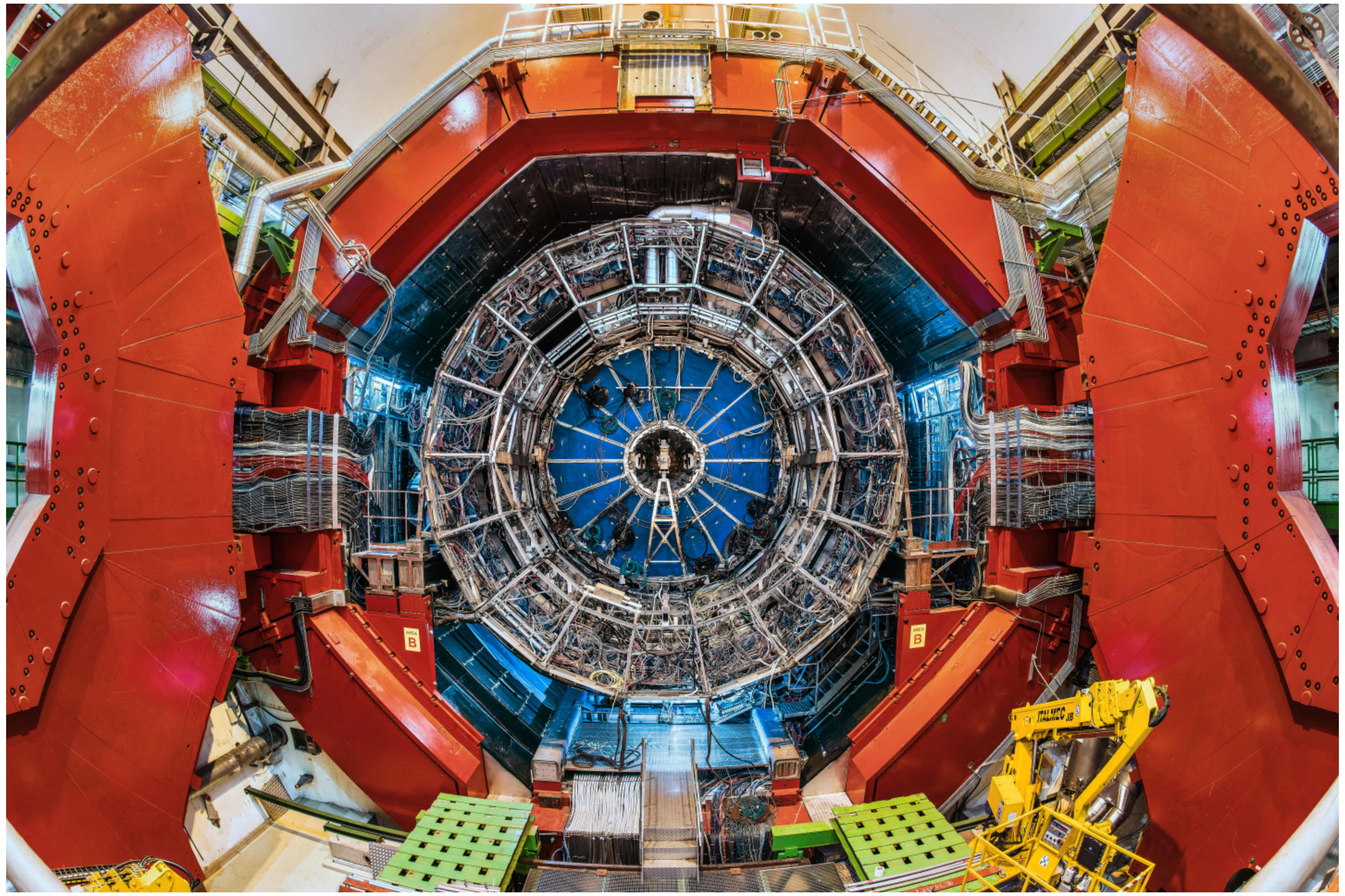
ALICE

Highlights from ALICE

Marco van Leeuwen,
Nikhef and CERN

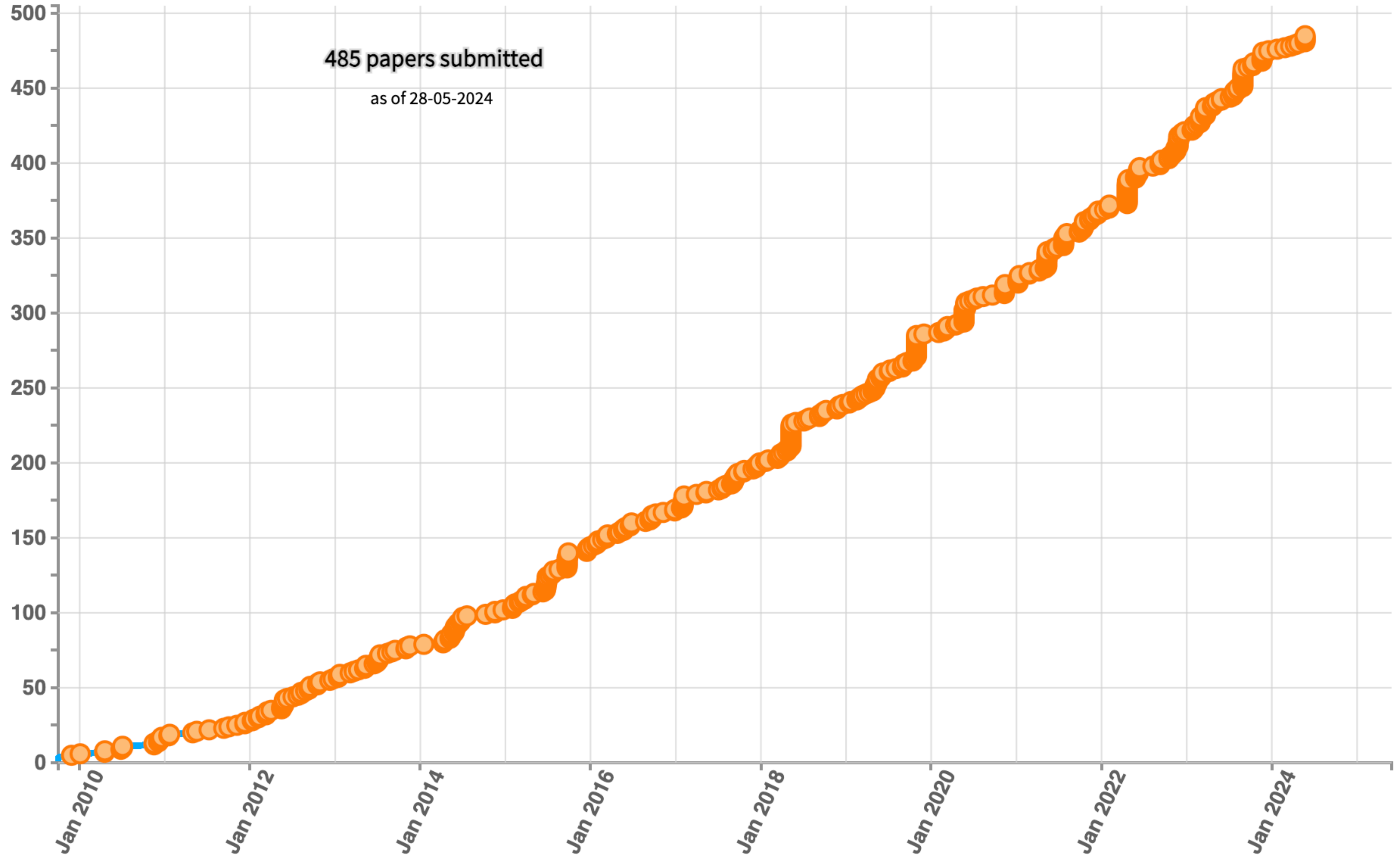


CERN - Ukraine 2024: "Past - Present – Future"
Kyiv Ukraine
May 28-29, 2024

The ALICE collaboration

ALICE Week, March 2024

ALICE publications over the years



ALICE collaboration:

- 1069 authors
- 157 institutes, 19 associate institutes
- 40 countries

New results in preparation for

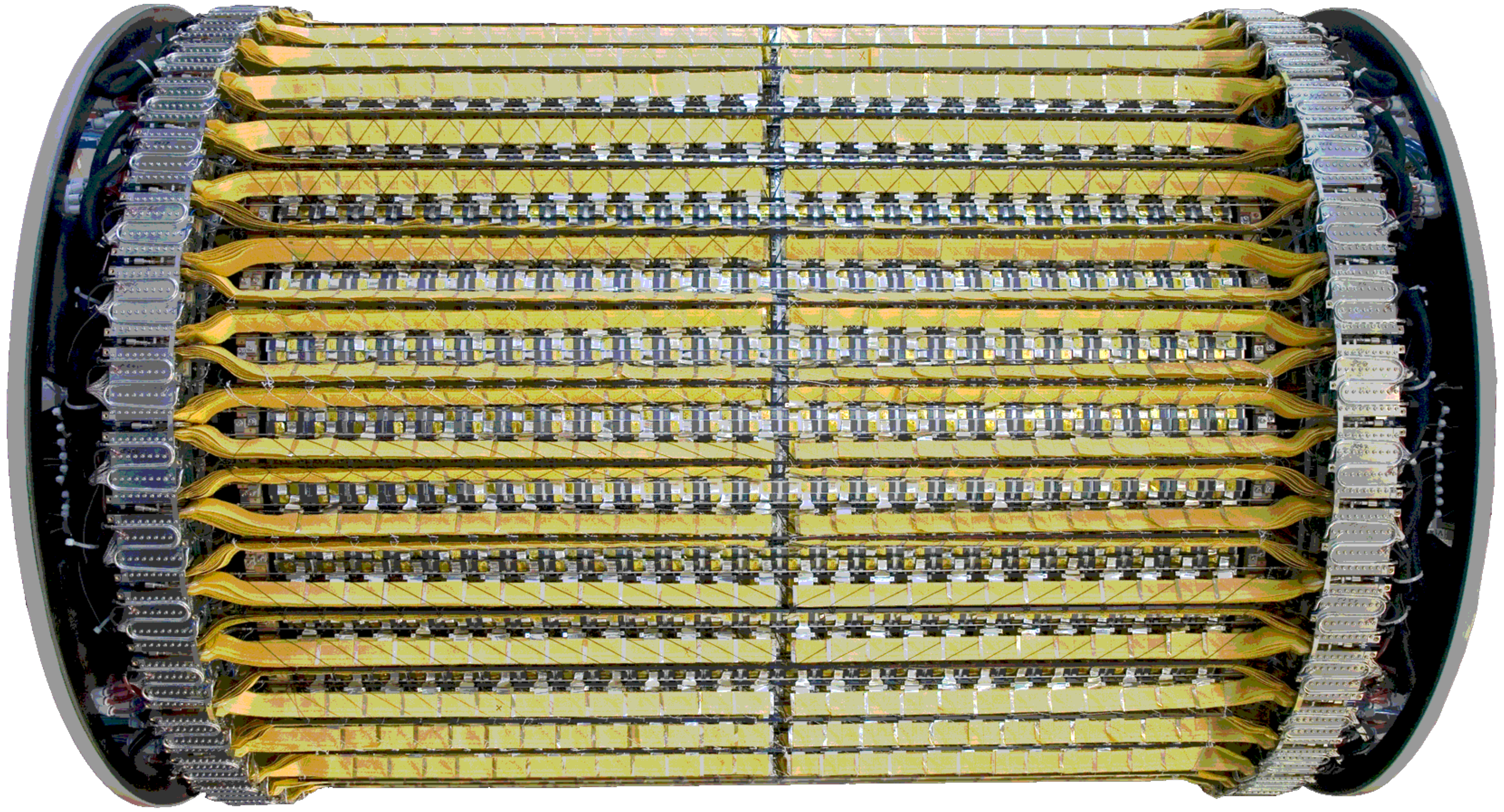
SQM 2024 — The 21st International Conference on Strangeness in Quark Matter, 3-7 June 2024, Strasbourg, France

LHCP Boston 2024

ICHEP 2024 PRAGUE — 42nd International Conference on High Energy Physics, 18-24 July 2024, Prague, Czech Republic

Evolution of the Inner Tracking system: ITS1

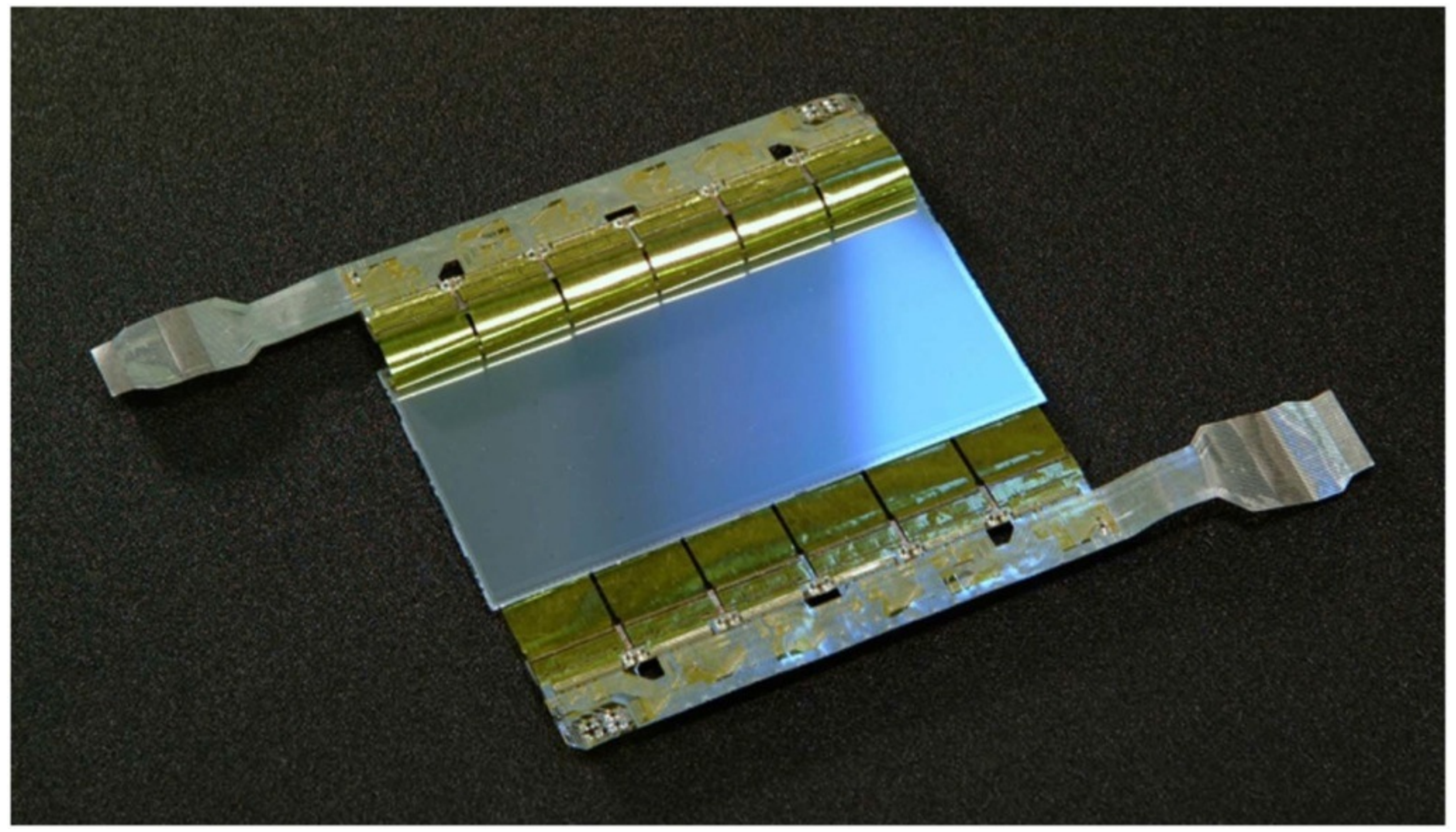
The completed detector with the teams from Ukraine and Netherlands



Original ITS: 3 technologies
- 2 silicon (hybrid) pixel detector layers
- 2 silicon drift detector layers
- 2 silicon strip detector layers

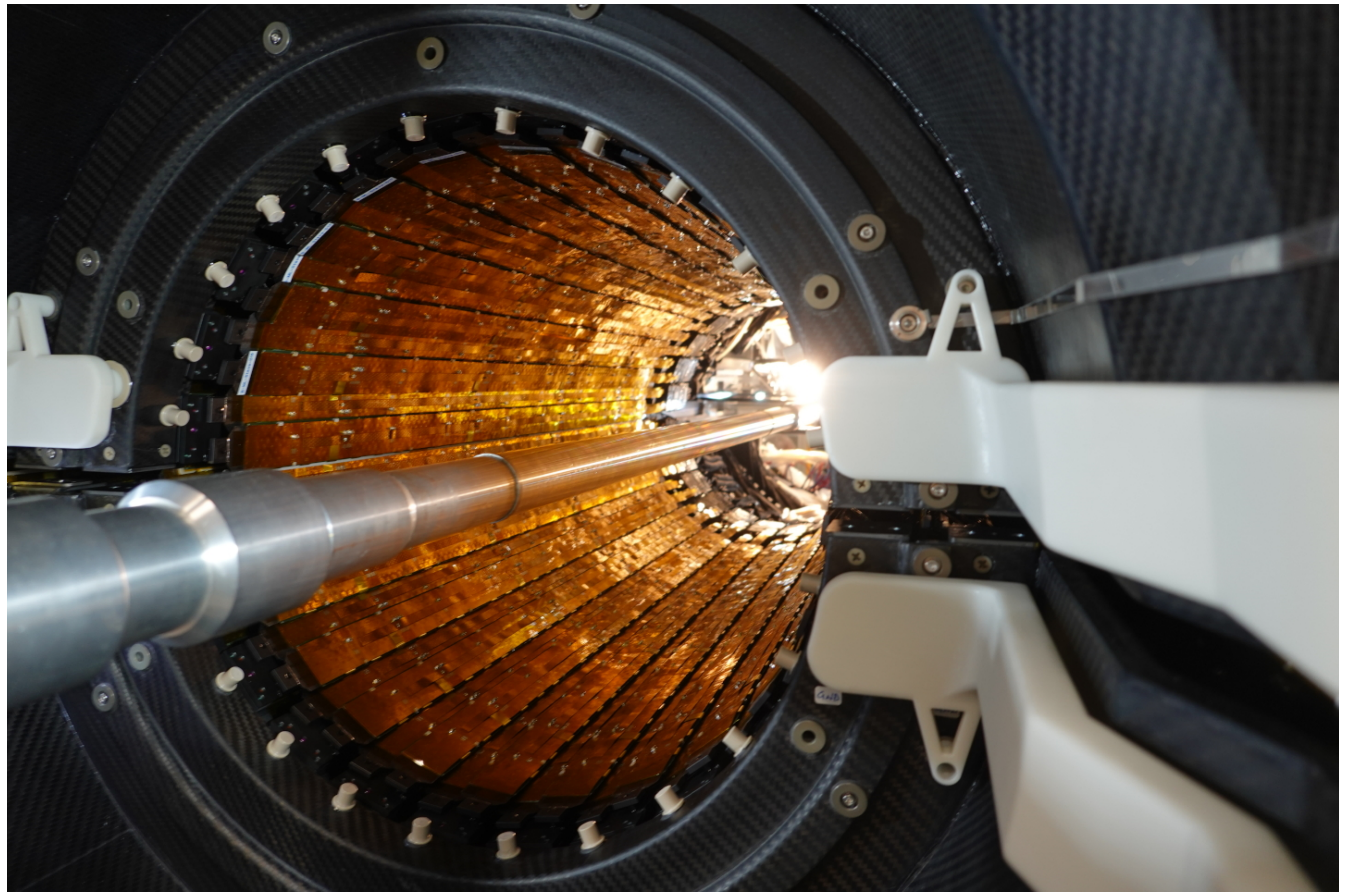
Installed in 2007

Silicon strip sensor module

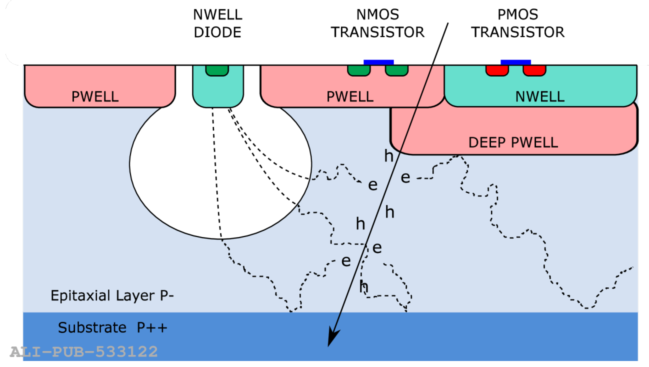


ITS2 and ITS3

ITS2: installed in 2021



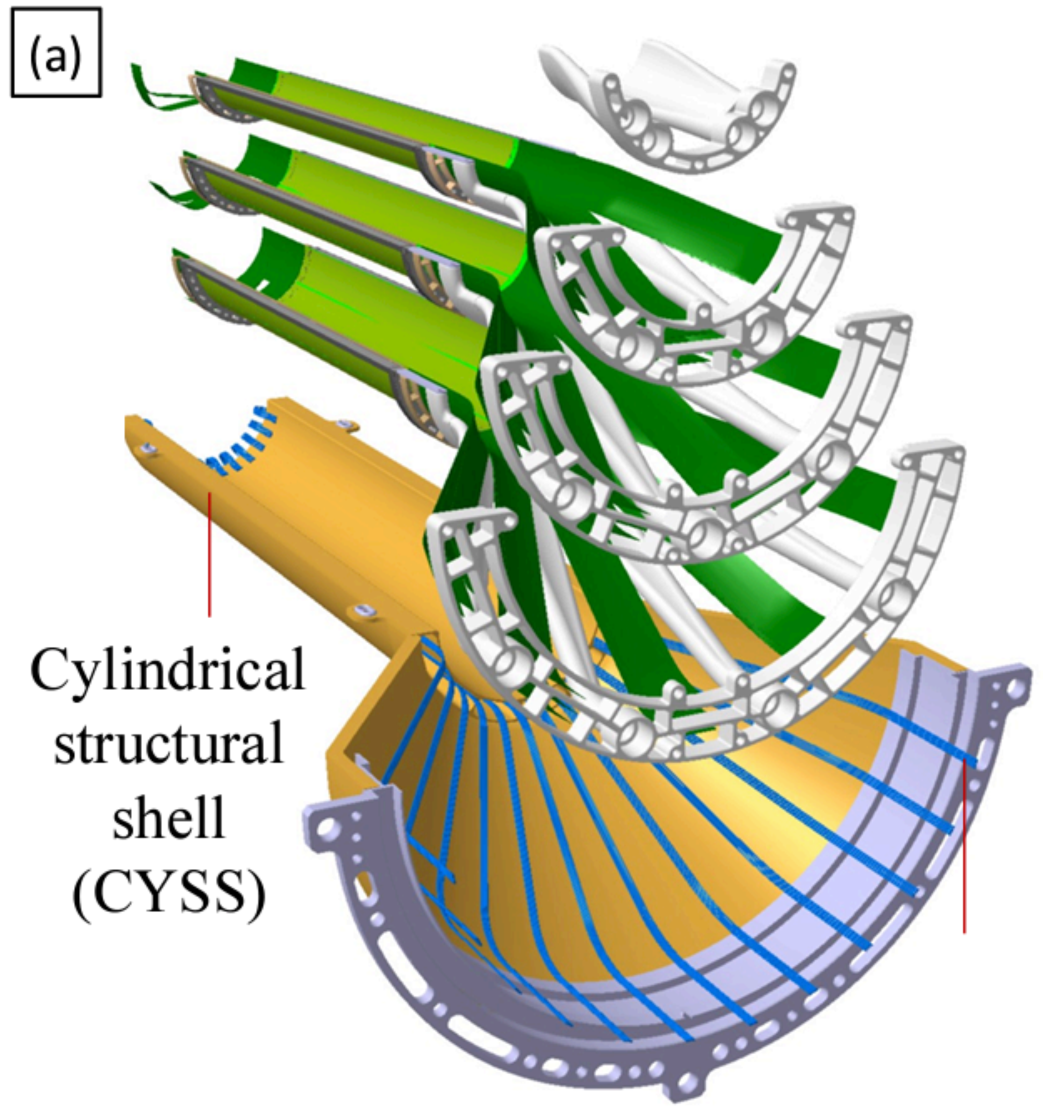
Completely new system:
7 layers of monolithic active pixels



ALPIDE pixel sensors developed by/for ALICE

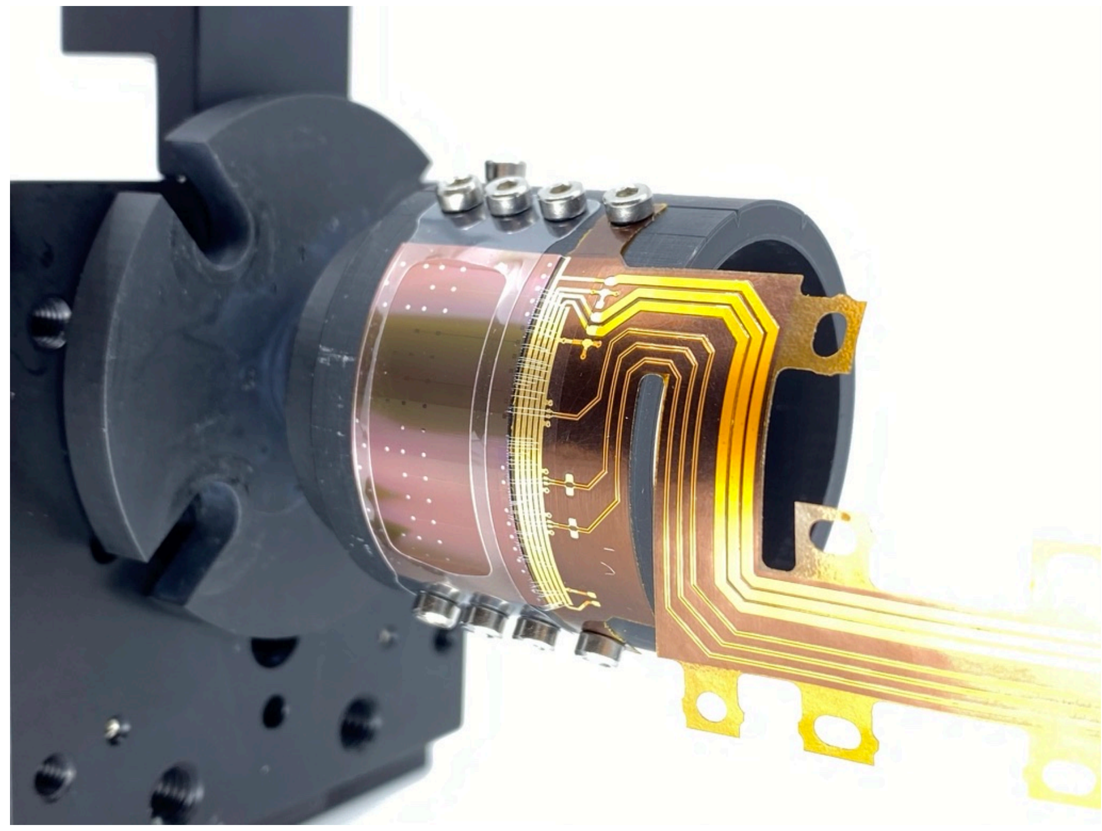
Power bus cables produced in Ukraine

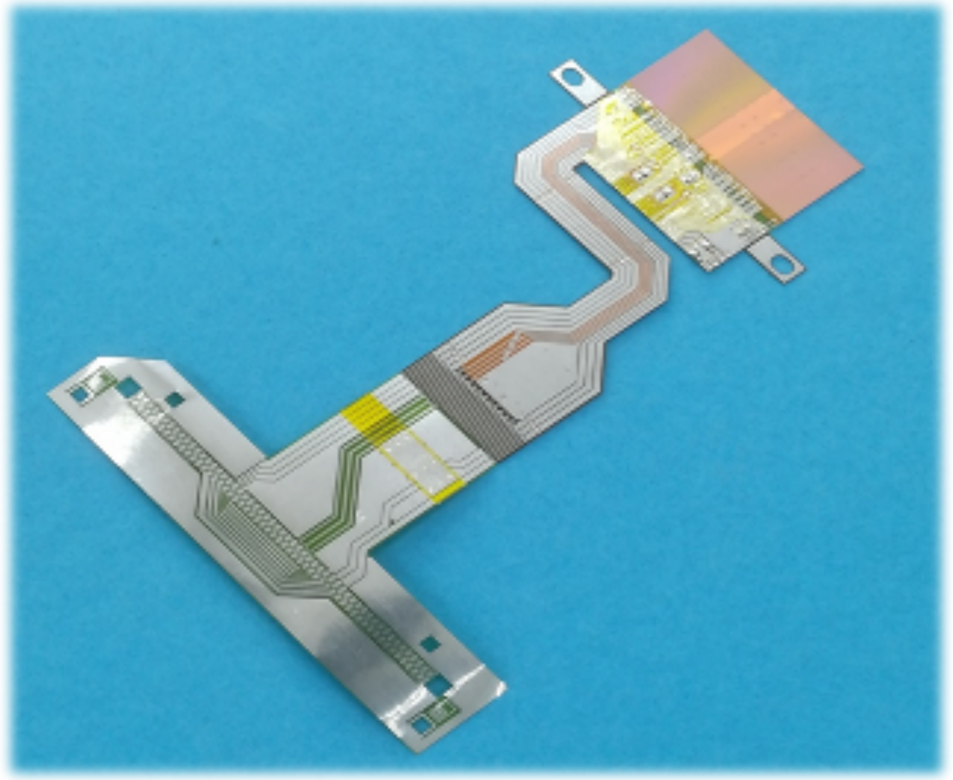
ITS3 upgrade under development



Replace inner layers by
ultra-thin, large-area, curved sensors
to improve pointing resolution

Curved sensor prototypes

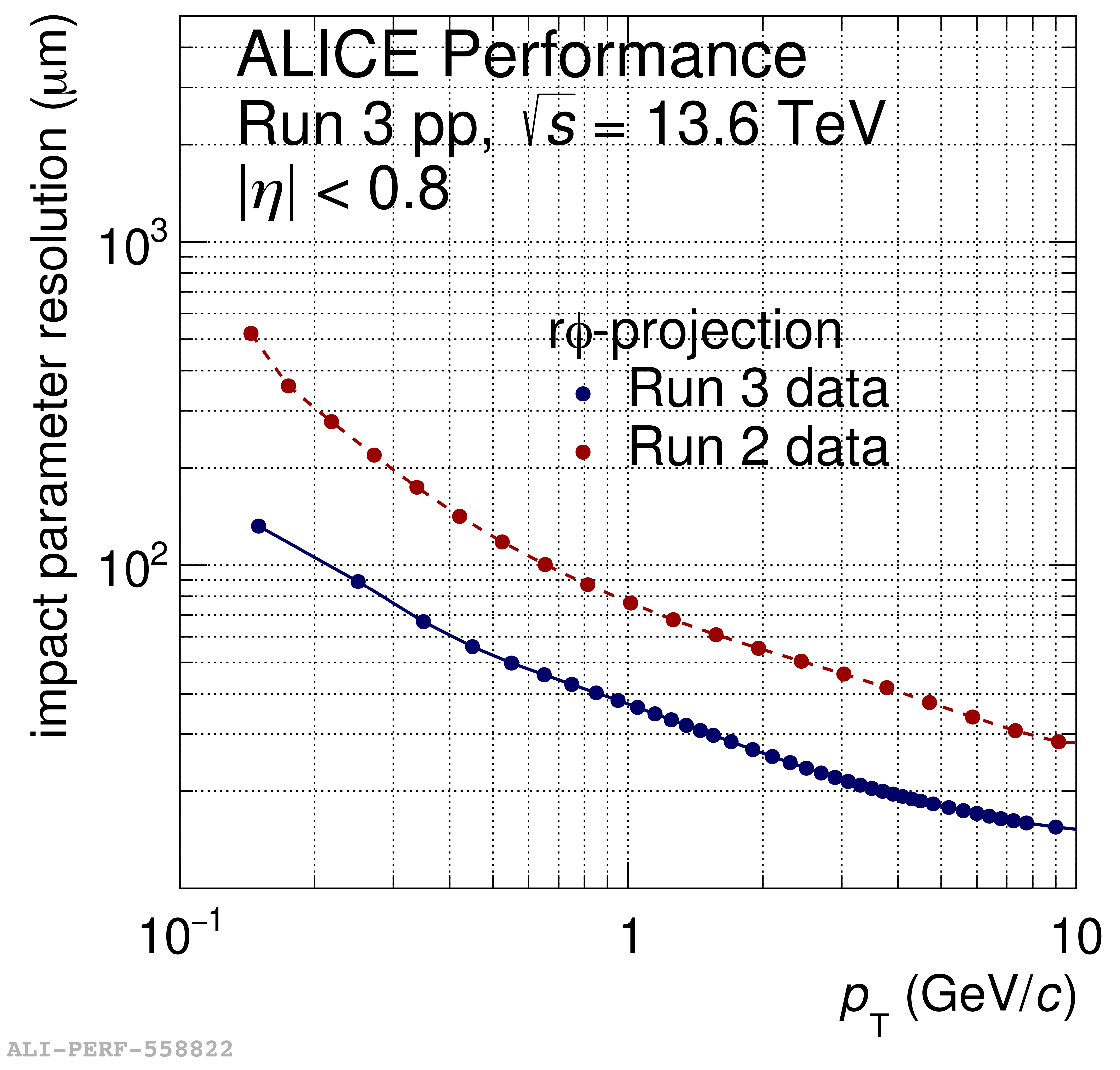




TDR approved — design of final sensor in progress

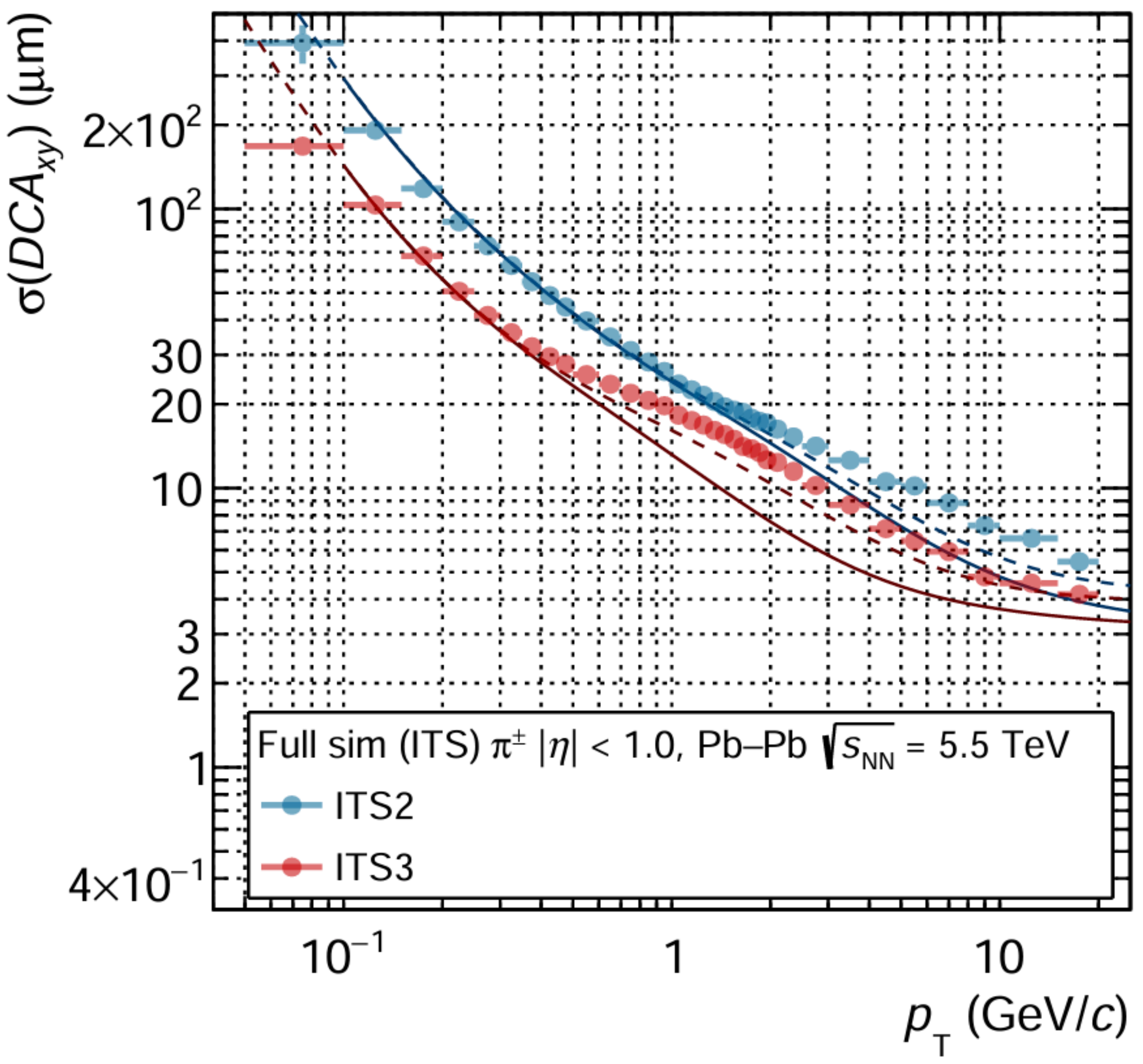
Inner tracking system performance: pointing resolution

Impact parameter resolution: ITS and ITS2



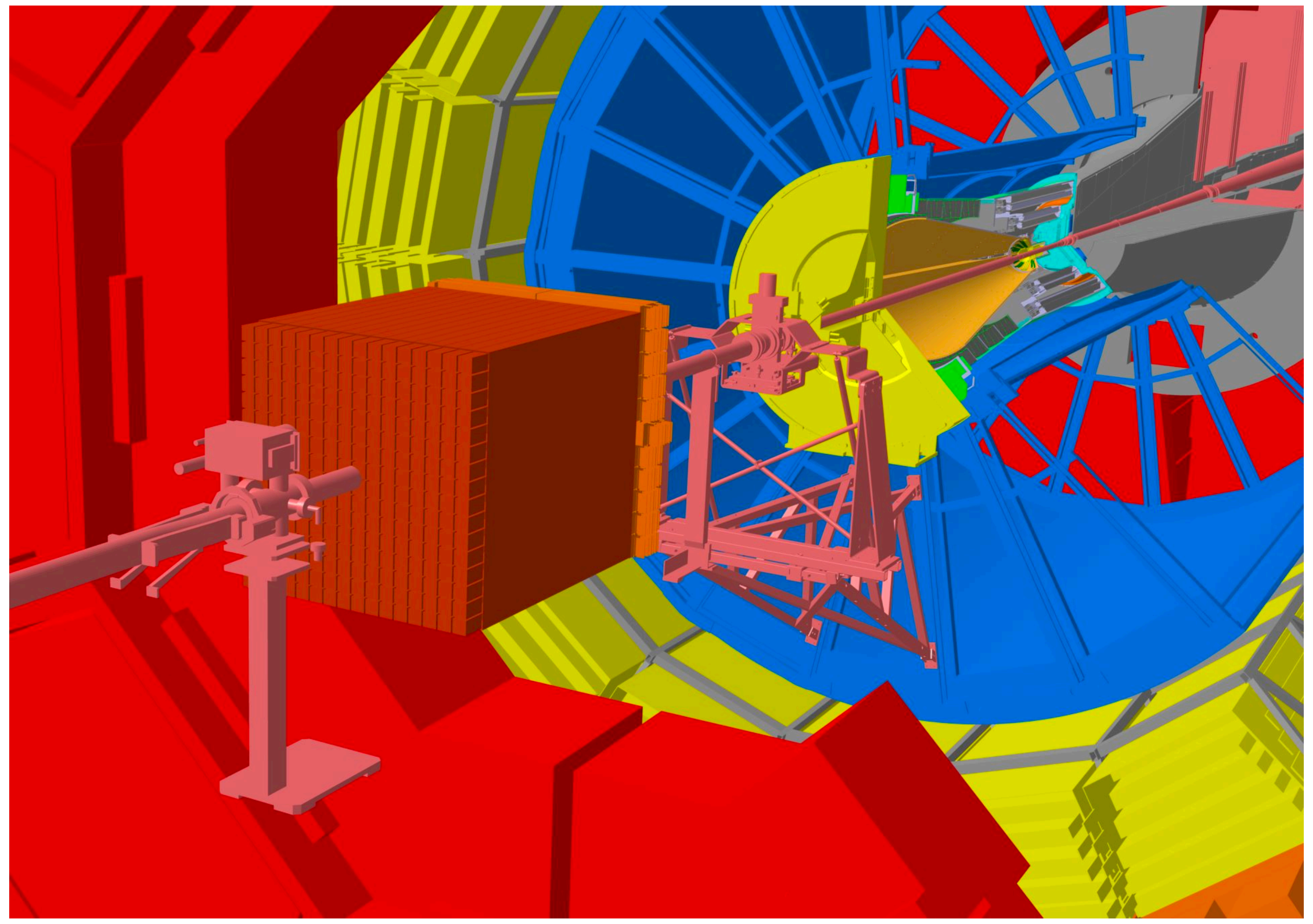
Impact parameter resolution improved by a factor 2-3
Final alignment will bring further improvement

ITS2 and ITS3

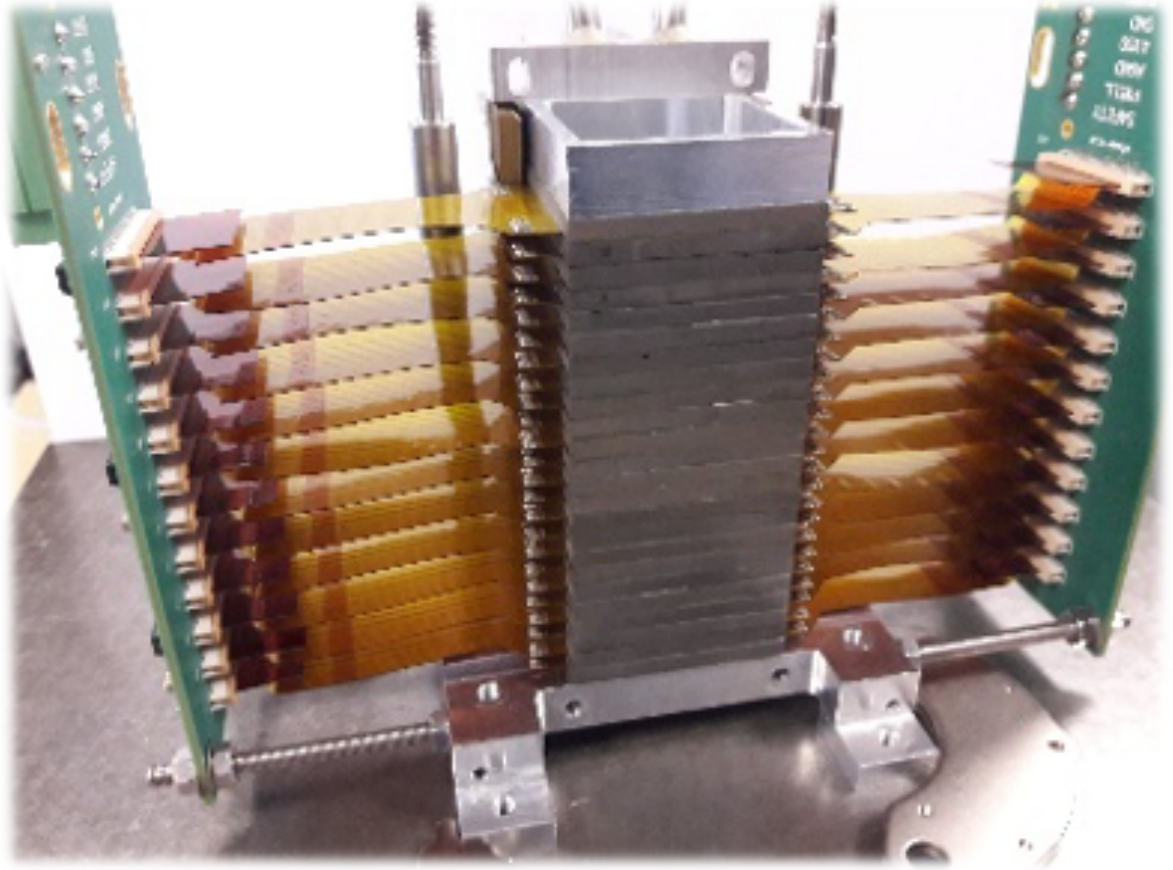


ITS3 provides additional
factor ~2 improvement at low p_T

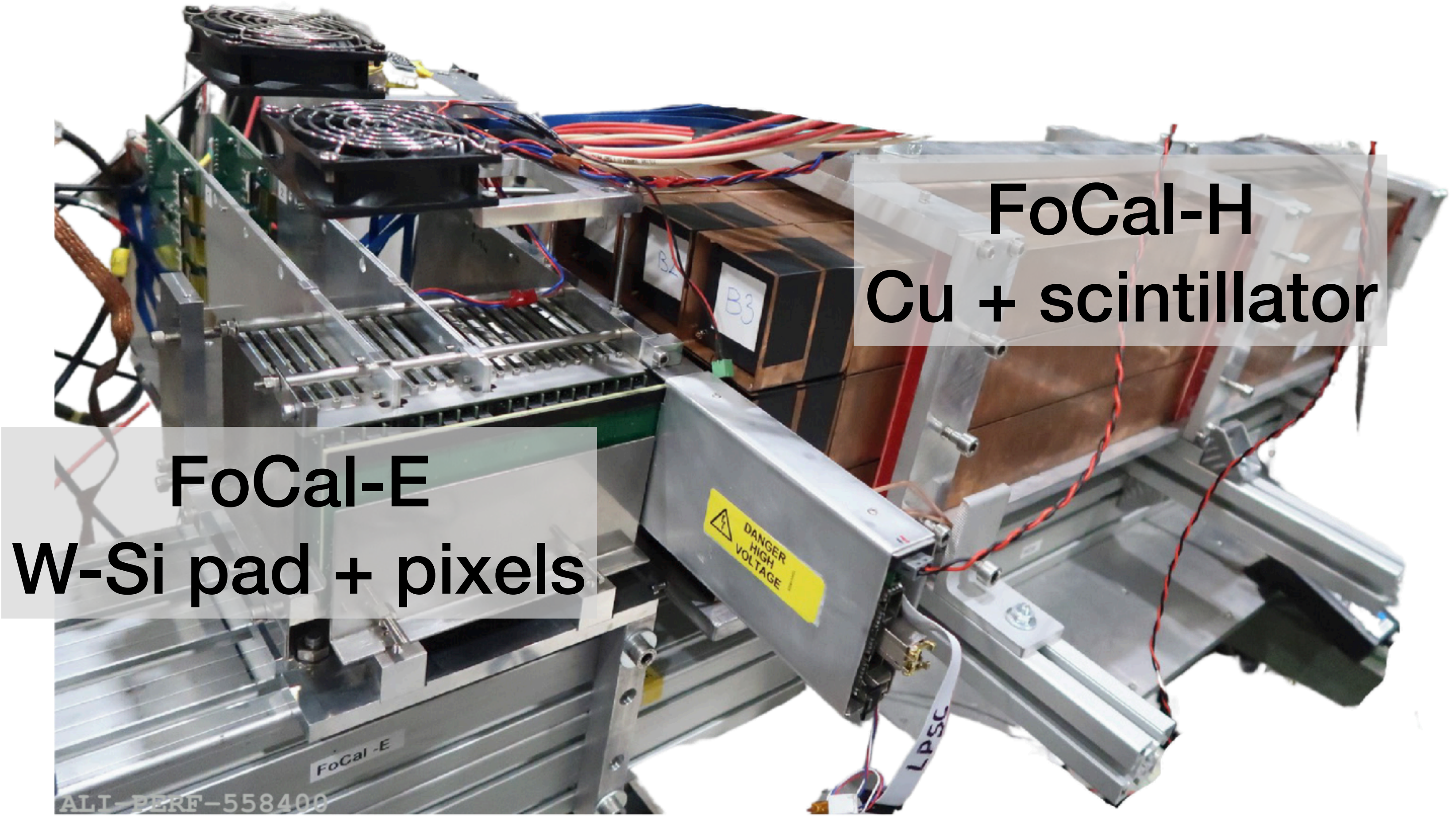
LS3 upgrades: FoCal



EPICAL: a Si-W pixel calorimeter



J Alme et al, JINST 18, 01, P01038



Aehle et al, arXiv:2311.07413

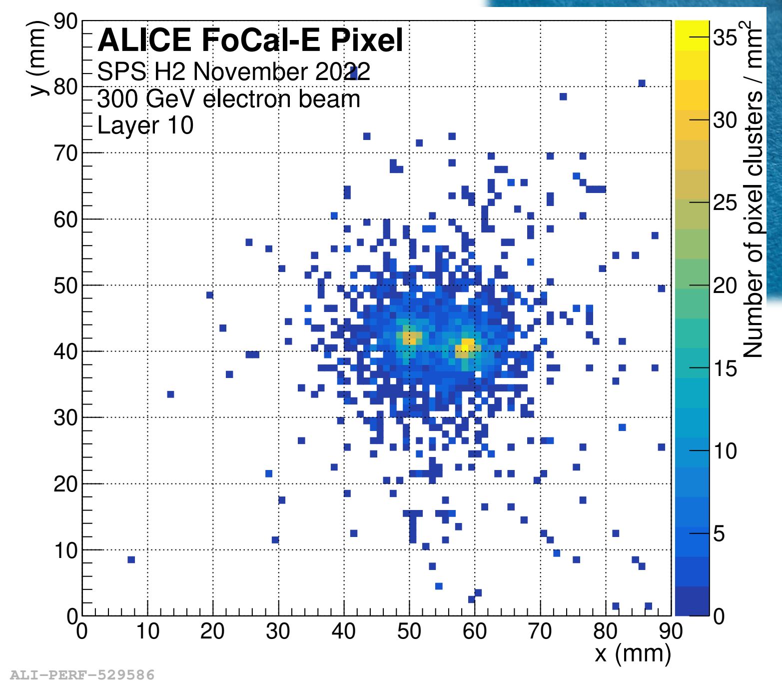
Forward Calorimeter upgrade: 3.4 < η < 5.8

- High-granularity Si-W electromagnetic calorimeter
- Hadron calorimeter: Cu-scintillator

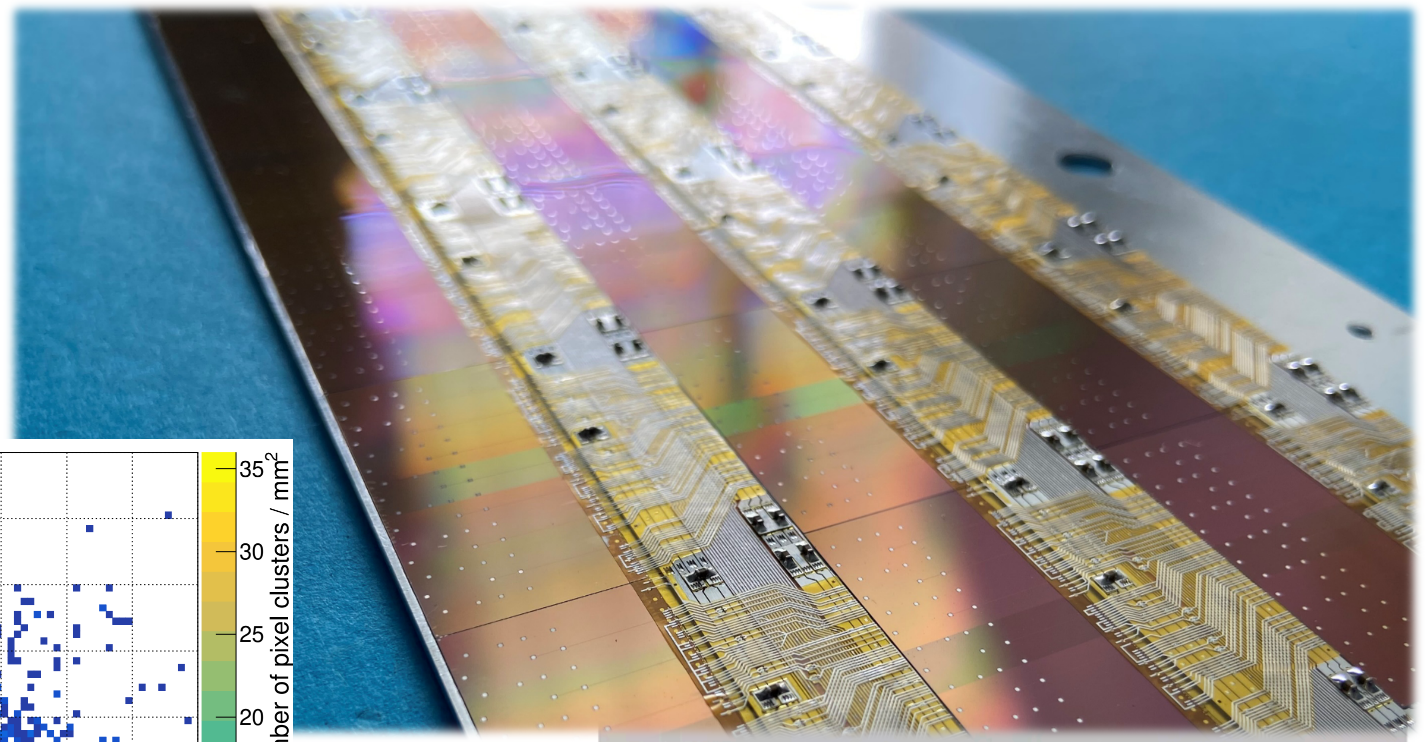
- Goal: *determine small-x gluon density in the nucleus* by measuring forward production of isolated direct photons, π^0, jets …

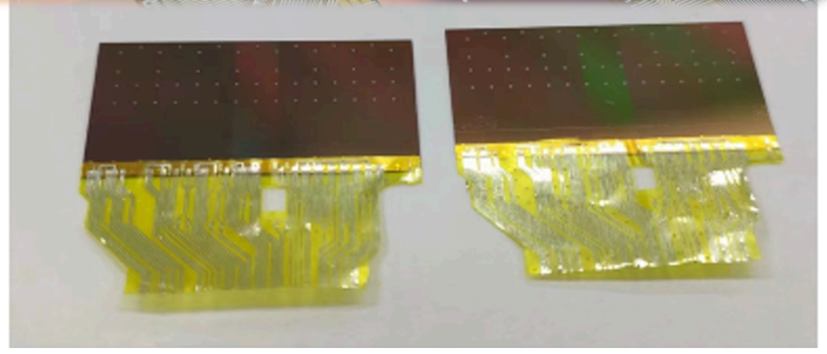
TDR approved — moving towards mass production

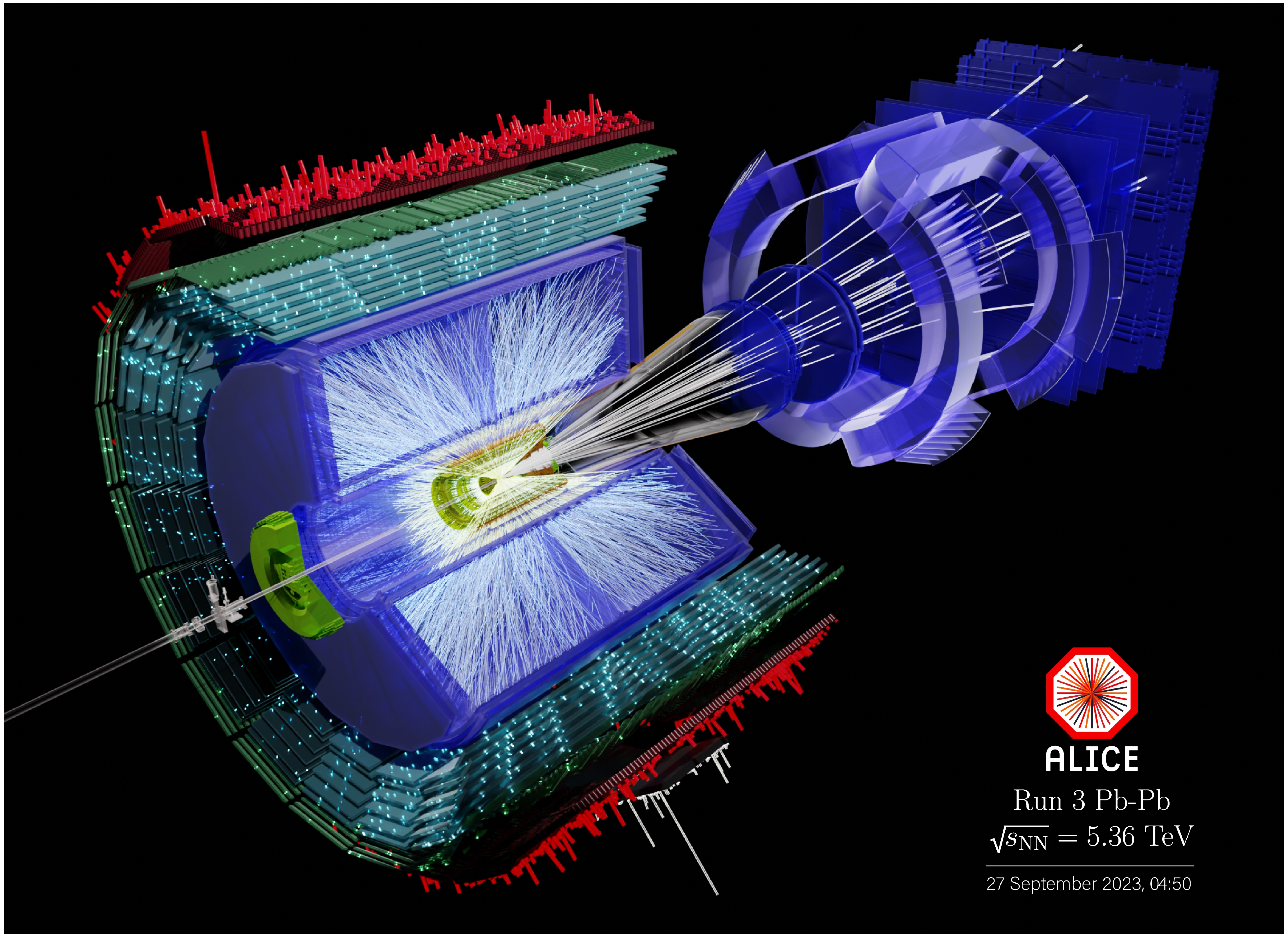
EPICal half-layer



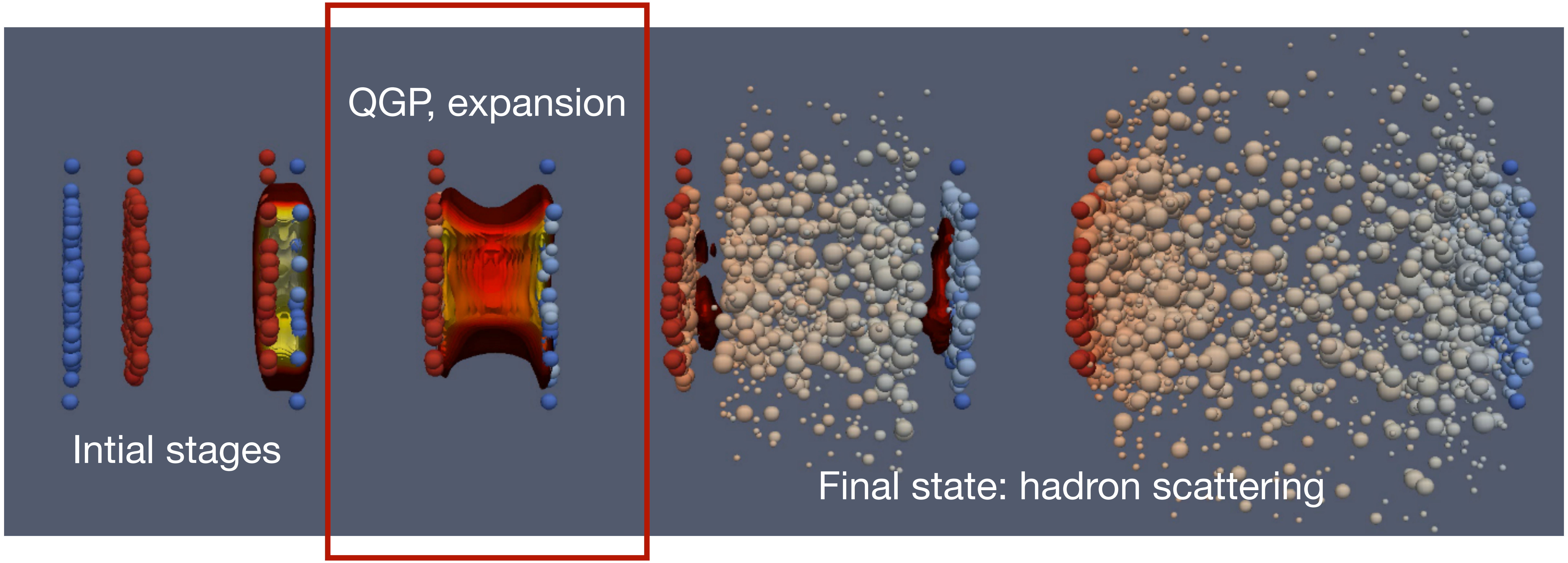
FoCal-E pixel layers






ALICE
Run 3 Pb-Pb
$\sqrt{s_{NN}} = 5.36$ TeV
27 September 2023, 04:50

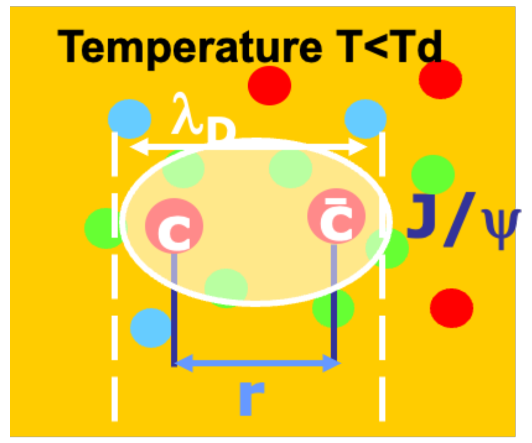
Heavy-ion collisions and the quark-gluon plasma

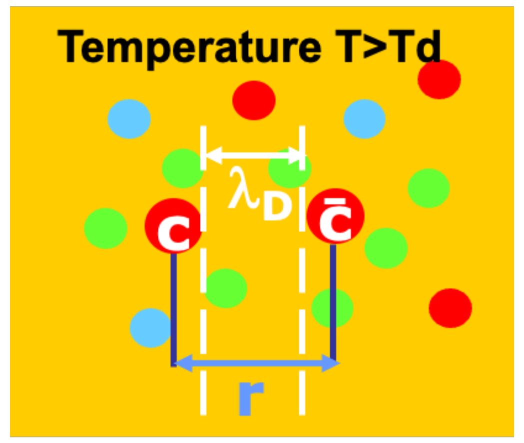


Properties of **equilibrium matter**: equation of state, transport coefficients

Dynamics: hadronisation, interactions of partons with the medium

High-temperature QCD and deconfinement: melting of quarkonia





Binding force screened when
$r > \lambda_d$

Binding of quarkonia
($b\bar{b}$, $c\bar{c}$ bound states)
screened at higher
temperature, density

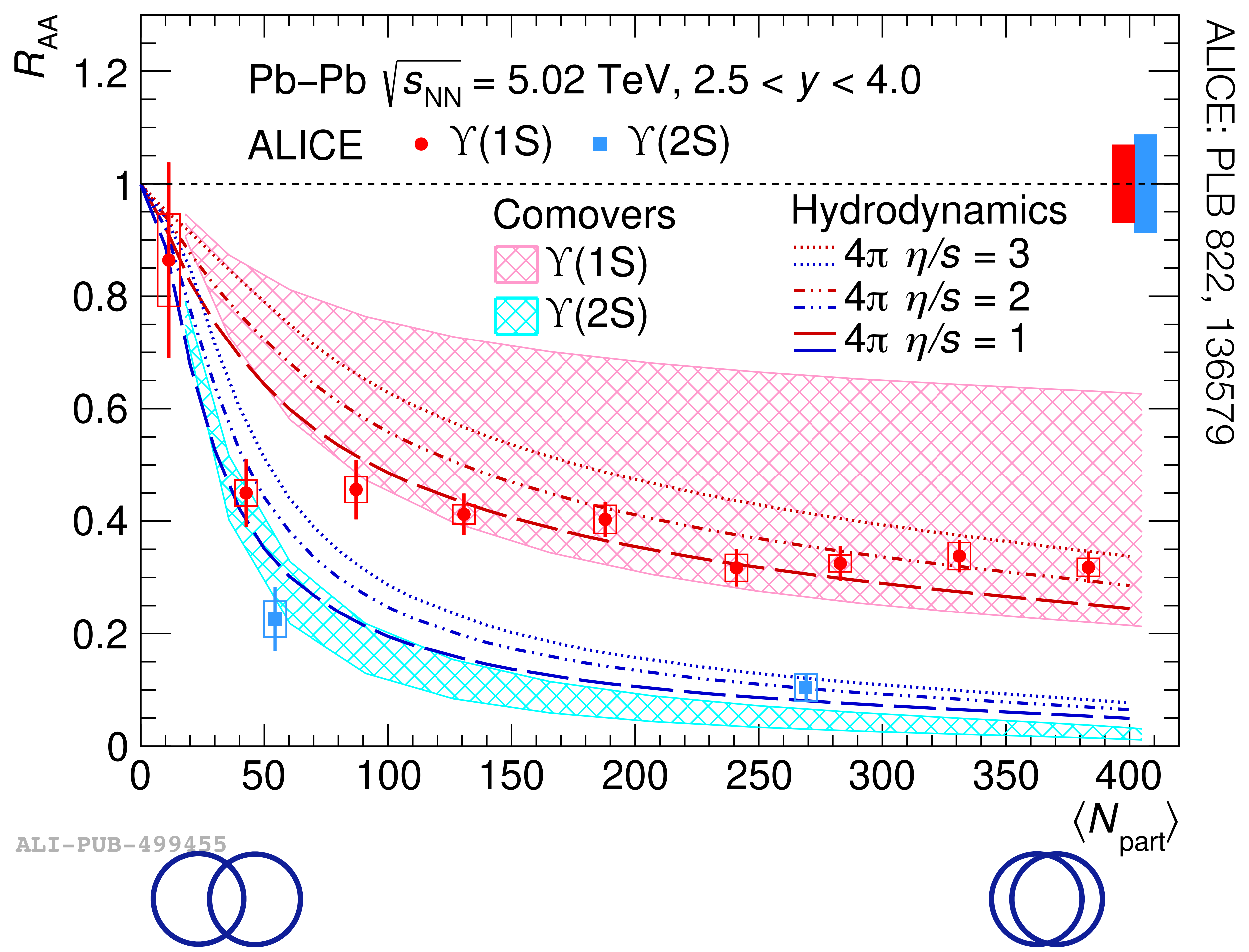
Nuclear modification factor

$$R_{AA} = \frac{dN/dp_T|_{AA}}{\langle N_{coll}\rangle \; dN/dp_T|_{pp}}$$

R_{AA} = 1: no effect

R_{AA} = 0: complete suppression

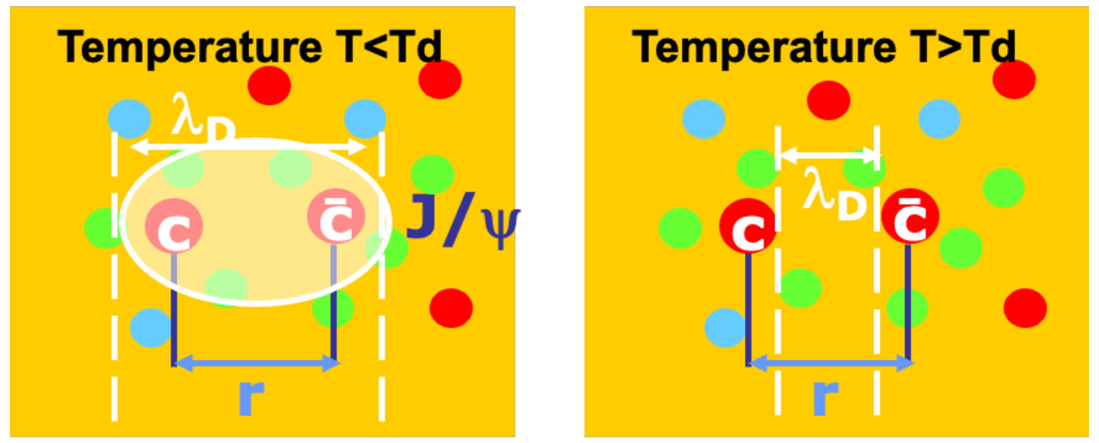
$\Upsilon(b\bar{b})$ nuclear modification vs centrality



Large suppression — dissociation in central events

Larger effect for higher states — weaker binding

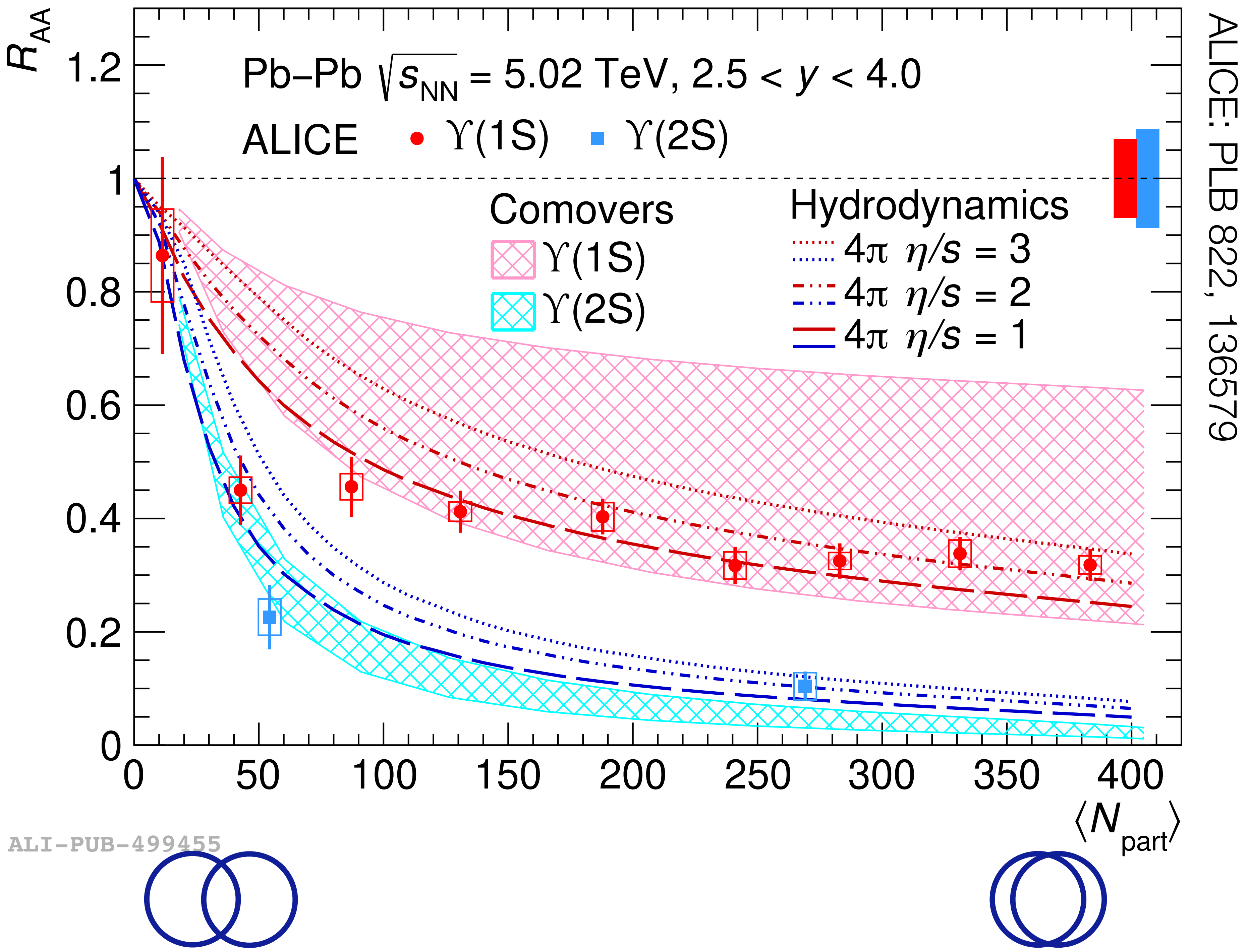
High-temperature QCD and deconfinement: melting of quarkonia



Binding force screened when $r > \lambda_d$

Binding of quarkonia ($b\bar{b}$, $c\bar{c}$ bound states) screened at higher temperature, density

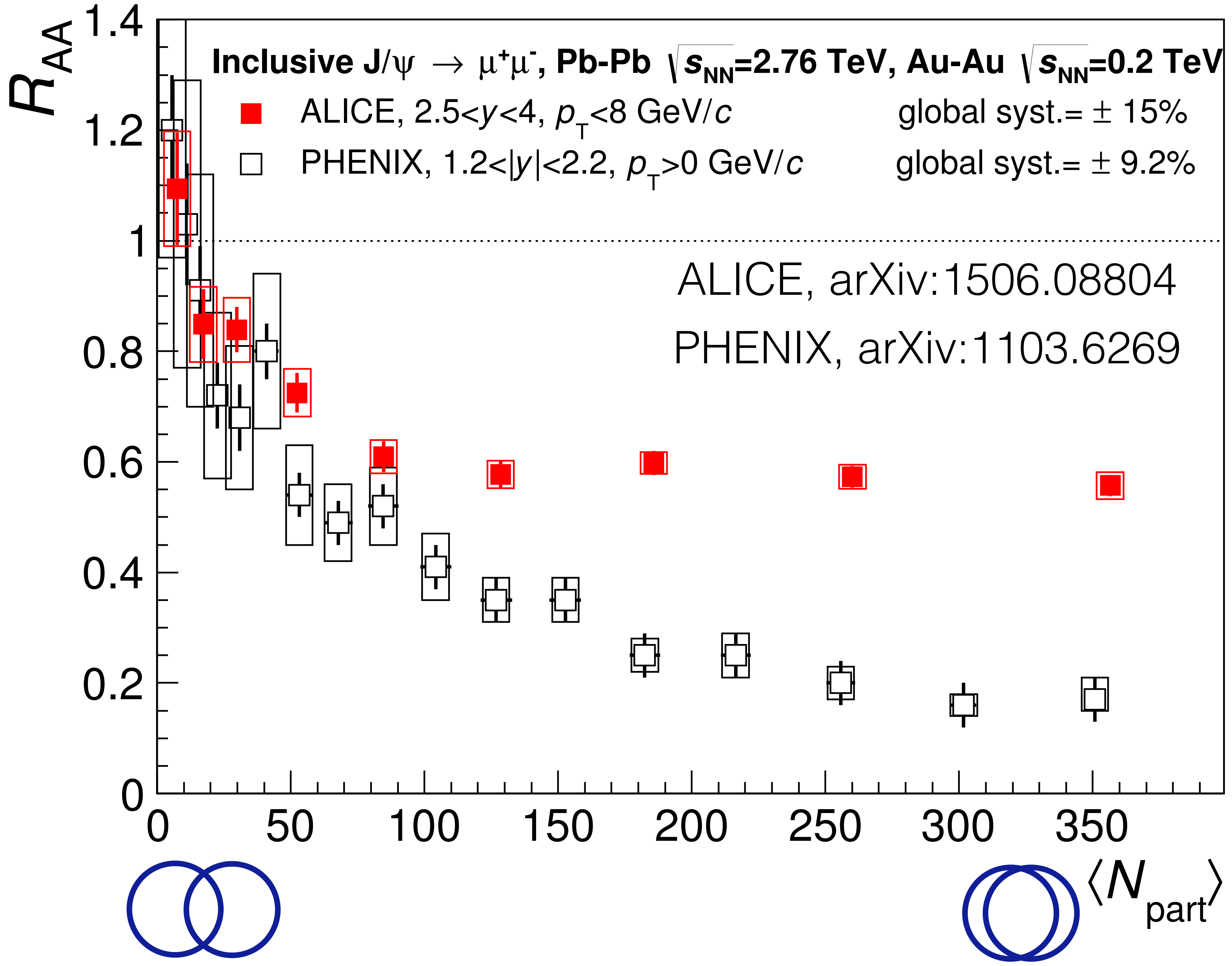
$\Upsilon(b\bar{b})$ nuclear modification vs centrality



Large suppression — dissociation in central events

Larger effect for higher states — weaker binding

J/ψ modification vs centrality



J/ψ : $c\bar{c}$ bound state shows smaller suppression

Nuclear modification factor

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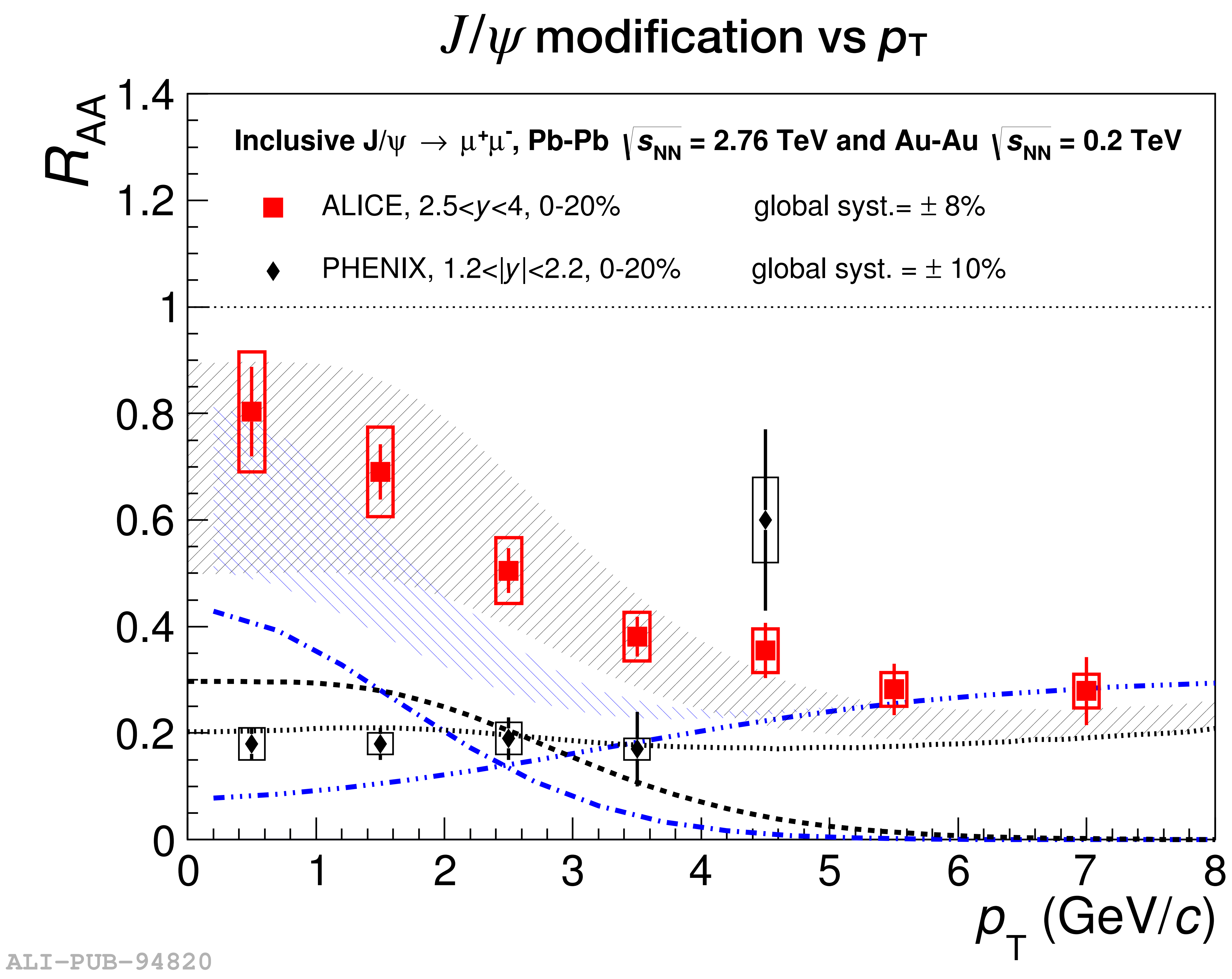
R_{AA} = 0: complete suppression

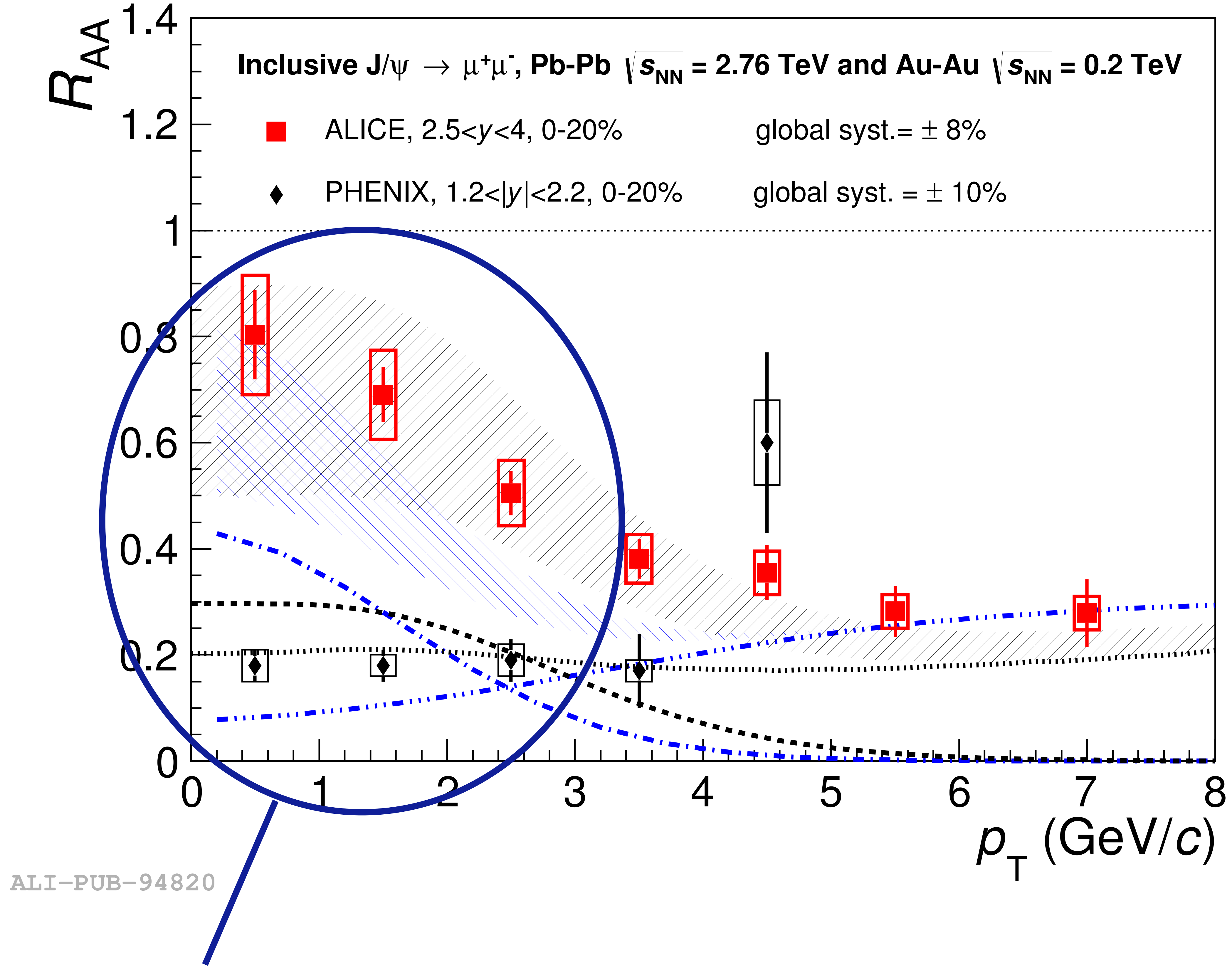
Early stage temperature: melting of charmonia (J/ψ)



ALICE, arXiv:1506.08804 PHENIX, arXiv:1103.6269
Transport models: arXiv:1102.2194, arXiv:1401.5845

Early stage temperature: melting of charmonia (J/ψ)

J/ψ modification vs p_T



Less suppression at low p_T

$c\bar{c}$ recombination

ALICE, arXiv:1506.08804 PHENIX, arXiv:1103.6269
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Early stage temperature: melting of charmonia (J/ψ)

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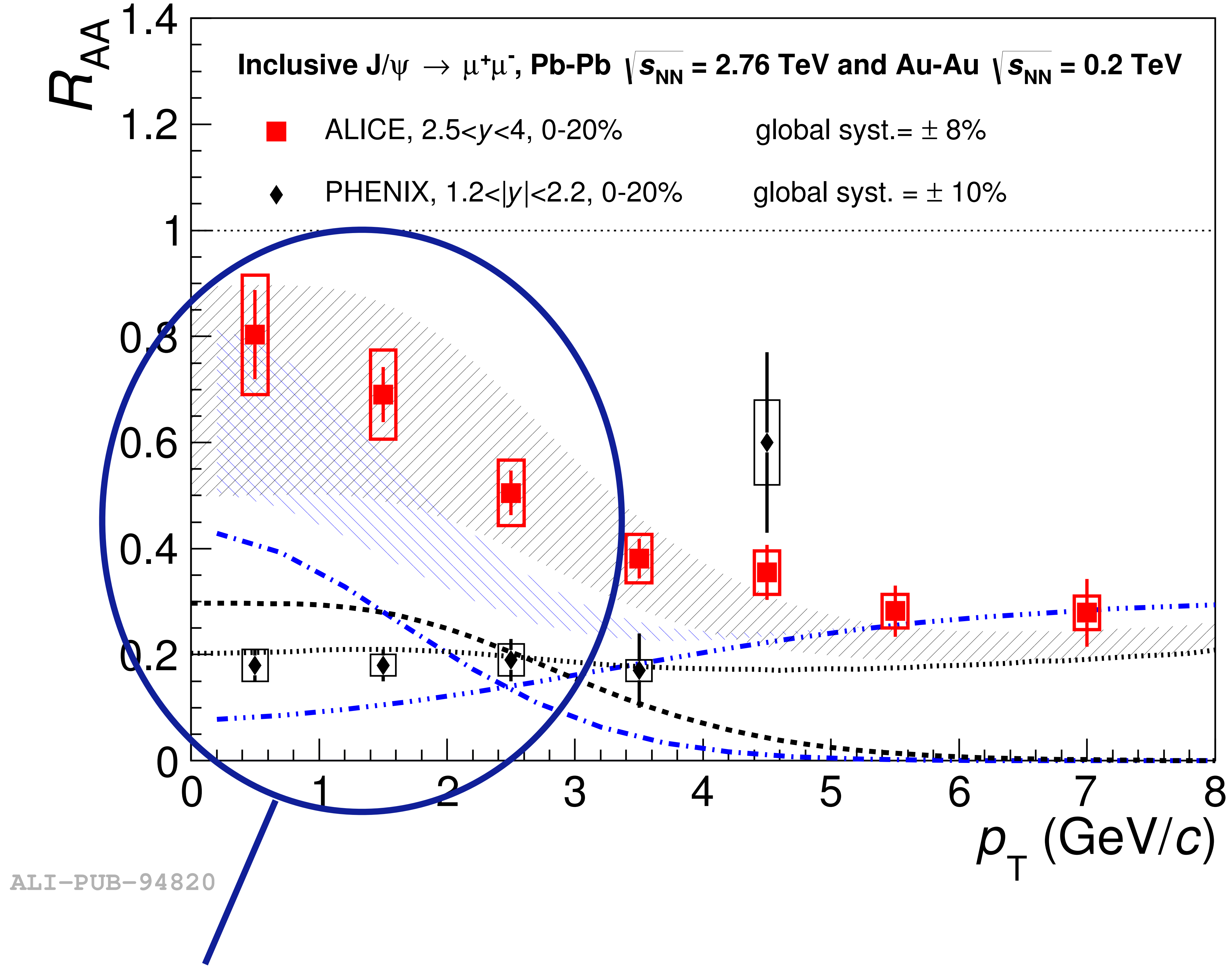
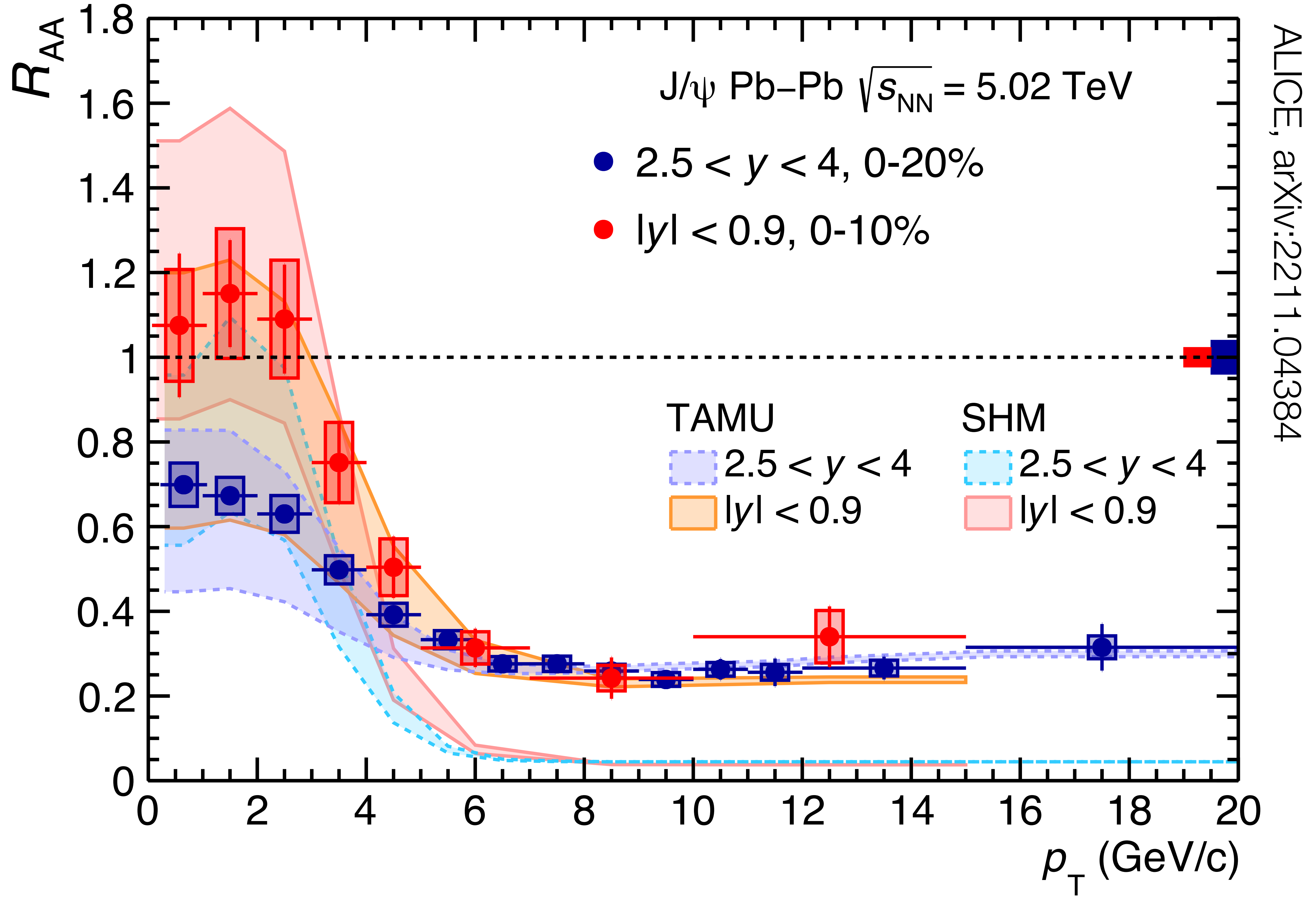


Less suppression at low p_T

$c\bar{c}$ recombination

J/ψ modification at forward and mid-rapidity

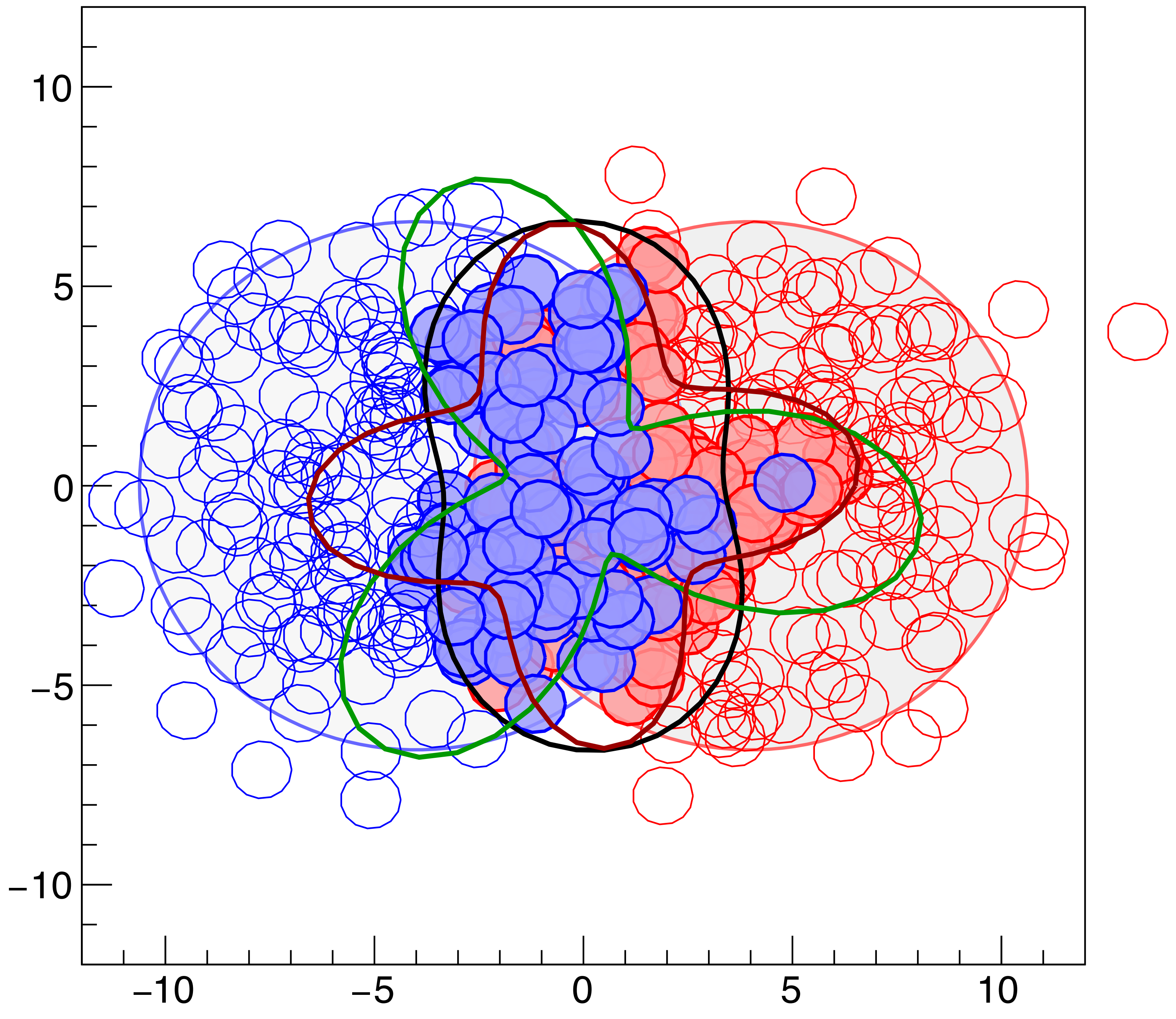


In agreement with coalescence expectation:
larger $c\bar{c}$ density at mid-rapidity

ALICE, arXiv:1506.08804 PHENIX, arXiv:1103.6269
Transport models: arXiv:1102.2194, arXiv:1401.5845

Azimuthal anisotropy: initial and final states

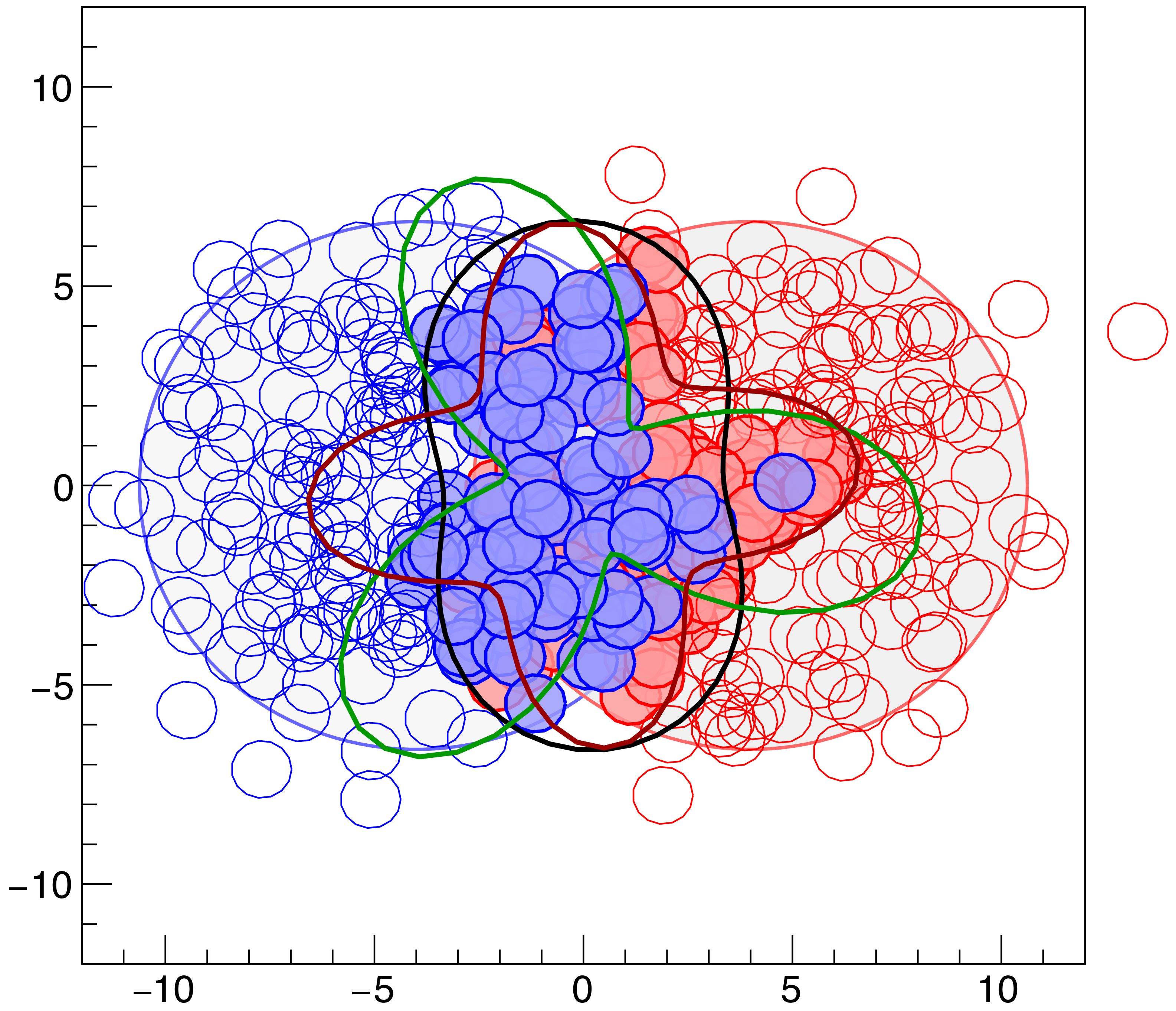
Simulated event: location of nucleons



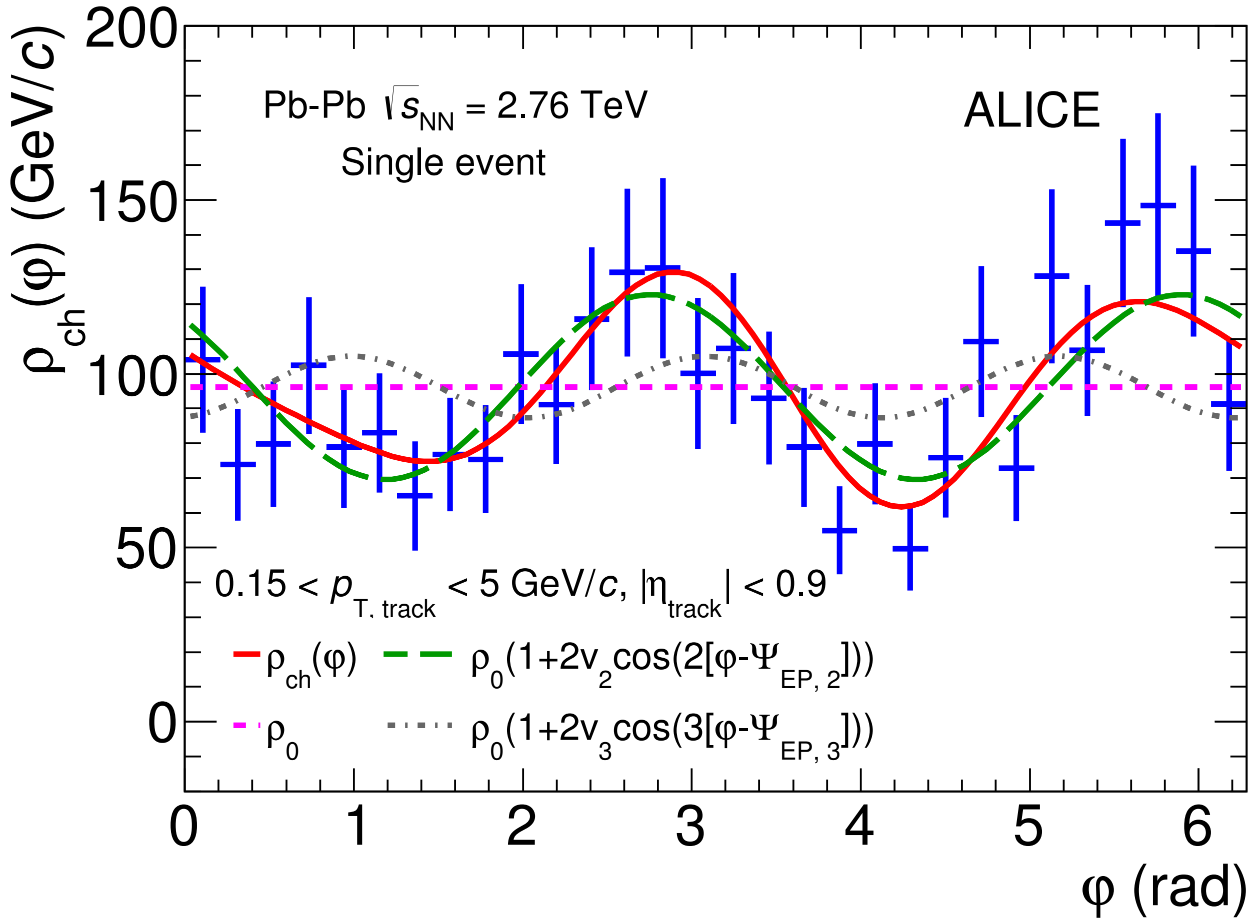
Initial state spatial anisotropies ε_n are transferred into final state momentum anisotropies v_n by pressure gradients, flow of the Quark Gluon Plasma

Azimuthal anisotropy: initial and final states

Simulated event: location of nucleons



Azimuthal distribution single event

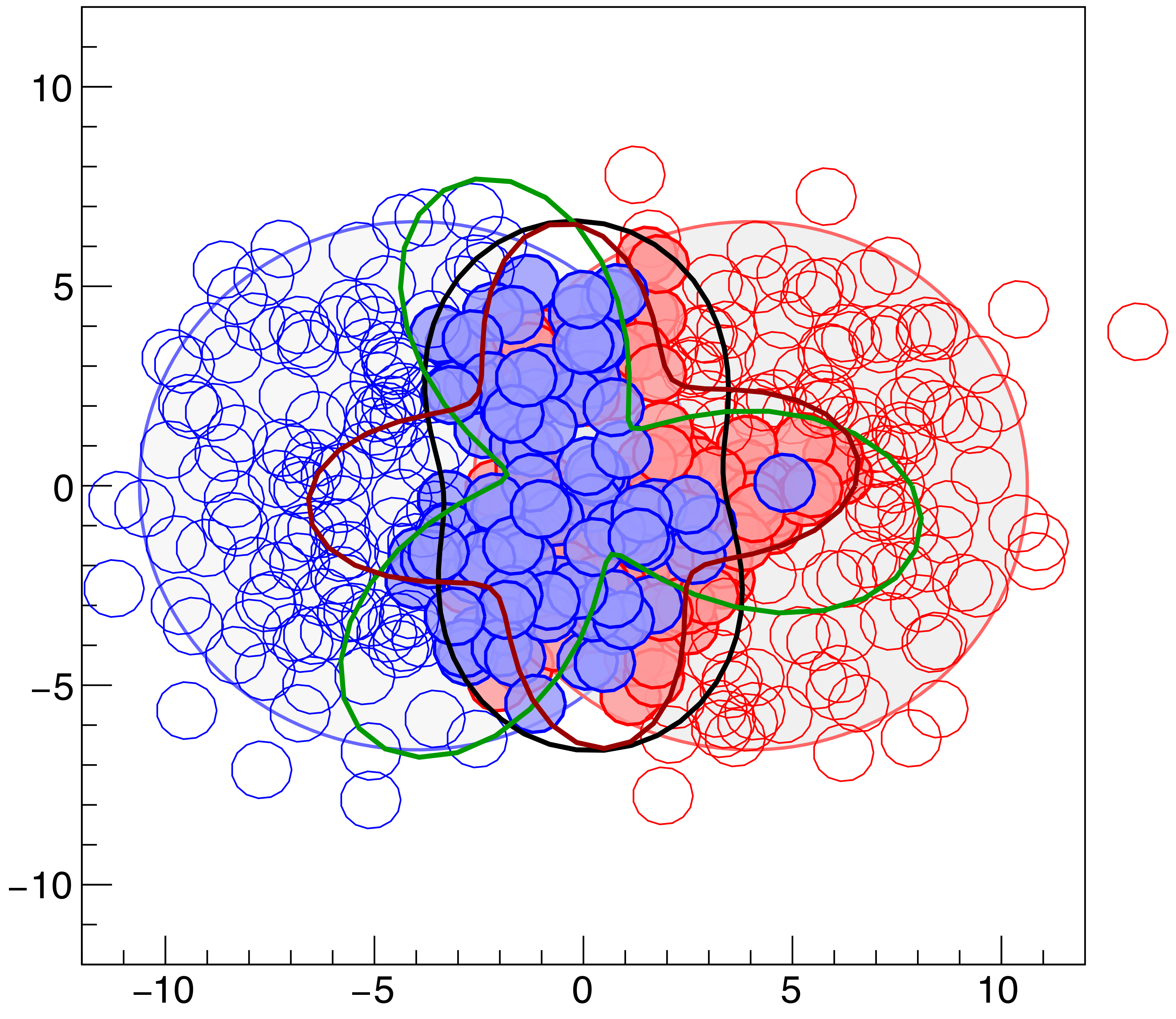


ALICE, PLB 753, 511

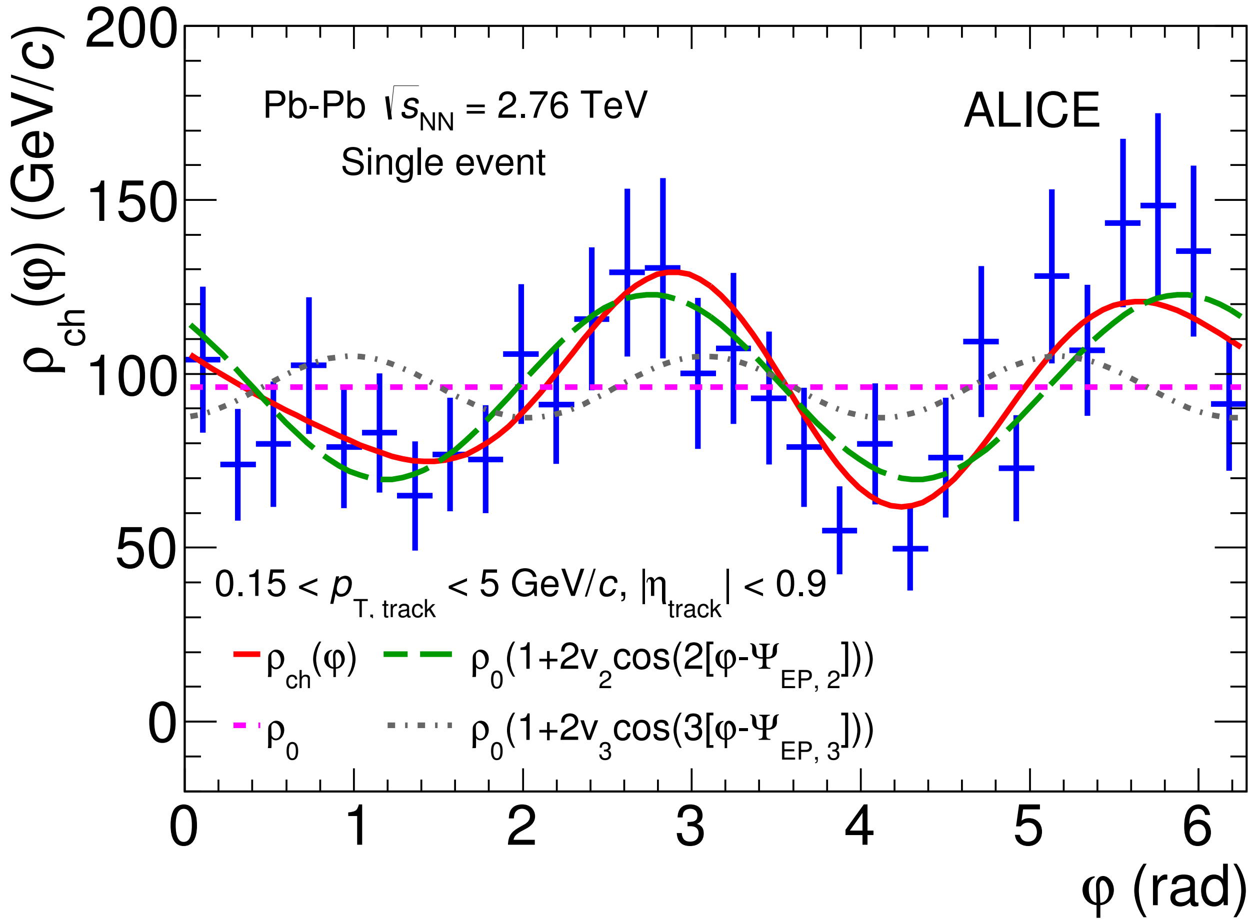
Initial state spatial anisotropies ε_n are transferred into final state momentum anisotropies v_n by pressure gradients, flow of the Quark Gluon Plasma

Azimuthal anisotropy: initial and final states

Simulated event: location of nucleons

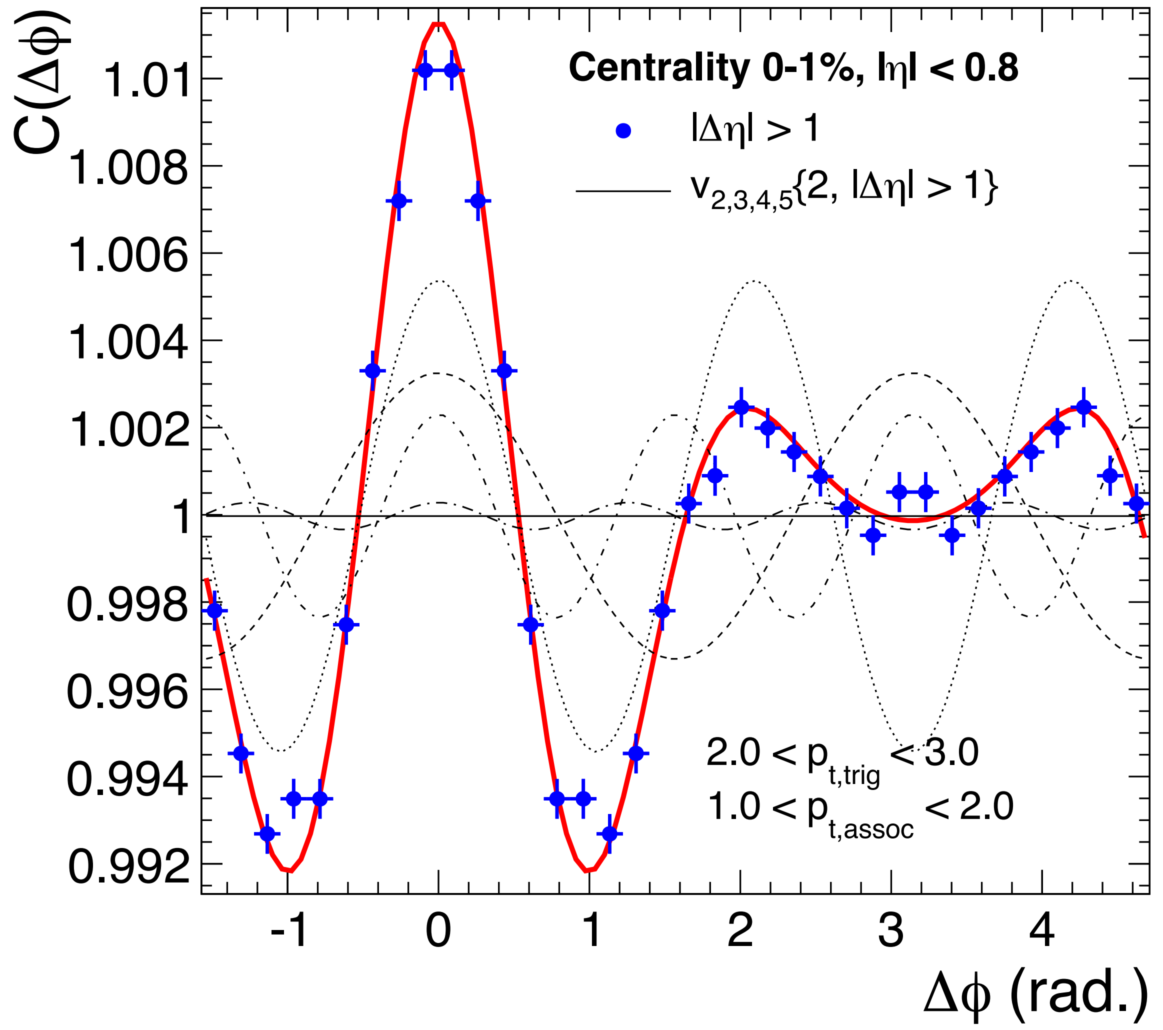


Azimuthal distribution single event



ALICE, PLB 753, 511

Sum over many events

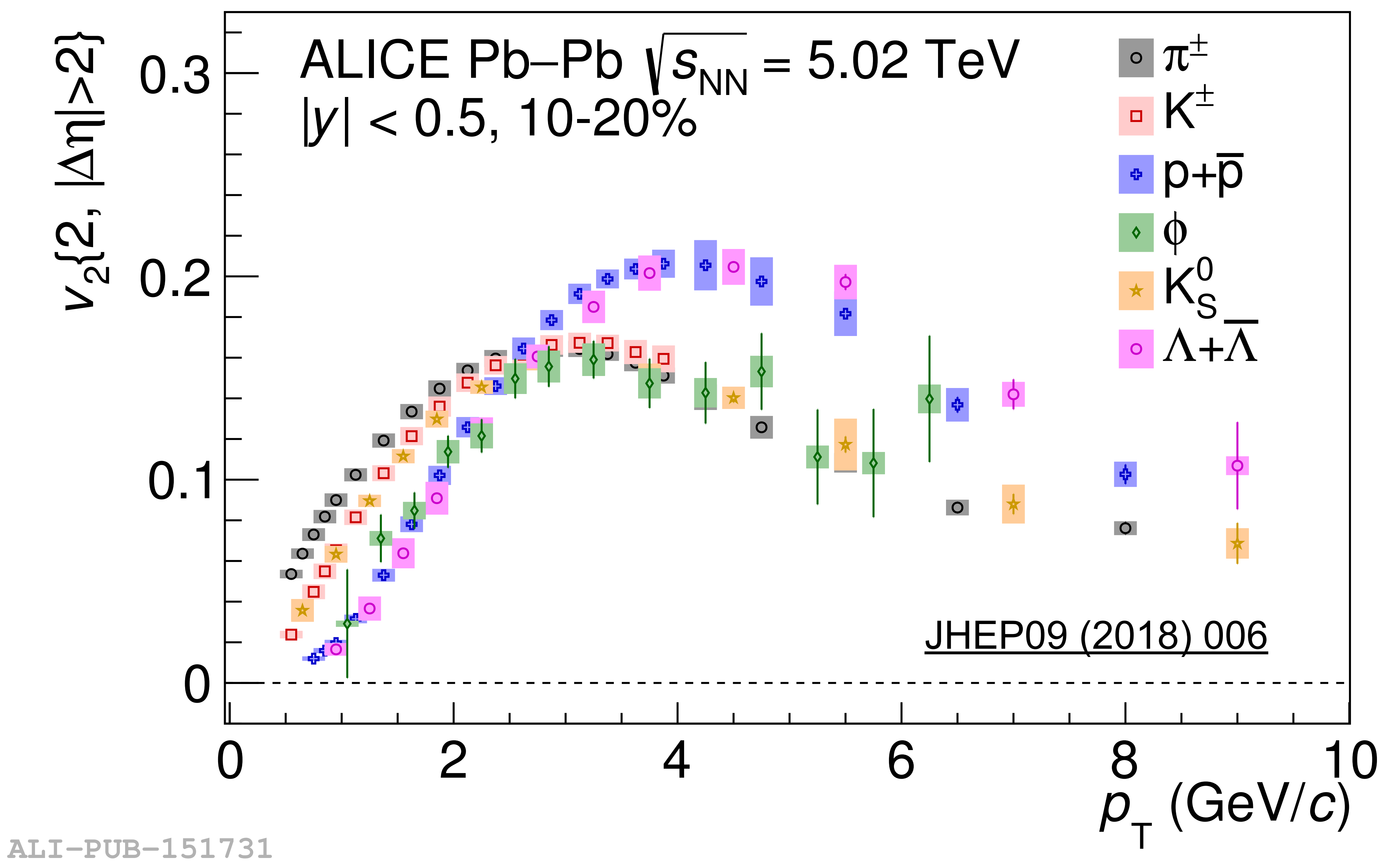


ALICE PRL. 107, 032301

Initial state spatial anisotropies ε_n are transferred into final state momentum anisotropies v_n by pressure gradients, flow of the Quark Gluon Plasma

Anisotropic flow: initial state and QGP expansion

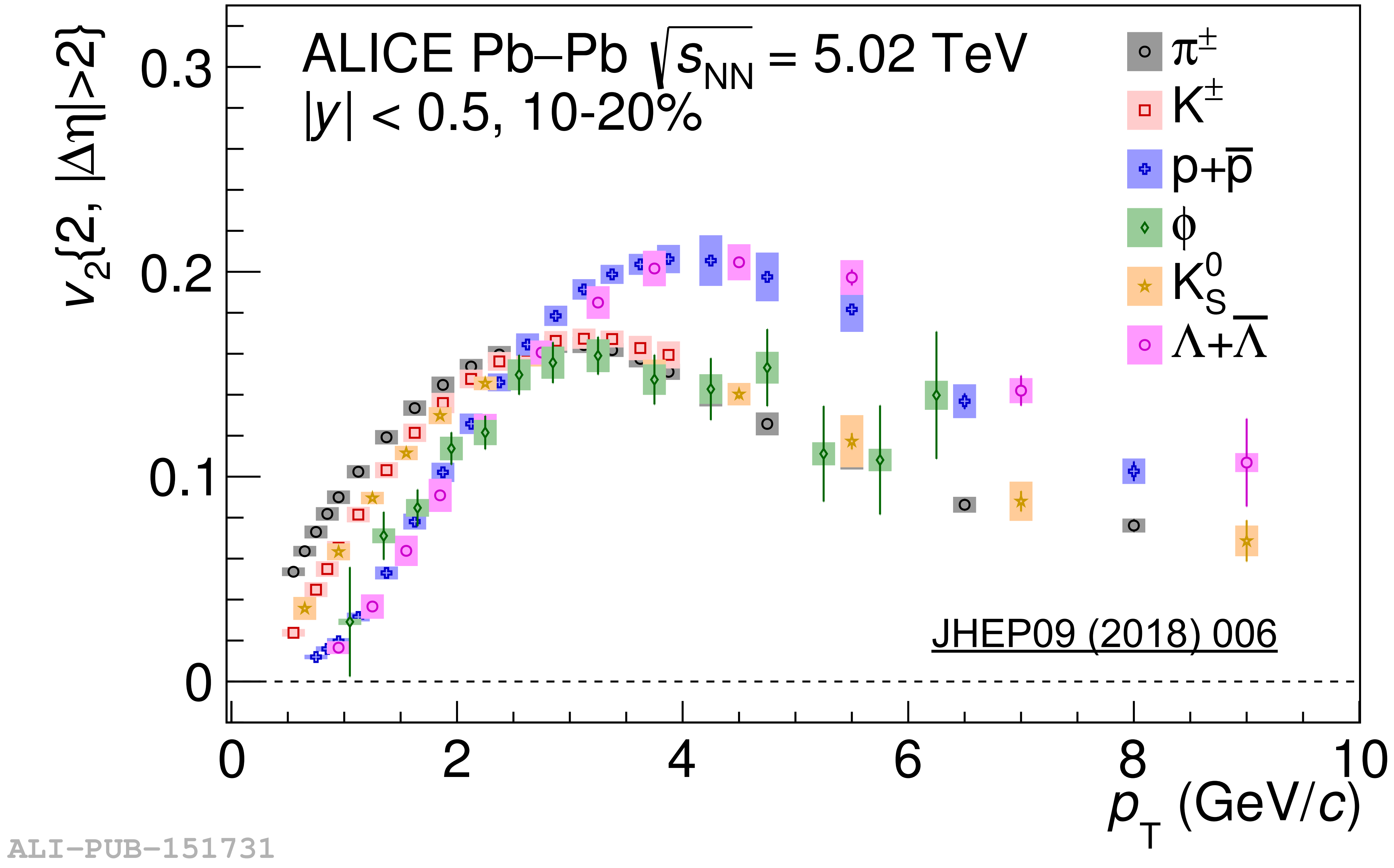
Elliptic flow v_2



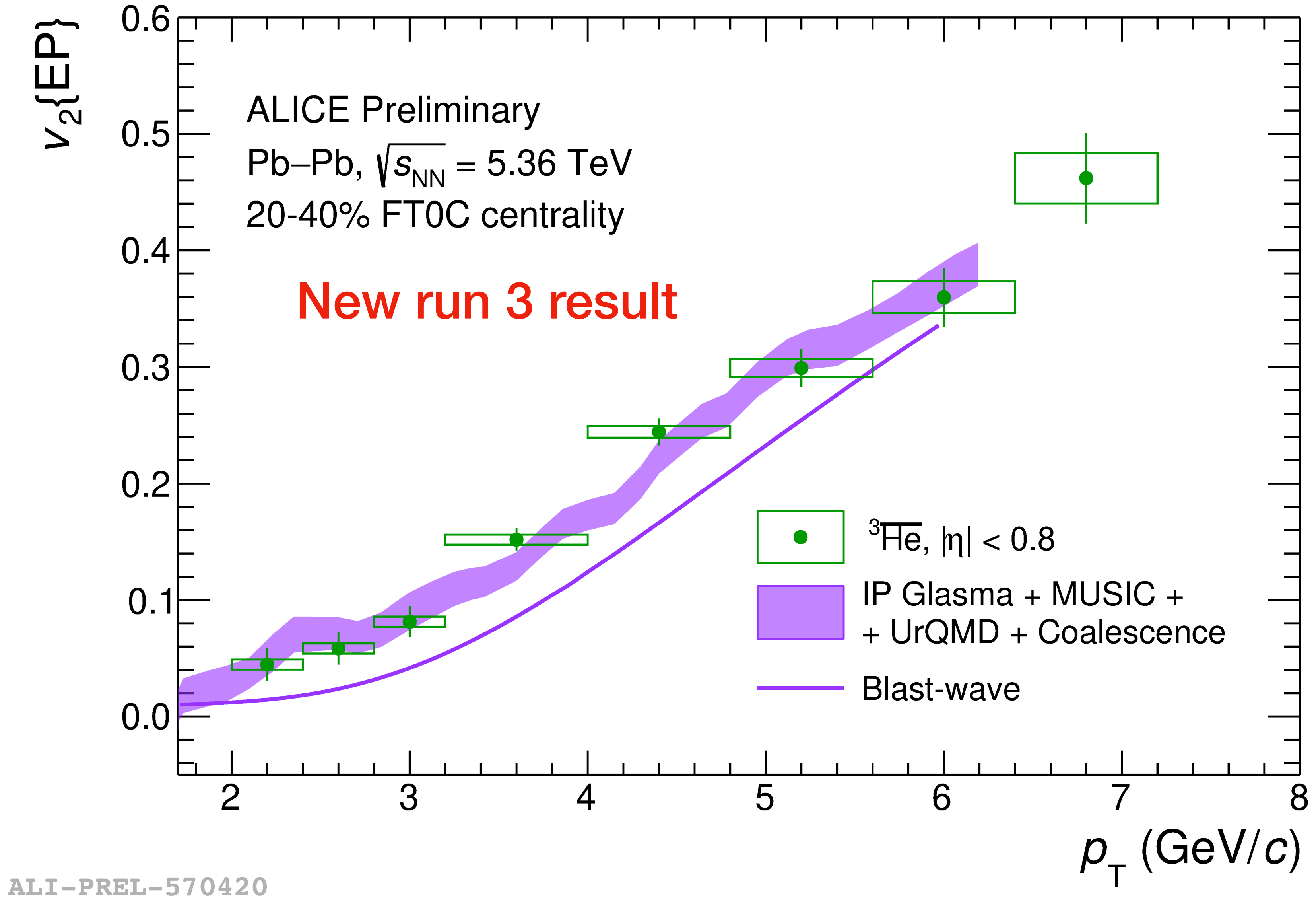
Mass-dependence of v_2 measures flow velocity

Anisotropic flow: initial state and QGP expansion

Elliptic flow v_2



v_2 of $^3\overline{He}$



Even nuclei flow !

Mass-dependence of v_2 measures flow velocity

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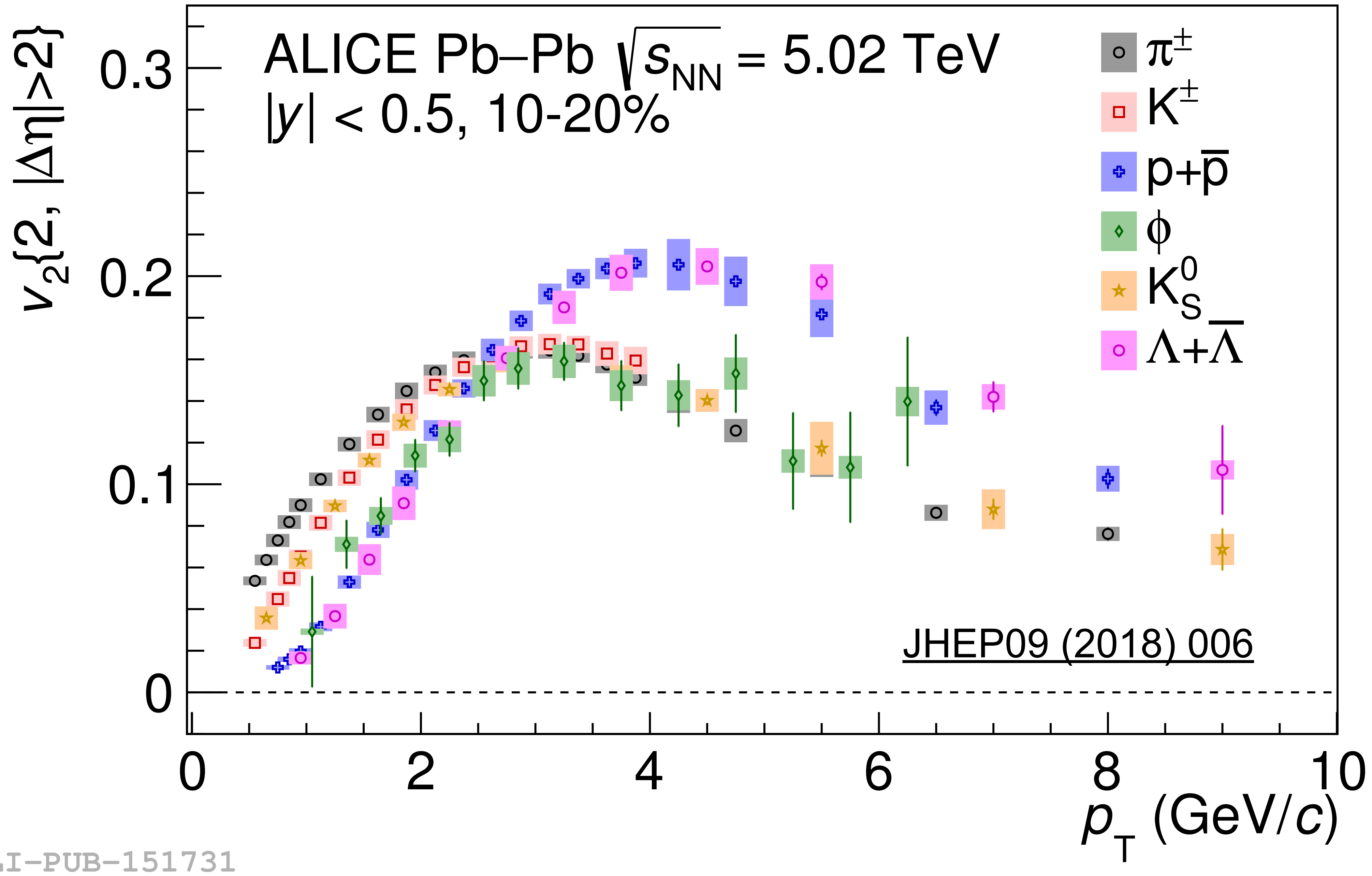
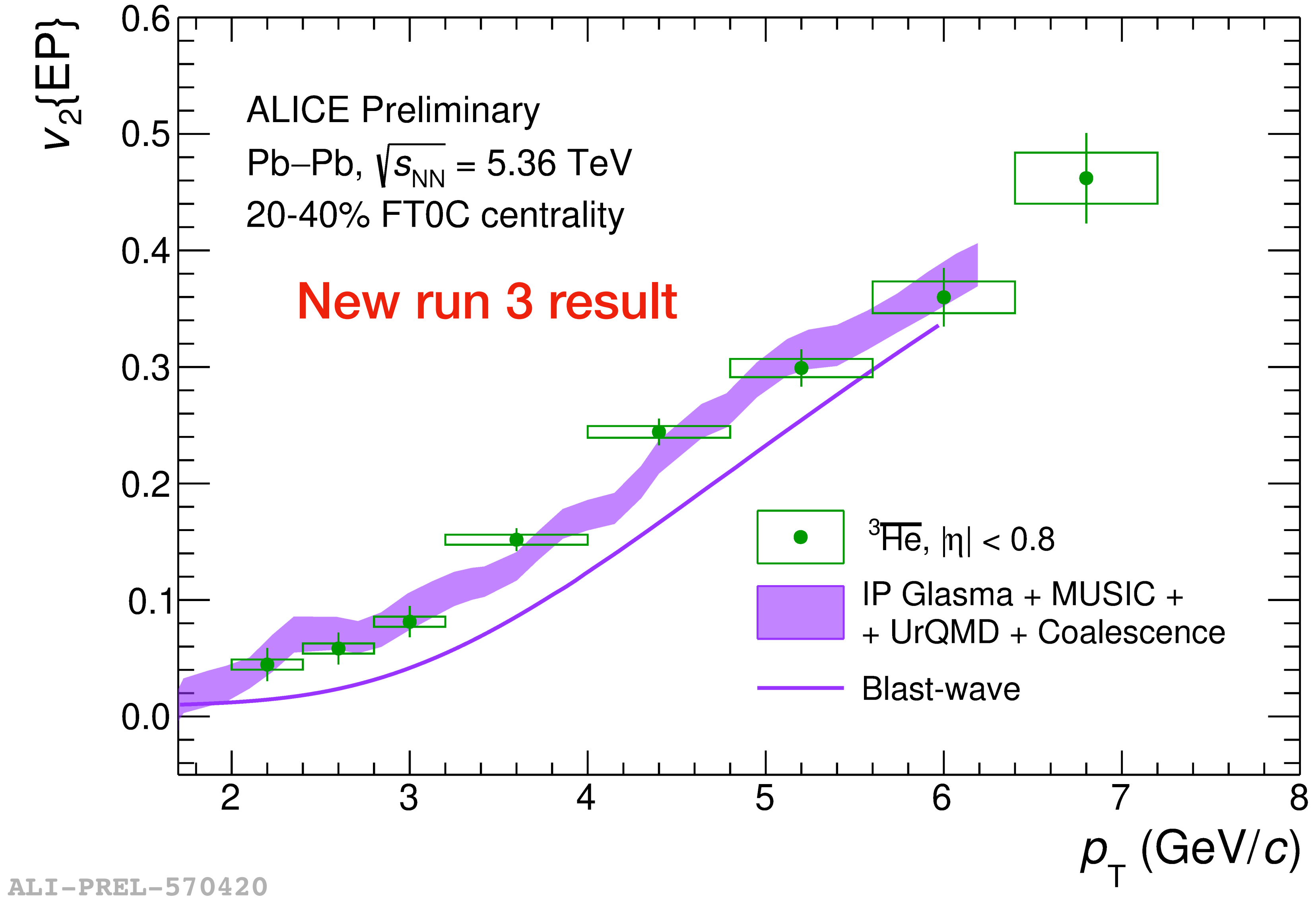
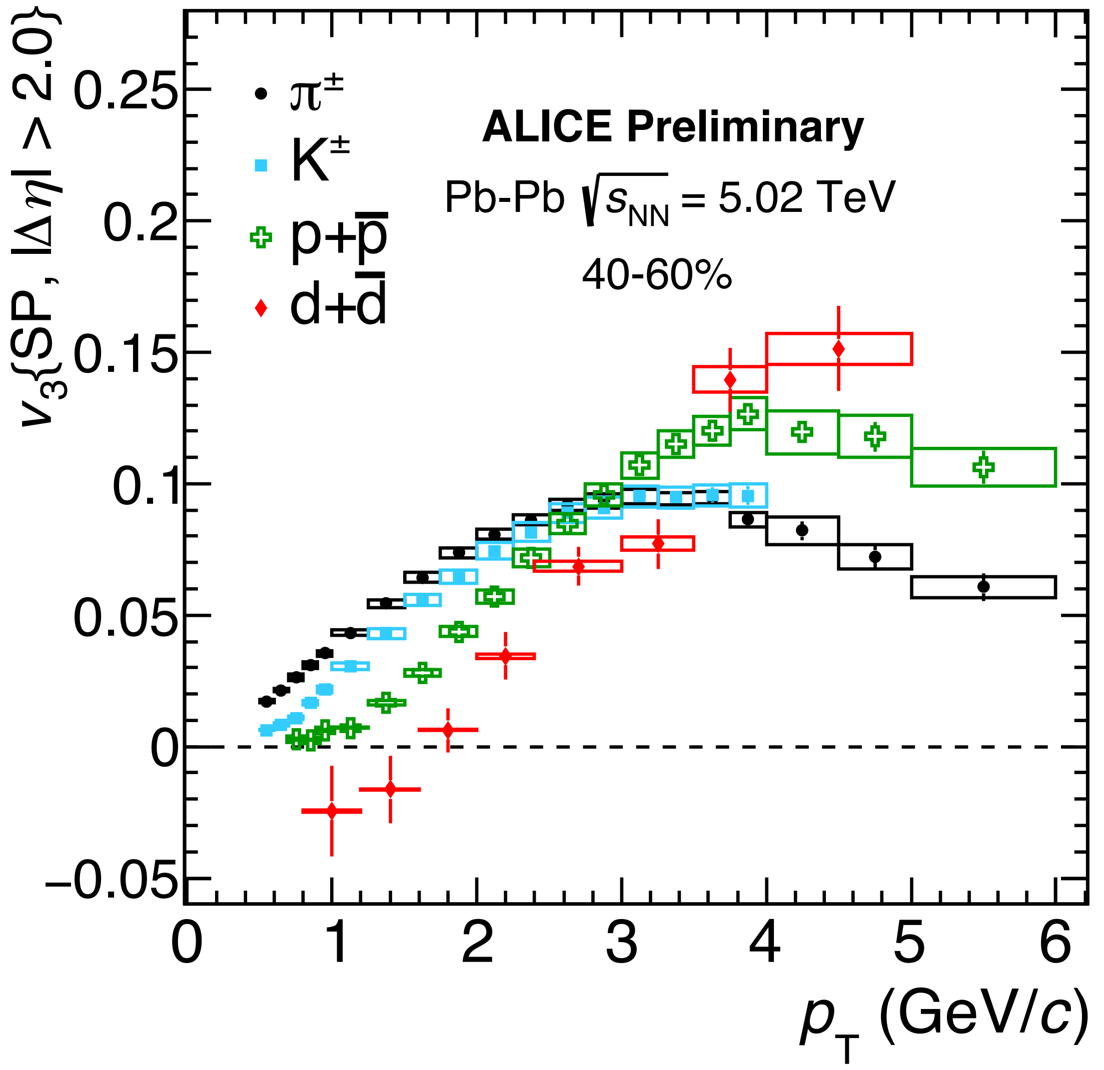


v_2 of $^3\overline{He}$

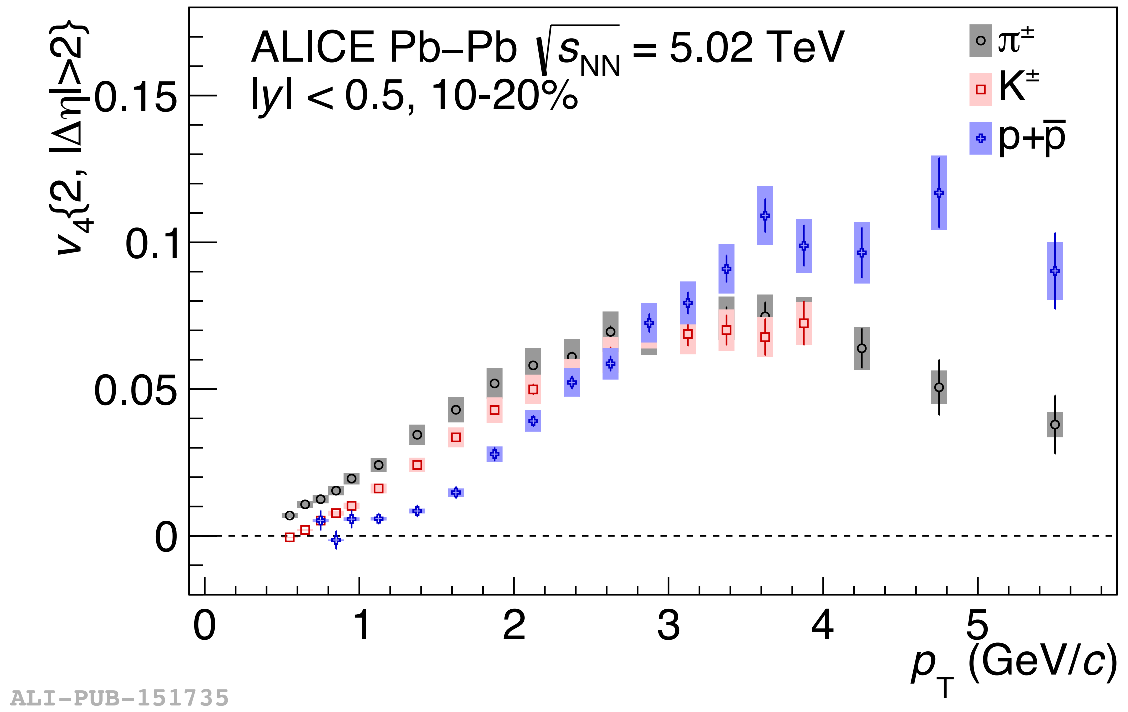


Even nuclei flow !

v_3



v_4

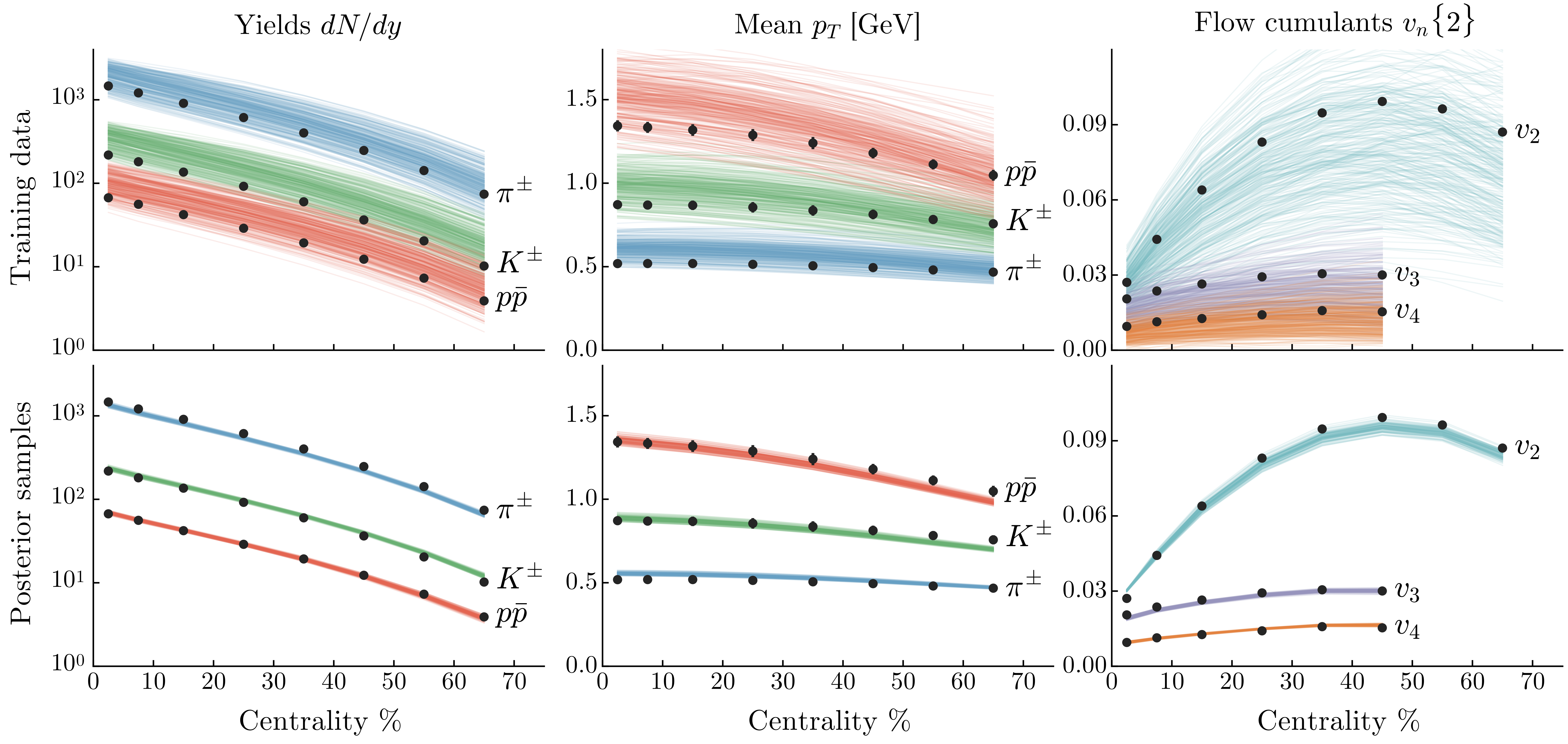


Mass-dependence of v_2 measures flow velocity

Constraining initial state and plasma properties simultaneously: Bayesian inference

J. E. Bernhard et al, arXiv: 1605.03954

Experimental input: yields, mean p_T and harmonic flow vs p_T



Model: initial anisotropies + medium response

Explores a large parameter space to investigate reliability/robustness of the modeling

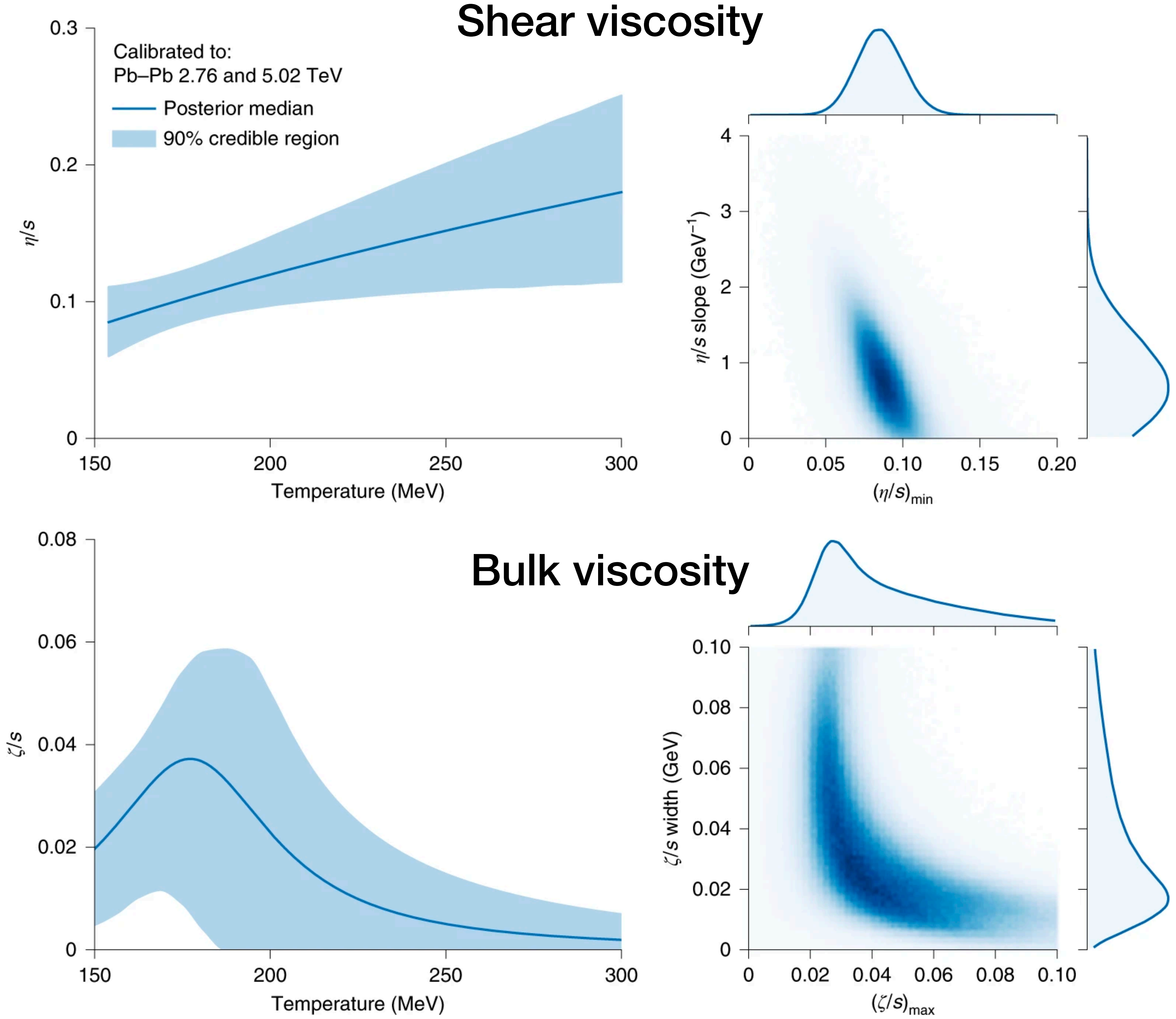
A global fit to anisotropic flow: main result

J. E. Bernhard et al, Nature Physics 15, 1113–1117, arXiv: 1605.03954

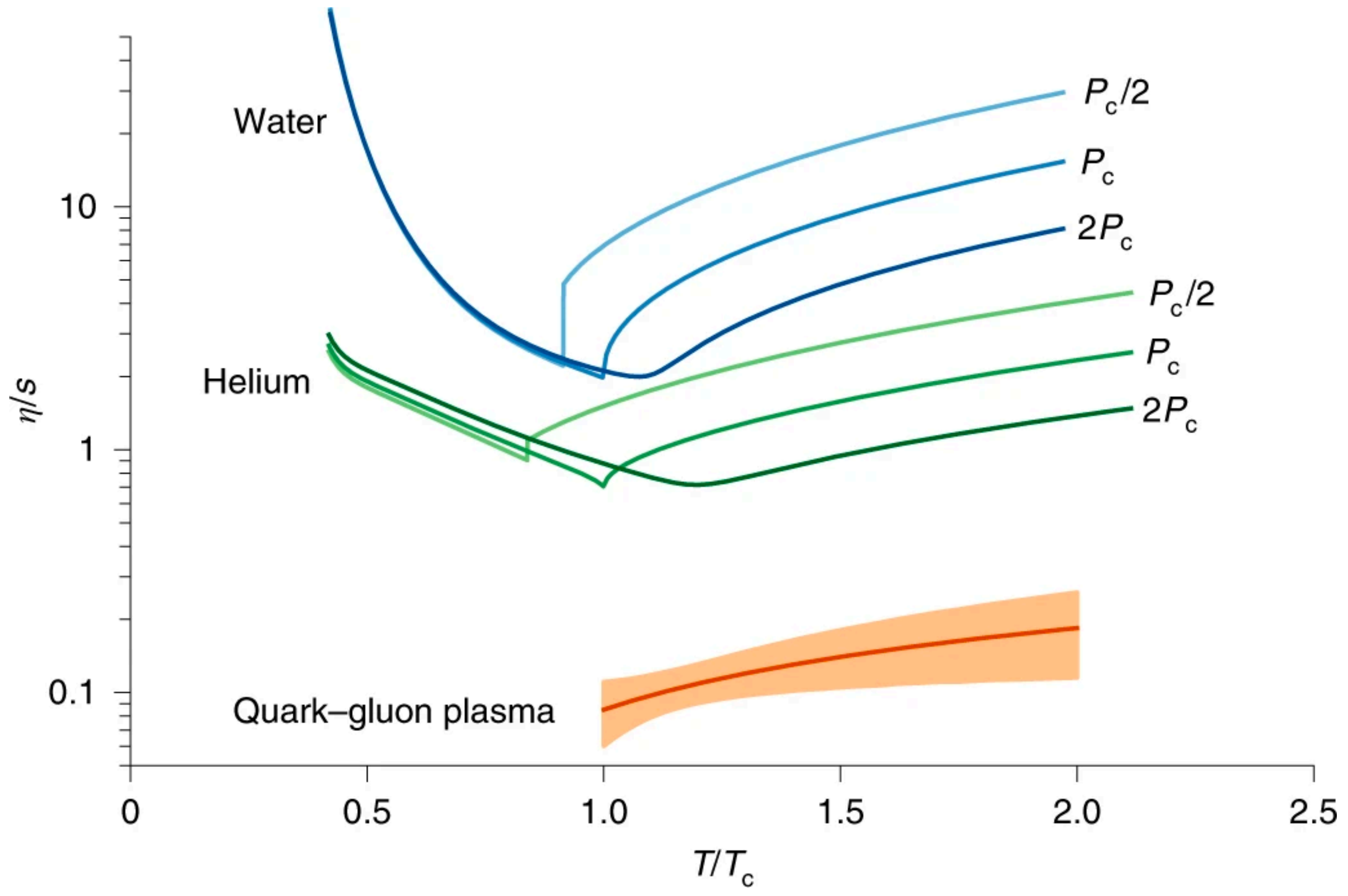
Viscosity vs *T*

Shear viscosity

Bulk viscosity



Comparison to well-known liquids



QGP has a very small 'specific viscosity' ⇒ small mean free path $\eta = \frac{1}{3} n p \lambda$

Viscosity close to fundamental lower bound

Messengers of the Plasma: soft and hard processes

Soft processes

Momenta comparable to QGP temperature

$p_T \lesssim 3\ \mathrm{GeV}/c$

Near thermal equilibrium with the plasma

'particles from the QGP'

Messengers of the Plasma: soft and hard processes

Soft processes

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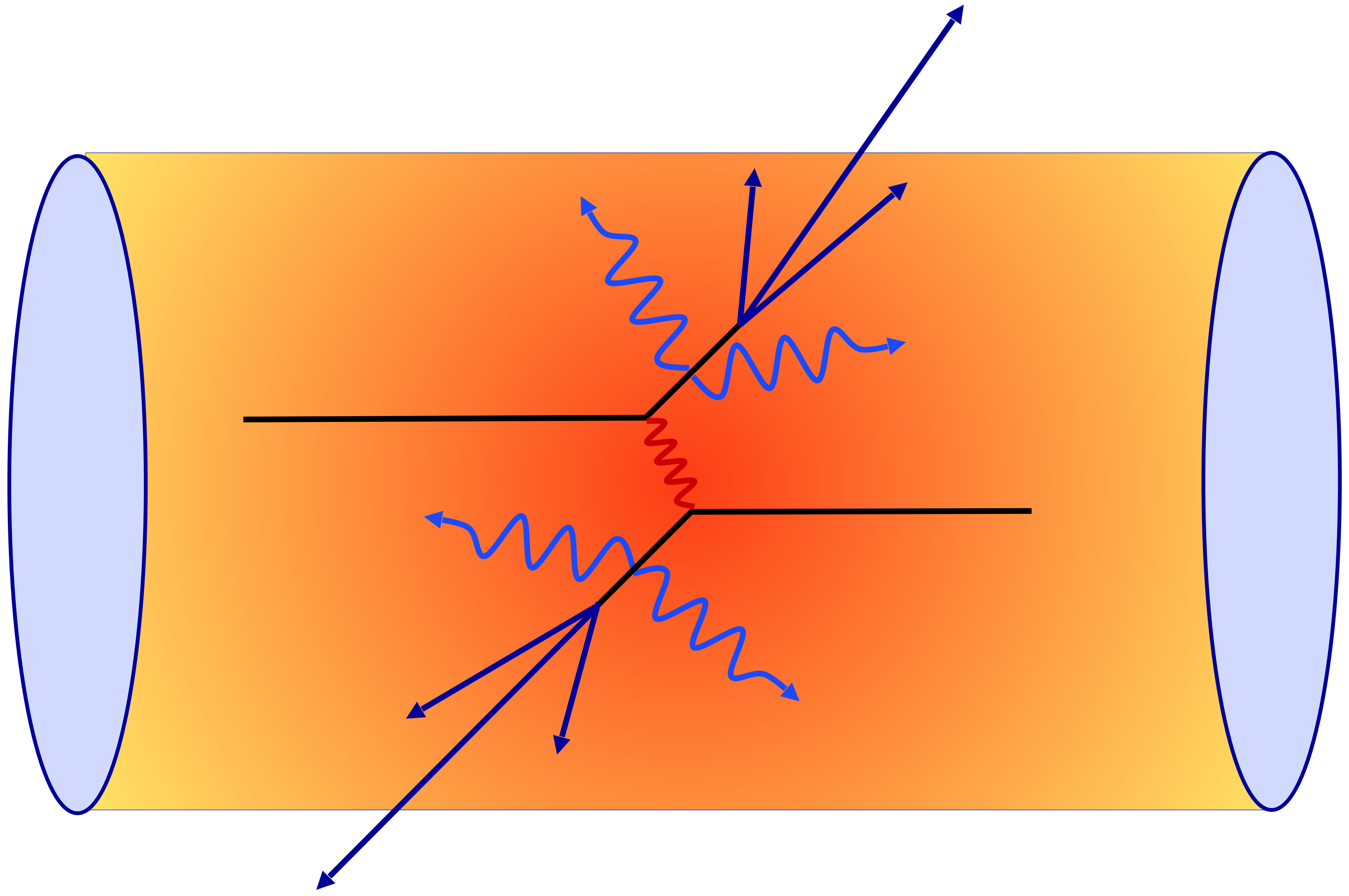


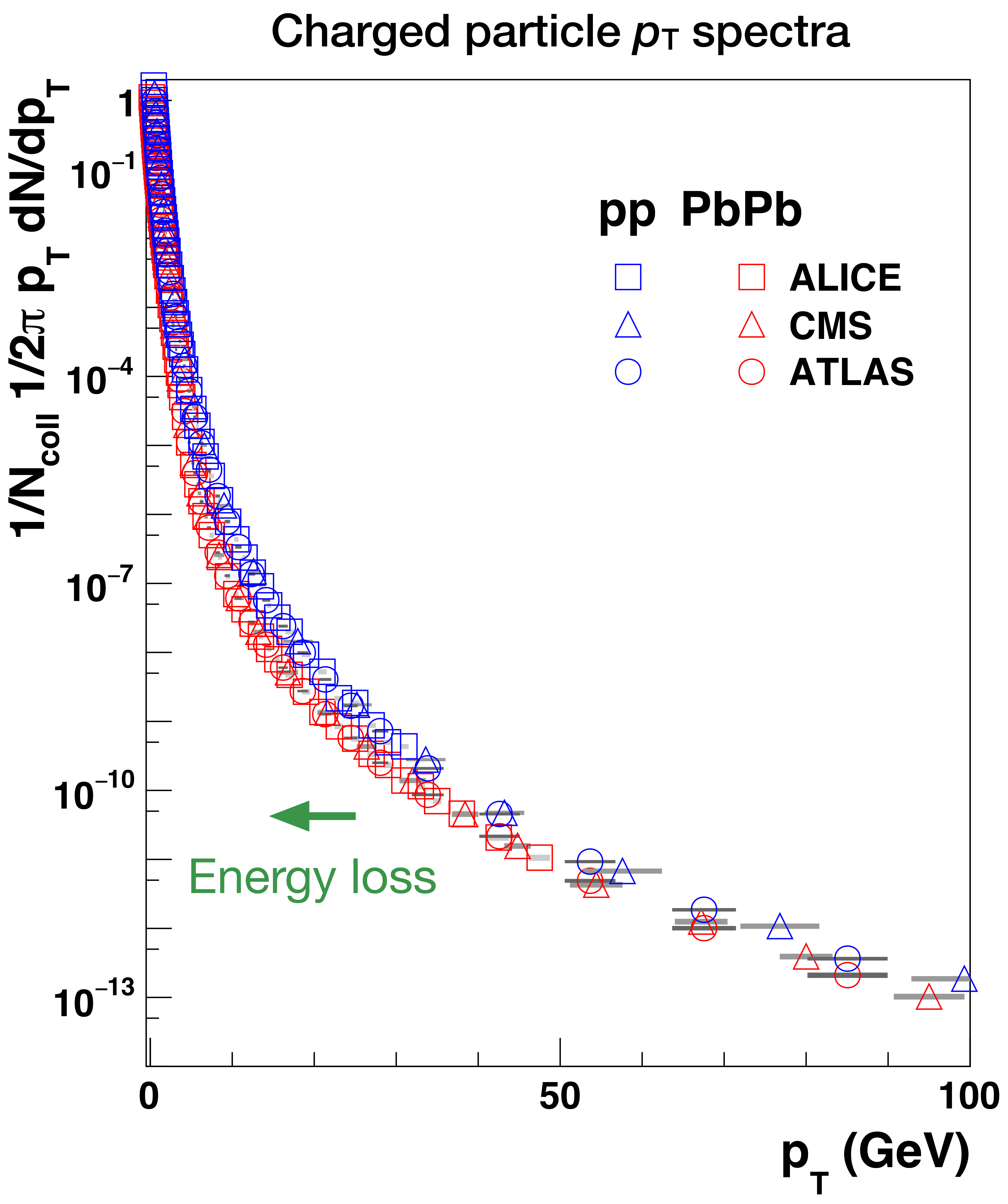
Hard processes: large momenta >> T_{QGP}

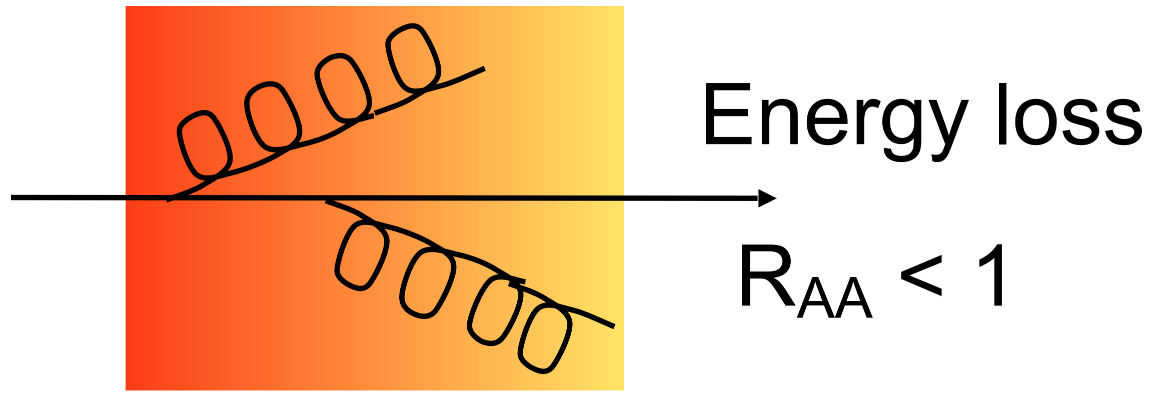
- Short formation time: initial production independent of QGP formation
- Start out far out of thermal equilibrium: **approach equilibrium through interactions**
- Short life time: expect only partial equilibration

‘Hard probes’ of interactions with the QGP

Nuclear modification of p_T spectra

ALICE, PLB720, 52
CMS, EPJC, 72, 1945
ATLAS, arXiv:1504.04337

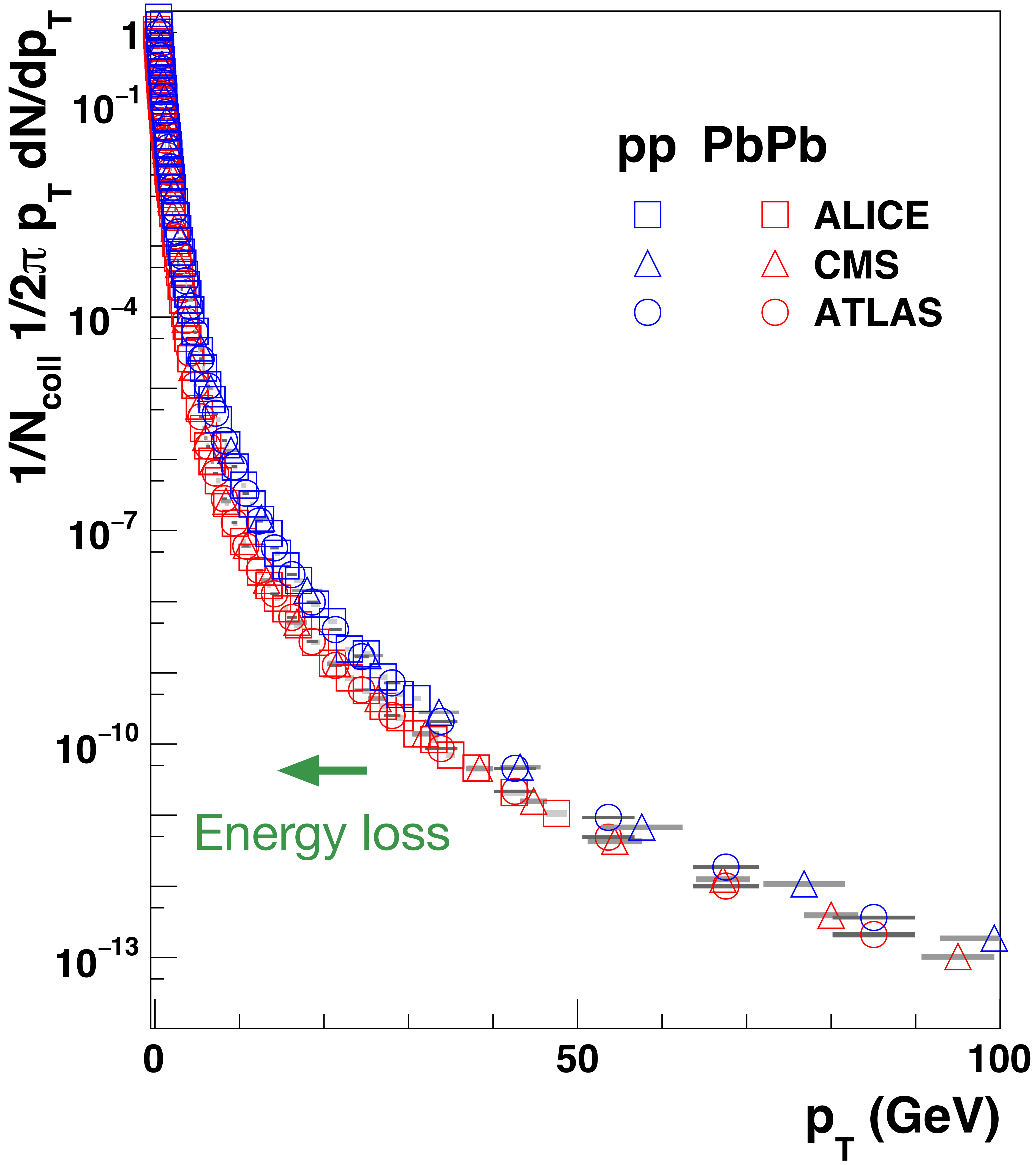




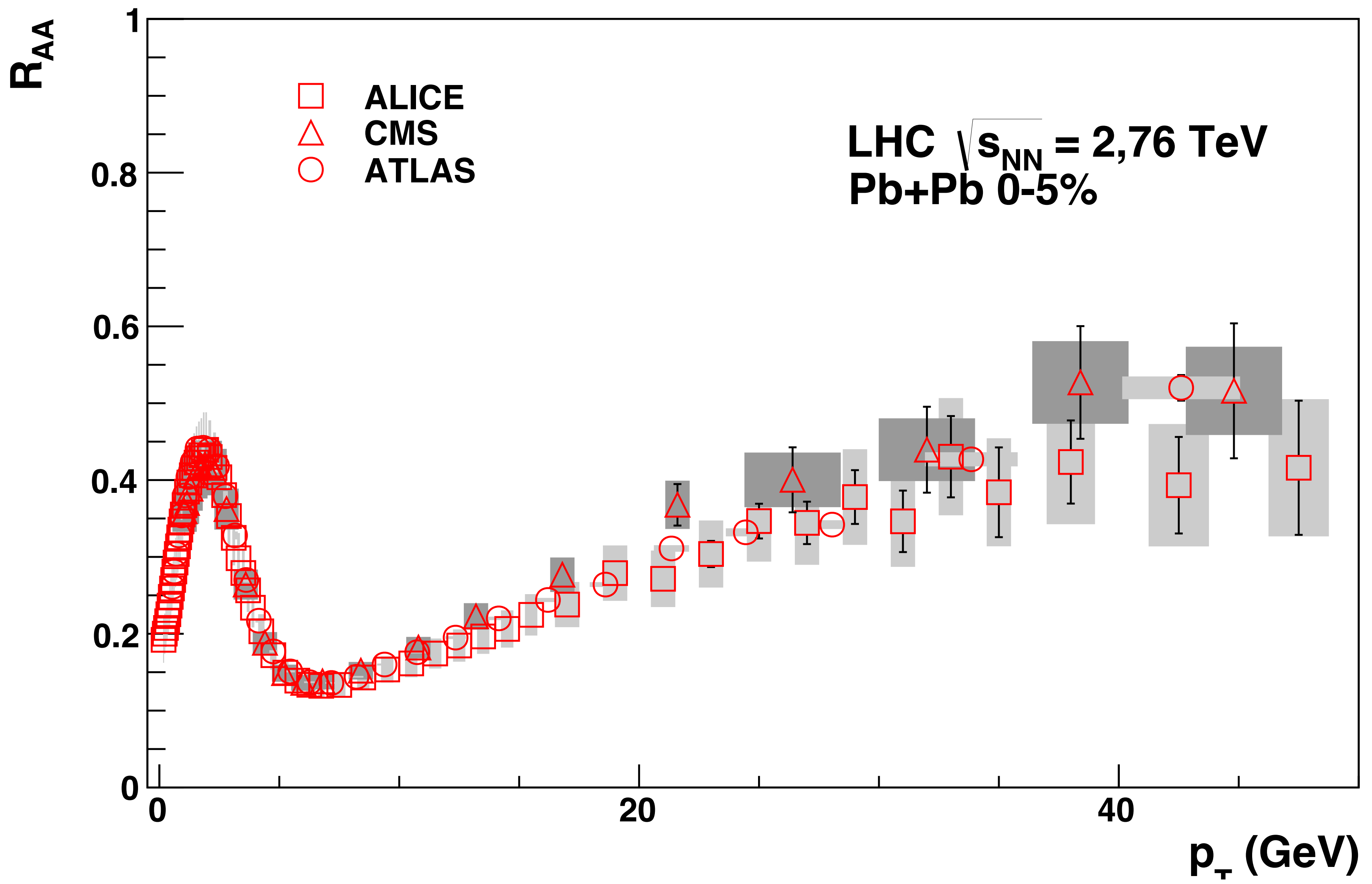
Nuclear modification of p_T spectra

ALICE, PLB720, 52
CMS, EPJC, 72, 1945
ATLAS, arXiv:1504.04337

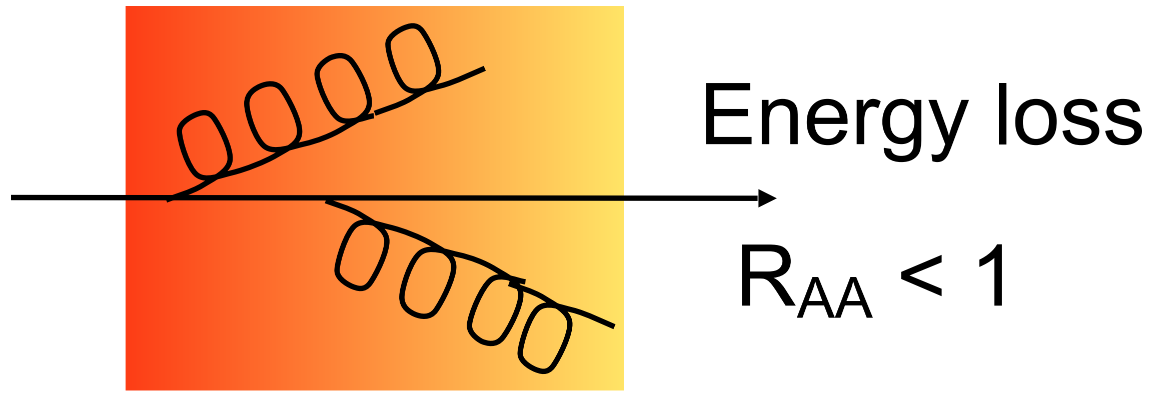
Charged particle p_T spectra



Nuclear modification factor



$$R_{AA} = \frac{dN/dp_T|_{A+A}}{N_{coll}\ dN/dp_T|_{p+p}}$$

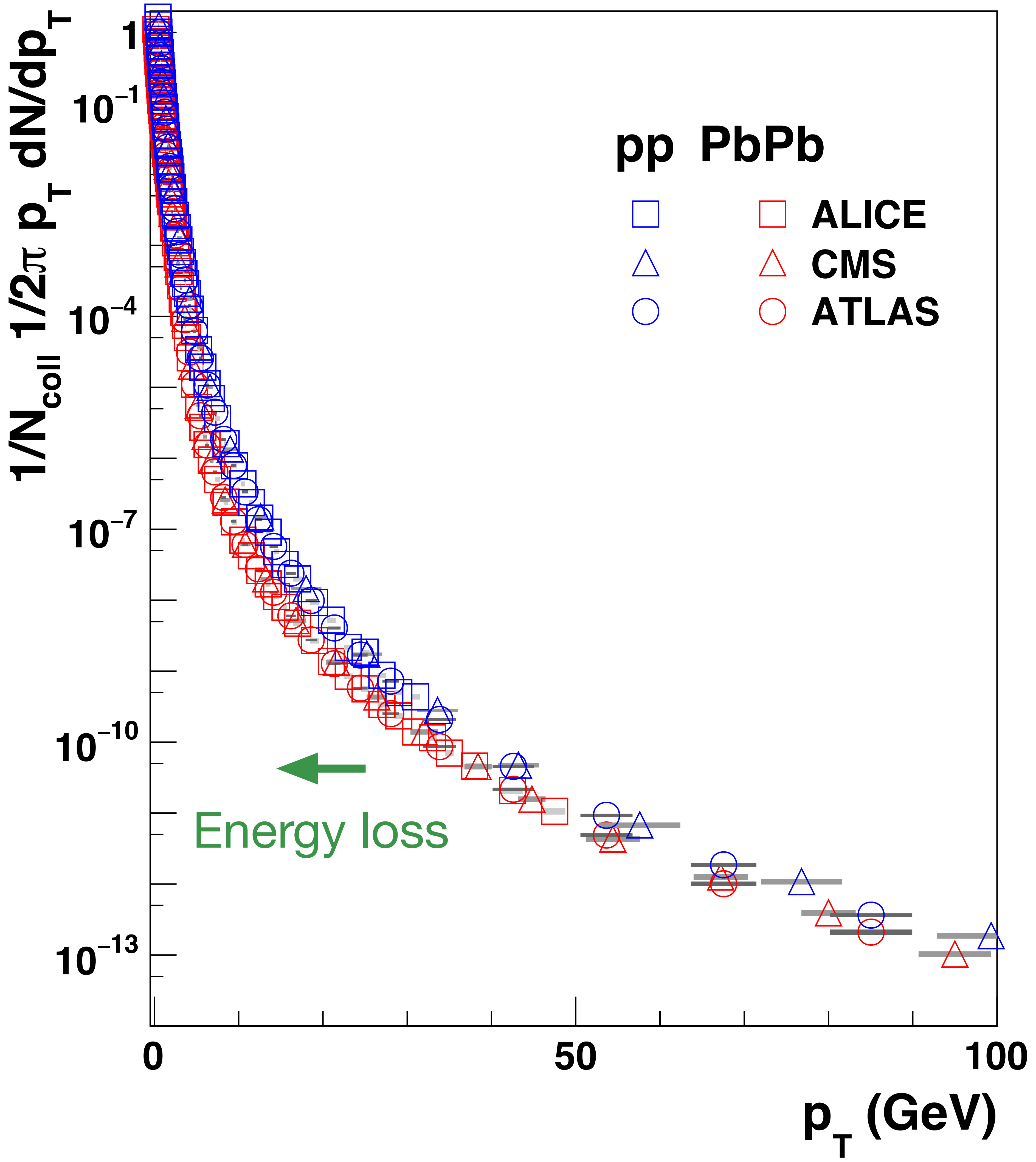


Pb+Pb: clear suppression ($R_{AA} < 1$): parton energy loss

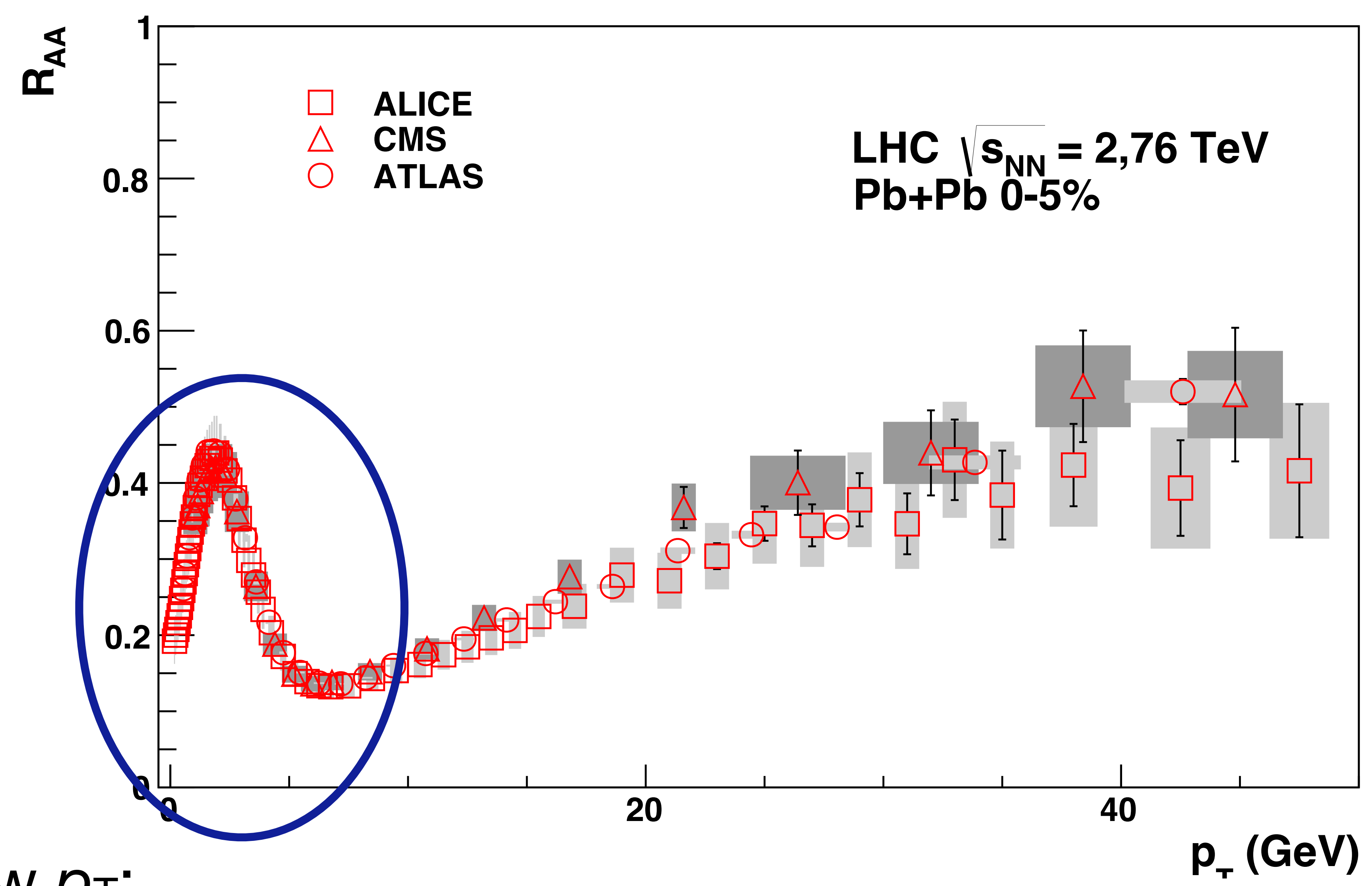
Nuclear modification of p_T spectra

ALICE, PLB720, 52
CMS, EPJC, 72, 1945
ATLAS, arXiv:1504.04337

Charged particle p_T spectra

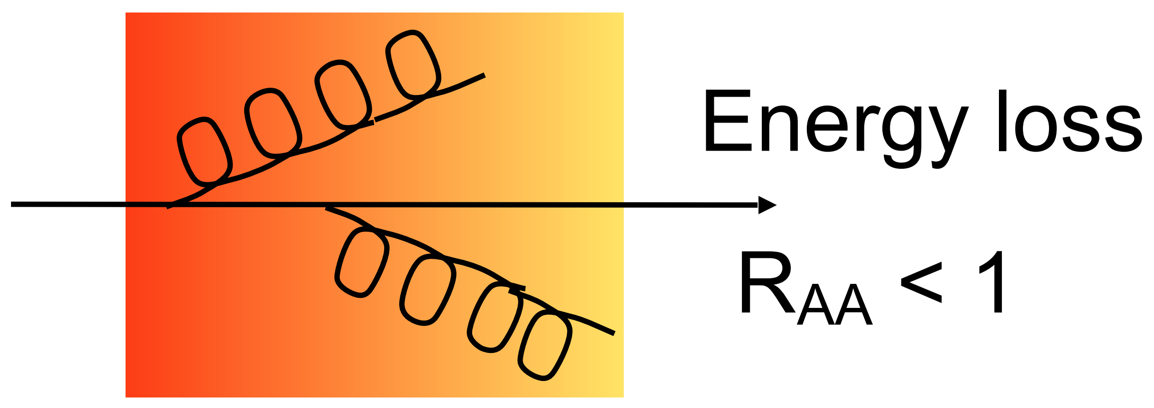


Nuclear modification factor



Low p_T:
soft production,
N_{part} scaling

$$R_{AA} = \frac{dN/dp_T|_{A+A}}{N_{coll}\; dN/dp_T|_{p+p}}$$

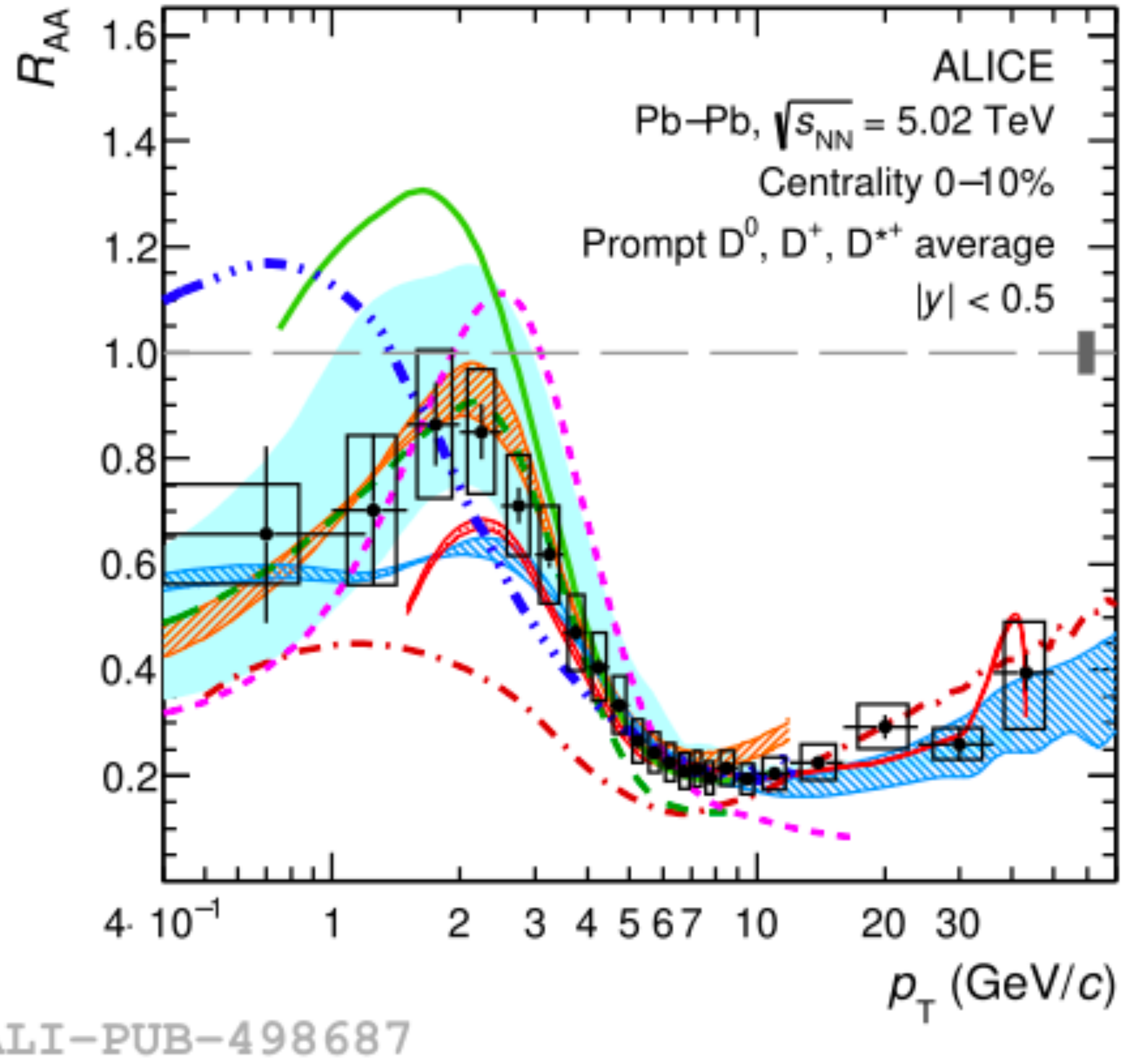


Pb+Pb: clear suppression ($R_{AA} < 1$): parton energy loss

Nuclear modification and elliptic flow of D mesons

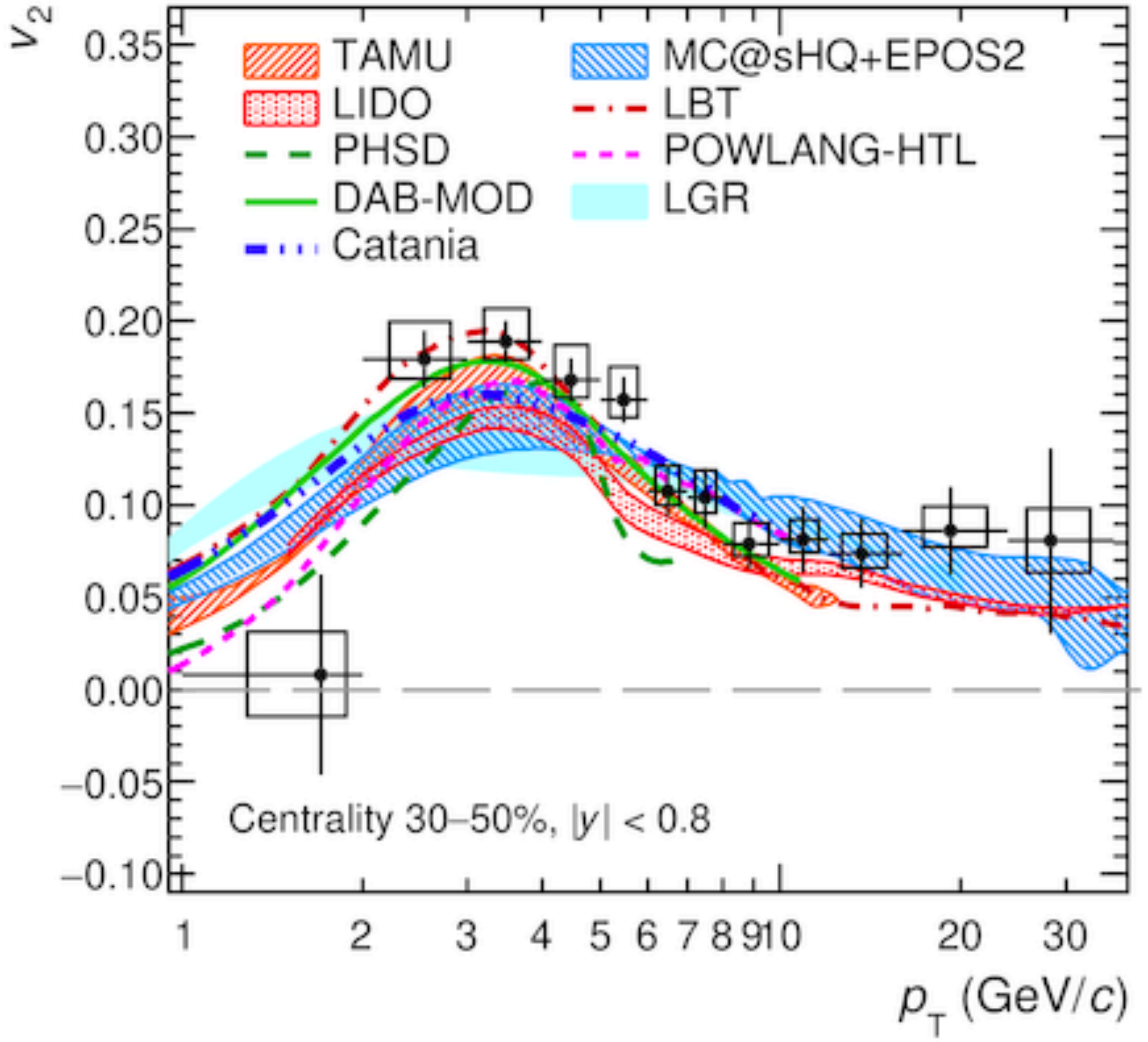
D mesons contain a charm quark m >> T, that is produced in an initial hard scattering

Nuclear modification factor



ALICE, JHEP 01 (2022) 174

Elliptic flow v_2

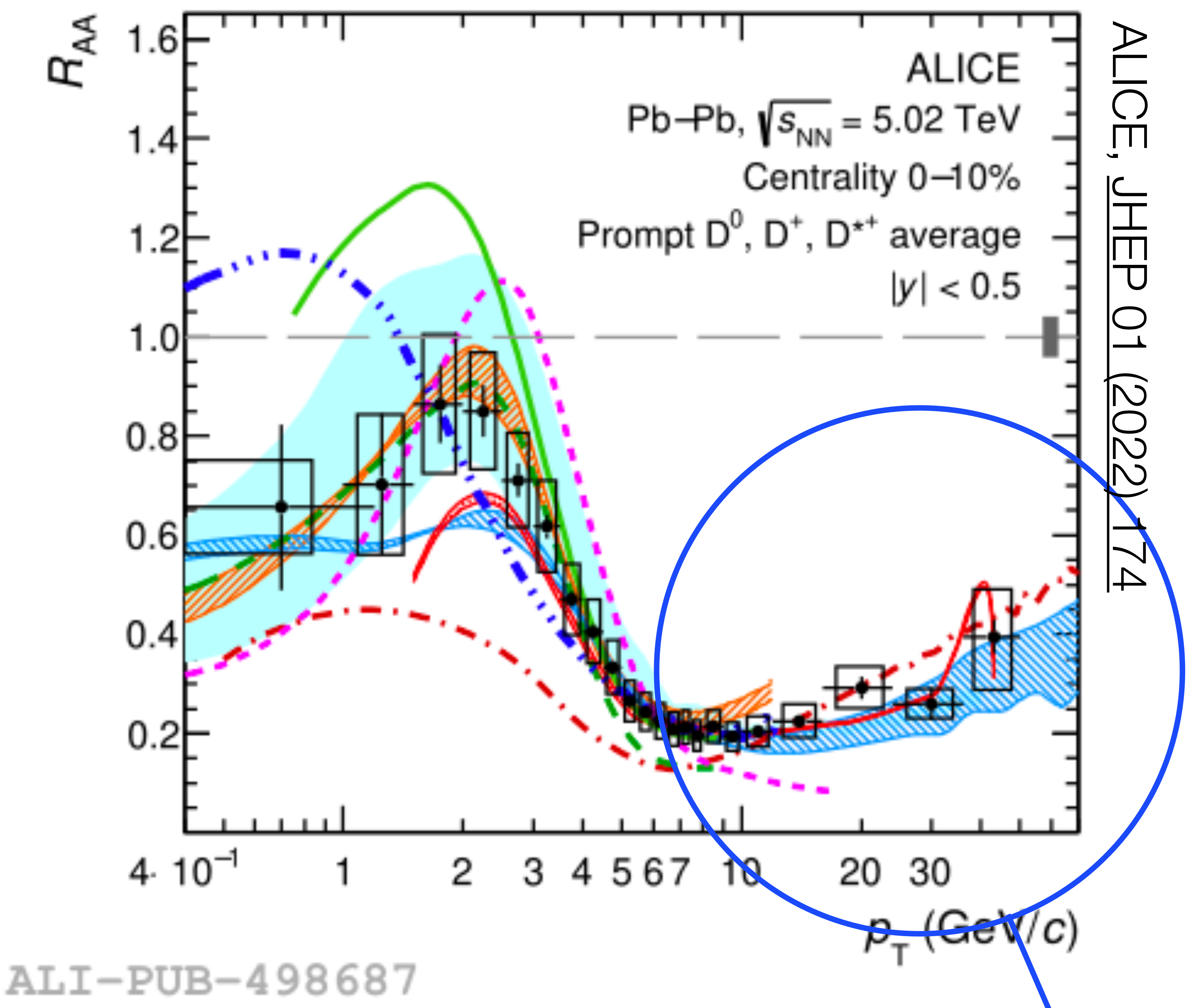


ALICE, JHEP 01 (2022) 174

Nuclear modification and elliptic flow of D mesons

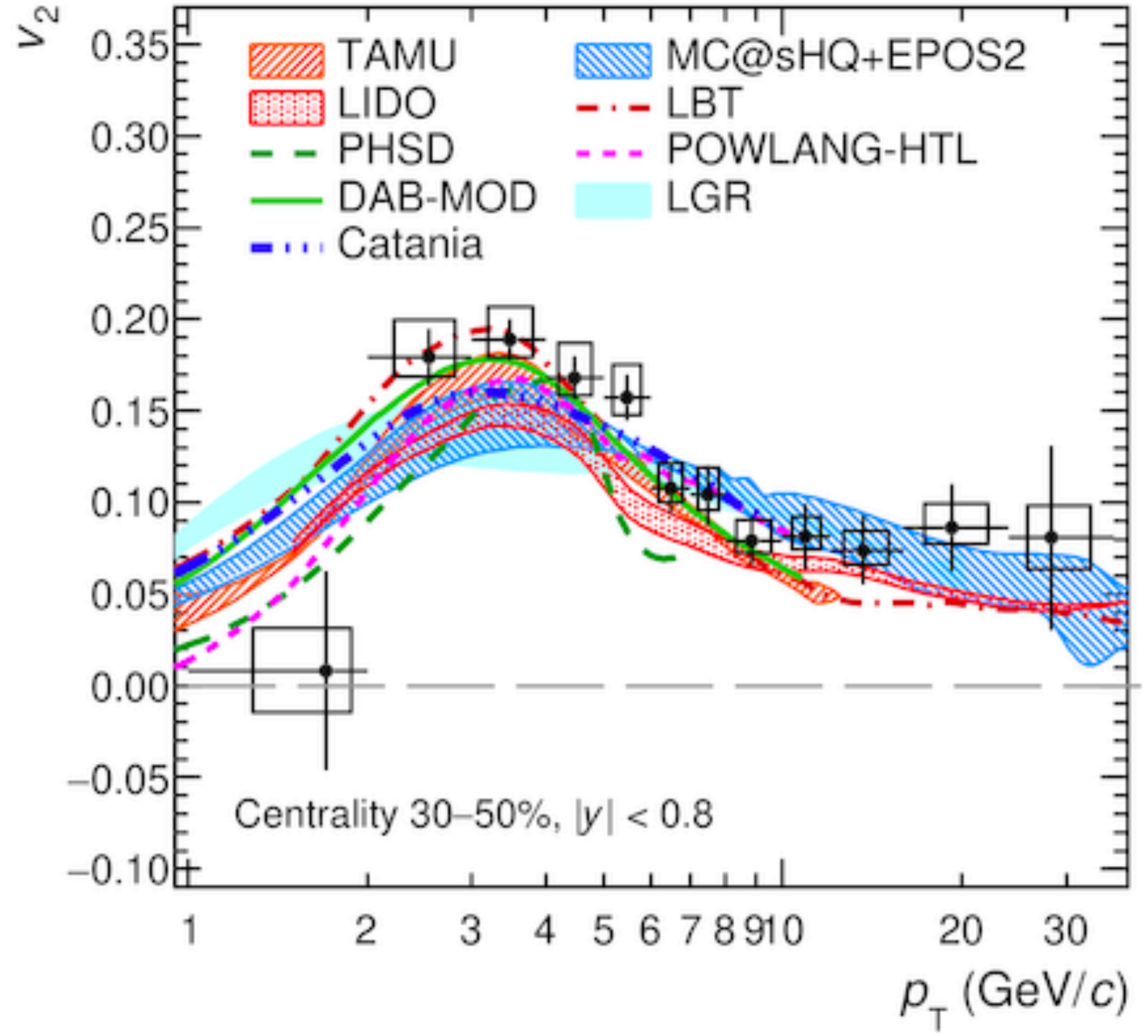
D mesons contain a charm quark m >> T, that is produced in an initial hard scattering

Nuclear modification factor



ALICE, JHEP 01 (2022) 174

Elliptic flow v2



ALICE, JHEP 01 (2022) 174

High-p_T suppression:
due to energy loss

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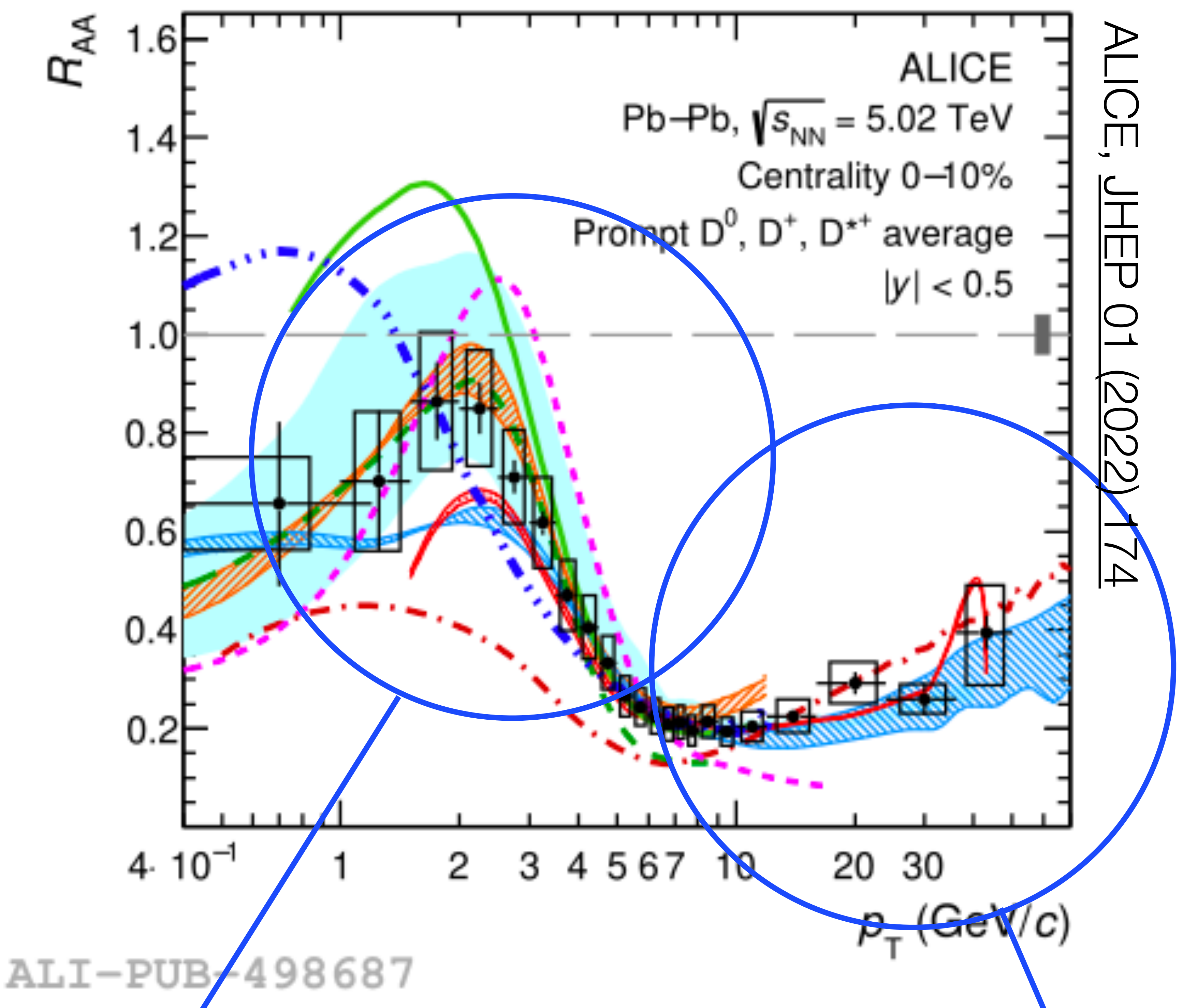

ALICE, JHEP 01 (2022) 174

Low p_T: no change/enhancement: charm conservation + diffusion

High-p_T suppression: due to energy loss

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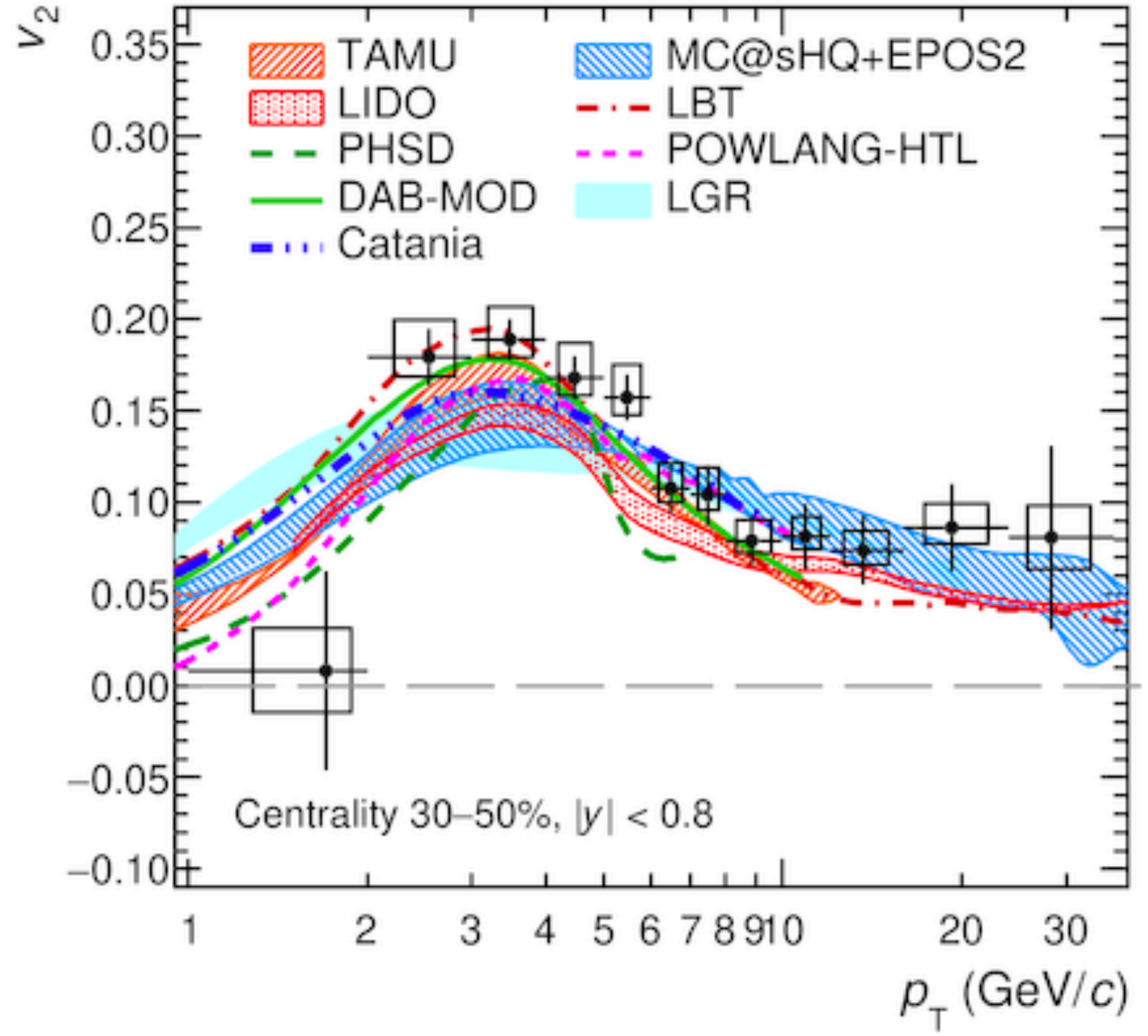

ALICE, JHEP 01 (2022) 174

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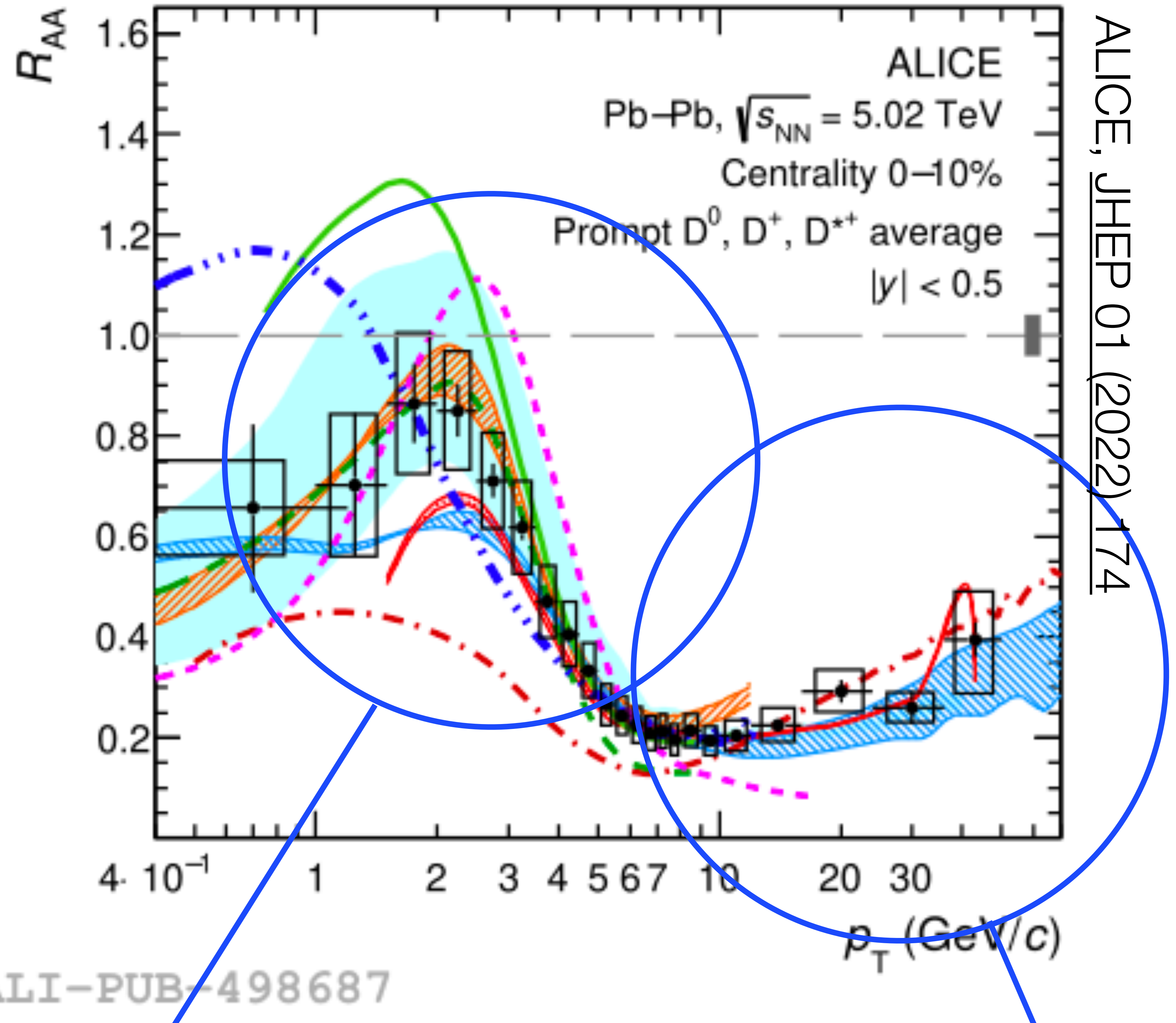

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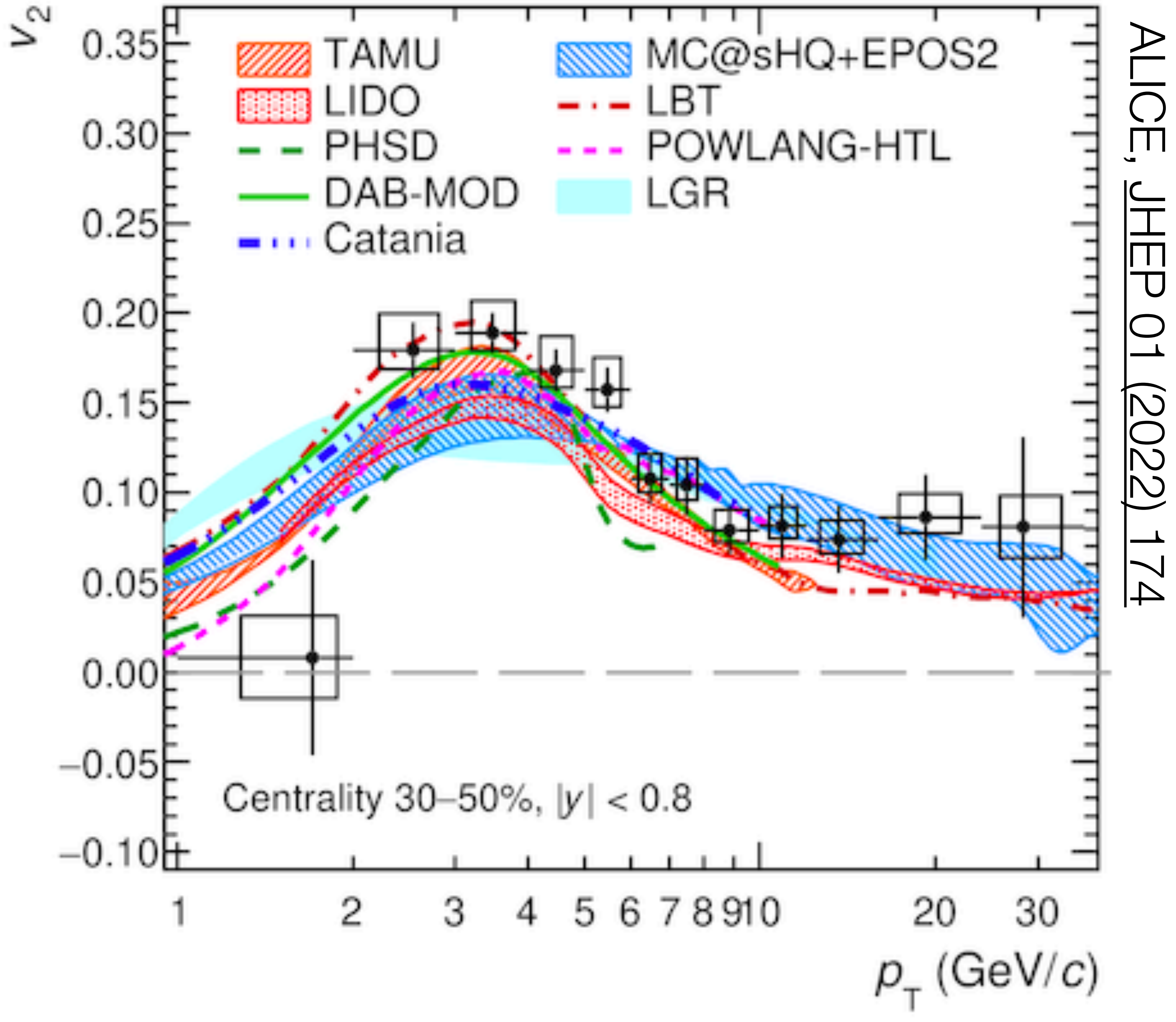
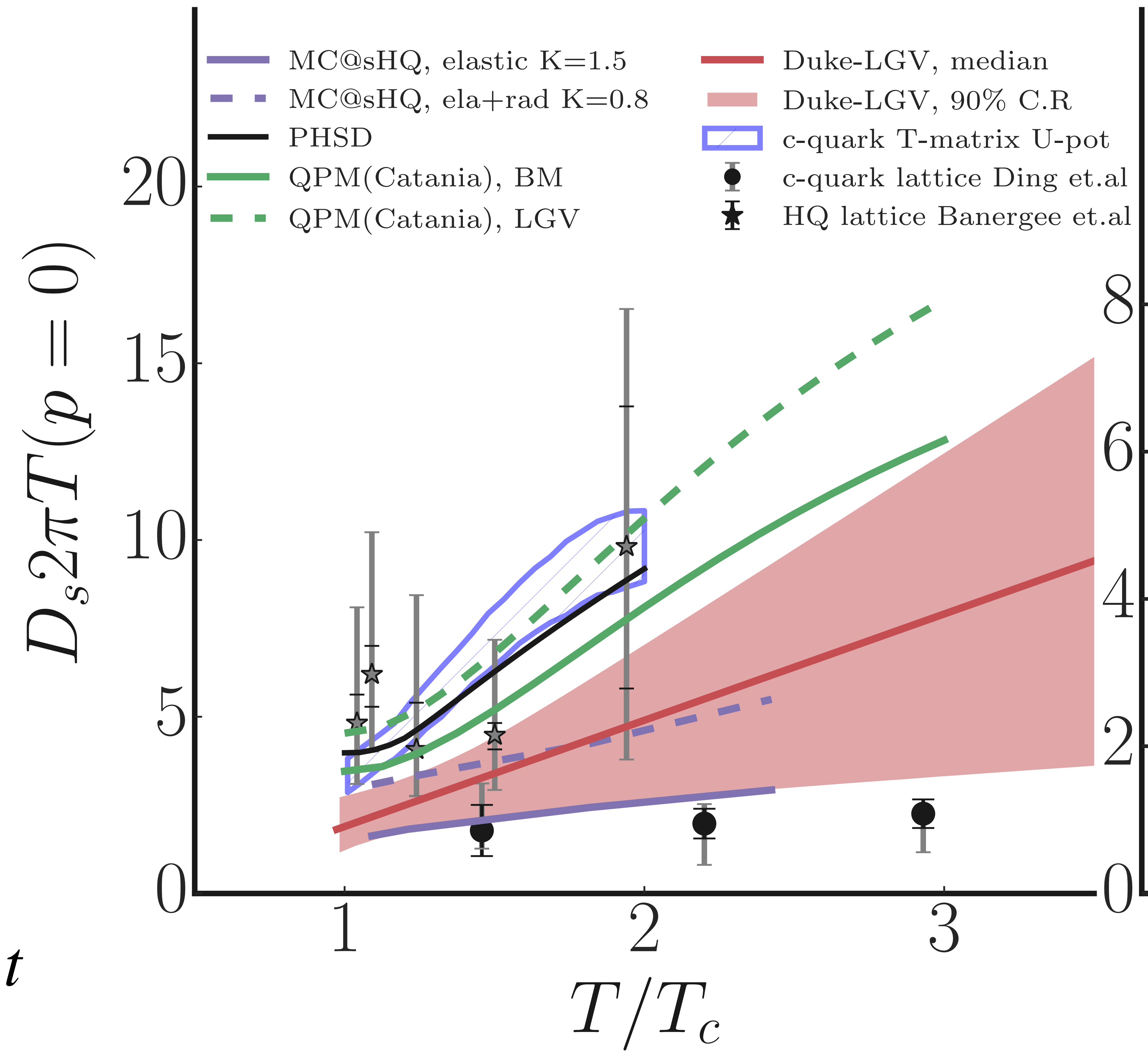


Azimuthal anisotropy:
Full effect generated by interactions

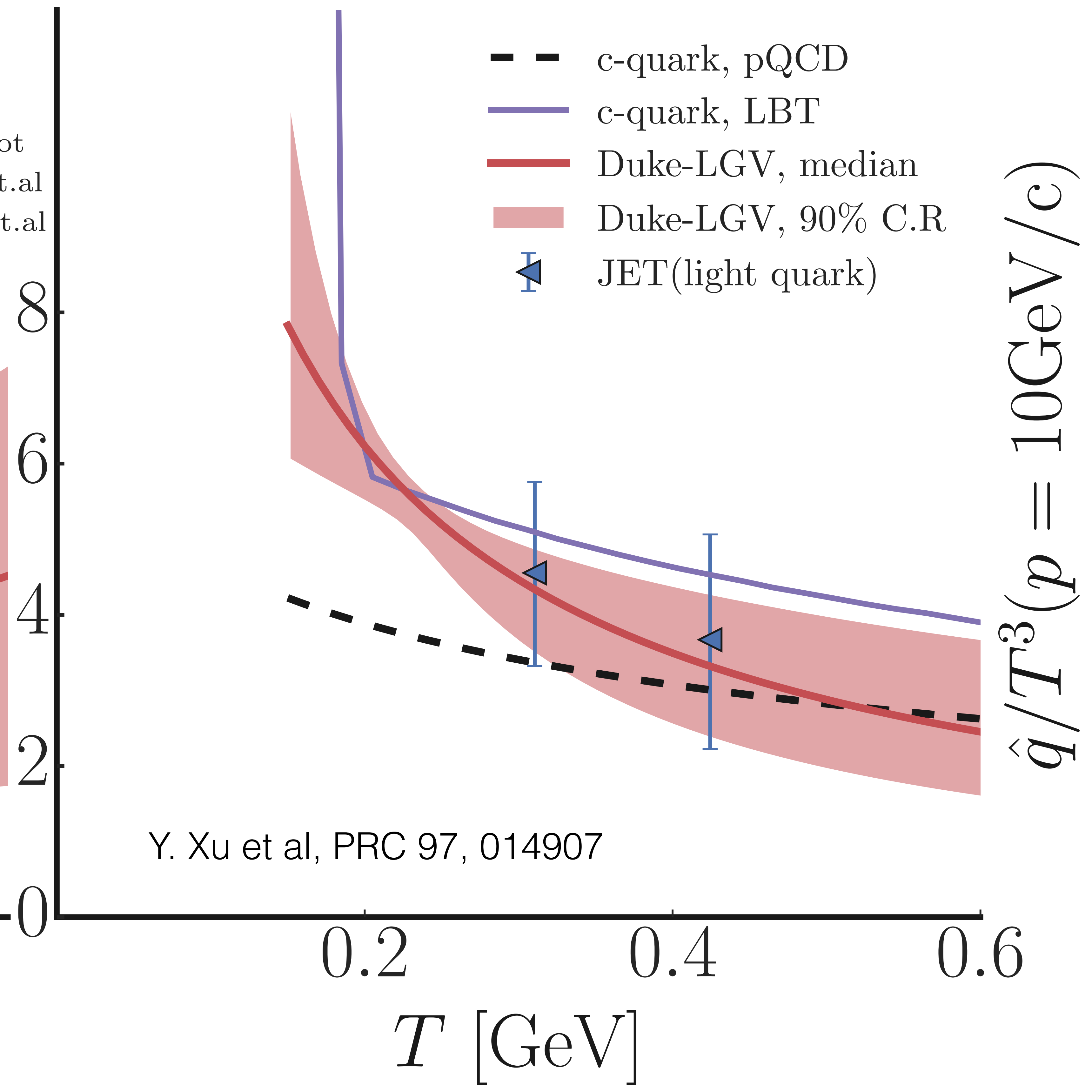
Heavy flavor transport coefficient: Bayesian fit

Diffusion coefficient D_s



$$\langle r^2 \rangle = 6\, D_s\, t$$

Transport coefficient $\hat{q}$



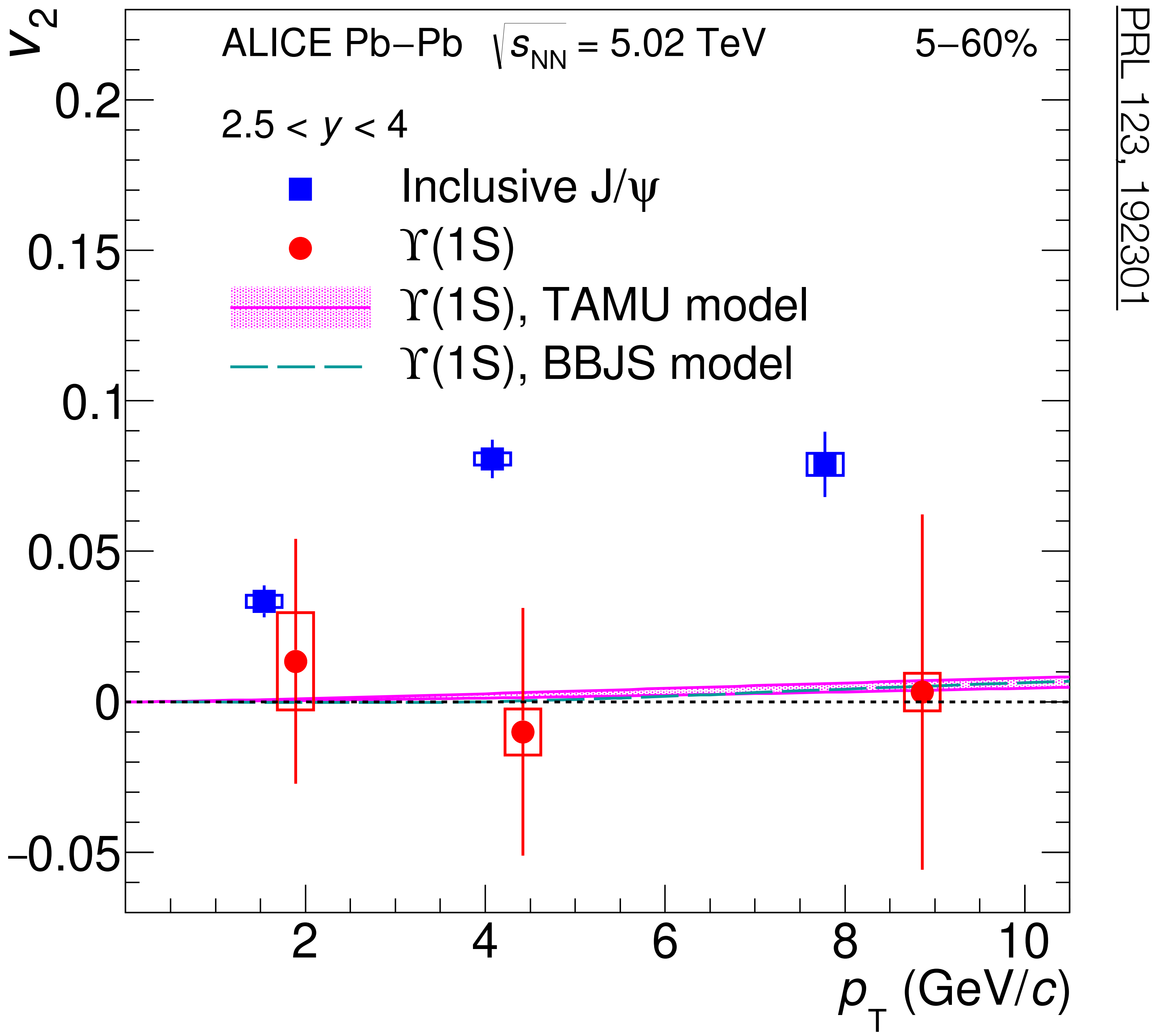
$$\hat{q} = \frac{\langle q_\perp^2 \rangle}{\lambda}$$

Data constrain transport properties of the QGP

Results agree with lattice QCD/pQCD expectations
and between light and heavy flavour sector

Elliptic flow of charm beauty quarks: effect of mass

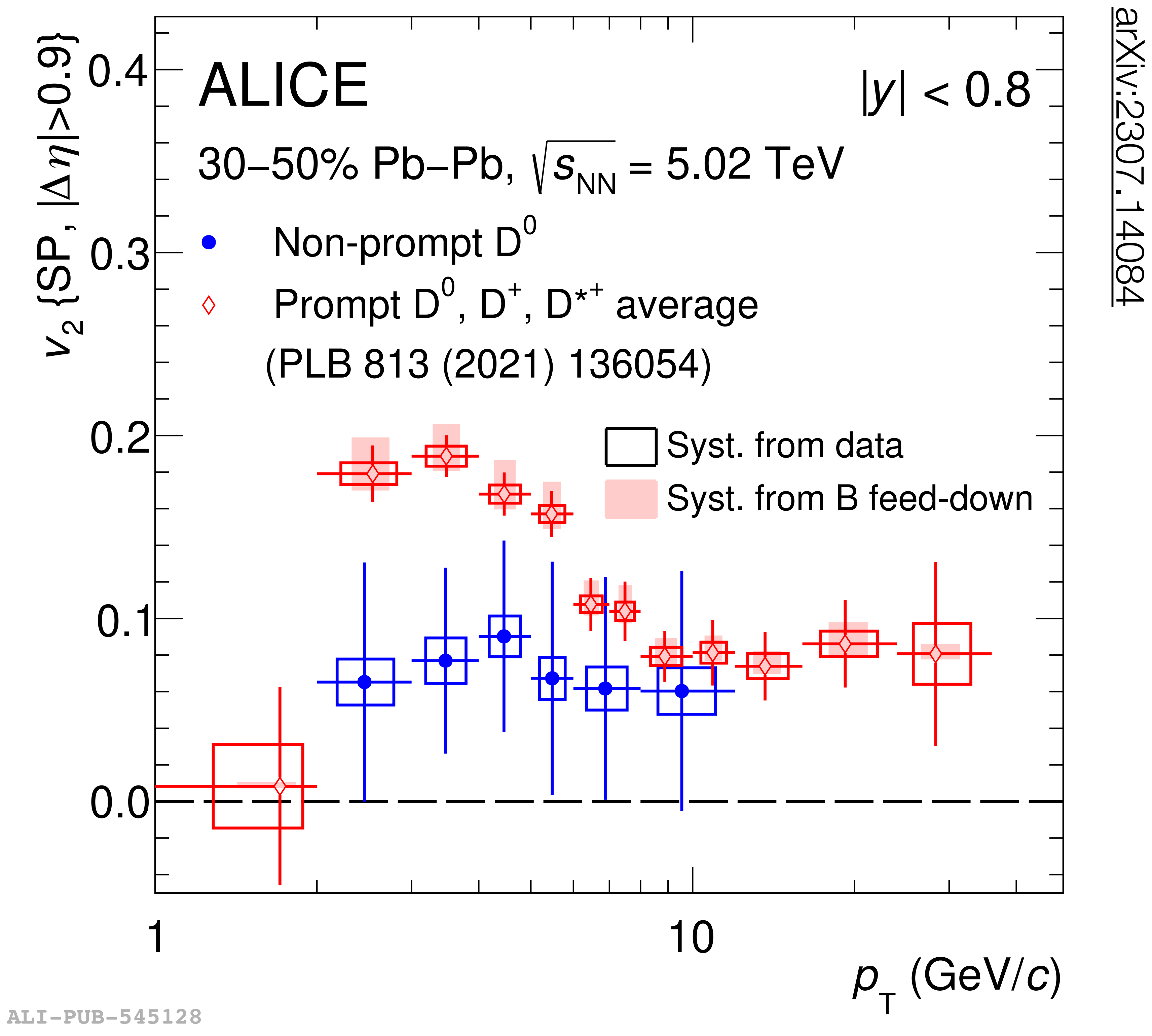
J/ψ ($c\bar{c}$) and Υ ($b\bar{b}$) elliptic flow



Quarkonia: flow generated by quark flow and coalescence

Charmonia: large elliptic flow — Bottomonia: compatible with no flow

Open charm, beauty elliptic flow



Non-prompt D mesons (open beauty) show smaller v_2

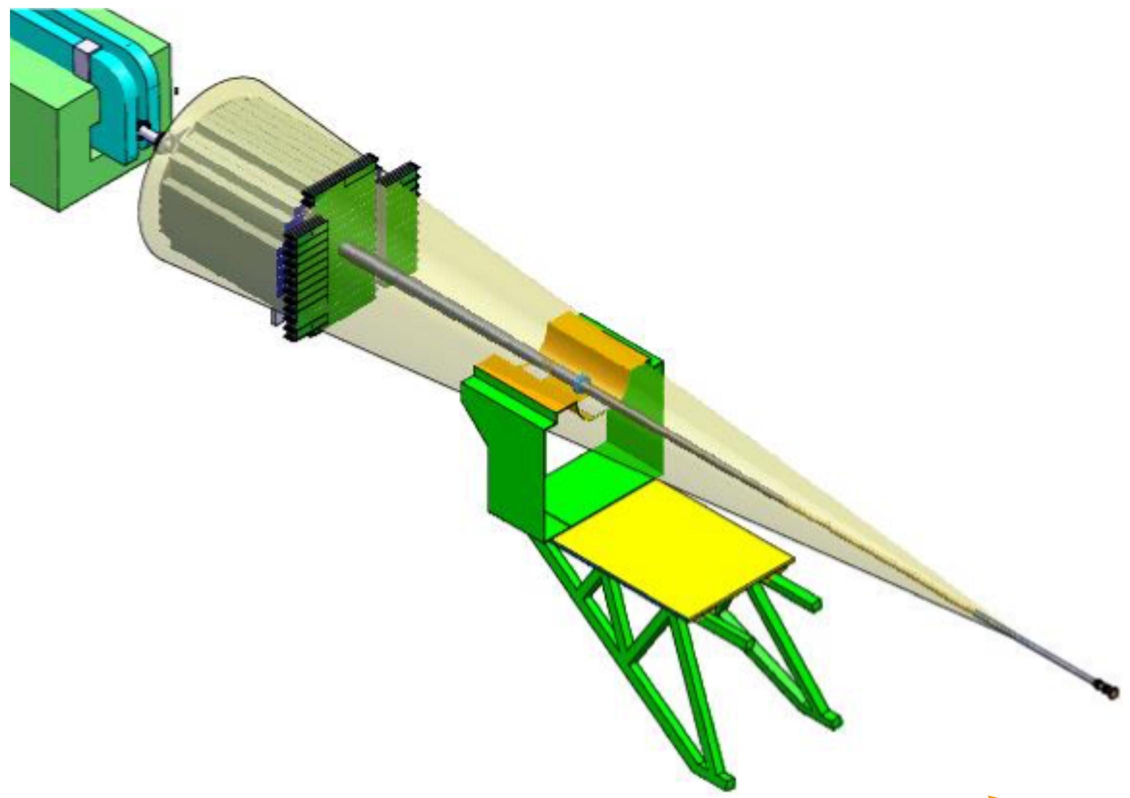
Beauty quarks flow less than charm quarks: larger mass, slower thermalisation

Open and hidden flavor allow to investigate impact of hadronisation, light quark flow

Future plans: upgrades

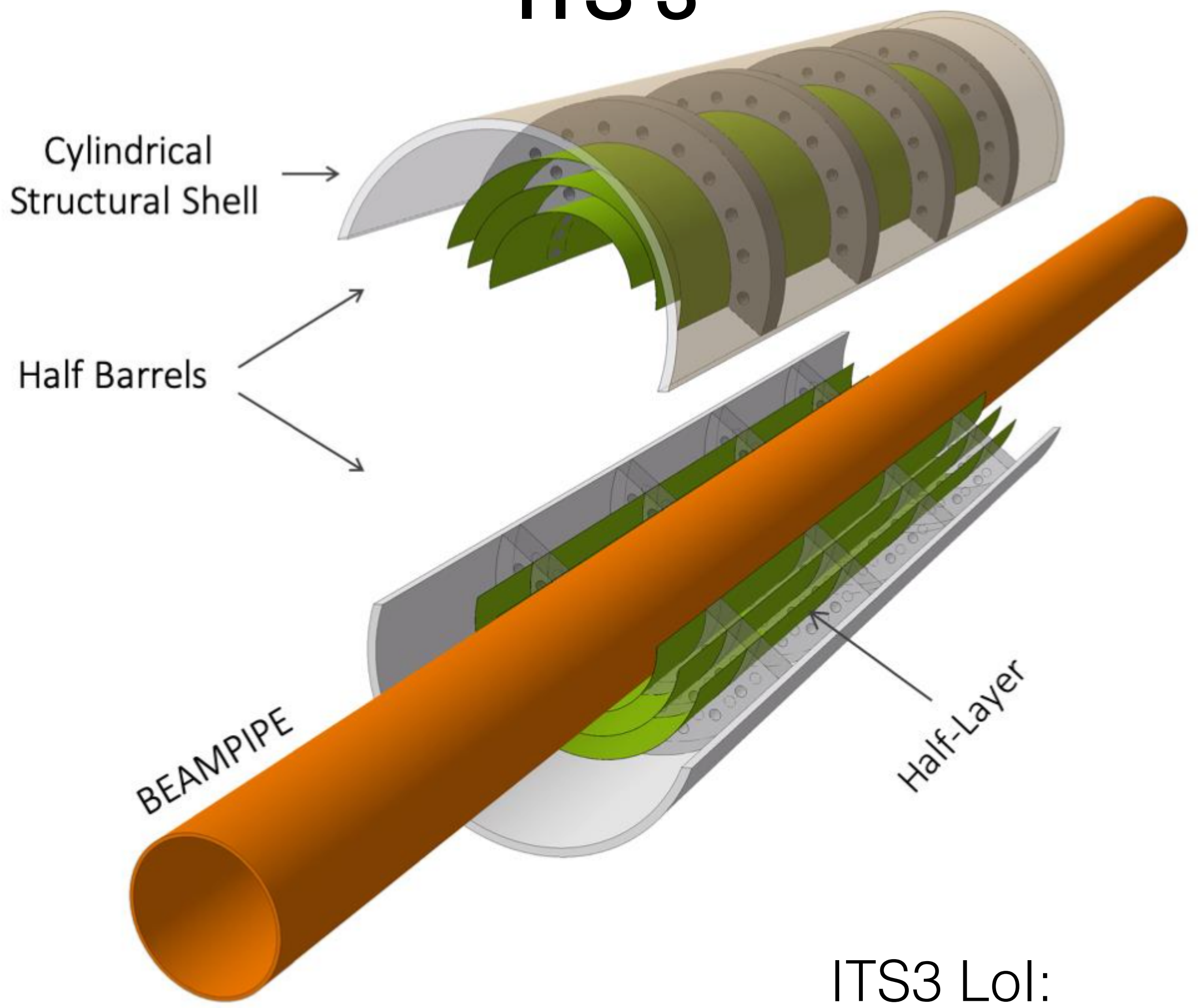
LS3 upgrades

Forward Calorimeter



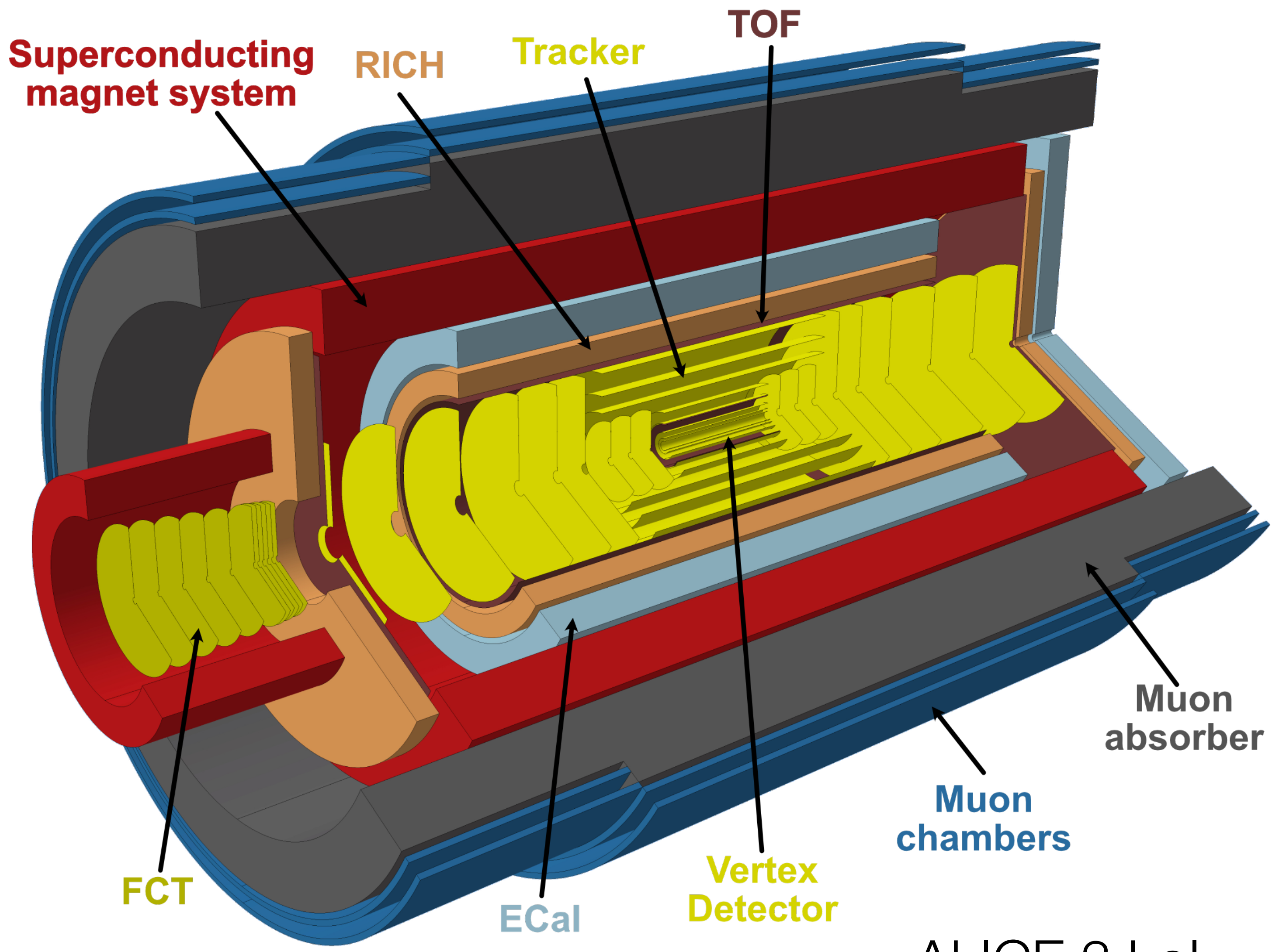
FoCal LoI:
CERN-LHCC-2020-009

ITS 3

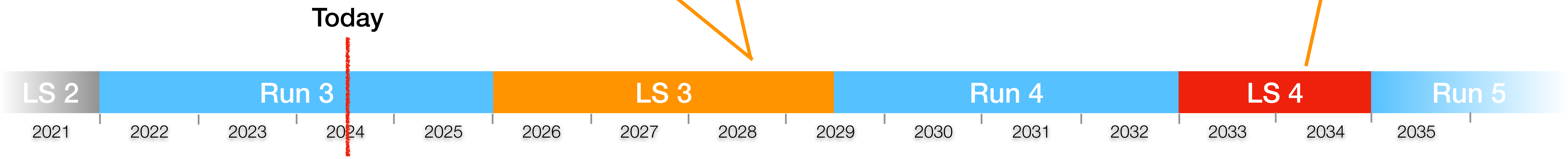


ITS3 LoI:
CERN-LHCC-2019-018

ALICE 3: LS4

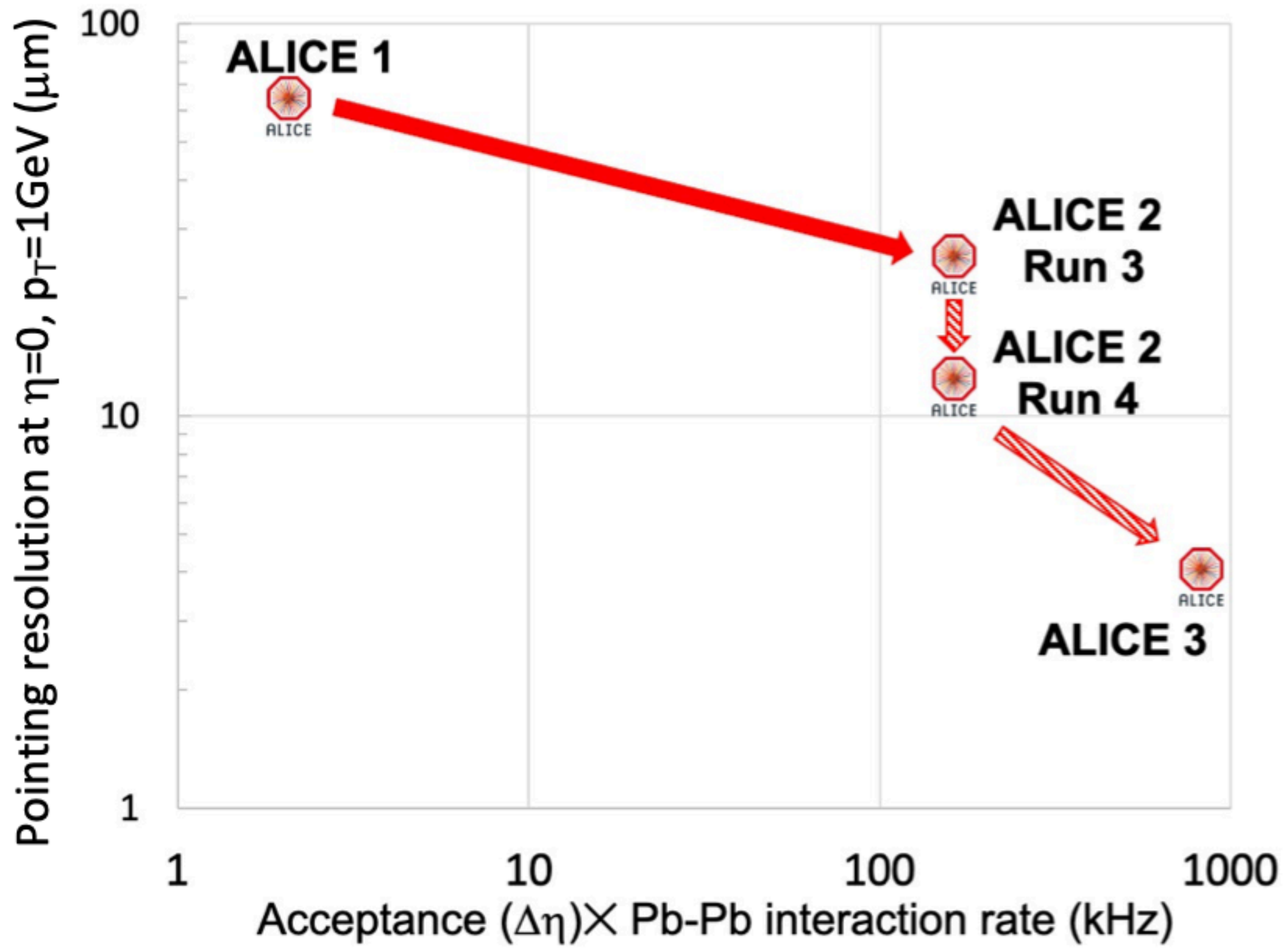


ALICE 3 LoI:
CERN-LHCC-2022-009

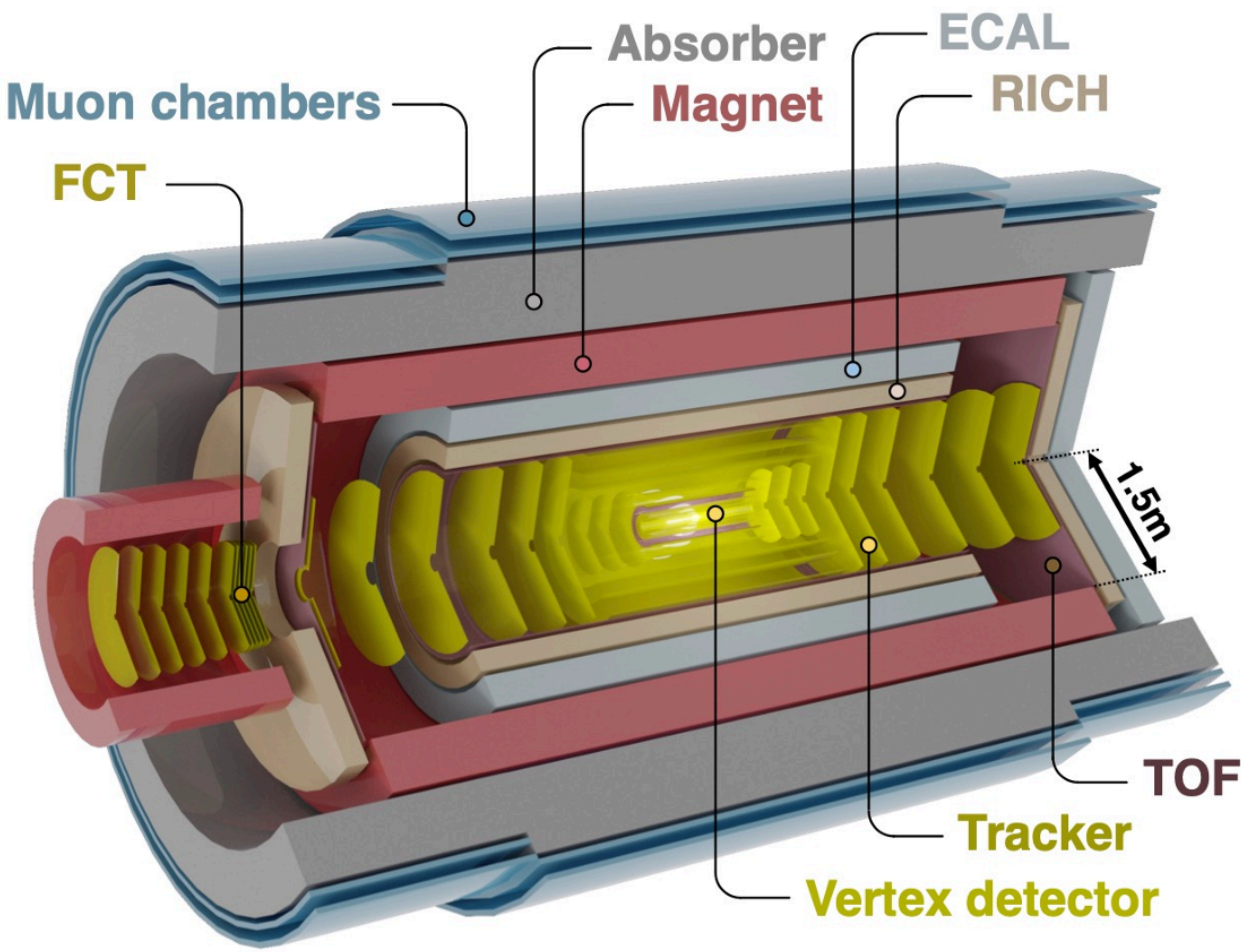


LHC Run 5 and 6: ALICE 3

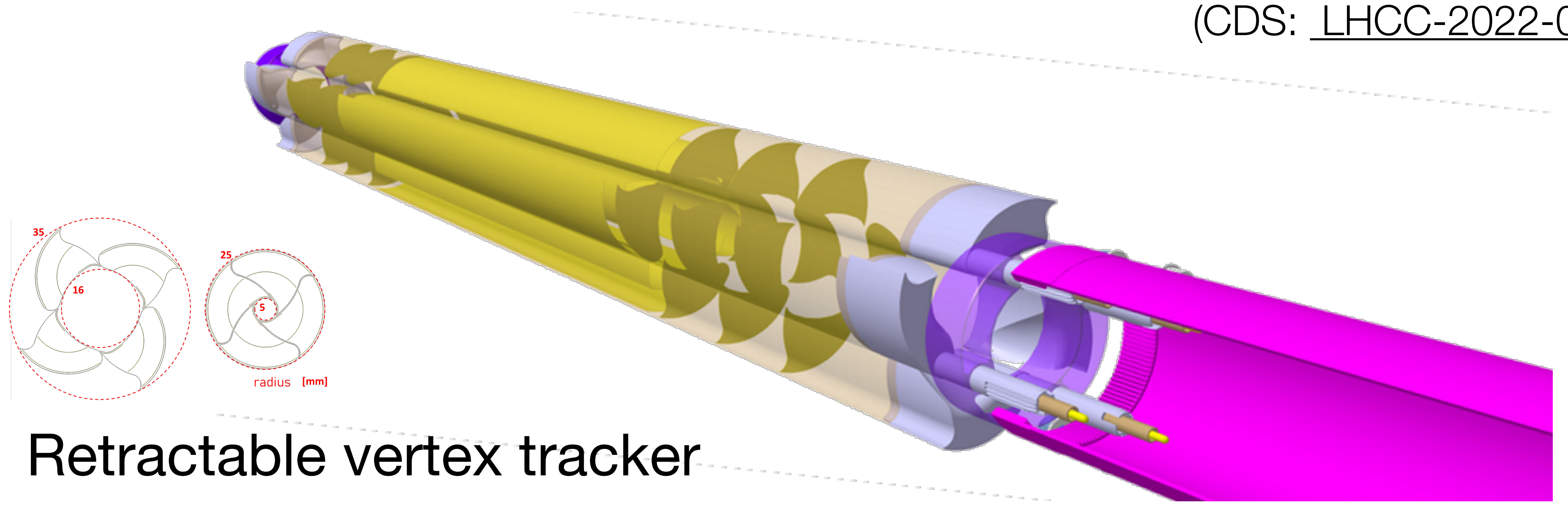
- Compact all-silicon tracker
  with high-resolution vertex detector
- Particle Identification over large acceptance:
  muons, electrons, hadrons, photons
- Fast read-out and online processing



Upgrades: improvements in precision, rate, acceptance



ALICE 3 Letter of Intent
(CDS: LHCC-2022-009)



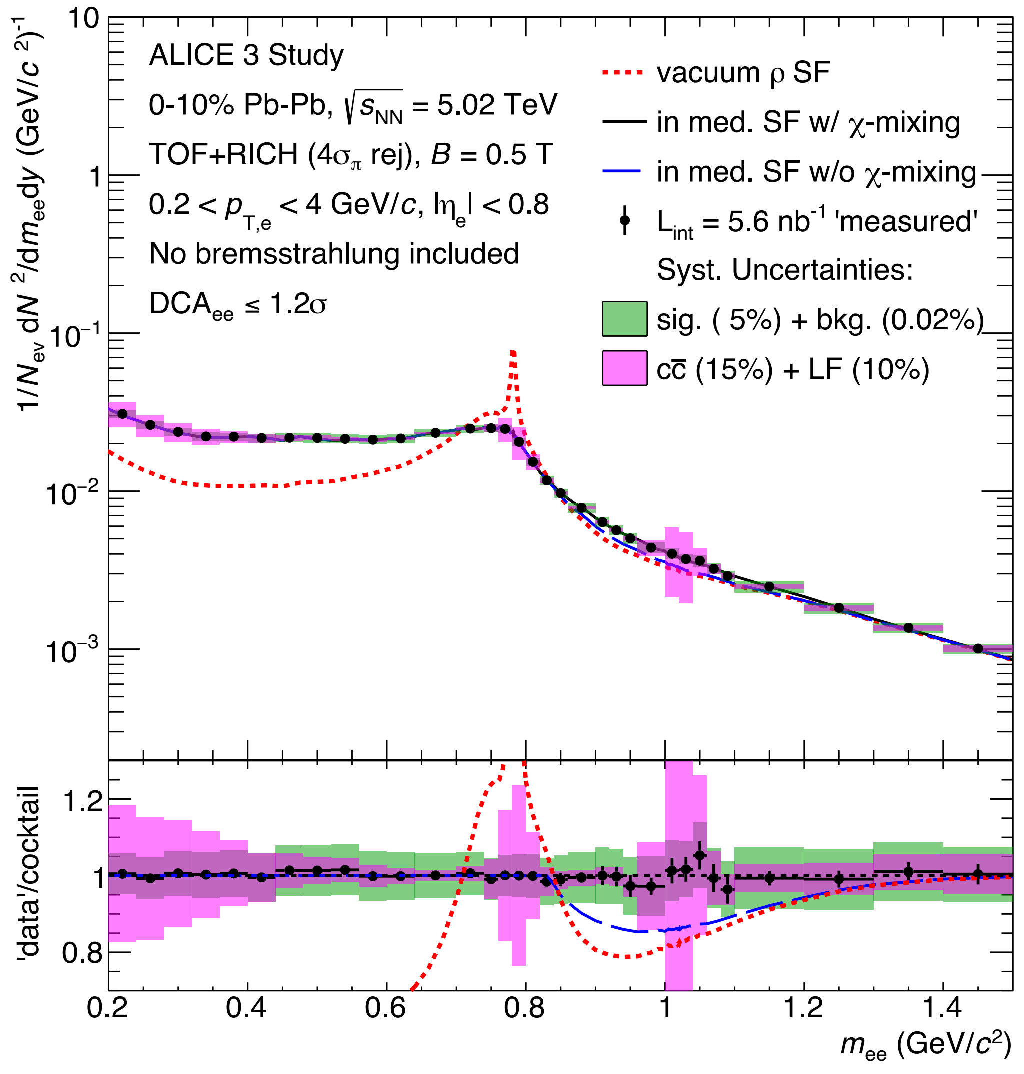
Retractable vertex tracker

ALICE 3 physics program

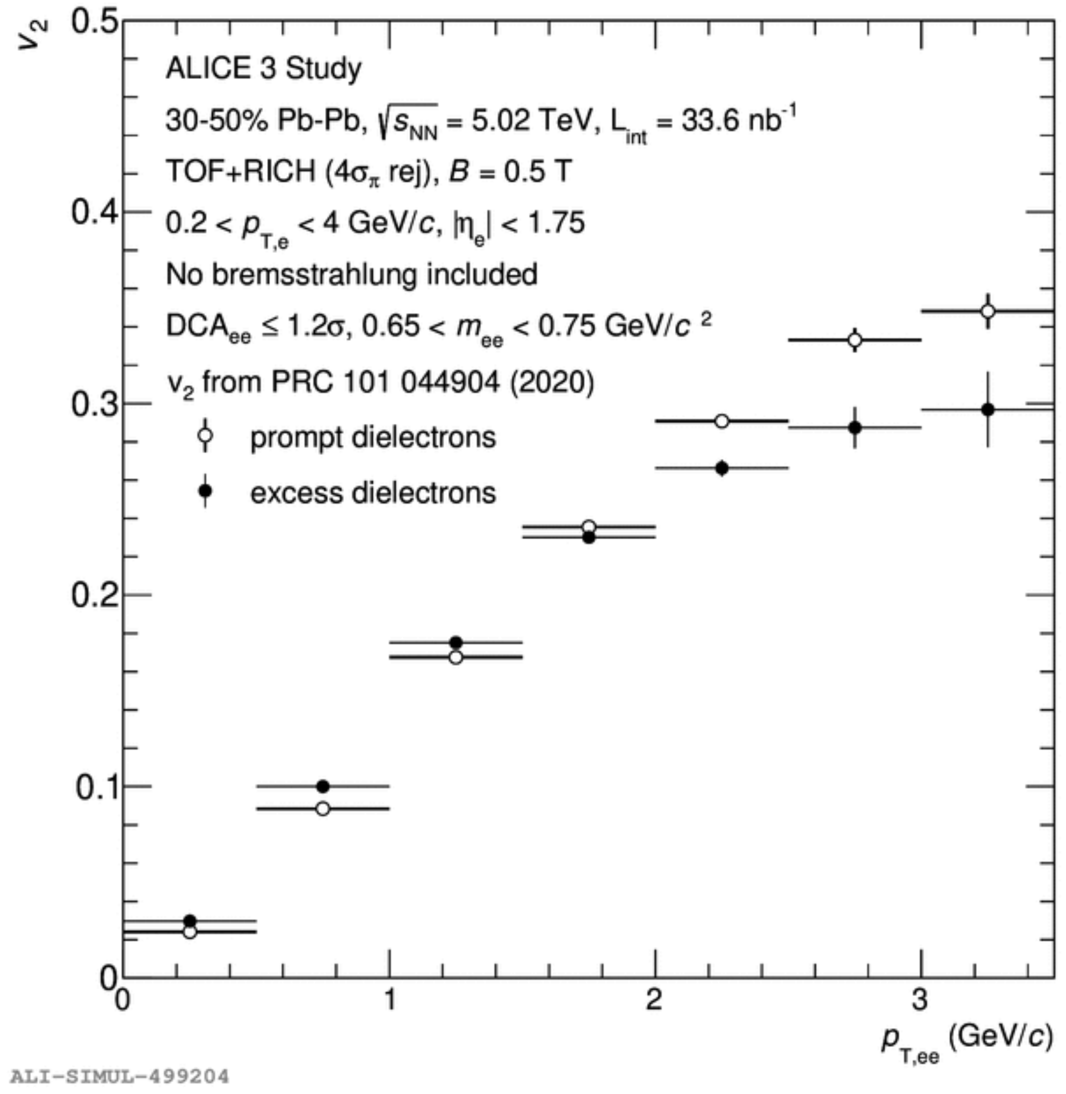
- Thermal radiation from the QGP phase and chiral symmetry restoration
  - Dilepton production
- Interactions of heavy flavour hadrons with the QGP — thermalisation
  - $D\overline{D}$ azimuthal correlations
  - Multi-charm baryon production
  - P-wave quarkonia
- Hadron physics — structure of exotic hadrons
  - Femtoscopic correlations
  - Production exotic in pp, PbPb
- …

ALICE 3 Letter of Intent
(CDS: LHCC-2022-009)

Dielectron mass spectrum

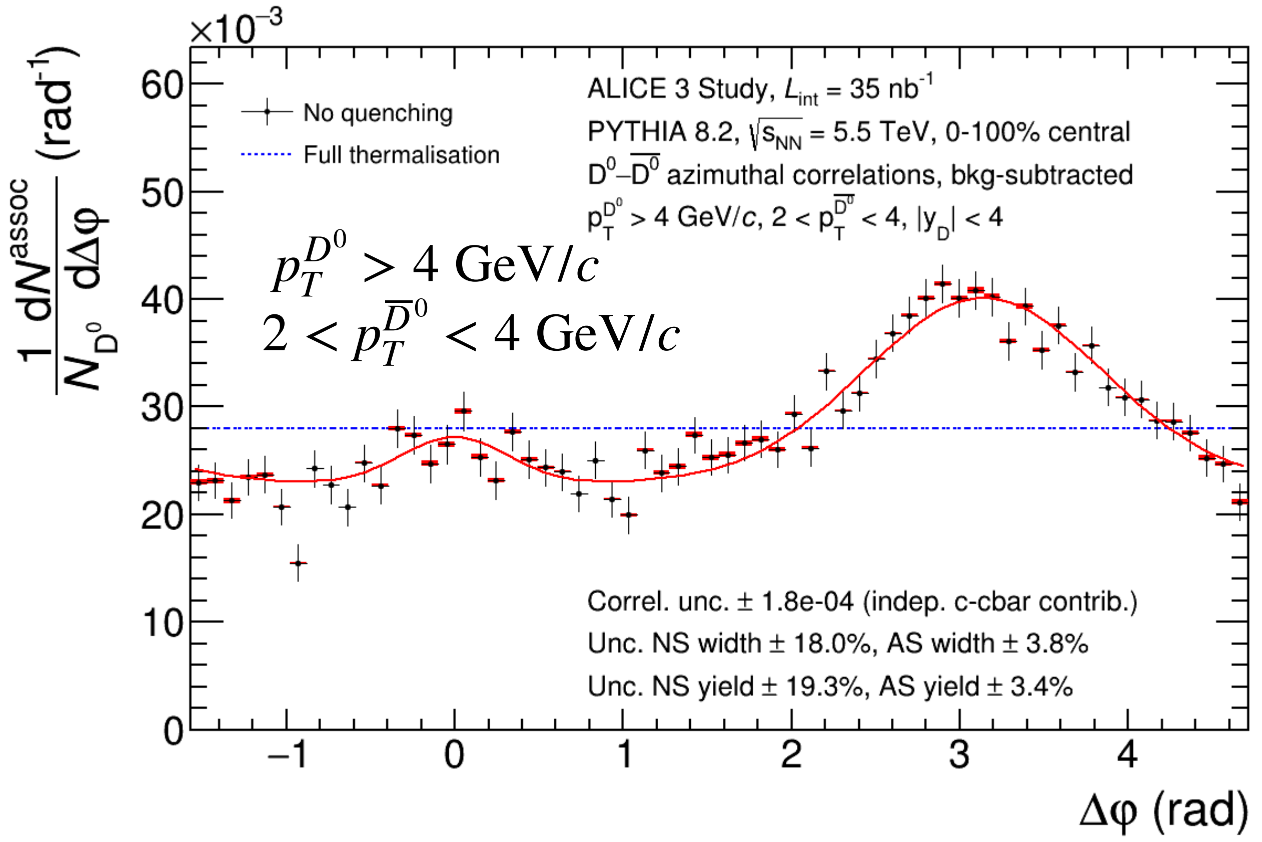


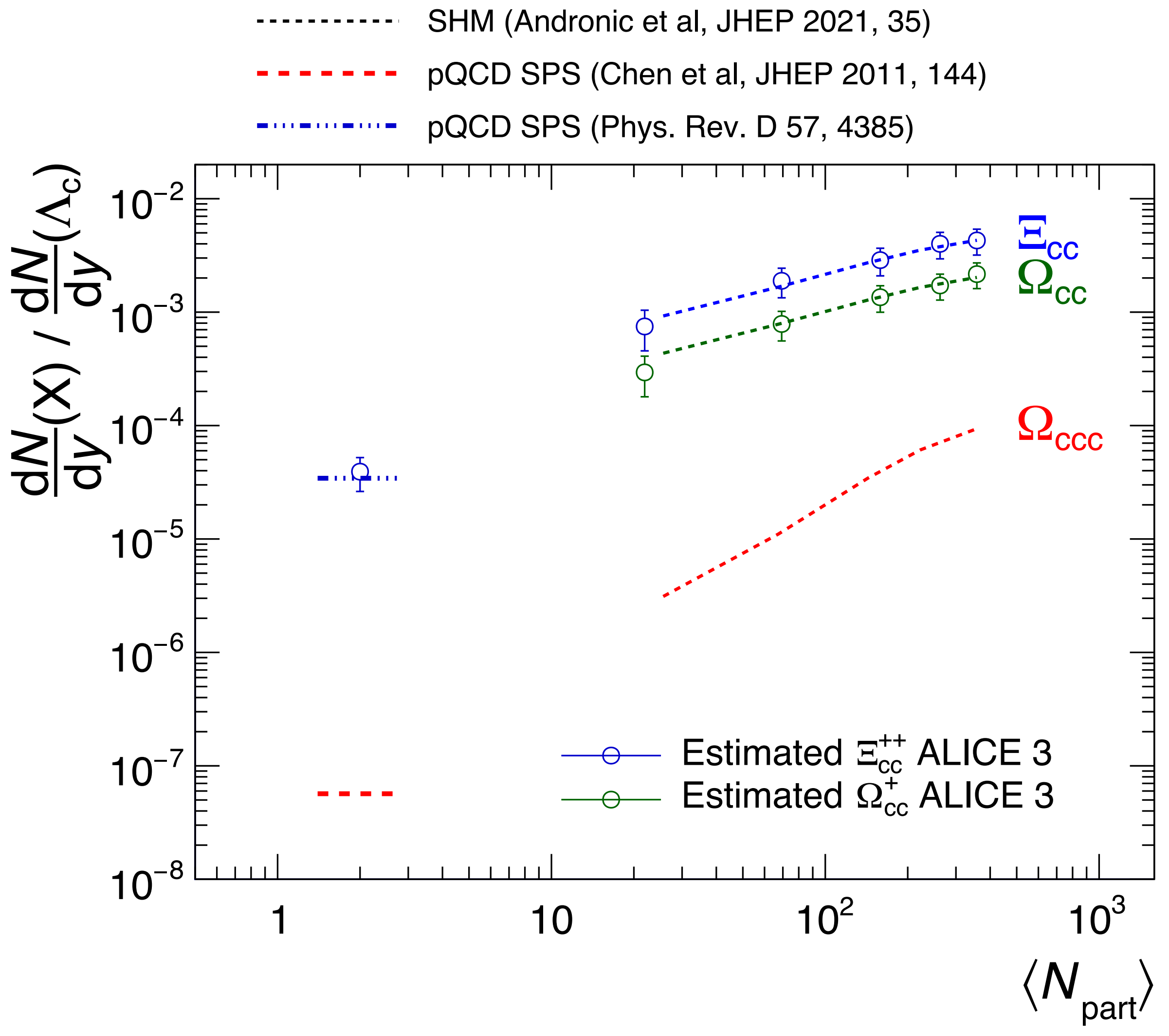
Dielectron v2



access to $\rho - a_1$ mixing, time evolution of temperature

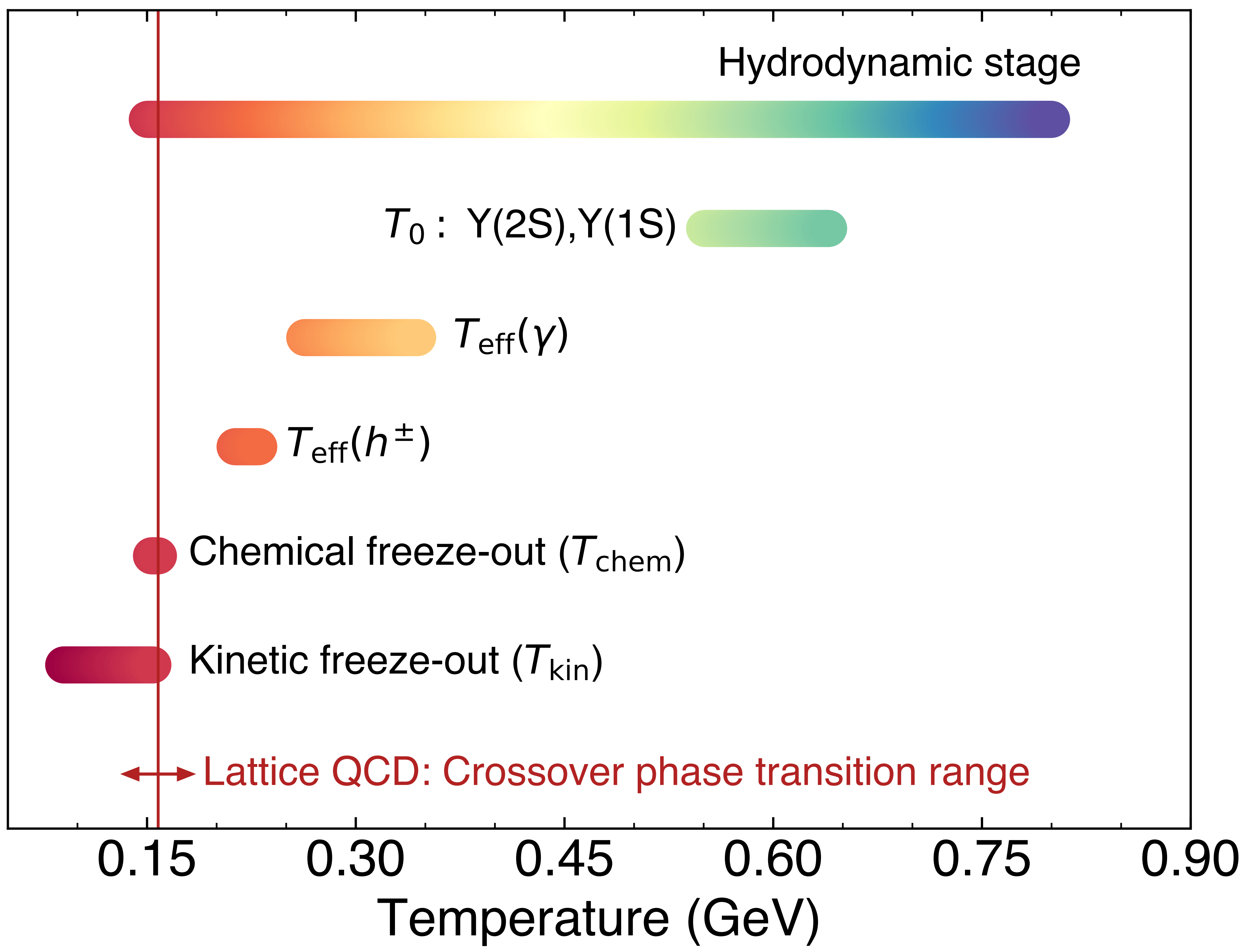
$D\overline{D}$ correlations





Conclusion

- LHC heavy-ion program: multi-body QCD and the properties of strongly interacting matter at high *T*
- Dissociation ('melting') of quarkonia: very high density and *T*
- Determine properties of QGP: viscosity and transport coefficients
  - Viscosity very small: close to lower limit $\eta/s = 1/4\pi$
  - Slower thermalisation for beauty than charm
- First measurements of thermal radiation expected with upgraded detector in Run 3 + 4
  - ALICE 3: next-generation upgrade for run 5 and 6



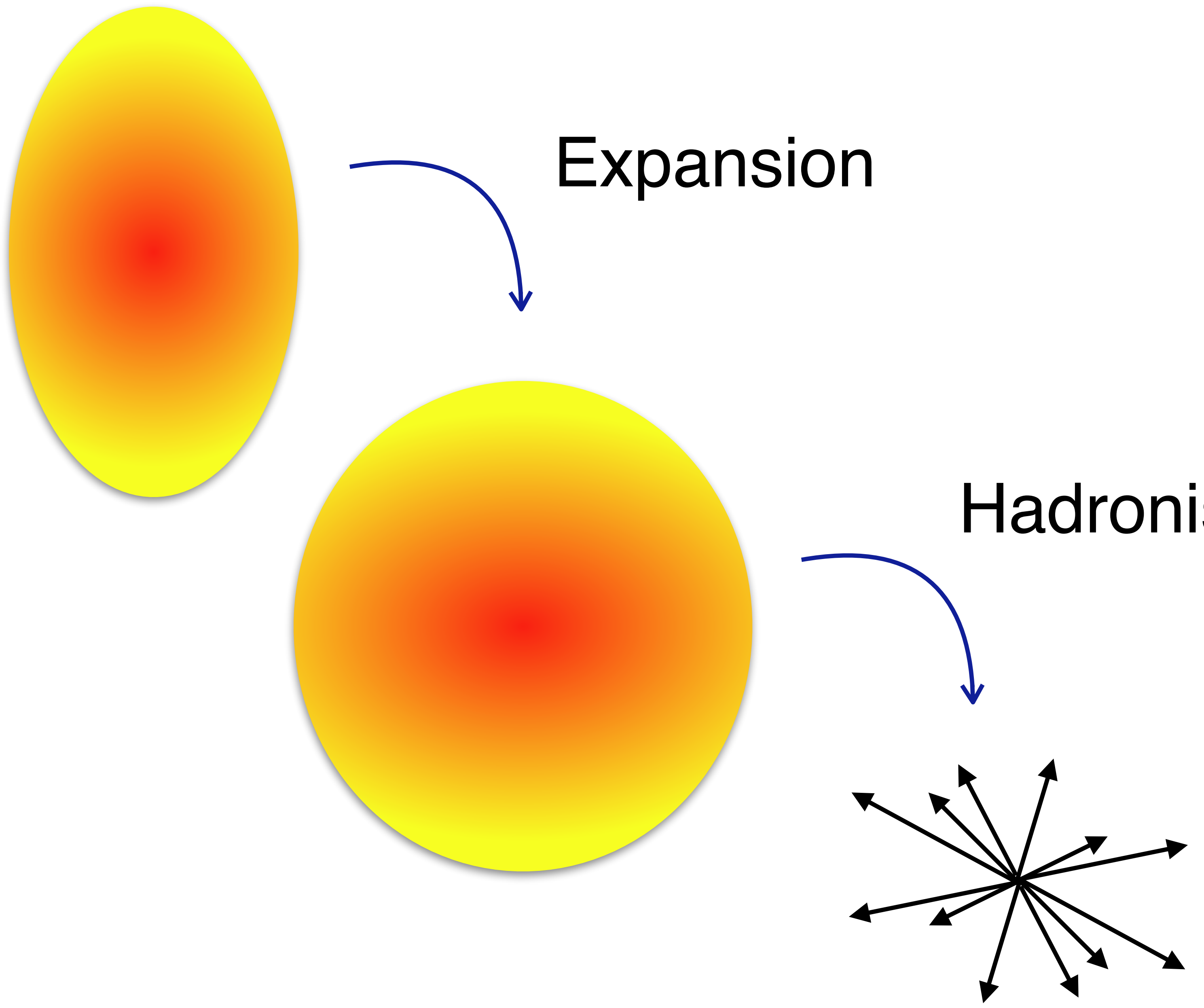
ALICE, arXiv:2211.04384


Thank you for your attention

Azimuthal anisotropy: two mechanisms

Hydrodynamical expansion

Conversion of pressure gradients into momentum space anisotropy



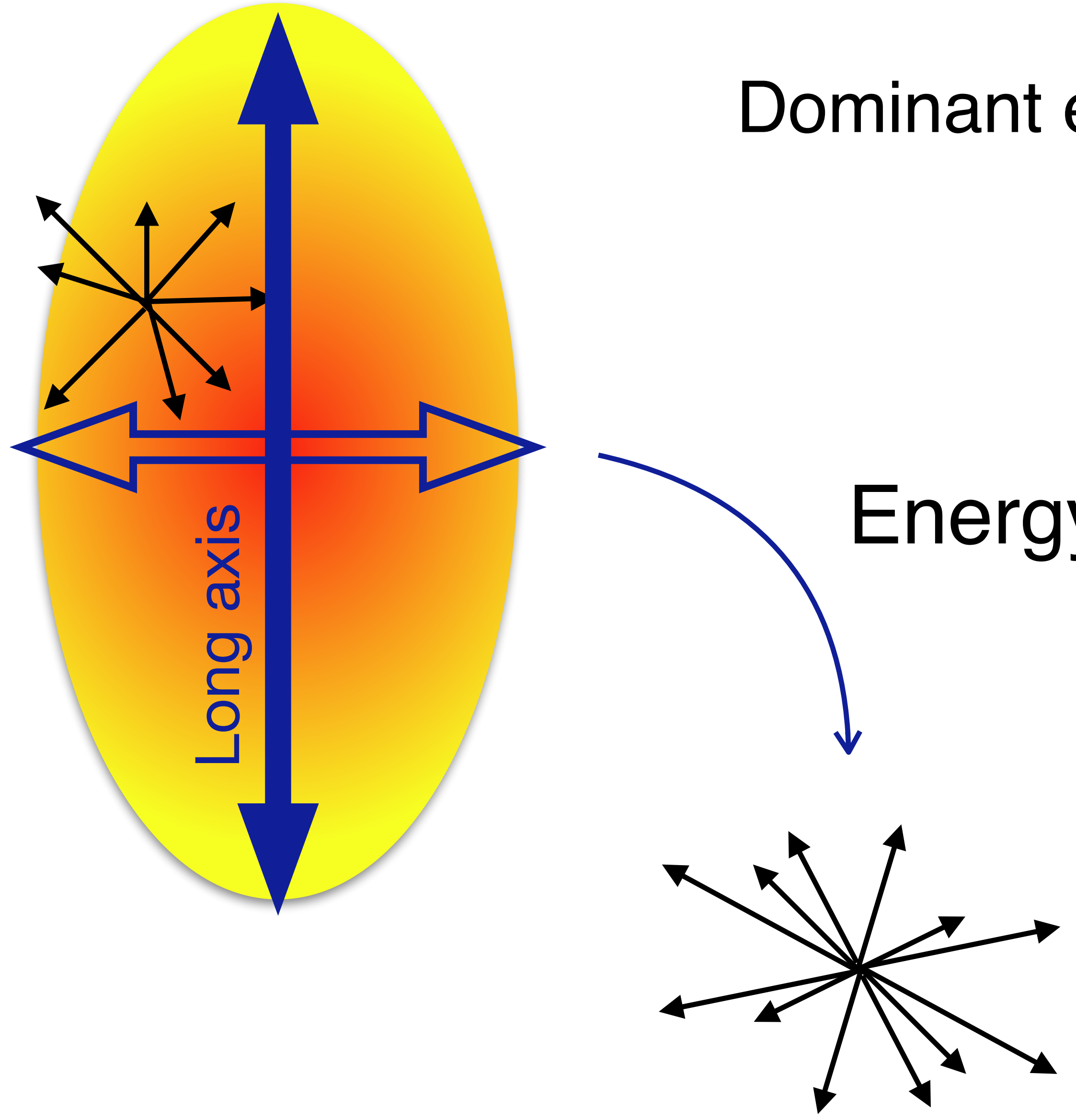
$$\nabla p = \rho \frac{d\vec{v}}{dt}$$

Equilibrium processes: soft particle production and low-p_T heavy flavour

Parton energy loss

Anisotropy due to energy loss and path length differences

Dominant effect at high p_T



More energy loss along long axis than short axis

$$\Delta E_{med} \sim \alpha_S \hat{q} L^2$$

Out-of-equilibrium: high-p_T processes