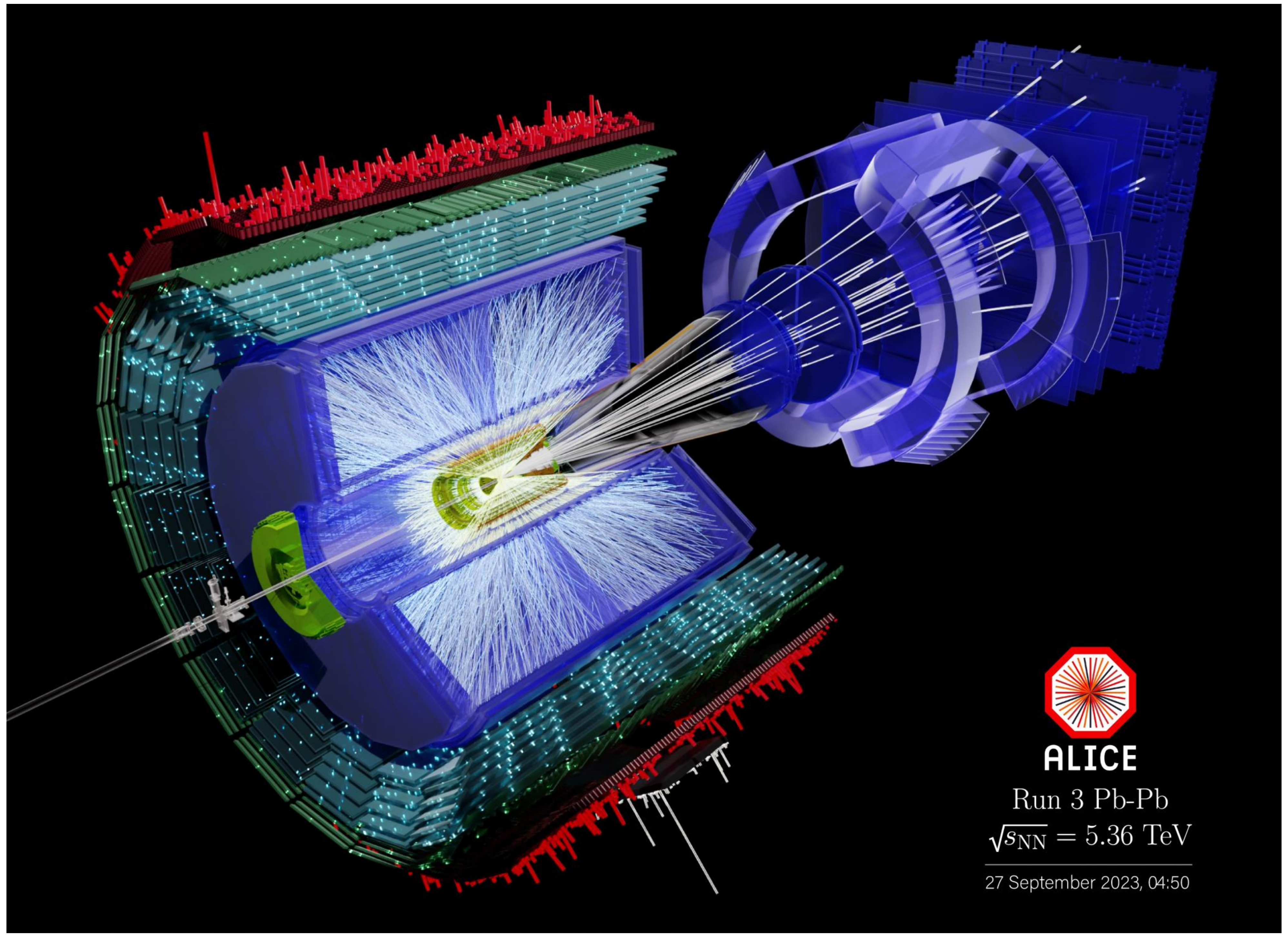
ALICE and heavy-ion program at CERN

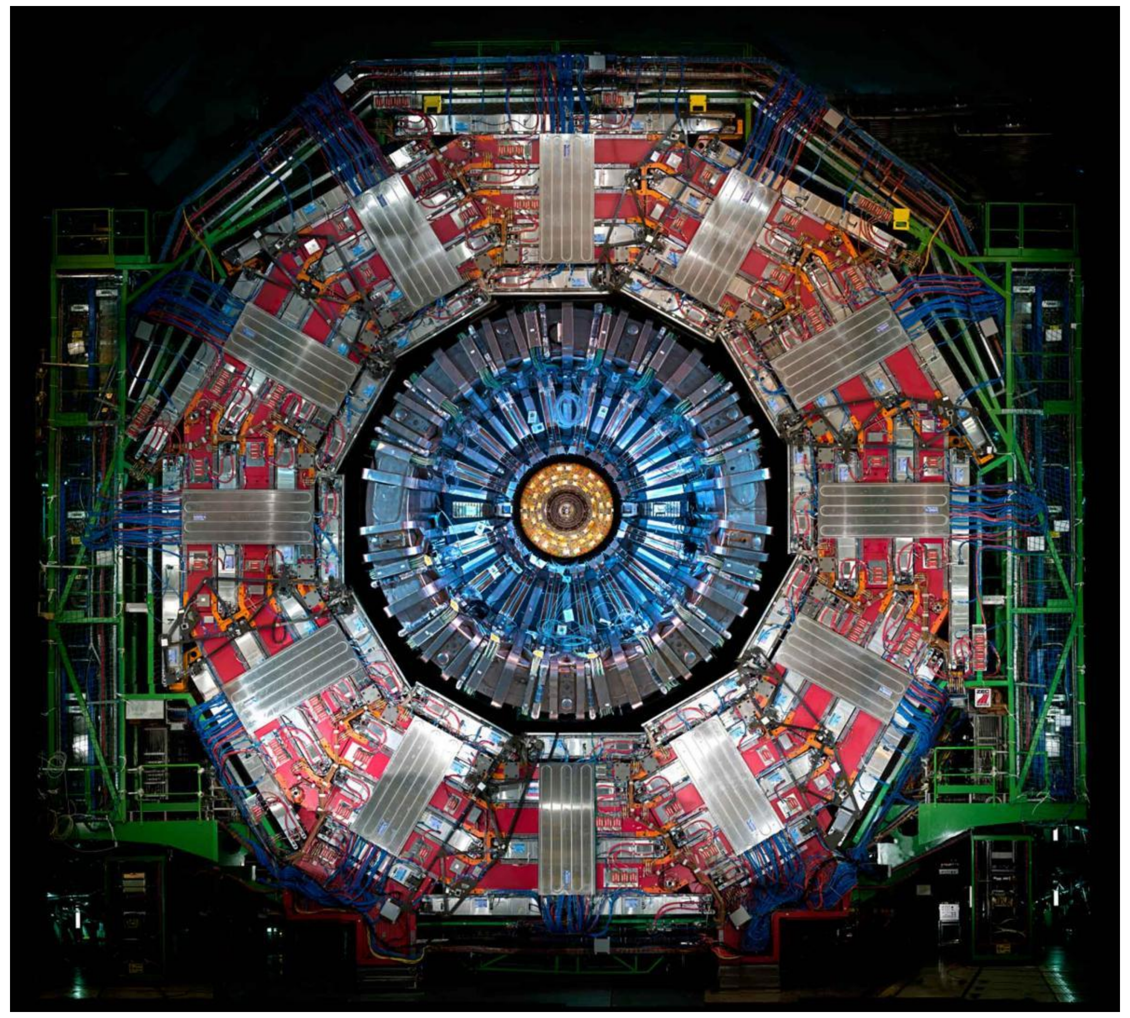
Marco van Leeuwen, Nikhef and CERN



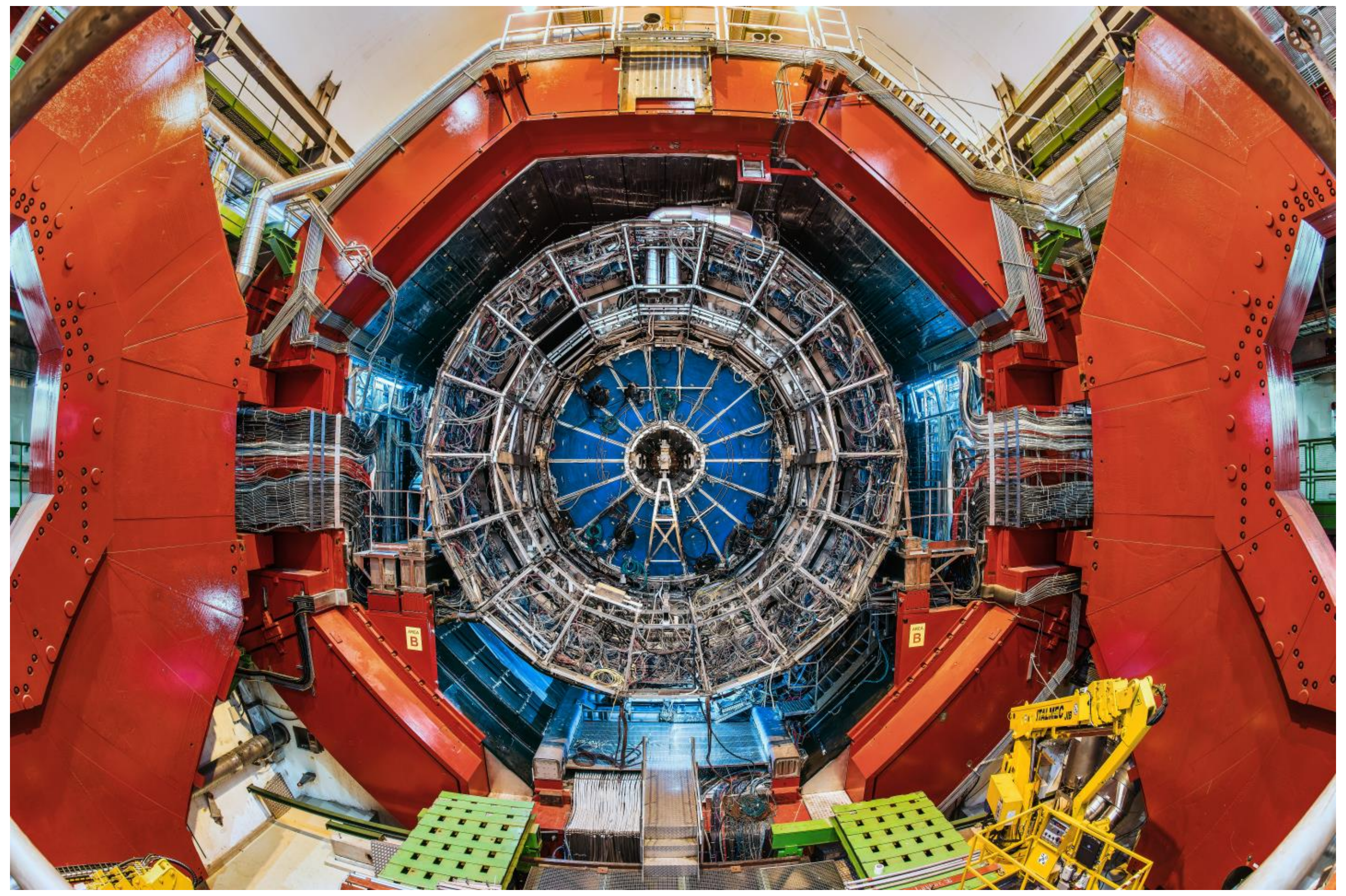
IoP joint APP, HEPP, and NP conference
8-12 April 2024, Liverpool

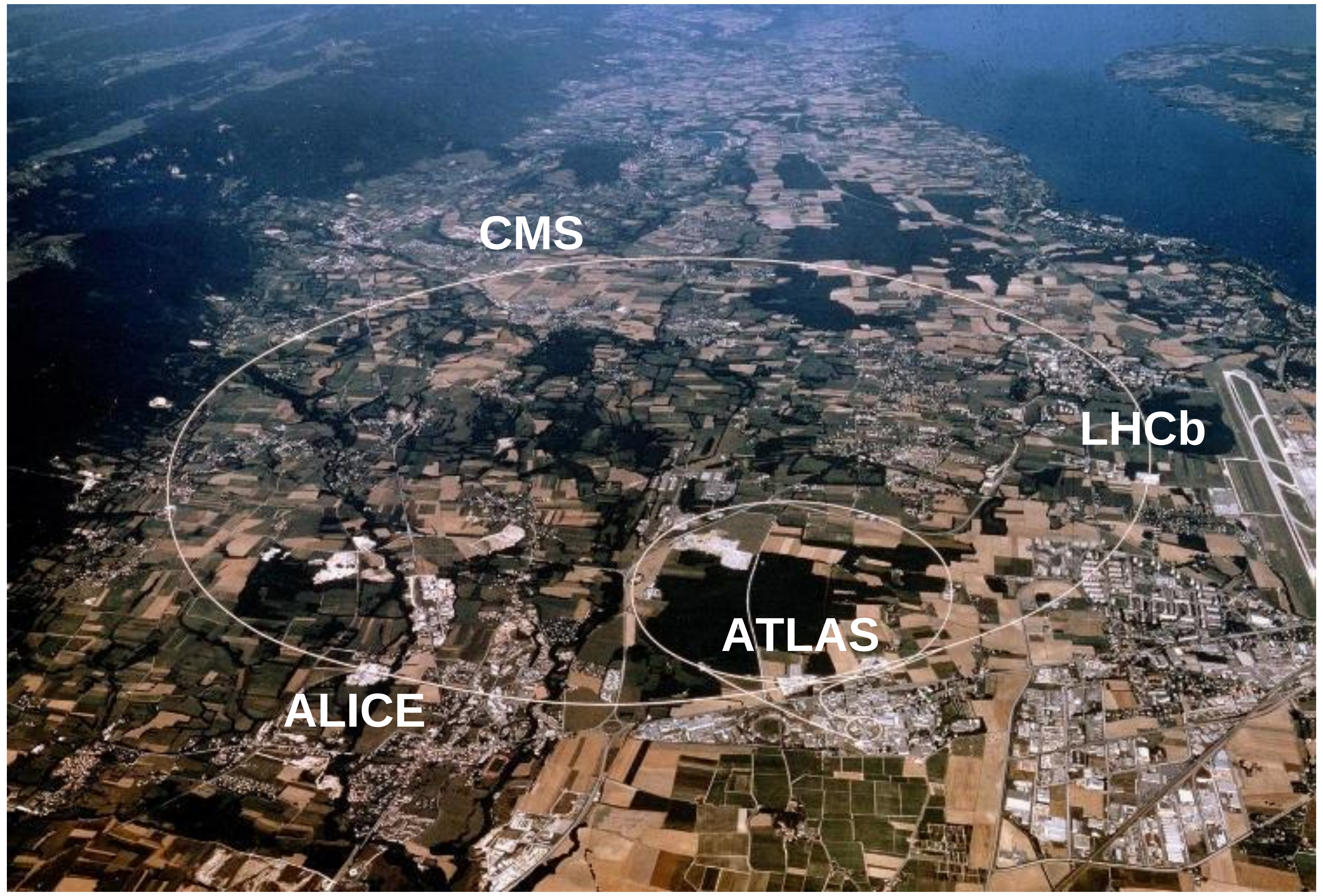
The Large Hadron Collider

CMS

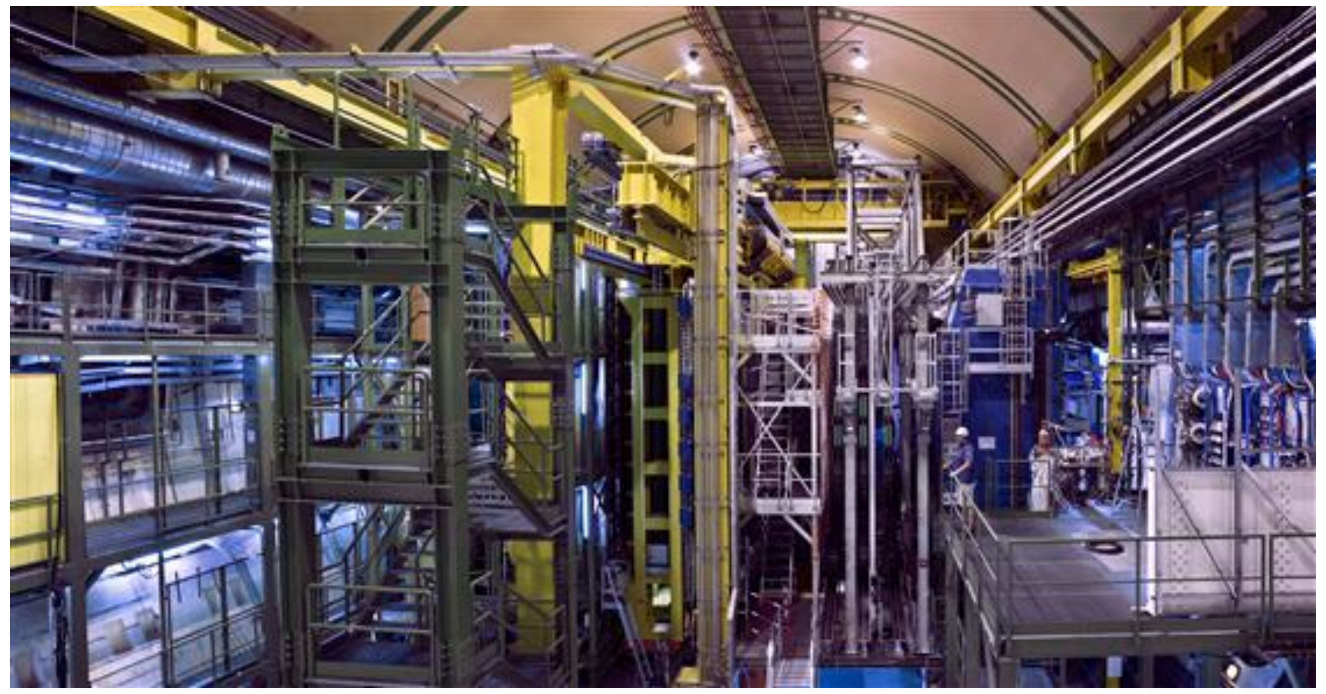


ALICE

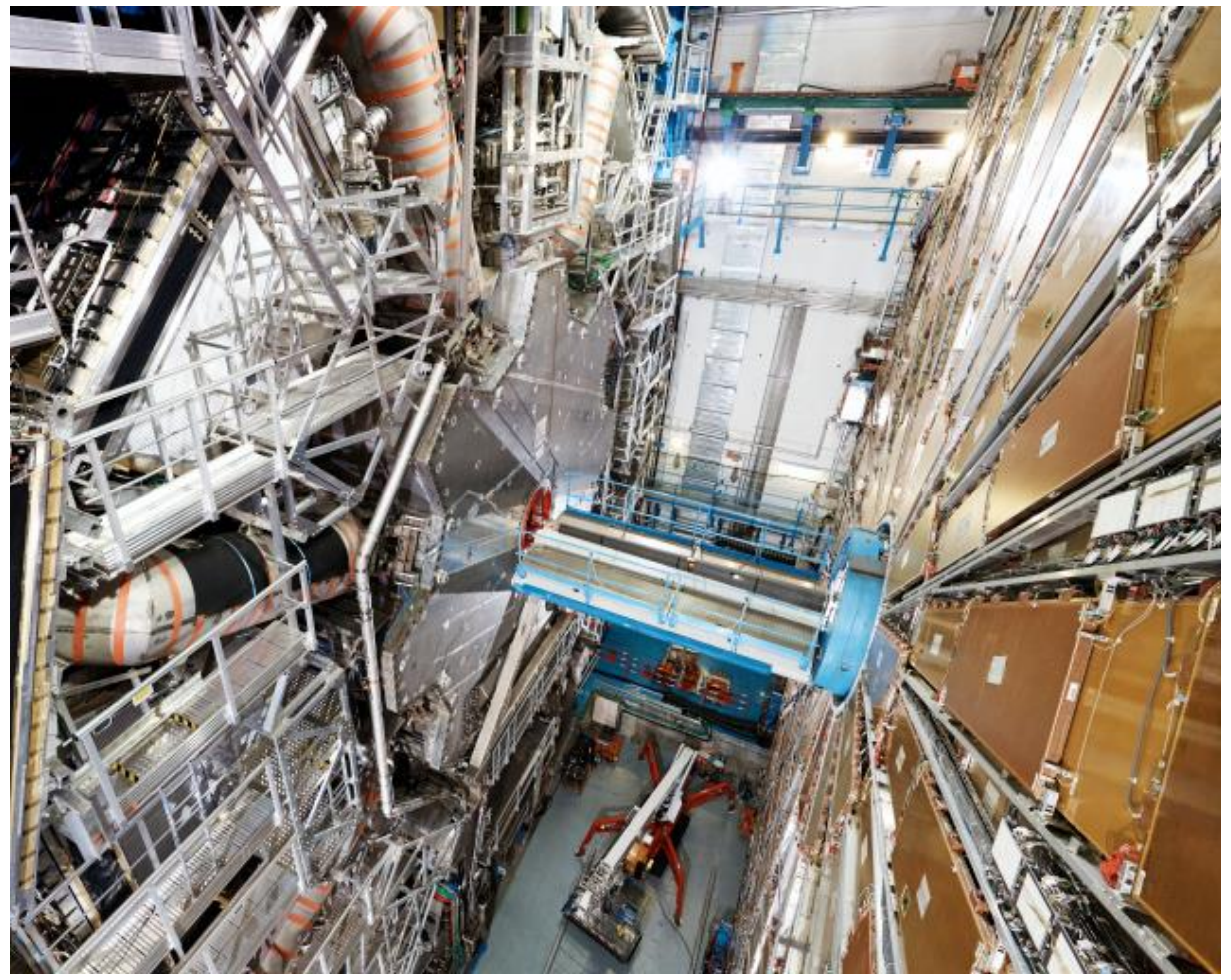




LHCb



ATLAS



ALICE: dedicated heavy-ion experiment

ATLAS, CMS: general purpose pp detectors

LHCb: forward detector, optimised for flavour physics

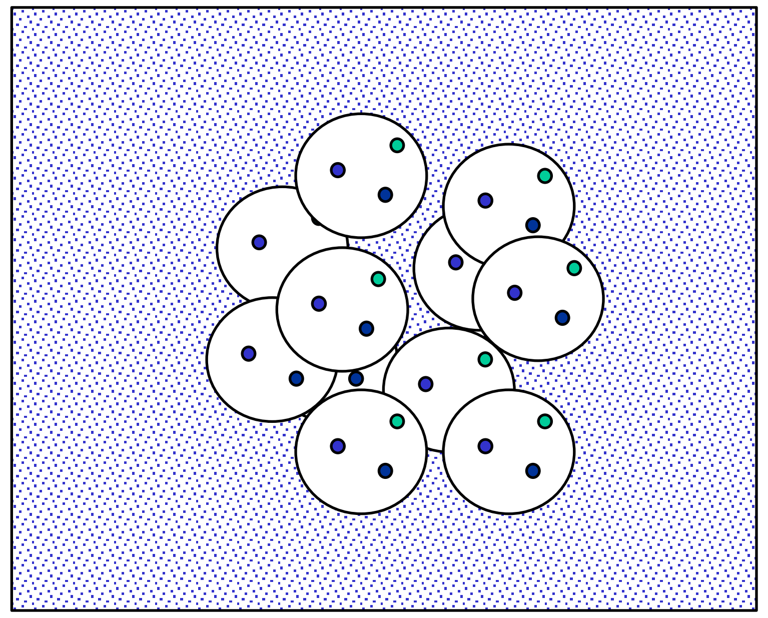
Pb-Pb collisions: $\sqrt{s_{NN}}$ = 2.76, 5.02, 5.36 TeV

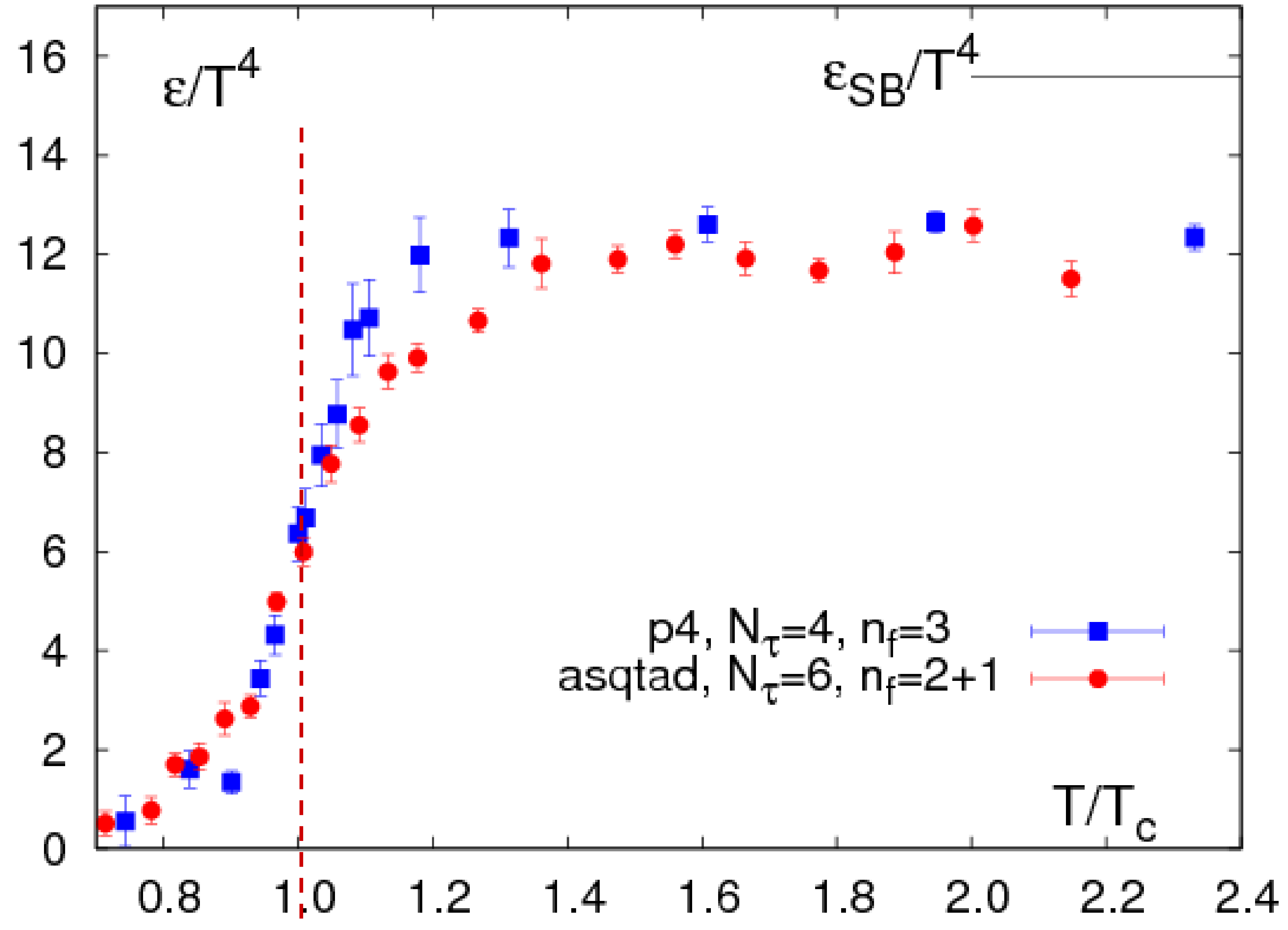
pp collisions $\sqrt{s}$ = 7, 8, 13, 13.6 TeV

other systems: p-Pb, Xe-Xe, O-O, p-O

Condensed matter of QCD: the quark-gluon plasma

Lattice QCD calculations: energy density vs temperature

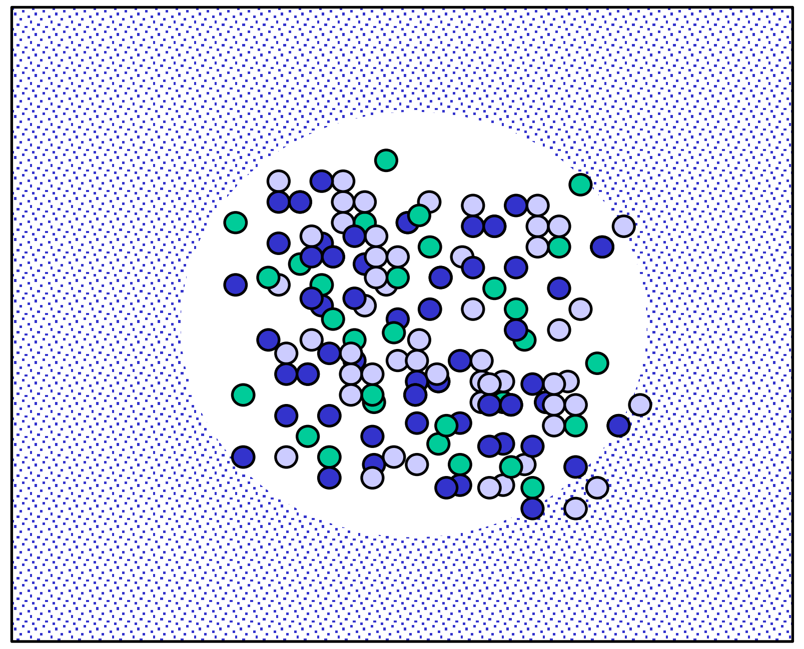




T_c ~ 155 MeV

ε_c ~ 1 GeV/fm³

Bernard et al. hep-lat/0610017



$\varepsilon \propto gT^4$

g: degrees of freedom

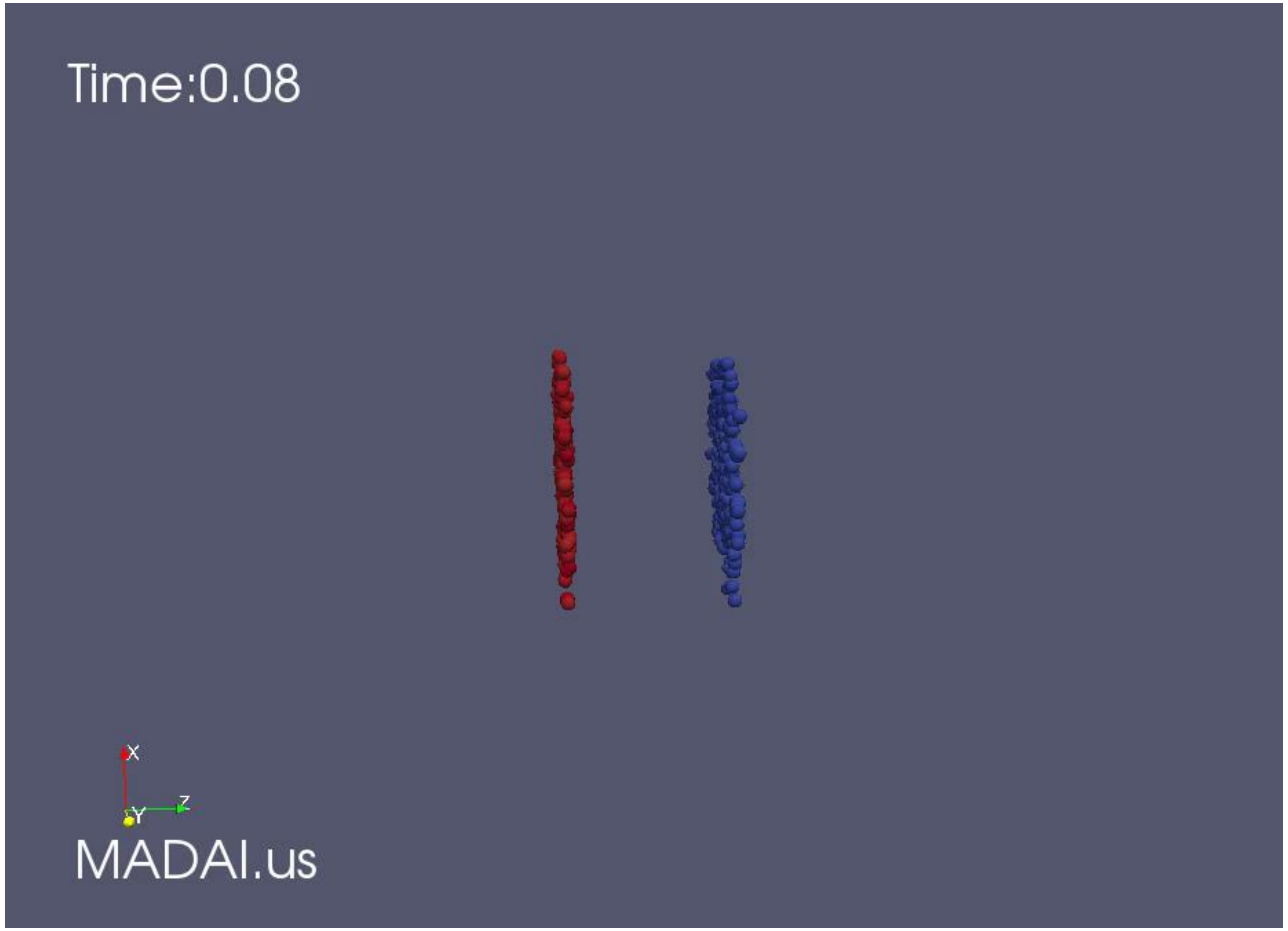
Low temperature:
quarks and gluons confined in hadrons

High temperature:
deconfined quark-gluon plasma

Phase transition at critical temperature $T_c \approx$ 155 MeV ≈ 10^{12} K

Increase of number of degrees of freedom: hadrons (3 pions) → quarks+gluons (37)

Heavy ion collisions: Little Bangs

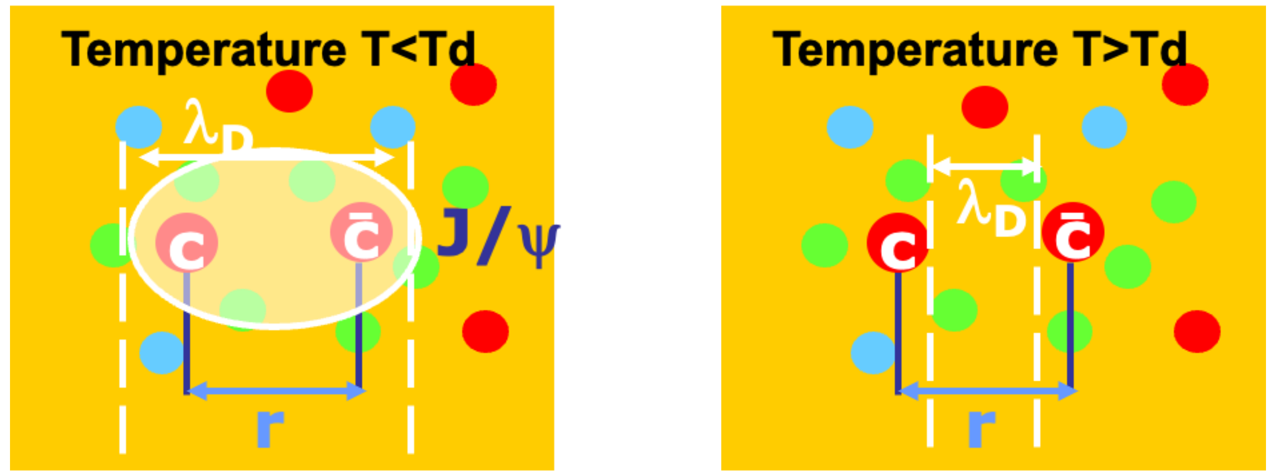


MADAI

Stages of the collision: initial stages — QGP/fluid stage — hadron formation (freeze out)

'Little Bang': recreate primordial matter in the laboratory

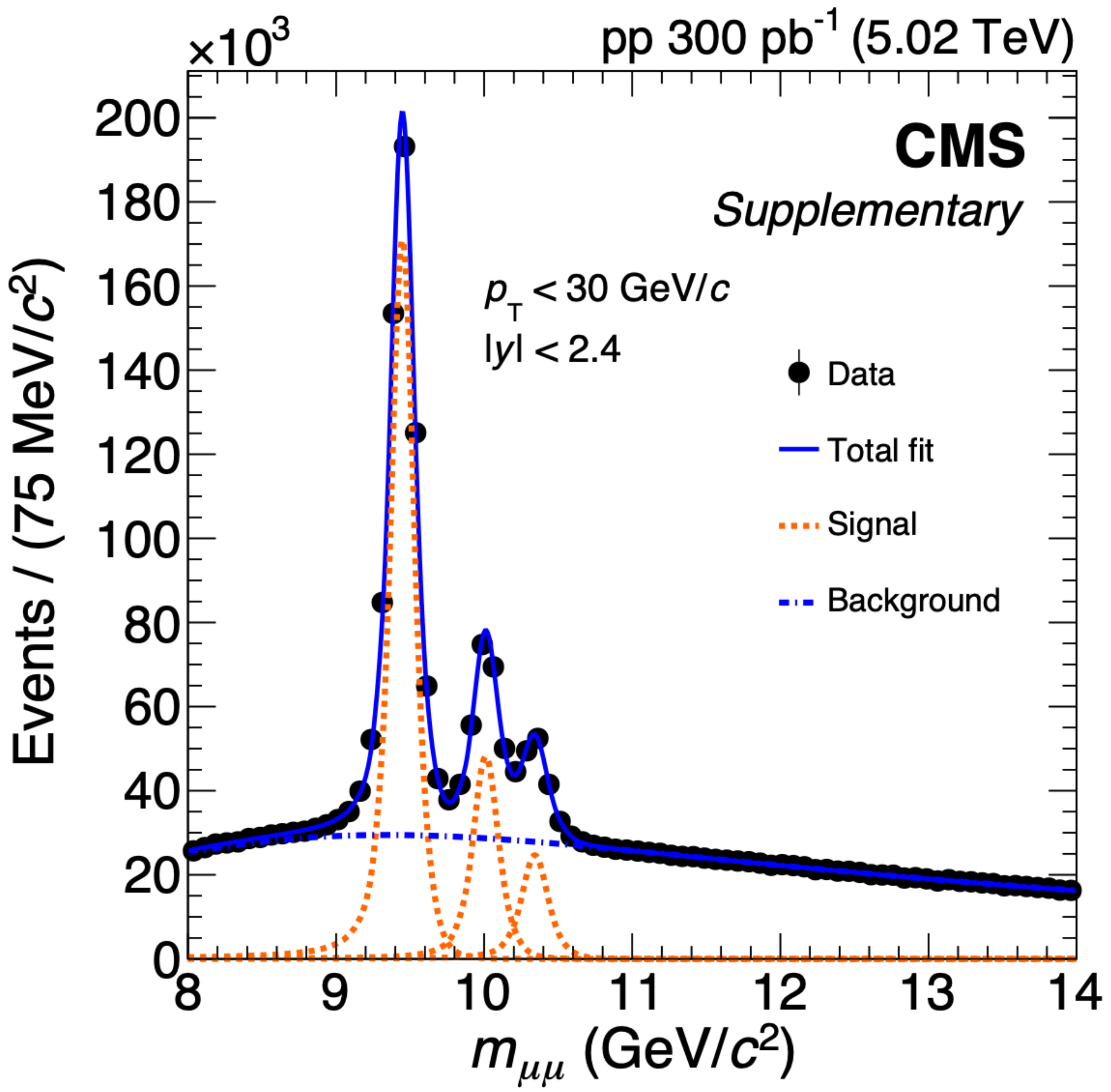
Gauging the temperature: melting of quarkonia



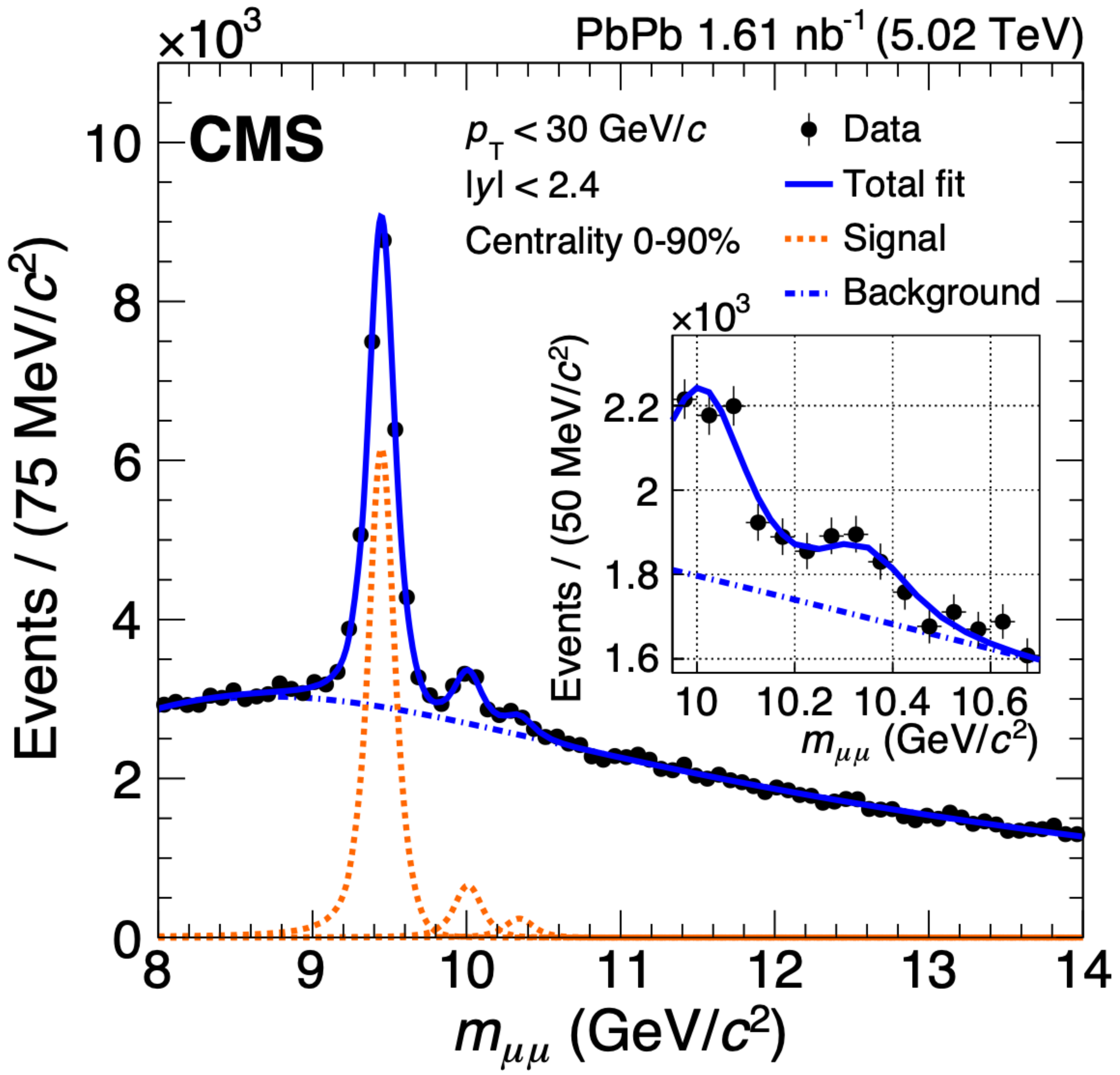
Binding force screened when
$r > \lambda_d$

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

Di-muon mass spectrum: pp



Di-muon mass spectrum: Pb-Pb



Higher states suppressed in Pb-Pb collisions

CMS, arXiv:2303.17026 ATLAS, PRC 107, 054912

TAMU: Du, He, Rapp, PRC 96, 054901

Quarkonia: nuclear modification factor

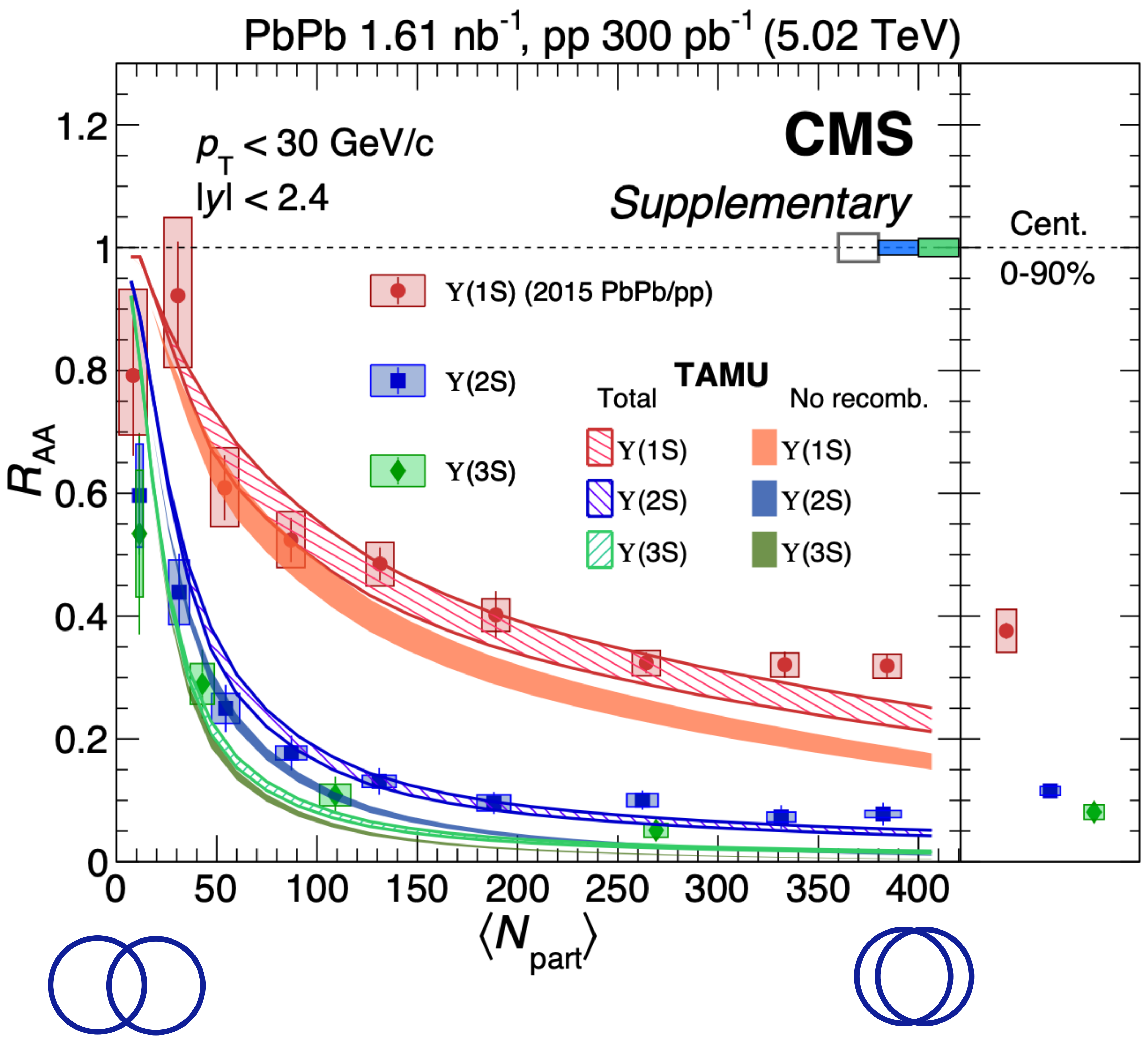
Nuclear modification factor

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

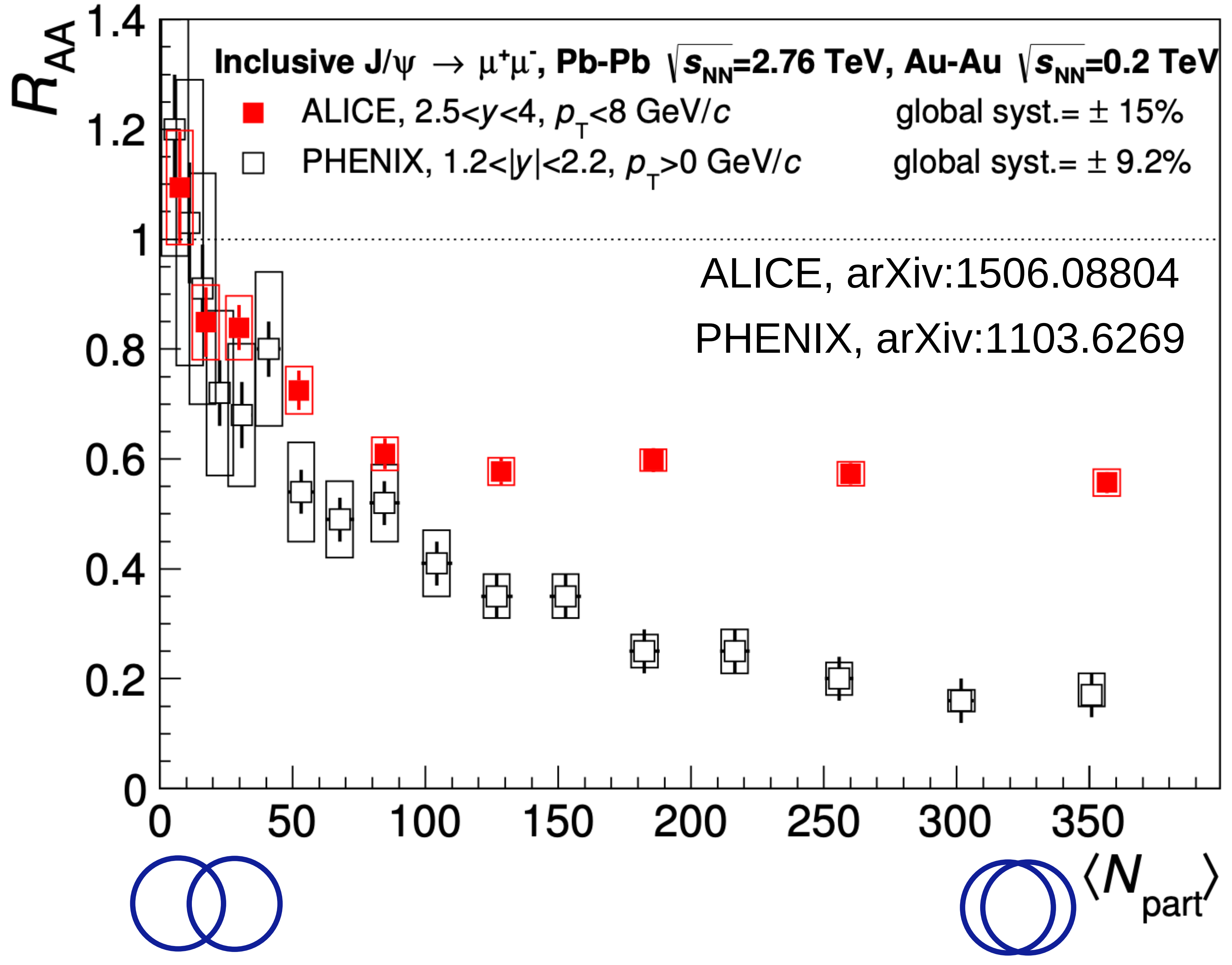
R_{AA} = 1: no effect

R_{AA} = 0: complete suppression

Nuclear modification vs centrality



J/ψ modification vs centrality



Large suppression — dissociation in central events

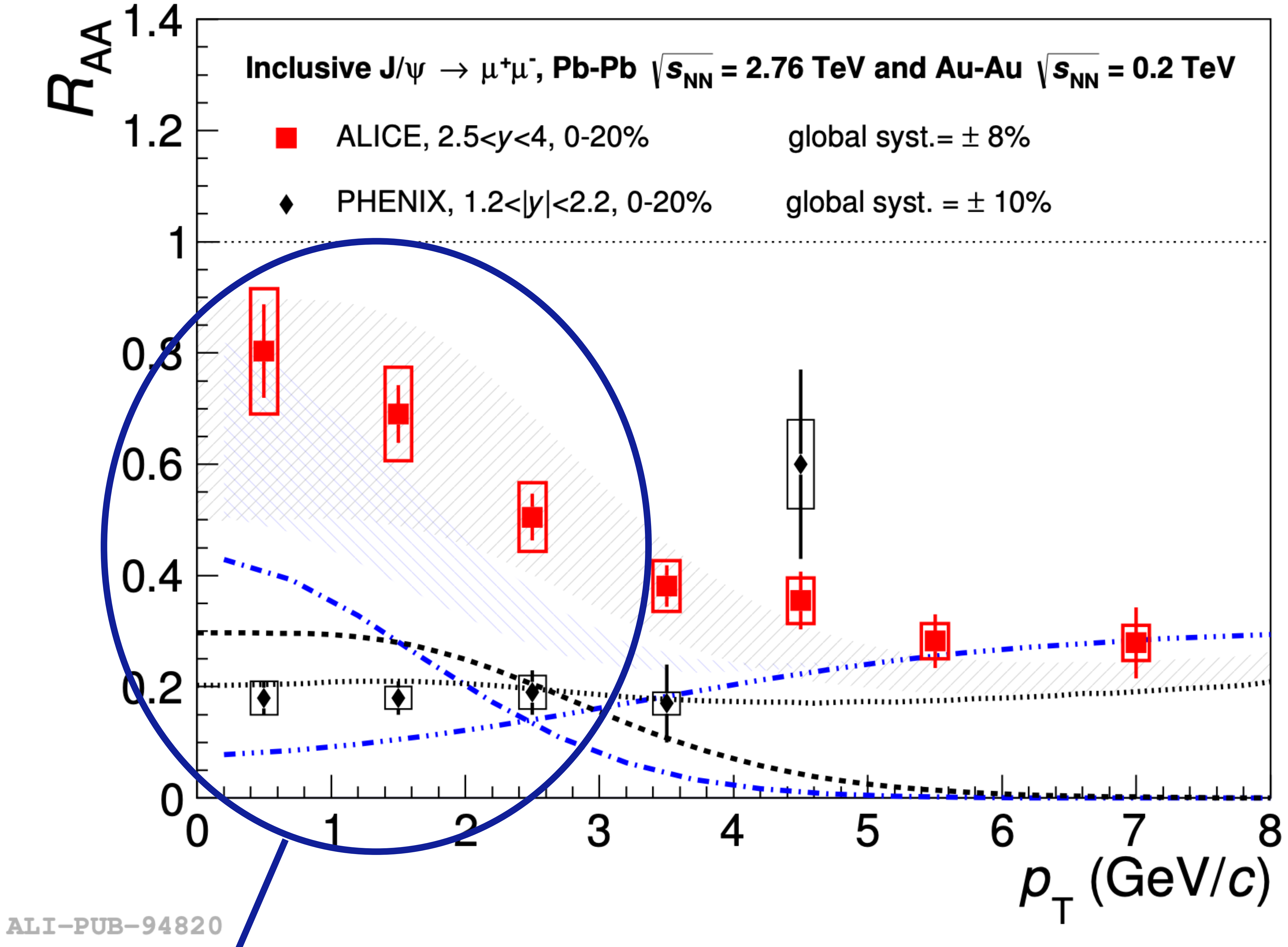
Larger effect for higher states — weaker binding

J/ψ : $c\bar{c}$ bound state

shows smaller suppression

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

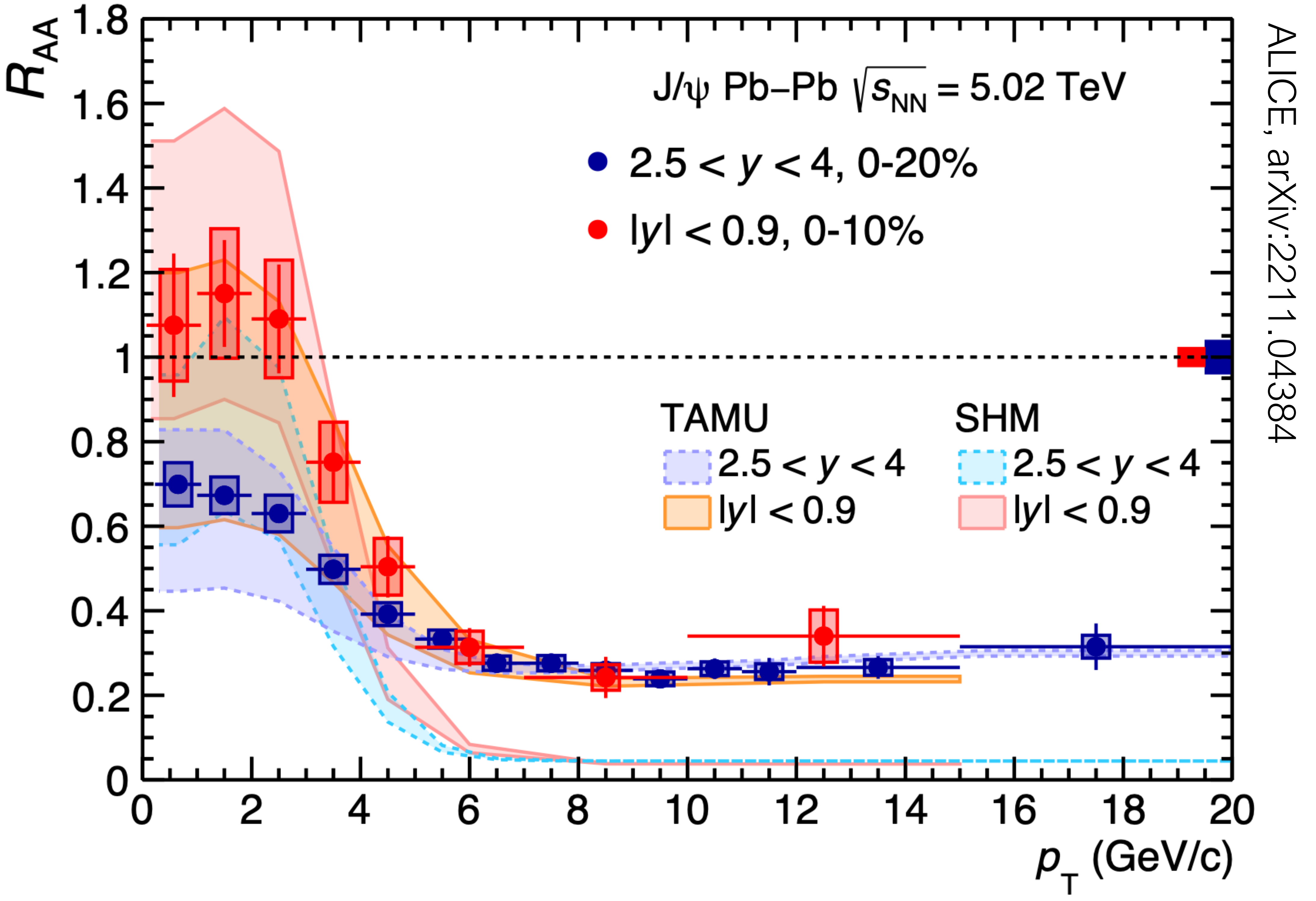
J/ψ modification vs p_T



Less suppression at low p_T

$c\bar{c}$ recombination

J/ψ modification at forward and mid-rapidity

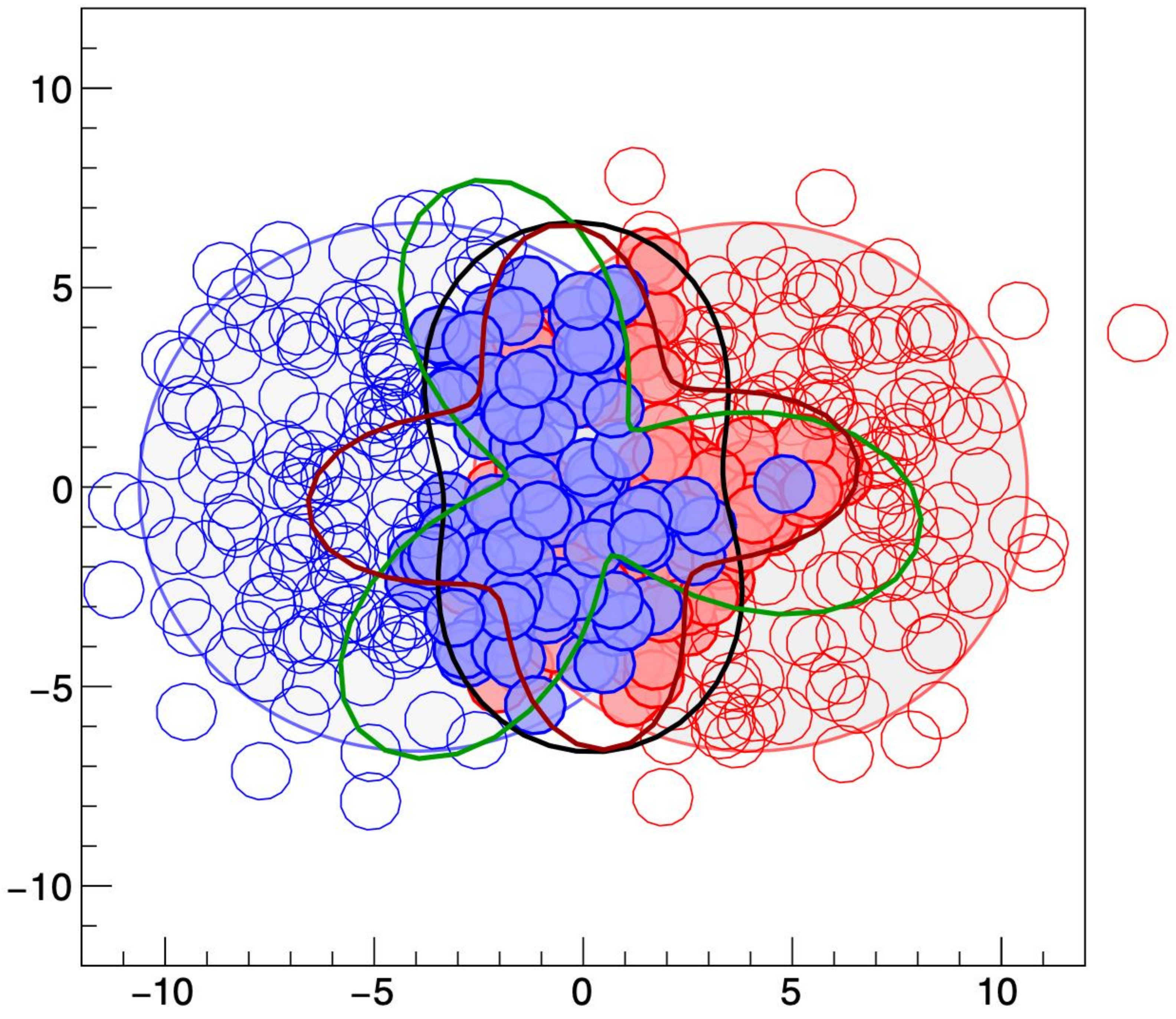


In agreement with coalescence expectation: larger $c\bar{c}$ density at mid-rapidity

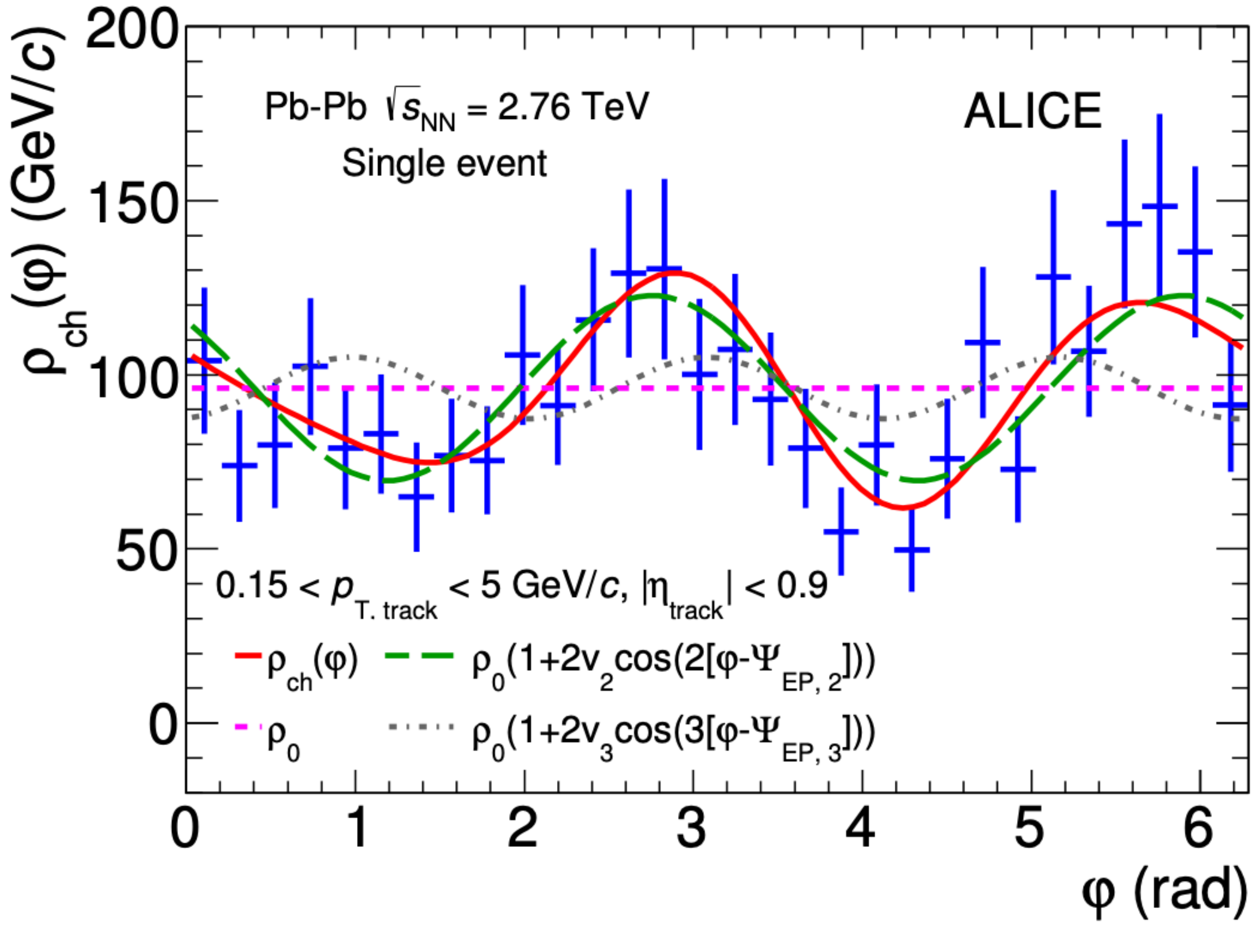
ALICE, arXiv:1506.08804 PHENIX, arXiv:1103.6269
Transport models: arXiv:1102.2194, arXiv:1401.5845

Azimuthal anisotropy: initial and final states

Simulated event: location of nucleons

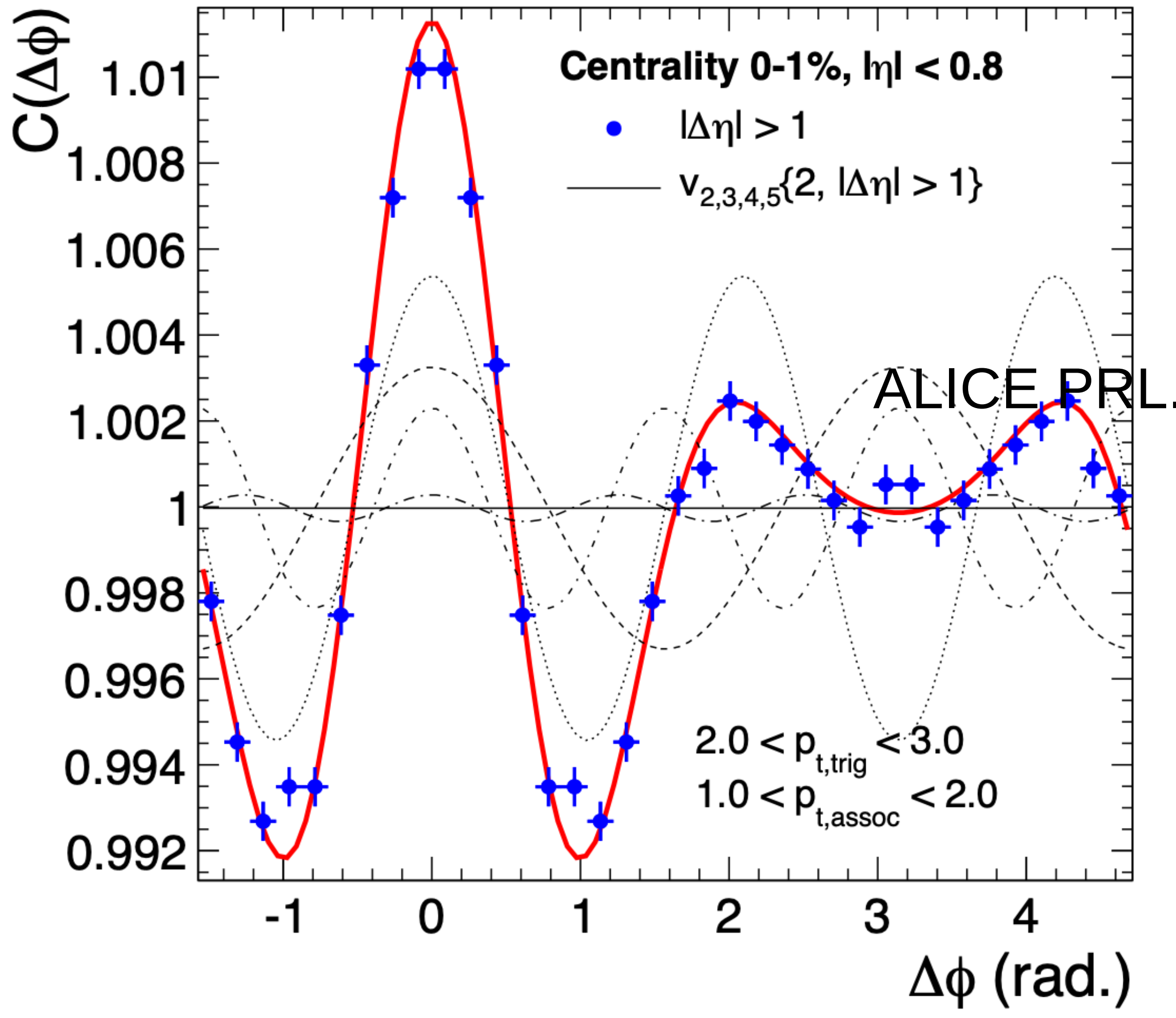


Azimuthal distribution single event



ALICE, PLB 753, 511

Sum over many events

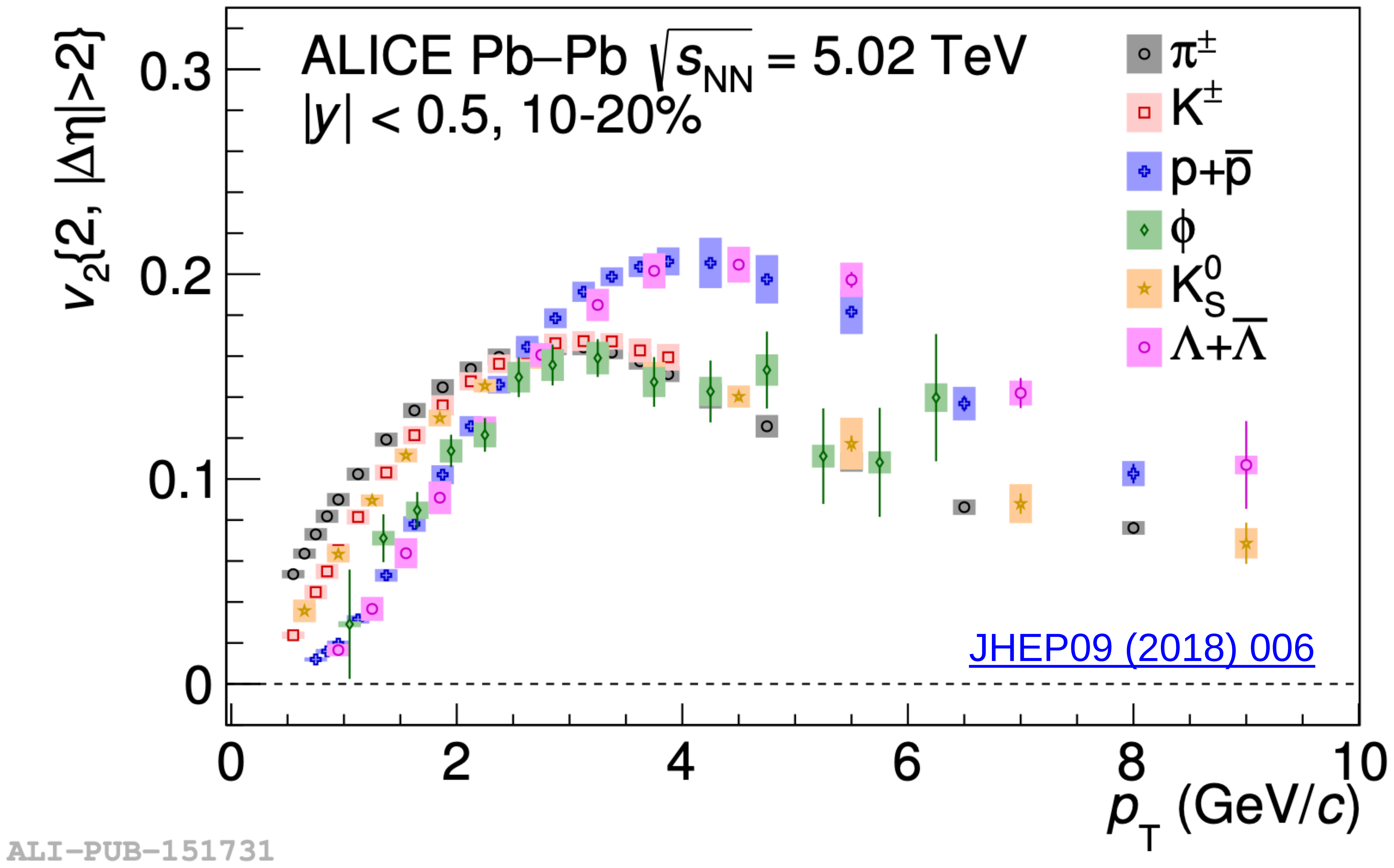


ALICE PRL. 107, 032301

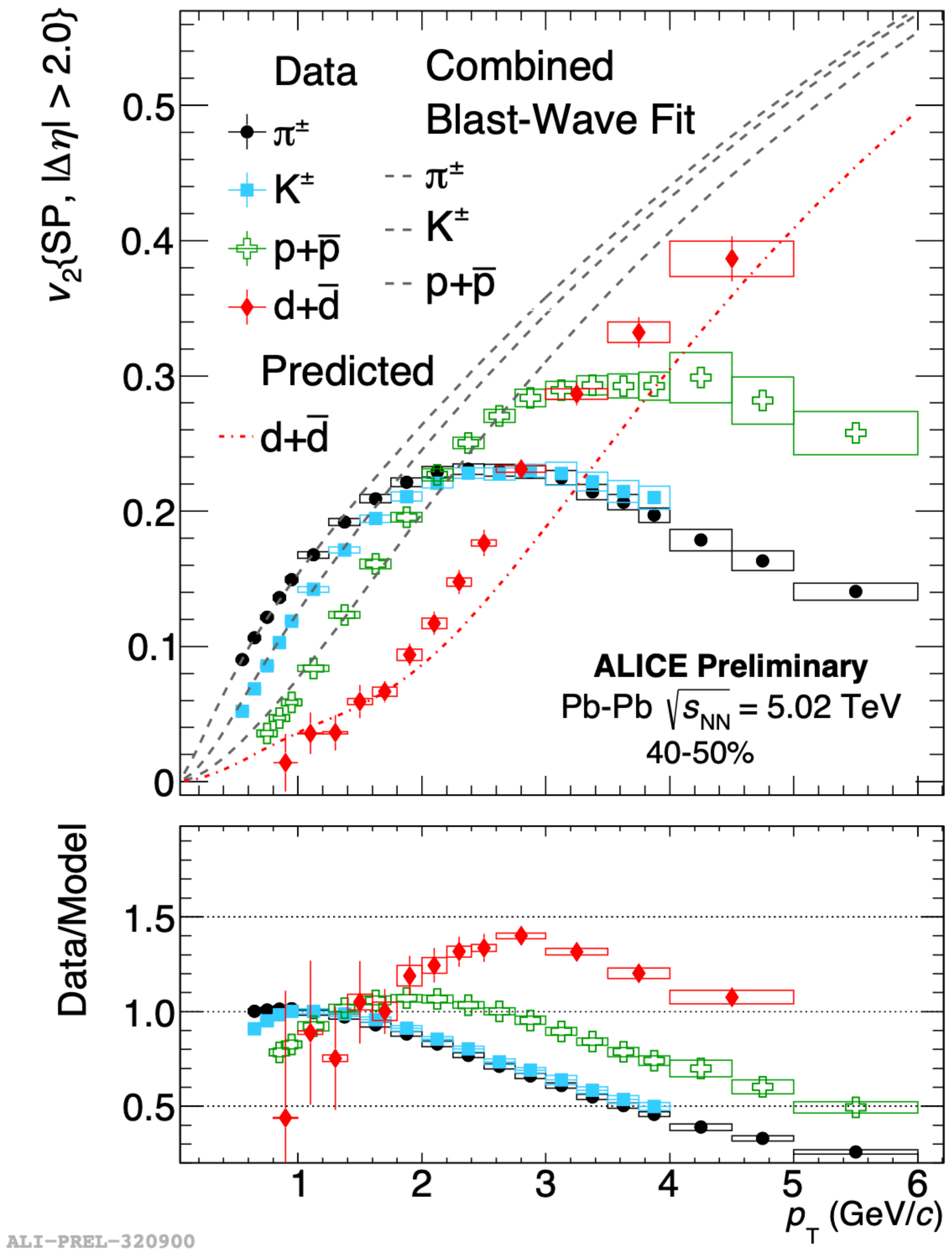
Initial state spatial anisotropies ε_n are transferred into final state momentum anisotropies v_n by pressure gradients, flow of the Quark Gluon Plasma

Anisotropic flow: initial state and QGP expansion

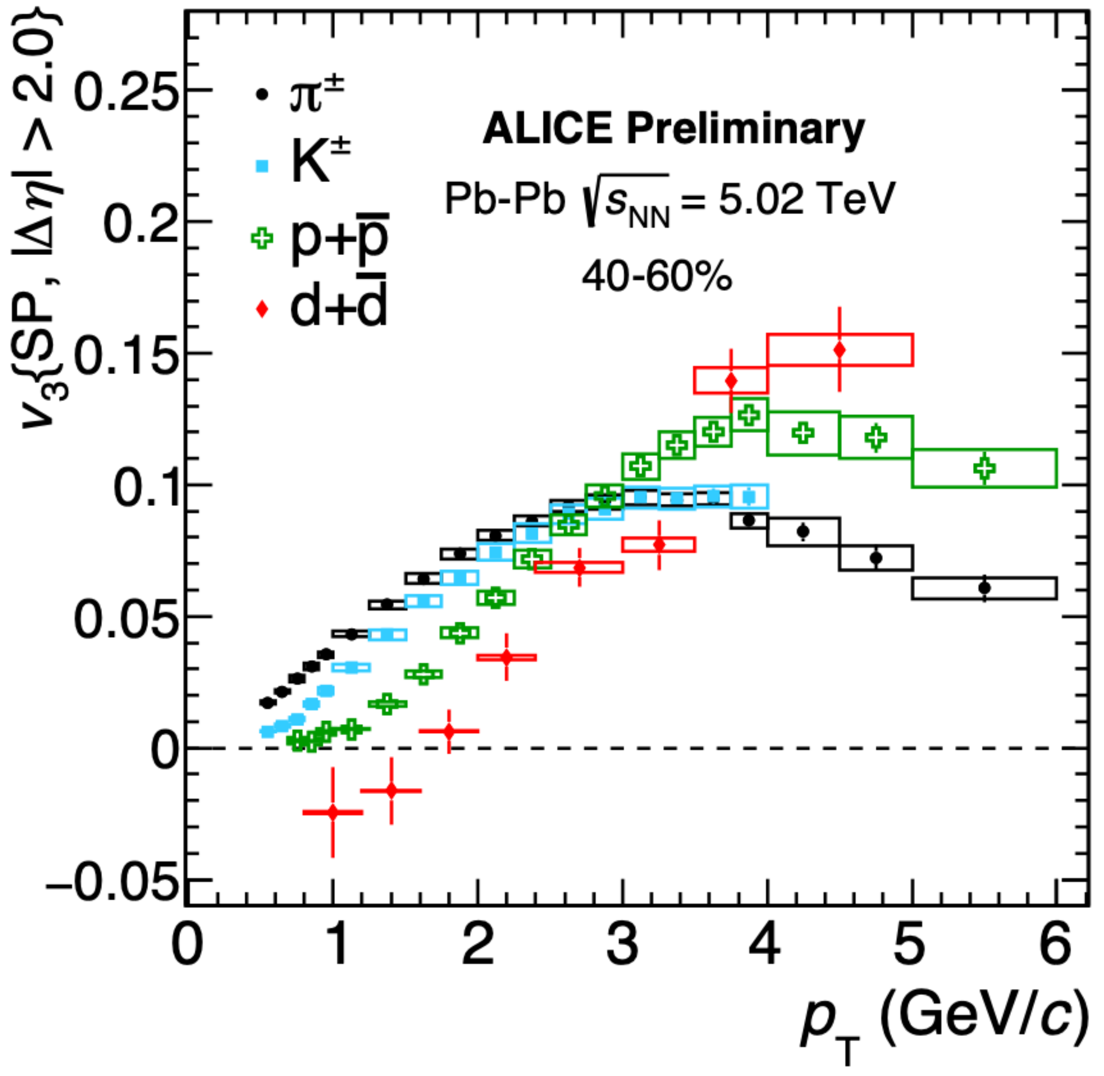
Elliptic flow v_2



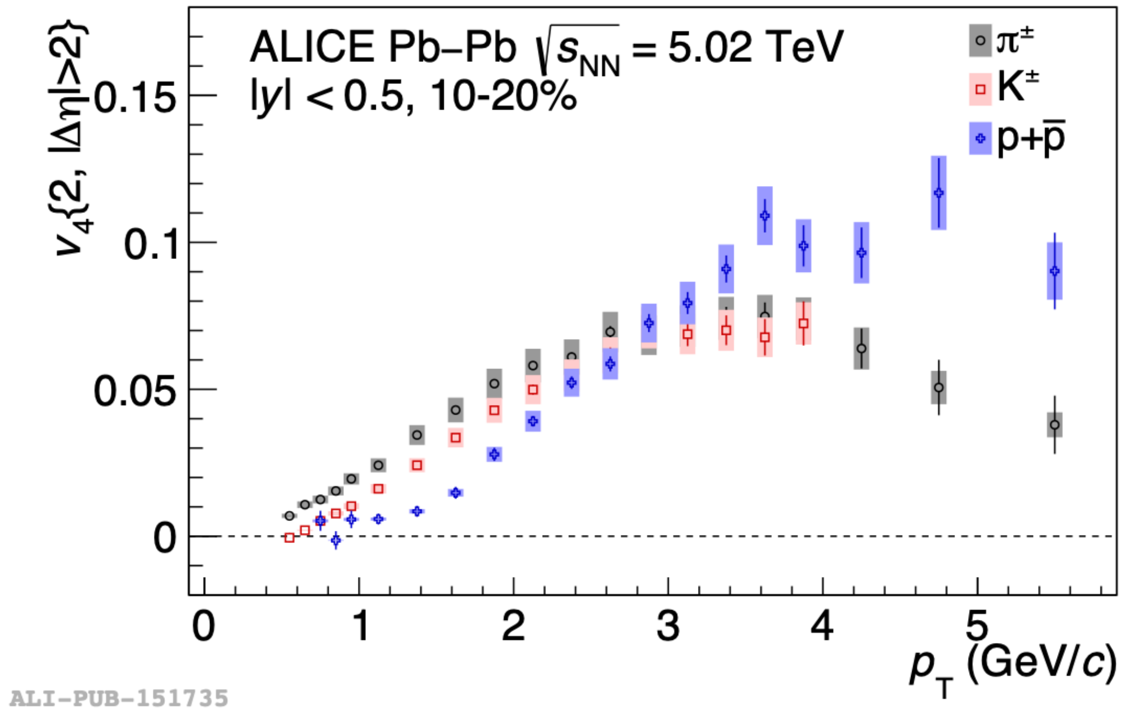
v_2 of deuterons



v_3



v_4



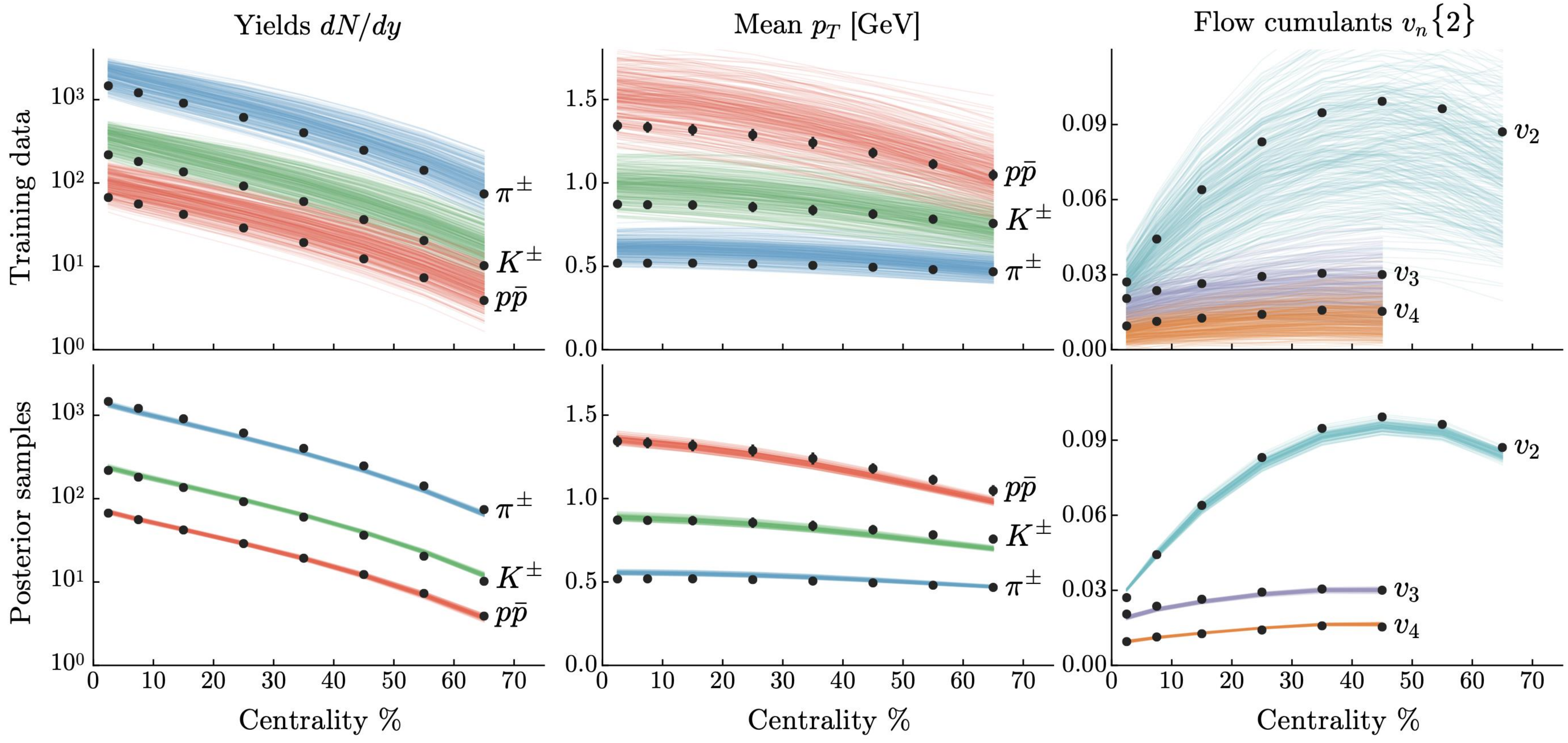
Mass-dependence of v_2 measures flow velocity

Even nuclei flow !

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

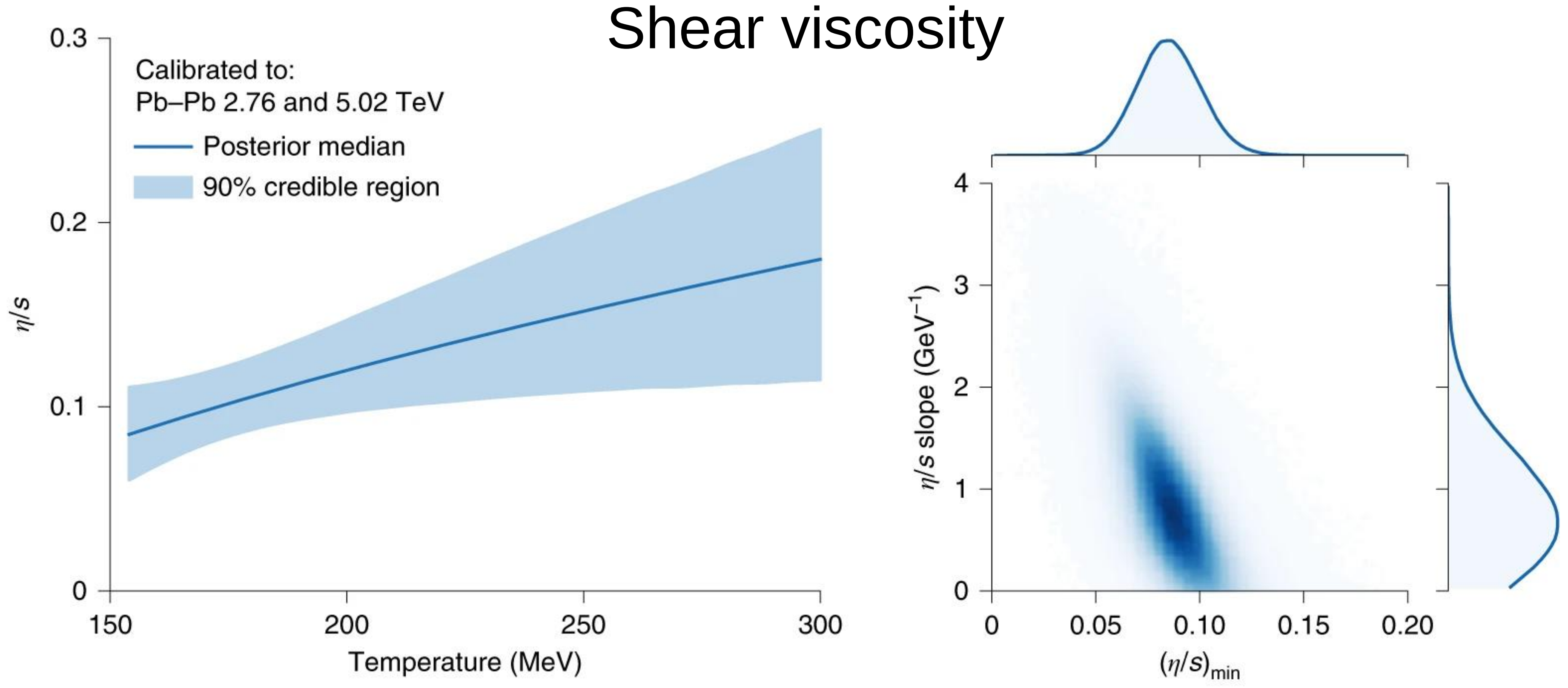
Explores a large parameter space to investigate reliability/robustness of the modeling

A global fit to anisotropic flow: main result

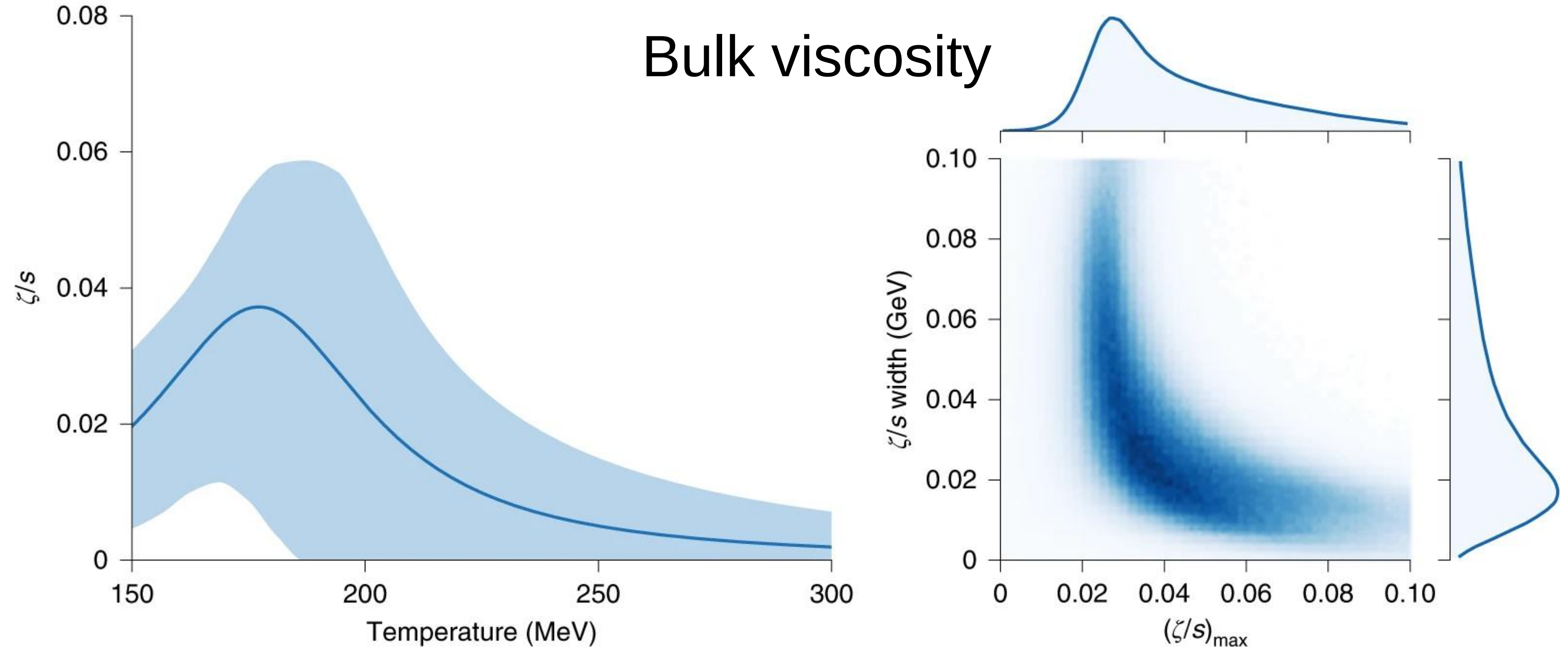
J. E. Bernhard et al, Nature Physics 15, 1113–1117, arXiv: 1605.03954

Viscosity vs T

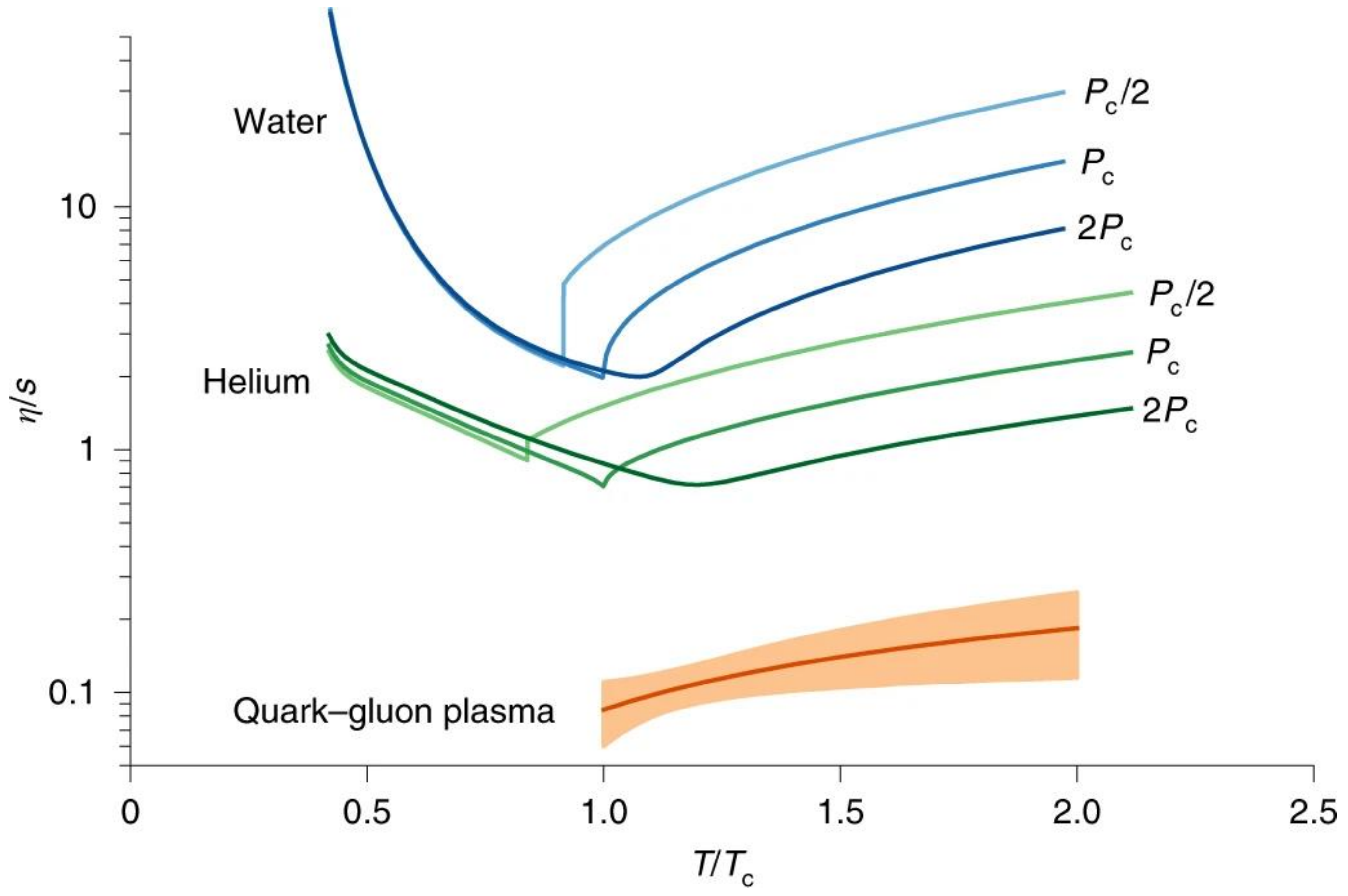
Shear viscosity



Bulk viscosity



Comparison to well-known liquids



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

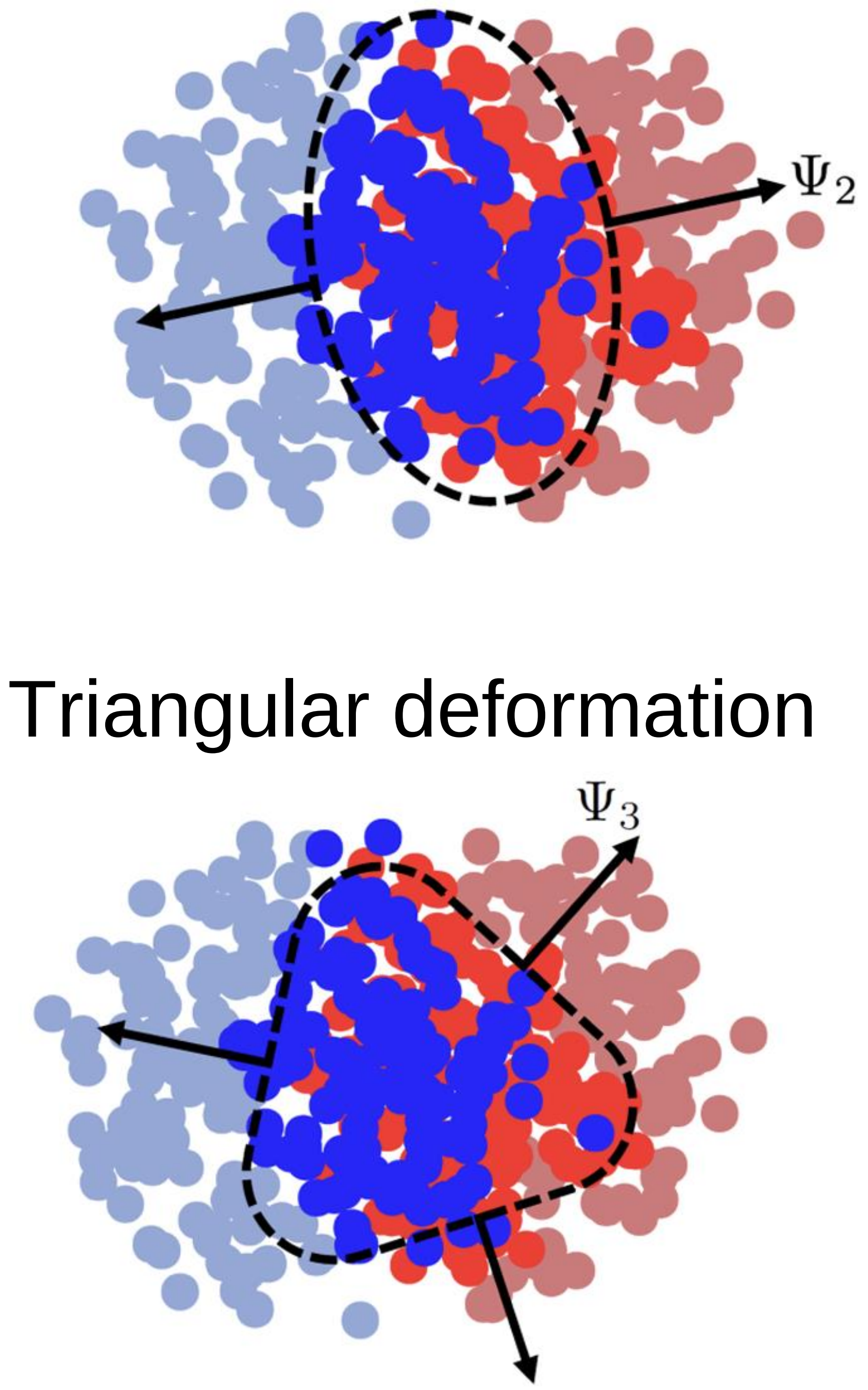
Viscosity close to fundamental lower bound

Exploring initial state geometry: event plane correlations

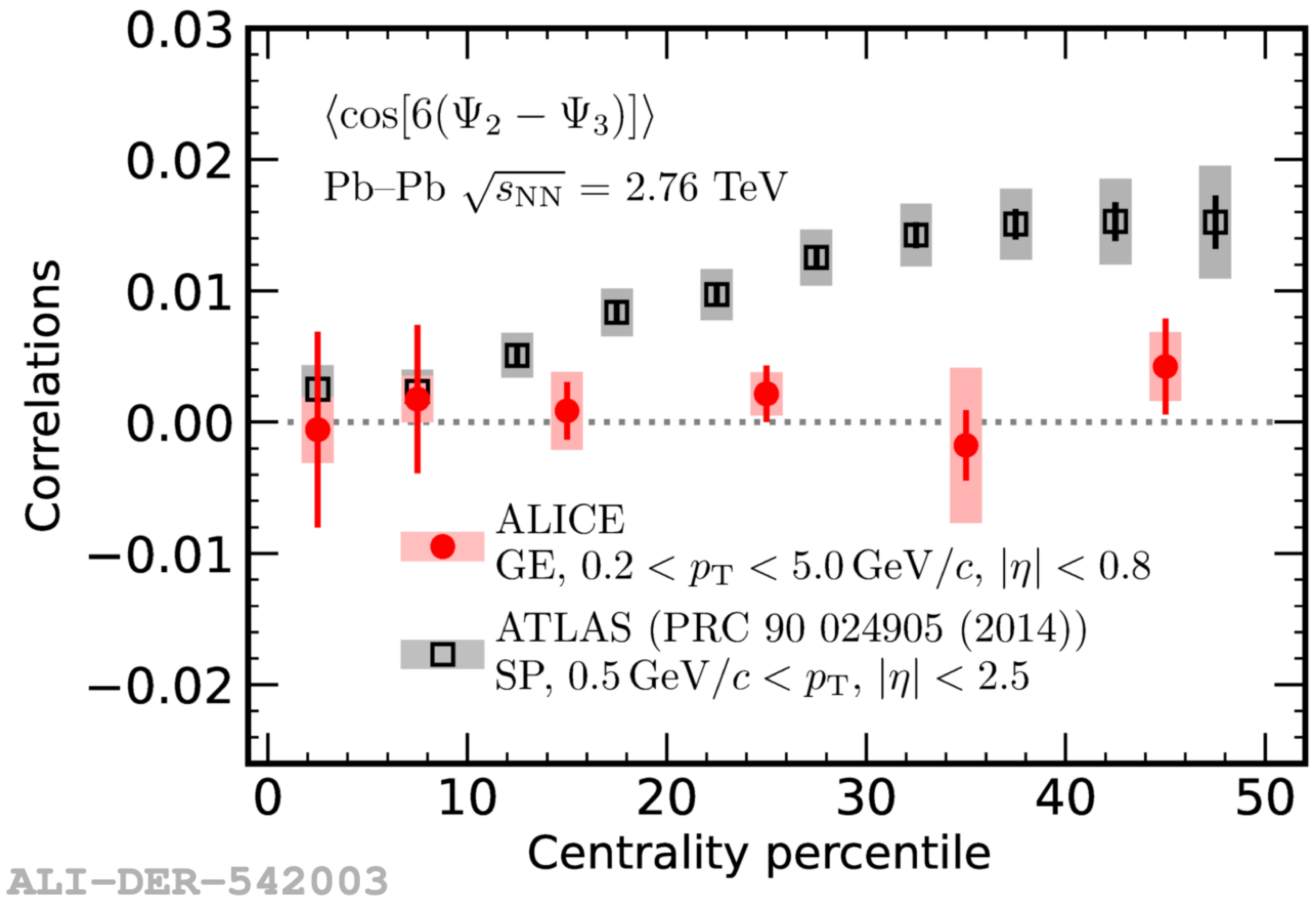
ALICE, arXiv:2302.01234

Elliptic deformation

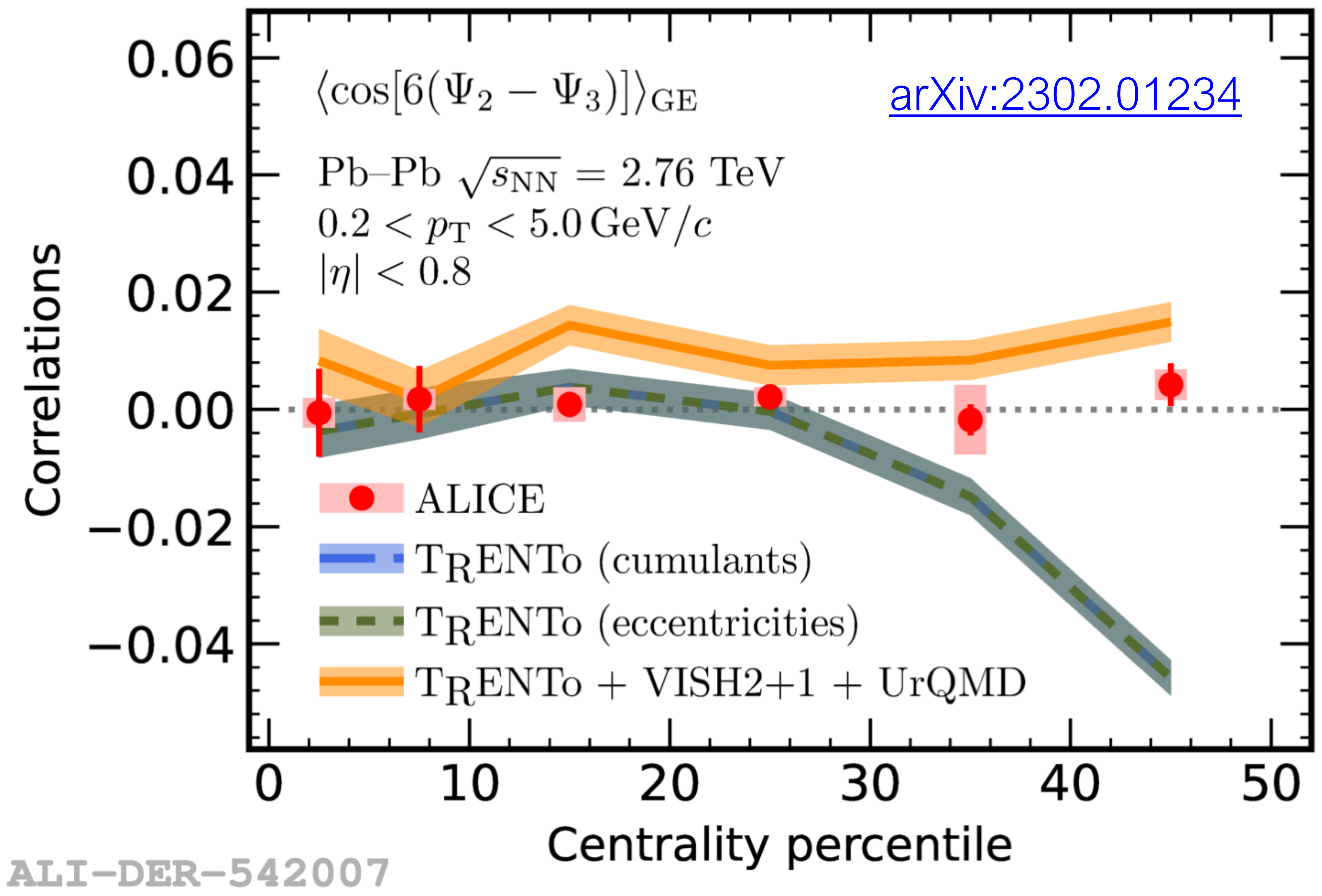
Triangular deformation



Comparison to previous results



Comparison to theory



New result: No significant correlations between Ψ_2 and Ψ_3
In line with expectations from initial state geometry

Messengers of the Plasma: soft and hard processes

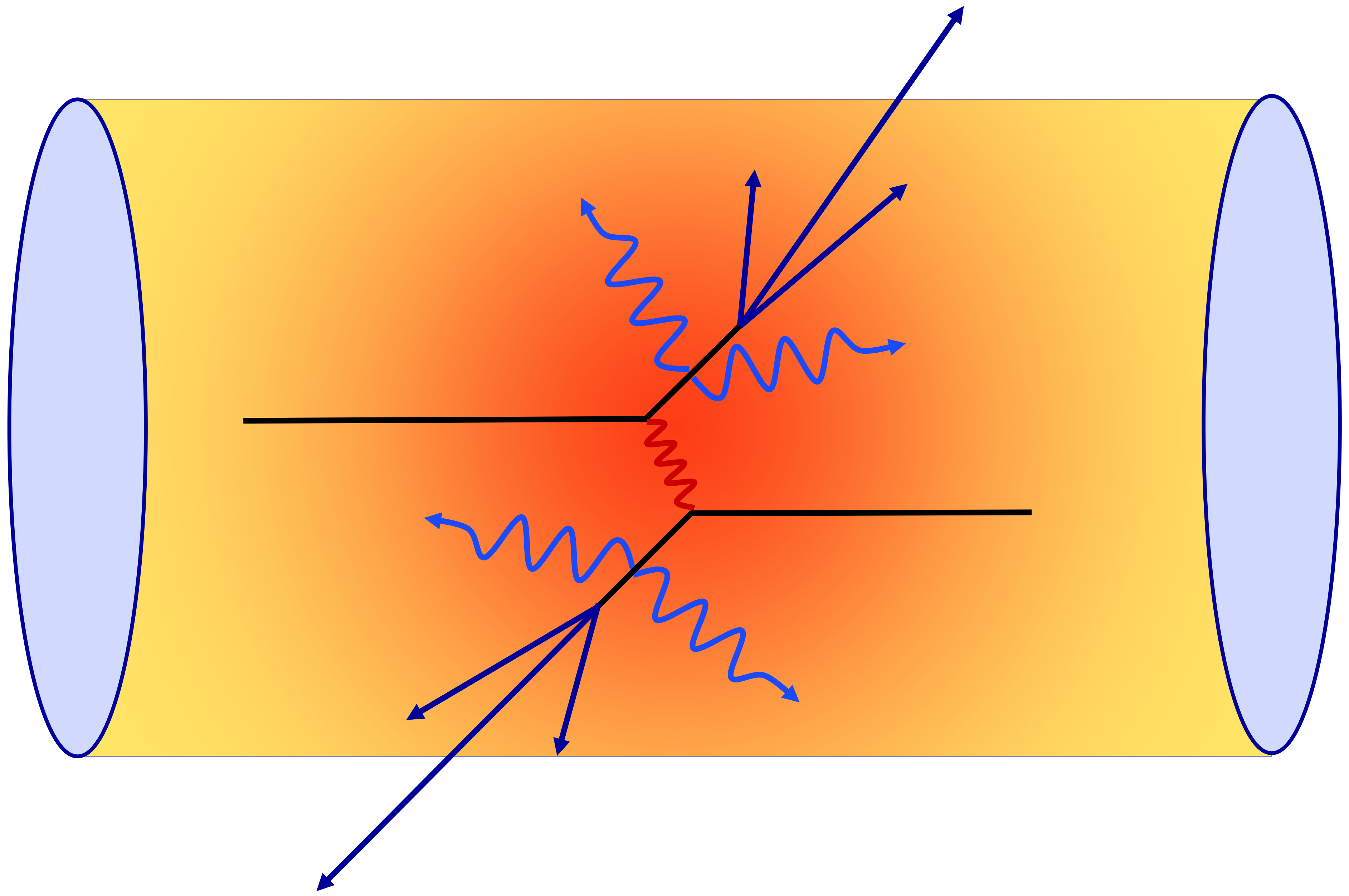
Soft processes

Momenta comparable to QGP temperature

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

Near thermal equilibrium with the plasma

'particles from the QGP'



Hard processes: large momenta >> T_{QGP}

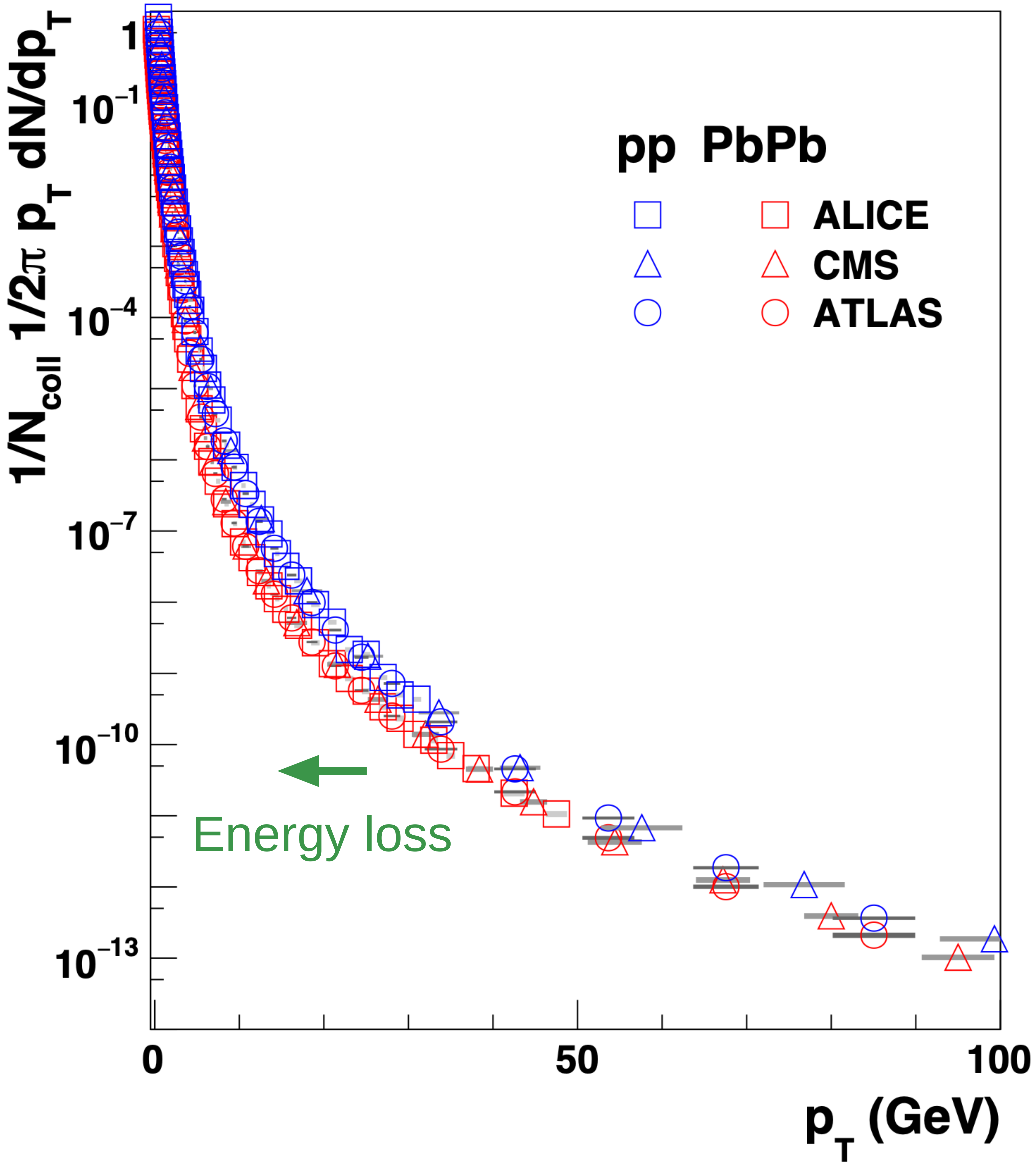
- Short formation time: initial production independent of QGP formation
- Start out far out of thermal equilibrium: **approach equilibrium through interactions**
- Short life time: expect only partial equilibration

'Hard probes' of interactions with the QGP

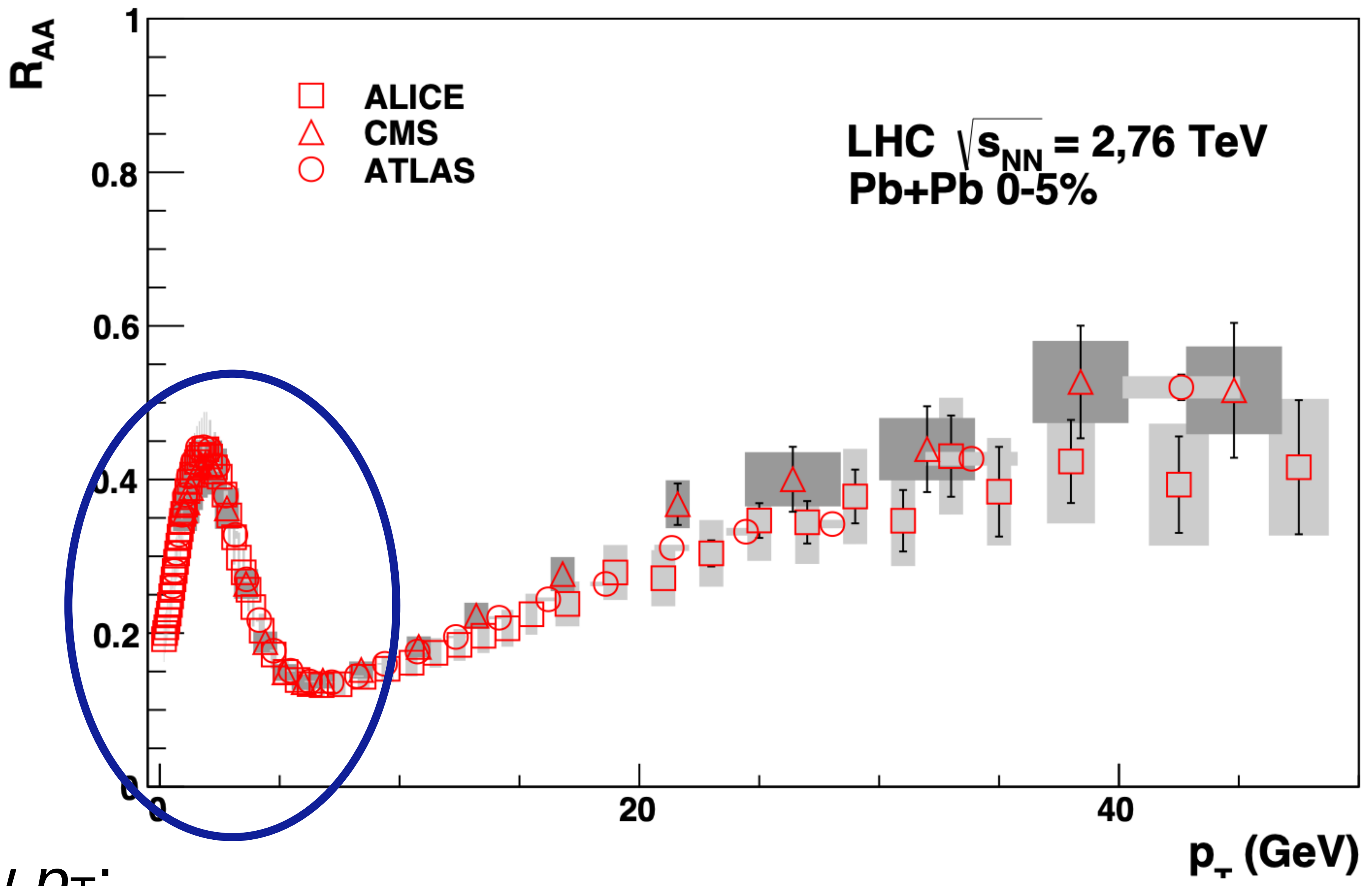
Nuclear modification of p_T spectra

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

Charged particle p_T spectra

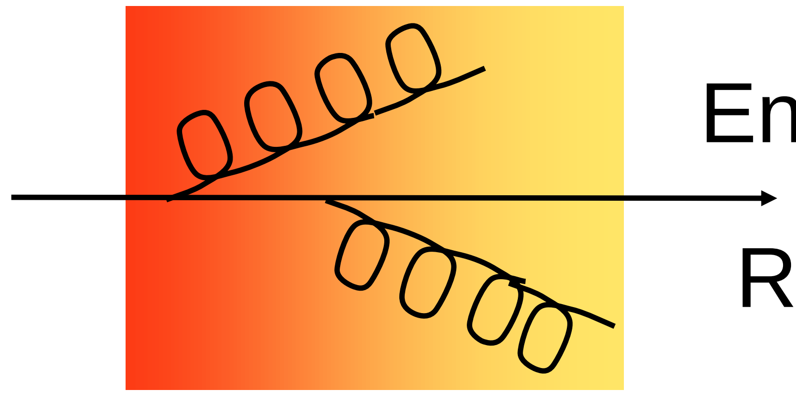


Nuclear modification factor



Low p_T:
soft production,
N_{part} scaling

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



Energy loss

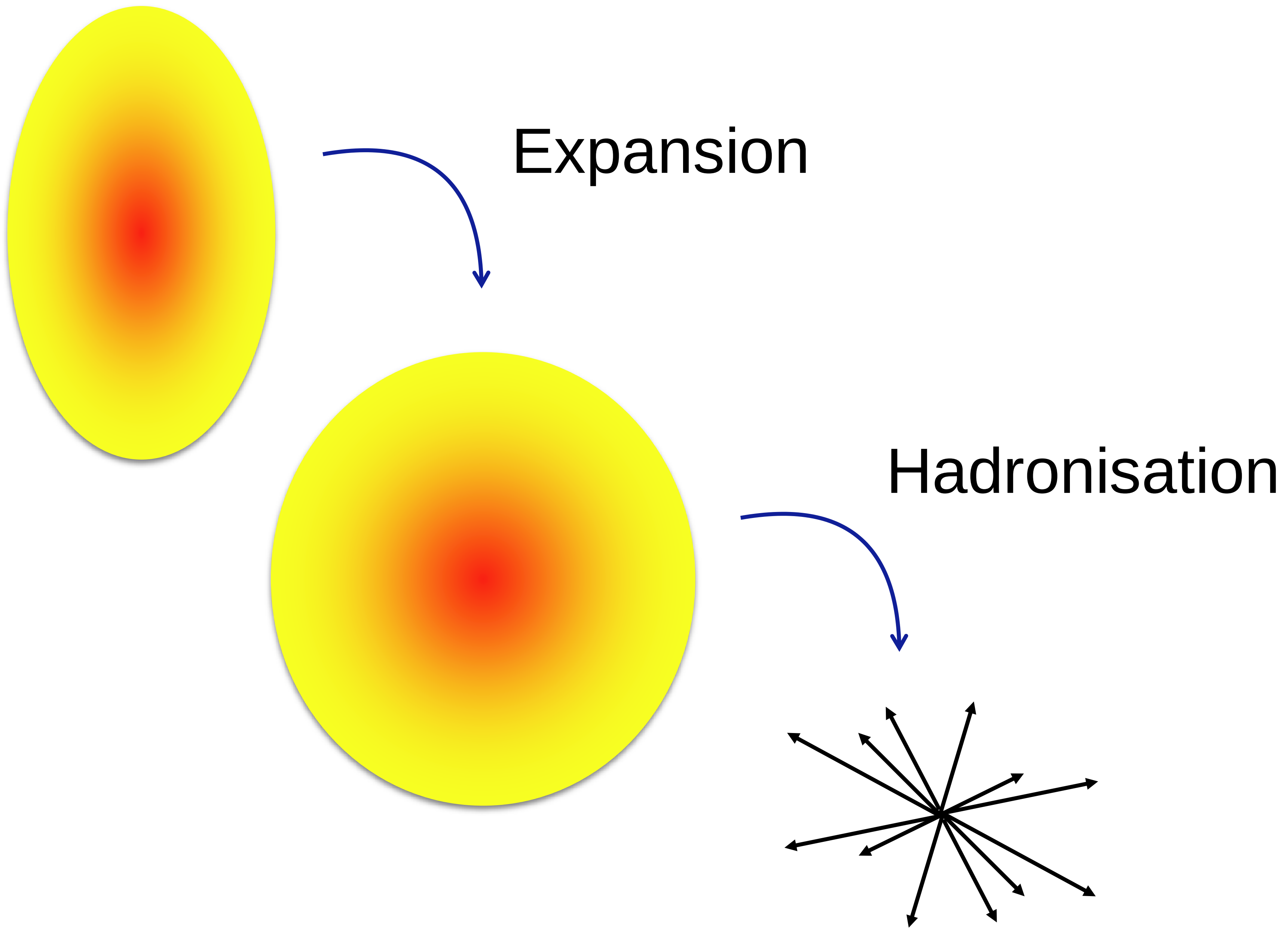
$R_{AA} < 1$

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

Azimuthal anisotropy: two mechanisms

Hydrodynamical expansion

Conversion of pressure gradients into momentum space anisotropy

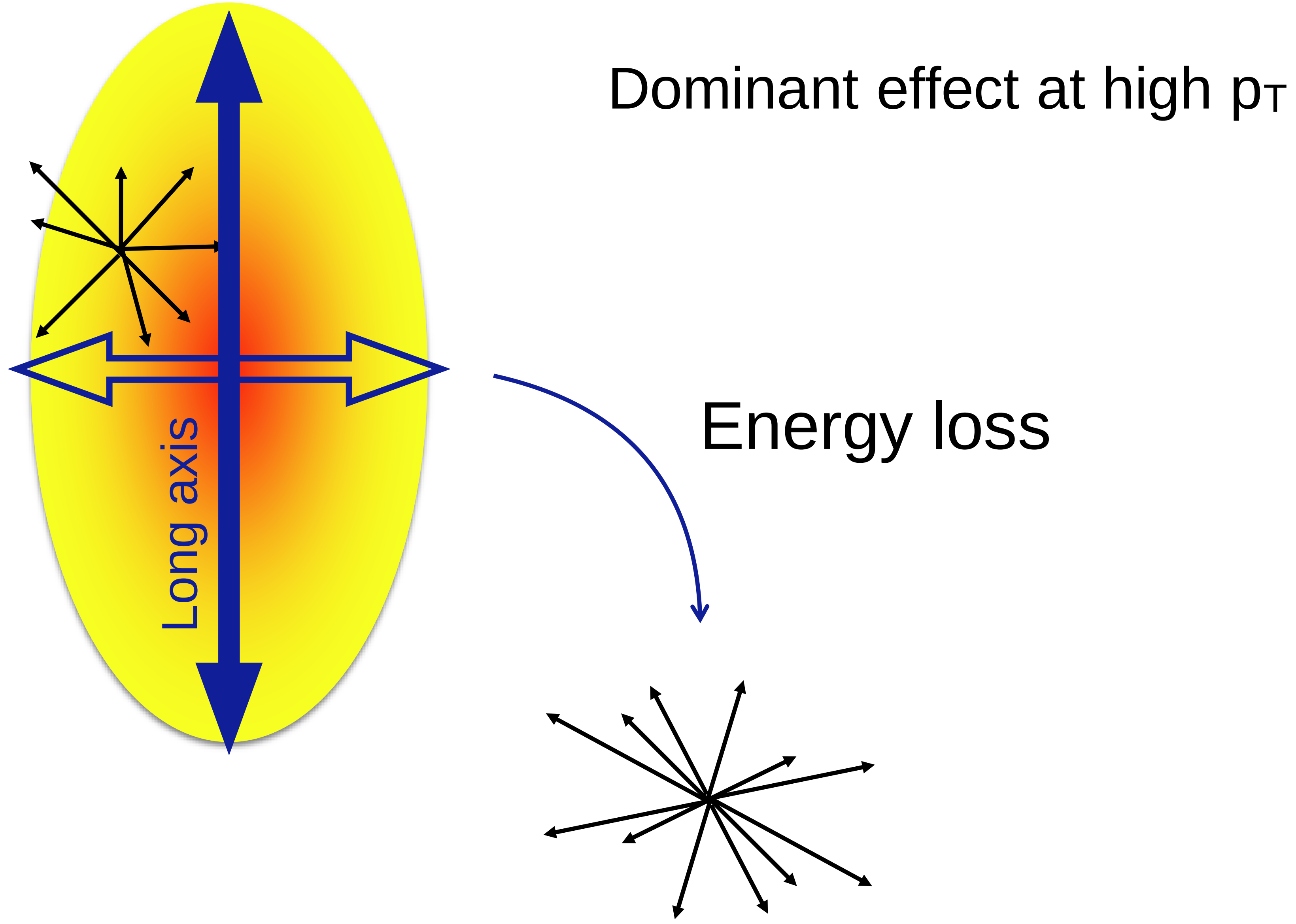


$$\nabla p = \rho \frac{d\vec{v}}{dt}$$

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

Parton energy loss

Anisotropy due to energy loss and path length differences



More energy loss along long axis than short axis

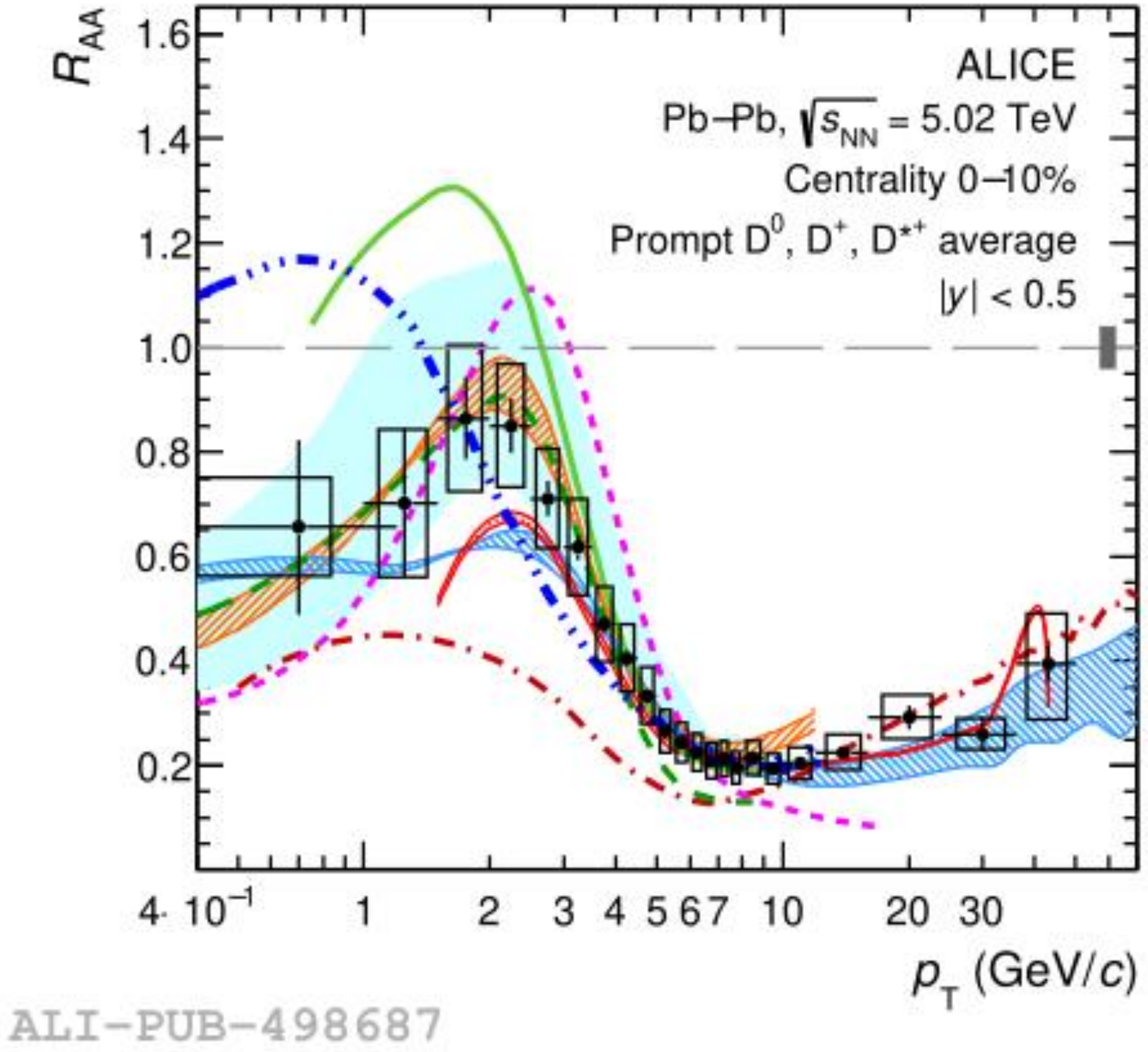
$$\Delta E_{med} \sim \alpha_S \hat{q} L^2$$

Out-of-equilibrium: high-p_T processes

Nuclear modification and elliptic flow of D mesons

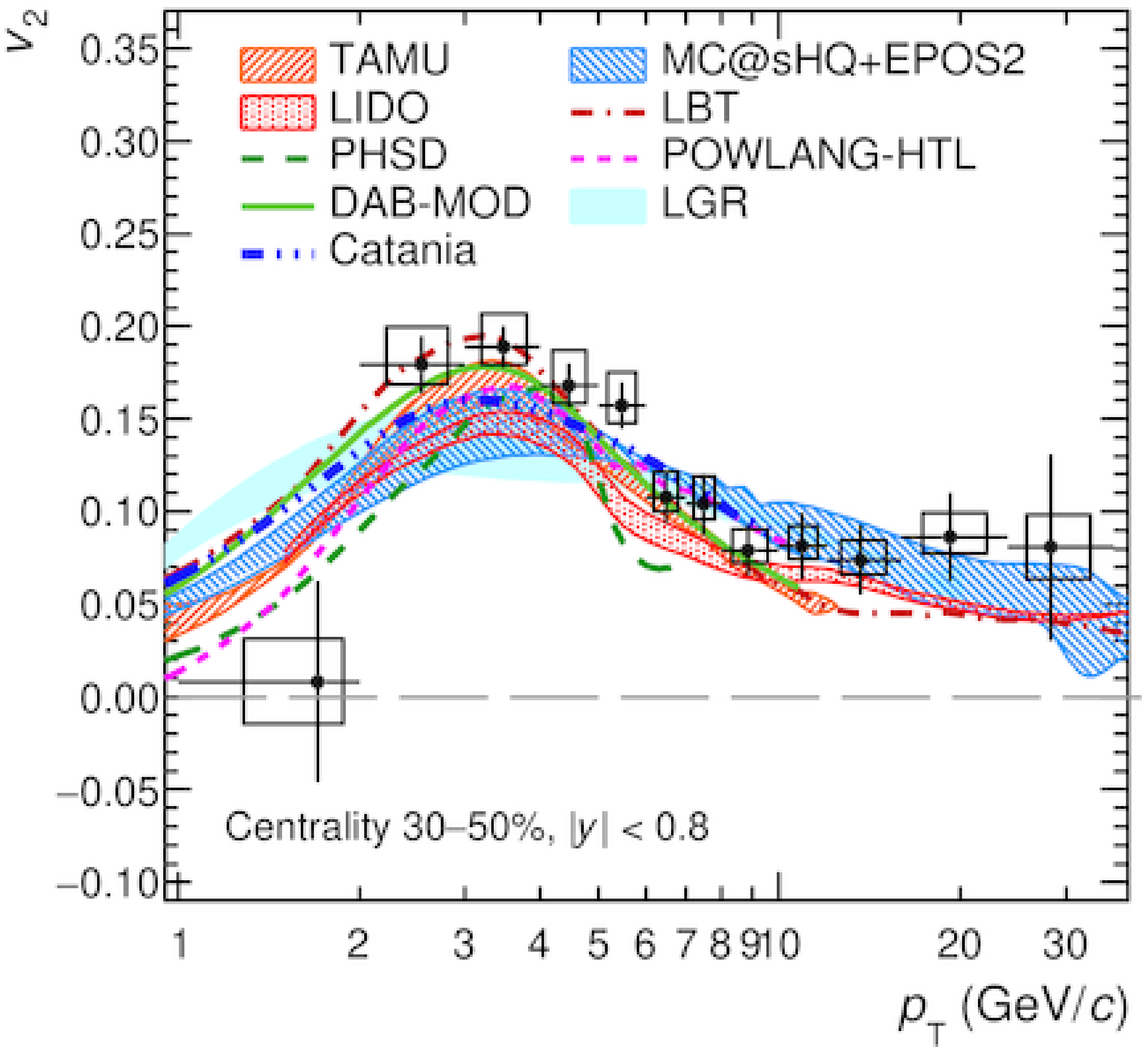
charm quarks, m >> T are produced in an initial hard scattering

Nuclear modification factor



ALICE, JHEP 01 (2022) 174

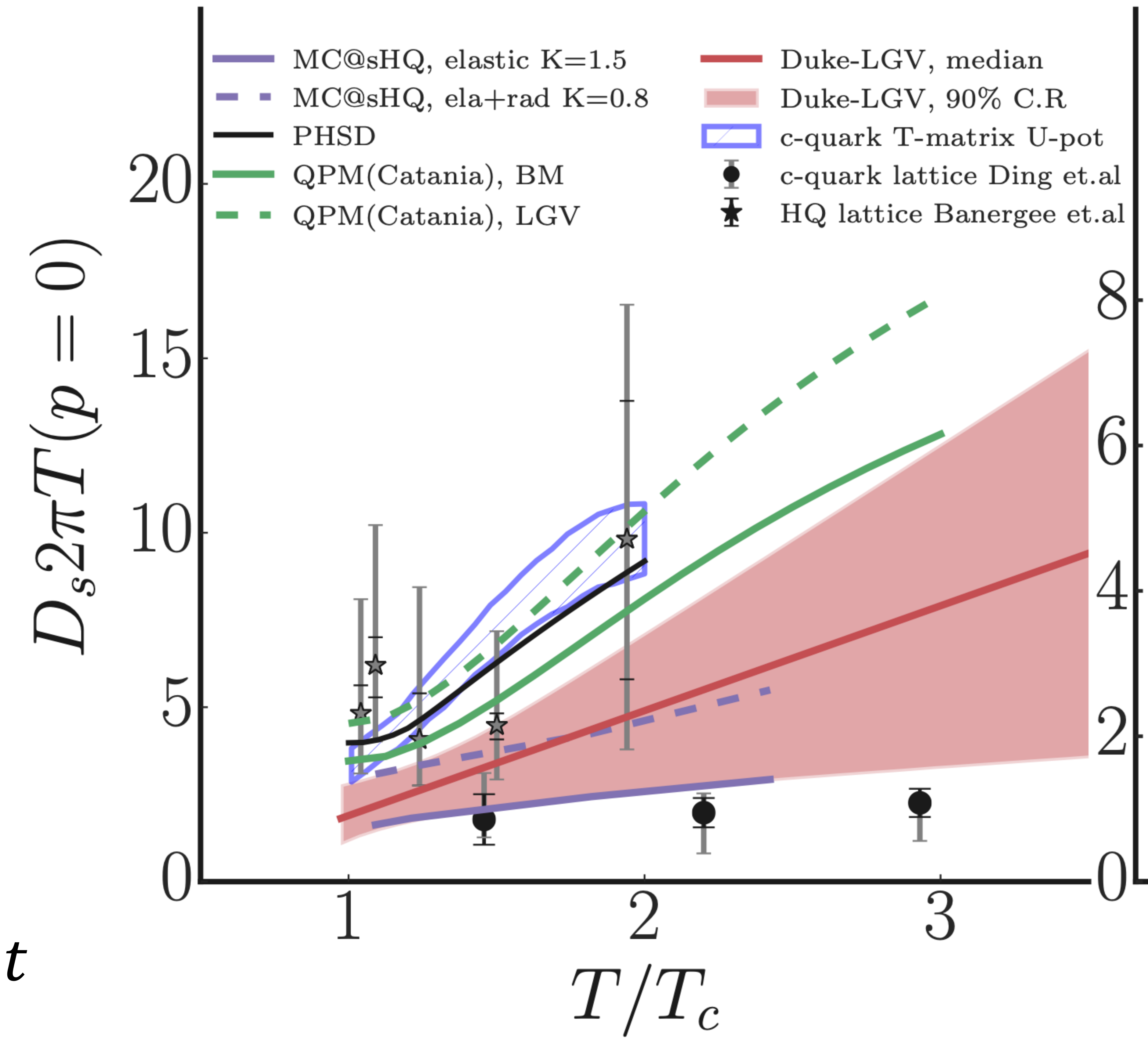
Elliptic flow v_2



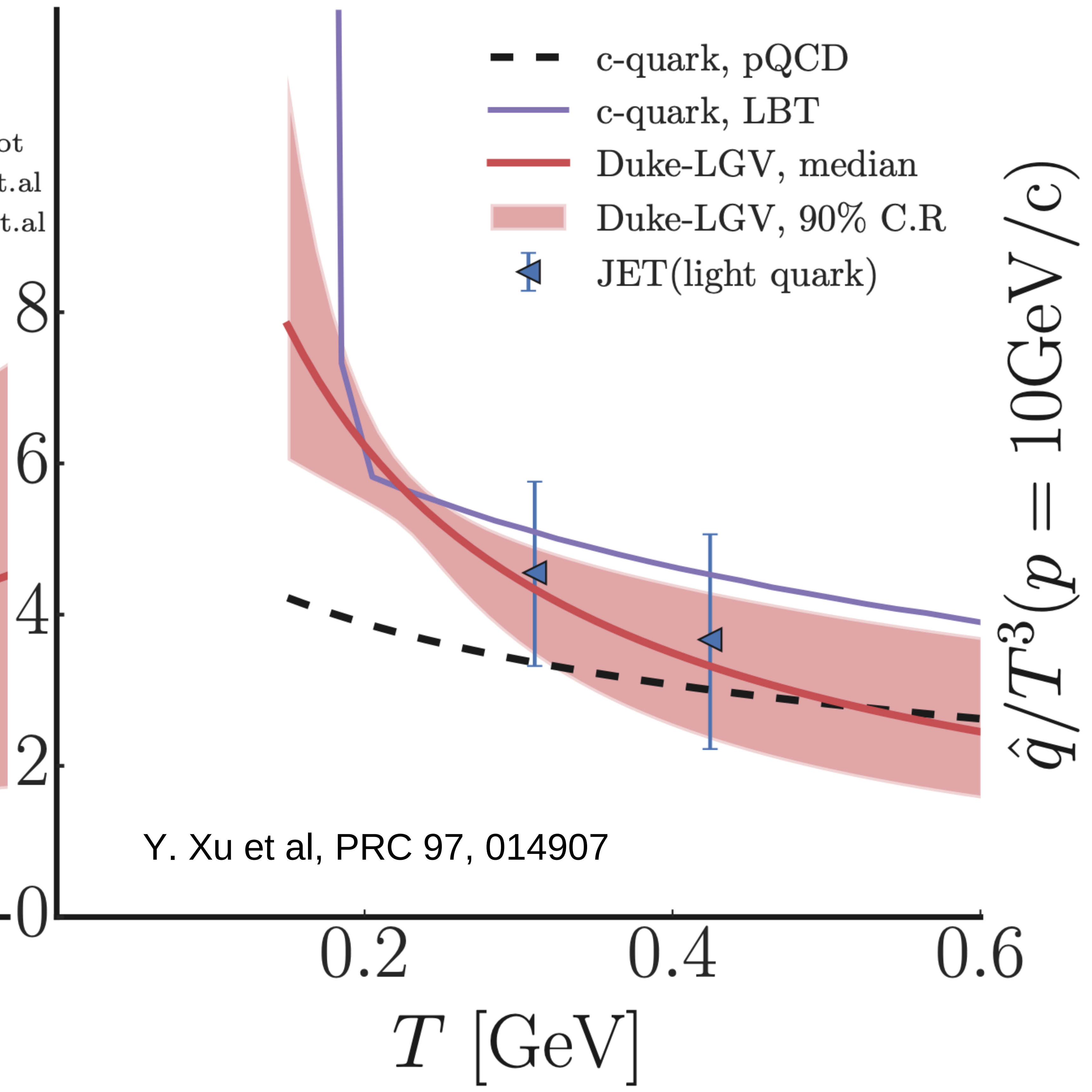
ALICE, JHEP 01 (2022) 174

Heavy flavor transport coefficient: Bayesian fit

Diffusion coefficient D_s



Transport coefficient $\hat{q}$



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

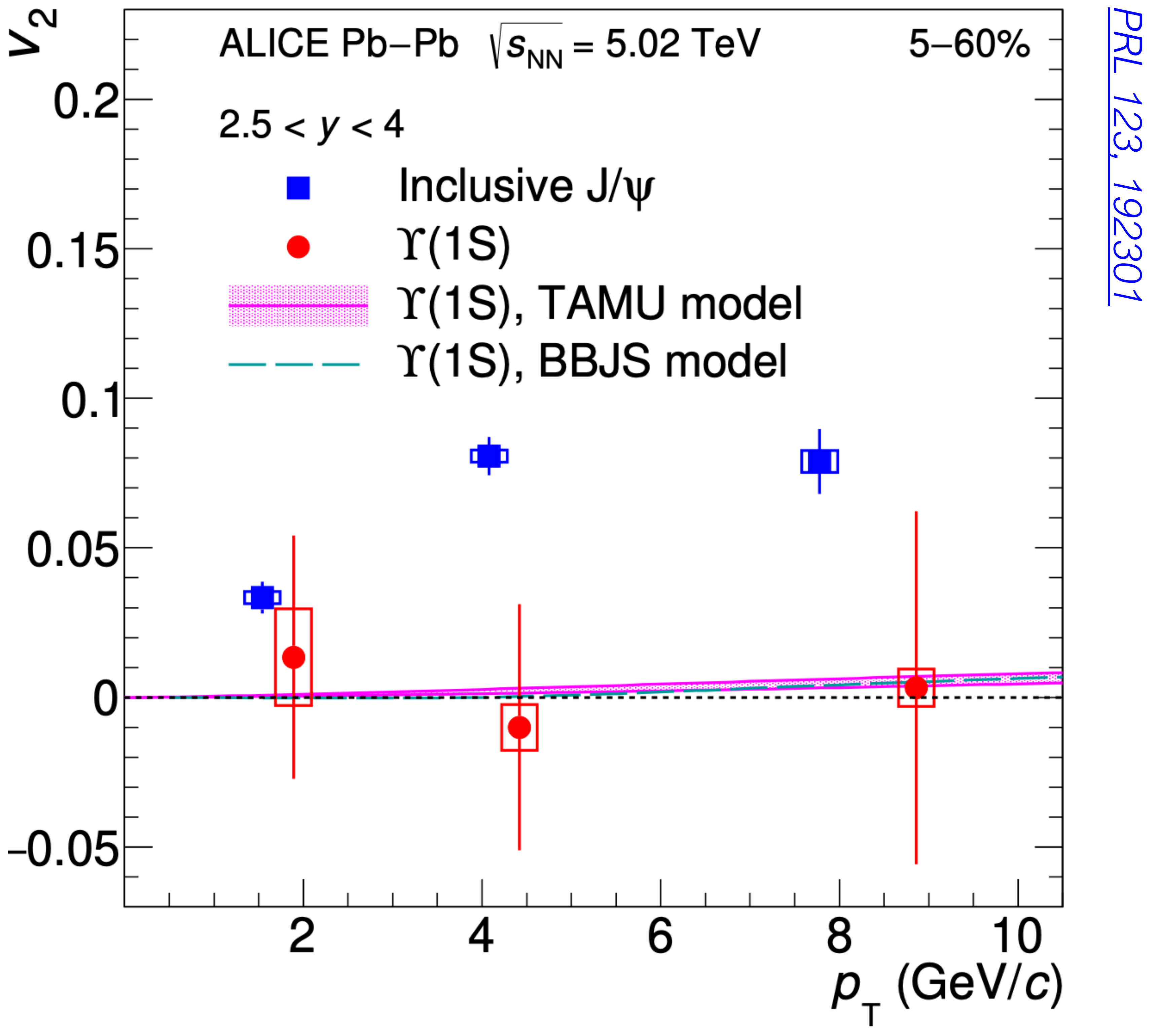
$$\hat{q} = \frac{\langle q_\perp^2 \rangle}{\lambda}$$

Data constrain transport properties of the QGP

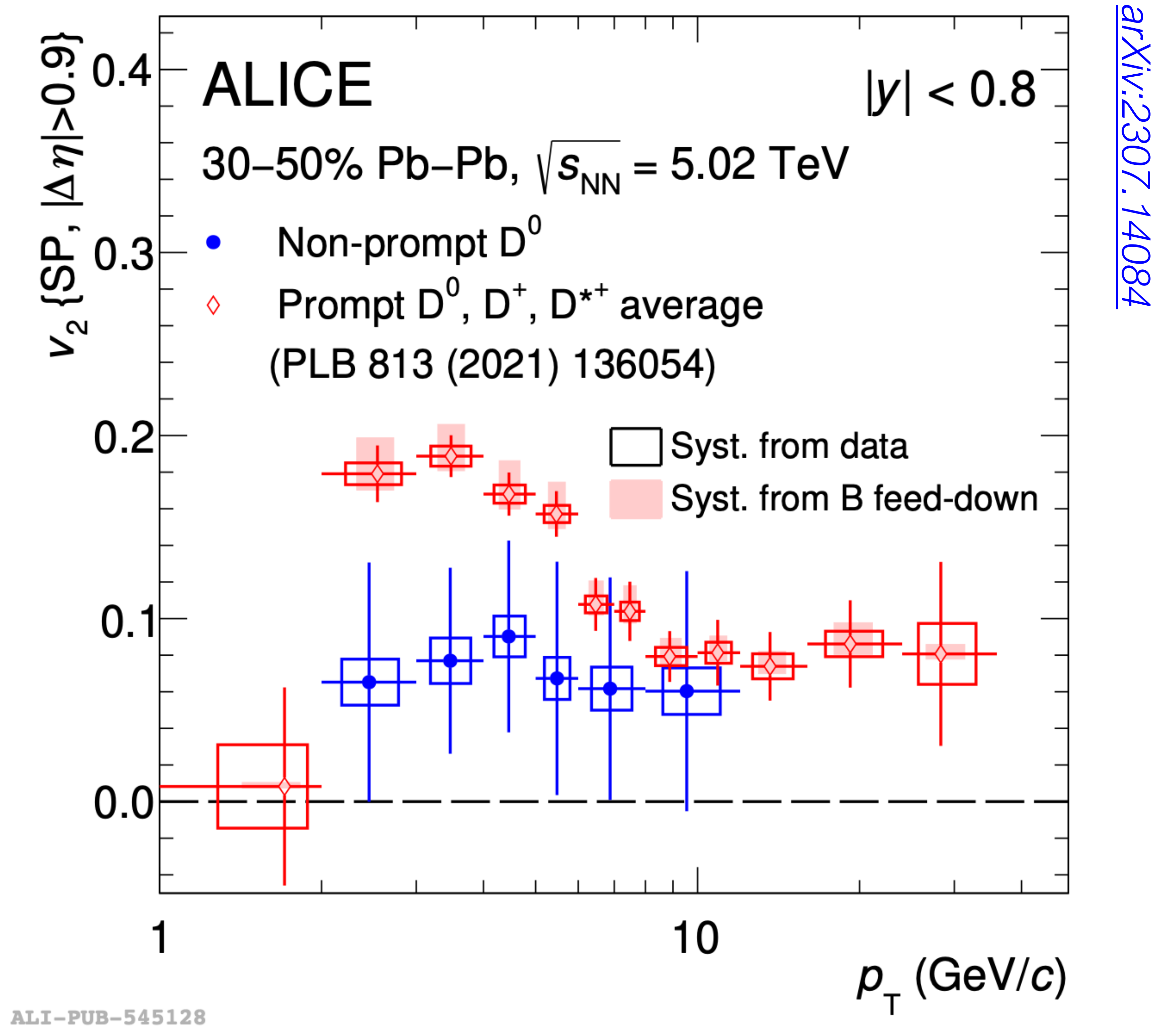
Results agree with lattice QCD/pQCD expectations
and between light and heavy flavour sector

Elliptic flow of charm beauty quarks: effect of mass

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



Open charm, beauty elliptic flow



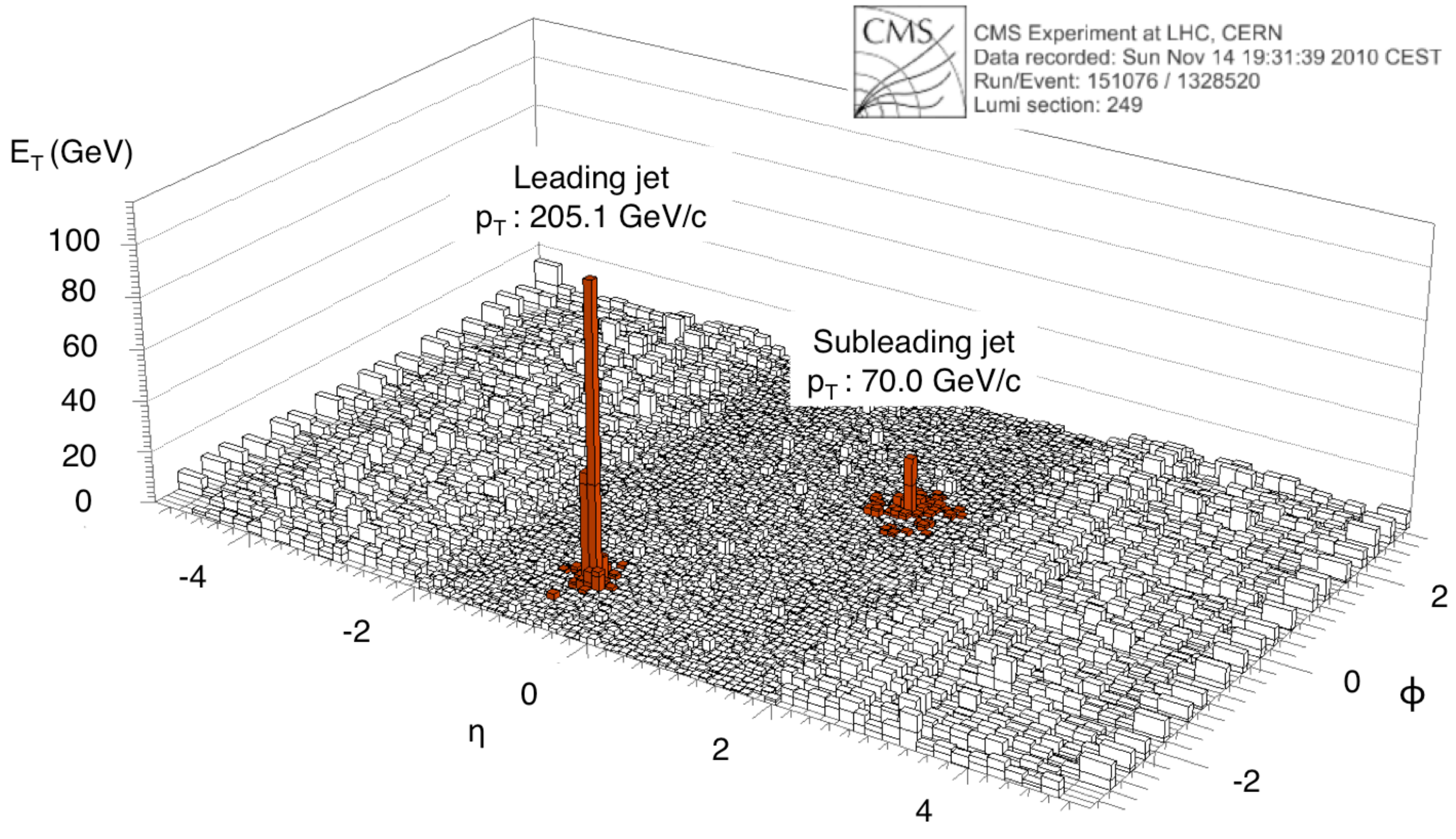
Quarkonia: flow generated by quark flow and coalescence
Charmonia: large elliptic flow — Bottomonia: compatible with no flow

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

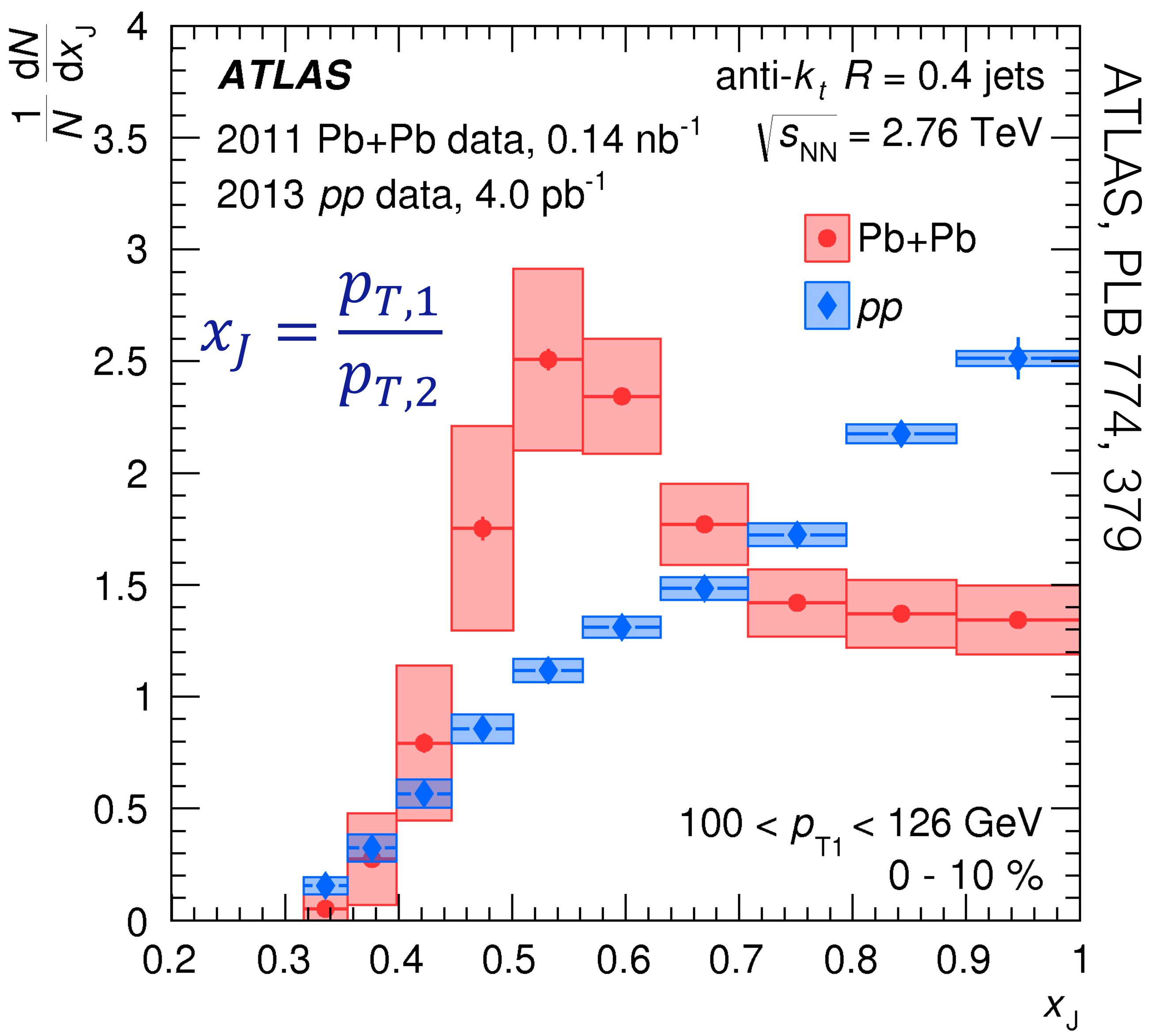
Beauty quarks flow less than charm quarks: larger mass, slower thermalisation

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

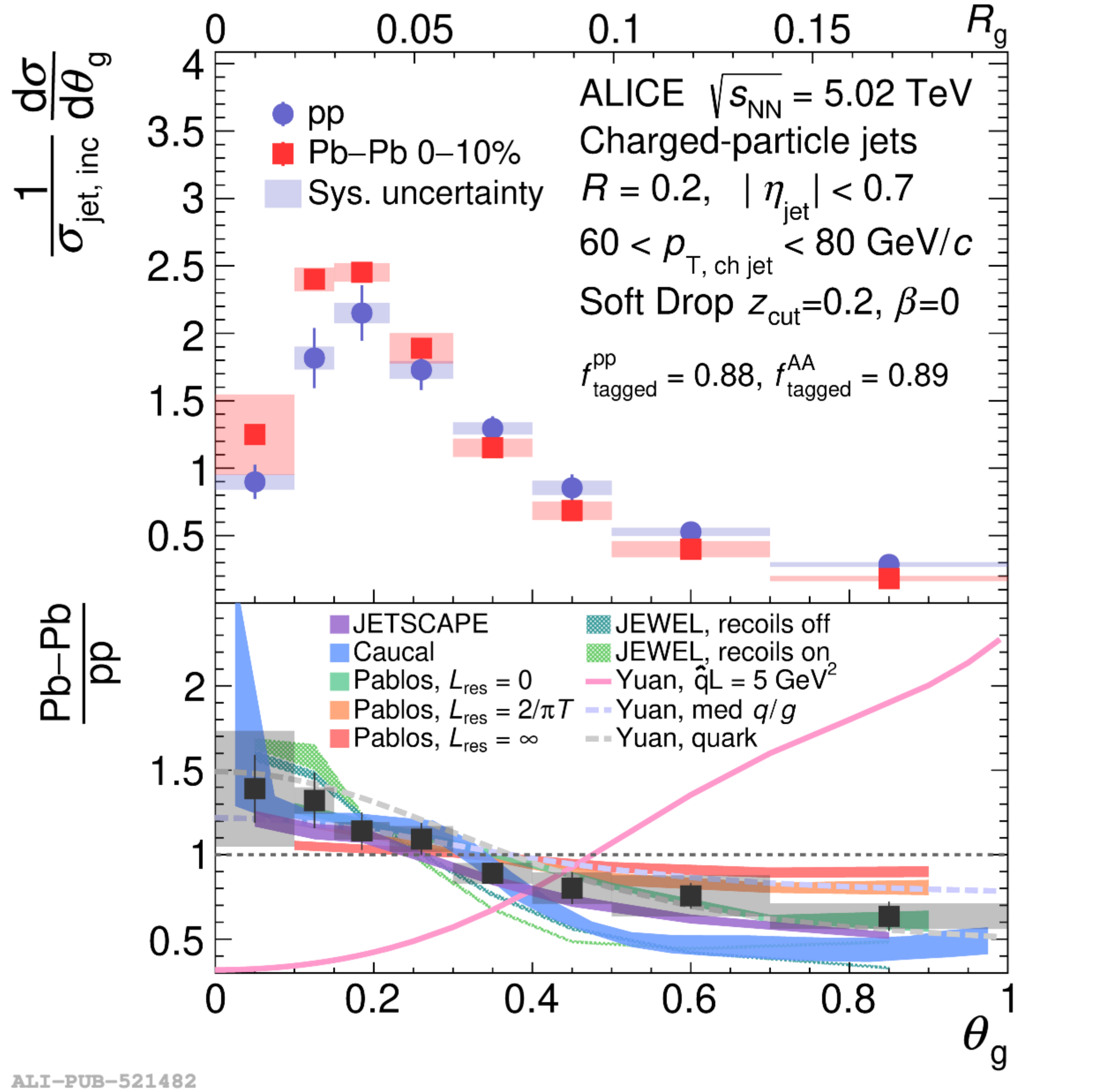
Energy loss: di-jet asymmetry



Energy fraction of second jet

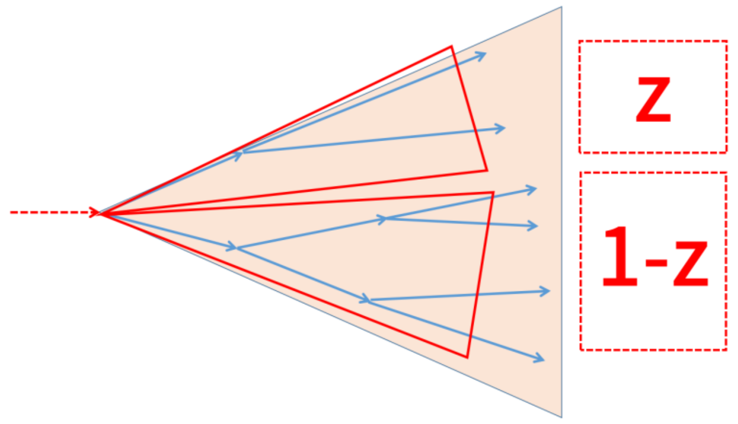


Softdrop splitting angle θ_g



ALICE, PRL 128, 102001

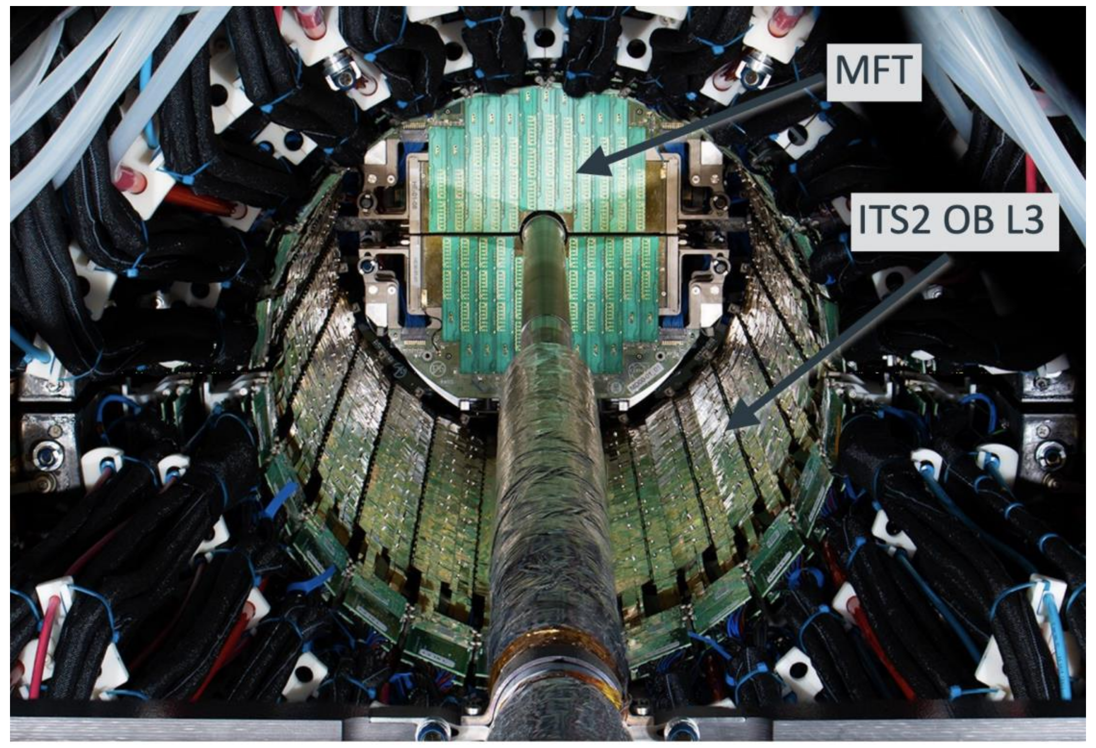
Di-jet energy imbalance: jets lose energy as they propagate through the plasma



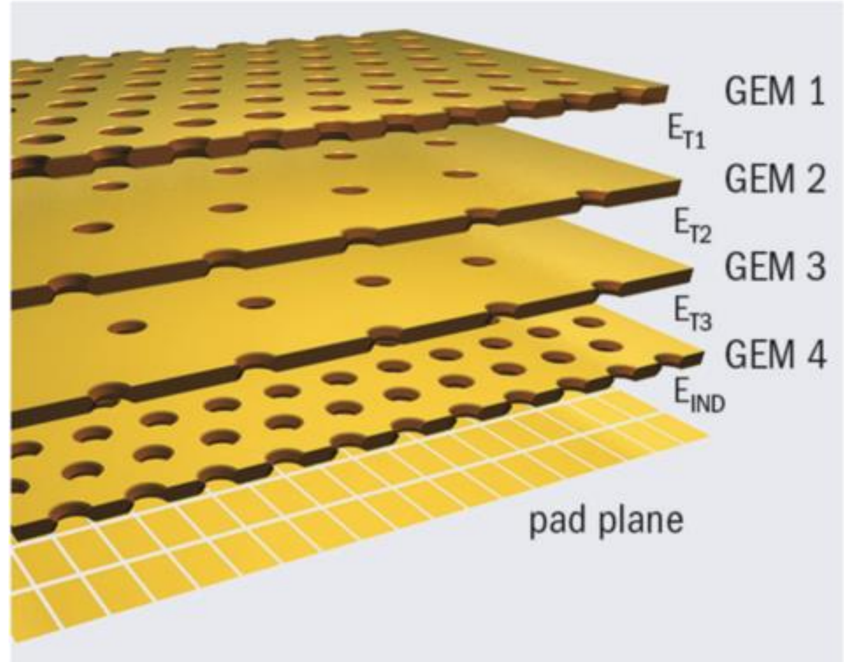
More in K Rajagopal's presentation Tuesday

ALICE upgrades for Run 3 and 4

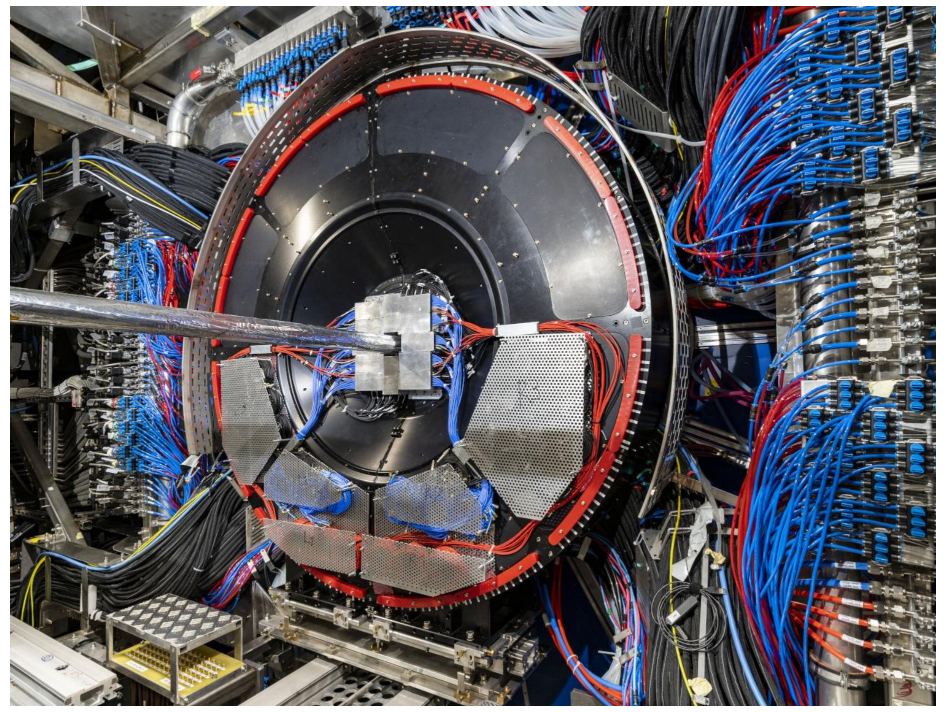
New ITS and MFT



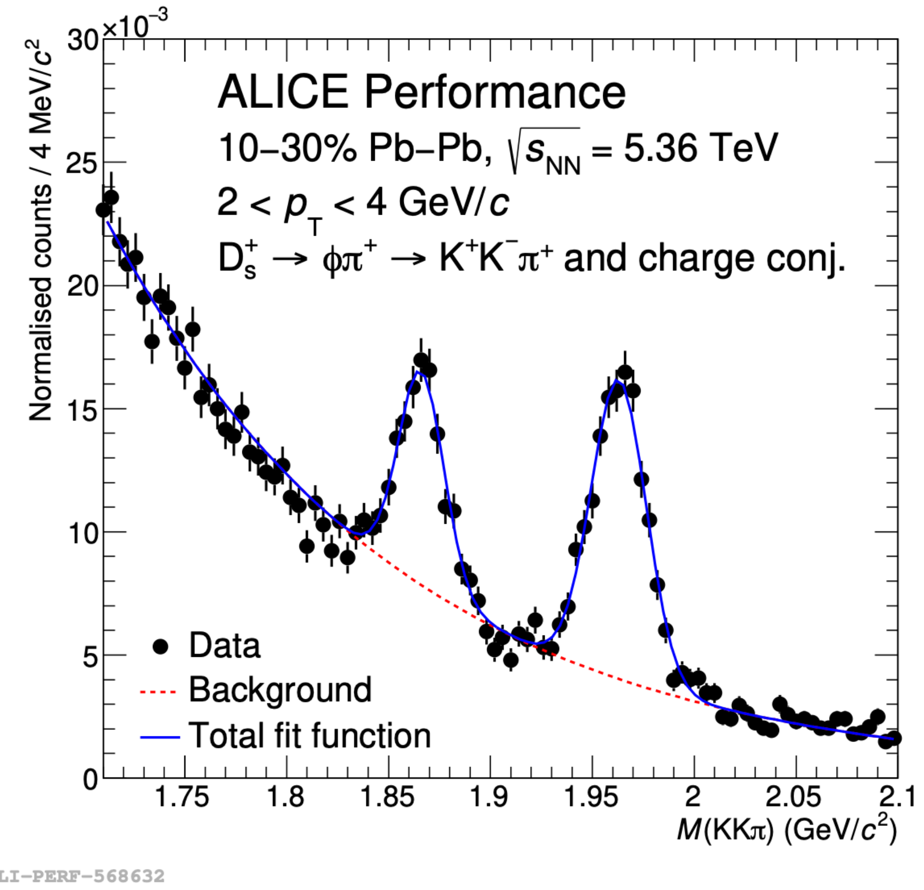
TPC: GEM readout



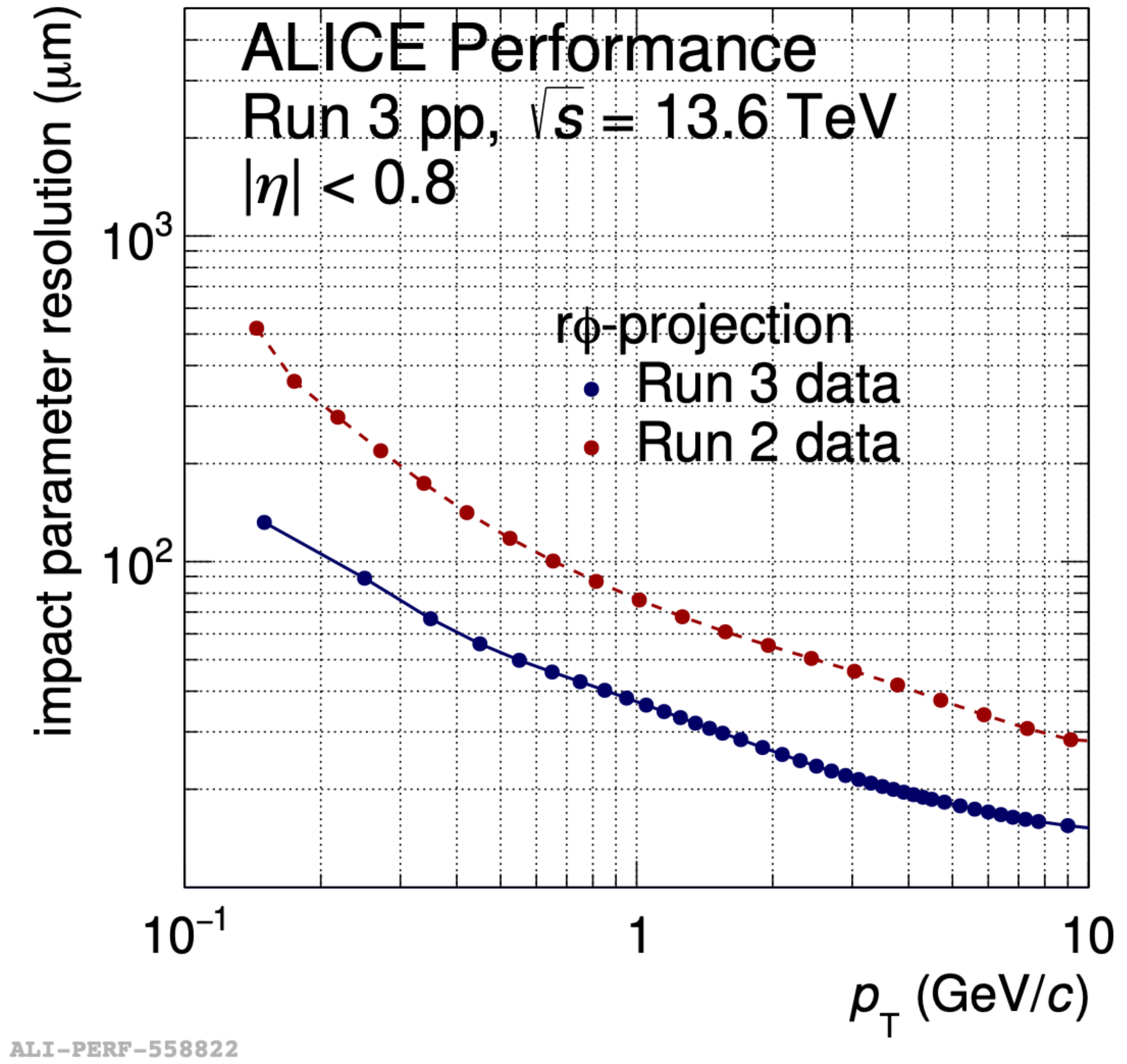
Fast Interaction Trigger



D^+ and D_s^+ in Pb-Pb



Impact parameter resolution



Full pixel detector 13 Gpixels

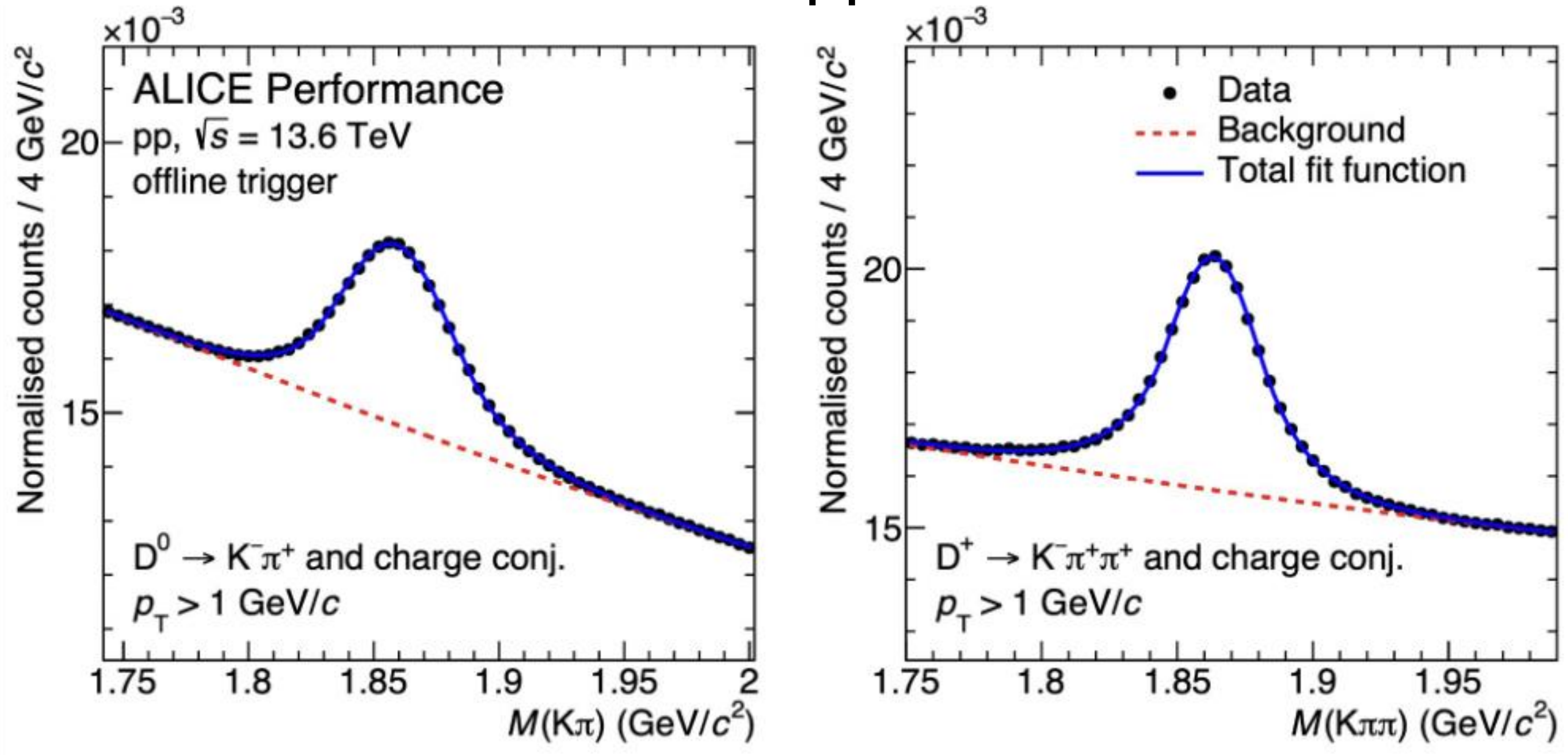
Improved spatial resolution

Online event processing

+ readout upgrades for
muon system, TRD, EMCal

ALICE LS2 upgrade paper: [arXiv:2302.01238](https://arxiv.org/abs/2302.01238)

D mesons in pp collisions

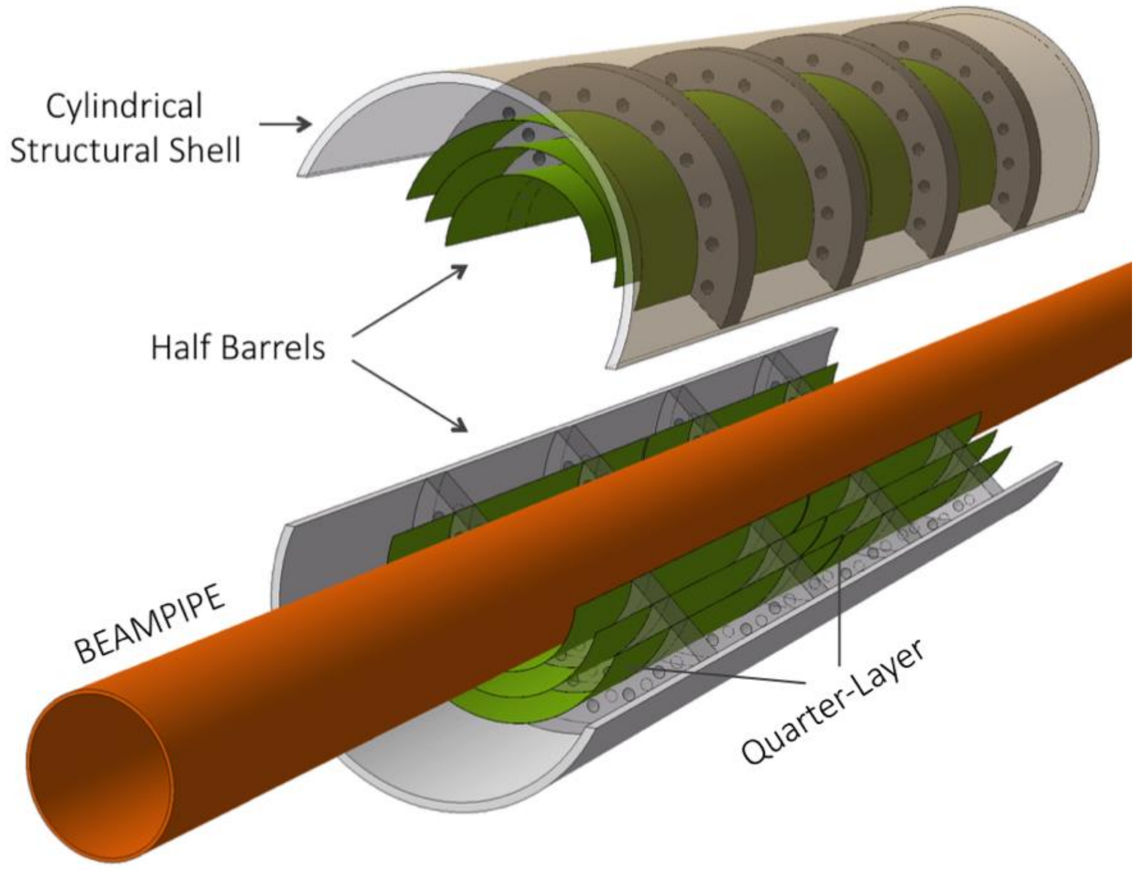


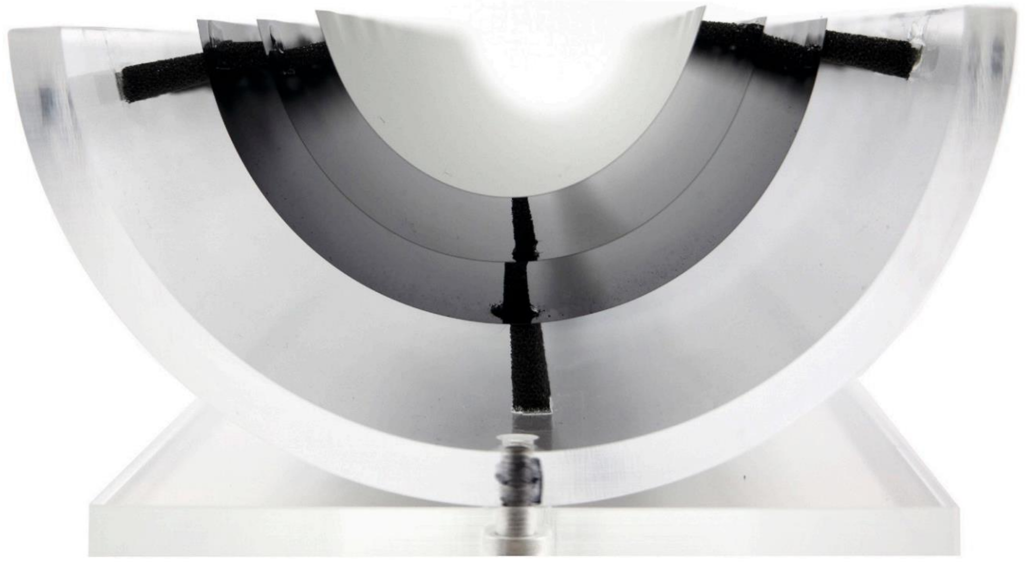
Large data samples — offline event selection for pp

Improved pointing resolution and readout rate:
record 50 kHz Pb-Pb collisions (50x more minimum bias events)

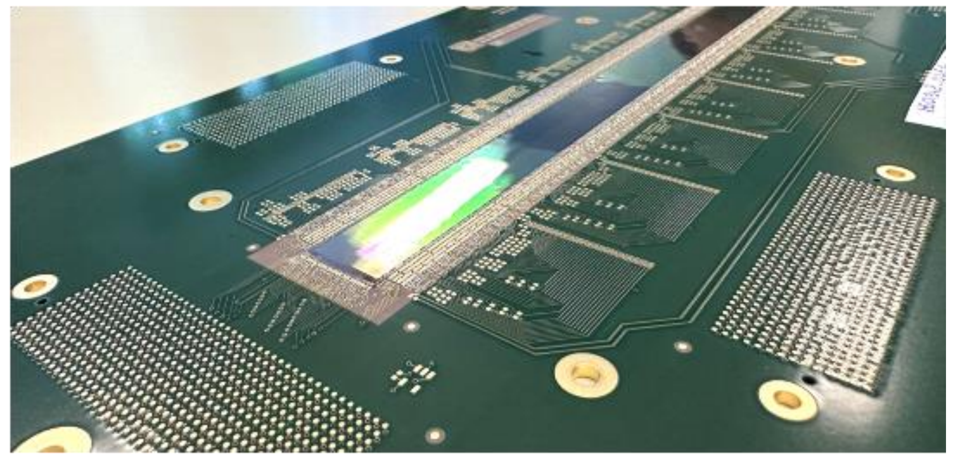
ITS 3 and FoCal for Run 4

ITS 3: ultra-light, fully cylindrical tracking layers





Stitched sensor

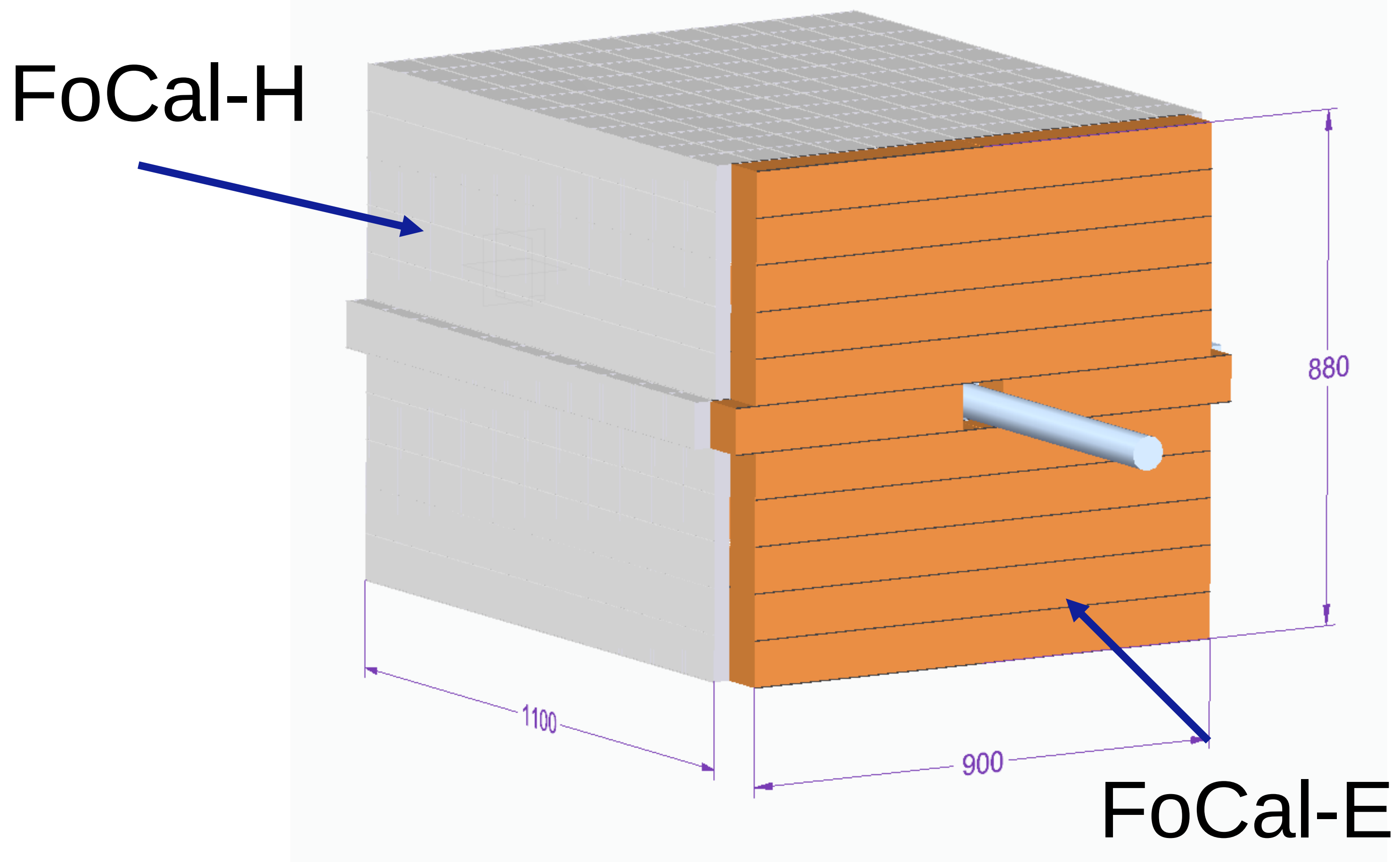


LoI: CERN-LHCC-2019-018
DPTS test paper arXiv:2212.08621

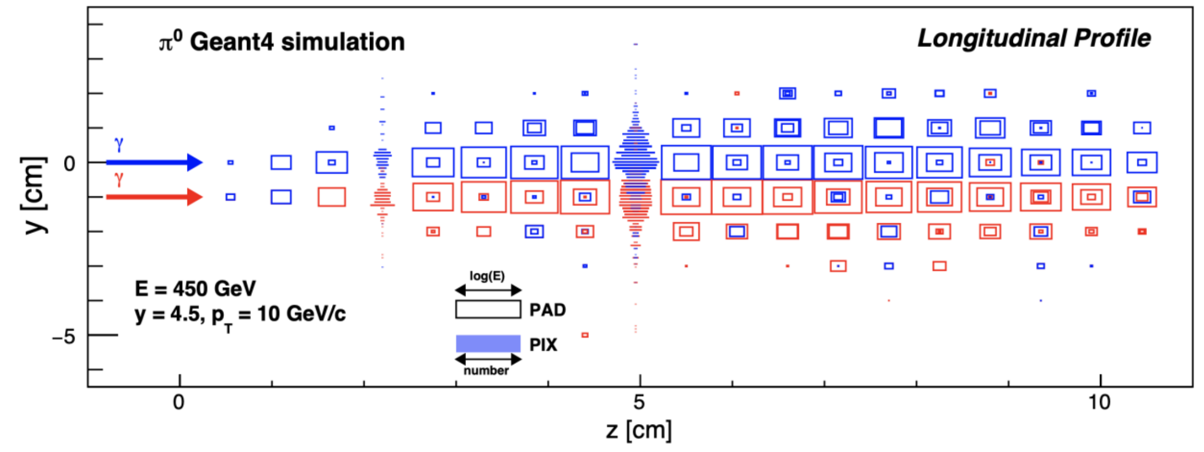
Improved performance for
- Heavy flavour reconstruction
- Di-lepton measurements

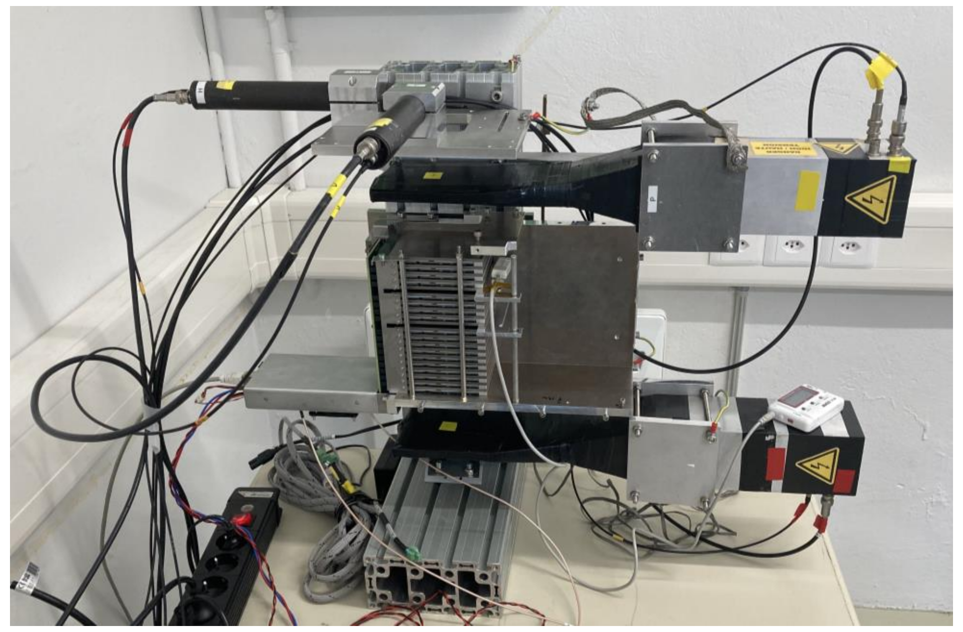
FoCal: high-granularity foward calorimeter

$3.4 < \eta < 5.8$



Longitudinal profile (2γ showers)



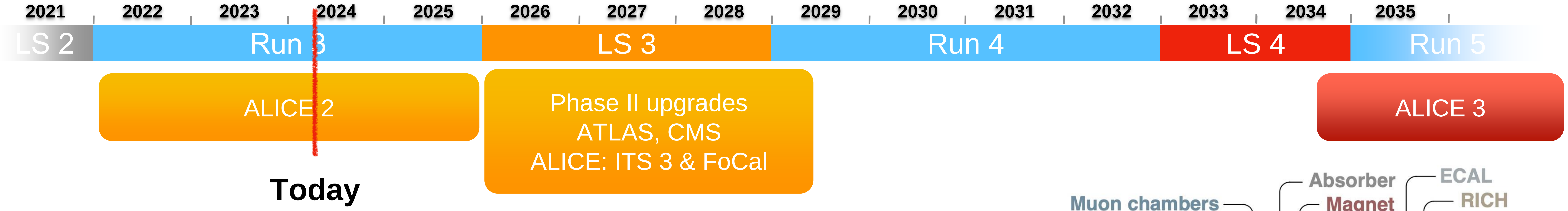


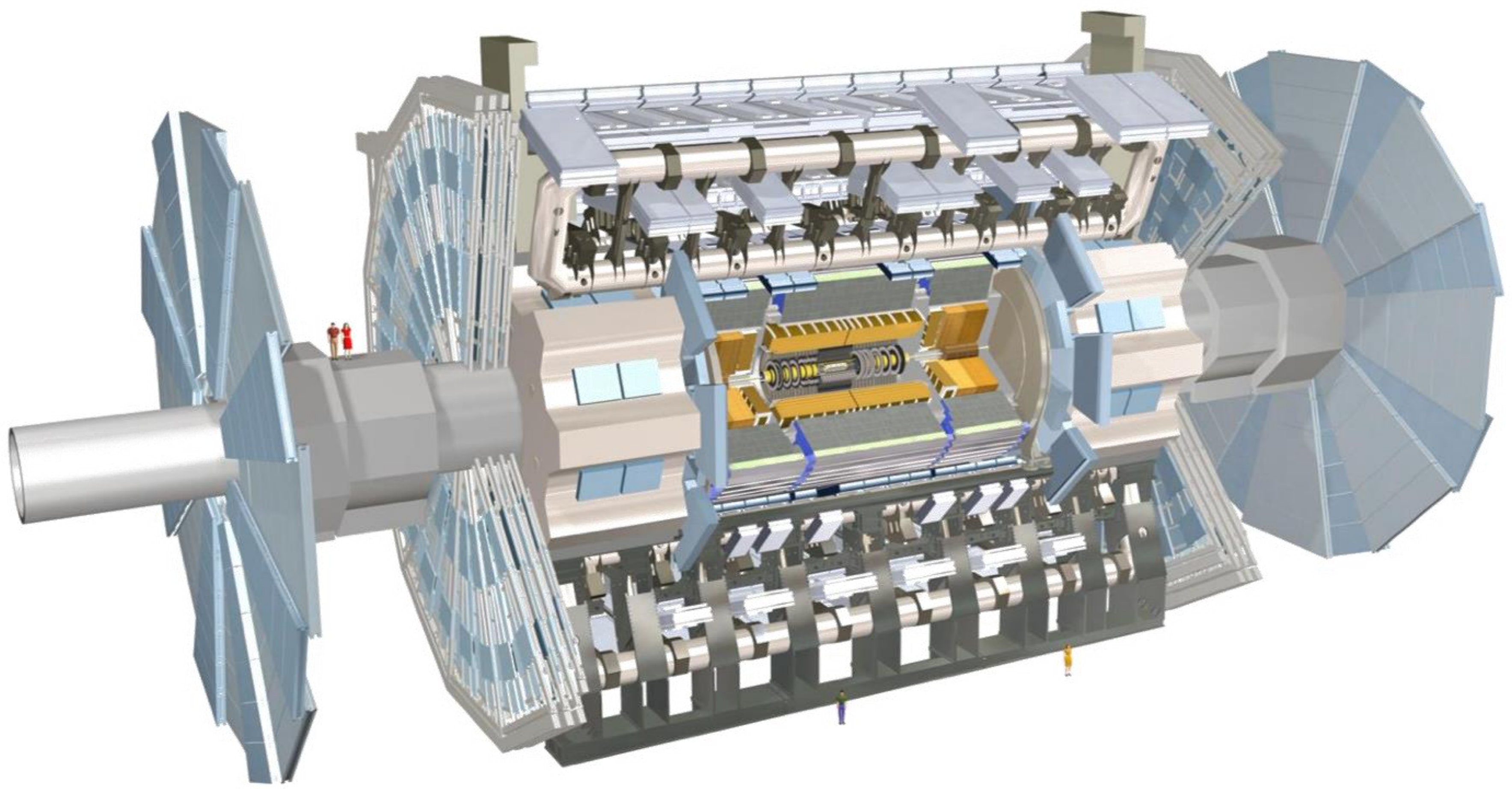
LoI: CERN-LHCC-2020-009

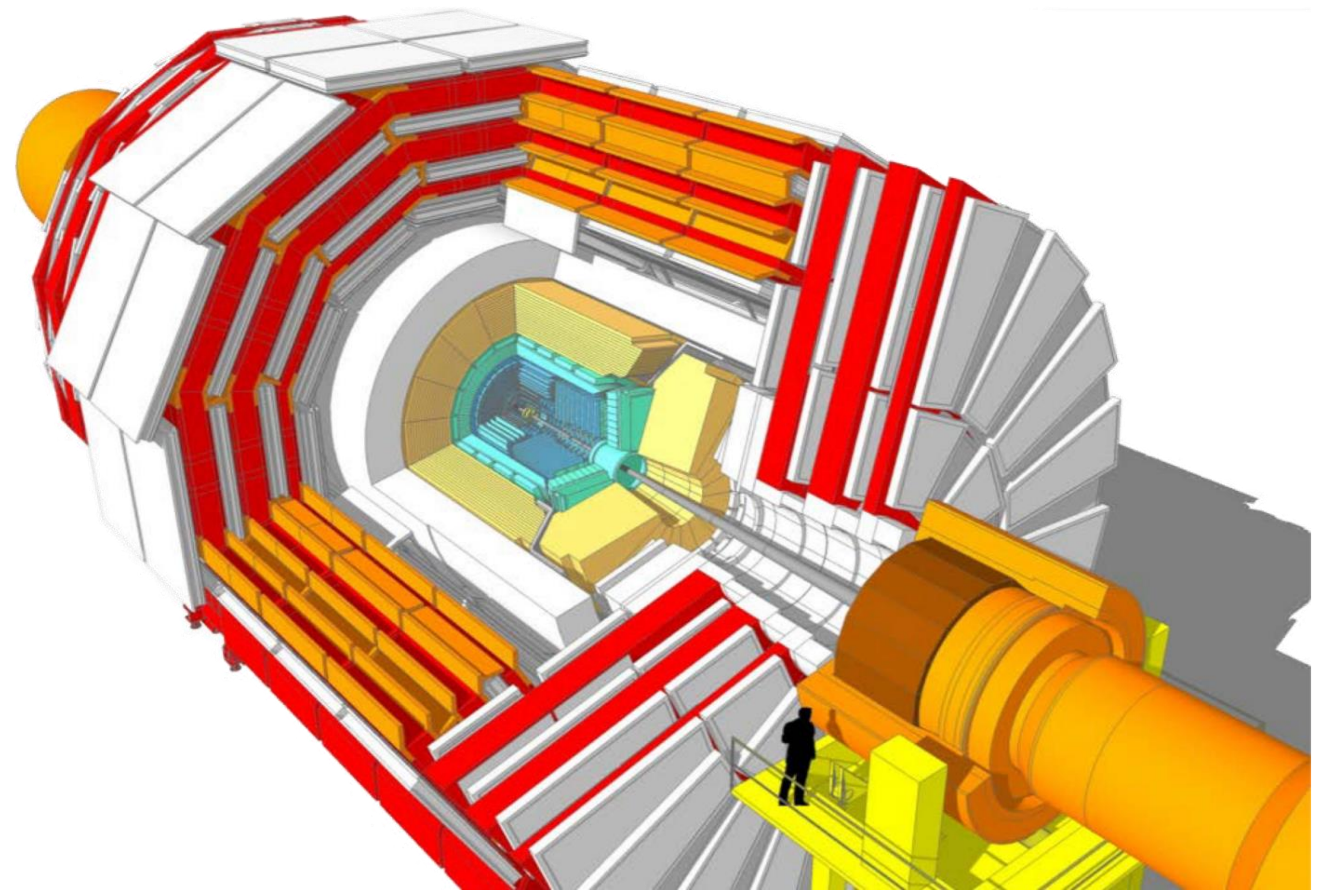
High-granularity Si-W EM calorimeter for **photons and π^0**
- **Small-x physics** in pp and p-Pb
- Forward π^0 in Pb-Pb

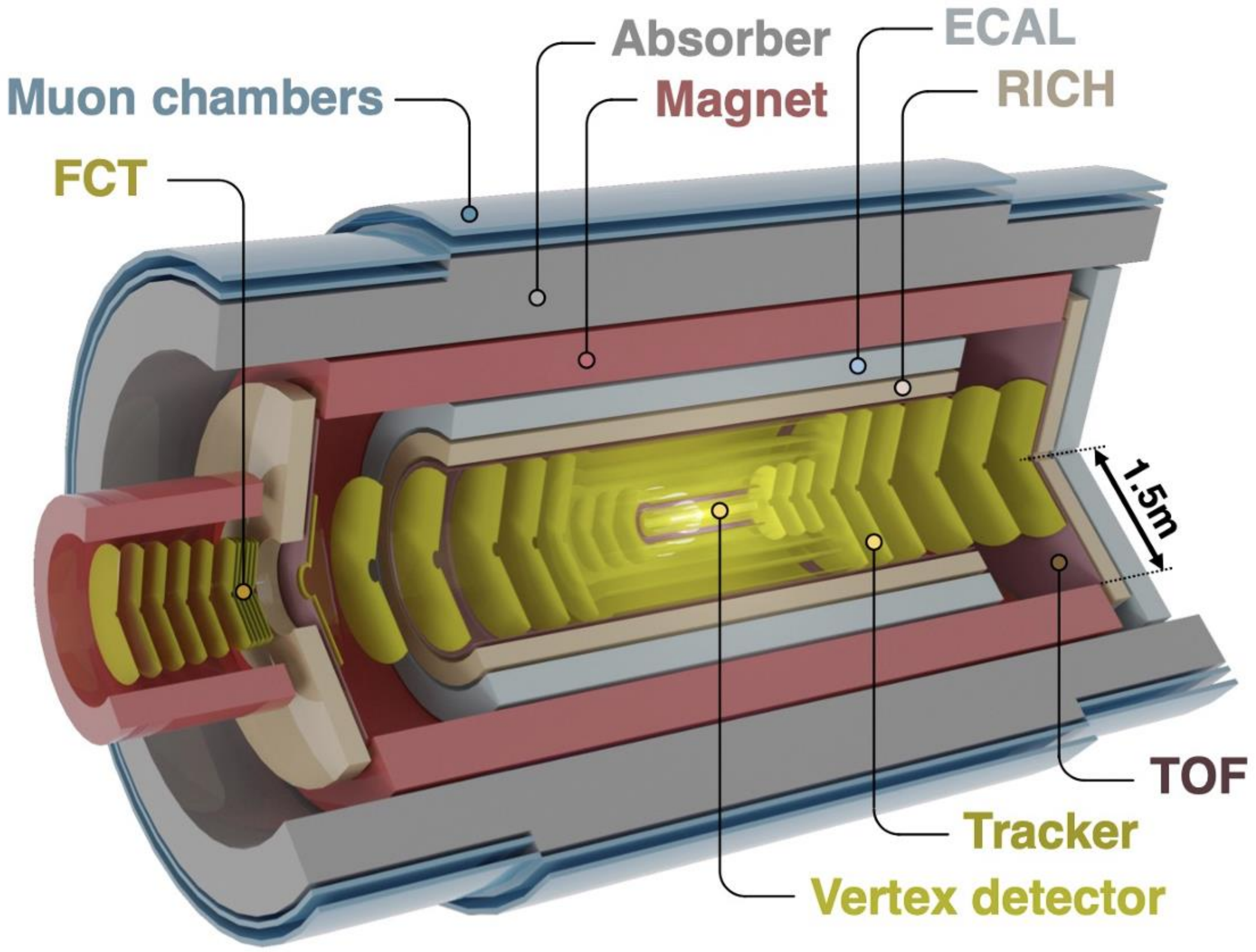
TDRs approved, installation in LS3: 2026-2028

LHC program time line









ATLAS and CMS Phase II upgrades:

- New trackers: HI tracking up to η = 4
- Timing layers: PID
- New ZDCs
- …

ALICE 3 LoI: CERN-LHCC-2022-009

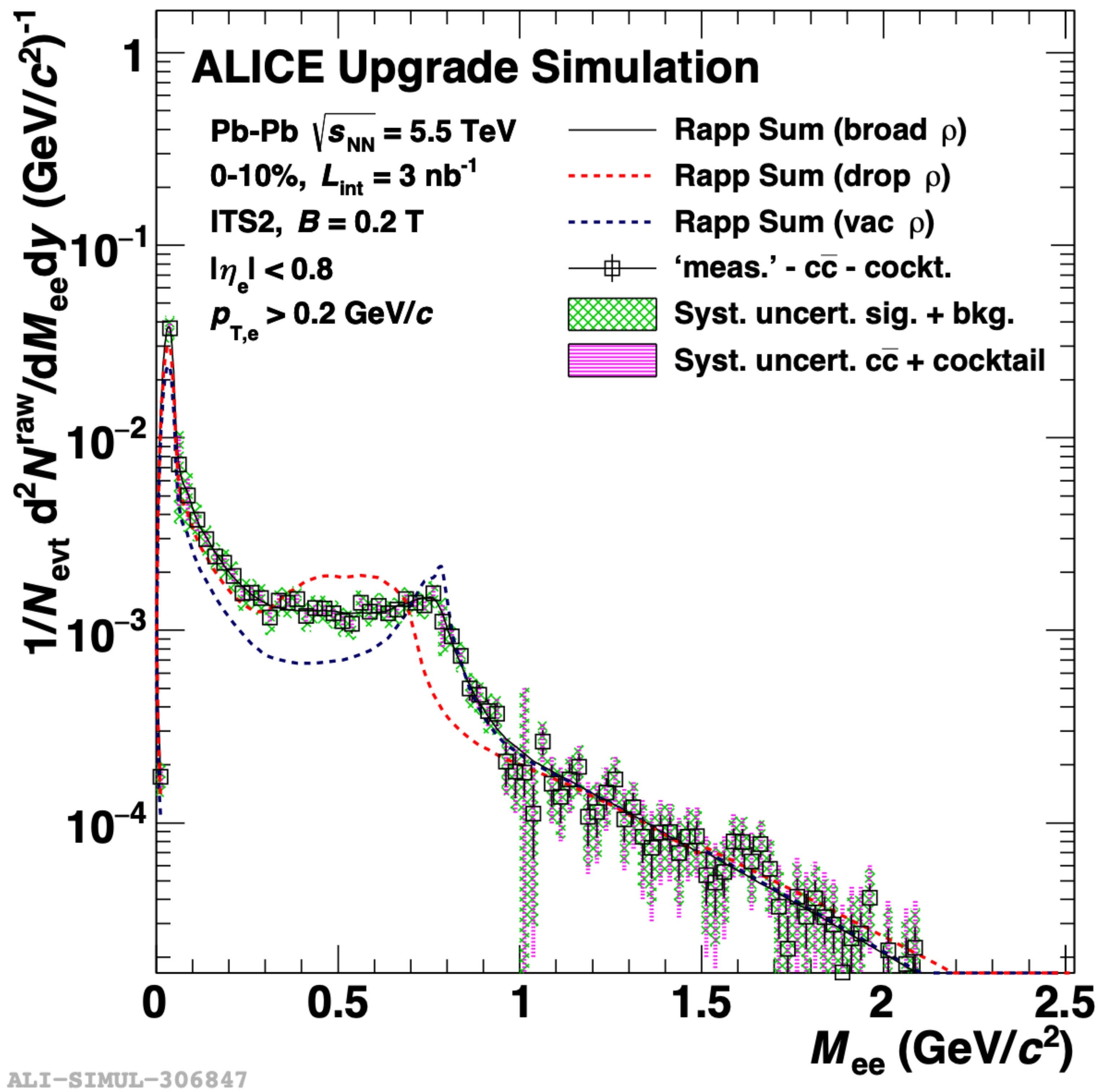
ALICE 3:

- Excellent pointing resolution
- Large η coverage
- Excellent PID: TOF, RICH, muons, EMCal

LHCb: Phase IIb upgrades

Dielectrons: chiral symmetry and thermal emission

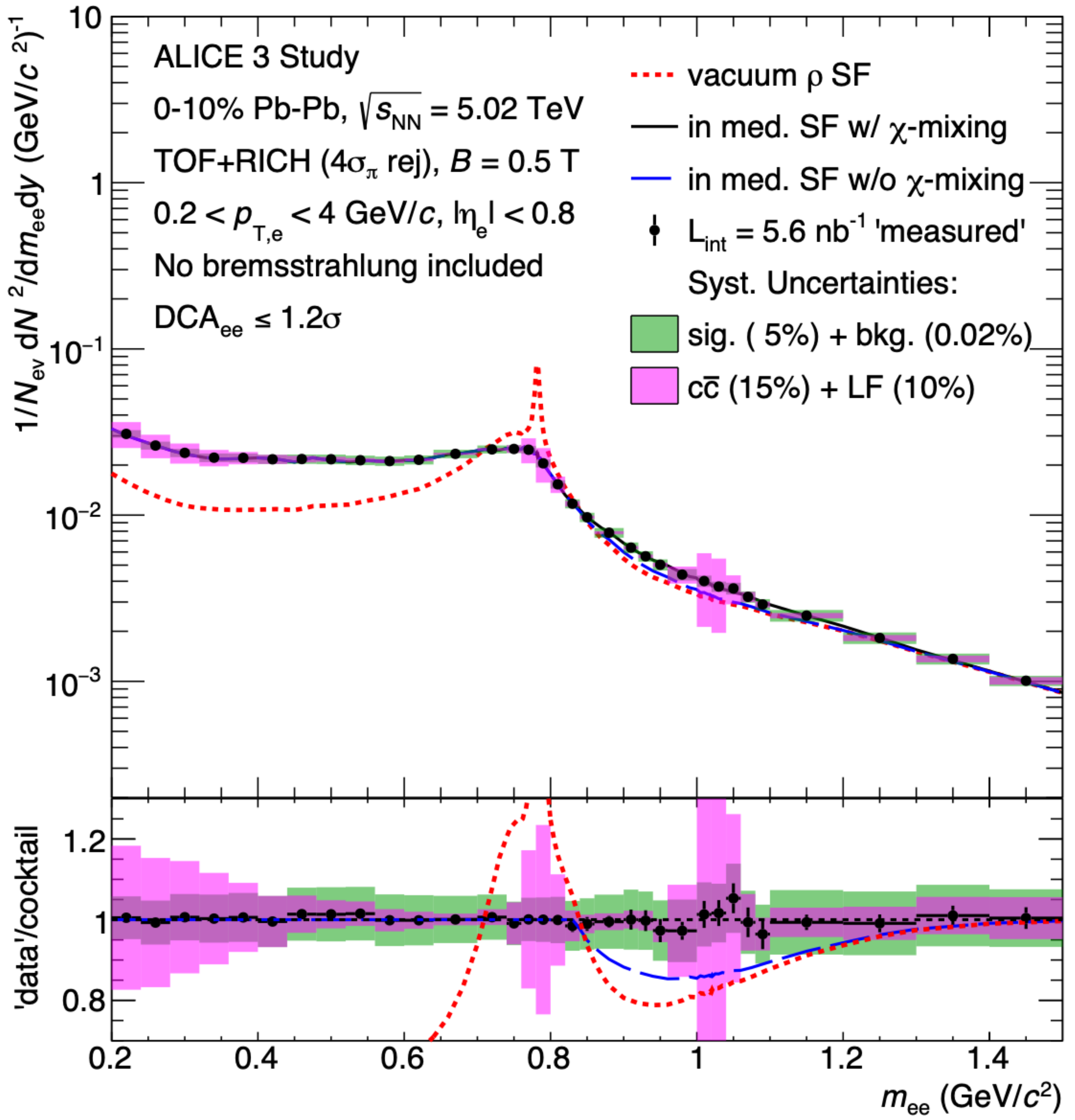
Dileptons in run 3 and 4



ALI-SIMUL-306847

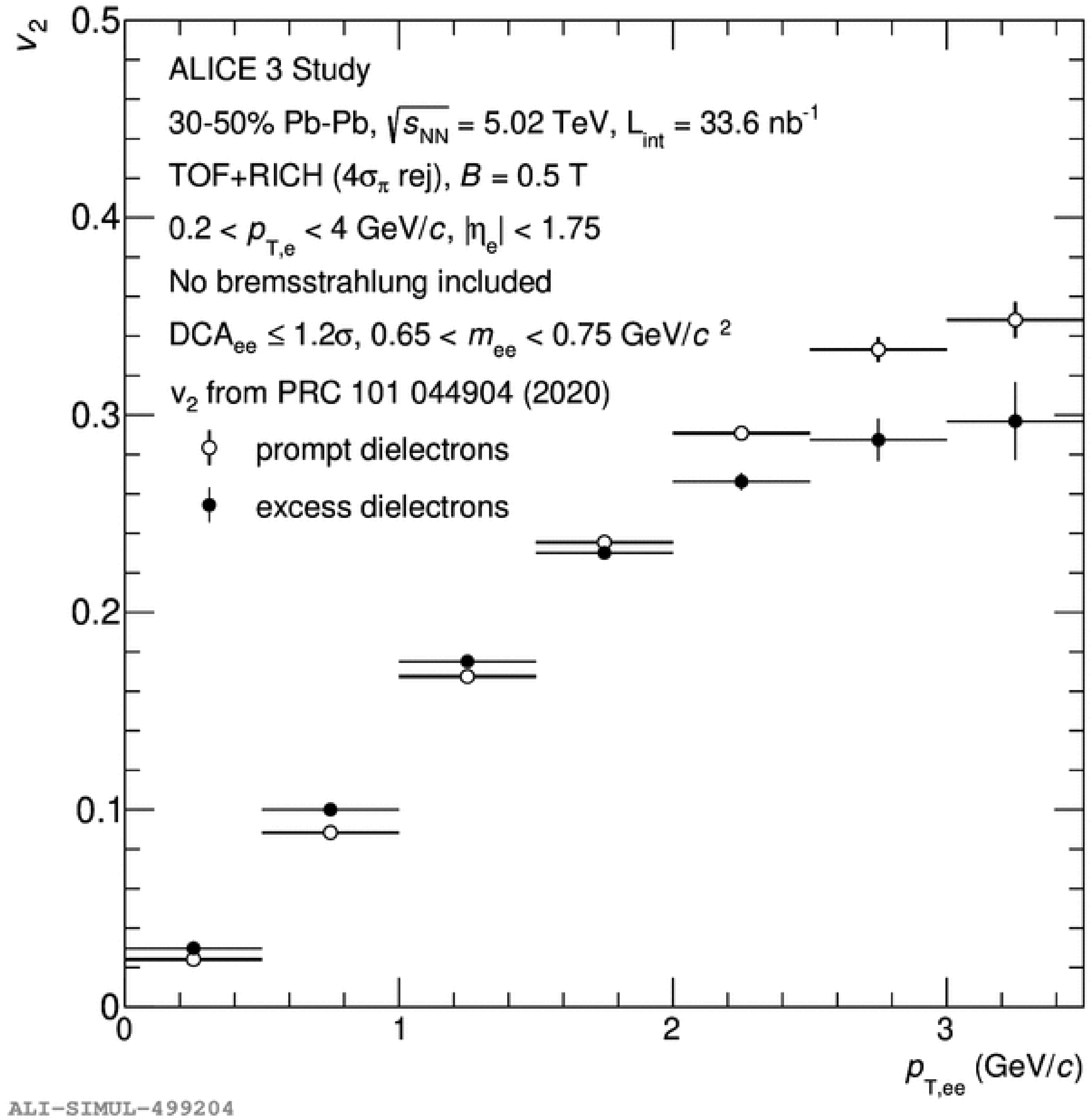
Run 3 and 4: first measurements of thermal dilepton emission at LHC → first access to average T

ALICE 3 mass spectrum



High precision:
access $\rho - a_1$ mixing

Dielectron v2

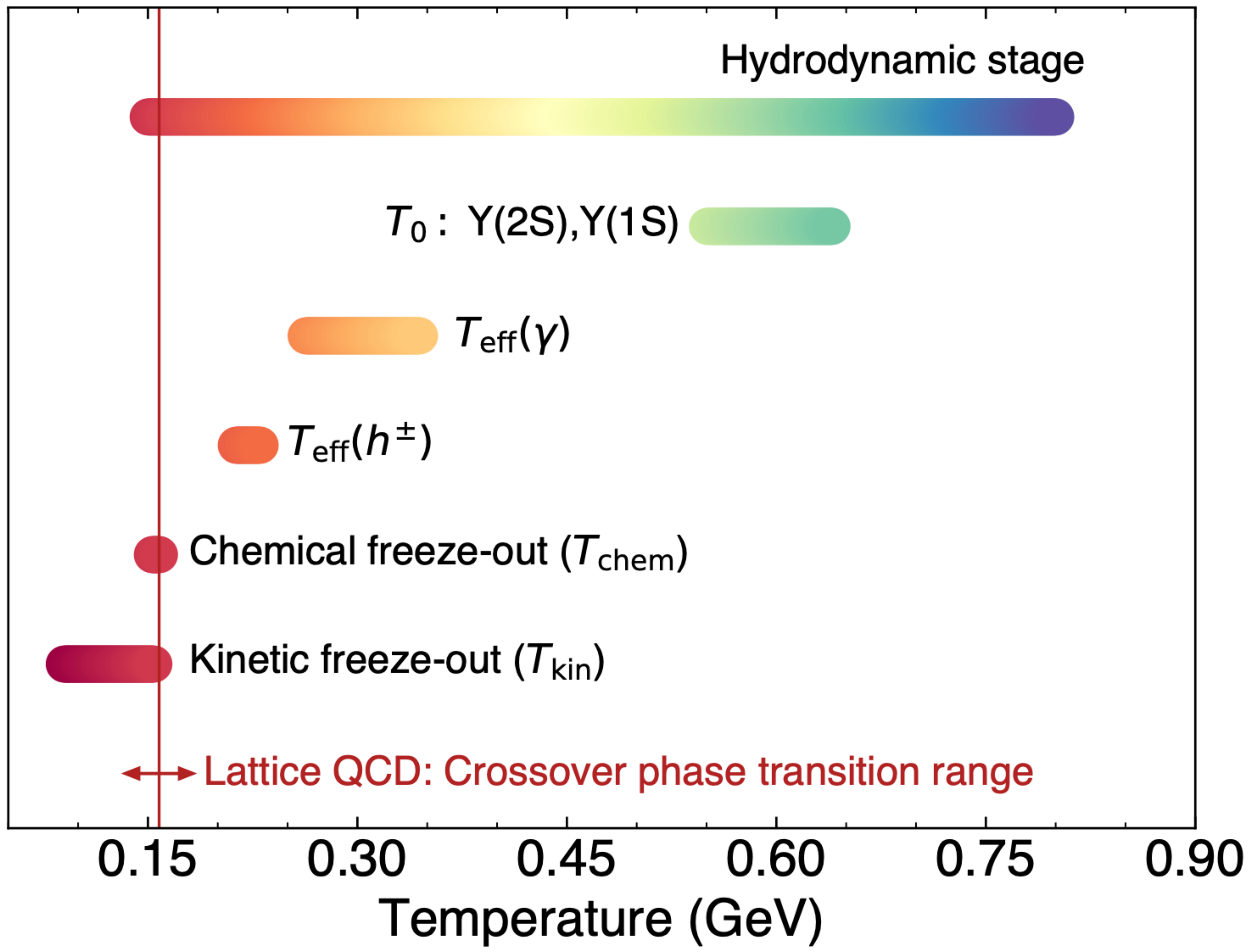


ALI-SIMUL-499204

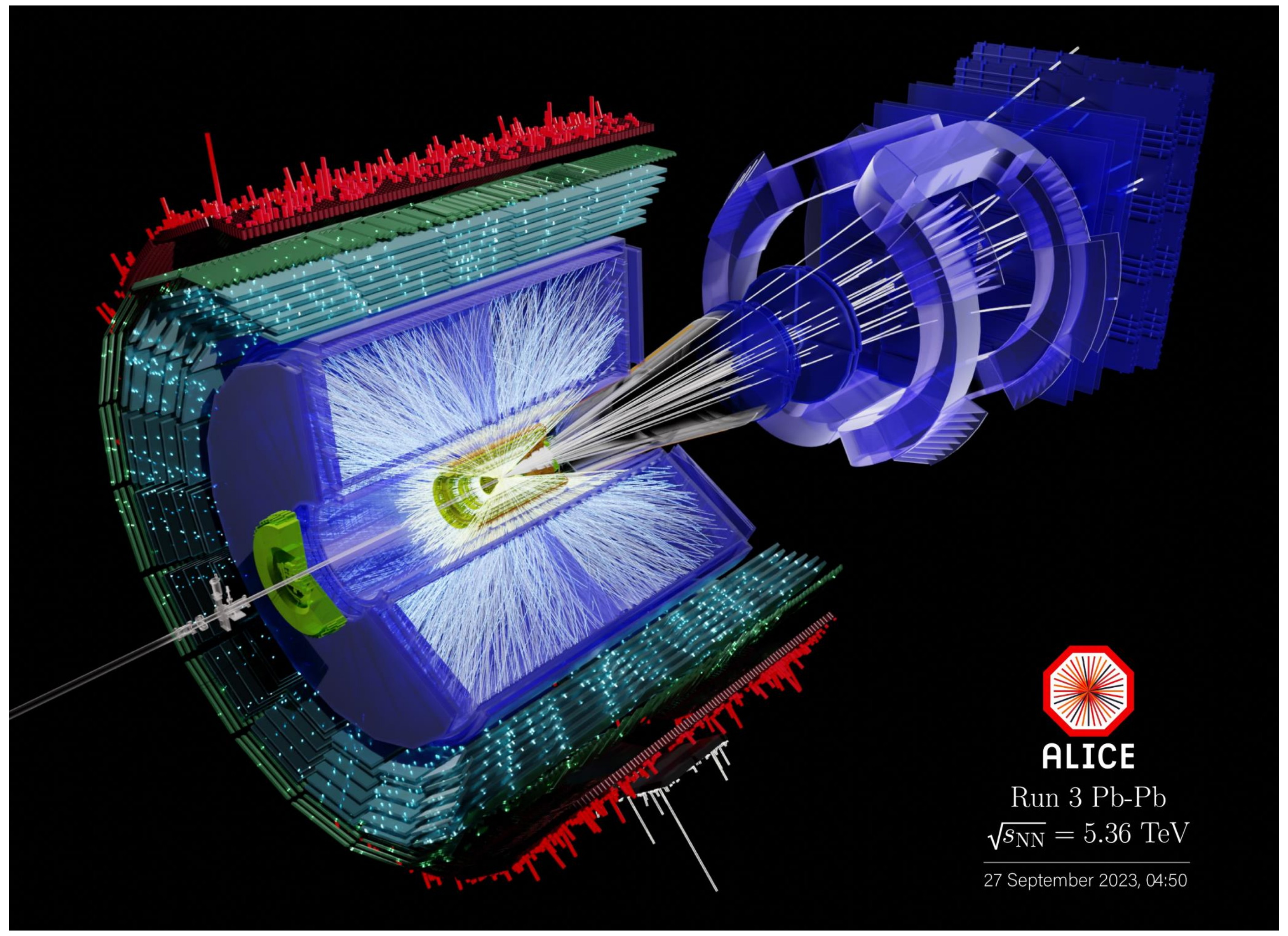
Excellent precision for dilepton v_2 vs p_T in different mass ranges
→ **time evolution of temperature**

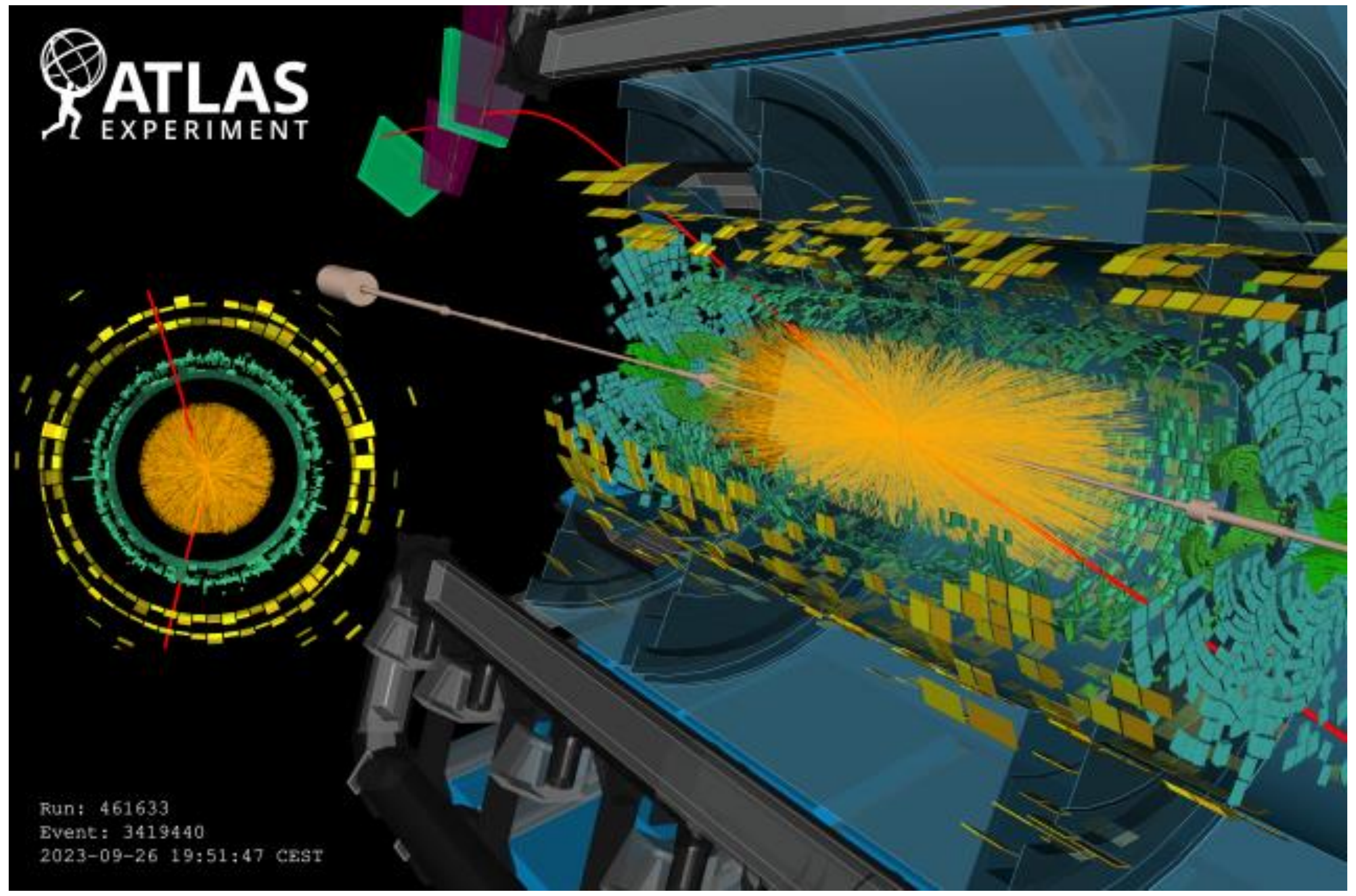
Summary

- 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 $\eta/s = 1/4\pi$
  - Longer thermalization time 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

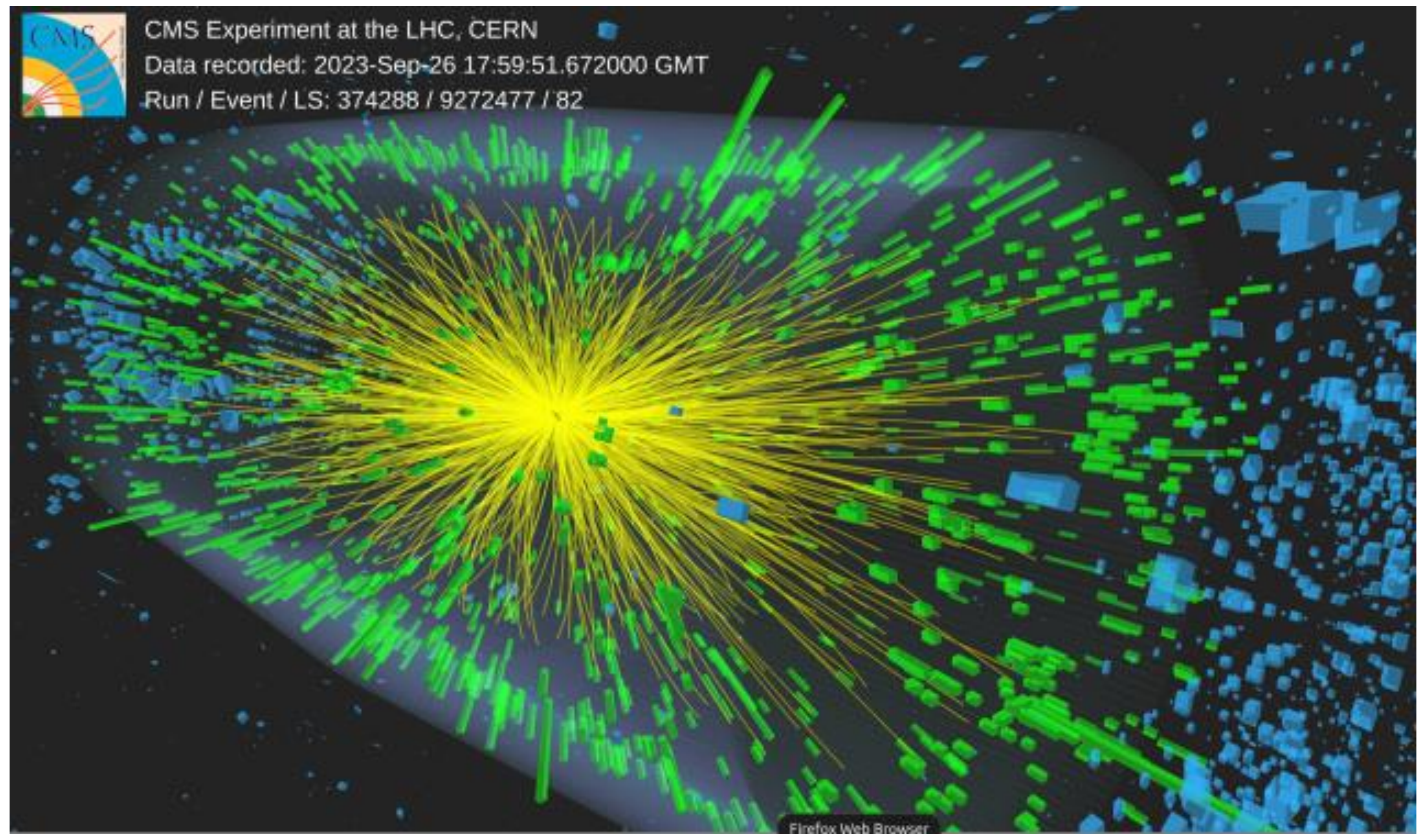


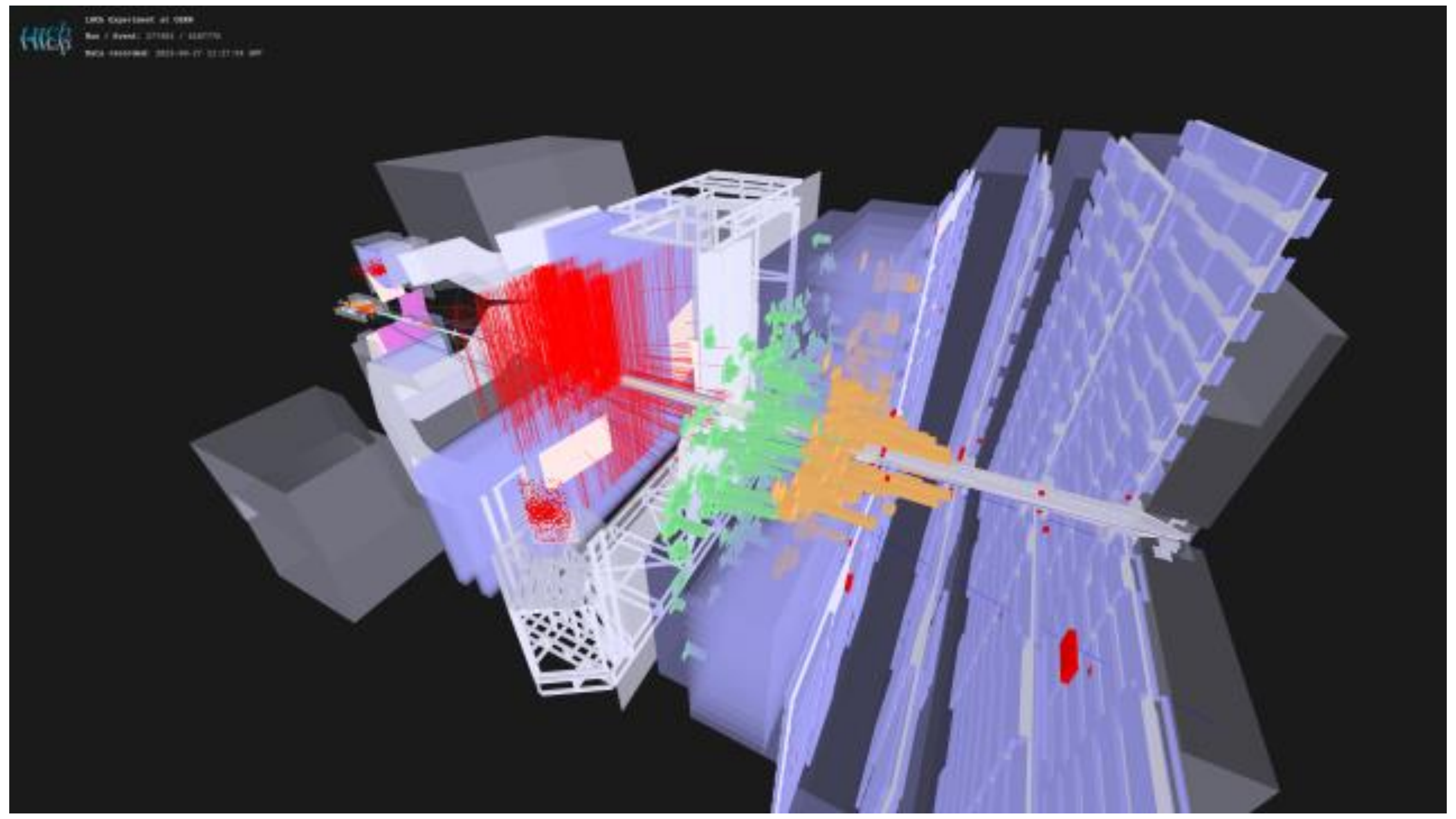
ALICE, arXiv:2211.04384



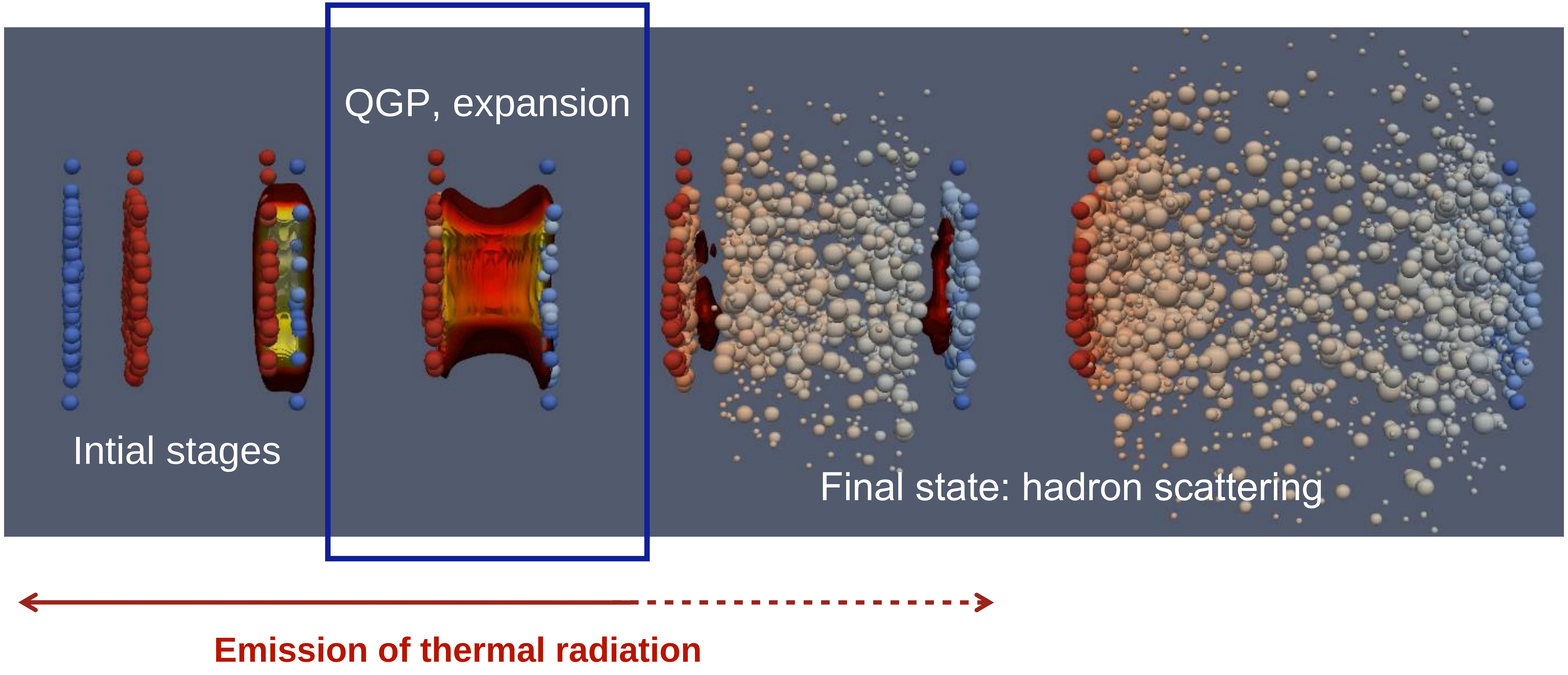


Thank you for your attention



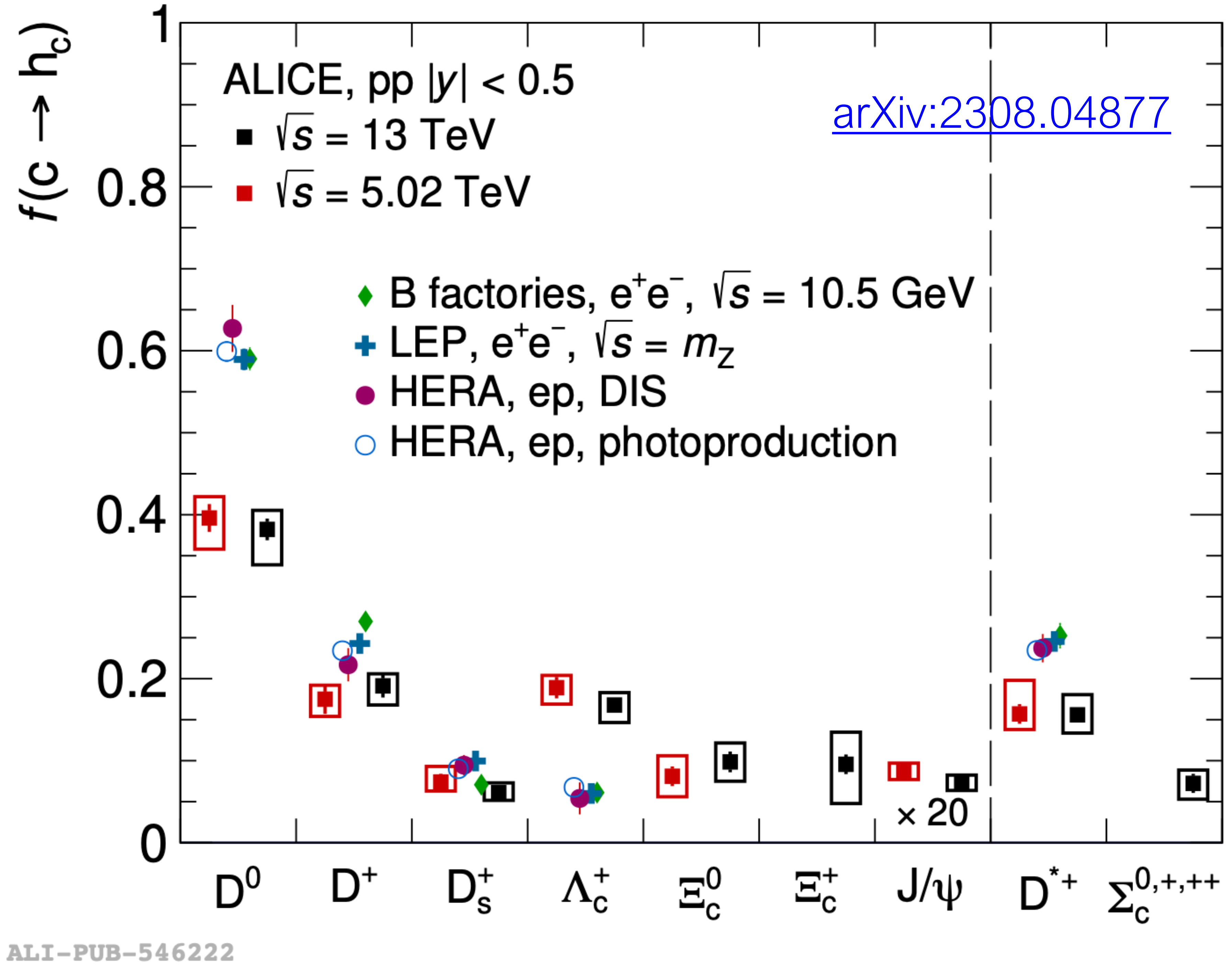


Heavy Ion Physics: thermal radiation from the early stages



Baryon to meson ratio: beauty sector (non-prompt charm)

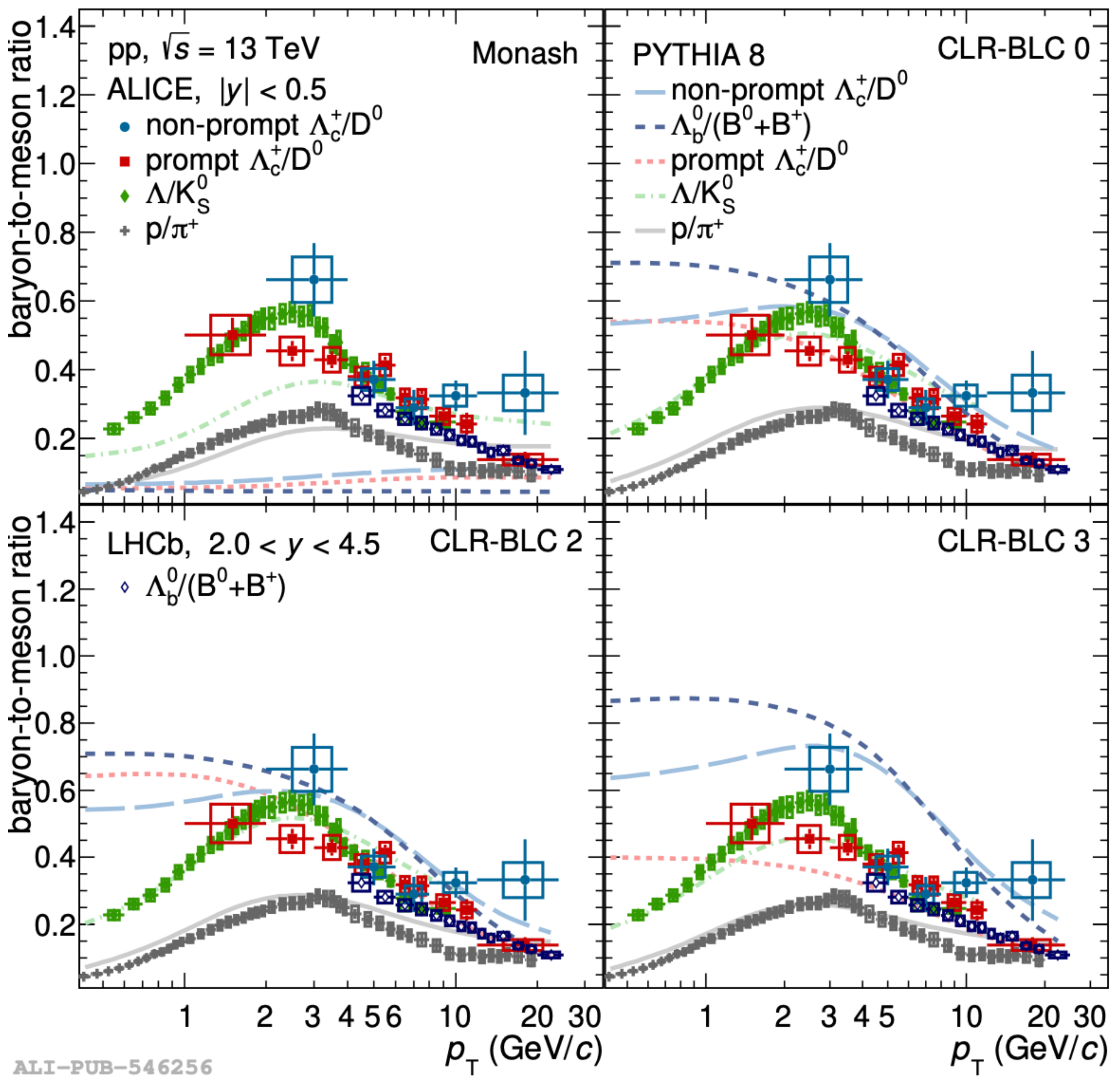
Charm fragmentation fraction



Baryon production larger in pp than e^+e^-

Λ_c, Ξ_c, Σ_c measured

Prompt and non-prompt Λ_c/D

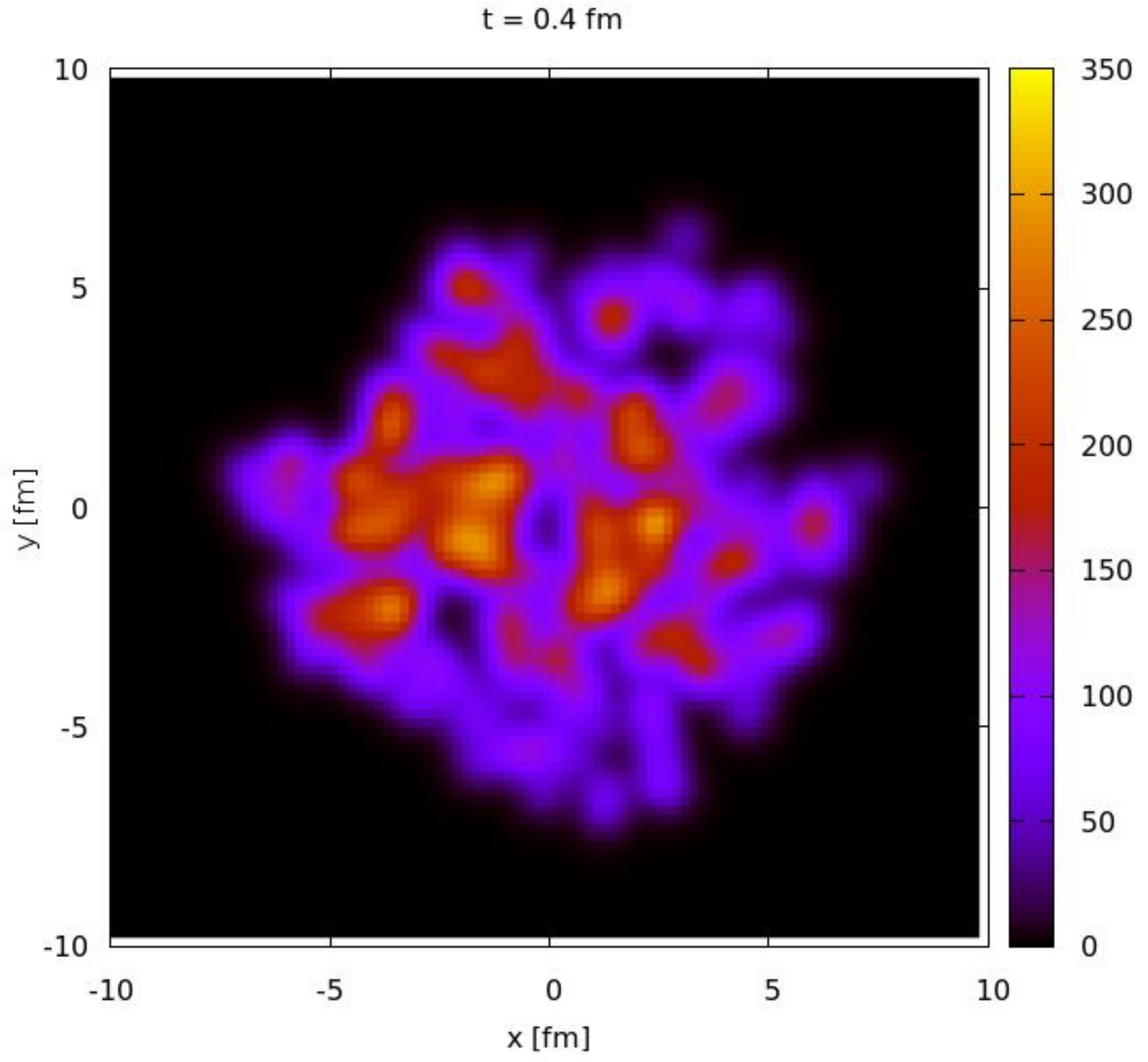


arXiv:2308.04873

Baryon enhancement also present in beauty sector

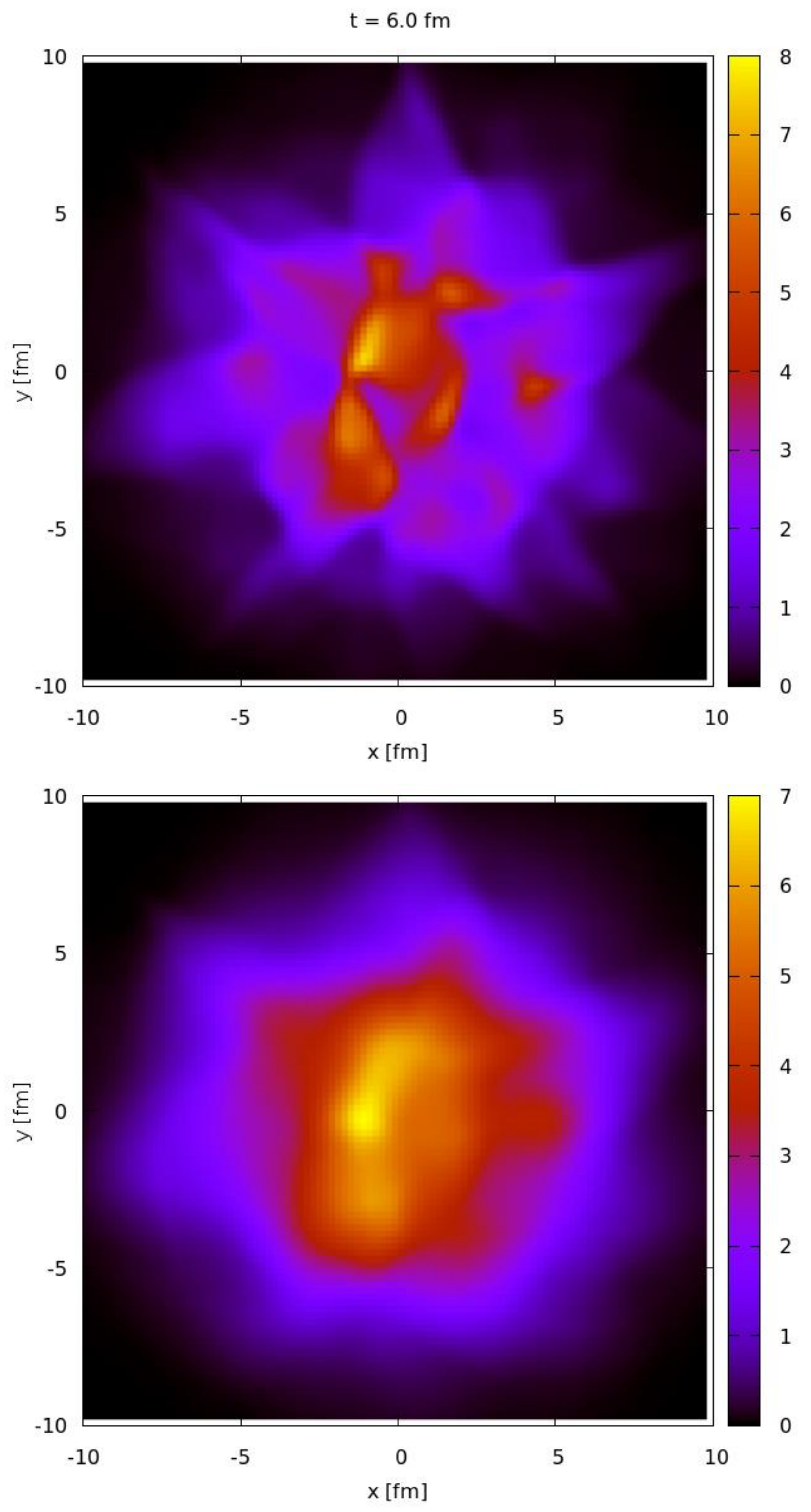
In line with expectation from color-reconnection models

Azimuthal anisotropy: initial and final state



No viscosity
$\eta/s = 0$

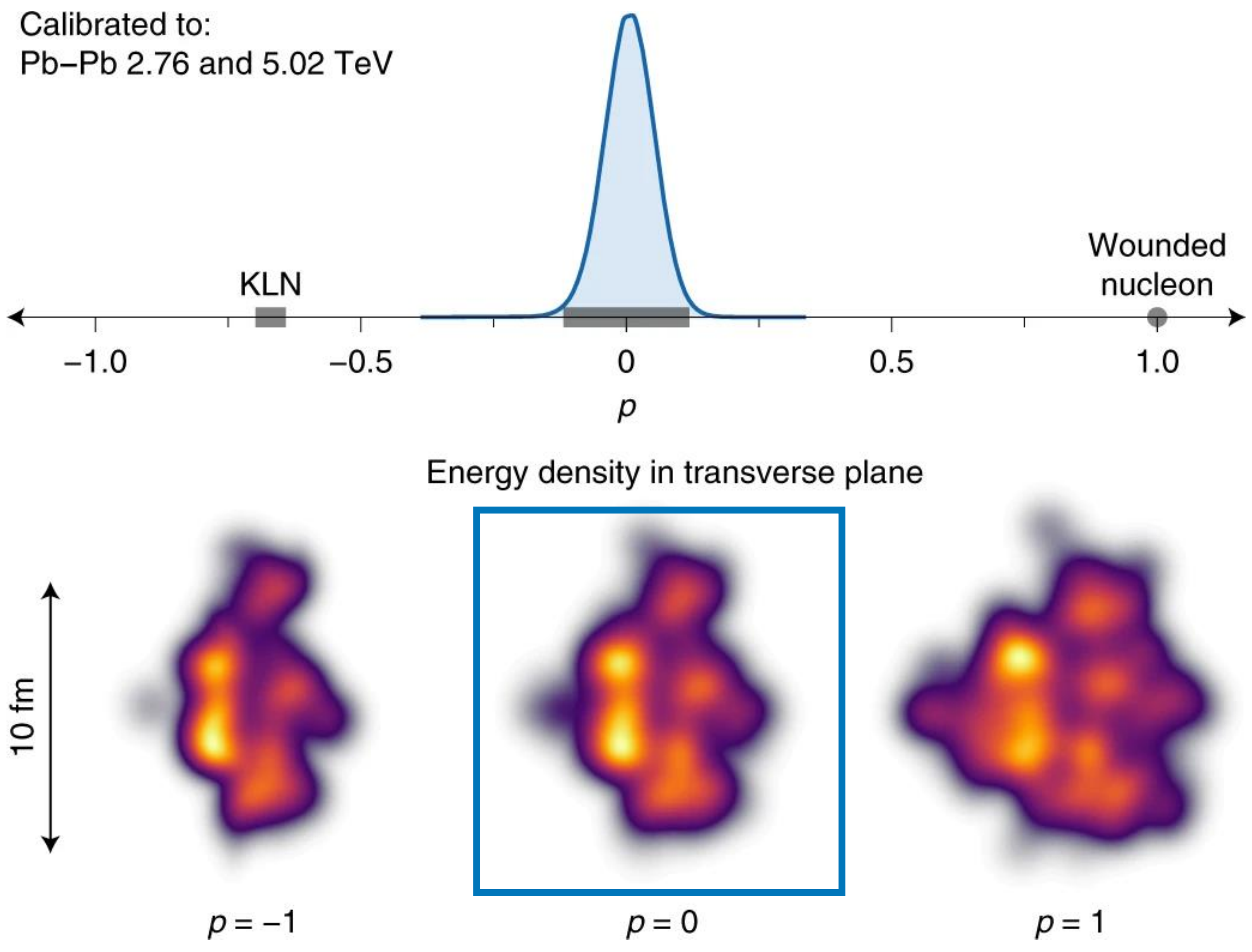
$\eta/s = 0.16$
Low viscosity



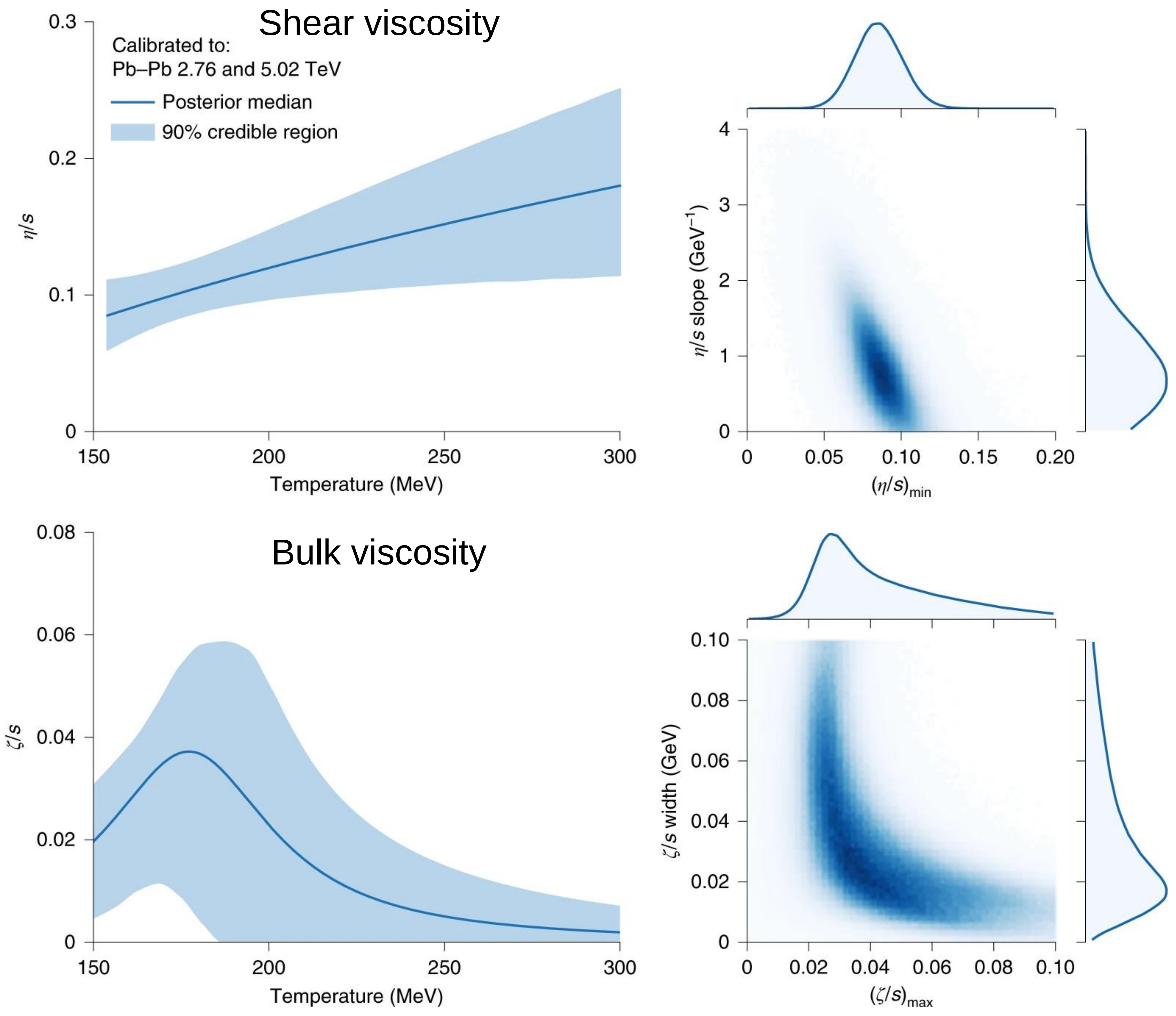
Schenke and Jeon,
Phys.Rev.Lett.106:042301

Bayesian analysis of flow: results

Initial state geometry



Viscosity vs T



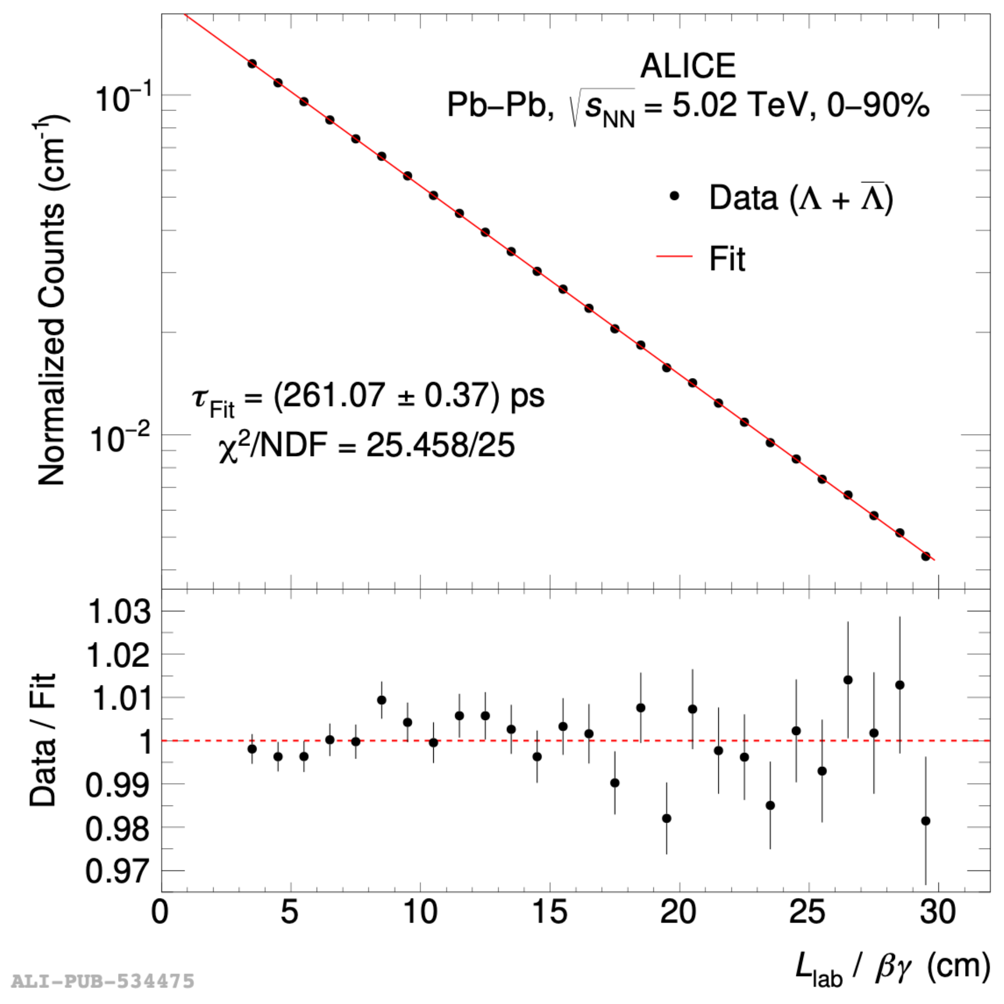
J. E. Bernhard et al, arXiv: 1605.03954

Flow data provide information on initial geometry and viscosity of the QGP at the same time

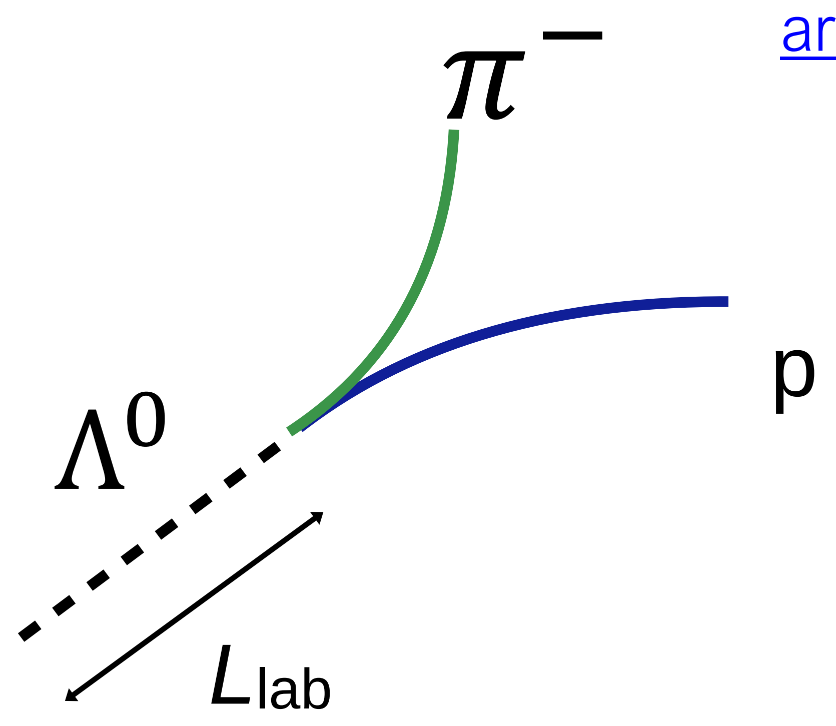
Heavy-ion collisions as a laboratory for nuclear and hadron physics

Example: life time of strange baryons and nuclei

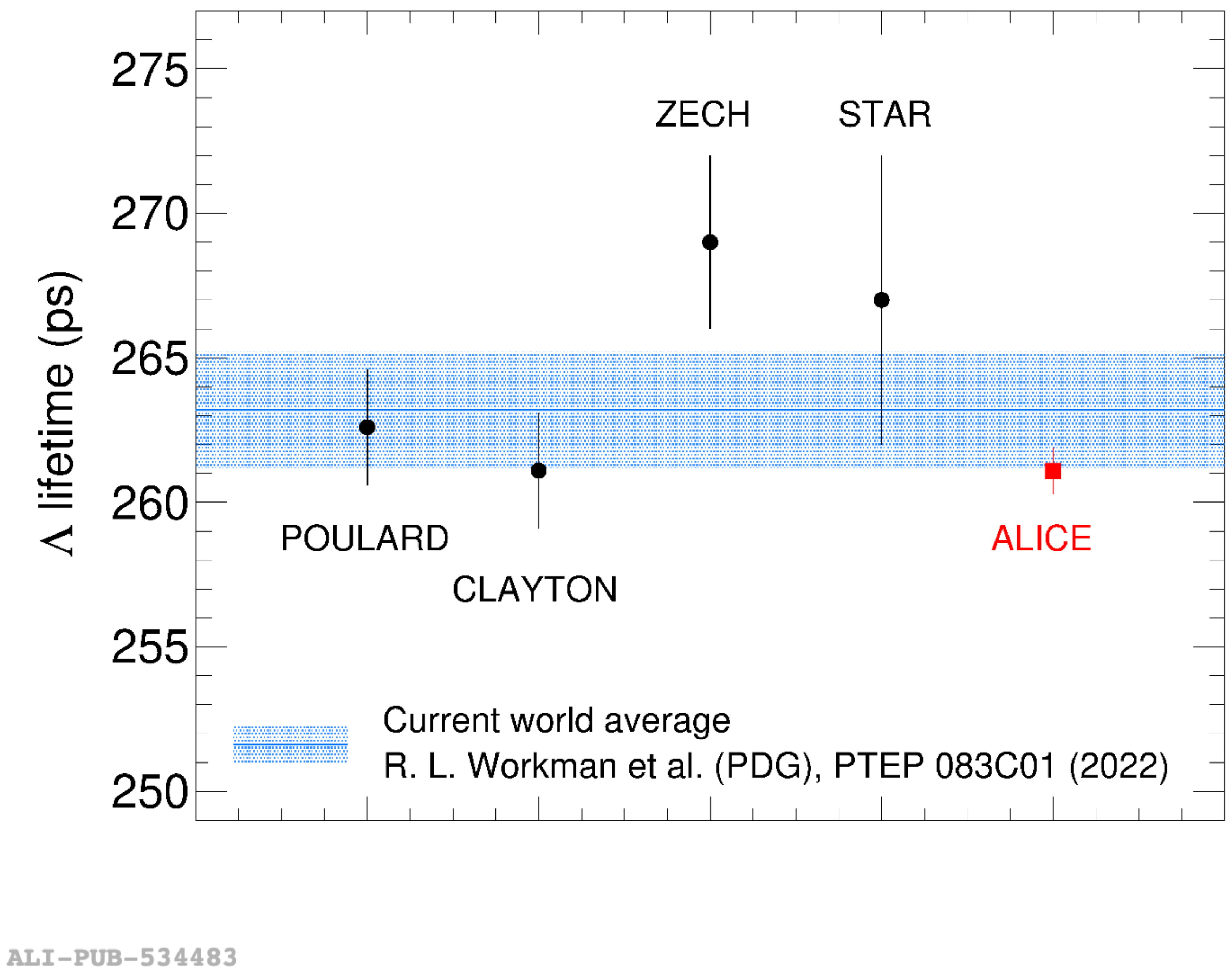
Proper decay length distribution



arXiv:2303.00606

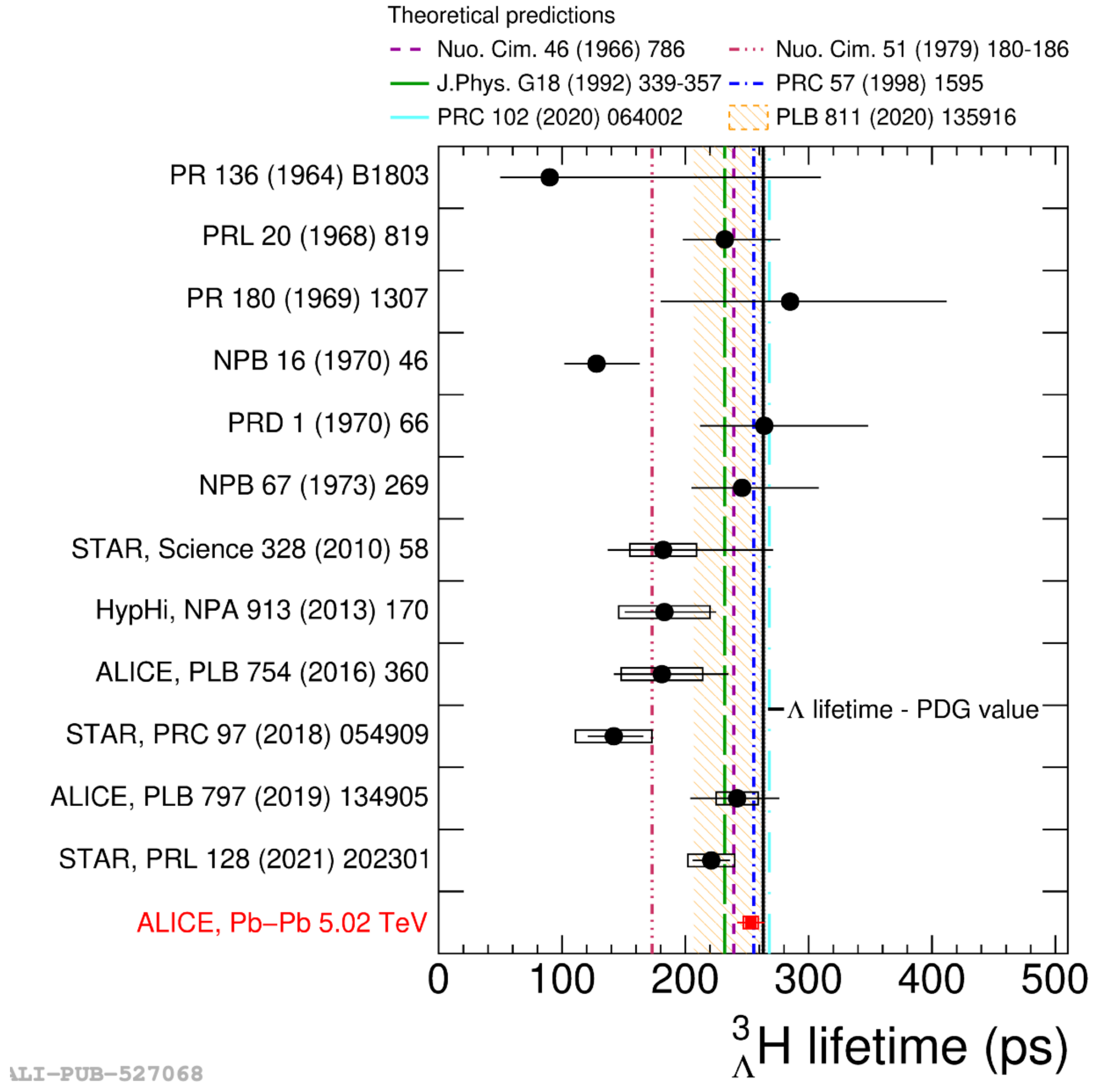


Life time: comparison to existing results

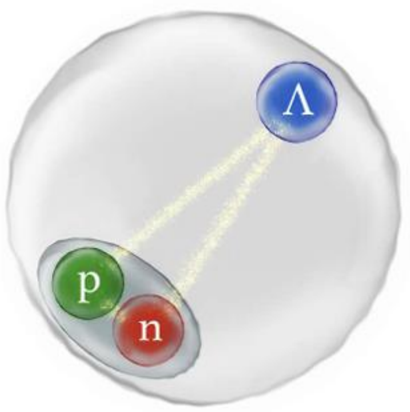


$$\tau_{\Lambda+\bar{\Lambda}} = [261.07 \pm 0.37(\mathrm{stat.}) \pm 0.72(\mathrm{syst.})]\ \mathrm{ps}.$$

Hypernuclei life time



arXiv:2209.07360

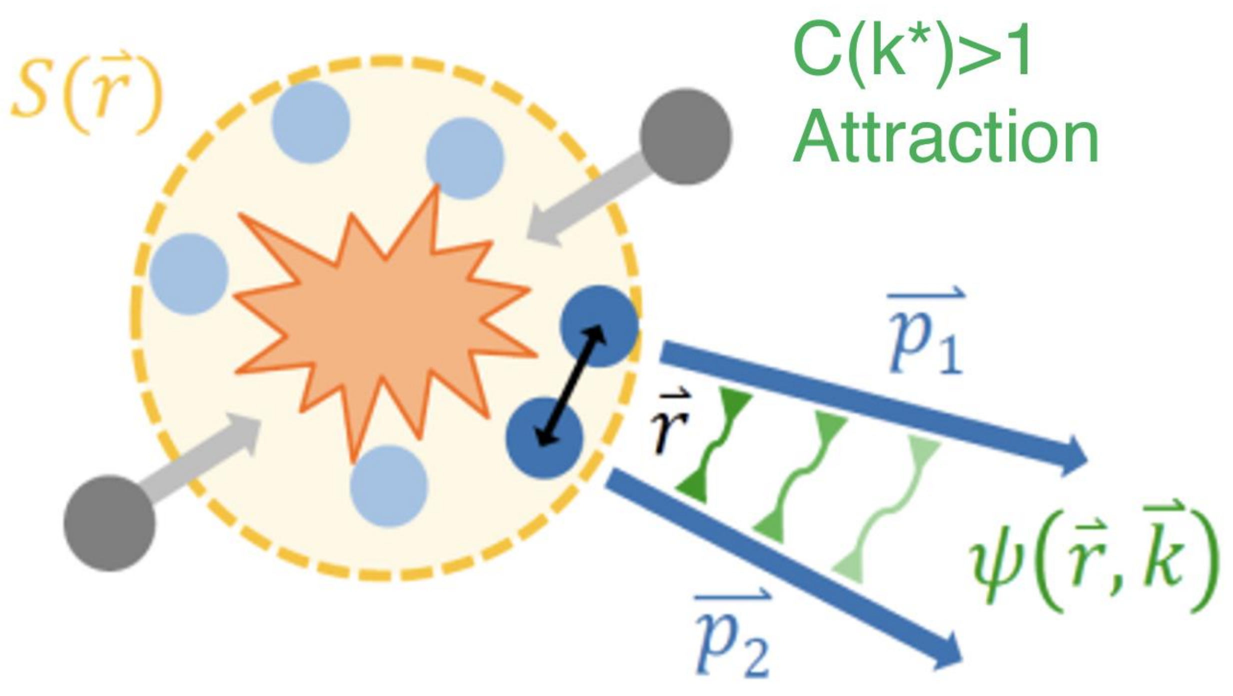


Life time measurements of hyperons and hypernuclei competitive with world data

ALICE

Measuring hadron interaction potentials via femtoscopic correlations

Momentum correlations of low-k pairs



$$C(k^*) = \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

$$k* = \vec{k}_1 - \vec{k}_2$$

Known from Bose-Einstein correlations of identical bosons
Hanbury-Brown Twiss interferometry

Correlation function depends on source distribution and interaction potential:

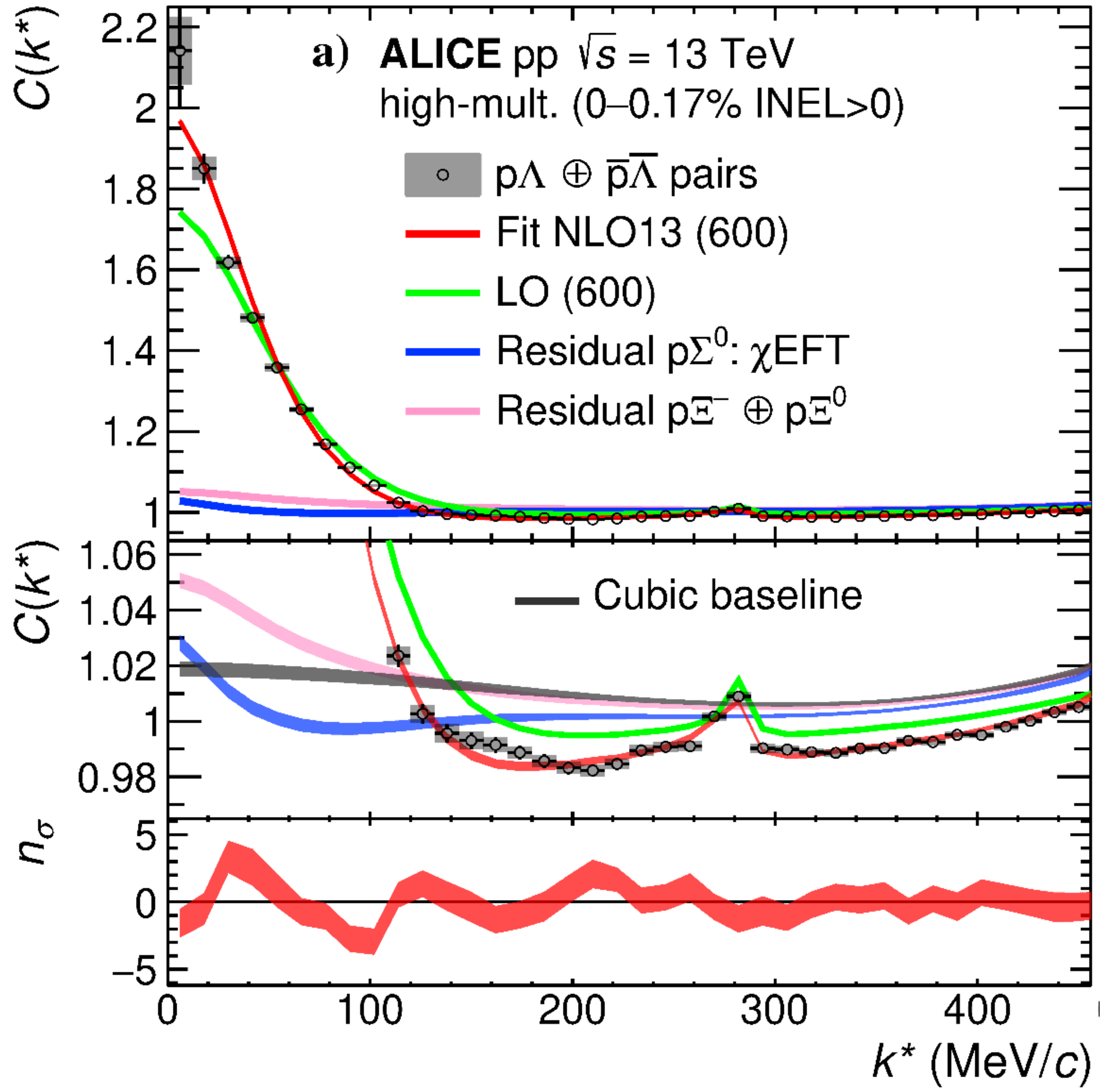
$$C(k*) = \int S(\vec{r})|\Psi(\vec{k}^*,\vec{r})|^2 d^3\vec{r}$$

With known source distribution (e.g. from pion or proton pairs) determine interaction potential

Gives access hadron interaction potentials of unstable hadrons
⇒ Connections to hadron and nuclear physics

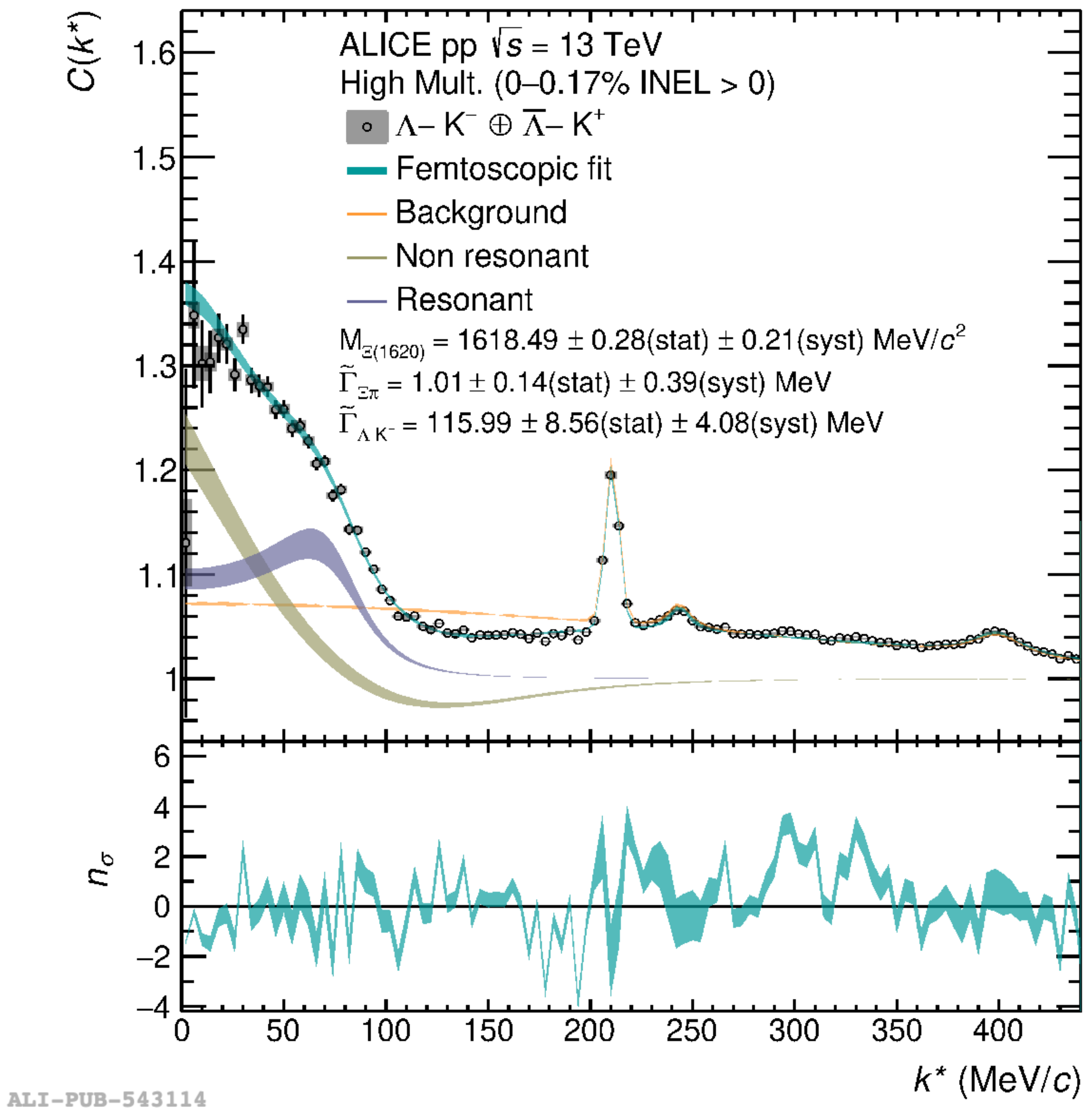
Correlation measurements of strong 2-body interactions

pΛ correlations



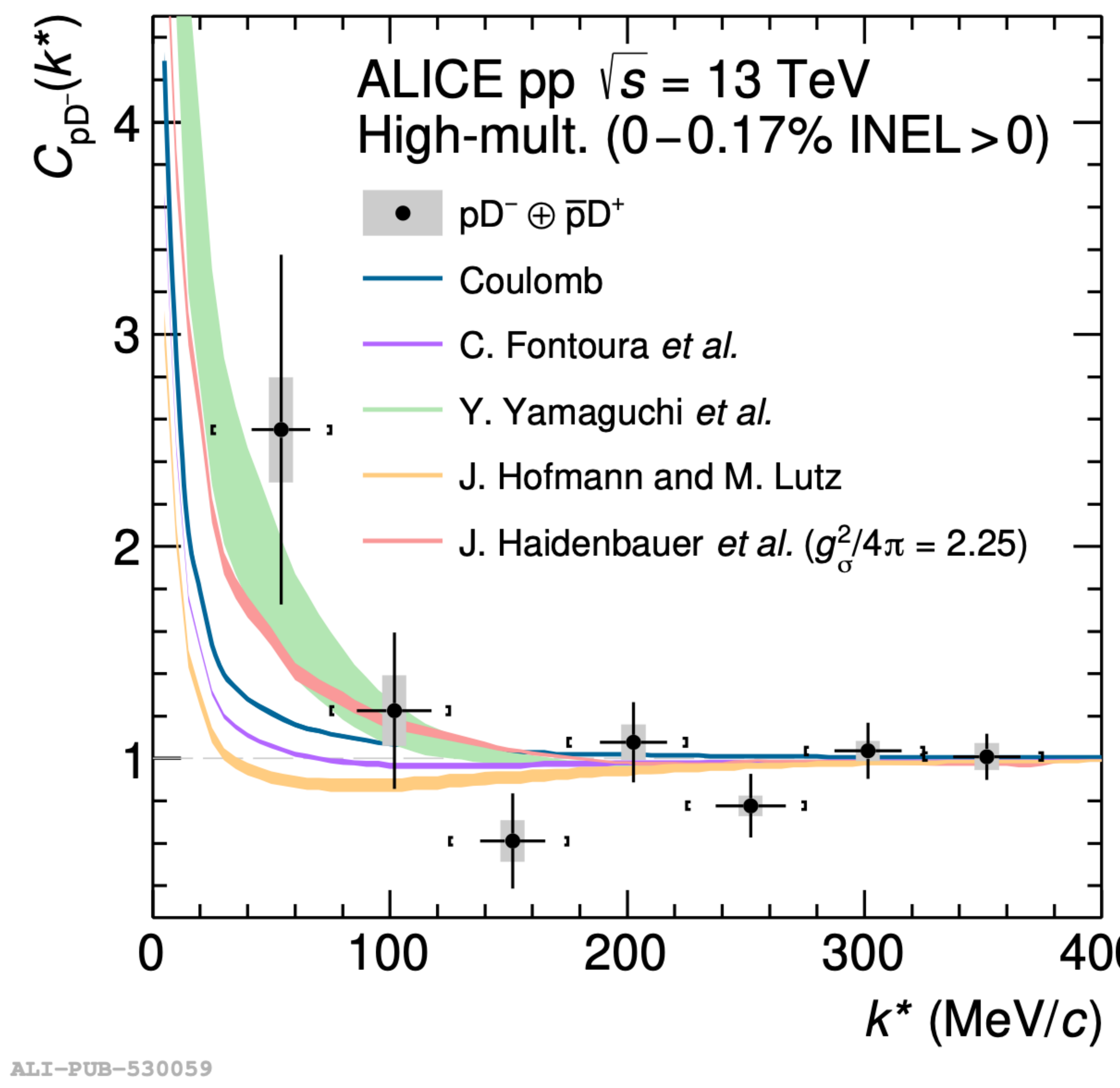
Phys. Lett. B 833 (2022) 137272

ΛK correlations



arXiv:2305.19093

pD correlations



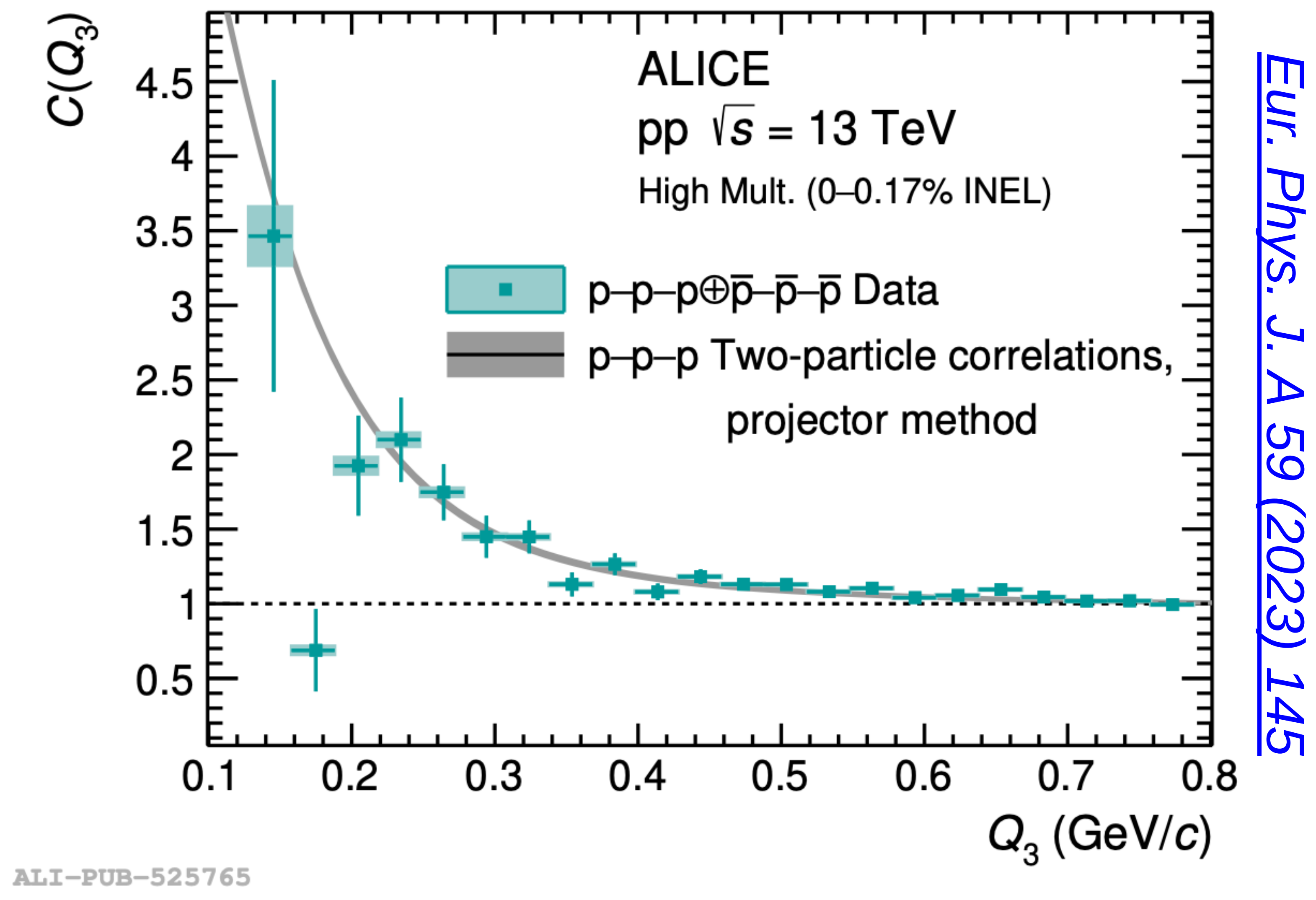
Phys. Rev. D 106 (2022) 052010

Large number of channels being explored, baryon-baryon and baryon-meson, including charm mesons

Close contact with theory community to provide feedback on models and lattice calculations

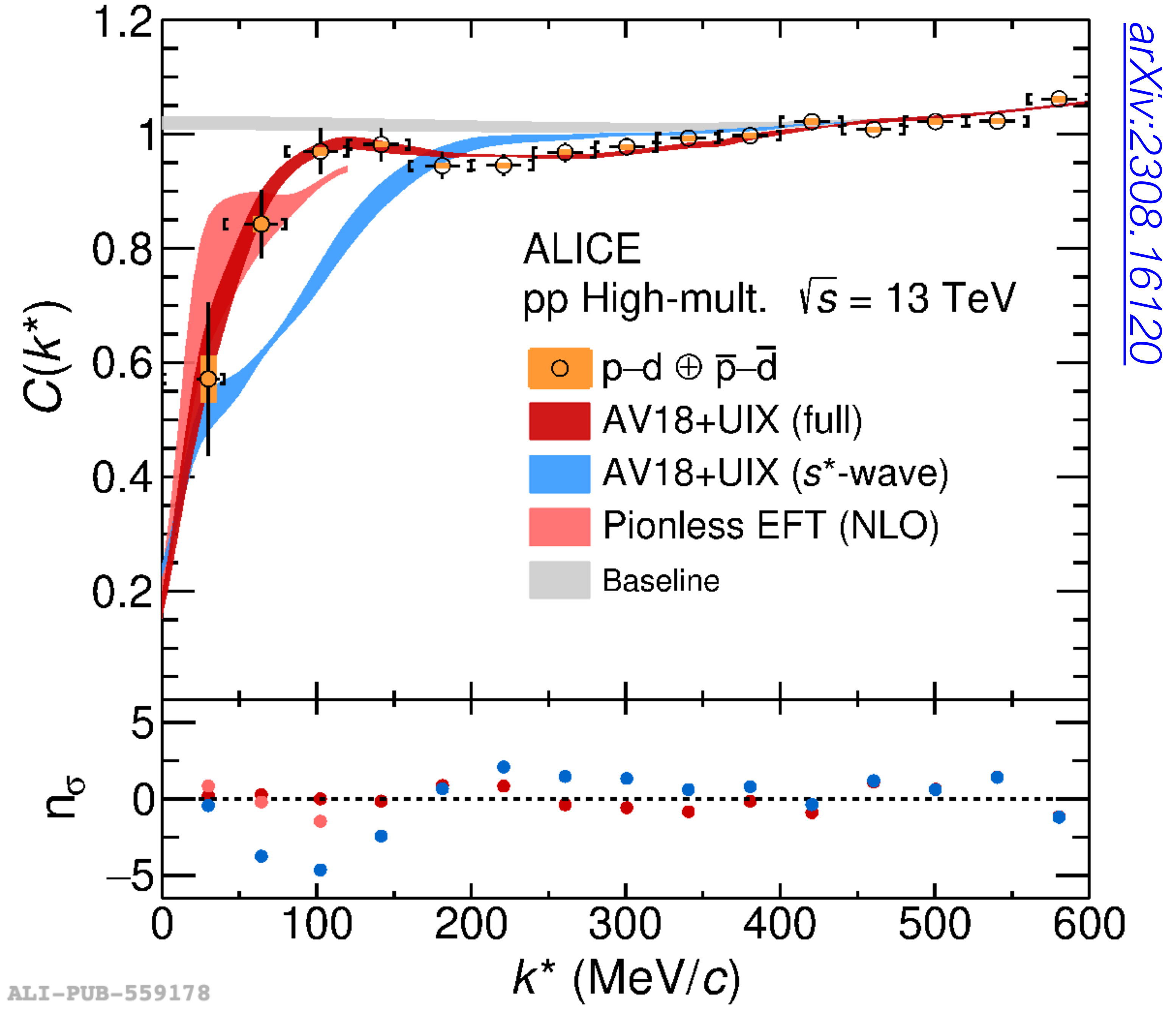
Strong interaction potentials: 3-body interactions

ppp correlations



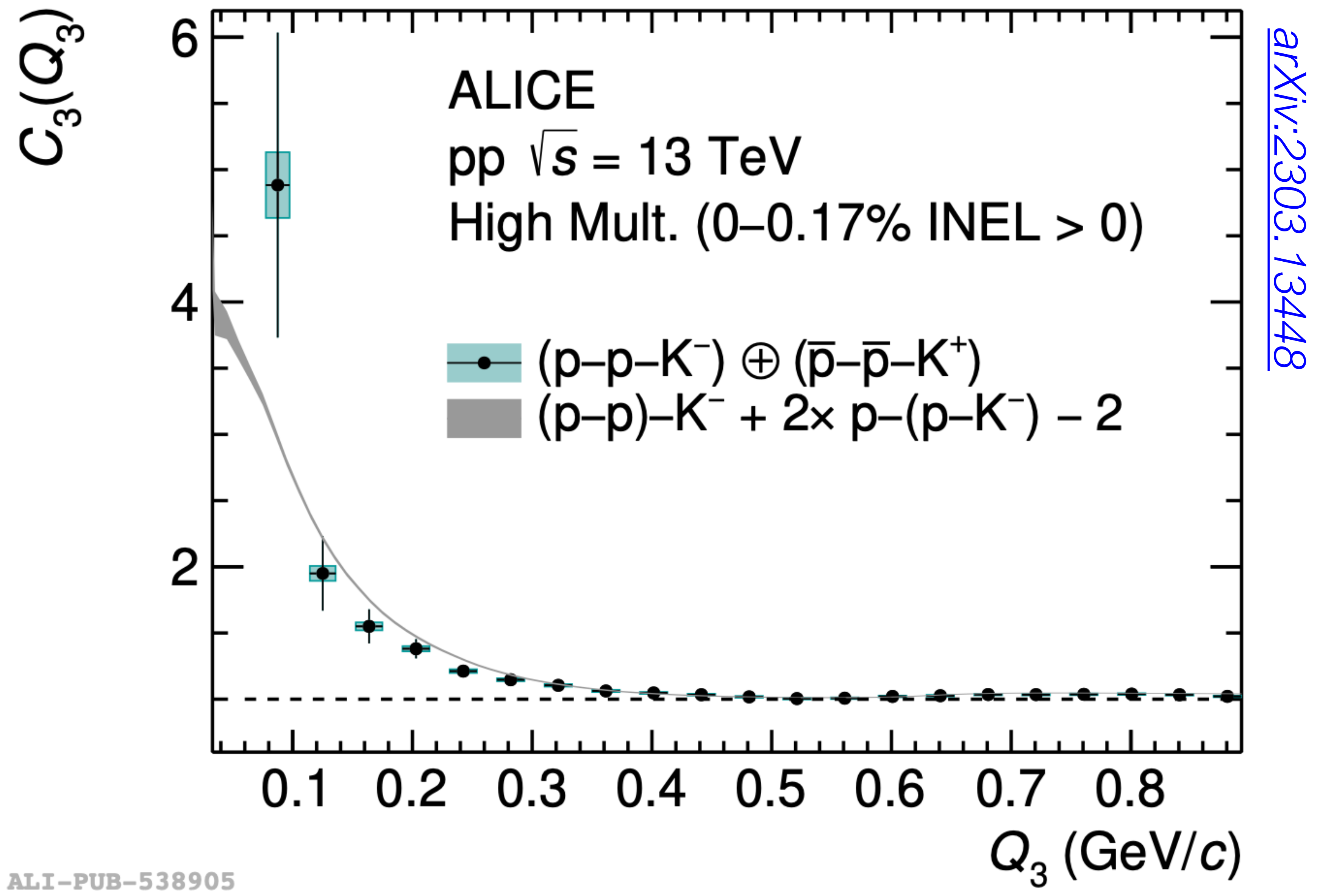
Significant deviation at small Q_3: sign of direct three-body interactions

p-d correlations



Need full three-body calculation to explain measurement

ppK correlations



No significant effect of three-body interactions

More to come with run-3 event selection: input for 3-body effects in hadron/nuclear physics

Back to the earliest stages: direct photon production

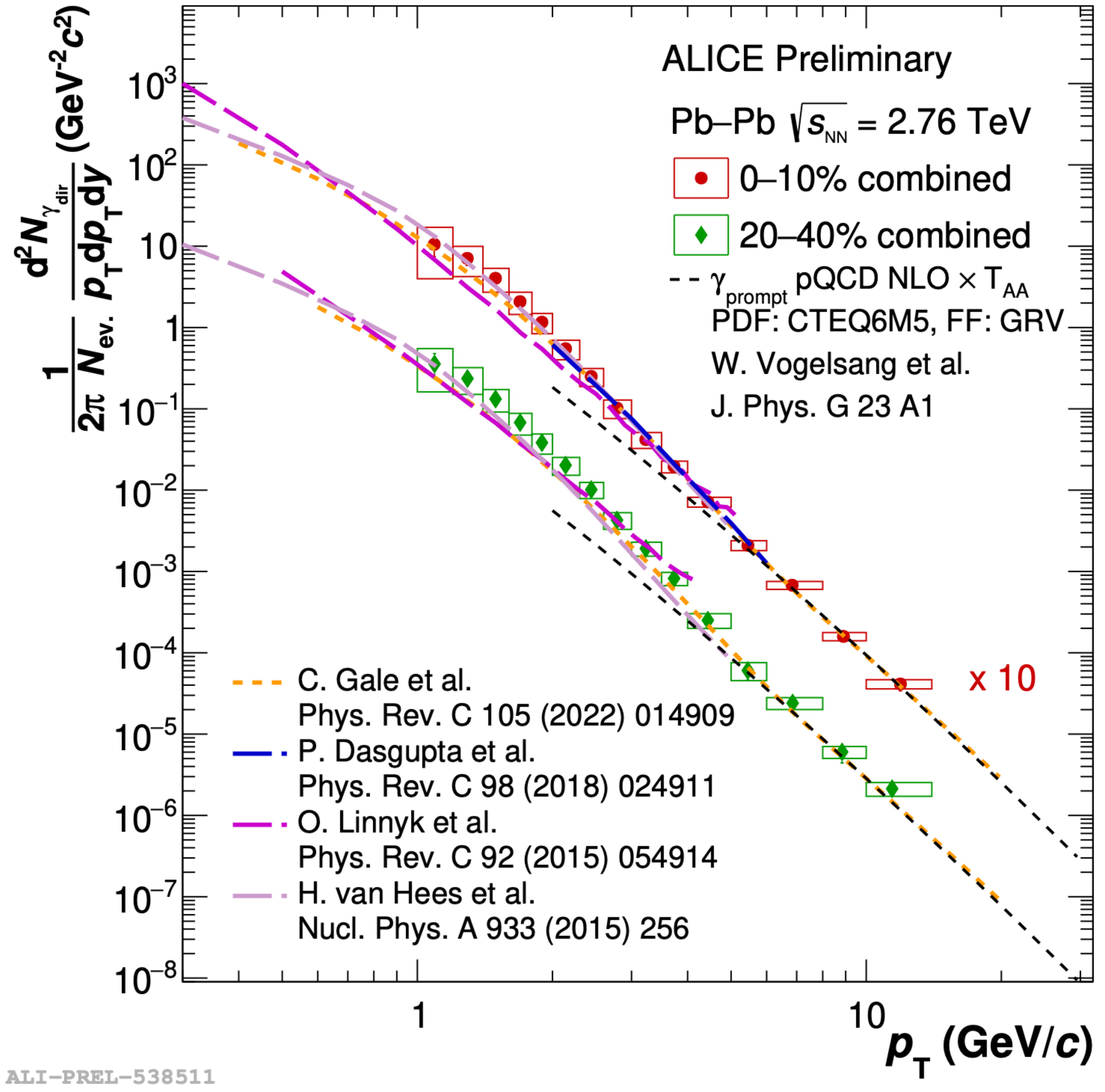
Large background: decay photons from π^0, η, …

⇒ Challenging measurement

Main sources:

- High p_T: hard scattering; quark-gluon Compton process
- Low p_T: thermal radiation

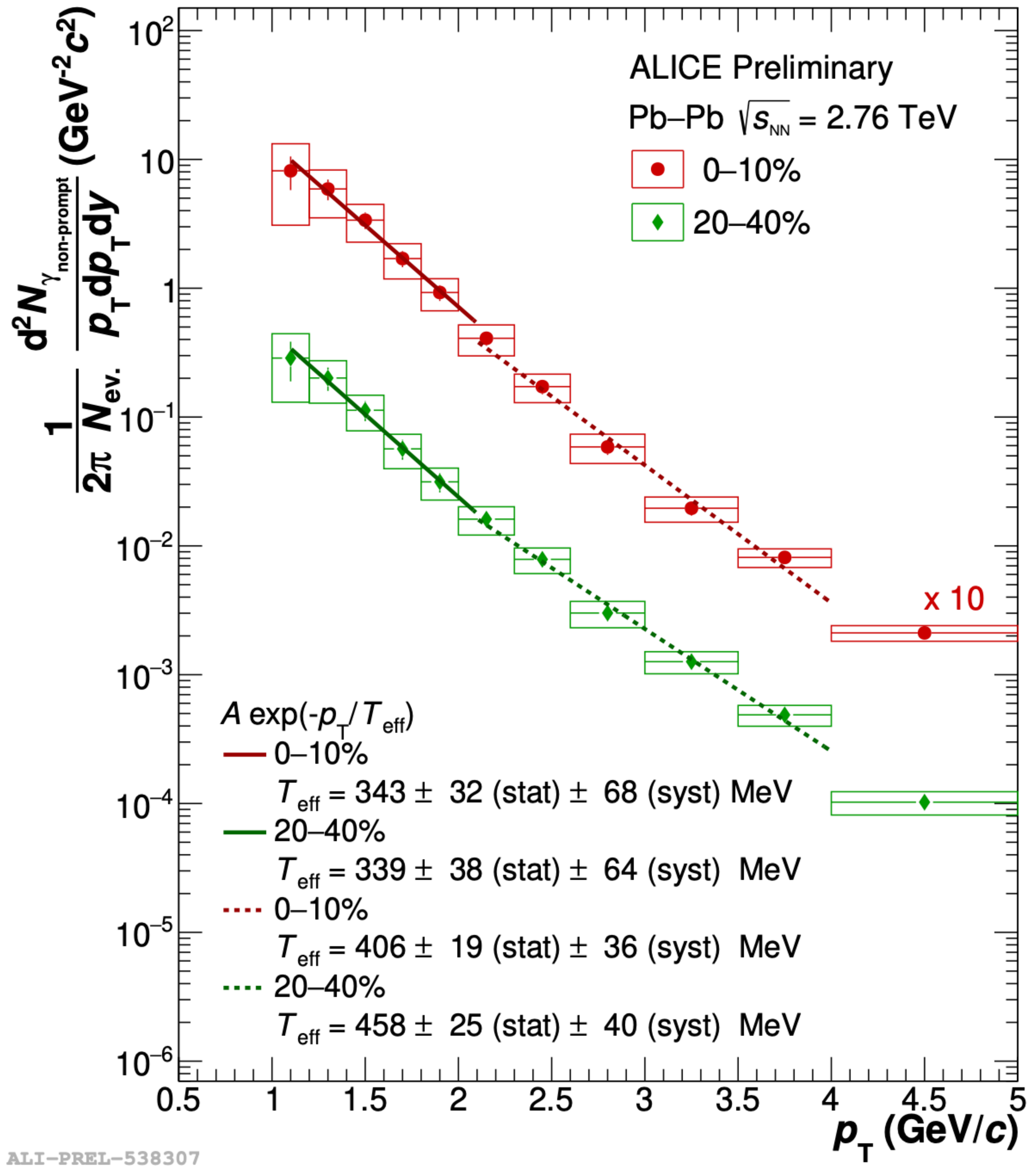
Excess at low p_T: thermal photons



ALICE, PLB 754, 235

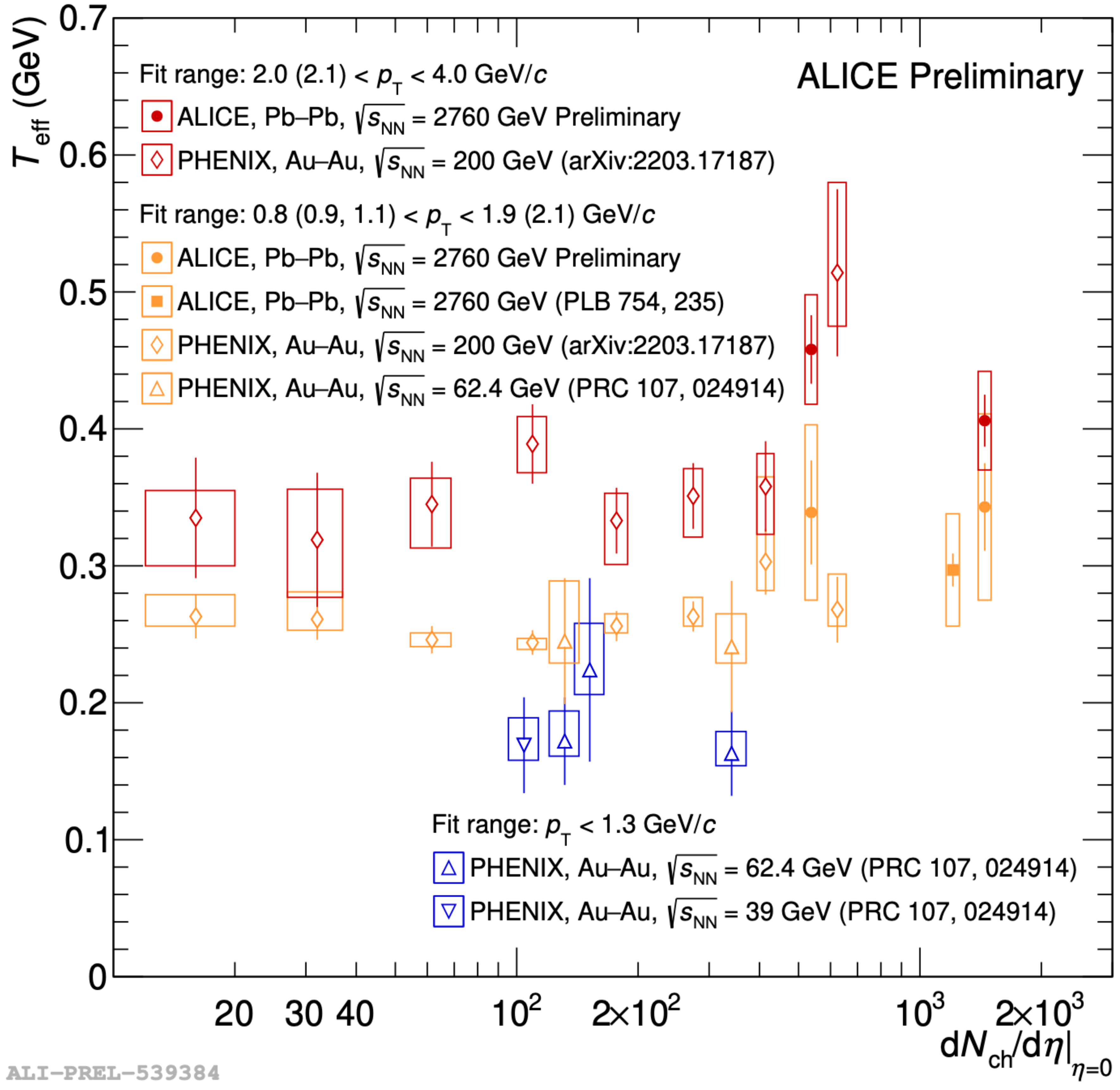
Direct photon excess: thermal production

Direct photon excess spectrum



Thermal emission visible for mid-central and central events

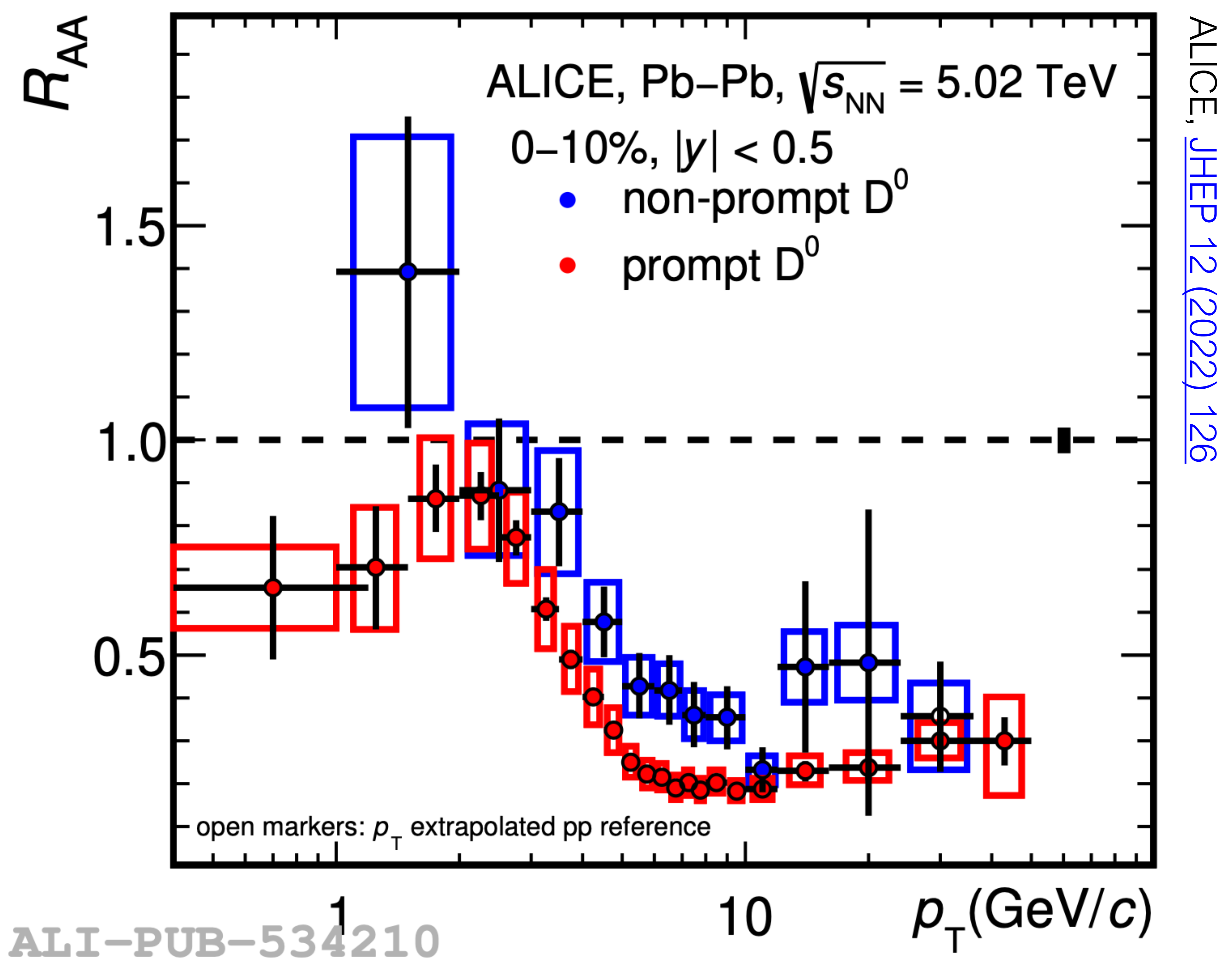
Spectral slope: apparent temperature



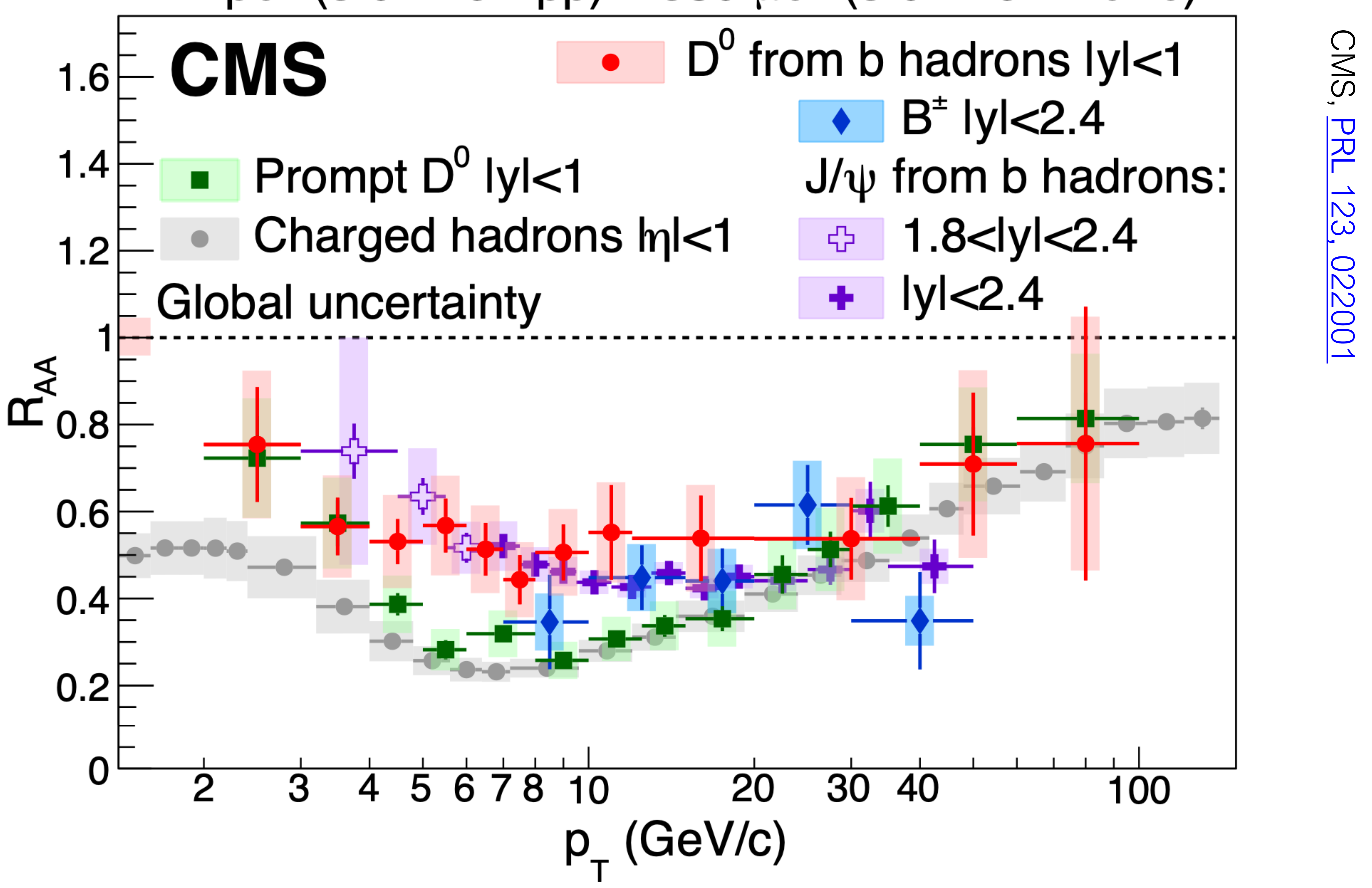
Apparent temperature larger at LHC than RHIC
Absolute temperature depends on blue shift

Mass dependence: charm and beauty

Prompt and non-prompt D^0



R_{AA} overview

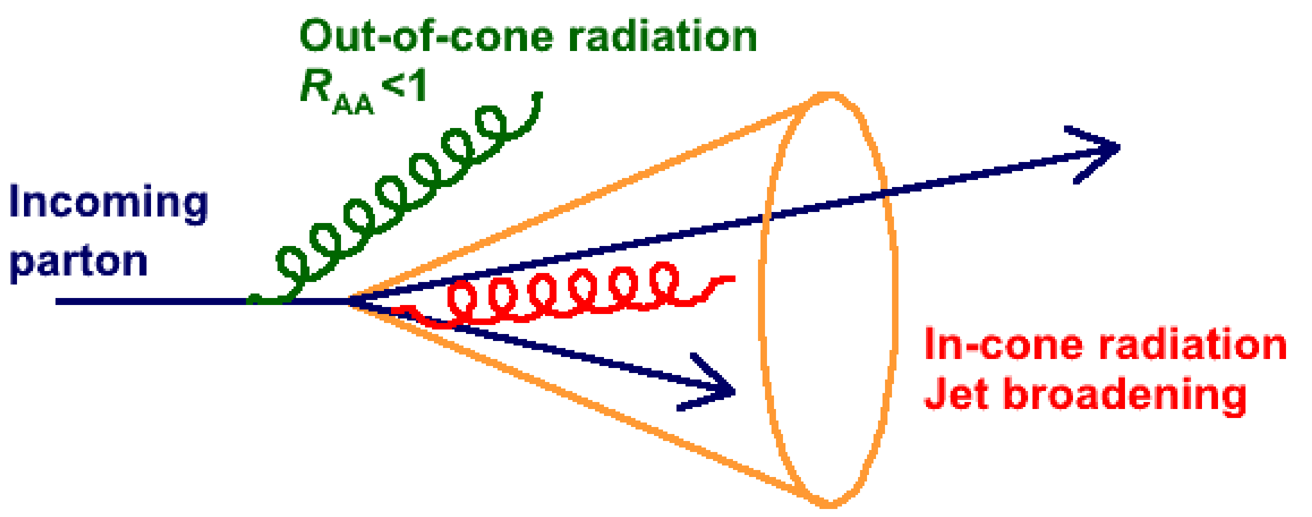


R_{AA} smaller for beauty than for charm at p_T < 20 GeV

In line with qualitative expectations for both collisional and radiative mechanisms

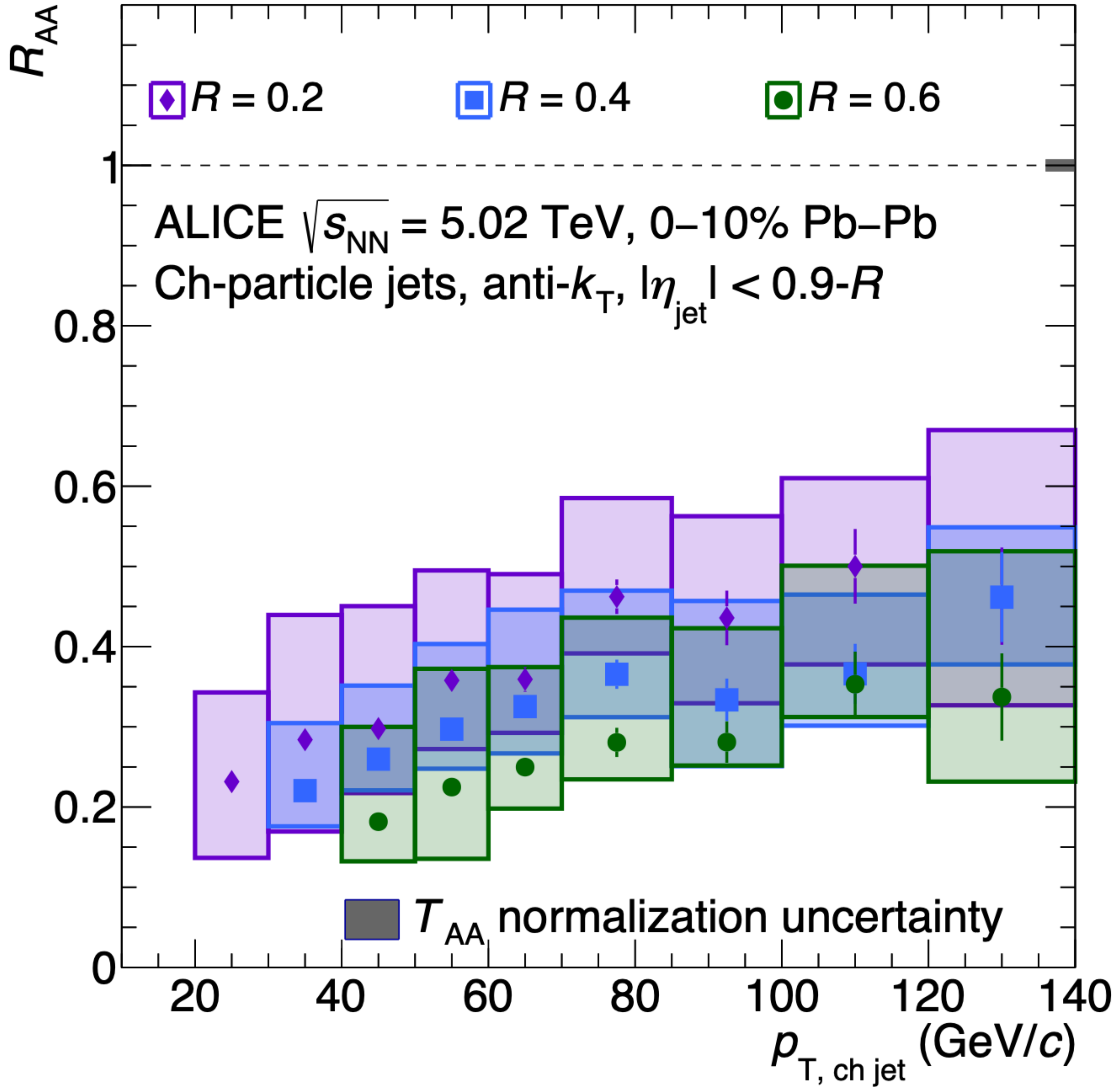
Jet-radius dependence of energy loss in Pb-Pb collisions

ALICE, arXiv:2303.00592

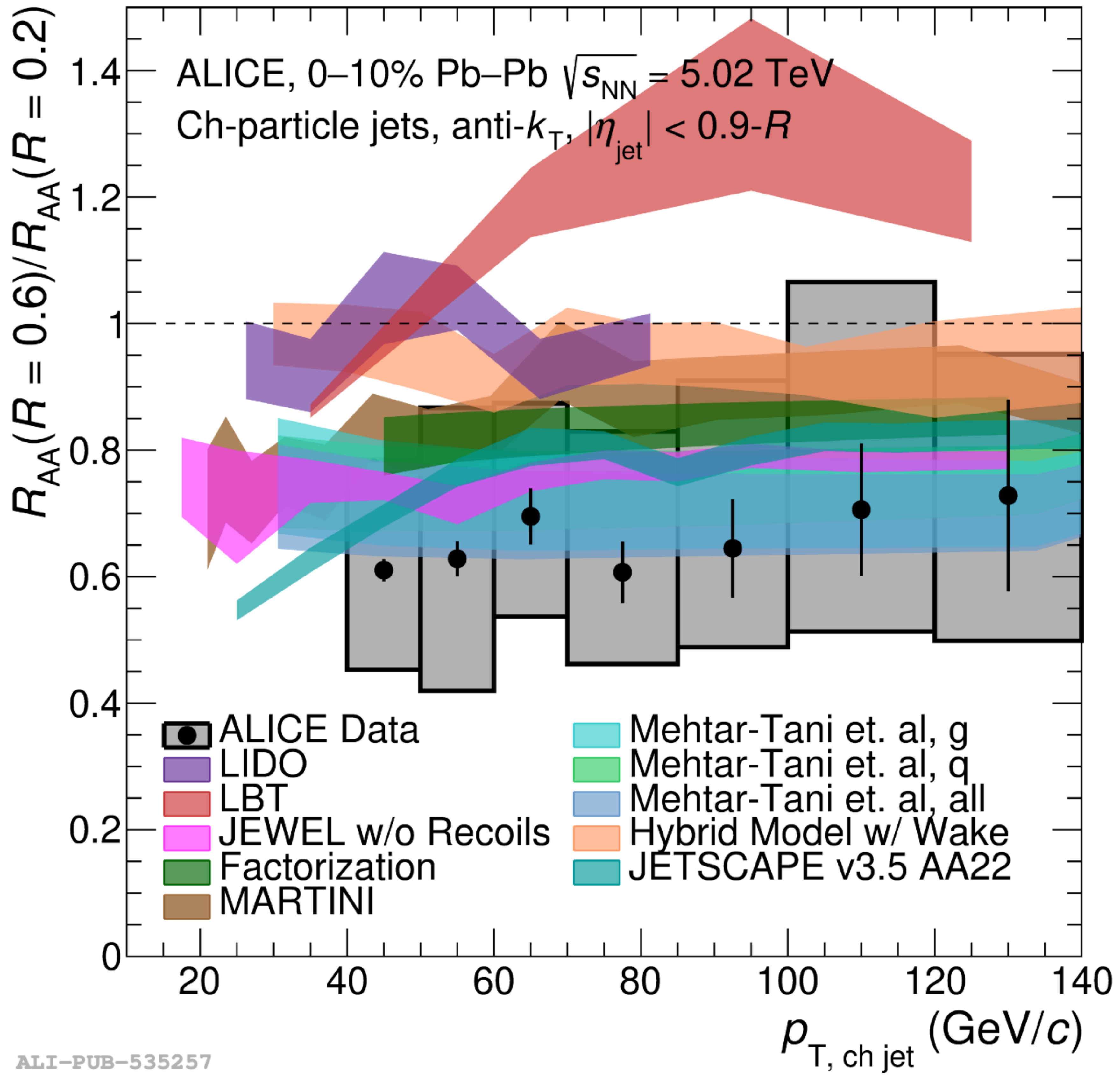


Quantify in- and out-of-cone radiation by measuring jet quenching vs cone radius

Nuclear modification factor



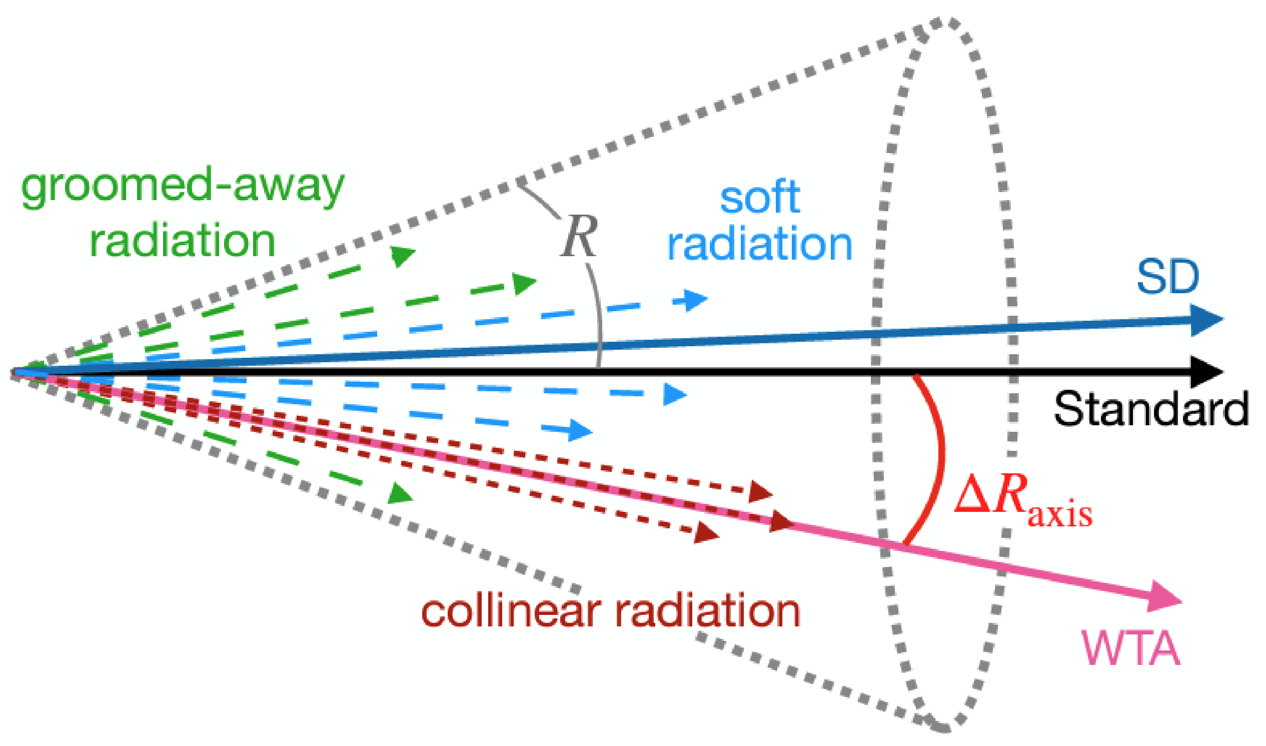
R-dependence: ratio *R*=0.6/*R*=0.2

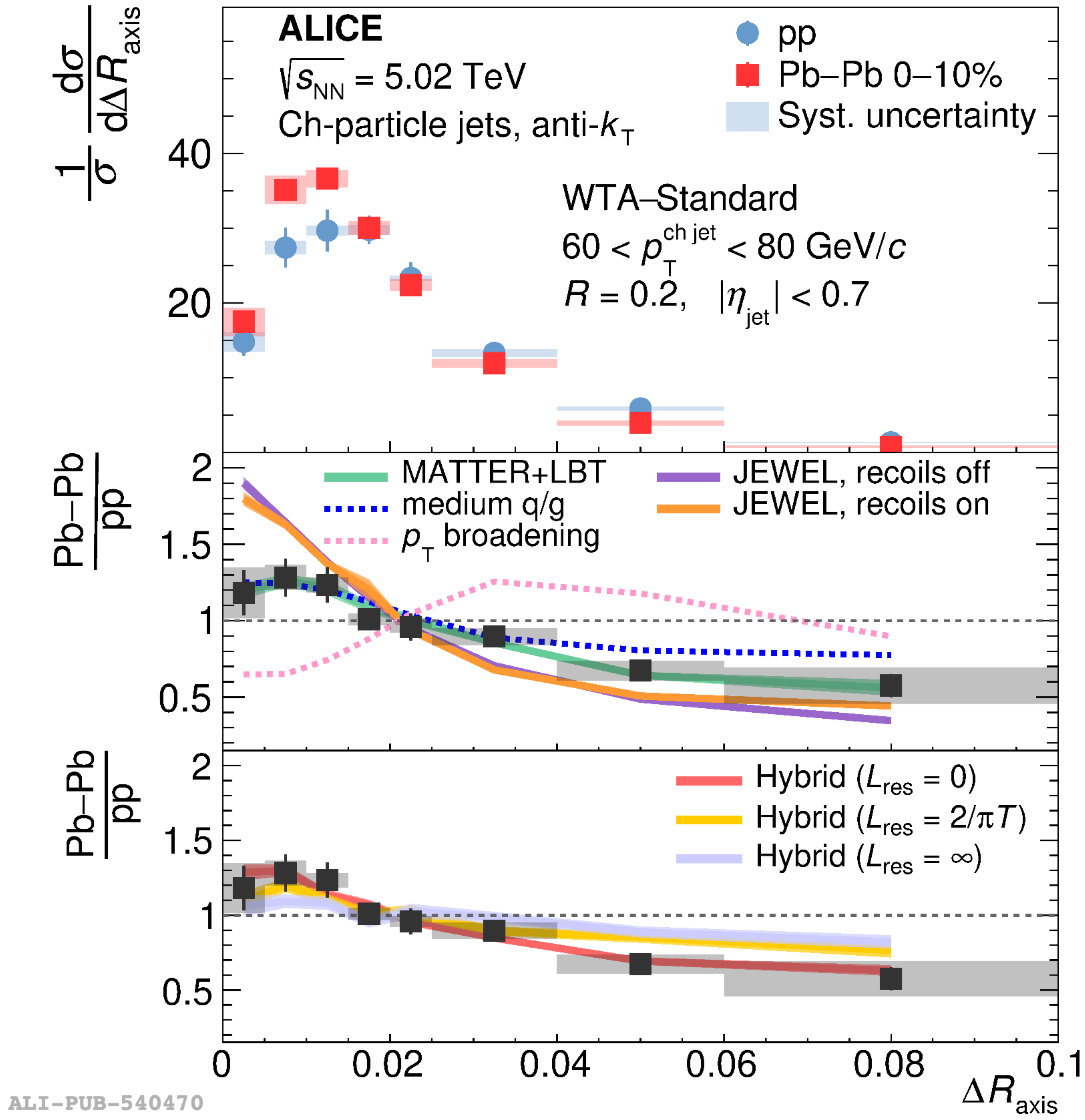


- Machine-learning based background subtraction enables jet measurements with *R* up to 0.6 at p_T ~ 50 GeV
- Jet suppression increases with increasing *R*: wider jets lose more energy

Jet energy loss: difference of jet axis directions

arXiv:2303.13347





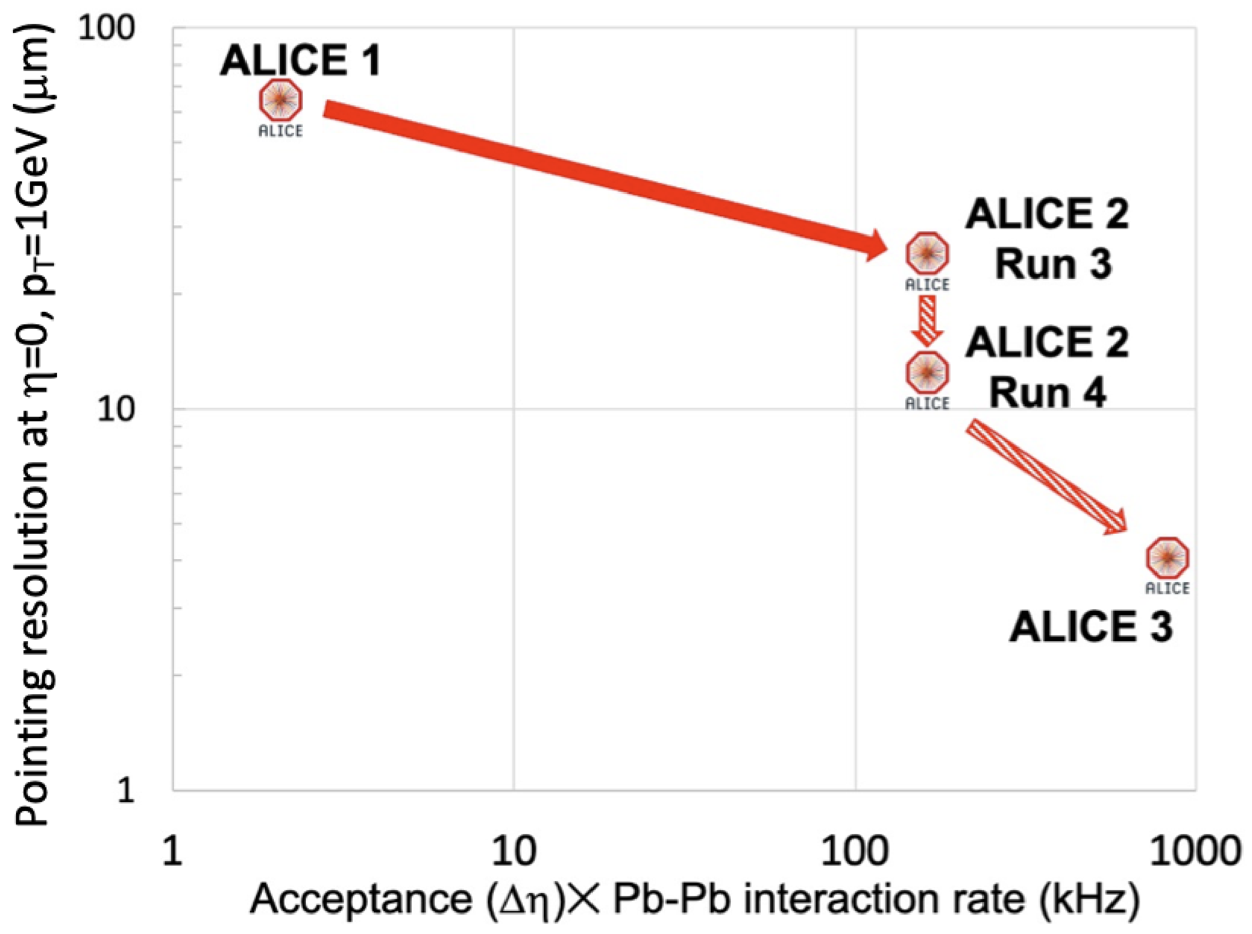
- Difference of jet axis direction, e.g.
  - winner-takes-all vs standard average
  - winner-takes-all vs Softdrop declustering
- Hybrid model: results indicate incoherent energy loss

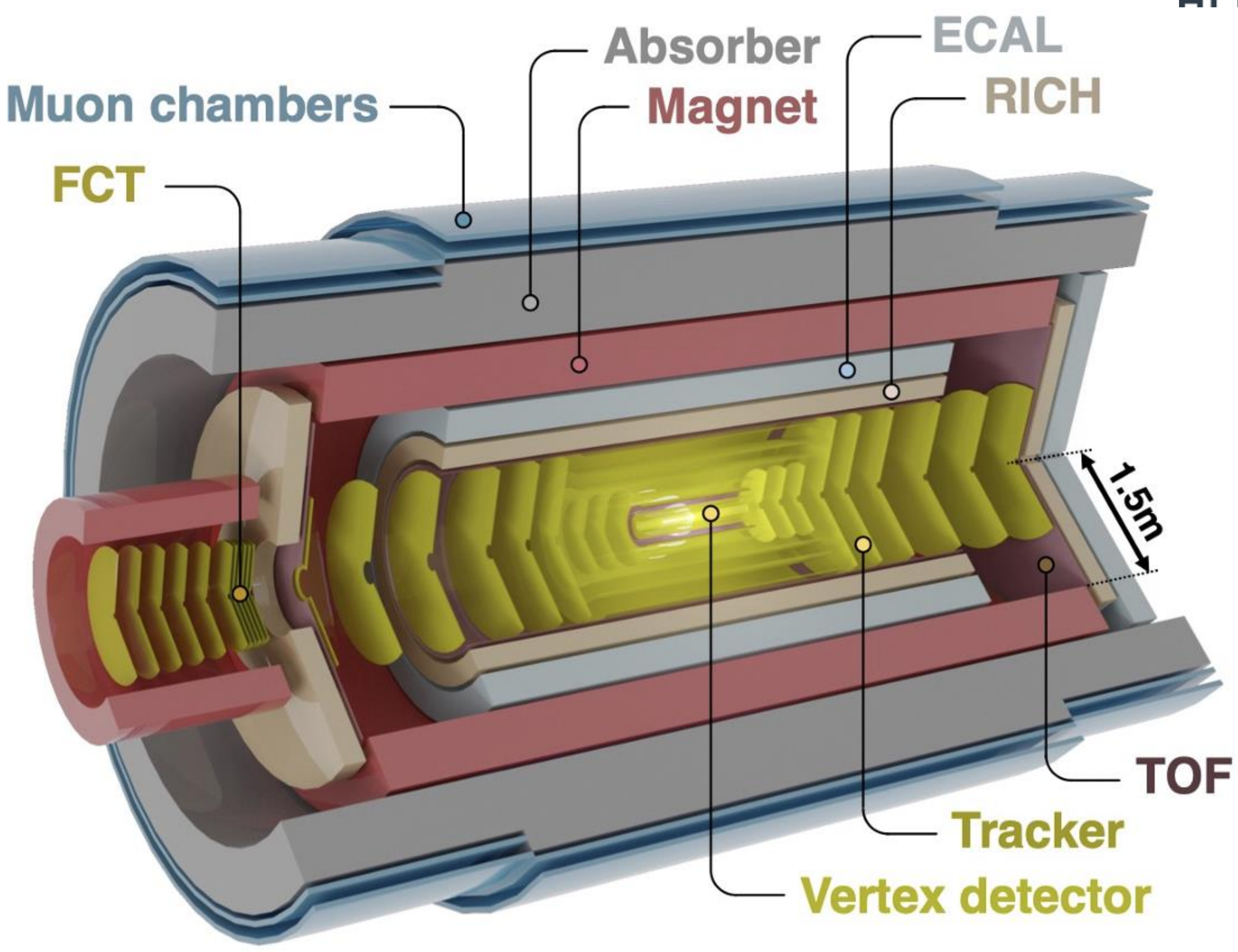
LHC Run 5 and 6: ALICE 3

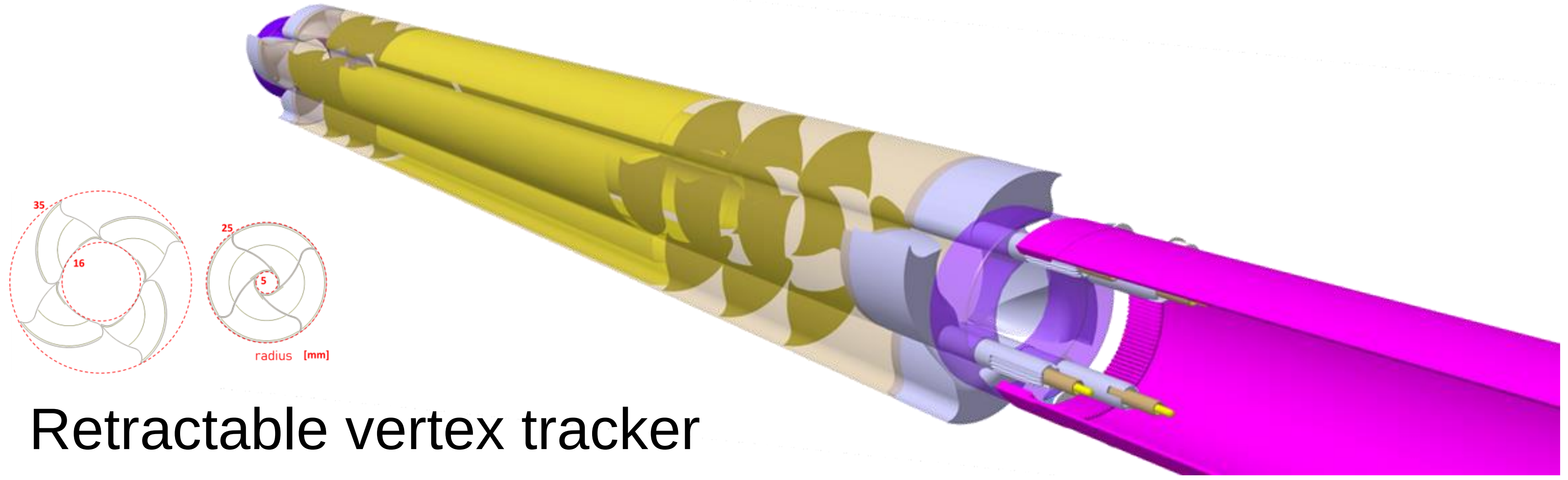
- Compact all-silicon tracker
  with high-resolution vertex detector
- Particle Identification over large acceptance:
  muons, electrons, hadrons, photons
- Fast read-out and online processing

Letter of Intent: LHCC-2022-009

ALICE upgrade path:
improvement of
detector performance





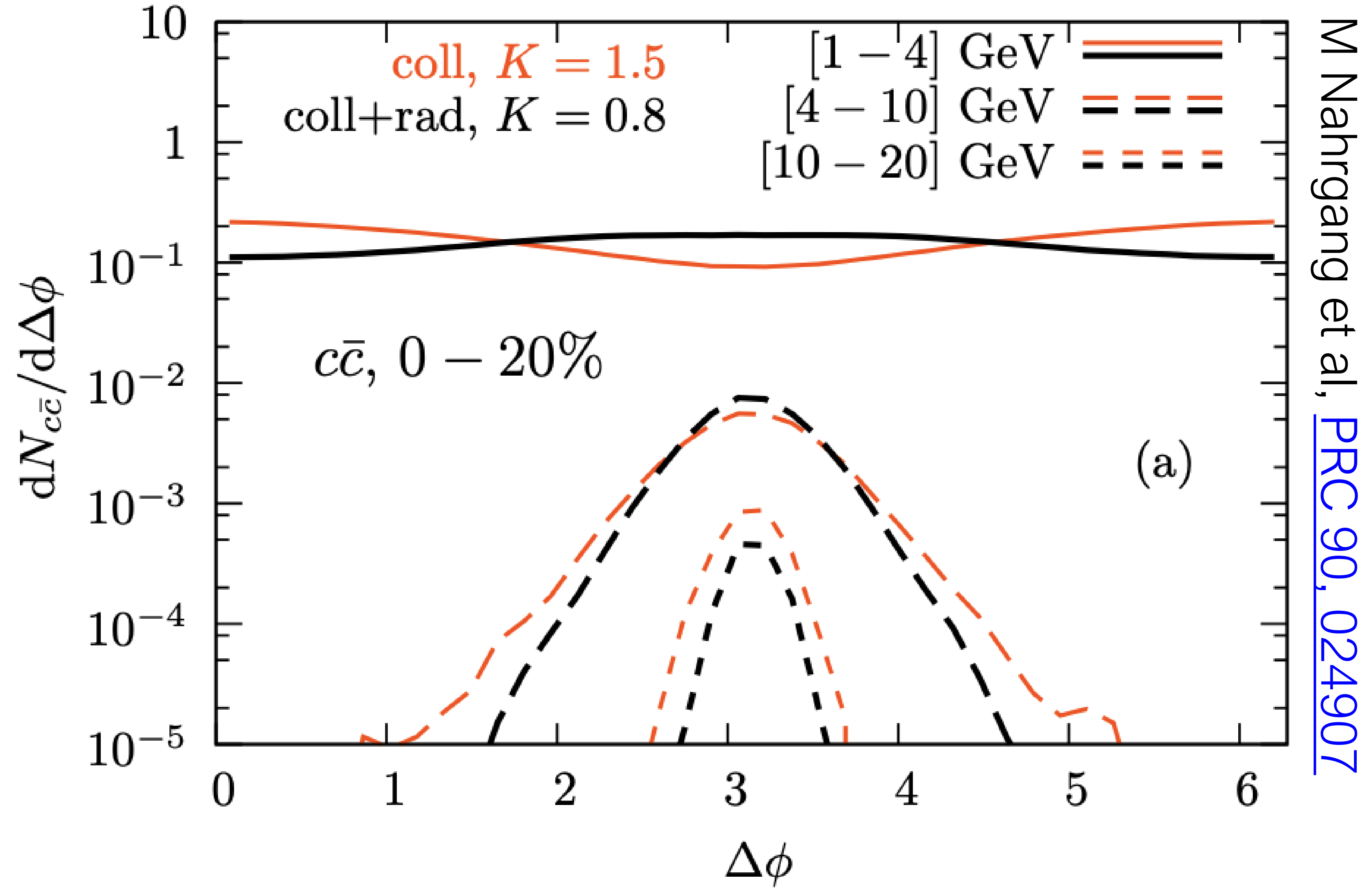


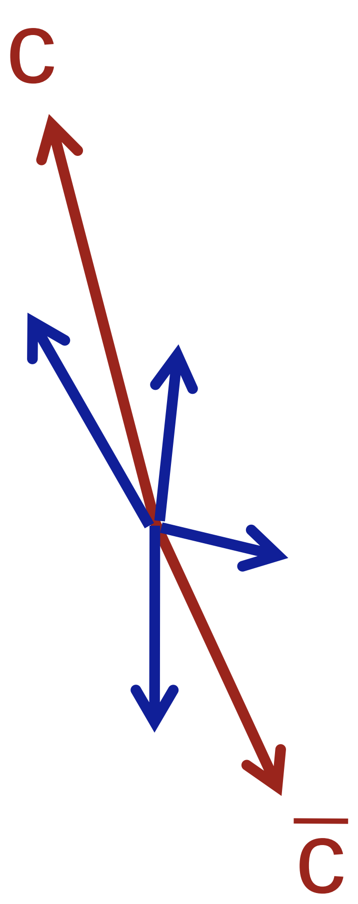
Retractable vertex tracker

R&D and scoping discussions ongoing: more in Dec meeting

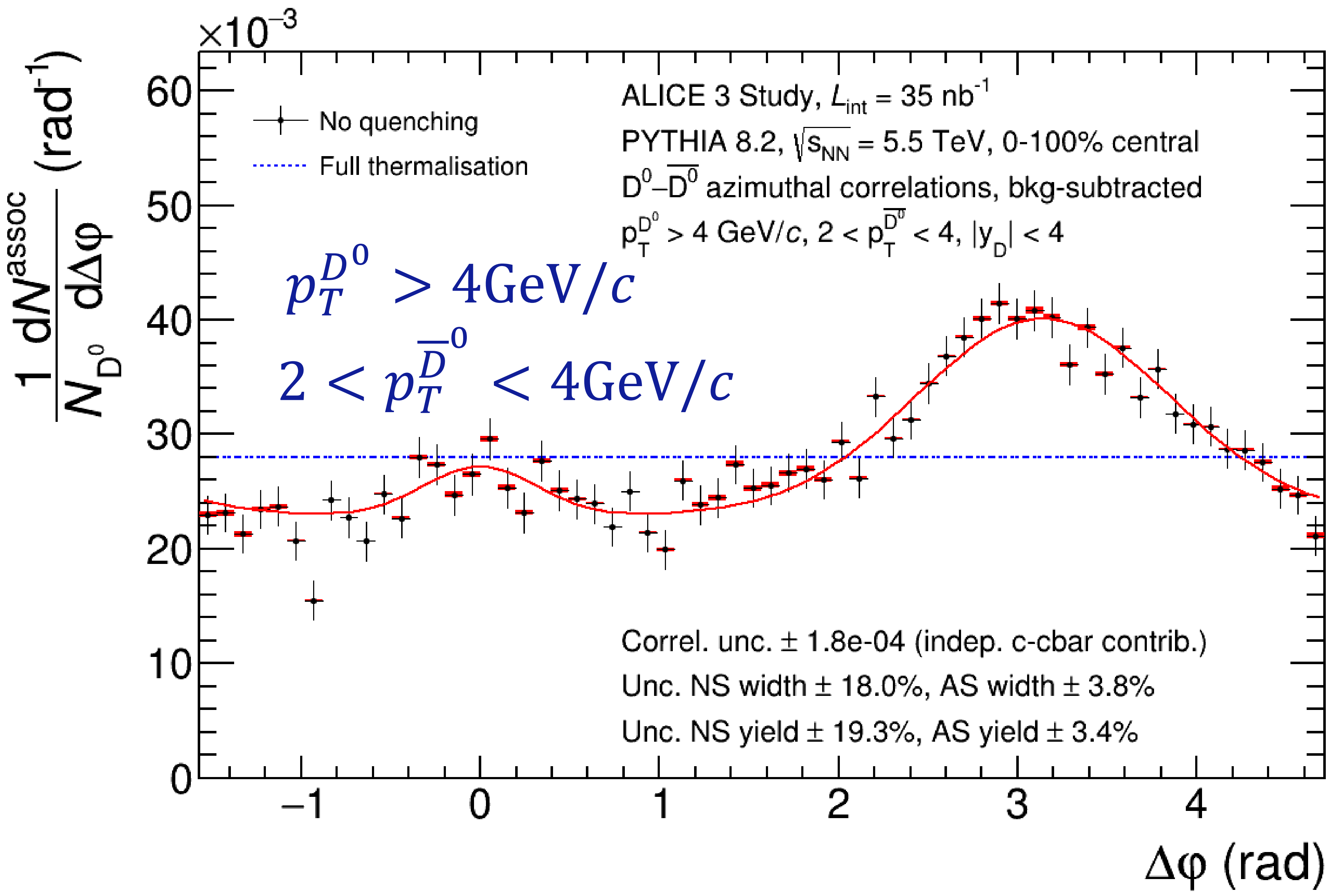
$D\overline{D}$ azimuthal correlations

Charm azimuthal correlations

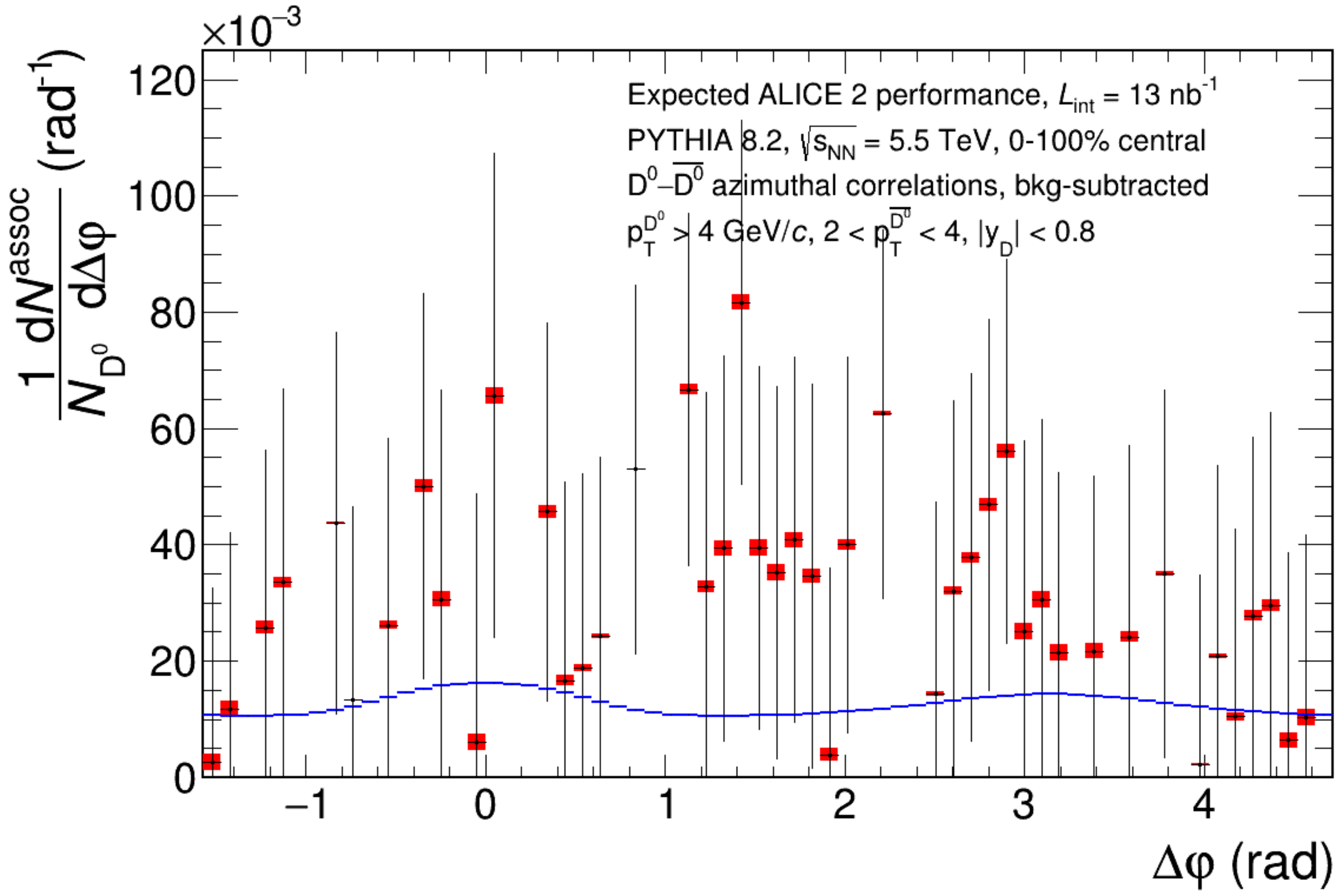




ALICE 3 projection: $D\overline{D}$ correlations



ALICE Run 3 + 4 projection



- Angular decorrelation directly probes QGP scattering
  - Signal strongest at low p_T
- Very challenging measurement:
  need good purity, efficiency and η coverage
  → heavy-ion measurement only possible with ALICE 3