Constraints and unconstraints for nuclear gluons from the LHC

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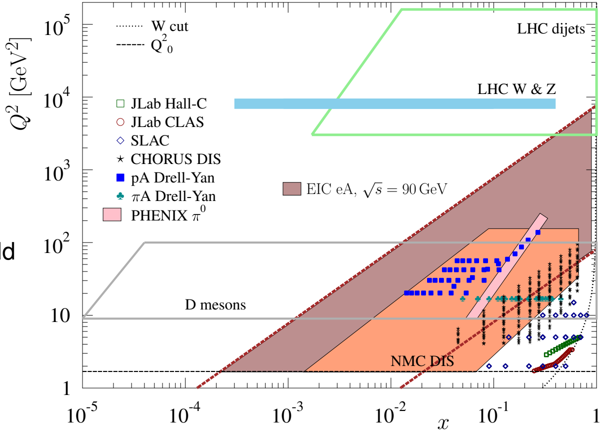
The kinematic/virtuality reach in global analysis of nuclear PDFs

- The variety & precision of data begins to be high enough to challence the picture of collinear factorization and to look for e.g.
  - **onset of non-linear dynamics**
  - **partonic energy loss**
  - **collectivity in small systems**
  - **. . .**

  in p-Pb type collisions

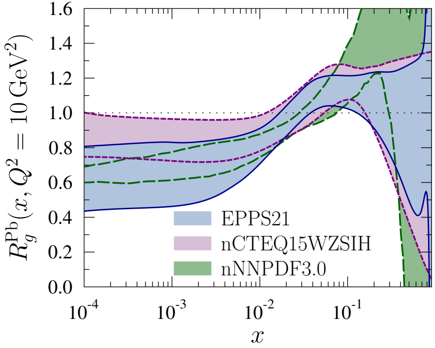
- Non-factorizable non-universal effects should become visible in global fits, $\chi^2/N_{\rm data} \gg 1$

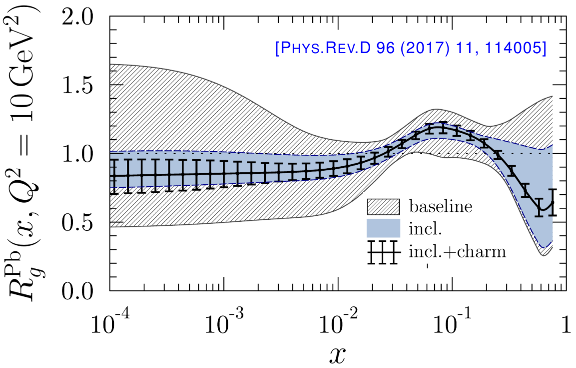
- Global analysis of nuclear PDFs can be seen as a **search** for these effects – not something that overlooks them



Comparison of current nuclear gluons vs. EIC projections

- Nuclear modification of gluons $R_g^{\rm Pb}(x, Q^2) = g^{\rm Pb}(x, Q^2)/Ag^p(x, Q^2)$



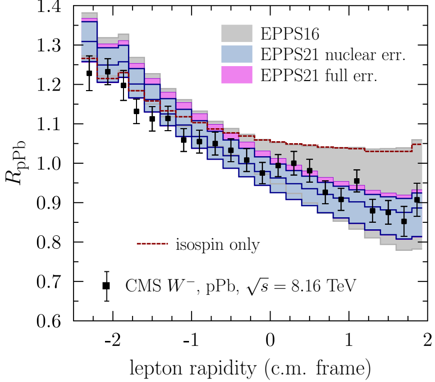


- At small-x the EIC projections look comparable to precision of recent global fits
- How do we end up with the current gluon PDFs? Can we trust them?

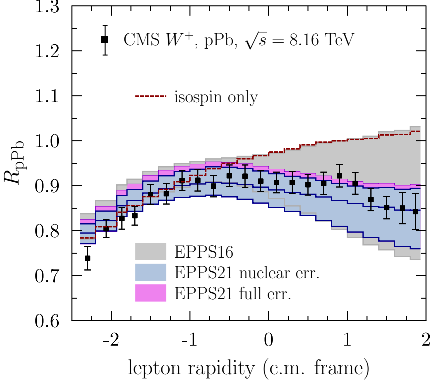
Electroweak boson production

- The CMS p-Pb 8.16TeV $W^{\pm}$-bosons [Phys.Lett.B 800 (2020) 135048] vs. EPPS16 and EPPS21

[Eur.Phys.J.C 82 (2022) 5, 413]



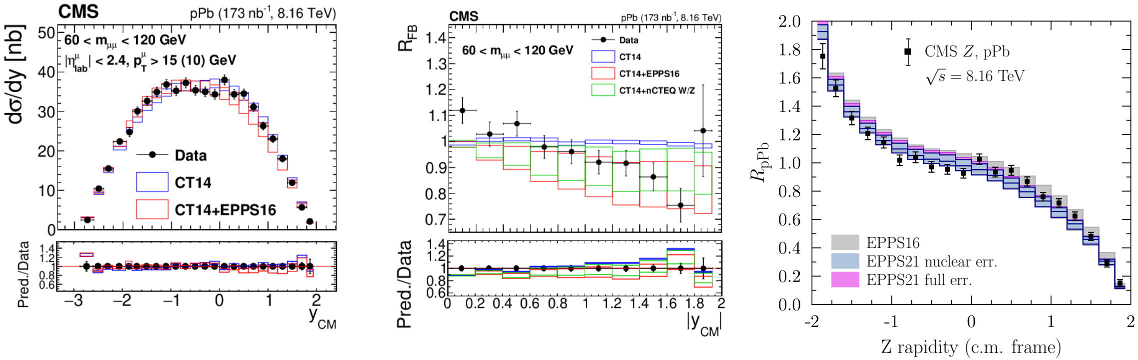
[Eur.Phys.J.C 82 (2022) 5, 413]



- At the parametrization scale these data constrain **almost exclusively gluons** [Eur.Phys.J.C 82 (2022) 3, 271]
- Long lever arm in rapidity helps to tame the normalization uncertainty

Electroweak boson production

- The CMS p-Pb 8.16TeV Z bosons [JHEP 05 (2021) 182] vs. nuclear PDFs

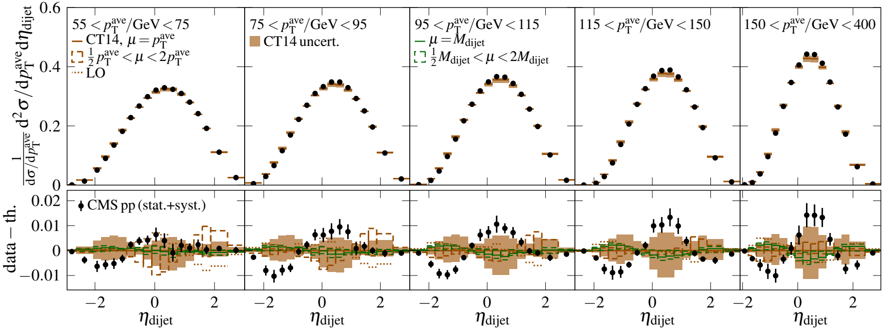


- Large fluctuations around $y = 0 \implies$ **Forward-to-backward ratio does not tend to unity**
- $\chi^2/N_{\rm data} \sim 2$ – fitting nor NNLO corrections help here

Inclusive 5 TeV dijets

- A precision dijet observable by CMS [Phys.Rev.Lett. 121 (2018) 6, 062002]

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



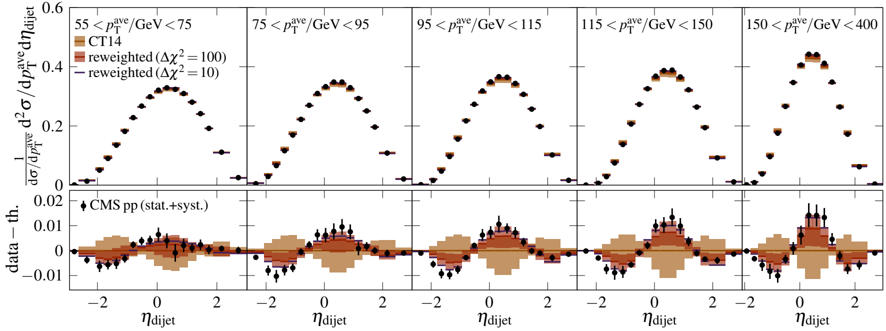
[Eur.Phys.J.C 79 (2019) 6, 511]

- NLO QCD differs significantly from the data. **NNLO? Resummation due to smallish cone $R = 0.3$?**

Inclusive 5 TeV dijets

- A precision dijet observable by CMS [Phys.Rev.Lett. 121 (2018) 6, 062002]

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

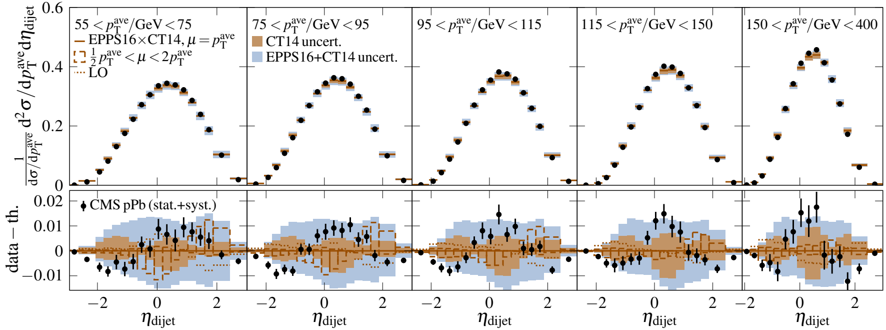


[Eur.Phys.J.C 79 (2019) 6, 511]

- Can improve (but not cure) the description by **refitting the proton PDFs** (reweighting/profiling)

- A precision dijet observable by CMS [PHYS.REV.LETT. 121 (2018) 6, 062002]

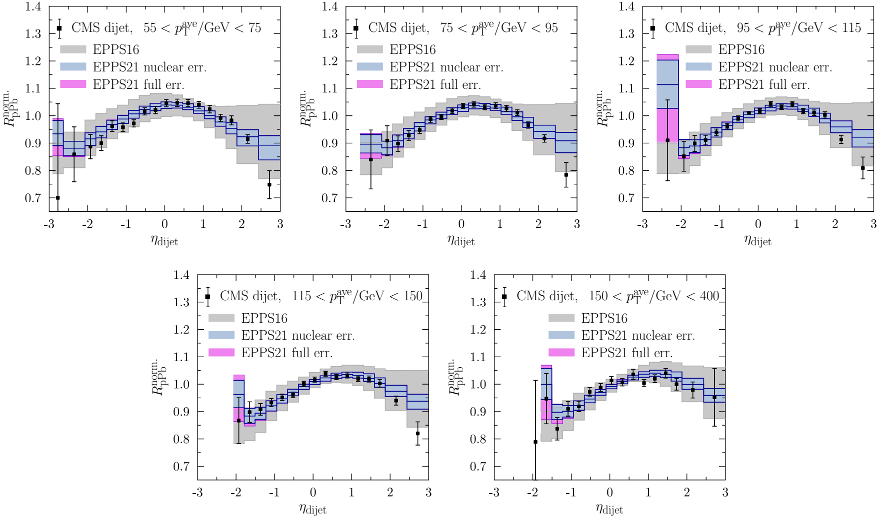
$$\frac{d^2\sigma^{\mathrm{pPb}}}{dp_{\mathrm{T}}^{\mathrm{ave}}d\eta_{\mathrm{dijet}}}\left(\frac{d\sigma^{\mathrm{pPb}}}{dp_{\mathrm{T}}^{\mathrm{ave}}}\right)^{-1}$$



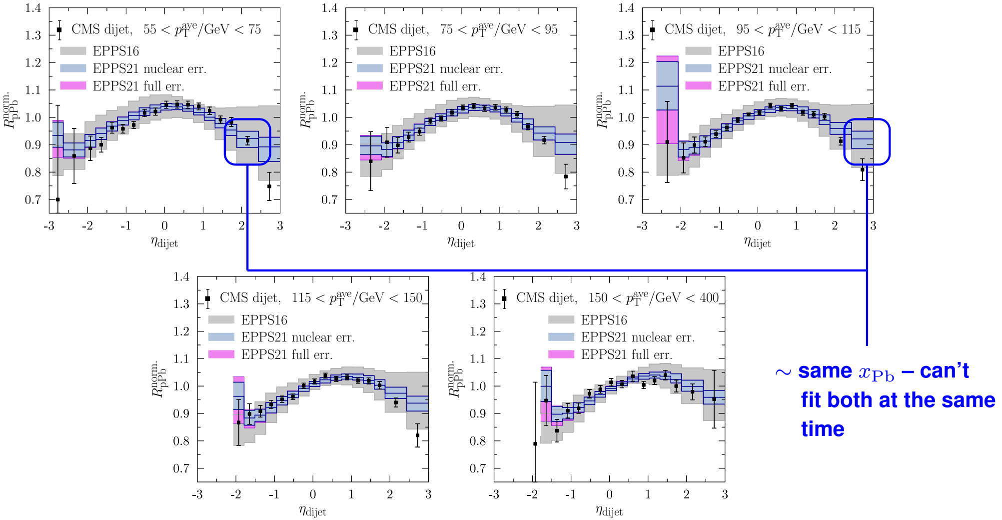
[EUR.PHYS.J.C 79 (2019) 6, 511]

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

Inclusive 5 TeV dijets



- EPPS21 and nNNPDF3.0 fit these data **except the most forward data points**



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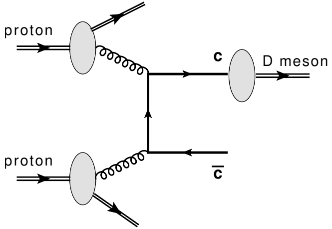
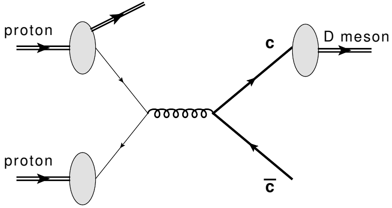
Open heavy-flavour

- The potential of heavy-flavour as a nuclear gluon constraint understood
  [Kusina et.al. Phys.Rev.Lett. 121 (2018) 5, 052004 ; Eskola et.al. JHEP 05 (2020) 037]





- Differing theoretical setups:

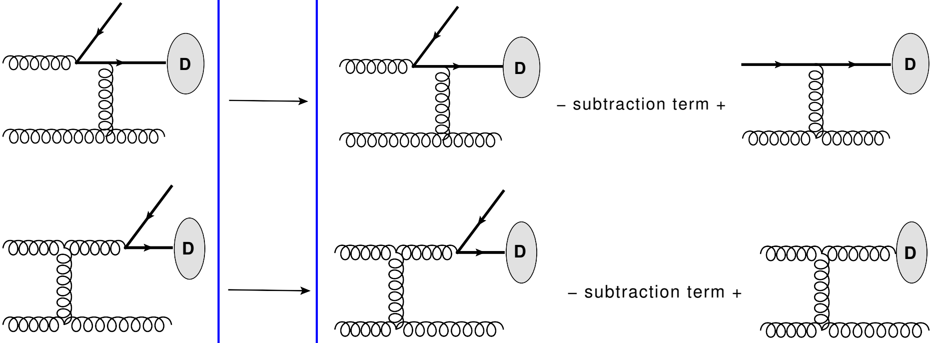
  - Fixed-order + Pythia parton shower [Frixione et.al. JHEP 0709, 126] – **Used in nNNPDF fits**

  - General-mass variable-flavour-number scheme (GM-VFNS) – **Used in EPPS fits**
    [Kniehl et.al PRD71, 014018; Helenius, Paukkunen, JHEP 1805 (2018) 196]

  - Matrix-element fitting [Lansberg, Shao, Eur.Phys.J.C 77 (2017) 1, 1] – **Used in nCTEQ fits**

Open heavy-flavour in GM-VFNS

Fixed-order calculation | **General-mass variable-flavour-number scheme**



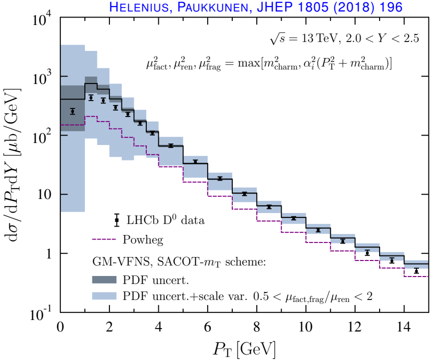
$\sim \log\left(p_T^2/m^2\right)$

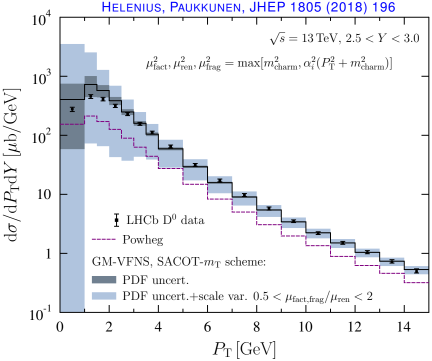
free from $\log\left(p_T^2/m^2\right)$

- EPPS fits use the NLO **SACOT-m_T** GM-VFNS [Helenius, Paukkunen, JHEP 1805 (2018) 196]

Open heavy-flavour in GM-VFNS – comparison with the LHCb 13 TeV D^0 p-p data

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

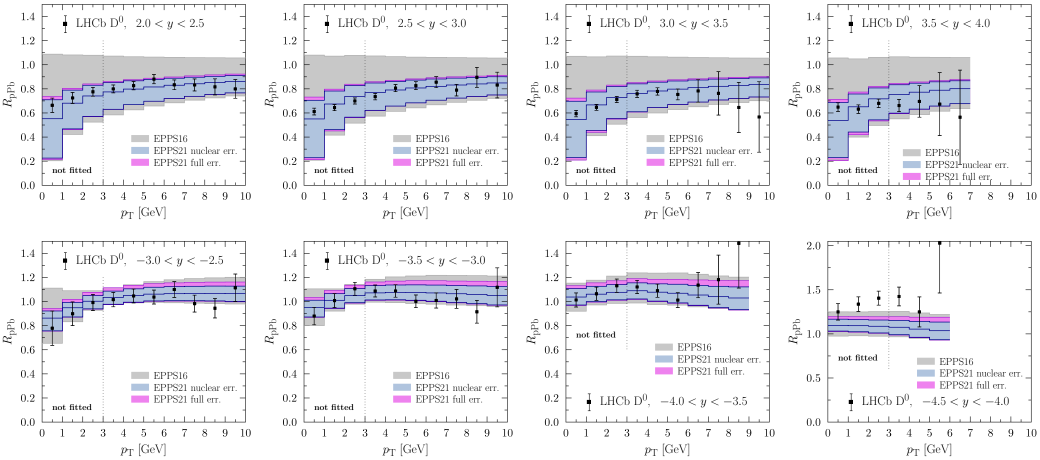




PDF = NNPDF3.1NLO (pch)
FF = KKKS08

- Sizable theory uncertainties at low $p_{\rm T}$ – most cancel in $\sigma_{\rm pPb}/\sigma_{\rm pp}$

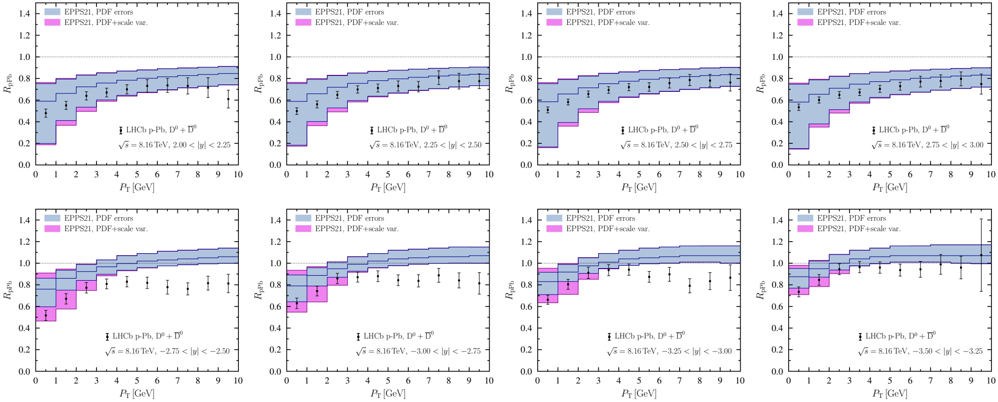
LHCb 5 TeV D^0 p-Pb data [JHEP 10 (2017) 090] $\sigma_{\rm pPb}/\sigma_{\rm pp}$ vs. EPPS21



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

LHCb 8 TeV D^0 p-Pb data [arXiv:2205.03936] $\sigma_{\rm pPb}/\sigma_{\rm pp}$ vs. EPPS21

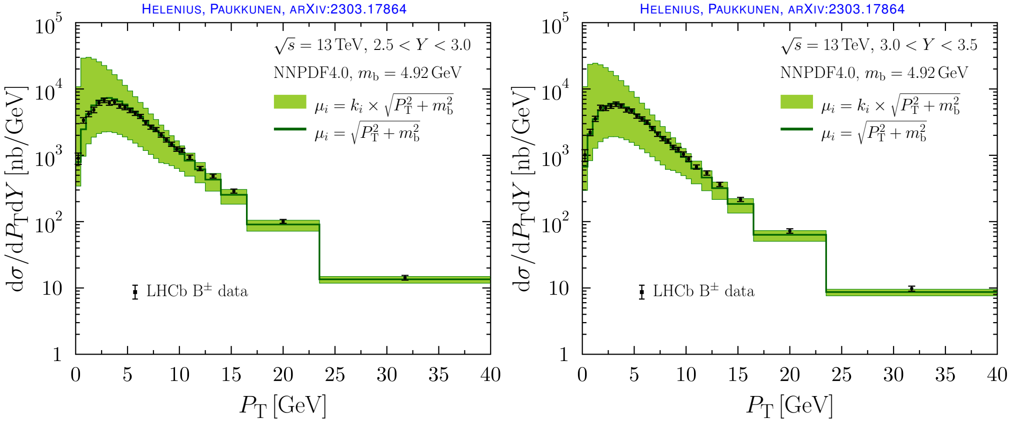
- Brand new results with the SACOT-$m_{\rm T}$ scheme! 🥳



- The data prefer a stronger $\sqrt{s}$ dependence – in the backward direction in particular
- Experimental result uses an interpolated p-p reference

LHCb 8 TeV B-meson data σ_{pp}

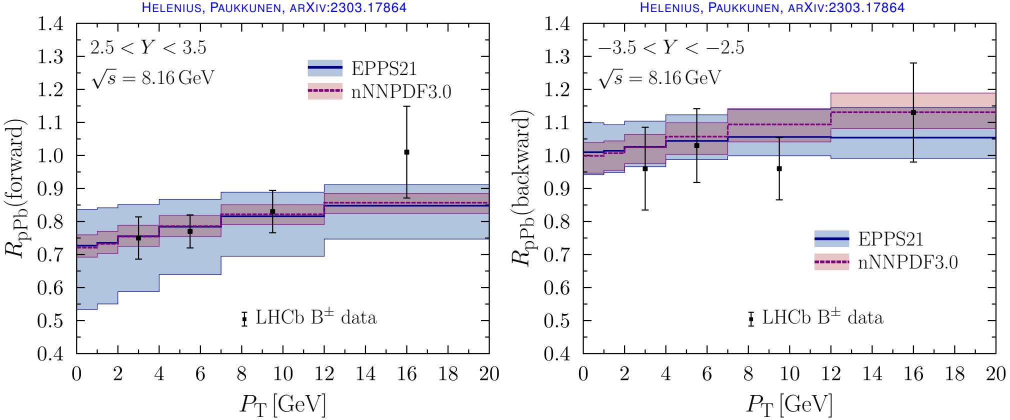
- Brand new results with the SACOT-m_T scheme! 🥳



- The p-p baseline well reproduced within the uncertainties

LHCb 8 TeV B-meson data [Phys. Rev. D99 052011 (2019)] $\sigma_{\mathrm{pPb}}/\sigma_{\mathrm{pp}}$

- Brand new results with the SACOT-m_{T} scheme! 🥳



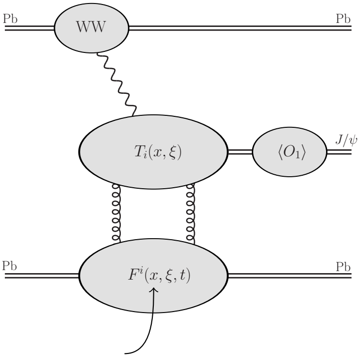
- Both EPPS21 and nNNPDF3.0 do a good job – more statistics needed for quantitative constraints

Nuclear PDFs from exclusive J/ψ production in Pb-Pb?

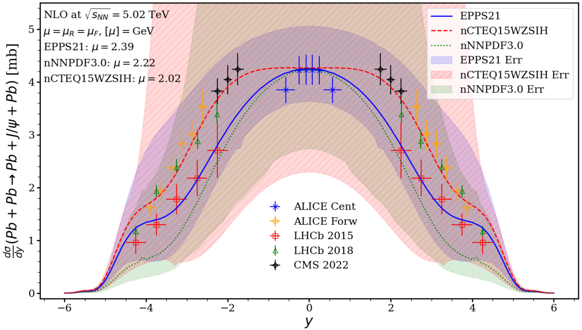
- Exclusive J/ψ production very sensitive to nuclear PDFs

quarks enter at NLO

$$\mathcal{M}^{AA\to AA+J/\psi} \sim f^A_{\rm gluon}(\mu) \otimes T_g(\mu) + f^A_{\rm quark}(\mu) \otimes T_q(\mu)$$



[Eskola et.al., Phys.Rev.C 106 3, 035202 + Phys.Rev.C 107 4, 044912]



- Generalized PDFs approximated here by PDFs and scales tuned to match the $y = 0$ data

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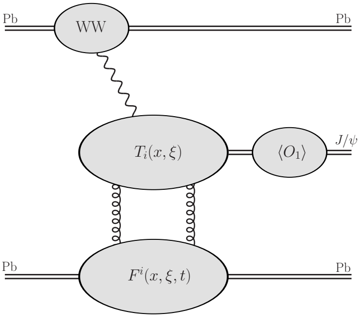

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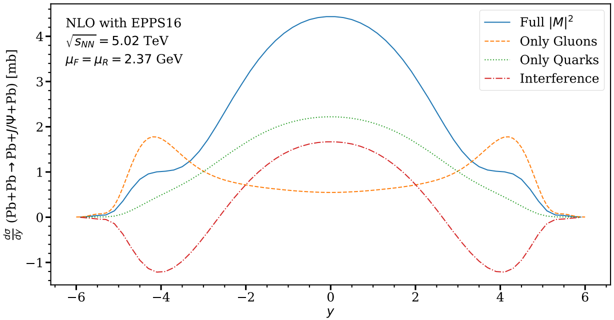

- Perturbatively unstable: only gluons at LO – quarks dominate at NLO! What happens at NNLO?

Nuclear PDFs from exclusive J/ψ production in Pb-Pb?

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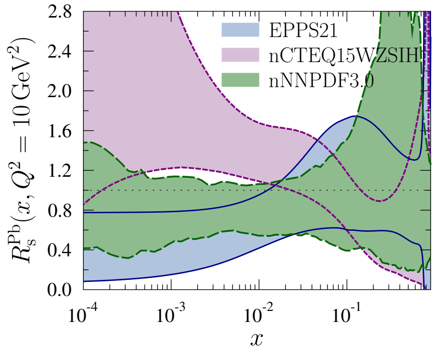

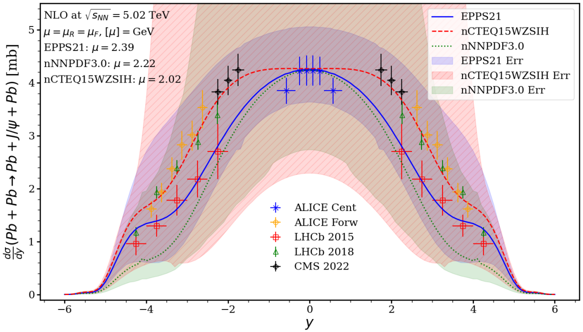

- nCTEQ15WZSIH reproduces the shape due to its hugely enhanced **strange-quark PDFs!**

Summary

- Discussed some recent (but not all) LHC data relevant for nuclear gluons:

  - CMS 8 TeV $W^{\pm}$ $\rightsquigarrow$ indirect sensitivity
  - CMS 8 TeV Z $\rightsquigarrow$ indirect sensitivity

    the data are inconsistent with nuclear PDFs
  - CMS double diff. dijets $\rightsquigarrow$ direct sensitivity

    systematic anomalies in the most forward data points
  - LHCb double diff. D and B mesons $\rightsquigarrow$ direct sensitivity

    8 TeV $y < 0$ D^0 data not compatible with nuclear PDFs
  - Exclusive J/Ψ production $\rightsquigarrow$ direct sensitivity?

    standard QCD calculations unstable

- More work and data required to make sure that we are not shoveling non-factorizable effects into nuclear PDFs – **EIC will ultimately tell**