IS2021

What have we learned and what do we still need to learn about nPDF?

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XUNTA DE GALICIA

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...

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

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

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

For a nucleus A, one can decompose

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

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 [see M. Constantinou, Thu 15:30]
- Fit to data: parametrize the x- and A-dependence – the global analysis approach This talk!

... and what they are *not!*

Not the complete picture of nuclear structure!

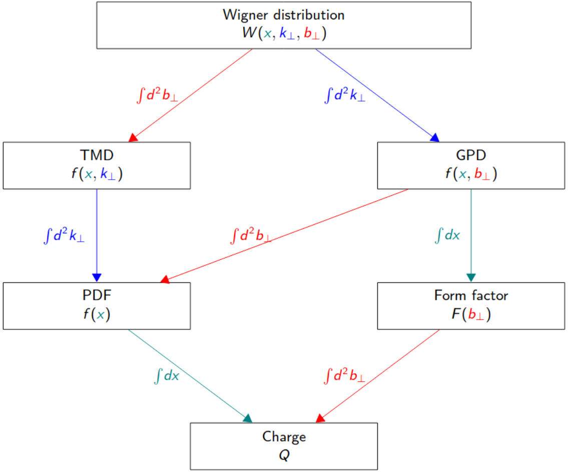
Can be generalized to include

- Transverse-momentum dependence (TMD)
  - connection to CGC
    [see P. Taels, Sun 18:55]
- Impact-parameter dependence (GPD)
  - connection to exclusive processes
    [see A. Soto-Ontoso, Fri 17:20]
- Double-parton correlations (DPD)
  - connection to multi-parton interactions
    [see J. Gaunt, Wed 18:05]
- Their polarization-dependent counterparts

... etc.

This talk will only discuss the unpolarized, collinearly factorized nPDFs

[fig. from R. Boussarie, IS2019]

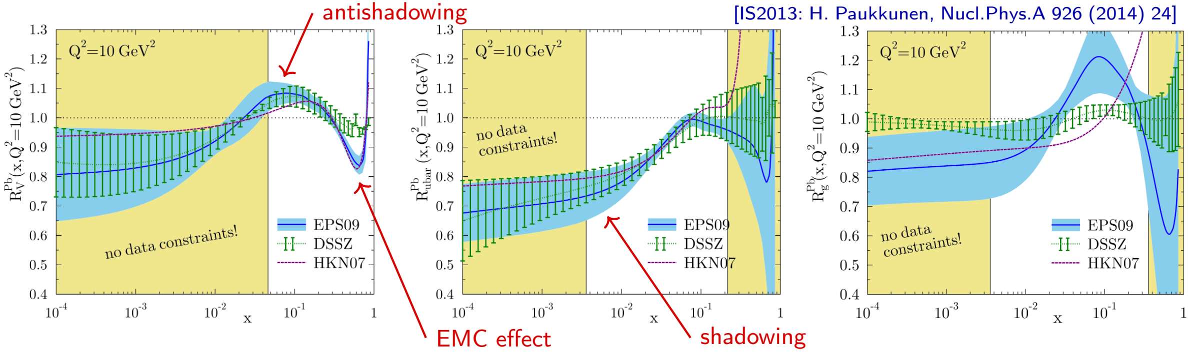


Section 1

What have we learned so far?

Pre-LHC analyses

[IS2013: H. Paukkunen, Nucl.Phys.A 926 (2014) 24]



Fixed-target DIS and DY data had established the basic picture of:

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

bound-proton PDF — free-proton PDF

- EMC suppression and antishadowing for valence quarks
- Small-x shadowing and no antishadowing for sea quarks
- ! Not possible to parametrize all flavours independently → Simplifying assumptions

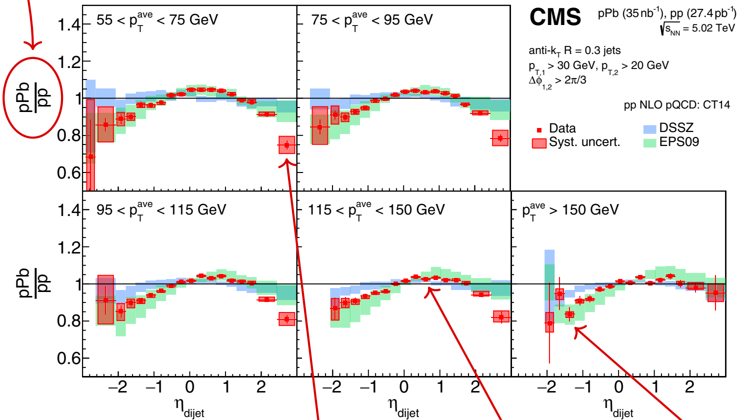
For gluons the situation was even more difficult:

- Direct constraints only from RHIC inclusive pion production
- Could be described also with nuclear effects in fragmentation functions (nFF → DSSZ)

Enter the LHC: Dijets at 5.02 TeV

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

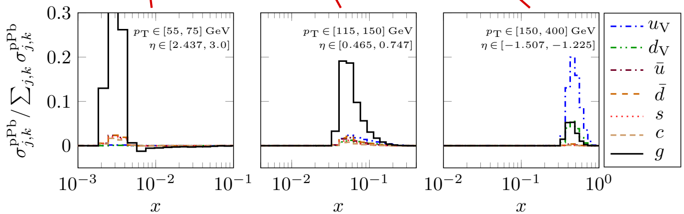
[CMS Collaboration, Phys.Rev.Lett. 121 (2018) 062002]



Double ratio convenient for:

- Cancellation of hadronization and luminosity uncertainties separately for pPb and pp
  - do not expect strong final-state effects
  - should resolve the nPDF vs. nFF debate
- Cancellation of free-proton PDF uncertainties in pPb/pp

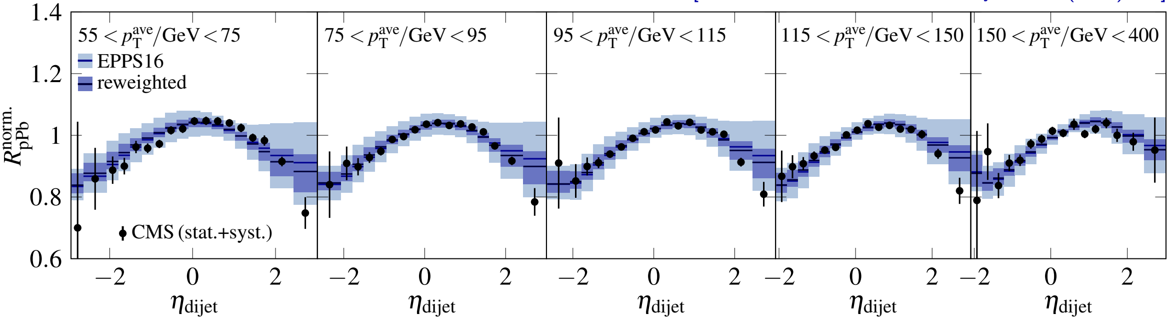
NLO pQCD:



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

Dijets at 5.02 TeV – EPPS16 reweighted

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

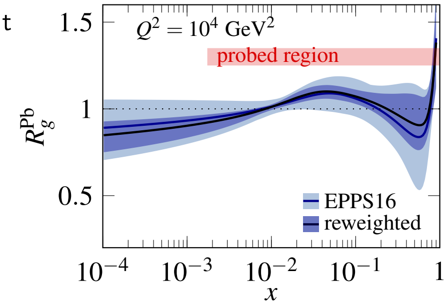


A Hessian PDF reweighting study shows that these data can put stringent constraints on the gluon modifications

- 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 $x < 10^{-3}$?

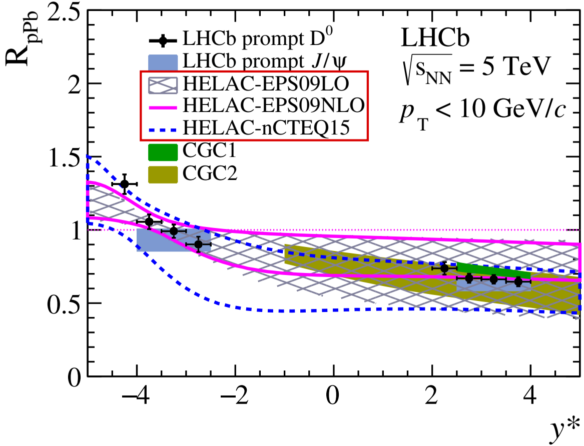


$$R_i^A(x, Q^2) = f_i^{p/A}(x, Q^2) \; / \; f_i^{p}(x, Q^2)$$

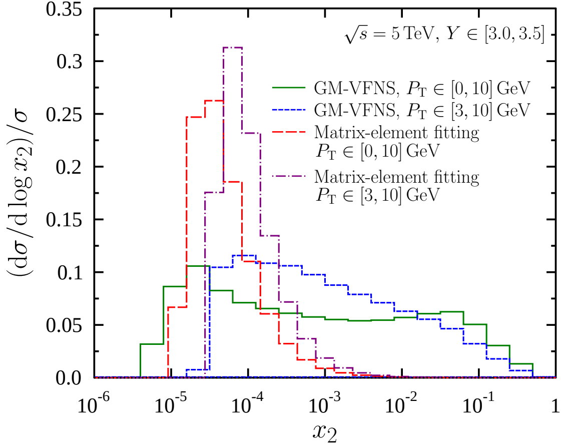
bound-proton PDF   free-proton PDF

D-mesons 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 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}

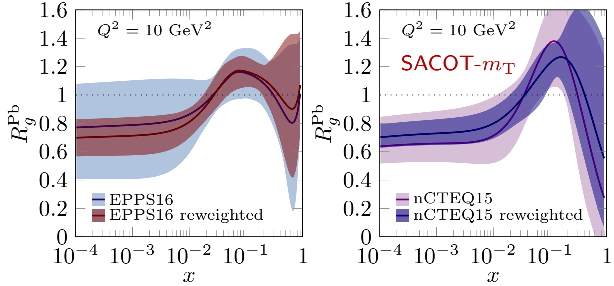
  see the refs. for comparison with POWHEG+PYTHIA, FONLL

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

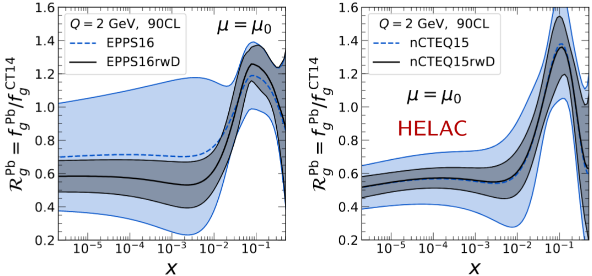
Striking similarity with the results with dijets

- ➔ Supports the validity of collinear factorization in pPb and the universality of nPDFs
  - ▶ further confirmation possible from forward photons [N. Novitzky, Thu 17:50], low-mass DY & W/Z-bosons

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

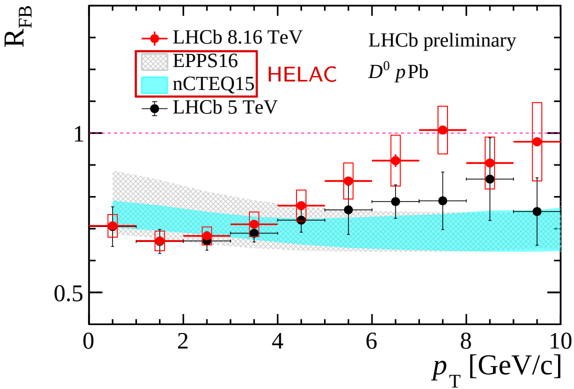


[Kusina, Lansberg, Schienbein & Shao, PRL 121 (2018) 052004, fig. from arXiv:2012.11462]



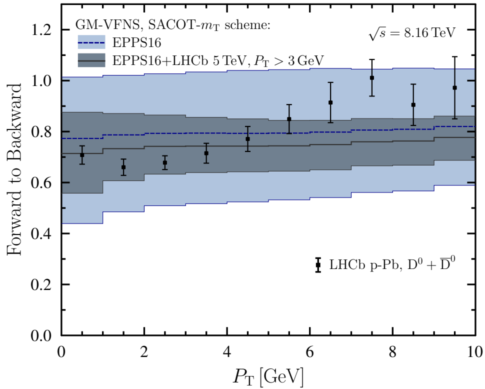
D-mesons at 8.16 TeV – do we have tension?

[Y. Luo, Wed 19:05; LHCb-CONF-2019-004]



➔

[Eskola, Helenius, PP & Paukkunen, unpublished]



QM2019 LHCb summary talk:

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

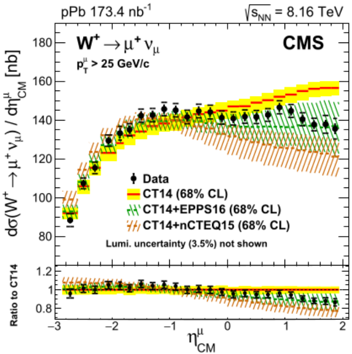
➔ *Theoretical description matters, HELAC predicts much smaller nPDF uncertainties for R_{FB} than SACOT-m_{T}!*

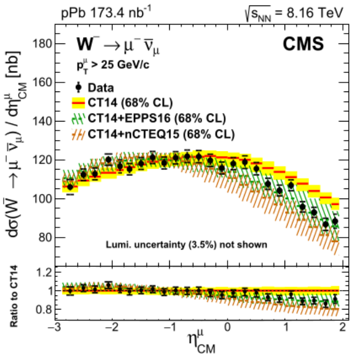
The slope of the 8.16 TeV data still differs from that in nPDF predictions and in 5.02 TeV data

➔ How can we explain the difference?

W/Z bosons in pPb at 5.02 TeV and 8.16 TeV [see also Y. Go, Mon 17:00]

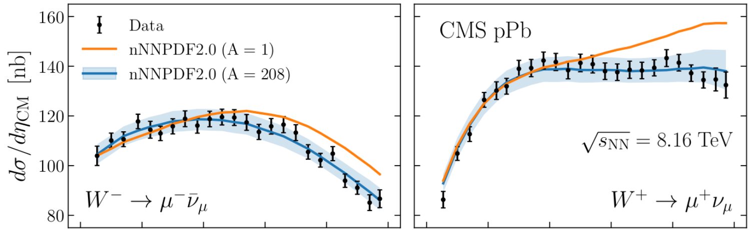
[Phys.Lett.B 800 (2020) 135048]





→

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



Clean probes of the initial stage:

- $u\bar{d} \to W^+$, $d\bar{u} \to W^-$ (flavour separation)
- $q\bar{q} \to Z$ (strangeness)

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

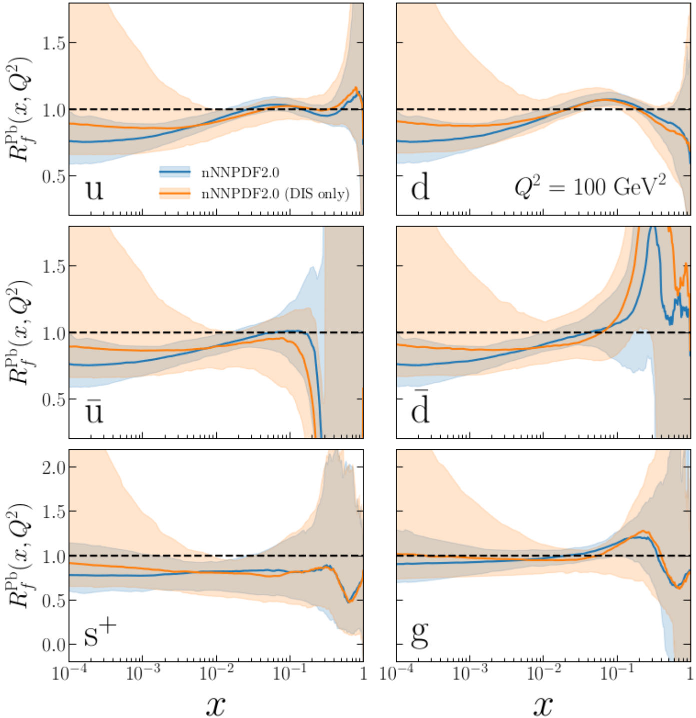
Increased statistics in the 8.16 TeV data set

➔ Included in nNNPDF2.0 and nCTEQ15WZ

In PbPb model dependency from nuclear overlap function $\langle T_{AA} \rangle$
[see I. Helenius, Mon 17:45]

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

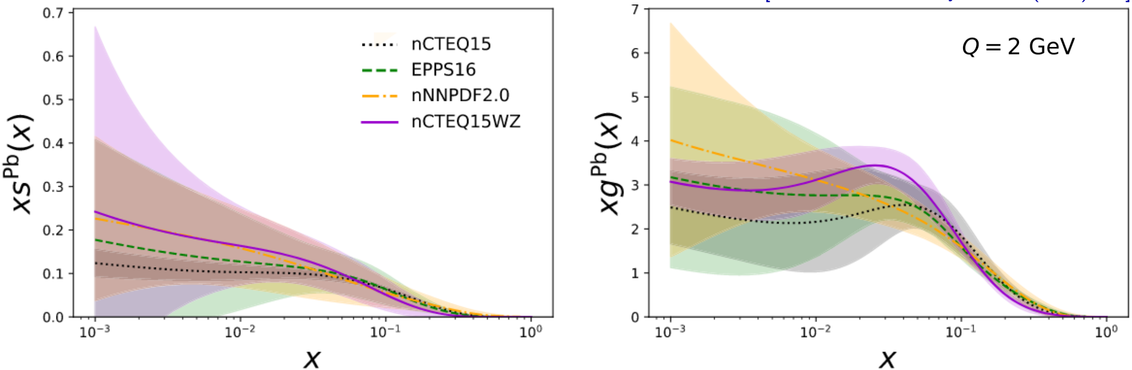
nNNPDF2.0 does not use fixed-target DY data

→ W/Z data have to compensate for this

Here:

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

[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
  - still consistent with the forward (& backward) D-mesons (?)

			$\sqrt{s_{NN}}$ [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

Section 2

What do we still need to learn?

Most nuclei are close to isoscalar

- ➔ Nearly equal amout of u and d quarks

For example, we can write

$$f_{u_V}^A = R_{u_V+d_V}^A \left(1 - \frac{A-2Z}{A}\mathcal{A}_{u_V-d_V}^A\right)\frac{A}{2}(f_{u_V}^p + f_{d_V}^p)$$

$$f_{d_V}^A = R_{u_V+d_V}^A \left(1 + \frac{A-2Z}{A}\mathcal{A}_{u_V-d_V}^A\right)\frac{A}{2}(f_{u_V}^p + f_{d_V}^p)$$

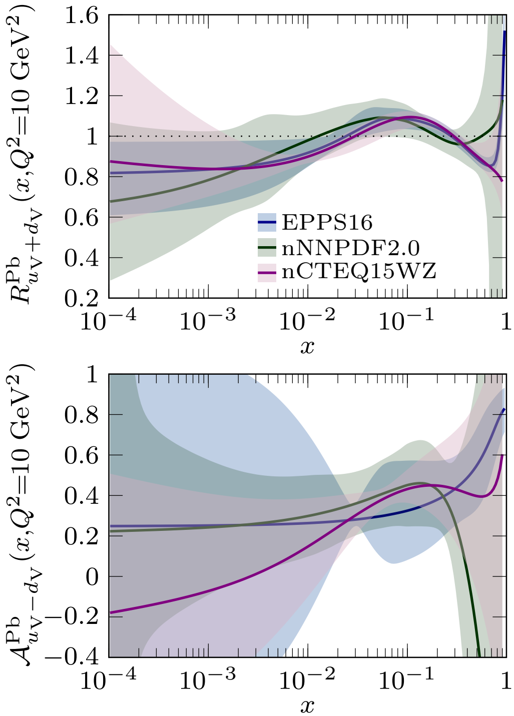
where

$$R_{u_V+d_V}^A = \frac{f_{u_V}^{p/A} + f_{d_V}^{p/A}}{f_{u_V}^p + f_{d_V}^p} \qquad \mathcal{A}_{u_V-d_V}^A = \frac{f_{u_V}^{p/A} - f_{d_V}^{p/A}}{f_{u_V}^{p/A} + f_{d_V}^{p/A}}$$

and neutron excess $\dfrac{A-2Z}{A} \approx 0.2$ for Pb

- ➔ Need high-precision data on non-isoscalar nuclei to constrain the asymmetry

Important for studying the physical origin of the EMC effect



Flavour separation remains hard to constrain also for sea quarks

Most nuclei are close to isoscalar

- ➔ Nearly equal amout of $\bar{u}$ and $\bar{d}$ quarks

Here

$$f_{\bar{u}}^{A} = R_{\bar{u}+\bar{d}}^{A}\left(1 - \frac{A-2Z}{A}\mathcal{A}_{\bar{u}-\bar{d}}^{A}\right)\frac{A}{2}(f_{\bar{u}}^{p} + f_{\bar{d}}^{p})$$

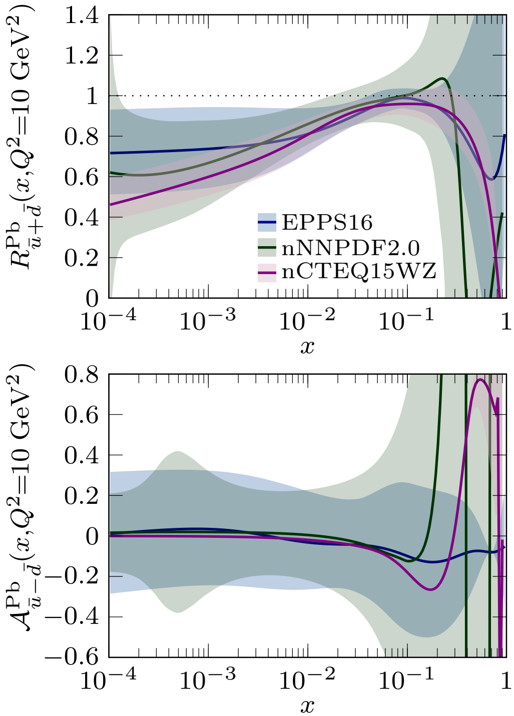
$$f_{\bar{d}}^{A} = R_{\bar{u}+\bar{d}}^{A}\left(1 + \frac{A-2Z}{A}\mathcal{A}_{\bar{u}-\bar{d}}^{A}\right)\frac{A}{2}(f_{\bar{u}}^{p} + f_{\bar{d}}^{p})$$

with

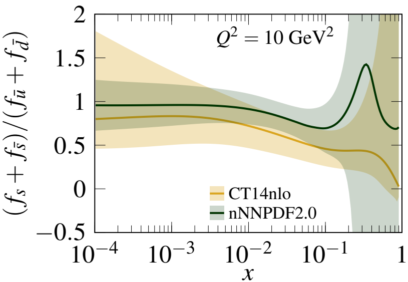
$$R_{\bar{u}+\bar{d}}^{A} = \frac{f_{\bar{u}}^{p/A} + f_{\bar{d}}^{p/A}}{f_{\bar{u}}^{p} + f_{\bar{d}}^{p}} \qquad \mathcal{A}_{\bar{u}-\bar{d}}^{A} = \frac{f_{\bar{u}}^{p/A} - f_{\bar{d}}^{p/A}}{f_{\bar{u}}^{p/A} + f_{\bar{d}}^{p/A}}$$

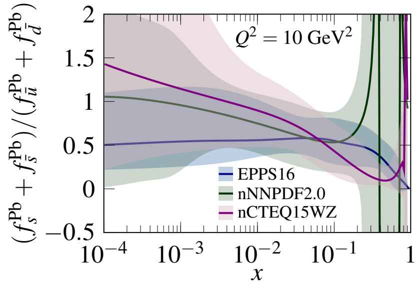
Flavour separation only a small correction

- ➔ Most HIC observables insensitive to it
  - ▶ Relief for phenomenology
  - ▶ Curse for fitters

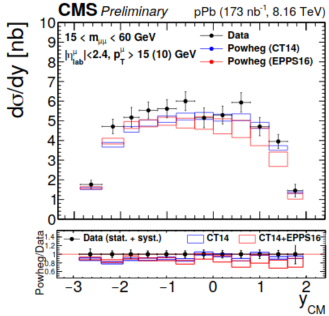


How strange are the nuclei?





[A. Baty, Thu 17:50;
CMS PAS HIN-18-003]

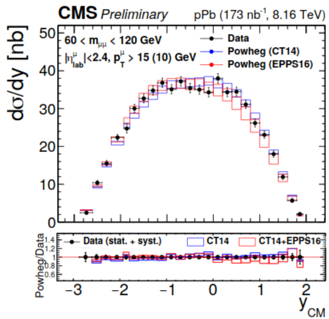


Strangeness very difficult to constrain already for free-proton fits

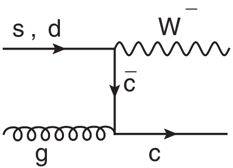
- Some analyses use dimuon νA-DIS as a constraint

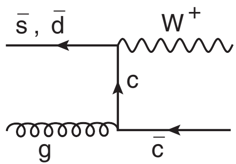
Z-boson production has significant $s\bar{s}$ contribution

- Any help from the 8.16 TeV data?

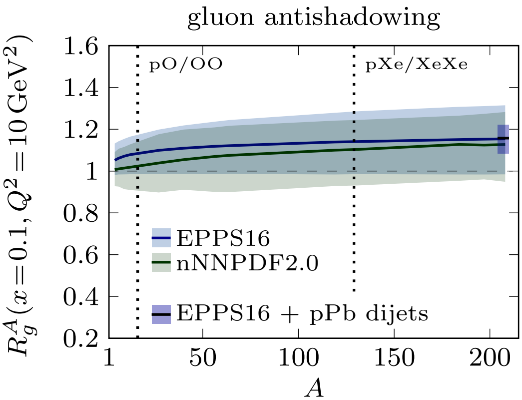


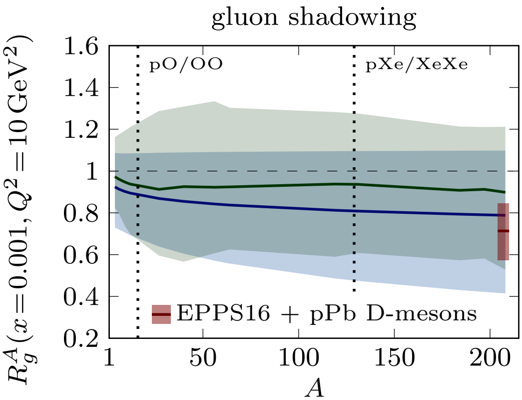
W+charm measured in pp, doable in pPb?





A-dependence of gluon modifications





Direct gluon constraints available only for heavy nuclei (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 [S. Belin, Sun 16:05] and RHIC (e.g. pAl) can help for the large x
- ➔ Need for lighter-ion pA runs! [see also: Opportunities of OO and pO collisions at the LHC, 4-10 February 2021]

[Walt, Helenius & Vogelsang, Phys.Rev.D 100 (2019) 096015]

Several NNLO analyses appeared over the past years

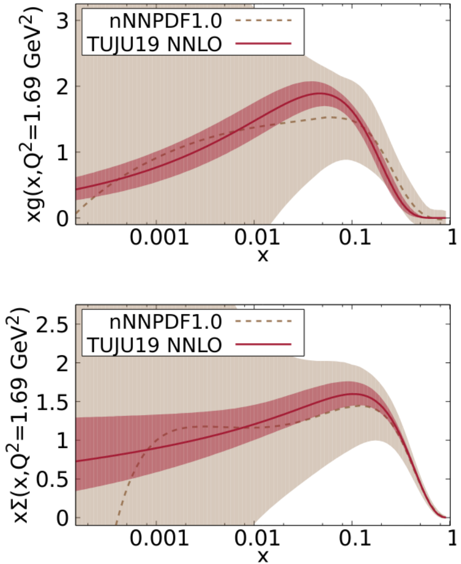
- KA15 [PRD 93 (2016) 014026] (NC DIS, DY)
- nNNPDF1.0 [EPJ C79 (2019) 471] (NC DIS)
- TuJu19 [PRD 100 (2019) 096015] (NC DIS, CC ν-DIS)
- KSASG20 [arXiv:2010.00555] (NC DIS, CC ν-DIS)

Limited currently to fixed-target data

- → No direct gluon constraints
- → Large uncertainties / parametrization dependence

Future prospects:

- Public codes available for DY/W/Z at NNLO
- For hadronic observables NNLO calculations exist, but no public codes yet available



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?

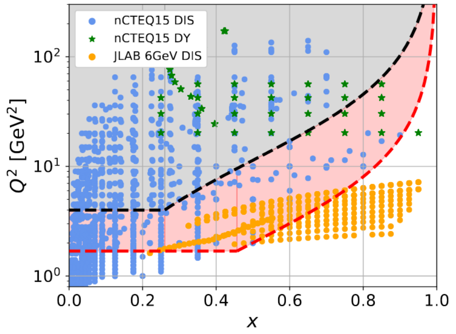
  [see M. van Leeuwen, Mon 17:00]

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

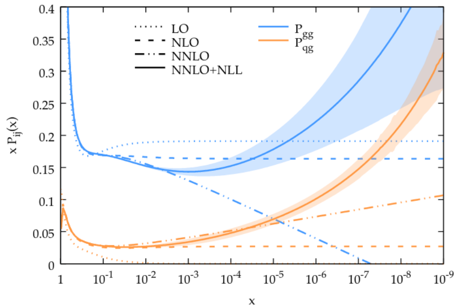
- Do these become important before saturation kicks in?

➔ Many opportunities for the EIC & LHeC

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



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



Summary

What have we learned so far?

- Quarks (on average) experience EMC suppression, antishadowing and shadowing
- Strong evidence from LHC (both hadronic & EW probes) for gluon shadowing & antishadowing
  - Lot of activity by different groups to include LHC data in their analyses

What do we still need to learn?

- Flavour separation and strangeness remain difficult to constrain
- A-dependence of gluons not known
- Where are the limits of collinear factorization / DGLAP picture?

Other areas of (future) progress:

- Pushing for NNLO precision
- Including small-x resummation
- Multi-dimensional distributions ($k_{\mathrm{T}}, b_{\mathrm{T}}$ dependence)
- Can we put limits on what are the *physical* causes of the nuclear modifications?

Thank you!