Studies of the cold nuclear matter (nPDFs)

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Introduction

- Cold Nuclear Matter (CNM) effects: modifications of particle production yields in ion collisions with respect to pp that are not due to formation of a deconfined medium, including:
  - Final state effects
  - **Initial state effects**
- Crucial to set the baseline to study AA collisions
- Collinear factorisation approach in pQCD:

$$d\sigma^{\mathrm{AB}\to k+X}(Q^2) = \sum_{i,j,X'} f_{i/A}(x_1, Q^2) \otimes f_{i/B}(x_2, Q^2) \otimes d\hat{\sigma}^{ij\to k+X'}(Q^2), \text{ for } Q^2 \gg \Lambda_{\mathrm{QCD}}$$

- Nuclear Parton Distribution Functions (nPDFs)

$$R_i^A(x, Q^2) = \frac{f_i^A(x, Q^2)}{A\ f_i^p(x, Q^2)}; \qquad i = u, d, s, c, ..$$

- Fitted with global analyses considering different processes
- Validity of collinear factorisation approach needs to be constantly monitored

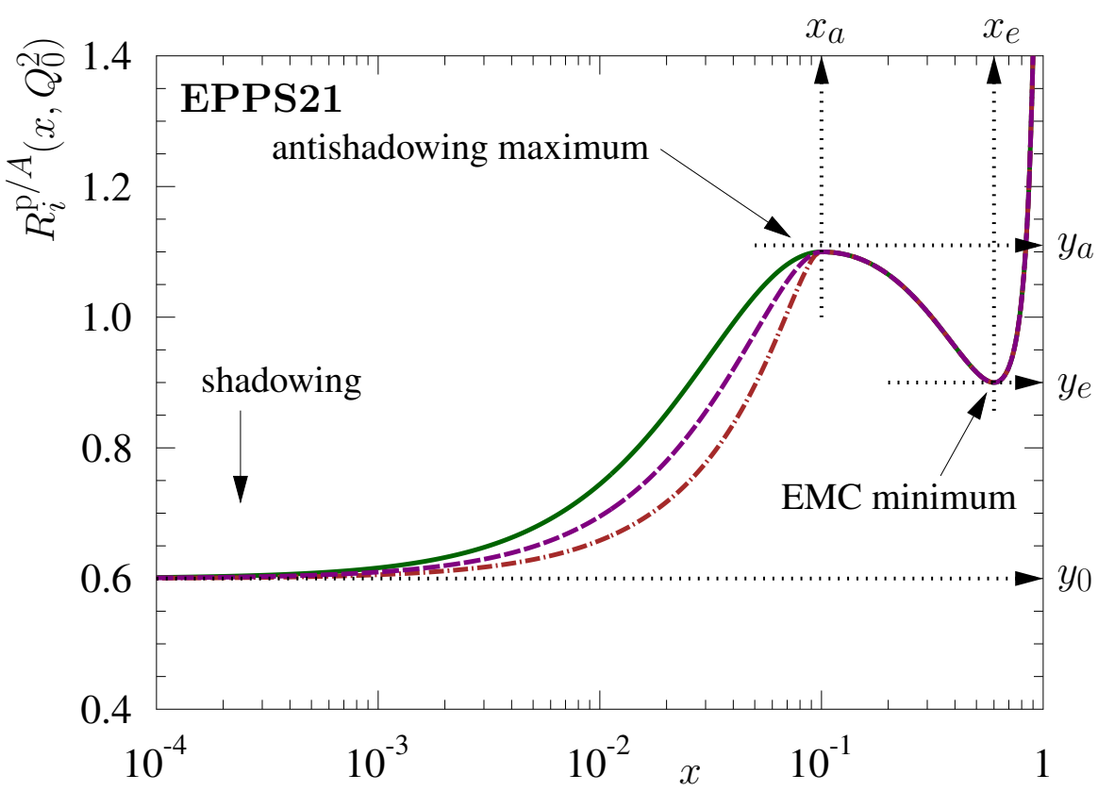


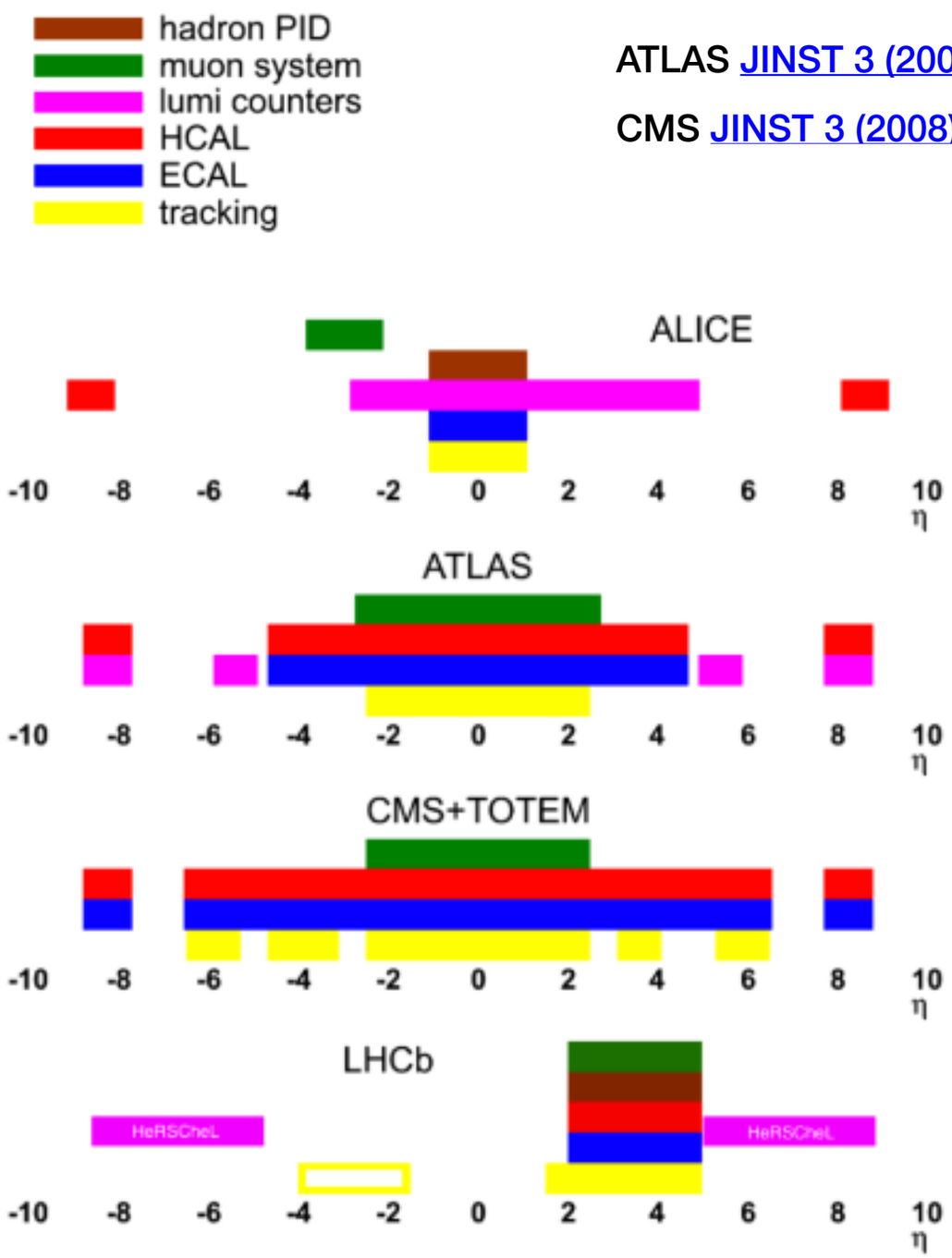
Figure from Eur.Phys.J.C 82 (2022) 5, 413

Constraining nPDFs with LHC data

- A variety of LHC datasets have potential to be used to constrain nPDFs:
  - pPb collisions
  - γPb collisions (UPC PbPb)
  - fixed target collisions (Wed 14:00 K. Mattioli talk, parallel A)
- Many channels of interest:
  - Dijets
  - Z and W boson
  - Drell-yan
  - Charm hadrons
  - Light hadrons
  - Direct photons
  - diffractive processes
- Observables: production cross-sections, $R_{p\mathrm{A}}$, R_{FB}, di-particle(jet) correlations…
- Need to keep open many channels simultaneously to understand well the interplay between CNM effects and to extend (x, Q^2) coverage
- Run1 and Run 2 LHC data included in several recent nPDF analyses:
  - EPPS21 (EPJ C82 (2022) 5, 413), nNNPDF3.0 (EPJ C82 (2022) 6, 50), nCTEQ15WZSIH (PR D104 (2021) 094005), TUJU21 (PR D105 (2022) 9, 9)

LHC experiment comparison

- Very good complementarity between the four LHC experiments

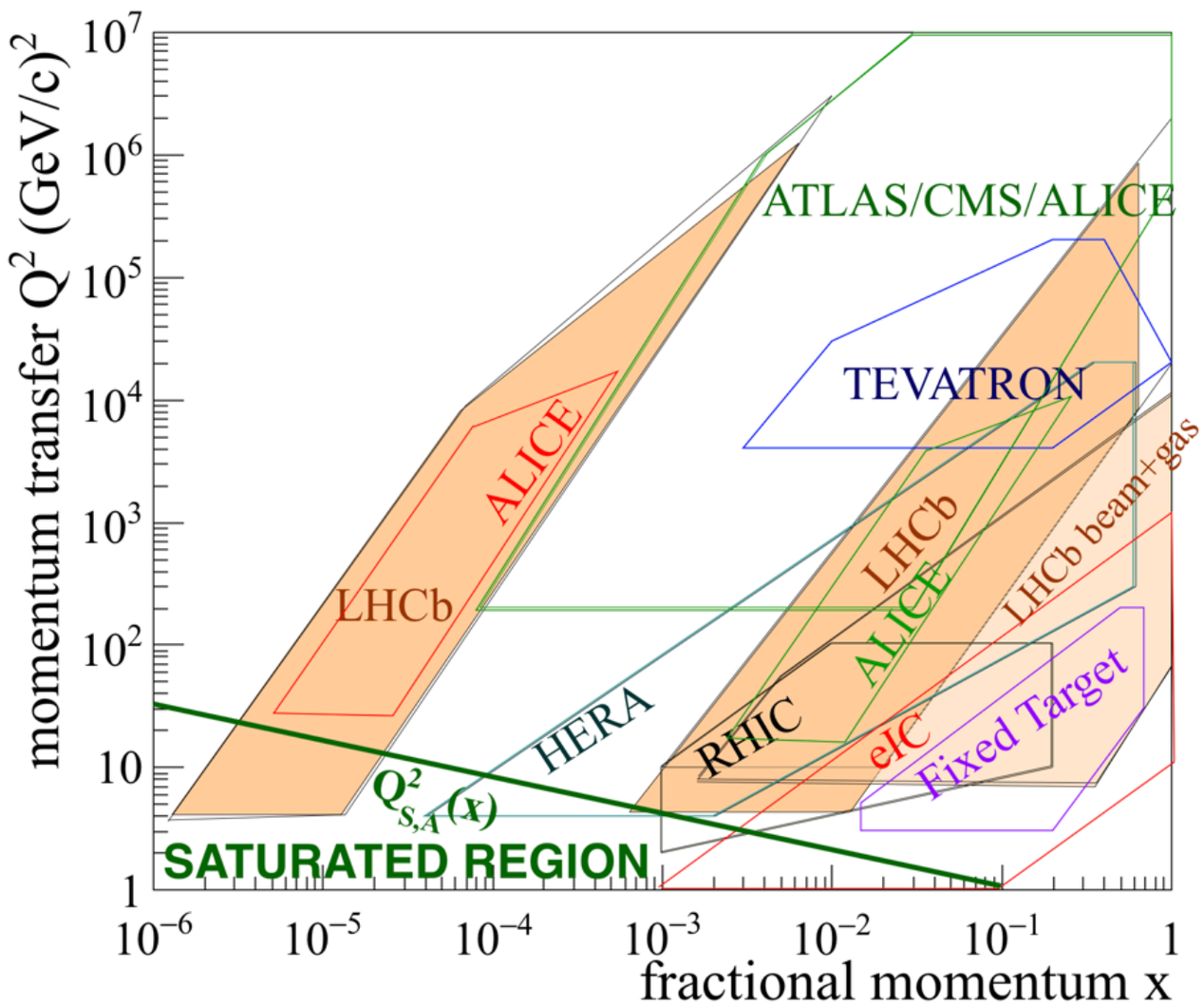


ATLAS JINST 3 (2008) S08003

ALICE JINST 3 (2008) S08002

CMS JINST 3 (2008) S08004

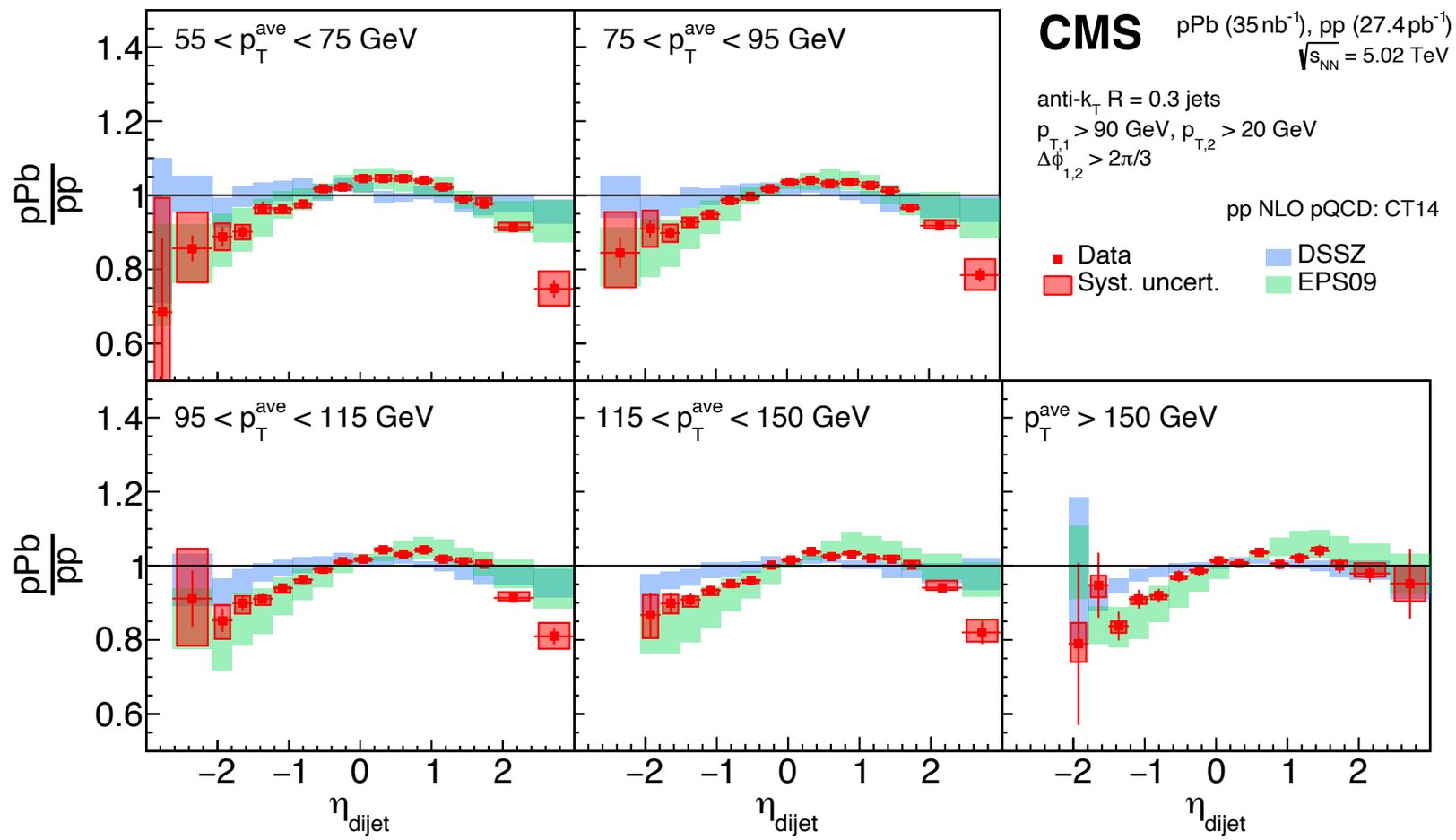
LHCb JINST 3 (2008) S08005

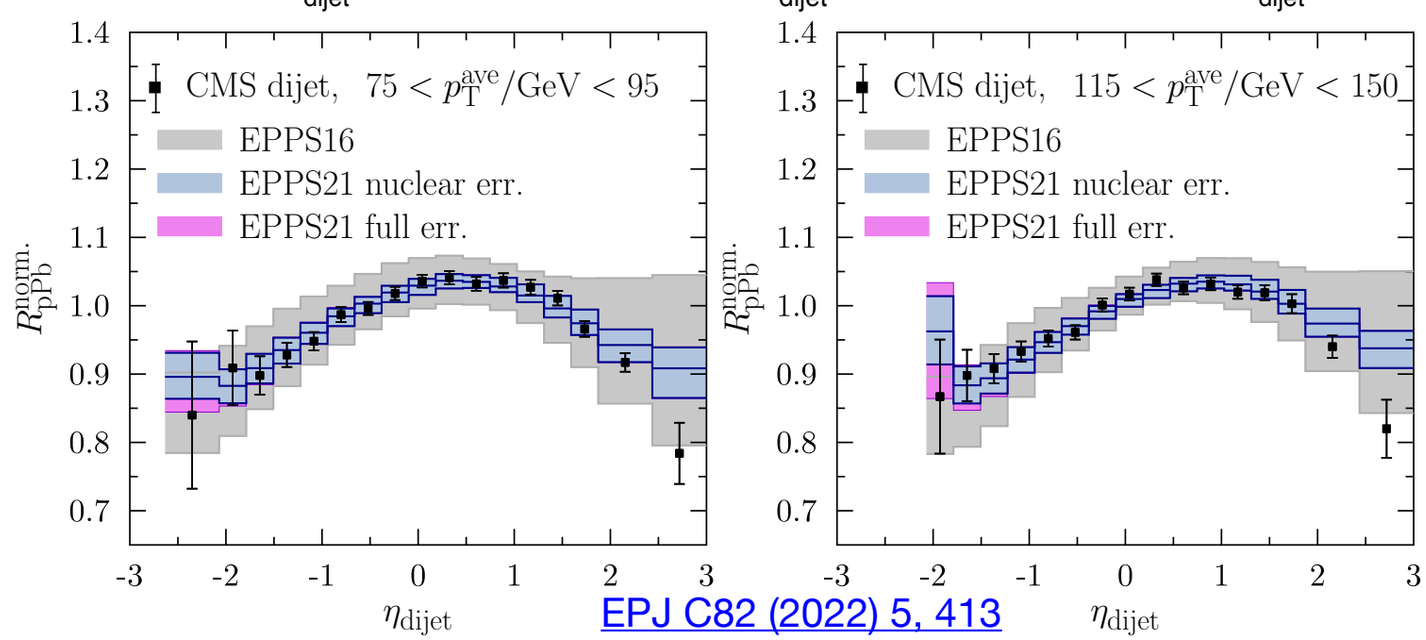


Dijet production in pPb collisions

Phys.Rev.Lett. 121 (2018) 6, 062002

- Dijet production in pPb and pp at $5\,\mathrm{TeV}$
  - Using $\mathscr{L}_{p\mathrm{Pb}} = 35 \pm 1\,\mathrm{nb}^{-1}$ and $\mathscr{L}_{pp} = 27.4 \pm 0.6\,\mathrm{pb}^{-1}$
  - $\eta_{\mathrm{dijet}} = (\eta_1 + \eta_2)/2$
  - precision from $2\,\%$ to $20\,\%$
  - suppression even at large Bjorken-x ($x \sim 10^{-1}$) (EMC effect)
- Data included in EPPS21 and nNNPDF3.0
  - Important reduction of nPDF uncertainties! EPJ C82 (2022) 6, 507 EPJ C82 (2022) 5, 413
- Future: triple-differential $(y^*, y^b, p_T^{\mathrm{ave}})$ dijets?
  - see pp result at $8\,\mathrm{TeV}$ (EPJ C77 (2017) 11, 746) with $19.7\,\mathrm{fb}^{-1}$





EPJ C82 (2022) 5, 413

Dijet correlations in pPb collisions

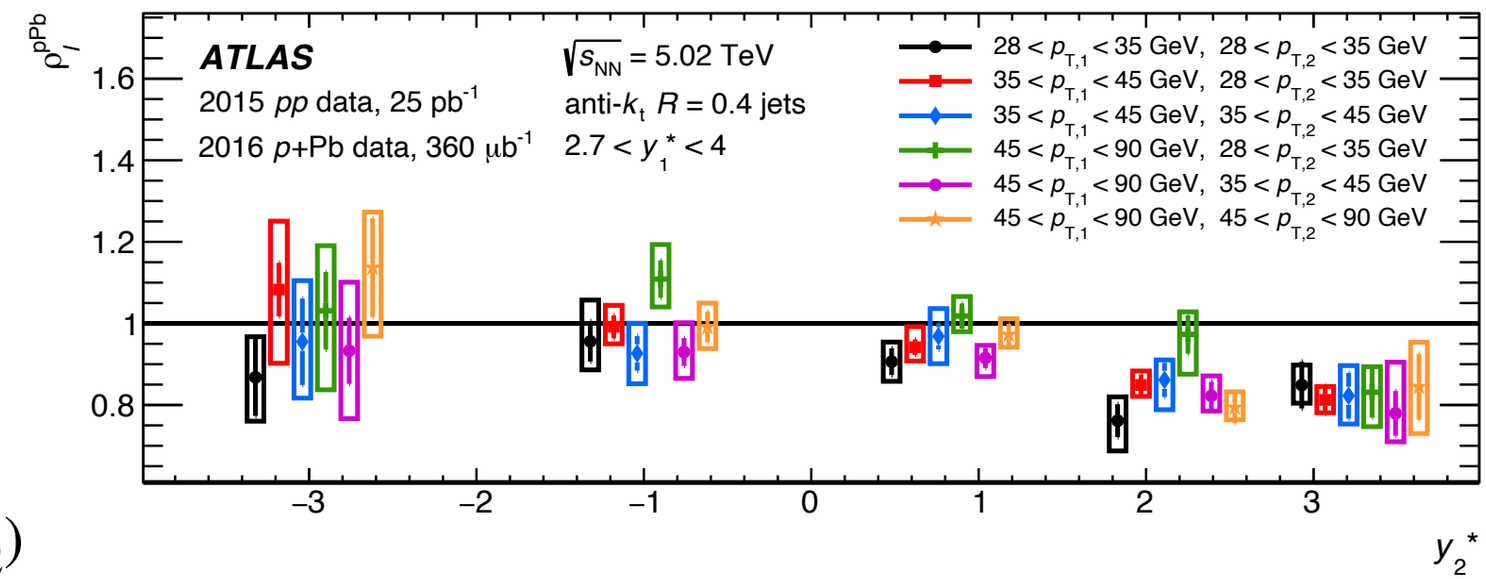
- Dijet correlations and yields from ATLAS (PR C100 (2019) 034903)
  - Using $\mathscr{L}_{p\mathrm{Pb}} = 0.36\,\mathrm{nb}^{-1}$ and $\mathscr{L}_{pp} = 25\,\mathrm{pb}^{-1}$ at $5\,\mathrm{TeV}$
  - Jets of $R = 0.4$ and in $|y^*| < 4$
  - Observables:

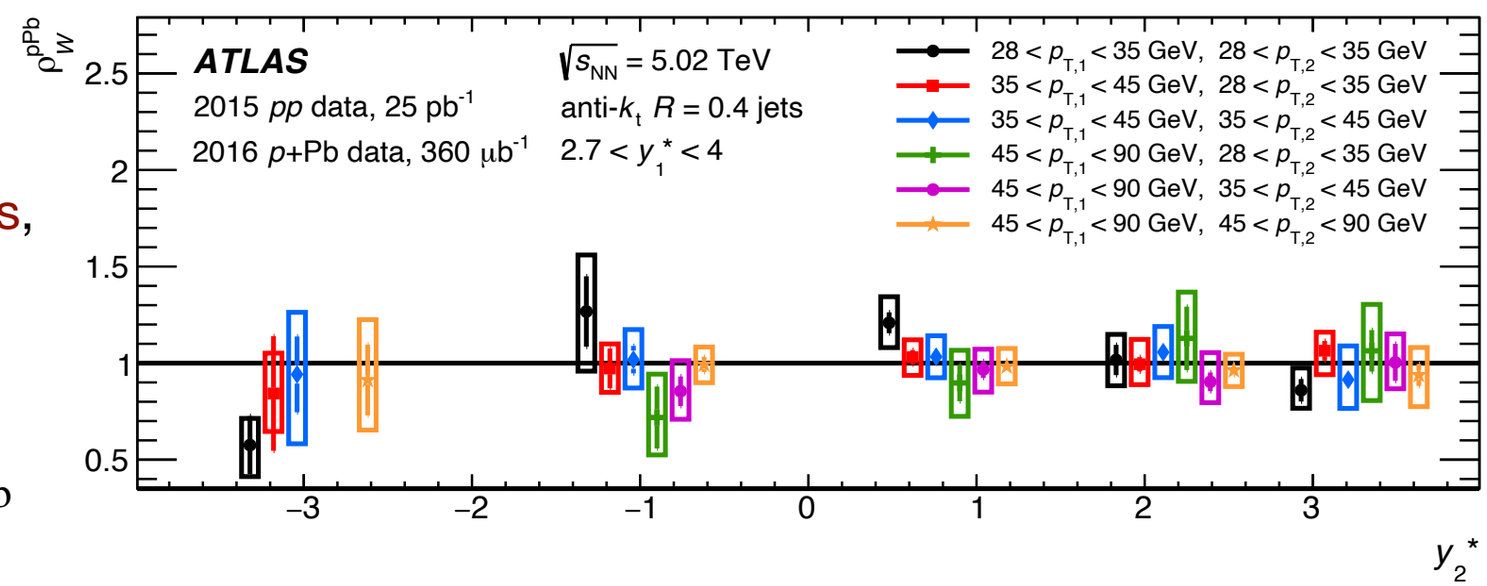
$$C_{12}(p_{\mathrm{T},1}p_{\mathrm{T},2}, y_1^*, y_2^*) = \frac{1}{N_1}\frac{dN_{12}}{d\Delta\phi}$$

$\rho_W^{p\mathrm{Pb}} = W_{12}^{p\mathrm{Pb}}/W_{12}^{pp}$, with $W_{12} = \mathrm{RMS}(C_{12})$

$\rho_I^{p\mathrm{Pb}} = I_{12}^{p\mathrm{Pb}}/I_{12}^{pp}$, with I_{12} dijet conditional yields

PR C100 (2019) 034903

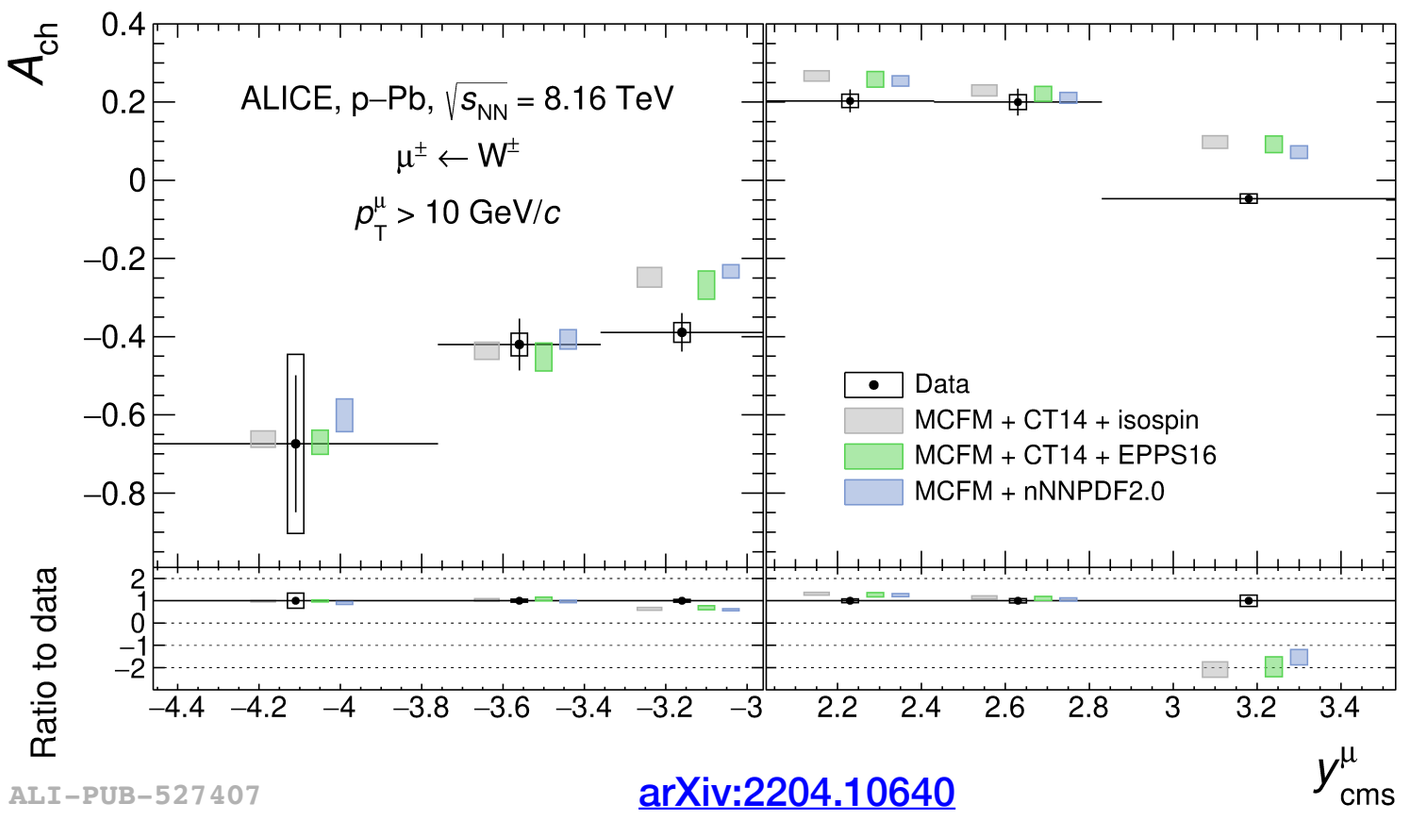




- $\rho_I^{p\mathrm{Pb}}$ suppressed for forward dijets pairs, (shadowing region $x \lesssim 10^{-3}$)
- No modification for backward-forward jets
- Ratio of correlation functions RMS $\rho_W^{p\mathrm{Pb}}$ does not show modification

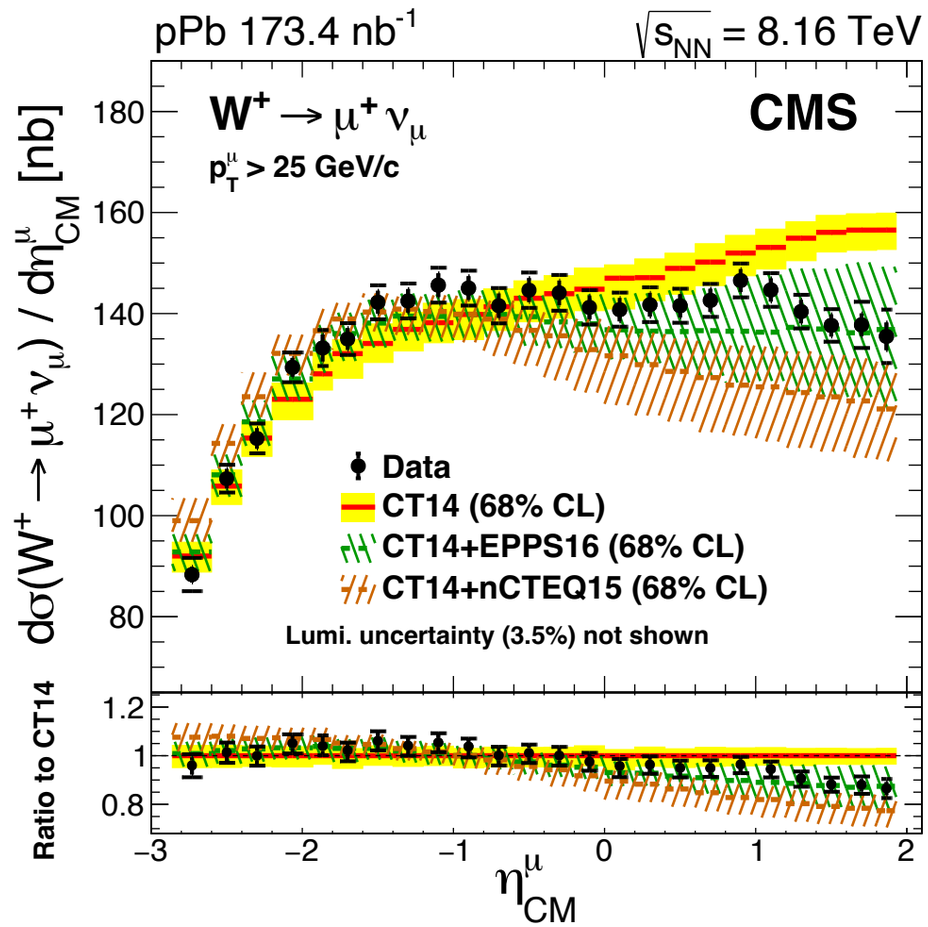
Production of W bosons in pPb

- Charge asymmetry A_{ch} helps to separate $u\bar{d}$ (W^+) and $\bar{u}d$ (W^-) flavours
- Run 2 data from CMS and ALICE
- CMS data included in most nPDF fits
- ALICE A_{ch} in forward bin not reproduced by models (more than 5σ discrepancy)
- $R_{p\mathrm{Pb}}$ of W^- shows tension in backward region with models
- No variation of $\sigma_{p\mathrm{Pb}}^{W^\pm}$ with respect to centrality



arXiv:2204.10640

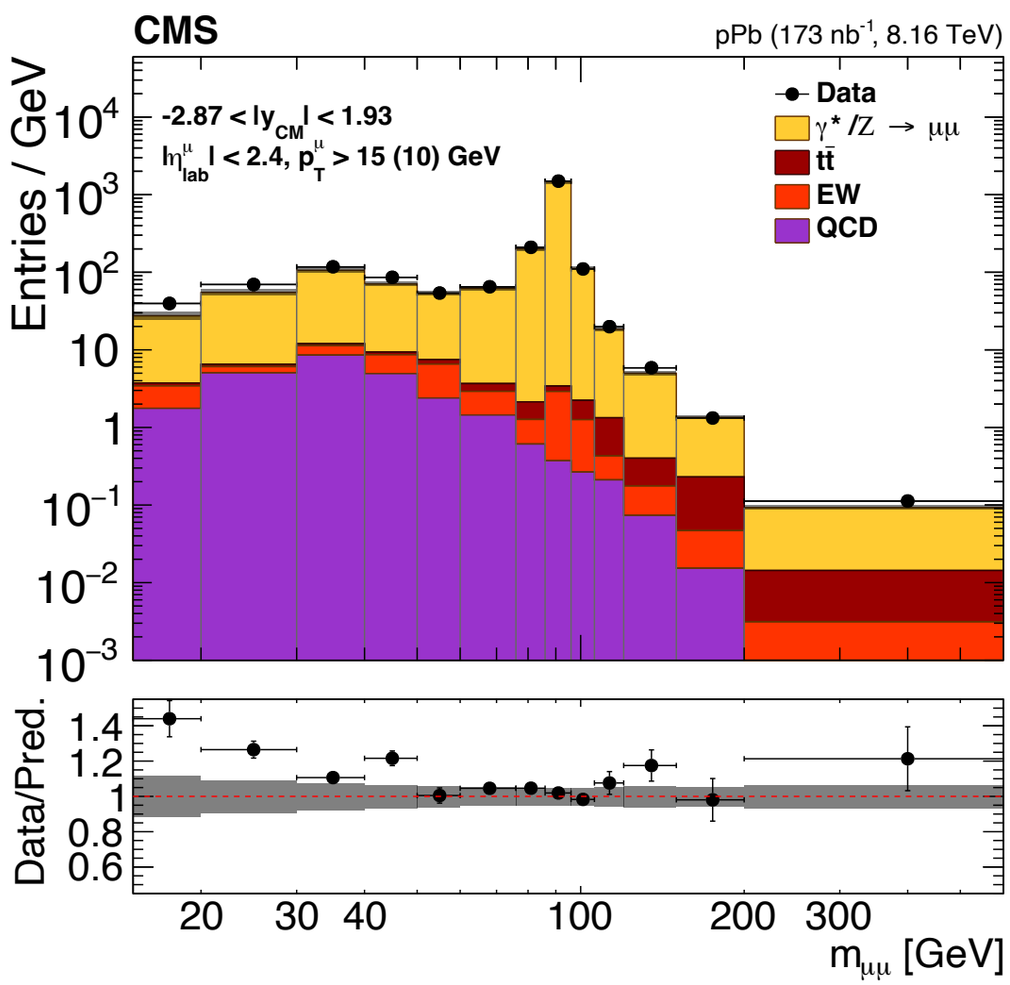
PL B800 (2020) 135048

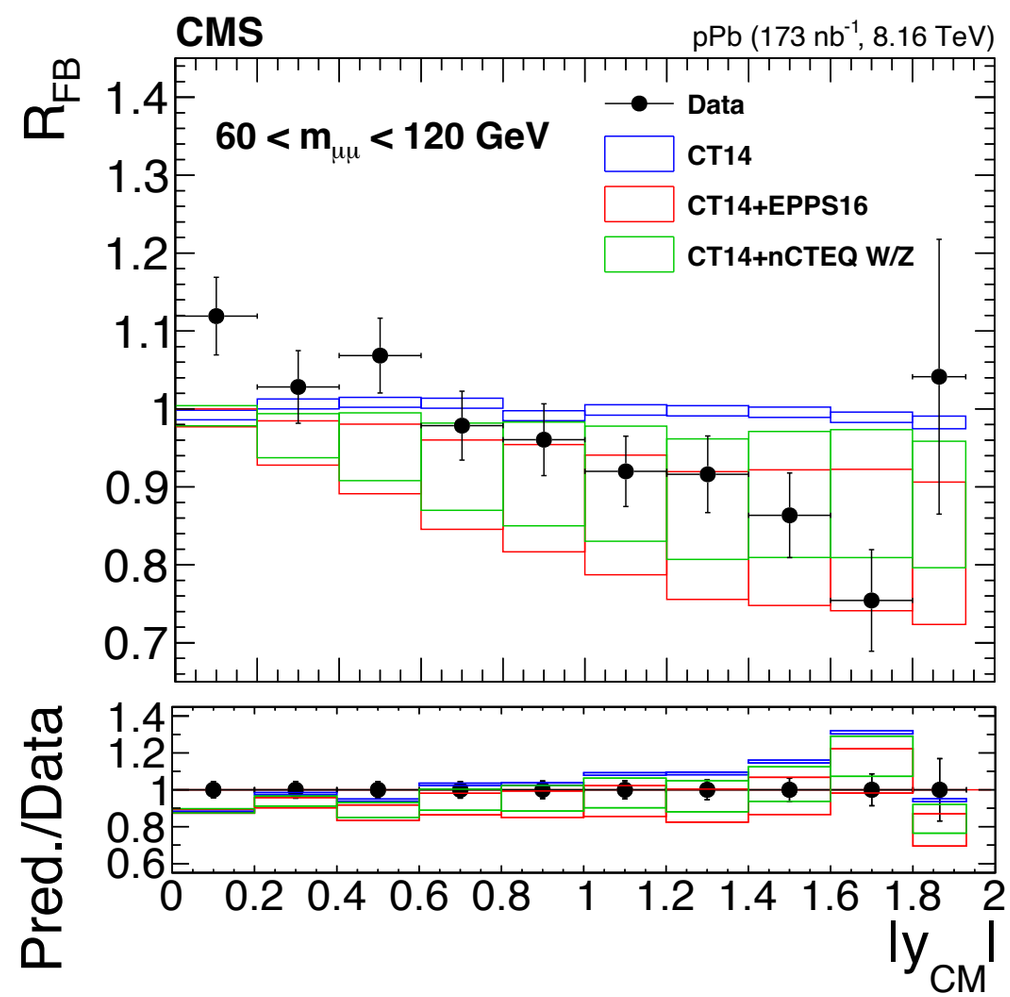


Drell-Yan and Z production in central region

JHEP 05 (2021) 182

- CMS measurement with Run2 data at $8.16\,\mathrm{TeV}$
- Low-mass ($15 < m_{\mu\mu} < 60\,\mathrm{GeV}/c$) and high-mass ($60 < m_{\mu\mu} < 120\,\mathrm{GeV}/c$) regions
  - First measurement at LHC of low-mass in pPb! covering $-2.87 < |\eta_{\mathrm{lab}}| < 1.93$
  - Measurement in $m_{\mu\mu}$ y_{CM}, p_{T} and ϕ^*, where $\phi^* = \tan(\frac{\pi - \Delta\phi}{2})\sin(\theta^*_\eta)$ with $\cos(\theta^*_\eta) = \tanh(\Delta\eta/2)$
  - Correlation matrices of systematic uncertainties
- Forward-to-backward ratio shows more precision than EPPS16 and nCTEQW/Z

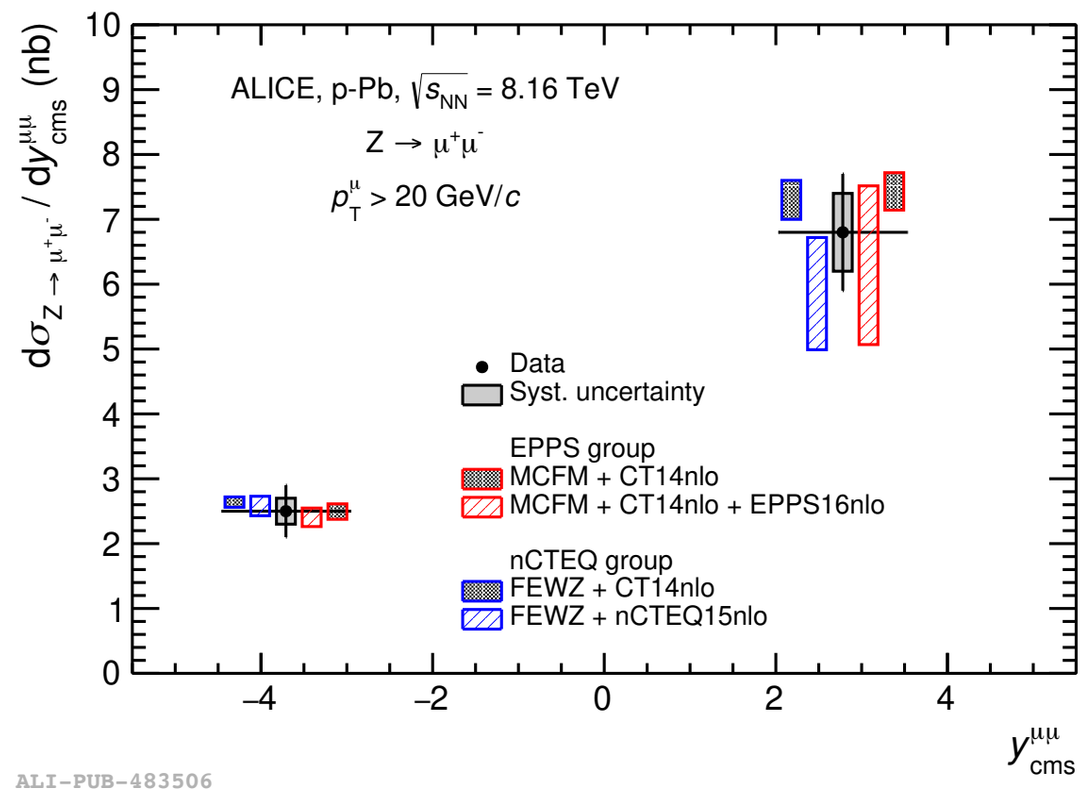




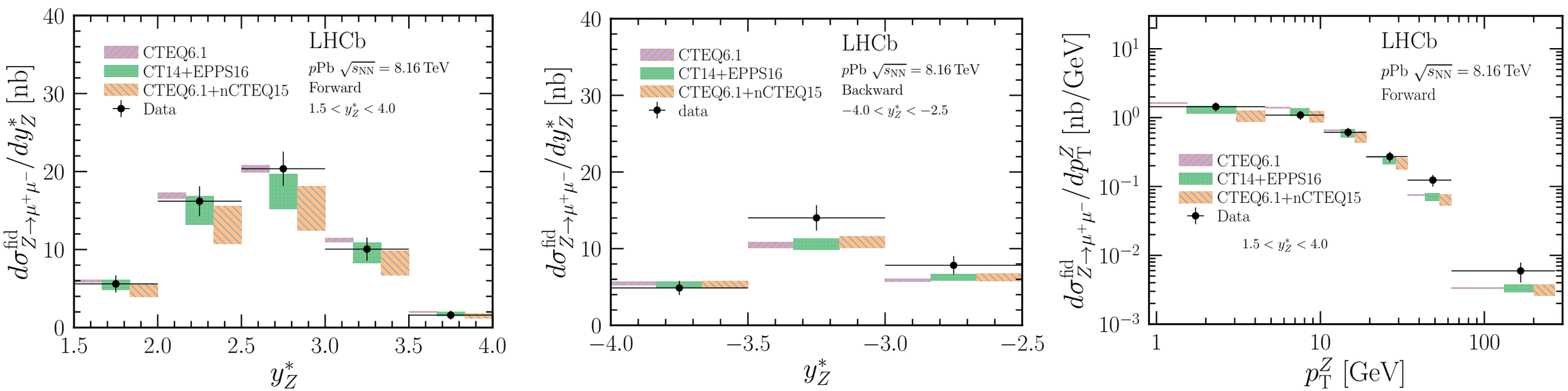
Z boson in forward and backward regions

- LHCb and ALICE measured $Z \to \mu^+\mu^-$ in the forward and backward regions with Run 2
  - LHCb measurement includes p_T, y^* and ϕ^* dependance, R_{FB} and R_{pPb}
  - correlation matrices of systematic uncertainties
- Can extend CMS constrains towards lower and higher x
- Both measurements in general agreement with EPPS16 and nCTEQ15 predictions
- ALICE data included in nNNPDF3.0 (EPJ C82 (2022) 6, 50), LHCb not yet

ALICE: JHEP 2009 (2020) 076



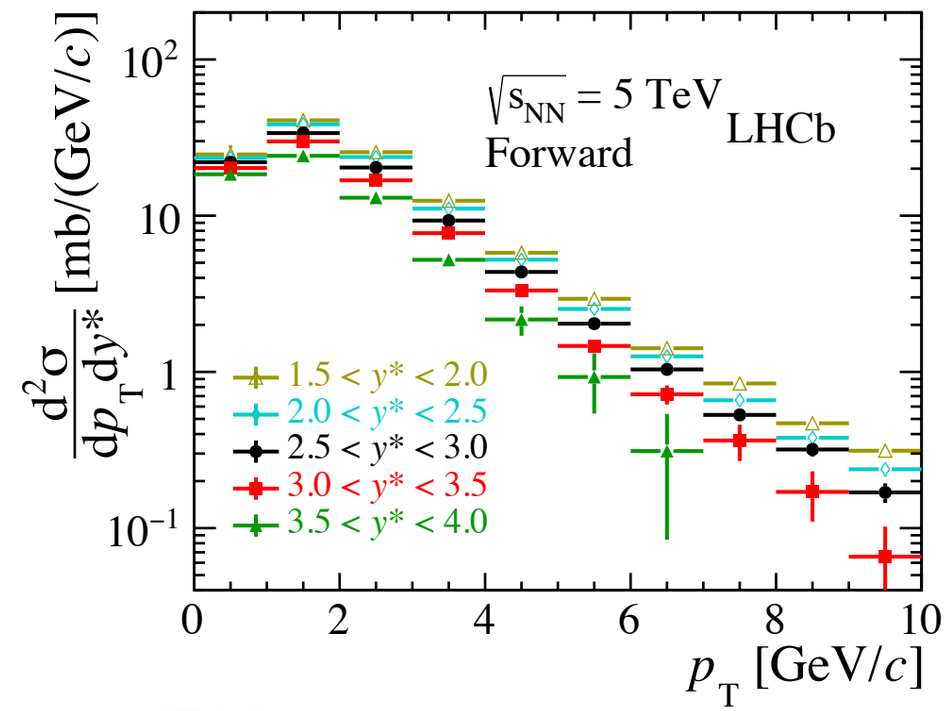
LHCb: arXiv:2205.10213



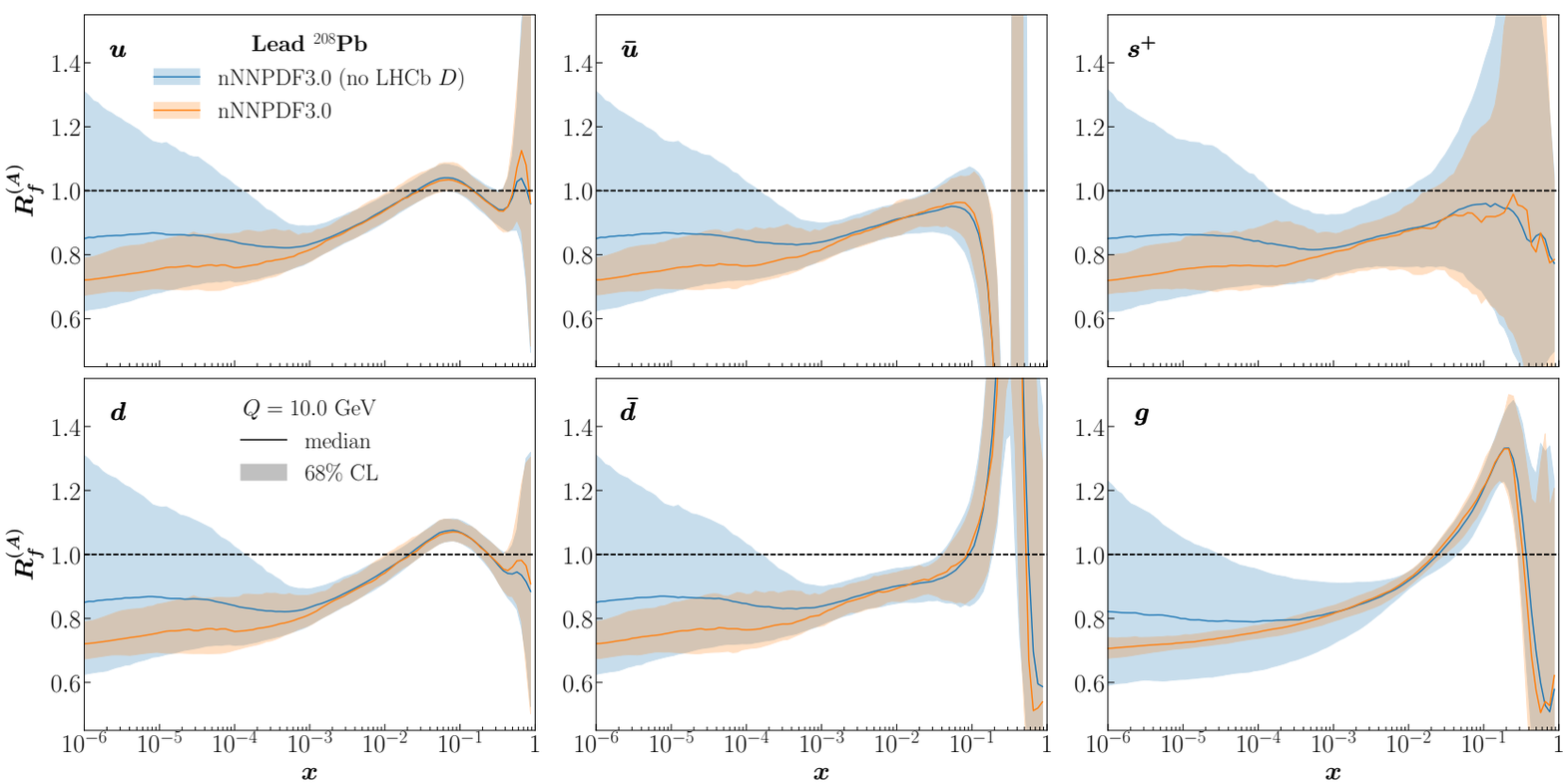
D^0 meson production

JHEP 10 (2017) 090

- LHCb measured D^0 meson production with Run 1 data ($\mathscr{L}_{p\mathrm{Pb}} \sim 1.5\,\mathrm{nb}^{-1}$) in $1.5 < y^* < 4.0$ and $-5.0 < y^* < -2.5$
- Measure double-differential cross-sections, $R_{p\mathrm{Pb}}$ and R_{FB}
- Data included in EPPS21 (EPJ C82 (2022) 5, 413) and nNNPDF3.0 (EPJ C82 (2022) 6, 50)
  - Drastic reduction of nPDF uncertainties down to $x \sim 10^{-6}$



EPJ C82 (2022) 6, 50



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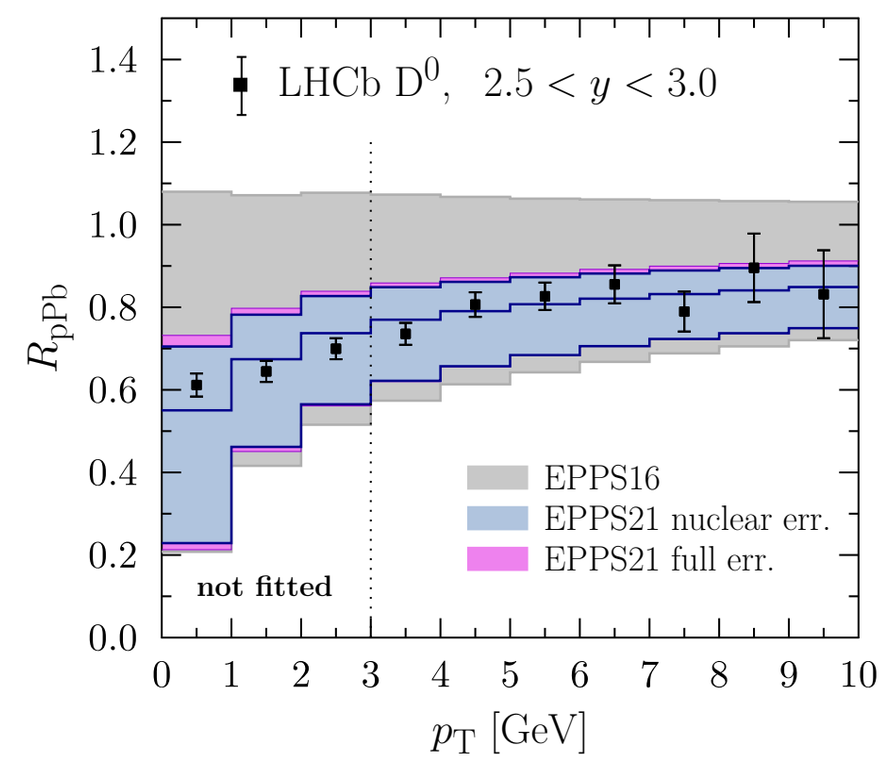


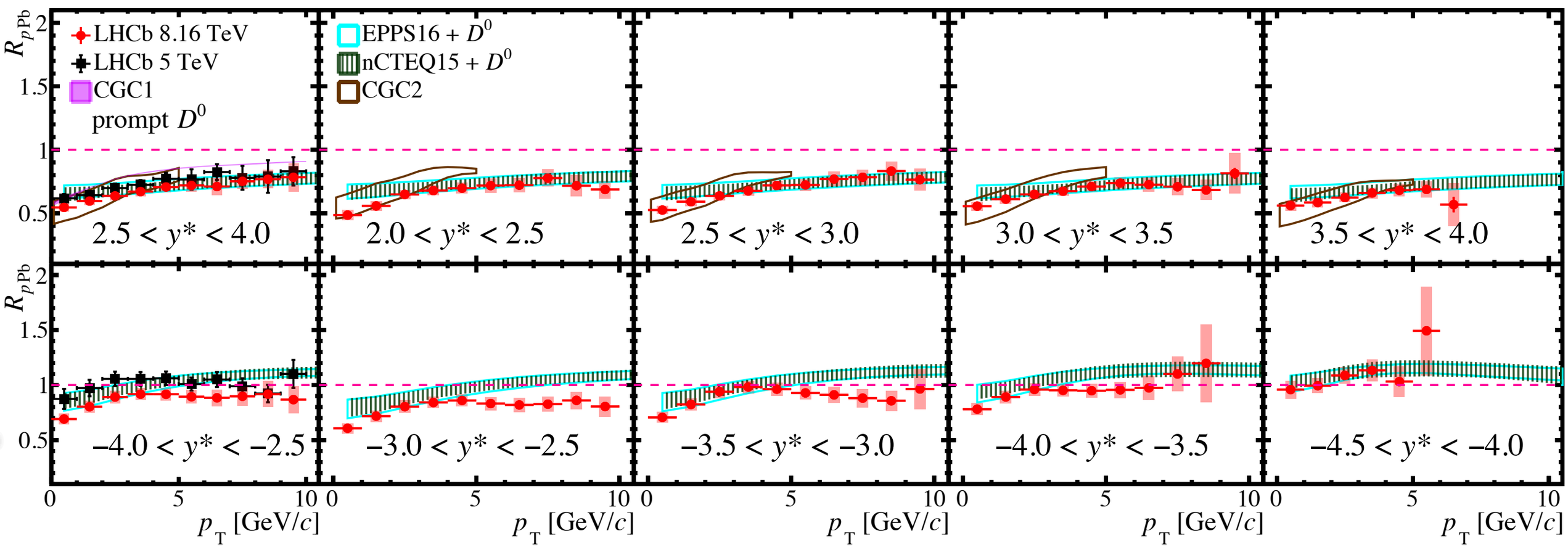
D^0 meson production

arXiv:2205.03936

- New LHCb D^0 meson production measurement with Run 2 data ($\mathscr{L}_{p\mathrm{Pb}} \sim 30\,\mathrm{nb}^{-1}$)
- Finer y^* binning and extended range to $p_\mathrm{T} \in [0,30]\,\mathrm{GeV}/c$
- Comparison with HELAC-Onia predictions with EPPS16 and nCTEQ15 weighted with Run1 D^0 data
  - Discrepancy in backward rapidity at high p_T with reweighted nPDF predictions
  - Great potential for additional constrains

y^* integrated

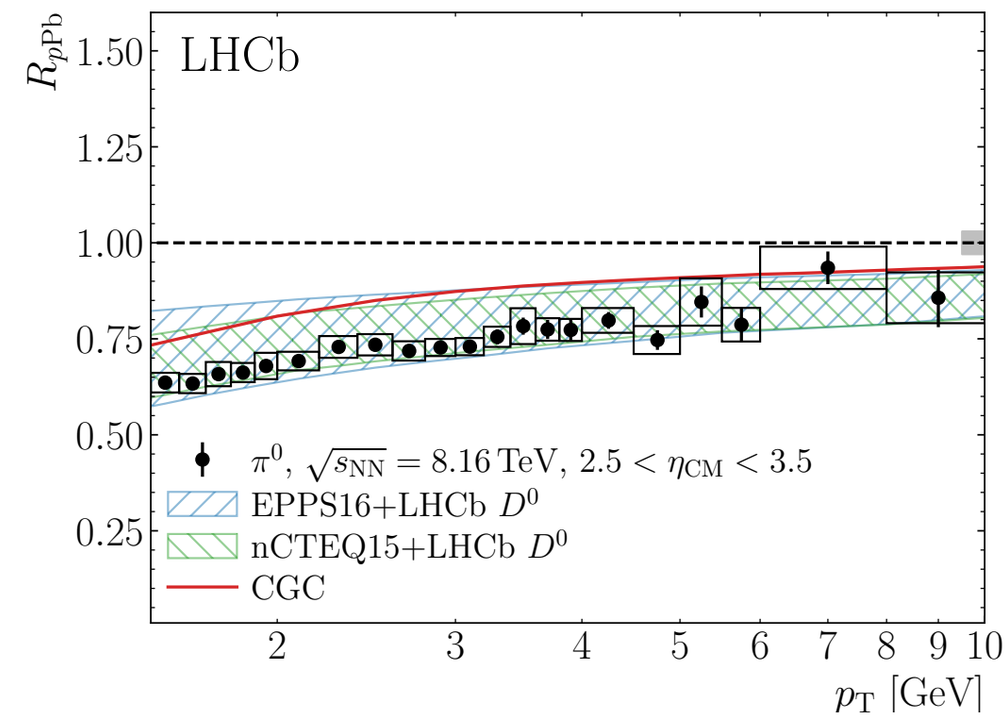
in y^* intervals

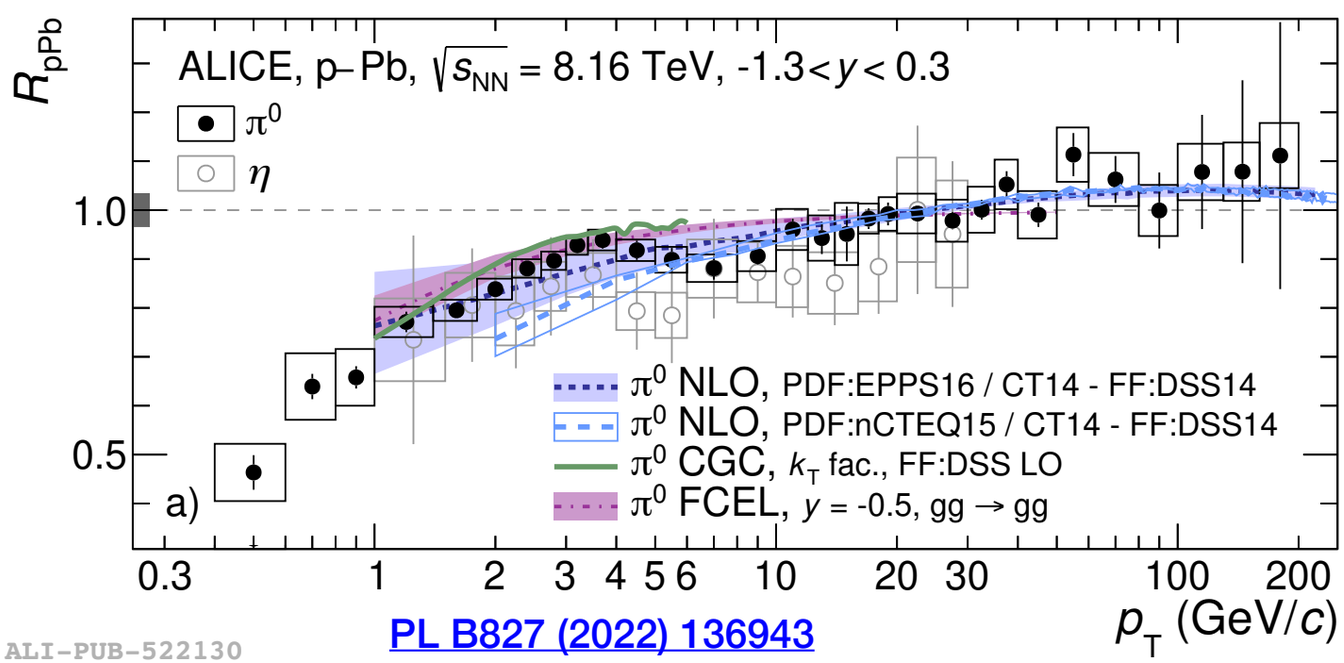


Hadrons: π^0 meson production

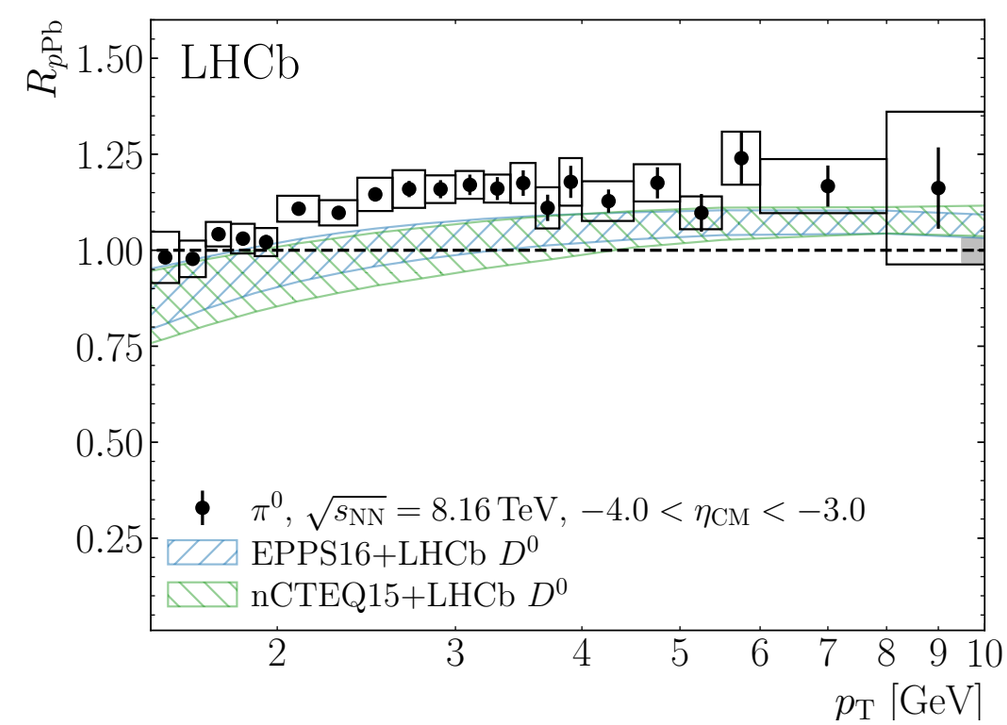
- Precise measurement π^0 spectrum from ALICE and LHCb Run 2 data
- Very wide phase-space coverage:
  - ALICE: $-0.3 < y < 1.3$ and $0.3 < p_{\mathrm{T}} < 200\,\mathrm{GeV}/c$
  - LHCb: $2.5 < \eta_{\mathrm{CM}} < 3.5$, $-4.0 < \eta_{\mathrm{CM}} < -3.0$ and $1.5 < p_{\mathrm{T}} < 10\,\mathrm{GeV}/c$
- Excess in backward region over nPDF predictions
  - ALICE data included in nCTEQ15WZSIH (PR D104, 094005)
  - Considers $\pi^{\pm}, K^{\pm}$ ALICE data (PL B760, 720 (2016))
- Also new LHCb charged hadron result with wide η coverage in $-5.3 < \eta < -2.5$ and $2.0 < \eta < 4.3$ (PRL 128 (2022) 142004)

arXiv:2204.10608





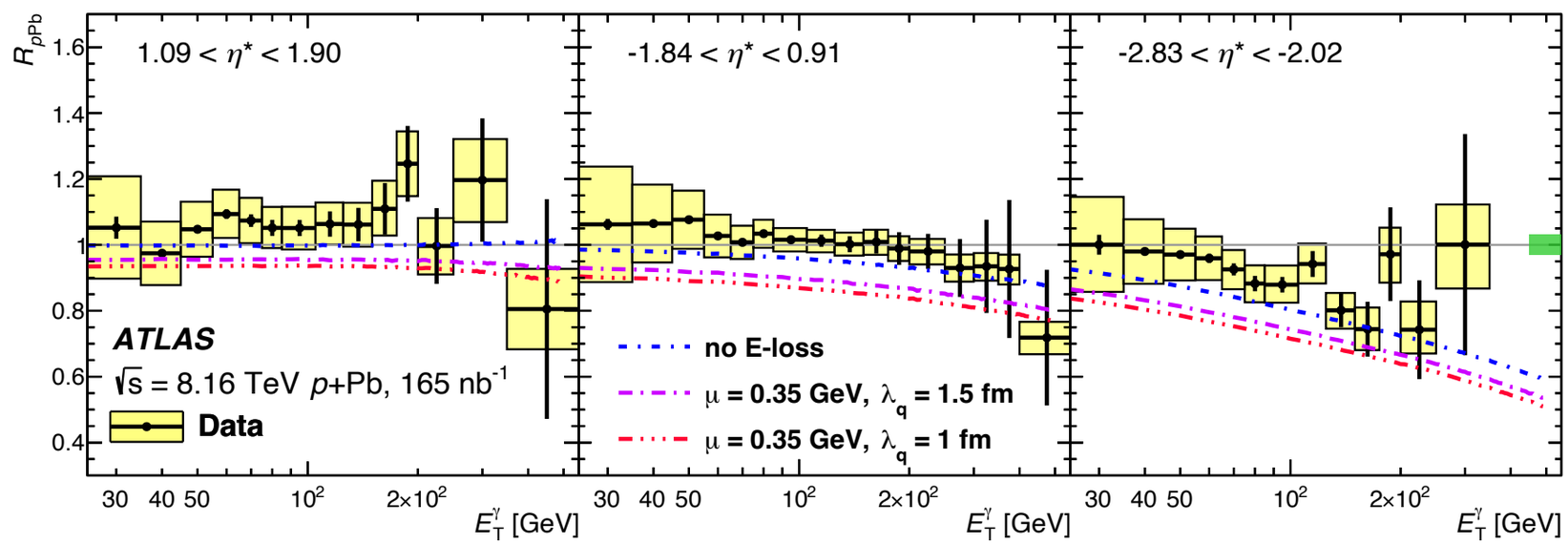
PL B827 (2022) 136943



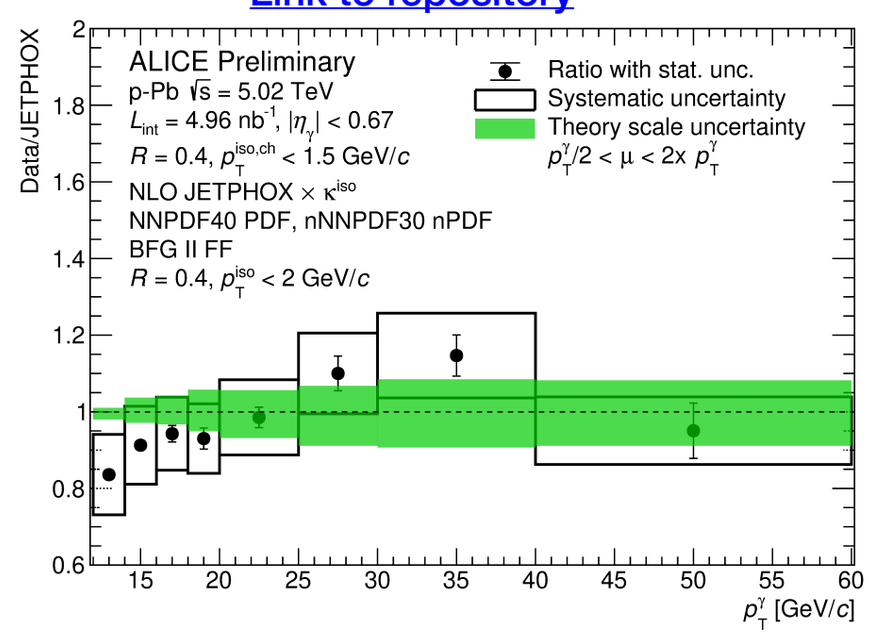
Prompt photons in pPb

- Direct/prompt photons provide direct access to initial conditions of nuclei
- ATLAS measurement with Run2 data
  - Isolated photons in cone of $\Delta R = 0.4$
  - measured $d\sigma/E_{\mathrm{T}}^{\gamma}$, $R_{p\mathrm{Pb}}$ and R_{FB}
  - large energy-loss contribution is not observed
  - compatible with expectations from EPPS16 and nCTEQ15
  - Included in nNNPDF3.0 fit (EPJ C82 (2022) 6, 50)
- Access to lower γ energy?
  - Preliminary plot from ALICE
  - LHCb potential in forward & backward regions
  - ALICE FoCal detector in Run4: photons of $p_{\mathrm{T}} > 2\,\mathrm{GeV}/c$ in $3.4 < \eta < 5.8$

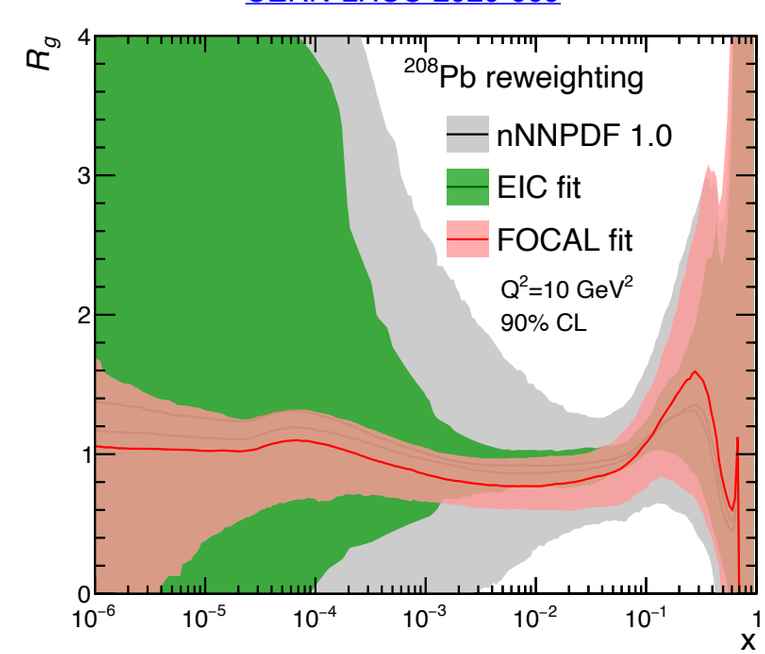
PL B796 (2019) 230



Link to repository



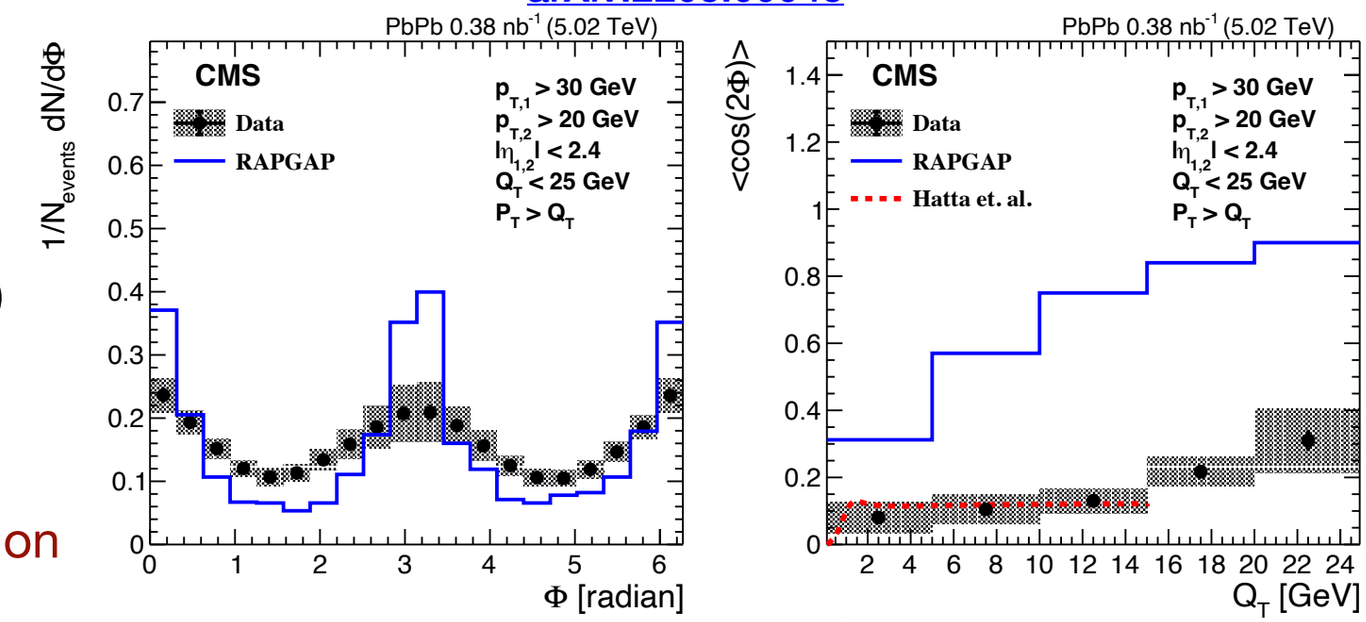
CERN-LHCC-2020-009



Constrains from γPb process

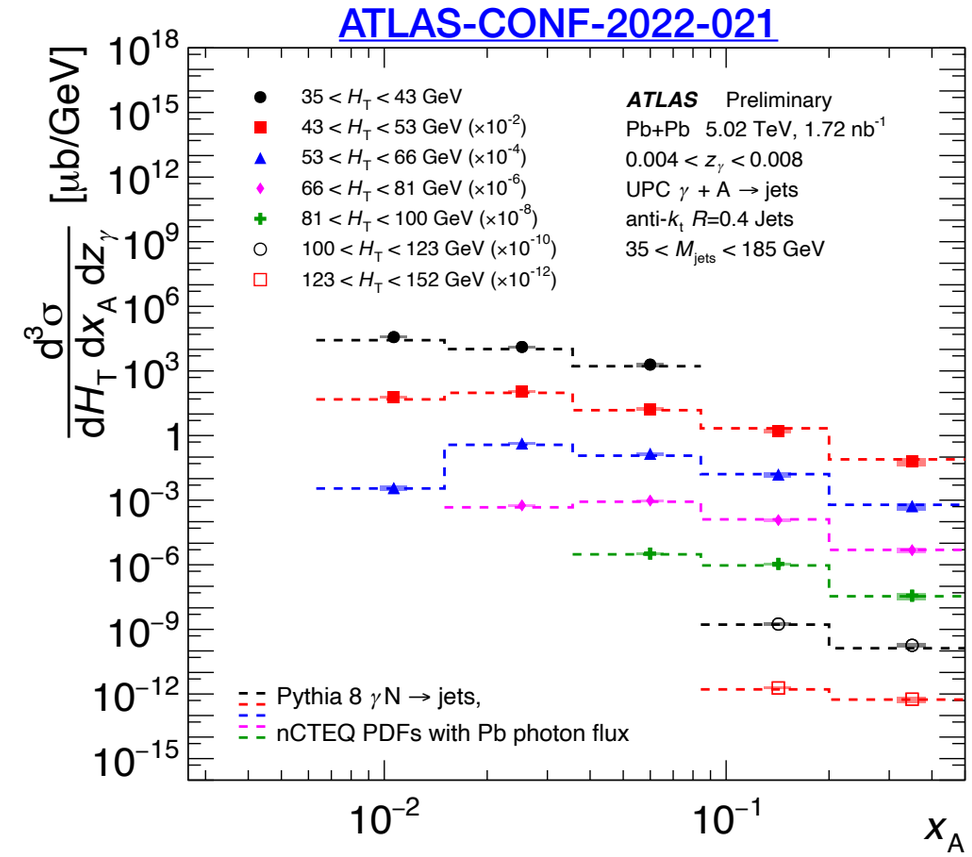
- CMS measured dijet azimutal correlations in exclusive γPb processes
  - RAPGAP model overestimates strength of correlations CPC 86 (1995) 147
  - soft gluon radiation calculation (Hatta et. al.) reproduces low Q_T PRL 126 (2021) 142001
  - information of gluon polarization in nuclei
- Preliminar ATLAS measurement of dijet production in γPb
  - ZDC tag events without nuclear break-up, results for results for $0nXn$ condition
  - Complementary (x, Q^2) coverage to pPb dijets
  - expectations to increase precision in final result
- Exclusive quarkonia production in UPC → see Wed. 16:00, A. Matyja talk, parallel A

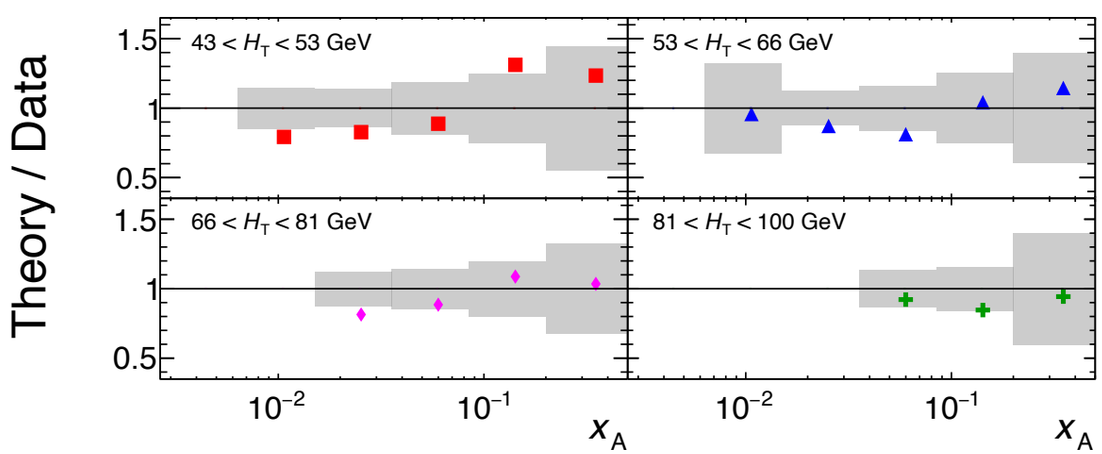
arXiv:2205.00045



$$\overrightarrow{Q_T} = \overrightarrow{p}_{T,1} + \overrightarrow{p}_{T,2}$$

ATLAS-CONF-2022-021





Conclusions and prospects

- Huge progress of the understanding of CNM in the recent years, with LHC data playing a major role
- LHC pPb data (dijets, D^0,...) sets unprecedented constraints to nPDF
- Tensions with nPDF predictions in several recent measurements not yet included in global analyses, such as:
  - $W^{\pm}$ production in forward/backward regions (ALICE)
  - D^0 production in backward region (LHCb)
- $\gamma\mathrm{Pb}$ interactions in UPCs provide a unique source of information (strength of gluon polarization)

- Prospects for Run3/Run4:
  - great increase in statistics from a new $p\mathrm{Pb}$ run, several measurements now limited to pp collisions would become possible
  - Future $p\mathrm{O}$ run crucial do reduce nPDF uncertainties by setting constrains to a medium size nucleus
    - ✳ Some of the mentioned measurements can be performed with very limited statistics (i. e. light hadron production)

Backup