Recent ALICE results on cold nuclear matter effects

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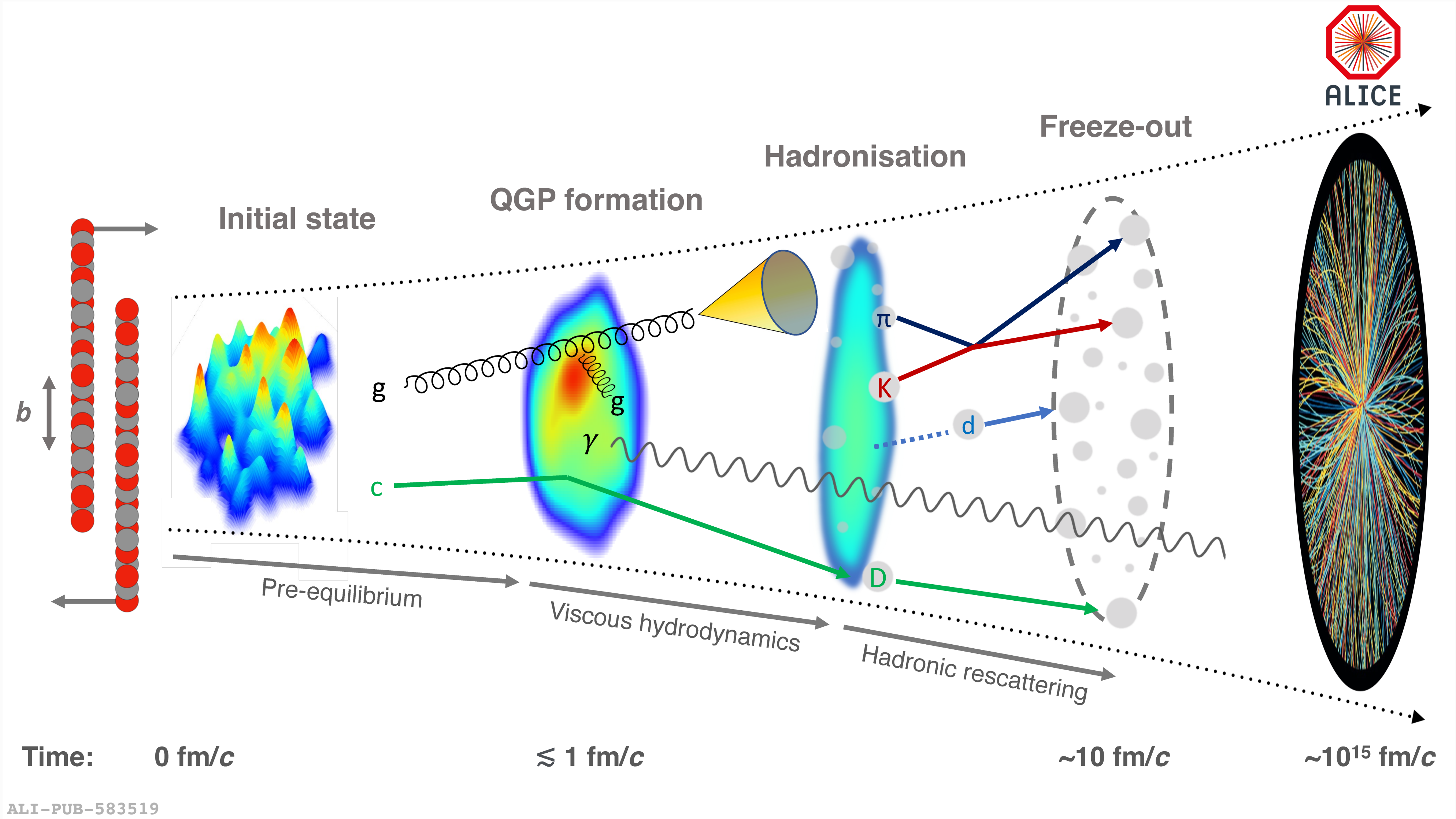
Cold Nuclear Matter Effects: From the LHC to the EIC

13. Jan. 2025 - 16. Jan. 2025

Stony Brook

Hard probes in heavy-ion collisions



- High momentum-transfer (high-Q2) production:
  - Jets: high-p_T
  - Heavy quarks: quark mass
- Production cross sections in pp collisions are calculable with controlled and improvable accuracy using the tools of pQCD

$$\frac{d\sigma^H}{dp_T} = \boxed{PDF(x_1)PDF(x_2)} \times \boxed{\frac{d\sigma^q}{dp_T^q}} \times \boxed{D_{q\to H}(z = p_H/p_q)}$$

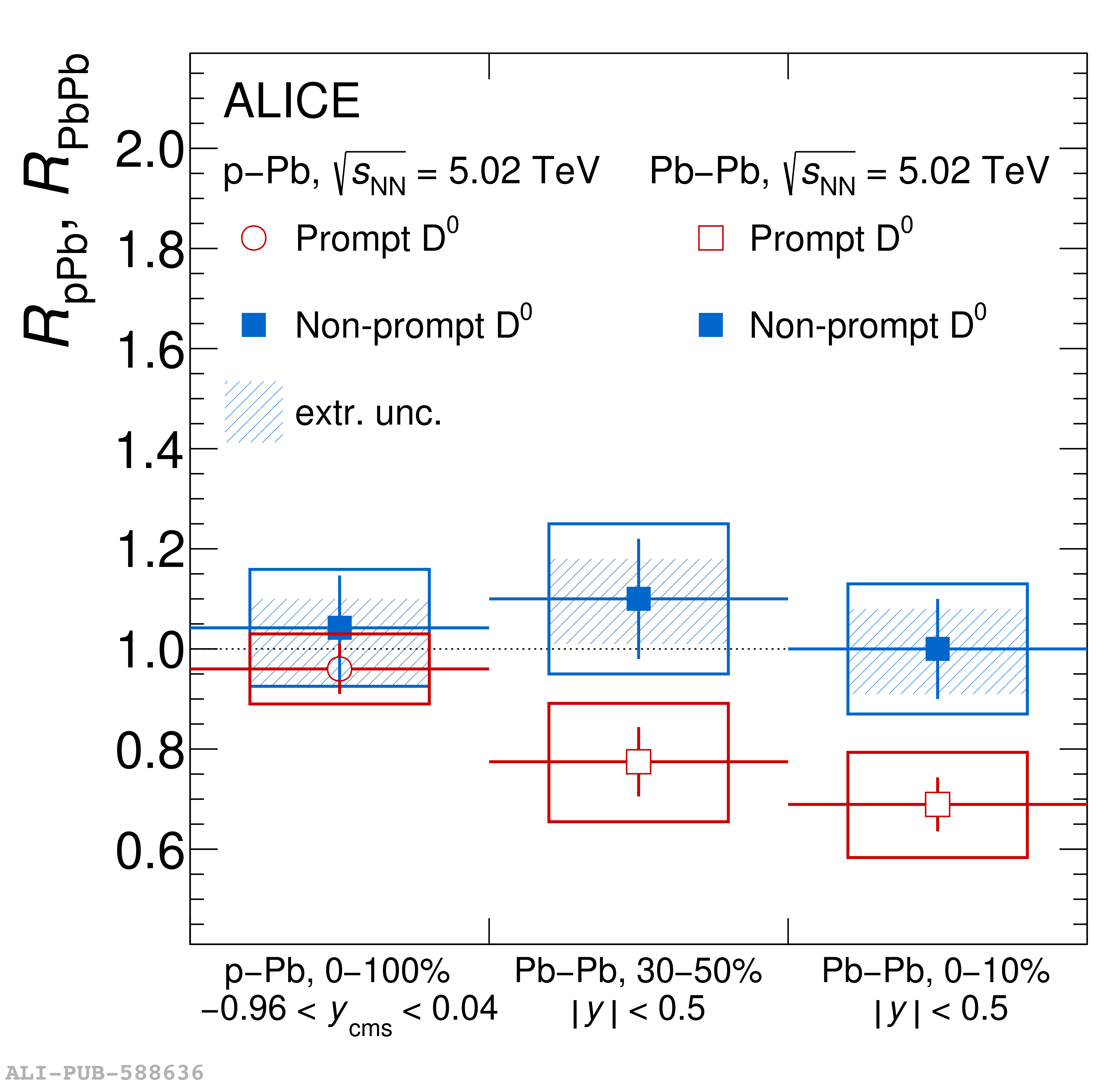
- non-perturbative
- initial condition from data

- perturbative (pQCD)

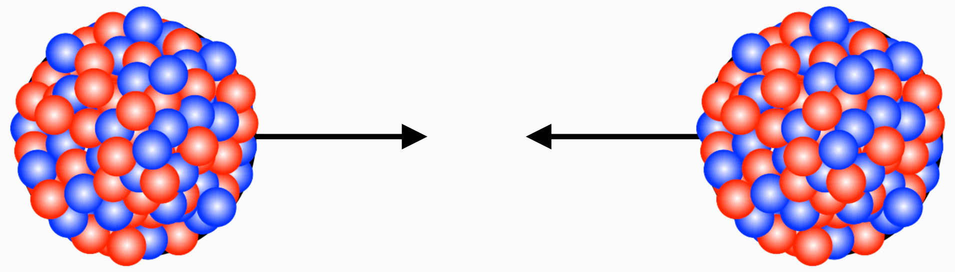
- Fragmentation/ hadronization
- non-perturbative
- fit to data

- Based on considerations of the uncertainty principle and QCD factorisation, hard process expected to occur at the earliest stage of a heavy-ion collision, prior to equilibration of the QGP

Hard probes in heavy-ion collisions

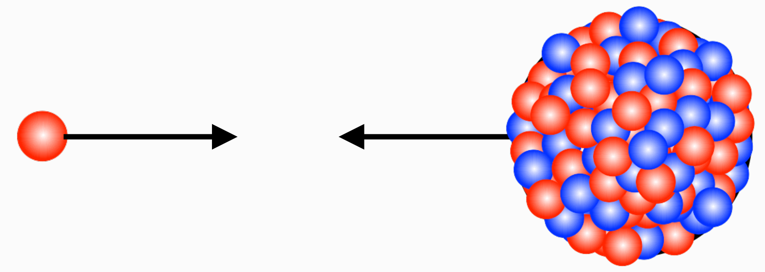


A–A collisions



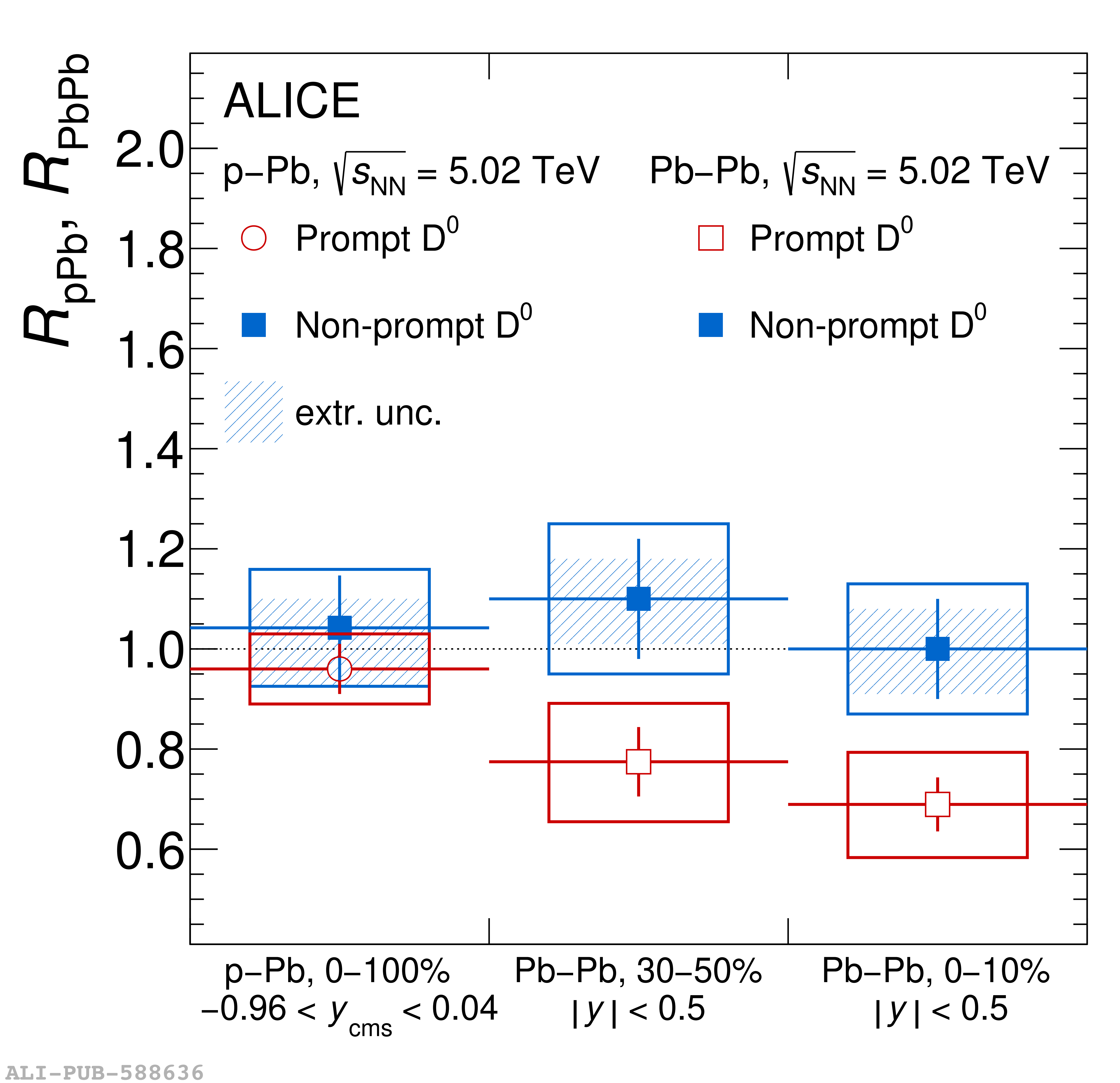
- Probe in medium energy loss mechanisms to characterize the QGP medium

p–A collisions

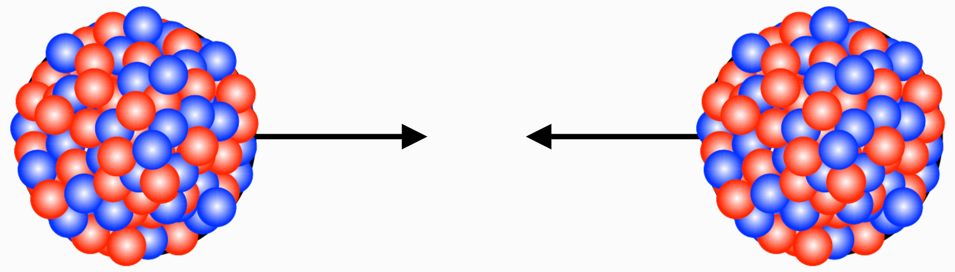


- Study cold nuclear matter (CNM) effects: i.e. nuclear modification of parton distribution functions, saturation in the colour Glass Condensate (CGC) approach , multiple scattering and energy loss, breakup by comovers …

Hard probes in heavy-ion collisions

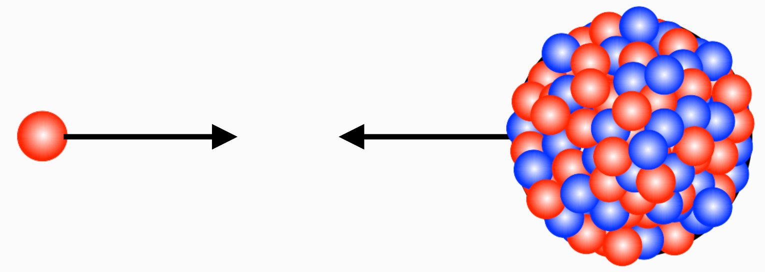


A–A collisions



- **Probe in medium energy loss mechanisms to characterize the QGP medium**

p–A collisions

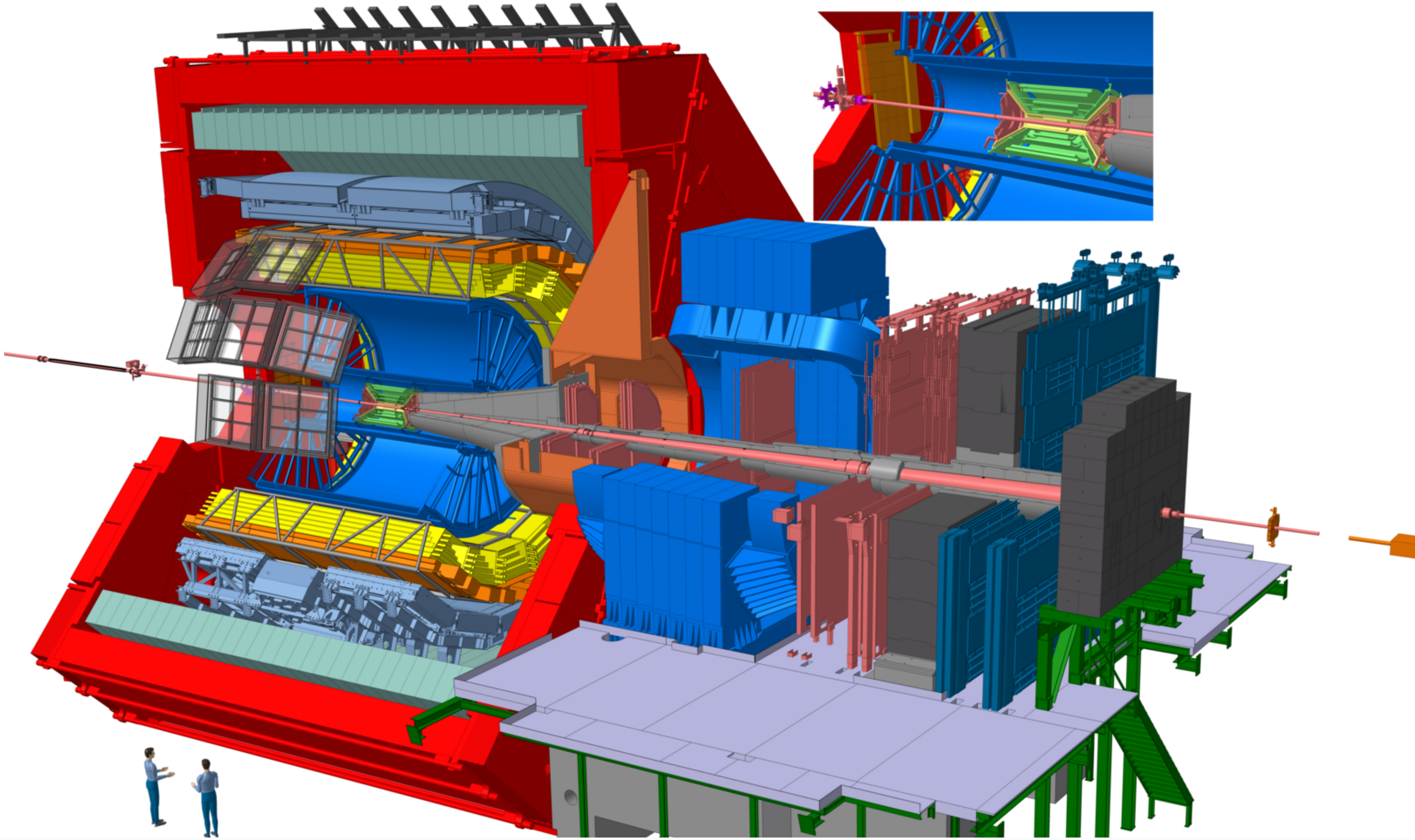


- **Study cold nuclear matter (CNM) effects: i.e.** nuclear modification of parton distribution functions, saturation in the colour Glass Condensate (CGC) approach , multiple scattering and energy loss, breakup by comovers …

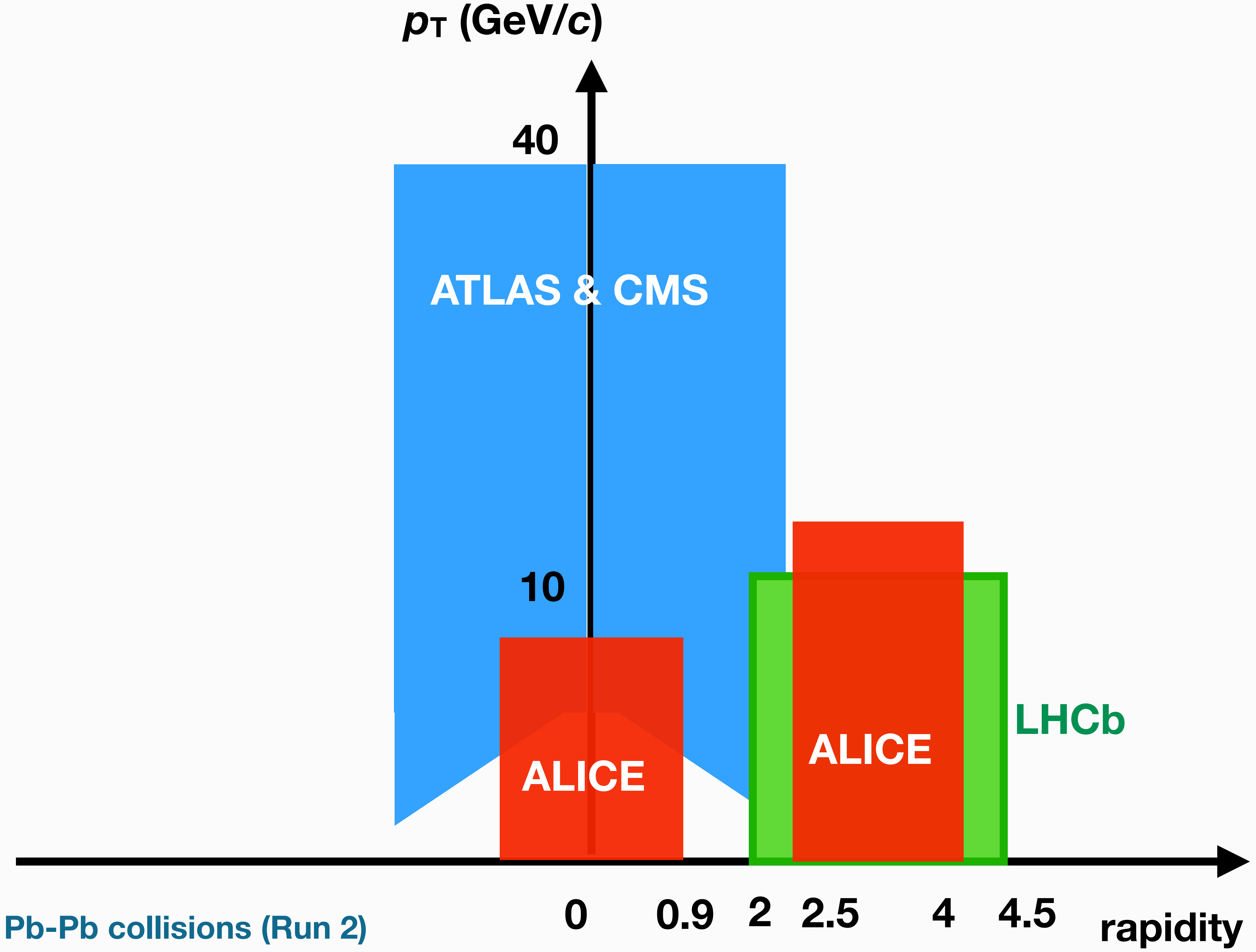
Caveat: can we simply conclude
➡CNM effect is negligible
➡Deviation from unity in Pb–Pb expected to be due to hot nuclear effects
as R_{pA} is consistent with 1?

ALICE experiment in Run 2

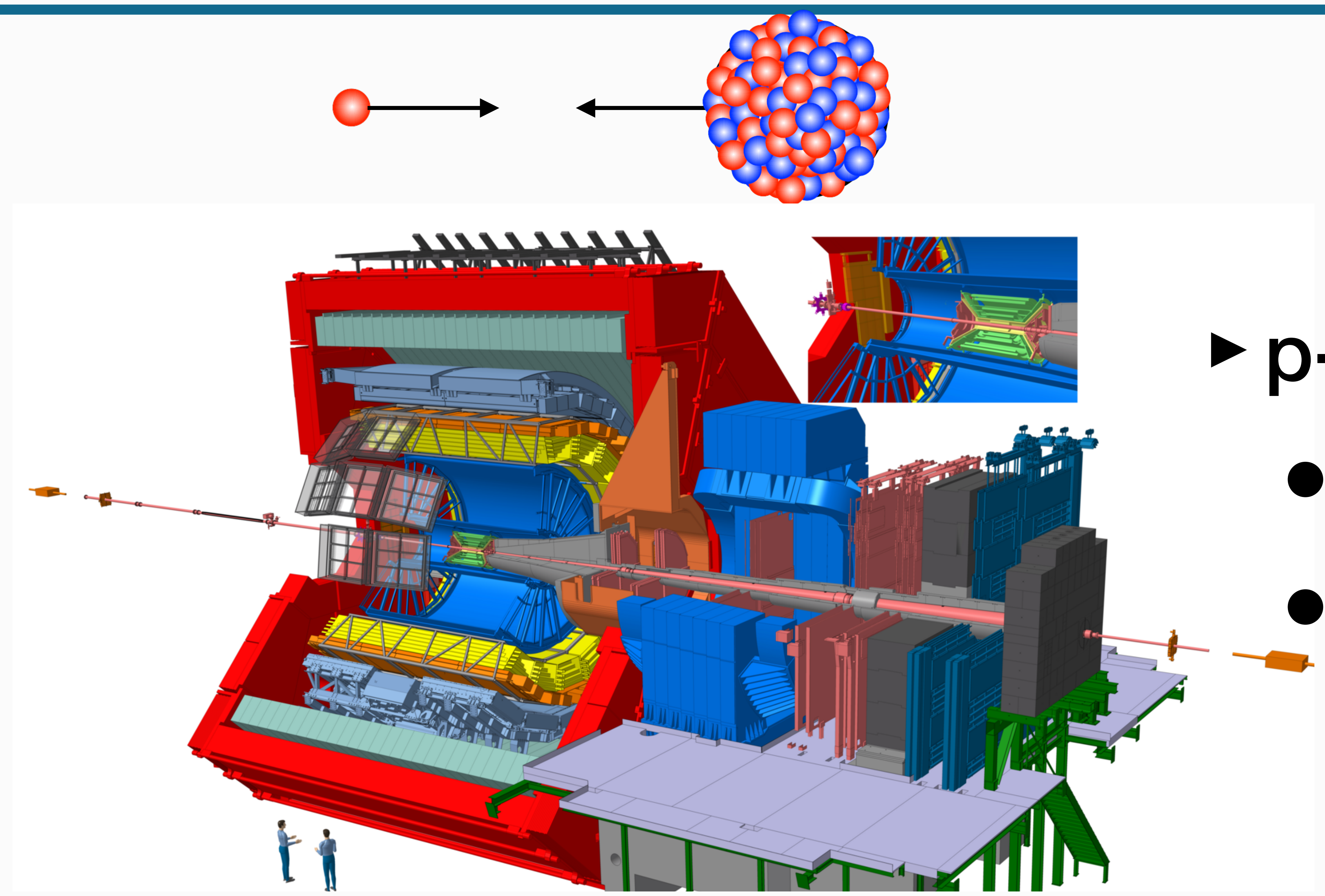
- Central Barrel: Charged particle down to 150 MeV with particle identification:
  - Heavy flavour hadrons (charm and beauty separation)
  - Quarknoium via e+e-
  - Charged jets
  - ……..
- Muon System: Separate trigger mode; larger data sample w.r.t. central barrel minimum bias events
  - Heavy flavour and W/Z boson decay muon
  - Quarknoium via $\mu^+\mu^-$



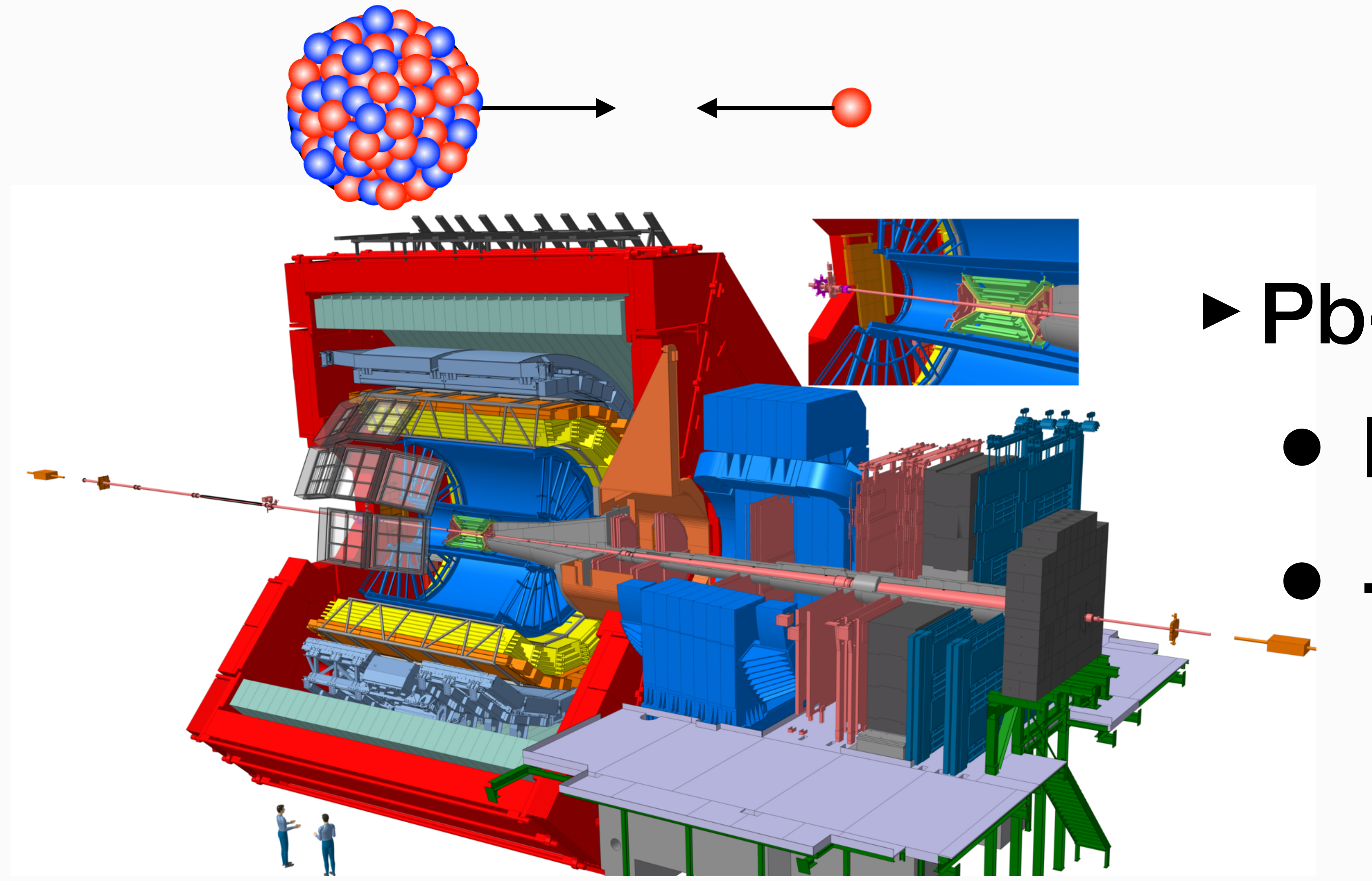
ALICE experiment in Run 2



*For J/ψ in Pb-Pb collisions (Run 2)



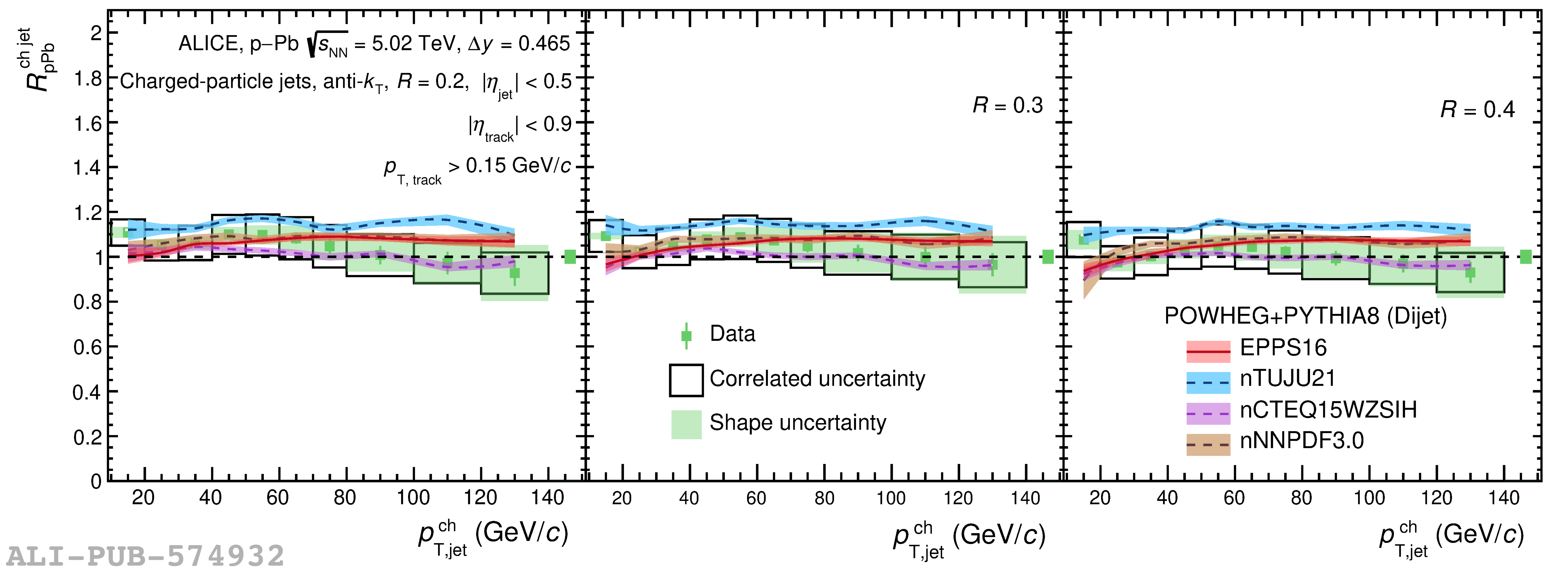
- p-going direction:
  - Forward rapidity
  - $2.03 < y < 3.53$



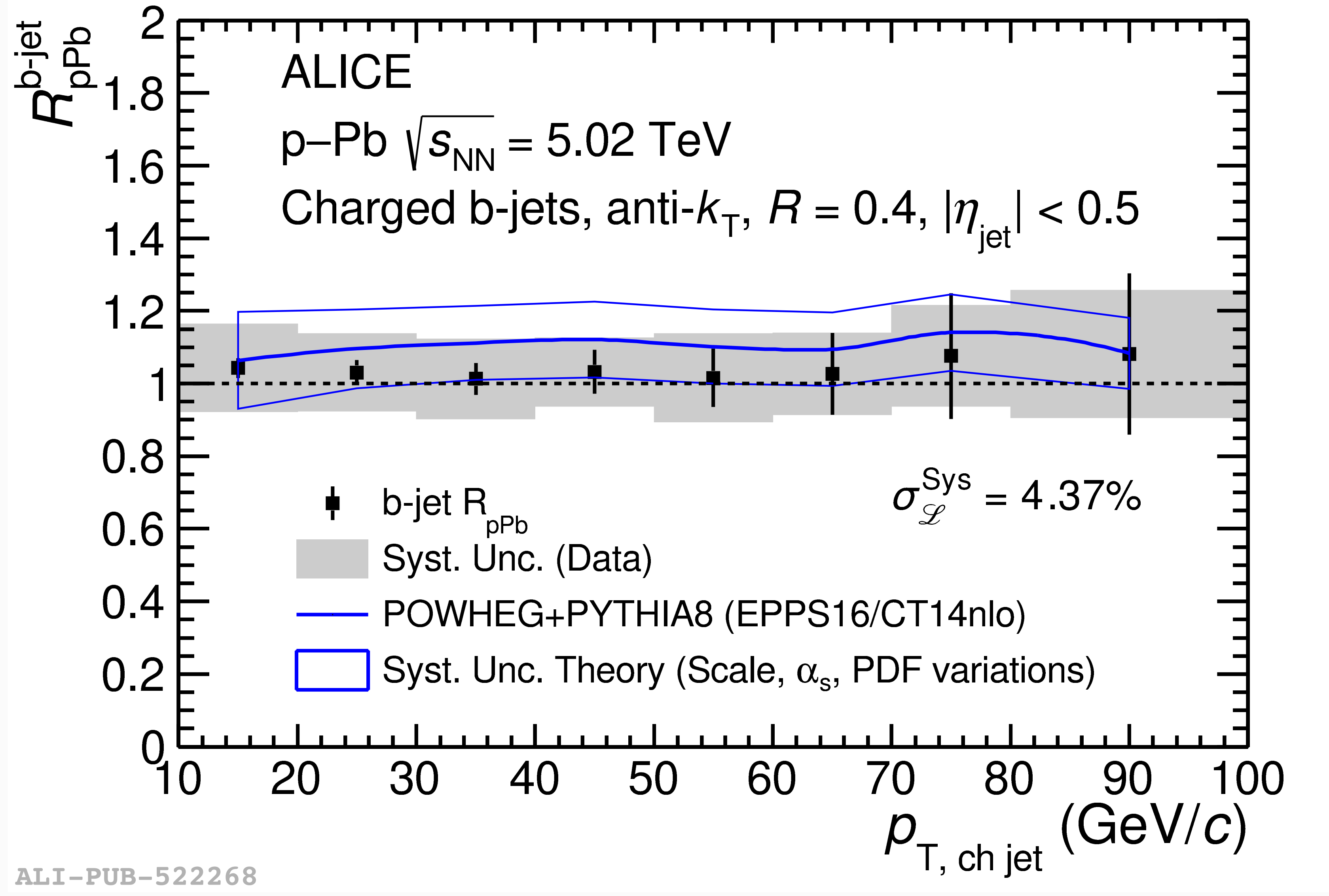
- Pb-going direction:
  - Backward rapidity
  - $-4.46 < y < -2.96$

Charged jet R_{pA}

ALICE Collaboration, JHEP 05 (2024) 041



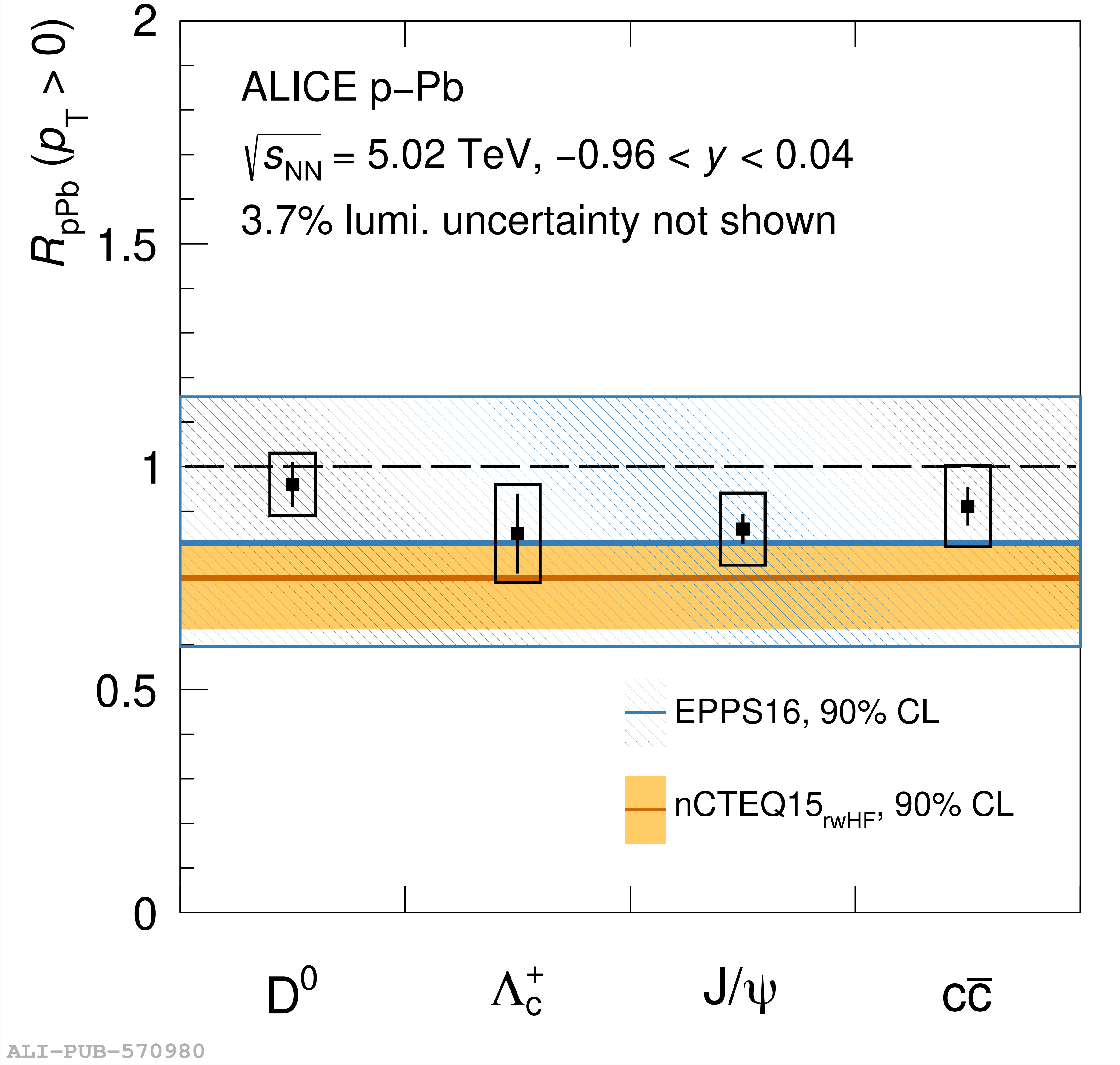
ALICE Collaboration, JHEP 01 (2022) 178



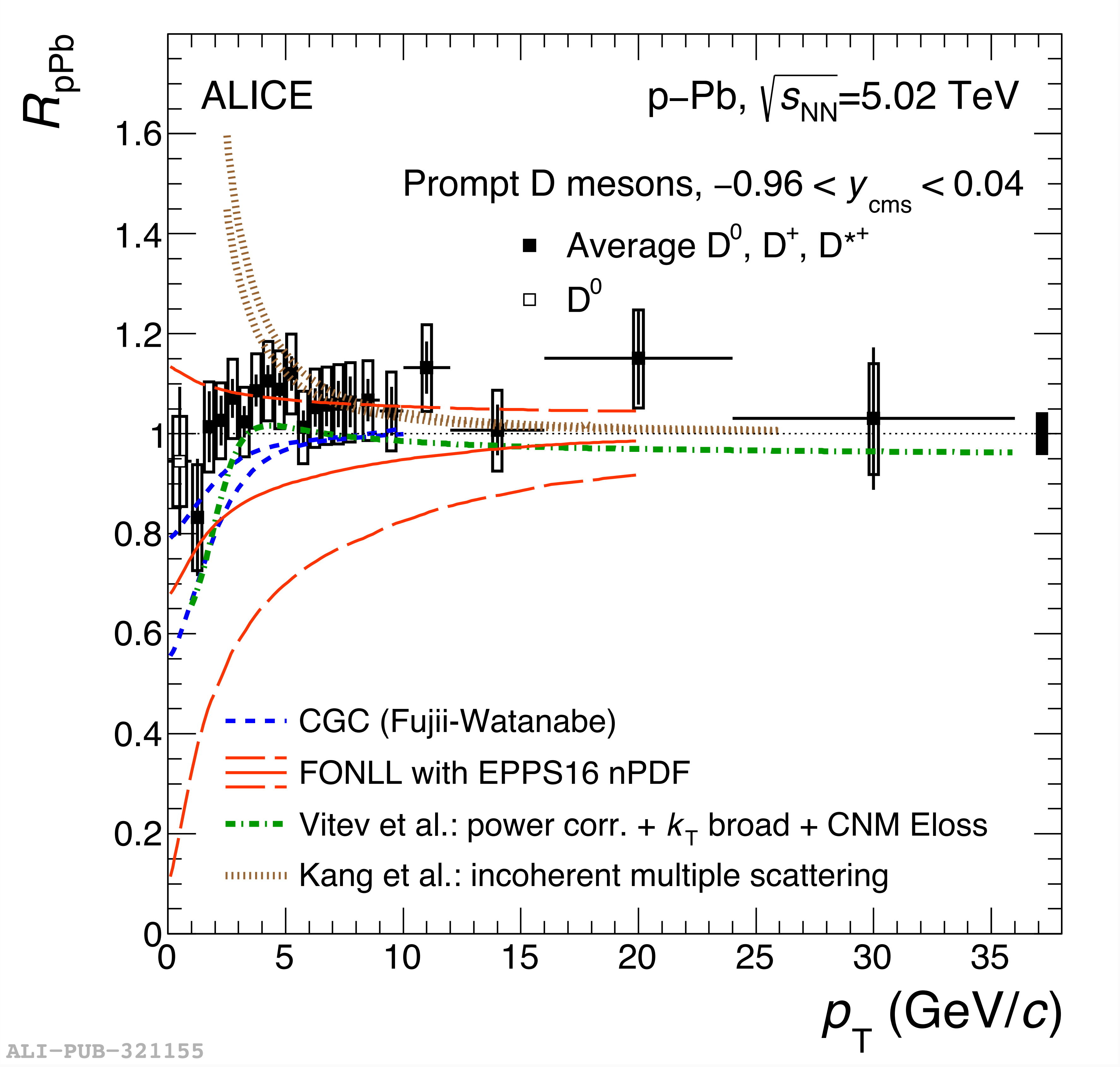
- R_{pA} consistent with unity: possible influence of cold nuclear matter effects on the cross section is smaller than the current precision
- Different sets of nPDF provides compatible calculations, describing measured data
- R_{pA} independent from resolution parameter (R); NNLO correction expected to have R-dependence
- Similar conclusion obtained from inclusive b-jet

Open charm hadrons R_{pA}

ALICE Collaboration, arXiv:2405.14571



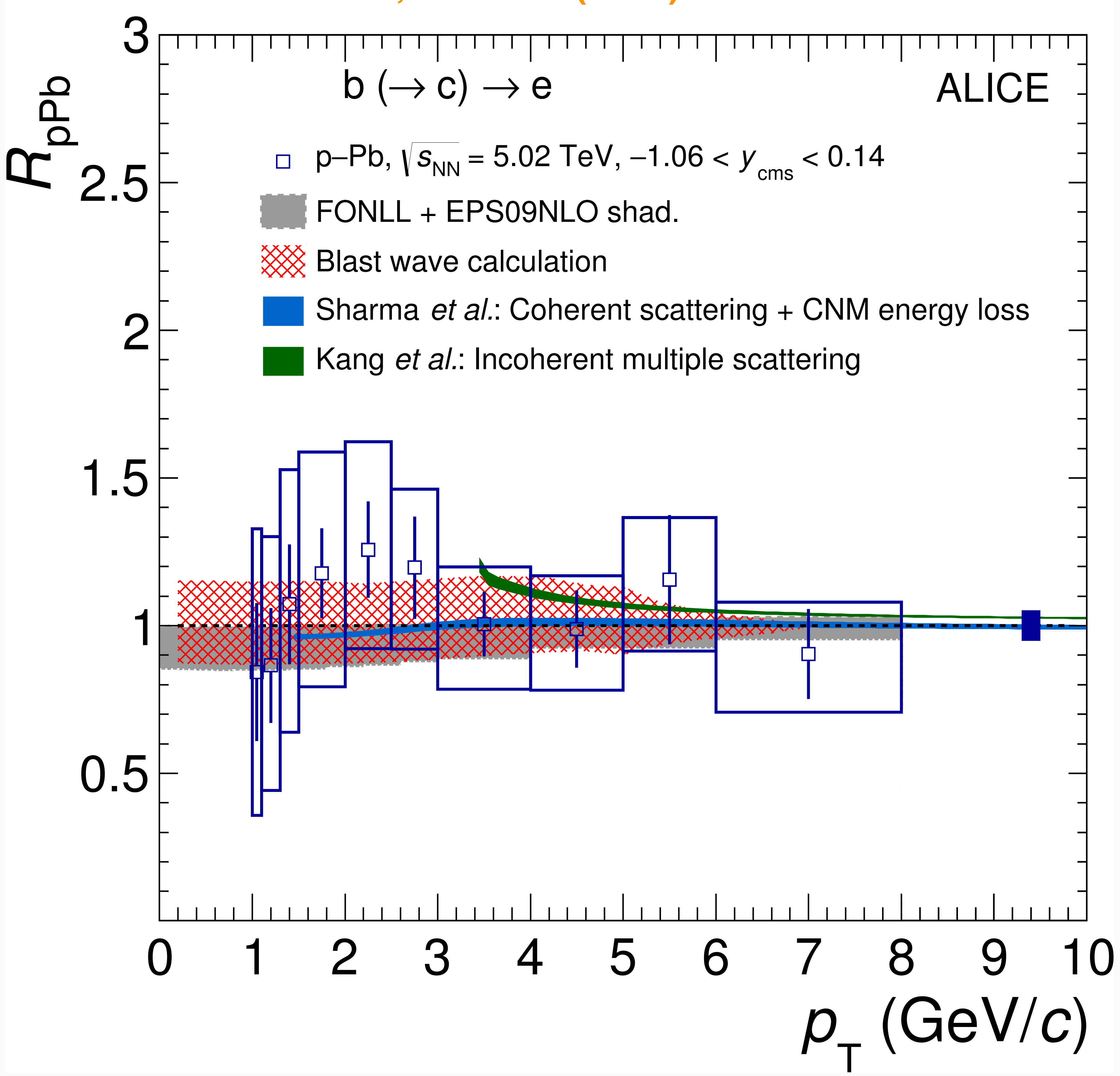
ALICE Collaboration, JHEP 12 (2019) 92



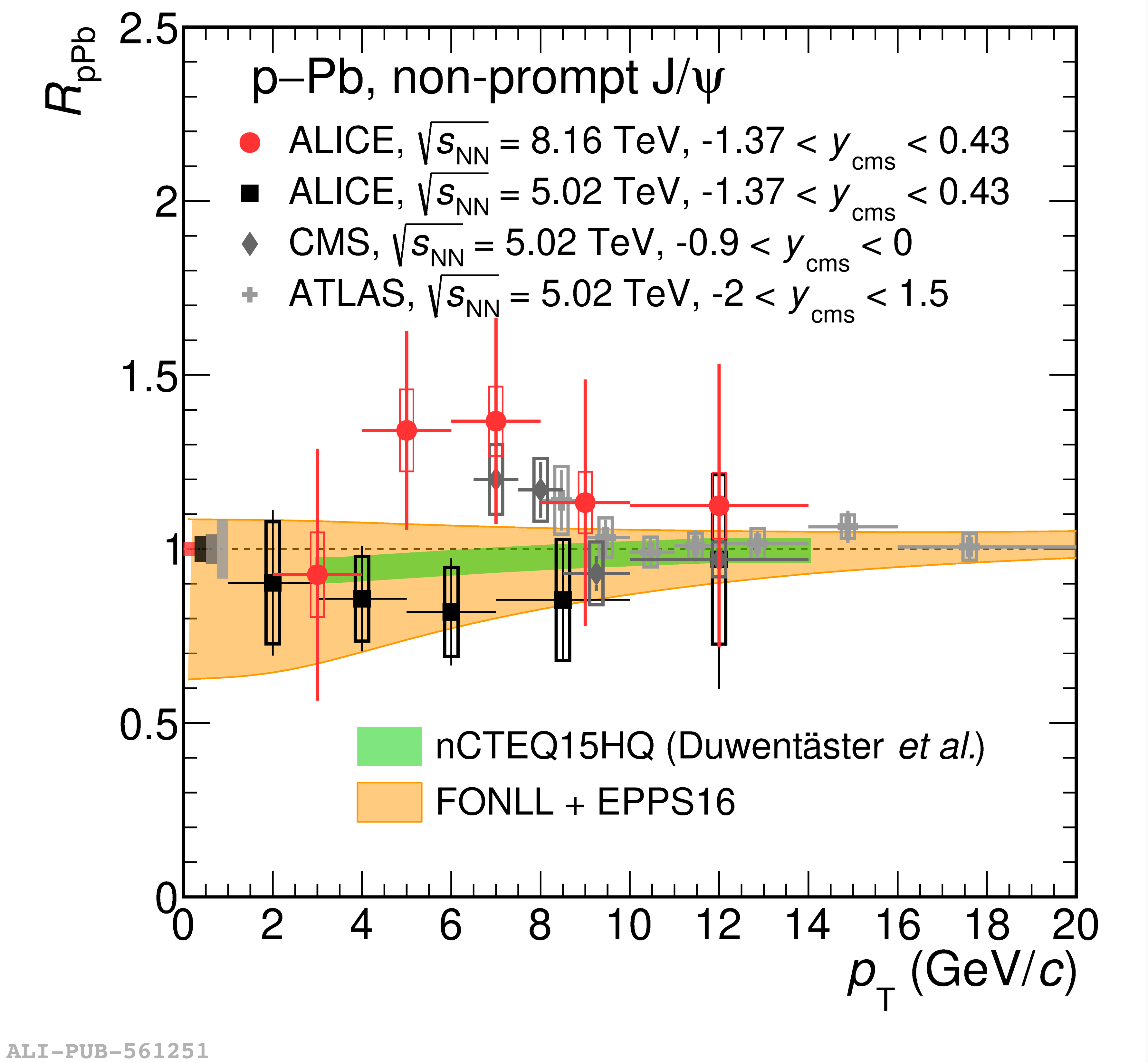
- p_T-Integrated R_{pA} of open charm meson and baryon, as well as cc-bar consistent with unity and with theoretical predictions including nuclear modifications of the parton distribution functions
- The models with different CNM effects qualitatively described R_{pA} of average D meson vs. p_T

(Indirect) open beauty hadrons R_{pA}

ALICE Collaboration, JHEP 07 (2017) 052



ALICE Collaboration, JHEP 07 (2023) 137



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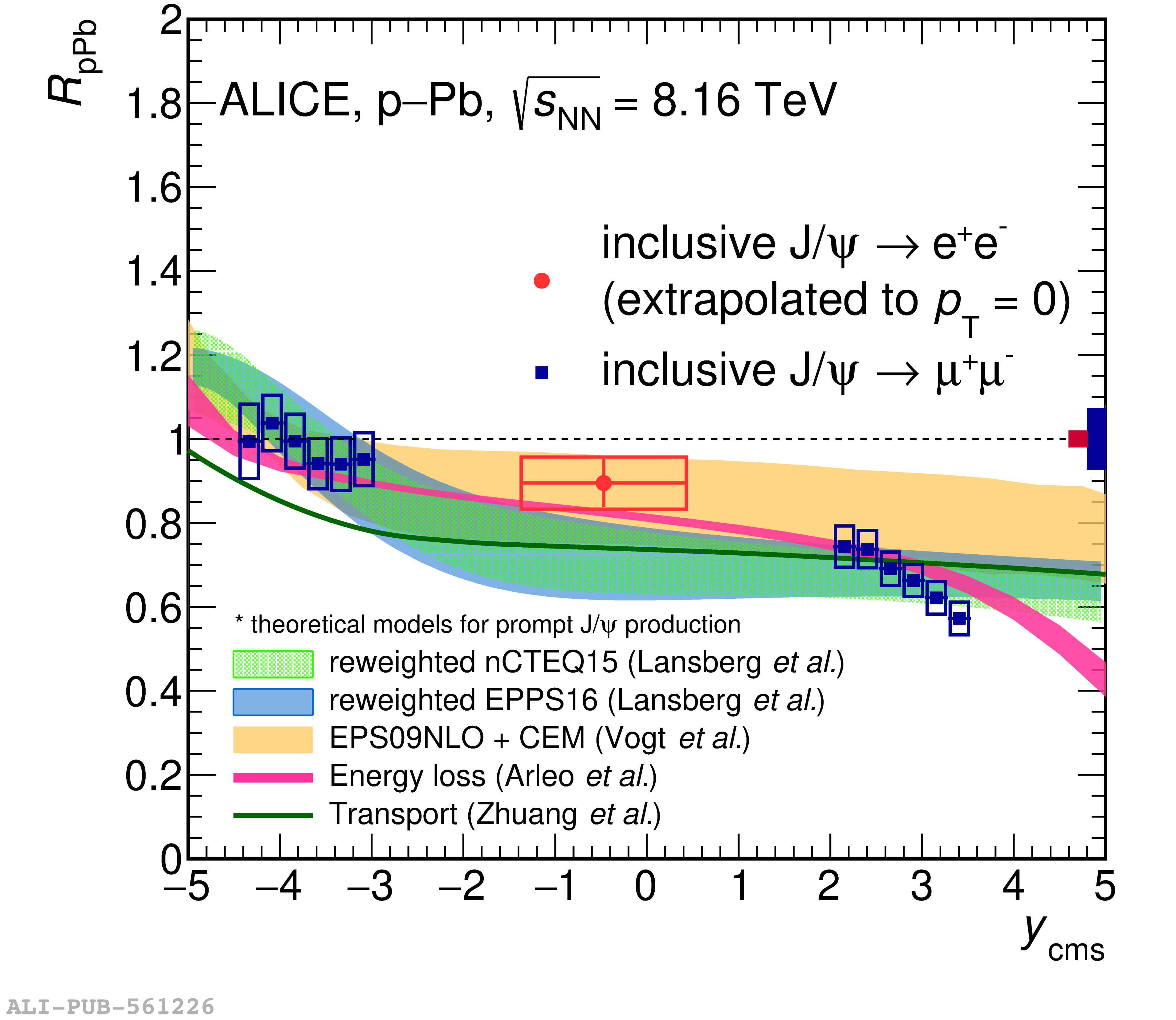
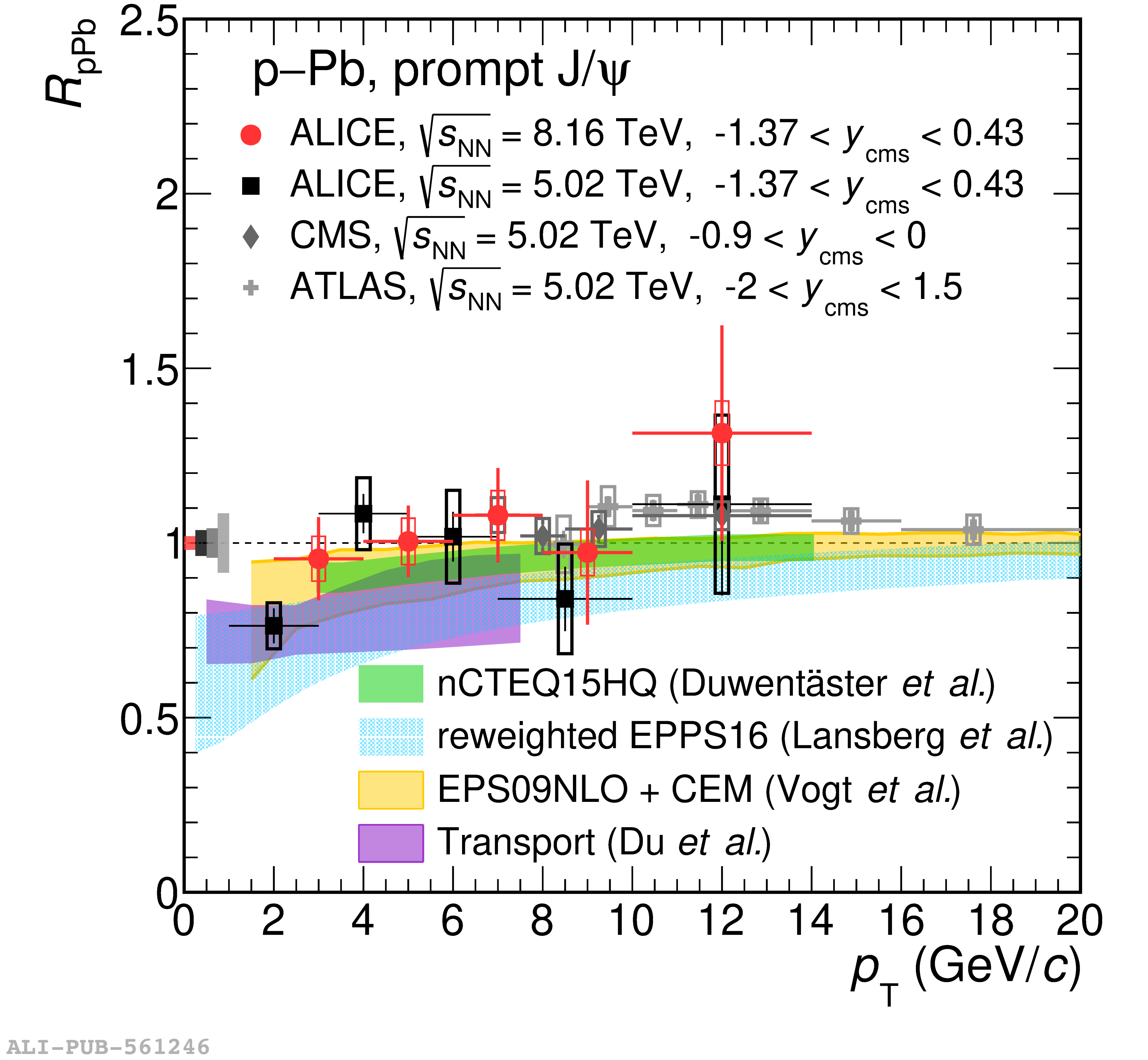
J/ψ R_{pA} in p-Pb collisions

ALICE Collaboration, JHEP 07 (2023) 137

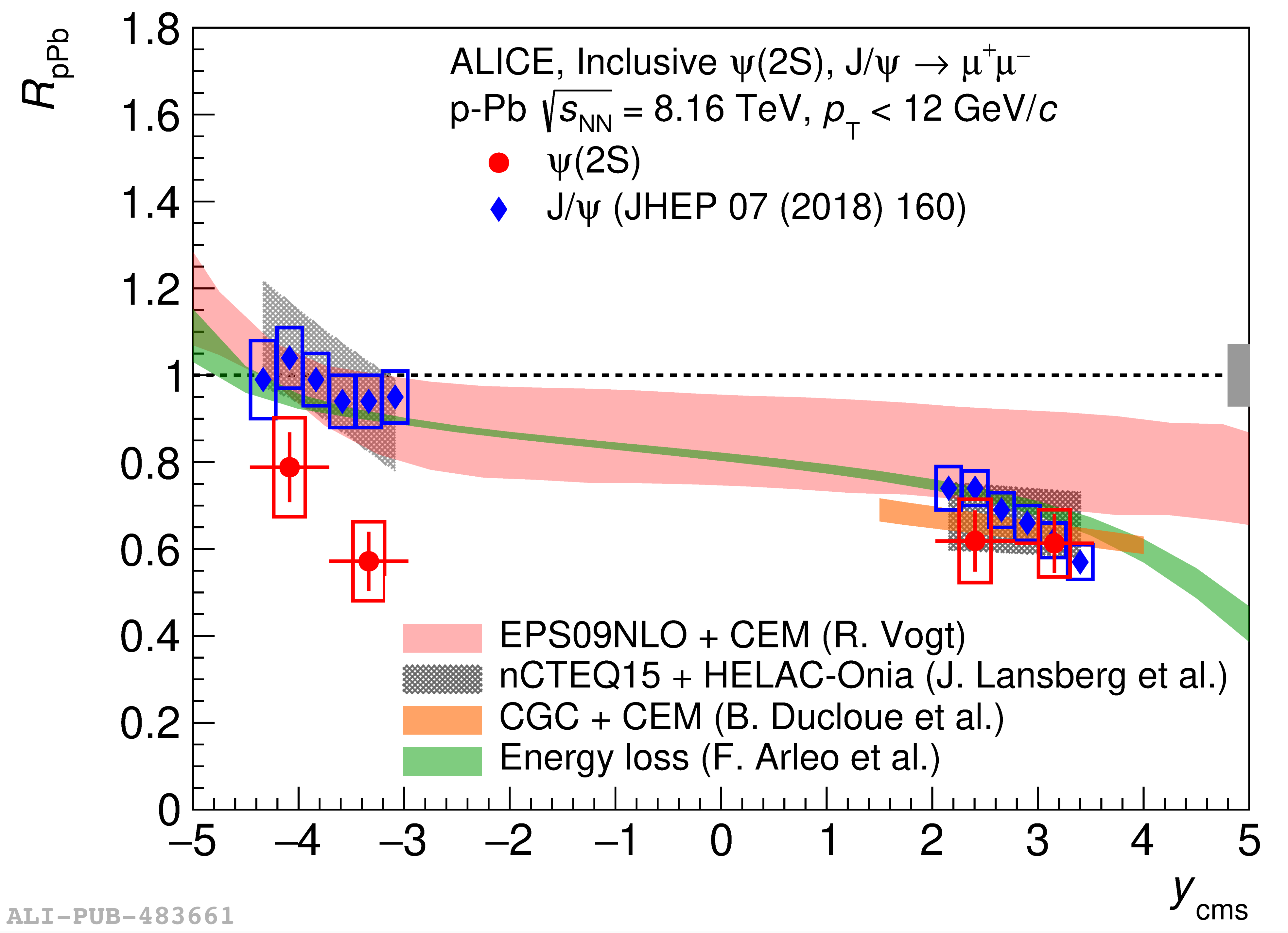


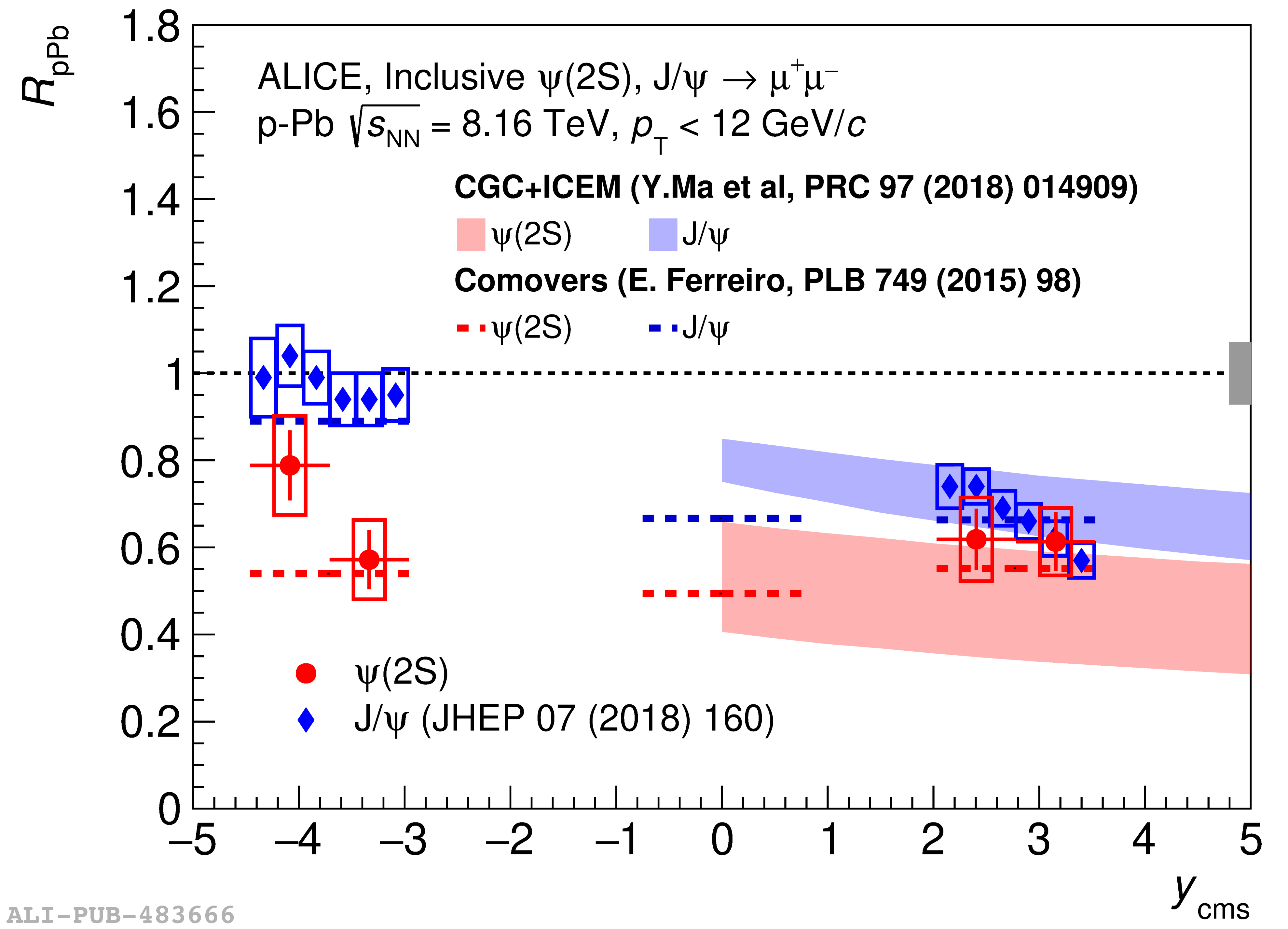


- Influence of rapidity dependent CNM effects; compatible with models including nPDF effects
- Suppression concentrated at low p_T; captured by models including nPDF effects as well as transport model

Excited charmonium states in p-Pb collisions

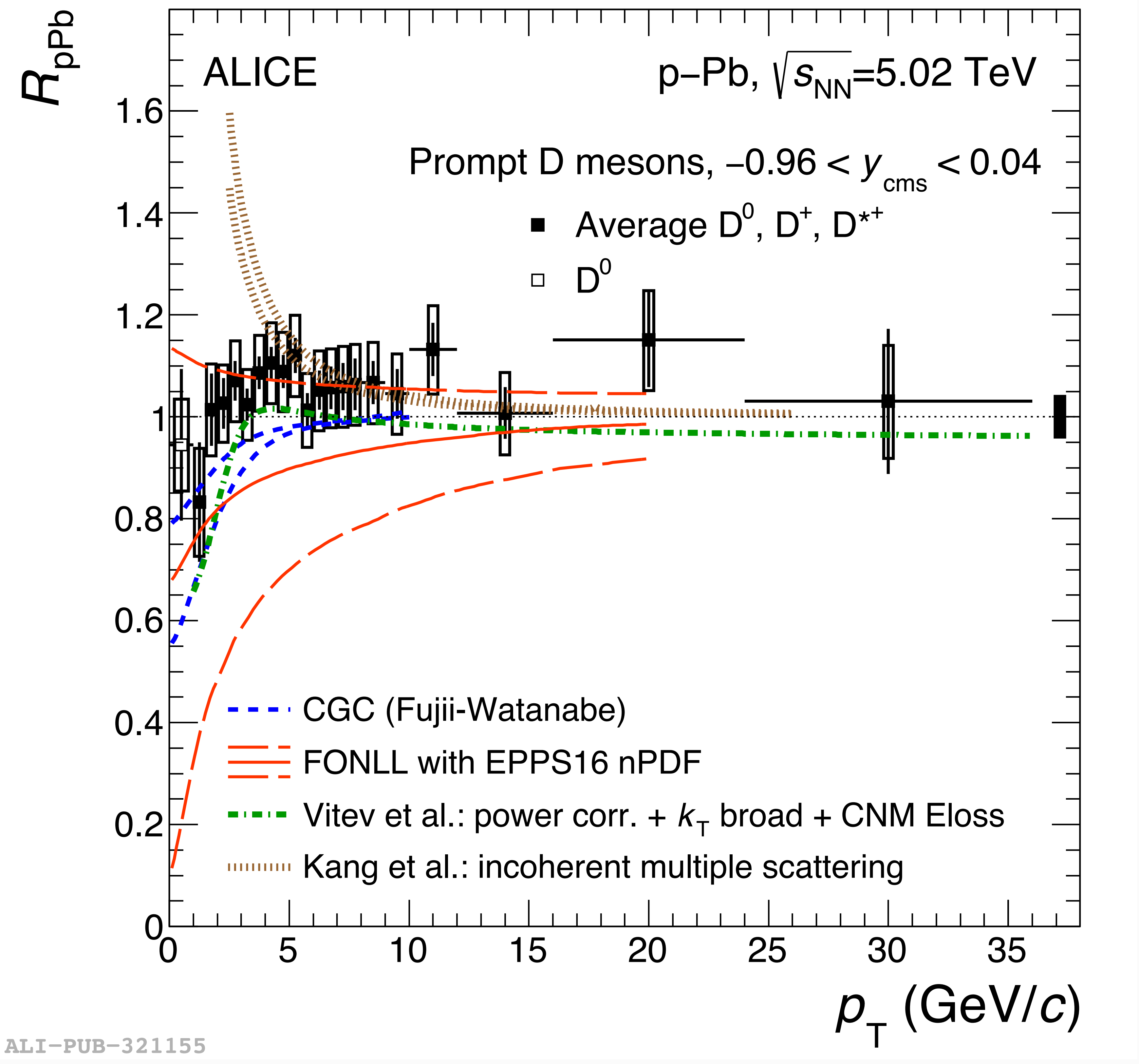
ALICE Collaboration, JHEP 07 (2020) 237

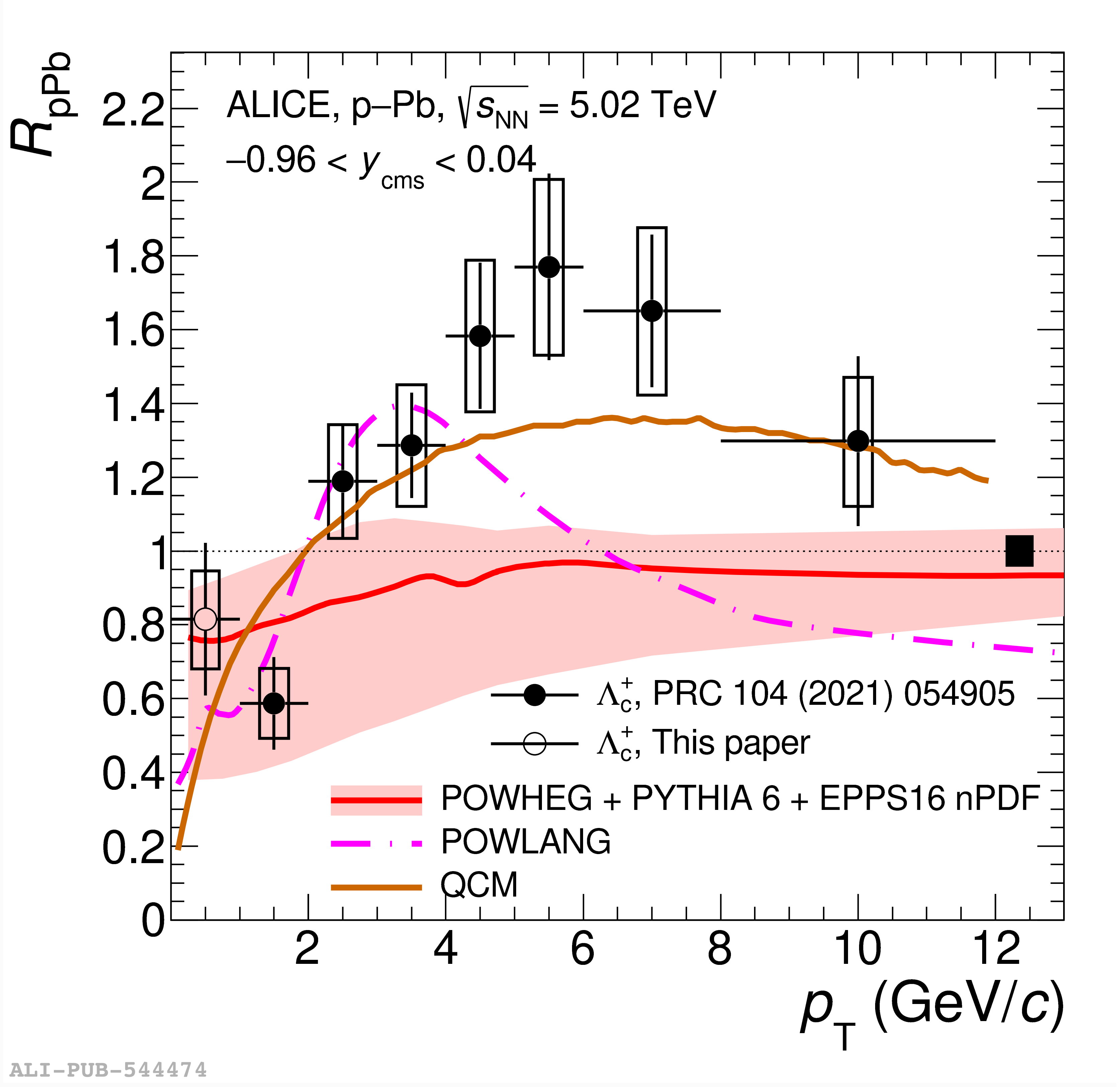


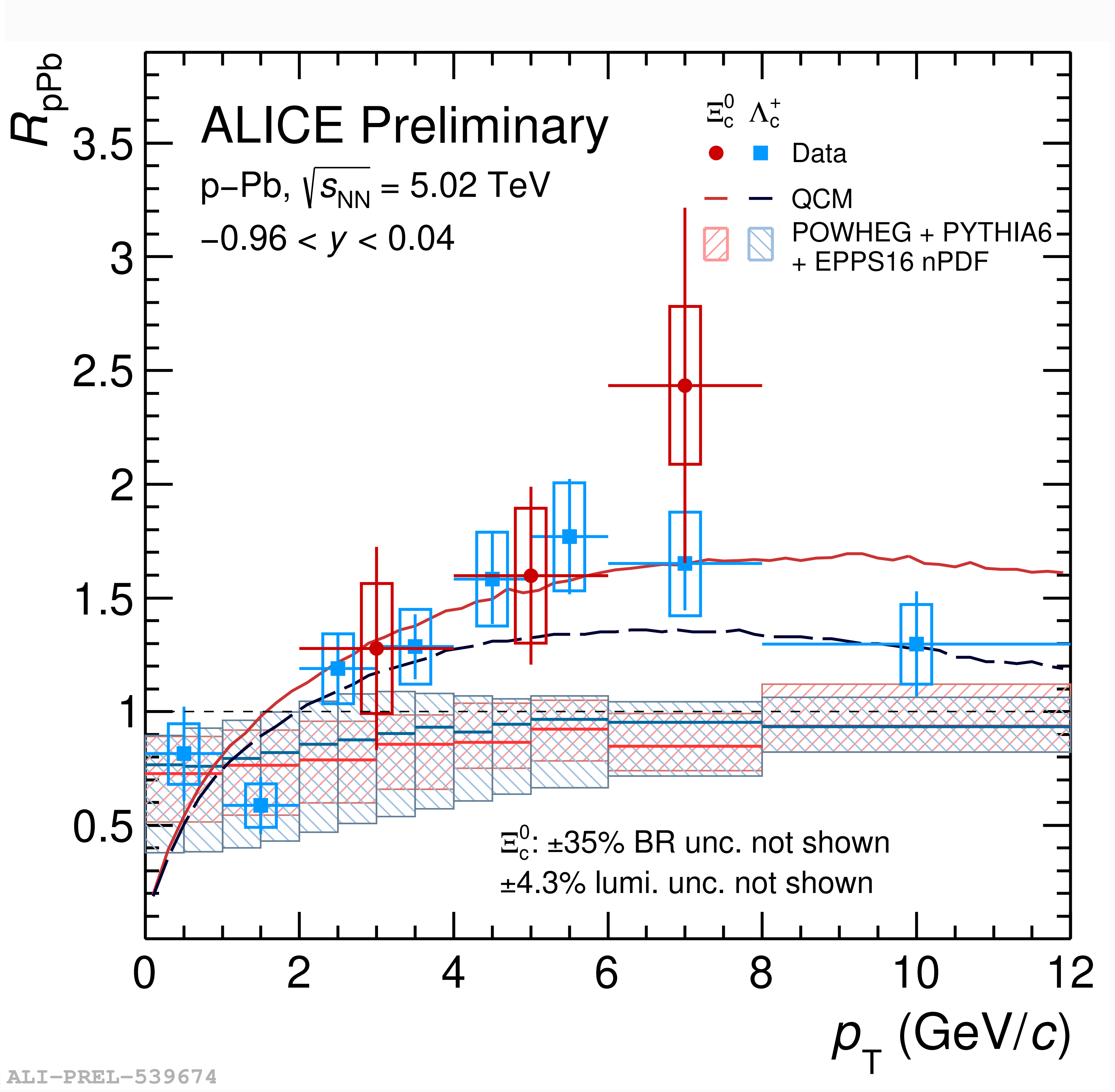


- Stronger suppression of ψ(2S) at backward rapidity; compatible at forward rapidity
- Initial-state effects or coherent energy loss; largely independent on the specific charmonium resonance → final-state effects? If so, initiated from what?

Closer look at open charm hadrons R_{pA}



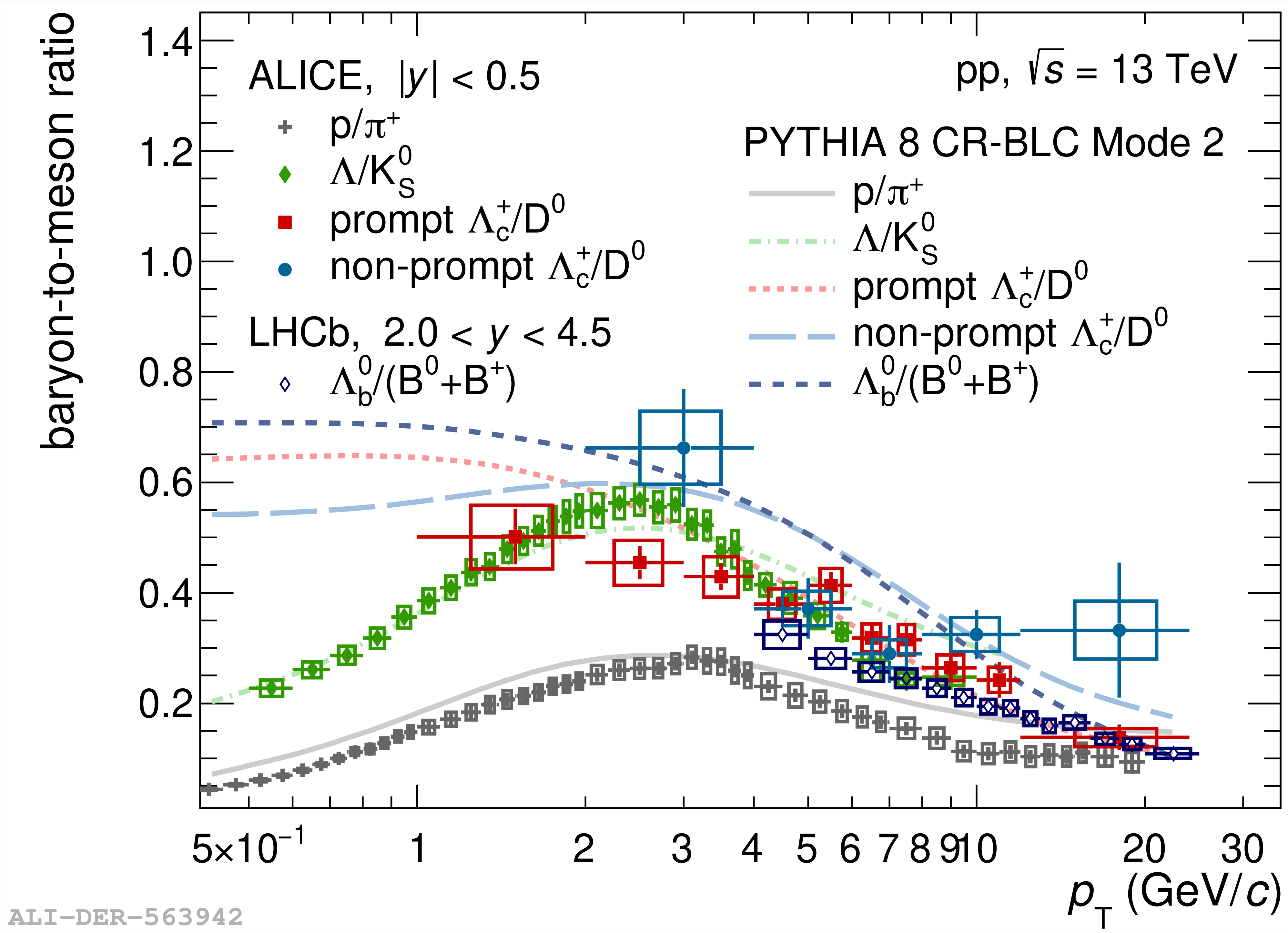


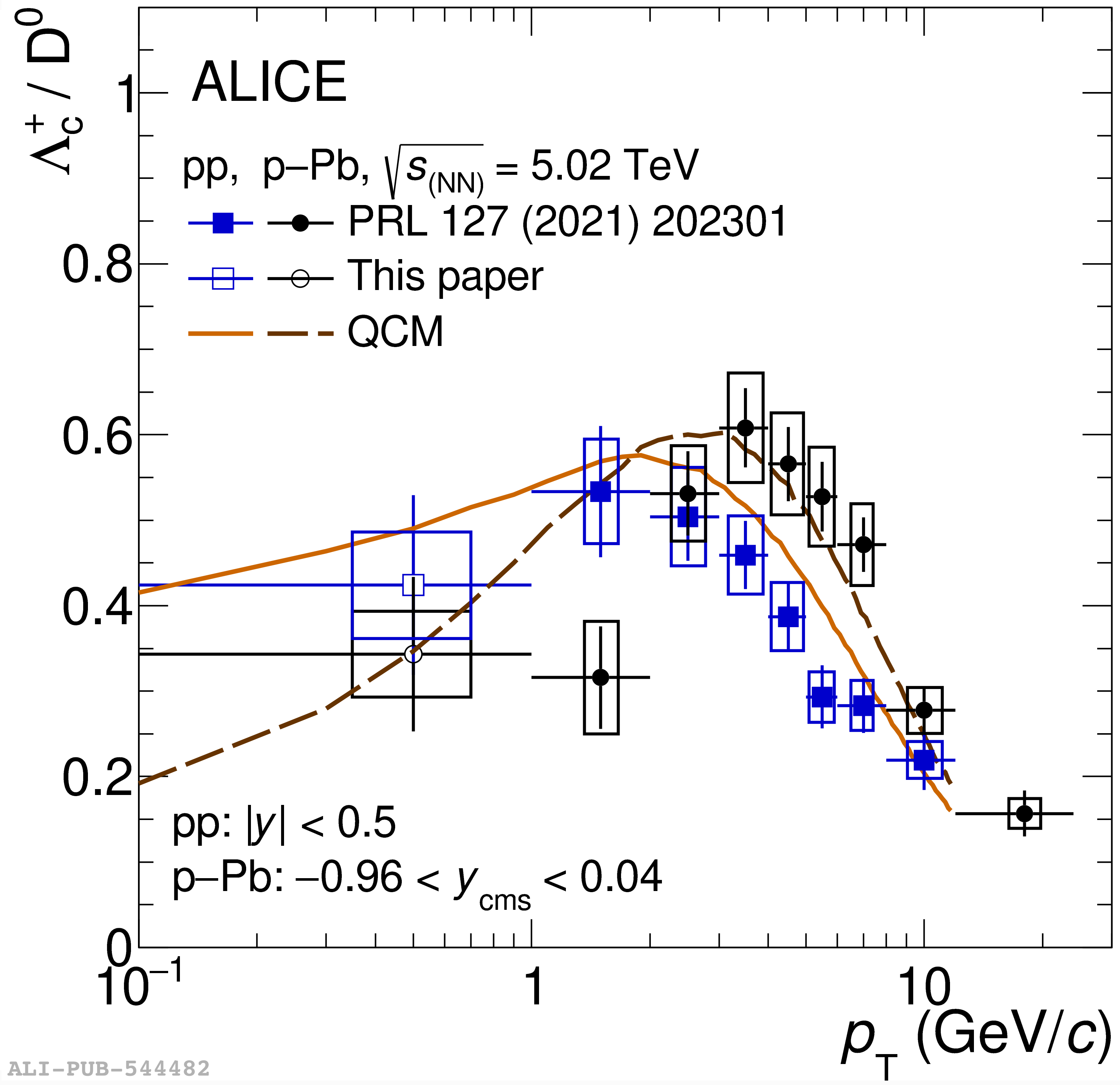


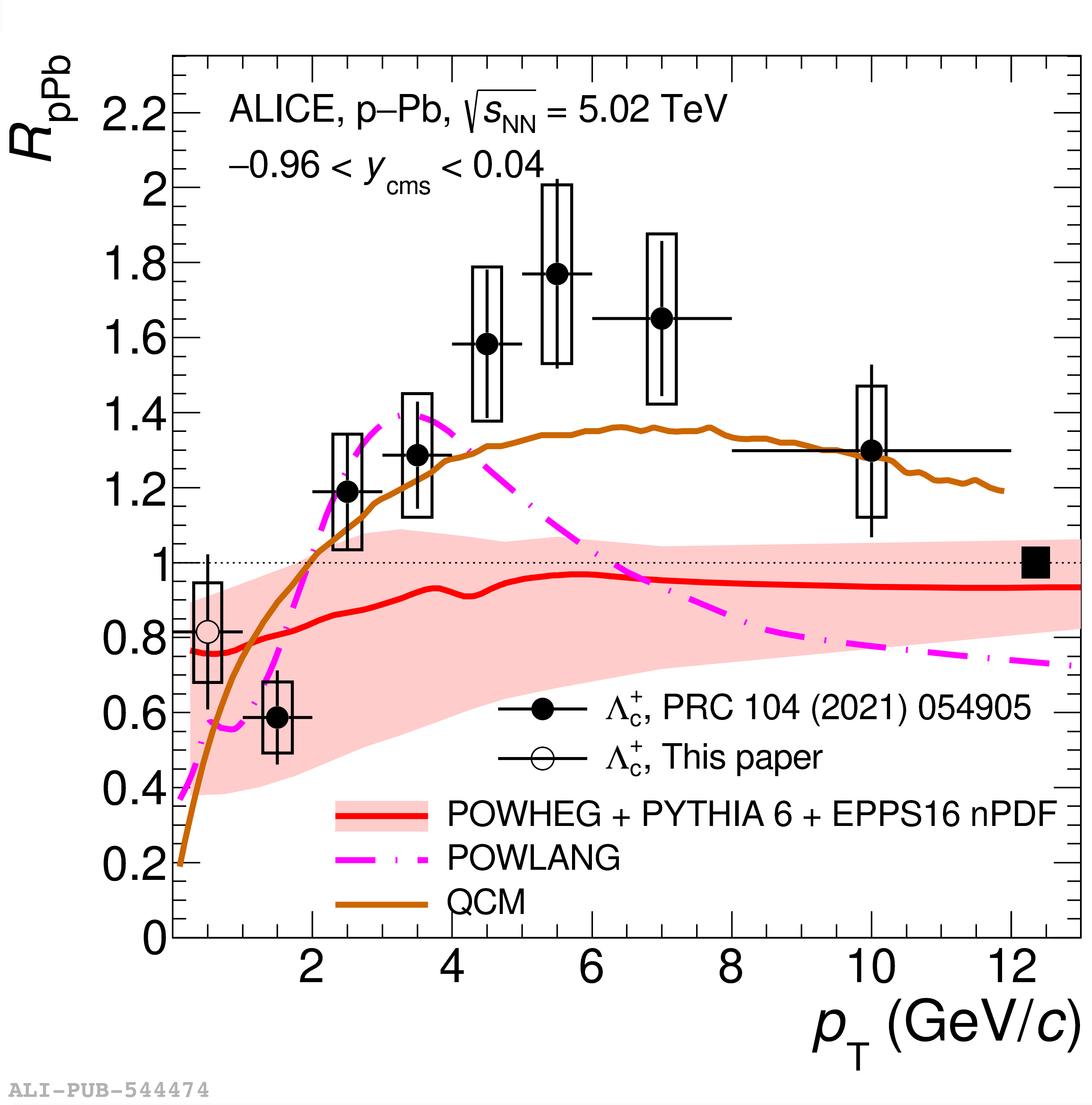
- D-meson R_{pPb} is compatible with unity and compared to model predictions including CNM effects
- Both Λ_c^+ and Ξ_c^0 R_{pPb} are compatible within uncertainties
  - Models reasonably describing D-meson underestimate the data (only Λ_c^+ R_{pPb} is described below 2 GeV/c)
  - Models including QGP effects also capture the trend as a function of p_T

Lesson from Λ_c/D^0 ratio

ALICE Collaboration, [Phys. Rev. D 108, 112003]



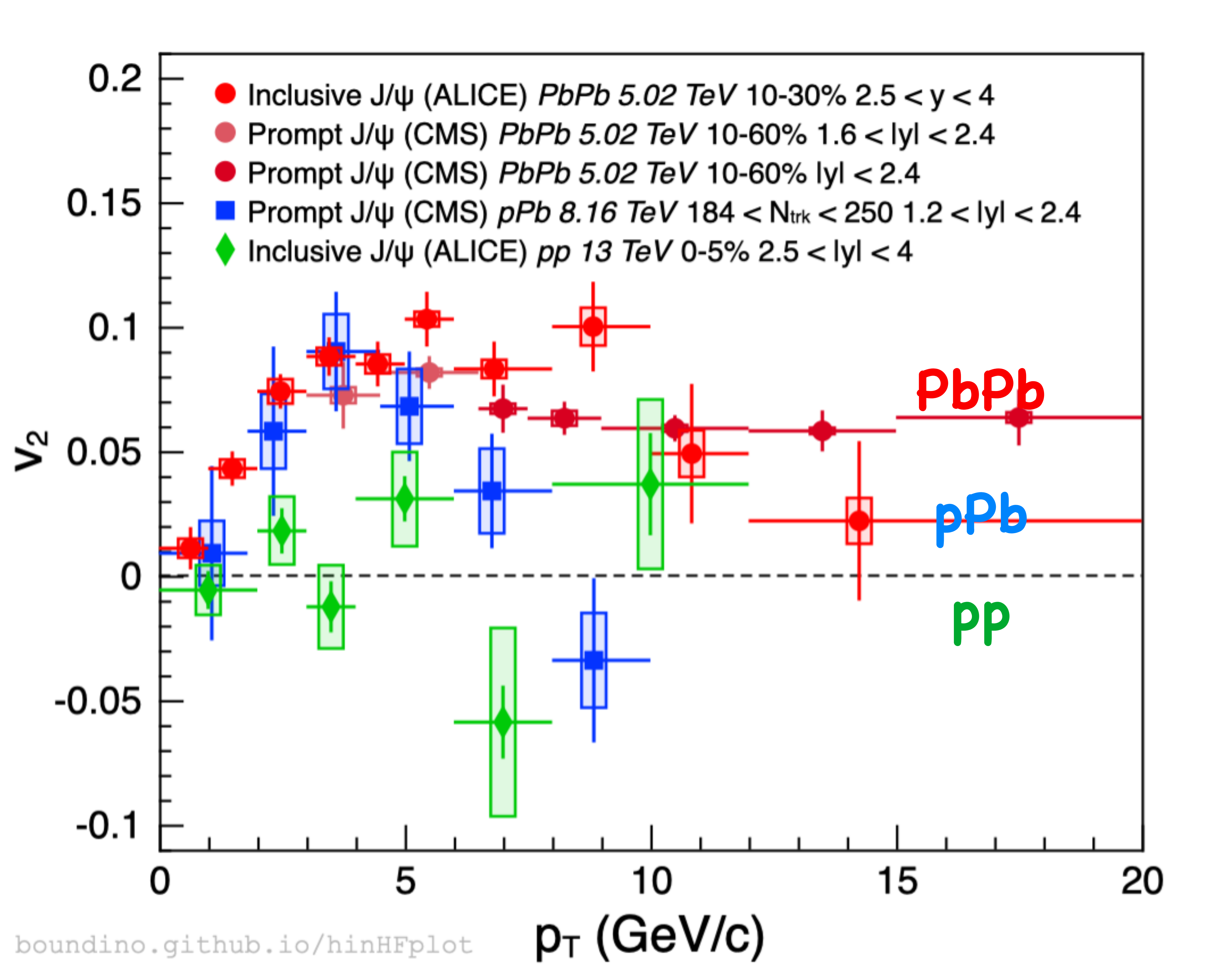


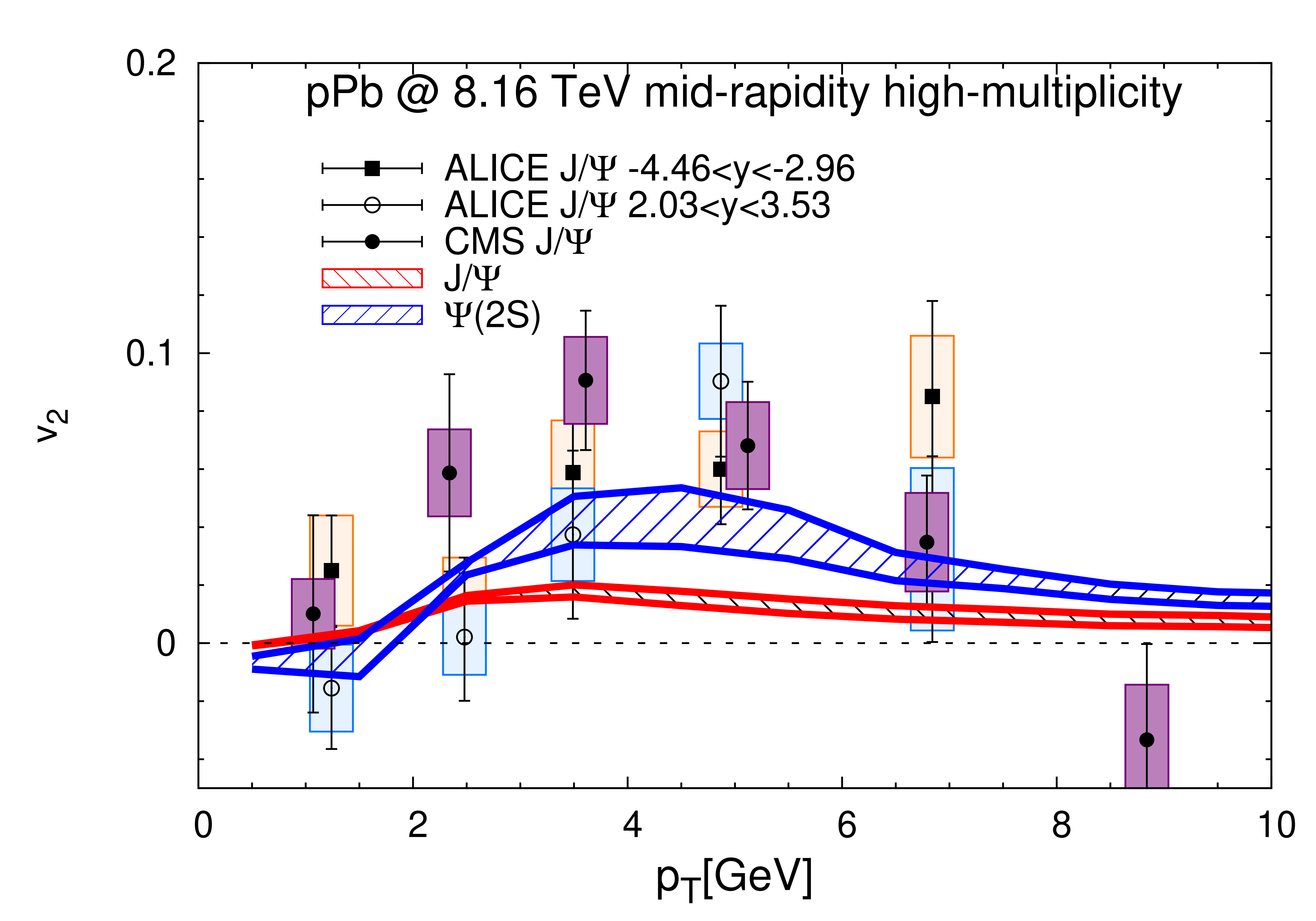


- Ratio of p_T-differential production cross section of baryon and meson
  - Charm, and strange hadrons have a similar trend and are compatible within uncertainties
- Similar trend of Λ_c^+/D^0 in both pp and p–Pb collisions
  - Different momentum redistribution; Shift towards higher pT in p–Pb collisions attributed to radial flow?

Quarkonium elliptic flow in small system

Rapp et al., JHEP 03 (2019) 015



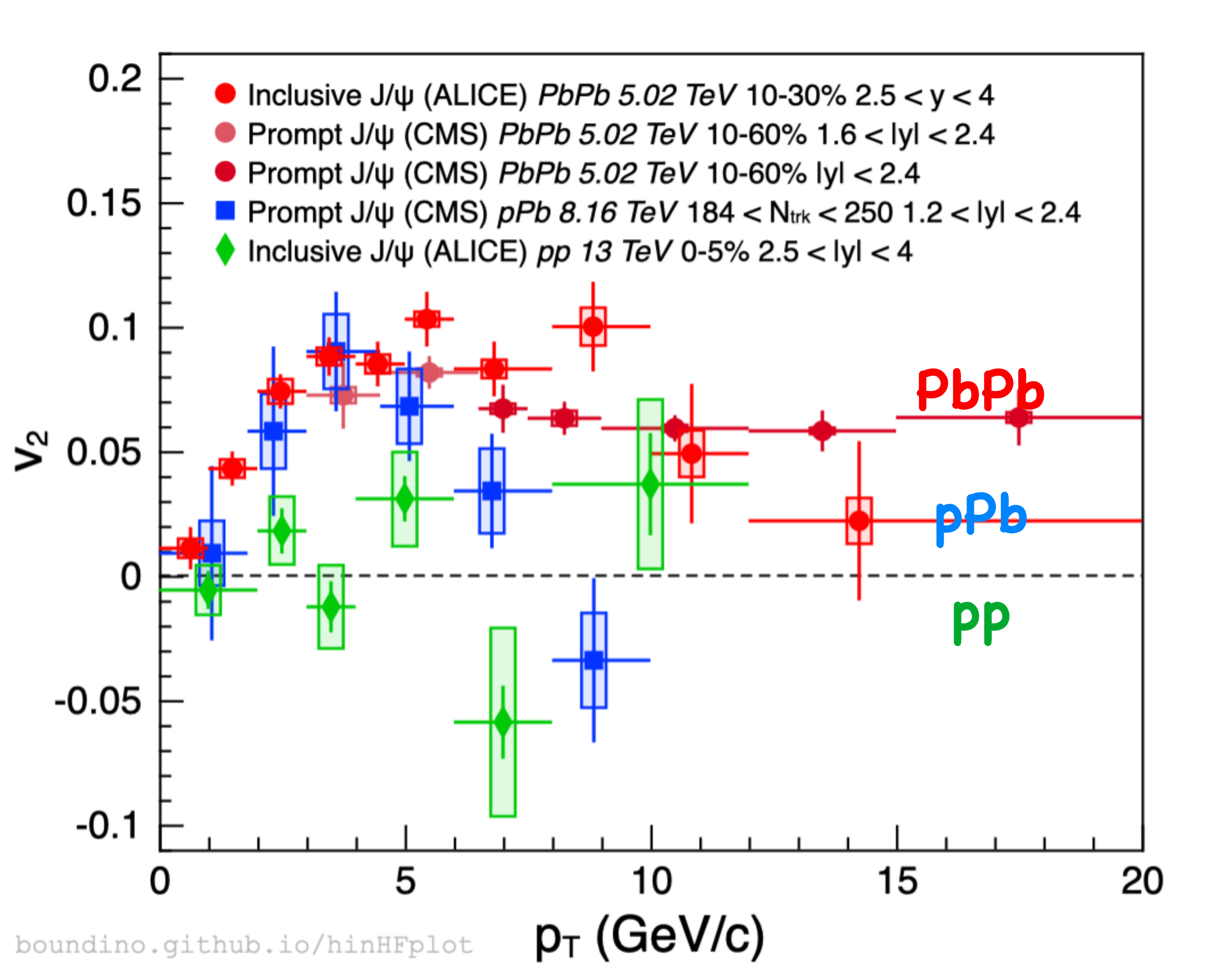


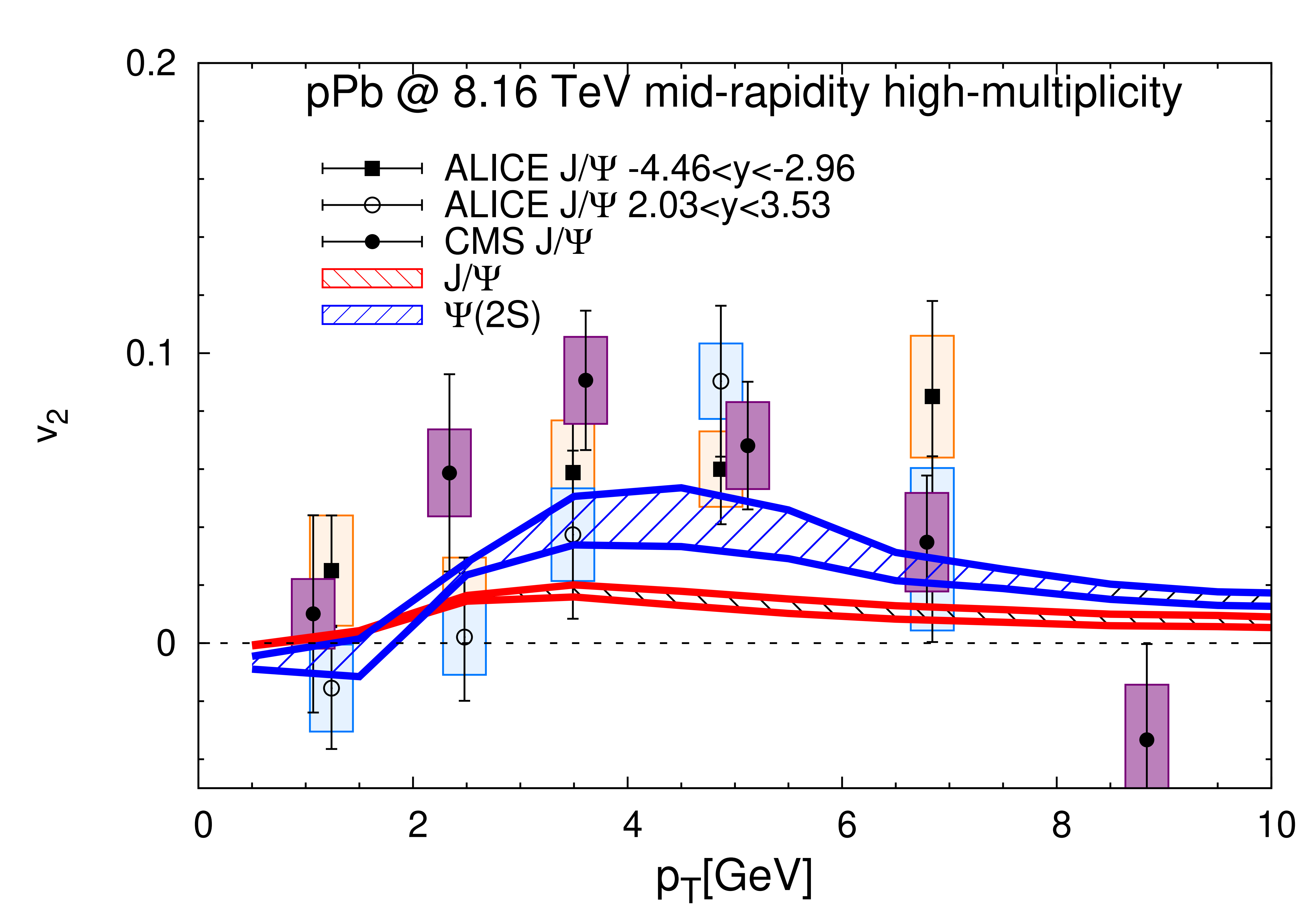
- CMS-PAS-HIN-21-008
- JHEP 10 (2020) 141
- PLB 791 (2019) 172
- ALICE Preliminary

- **J/ψ : PbPb $v_2 \geq$ pPb $v_2 >$ pp $v_2 \approx 0$**
- Non-zero J/ψ v_2 in high multiplicity p-Pb collisions, underpredicted by theory including final-state collectivity at intermediate p_T

Quarkonium elliptic flow in small system

Rapp et al., JHEP 03 (2019) 015





- CMS-PAS-HIN-21-008
- JHEP 10 (2020) 141
- PLB 791 (2019) 172
- ALICE Preliminary

Numerous unexpected results in small systems at the LHC

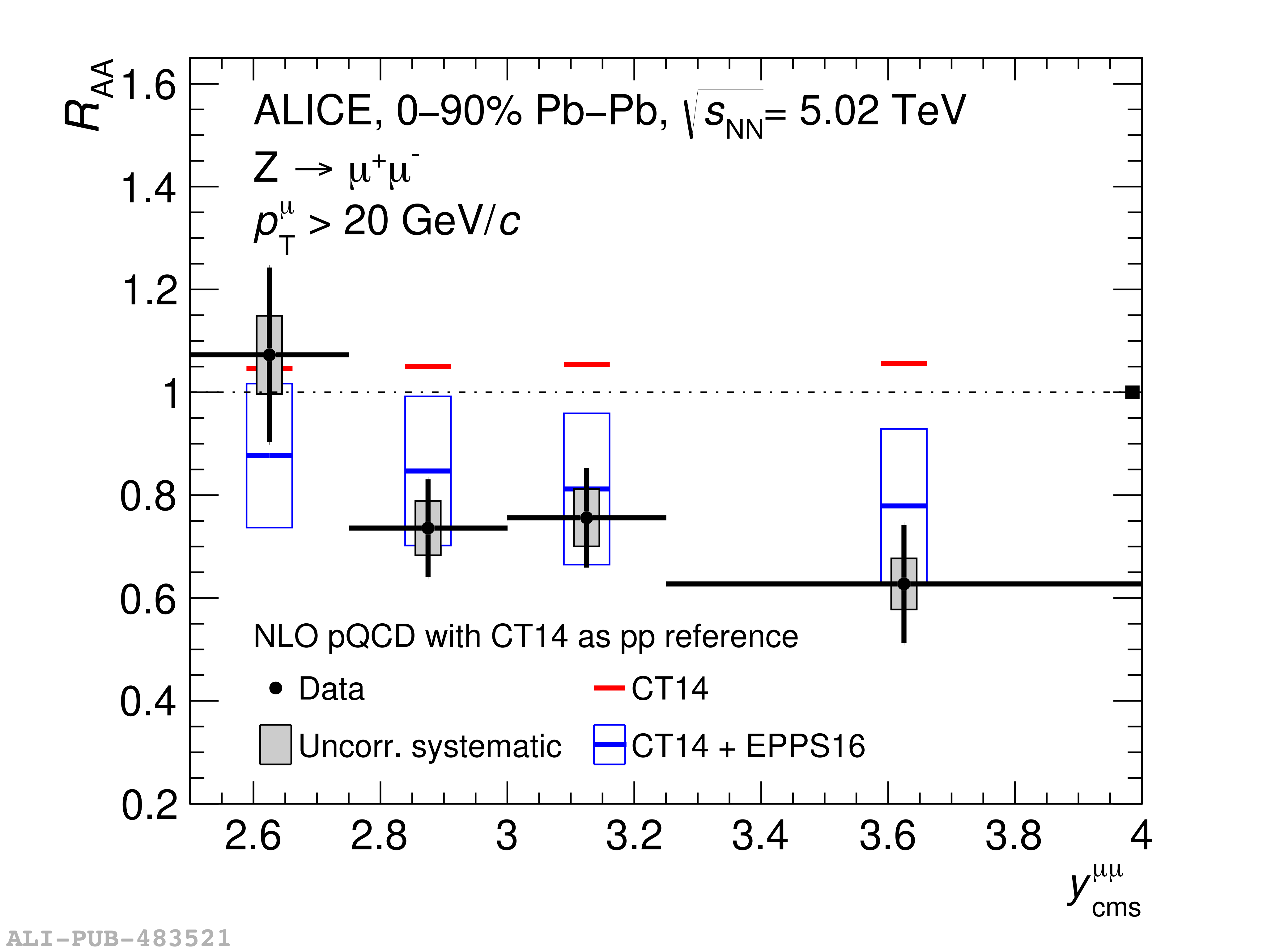
➡Not simple reference/control experiment for Pb-Pb collisions

➡Probing cold nuclear matter effects or initial state effects in different ways?

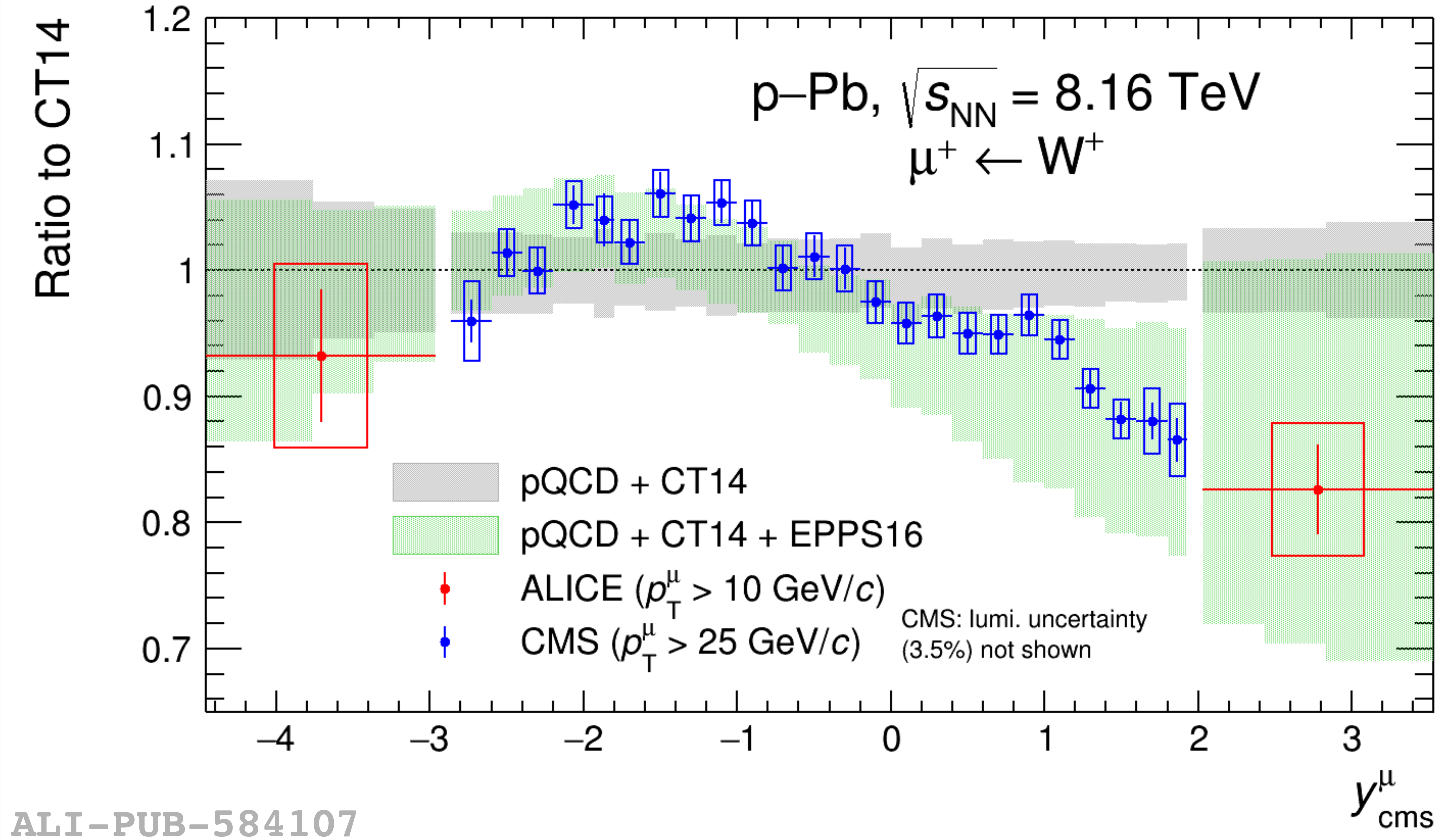
Electroweak vector-boson production in heavy ion collisions

- Produced predominantly via a quark – antiquark pair annihilation (Drell-Yan); Sensitive to parton distribution functions for up and down quarks
- Weakly interacting particles; Decay leptons insensitive to the strongly-interacting medium

ALICE Collaboration, JHEP 2009 (2020) 076

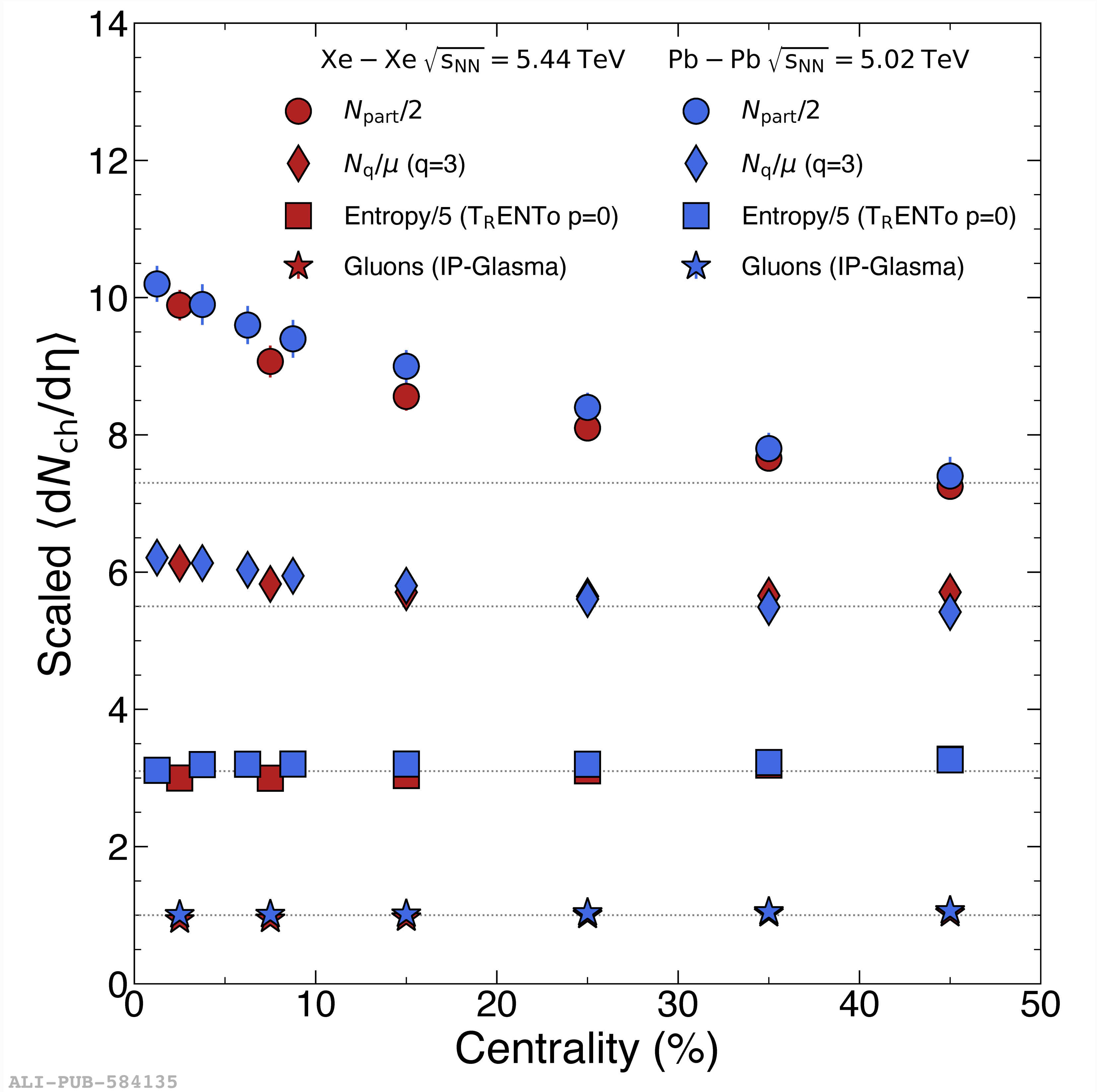


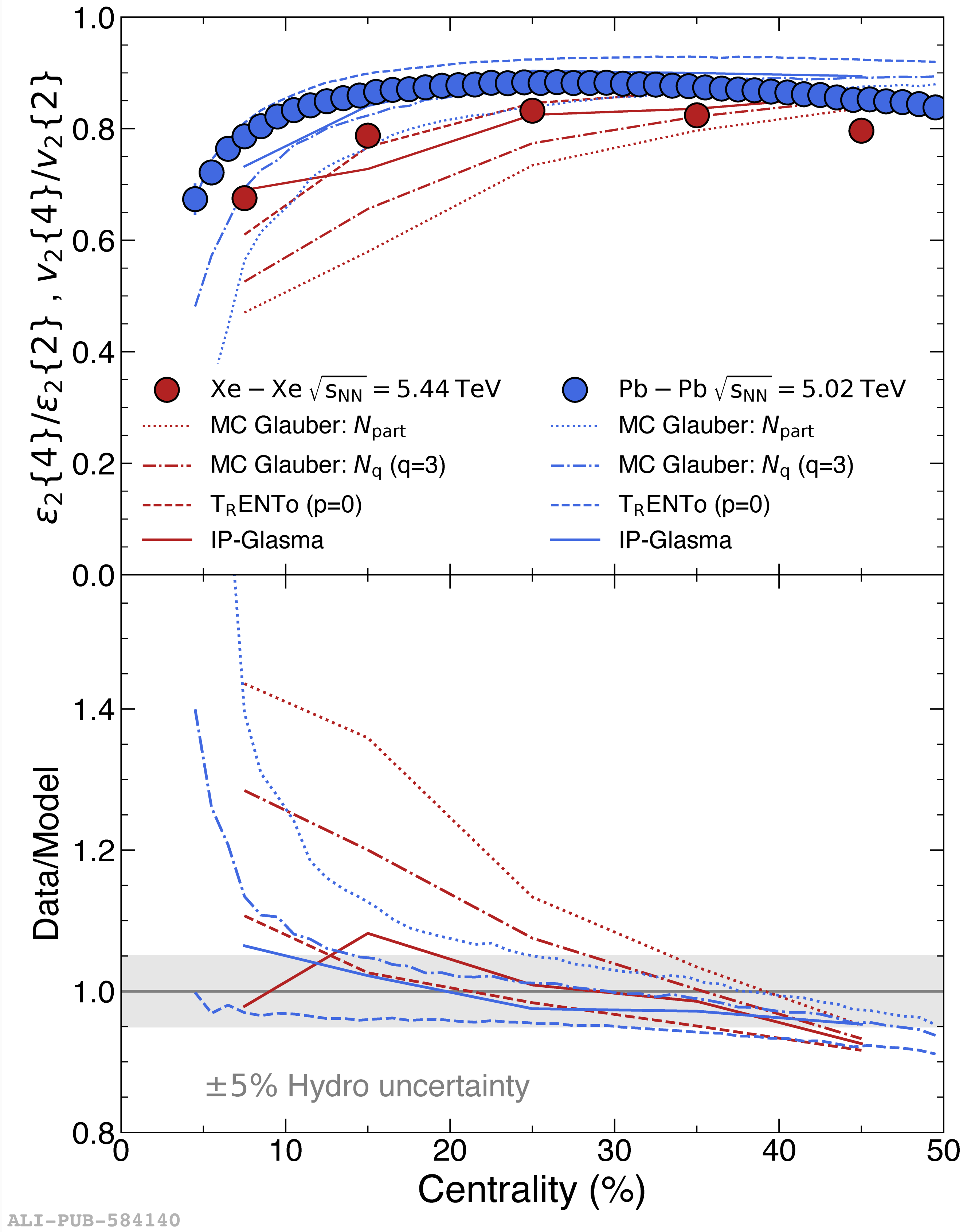
ALICE Collaboration, JHEP 05 (2022) 036

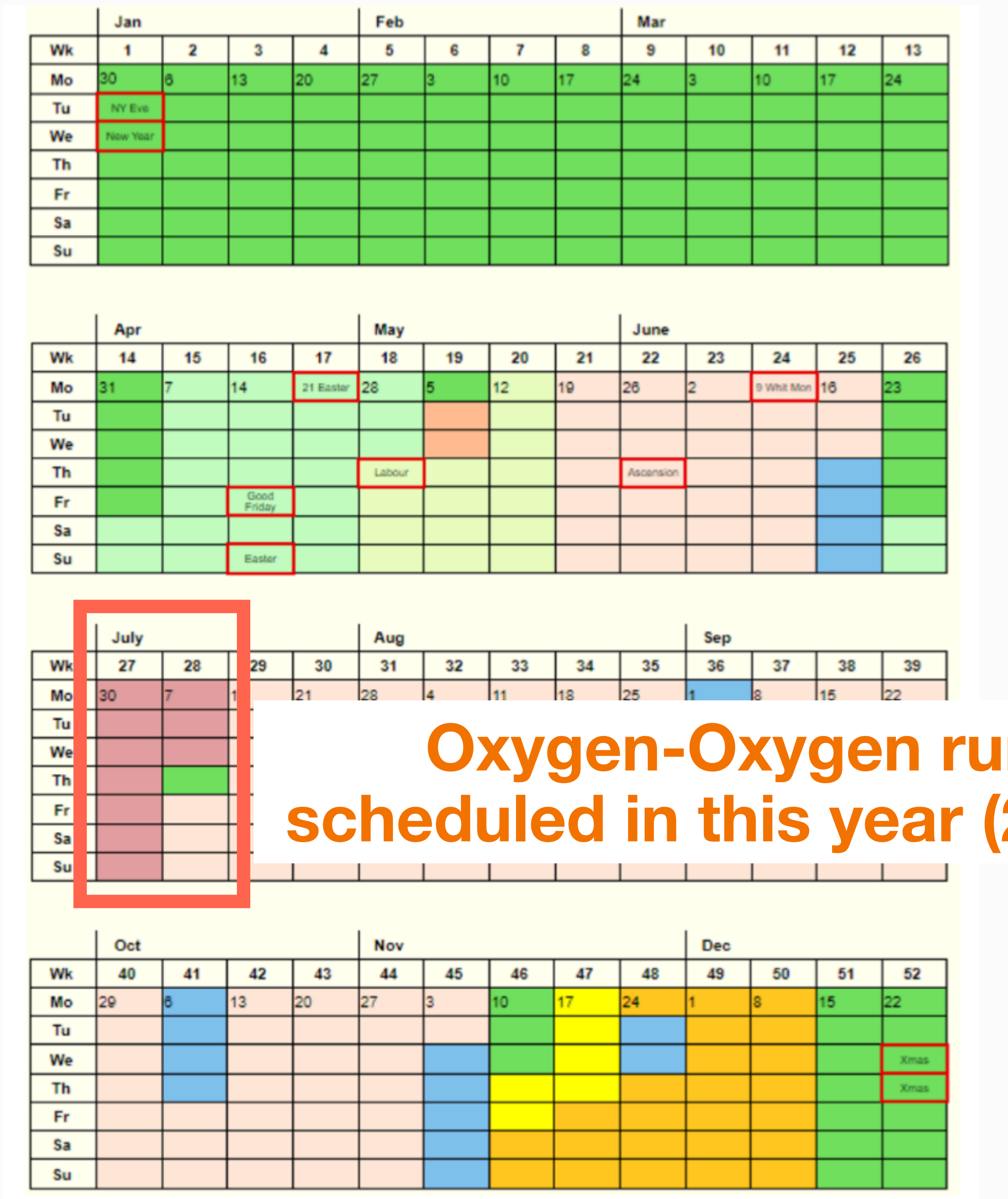


- Direct access of nPDF effects in Pb-Pb collisions and quantify the nPDF through p-Pb collisions

Connection to bulk properties in Pb-Pb collisions?



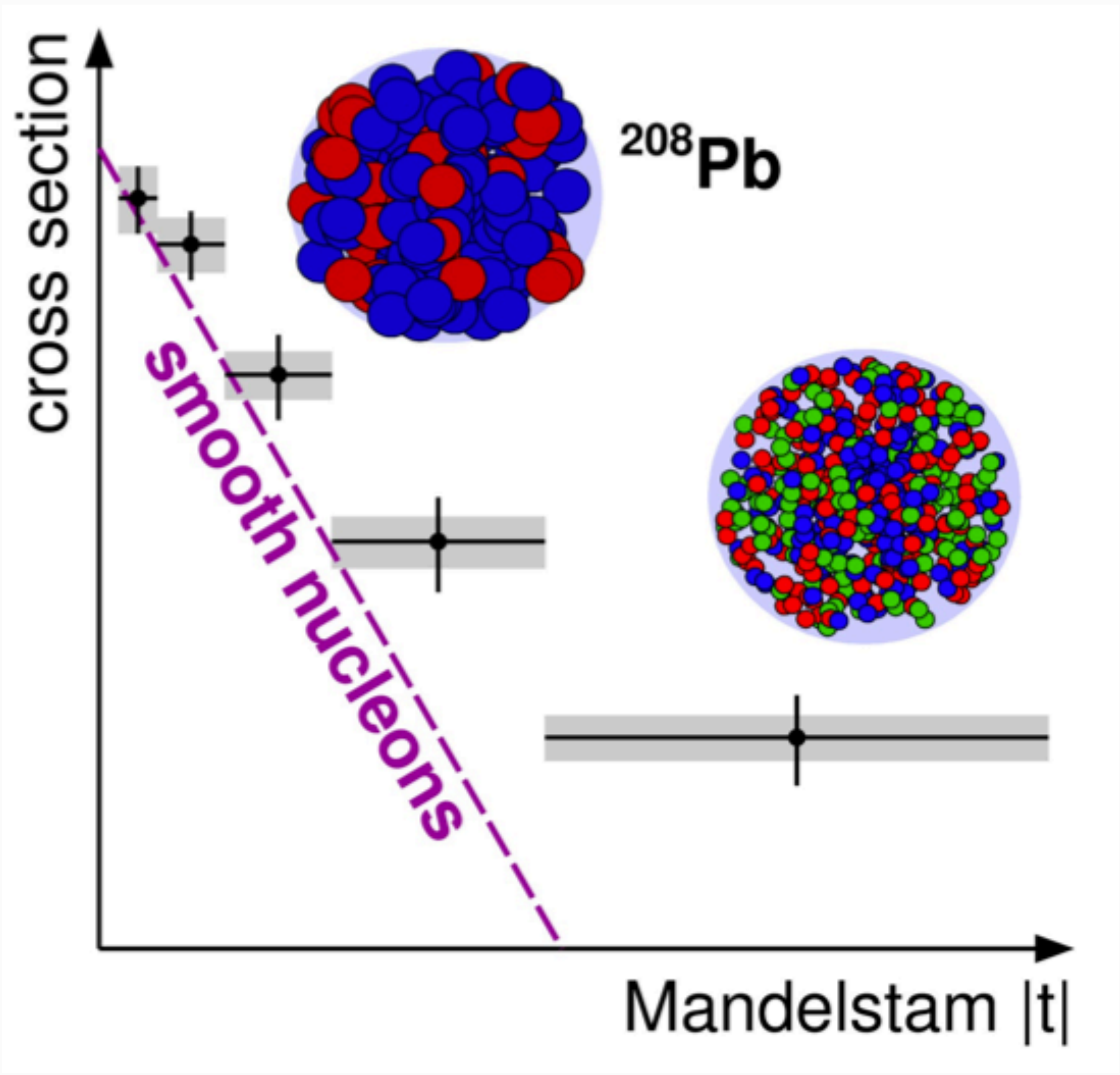




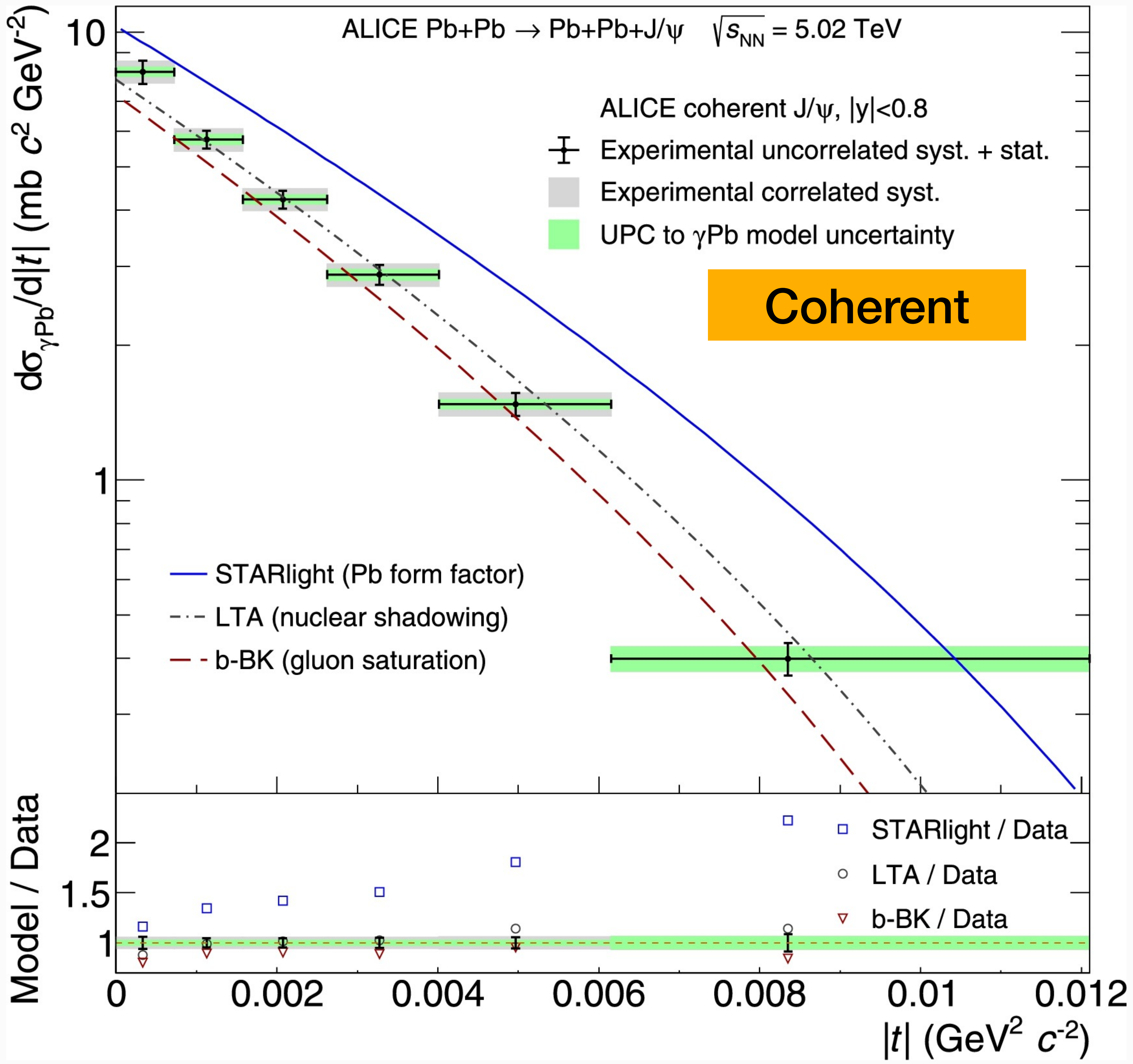
Oxygen-Oxygen run scheduled in this year (2025)!

- Entropy is approximately conserved through the evolution of the QGP using hydrodynamic simulations for η/s values around 1/4π
- The number of degrees of freedom in the initial state (or initial state entropy) should therefore be proportional to the number of particles produced in the final state
- Access to degrees of freedom from a initial state (Caveat: Strong model dependent studies)

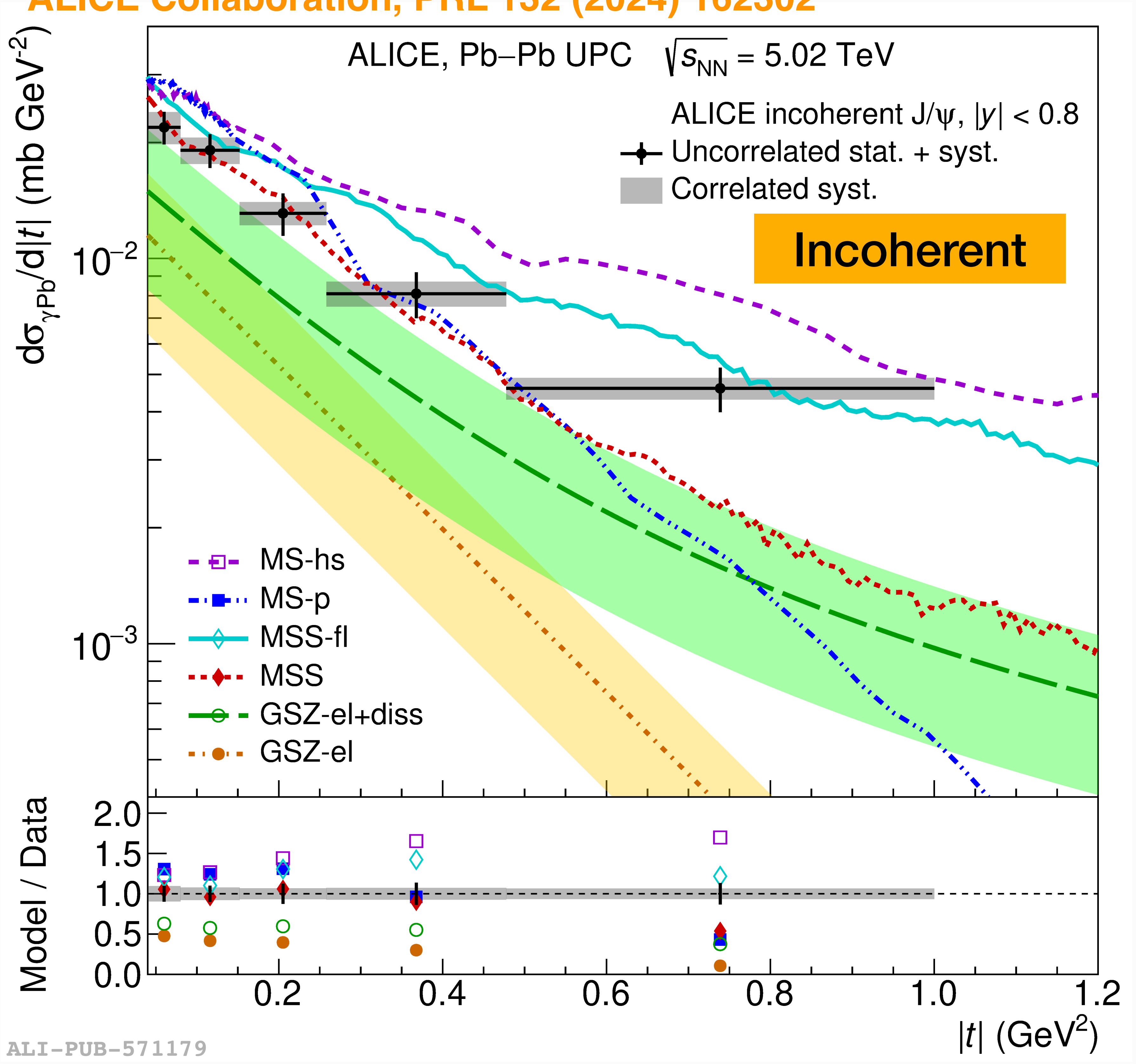
Imaging the nucleus with photoproduced J/ψ



ALICE Collaboration, PLB 817 (2021) 136280

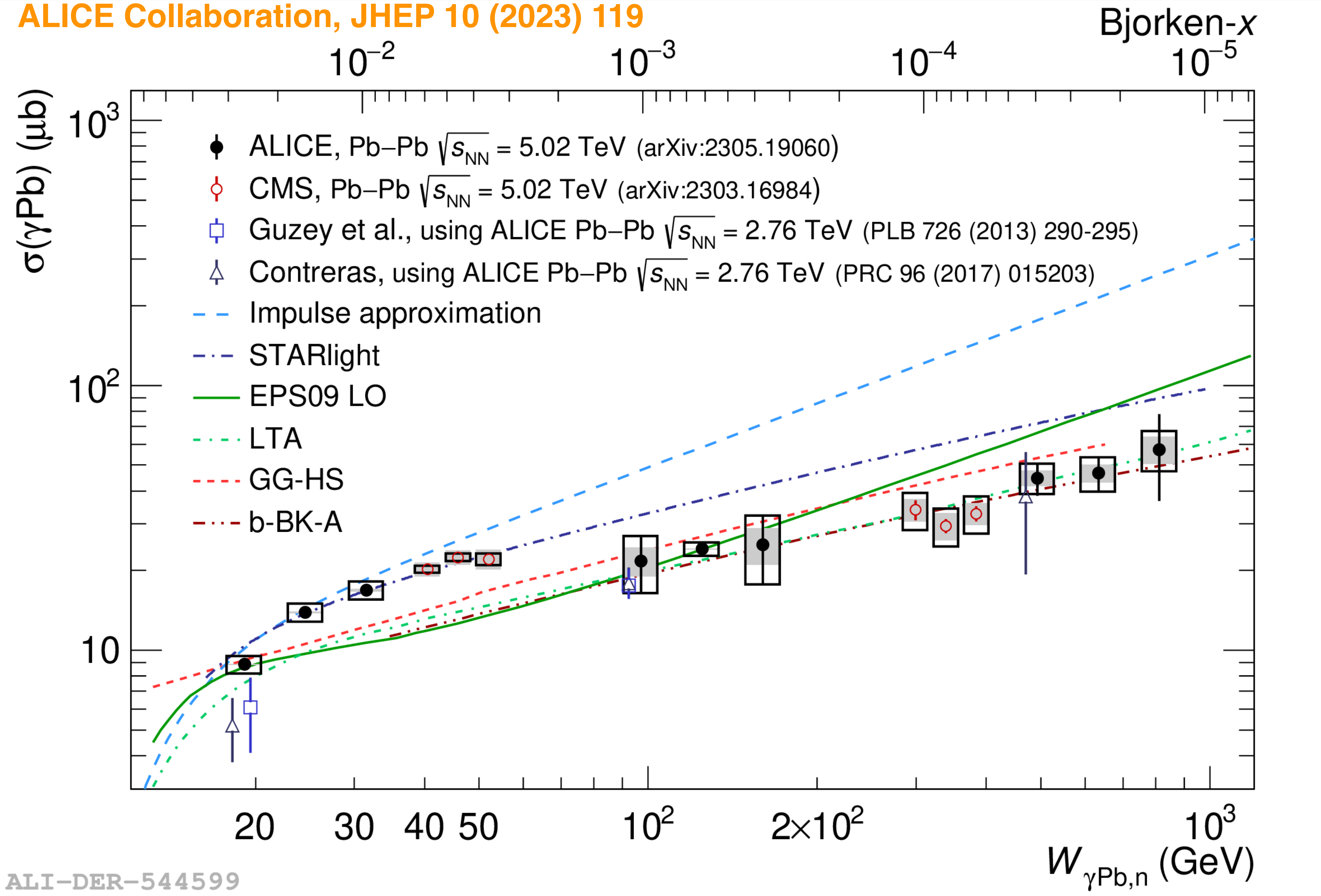


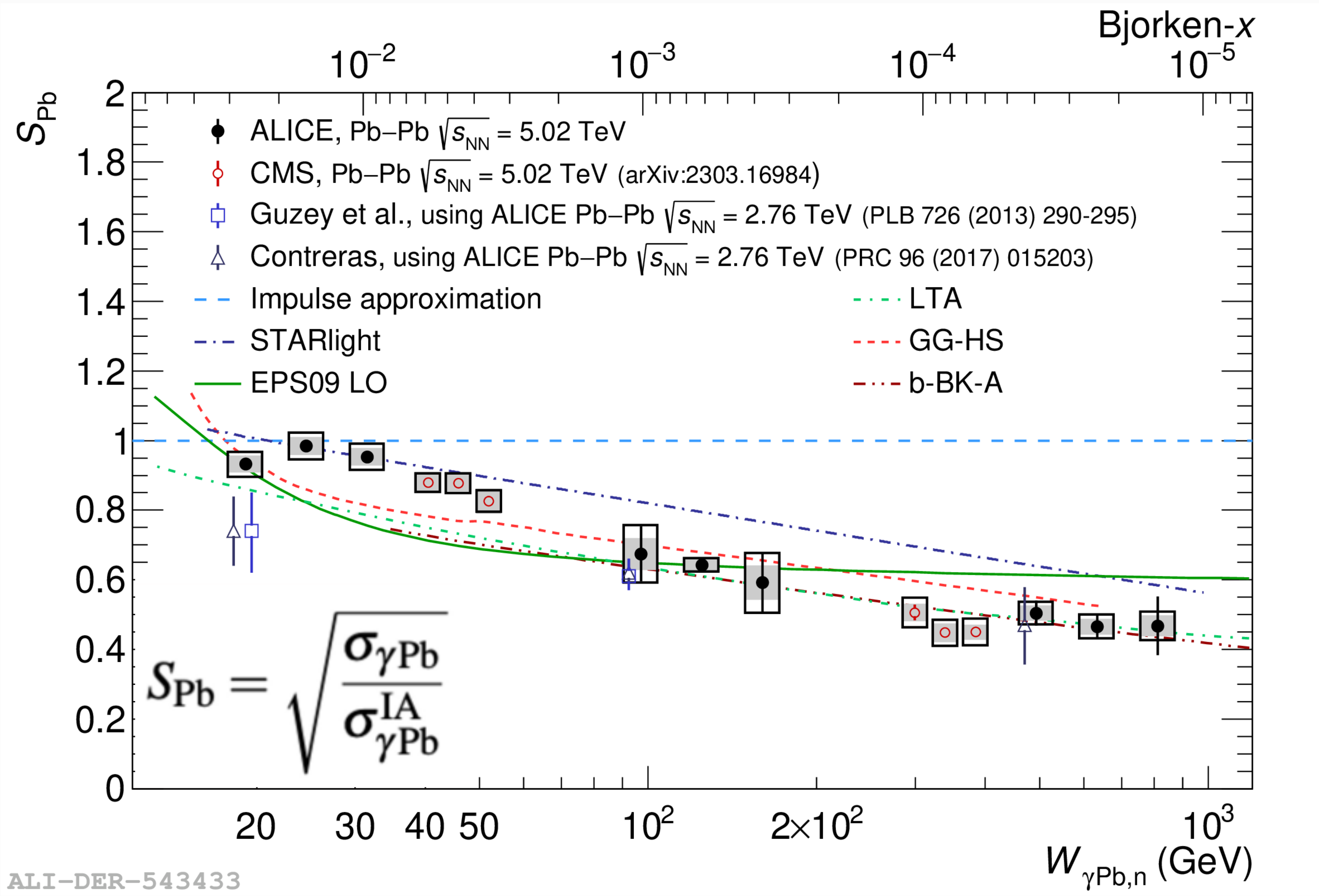
ALICE Collaboration, PRL 132 (2024) 162302



- **Large-|t|** Incoherent production: photon interacts with single nucleon/subnucleonic structure
- Slope better described by models including subnucleonic degree of freedom; target likely to be lumpy structure than smooth nucleons

Energy dependence of J/ψ photoproduction

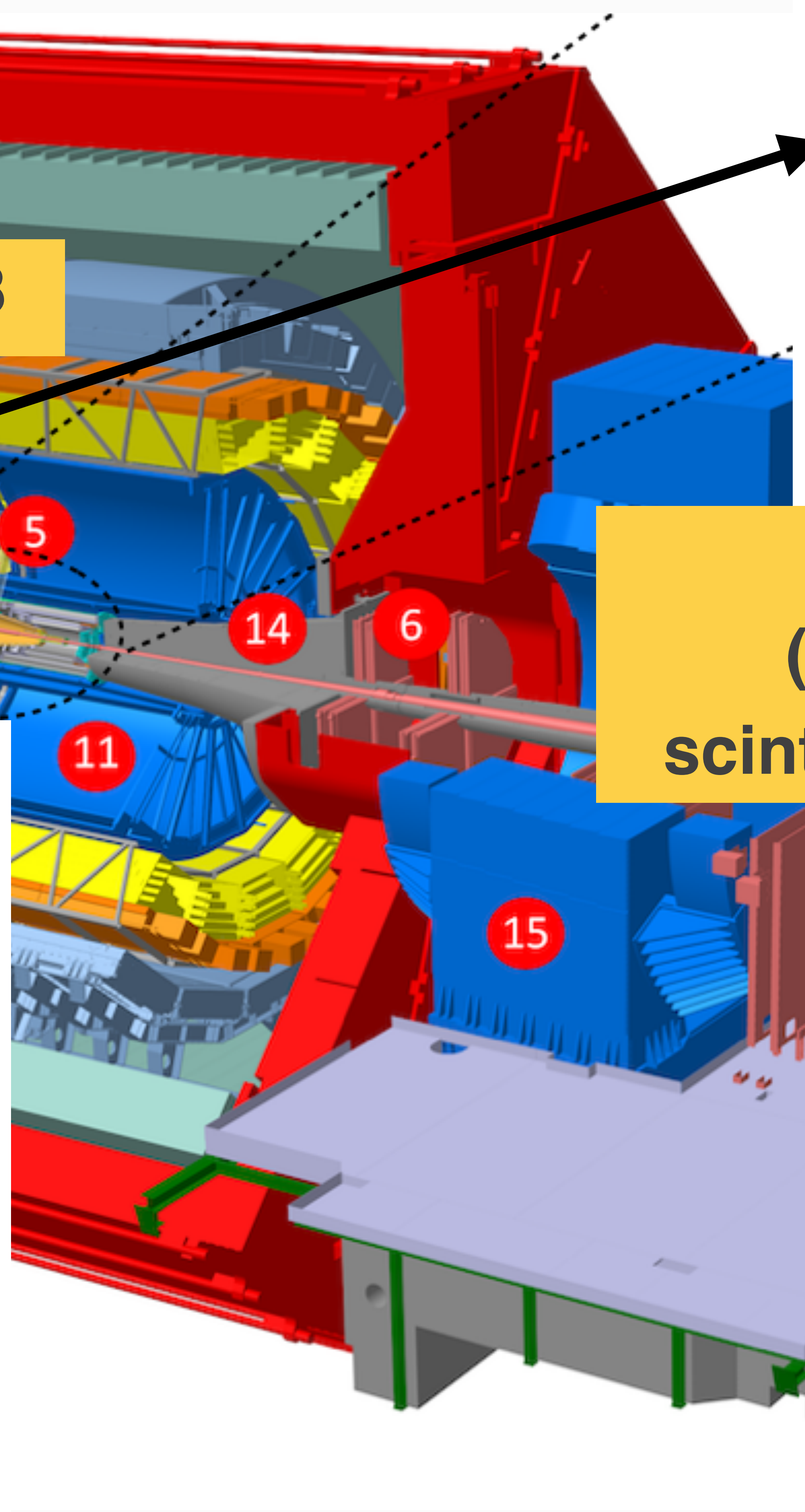


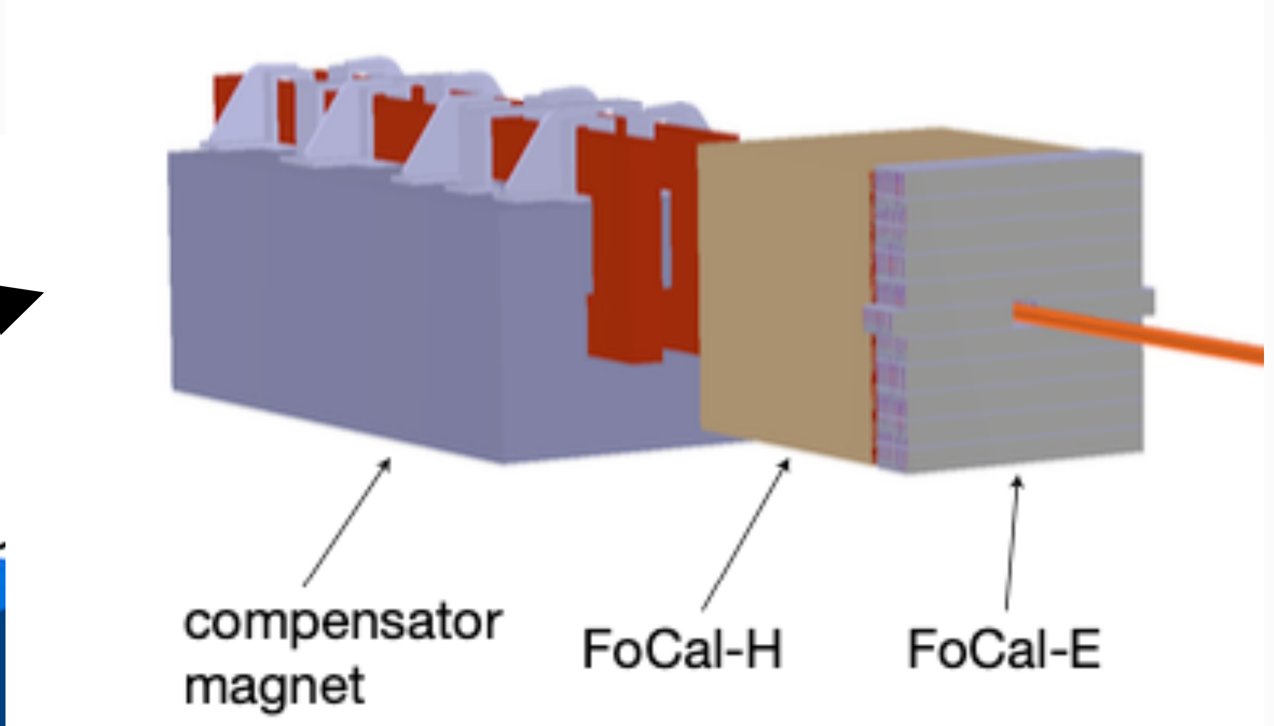


- No single model describes measured cross section in full range of center of mass energy (Bjorken *x*)
- Lower-x region better described with models including saturation while Glauber calculation works better in higher-x region
- Models based on saturation as well as shadowing picture describe the measurement well

ALICE experiment in Run 4 (scheduled 2031~): FOCAL

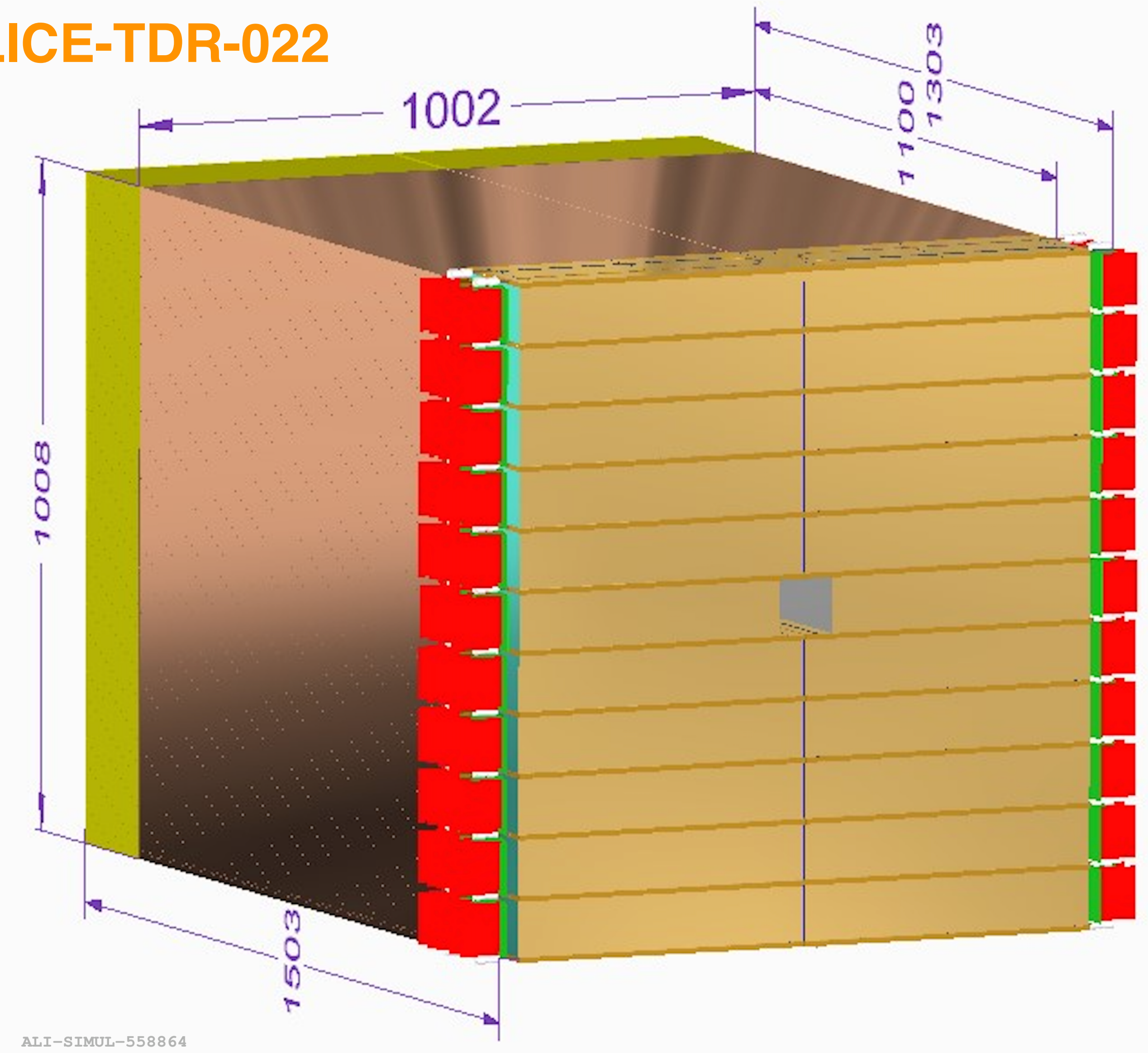
FOCAL for $3.2 < \eta < 5.8$

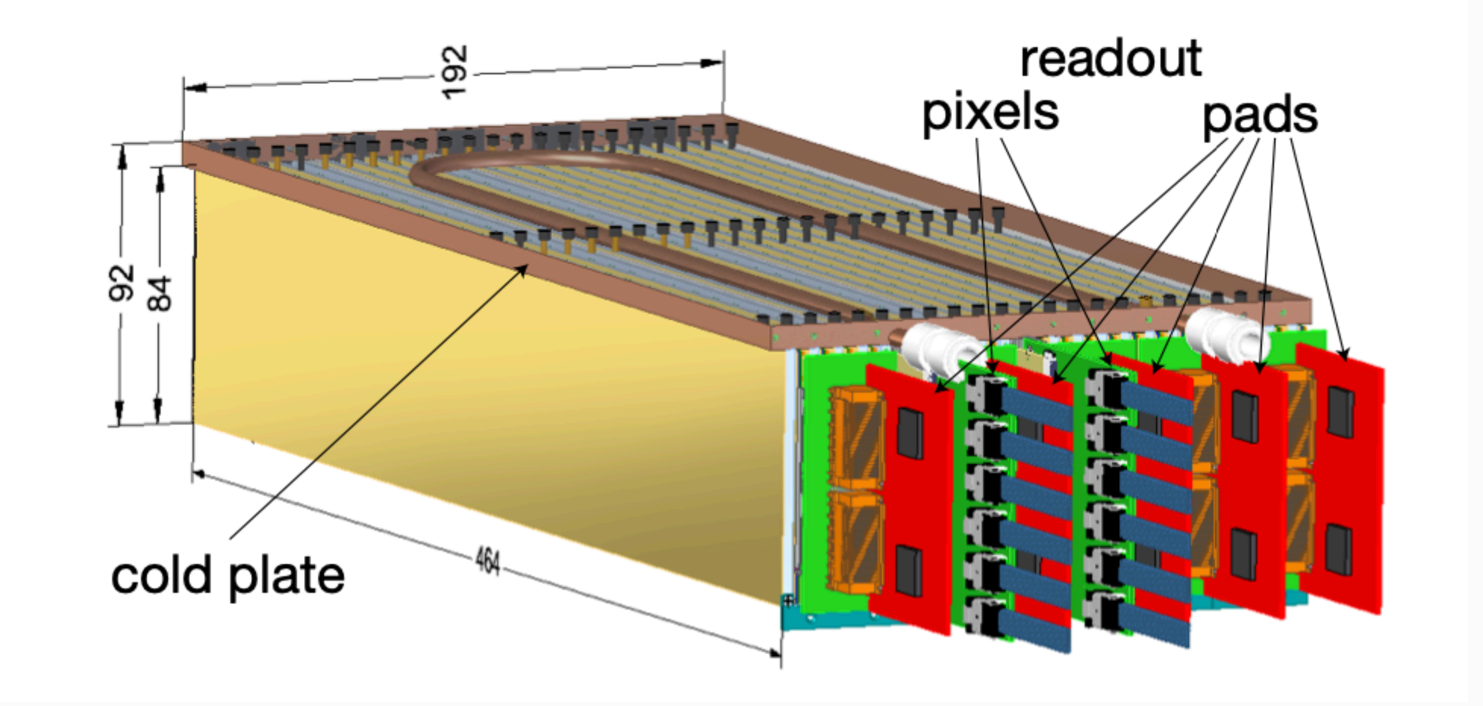




FOCAL-H
(Cu capillary tubes filled with scintillating fibers w/ SiPMs readout)

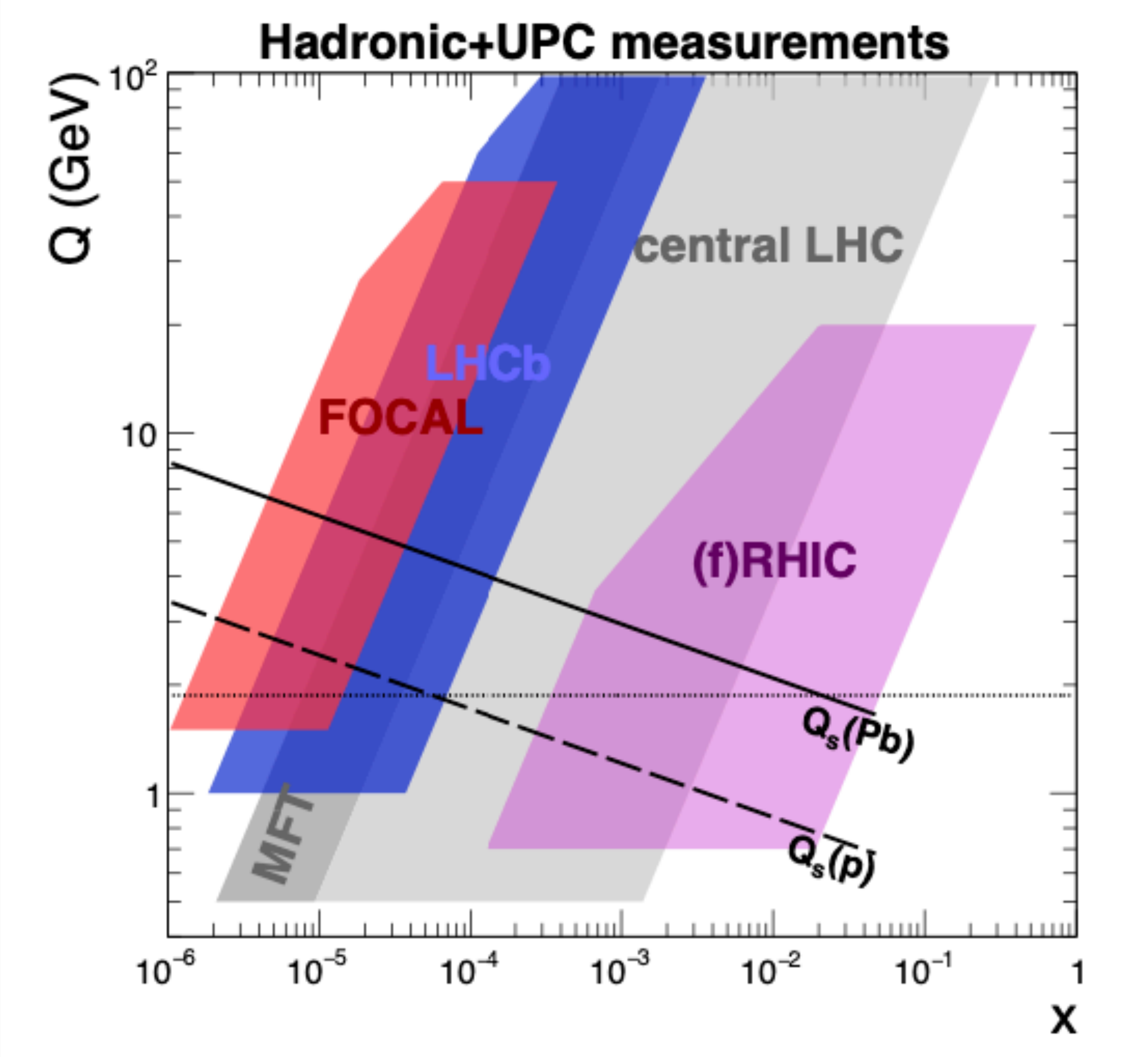
ALICE-TDR-022





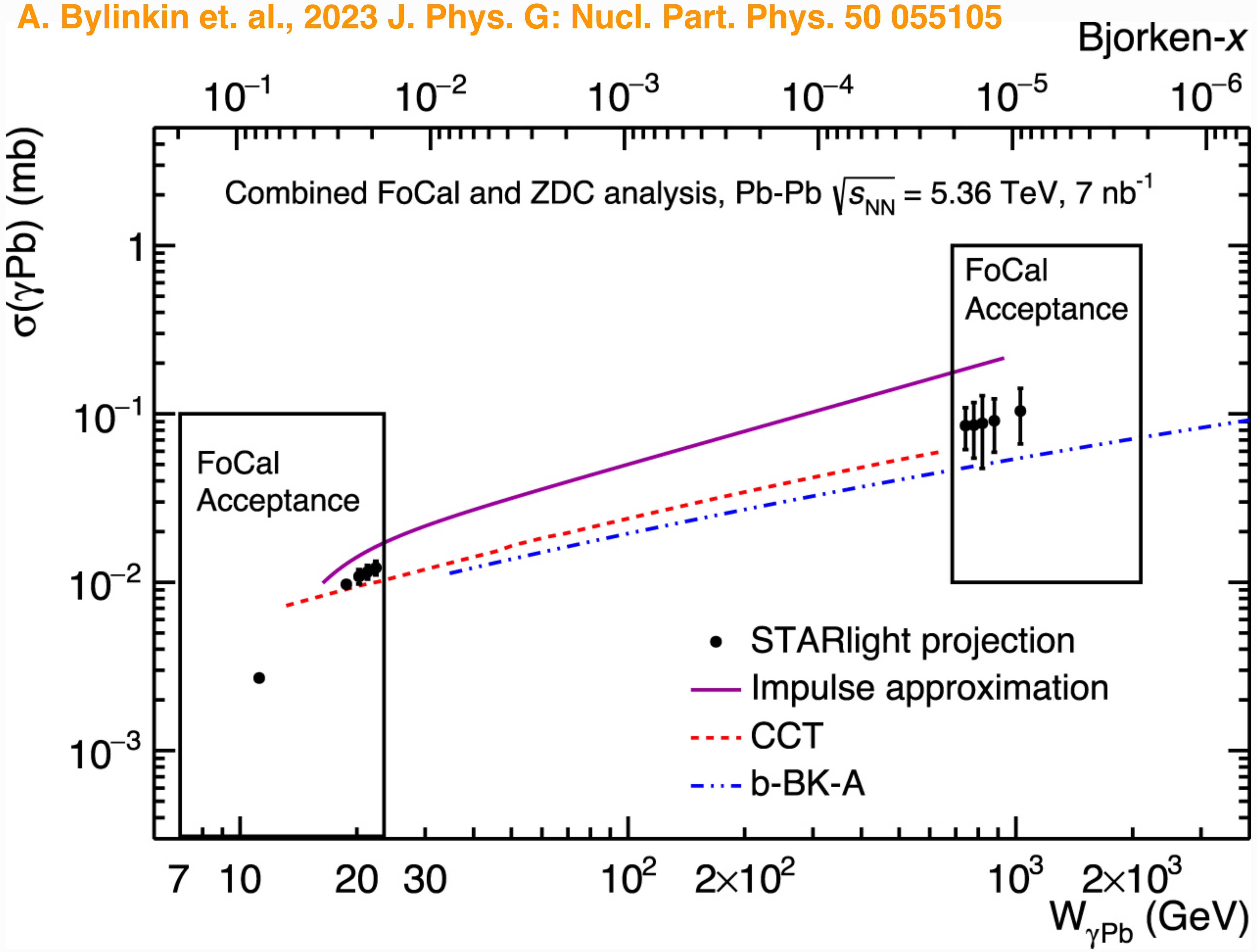
FOCAL-E modules
(Si-W EM calorimeter with hybrid Si readout technologies of pads and pixels)

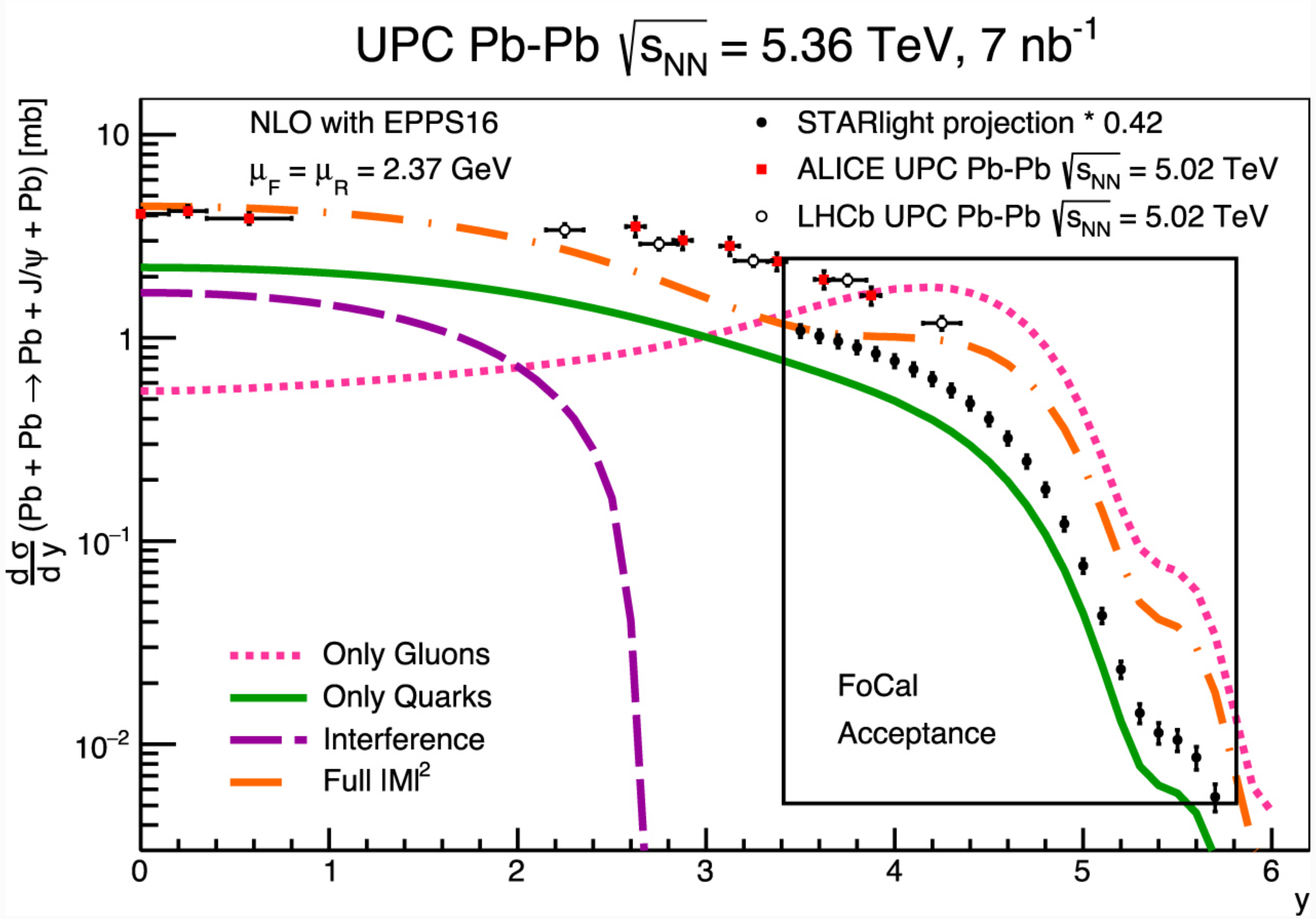
ALICE- PUBLIC-2023-001



Energy dependence of J/ψ photoproduction

A. Bylinkin et. al., 2023 J. Phys. G: Nucl. Part. Phys. 50 055105





- Extend kinematic coverage **down to lower *x* is foreseen in Run 4** with ALICE FoCAL
- J/ψ rapidity coverage expected to be gluon dominated in NLO calculation

Summary and outlook

- p-Pb collisions as control experiment for quantifying the possible CNM effects
  - Numerous observables, so-called hard probes of QGP
  - Production cross sections well agreed with nPDF based calculations but many results challenge the models only with initial state effects; unexpected collective-like behavior, suppression pattern of quarkonium, …..
  - Yet, the measurements not so much preferred the models including QGP effects in the market
- Explore different observables other than traditional hard probes of QGP to disentangle the initial state effects; modification of nuclear PDF, initial geometry fluctuation,….
- ALICE Run3 and Run4:
  - Increasing luminosity with better spatial resolution of tracking
  - O-O, p-Pb runs scheduled already in Run 3
  - Extended kinematic range (both Lower-x and higher-x region) expected with FoCAL in Run 4

Backup