

ALICE Highlights

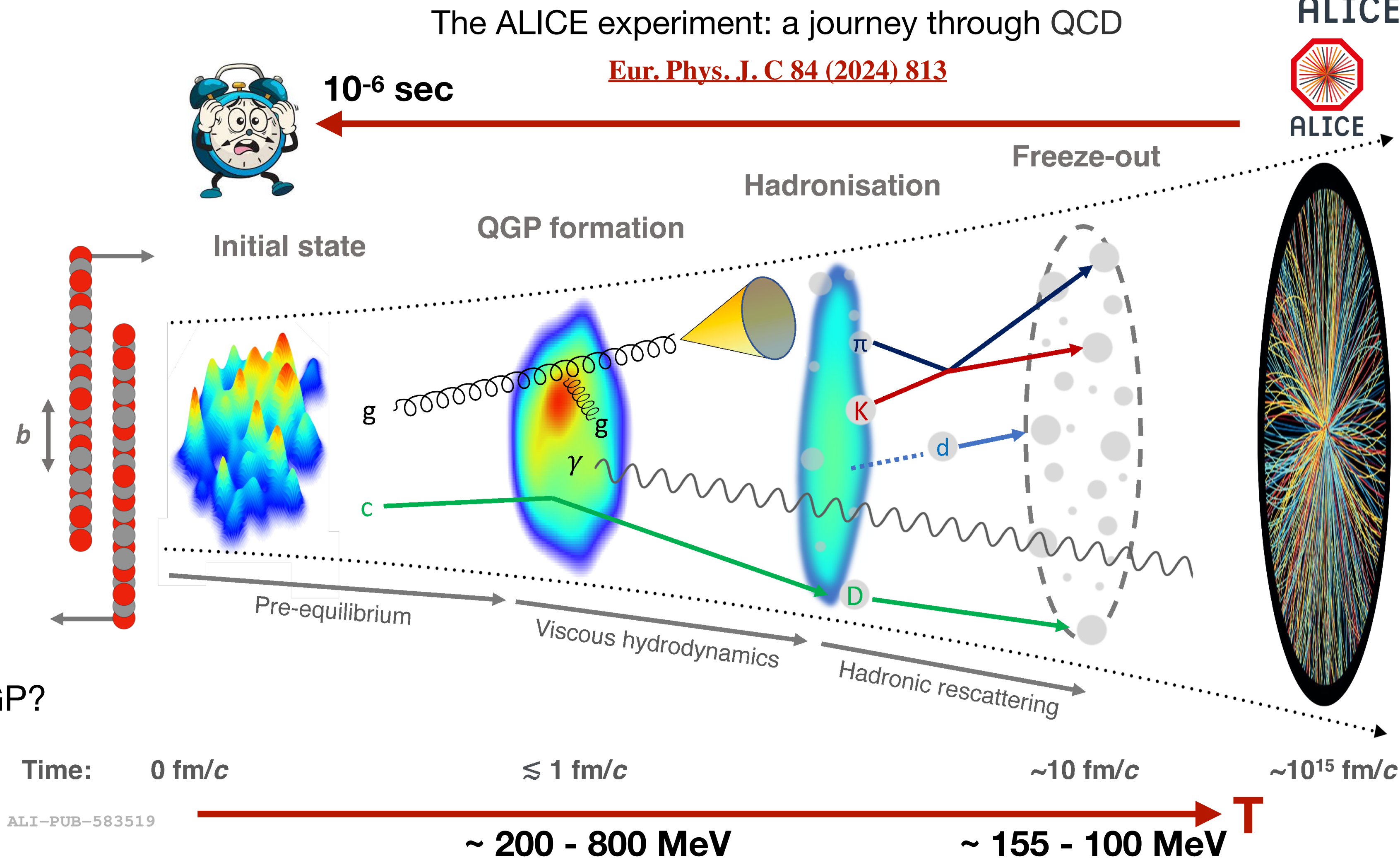
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EMMI Workshop: Mining for gluon saturation at the LHC and the future EIC
GSI Darmstadt, Germany
09/07/2026

ALICE: Constraining QCD across scales

- Initial state (small-x gluons, UPC)
- Deconfined medium (Pb–Pb)
- Hadronisation (pp, pA, small systems)

- Is the QGP a perfect liquid?
- How do heavy quarks interact with QGP?
- Do small systems form QGP?
- How is the gluon structure of nuclei modified?



What have we learned since we first asked these questions?

Recreating conditions similar to the big bang in the laboratory!

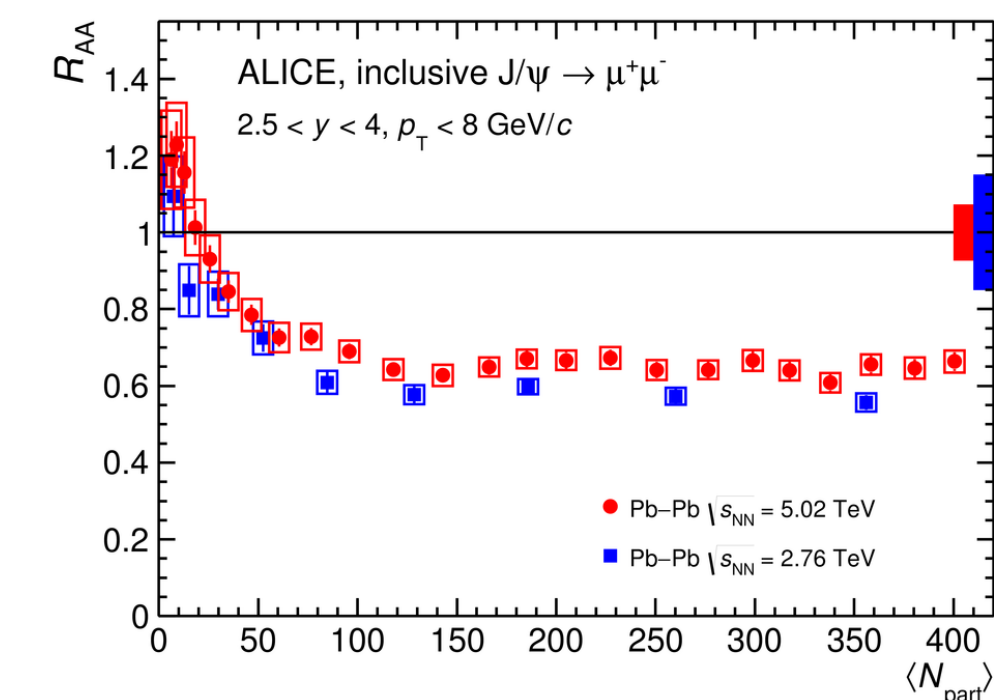
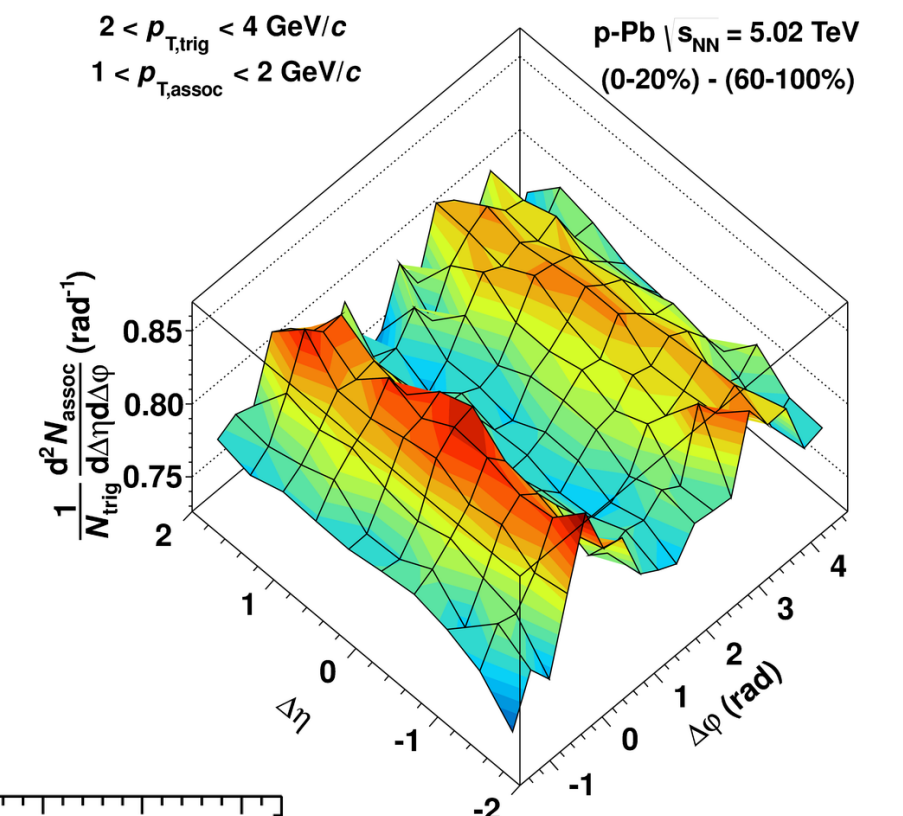
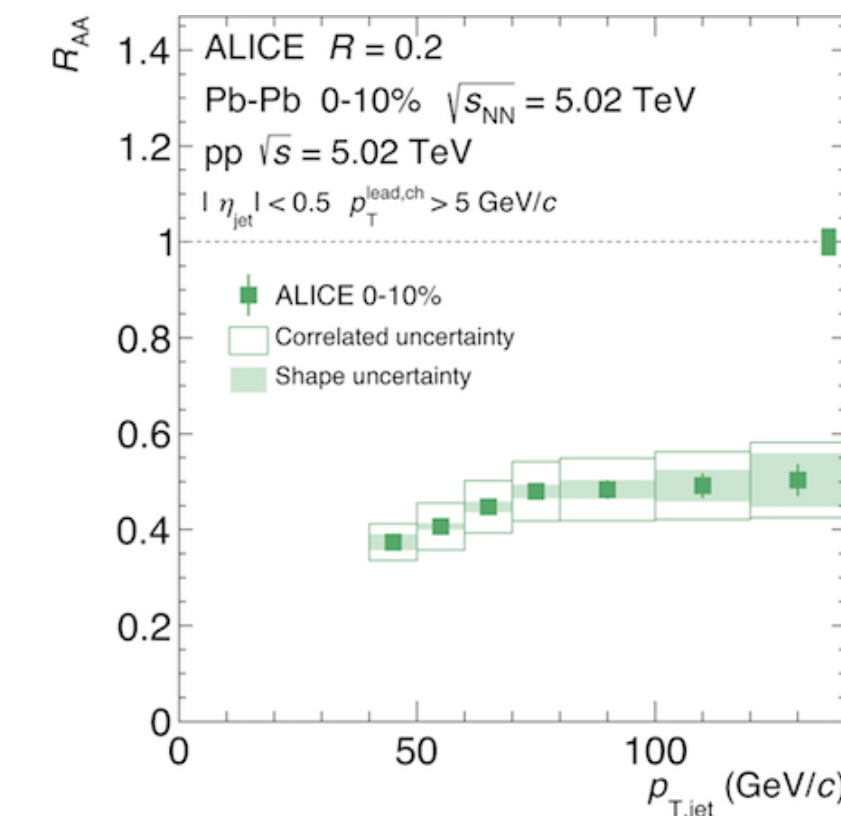
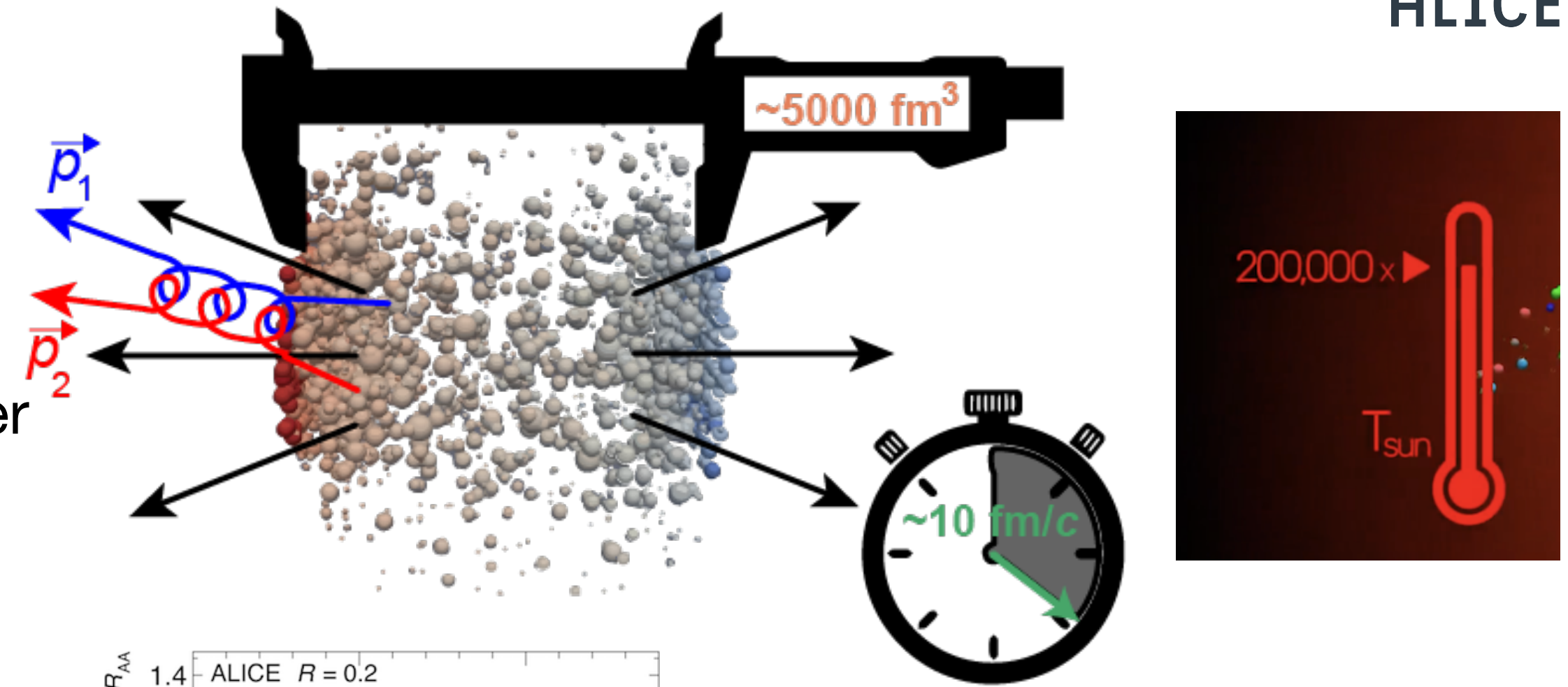
ALICE at the LHC: some key lessons from Runs 1–2

Eur. Phys. J. C 84 (2024) 813



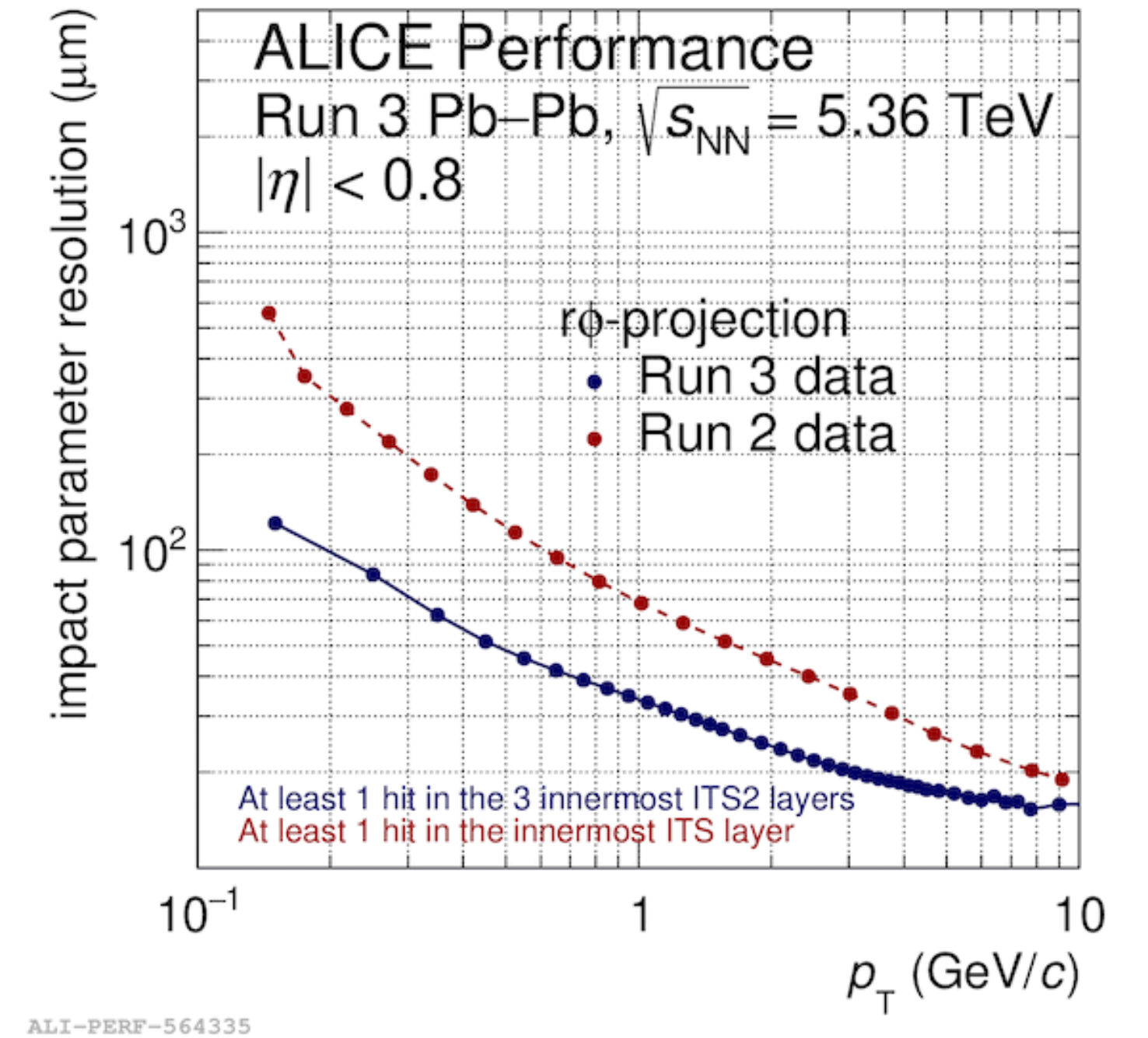
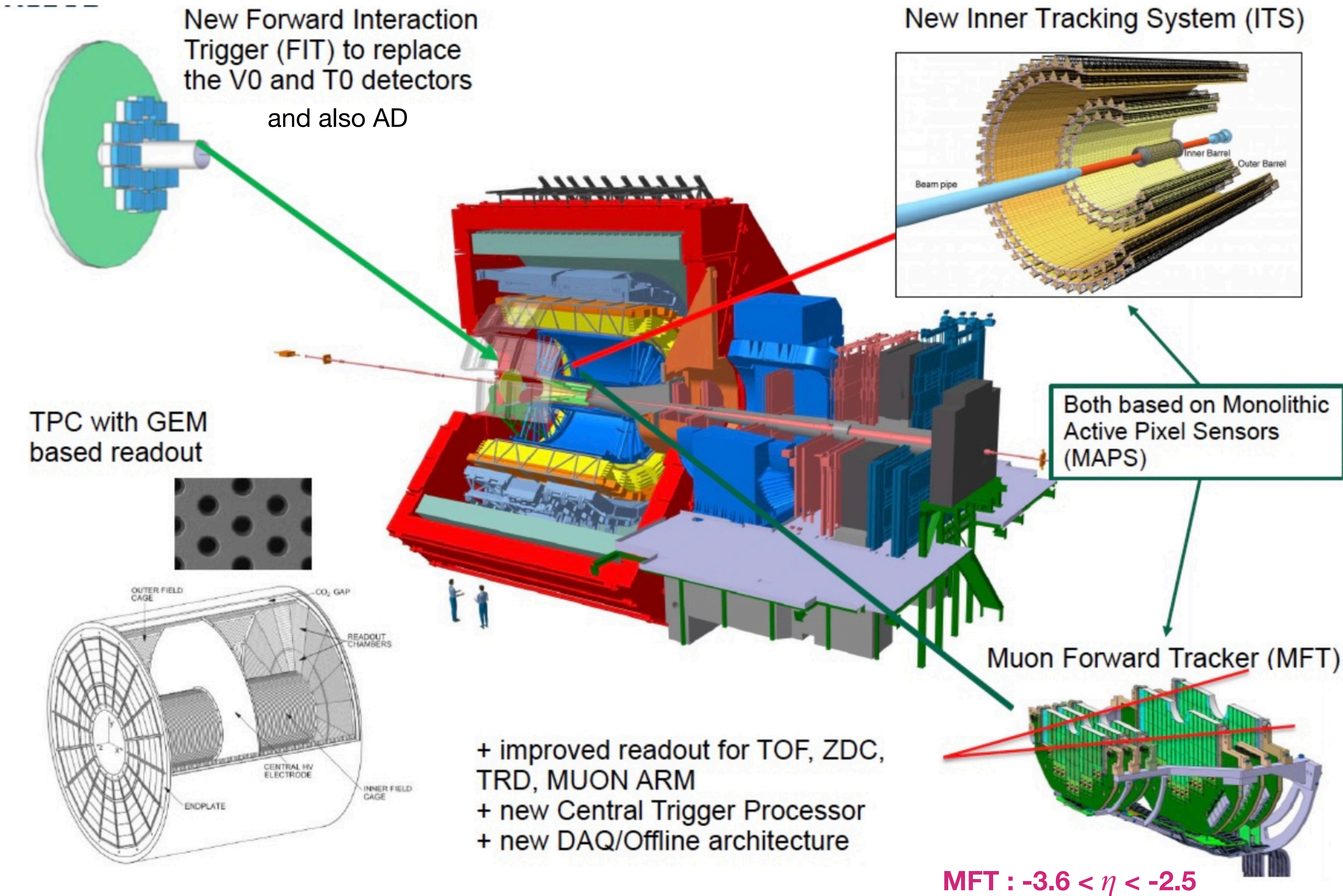
- ✓ **Near-perfect liquid behavior** [PRL 107 (2011) 032301, PRL 116 (2016) 132302]
→ strong anisotropic flow very small η/s
- ✓ **Hotter and longer-lived fireball** [PLB 696 (2011) 328]
→ HBT/femtoscopy shows larger homogeneity volumes than RHIC
- ✓ **Thermal radiation from the QGP** [PLB 754 (2016) 235]
→ Direct photons indicate effective temperature $T_{\text{LHC}} \sim 300$ MeV (order 10^{12} K), well above T_c .
- ✓ **Charmonium suppression and regeneration** [PLB 766 (2017) 212]
→ low- p_T rise in central Pb–Pb, recombination of charm
- ✓ **Parton energy loss across scales** [PRC 101(2020) 034911, Nature 605 (2022) 440]
→ Jet/hadron suppression, mass-dependent heavy-flavour transport and direct observation of dead-cone effect!
- ✓ **Strangeness as a multiplicity-driven phenomenon** [Nature 13 (2017) 535]
→ Increased strangeness production already in high-multiplicity pp → p–Pb → AA
- ✓ **Collectivity in small systems** [PLB 719 (2013) 29]
→ Ridge and flow-like signatures in high-multiplicity pp and p–Pb

By the end of Run 2, ALICE provided precision constraints on QGP properties and revealed QGP-like signatures in high-multiplicity small systems.



What comes next?

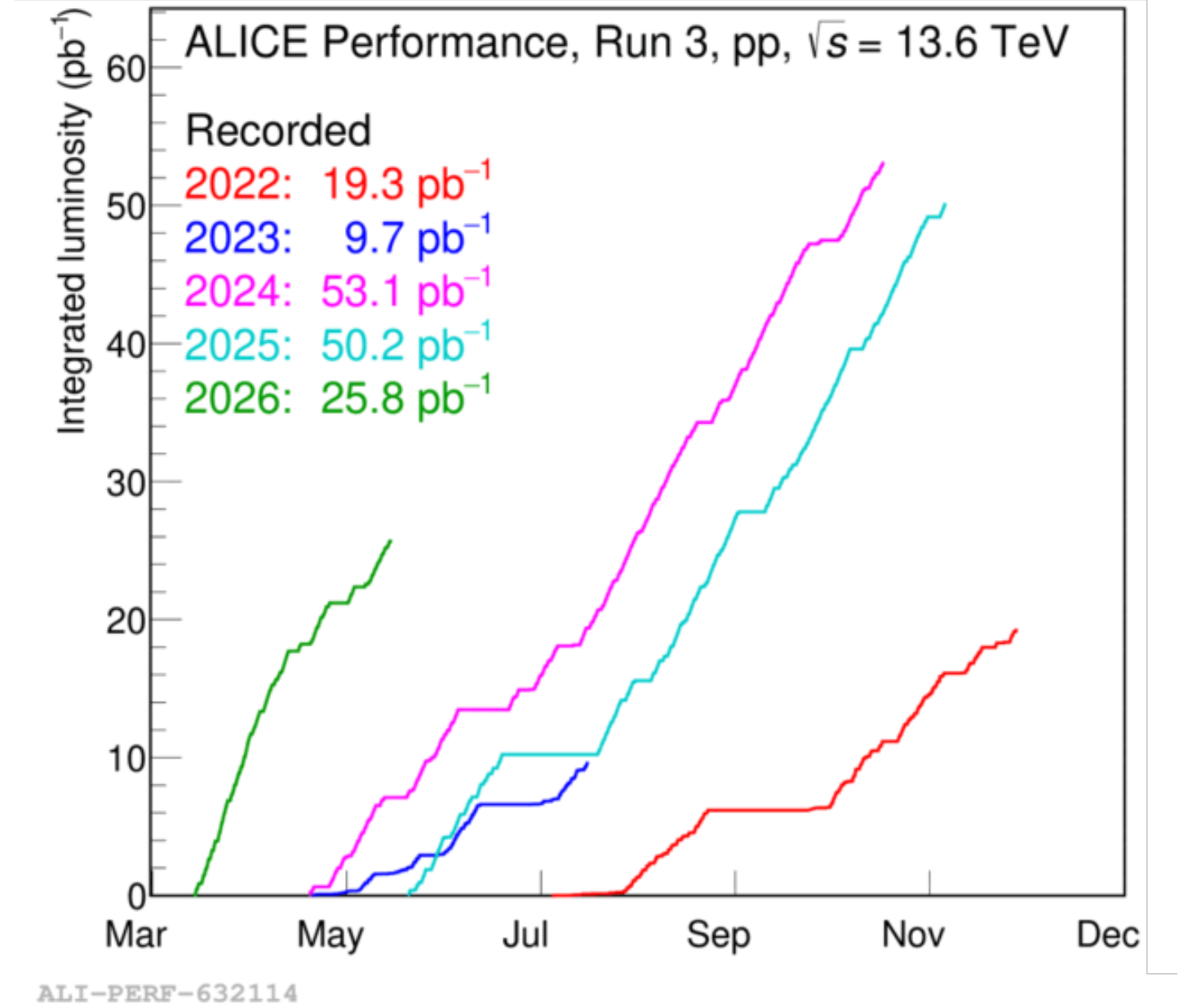
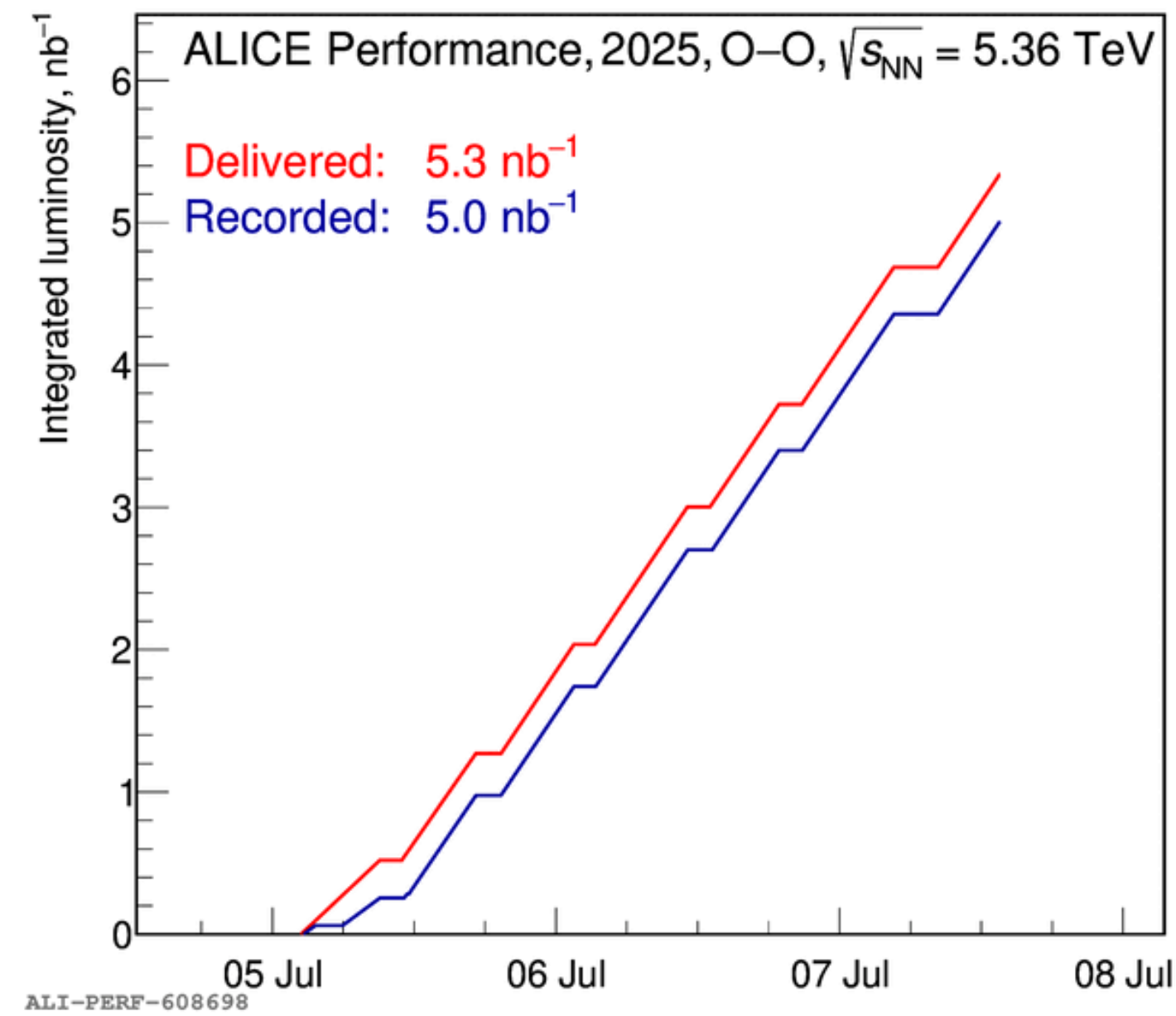
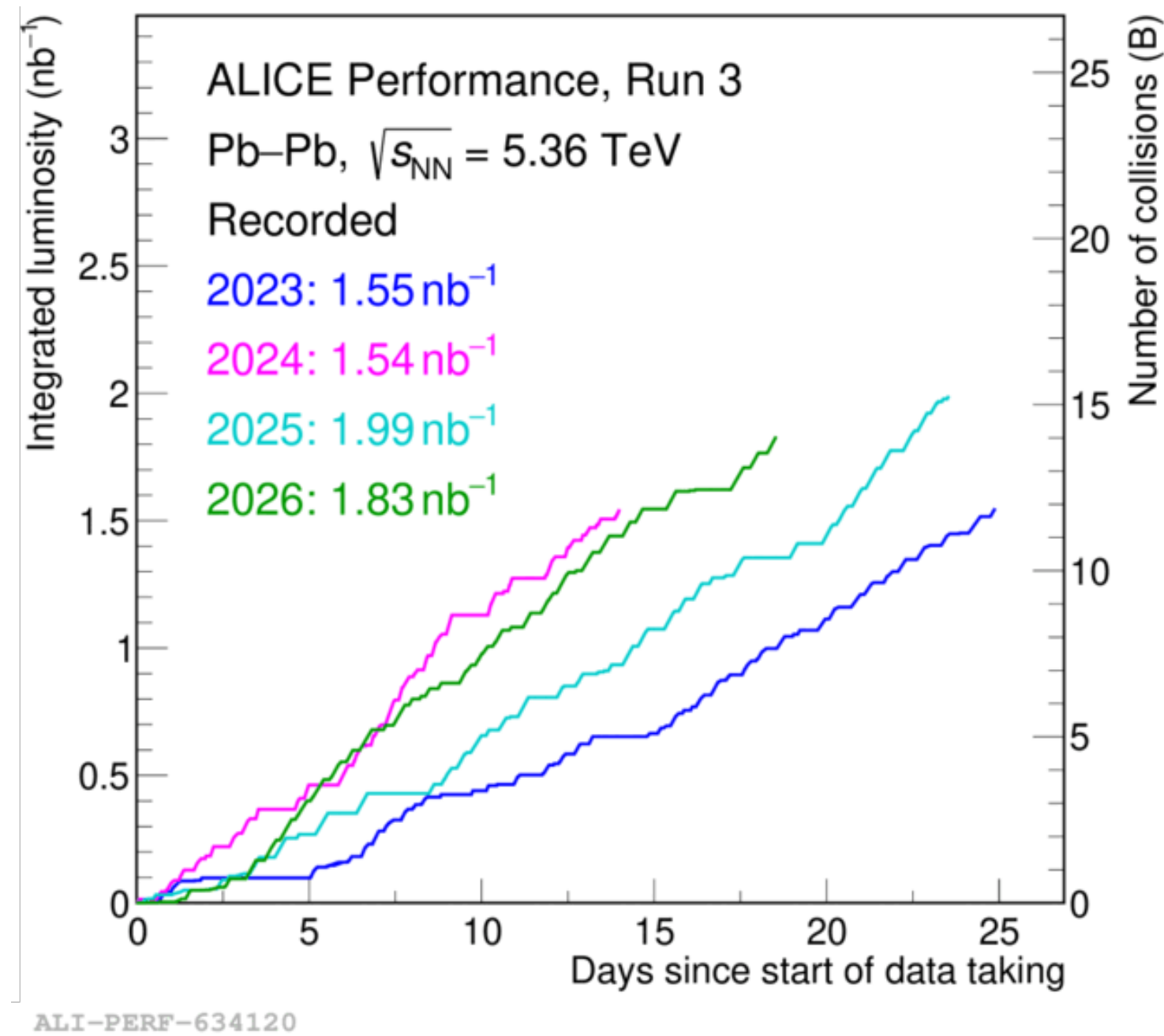
The ALICE experiment in Run 3 (2022 - 2026)



- Improved vertexing (ITS2, MFT)
- Improved tracking resolutions at low- p_T

*For full description see backup

ALICE: Run 3 precision era



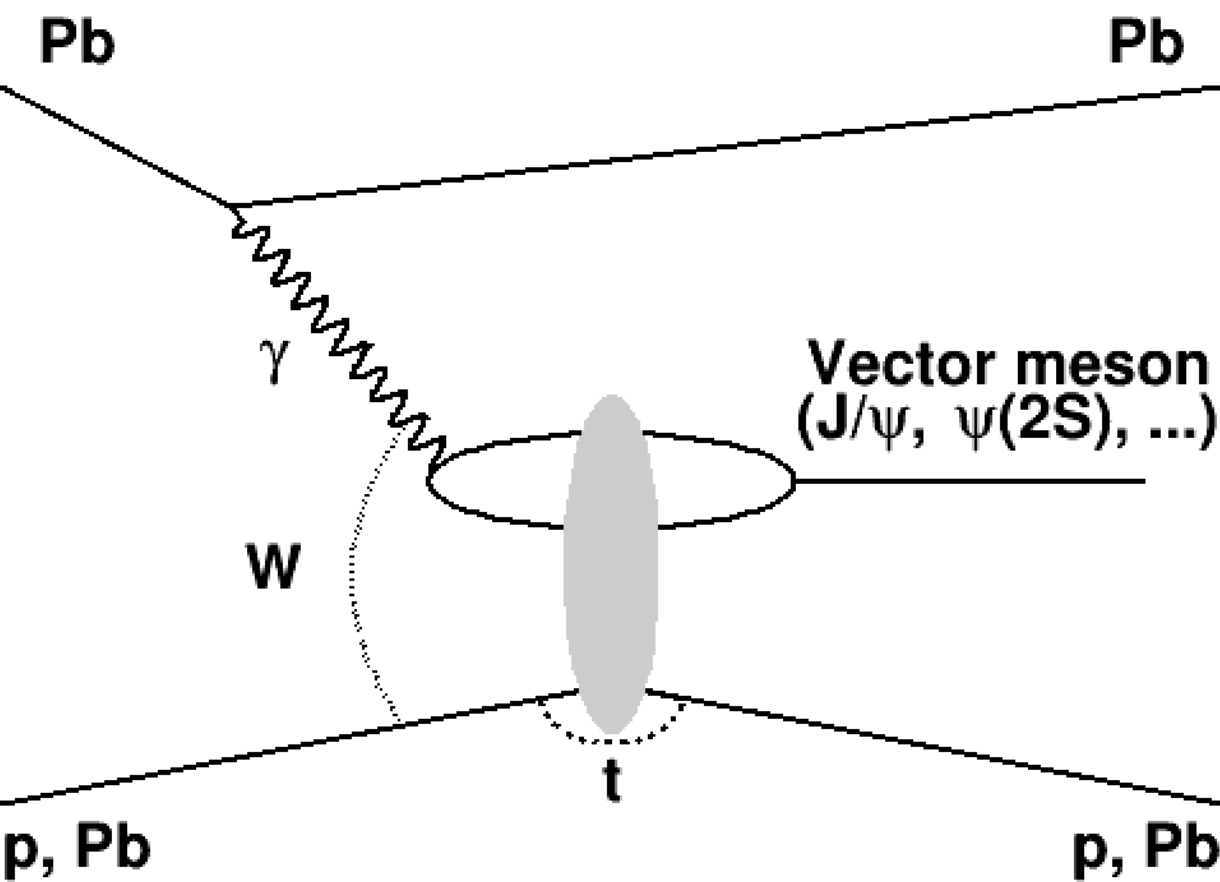
- ✓ $\sim \times 140$ times more MB events in Pb-Pb compared to Run 1 + 2
- ✓ $\sim \times 2000$ times more MB events in pp compared Run 1+ 2
- ✓ OO and Ne-Ne at 5.36 TeV with 5.0 nb^{-1} and 0.87 nb^{-1} recorded luminosity
- ✓ pO at 9.61 TeV with 7.3 nb^{-1} recorded luminosity
- ✓ The collected light-ion collision data sample sizes exceeded expectations!
- ✓ Continuous readout and events with physics interest can be selected using offline software triggers
- ✓ Run 3 allows for more differential and precision measurements

Part I — Early-time dynamics and initial state

Gluon structure of nuclei

☑ To study CNM via nuclear modification function $\rightarrow R_{iA}(x, Q^2) = \frac{f_{iA}(x, Q^2)}{f_i(x, Q^2)}$

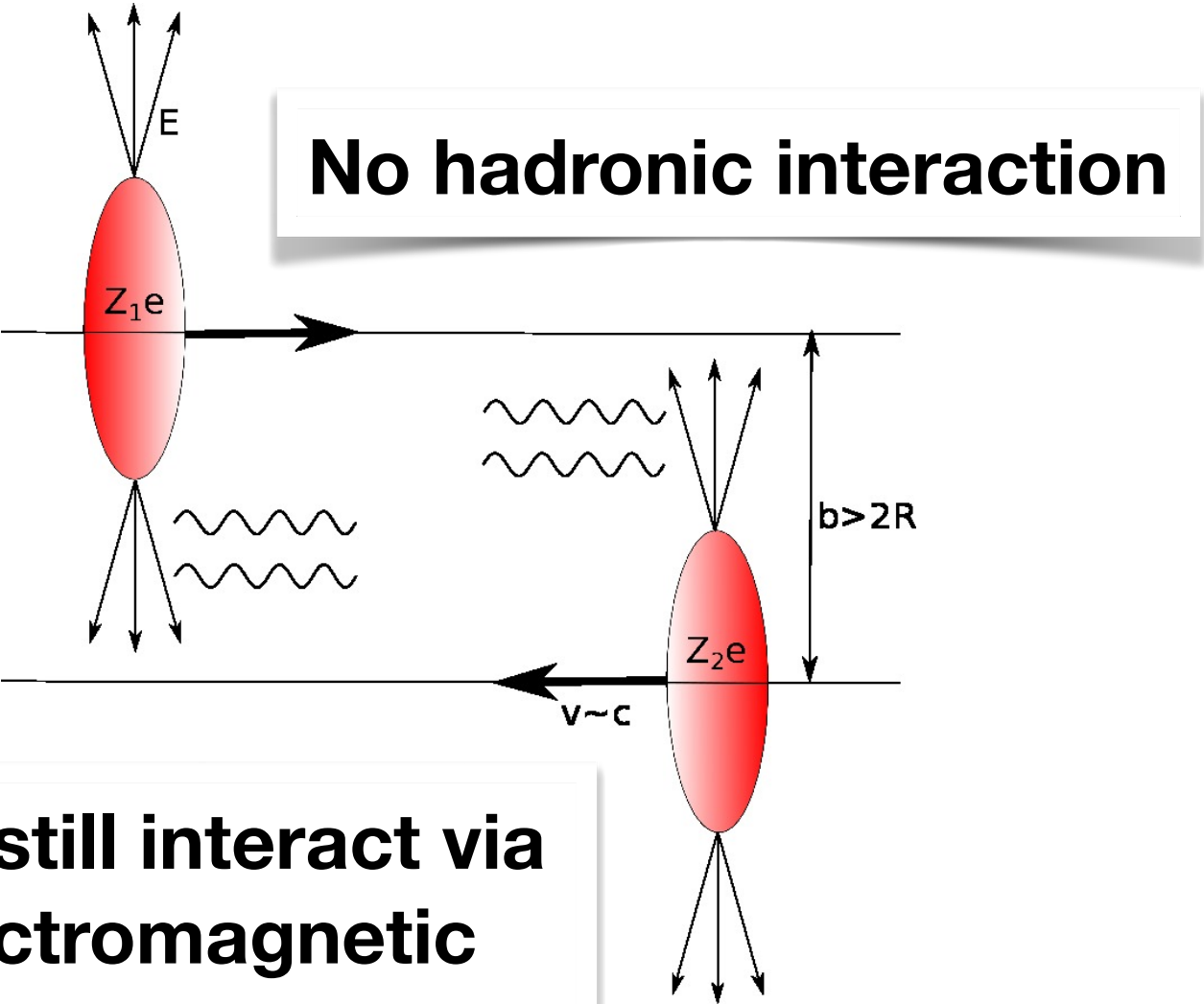
☑ PDF depends on both x and Q^2 ,
 $R_{iA}(x, Q^2) = 1$, for no nuclear effect



$$W_{\gamma A}^2 = \sqrt{s} M_{VM} e^{\pm y}$$

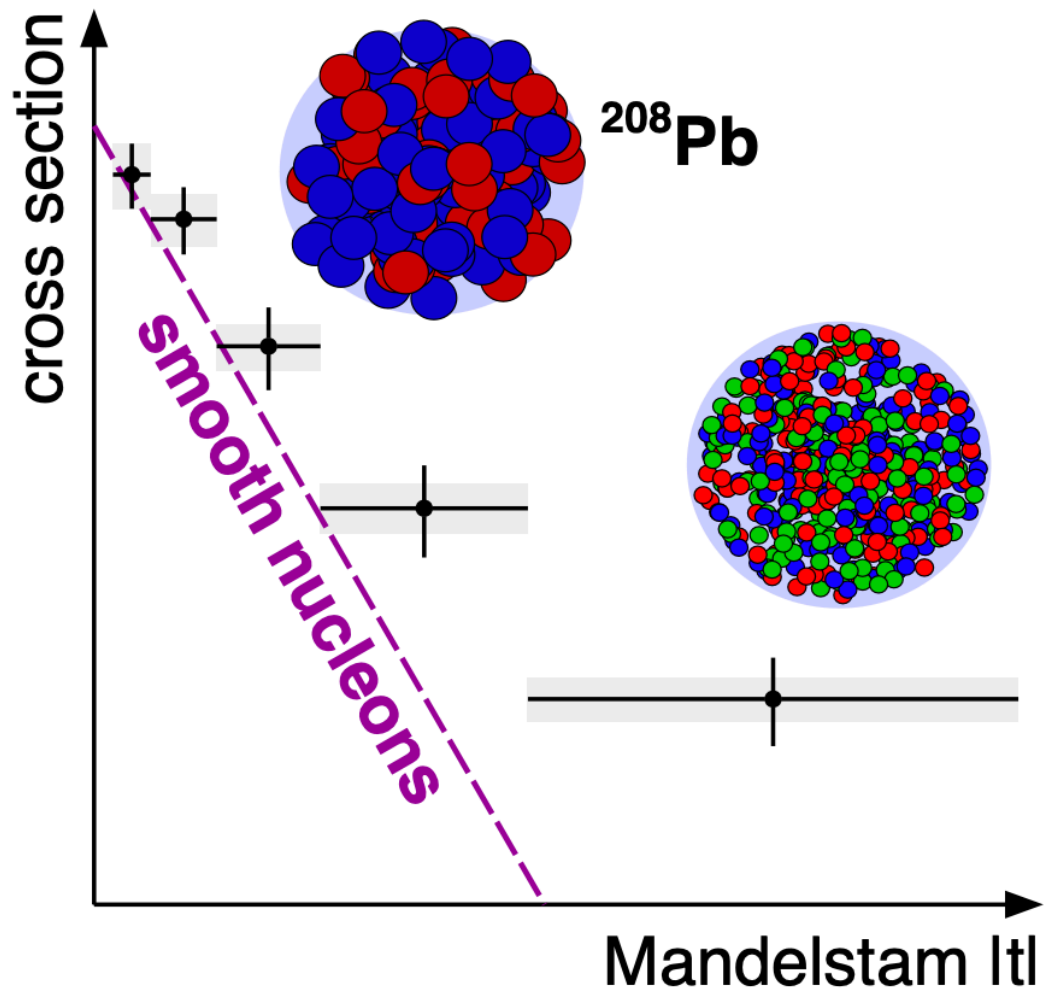
$$x = \frac{M_{VM}^2}{W_{\gamma A}^2} = \frac{M_{VM}}{\sqrt{s}} e^{\pm y}$$

$$t \approx -p_T^2$$

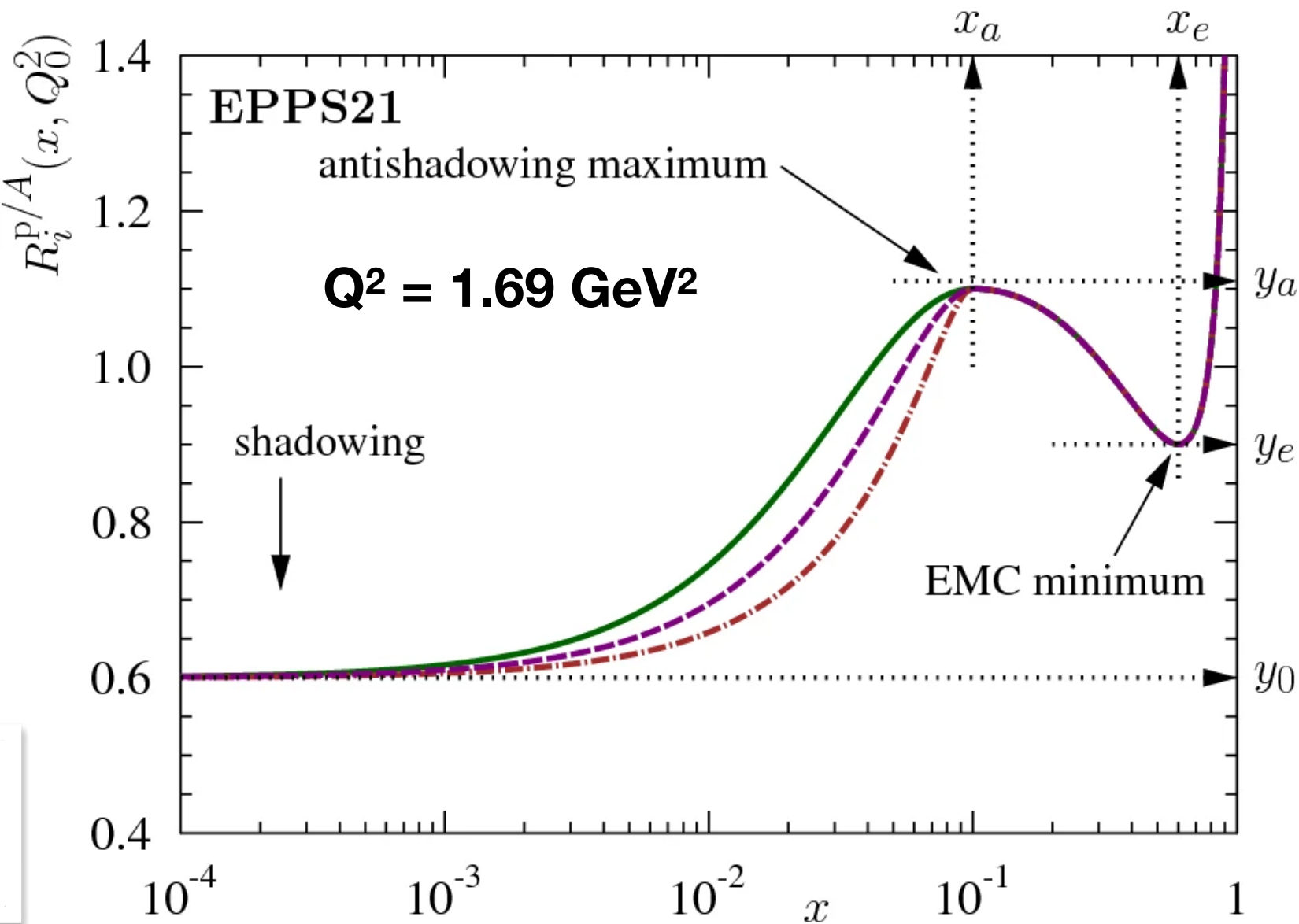


Ions still interact via electromagnetic processes

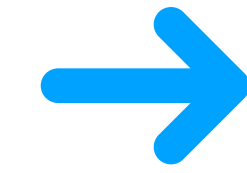
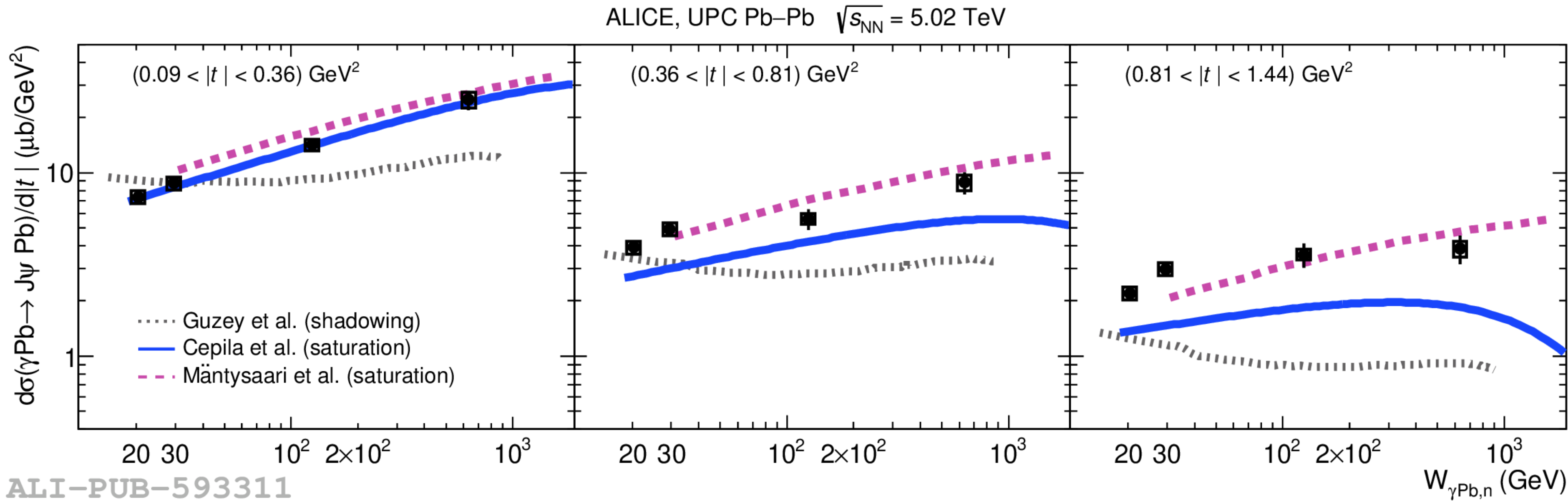
Saturation
 $< 10^{-4}$



Eur.Phys.J.C 82 (2022) 413



- ☑ At low x the gluon density increases with energy and approaches saturation.
- ☑ Two key CNM effects: gluon shadowing and possible gluon saturation, probed with UPC at Bjorken- x down to $\sim 10^{-6}$.



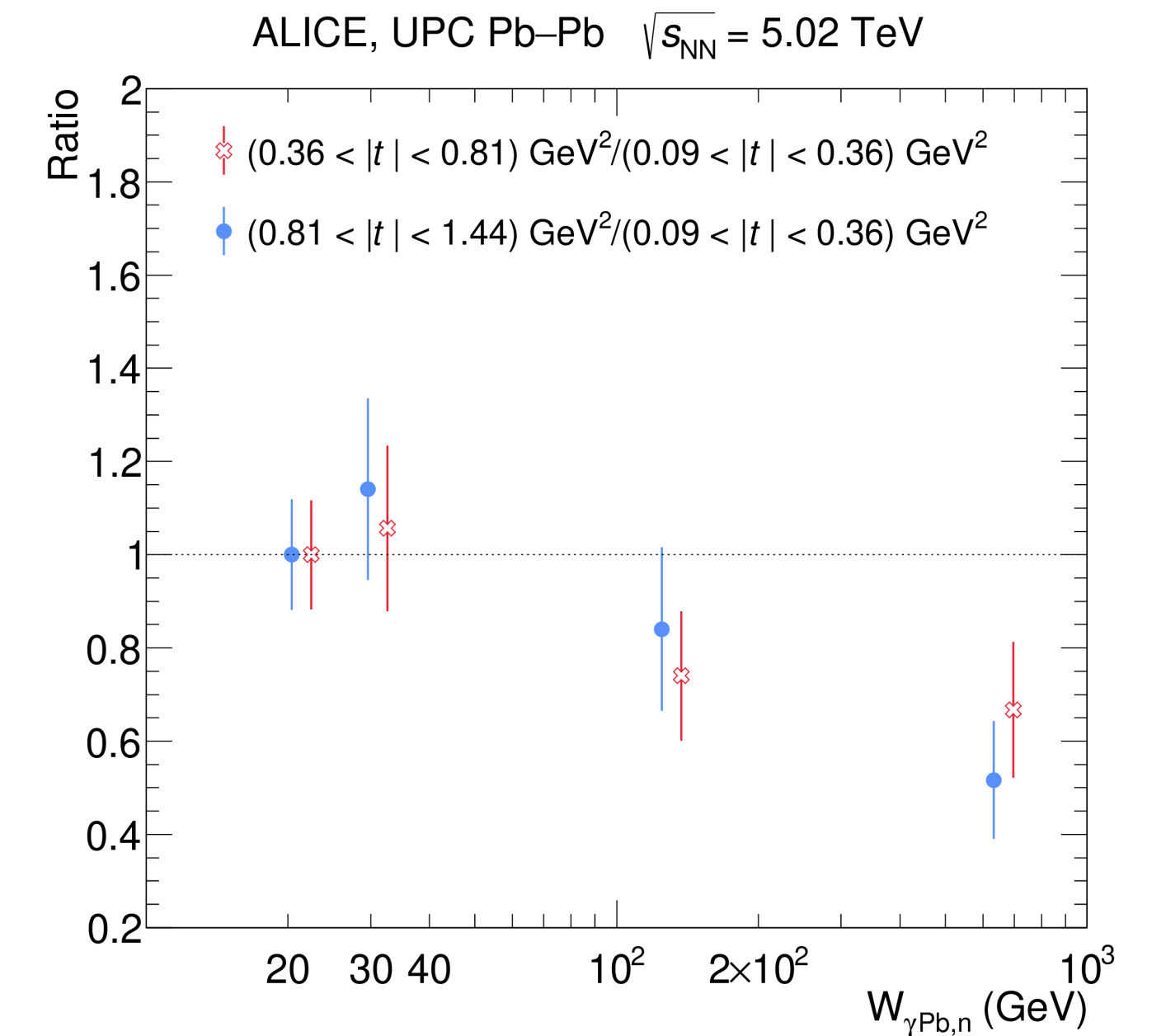
See talk by G. Contreras on Friday!

Guzey et al., PRC 99 (2019) 015201

Cepila et al., PLB 852 (2024) 138613

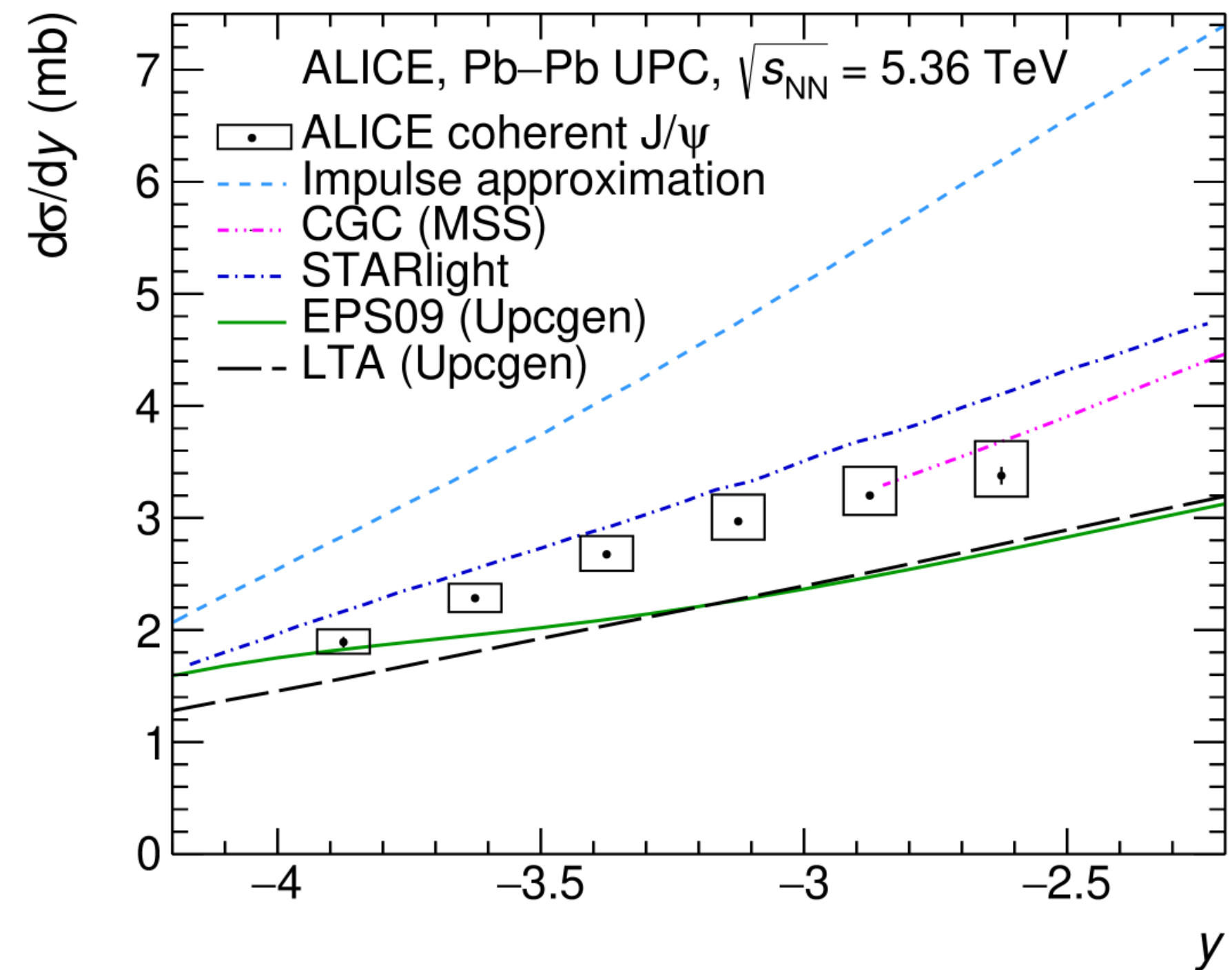
Mäntysaari et al., PRD 109 (2024) L071504

- ☑ Multi-differential incoherent J/ψ photoproduction as a function of both energy and Mandelstam- $|t|$ with neutron tagging
- ☑ Demonstrates how combining **$|t|$ ranges + EMD classes** probes spatial structure of gluon fields at nucleonic and subnucleonic scales at forward rapidity
- ☑ Evidence of suppression of the growth of yield with energy at large $|t|$
- ☑ Ratio of cross section shows $\sim 3\sigma$ deviation from unity
- ☑ Data favour saturation-based models over shadowing-based model
- ☑ We probe spatial gluon fluctuations in nuclei.

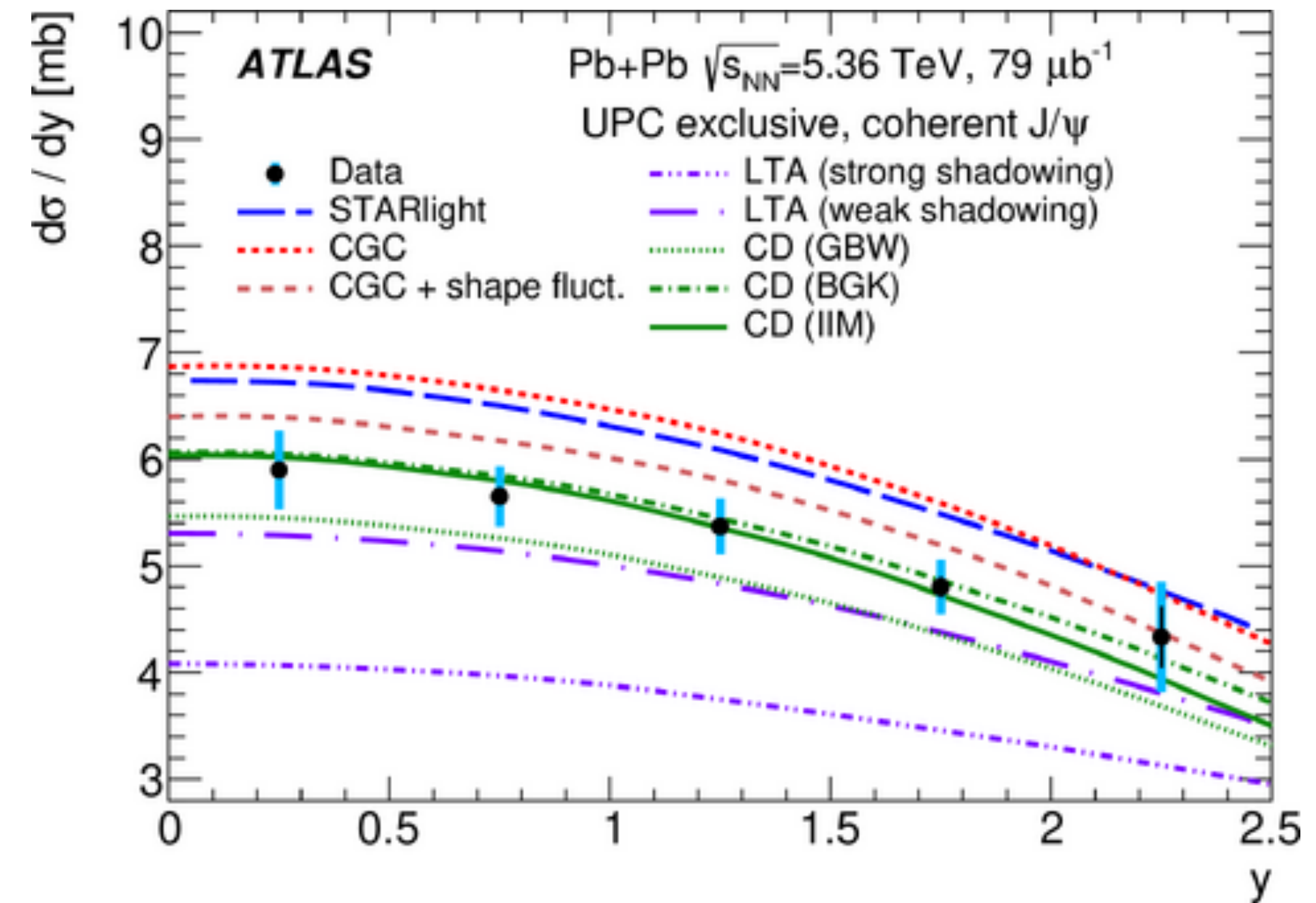


Run 3 coherent J/ψ photoproduction

ATLAS, JHEP 04 (2026) 020



ALI-PUB-630276



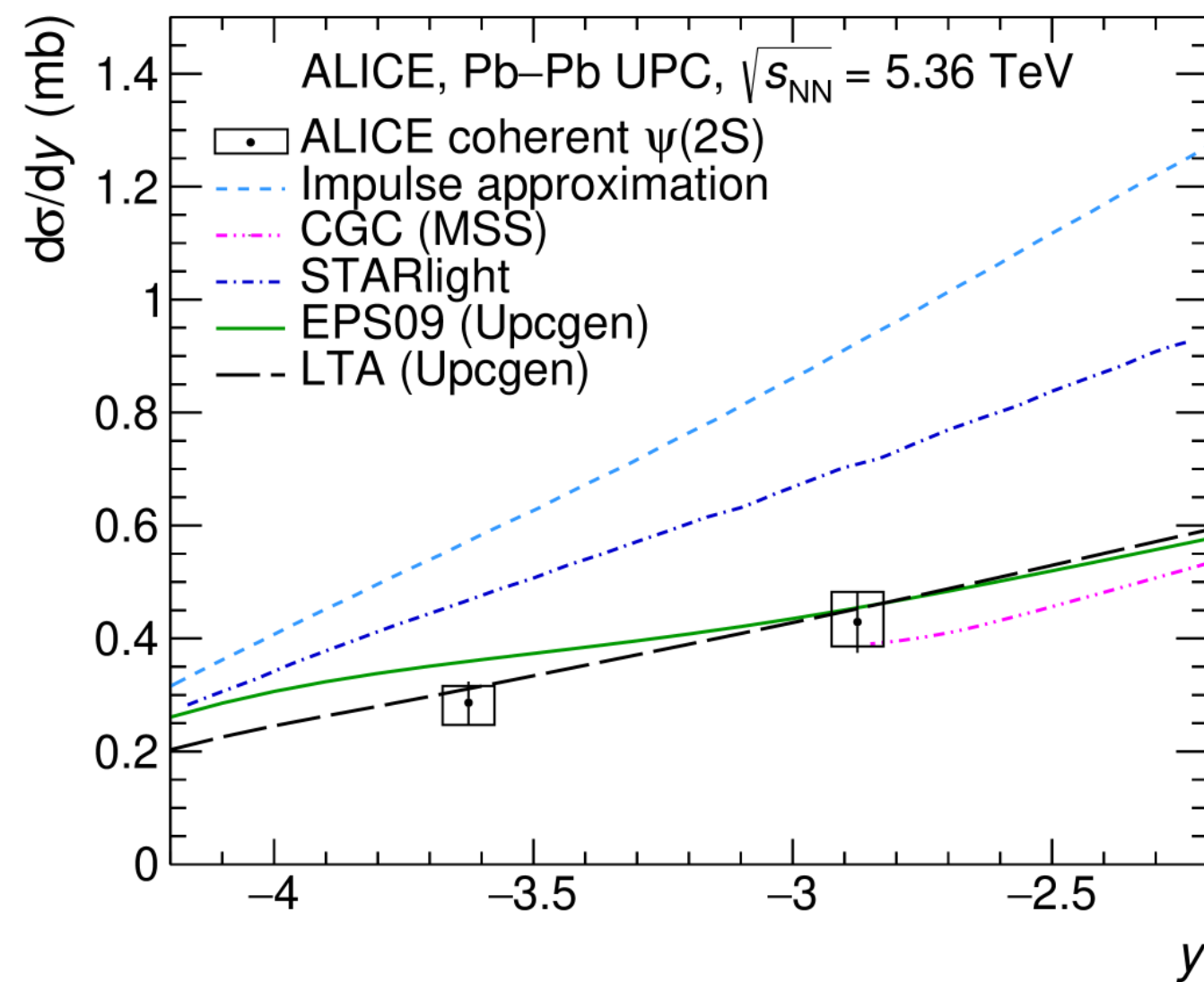
- ✓ First Run 3 coherent J/ψ measurements at forward rapidity
- ✓ Strong nuclear suppression persists similar to Run 2, w.r.t impulse approximation
- ✓ ALICE and ATLAS provide complementary rapidity coverage

STARlight: Klein, Nystrand et al., CPC 212 (2017) 258–268
 Upccgen: CPC, 277 (2022) 108388 based on
 Guzey, Kryshen, Zhalov, PRC 93 (2016) 055206
 CGC: Mantysaari, Salazar, Schenke, PRD 109 (2024) L071504

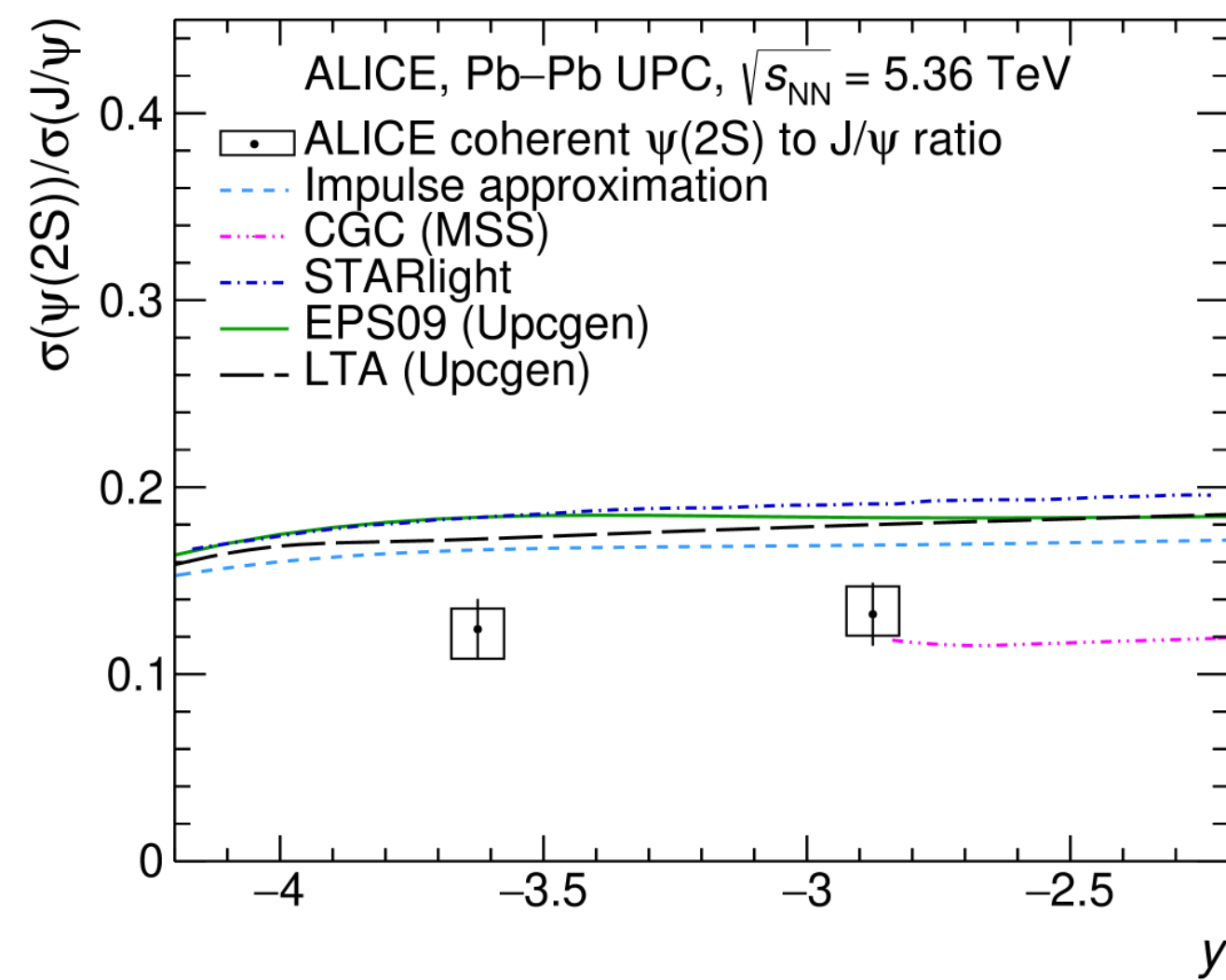
[arXiv:2605.13569 \[nucl-ex\]](https://arxiv.org/abs/2605.13569)

Run 3 coherent $\psi(2S)$ + dimuon continuum

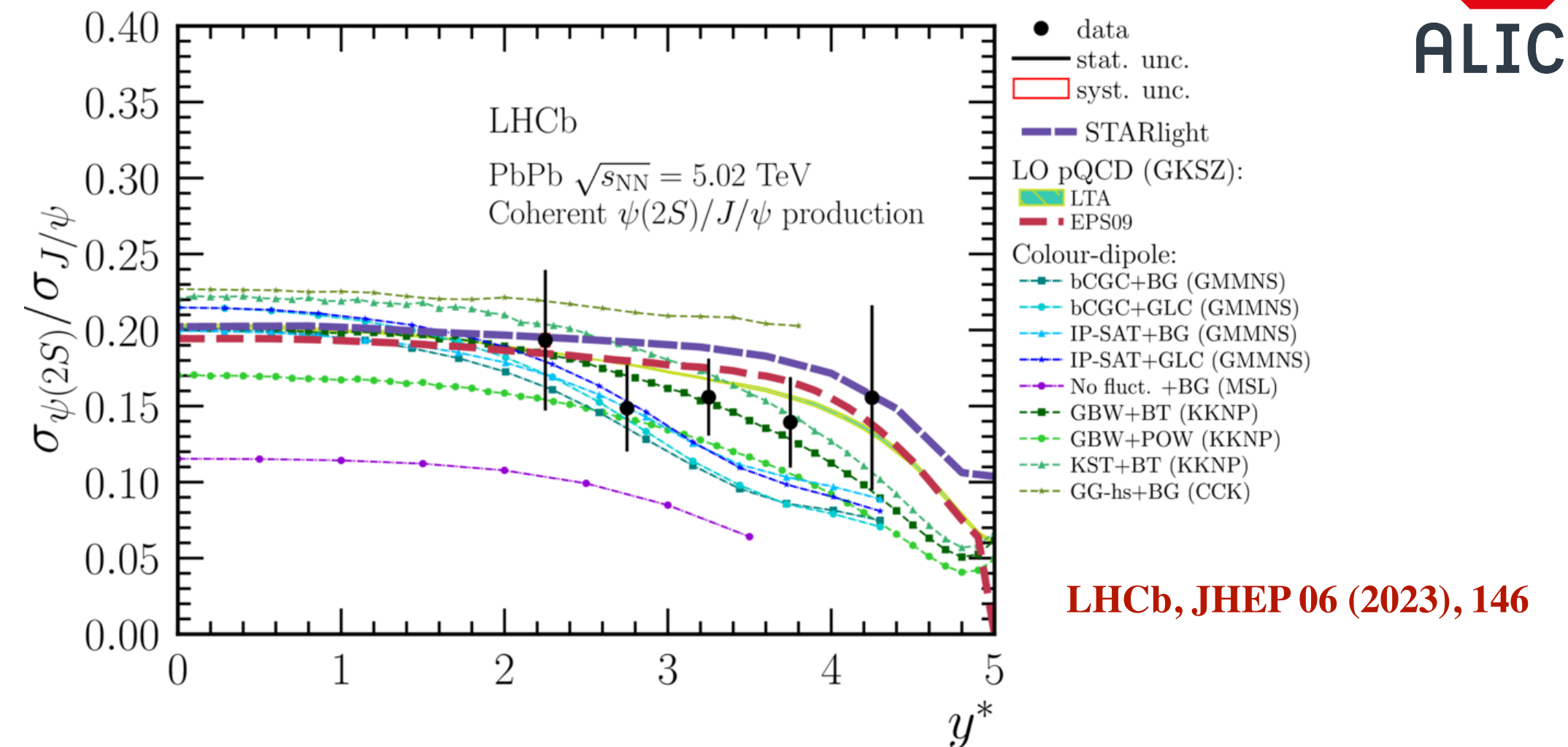
arXiv:2605.13569 [nucl-ex]



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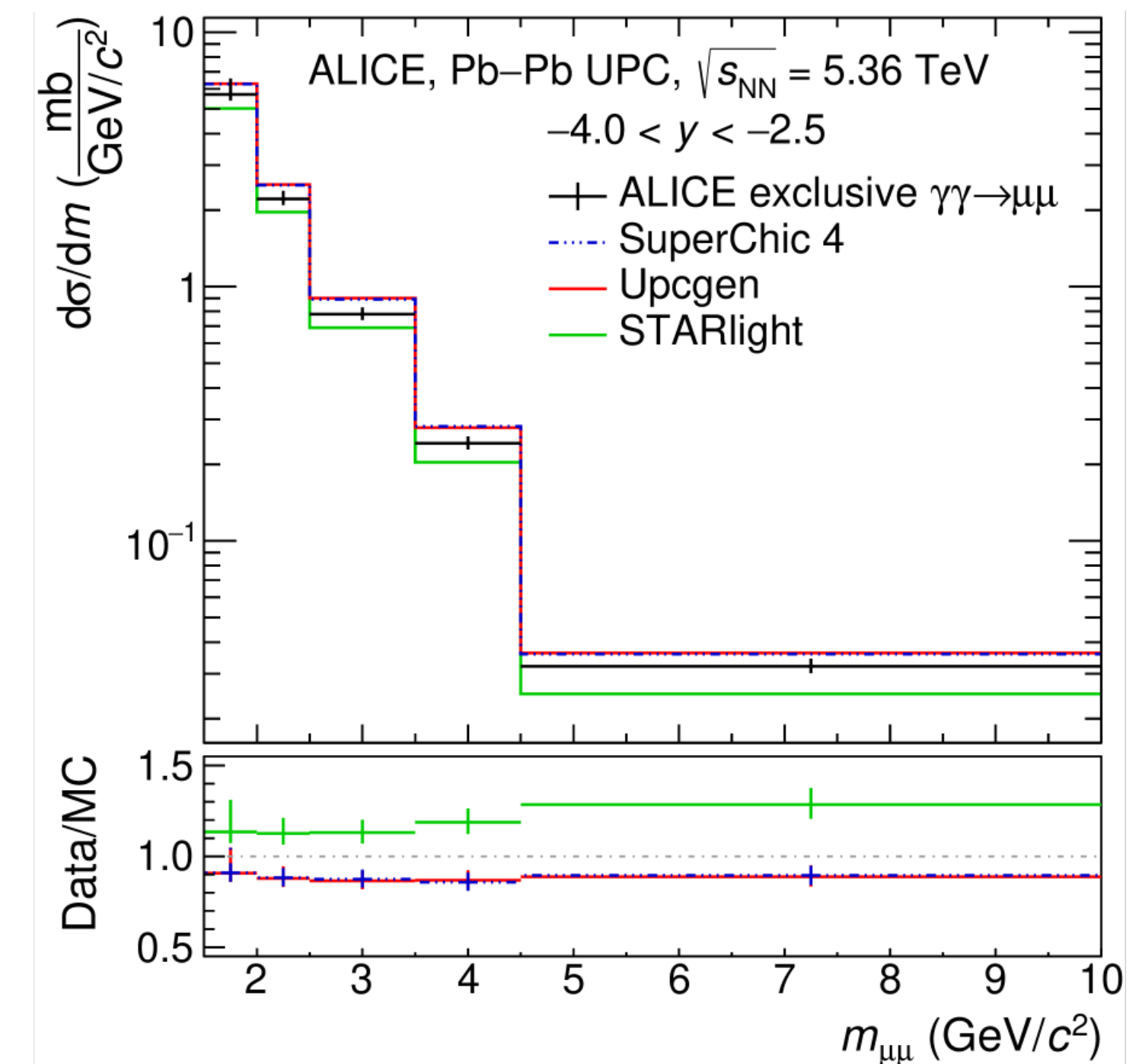


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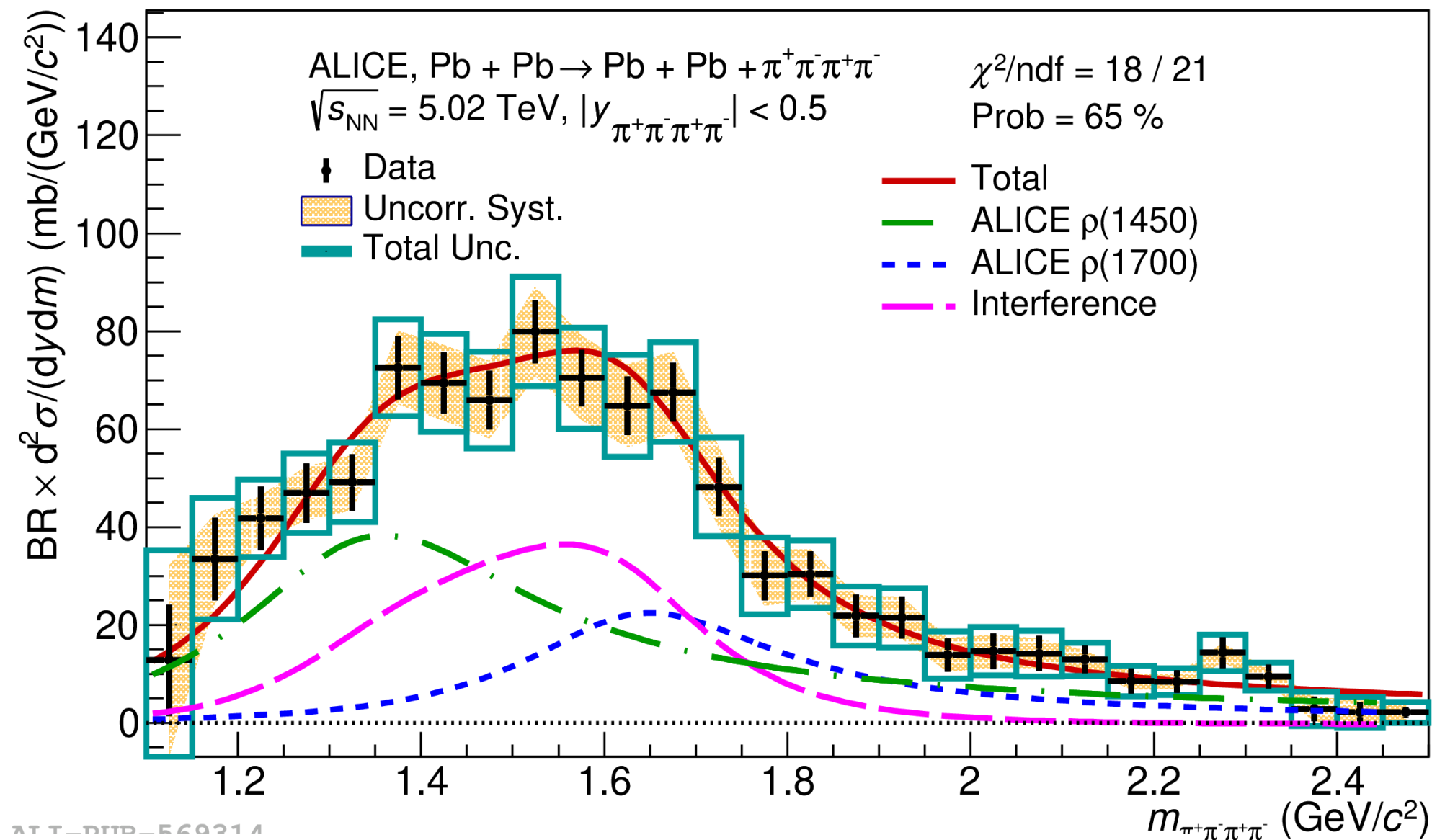


LHCb, JHEP 06 (2023), 146

- ✓ First run 3 excited charmonium state with improved precision
- ✓ Consistent within 1σ with the ALICE and LHCb Run 2 results
- ✓ Current uncertainties are compatible with all considered shadowing/CGC models ($<2\sigma$)
- ✓ The exclusive dimuon continuum measurement possible with Run 3
- ✓ Providing new constraints on nuclear gluons and the photon flux

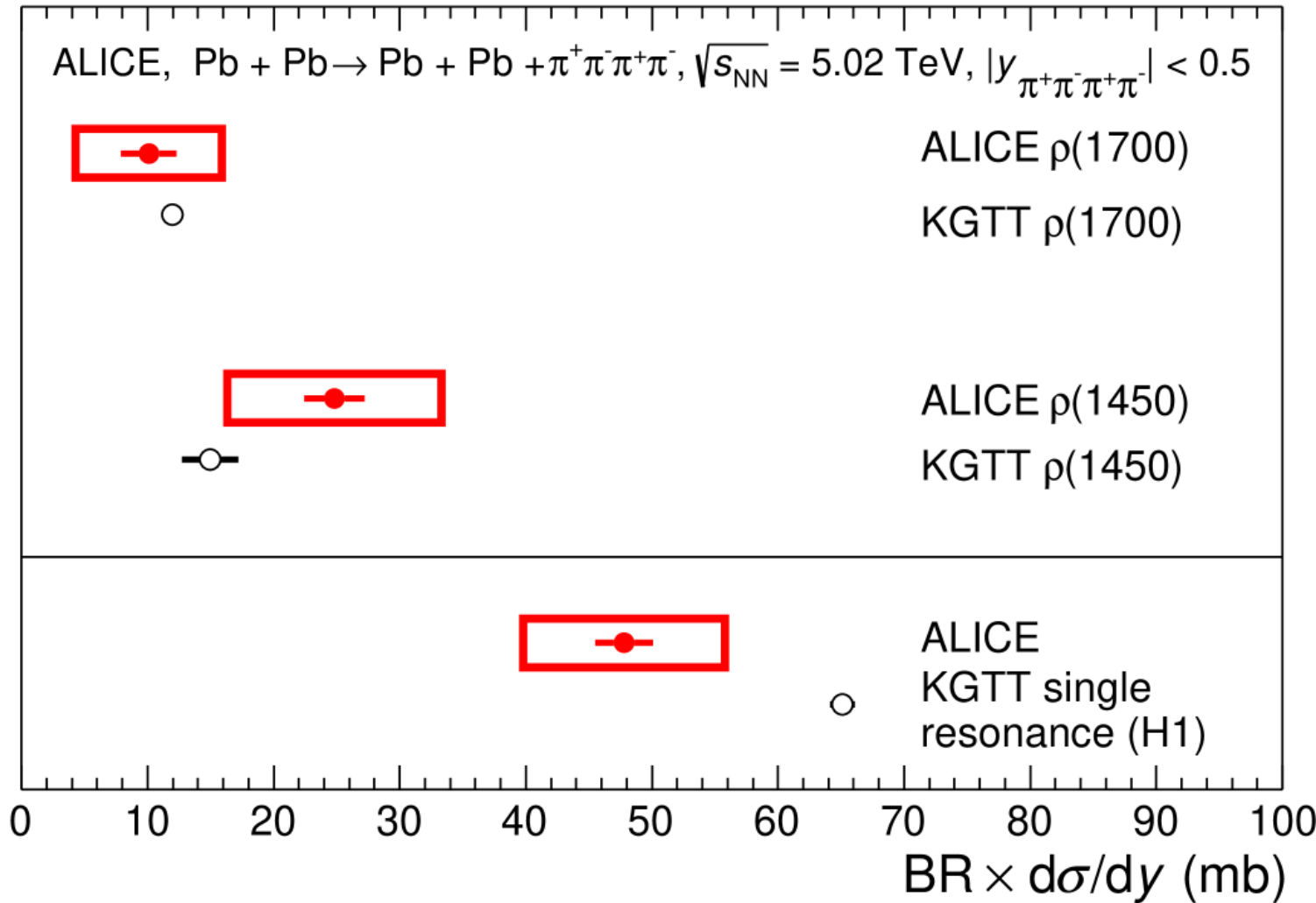


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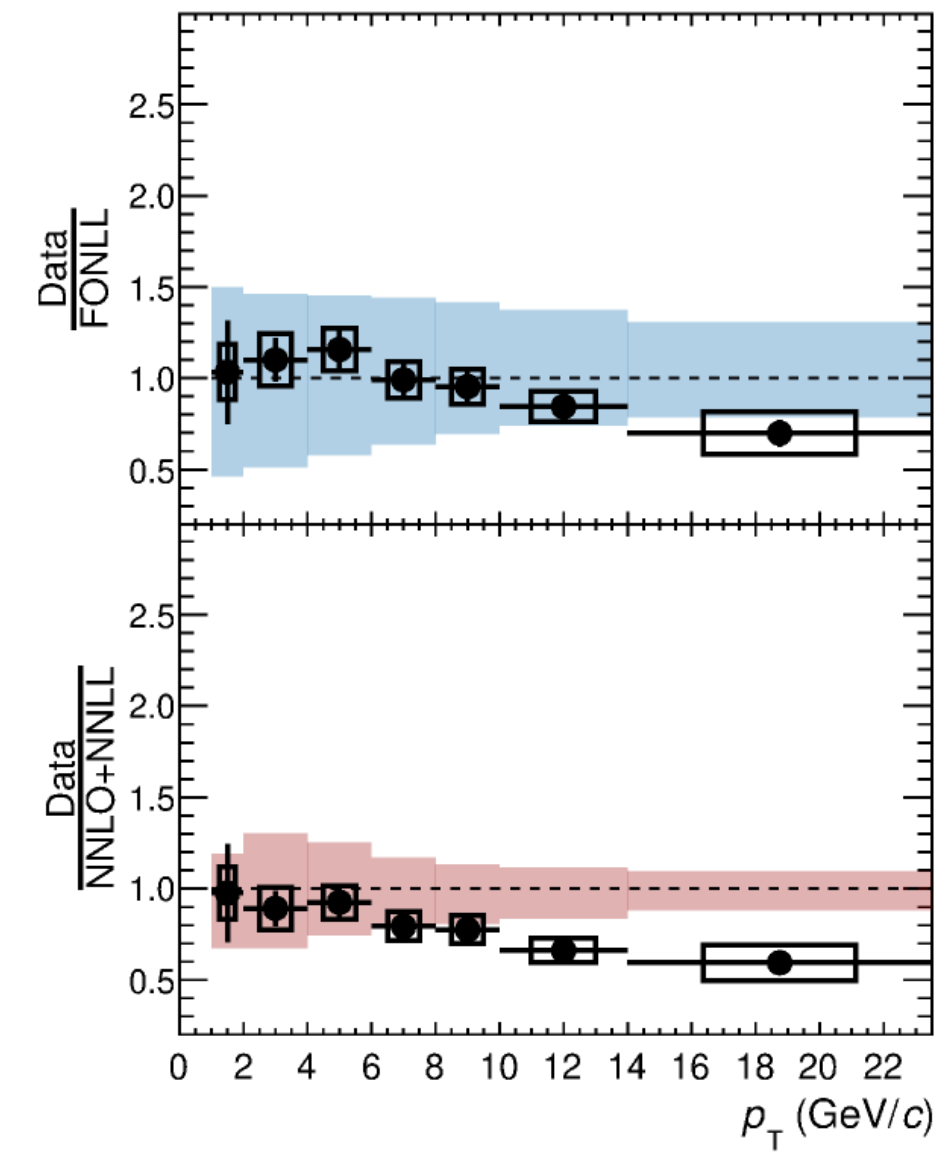
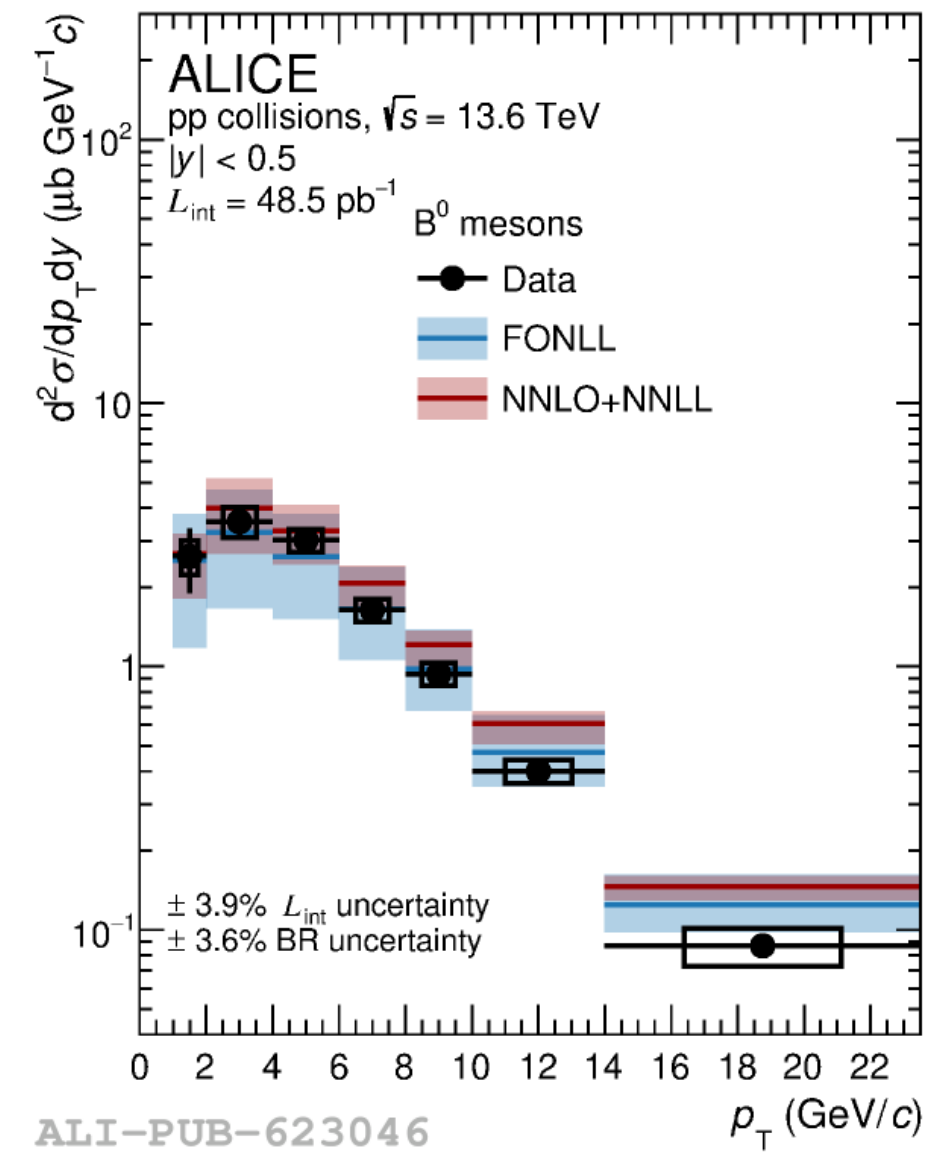
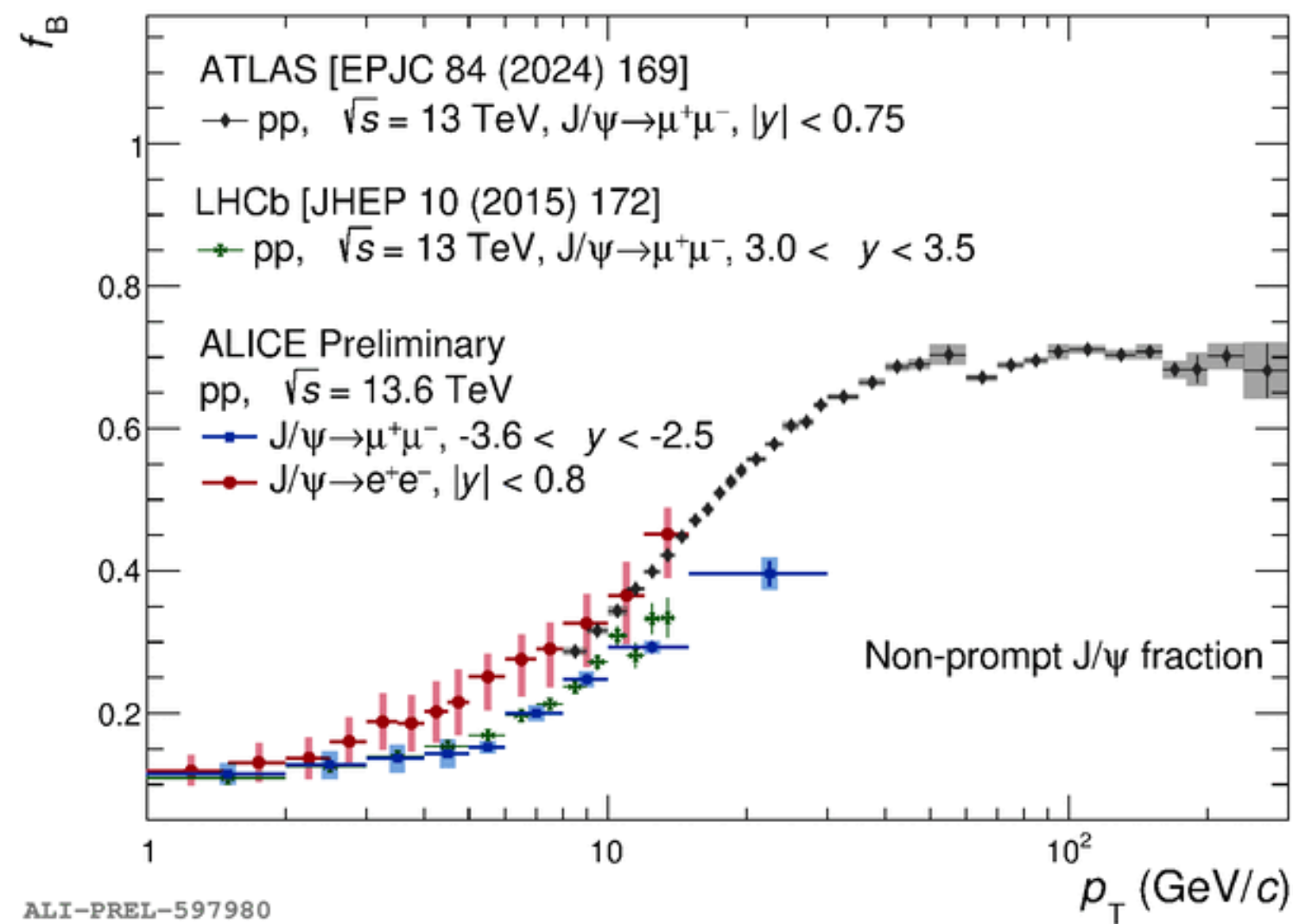
- ✓ The hardness of these probes lies between ρ^0 and J/ ψ masses, providing sensitivity to gluon dynamics in the perturbative regime.
- ✓ Coherent photoproduction of four pions in the final states
- ✓ The production of two interfering resonances, $\rho(1450)$ and $\rho(1700)$ provides a good description of the data
- ✓ Photon-induced processes constrain diffractive dynamics.
- ✓ More differential and inclusive UPCs with Run 3

See talk by M. Kim

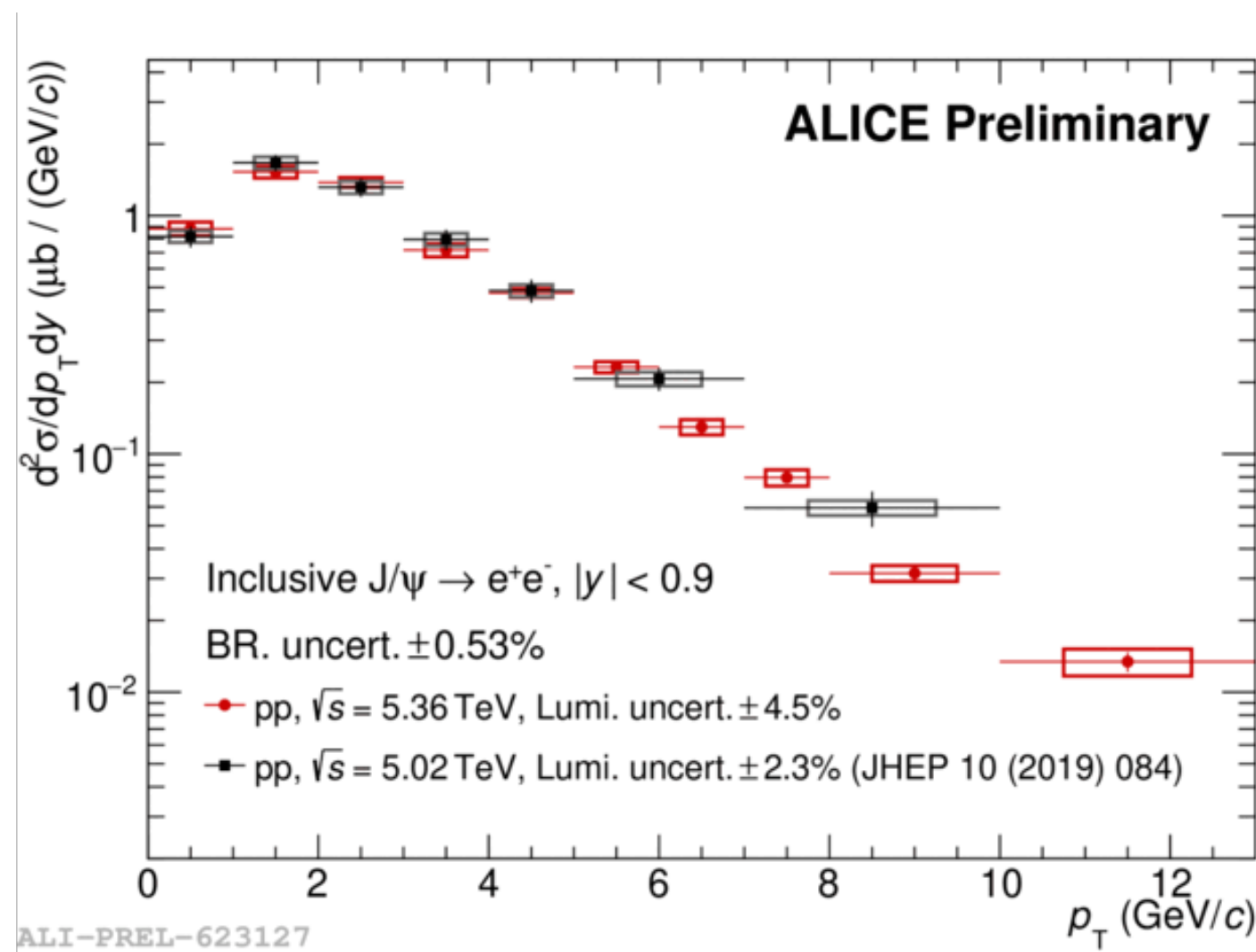
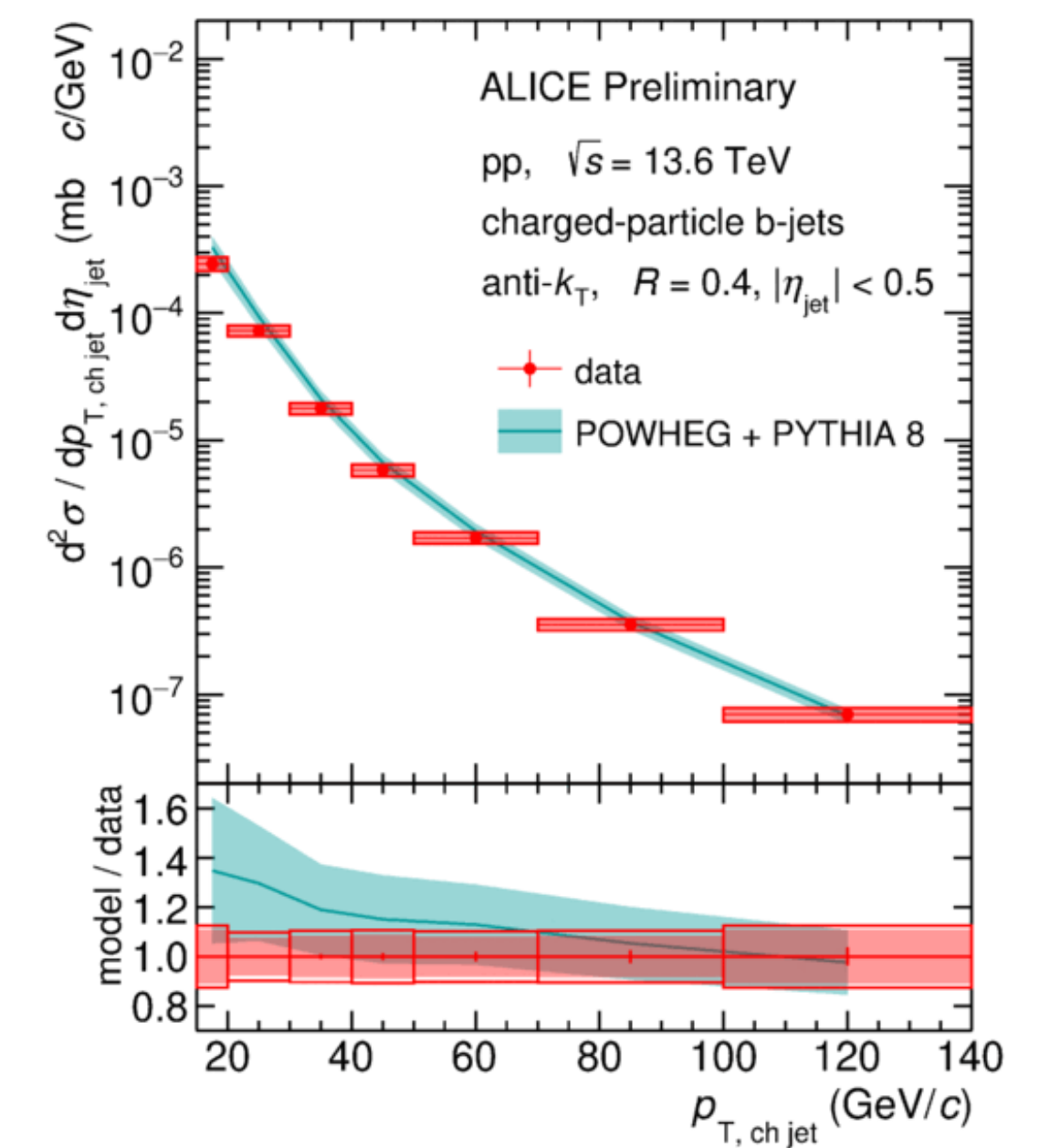


Part II — Energy loss and hard probes

Precision charm and new beauty measurements



[arXiv:2603.18904 \[hep-ex\]](https://arxiv.org/abs/2603.18904)



- ✓ Run 3 opens the precision era for heavy flavour and charmonium through improved ITS2/MFT vertexing and large statistics.
- ✓ First B^0 production measurement and precision beauty cross sections at low p_T .
- ✓ First non-prompt J/ψ measurement at forward rapidity with the MFT.
- ✓ Improved b-jet tagging with Graph Neural Networks paves the way for beauty energy-loss measurements.

See also: talk by G. Legras, “J/ψ-multiplicity results with ALICE”

Jet substructure and scale-dependent energy loss

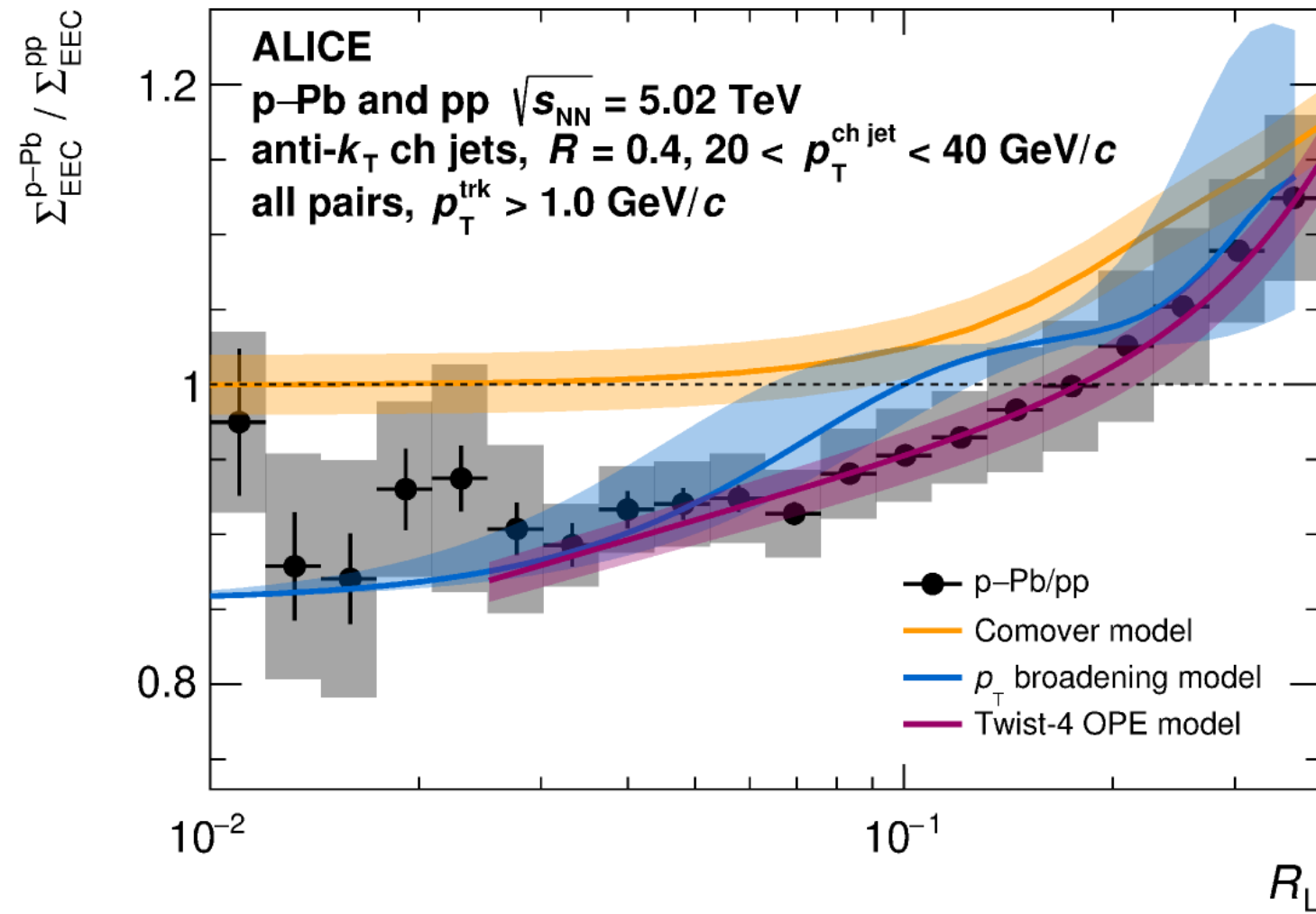
arXiv:2504.03431 [hep-ex]



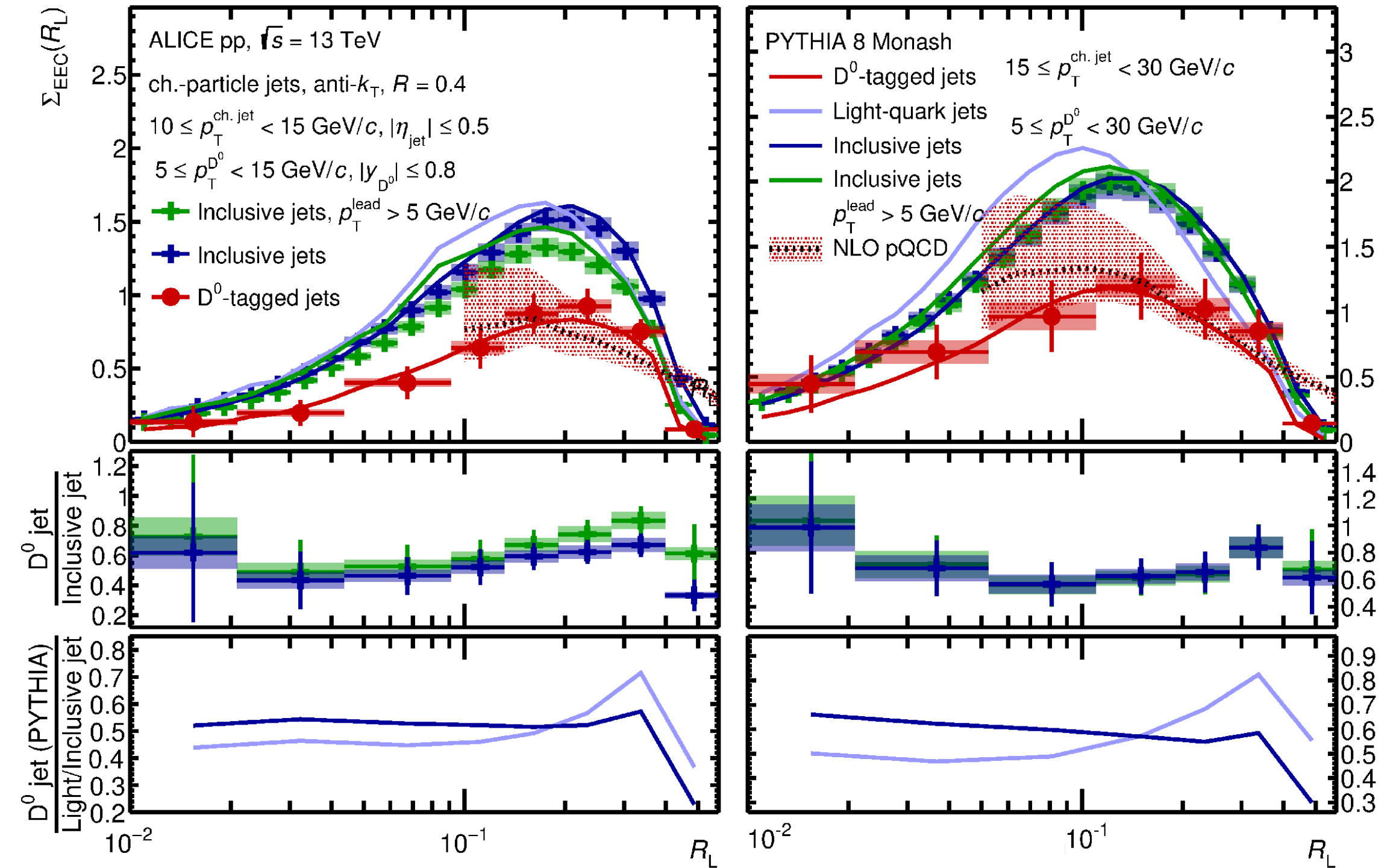
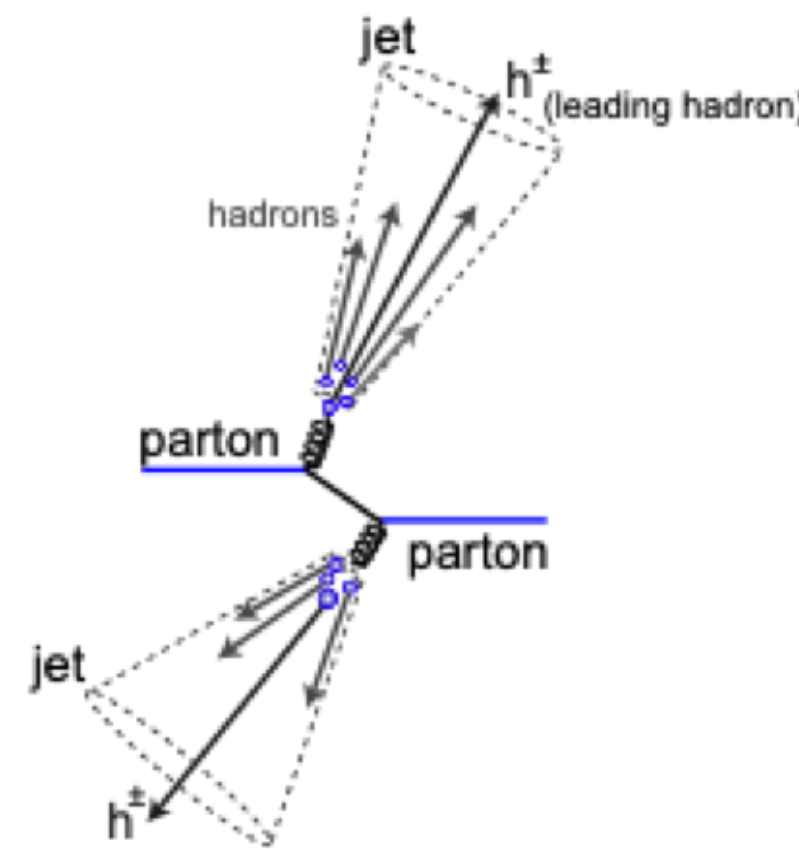
arXiv:2606.18143 [nucl-ex]

$$\frac{d\sigma_{EEC}}{dR_L} = \sum_{i,j} \int d\sigma(R'_L) \frac{p_{T,i} p_{T,j}}{p_{T,jet}^2} \delta(R'_L - R_{L,ij})$$

$$R_L = \sqrt{\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2}$$



Largest distance in (η, ϕ)
between any two particles



ALI-PUB-635030

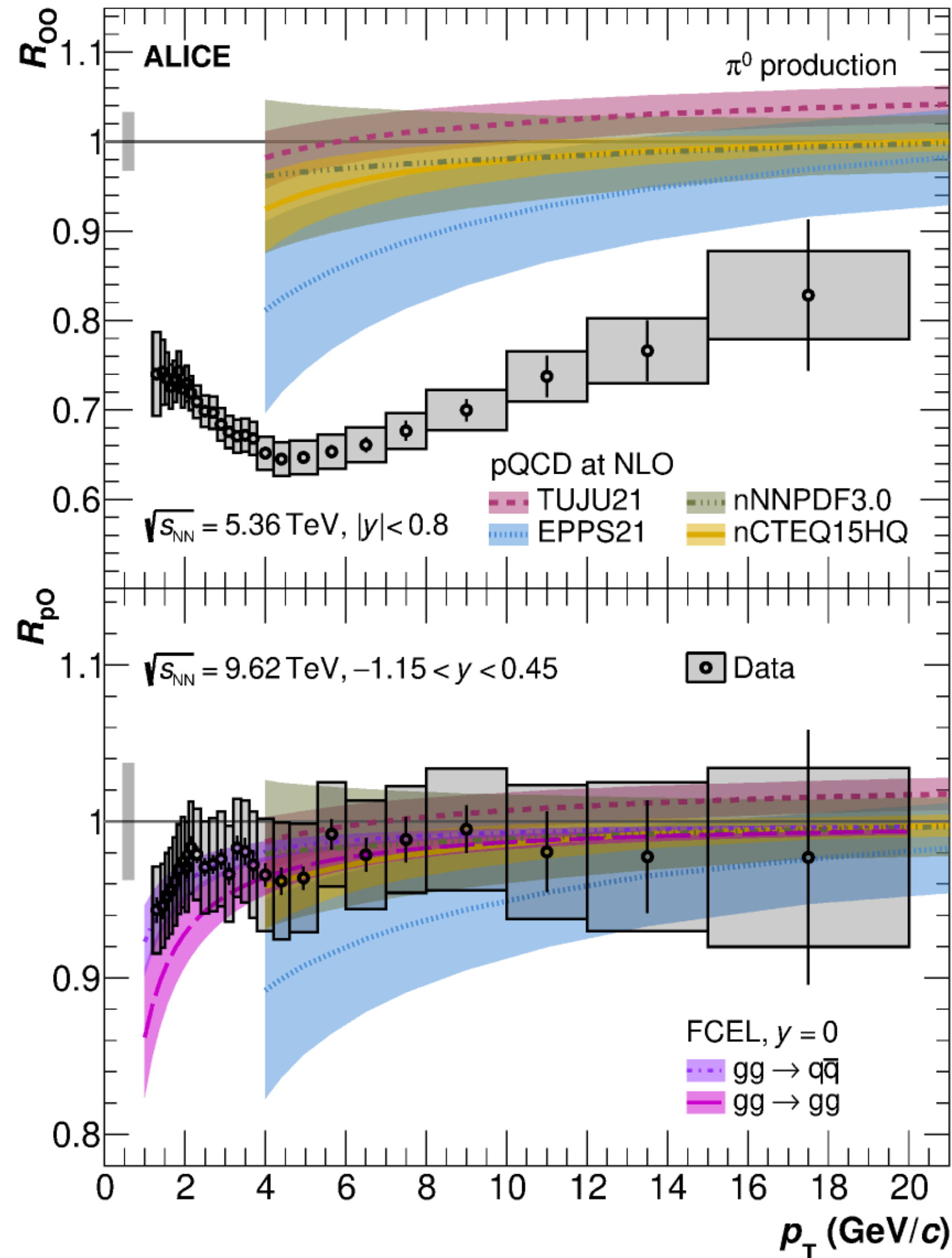
- ✓ EEC probes angular energy flow inside jets
- ✓ EEC_{pPb}/EEC_{pp} shows a modification for 20-40 GeV/c jets
- ✓ Data discriminate between competing CNM descriptions (p_T broadening, comovers, Twist-4 OPE)
- ✓ Establishes the CNM baseline for future heavy-ion EEC measurements

A. Khatun

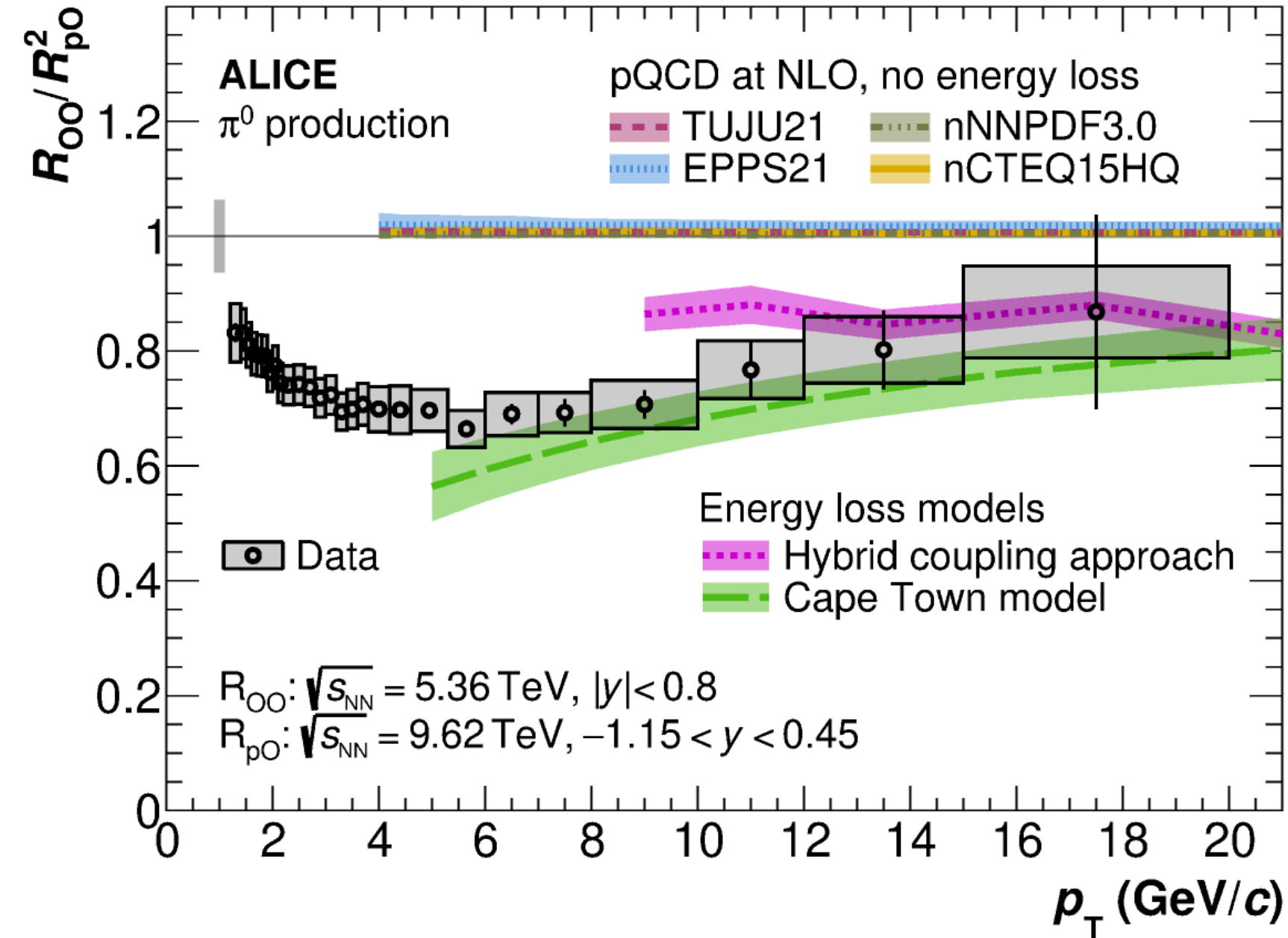
- ✓ Charm-tagged jets show lower EEC amplitude than inclusive jets
- ✓ Consistent with suppressed radiation from massive quarks
- ✓ Peak position similar to inclusive (gluon-dominated) jets
- ✓ Motivates improved pQCD description of heavy-quark radiation

ALI-PUB-604529

EMMI 2026



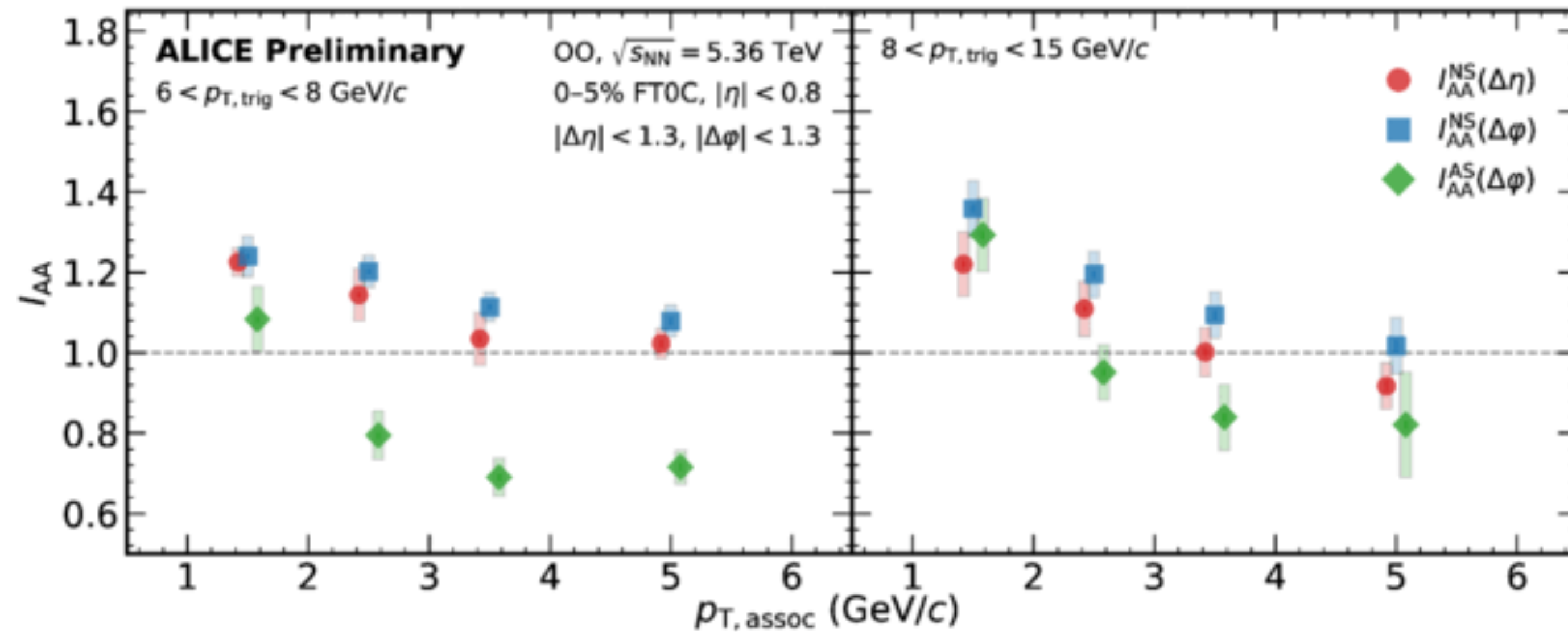
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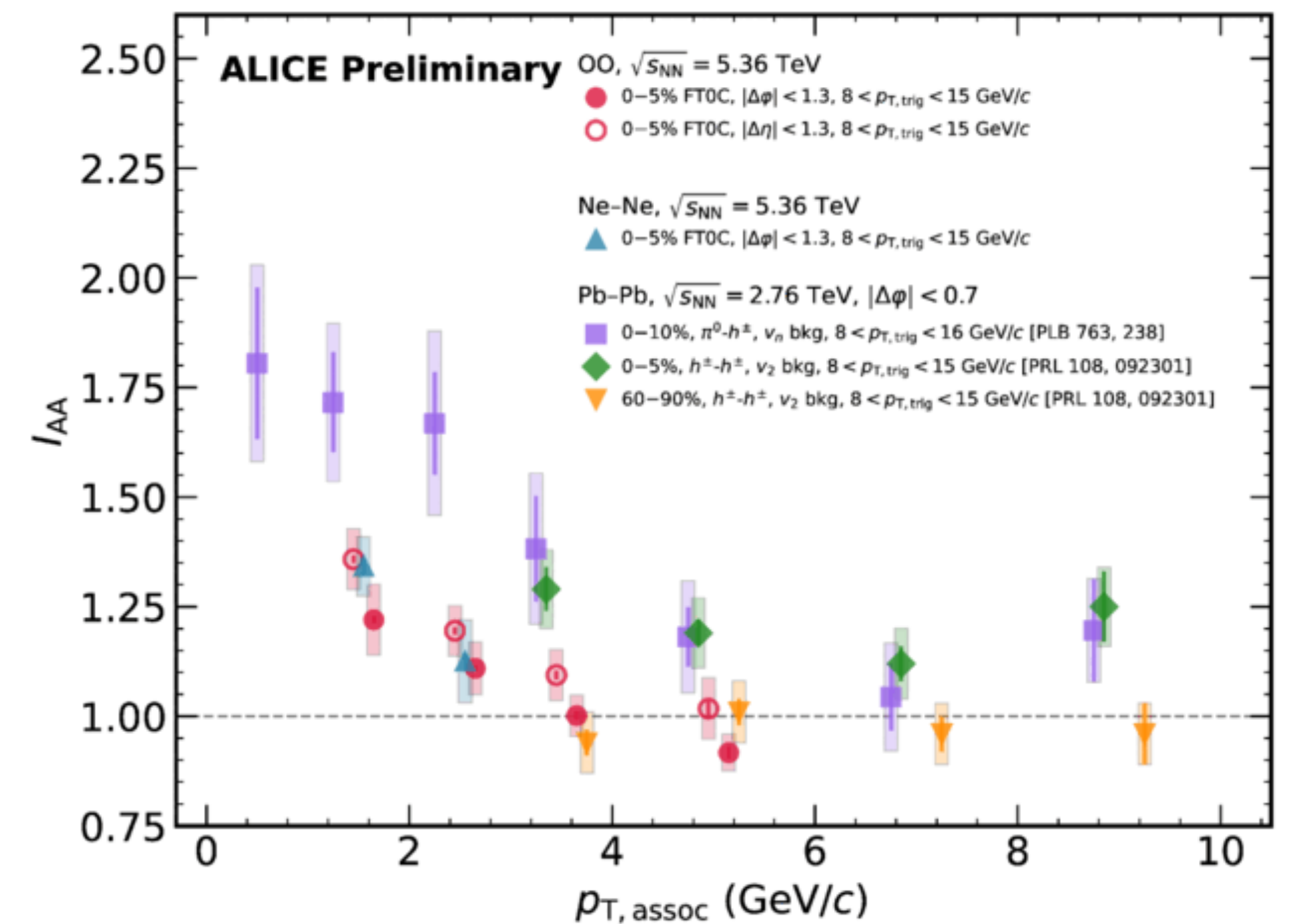
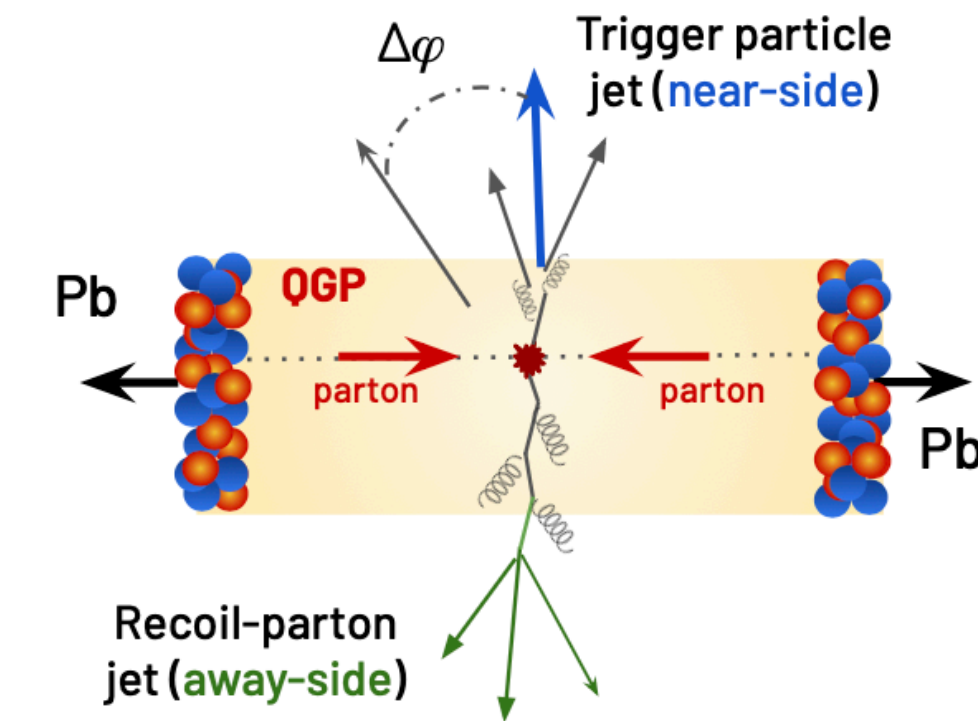
- ✓ R_{p0} provides the first constraints on CNM effects in light-ions
- ✓ The double ratio removes CNM effects and is incompatible with nPDF-only descriptions
- ✓ Data show $\sim 4.9\sigma$ deviation from CNM-only baseline
- ✓ Suppression consistent with dominant QGP energy loss
- ✓ Compatible with radiative + collisional energy-loss calculations

Probing parton energy loss with high- p_T hadron correlations



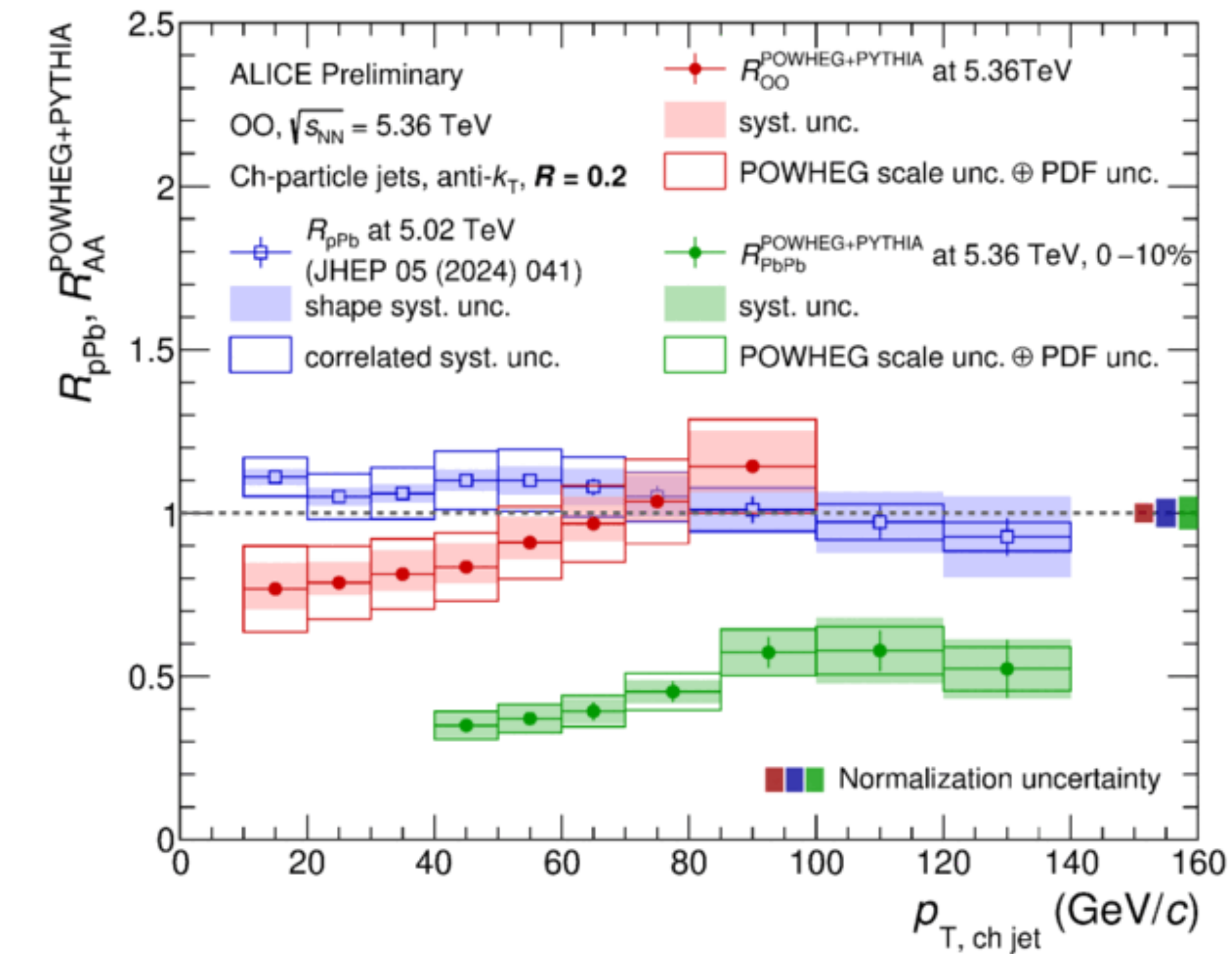
ALI-PREL-635744

- ✓ Near- and away-side correlations provide complementary probes of jet-medium interactions
- ✓ A decreasing recoil-jet I_{AA} with increasing associated-particle p_T indicates parton energy loss
- ✓ The I_{AA} evolution with associated-particle p_T in O-O and Ne-Ne resembles the qualitative behavior observed in Pb-Pb collisions
- ✓ The measurements indicate medium-induced modifications of jet fragmentation in light-ion collisions

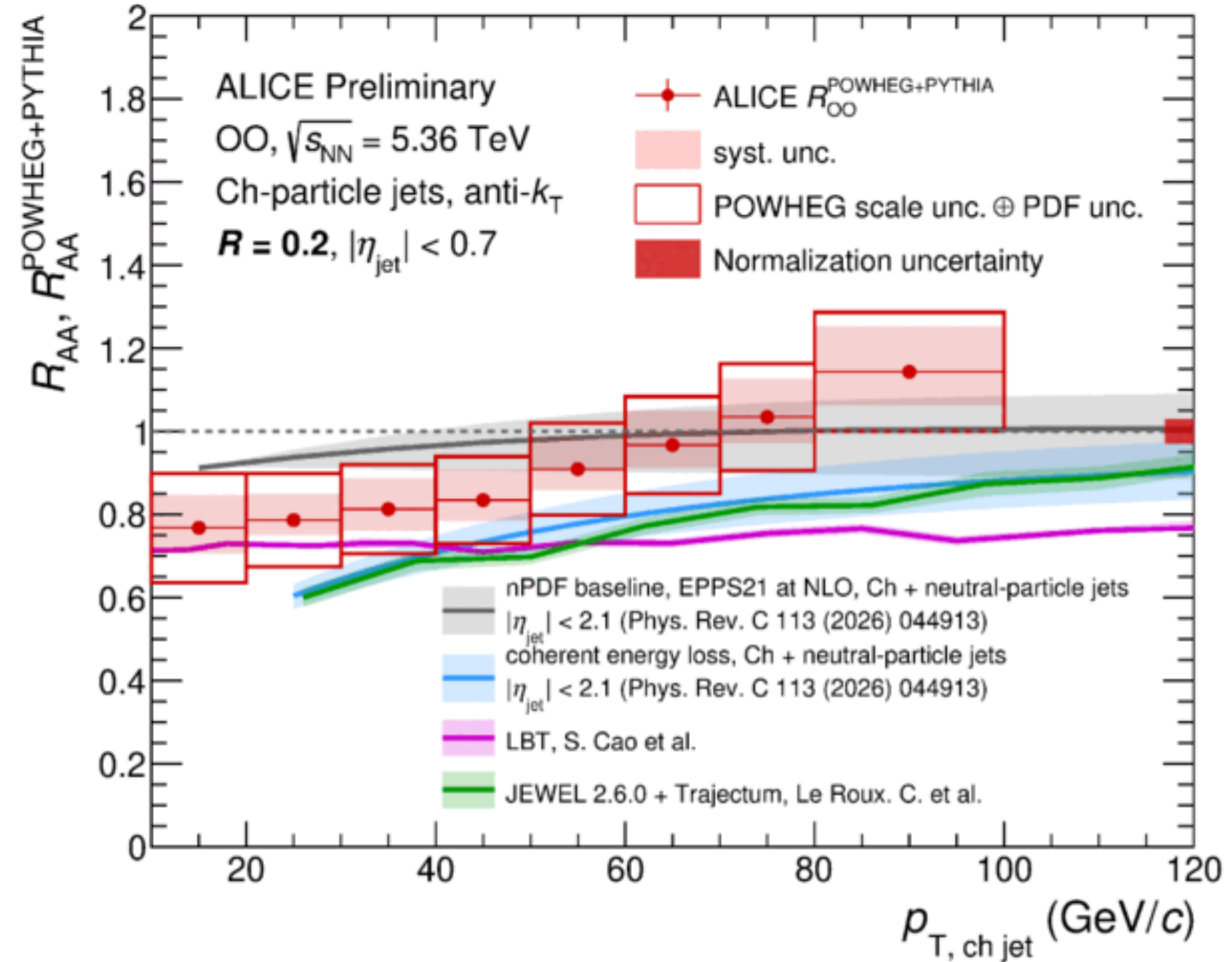


ALI-PREL-635754

Inclusive jet suppression in OO



ALI-PREL-635353



ALI-PREL-635343

- ✓ Inclusive jet measurements extend jet-quenching studies to light-ion collisions
- ✓ The observed suppression hierarchy (R_{AA} (Pb-Pb) $<$ R_{OO} $<$ $R_{pPb} \approx 1$) is consistent with increasing medium effects with system size
- ✓ Future Run 3 statistics will enable quantitative discrimination between competing energy-loss models

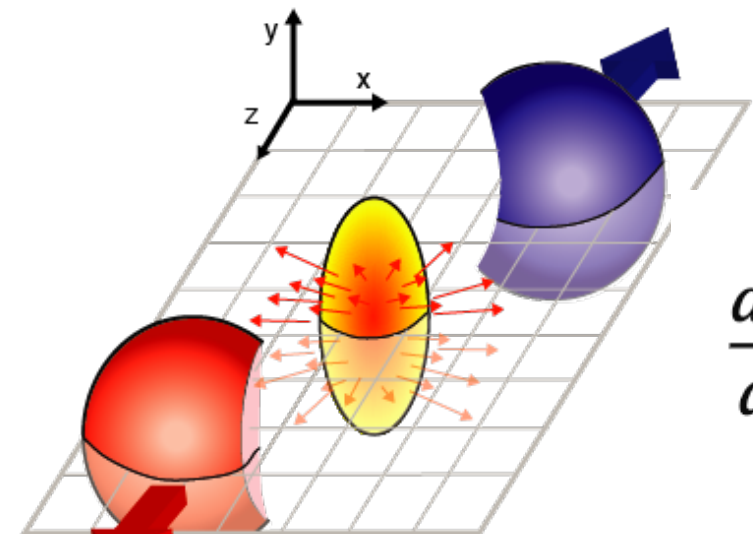
Part III — The QGP: A strongly coupled medium

Anisotropic flow across system sizes



ALICE

Nat. Comm. 17 (2026), 2585

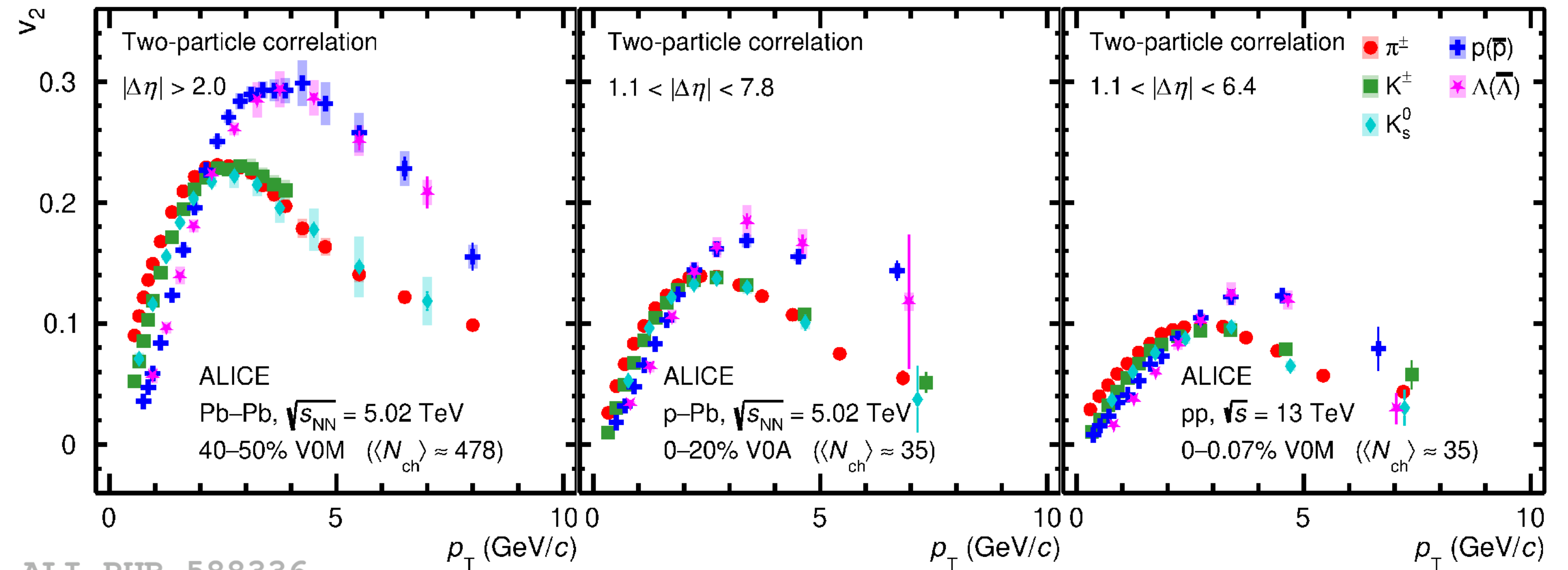


$$\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n))$$

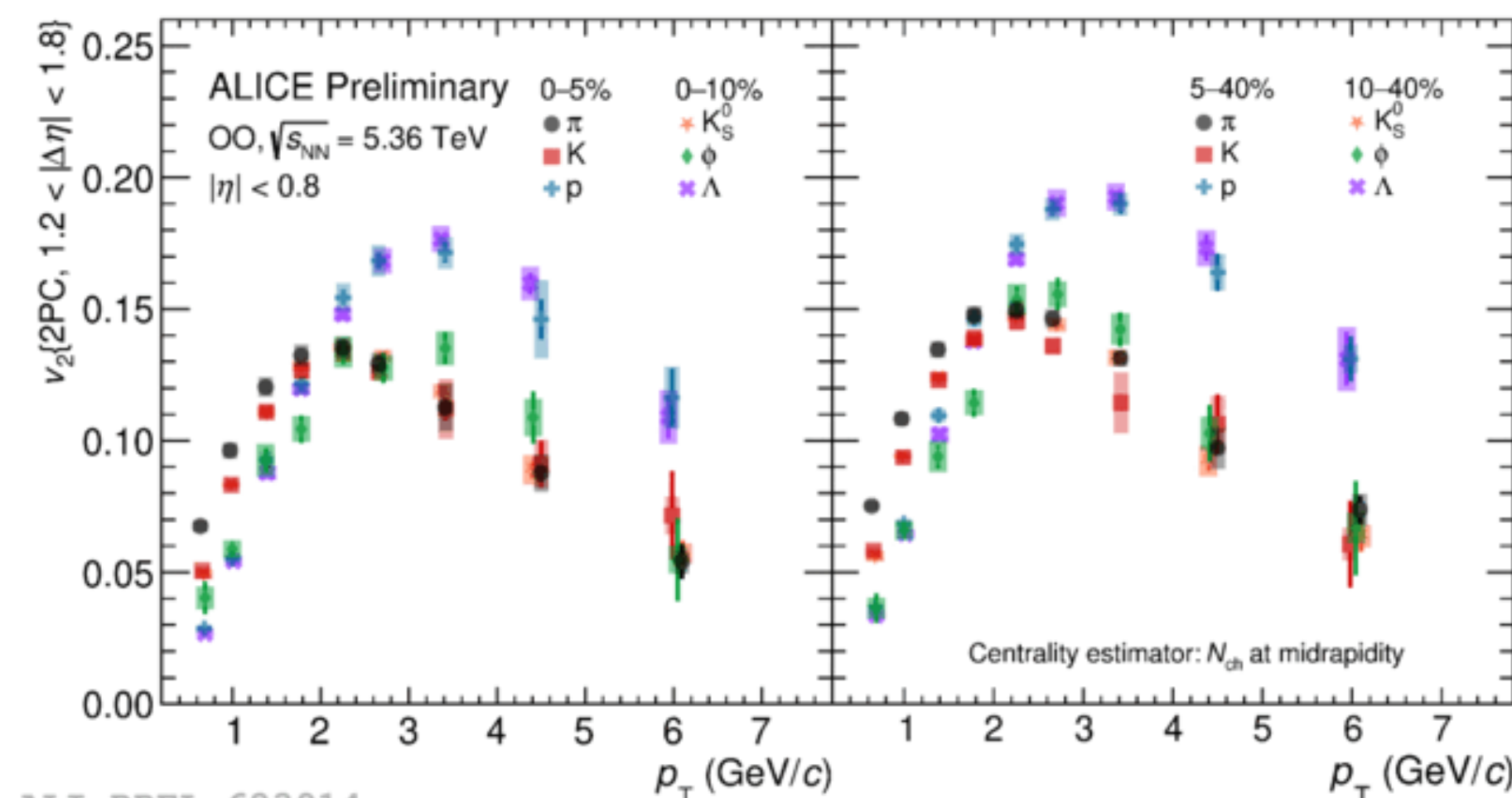
$$\frac{dN}{d\phi} \propto 1 + 2v_1 \cos(\phi - \Psi_{RP}) + 2v_2 \cos(2(\phi - \Psi_{RP})) + \dots$$

Partonic collectivity across collision systems

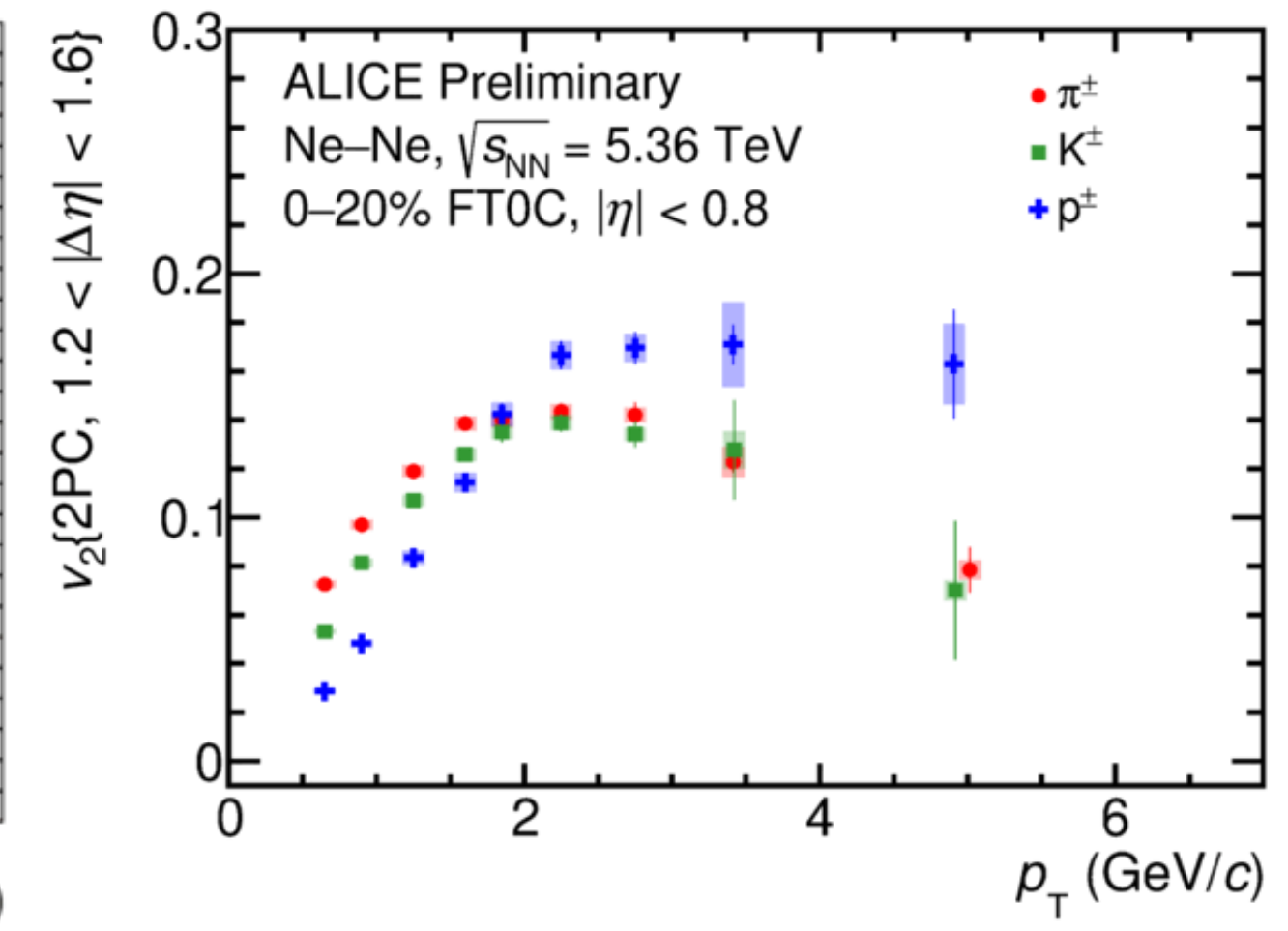
- ☑ Identified-particle v_2 measured in Pb–Pb, p–Pb and high-multiplicity pp
- ☑ Clear mass ordering at low- p_T (π , K, p)
- ☑ Baryon–meson splitting at intermediate p_T ($\sim 5\sigma$ significance)
- ☑ Similar patterns across systems
- ☑ Suggest collective expansion of partonic matter



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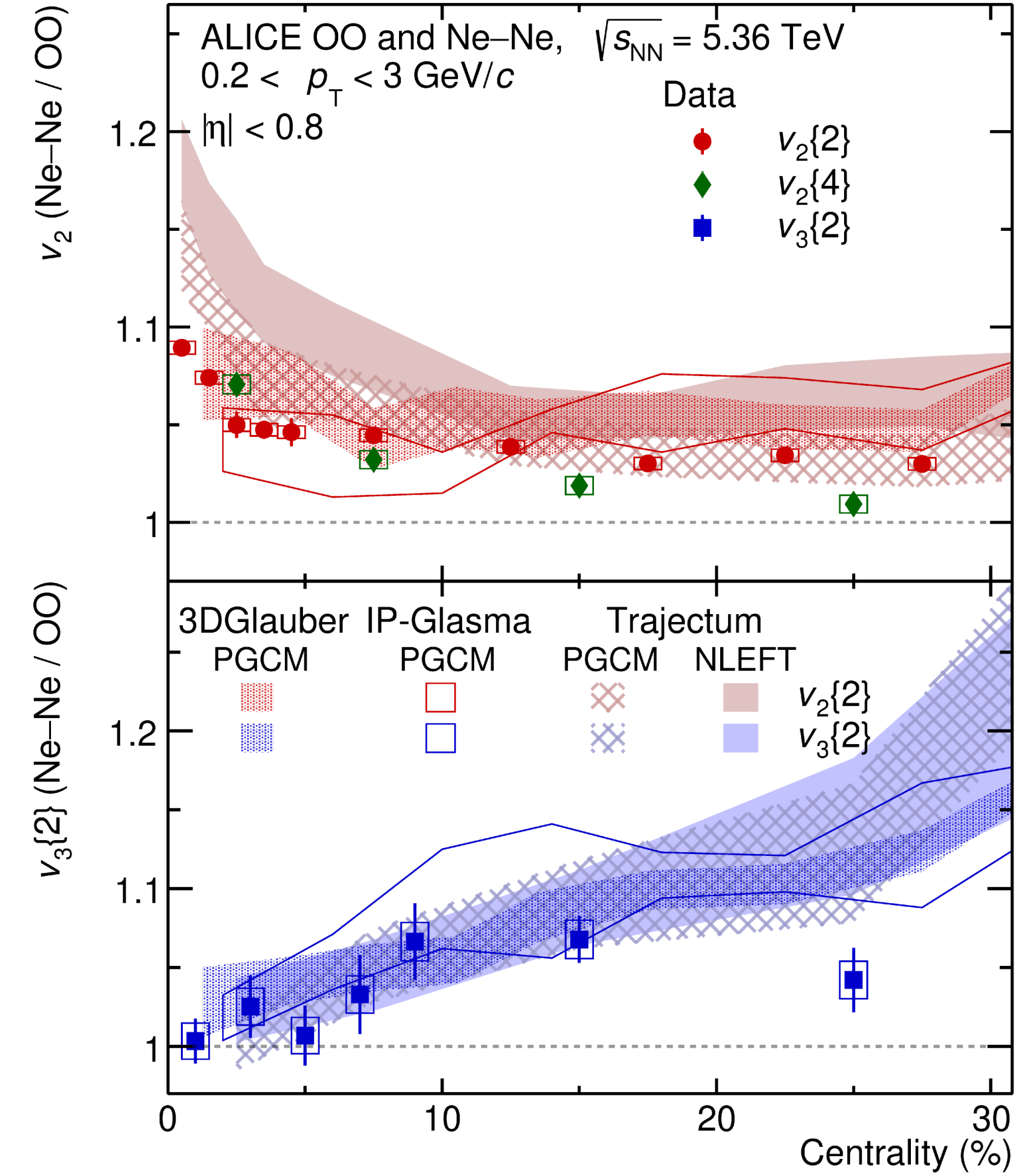
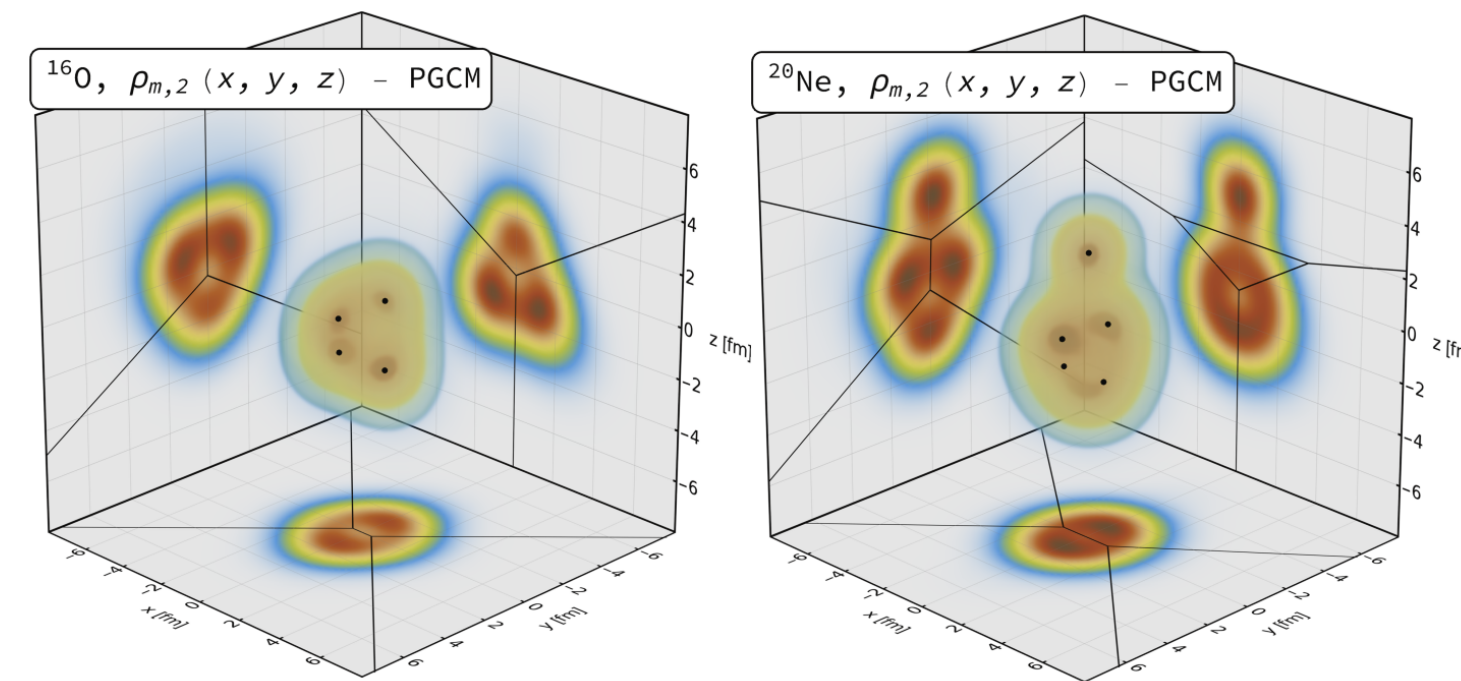
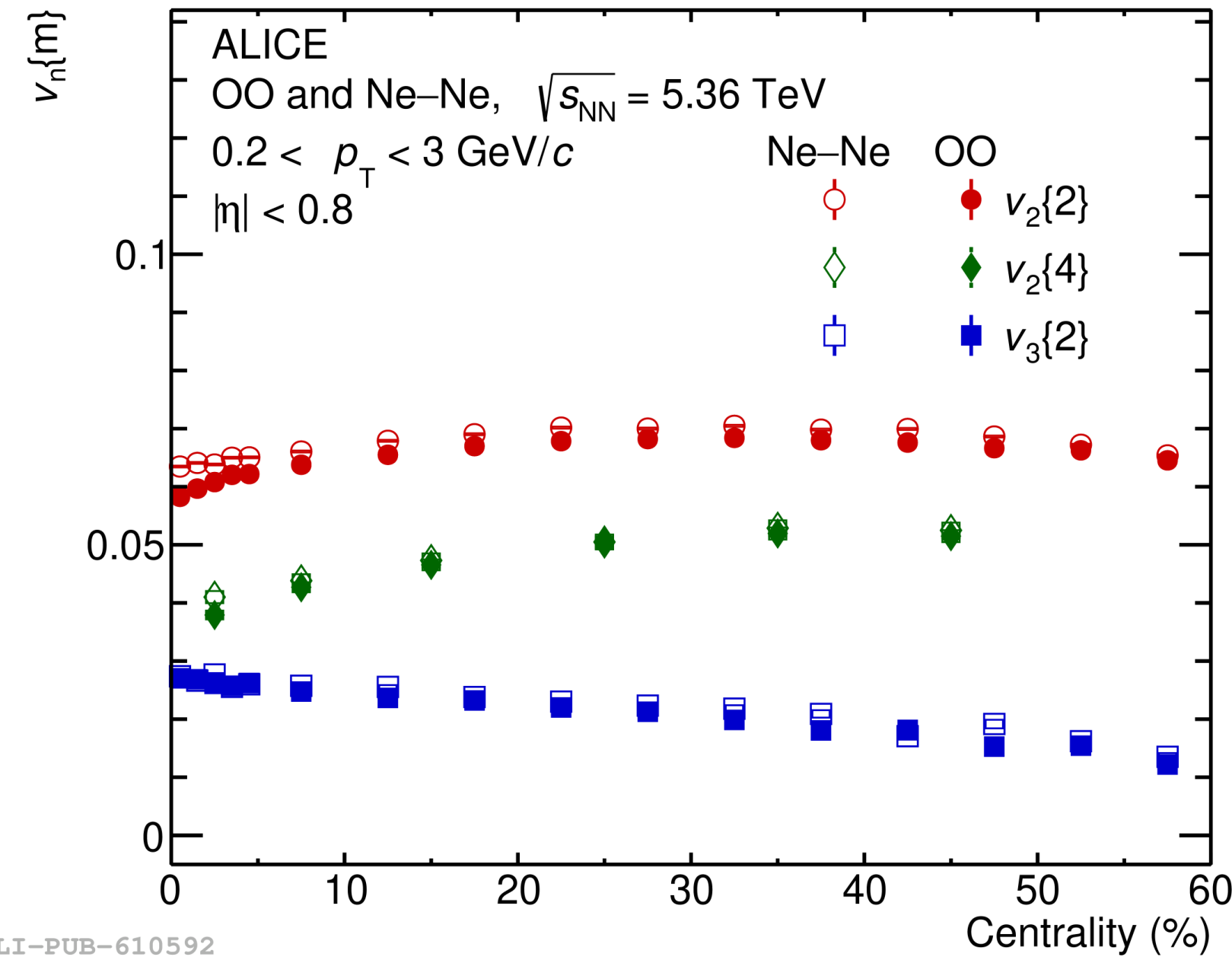
ALI-PREL-623914



ALI-PREL-635195

- ✓ First measurements of v_2 and v_3 in OO and Ne–Ne at 5.36 TeV
- ✓ Sizeable v_2 and v_3 with weak centrality dependence
- ✓ Enhanced v_2 in central Ne–Ne collisions consistent with hydrodynamic expectations
- ✓ Ratios help isolate initial state geometry effect
- ✓ Comparisons between OO and Ne–Ne provide new constraints on the interplay between the initial geometry and the collective expansion

A unique laboratory to test the interplay between the initial geometry and the collective expansion of the medium.

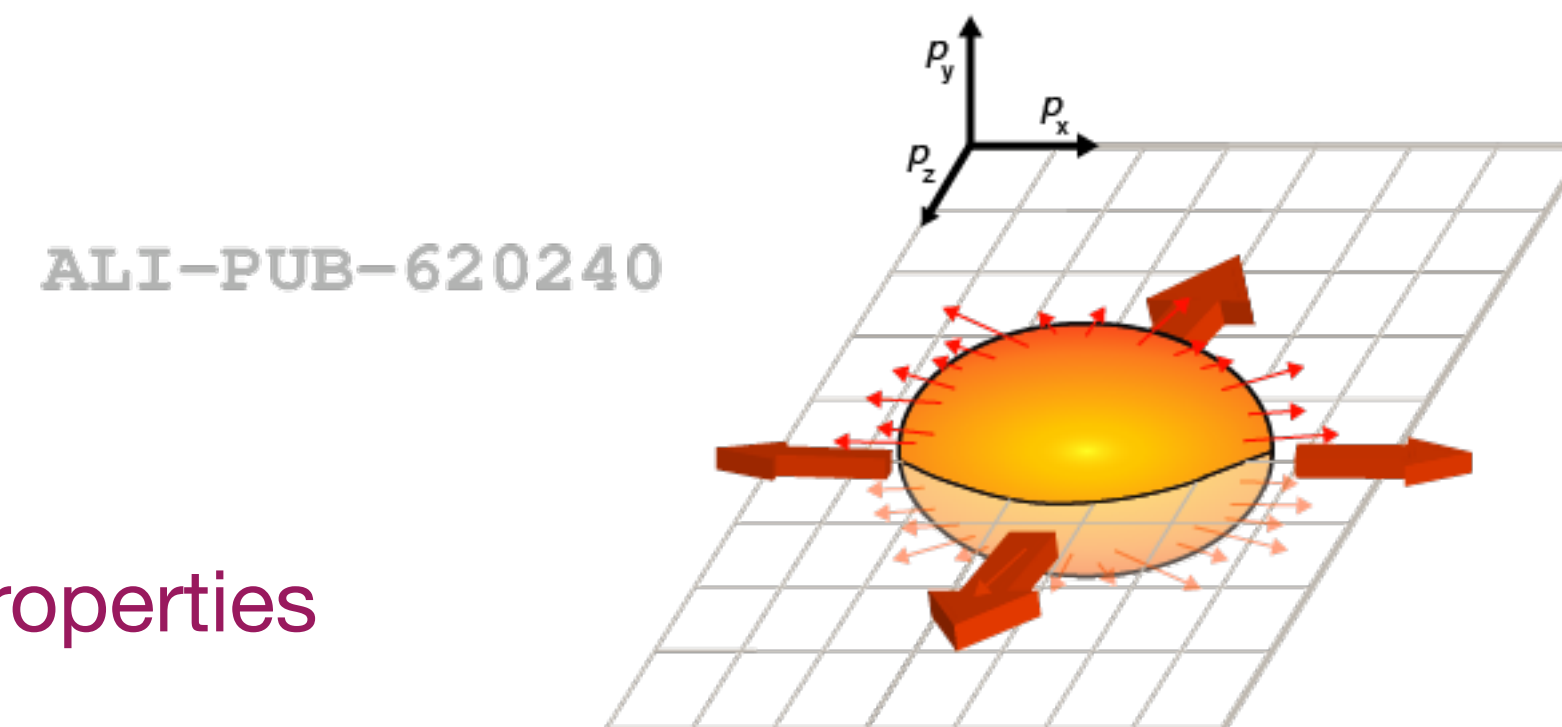
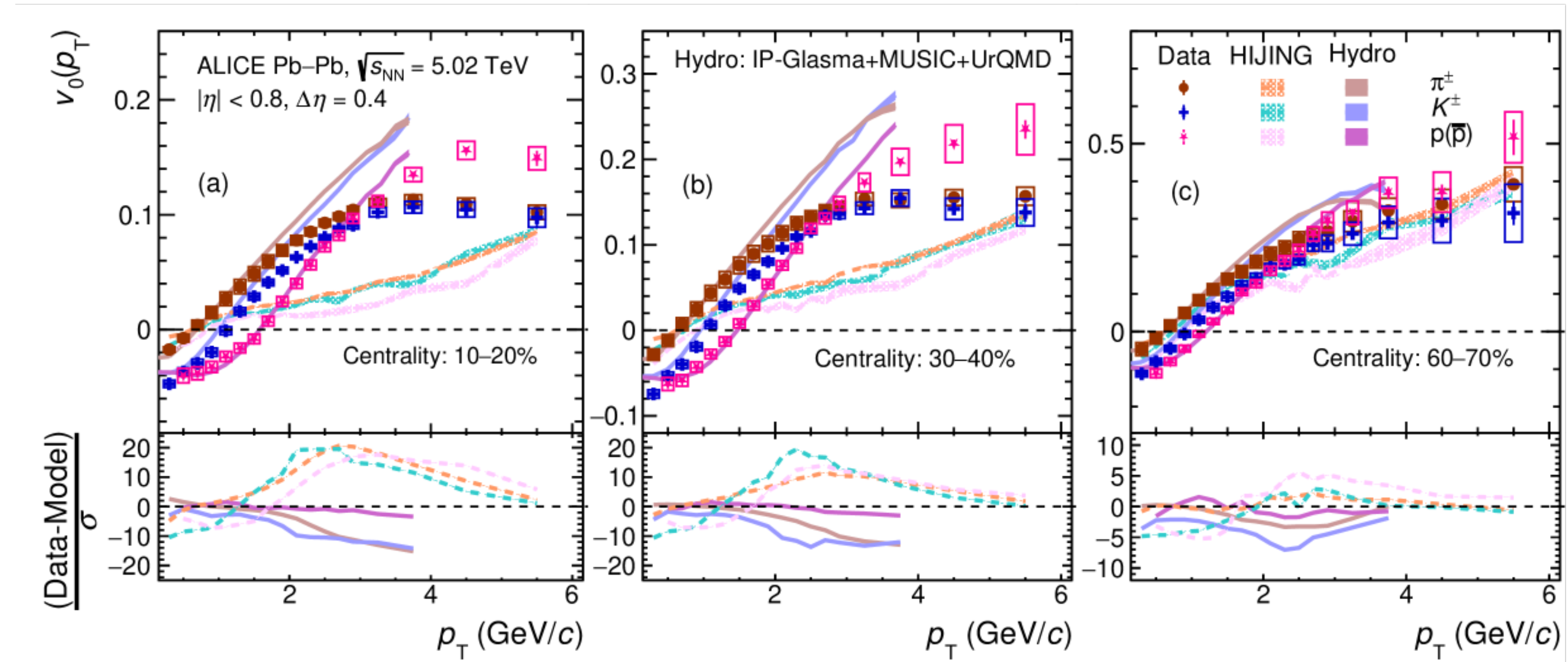


ALI-PUB-610602

Radial flow: Collective transverse expansion

Radial flow fluctuations: $v_0(p_T)$ at Pb–Pb $\sqrt{s_{NN}} = 5.02$ TeV

- ✓ New observable probing event-by-event radial flow fluctuations
- ✓ Clear mass ordering at low p_T (π , K, p)
- ✓ Baryon–meson splitting at intermediate p_T
→ consistent with quark recombination
- ✓ Hydrodynamic models describe data up to $\sim 2\text{--}3$ GeV/c
- ✓ Sensitive to:
 - ✓ Bulk viscosity (ζ/s)
 - ✓ Equation of State
 - ✓ Initial-state fluctuations

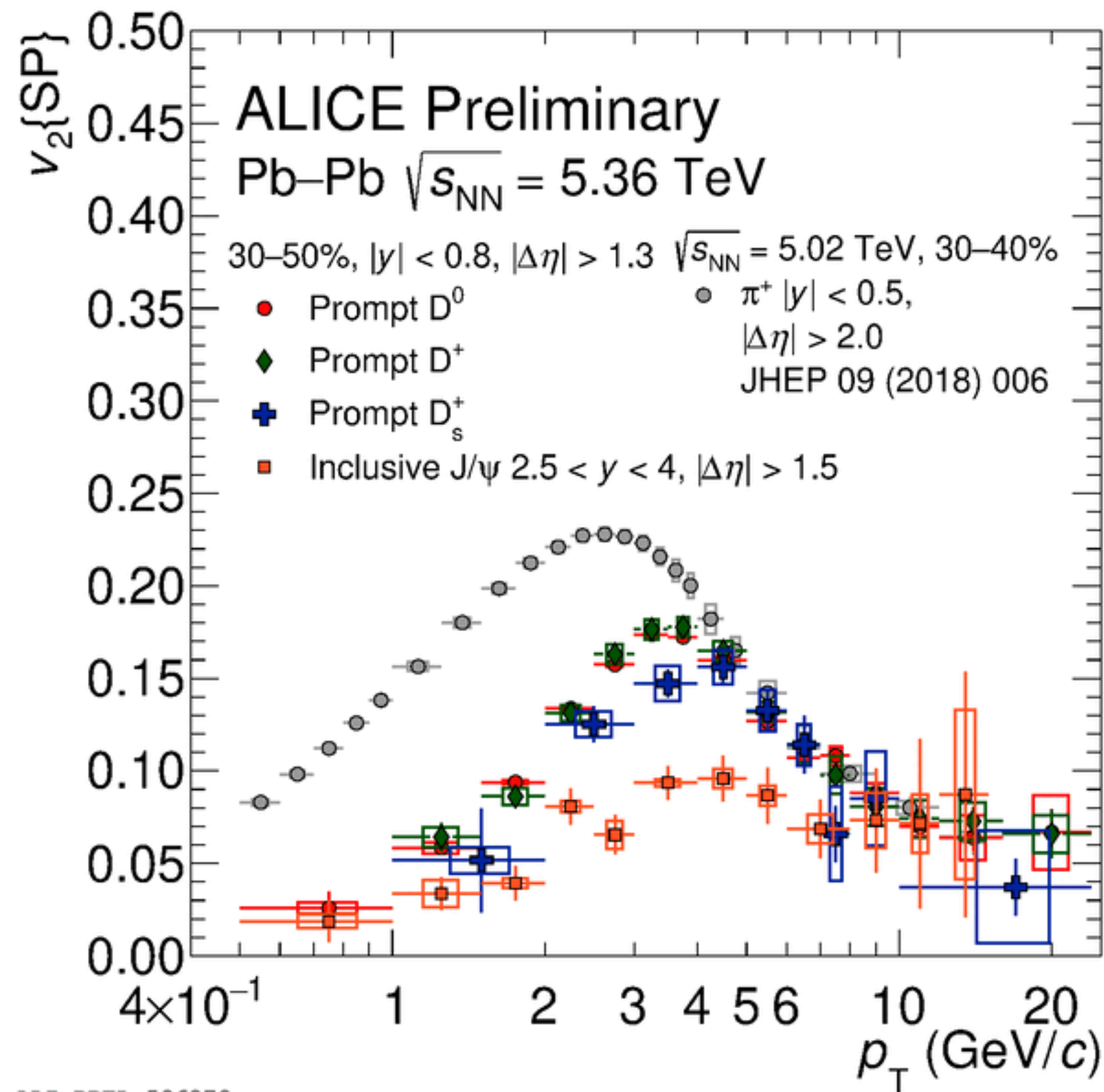


$v_0(p_T)$ adds new constraints on QGP transport properties

Phys. Rev. Lett. 136, 032302 (2026)

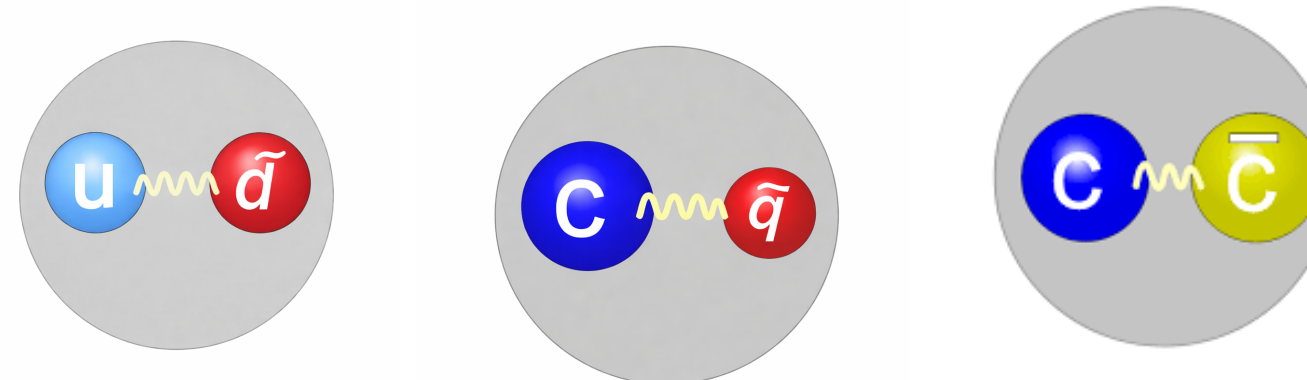
B. Schenke, et al., PRC 102, (2020) 034905

Part IV — Heavy quarks: Probing the medium

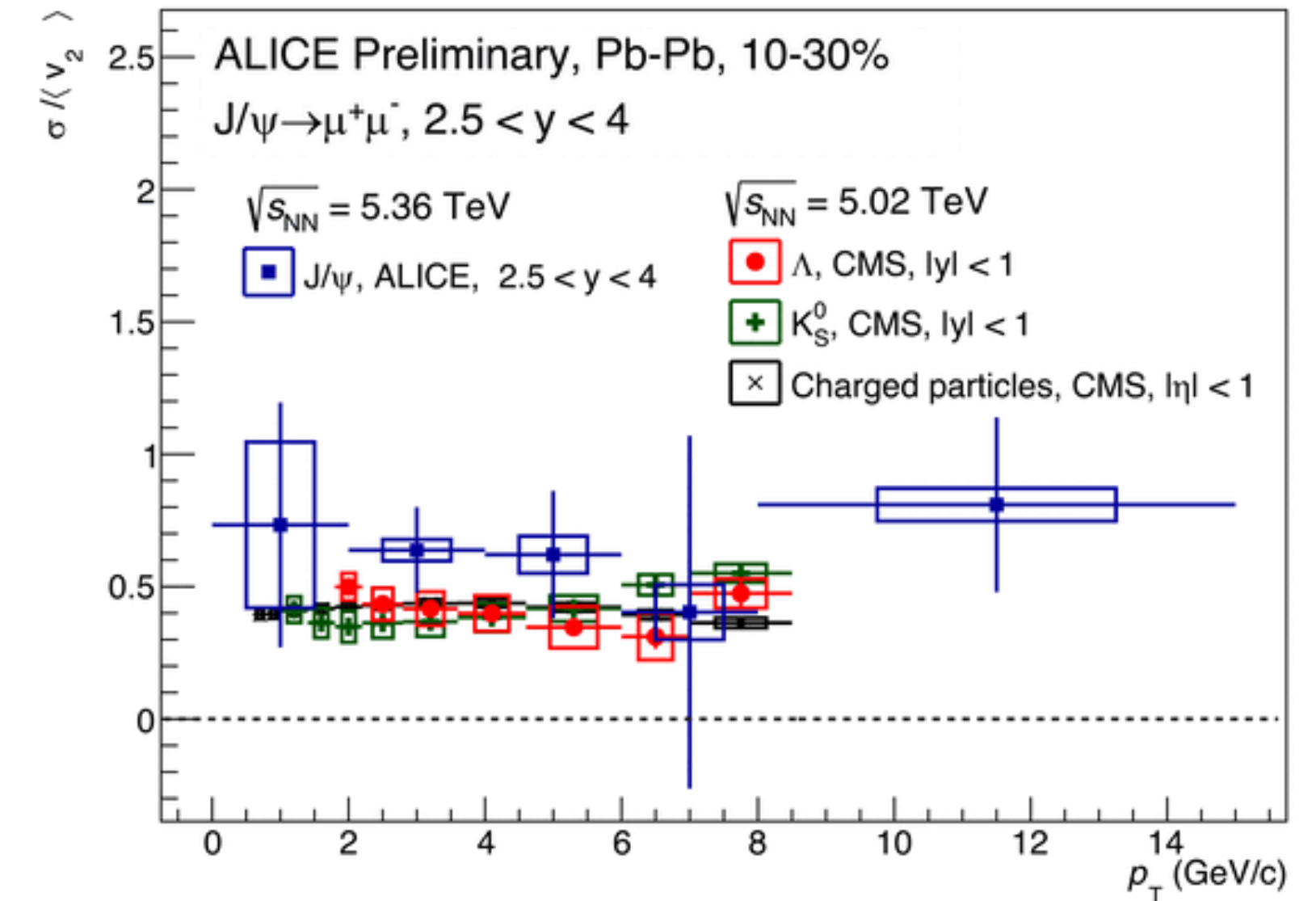


Thermalisation time scales with mass: $\tau_Q \sim m_Q D_s / T$

- ✓ Significant positive v_2 down to $p_T < 1$ GeV/c
- ✓ $v_2(D) \sim v_2(J/\psi)$, mass ordering **relative to pions at low p_T** → collective charm flow
- ✓ $v_2(D) > v_2(J/\psi)$ at **intermediate p_T** → recombination effects
- ✓ $v_2(D) \sim v_2(J/\psi)$ relative to pions **at high p_T** → path-length dependent energy loss
- ✓ Indicates strong charm-medium interaction and partial thermalisation



$$\frac{\sigma}{\langle v_2 \rangle} = \sqrt{\frac{v_2\{SP\}^2 - v_2\{4\}^2}{v_2\{SP\}^2 + v_2\{4\}^2}}$$

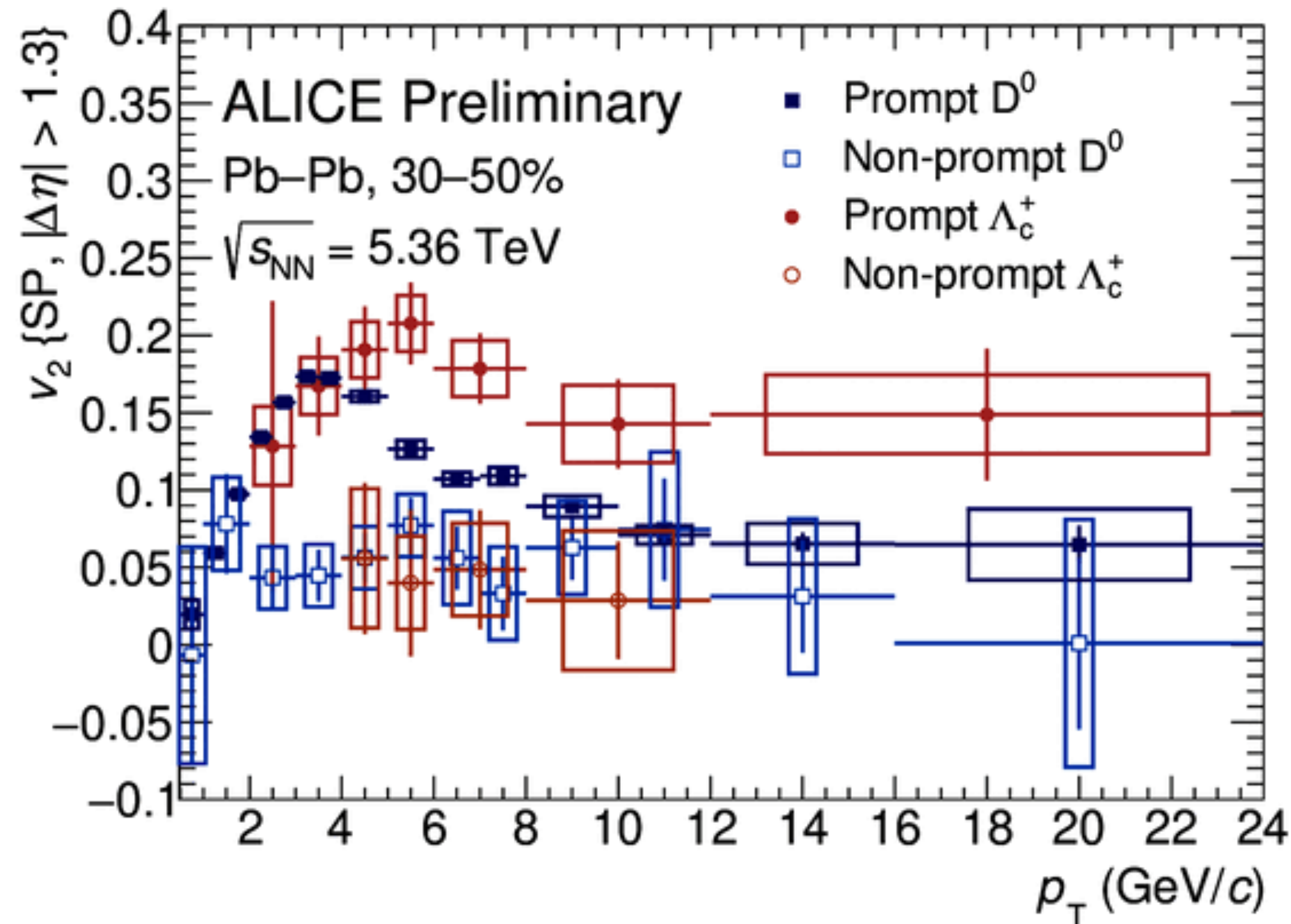


✓ First J/ψ $v_2\{2\}$ and $v_2\{4\}$ measurement at the LHC !

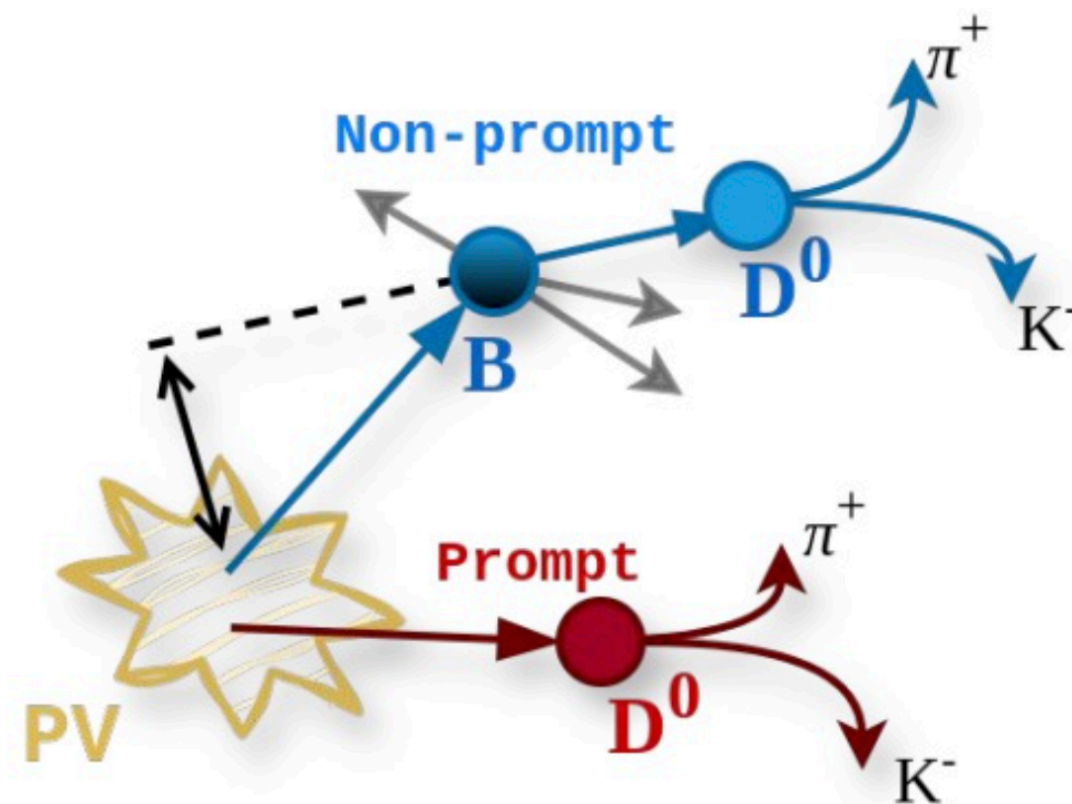
✓ $v_2(J/\psi)\{SP\} > v_2(J/\psi)\{4\}$ with $\sim 2.6\sigma$ significance

✓ Flow fluctuation ratio, $\sigma/\langle v_2 \rangle$ is currently limited by statistics,

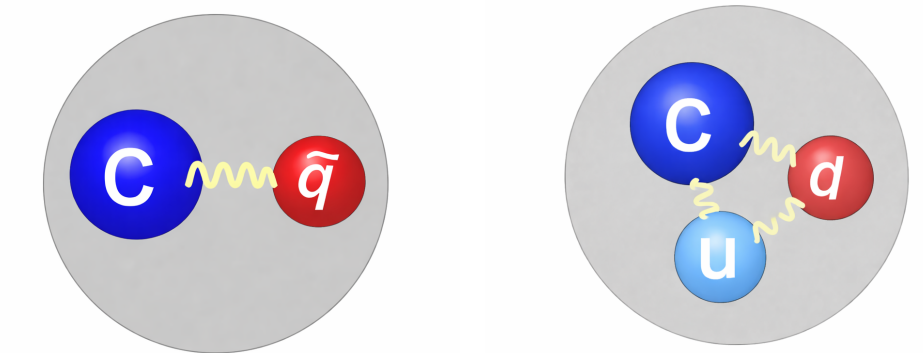
✓ Hint of no p_T dependence most likely due to variations in the initial-state geometry



ALI-PREL-596368

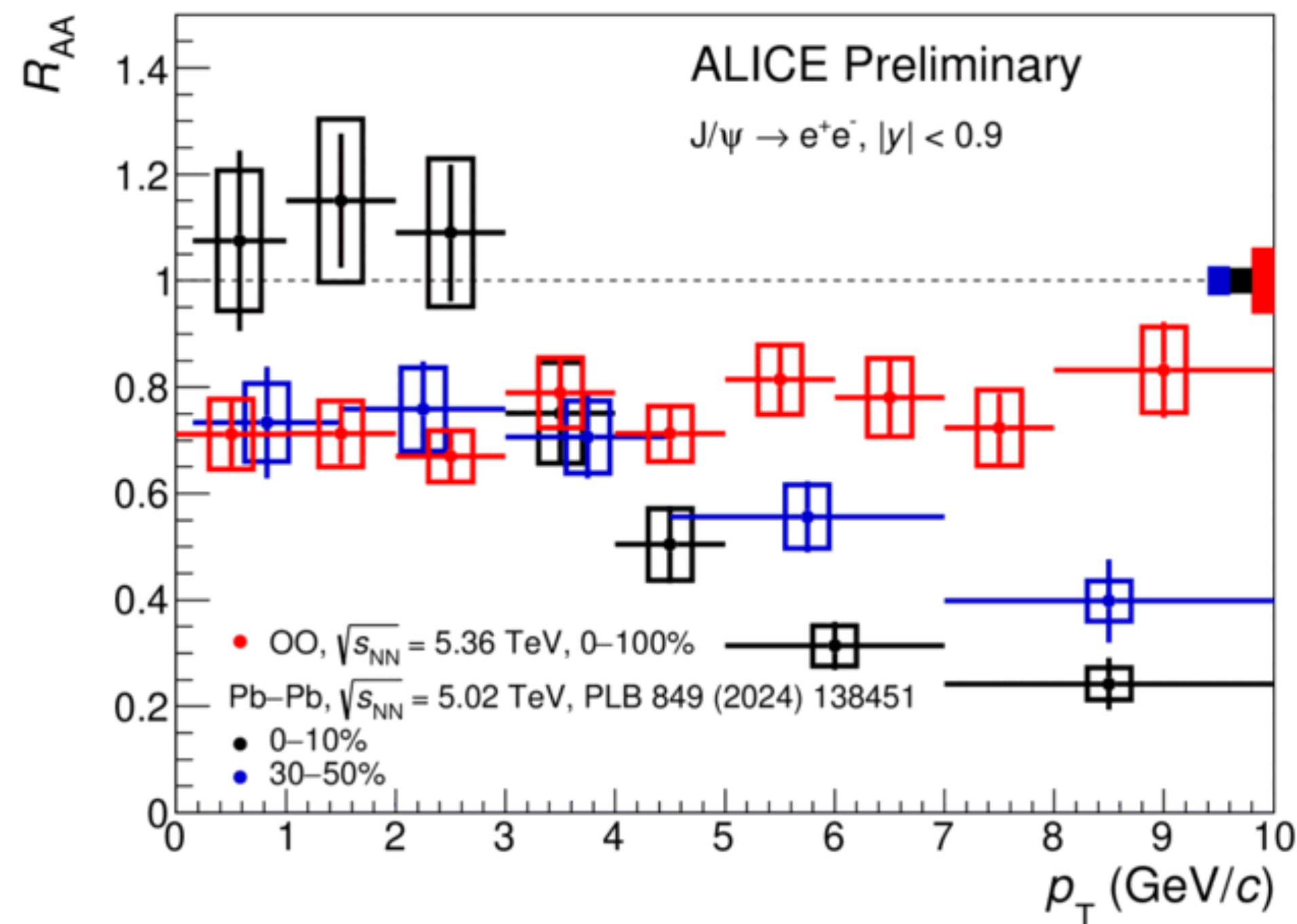


- ✓ Non-prompt $v_2(D^0)$: smaller beauty flow at $p_T < 8$ GeV/c
- ✓ Clear mass hierarchy: $v_2(b) < v_2(c)$
- ✓ Non-zero beauty v_2 at **low- p_T** indicating substantial coupling to the medium
- ✓ At **high p_T** $v_2(b \rightarrow D^0) \sim v_2(D)$ within uncertainties (energy-loss dominated regime)

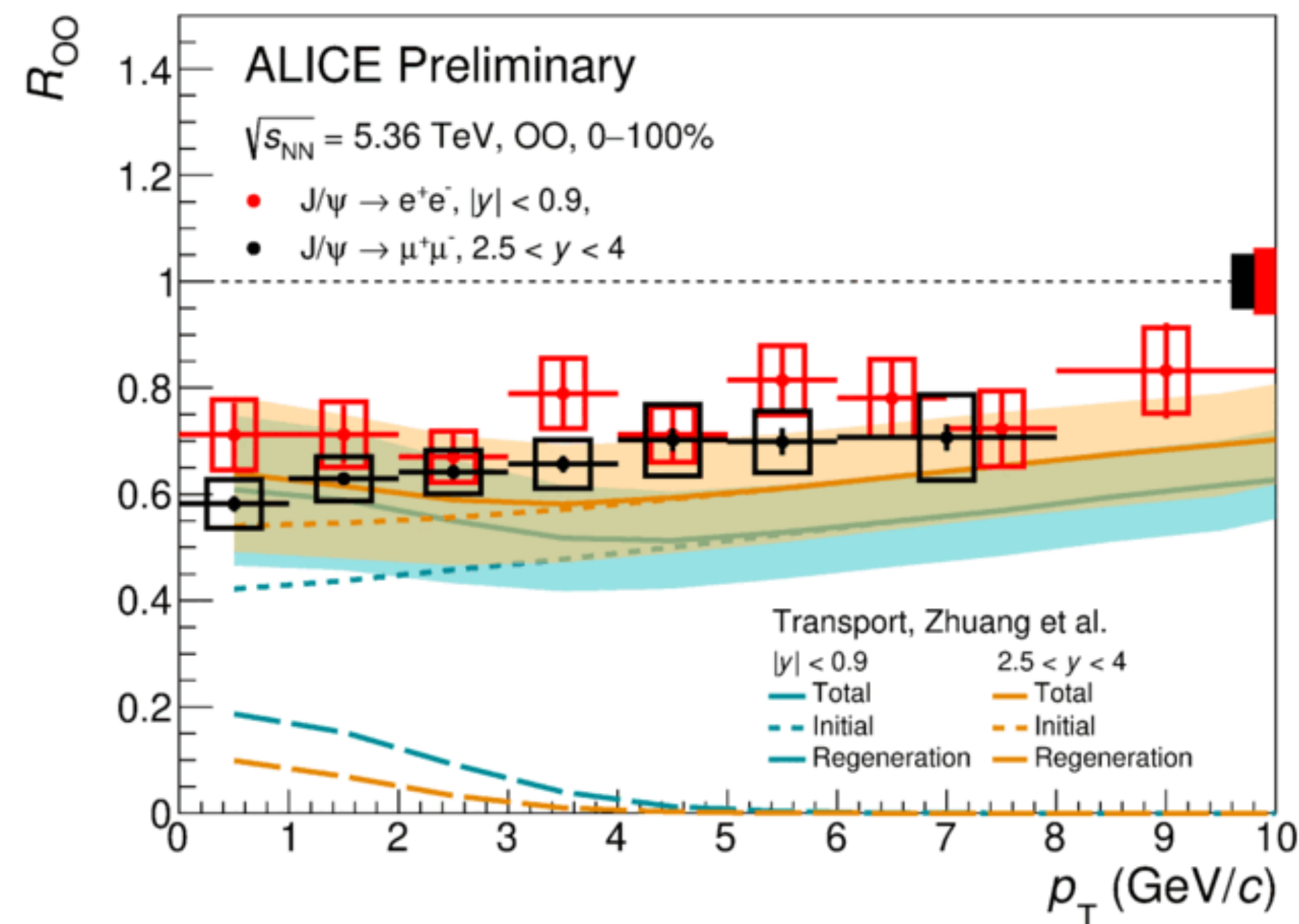


- ✓ First **charm baryon v_2** measurement in heavy-ion collisions!
- ✓ Enabled by improved Run 3 vertexing performance, high IR and continuous readout
- ✓ Low- p_T : $v_2(\Lambda_c) \sim v_2(D^0) \rightarrow$ consistent with collective charm flow
- ✓ Intermediate $p_T > 3 - 4$ GeV/c : $v_2(\Lambda_c) > v_2(D^0)$
- ✓ Evidence for recombination and mass hierarchy in heavy flavour!

Quarkonium: screening and regeneration



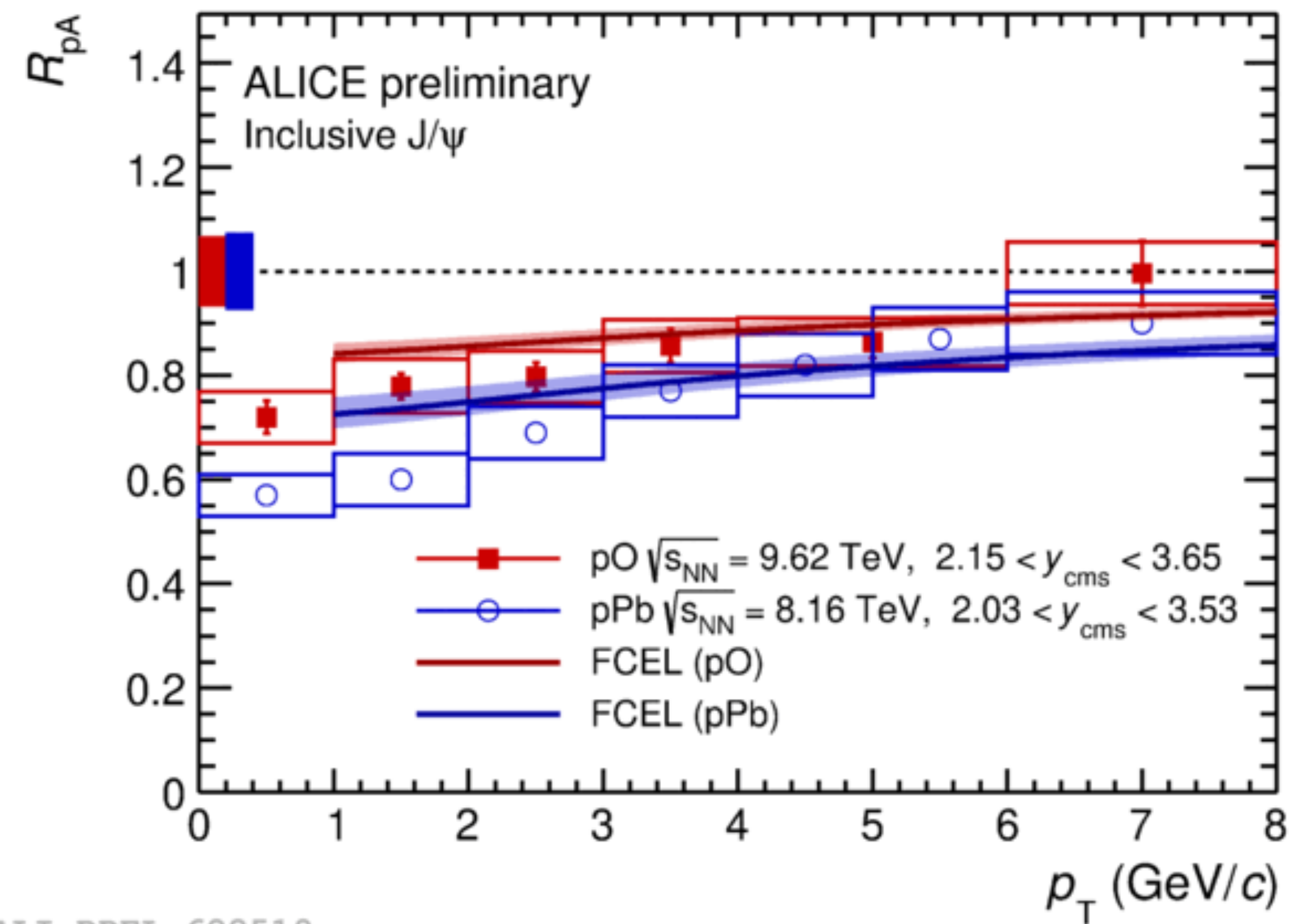
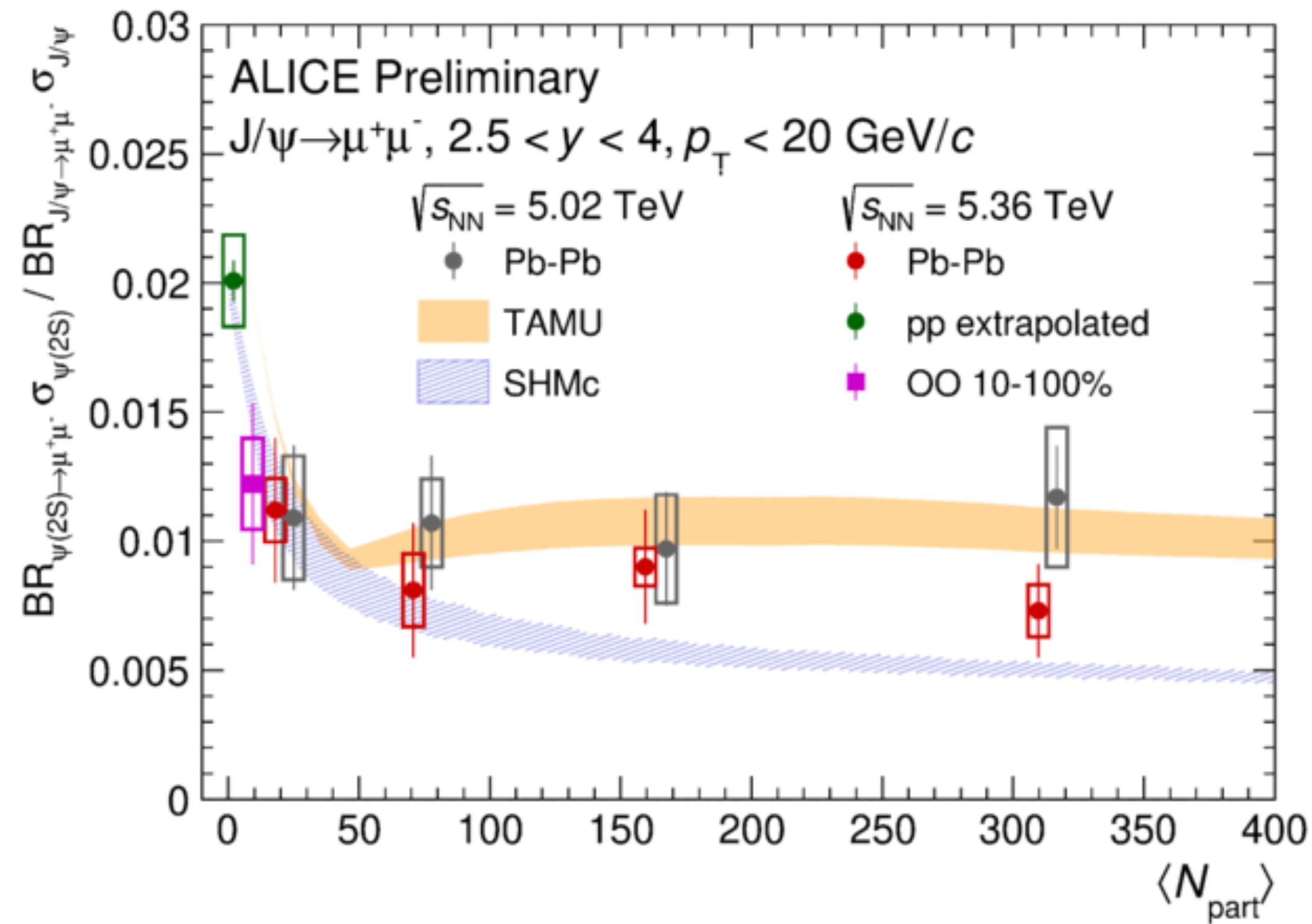
ALI-PREL-633557



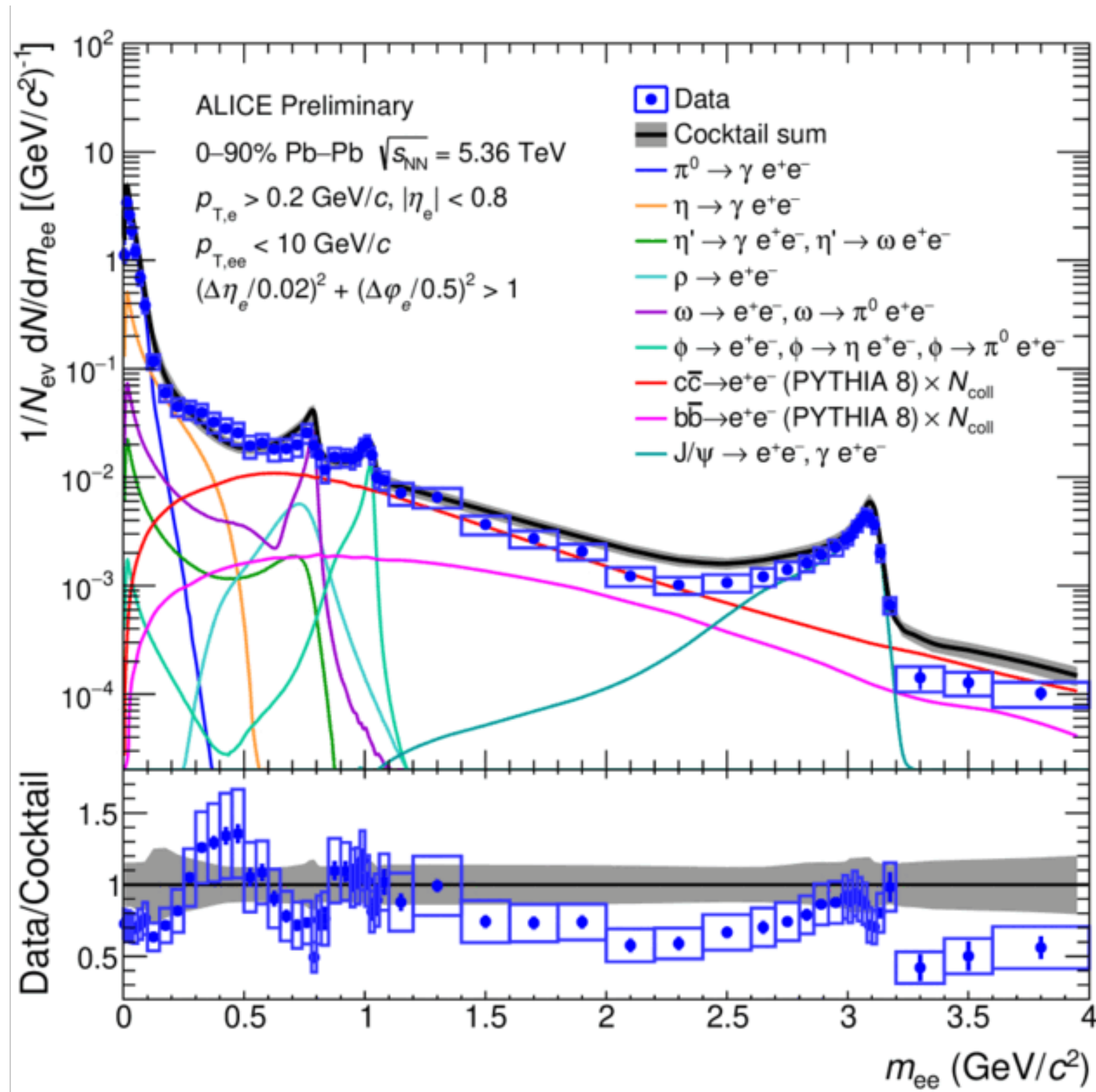
ALI-PREL-633552

- ✓ Inclusive J/ψ suppression in OO compatible with transport models
- ✓ Inclusive J/ψ suppression increases with collision centrality
- ✓ Color screening reduces quarkonium binding in hot QGP -> Strong suppression at high p_T
- ✓ Low- p_T region influenced by regeneration and photoproduction effects **Phys. Lett. B 871 (2025) 139952**
- ✓ Coherent J/ψ photoproduction also contributes to low- p_T R_{AA} enhancement present in total hadronic cross-section
- ✓ This excess is more prominent at forward rapidity **Phys. Lett. B 846 (2023) 137467**

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$



- ✓ $\psi(2S)/J/\psi$ ratio measured from pp to OO to Pb–Pb.
- ✓ Similar relative $\psi(2S)$ suppression in OO and peripheral Pb–Pb collisions.
- ✓ R_{pO} constrains cold nuclear matter effects for quarkonium production.
- ✓ Provides a bridge between pp, light ions and heavy-ion collisions.



- ✓ First statistically precise low-mass dielectron measurement at the LHC
- ✓ Run 3 precision begins to reveal the expected excess over the hadronic cocktail
- ✓ Sensitive to thermal radiation and in-medium vector-meson modifications
- ✓ Opens the precision era for electromagnetic probes with large statistics and dedicated low-field data

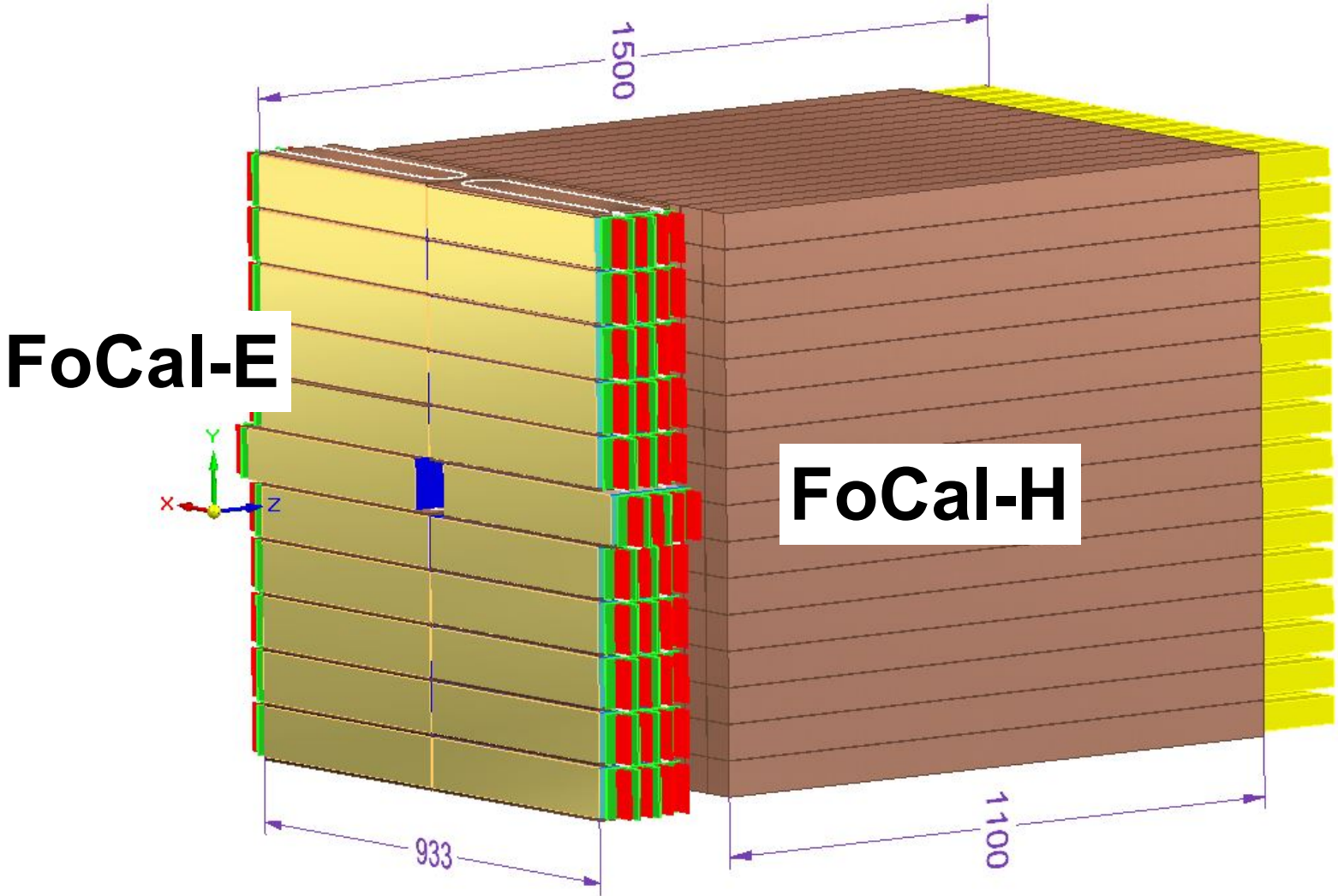
ALI-PREL-633063

Part V —Upgrades

Forward Calorimeter (FoCal) in Run 4 (2030 - 2034)



- ✓ **FoCal**: Part of ALICE upgrade for Run 4 (starting from 2029)
Positioned 7 m from IP2 (A-side), covering $3.4 < \eta < 5.8$
- ✓ FoCal-E: Direct photons and high p_T neutral π in forward direction.
- ✓ FoCal-H: Jets + photon isolation.

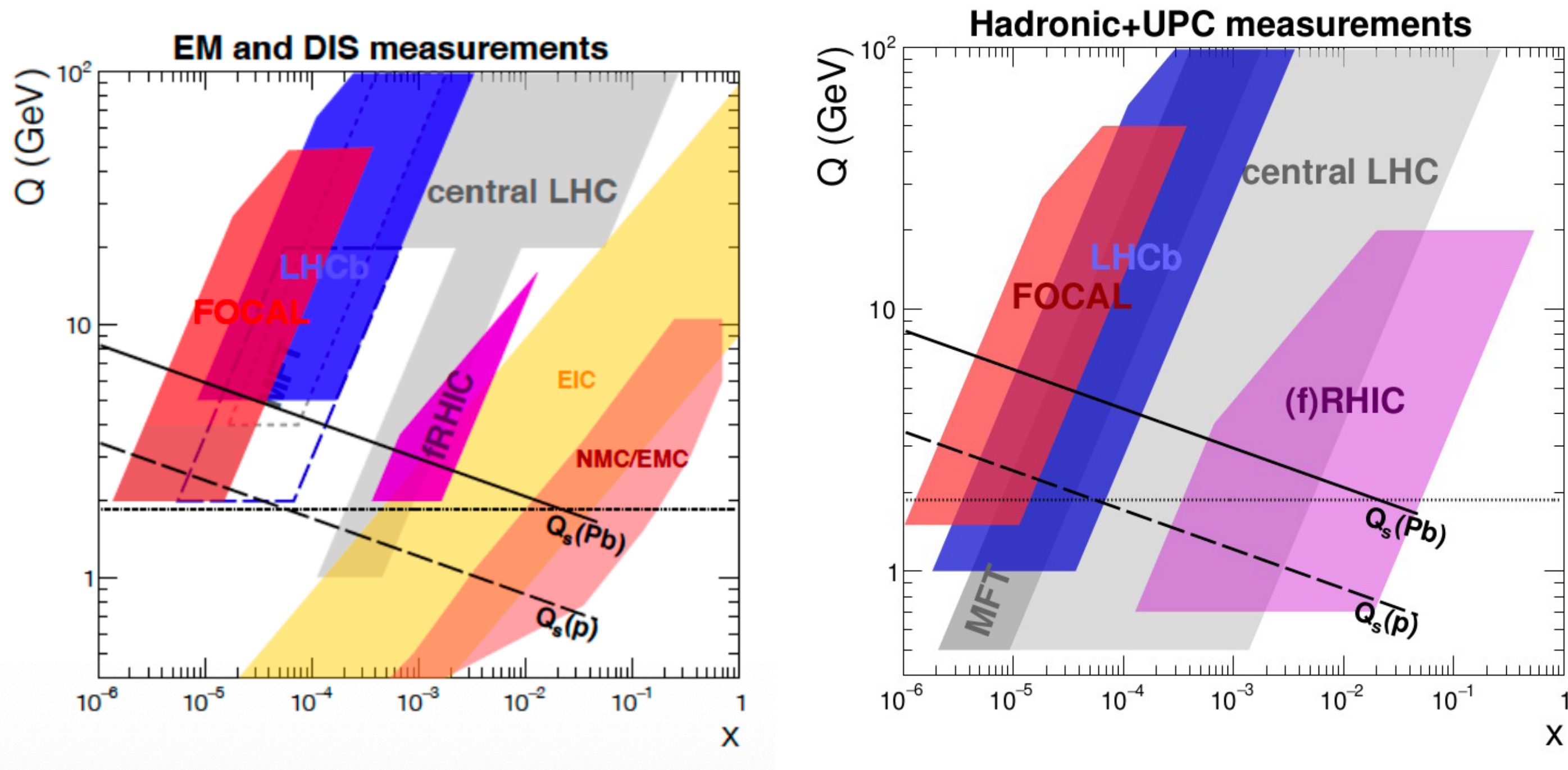


[TDR: CERN-LHCC-2024-004,
ALICE-TDR-022]

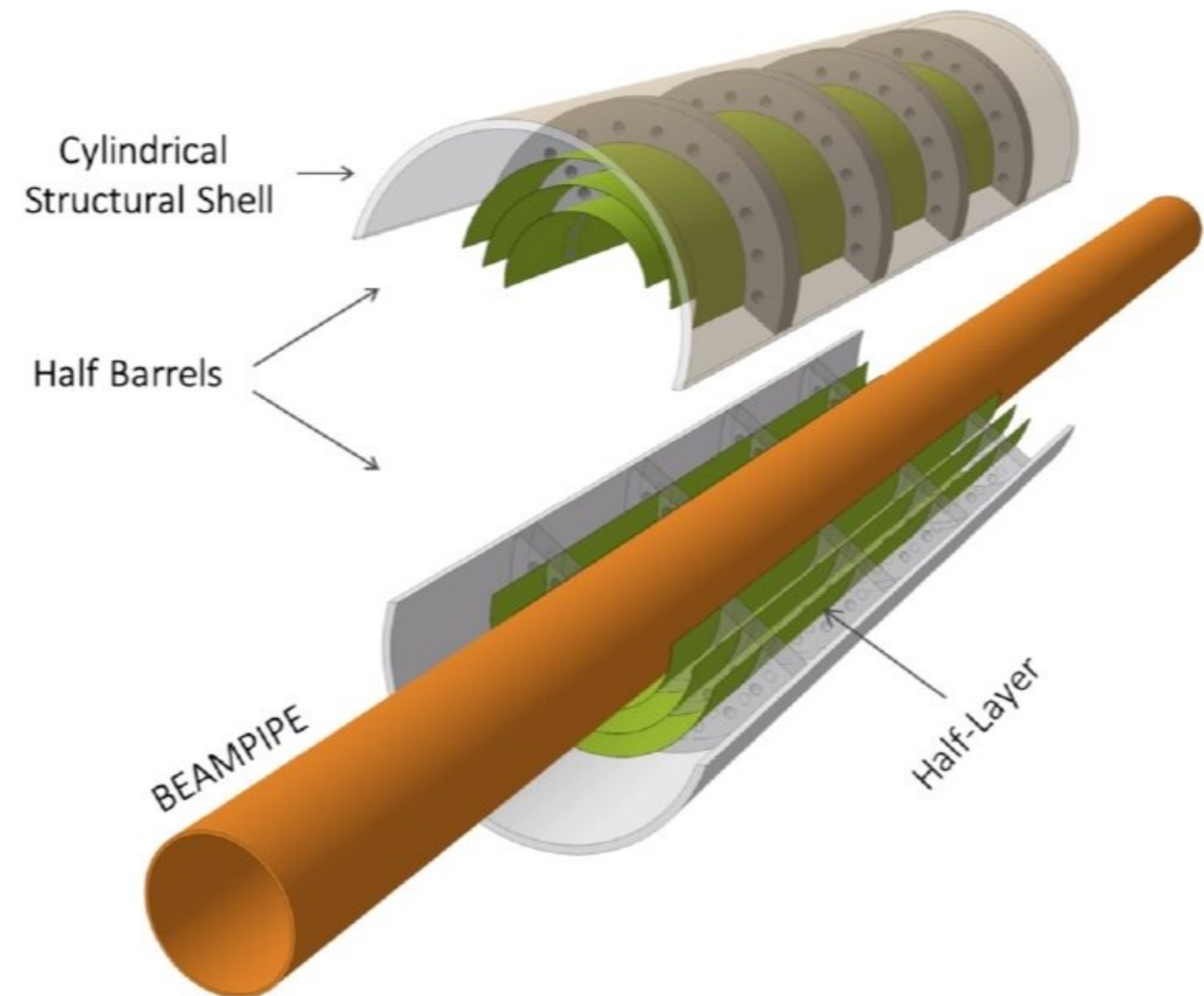
Run 4

Most wide (with MFT) forward rapidity reach at LHC!

Direct probe gluon saturation at low-x will be possible, even below 10^{-6} with ZDC



- ✓ Replacement of the three innermost ITS2 layers during LS3 (2026–2028)
- ✓ Wafer-scale, stitched monolithic pixel sensors (65 nm CMOS)
- ✓ Cylindrically bent silicon layers $\rightarrow$ truly cylindrical geometry
- ✓ Ultra-low material budget: $\sim 0.05\%$ X/X_0 per layer
- ✓ Improved tracking efficiency and impact-parameter resolution
- ✓ Extends precision measurements down to $p_T \approx 0.1$ GeV/c



ITS3 TDR: CERN-LHCC-2024-003 ;
ALICE-TDR-021



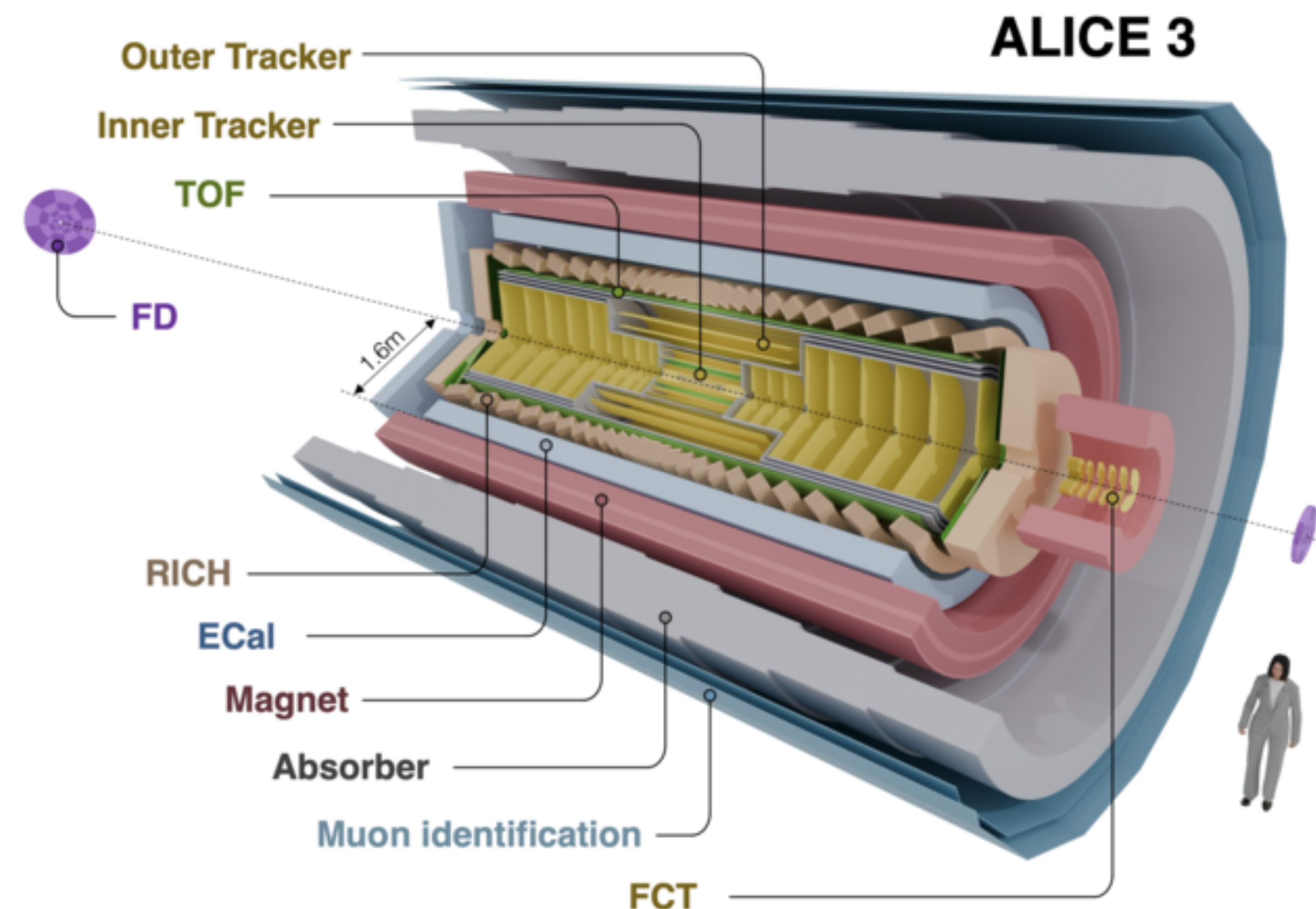
Physics Goals

- ✓ Direct measurement of QGP temperature via thermal di-electrons
- ✓ Time evolution of temperature before hadronisation
- ✓ Study chiral symmetry restoration through ρ - a_1 mixing, dileptons & photons
- ✓ Precision heavy-flavour transport (charm & beauty)
- ✓ Multi-charm baryons → test degree of thermal equilibrium
- ✓ Broader BSM searches in photon-induced processes

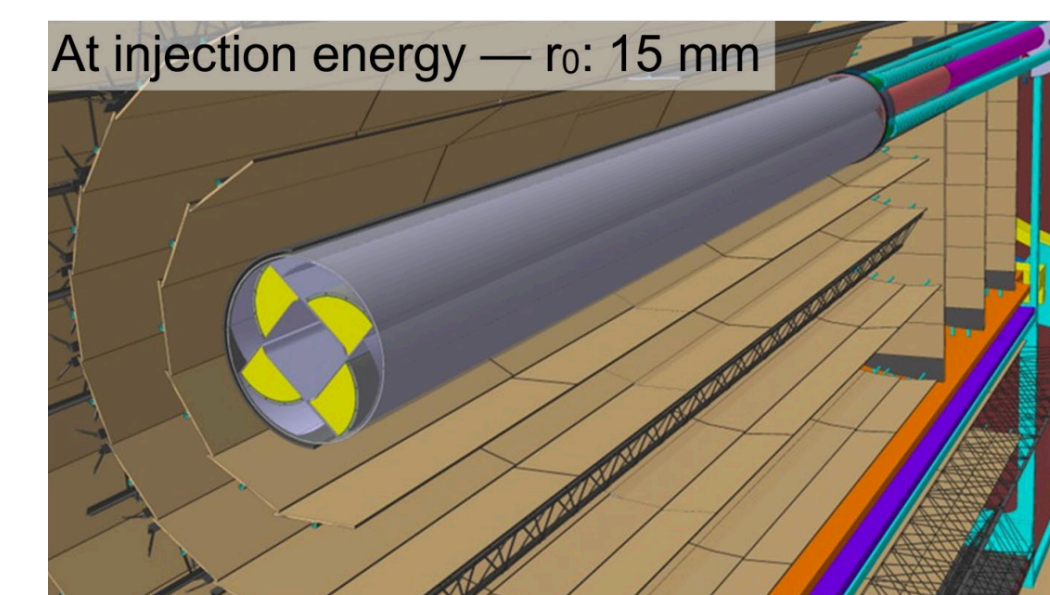
Detector Innovations

- ✓ Ultra-low material silicon vertex detector ($\sim 0.05\%$ X/X_0 per layer)
- ✓ Large-acceptance all-silicon tracker ($-2.5 < \eta < 2.5$)
- ✓ Excellent pointing resolution and particle identification

A. Khatun



Inner tracker vertex detector IRIS, inside the beam pipe !



✓ Constraining Initial-State Gluon Structure

- ✓ Hint of gluon saturation and observation of new resonance structures with UPC measurements
- ✓ Run 3 will significantly extend ALICE's reach from small-gluon dynamics

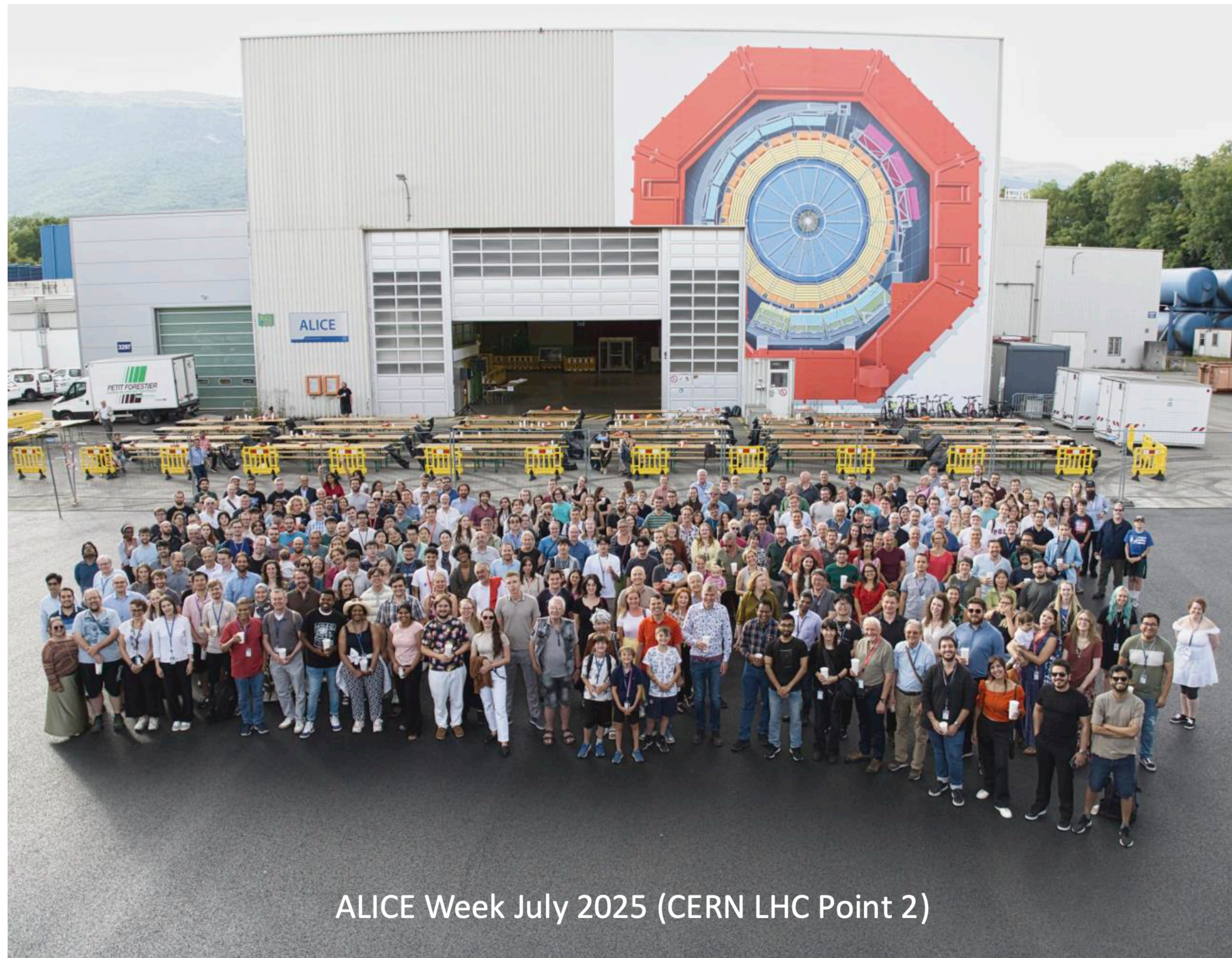
✓ The QGP as a Strongly Coupled Medium

- ✓ Light-ion collisions establish a bridge between small and large systems
- ✓ Collective flow, jet quenching and quarkonium measurements point to QGP-like behaviour in increasingly small systems
- ✓ Heavy flavour, jets and electromagnetic probes provide complementary constraints on QGP properties

✓ Toward Precision QCD

- ✓ Run 3 marks the beginning of a new precision era, including world-first charm-baryon flow measurements
- ✓ Many results are emerging: deeper constraints on QGP transport, small-system dynamics, and gluon structure
- ✓ Future upgrades, **ITS3**, **FoCal**, and **ALICE 3**, will extend ALICE into a true precision laboratory for QCD across all scales

ALICE continues its journey through QCD —> from the early universe to precision laboratory studies.



Thank you!

ALICE Week July 2025 (CERN LHC Point 2)

Back-Up

The ALICE experiment in Run 2 (2015 - 2018)

Studies at mid rapidity

$$|\eta| < 0.9$$

Central barrel : ITS+TPC+TOF

Veto : V0 and AD

$$|y| < 0.8 \rightarrow x \sim 10^{-3}$$

Studies with neutron & proton emissions at both mid & forward rapidity

Studies at forward rapidity

$$-4.0 < \eta < -2.5$$

Central barrel : MCH+MTR

Veto : V0 and AD

$$-4.0 < y < -2.5 \rightarrow x \sim 10^{-2} \text{ or } 10^{-5}$$

1. Inner Tracking System (ITS) : Tracking, triggering, vertexing

2. Time Projection Chamber (TPC) : Tracking + PID

3. Time-Of-Flight (TOF) : Triggering + PID

4. V0 : Triggering and vetoing

5. T0 : Triggering

6. Muon Tracker (MCH) : Tracking

7. Muon Trigger (MTR) : Triggering

8. ALICE Diffractive (AD) : vetoing

9. Zero Degree Calorimeter (ZDC) : vetoing, EMD

10. Electromagnetic Calorimeter (EMCal) : photons, electron, neutral pions

