Istituto Nazionale di Fisica Nucleare

Highlights on heavy-ion collisions at the LHC

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INFN Trieste

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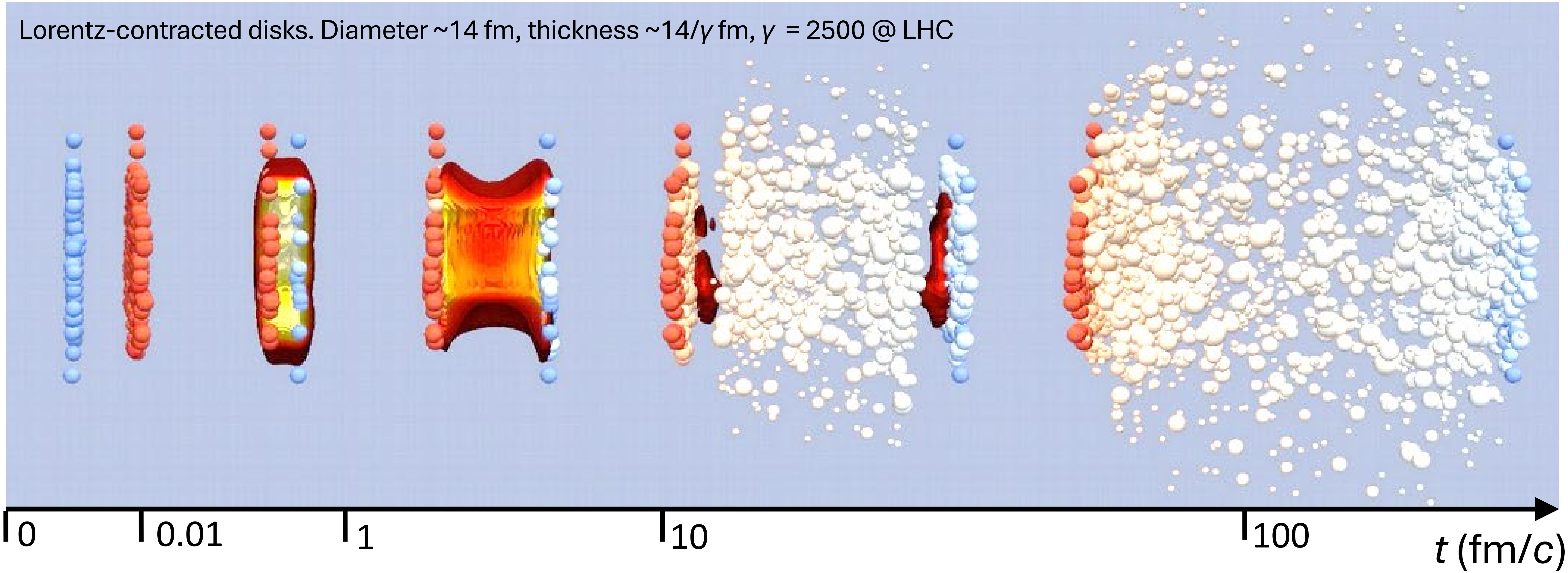
Relativistic heavy-ion collision and evolution



Credits: MADAI Collab., Petersen and Bernhard

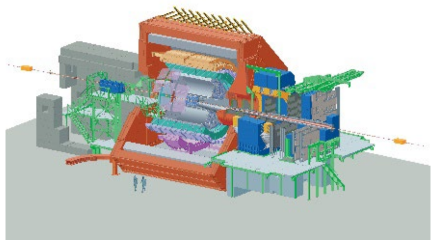
Initial stage
nPDF,
saturation,
shadowing

Gluon and
quark-pair creation
All heavy quarks
created at this stage

QGP: deconfined
nuclear matter
expanding
hydrodynamically

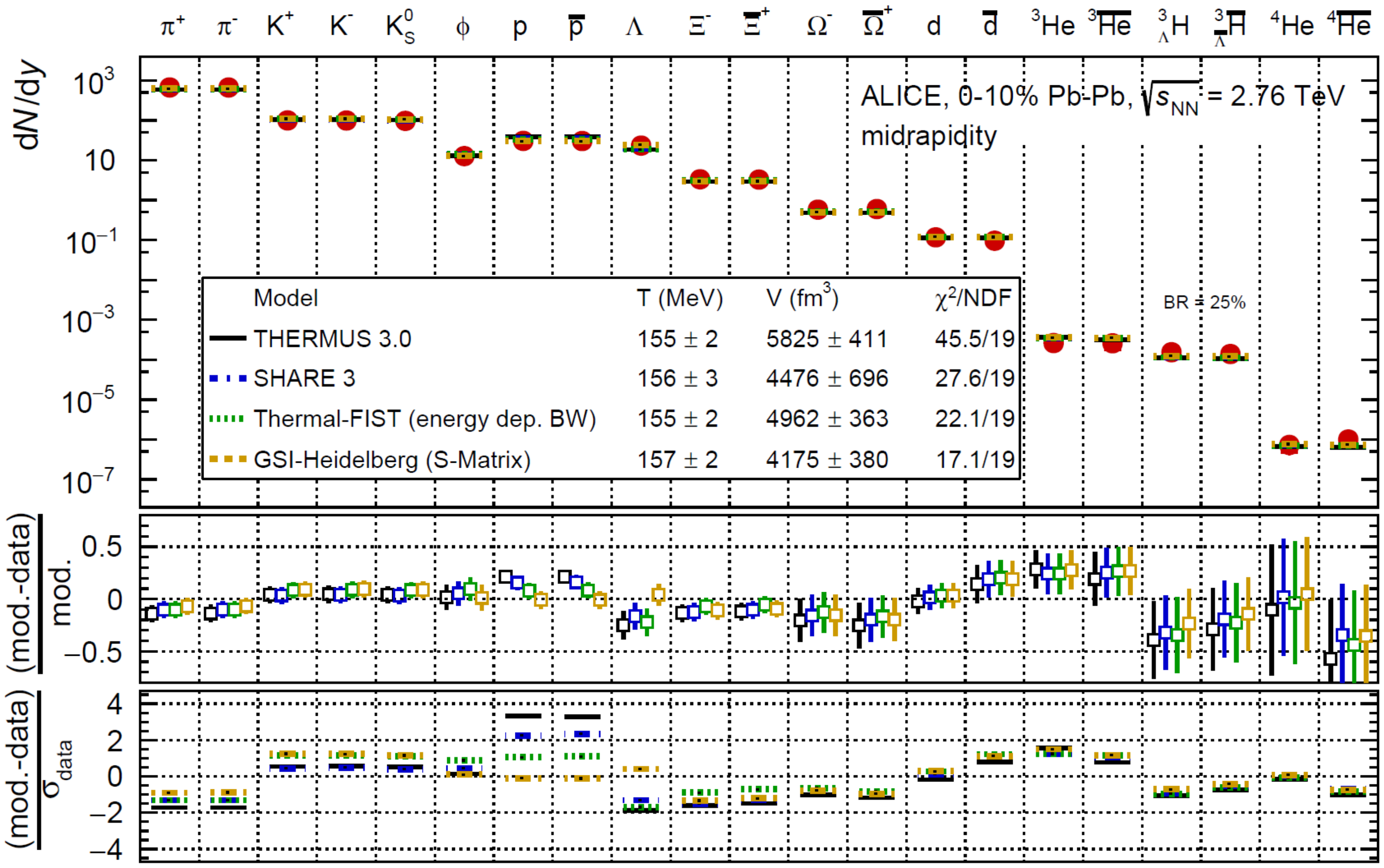
Hadronization and
chemical freeze-out
Inelastic collisions
cease

Kinetic freeze-out
Elastic collisions cease
Free streaming particles to
the detectors



Thermodynamics of the medium

Thermodynamics of the medium: statistical hadronization models (SHM)

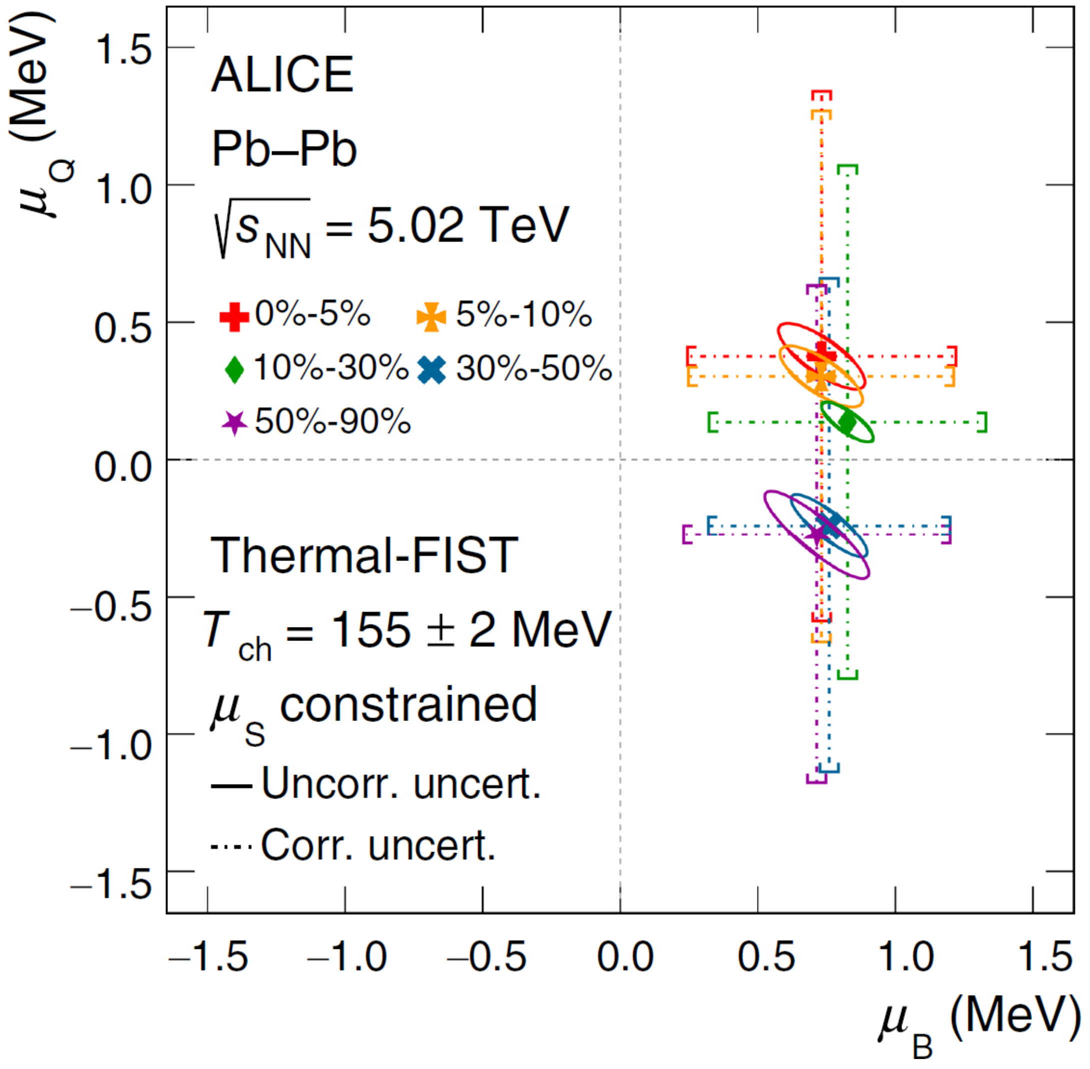


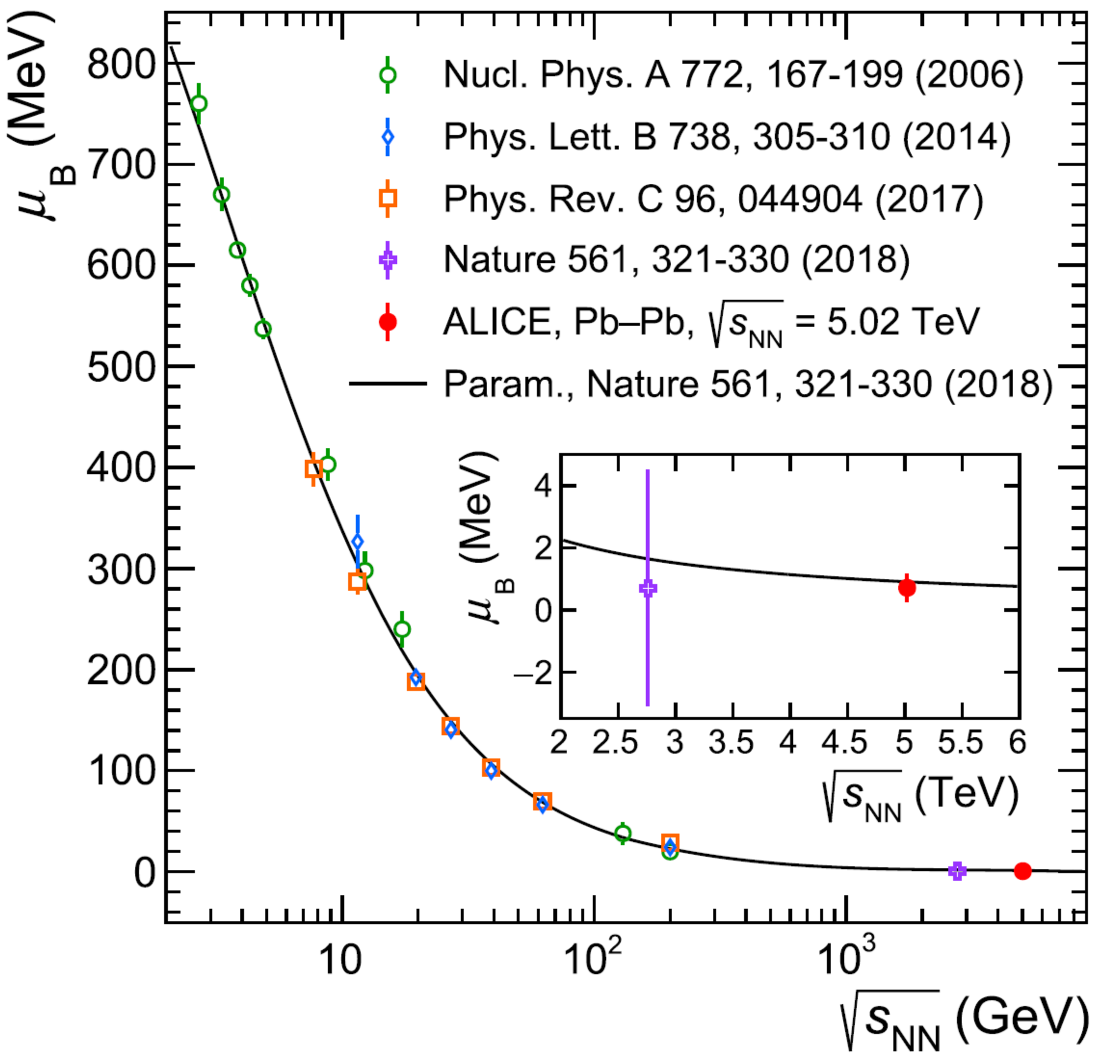
ALICE, arXiv:2211.04384

- At hadronization the system is close to thermal equilibrium
- A rapid hadrochemical freeze-out takes place at the phase boundary
- Hadron abundances described by SHM over 9 orders of magnitude!
- Also loosely bound objects (light nuclei and hyper-nuclei) are described by SHM

System created at midrapidity in Pb-Pb collisions is baryon and electrically neutral on average

ALICE, Phys. Rev. Lett. 133, 092301(2024)

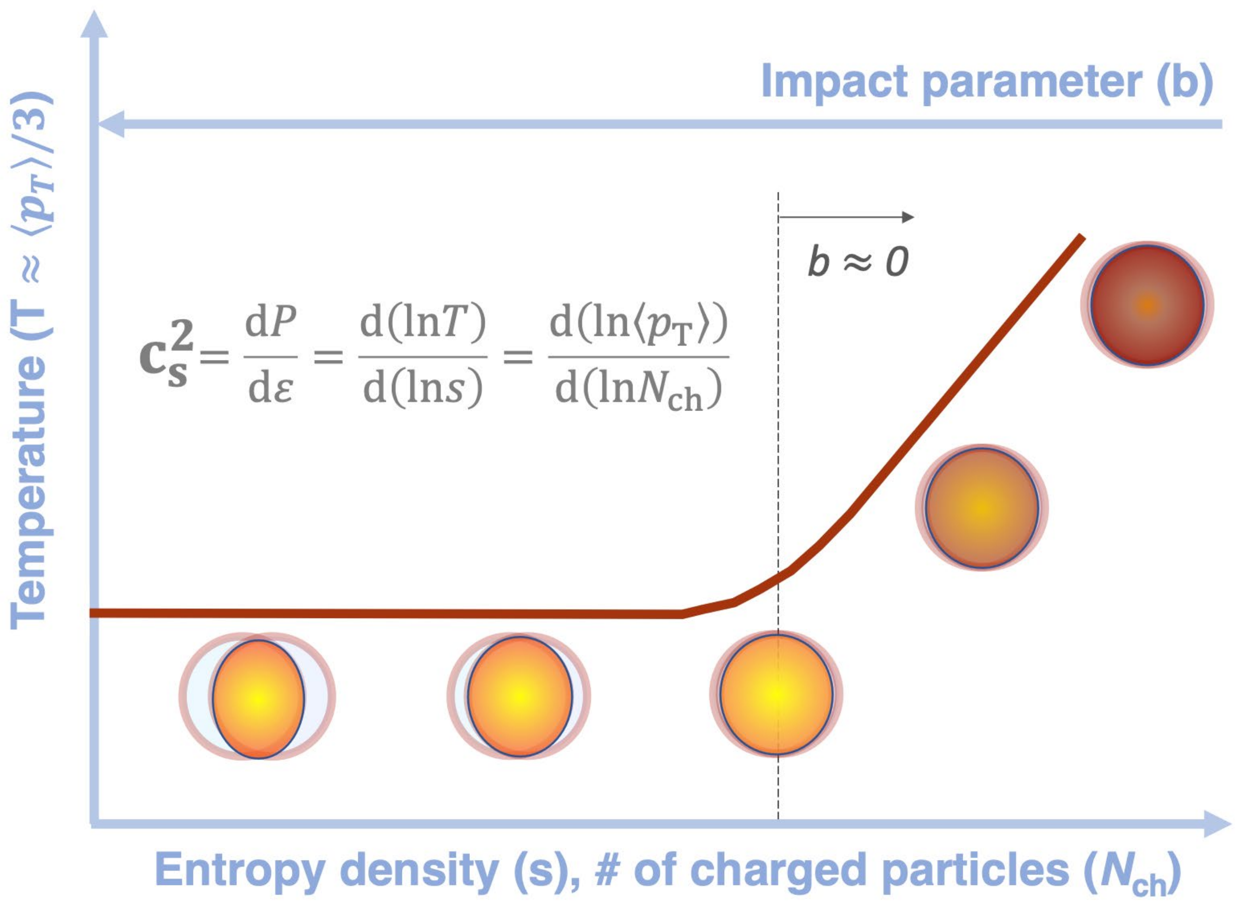




Speed of sound from ultra-central collisions

Original idea from F. Gardim et al., PLB 809 (2020) 135749

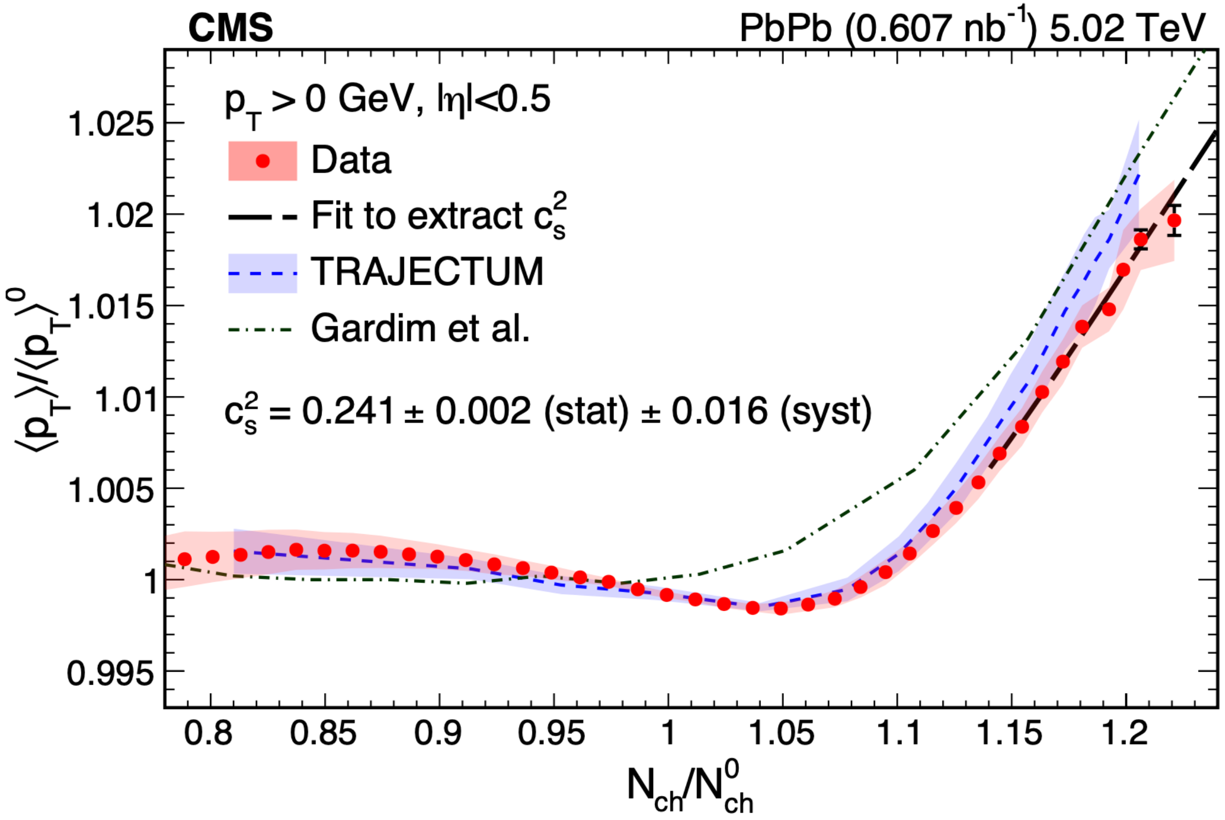
CMS, Rep. Prog. Phys. 87, 077801(2024)



Nat. Phys. 16 (2020) 6, 615-619

- Amount of energy deposited in the collision depends on the overlap among the nuclei
- With complete overlap, fluctuations in the number of partonic interactions can still change the amount of energy in the system
- At $b \sim 0$, $<p_T>$ and N_{ch} are proxies for temperature and entropy density

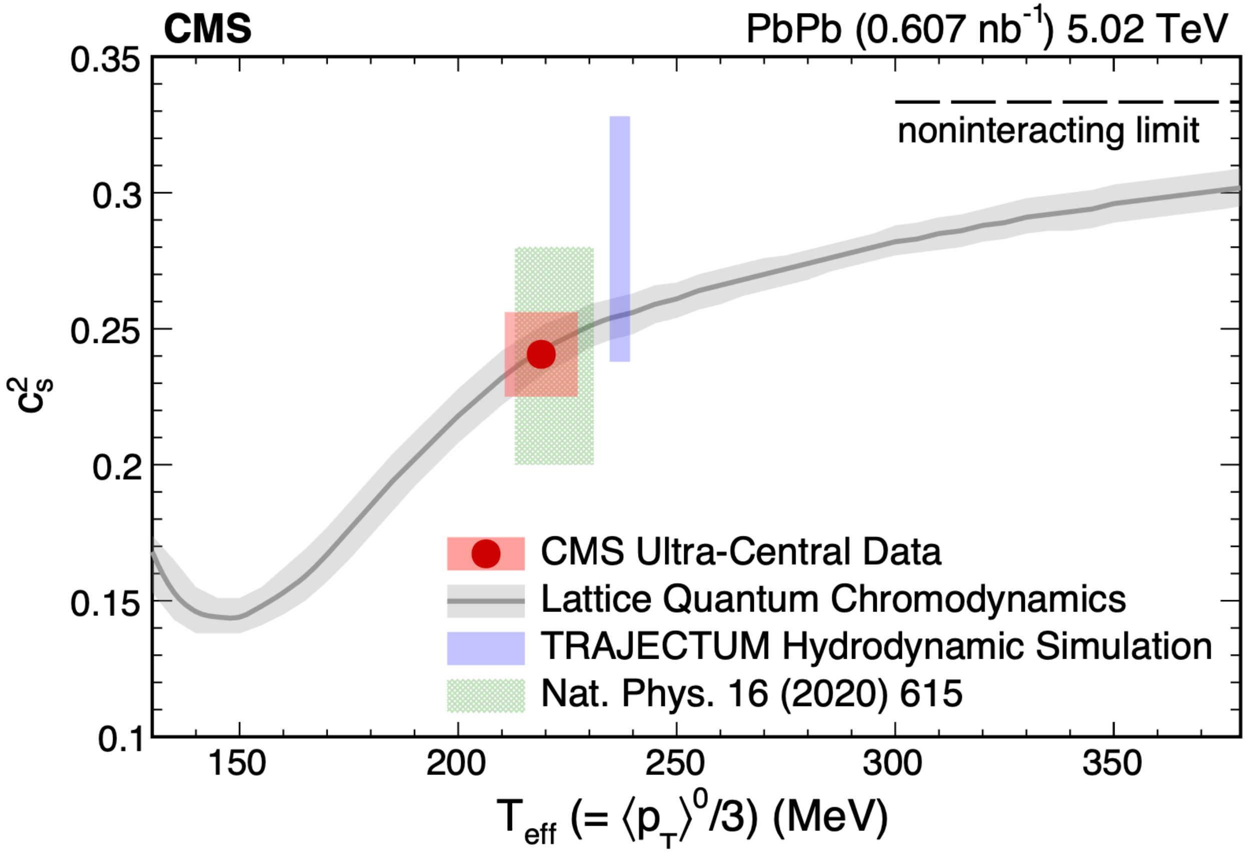
Speed of sound from ultra-central collisions



Measurement of $\langle p_T \rangle$ vs multiplicity, normalized by their values in the 0–5% most central events

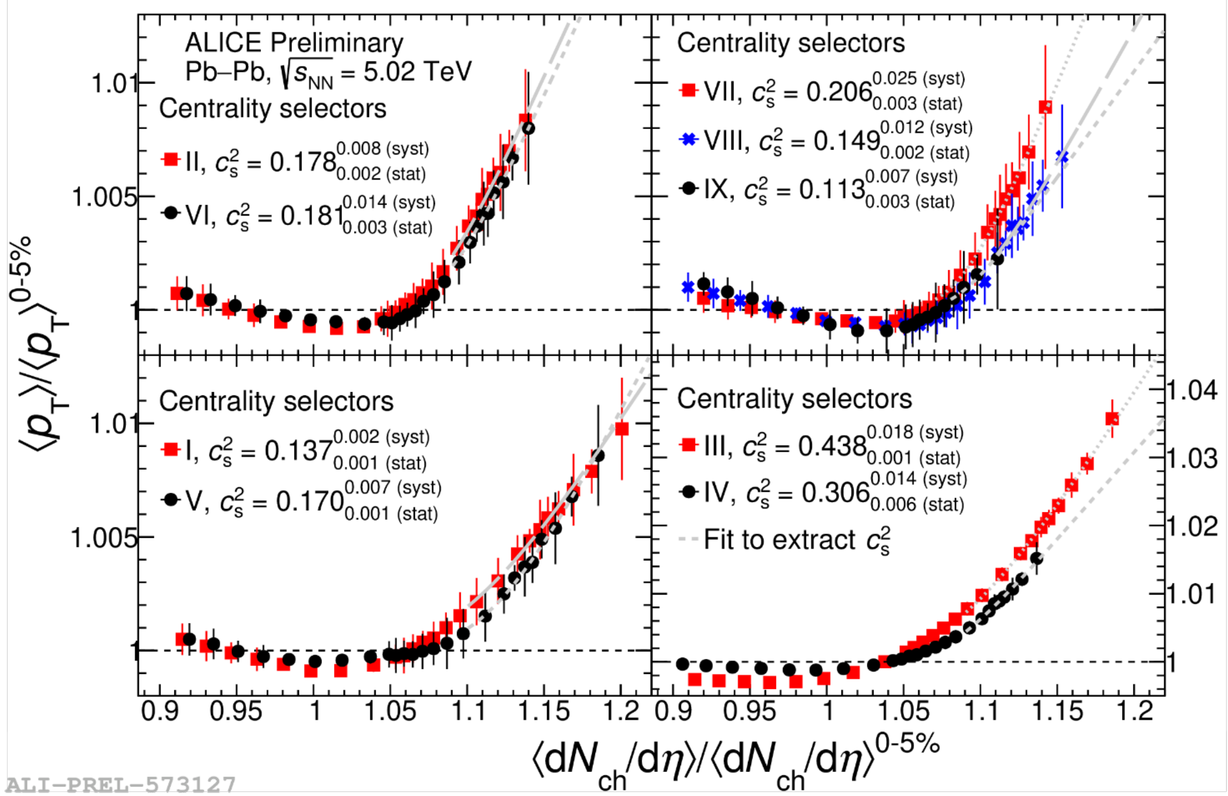
Steep rising trend matching the hydrodynamic model predictions

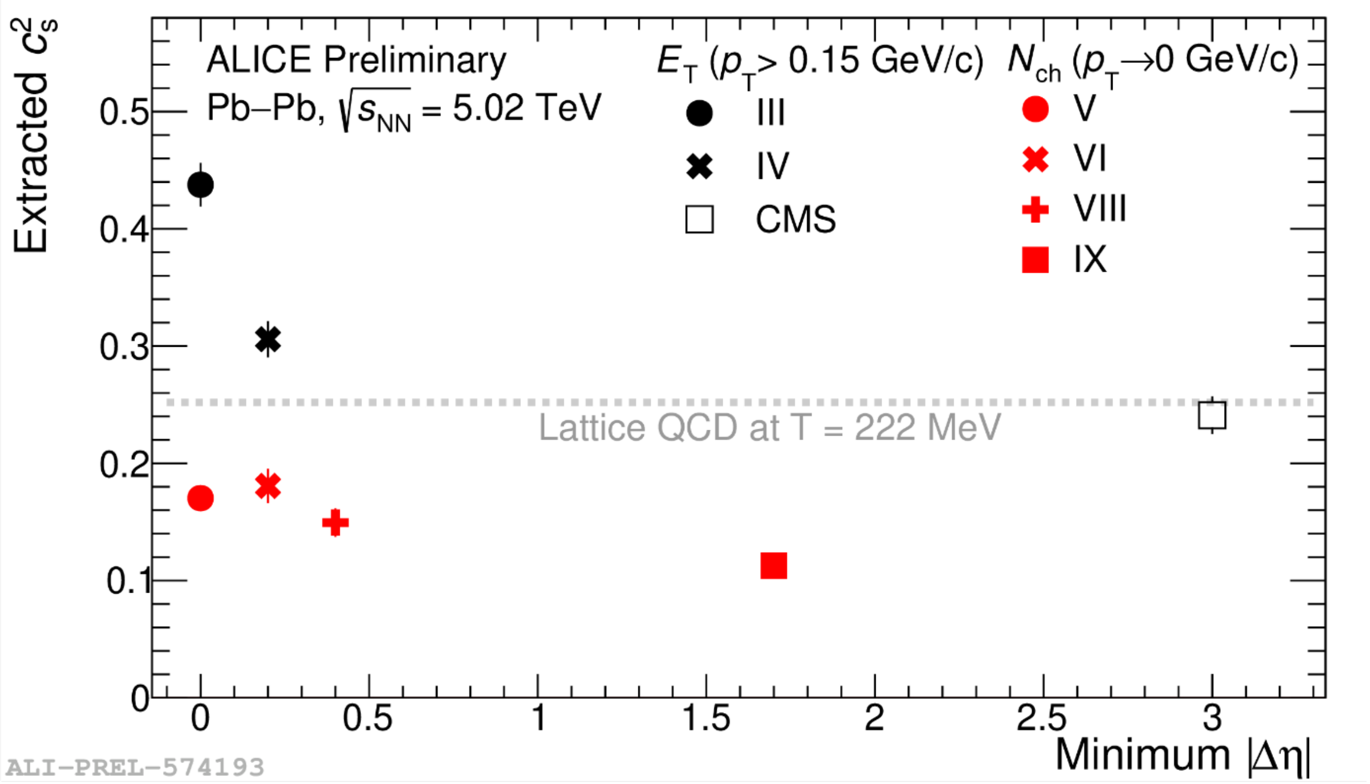
CMS, Rep. Prog. Phys. 87, 077801(2024)



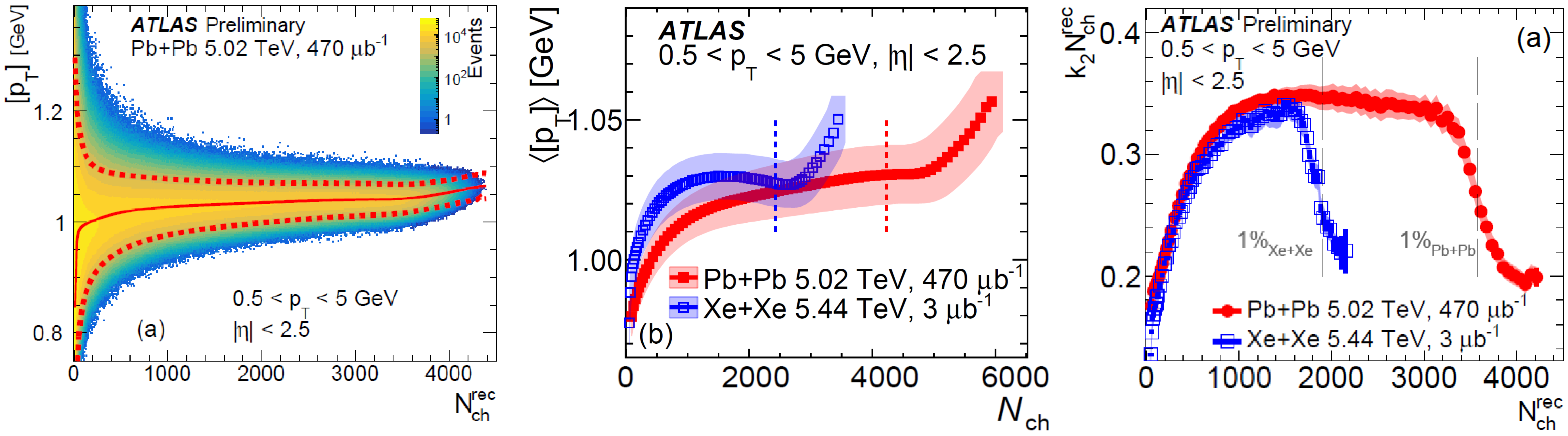
Data compatible with lQCD and state-of-the-art hydro simulations

Speed of sound from ultra-central collisions





Strong dependence on the kinematic acceptance and centrality estimator



$[p_T]$ is the mean p_T calculated for each event

$<[p_T]>$ is averaged over all events in a given class

$<c_2>$ is the variance, $k_2 \equiv <c_2>/<[p_T]>^2$

Assuming stochastic sources of the fluctuations:

$$k_2 \propto (N_{part})^{-1} \propto (N^{rec}{}_{ch})^{-1}$$

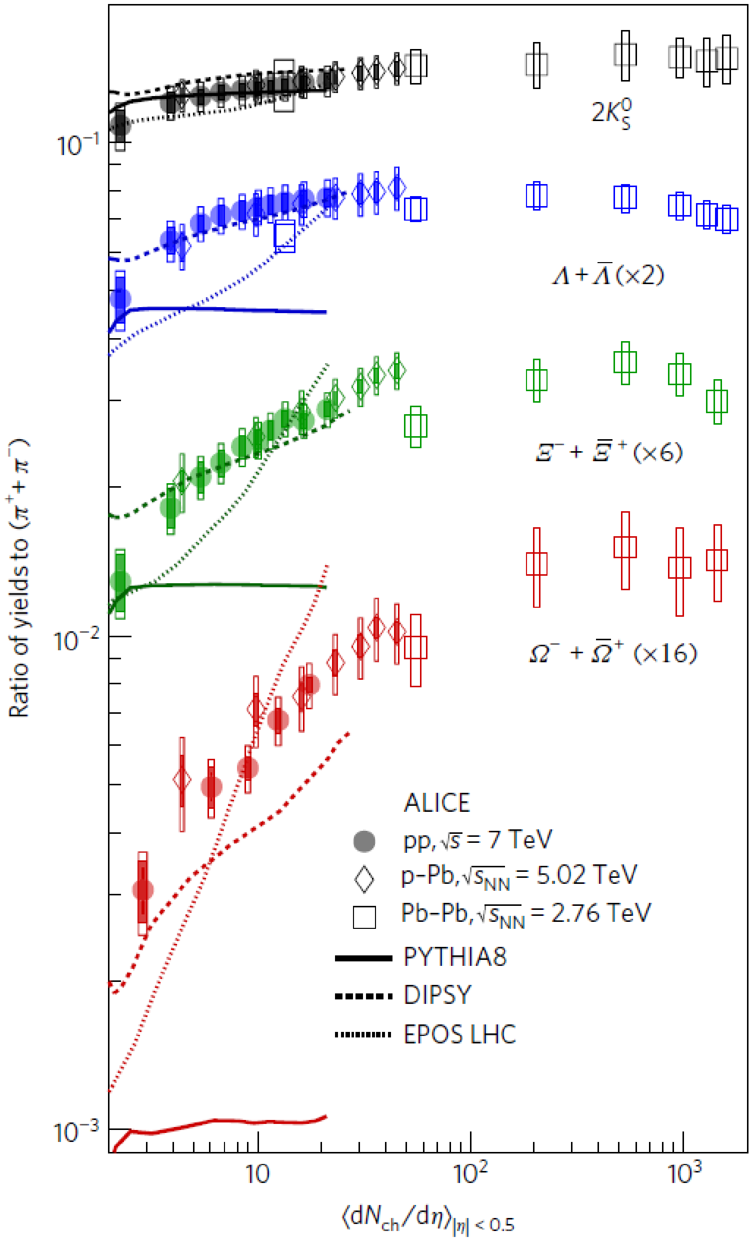
True for mid-central to central collisions

Not true for peripheral and very central collisions

Strangeness production in the QGP

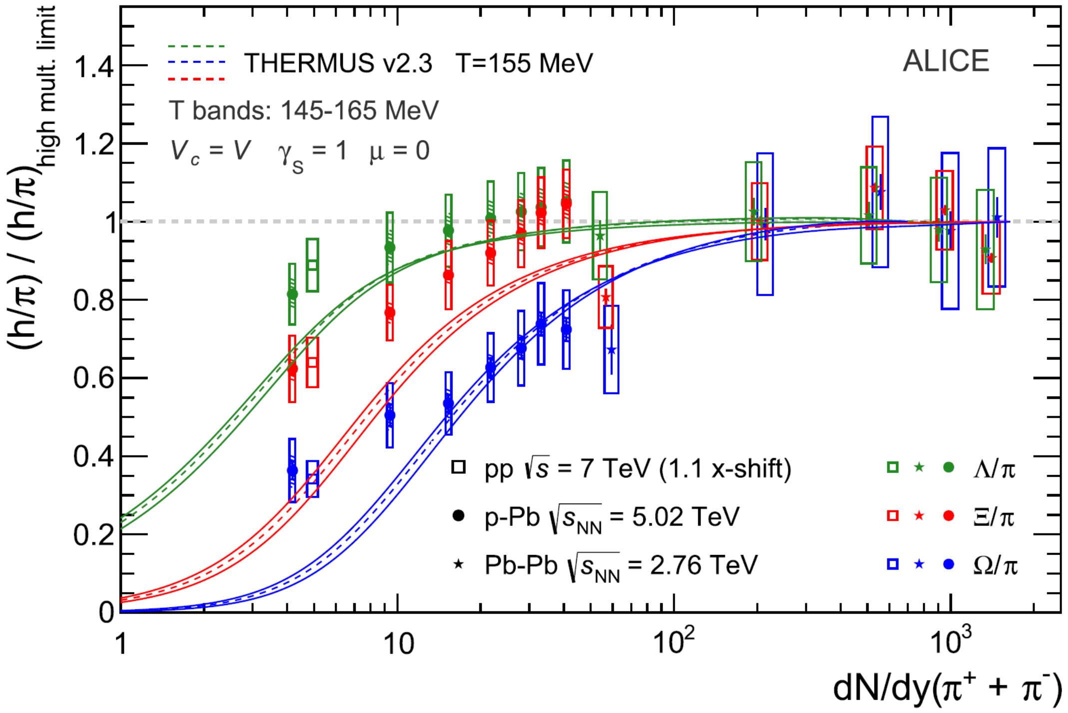
Understanding strangeness production

ALICE, Nat. Phys **13,** 535–539 (2017)



- Smooth evolution of particle production from small to large systems vs. charged-particle multiplicity
- Steeper increase for particles with more strangeness content
- High-multiplicity pp: same hadrochemistry as larger (p-Pb, peripheral Pb-Pb) systems
- Common particle production mechanism for all systems

ALICE, Phys. Lett. B 758 (2016) 389–401



- Local conservation law applied to strangeness quantum numbers
- Baryon numbers and charge treated grand-canonically

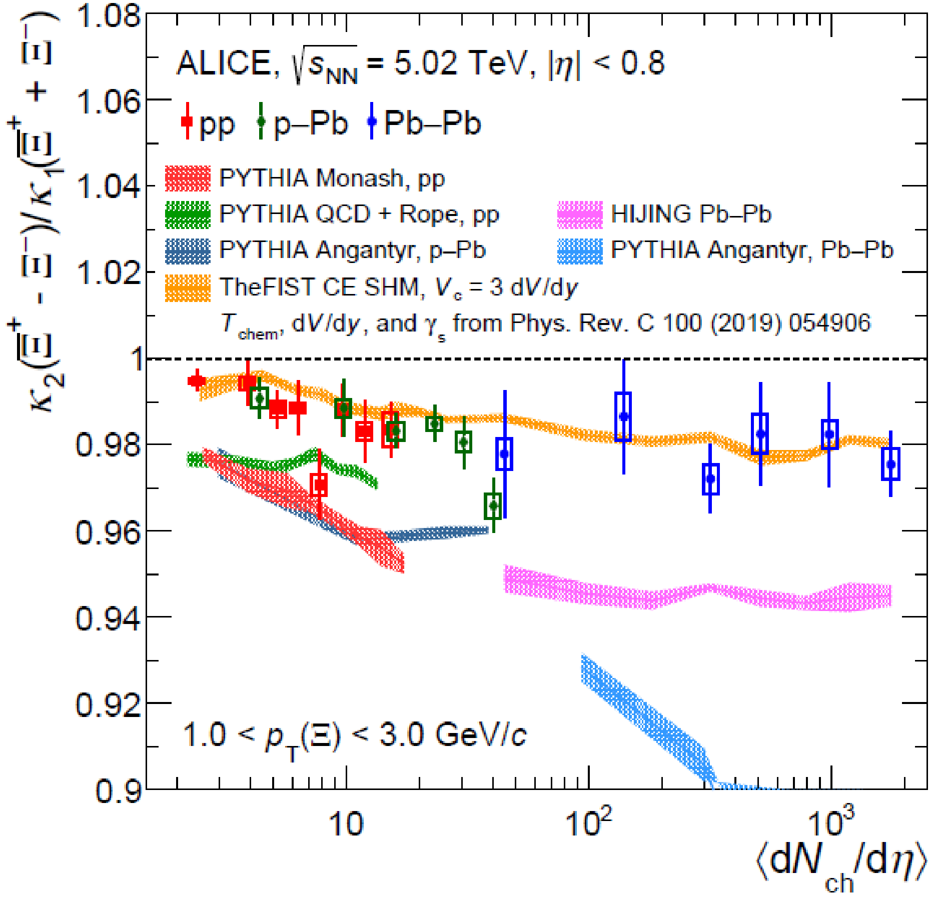
Understanding strangeness production with event-by-event fluctuations

String fragmentation (PYTHIA) and canonical statistical hadronization (SHM) provide different treatments of conservation laws.

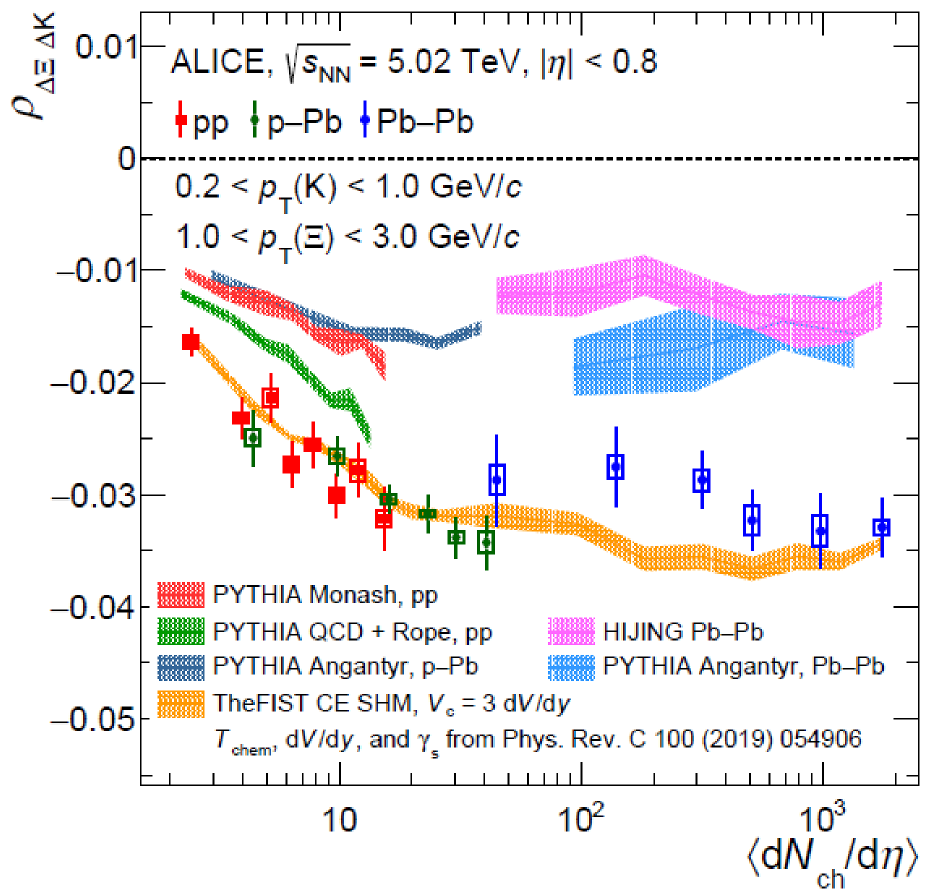
ALICE, arXiv:2405.19890

k_2/k_1 and $\rho_{\Delta\Xi\Delta K}$ are sensitive to the locality of strangeness conservation, which affects the magnitude of the correlations

k_2/k_1 is the normalized second-order cumulant of net-Ξ number



$\rho_{\Delta\Xi\Delta K}$ is the correlation between net-Ξ and net-kaon numbers

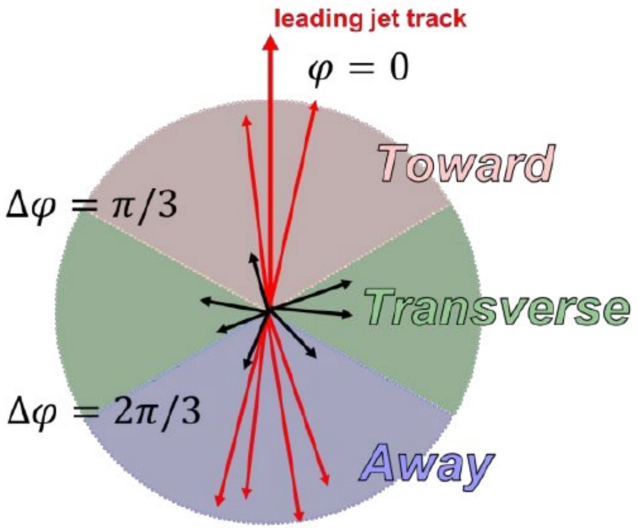


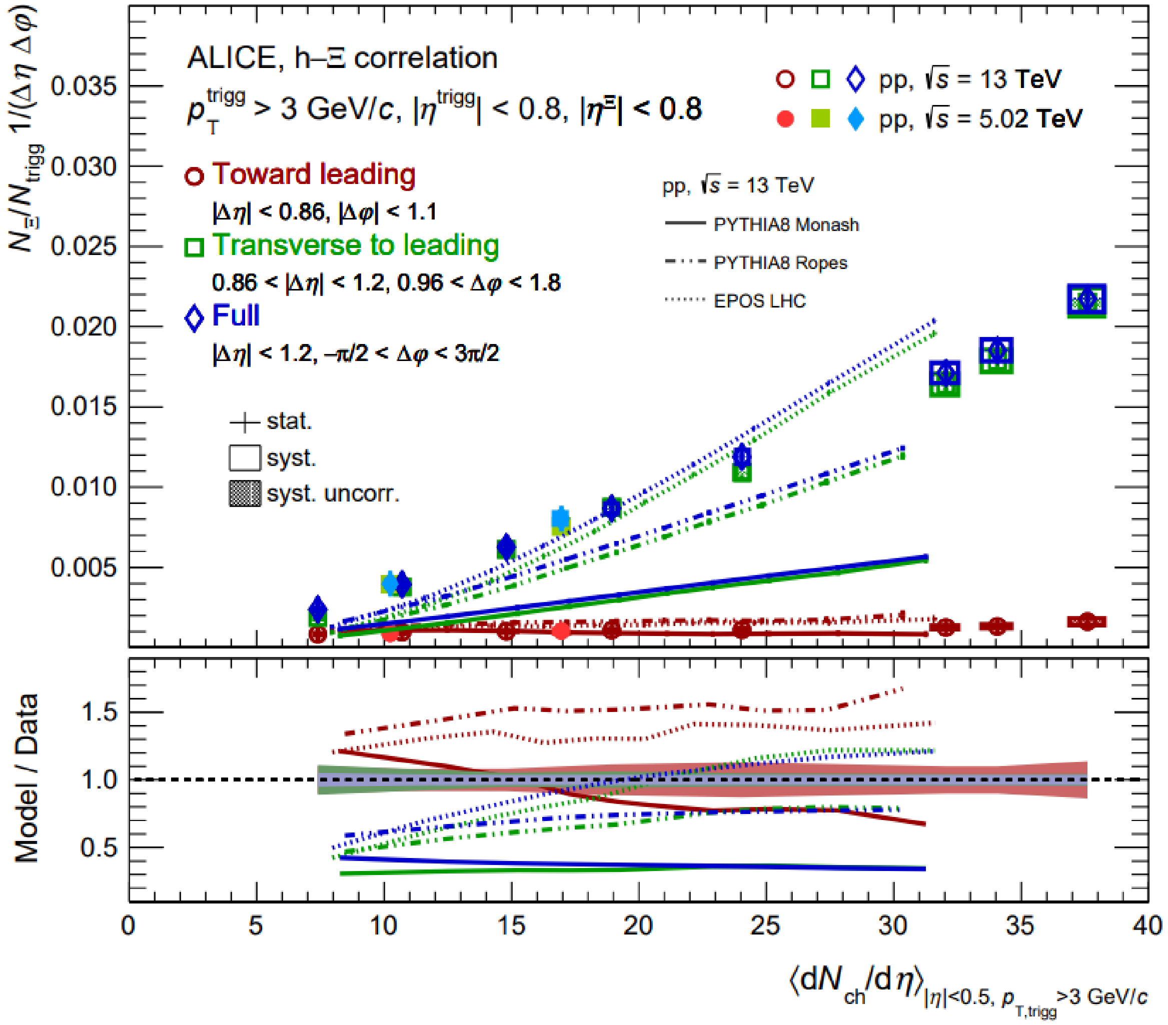
Understanding strangeness production with strange-hadron angular correlations

Strangeness in/out of the jets:

ALICE , JHEP 09 (2024) 204

- Yields dominated by transverse-to-leading production and increase with multiplicity
- toward-leading yields → milder dependence on multiplicity

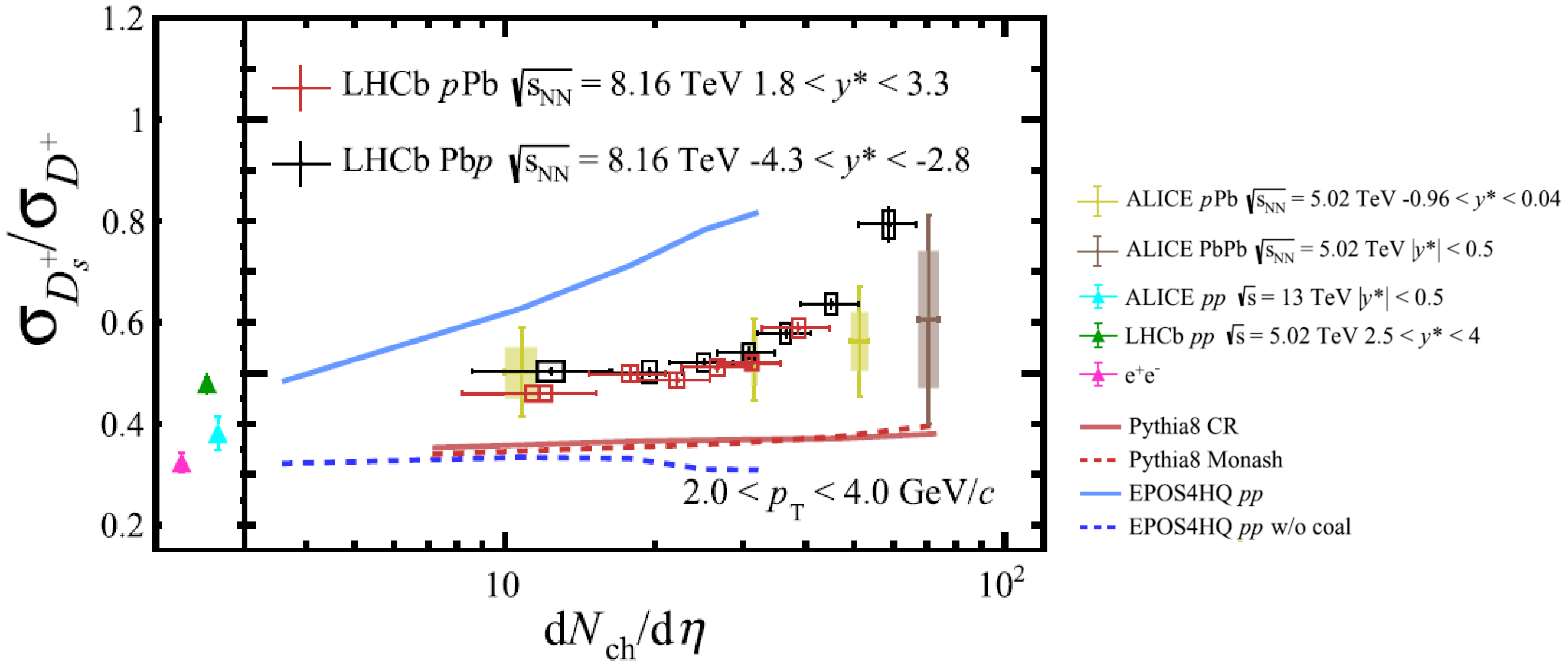




- Production in the direction of the trigger particle associated with hard scattering processes
- Production in the transverse-to-leading direction related to the underlying event

Strangeness enhancement with charmed mesons

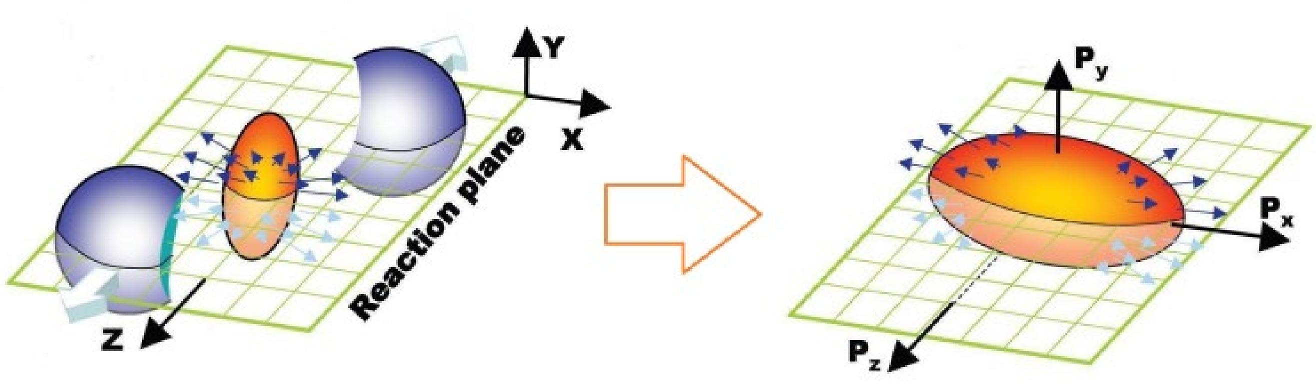
LHCb, Phys. Rev. D 110, L031105 (2024)



Hydrodynamics of the medium

Hydrodynamics of the medium: anisotropic flow

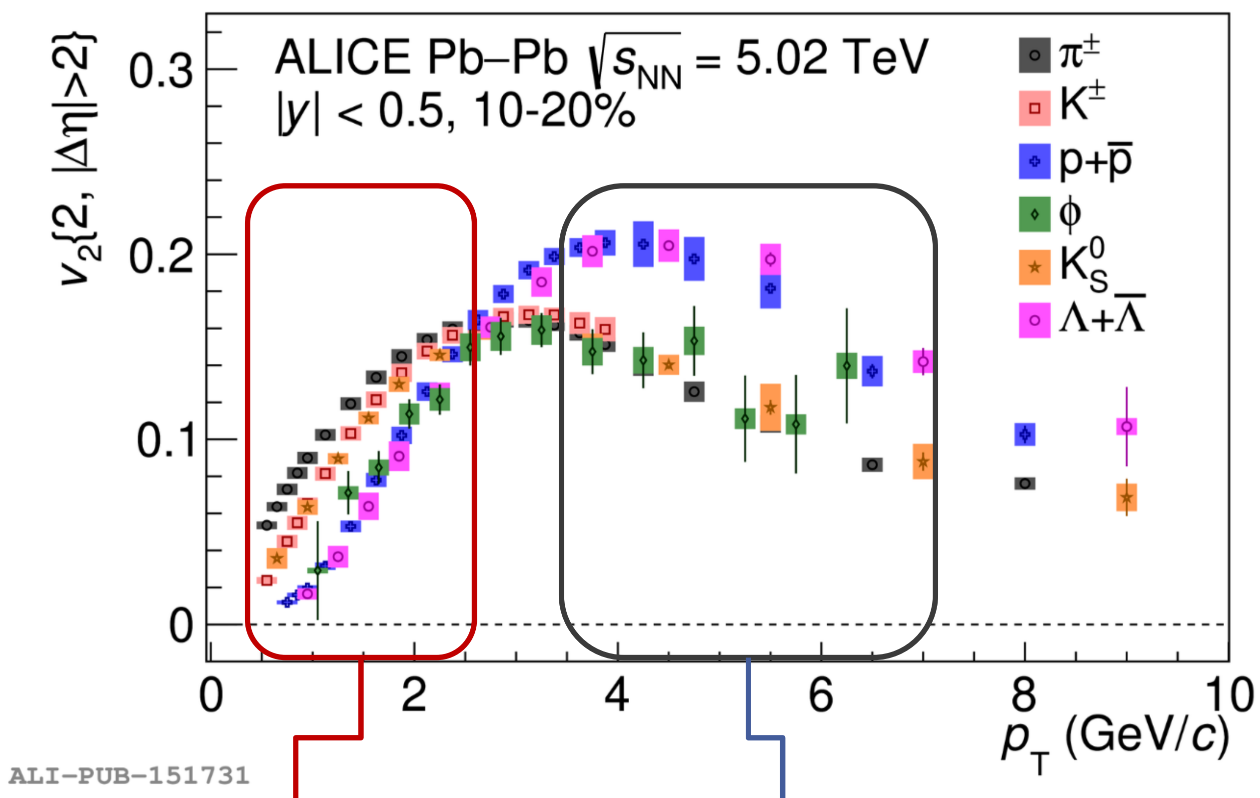
Anisotropies in the initial energy density distribution (eccentricity) lead to azimuthal anisotropies in particle production



- Depends on EOS and fluid viscosities
- Measured via Fourier expansion

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \psi_n)]$$

ALICE, JHEP 09 (2018) 006



Mass ordering (higher mass → lower v_2): interplay between radial and elliptic flow

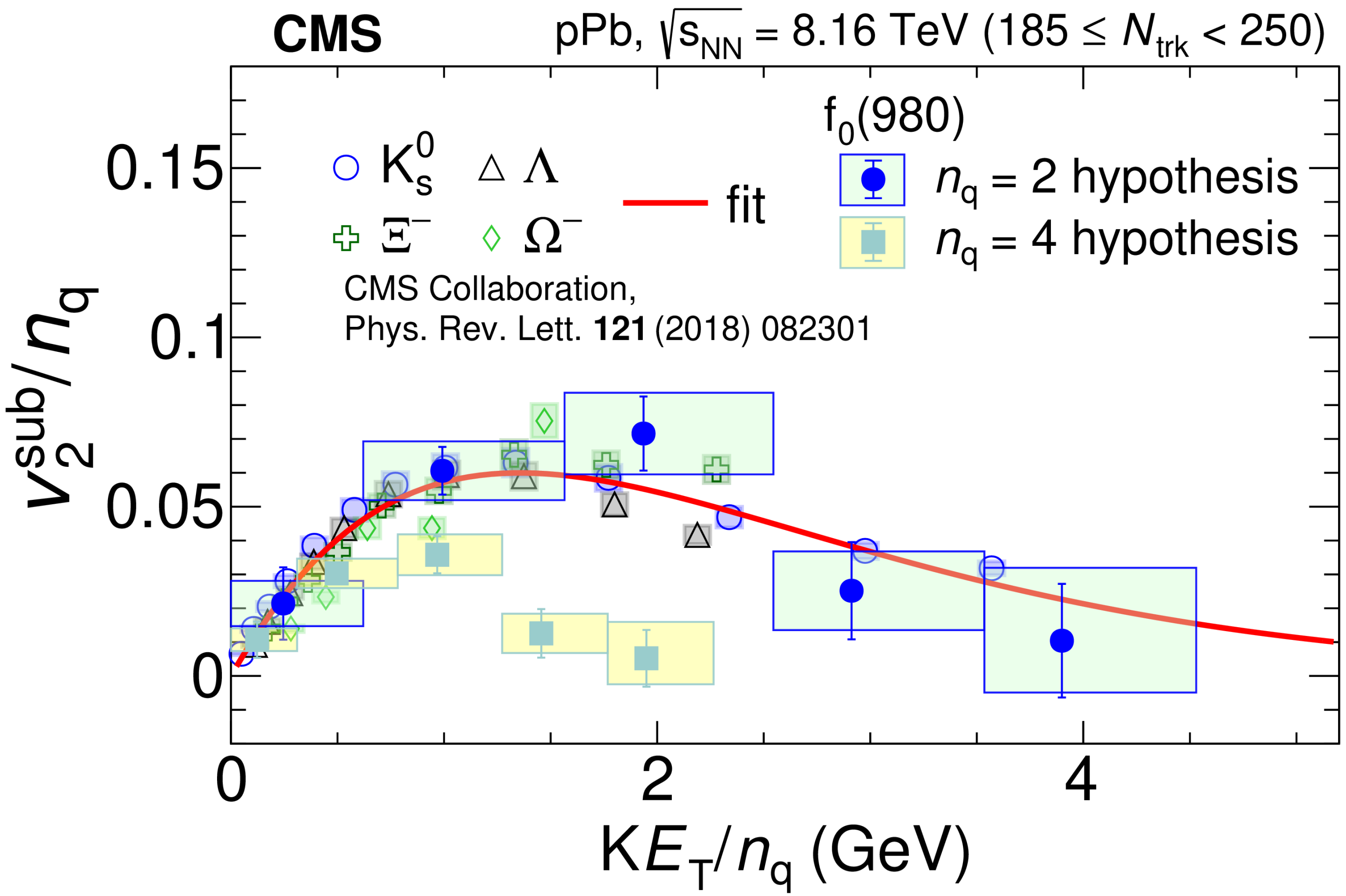
Higher n_q higher v_2 → quark coalescence as dominant particle production mechanism

Probing the structure of exotic particle with v_2

Nature of the $f_0(980)$ state has not yet been established

(ordinary qqbar meson, a tetraquark state, a KKbar molecule, or a qqbar-gluon hybrid state?)

CMS, arXiv:2312.17092



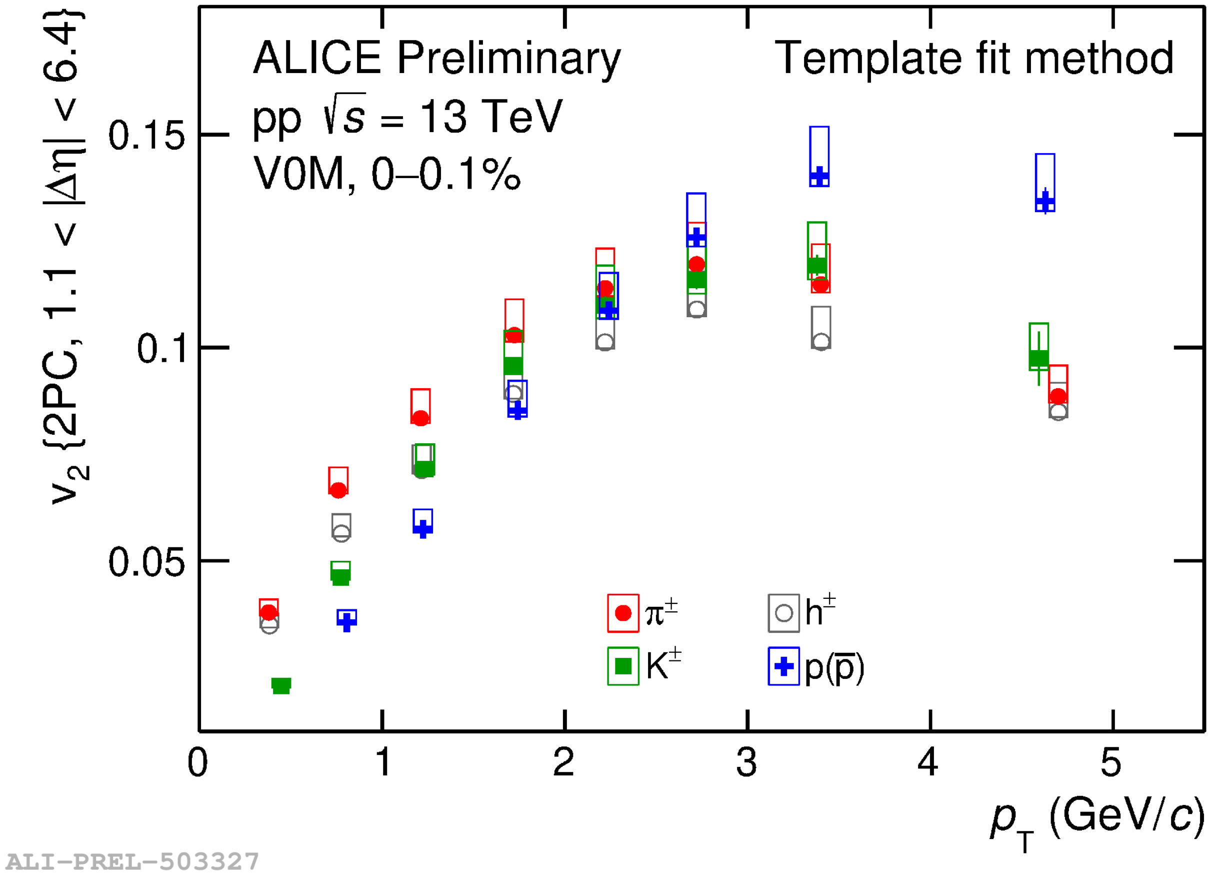
Number of constituent quarks (NCQ) scaling of the anisotropic flow

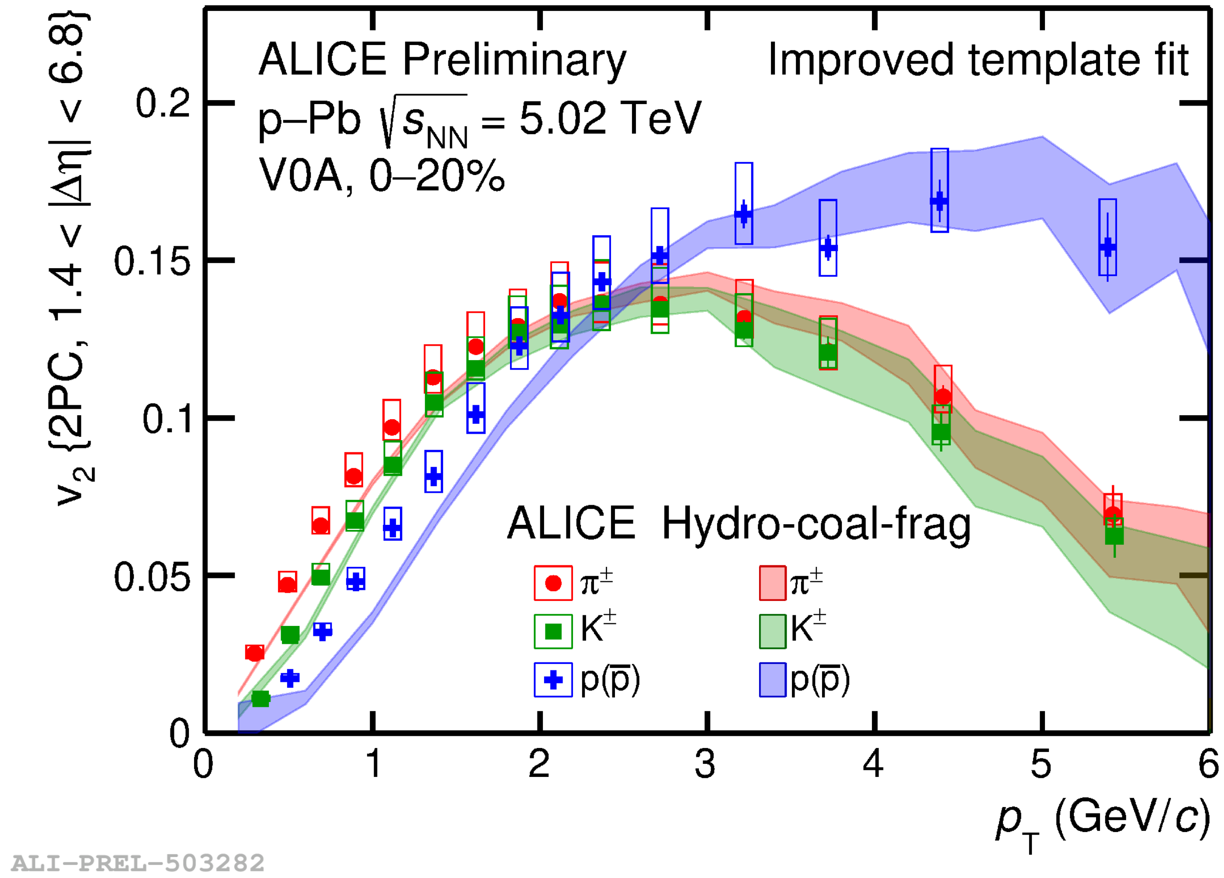
$$v_n(p_T) \approx n_q v_{n,q}(p_T/n_q)$$

Probe structure of exotic bound states in heavy-ion collisions

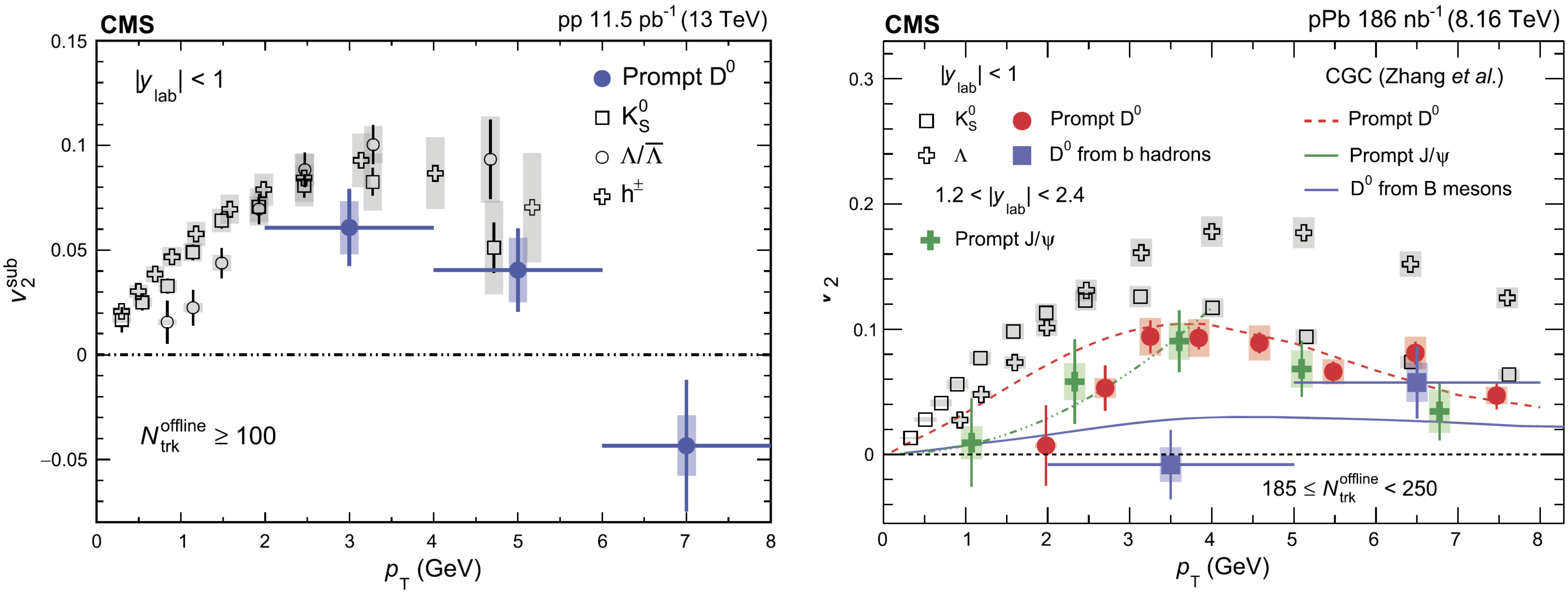
- Tetraquark and KKbar molecule hypotheses ruled out
- Not clear what v_2 a hybrid qqbar-gluon state would attain (if as n_q=3, ruled out with 3.5σ significance)

Observation of partonic flow in small systems





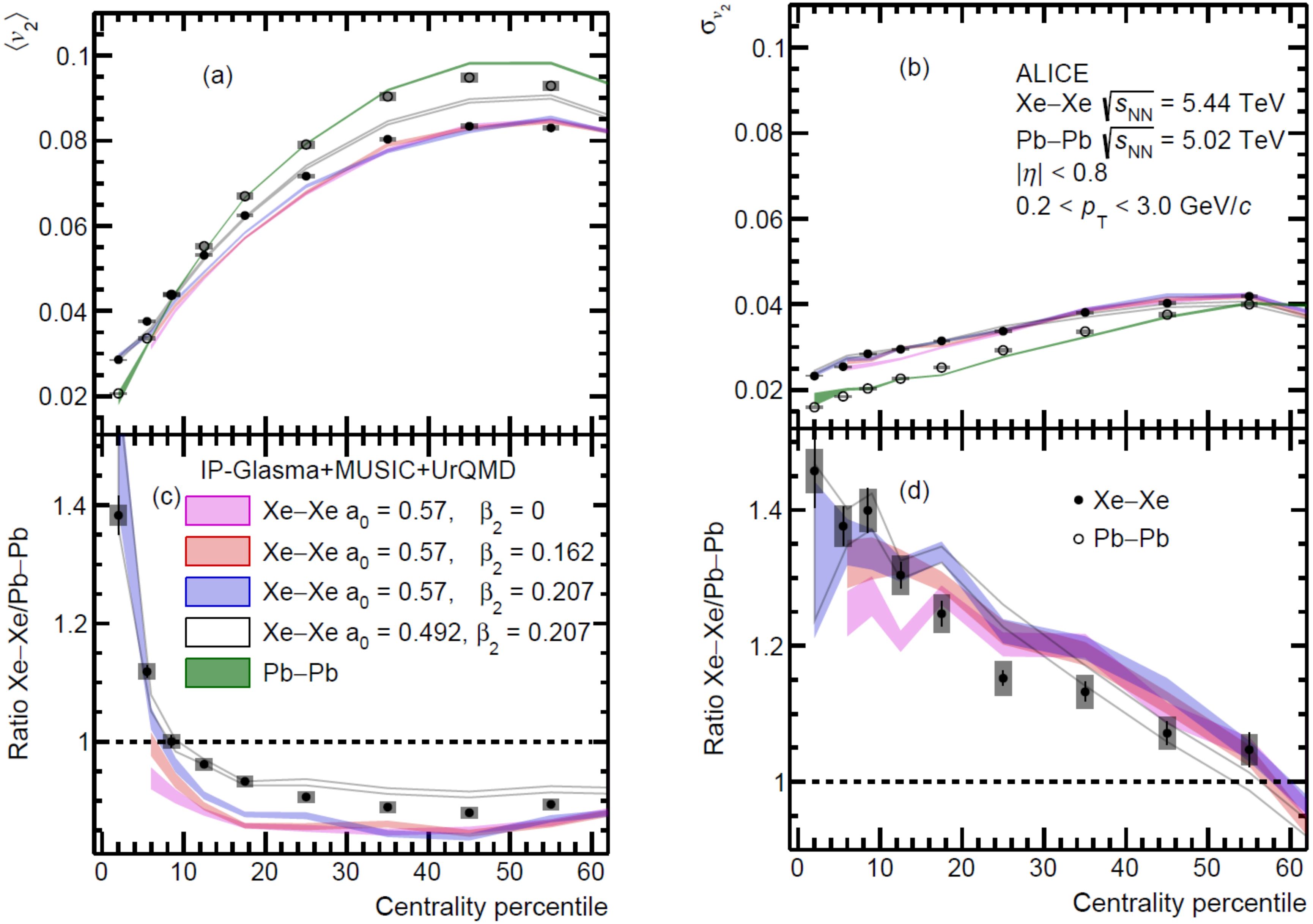
- Mass ordering at low transverse momentum
- Baryon-meson splitting at intermediate p_T
- Model indicates partonic flow + coalescence



- v_2 of prompt D^0 compatible light-flavor hadrons
- Beauty v_2 compatible with 0

Nuclear structure from fluctuations of v_2

- Colliding randomly oriented deformed nuclei impacts the initial geometry, enhancing the fluctuations of the eccentricity and v_n
- Structure of nuclear ground states is well constrained by nuclear experiments at low energy
- Studies using multiparticle azimuthal correlation at the LHC are opening new avenues for the investigation of nuclear structure at the energy frontier



Parton energy loss in the QGP

Nuclear modification factor from light to beauty flavour

CMS, arXiv:2409.07258

$$R_{AA}(p_T) = \frac{1}{< N_{coll} >} \times \frac{d^2N_{AA}/dp_T d\eta}{d^2N_{pp}/dp_T d\eta}$$

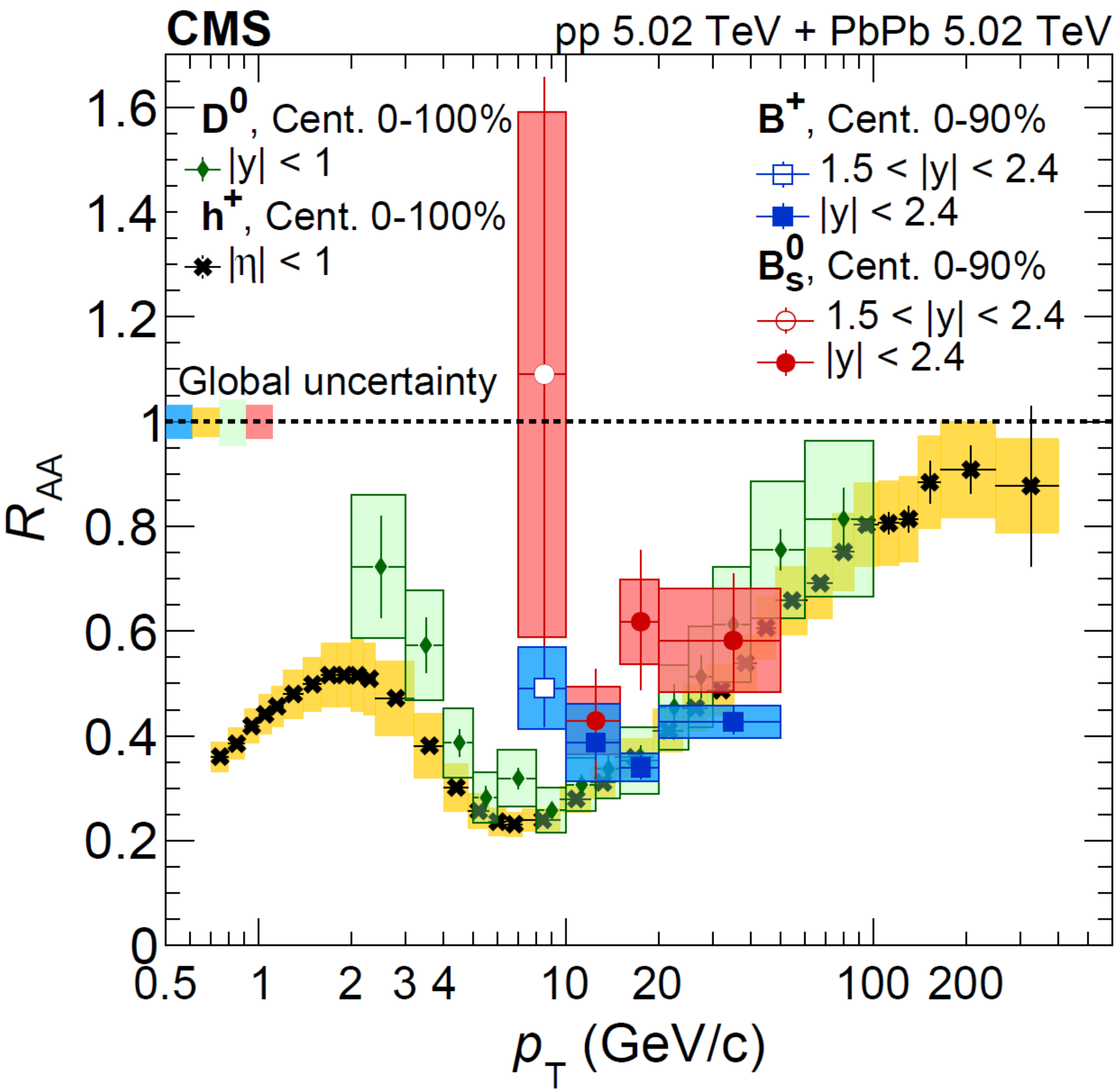
N_{coll}: Total number of nucleon pairs that collide, assuming transparency of the collision

In absence of nuclear effects:

→ collision is superposition of N_{coll} independent nucleon-nucleon collisions

→ R_{AA}=1 (N_{coll} scaling)

- R_{AA} of B^+ meson compatible with R_{AA} of charged hadrons and D^0 mesons for $10 < p_T < 30$ GeV/c
- R_{AA} for $7 < p_T < 10$ GeV/c consistent with expectations based on the quark mass dependence of parton energy loss



Nuclear modification factor of isolated photons

arXiv:2409.12641

$$R_{AA}(p_T) = \frac{1}{< N_{coll} >} \times \frac{d^2N_{AA}/dp_T d\eta}{d^2N_{pp}/dp_T d\eta}$$

N_{coll}: Total number of nucleon pairs that collide, assuming transparency of the collision

In absence of nuclear effects:

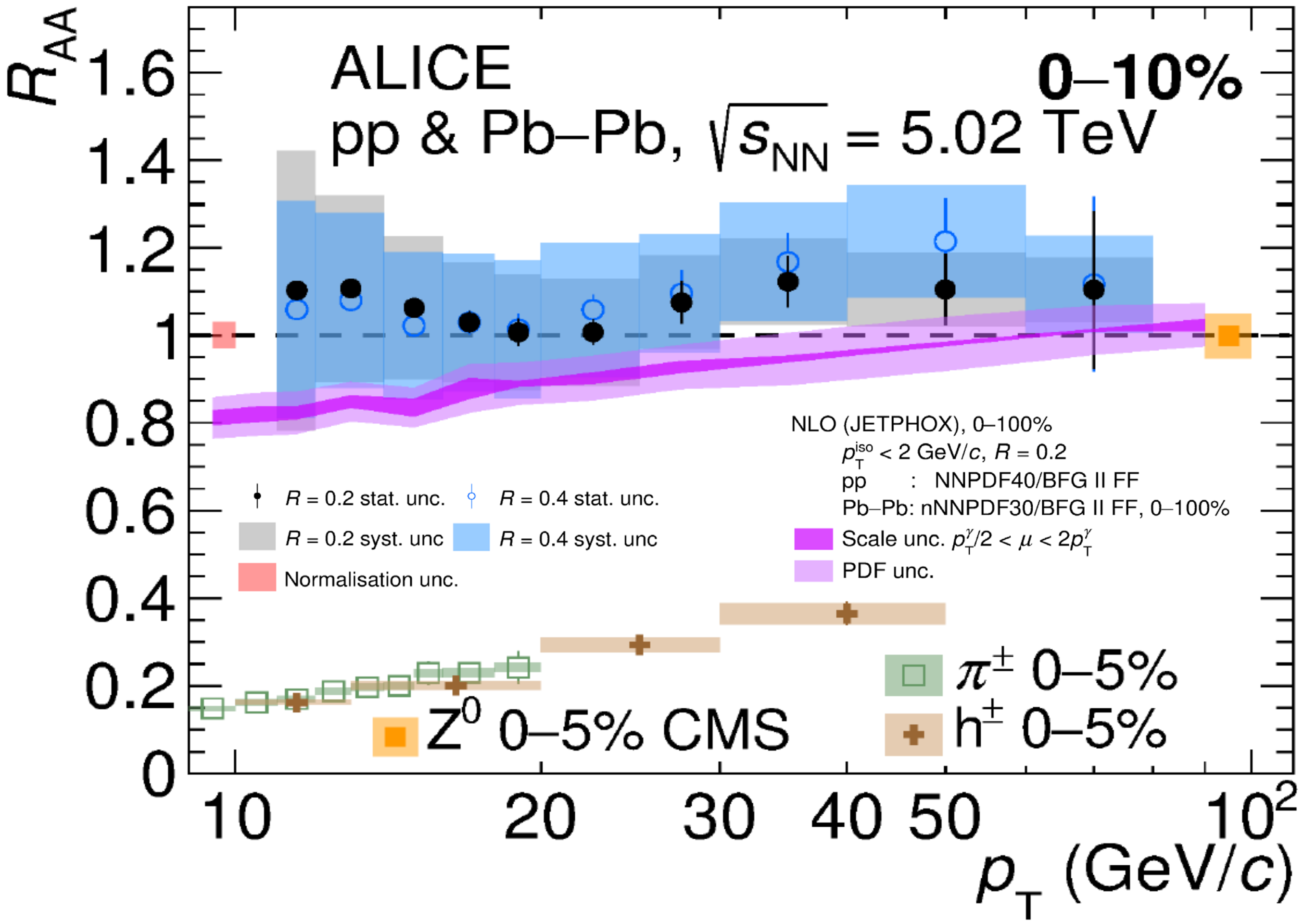
→ collision is superposition of N_{coll} independent nucleon-nucleon collisions

→ R_{AA}=1 (N_{coll} scaling)

Verified with EW probes

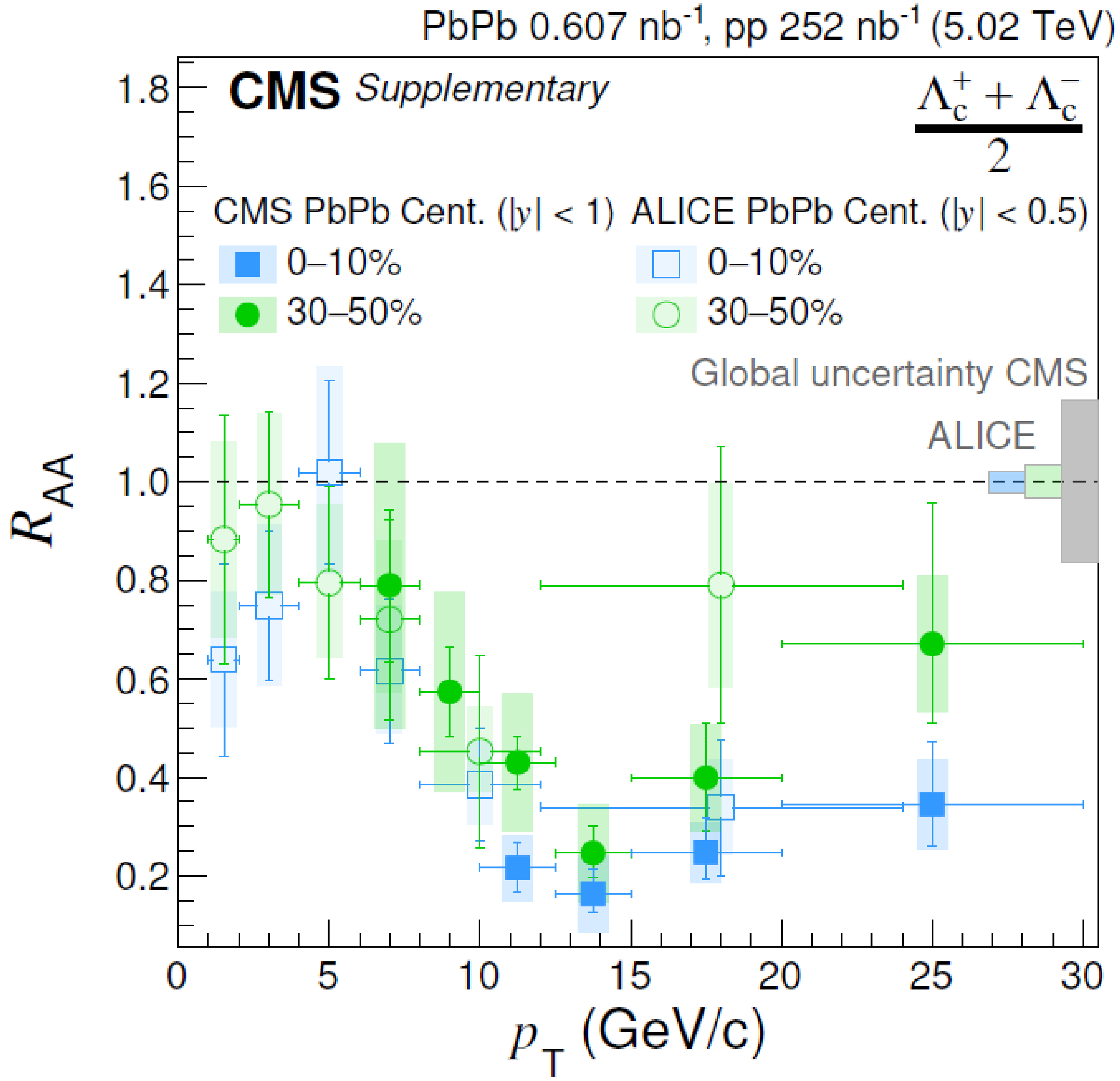
Isolated photons:

- Prompt photons from hard scatterings
- No contributions from fragmentation and bremsstrahlung
- Do not interact strongly and are produced before the QGP formation



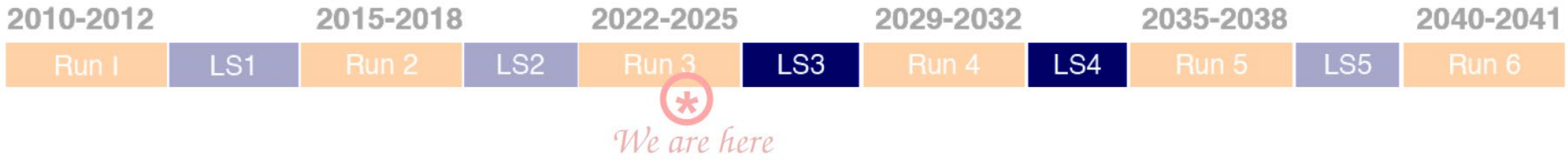
Nuclear modification factor of Λ_c

- R_{AA} of Λ_c smallest near $p_T \approx 14$ GeV/c,
- Trend is in general consistent with other heavy flavor hadron measurements, but p_T of the minimum R_{AA} is different (e.g. R_{AA} reaches a minimum at $p_T \approx 8$ GeV/c for nonprompt D^0 from b hadron decay and at $p_T \approx 9$ GeV/c for prompt D^0)



Conclusions

- ✓ Complementary approaches to relativistic heavy-ion collisions
- ✓ Observation in pp and pPb collisions of AA-typical phenomena are challenging our knowledge on particle production
- ✓ Require both a refinement of models and both new observables and new regime of investigation (e.g. ultra-central)



- ✓ Several ongoing heavy-flavour analyses on fresh collected Pb–Pb and pp Run 3 data…
- ✓ …and exciting upgrade programs ahead

THANK YOU FOR YOUR ATTENTION!