Properties of the medium formed in heavy-ion collisions at LHC

Based on arXiv:2211.04384

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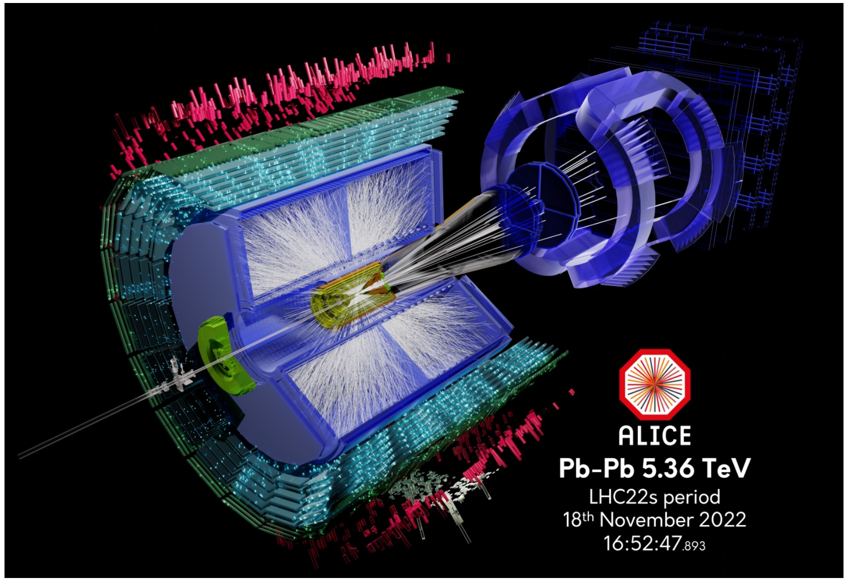
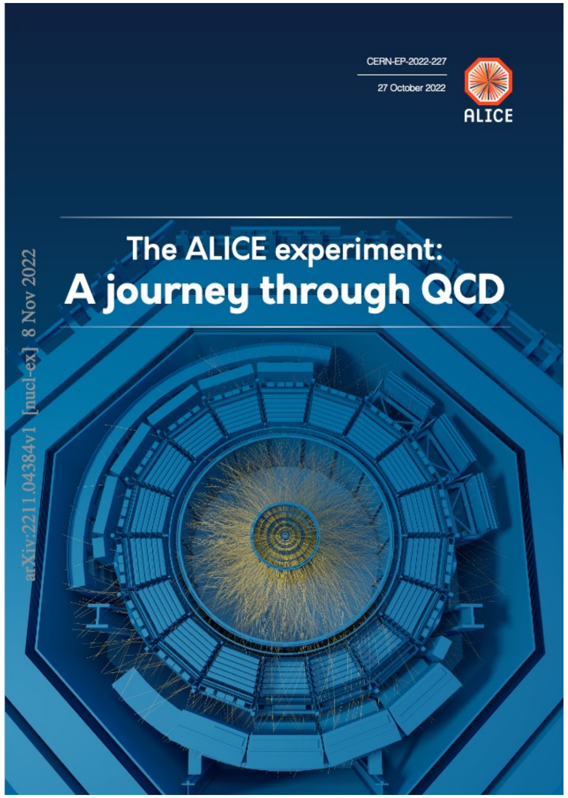
Outline
- ❑ Introduction
- ❑ ALICE experiment
- ❑ Measurements and properties of medium
- ❑ Future upgrades
- ❑ Summary

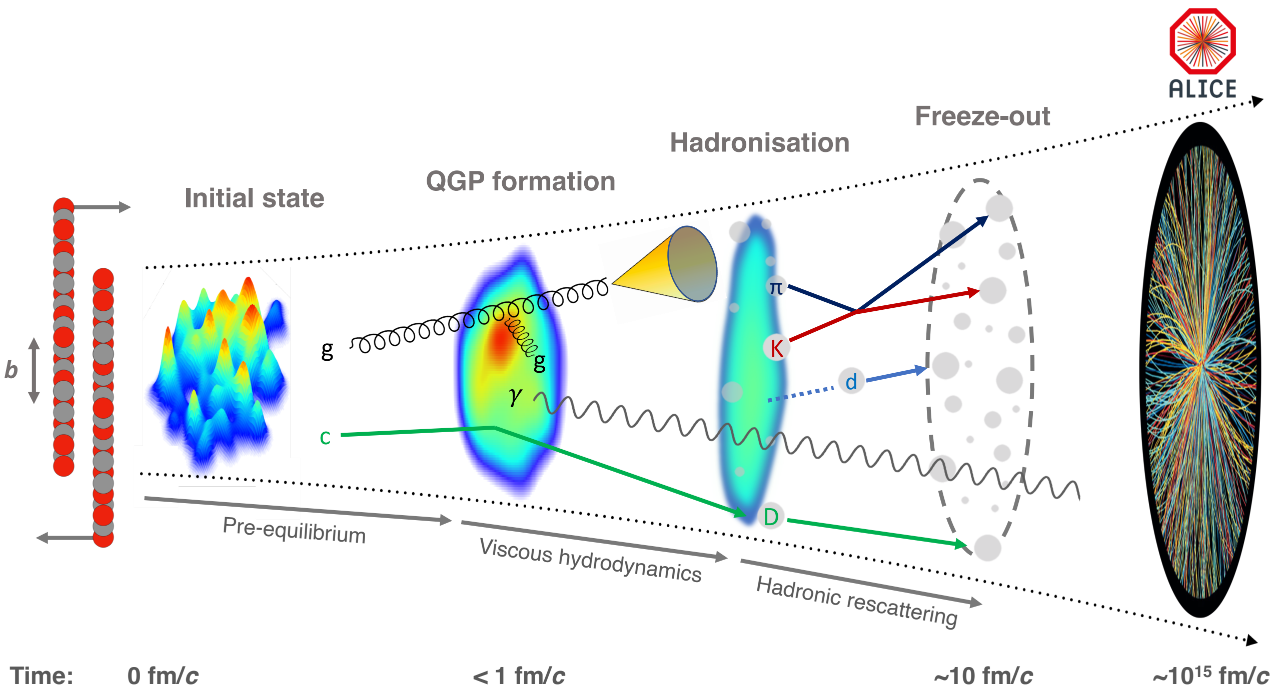


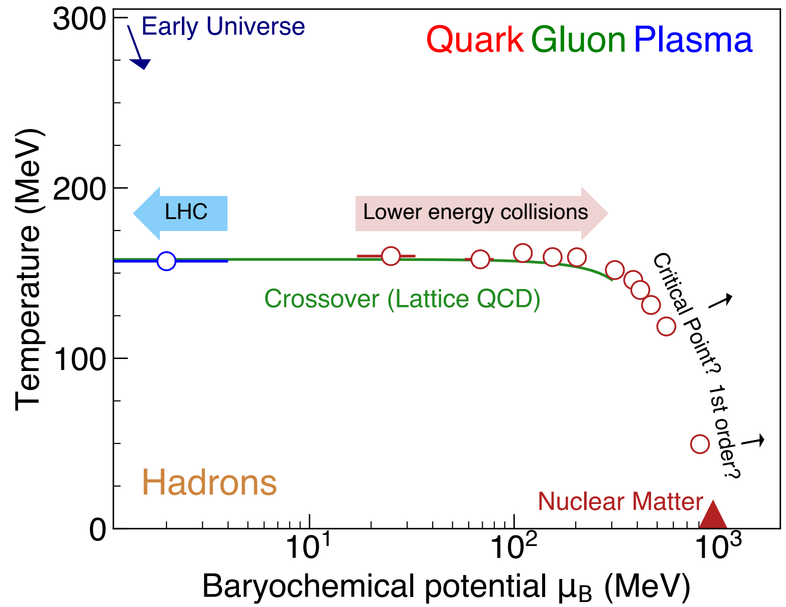


328 pages, 123 captioned figures, 3 tables, submitted to EPJC.

Also see talk on Hadronisation in dense (and not-so-dense) environments by Jan Fiete Grosse-Oetringhaus (CERN, Geneva)

Relativistic heavy-ion collisions at LHC

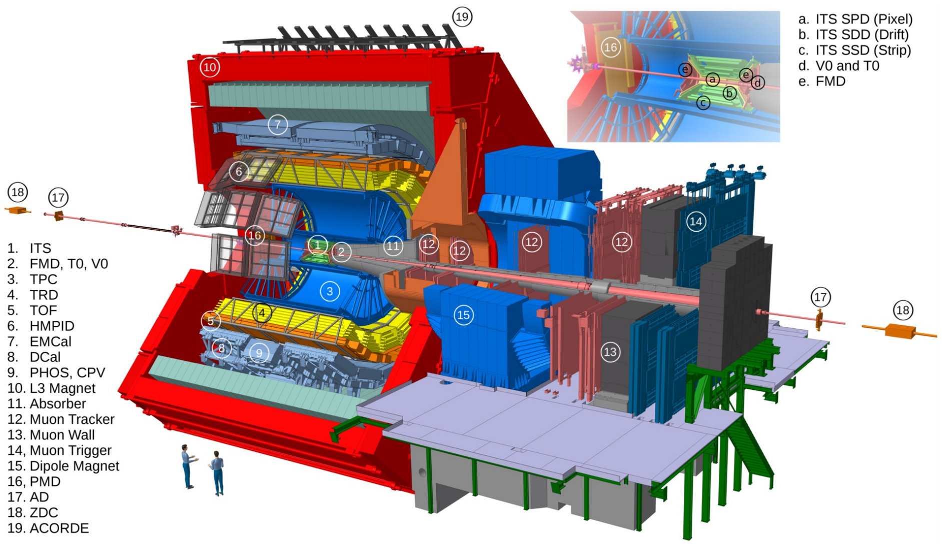




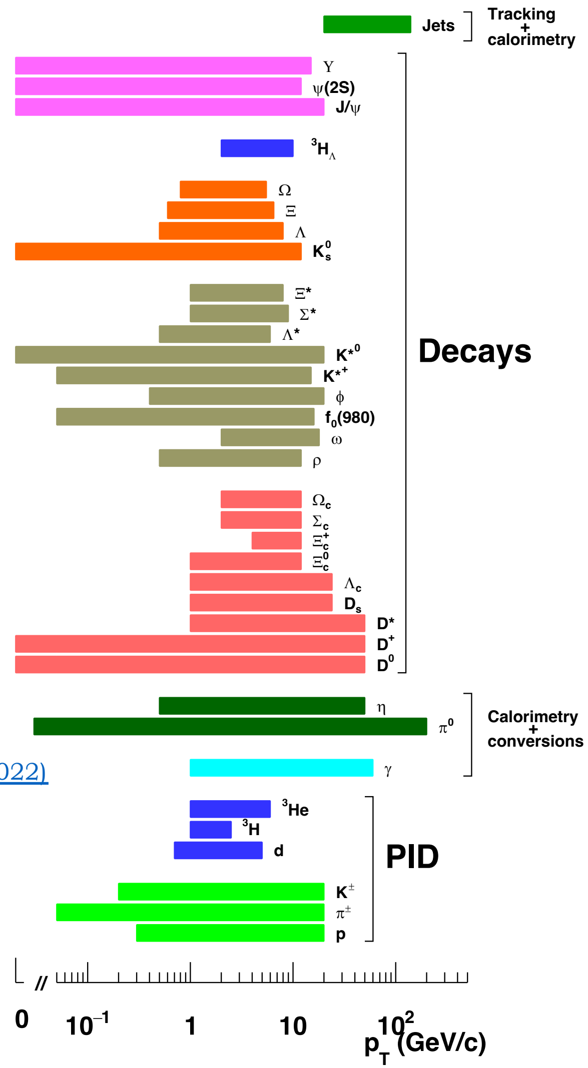
Time evolution of heavy-ion collisions

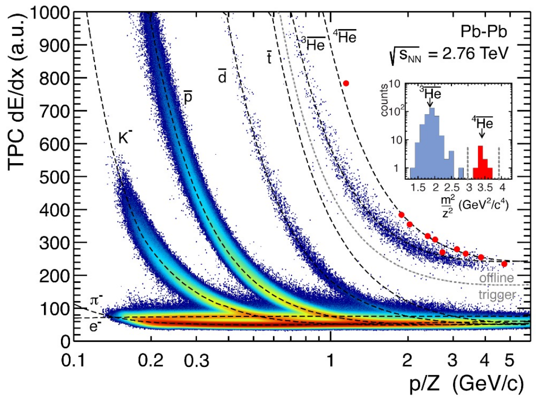
Phase diagram of QCD

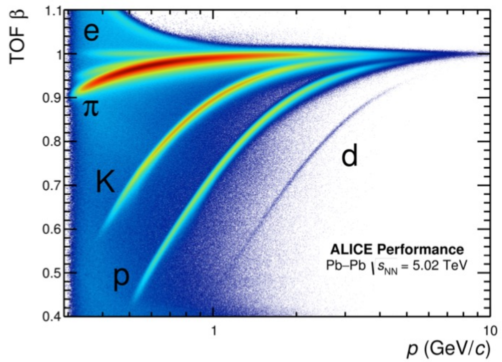
ALICE detector



Uniform acceptance at midrapidity and excellent particle identification capability







[(Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)]

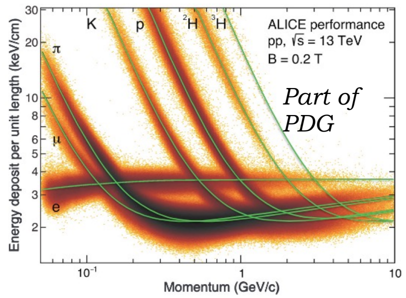


Figure 35.15: Energy deposit versus momentum measured in the ALICE TPC.

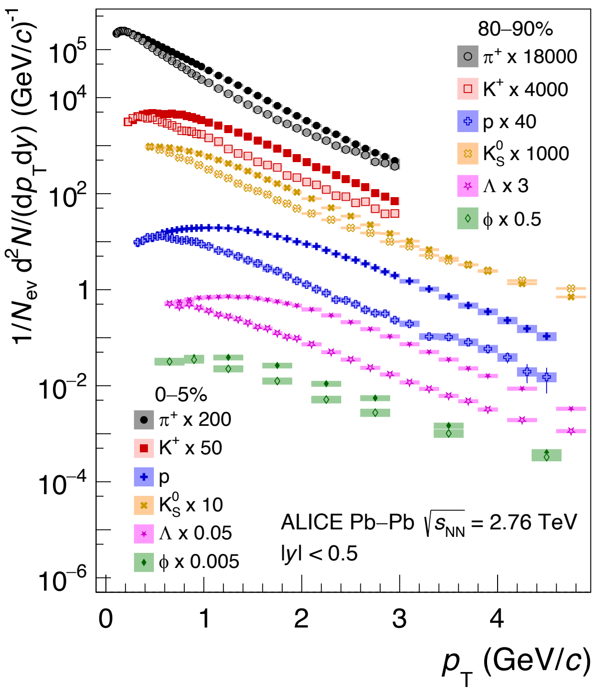
Dataset collected

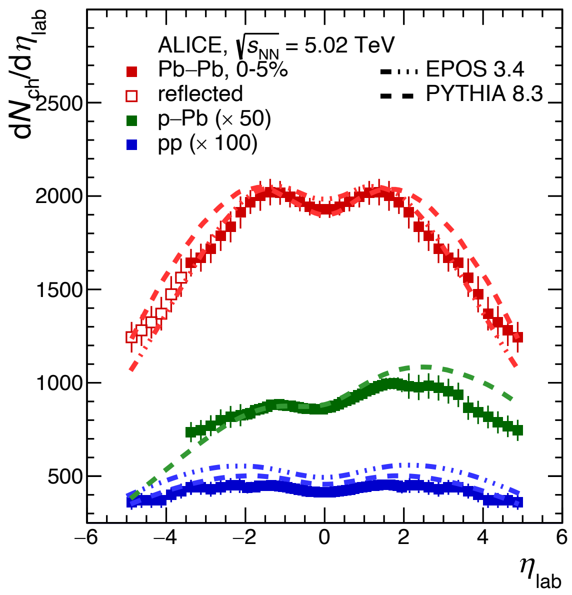
System	Year	Centre of mass energy (TeV)	Integrated luminosity
Pb-Pb	2010, 2011 2015, 2018	2.76 5.02	75 mb^{-1} 800 mb^{-1}
Xe-Xe	2017	5.44	0.3 mb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	15 nb^{-1} 3 nb^{-1} , 25 nb^{-1}
p-p	2009-2013 2015, 2017 2015-2018	0.9, 2.76, 7, 8 5.02 13	200 mb^{-1}, 100 nb^{-1}, 1.5 pb^{-1}, 2.5 pb^{-1} 1.3 pb^{-1} 136 pb^{-1}

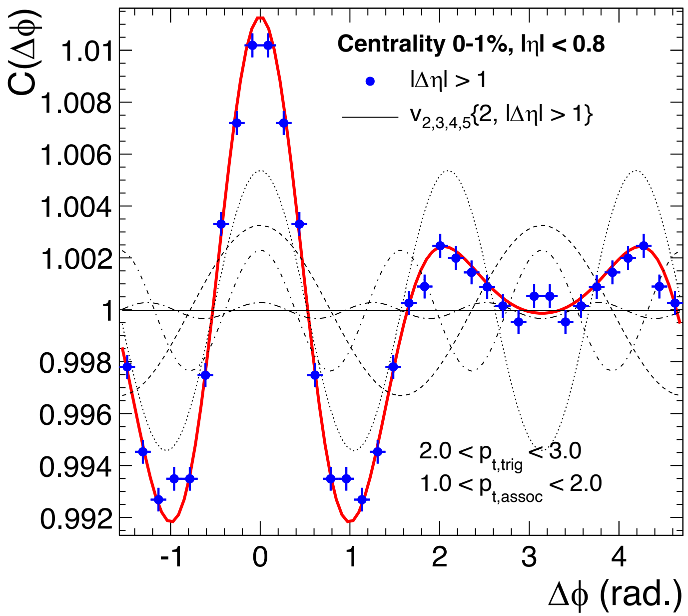
Run 3 – 700 billion pp events at 13.6 TeV collected.
Target for 2023 – 30 pb^{-1}

2023: 4-5 weeks of Pb-Pb run expected
Target for 2023 – 3.25 nb^{-1}

Basic measurements







Transverse momentum distributions
dN/dy, <p_T>, radial flow, effective temperature

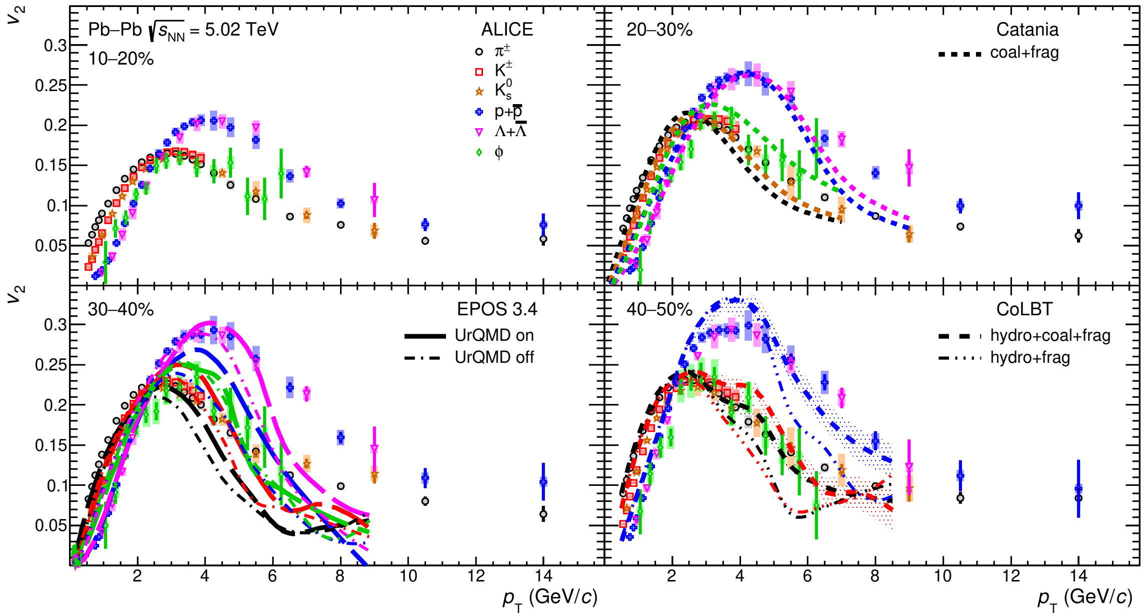
Angular distributions

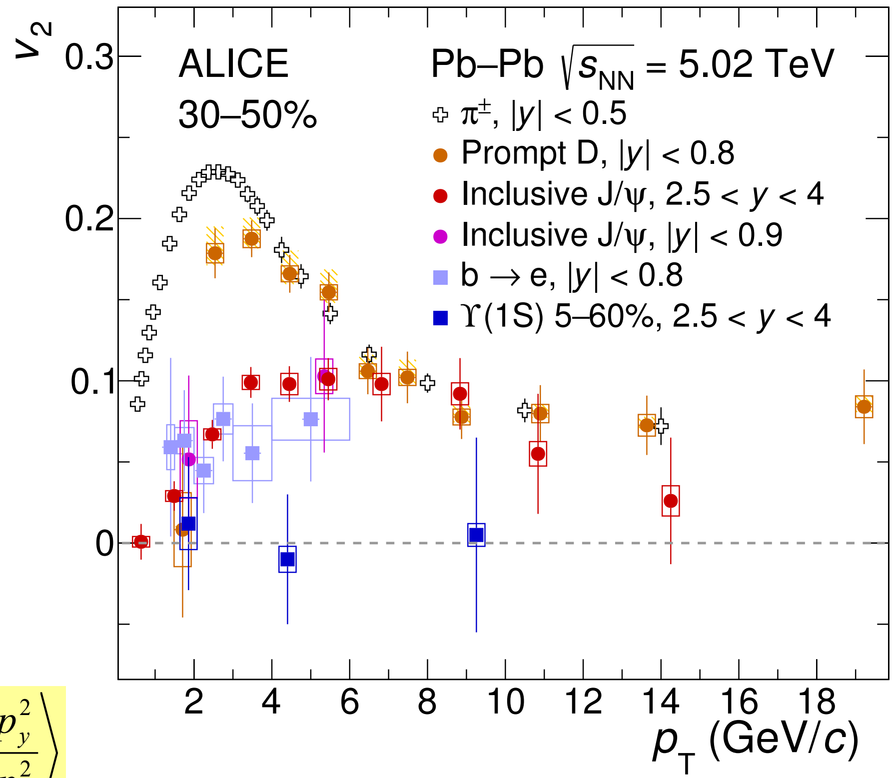
Pseudorapidity distributions
Azimuthal angle distributions

$$v_2 = \langle \cos 2\varphi \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{NN}/dp_T d\eta}$$ - Nuclear modification factor

Collectivity and hydrodynamics





Low transverse momentum – mass ordering - Hydrodynamic like.

$$v_2 = \langle \cos 2\varphi \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

Charm quark carrying hadrons also exhibit collectivity

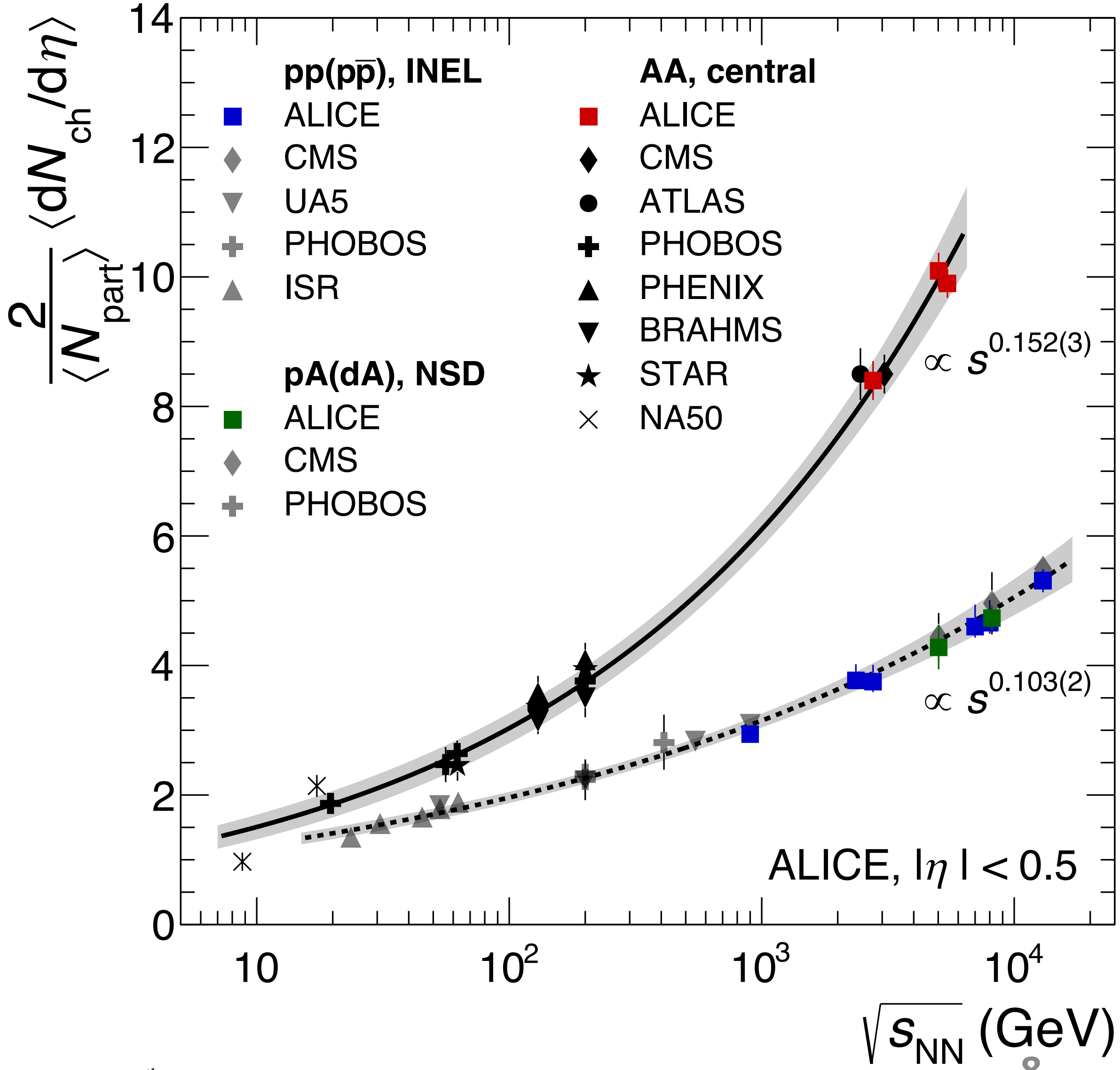
Intermediate transverse momentum – baryon – meson differences Consistent with parton recommendation to form hadrons.

Macroscopic properties

- Energy density
- Size and lifetime of the system
- Temperature

Multiplicity

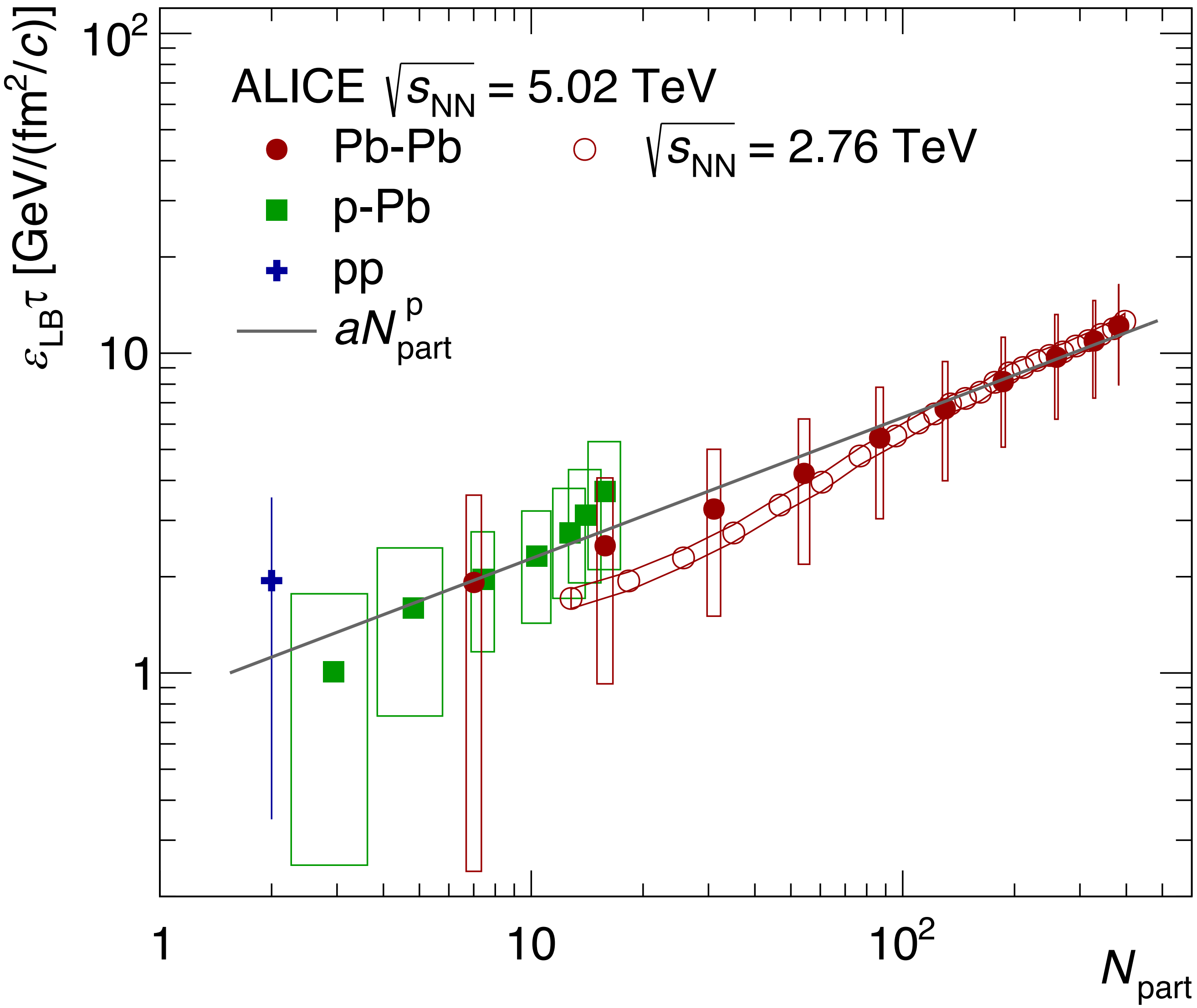
Stronger energy dependence than pp. Heavy-ion collisions are more efficient in transferring the initial beam energy into particle production.



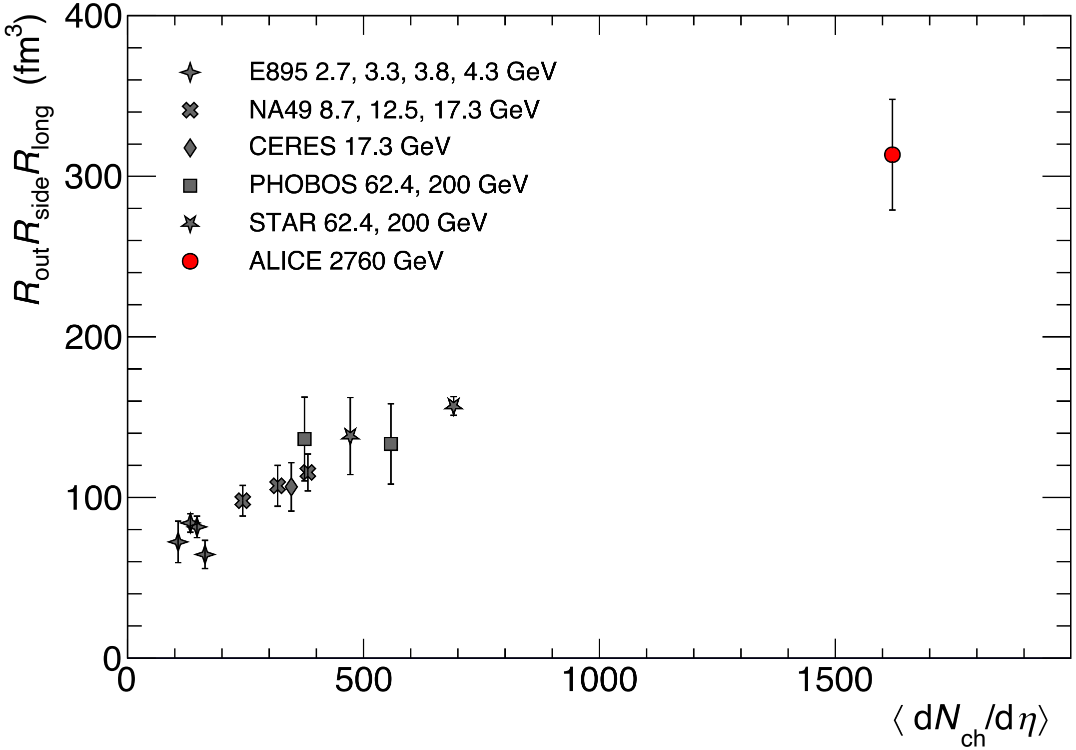
Energy density

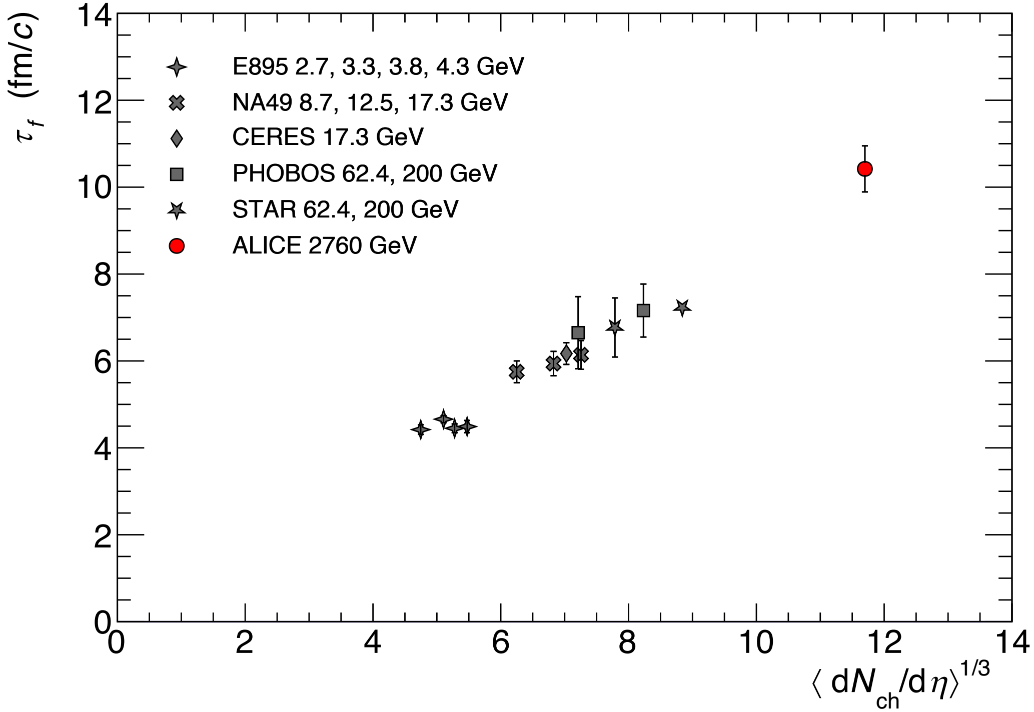
$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\langle m_T\rangle \frac{3}{2}\left(1 - \frac{m^2}{\langle m_T\rangle^2}\right)^{-1/2}\frac{dN_{ch}}{d\eta}$$

Assuming formation time ~ 1 fm/c, ε = 12.3 ± 1.0 GeV/fm³ in 0–5% Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV.



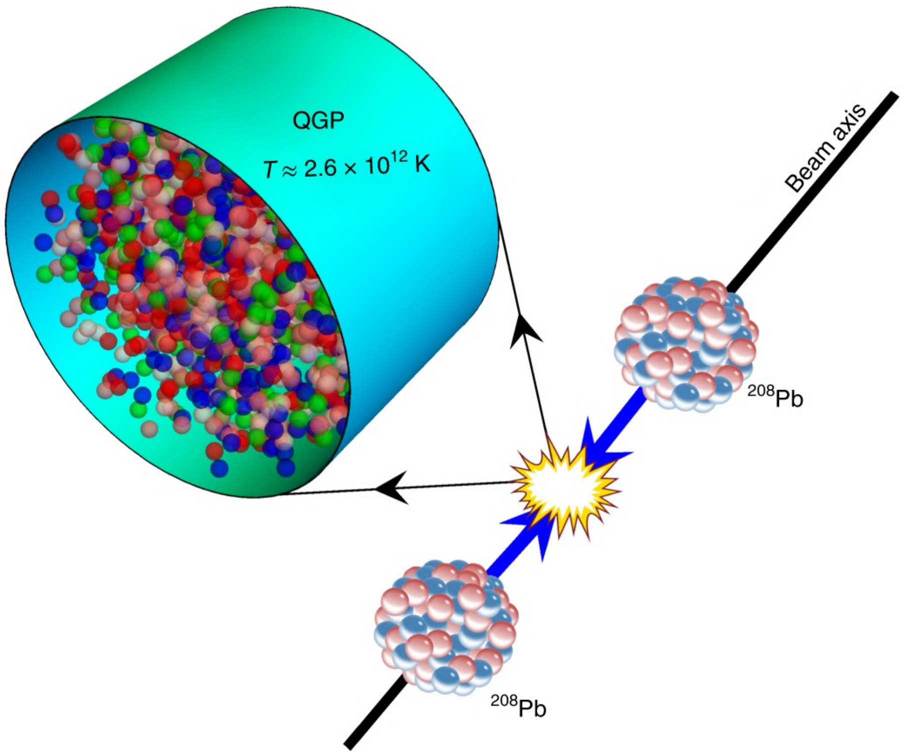
Source size & decoupling time





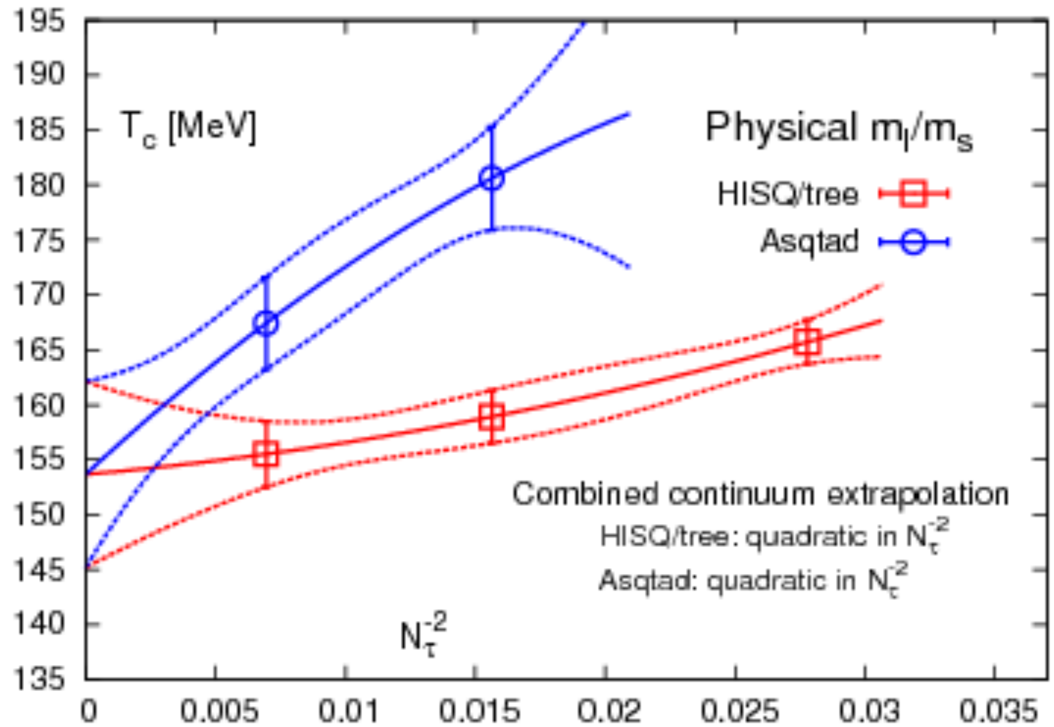
RHIC to the LHC - homogeneity region ~ twice larger. The decoupling time for midrapidity pions is ~ 40% larger.

Temperatures measured in ALICE at LHC



Nature Physics 16, 615–619 (2020)

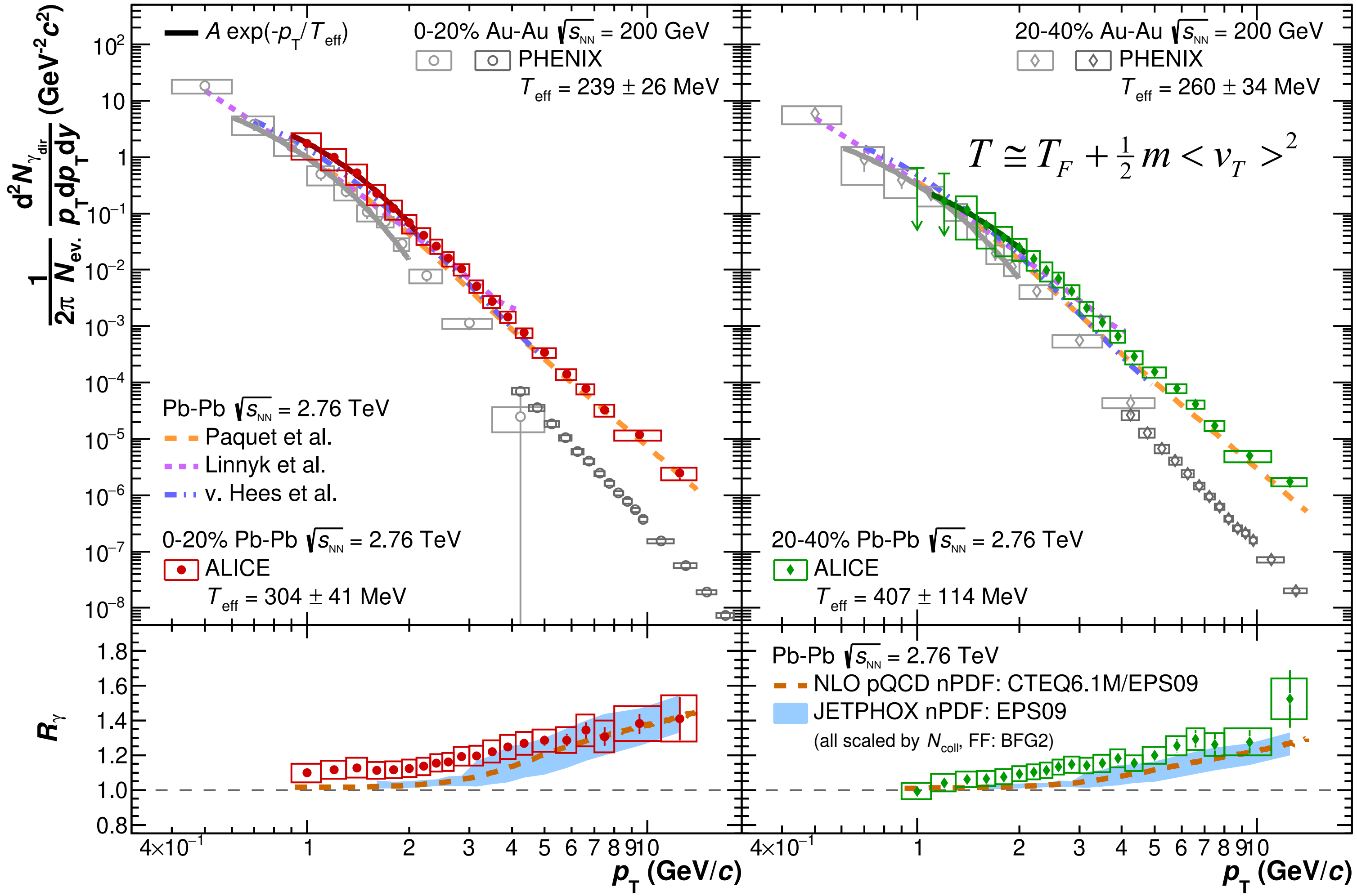
Phys.Rev.D 85 (2012) 054503



Lattice QCD – transition temperature, T_c=156.5 ± 1.5 MeV

Phys. Lett. B 795 (2019) 15–21

Temperatures from direct photons at ALICE

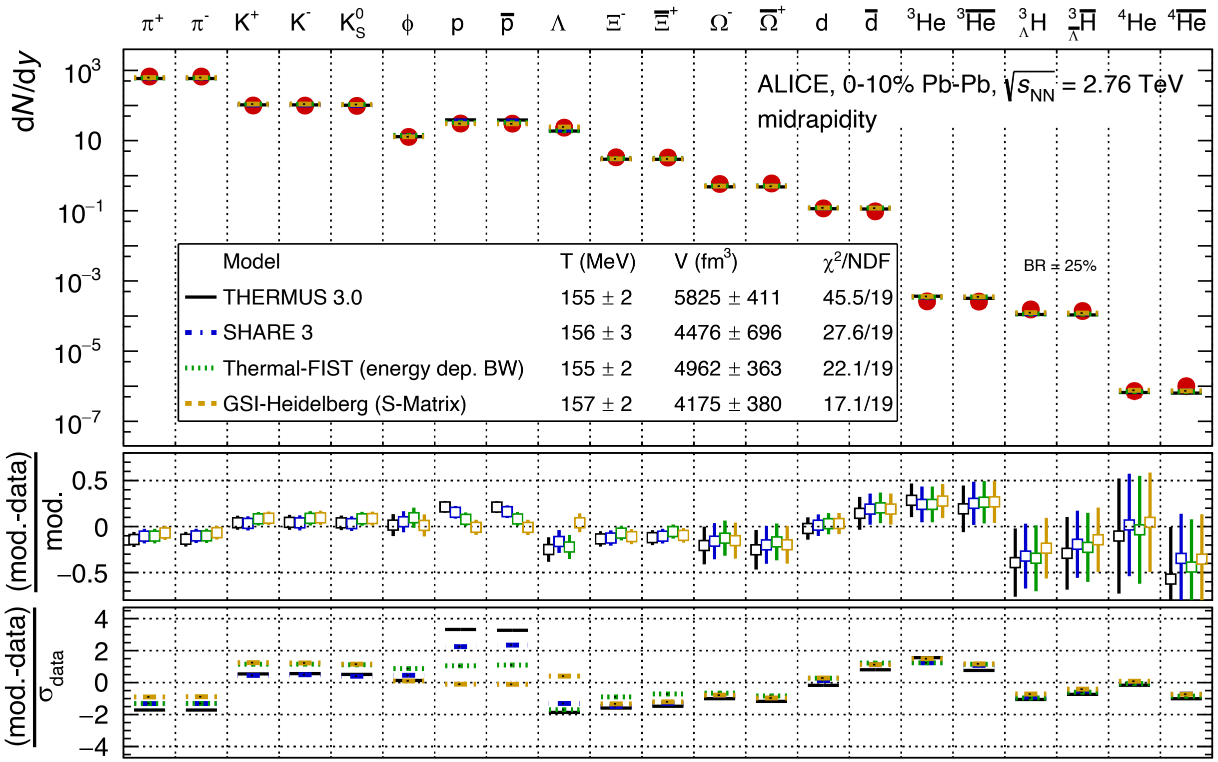


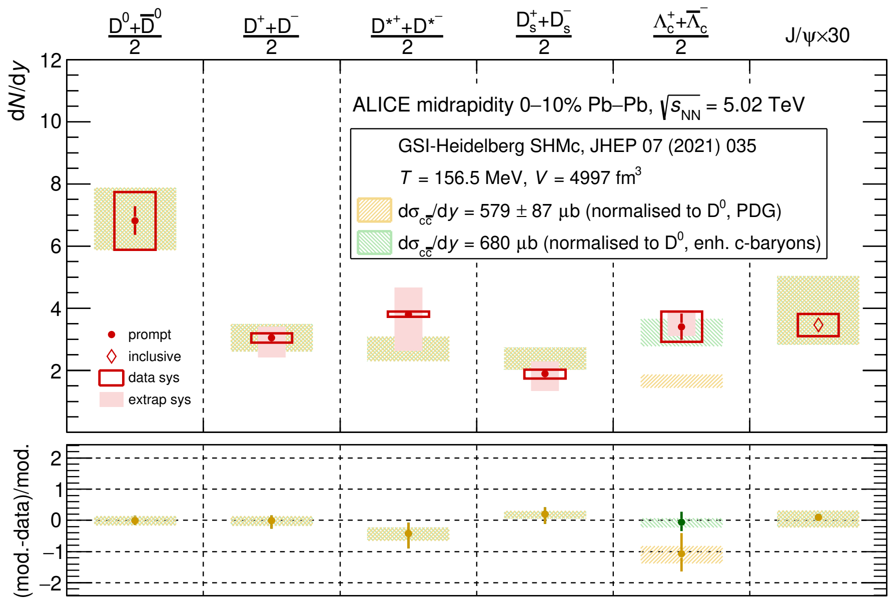
Effective temperature ~ 300-400 MeV. Much larger than T_c from LQCD (156 MeV).

QGP formation at LHC.

Photon spectra are blue shifted by radial flow and in future we will measure it with dileptons (p_T int.) invariant mass spectra.

Temperature from particle yields – chemical freeze-out



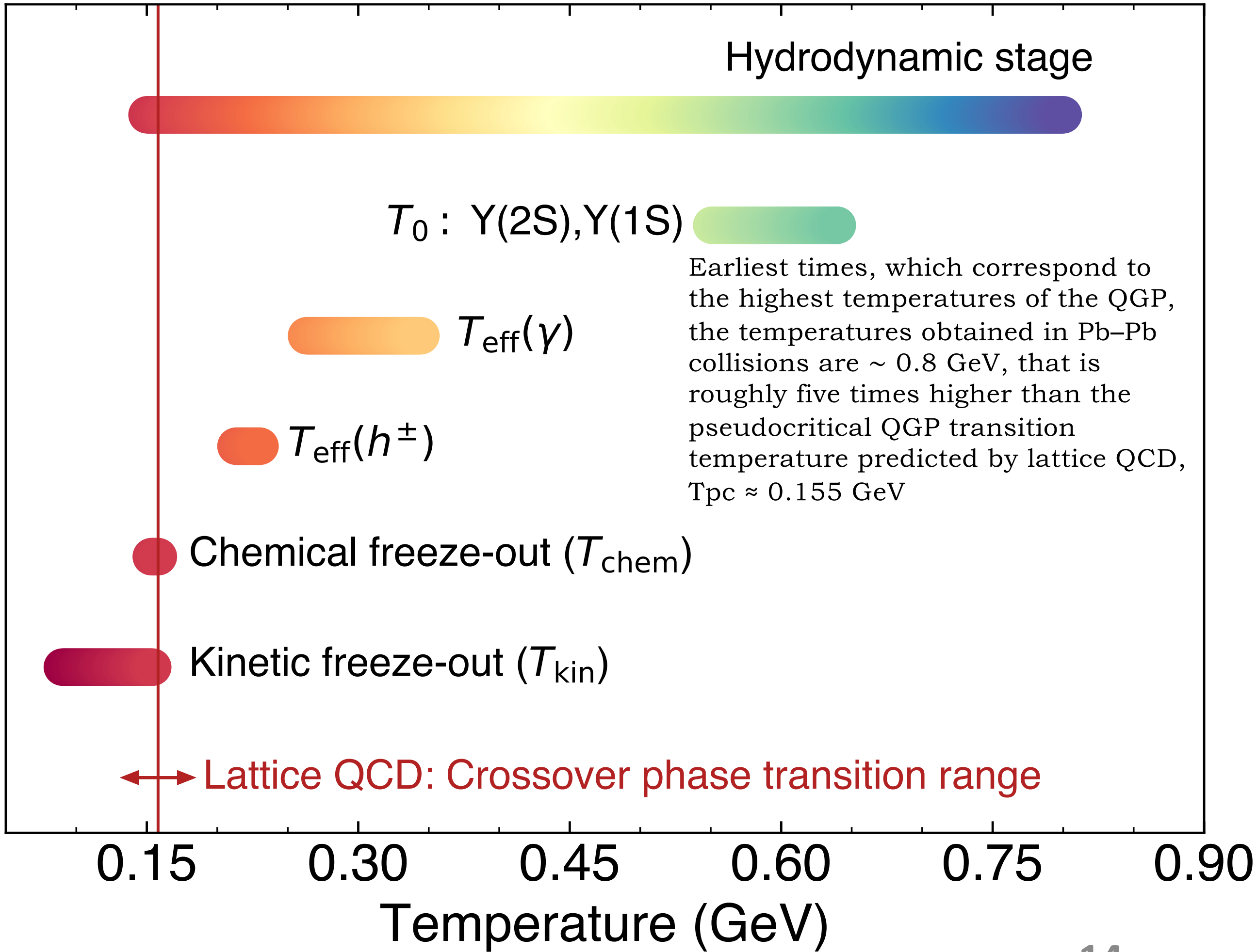


$$n = \frac{1}{V}\frac{\partial (T \ln Z)}{\partial \mu} = \frac{V.T.m_i^2 g_i}{2\pi^2}\sum_{k=1}^{\infty}\frac{(\pm 1)^{k+1}}{k}\left(e^{\beta k \mu_i}\right)K_2\left(\frac{k m_i}{T}\right)$$

Inelastic collisions cease at ~ 156 MeV.
Chemical freeze-out and quark-hadron transition around similar temperatures.

The temperatures ranges probed by central heavy-ion collisions at the LHC derived from ALICE measurements

- ❑ Thermal direct photons T_{eff}
- ❑ Temperatures needed to describe the relative bottomonia Y(2S) and Y(1S) yields.
- ❑ The effective charged-hadron temperature obtained using a hydrodynamic model to describe ALICE spectra measurements.
- ❑ The chemical freeze-out temperature from a statistical model fit to particle yields.
- ❑ Kinetic freeze-out temperature from blast-wave fits to spectra and identified particle v_n measurements.



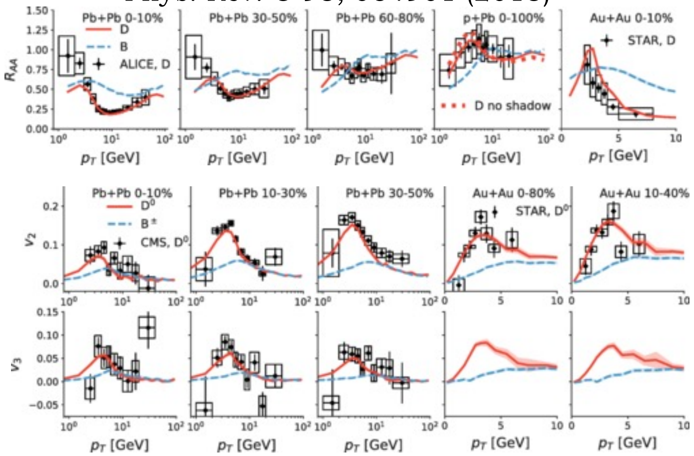
Earliest times, which correspond to the highest temperatures of the QGP, the temperatures obtained in Pb–Pb collisions are ~ 0.8 GeV, that is roughly five times higher than the pseudocritical QGP transition temperature predicted by lattice QCD, Tpc ≈ 0.155 GeV

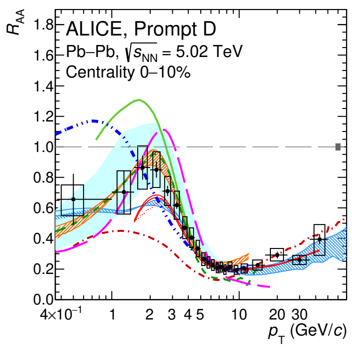
Transport properties of QGP (using ALICE data)

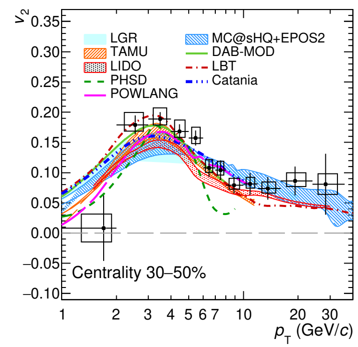
- ❑Shear viscosity
- ❑Bulk viscosity
- ❑Diffusion coefficient
- ❑Jet transport coefficient

Theory vs. ALICE data

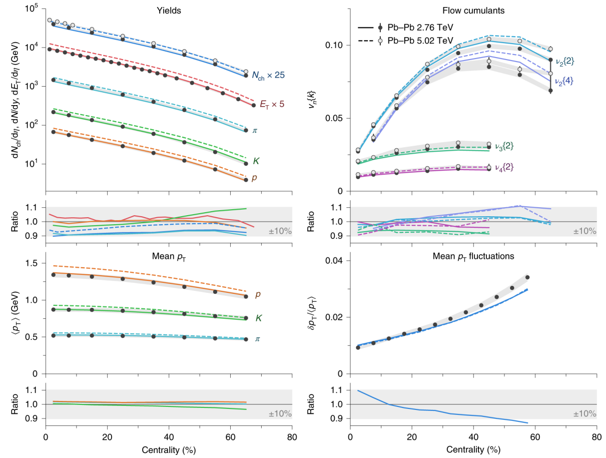
Phys. Rev. C 98, 064901 (2018)



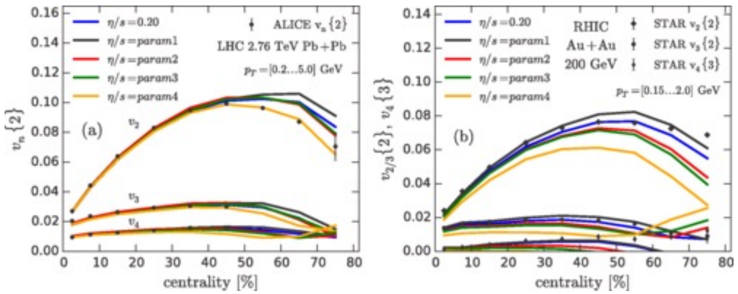


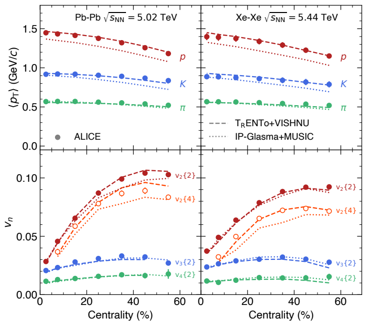


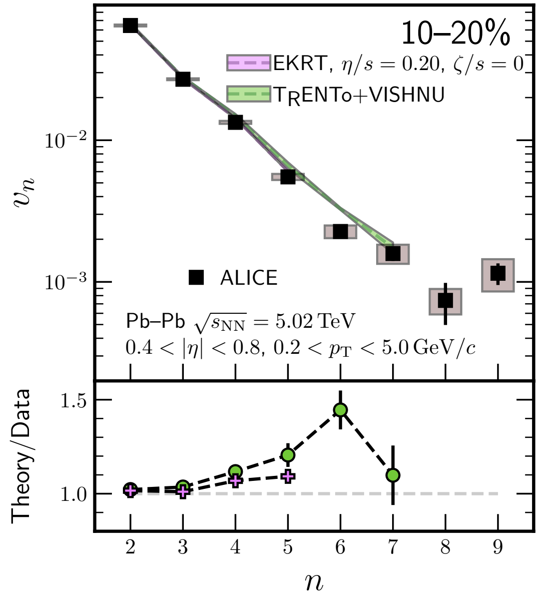
Nature Physics 15, pages 1113–1117 (2019)

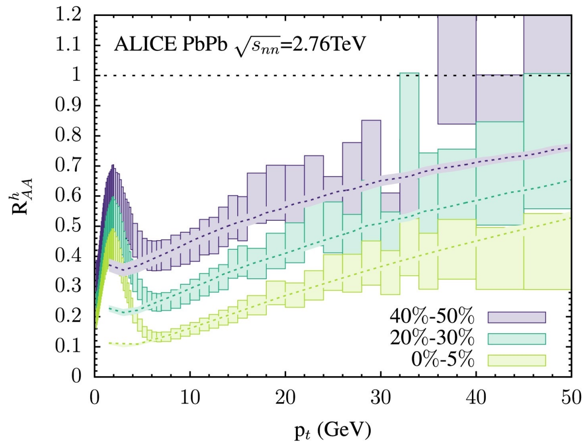


Phys. Rev. C 93, 024907 (2016)





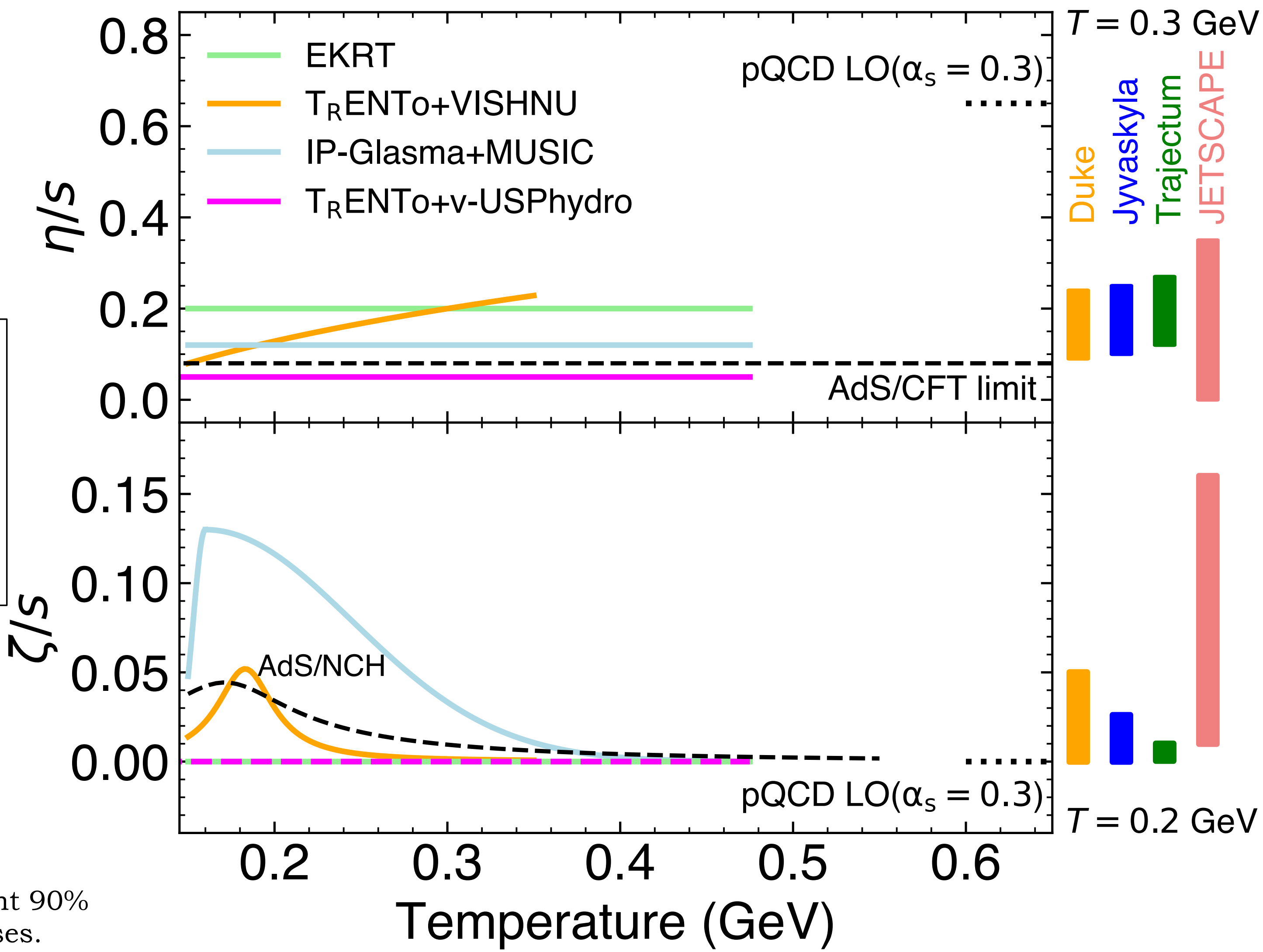




Physics Letters B 816, 136251 (2021)

Transport properties - Viscosity

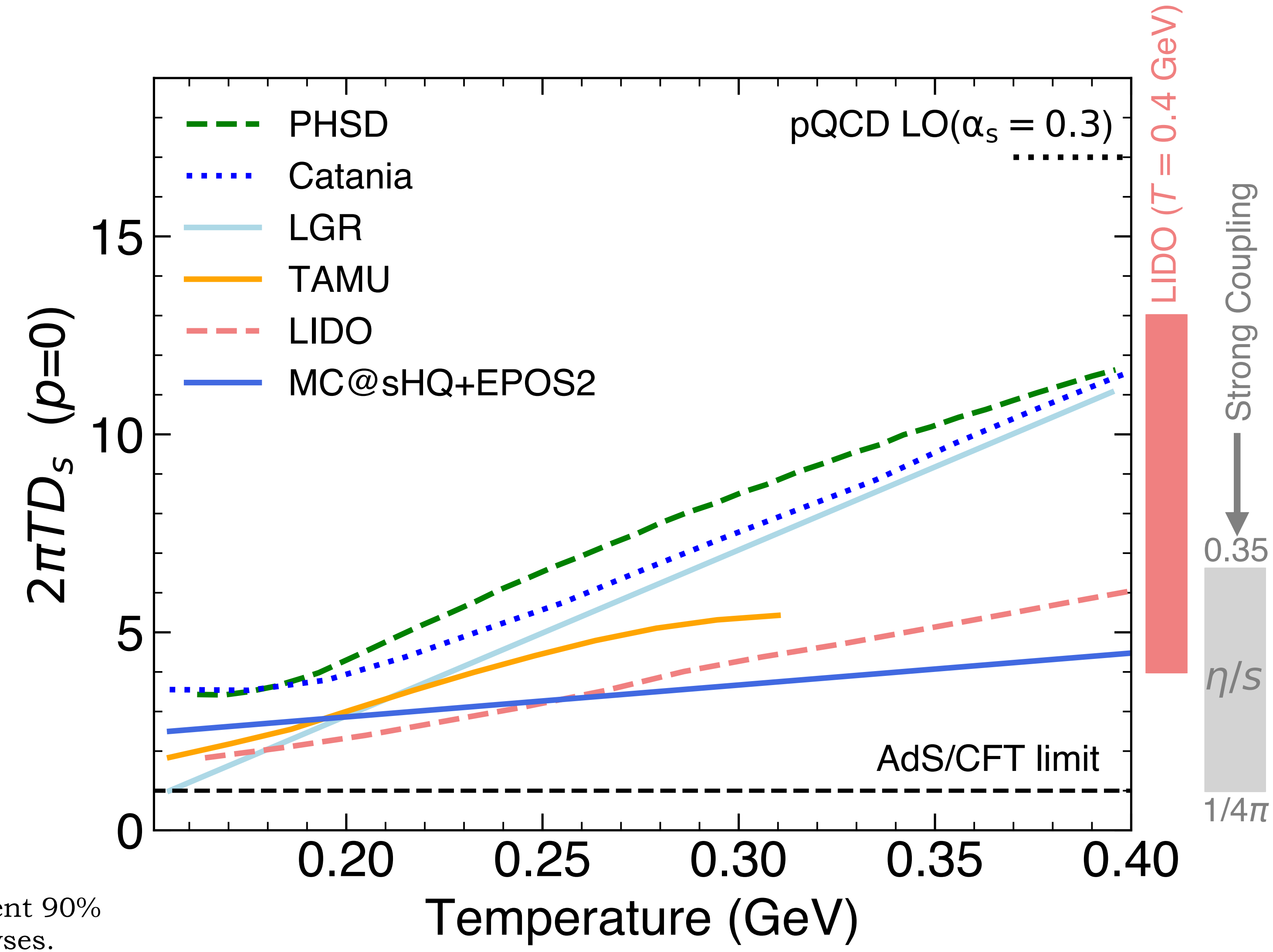
Using measurements of anisotropic flow and spectra by ALICE



The ranges on the right of the plots represent 90% posterior intervals from the Bayesian analyses.

Transport properties - Diffusion coefficient

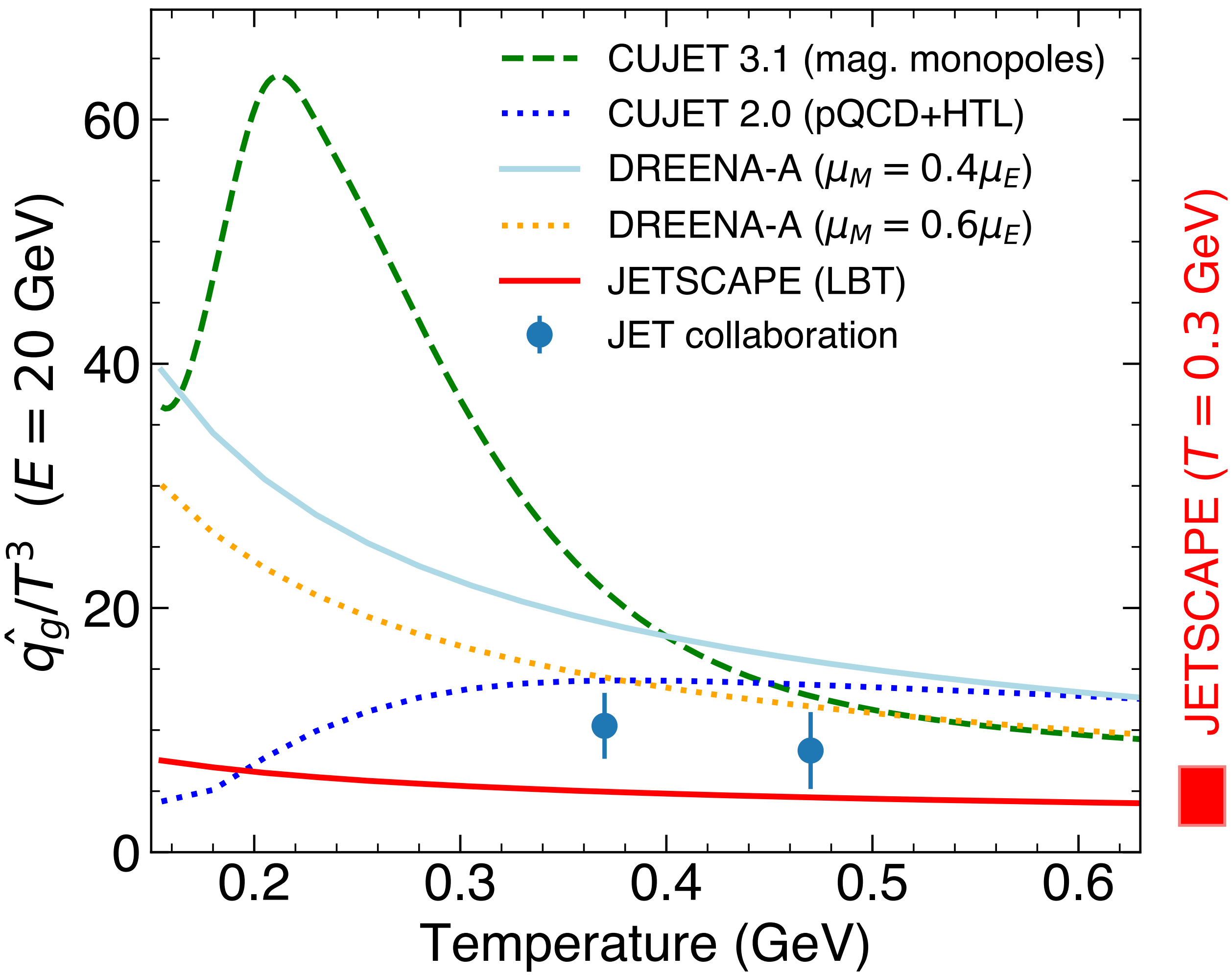
Using the D-meson v_2 and R_{AA} measurements



The ranges on the right of the plots represent 90% posterior intervals from the Bayesian analyses.

Transport properties - Jet transport coefficient

Using R_{AA} and v_n for light and charmed hadrons at high-p_T.



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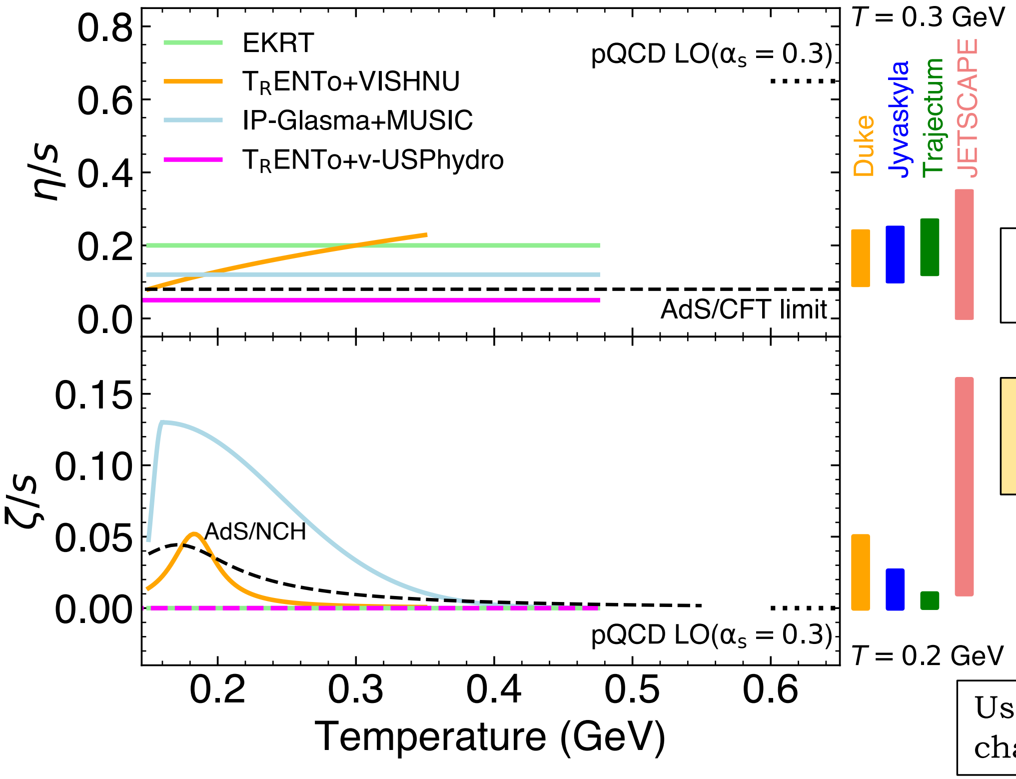
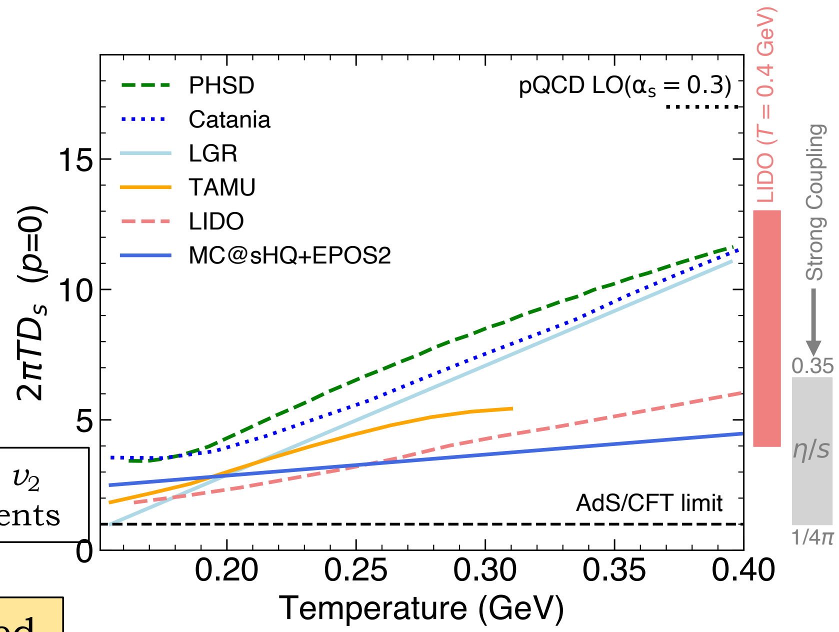
Transport properties



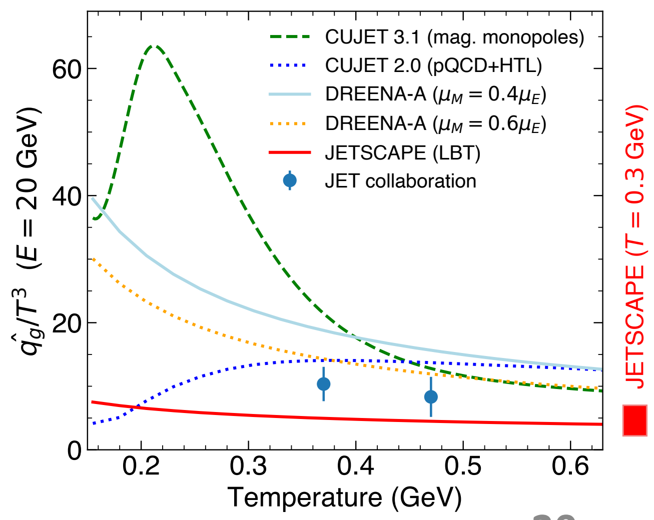


Using the D-meson v_2 and R_{AA} measurements

Strongly coupled perfect fluid

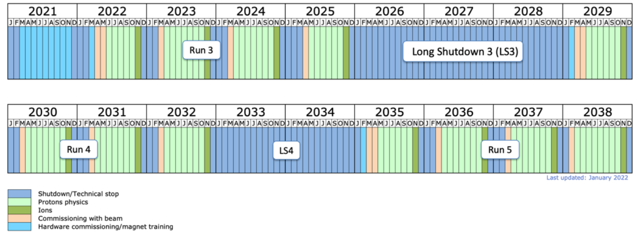
Using measurements of anisotropic flow and spectra by ALICE

Using R_{AA} and v_n for light and charmed hadrons at high-p_T.



The ranges on the right of the plots represent 90% posterior intervals from the Bayesian analyses.

ALICE@RUN-5 & 6



High-precision beauty measurements - to establish a firm connection between parton transport, collective flow and hadronization

DD correlations - to discriminate between the different regimes of in-medium energy loss and reveal the onset of charm isotropisation

Multi-charm baryons, P-wave quarkonia, exotic hadrons – Hadron formation

Azimuthal asymmetry of electromagnetic radiation.

Chiral symmetry restoration.

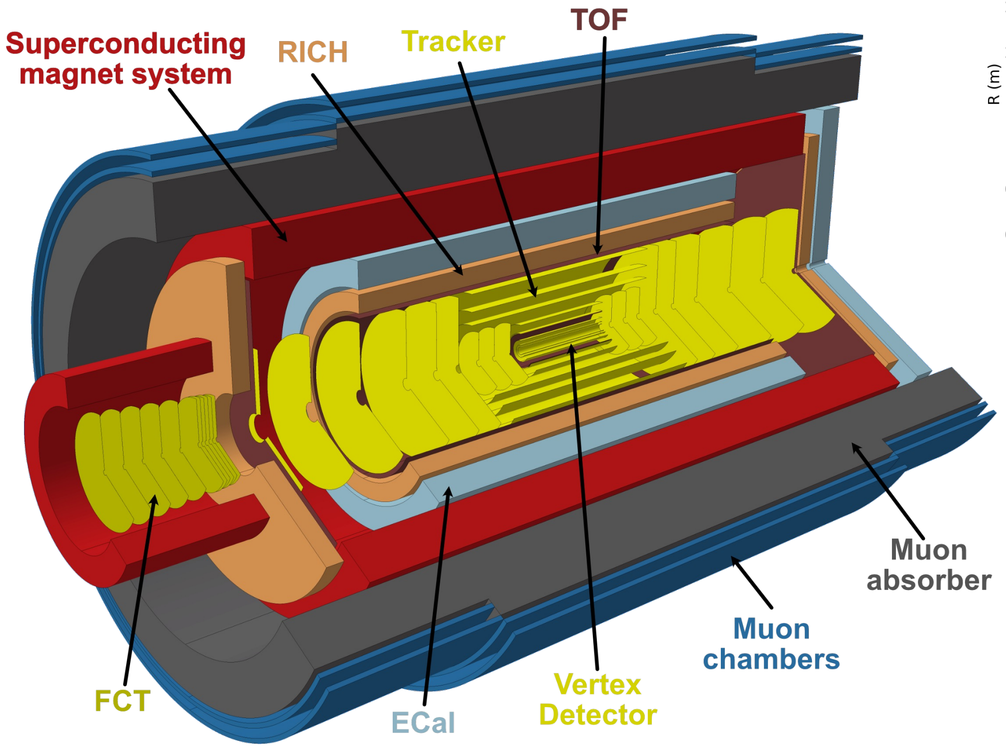
Collectivity in small systems

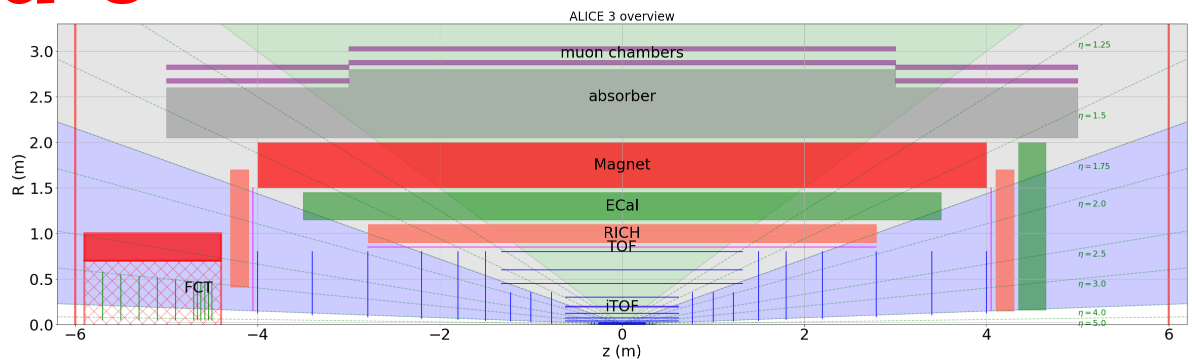
Observables	Kinematic range
Heavy-flavour hadrons	$p_T \to 0$, $\|\eta\| < 4$
Dielectrons	$p_T \approx 0.05$ to $3\,\mathrm{GeV}/c$, $M_{ee} \approx 0.05$ to $4\,\mathrm{GeV}/c^2$
Photons	$p_T \approx 0.1$ to $50\,\mathrm{GeV}/c$, $-2 < \eta < 4$
Quarkonia and exotica	$p_T \to 0$, $\|\eta\| < 1.75$
Ultrasoft photons	$p_T \approx 1$ to $50\,\mathrm{MeV}/c$, $3 < \eta < 5$
Nuclei	$p_T \to 0$, $\|\eta\| < 4$

The programme aims to collect an integrated luminosity of about 35 nb^{-1} with Pb–Pb collisions and 18 fb^{-1} with pp collisions at top LHC energy.

Letter of intent for ALICE 3: A next-generation heavy-ion experiment at the LHC, arXiv:2211.02491v1 [physics.ins-det]

ALICE 3 - Run 5 and 6





Component	**Observables**	**Barrel** ($|\eta| < 1.75$)	**Forward** ($1.75 < |\eta| < 4$)	**Detectors**
Vertexing	(Multi-)charm baryons, dielectrons	Best possible DCA resolution, $\sigma_{DCA} \approx 10\,\mu m$ at $p_T = 200\,MeV/c$, $\eta = 0$	Best possible DCA resolution, $\sigma_{DCA} \approx 30\,\mu m$ at $p_T = 200\,MeV/c$, $\eta = 3$	retractable Si-pixel tracker: $\sigma_{pos} \approx 2.5\,\mu m$, $R_{in} \approx 5\,mm$, $X/X_0 \approx 0.1\,\%$ for first layer
Tracking	(Multi-)charm baryons, dielectrons, photons ...	$\sigma_{p_T}/p_T \approx 1--2\,\%$		Silicon pixel tracker: $\sigma_{pos} \approx 10\,\mu m$, $R_{out} \approx 80\,cm$, $L \approx \pm 4\,m$ $X/X_0 \approx 1\,\%$ per layer
Hadron ID	(Multi-)charm baryons	$\pi/K/p$ separation up to a few GeV/c		Time of flight: $\sigma_{tof} \approx 20\,ps$ RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
Electron ID	Dielectrons, quarkonia, $\chi_{c1}(3872)$	pion rejection by 1000x up to 2–3 GeV/c		Time of flight: $\sigma_{tof} \approx 20\,ps$ RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
Muon ID	Quarkonia, $\chi_{c1}(3872)$	reconstruction of J/ψ at rest, i.e. muons from $p_T \sim 1.5\,GeV/c$ at $\eta = 0$		steel absorber: $L \approx 70\,cm$ muon detectors
ECal	Photons, jets	large acceptance		Pb-Sci sampling calorimeter
ECal	χ_c	high-resolution segment		$PbWO_4$ calorimeter
Soft photon detection	Ultra-soft photons		measurement of photons in p_T range 1–50 MeV/c	Forward conversion tracker based on silicon pixel tracker

Summary (selected)

What are the thermodynamic and global properties of the QGP at the LHC ?

1. LHC create conditions that very much exceed those needed to form the QGP.
2. The initial QGP temperature ~ 5 times higher than deconfinement temperature T_{pc} = 155–158 MeV.
3. Largest QGP energy densities ~ 12 GeV/fm^3 at the early time of 1 fm/c.
4. Volume at freeze-out is about 7000 fm^3 and about twice higher than at top RHIC energy.

What are the hydrodynamic and transport properties of the QGP?

1. System is strongly-coupled at the scale of the QGP temperatures
2. Extracted shear viscosity over entropy density (η/s) values in the range $1/4\pi < \eta/s < 0.3$.
3. The charm spatial-diffusion coefficient D_s in the range $1.5 < 2\pi D_s(T)T < 4.5$ at T_{pc}. Evidence that charm quarks couple strongly with the QGP at low momenta.

How does the QGP affect the formation of hadrons?

1. Statistical hadronization models describe the yields of various light-flavour and heavy-flavour hadron over many orders of magnitude.
2. The chemical freeze-out temperature of about 156 MeV ~ deconfinement temperature, suggesting chemical equilibrium cannot be maintained easily after the QGP hadronizes.
3. Measurements of resonance yields and femtoscopic radii show that hadronic phase is prolonged, and the decoupling of particles is likely to be a continuous process, rather than a sudden kinetic freeze-out of all particle species at the same temperature.

Exciting set of upgrades in place and planned - stay tuned to exciting results from ALICE.

Thanks