LHCPhysics
Belgrade, 22 - 26 May 2023

UNIVERSITY OF HOUSTON

Quark-gluon plasma properties from LHC data

Anthony Timmins

On behalf of

Quantum chromodynamics at high temperatures

Lattice QCD predicts **rapid change in hadronic thermodynamic properties** at critical temperature $T_c \approx 155$ MeV

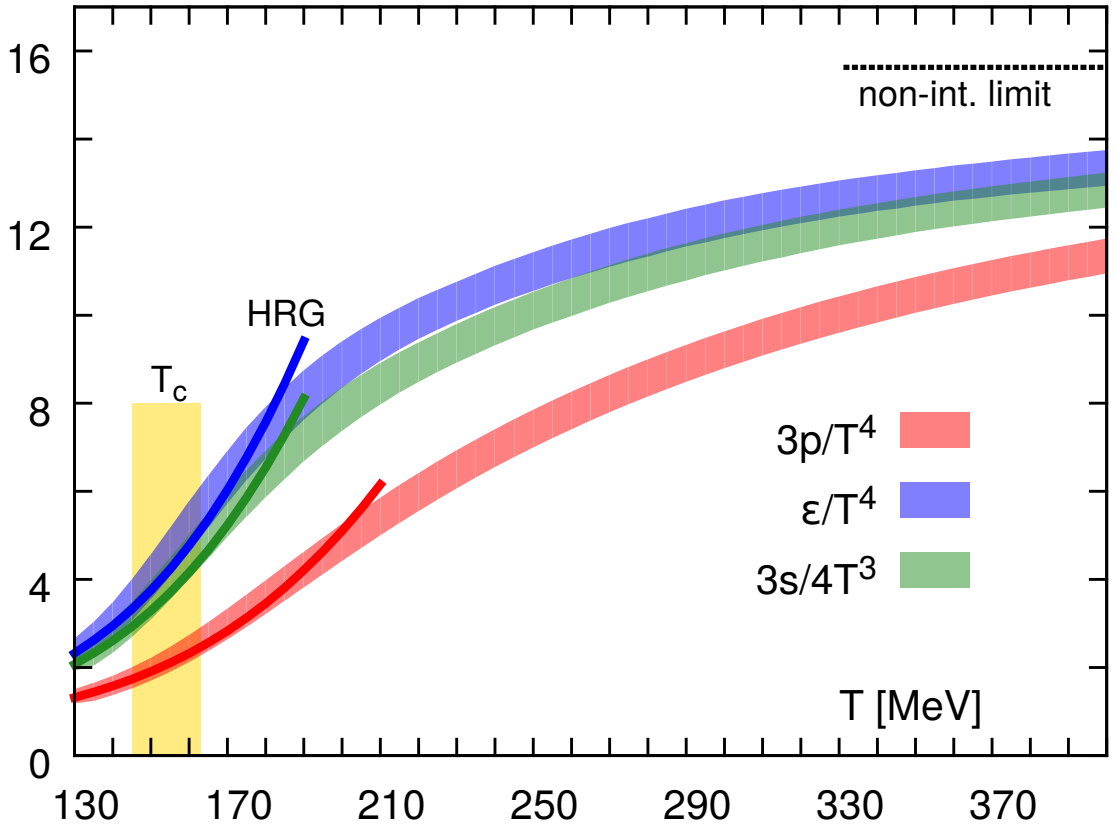
Formation of **quark-gluon plasma (QGP)**

✓ Quarks & gluons no longer confined

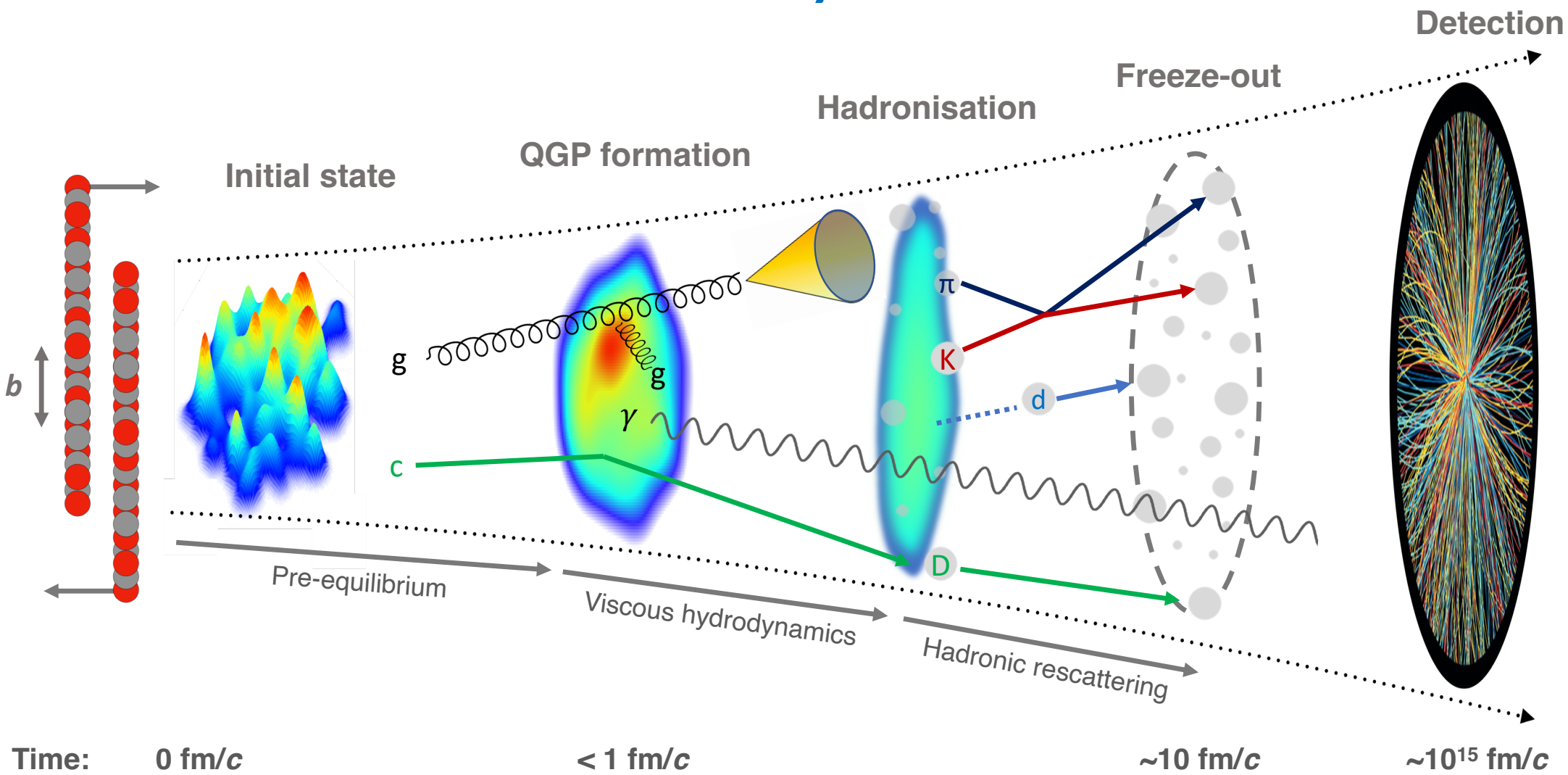
Crossover phase transition for matter-antimatter symmetric system

✓ Accompanied by **chiral symmetry restoration**

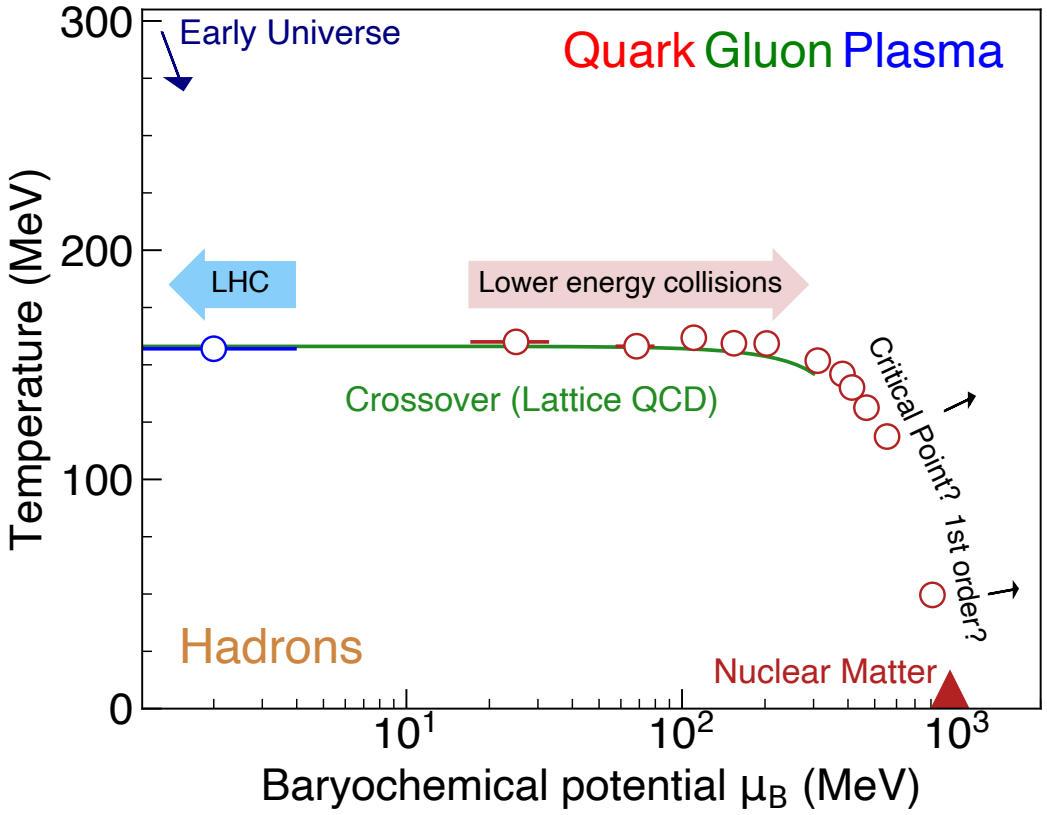
Hot QCD, PRD 90 (2014) 094503



“Standard model” of heavy-ion collisions



Worldwide QGP studies



Adapted from D. Perepelitsa

QGP at LHC has **highest temperatures** at $\mu_b \approx 0$ MeV

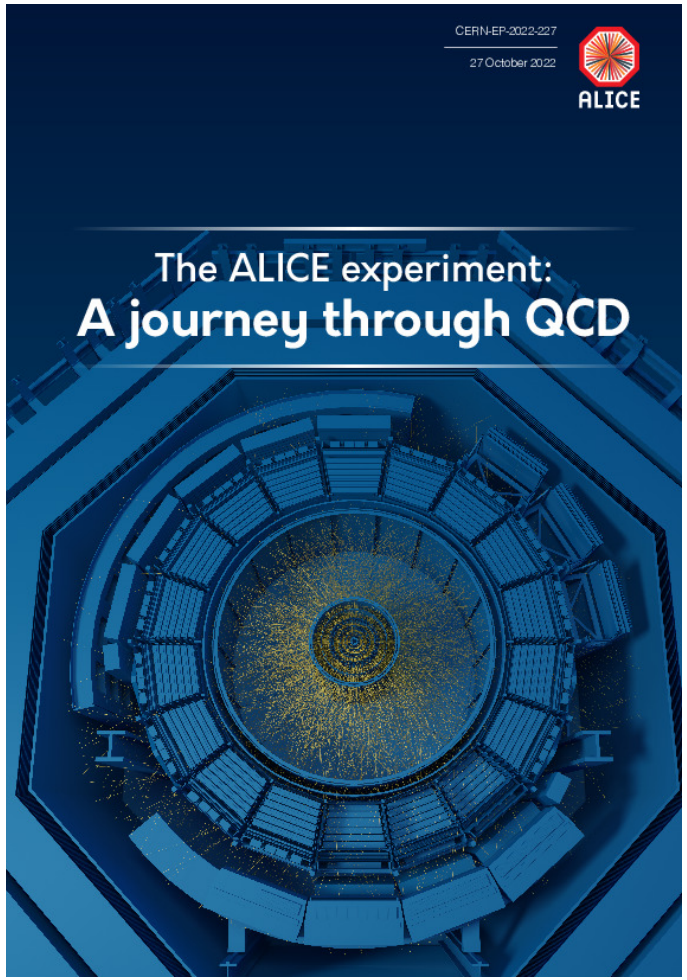
✓ Similar to early universe ~10^{-6} seconds after big bang

Ongoing high energy nuclear collisions at RHIC → **new sPHENIX detector** and STAR

✓ Other programs at lower energies (e.g. SPS, FAIR)

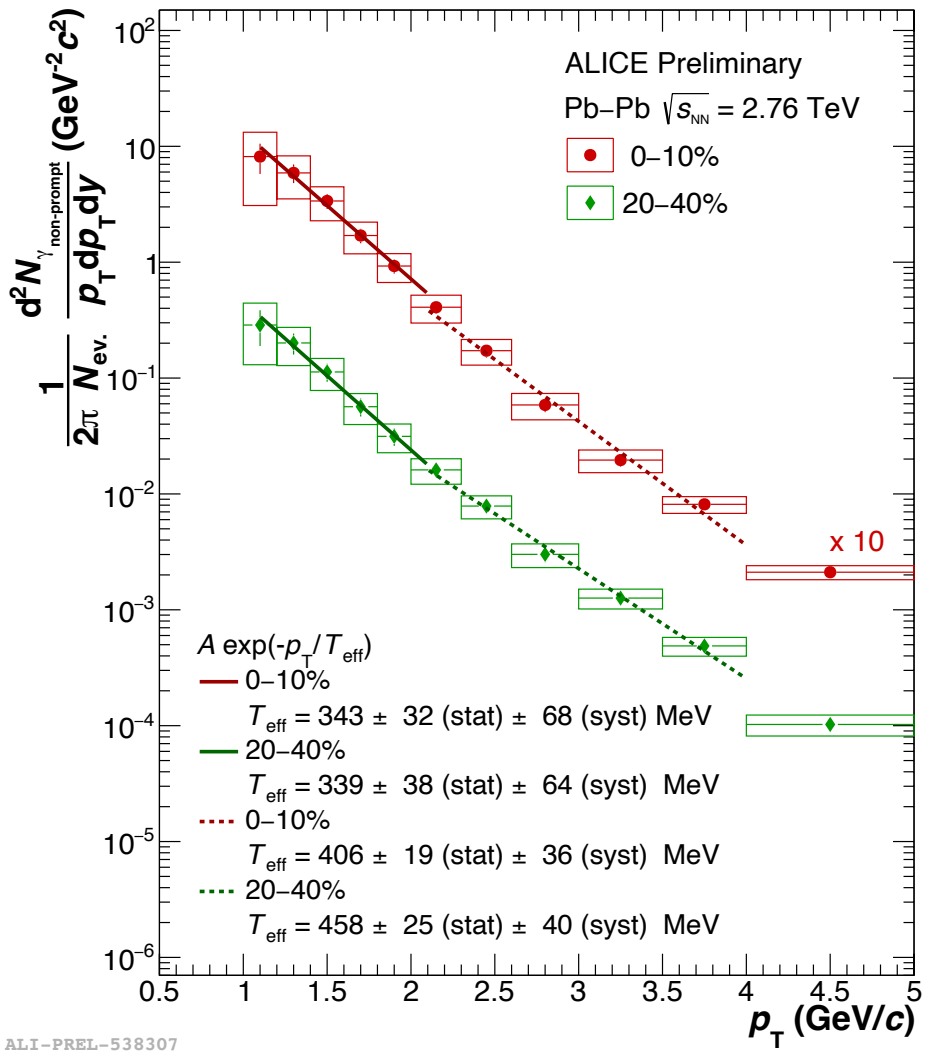
Emergent phenomena in deconfined systems

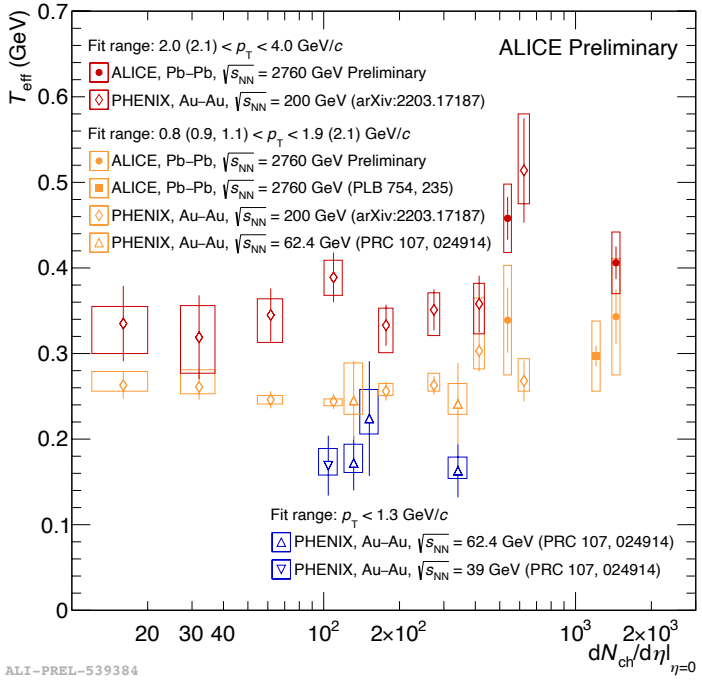
1. What are the **thermodynamic** and **global properties** of hot QCD matter?
2. How does the **QGP evolve dynamically**?
3. What is the nature of **microscopic interactions in the QGP**?
4. What are the **broader impacts** of QGP physics?



ALICE Review Paper, arXiv:2211.04384

QGP temperature from direct photons





LHC

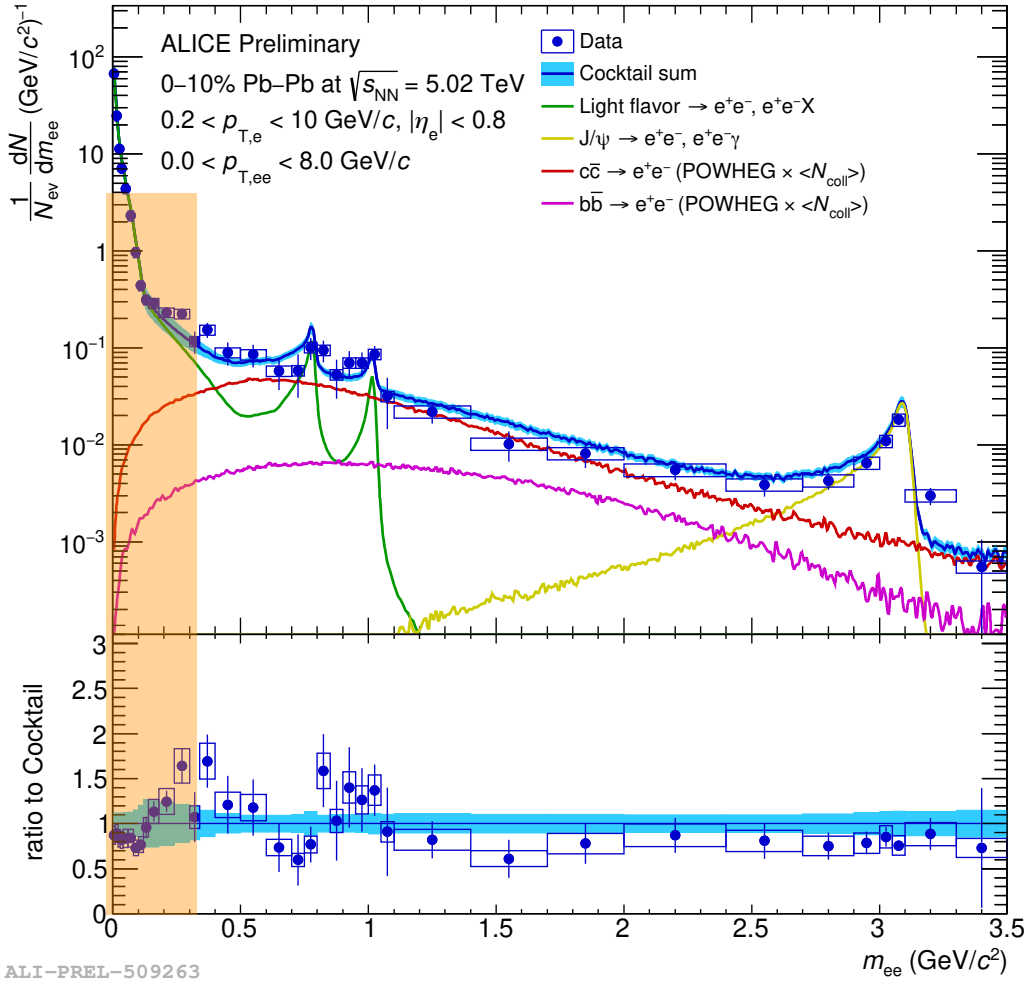
↓

RHIC

Photons produced in heavy-ion collisions at all stages

- ✓ Offer direct handle on **average temperature**
- ✓ Blue shifted temperatures 300 → 480 MeV
- ✓ **Higher than required QGP** temperature ≈ 155 MeV

Di-electron production in Pb-Pb collisions



Virtual photons in QGP produce finite mass electron-positron pairs

Ideal probe as invariant mass spectrum can determine **QGP temperature without blue-shift**

Current results dominated by background from hadronic decays

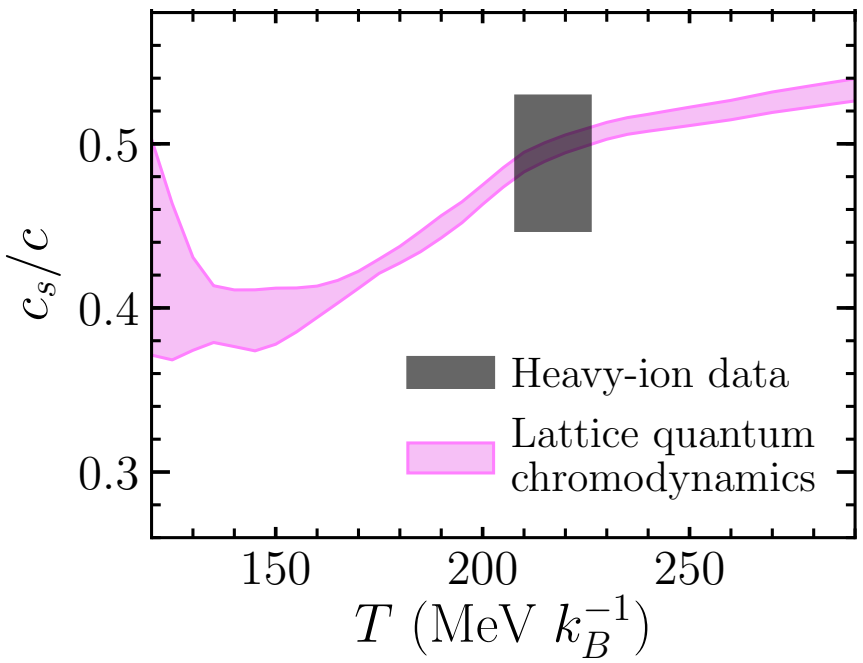
✓ Recent/future ALICE upgrades enhance signal and reduce relative contribution from backgrounds

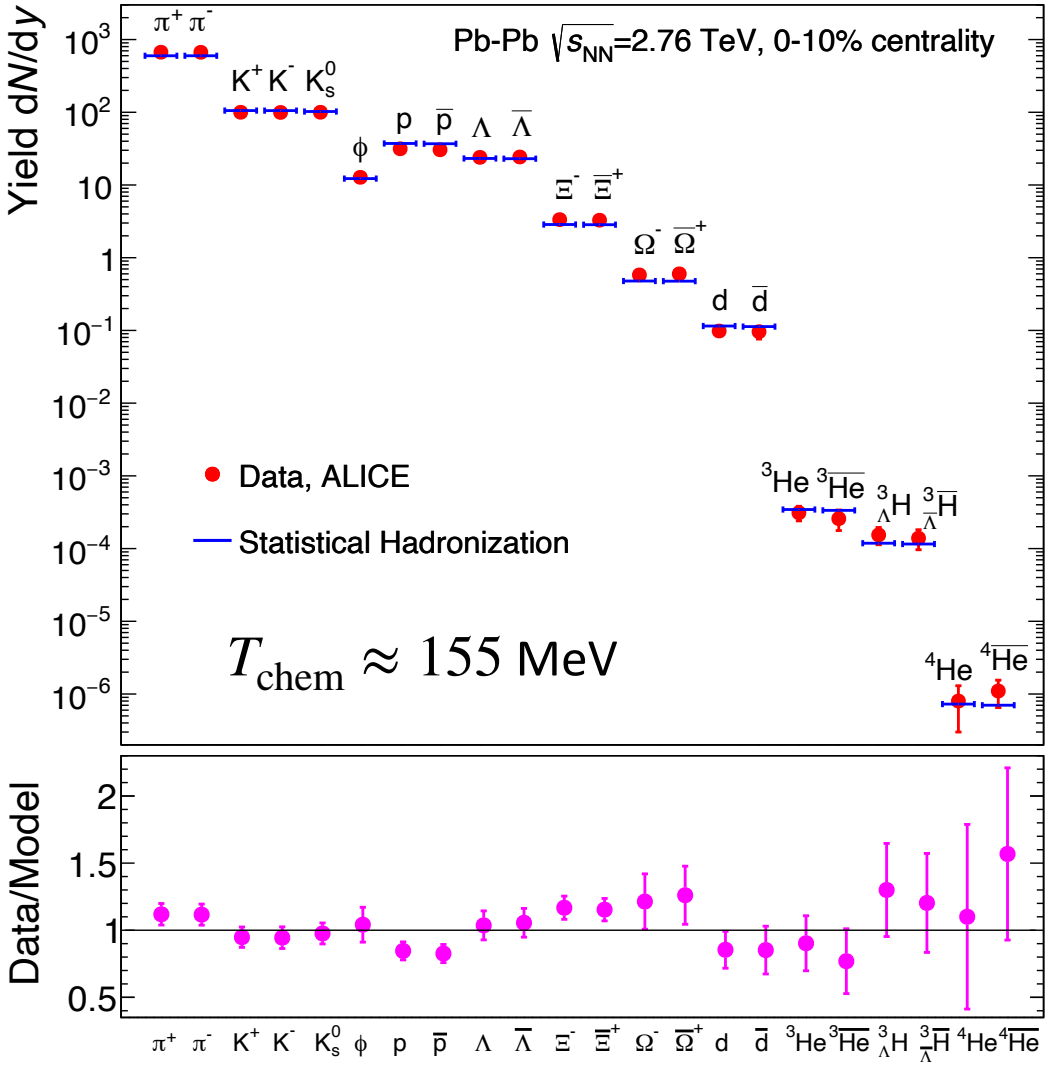
R. Munzer, Thursday at 17.25

Speed of sound and transition temperature

1

Gardim et al, Nature Physics 16 (2020) 615



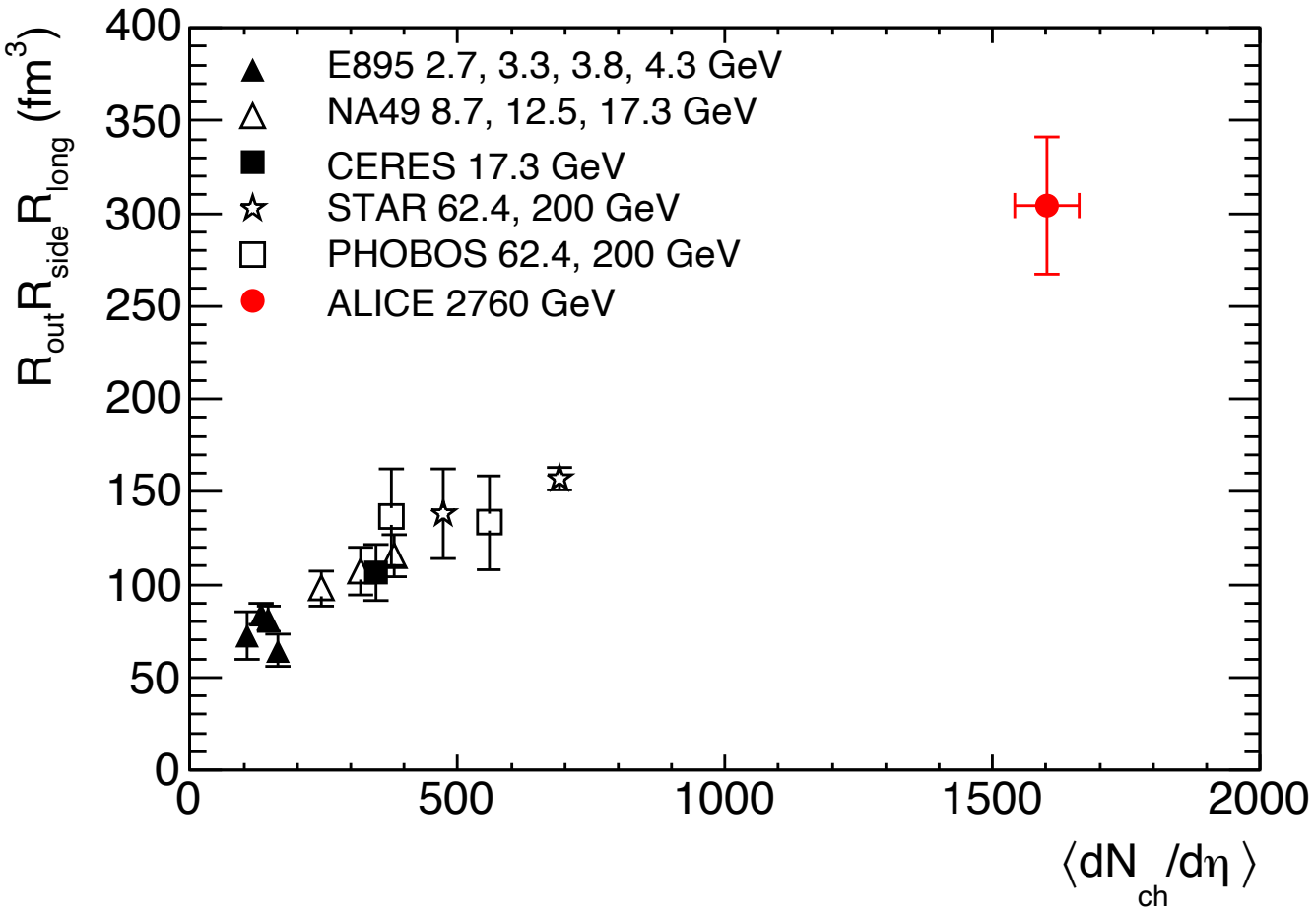


Hydrodynamic model + LHC data → **QGP speed of sound**

- ✓ **Chemistry** of produced **hadrons** described by **thermal model** over many orders of magnitude
- ✓ Chemical freeze-out temperature $T_{chem} \approx T_c$

Andronic et al, Nature 561 (2018) 7723

QGP size and lifetime



ALICE, PLB 696 (2011) 328-337

Quantum correlations of low momentum hadrons emitted from QGP **can measure source size and lifetime**

✓ Femtoscopic technique

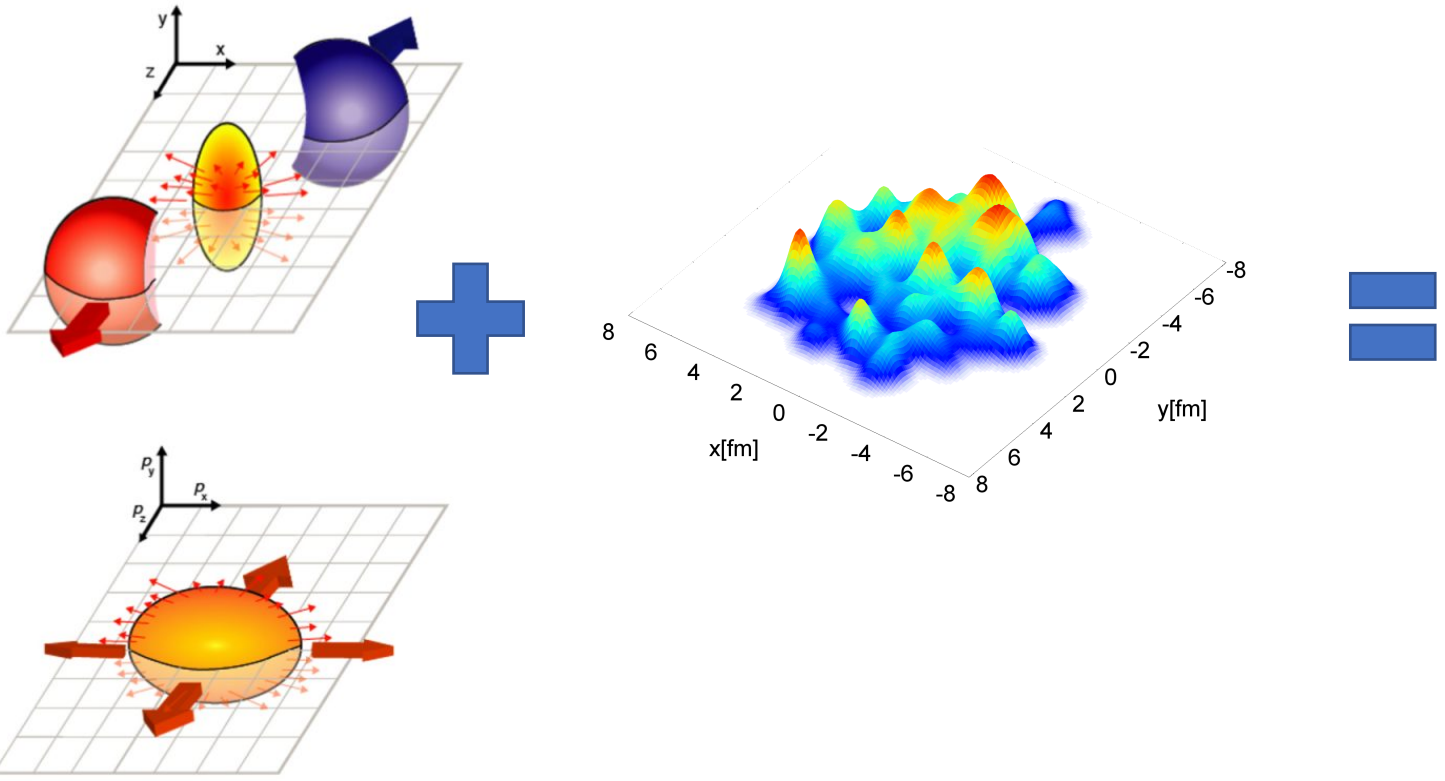
Volume twice as large as **top RHIC energy**

✓ LHC QGP timeline ≈ 10 fm/*c*

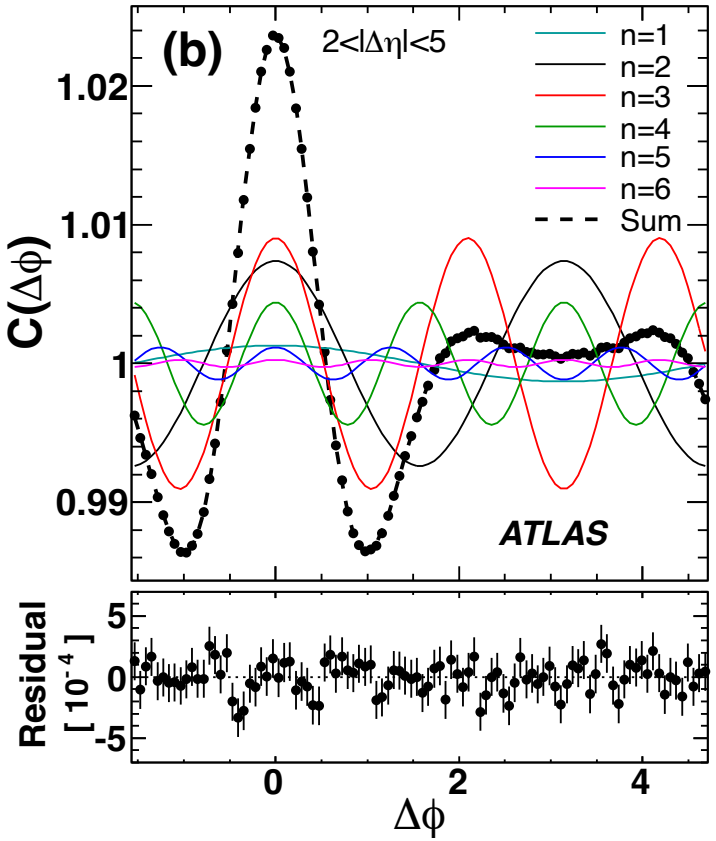
Femtoscopy also used to explore **hadron-hadron strong interaction potentials**

V. Mantovani Sarti, Tuesday at 9.25

Development of flow in a QGP



ATLAS, PRC 86 (2012) 014907

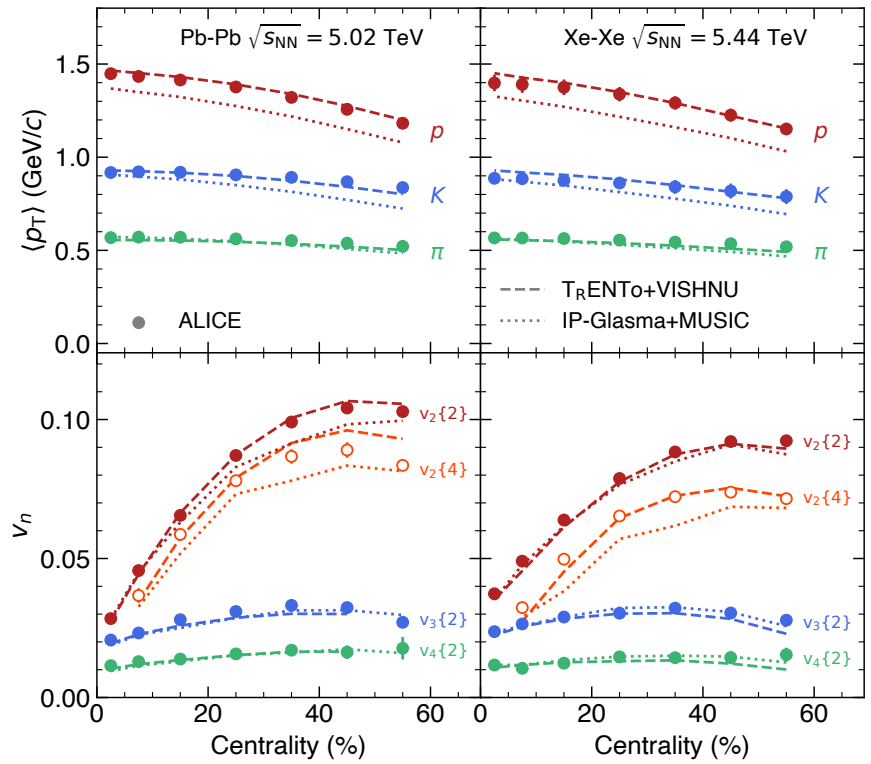


Spatially anisotropic initial state induces momentum anisotropy via QGP response

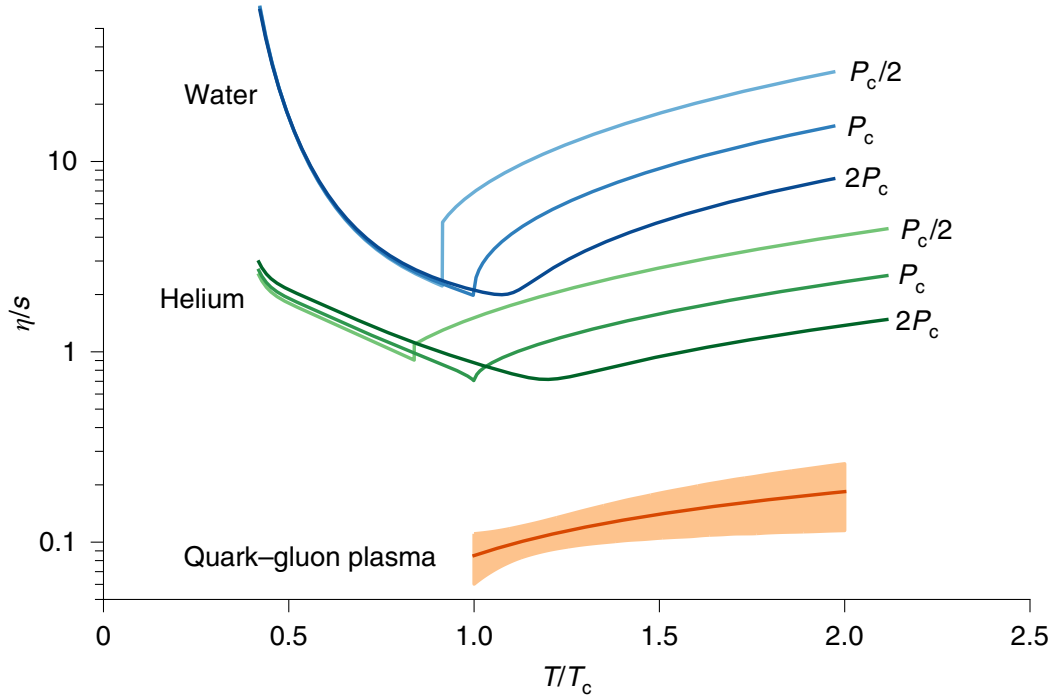
✓ Characterised by **anisotropic flow coefficients v_n** → Amplitudes of cosine contributions

The almost perfect liquid

ALICE, arXiv:2211.04384



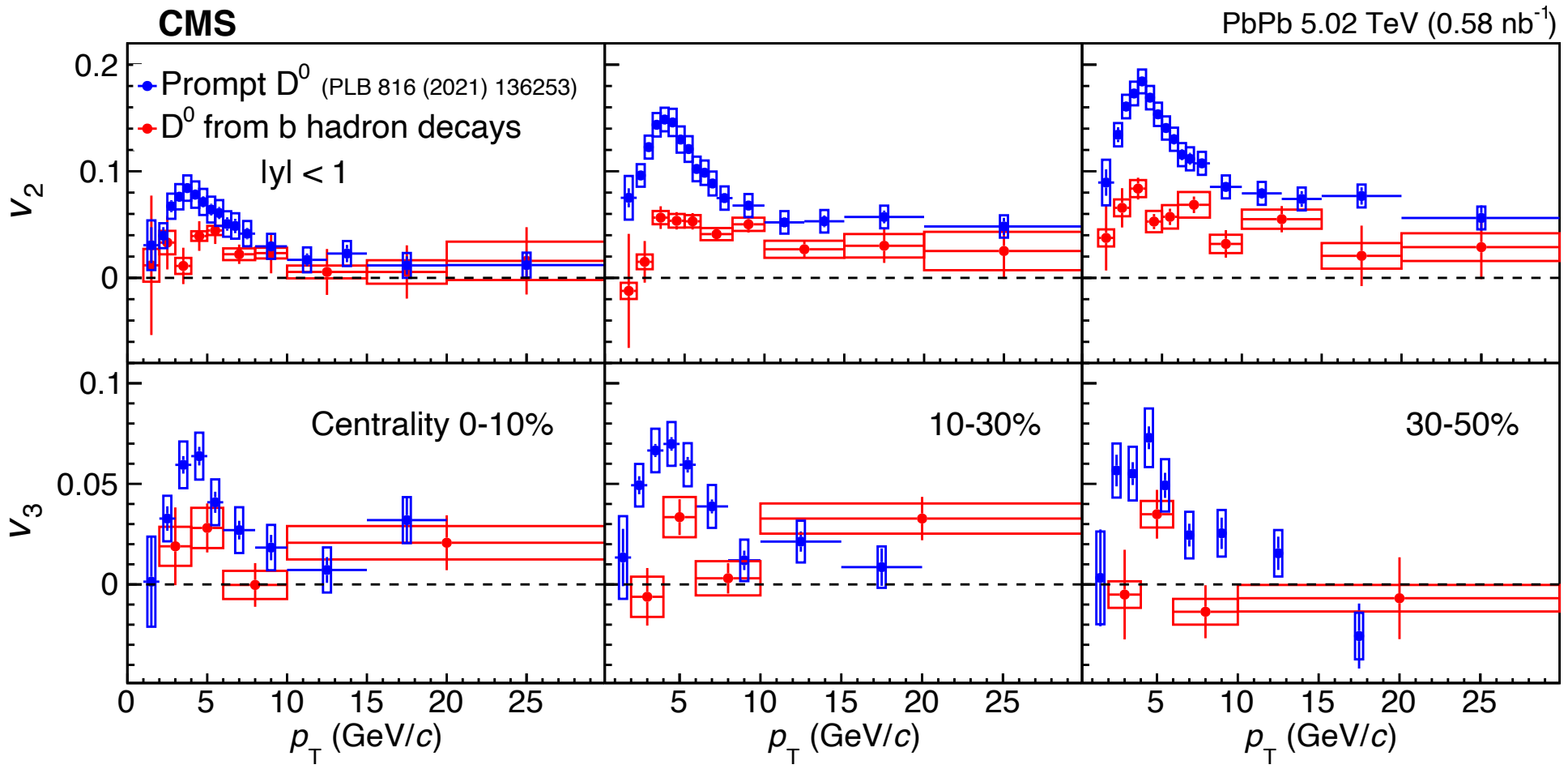
Bernhard et al, Nature Physics 15 (2019) 1113



Global **QGP radial and anisotropic expansion** described by **hydrodynamics** for light hadrons

✓ Achieved with QGP equation of state and **small but finite QGP viscosities**

Everything flows



D^0

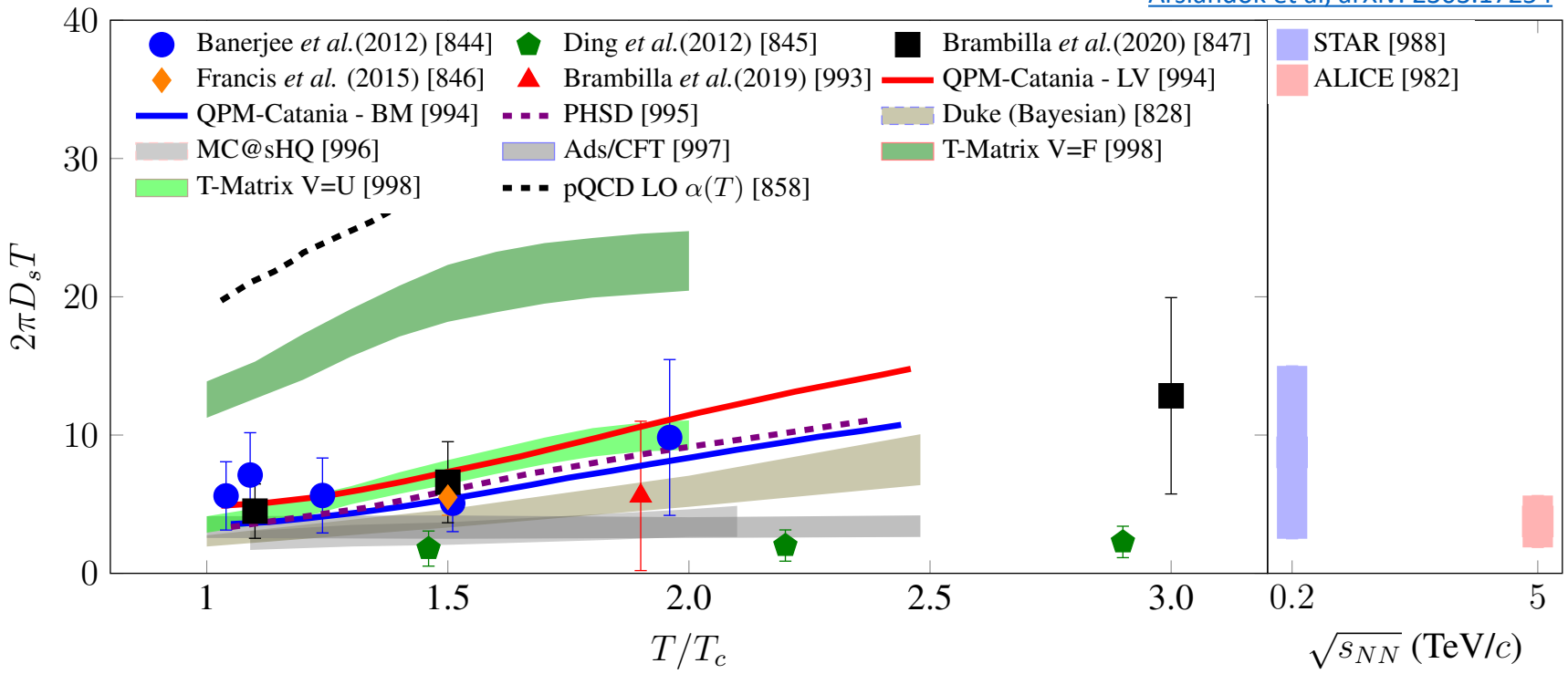
$b \rightarrow D^0$

CMS, arXiv:2212.01636

Charm and bottom quarks also couple with QGP medium and **flow**

Equilibration of heavy-quarks

Arslandok et al, arXiv: 2303.17254



Coupling increases

Diffusion coefficient

$$\tau_Q = \frac{m_Q}{T} D_s$$

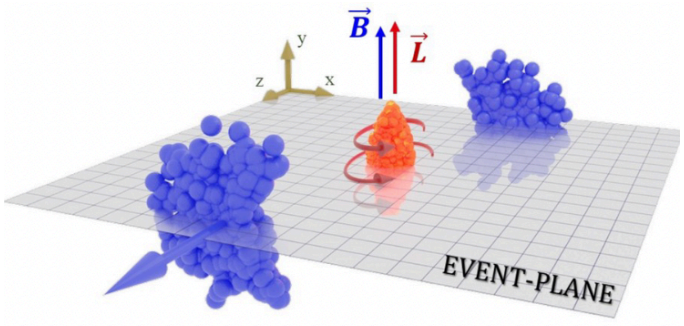
Equilibration time

Transport models require **small charm quark diffusion coefficient (D_s)** to describe heavy-flavor flow

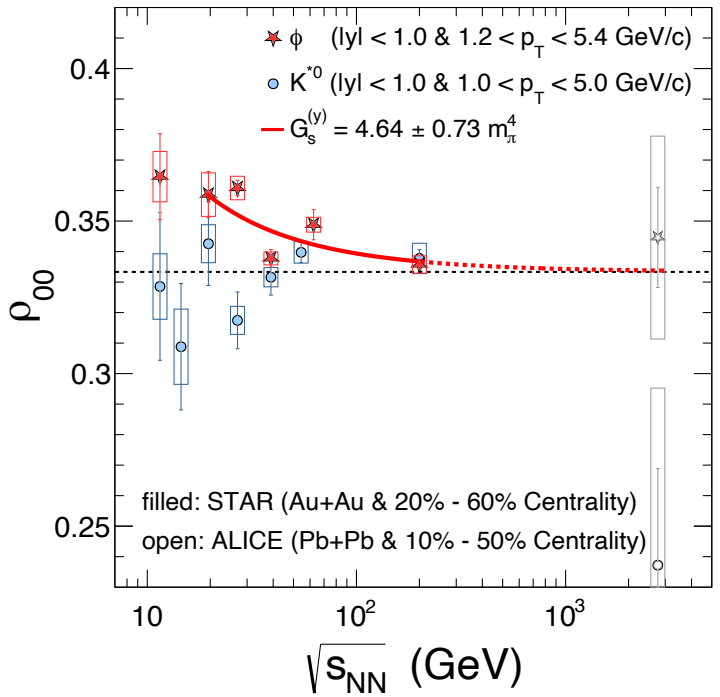
✓ Demonstrates how **heavy quarks equilibrate** on **extremely short timescales**

✓ $\tau_{charm}(T) \approx 1 - 9$ fm/c → **Always smaller** than **QGP lifetime** ≈ 10 fm/c

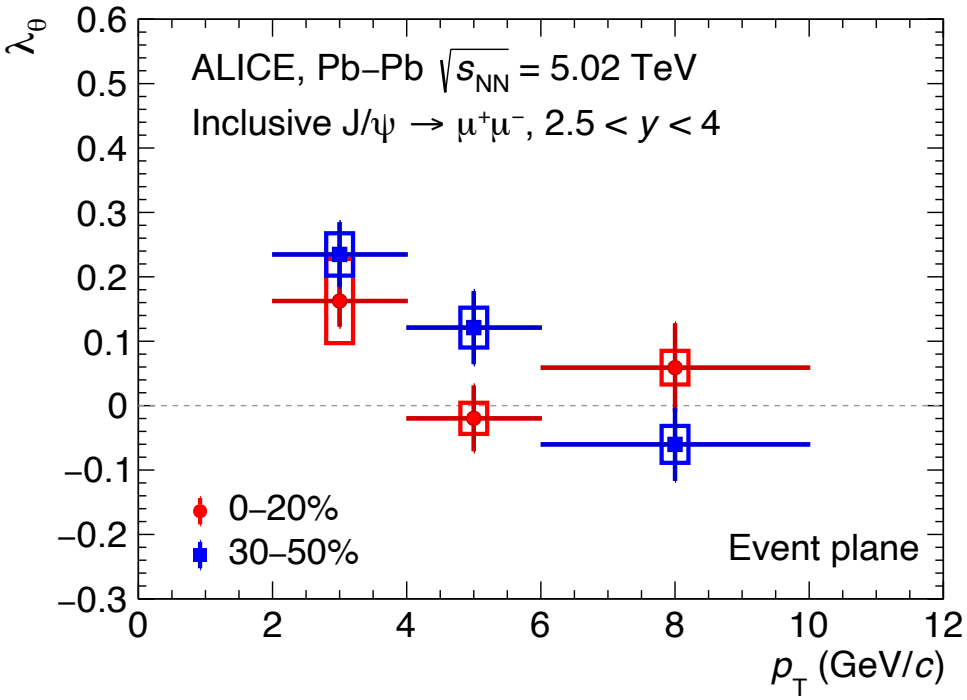
Polarisation of light and heavy hadrons



STAR, Nature 614 (2023) 244



ALICE, arXiv:2204.10171



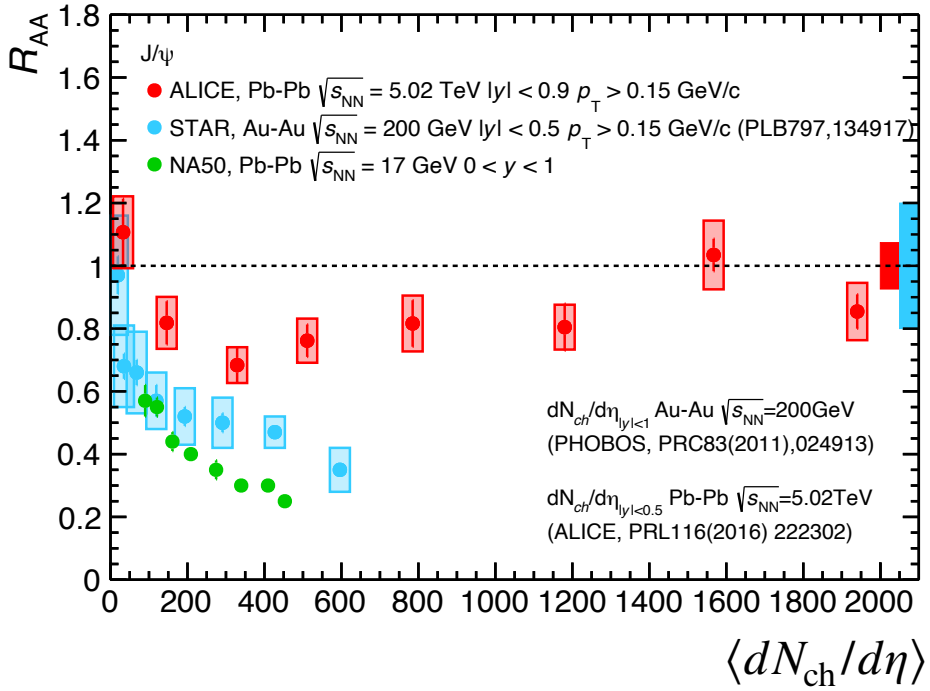
Angular momentum of QGP transferred to **polarisation** of produced decay particles

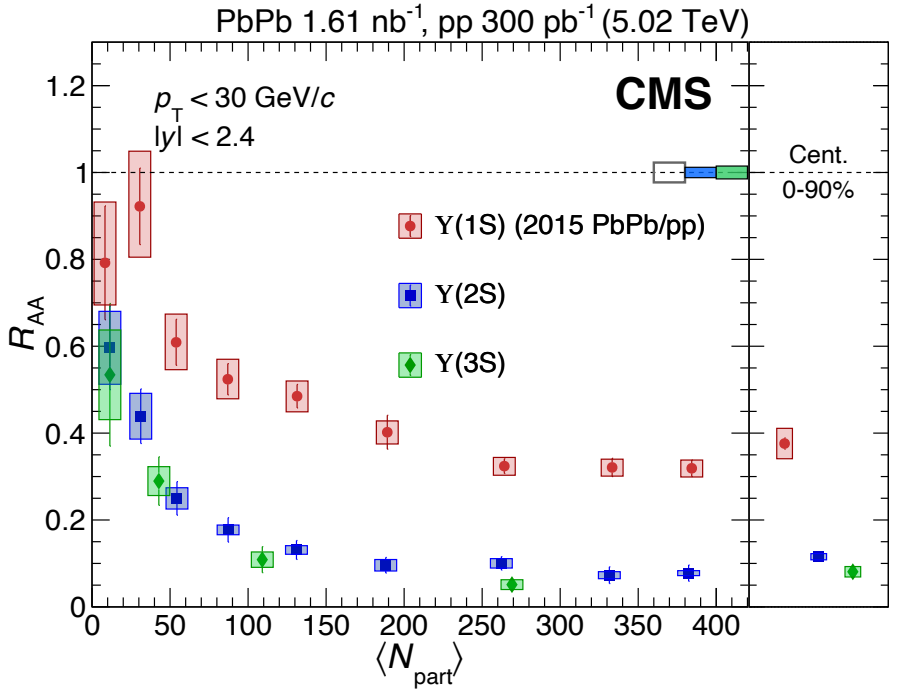
✓ Non-zero polarisation **K*⁰ and J/ψ mesons** observed at the LHC

✓ New avenue to explore meson fields and QGP properties

Quarkonia and QGP melting

ALICE, arXiv:2211.04384





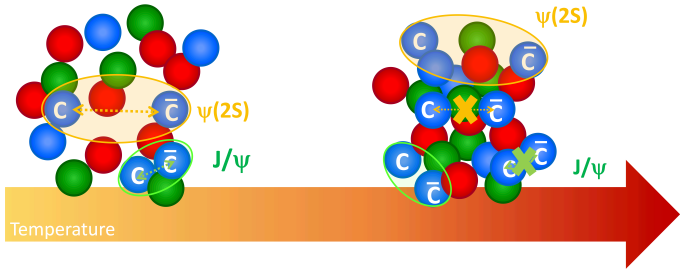
CMS, arXiv:2303.17026

Υ(1S)
Υ(2S)
Υ(3S)

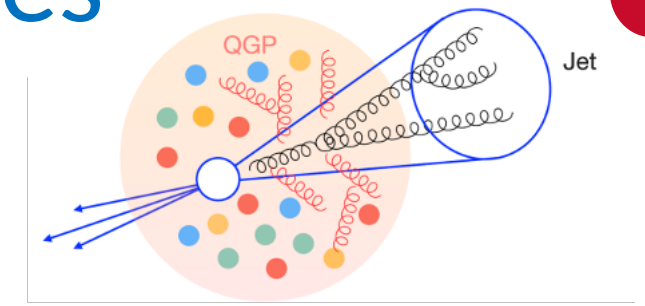
Quarkonia: sub fm bound state **affected by QGP environment**

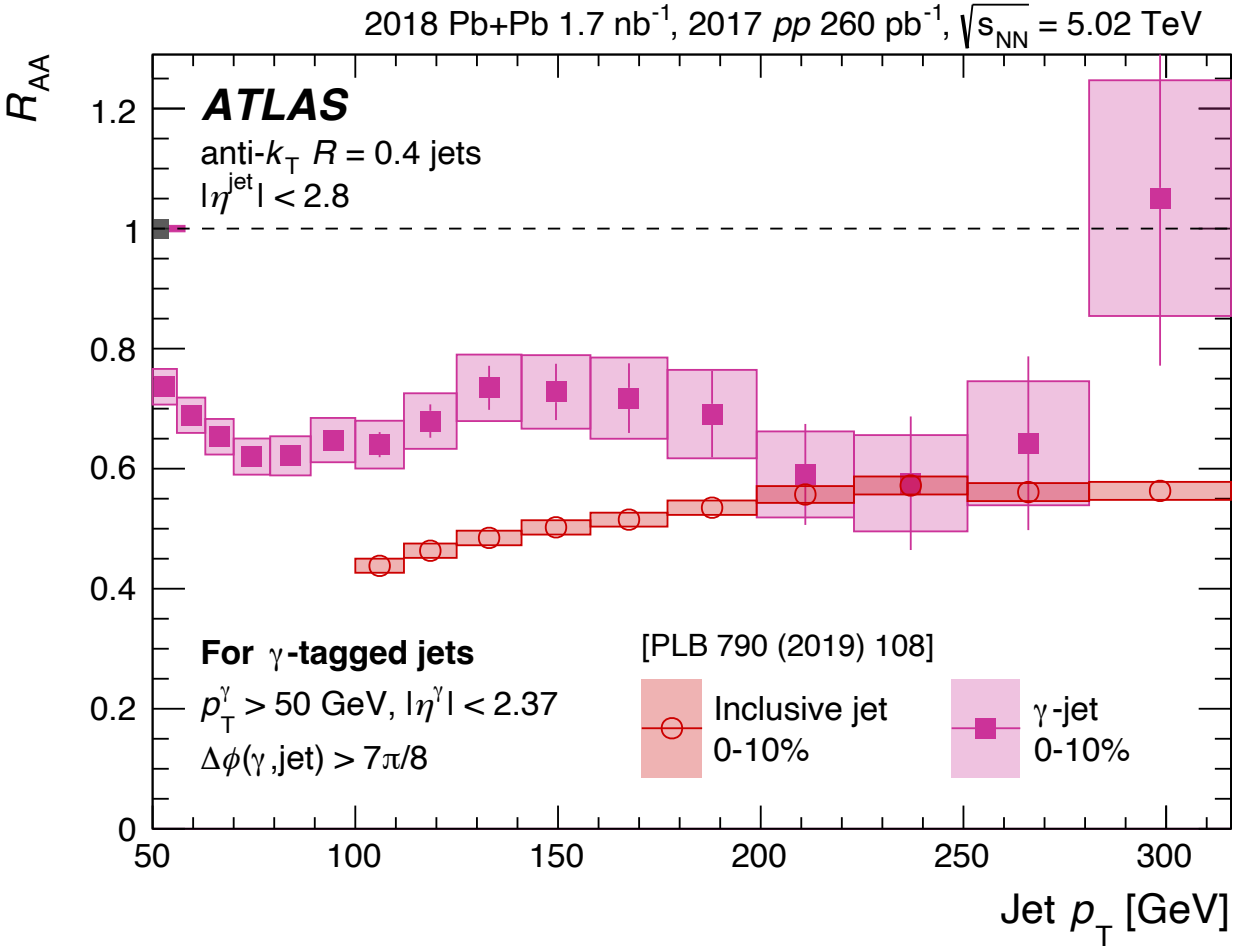
✓Charmonium → sequential melting + regeneration at LHC

✓Bottomonium → sequential melting with **new results for** Υ(3S)



Probing the QGP at the smallest scales





ATLAS, arXiv:2303.10090

Jets are highest momentum probes of a QGP

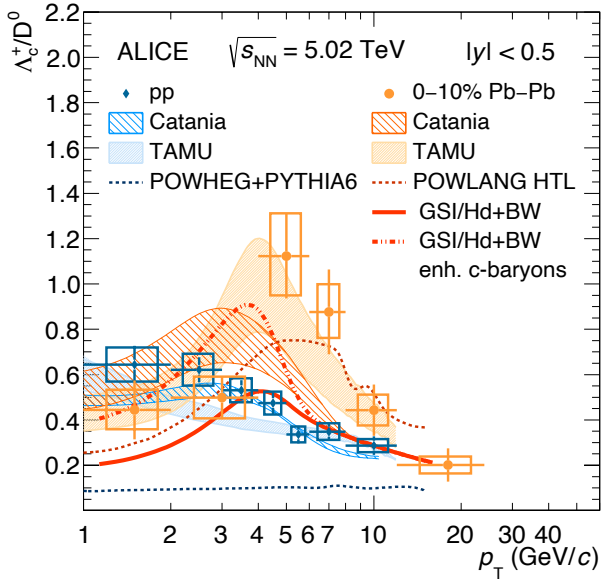
✓Finely resolve **microscopic QGP structure**

Quark jets less suppressed than gluon jets

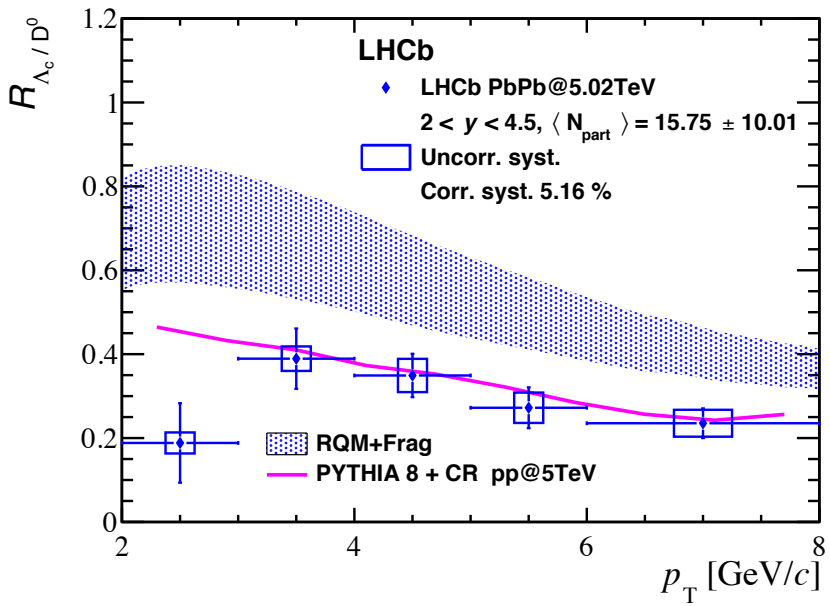
Demonstrate other **QGP modifications**

L. Cunqueiro Mendez, Wednesay at 9:00

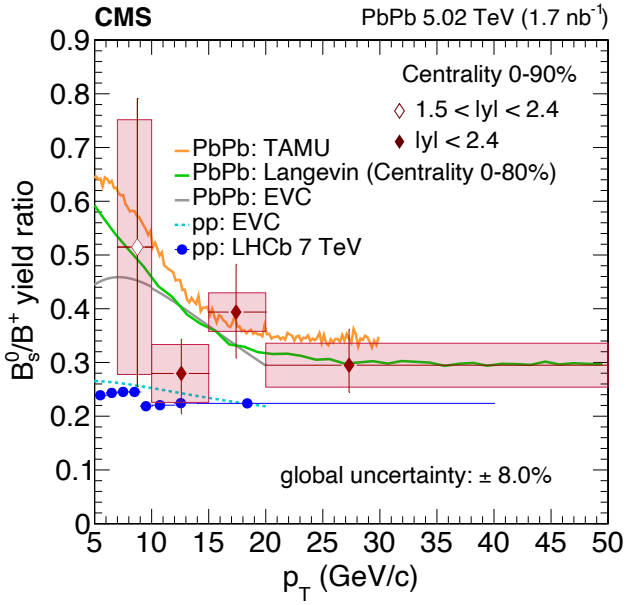
Microscopic hadronization mechanisms



ALICE, arXiv:2211.04384



LHCb, arXiv:2210.06939



CMS, PLB 829 (2022) 137062

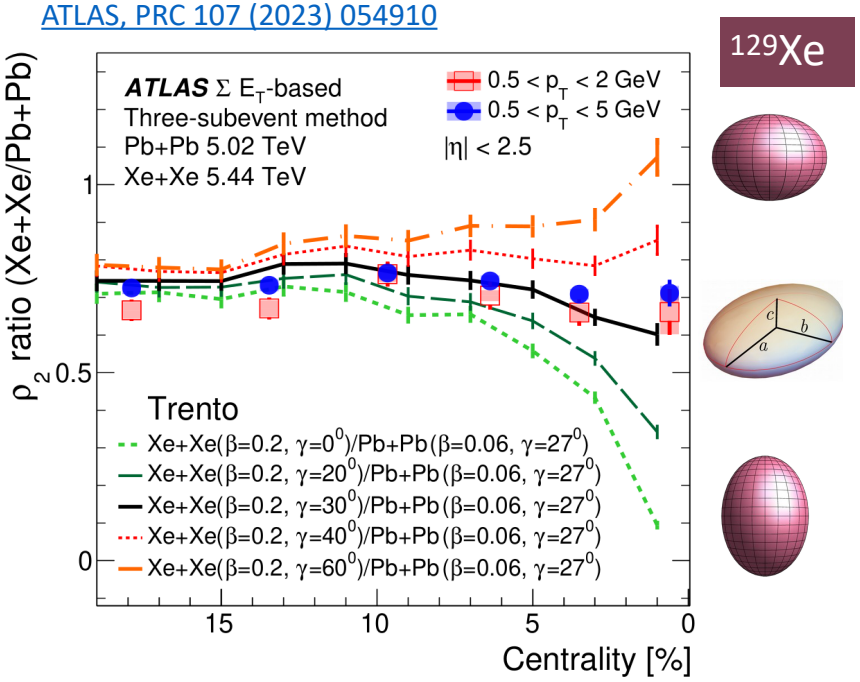
Quark coalescence → charmed **baryon/meson ratios** in central Pb-Pb collisions at **intermediate p_T**

✓PYTHIA with **colour reconnection** reproduces ratios **at forward rapidities** in **peripheral Pb-Pb**

✓**Beauty meson ratios** also compatible with models including **quark coalescence**

Imaging the nucleus using the QGP

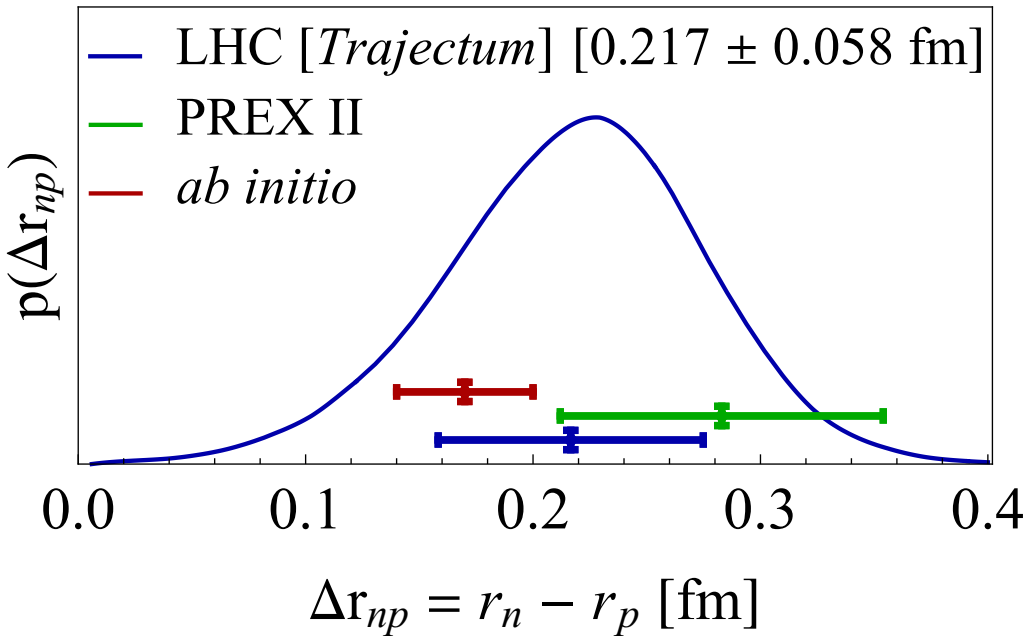
ATLAS, PRC 107 (2023) 054910



^{129}Xe

Giacalone et al, arXiv:2305.00015

^{208}Pb



Flow results from LHC demonstrate **deformation of ^{129}Xe** nucleus → No previous measurements

✓ Hydrodynamic response used to determine **^{208}Pb nuclei neutron skin** Δr_{np}

✓ **Relevant for neutron star equation of state** and competitive with dedicated experiments

Black holes and the QGP

ALICE, arXiv:2211.04384

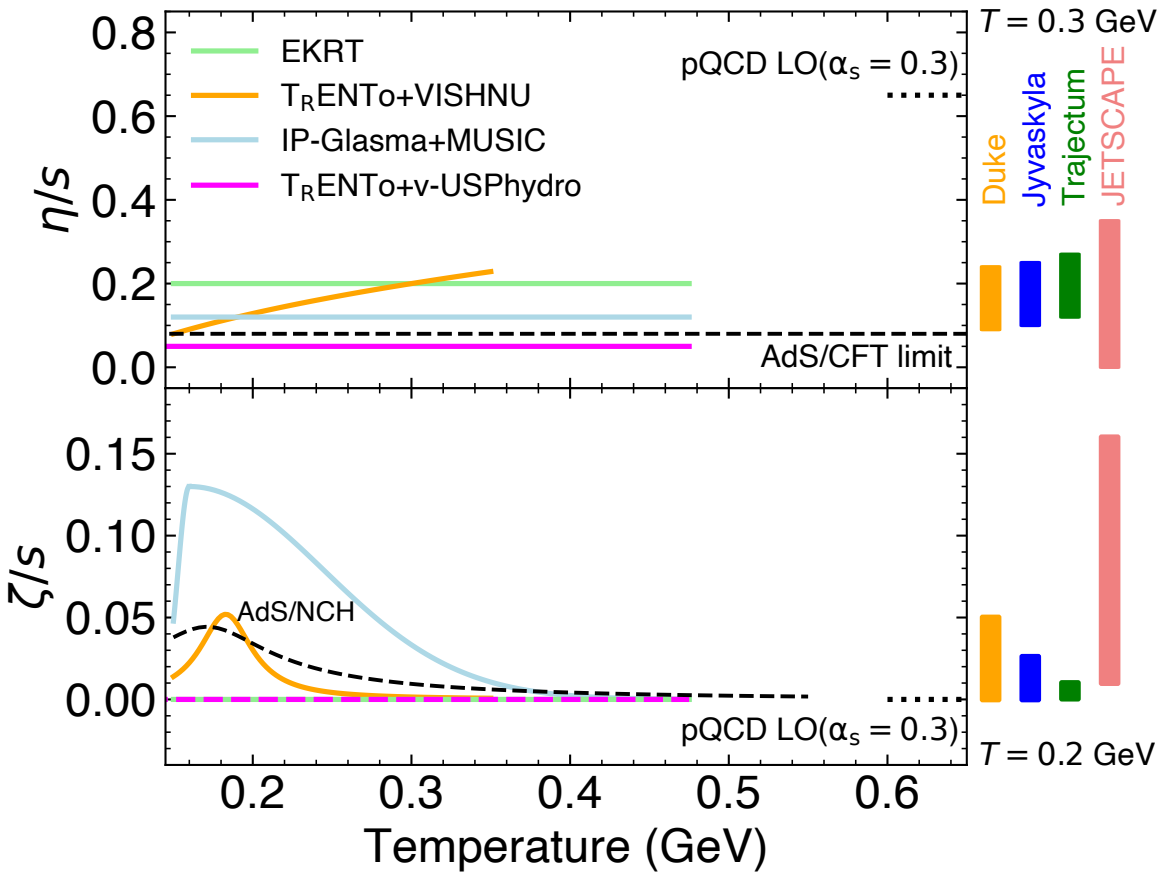


Image from Event Horizon Telescope

Kovtun et al, PRL 94 (2005) 111601

Holographic principle implies **black hole properties in Anti-de Sitter space (AdS) → QGP properties**

LHC shear (η/s) and bulk (ζ/s) viscosities **consistent with AdS predictions**

Summary

QGP properties

✓Hottest and most perfect liquid created in lab

✓Demonstrate how quarks can equilibrate on tiny timescales

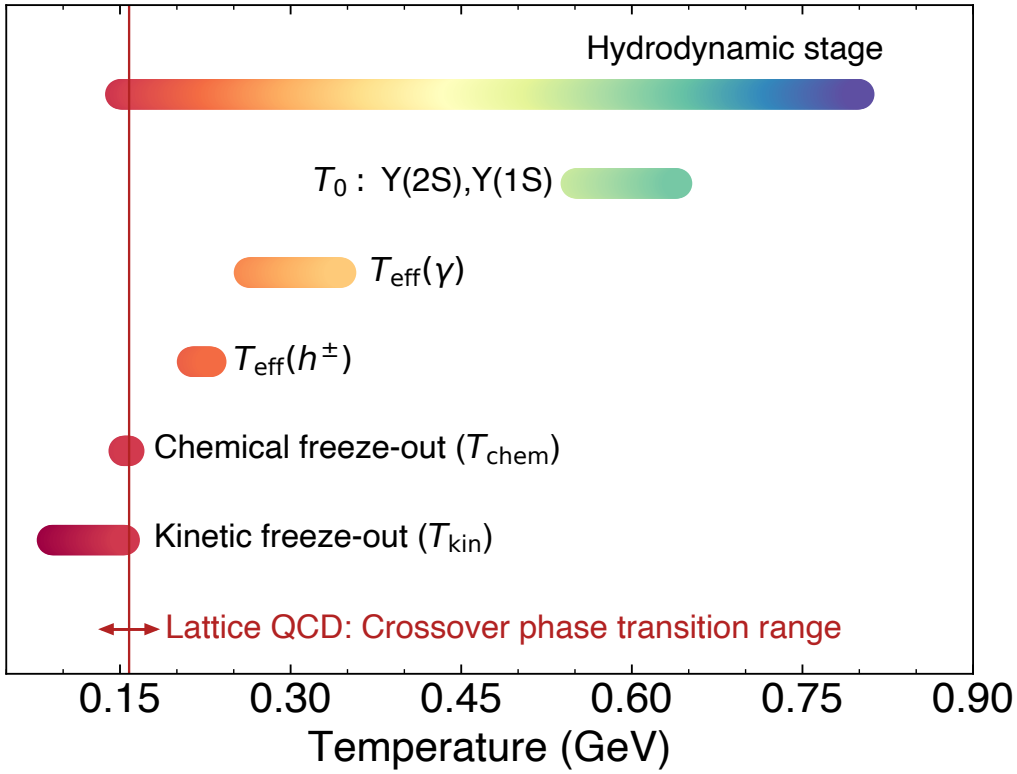
✓Produces hadrons in thermal equilibrium

Broader impact of QGP studies

✓Unique/competitive constraints on nuclear structure

✓Insights into proposed relation between fundamental forces

ALICE, arXiv:2211.04384



Smallest collision systems that exhibit QGP-like effects?

N. Jacazio, Tuesday at 10.35

Thanks → Looking ahead to the LHC future!