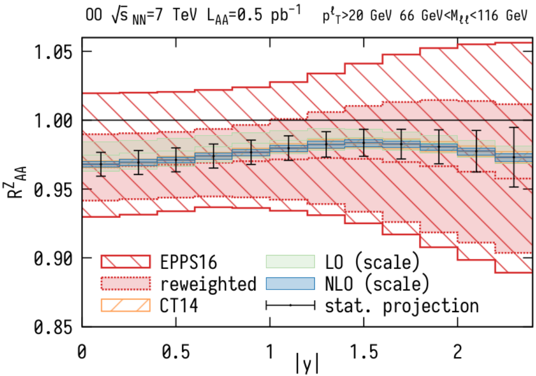
- We would need $\sim 2\ \mathrm{pb}^{-1}$ for pO to get the same statistics as in the 8.16 TeV pPb run
- Larger cross section in OO ➔ less luminosity needed
    - Accurate determination of the luminosity uncertainty important

Large part of the uncertainties in these observables come from the poorly known gluons

- These we can constrain already with the hadronic observables in pO

  (EW bosons still an important check
  for factorization / nPDF universality)

[Huss *et al.*, arXiv:2007.13754]



Since u/d flavour asymmetry does not contribute (isoscalarity), measuring W/Z bosons in pO/OO could provide unique constraints for strangeness nuclear modifications

➔ Requires a further study

Limits of applicability – large and small x

Large x subject to target-mass and higher-twist corrections

- Do these have sizable effect? (Yes)
- Can we still get a good fit with traditional nPDFs? (Yes)
- Any need for isospin-dependent modifications? (No)

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

  [Segarra *et al.*, arXiv:2012.11566]

Expect gluon density to saturate at small x

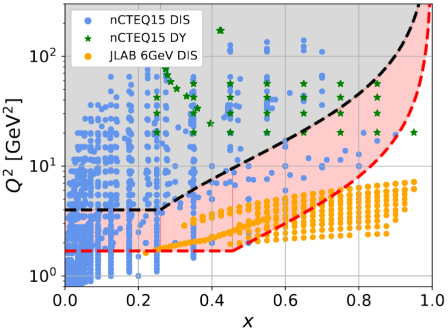
- When does the simple DGLAP picture break down?
- What experimental signatures do we need?

Small-x corrections already in the linear phase (BFKL)

- Do these become important before saturation kicks in?

➔ Many opportunities for the EIC & LHeC

[Segarra *et al.*, arXiv:2012.11566]



[Bonvini & Marzani, JHEP 06 (2018) 145]