Initial state and nPDF

experimental considerations

2023 CMS Heavy Ion Workshop

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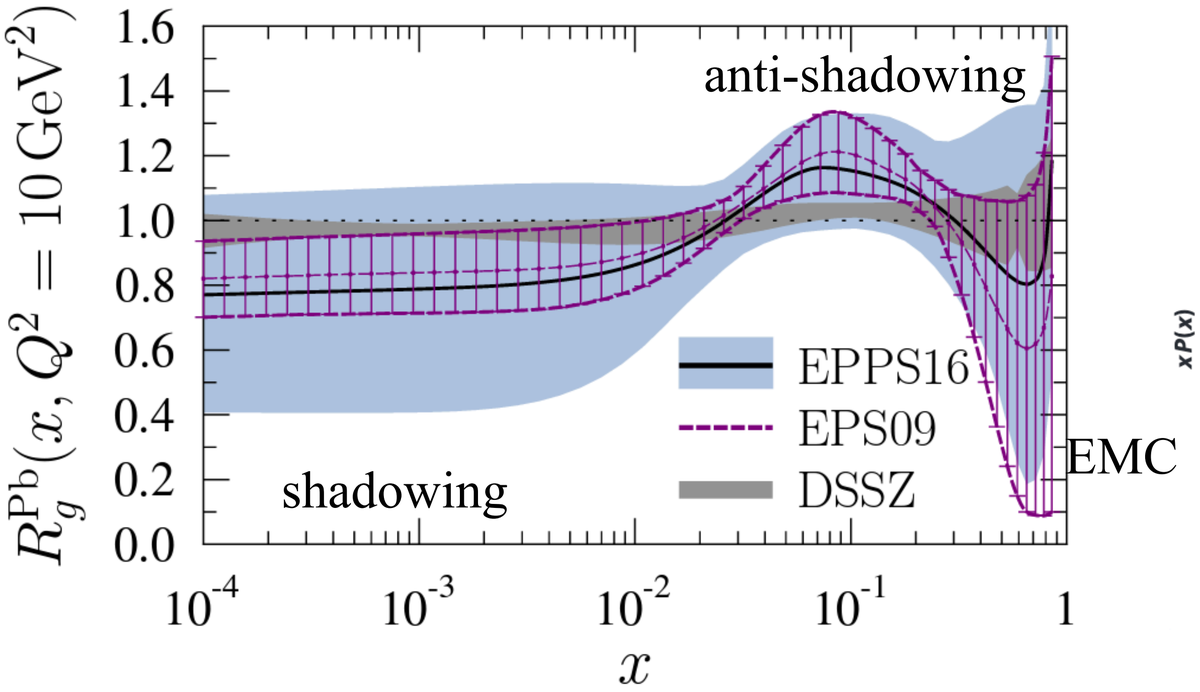
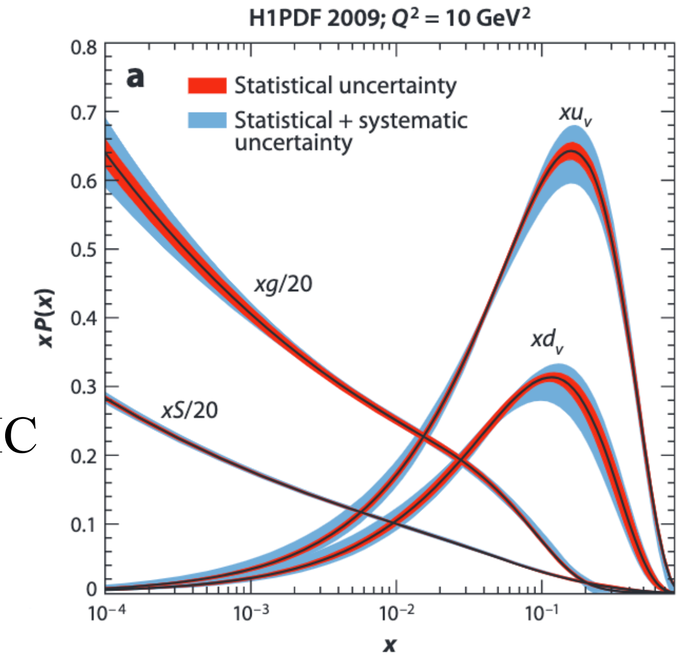
Initial state effects

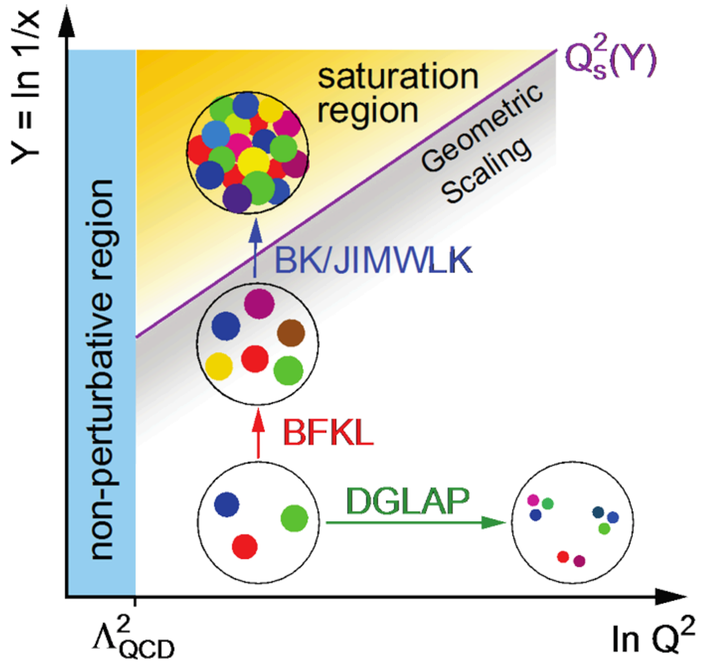
- Parton densities are modified in nuclei
  - Shadowing: depletion of the effective number of gluons in low-x.
  - Antishadowing, EMC effects…
  - Poorly constrained from previous data



arXiv:1612.05741

- Large number of small-x gluons, leading to a very dense saturated wave function known as the Color Glass Condensate (CGC)
  - Saturation scale $Q_s^2 \propto A^{1/3}$ (Lorentz contraction)
  - Expected in small x and small Q^2 region
- Initial state energy loss

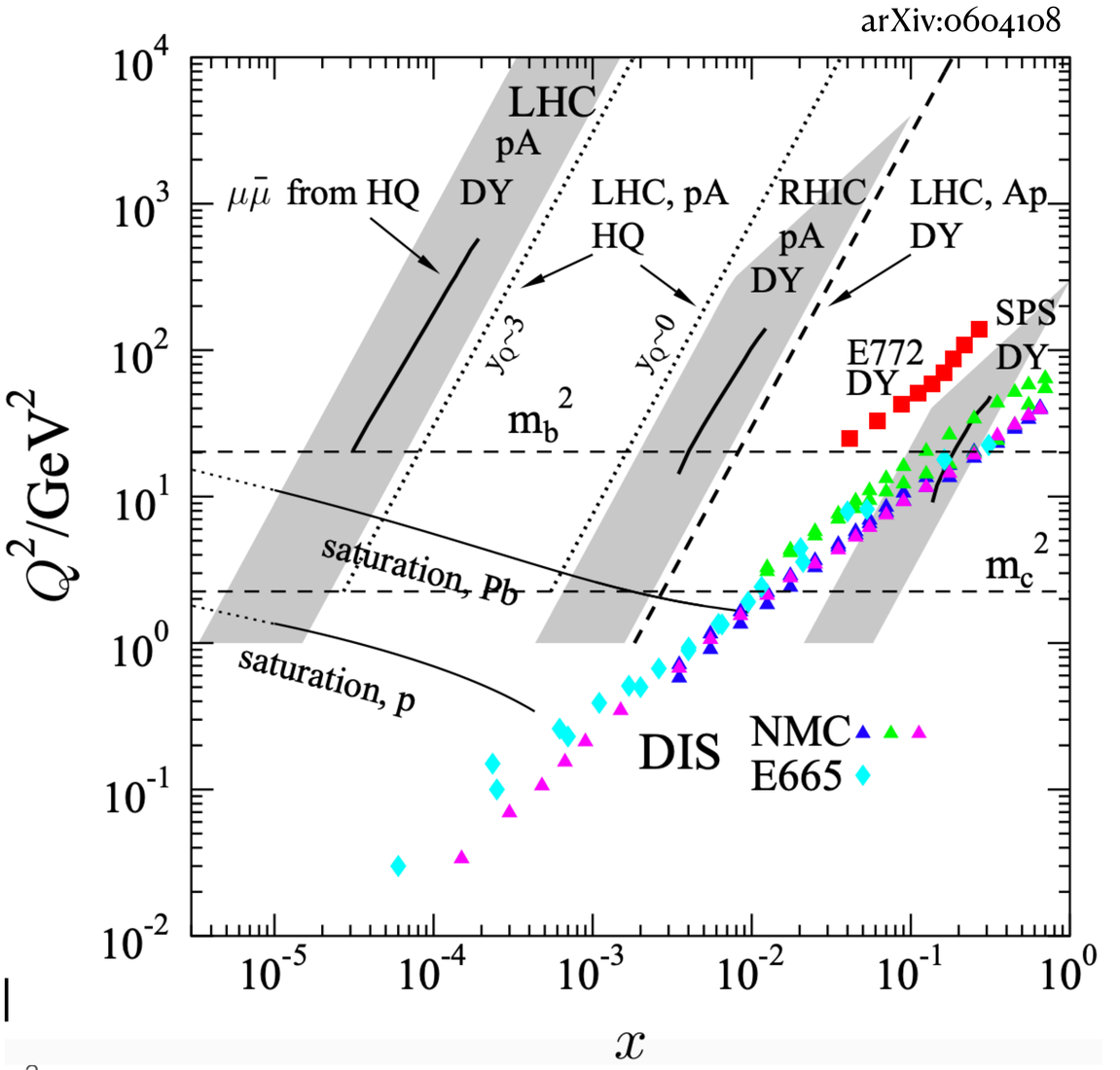




Annu. Rev. Nucl. Part. Sci. 60:463-89

Experimental approach

- Studied using pA collisions/γA collisions
- Probes:
  - Dijets
  - W/Z, Drell-Yan
  - Direct photons
  - Heavy flavor
  - Light hadrons
  - VM in Ultra-Peripheral AA Collisions
- Observables:
  - $R_{p\mathrm{Pb}}$, R_{FB}, production cross-section, angular correlations…



Recent measurements

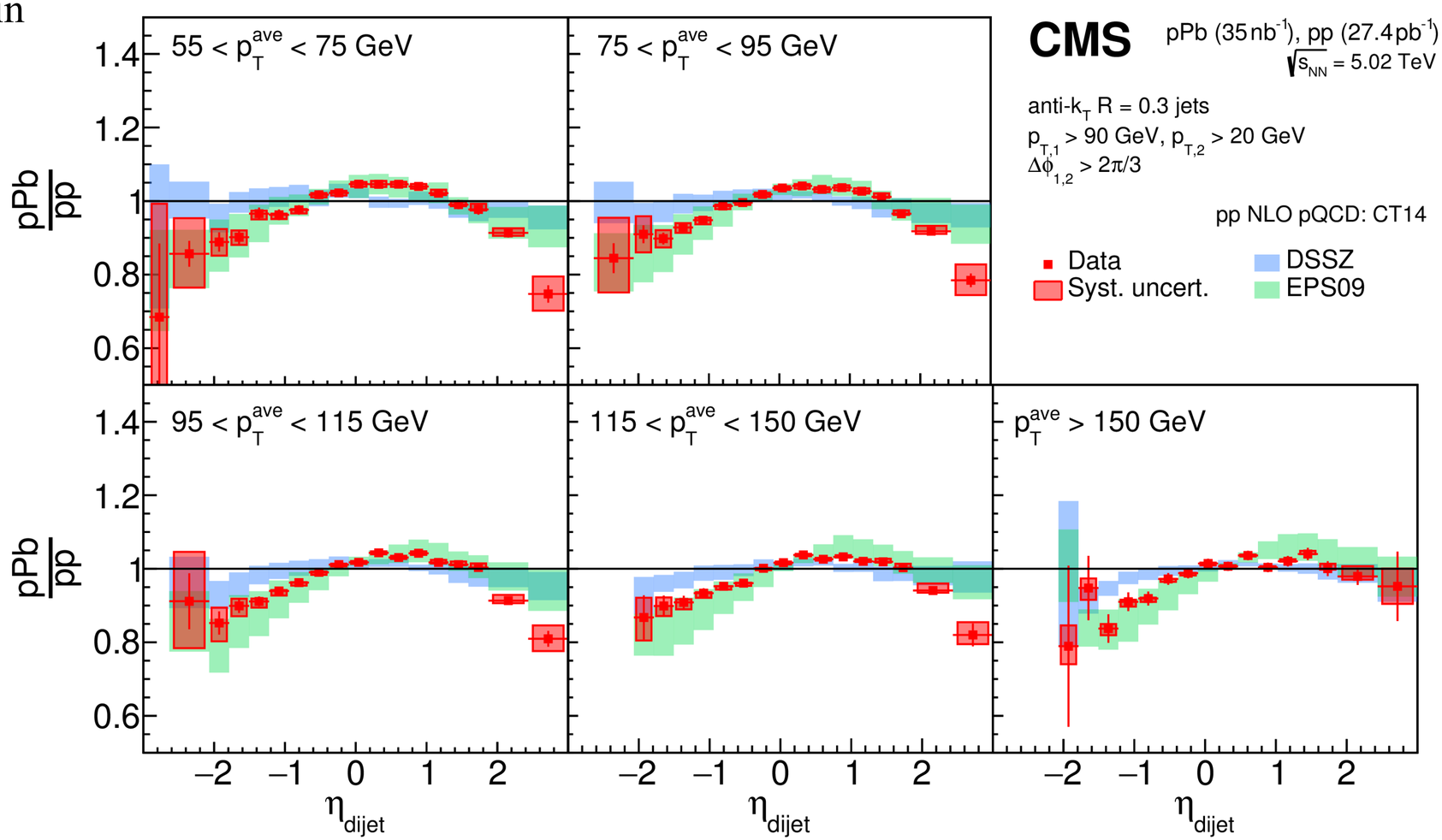
- Incomplete summary, LHC focused
- UPC results: dedicated talks on Tuesday
- New JLab precision data in EMC region- included in nCTEQ15HiX [arXiv:2012.11566]
- RHIC pion data constrain the gluon density down to $x \sim 10^{-3}$
- Recent LHC data provide constraints down to $x \sim 7 \times 10^{-6}$

Probes	ALICE	ATLAS	CMS	LHCb
Dijets		5 TeV	5 TeV	
W,Z,DY	W&Z @ 8.16TeV		W, Z&DY 8.16 TeV	Z 5, 8.16 TeV
Direct photon	$12 < p_{\mathrm{T}}^{\gamma} < 80$ GeV/c	$20 < E_{\mathrm{T}}^{\gamma} < 500$ GeV/c		
Heavy flavor	D mesons midrapidity			D, B mesons Fwd/bwd rapidity
Light flavor	$-1.3 < \eta < 0.3$		$\lvert\eta\rvert < 1$	Charged hadrons, neutral pions, Forward rapidity

Dijet production in 5 TeV *p*Pb collisions

PRL121(2018)062002

- Dijet pseudorapidity distribution in *p*Pb collisions provides strong constraints on the gluon nPDFs
- Shadowing:
  - $\eta_{dijet} > 1.5$
- Antishadowing
  - $-0.5 < \eta_{dijet} < 1.5$
- EMC effects
  - $\eta_{dijet} < -0.5$
- Data included in EPPS21 and nNNPDF3.0
  - Significant reduction of uncertainty

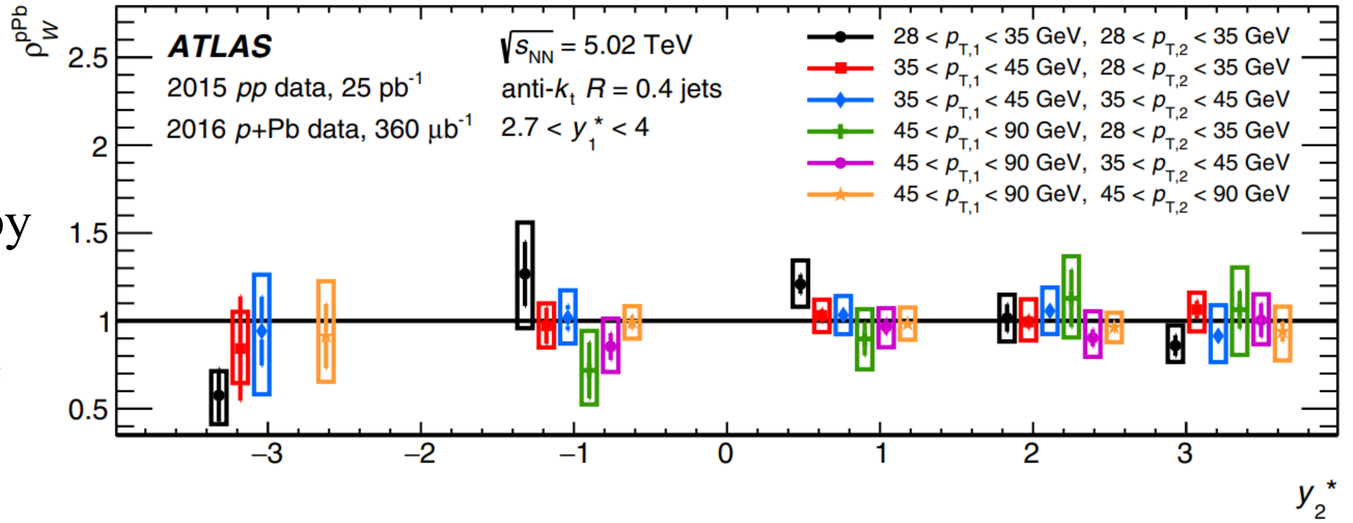


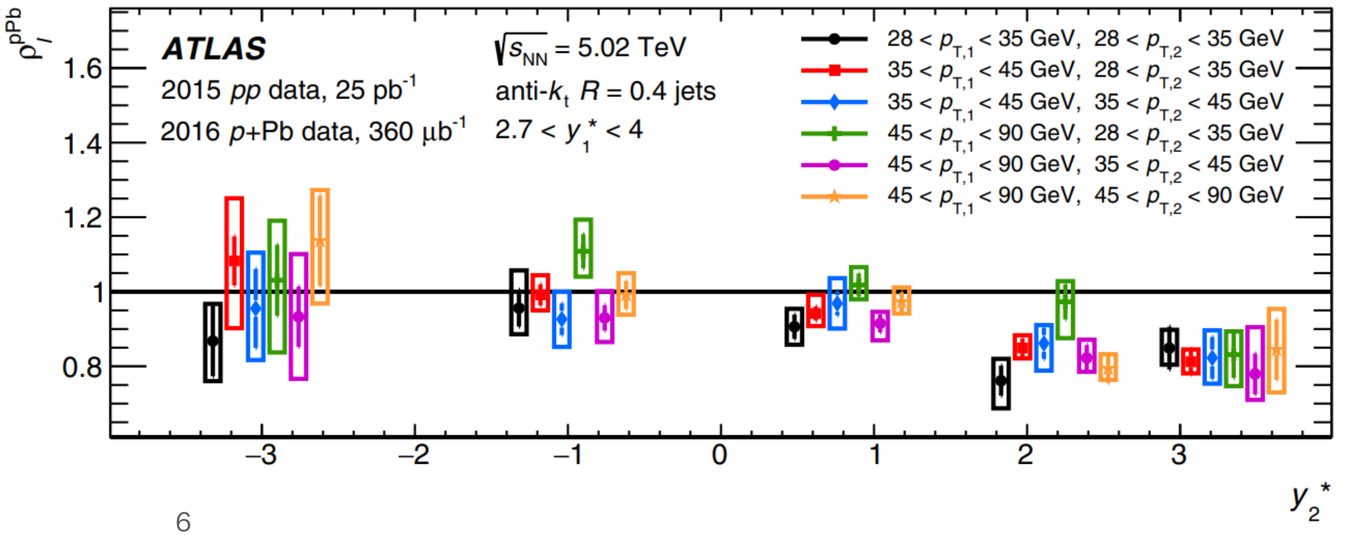
$$\eta_{dijet} = \frac{\eta_1 + \eta_2}{2}$$

Dijet correlations and yields in 5 TeV *p*Pb collisions

PRC100(2019)034903

- Probe gluon saturation in nuclear gluon densities with dijet azimuthal angular distribution at forward rapidities, proposed by CGC
- Back-to-back dijets probe gluon fields in the lead nucleus at low momentum
- No significant broadening of azimuthal angular correlations
- Conditional yields in *p*Pb in forward region suppressed by ~ 20%

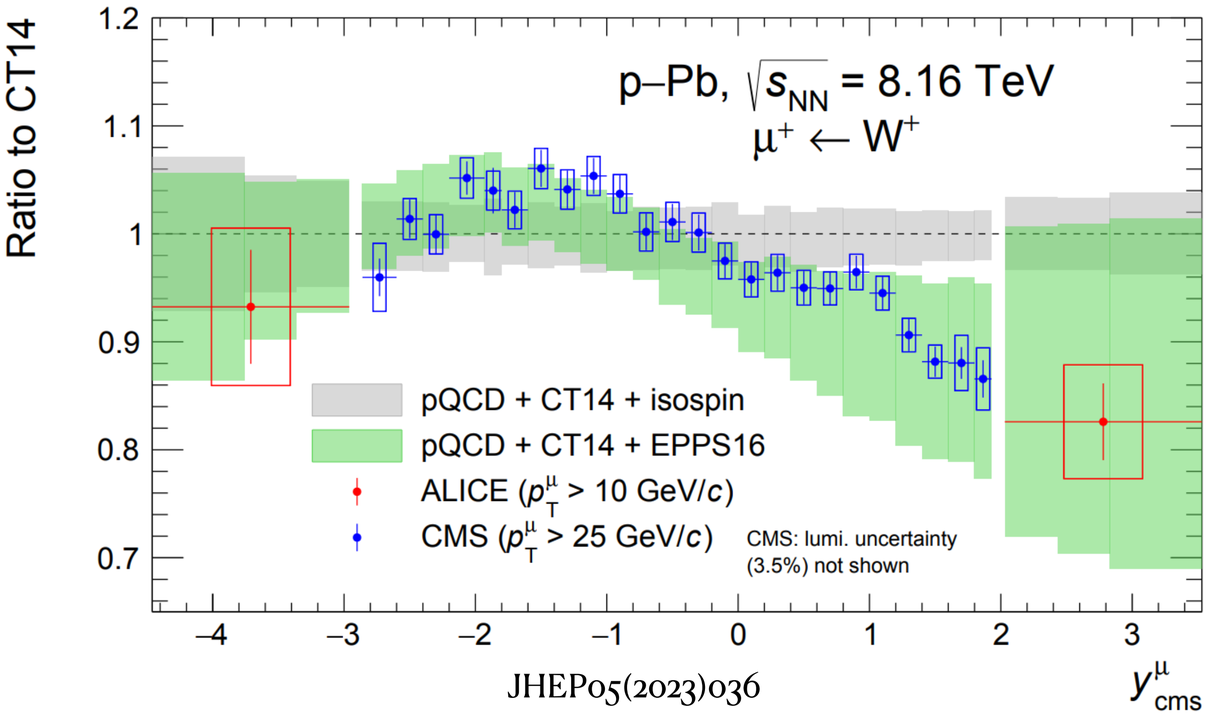




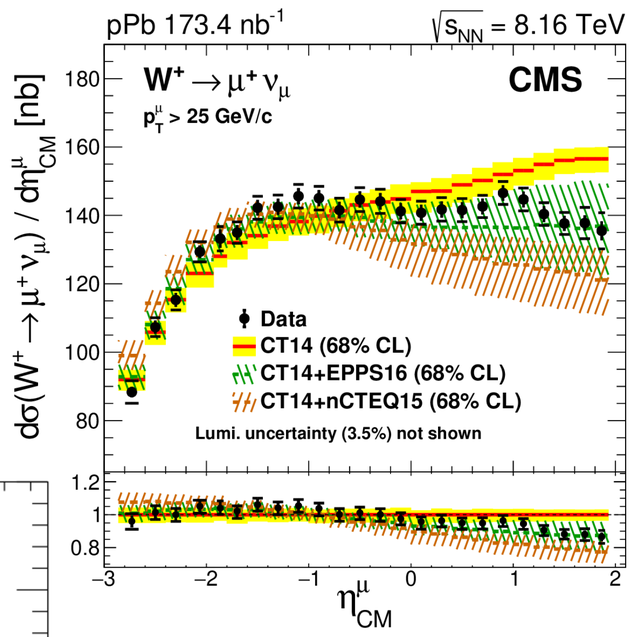
W production in 8.16TeV *p*Pb collisions

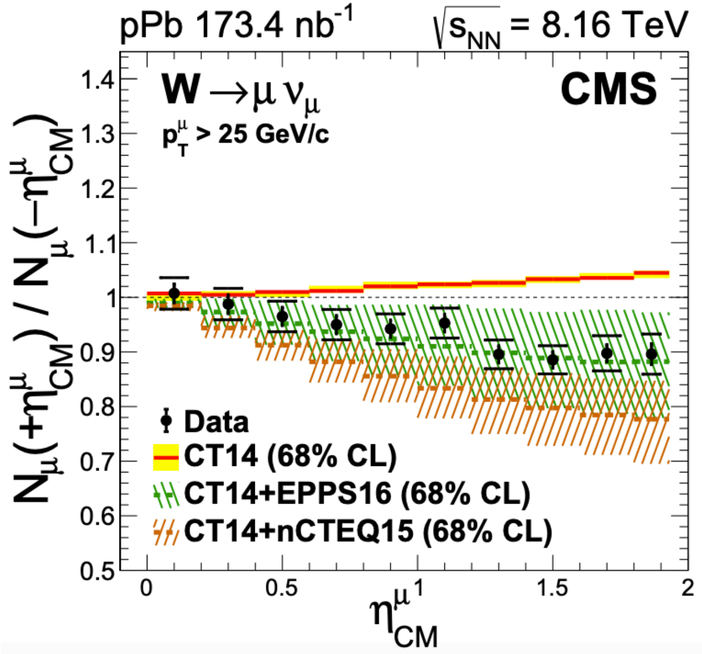
Phys. Lett. B 800 (2020) 135048

- Deviation from CT14 PDF
- Data favor calculations including nPDF effects
- Reduction of uncertainties of the quark and antiquark nPDFs in $10^{-1} < x < 10^{-3}$



JHEP05(2023)036

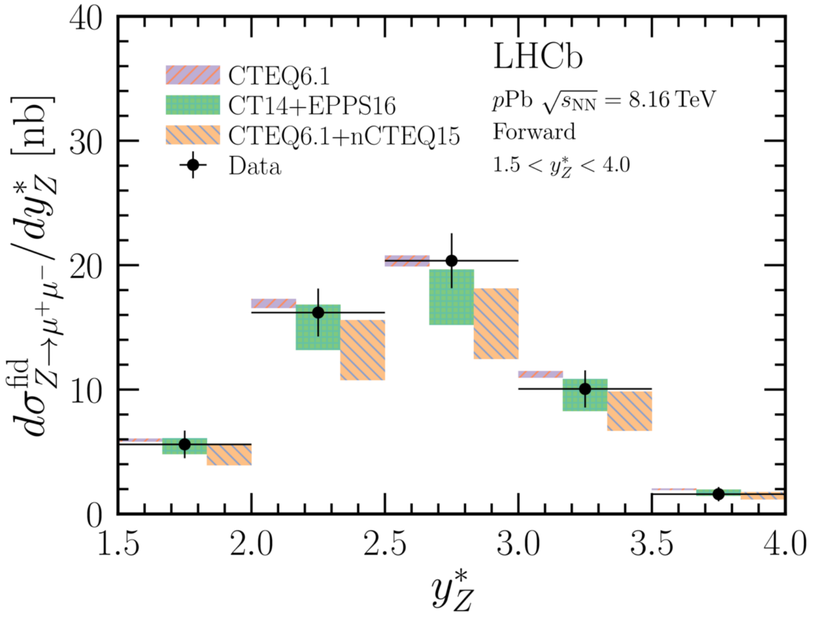


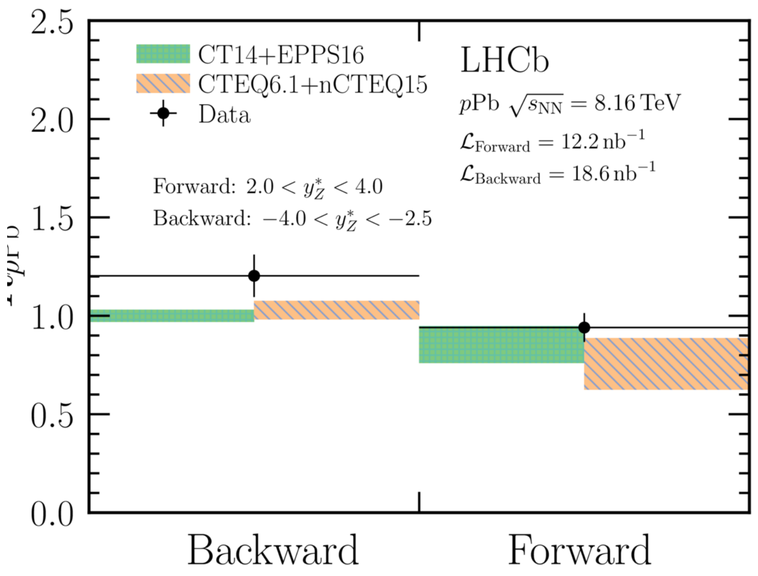


- reaches large |y| region ($x \sim 10^{-4}$ at forward region)
- ALICE data continue with the trend of CMS data
- Suppression at large rapidity
- Support shadowing of the nuclear PDFs
- Extend into EMC region

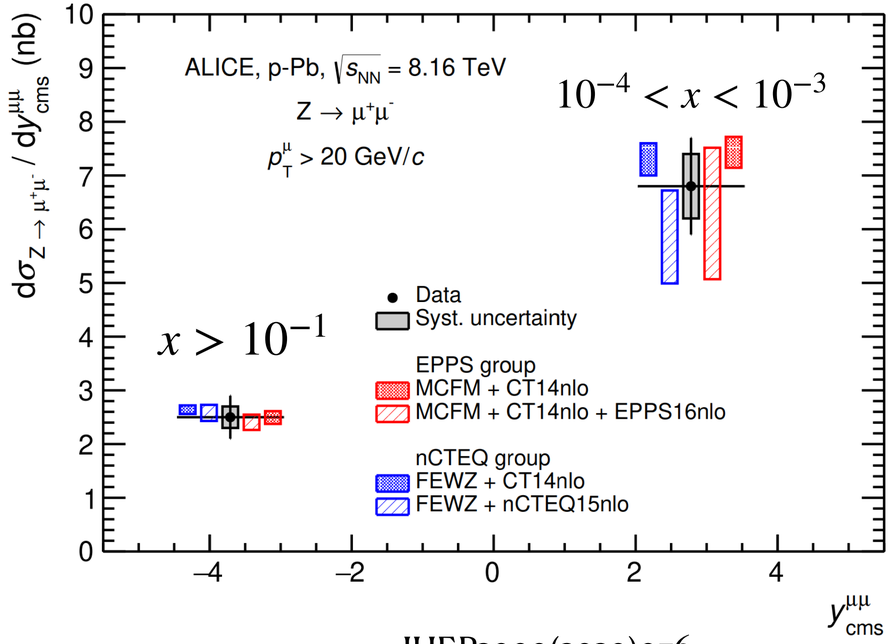
Z production in 8.16 TeV *p*Pb collisions

- Forward region: consistent with calculations with PDFs and nPDFs
- Backward region: data higher than theoretical calculations
- $R_{p\mathrm{Pb}}$: forward data more precise than nPDF calculations





- Consistent with pQCD calculations incorporating
  - free-nucleon PDF
  - nuclear-modified PDFs



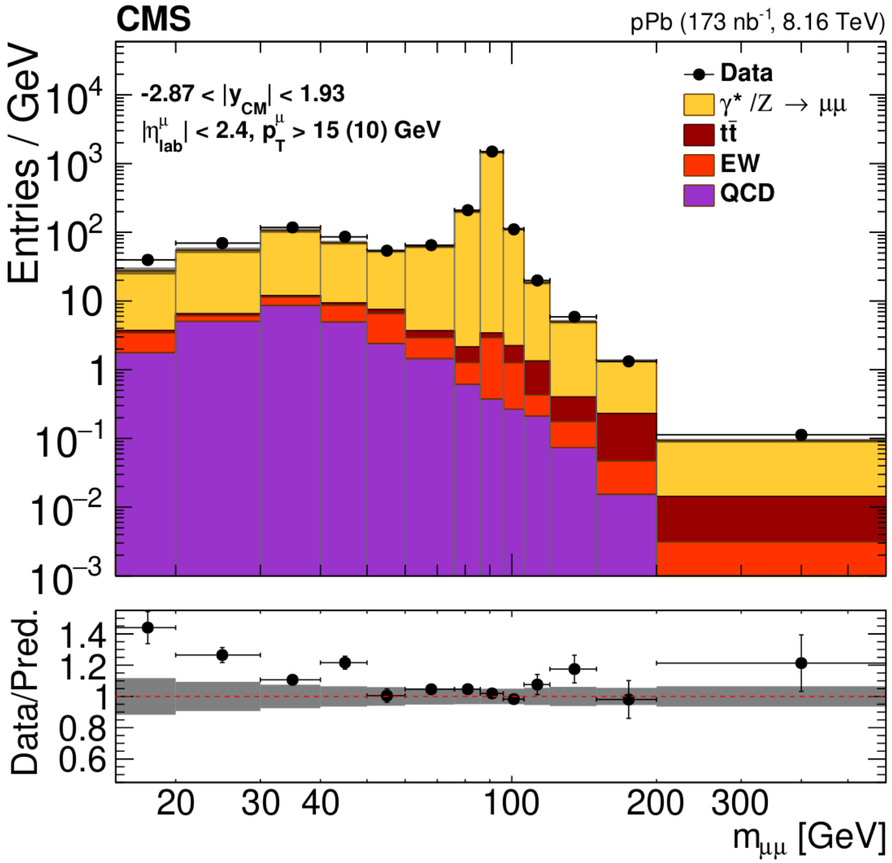
arXiv:2205.10213

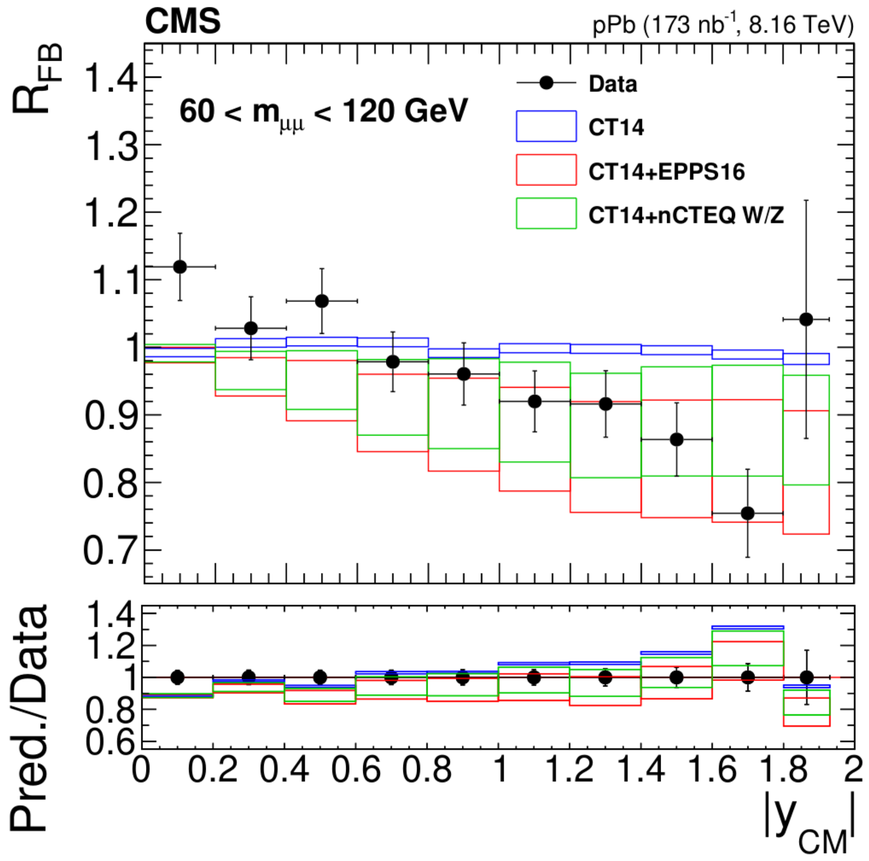
JHEP2009(2020)076

Drell-Yan and Z production in 8.16 TeV *p*Pb collisions

- Drell-Yan produced predominantly via a quark – antiquark pair annihilation
- Wide dimuon mass range
- R_{FB} of Z mass window more precise than nPDFs

JHEP 05 (2021) 182



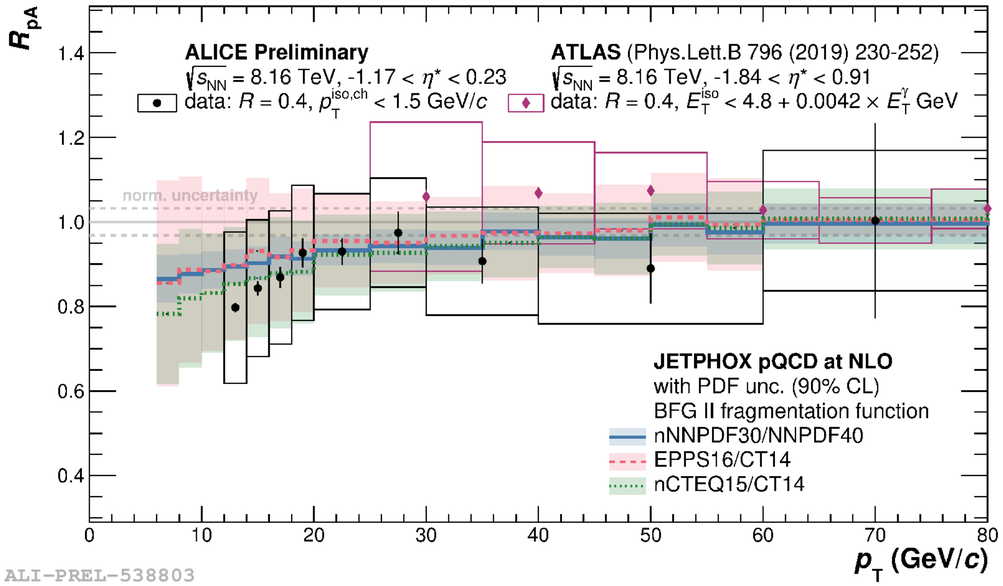


Direct photon production in 8.16 TeV *p*Pb collisions

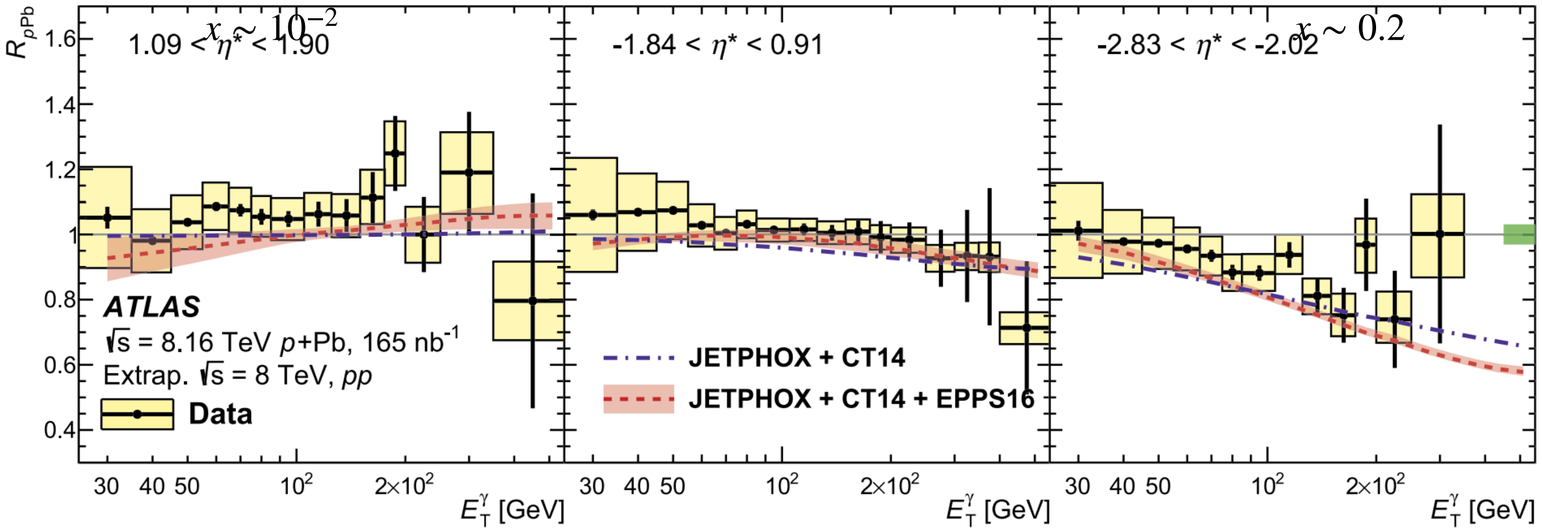
Small nuclear effects
Crossover between shadowing and antishadowing

Small nuclear effects
At larger E_T^γ the larger relative d-quark density decreases the photon yield

Crossover from the antishadowing to the EMC region



Physics Letters B 796 (2019) 230–252

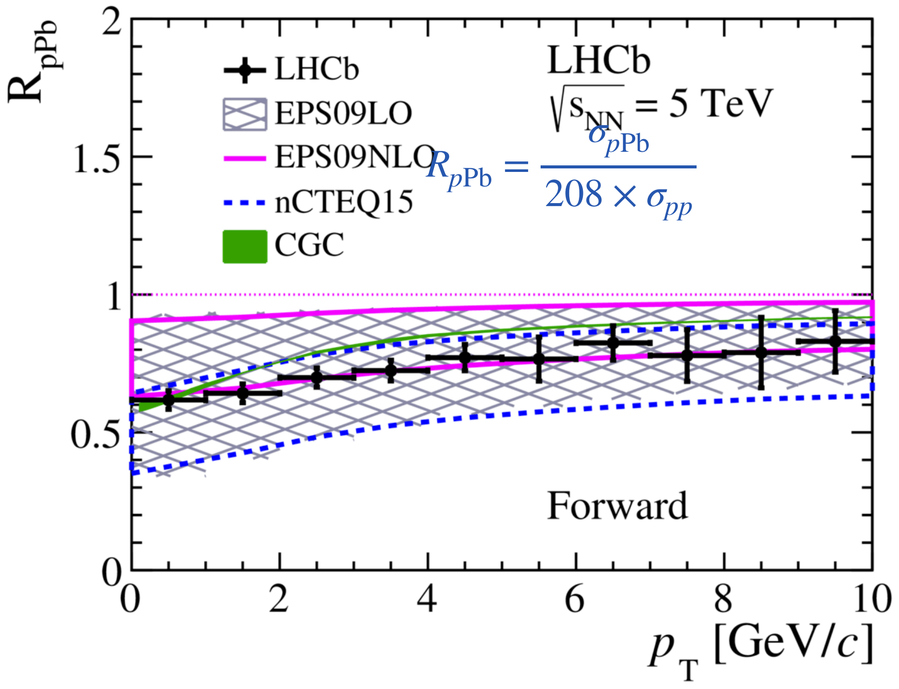


- $20 < E_T^\gamma < 500$ GeV/c $3 \times 10^{-3} < x < 4 \times 10^{-1}$

- $12 < p_T < 80$ GeV/c, $|\eta^{lab}| < 0.7$
- Hints of suppression at low p_T
- Agree with ATLAS result
- Comparable suppression in nPDFs including gluon shadowing

LHCb D^0 production in 5 TeV pPb collisions

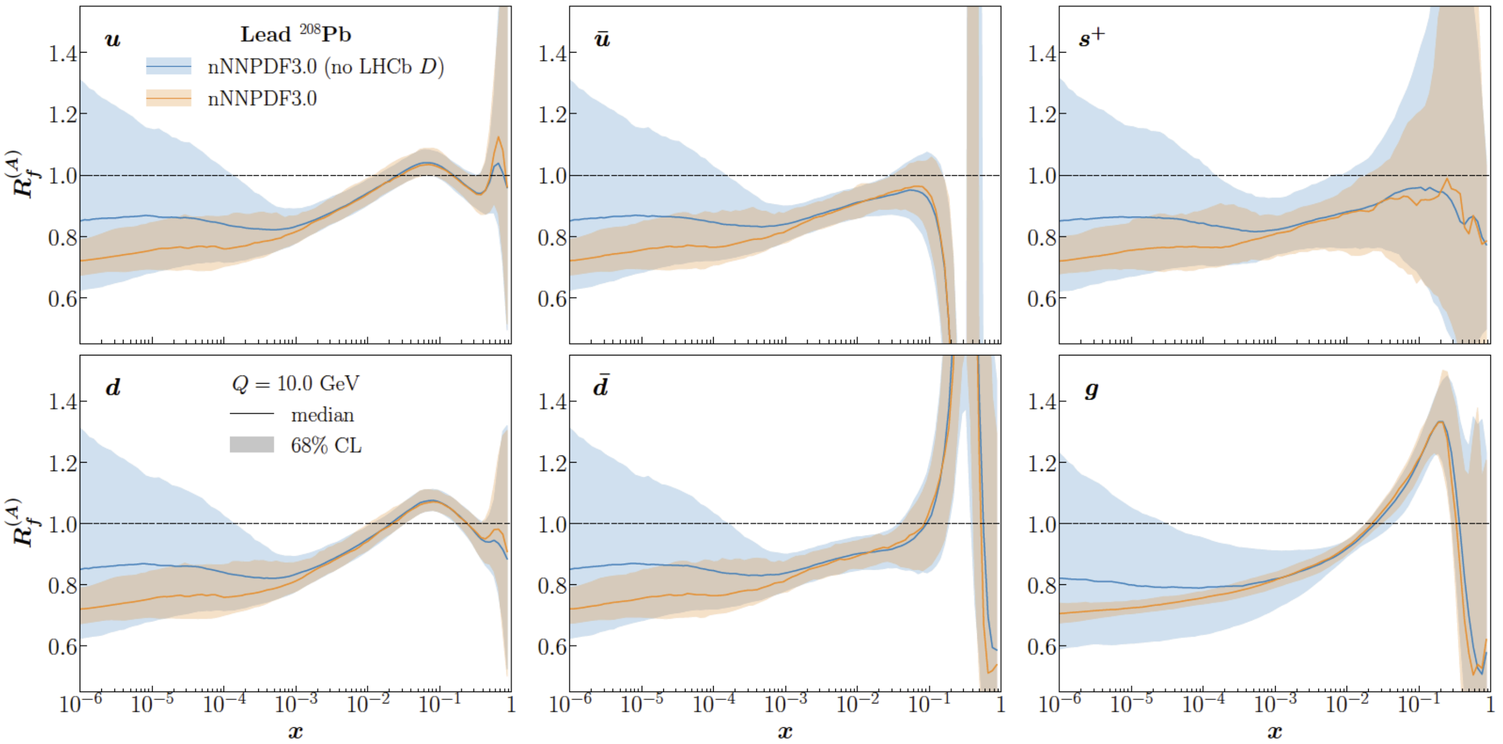
JHEP 10 (2017) 090



- Data included in EPPS21 and nNNPDF3.0

- nNNPDF3.0
- LHCb measurement of prompt D^0 production in pPb collisions at 5TeV makes an impressive impact on reducing nPDF uncertainty down to $x \sim 10^{-6}$

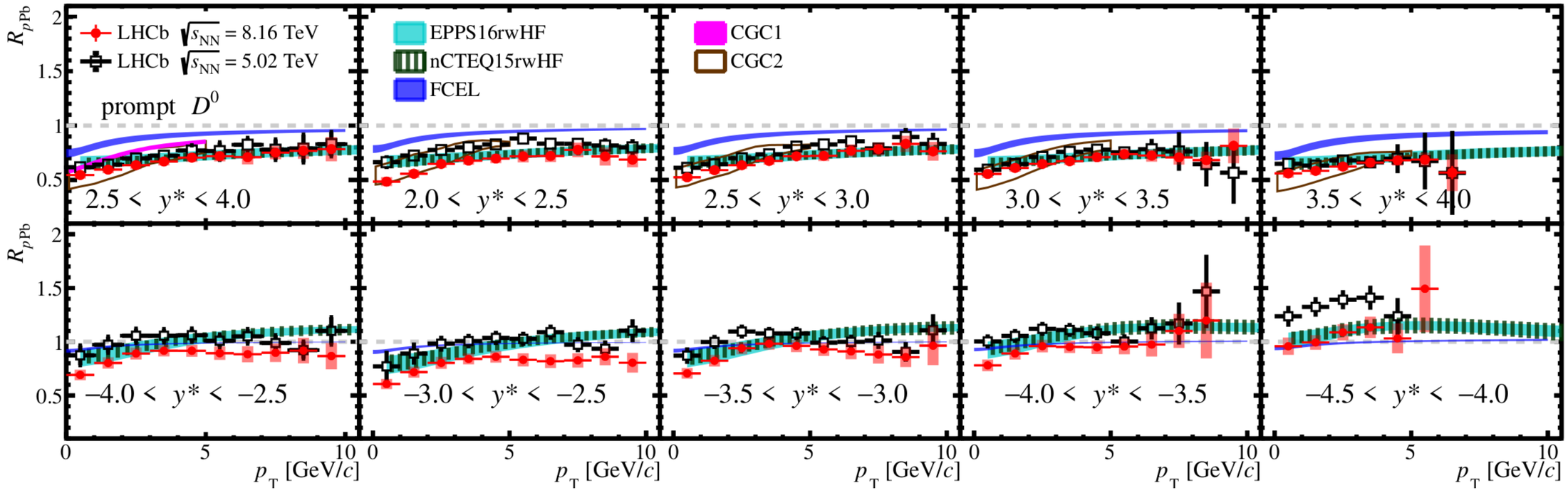
Eur. Phys. J. C 82, 507 (2022)



LHCb D^0 production in 8.16 TeV pPb collisions

- Forward:
  - Suppression consistent with 5TeV D^0 result
  - Consistent with nPDF and CGC
- Backward:
  - Data lower than nPDF at high p_T
  - Room for additional effects in the backward rapidity

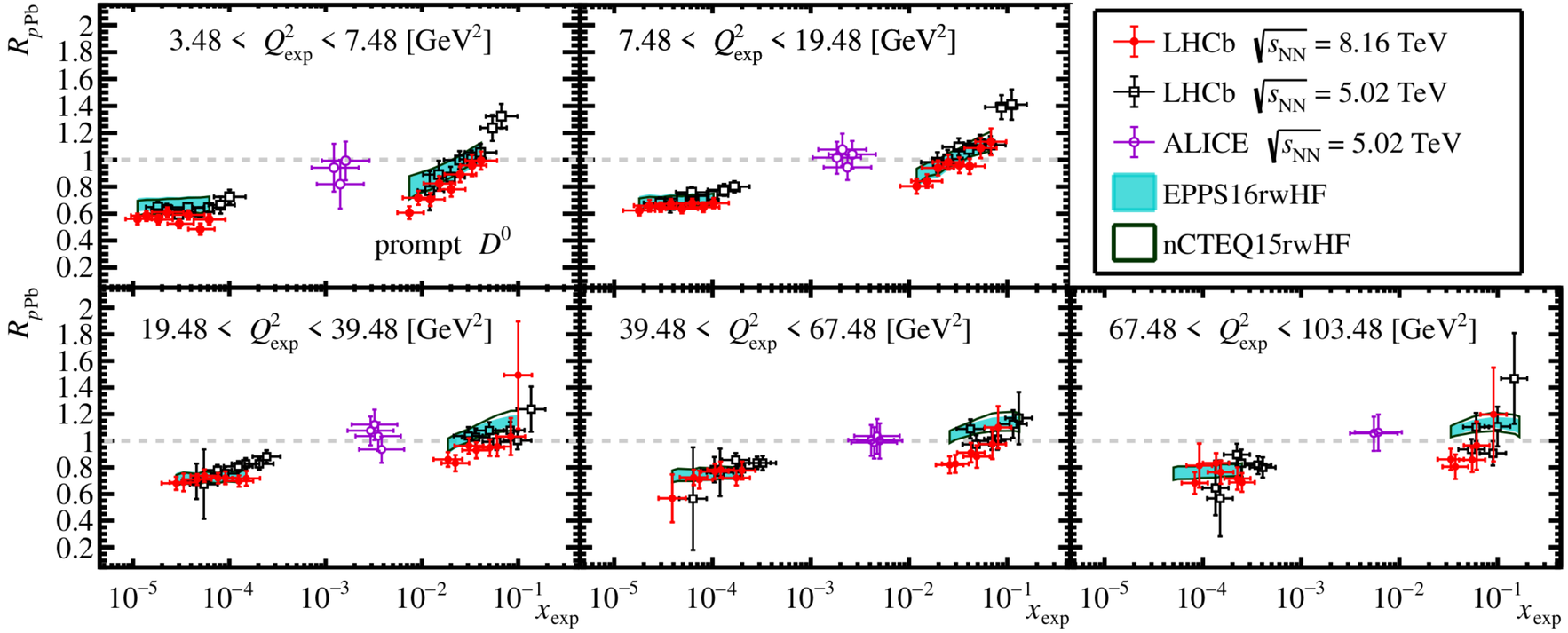
arXiv:2205.03936



LHCb D^0 production in 8.16 TeV pPb collisions

- Experimental proxies for x and Q^2
- Forms a continuous trend over wide x coverage
- Lower than nPDF at large x_{exp} and large Q^2_{exp}

arXiv:2205.03936



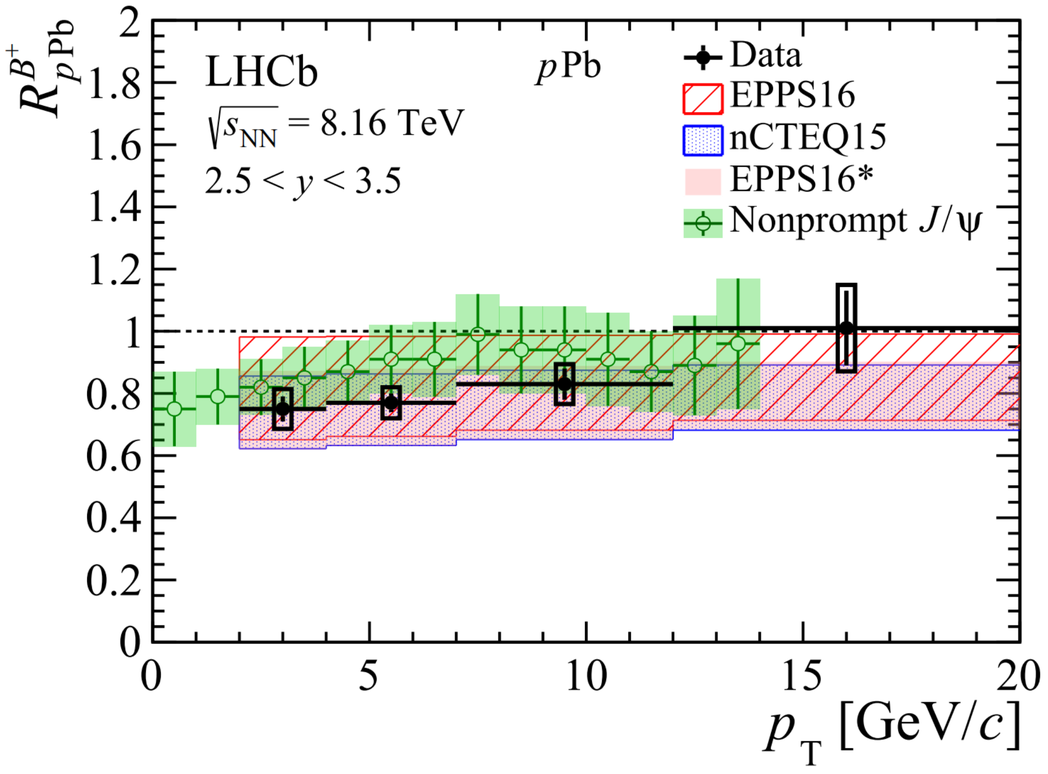
$$Q^2_{exp} \equiv m^2_{D^0} + p^2_{\mathrm{T}}$$

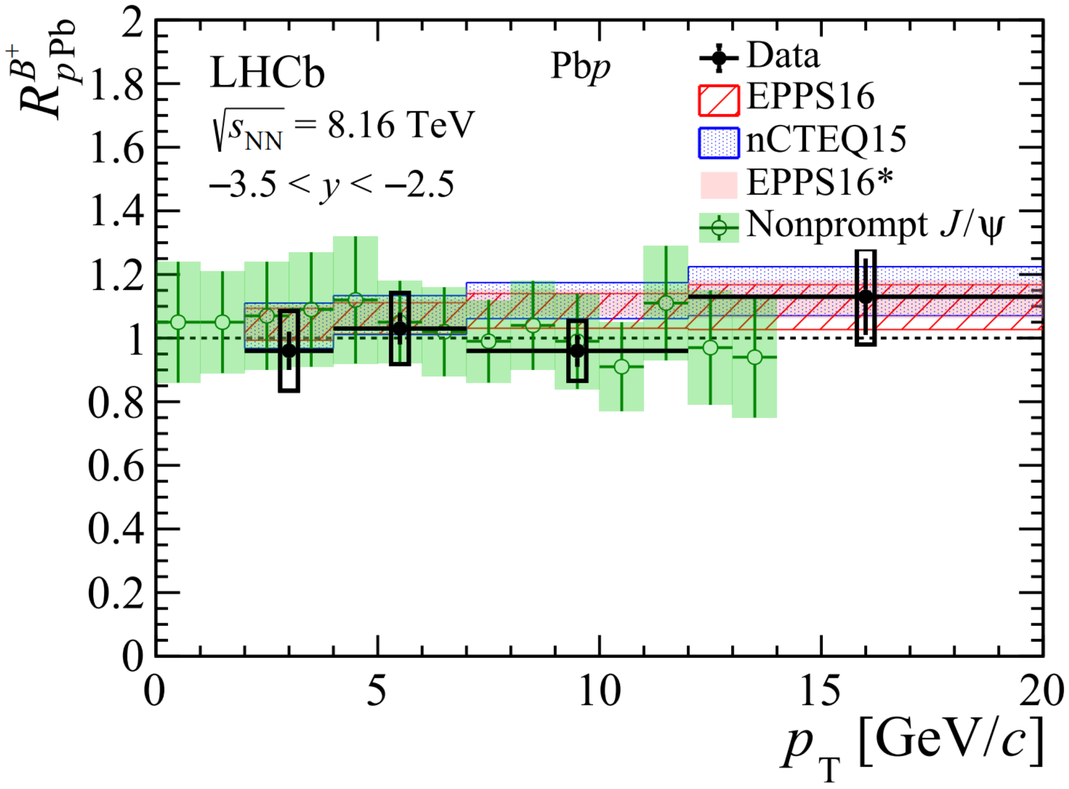
$$x_{exp} \equiv 2\frac{Q_{exp}}{\sqrt{s_{NN}}}e^{-y^*}$$

LHCb B mesons in 8.16TeV *p*Pb collisions

- B^+ $R_{p\mathrm{Pb}}$ forward: suppression down to ~0.7
- Backward: consistent with 1
- Consistent with nonprompt J/ψ and nPDFs

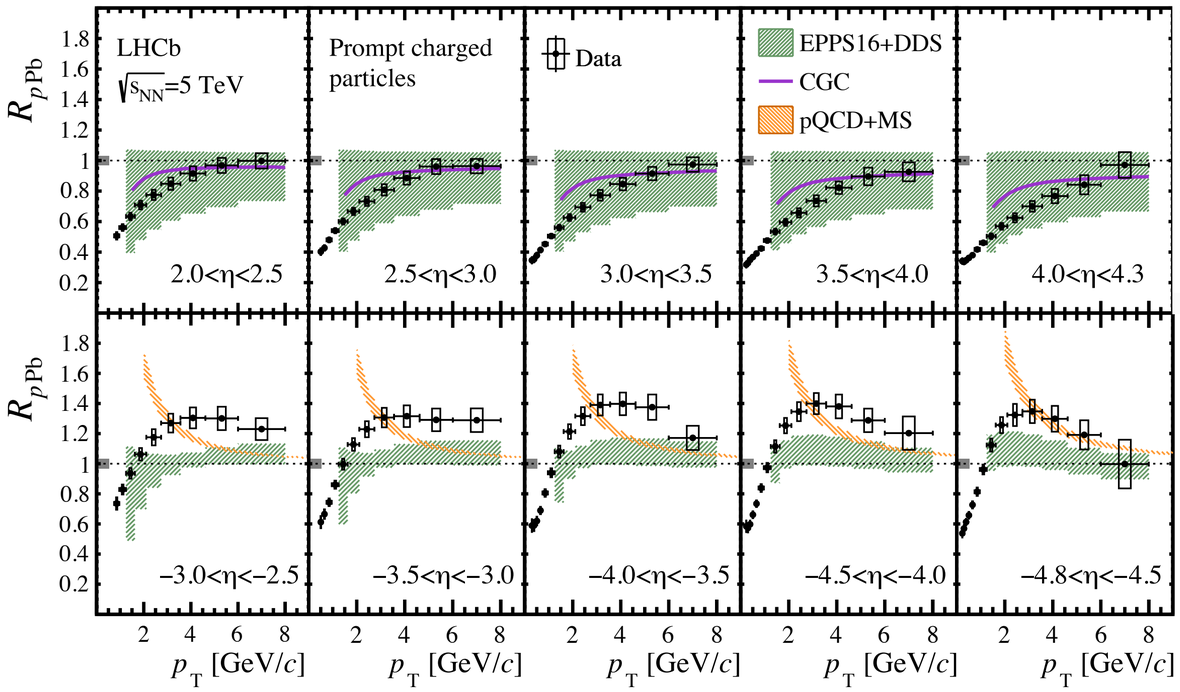
Phys. Rev. D99 052011 (2019)





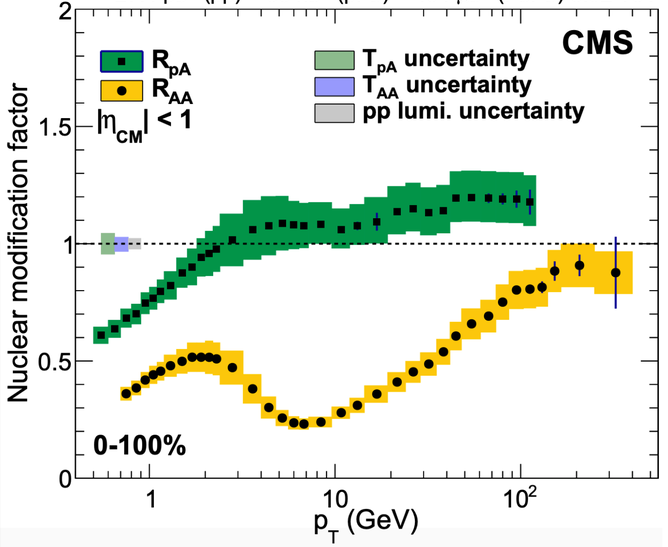
Light hadrons

- Strong suppression at forward rapidity
- Enhancement at backward rapidity for $p_T > 1.5$GeV/c
- Models do not describe data

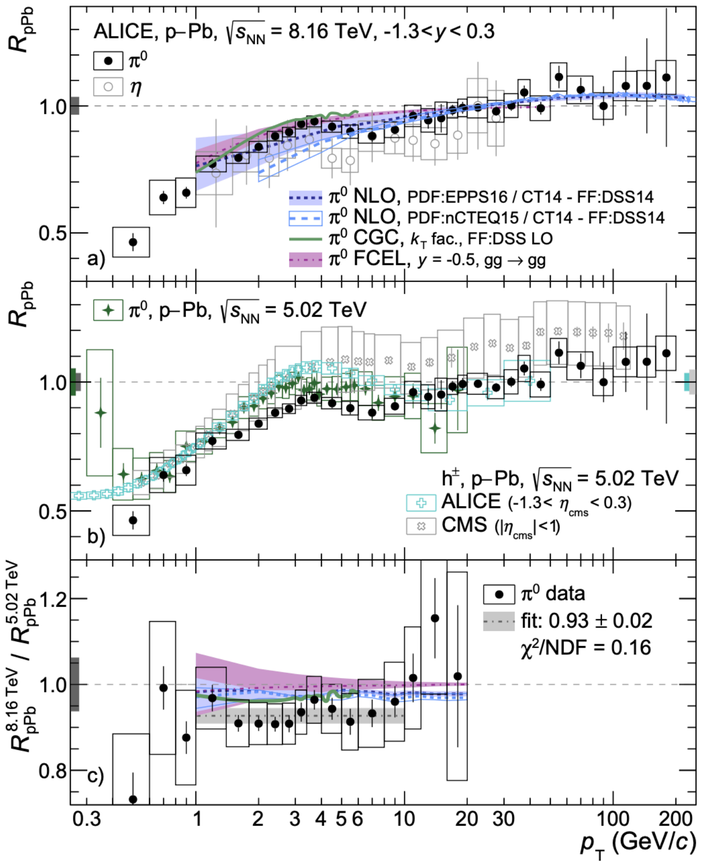


PhysRevLett. 128 (2022)142004

JHEP04 (2017)039



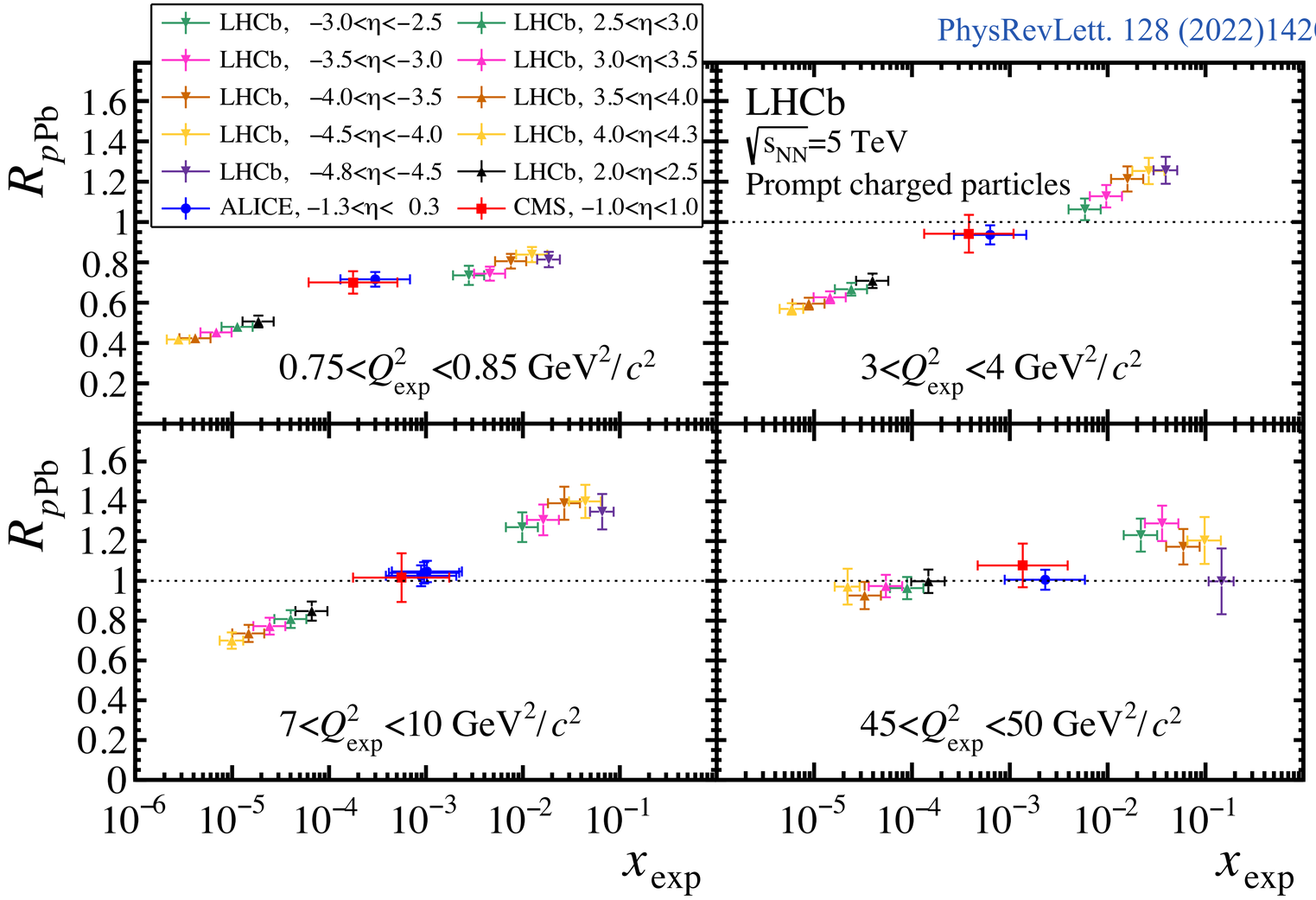
Phys. Lett. B 827 (2022) 136943



- Midrapidity
- Suppression for $p_T < 2$ GeV/c down to ~ 0.6
- Closer to 1 at higher p_T
- Consistent with saturation models and nPDF

Prompt charged particles in *p*Pb and *pp* collisions at 5 TeV

➤ Continuous trend of $R_{p\mathrm{Pb}}$ with x_{exp} at different Q^2_{exp} across forward, middle and backward rapidity regions



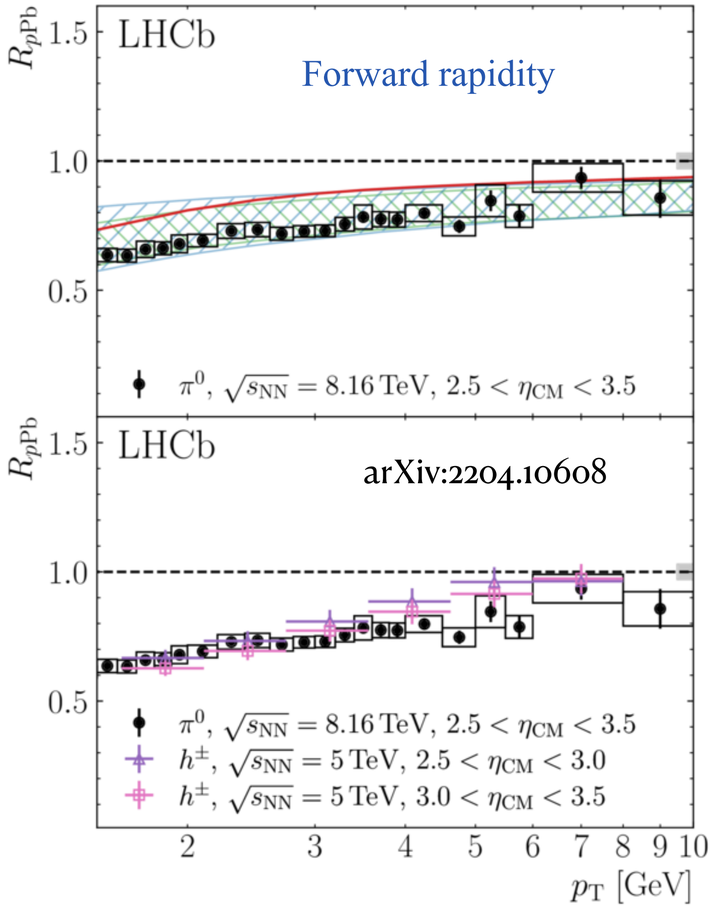
PhysRevLett. 128 (2022)142004

$$Q^2_{exp} \equiv m^2 + p_{\mathrm{T}}^2$$

$$x_{exp} \equiv \frac{Q_{exp}}{\sqrt{s_{nn}}} e^{-\eta}$$

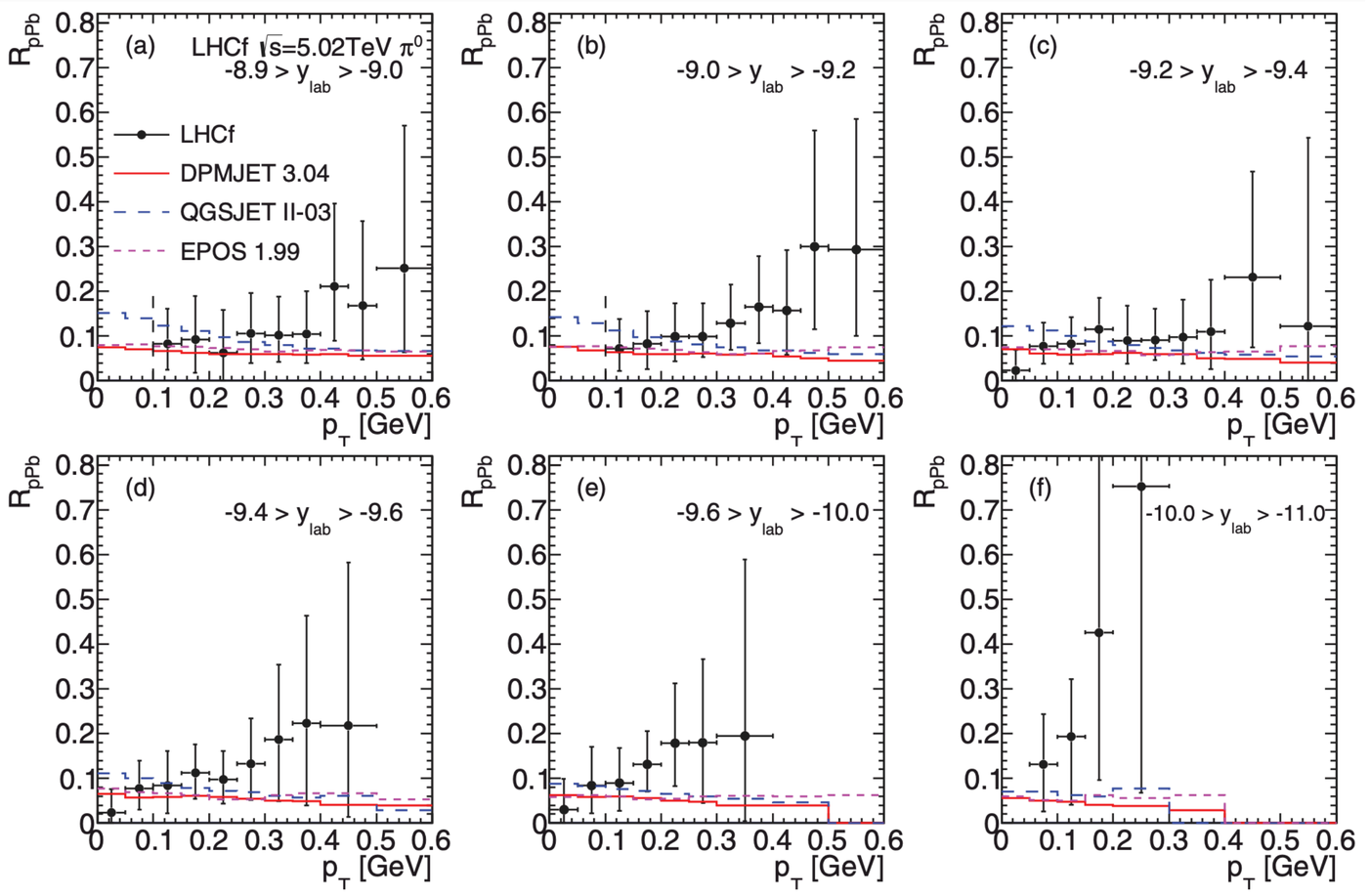
π^0 production in (very) forward rapidity

- More precise than nPDF calculations
- Consistent with charged hadrons



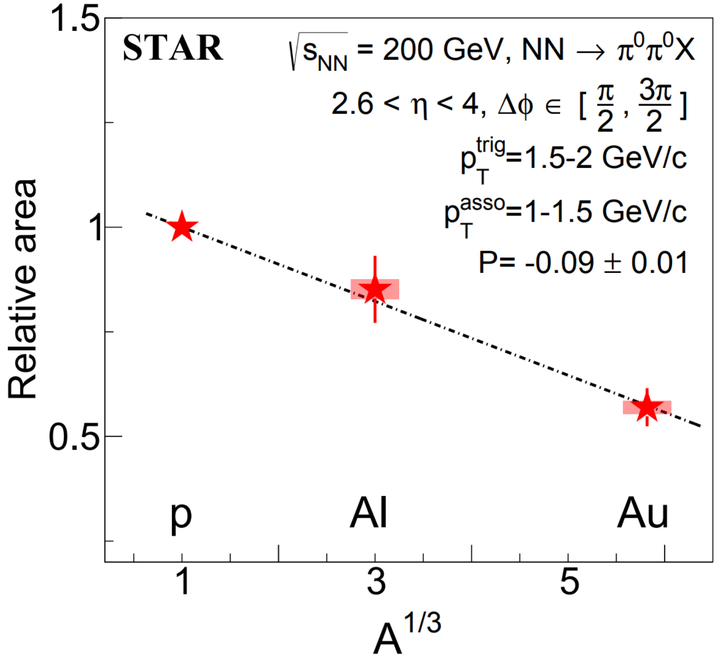
- Strong suppression in $-8.9 > y > -11$

PhysRevC.89.065209

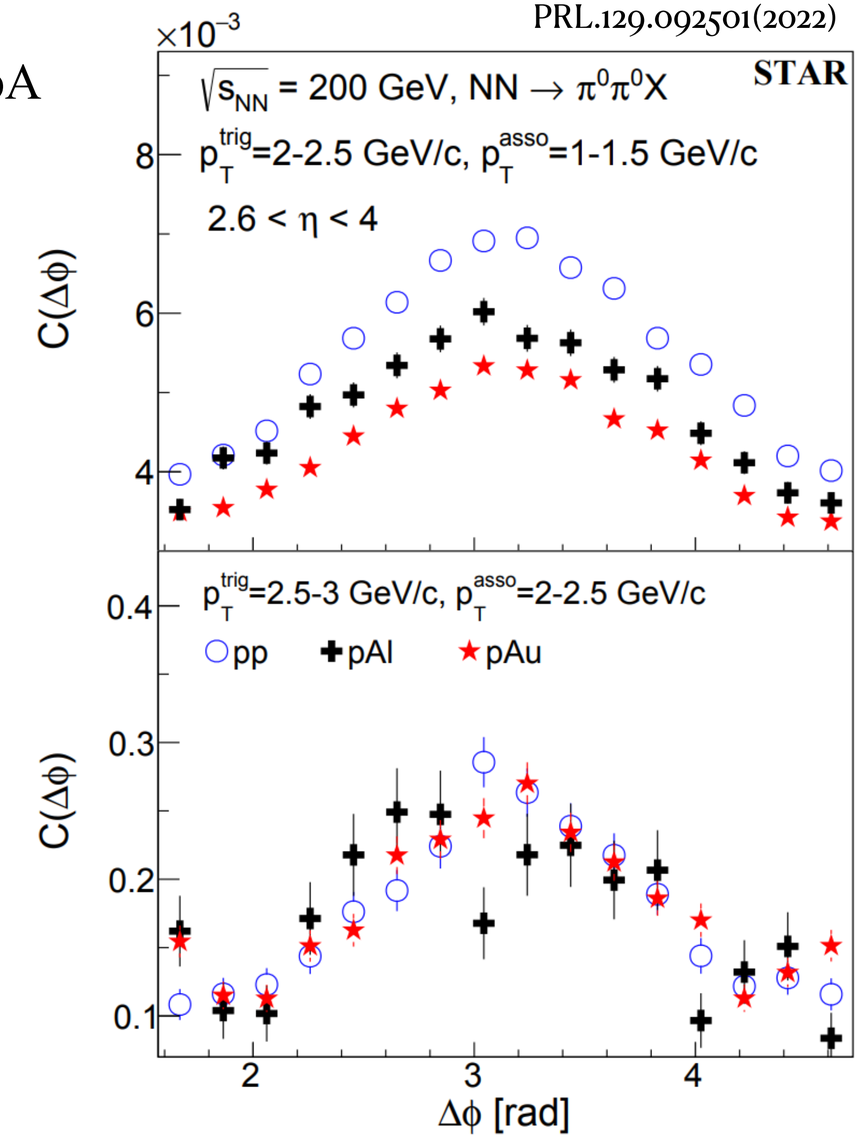


Forward di-π^0 azimuthal correlations in *pp*/*p*A collisions

- CGC predicts broadened away side peak and suppressed yields in pA collisions.
- Gaussian widths of the peak remain the same
- Observed a clear suppression of back-to-back yields
- Linear dependence of the suppression as a function of $A^{1/3}$



PRL.129.092501(2022)



Conclusion and outlook

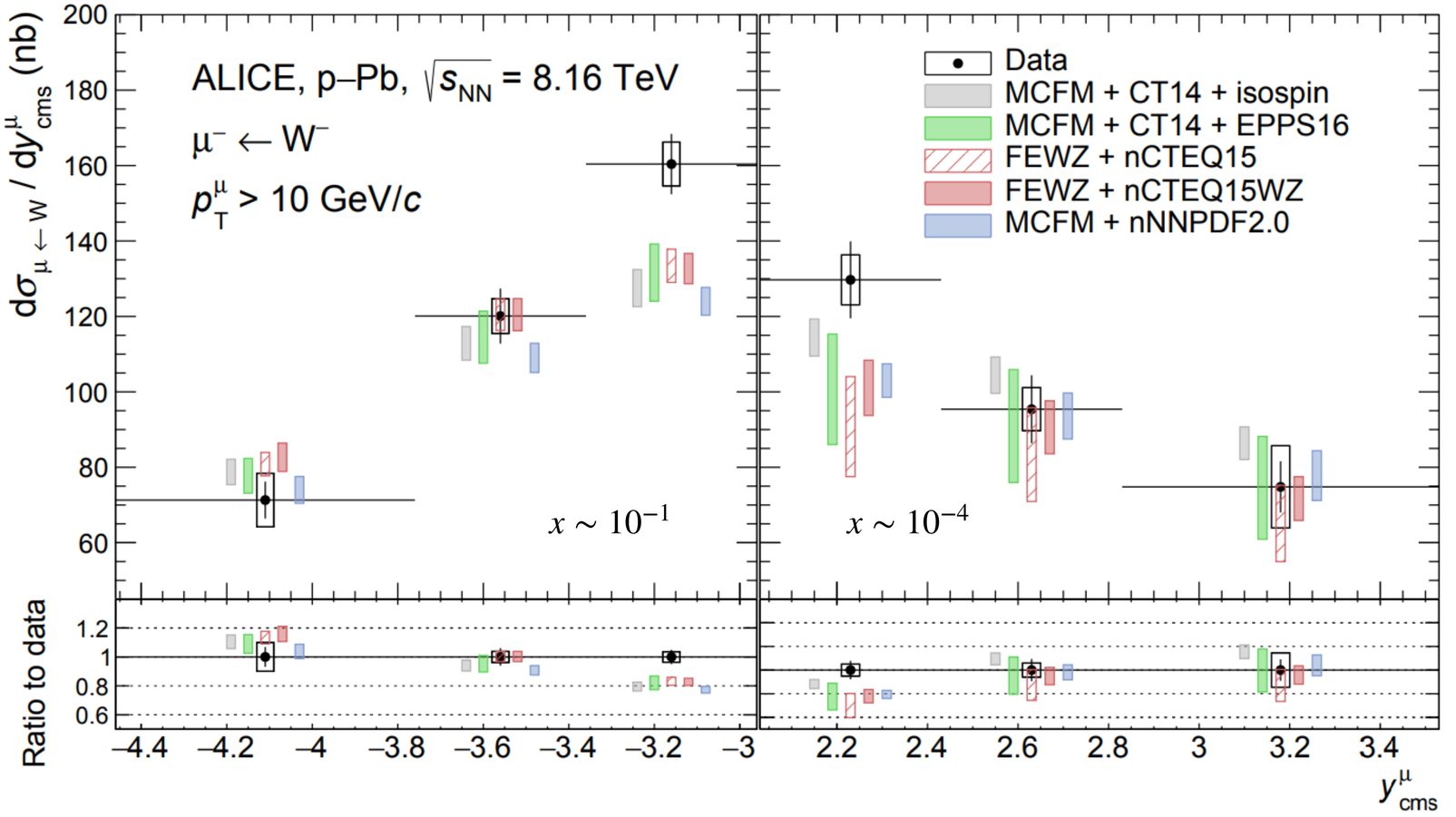
- Considerable progress: recent LHC precision data provide strong constraints to nPDF down to $x \sim 10^{-6} - 10^{-5}$. Previously RHIC data can constrain nPDF to $x \sim 10^{-3}$
- Significant suppression confirmed in forward rapidity, suppression particularly strong in lower Q^2
- Tensions with nPDFs observed (LHCb data in backward rapidity, ALICE W data…)
- Still looking for signs of gluon saturation

- LHC Run3/4 prospects:
  - New *p*Pb run with increased statistics: more valuable measurement can become possible:
    - B hadrons, direct photon in forward rapidity, Drell-Yan
  - New *p*O run: knowledge of nPDF in medium size nucleus crucial in understanding initial state physics

Backup

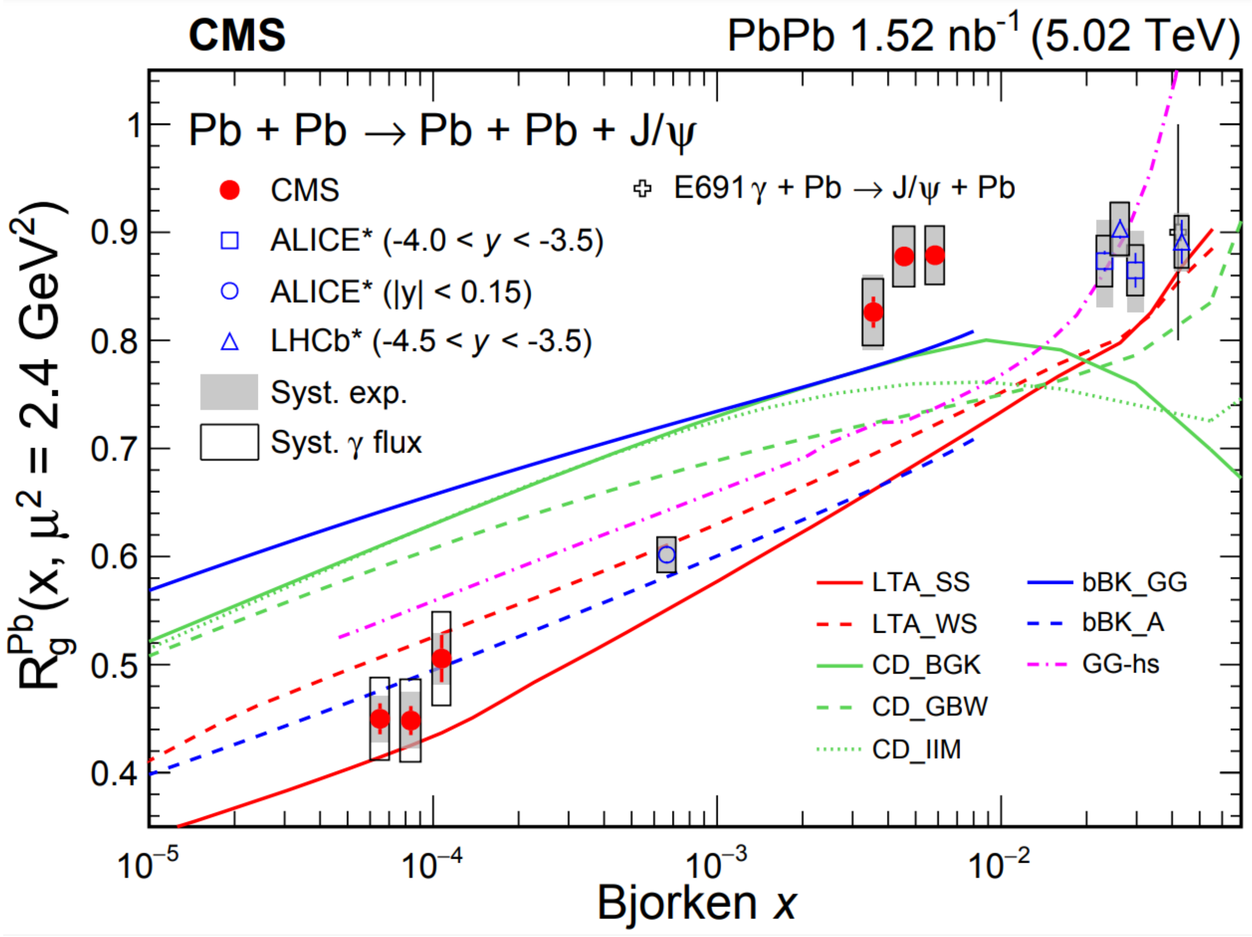
ALICE W in 8.16TeV pPb

arXiv:2204.10640



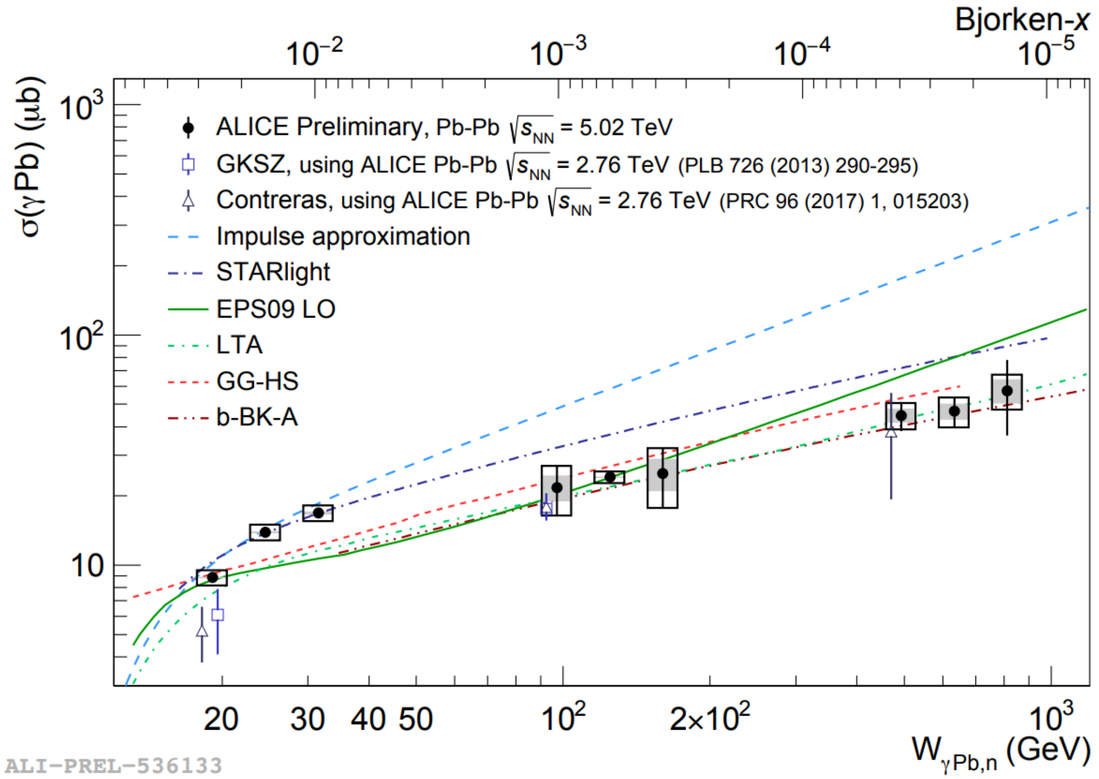
UPC

- arXiv:2303.16984

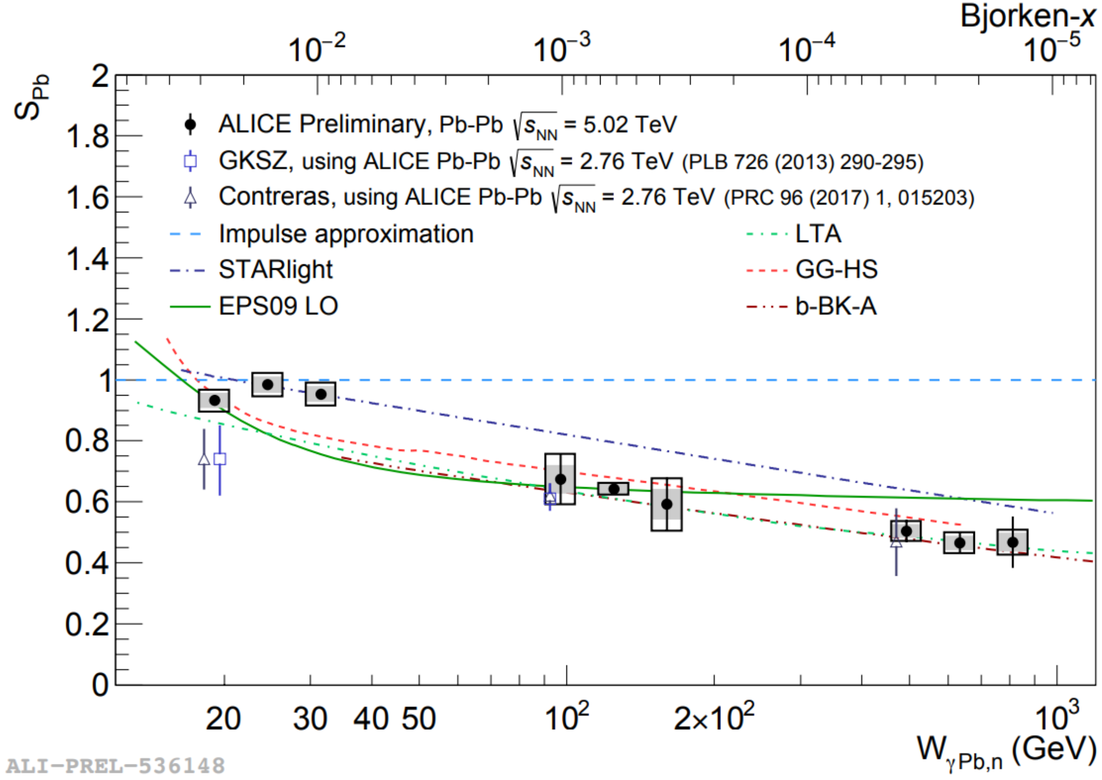


UPC

ALICE



ALI-PREL-536133

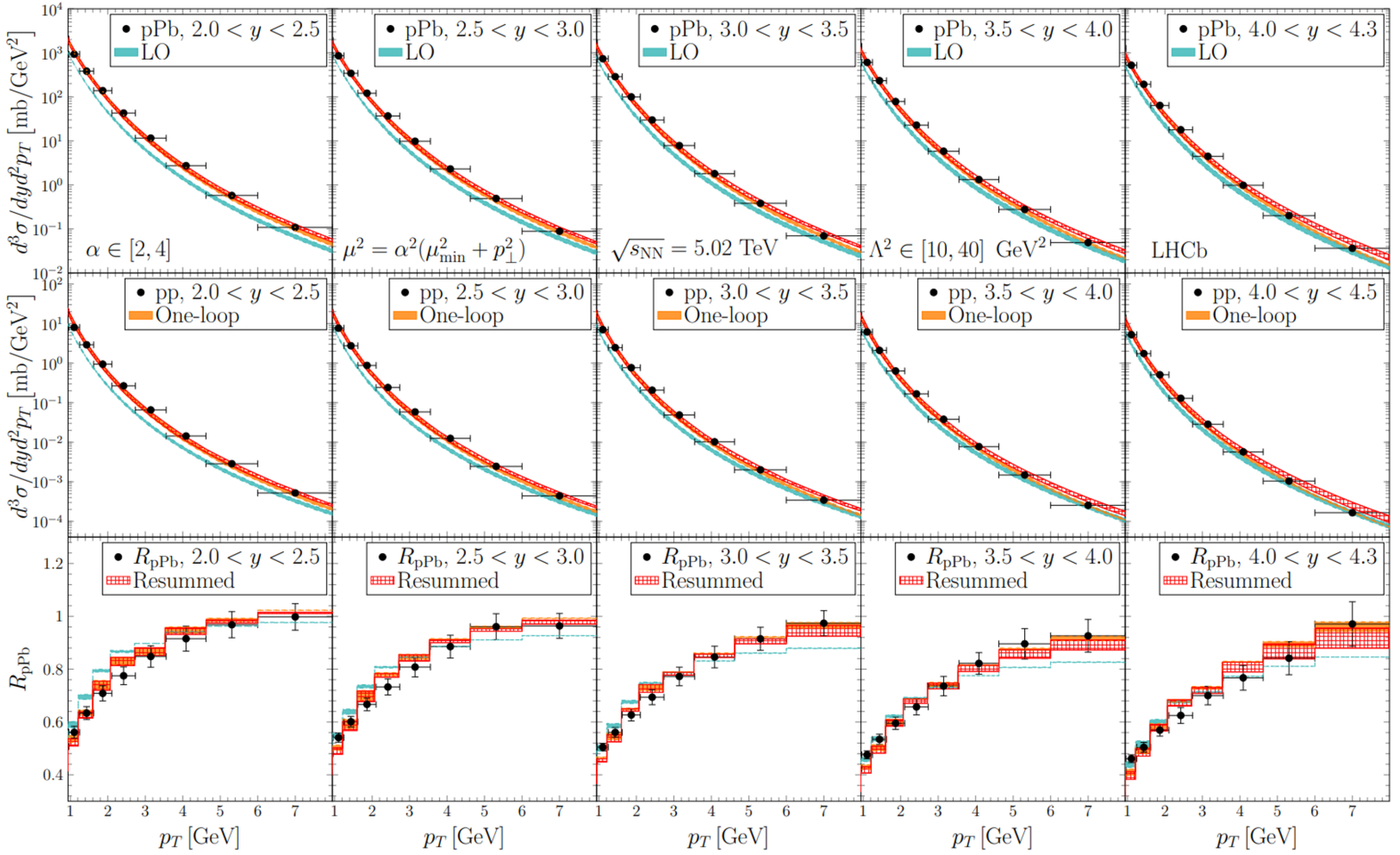


ALI-PREL-536148

PhysRevLett.128.202302(2022)

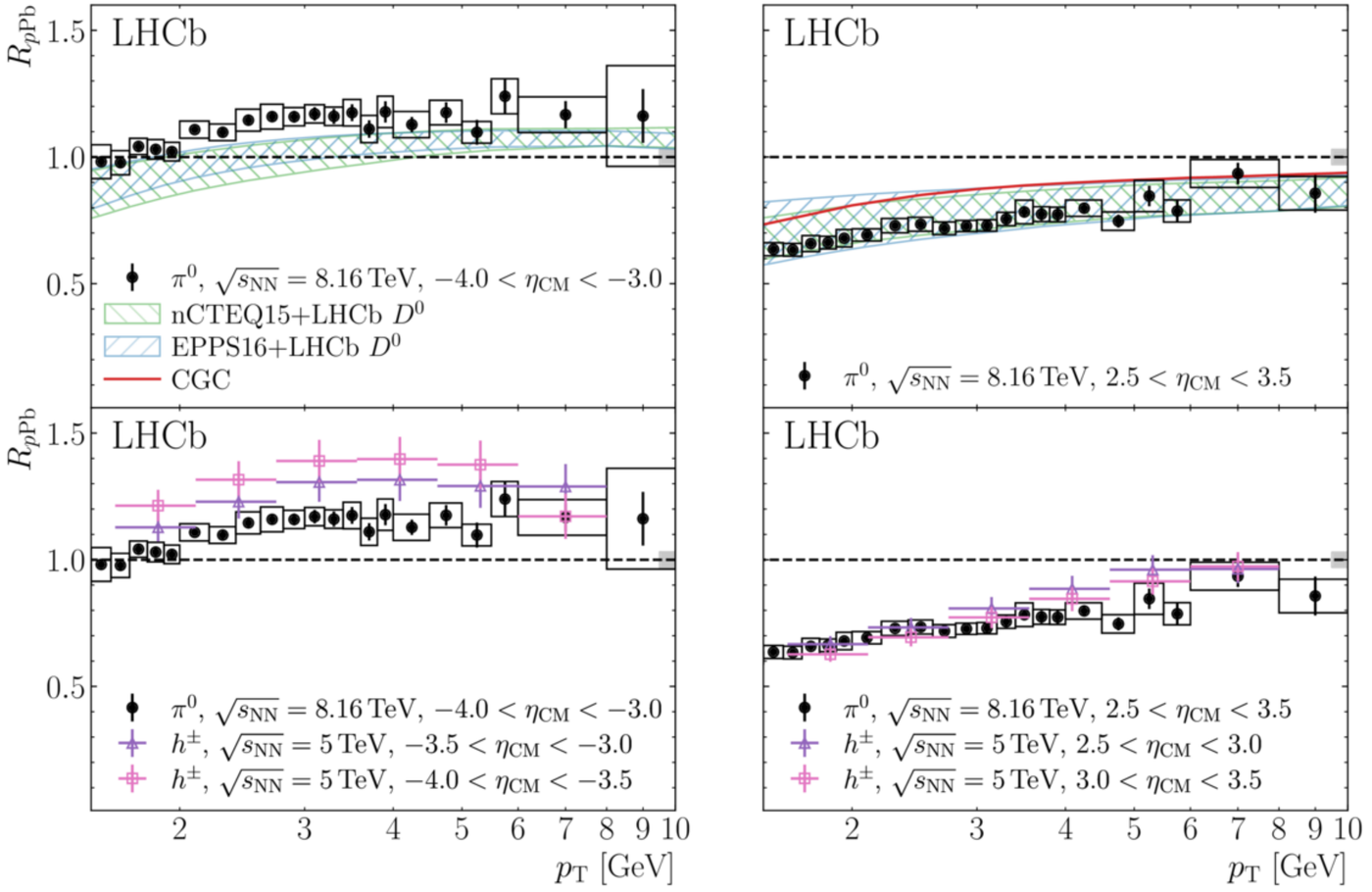
NLO CGC calculation by implementing threshold resummation

- UPDATE: recent NLO CGC calculation can reproduce LHCb forward data



LHCb π^0

arXiv:2204.10608



PHENIX ϕ meson in small systems

PhysRevC.106.014908