CERN Summer Student Lectures 2022

Heavy Ions 3/3

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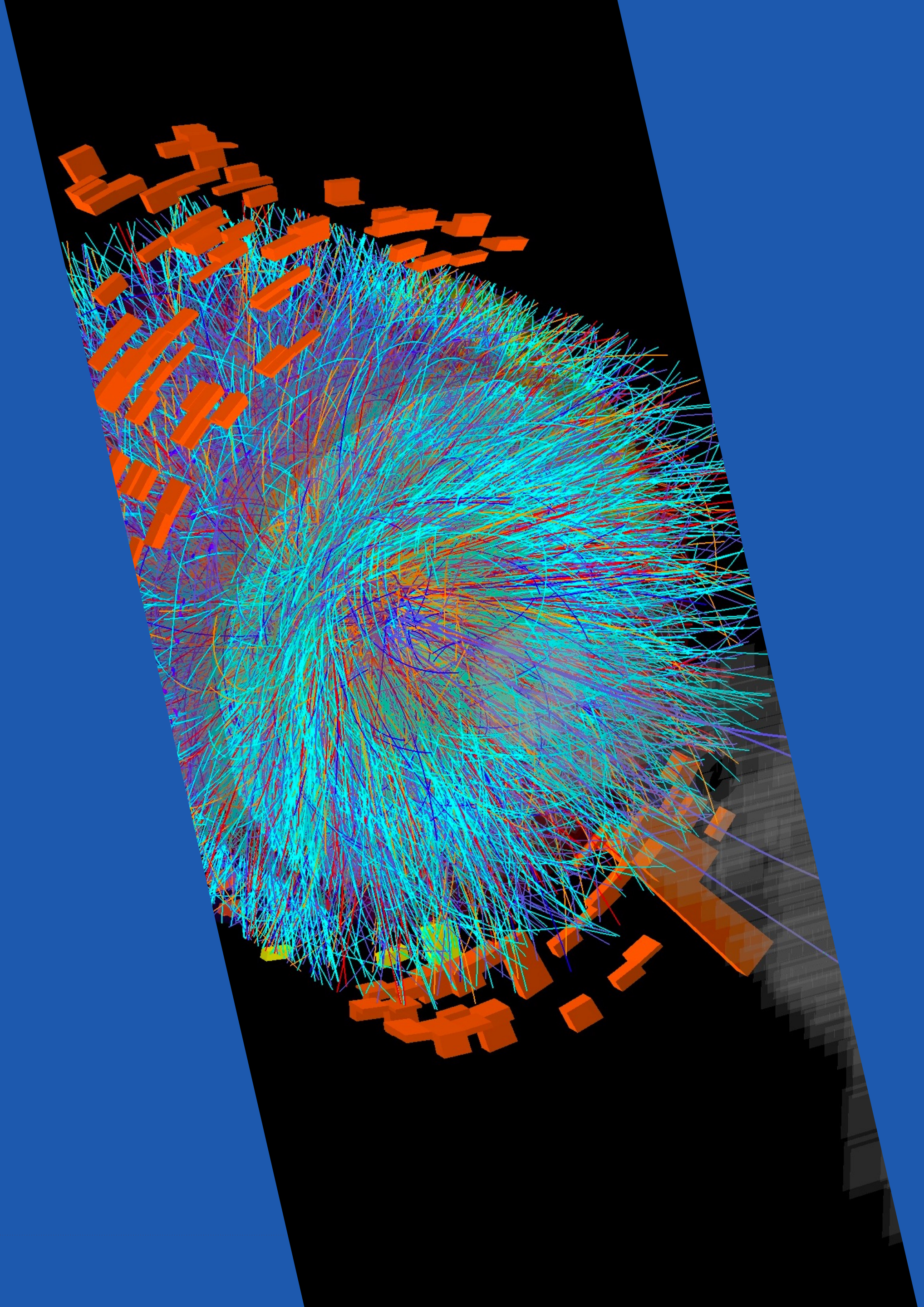
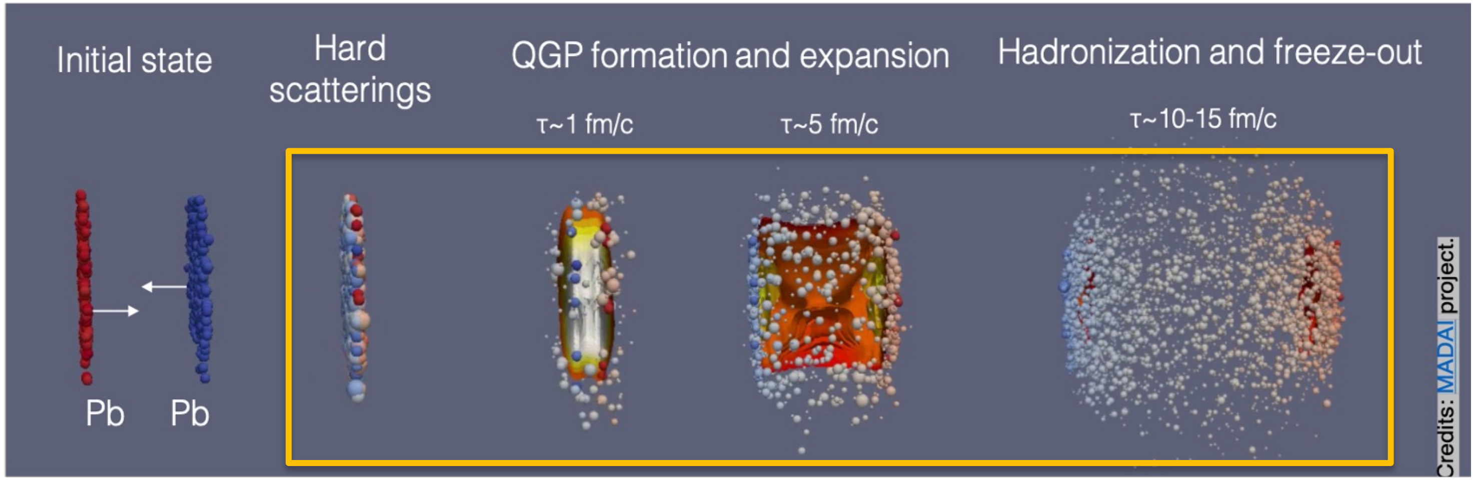


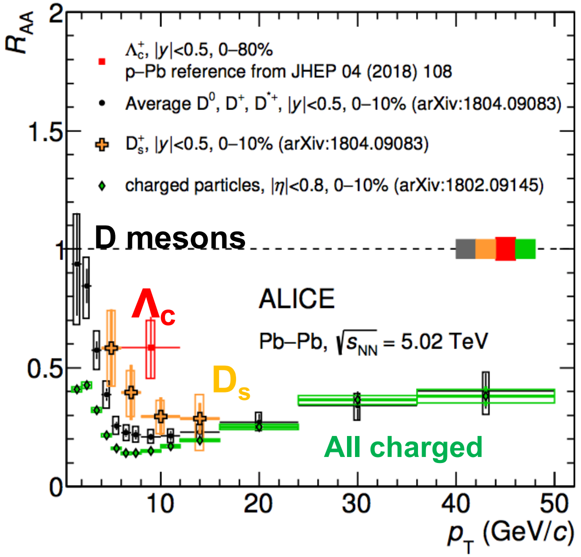
Recap: jets, heavy-flavour



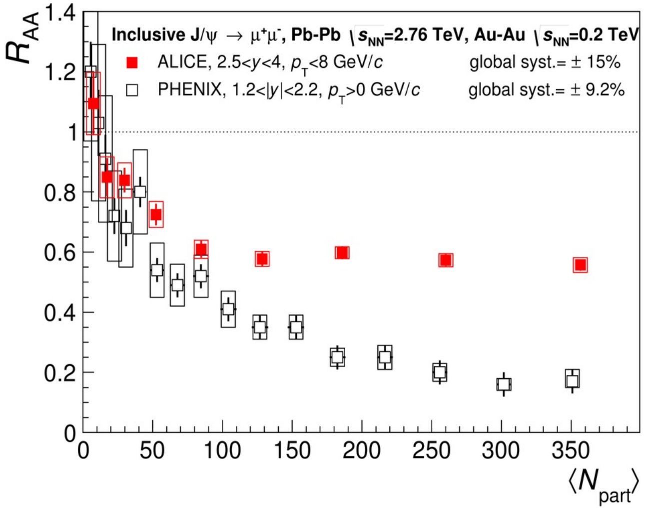
- Produced in hard scattering
- Early production
- Calibrated probes
- Experience the full evolution of the medium

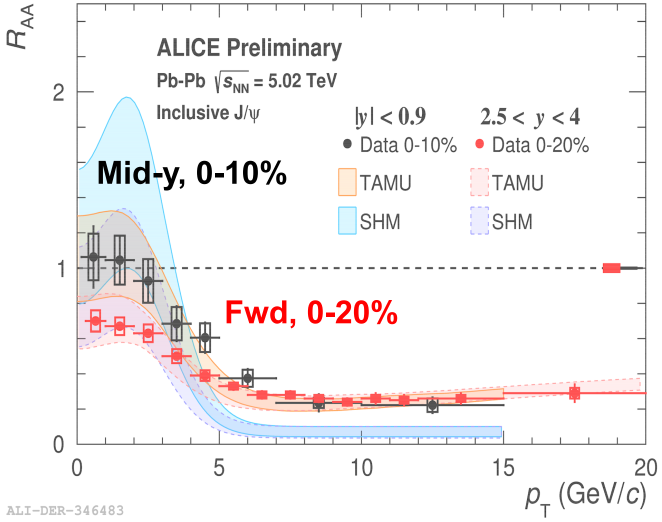
→ medium tomography

Jet quenching

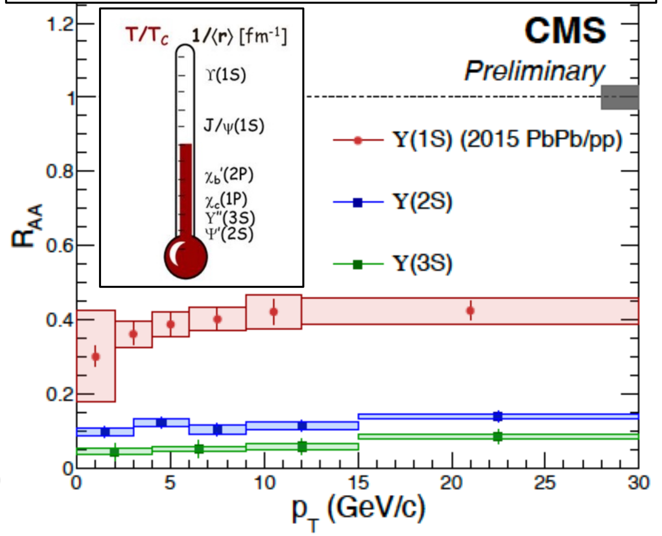


Charmonium suppression and regeneration

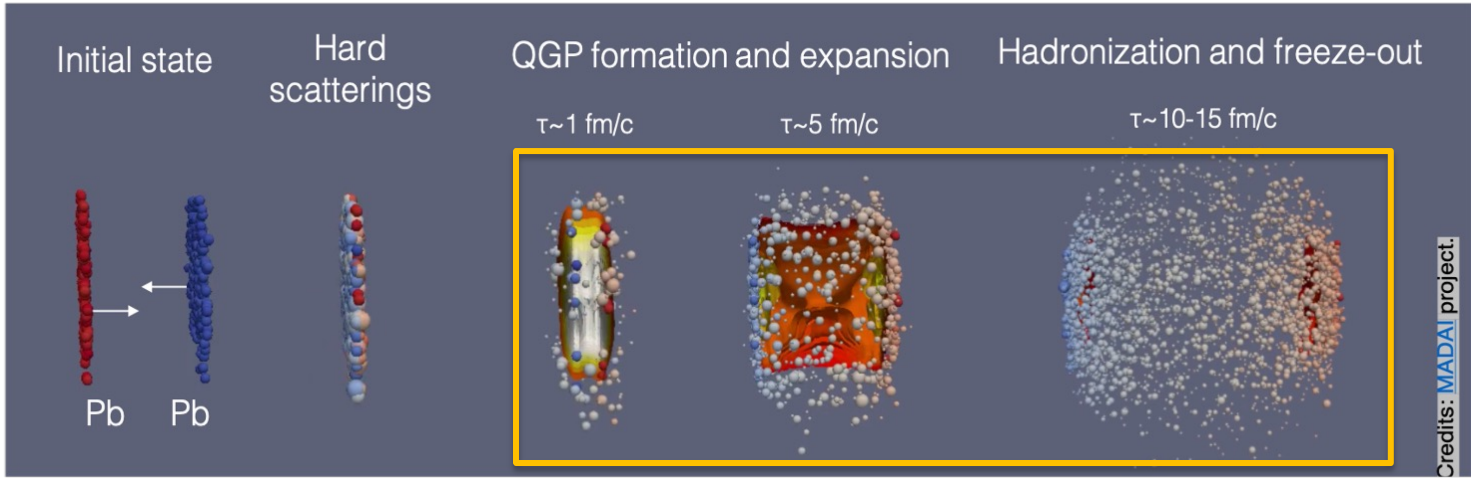


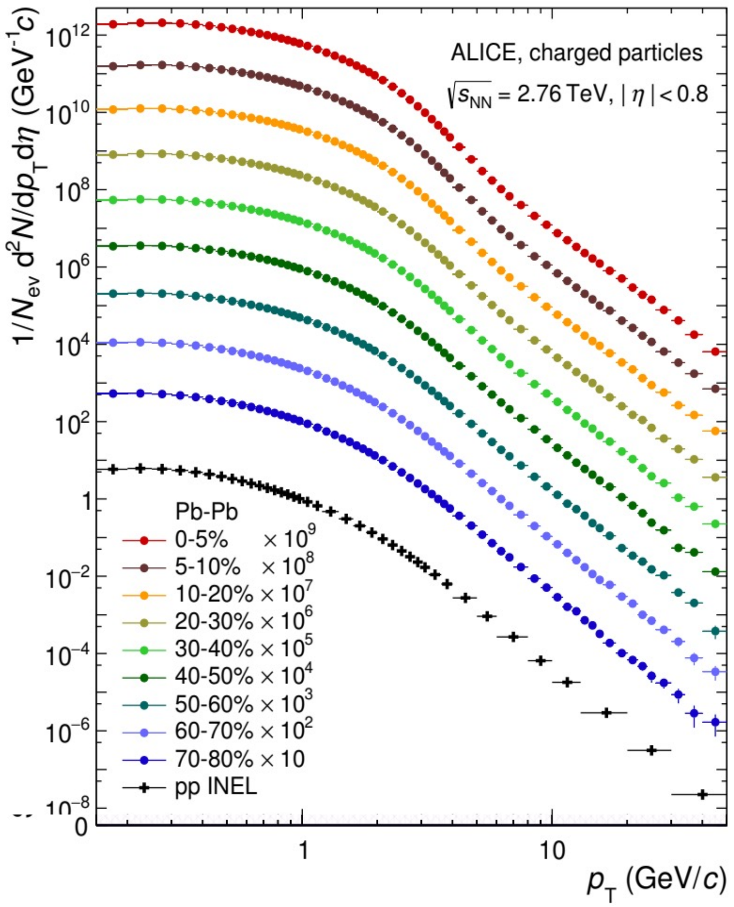


Sequential melting of quarkonia
–> QGP thermometer



Bulk particle production





The bulk of particles is **soft** and composed by **light flavour** hadrons that are produced when the QGP hadronises.

The p_T and azimuthal distributions of hadrons carry information about the **collective evolution** of the system and its thermodynamical properties.

Goal: determine the thermodynamical and transport properties of the QGP

The hadron-gas phase and freeze-outs

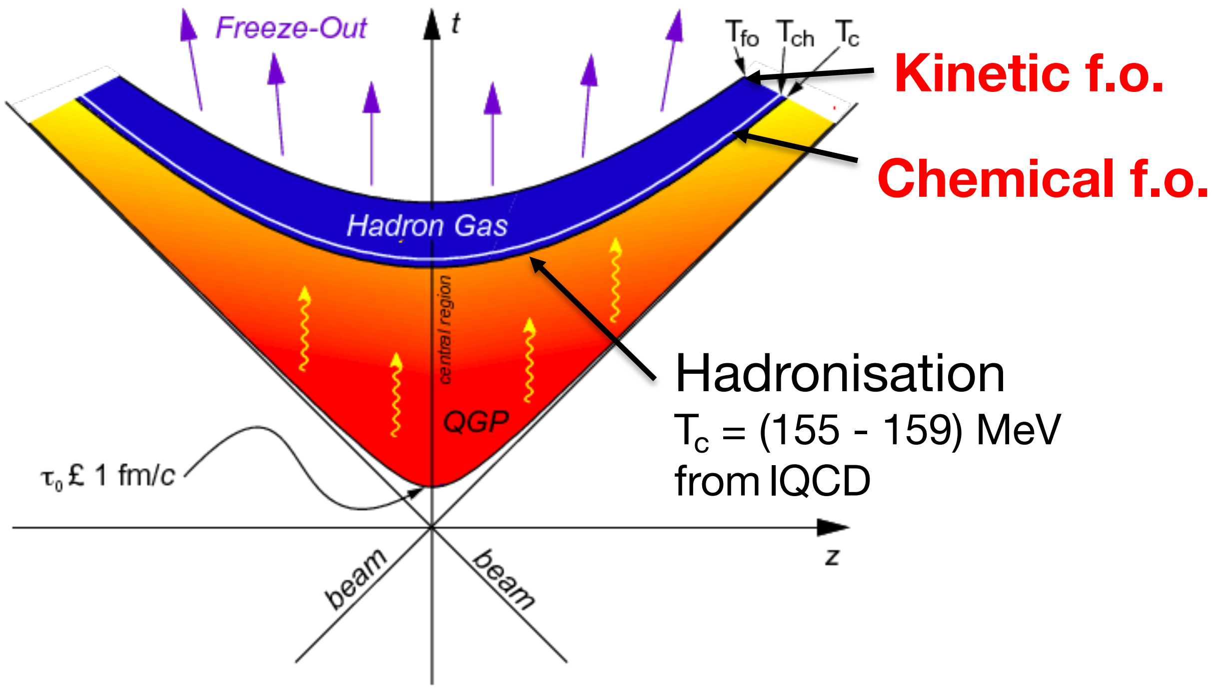
After hadronisation, the system is a hot (T< 155 MeV) and dense gas of hadrons and resonances.

Chemical freeze-out

- Inelastic collisions stop
- Relative particle abundances are fixed

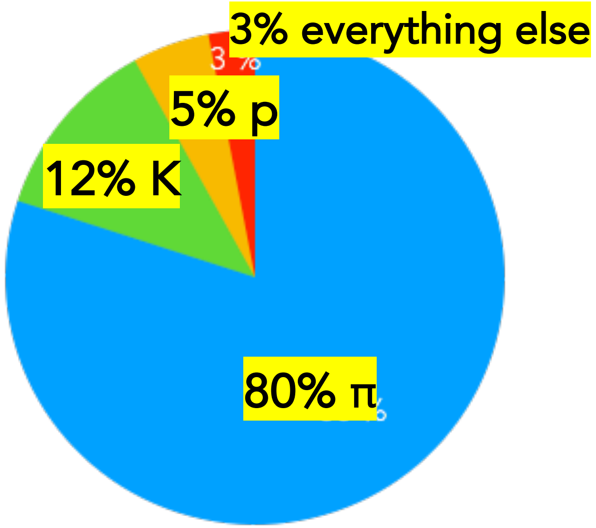
Kinetic freeze-out

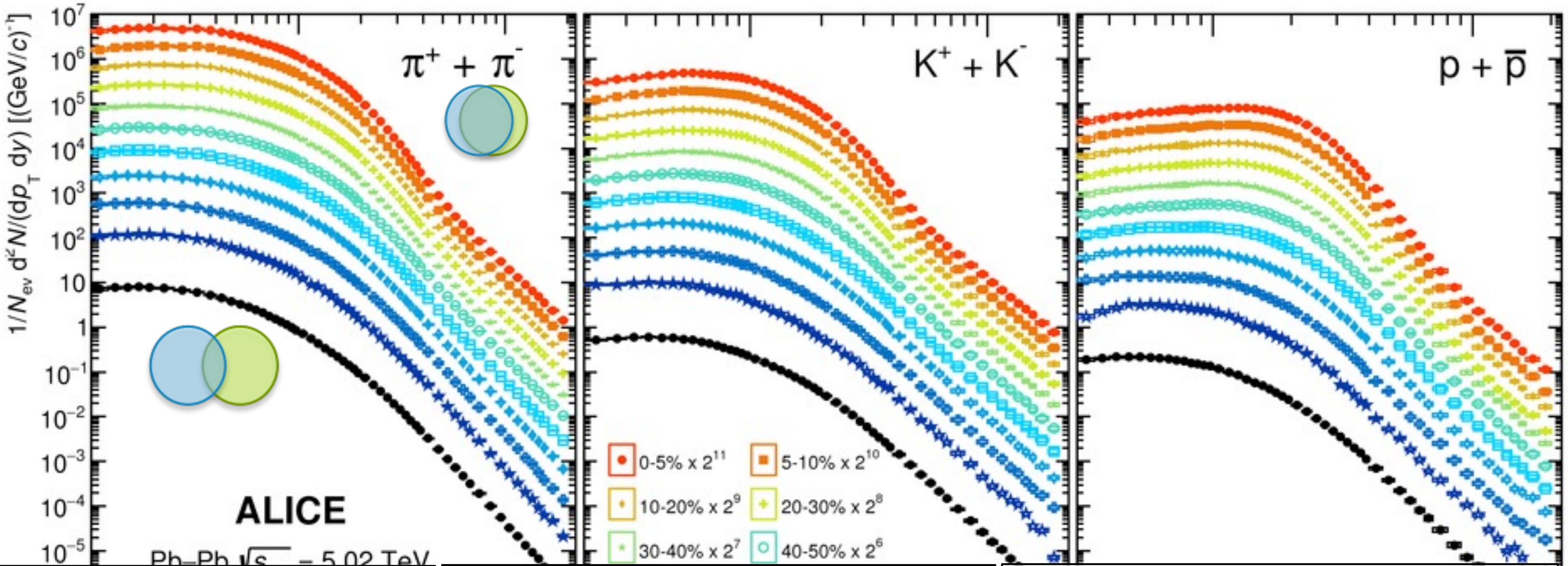
- (pseudo)elastic collisions stop
- Momentum distributions are fixed

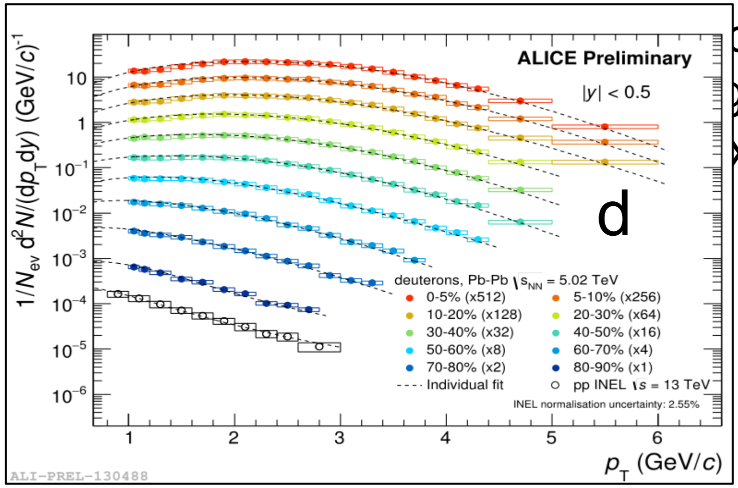


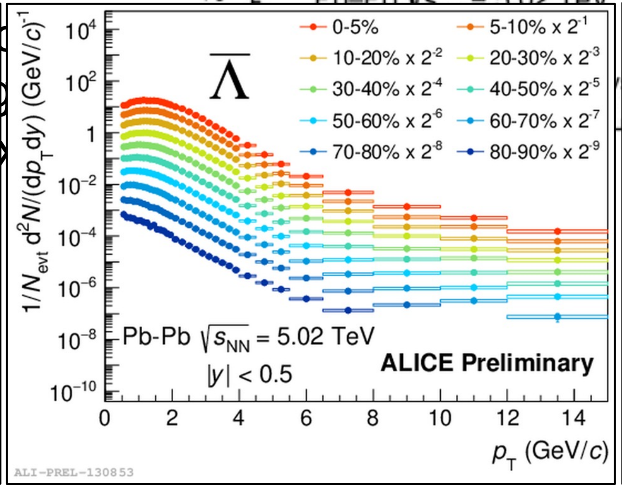
→ Fit abundance of identified hadrons: probe chemical equilibrium at **chemical freeze-out**
→ Fit shape of p_T spectra: probe final hadron kinematics at **kinetic freeze-out**

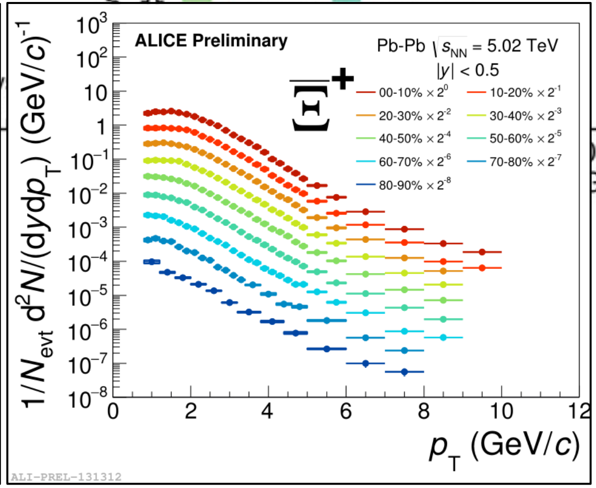
Identified particle production

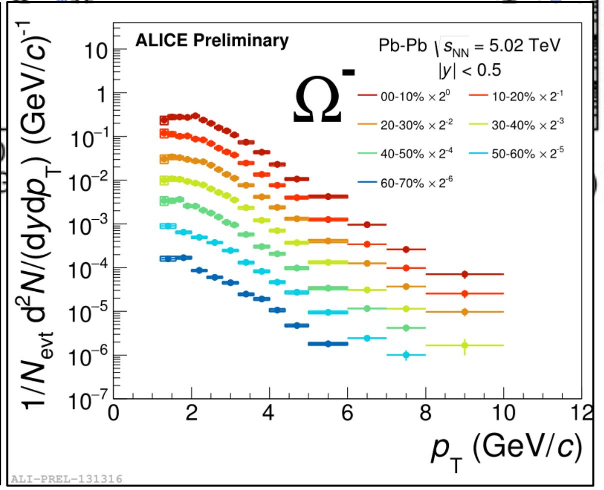












Statistical hadronisation model in a nutshell

It models an ideal relativistic gas of hadrons and resonances in **chemical equilibrium** (as the result of the hadronization of a QGP in thermodynamical equilibrium.

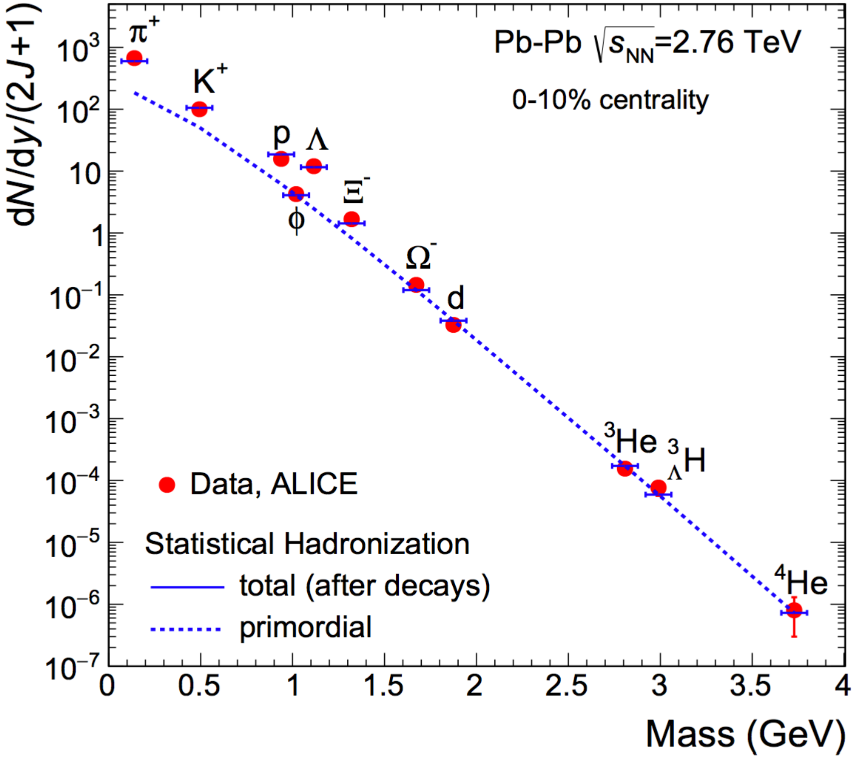
Particle abundances are obtained from the partition function of a Grand Canonical (GC) ensemble

$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i-\mu_i)/T] \pm 1}$$

where chemical potential for quantum numbers are constrained with conservation laws.

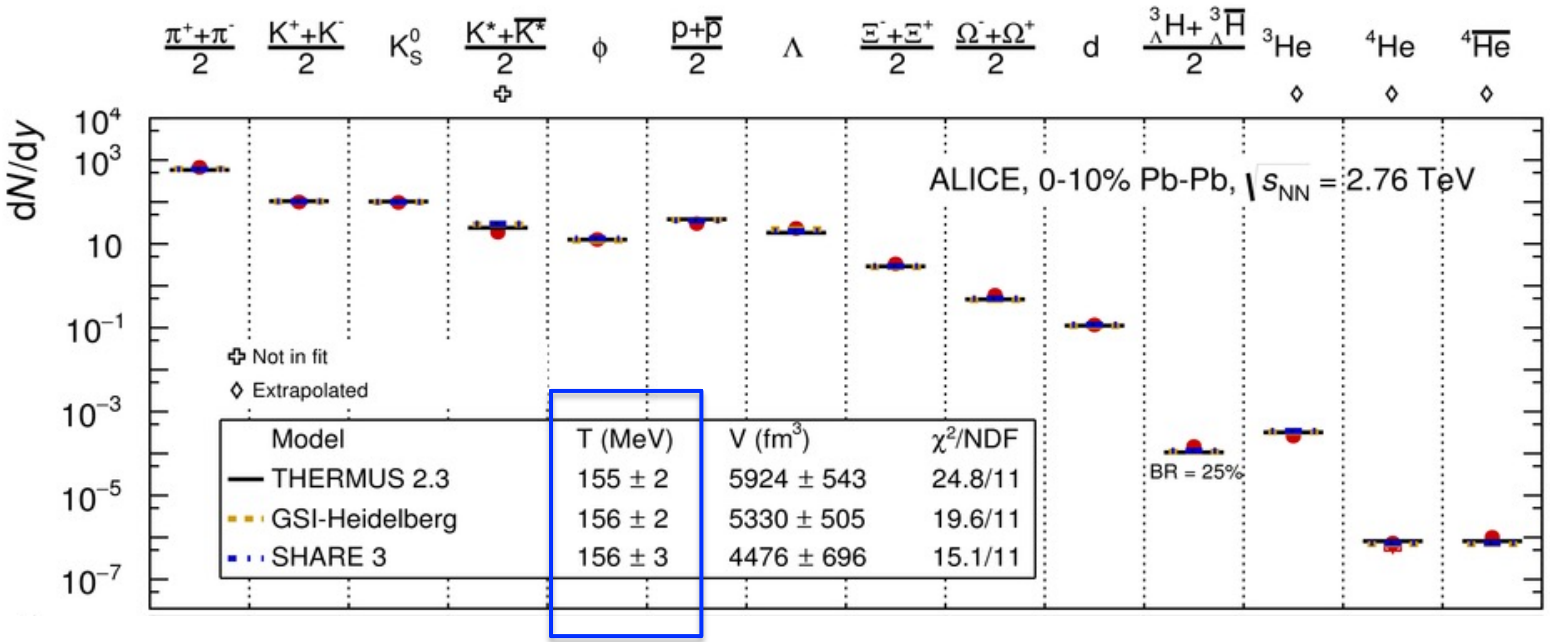
$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i} + \mu_C C_i$$

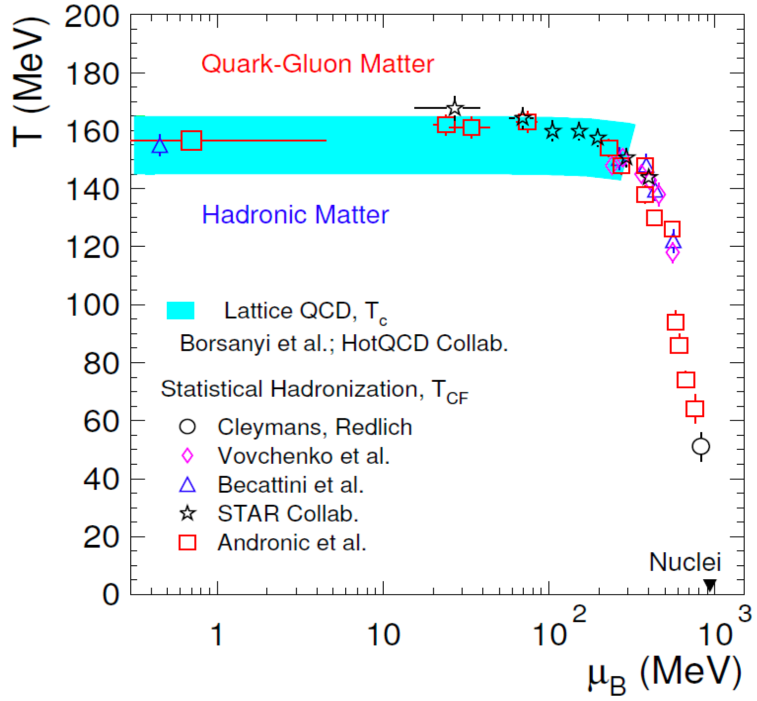
- ❑ Predict yields (see right figure) at a given temperature
- ❑ Fit measured particle yields (or ratios) to extract μ_B, T_{ch}, V.



A. Andronic et al., Nature 561, 321 (2018

Chemical freeze-out temperature





Production of (most) light-flavour hadrons (and anti-nuclei) is described (χ^2/ndf ~ 2) by thermal models with a **single chemical freeze-out** temperature, **T_{ch} ≈ 156 MeV**

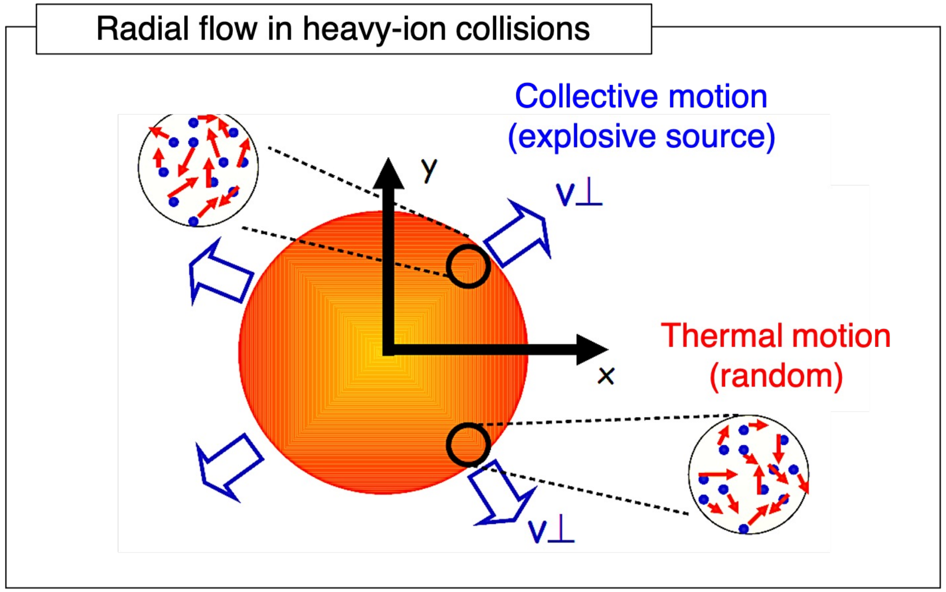
→ Approaches the critical temperature roof from lattice QCD: **limiting temperature** for hadrons!

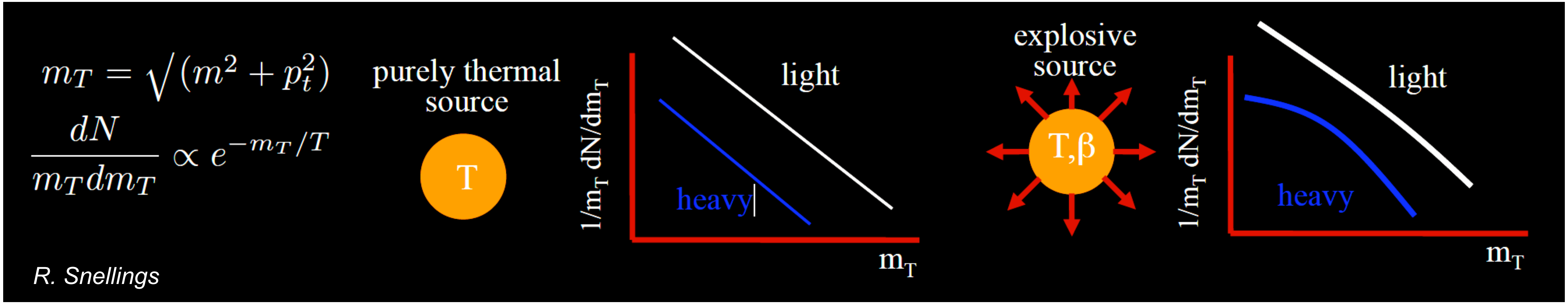
→ the success of the model in fitting yields over 10 orders of magnitude supports the picture of a system in **local thermodynamical equilibrium**

Hydrodynamics at play: radial flow 1/2

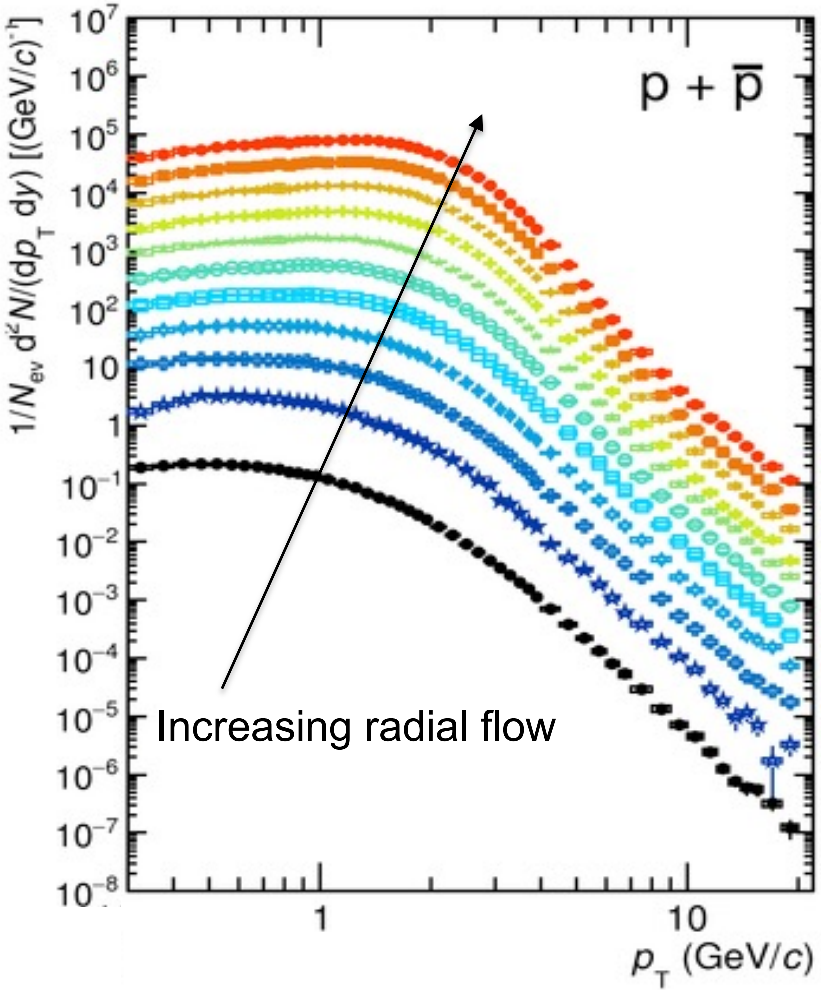
A **collective motion** is superimposed to the thermal motion of particles → the system as a **medium**

Radial flow
radial expansion of a medium in the vacuum under a common velocity field
→ Affects the low p_T distribution of hadrons and their ratios depending on their mass



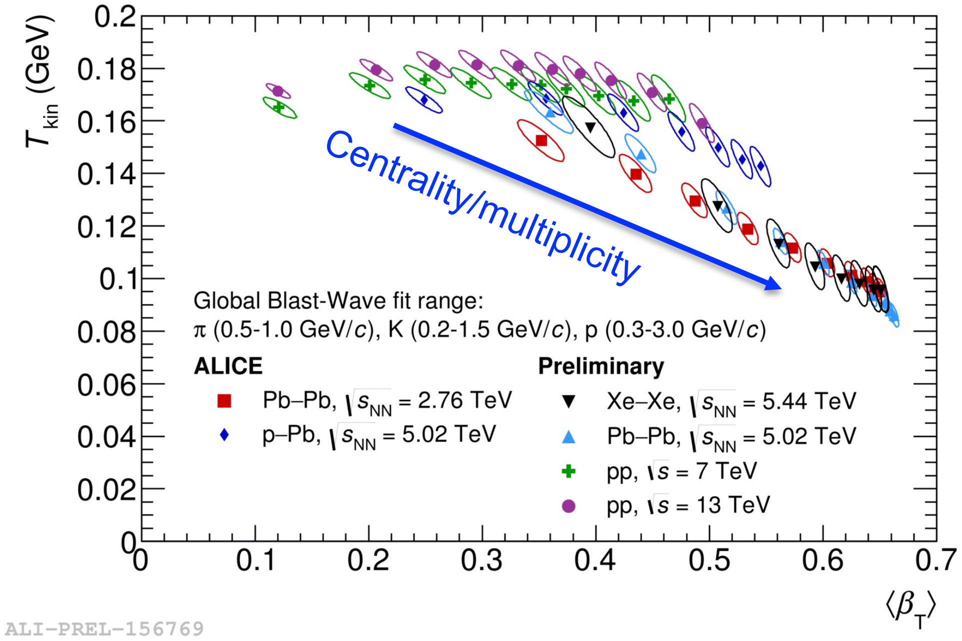


Hydrodynamics at play: radial flow 2/2



At low p_T, the radial flow "pushes" particles to higher momenta
→ spectra get "harder" for more central collisions
→ mass dependence

A simplified hydrodynamical model, the Boltzmann-Gibbs blast-wave model is used to **quantify radial flow and the kinetic freeze-out temperature.**



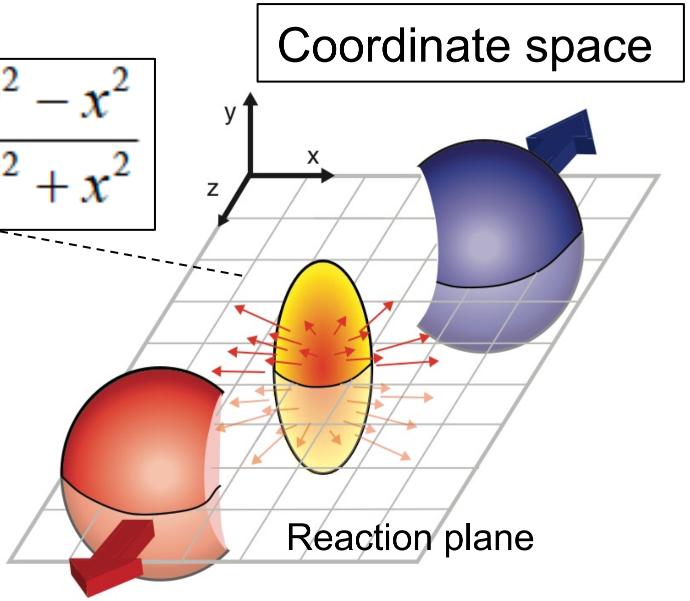
More central (higher multiplicity) events have lower T_{kin} and higher flow velocity

T_{kin} ~ 100-140 MeV

Hydrodynamics at play: anisotropic flow (1/2)

Initial geometrical anisotropy ("almond" shape) in non-central HI collisions → eccentricity

$$\varepsilon = \frac{y^2 - x^2}{y^2 + x^2}$$



Pressure gradients develop → more and faster particles along the reaction plane than out-of-plane

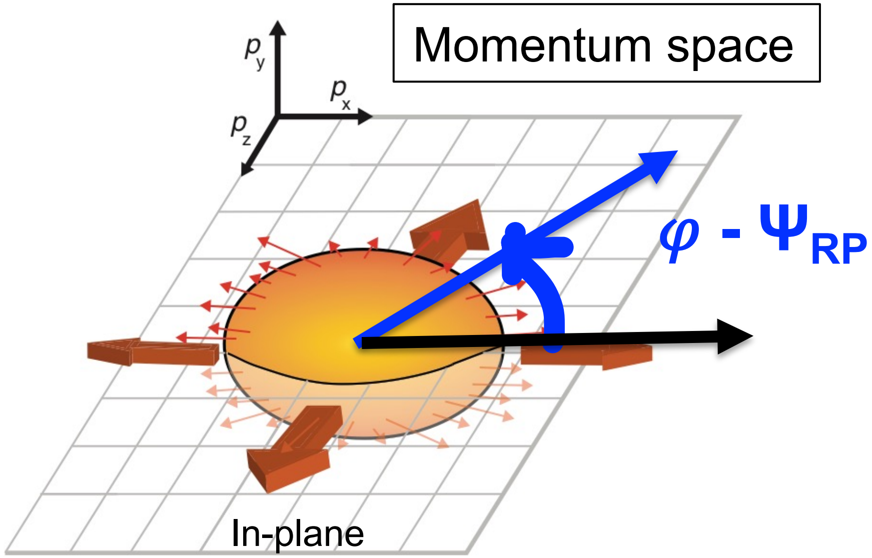
Scatterings among produced particles convert **anisotropy** in coordinate space into an observable momentum anisotropy

→ **anisotropic flow**

→ quantified by a Fourier expansion in azimuthal angle φ

v_n = **harmonics**

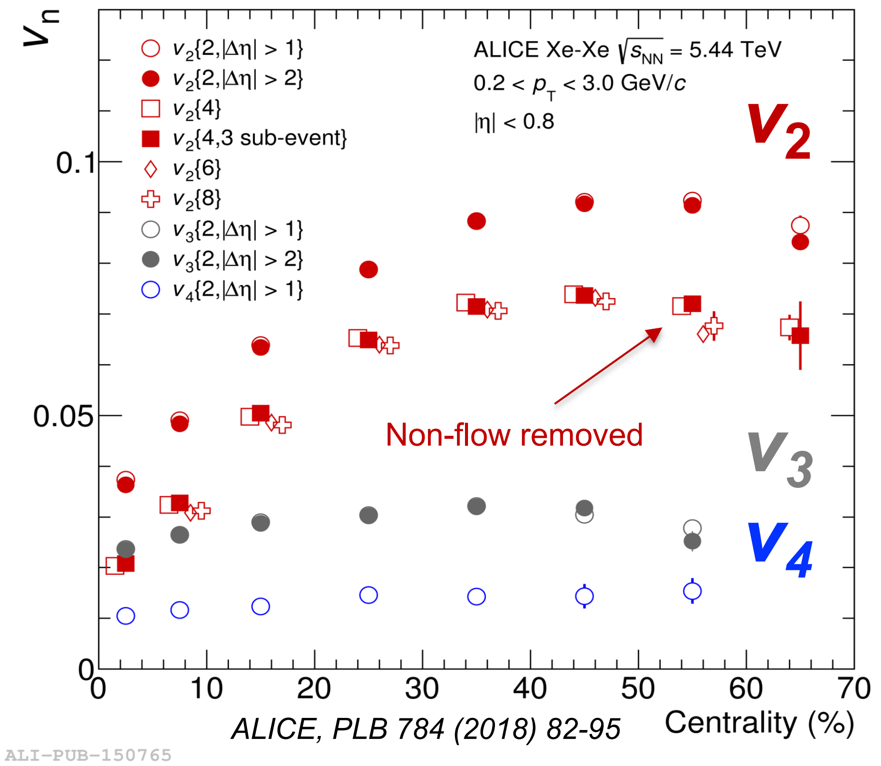
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+2\sum_{n=1}^{\infty} v_n \cos[n(\varphi-\Psi_n)]\right),$$

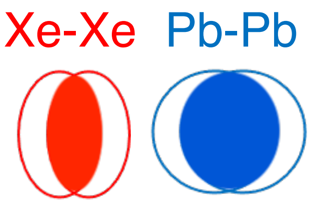


Hydrodynamics at play: anisotropic flow (2/2)

The **strong centrality dependence** of v_2 reflects the degree of "anisotropy" in initial geometry.

Fluctuations of the initial state energy-density lead to different shapes of the overlap region
→ **non-zero higher-order flow** coefficients ("harmonics")





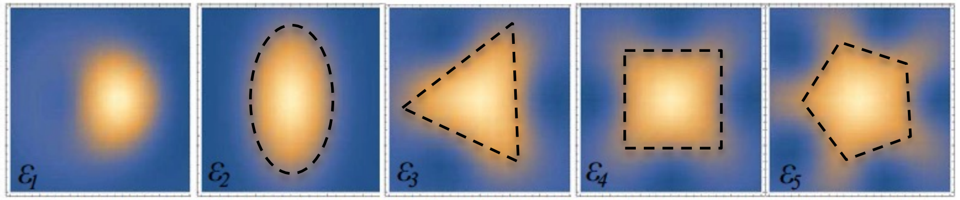
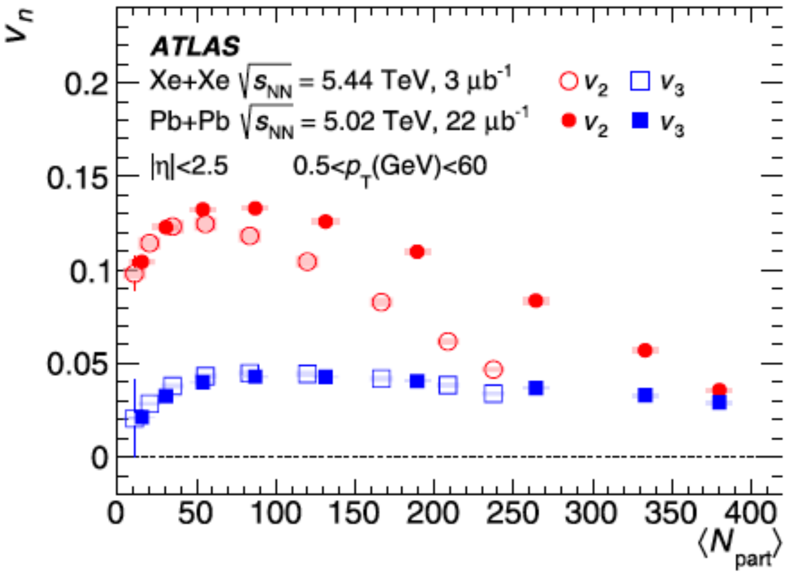
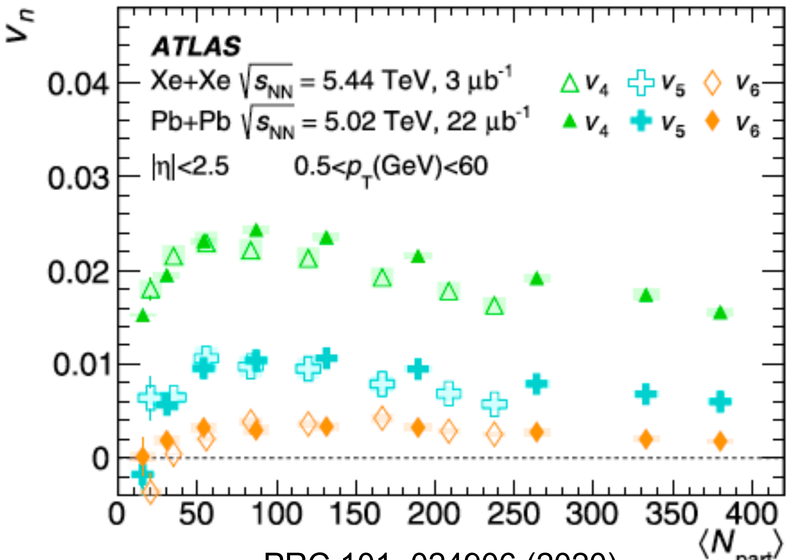


Fig. 2. (color online) Characteristic shapes of the deformed initial state density profile, corresponding to anisotropies of $\mathcal{E}_1$, $\mathcal{E}_2$, $\mathcal{E}_3$, $\mathcal{E}_4$ and $\mathcal{E}_5$ (from left to right).

Li Yan 2018 Chin. Phys. C 42 042001

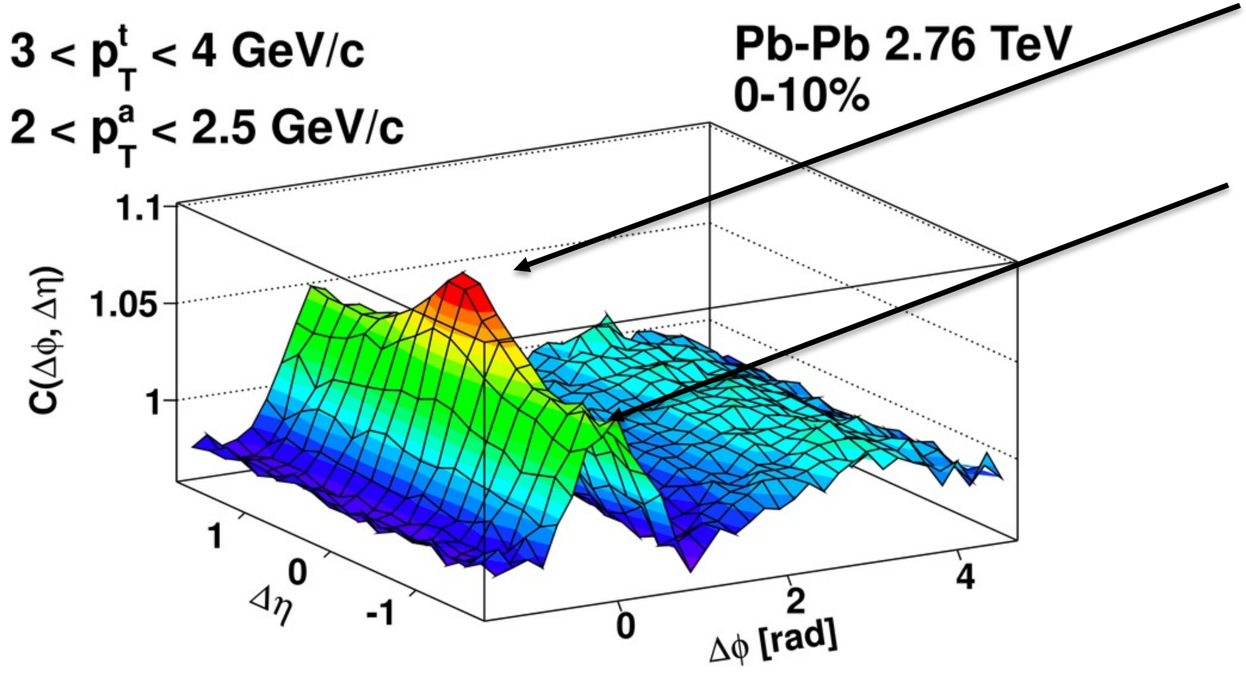




PRC 101, 024906 (2020)

Two-particle correlations in Pb-Pb collisions

Collectivity can also be studied by looking at correlations of two particles vs $\Delta\eta$ (difference in rapidity) and $\Delta\varphi$ (difference in azimuthal angle).



ALICE, Phys.Lett. B 708 (2012) 249-264

Peak at $\Delta\eta \sim 0$:
short-range correlations → **jets**

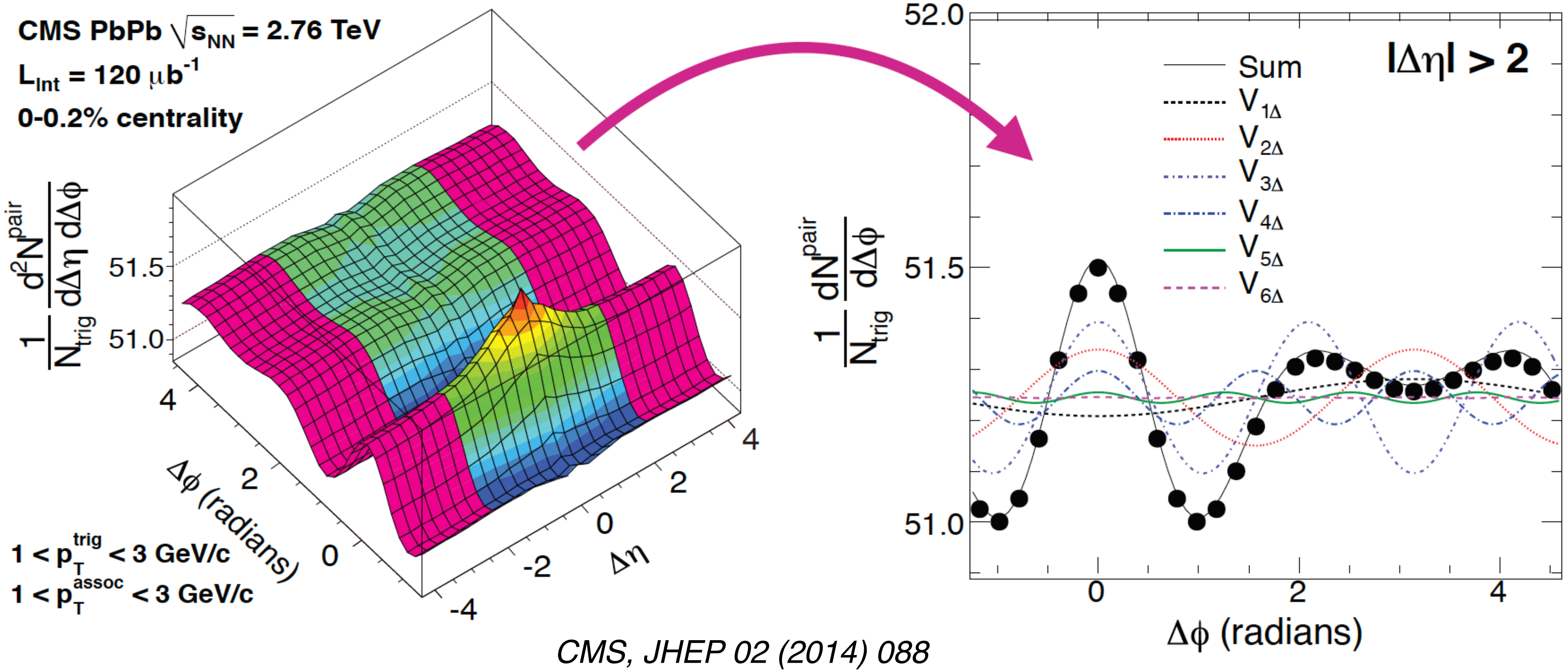
Broad **"ridge"** in a wide $\Delta\eta$ range:
long-range correlations emerging from early times (causality) → **anisotropic flow**

In azimuth: structure determined by the medium response to the initial transverse geometry

Two-particle correlations in Pb-Pb collisions

Collectivity can also be studied by looking at correlations of two particles vs $\Delta\eta$ (difference in rapidity) and $\Delta\varphi$ (difference in azimuthal angle).

→ Decomposition in Fourier series of the azimuthal distribution at large η.



CMS, JHEP 02 (2014) 088

Hydrodynamical modeling

Ideal hydrodynamics

$$\nabla_\mu T^{\mu\nu} = 0 \qquad \nabla_\mu J^\mu_B = 0$$

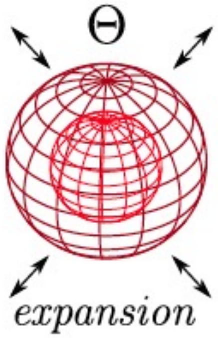
- applies to a system in local equilibrium (e.g. thermodynamical)
- requires energy and charge conservation
- system is described by energy density ε, pressure P, velocity u^ν, and charge n and by 5 equation of motion, closed by one equation-of-state (EOS) $\varepsilon = \varepsilon(P)$
- The response of the system to external solicitation is controlled by the EOS

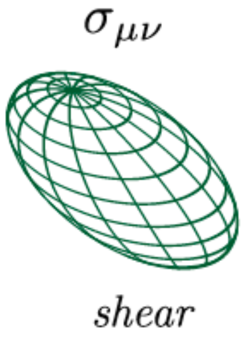
Viscous hydrodynamics

- Includes corrections for dissipative effects:
  bulk ζ and shear viscosity η, charge diffusion, κ

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (P - \zeta\Theta)\Delta^{\mu\nu} - 2\eta\sigma^{\mu\nu}$$

$$J^\mu = q u^\mu + \kappa \nabla^\mu_\perp (\mu/T)$$





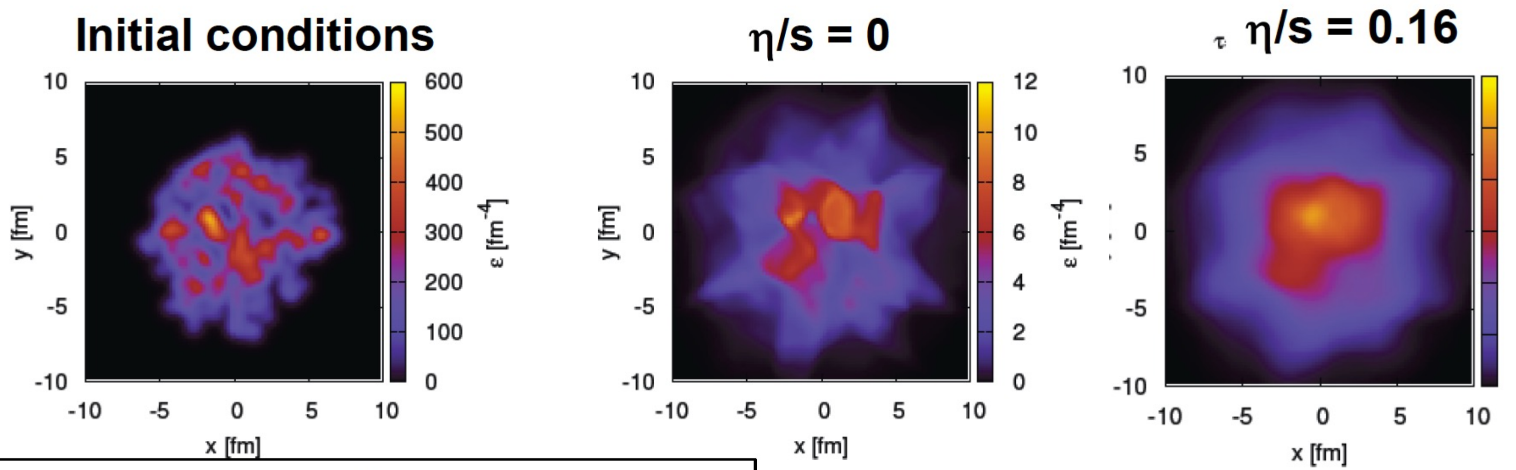
Diffusion

Figs. from Rezzolla and Zanotti, 2013

Shear viscosity

Shear viscosity (expressed as viscosity over entropy, η/s) washes out initial-state anisotropies

- Larger consequences on higher-order harmonics
- Larger η/s reduces flow

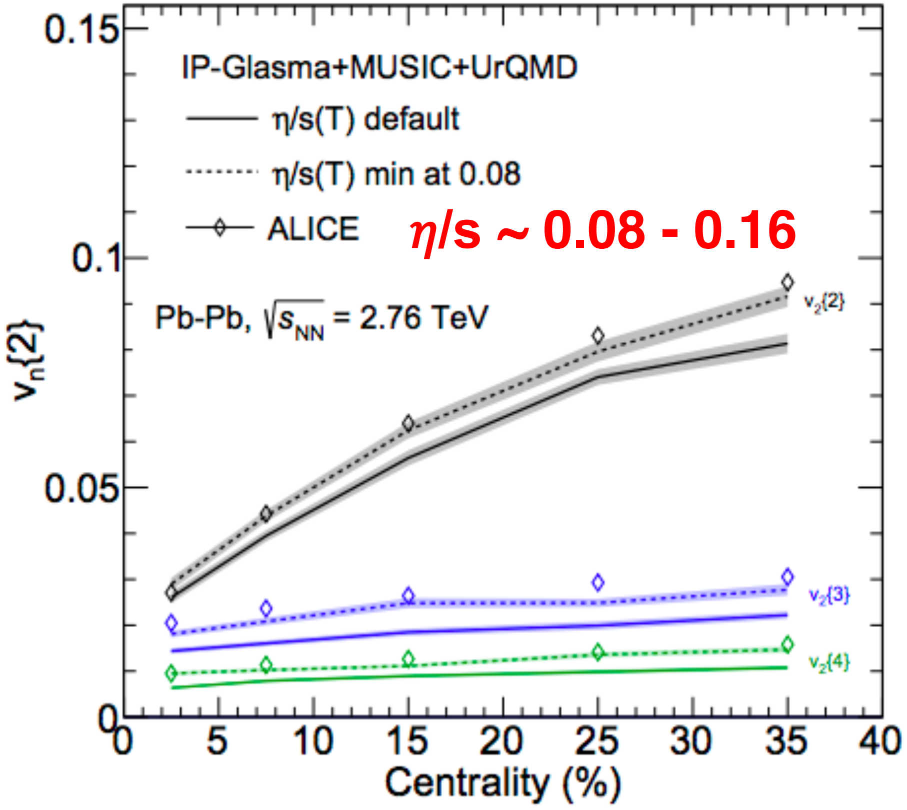


Water: η/s ~ 30 | Olive oil η/s ~ 240

MUSIC, Sangyo

Larger η/s reduces flow

Elliptic flow vs viscous hydro model

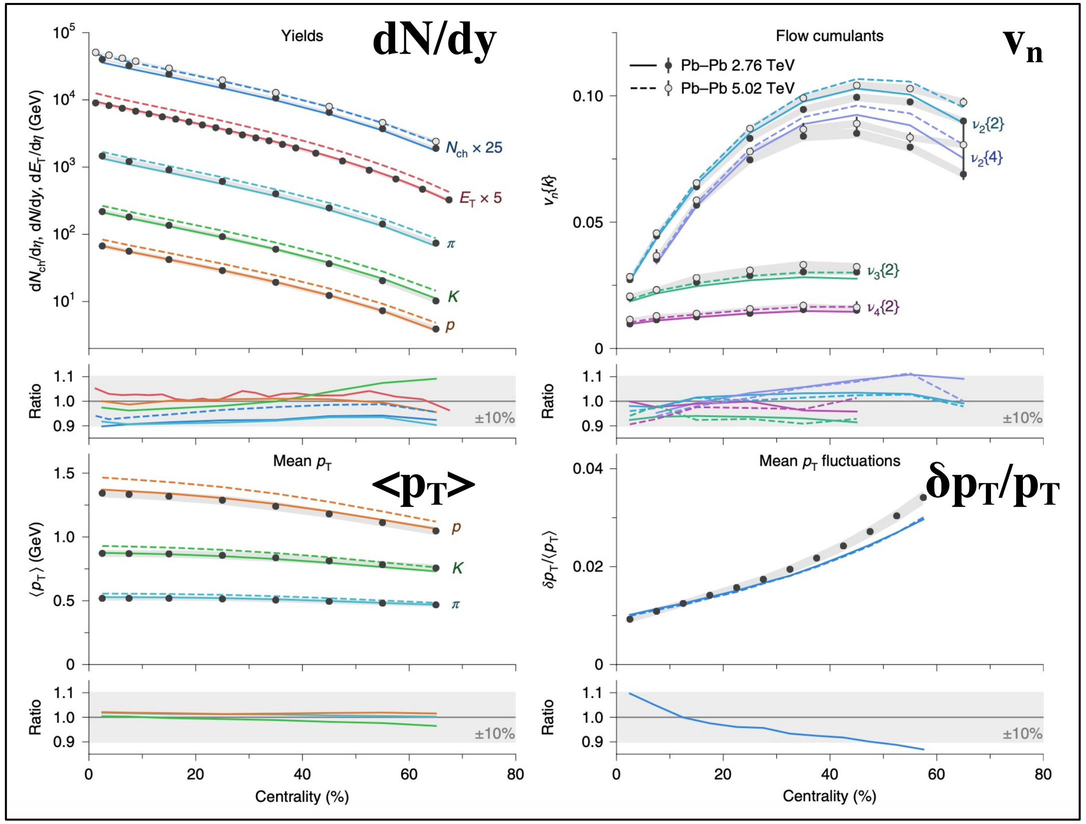


Kovtun, Son, and Starinets

Measured v_2 is described very well by hydrodynamic models
→ **QGP behaves as a ~perfect liquid!**

QGP properties from flow 1/2

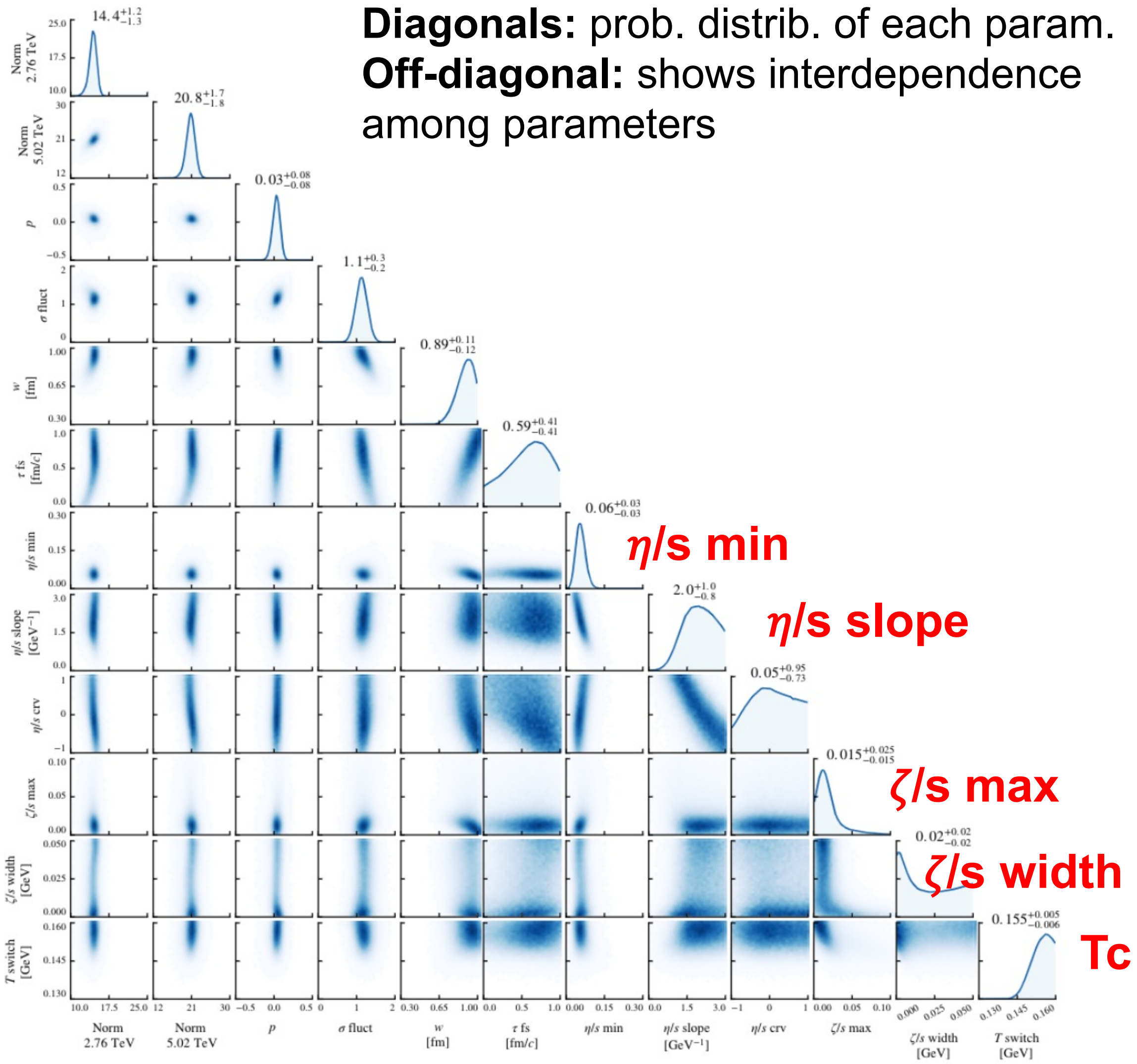
Bayesian analysis of yields, mean p_T, flow harmonics measured by ALICE has been used to extract the QGP properties.



J. E. Bernhard et al, Nature Physics 15 (2019) 1113

S.A. Bass et al. / Nuclear Physics A 967 (2017) 67–73

Diagonals: prob. distrib. of each param.
Off-diagonal: shows interdependence among parameters



QGP properties from flow 2/2

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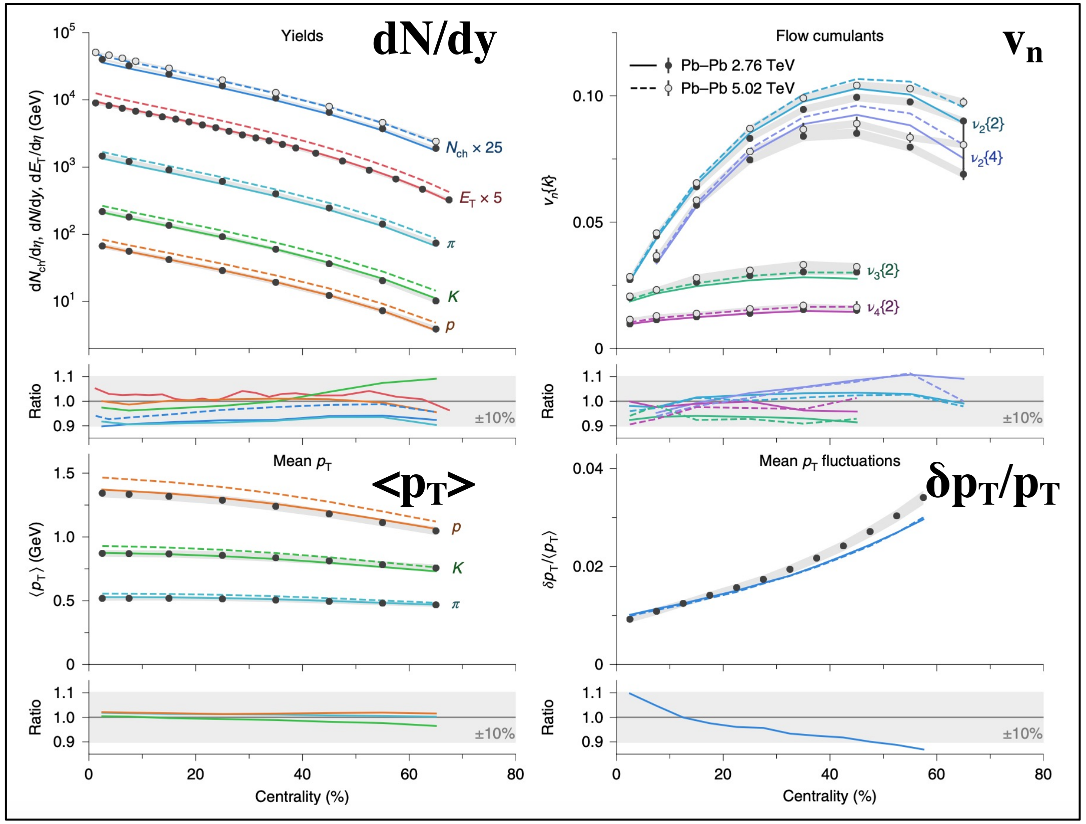

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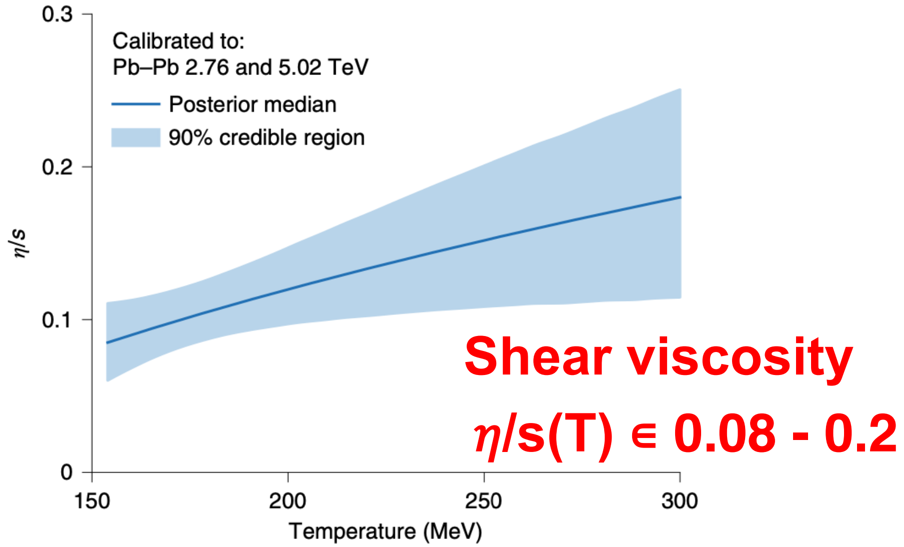
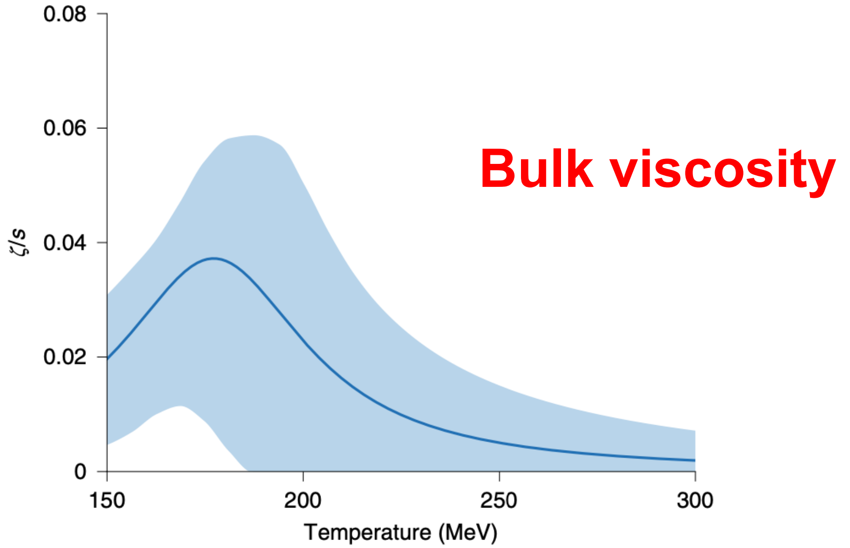




Hadronisation by fragmentation and recombination

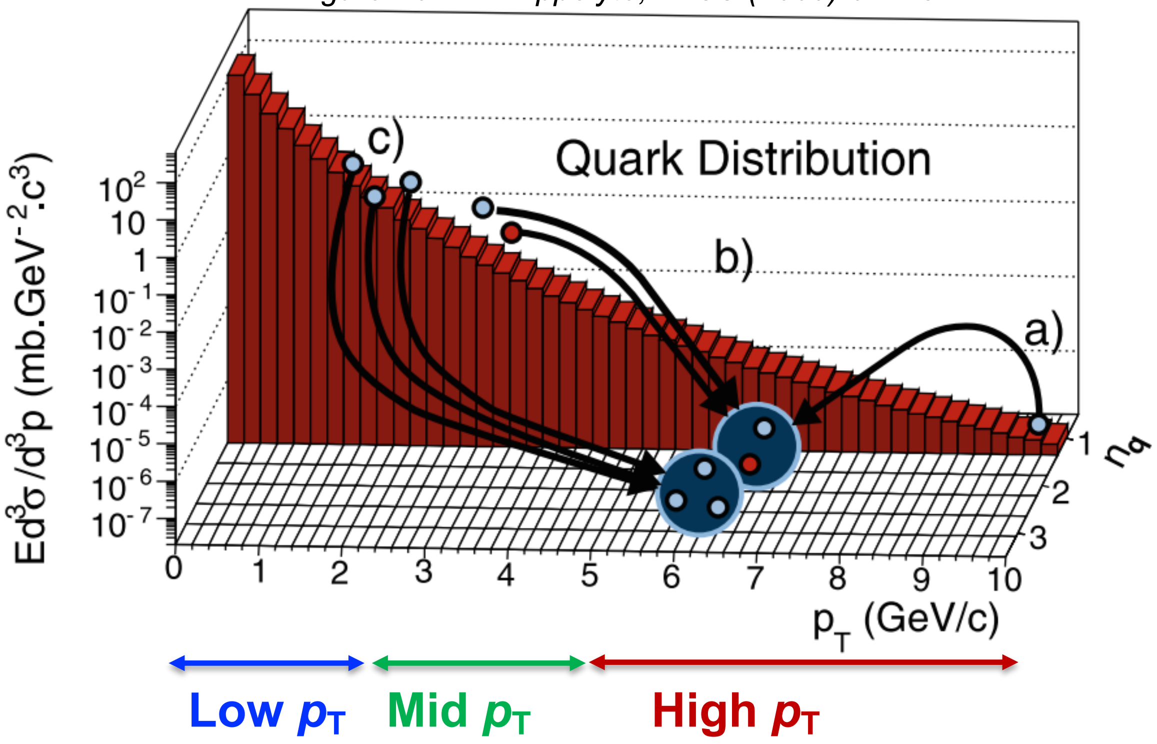
Ratios of production distribution of baryons to mesons are sensitive to competing particle production mechanisms, depending on transverse momentum

Fragmentation (a) of high-p_T partons into mid-p_T hadrons

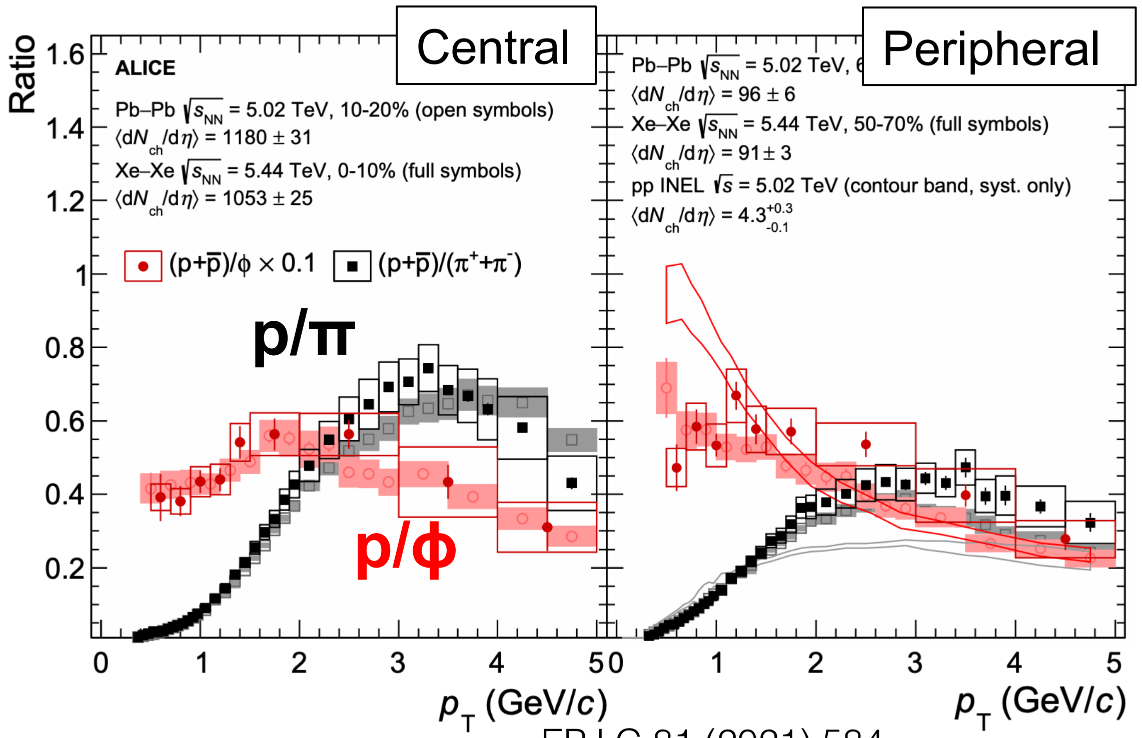
Recombination (b,c) of low-p_T partons close in phase space into mid-p_T hadrons via coalescence

+ influence of **collective flow**

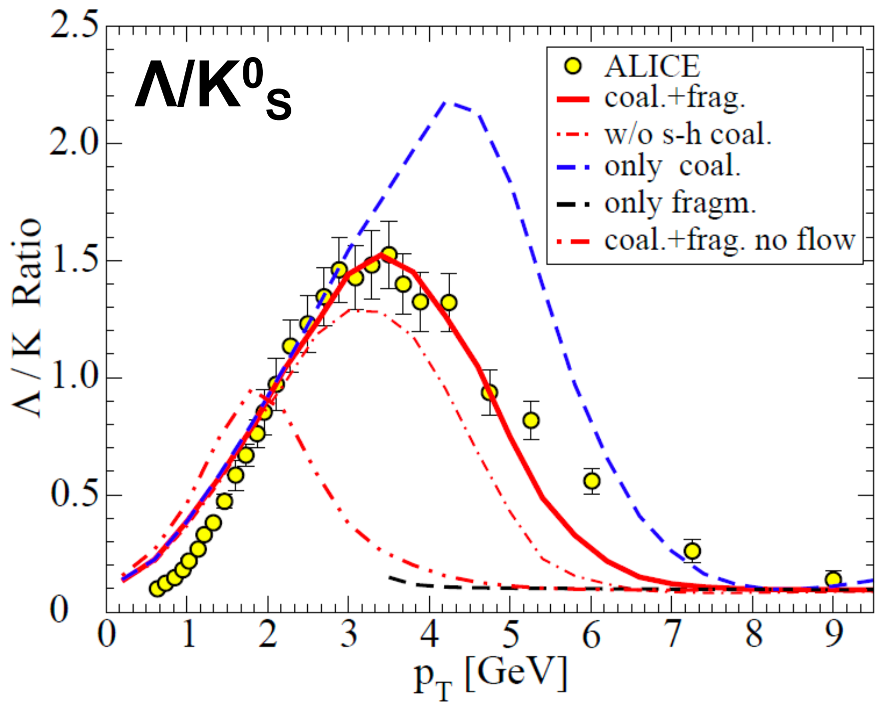
Figure from B. Hippolyte, EPJC (2009) 62: 237–242



Investigating hadronization mechanisms



EPJ C 81 (2021) 584



V. Minissale et al., PRC 92 (2015) 054904

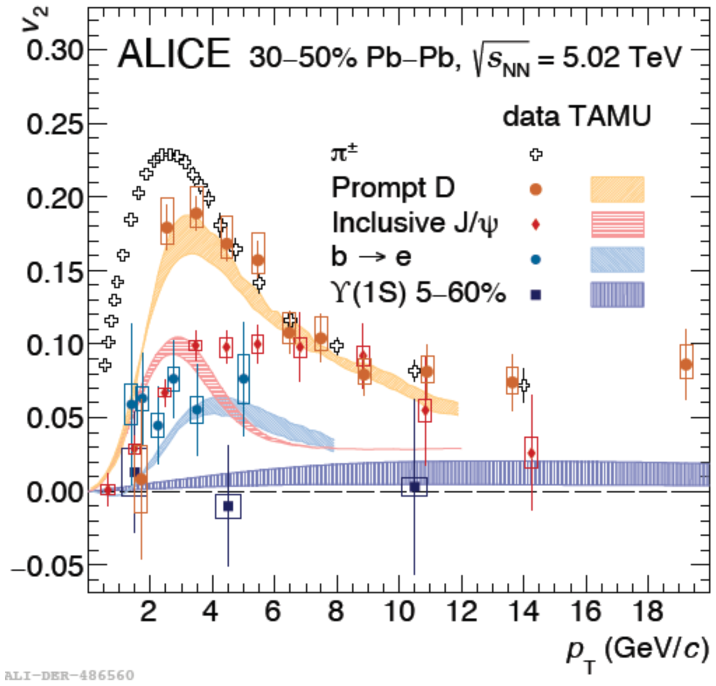
At intermediate p_T, a **baryon/meson enhancement** is observed and more evident for particle ratios where mass difference is larger, e.g. p/π, Λ/K^0_S and less evident for small Δm, e.g. p/ϕ

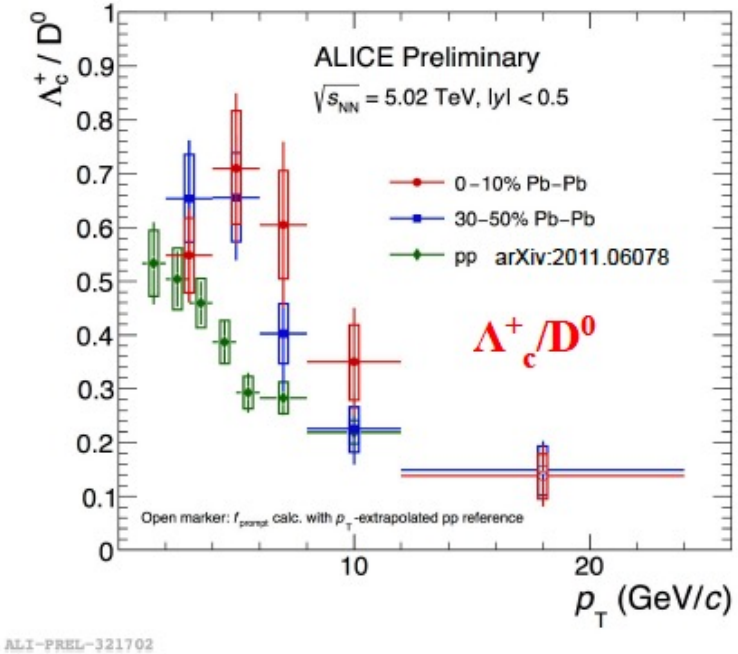
Baryon/meson ratios are sensitive to hadronisation mechanisms
→ interplay of **radial flow** and **recombination**

Hadronisation via recombination/coalescence

Recombination/coalescence of (hard) charm quarks traveling through the QGP with a light quarks from the medium (QGP) would result in modifications of the spectra and R_{AA} at low/mid p_T.

- Charm $v_2 > 0$ → initially produced isotropically, charm is strongly affected by the QCD medium
- Modification of the p_T distribution and v_2 of open-HF hadron → c picks up flow from the light q
- Modification of chemistry, e.g. enhancement of Λ_c/D





Summary

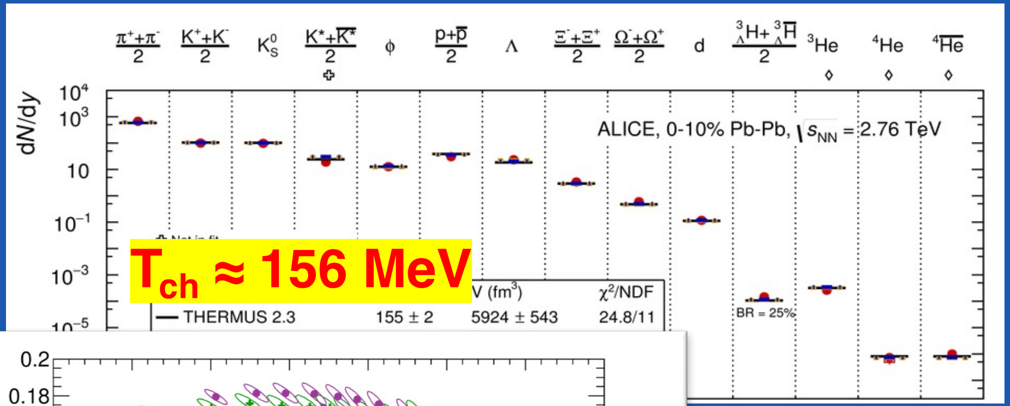
Bulk particle abundances are described by the statistical hadronization model assuming chemical equilibrium and with **T_{ch} ~ 156 MeV**

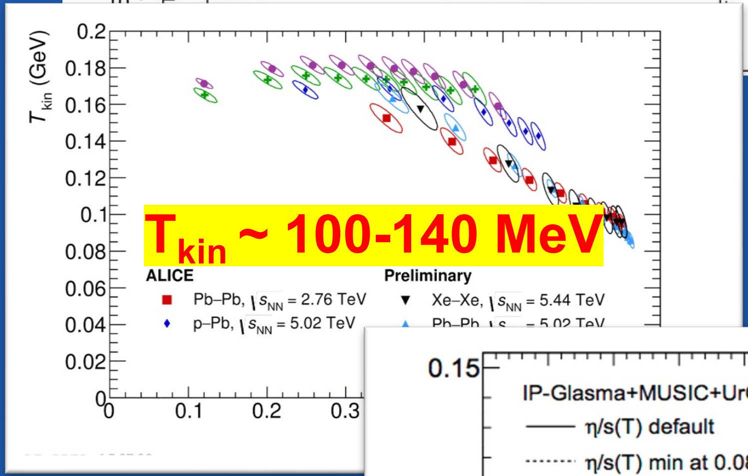
The QGP expands rapidly under **radial flow**.

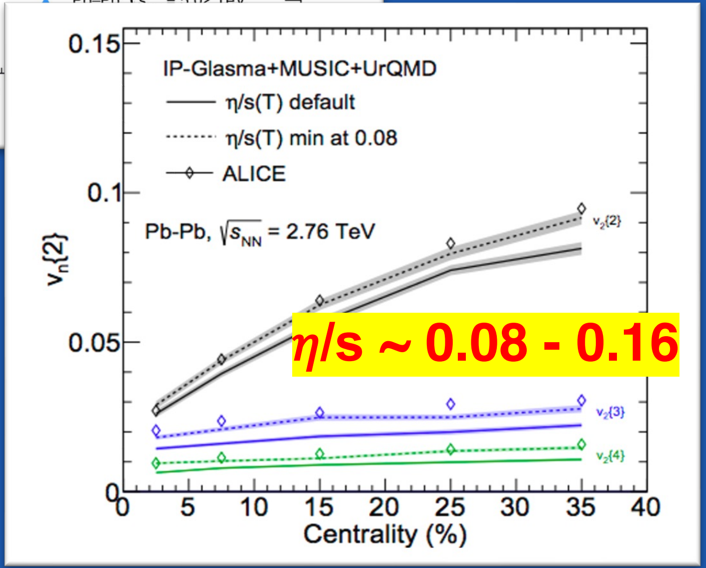
Spatial anisotropy of the initial collision region causes **anisotropic flow**.

Spectra and flow coefficients are well described by viscous hydrodynamics with a very low shear viscosity (**η/s ~ 0.08 –0.16**) → "perfect liquid"

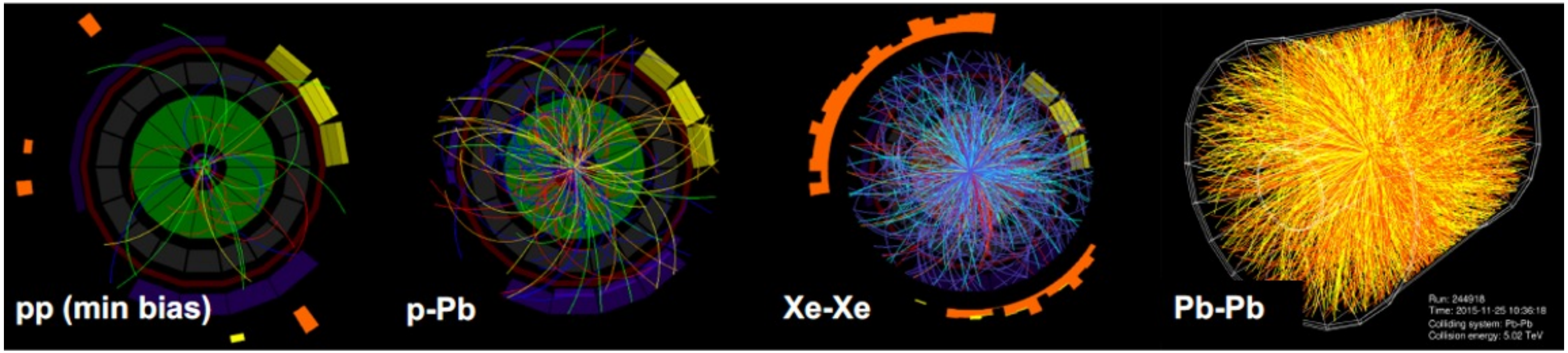
The **success of SHM and hydrodynamic** description also supports the idea of a medium in local **thermodynamical equilibrium.**







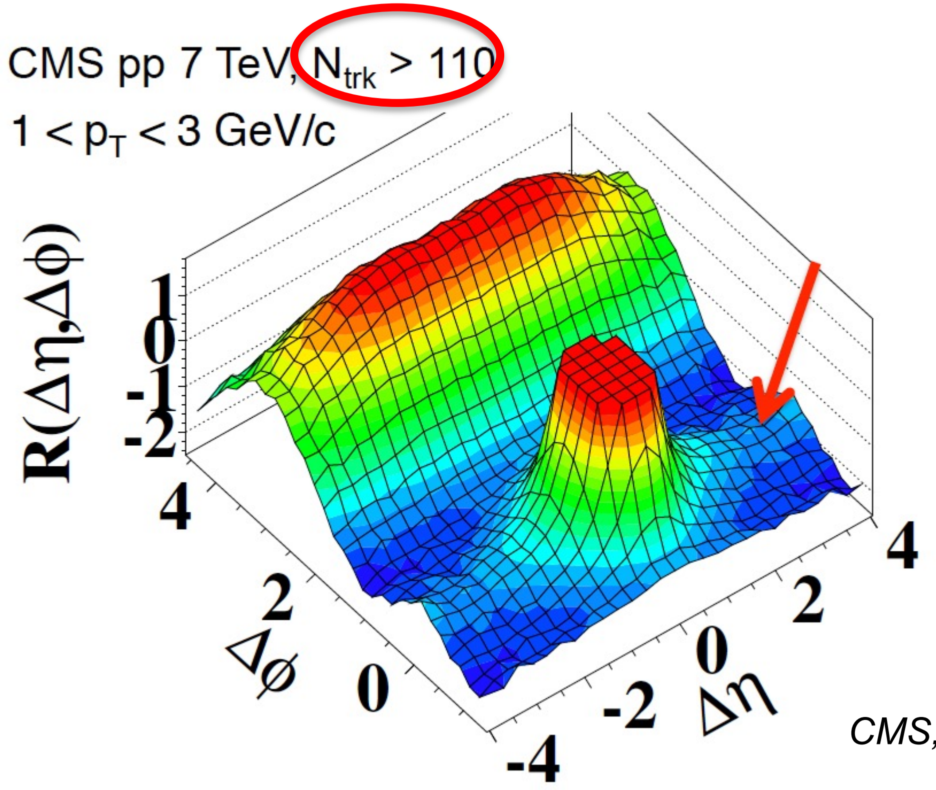
From large to small systems

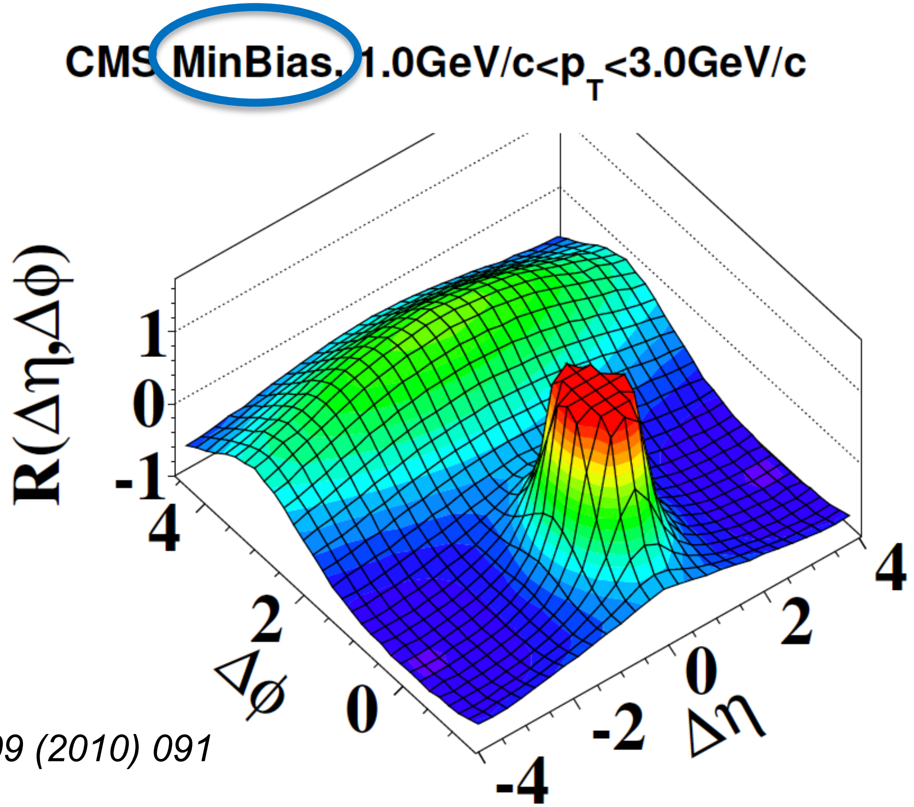


First signs of collectivity in small systems

The first indication of the presence of collective phenomena in high-multiplicity pp collisions came from the study of two-particle correlations vs $\Delta\eta$ and $\Delta\varphi$.

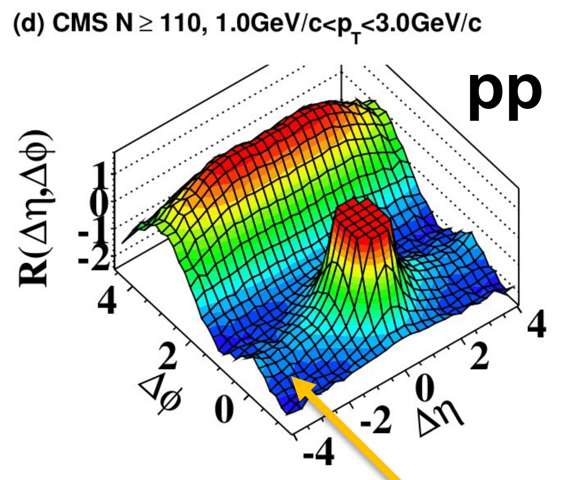
A **ridge** is observed in high multiplicity pp but not in minimum bias pp collisions!
The ridge is not reproduced by pp Monte Carlo generators, e.g. PYTHIA.



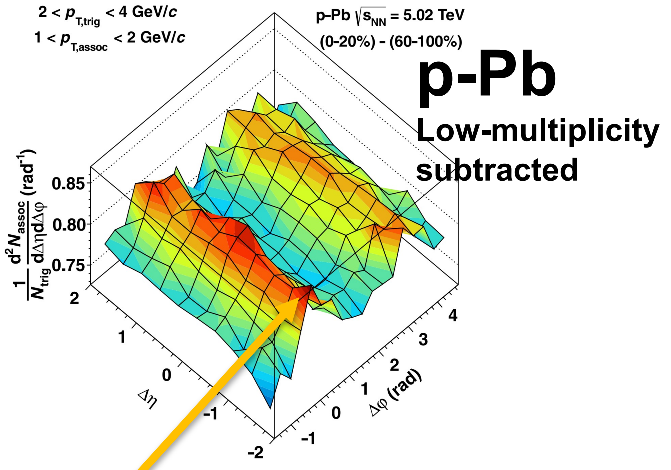


CMS, JHEP 09 (2010) 091

The “ridge” in pp, p-Pb collisions

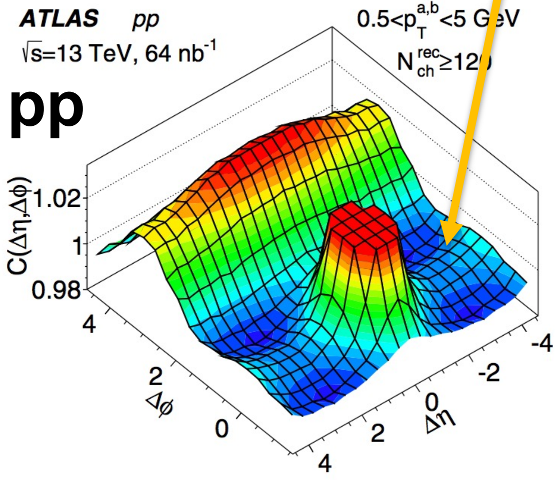


CMS, JHEP 09 (2010) 091

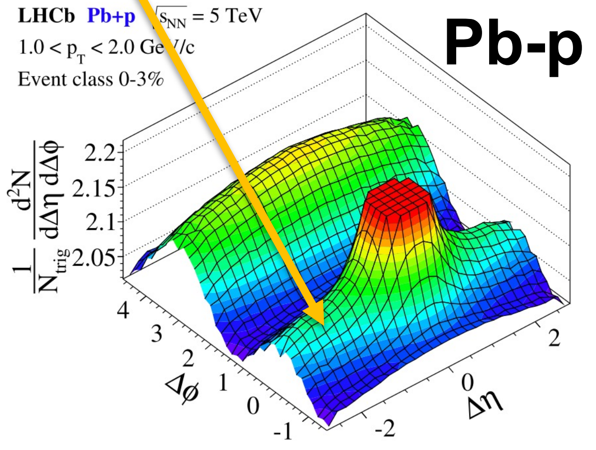


ALICE, PLB 719 (2013) 29

Near side ridge



ATLAS, PRC 96, (2017) 024908



LHCb, PLB 762 (2016) 473–483

Signs of collectivity in **small systems** “discovered” at the LHC in terms of long-range ($2 < |\Delta\eta| < 4$) near-side ($\Delta\phi = 0$) “ridge” in 2-particle correlations, visible in **high multiplicity** pp, p-Pb, Pb-p collisions

Are these long-range correlations coming from (hydrodynamic) flow?

Collectivity correlates many particles over a wide η range

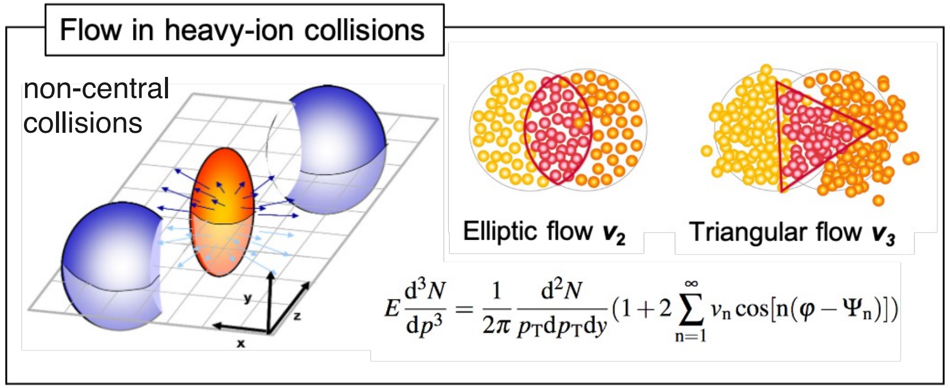
Elliptic flow from multi-particle correlations:

$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} > 0$

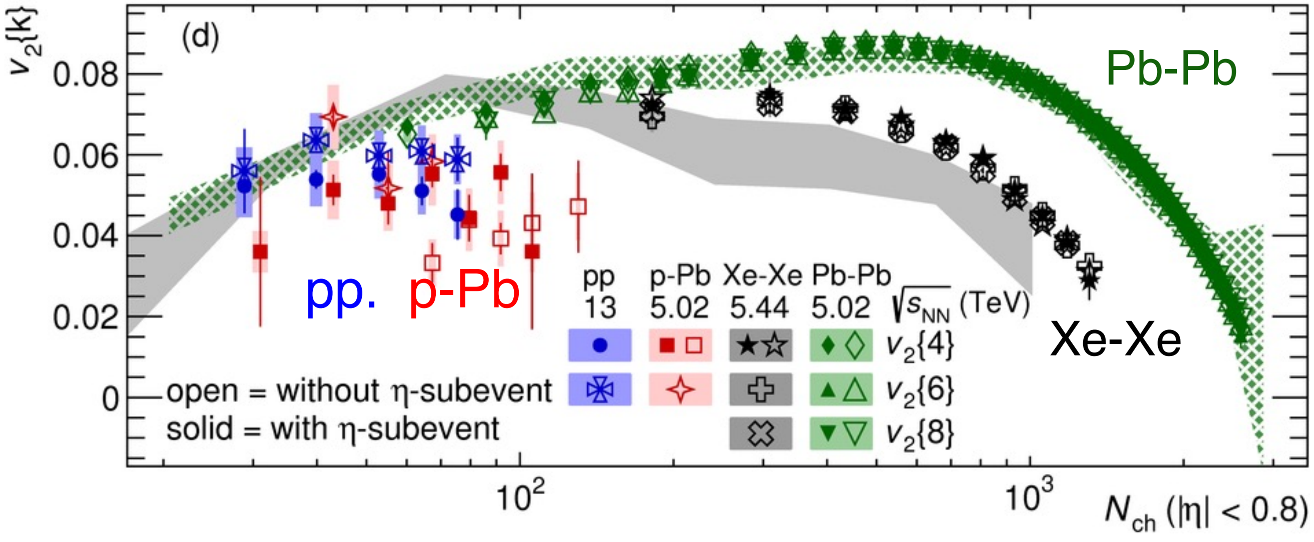
- subtract jets and other physical 2-particle correlations due to non-flow
- measure with rapidity gap

In AA collisions, collectivity originates from the presence of a strongly-interacting QGP

OPEN QUESTION: **what is the origin of the emerging collectivity in pp, p-Pb collisions?**



Elliptic flow from multi-particle correlations in all systems



PRL 123, 142301 (2019)

Chemistry from small to large systems

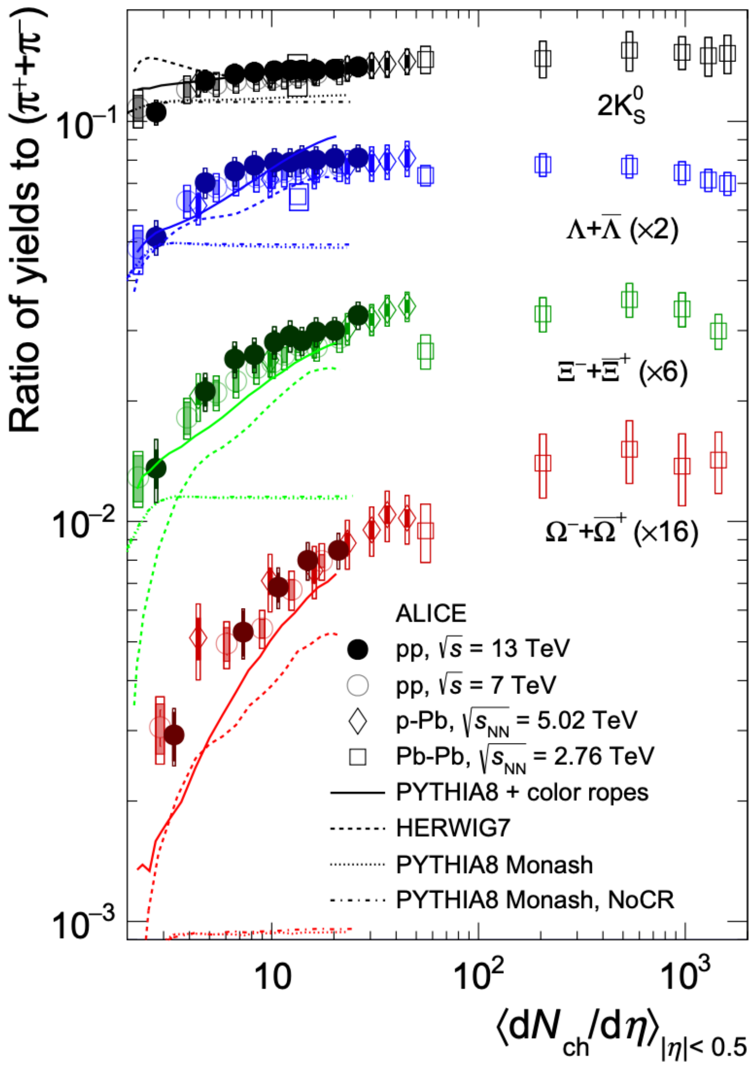
Multi-strange to non-strange yield ratios increase significantly and smoothly with multiplicity in pp and p-Pb collisions until saturation in Pb-Pb

- strangeness enhancement relative to pp suggested in the 1980's as QGP signature

→ **Particle composition evolves smoothly across collision systems, depending only on final-state multiplicity**

OPEN QUESTION: "**emergence**" in hadron production mechanism, **from microscopical hadron production mechanisms** (string overlap, color reconnection) **to the onset of a QGP** (thermalization, equilibration)**?**

→ A challenge for models!



Nature Physics 13 (2017) 535-539,
EPJC 80, (2020) 167 and 693

Summary and outlook

Experimental probes and evidence that a QGP is formed in heavy-ion collisions

- Strong jet quenching and medium-induced modification
- Quarkonium suppression → Melting of states as a function of temperature
- Regeneration and partial thermalisation of charm
- Radial and anisotropic flow → Collective behavior of a QGP with very low shear viscosity (η/s),
- High temperatures, mostly statistical particle production (Tchem, Tkin)
- Heavy-ion-like effects observed in pp and p-Pb collisions

A new frontier

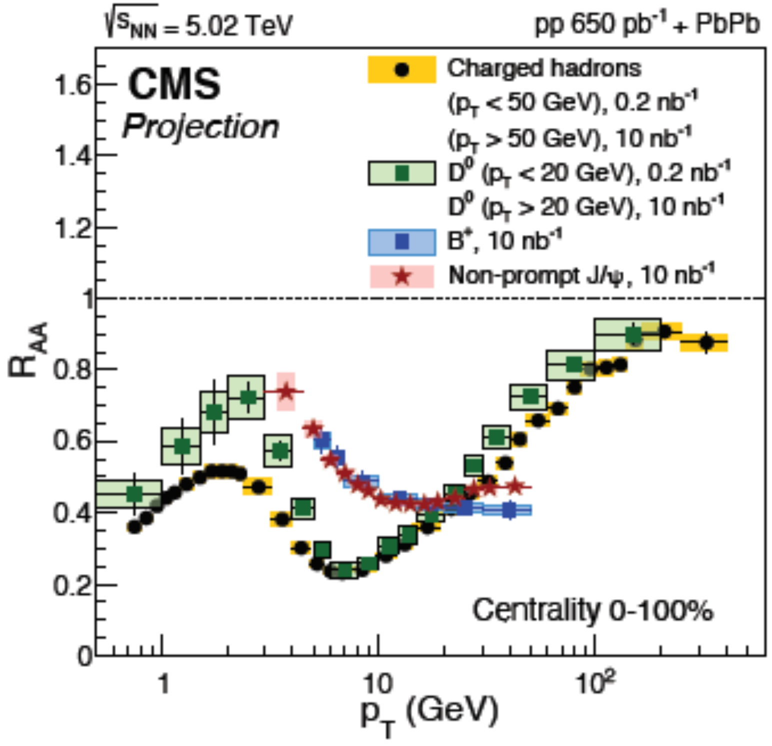
- Is there QGP in small systems?
- Can we explain these effects without a QGP?
- Can we describe these emerging phenomena in one unified picture across systems?

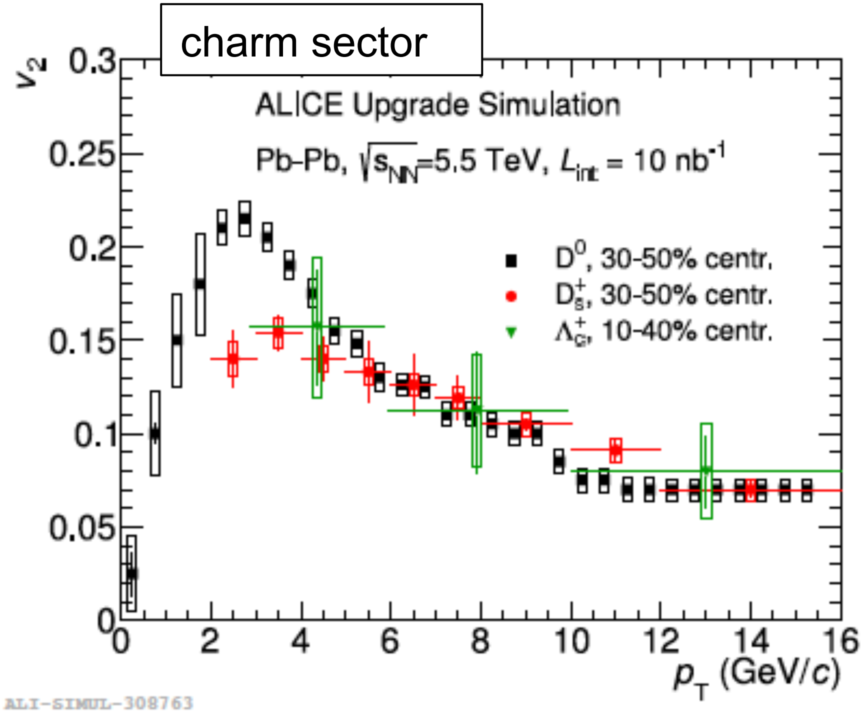
Big progress towards a quantitative characterisation of the properties of the QGP with still open questions to be addressed in Run3 and beyond.

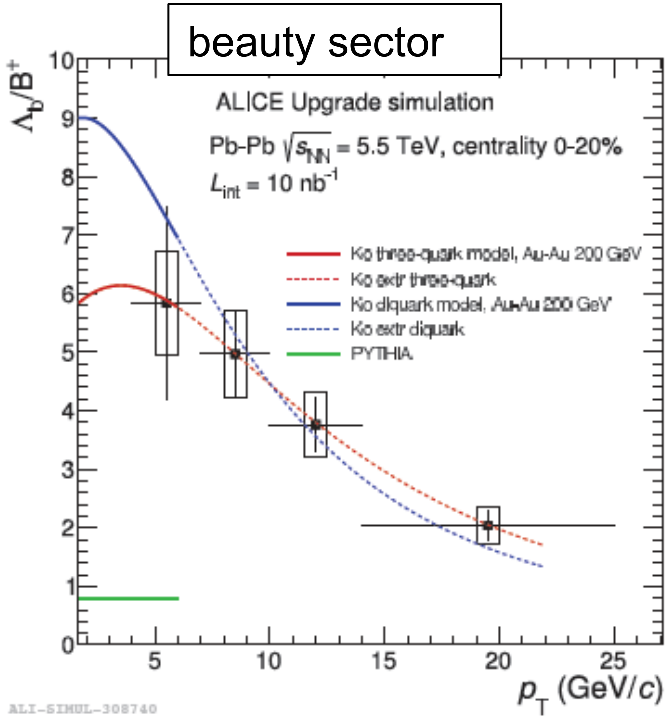
Open heavy-flavour: energy loss and hadronization

Study mass dependence of energy loss, in-medium thermalization of heavy-flavours and their hadronization as a probe of the medium transport properties (e.g. charm spatial diffusion coefficient)

High-precision elliptic-flow and R_{AA} measurement at mid- and forward rapidity for both c and b sectors



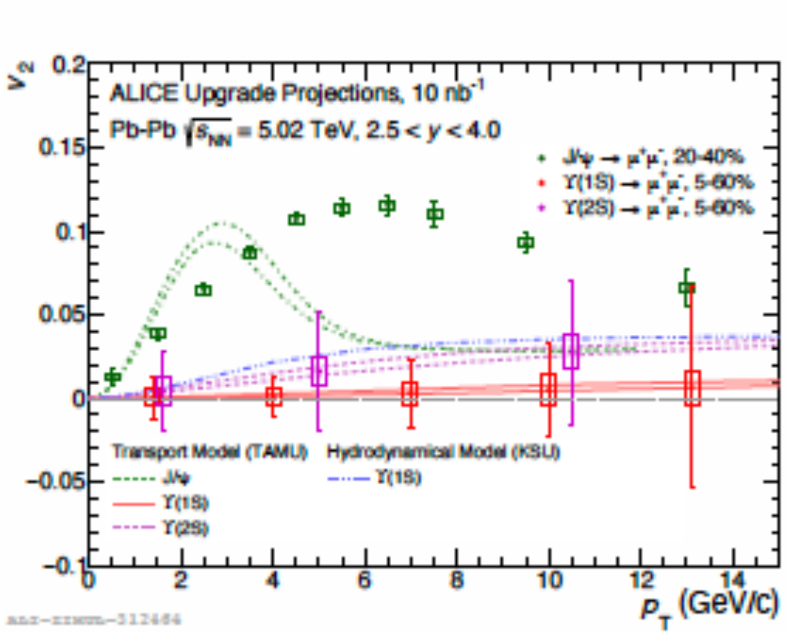


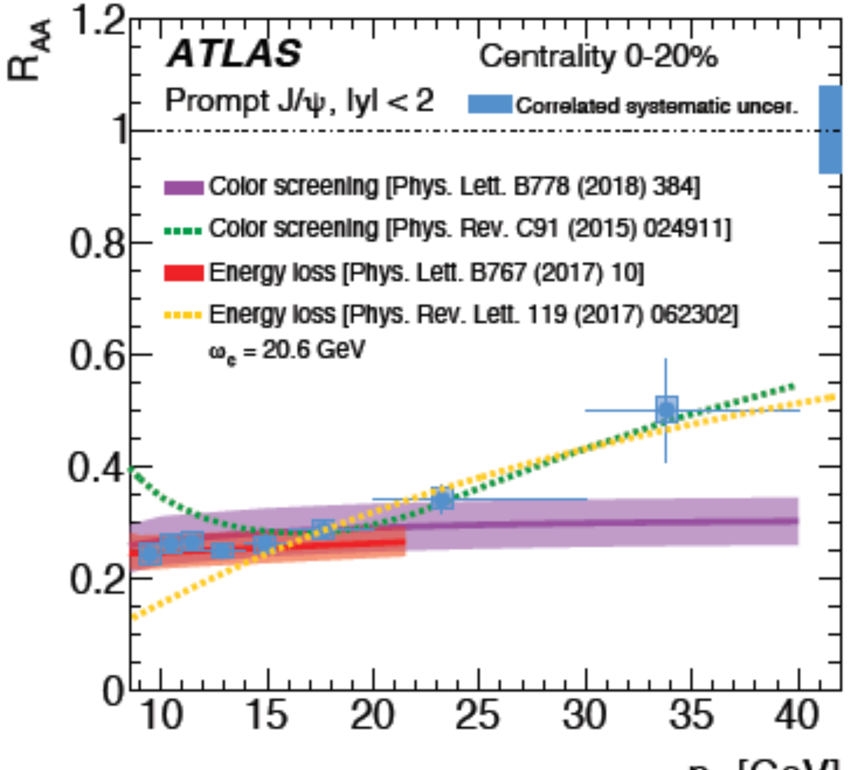


arXiv:1812.06772

Quarkonia: melting vs regeneration vs energy loss

Study regeneration and thermalization of heavy flavours with precision measurements of charmonia flow, RAA and ψ(2S)/J/ψ, explore feeddown





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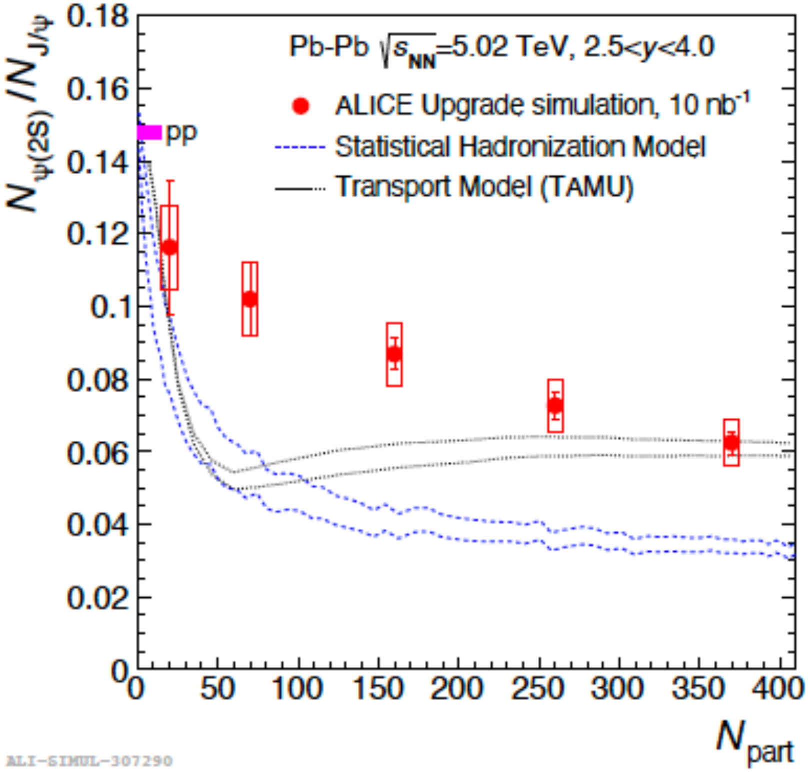
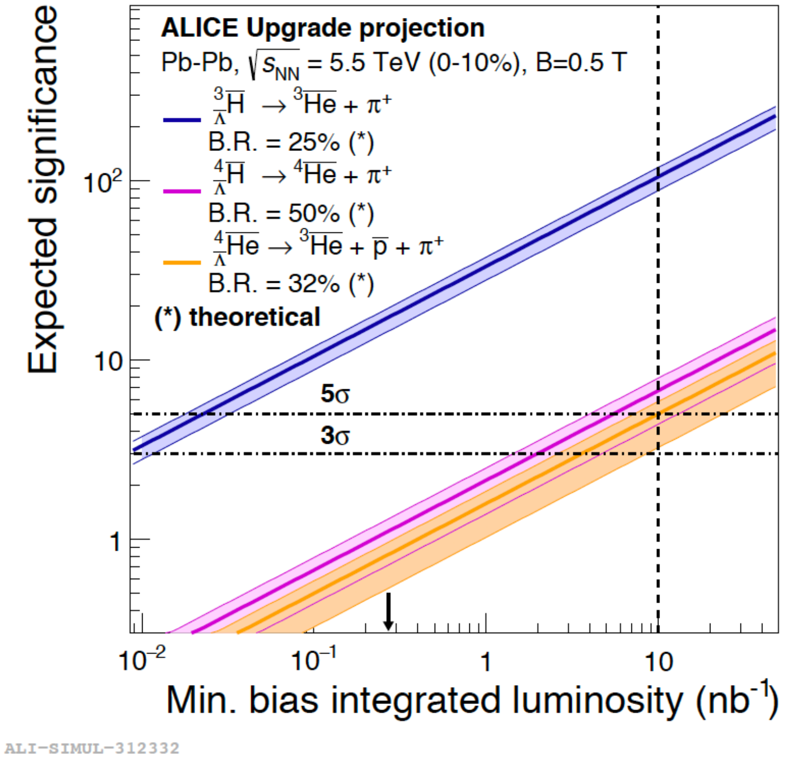


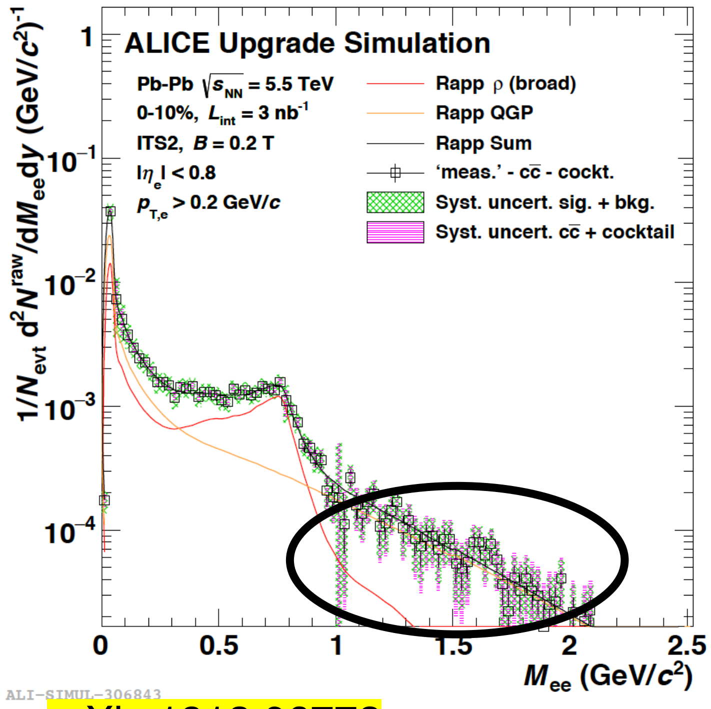
Nuclei, dileptons, small systems and more…

Clarify formation mechanisms of nuclear bound states from a dense partonic state: (anti-)nuclei and (anti-)(hyper-)nuclei up to A = 4

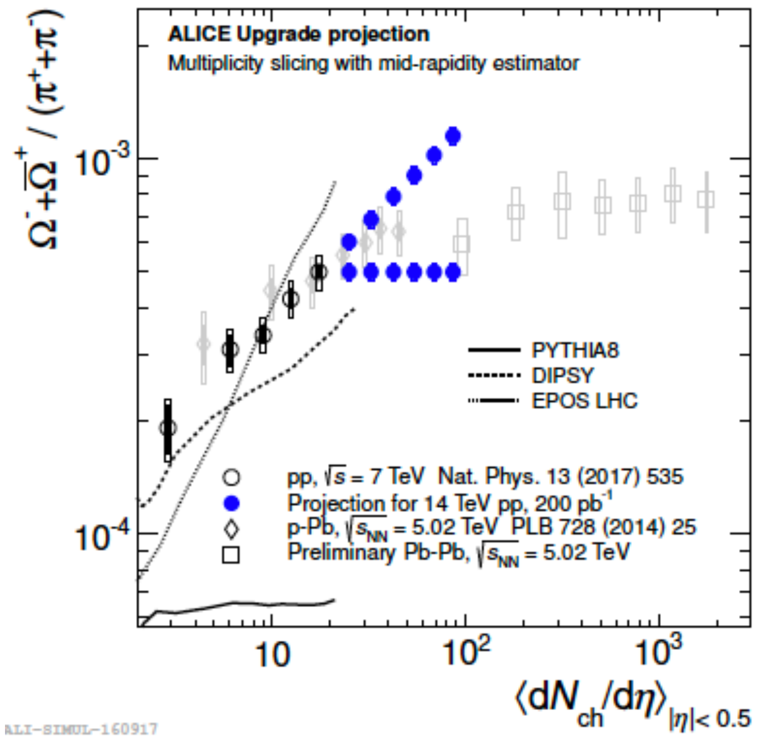
Access to the thermal dilepton excess after subtraction of light hadron decay and charm

A "small systems" programme to study collectivity, strangeness production, the onset of QGP like features



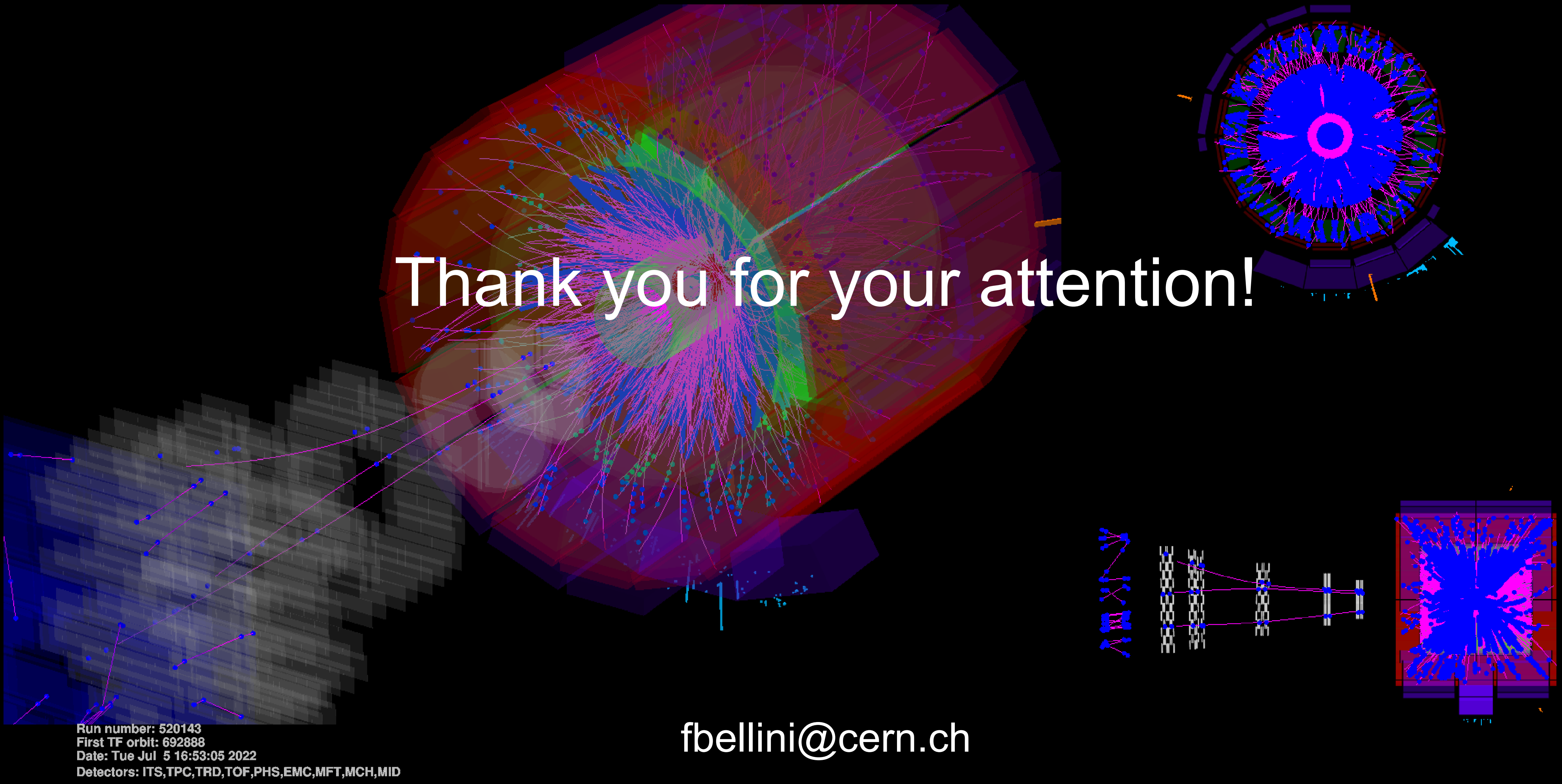


arXiv:1812.06772



+ net-charge fluctuations, jets (the QCD objects!), heavy-quark jets, light ions, nPDFs, low-x physics,…

Thank you for your attention!



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