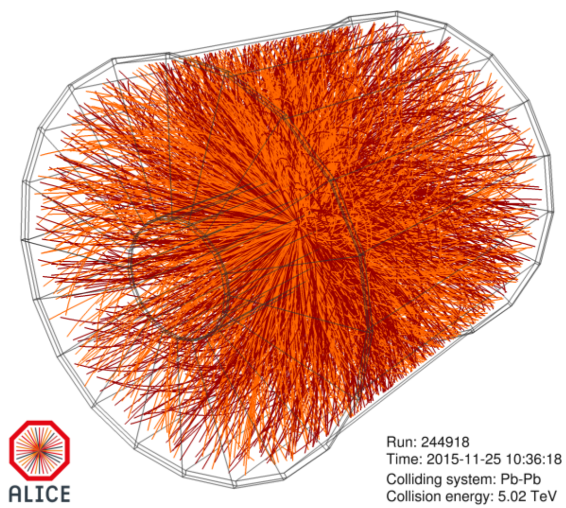
Physics at the LHC

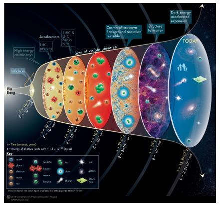
Hot QCD matter produced in ultra-relativistic heavy-ion collisions

Lecture 3
January 15, 2020

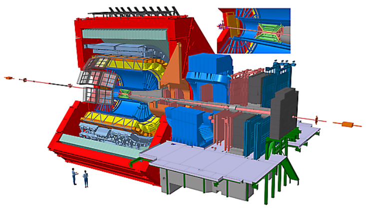


Silvia Masciocchi
GSI Darmstadt and Heidelberg University

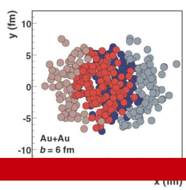
Outline



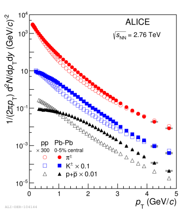
Heavy-ion collisions: Little Bangs



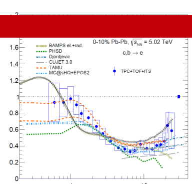
Experimental program at the LHC, ALICE



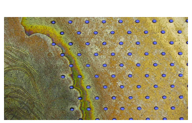
Global characteristics



Bulk particle production



Quark-gluon plasma tomography with hard probes



Research plans for near and further future

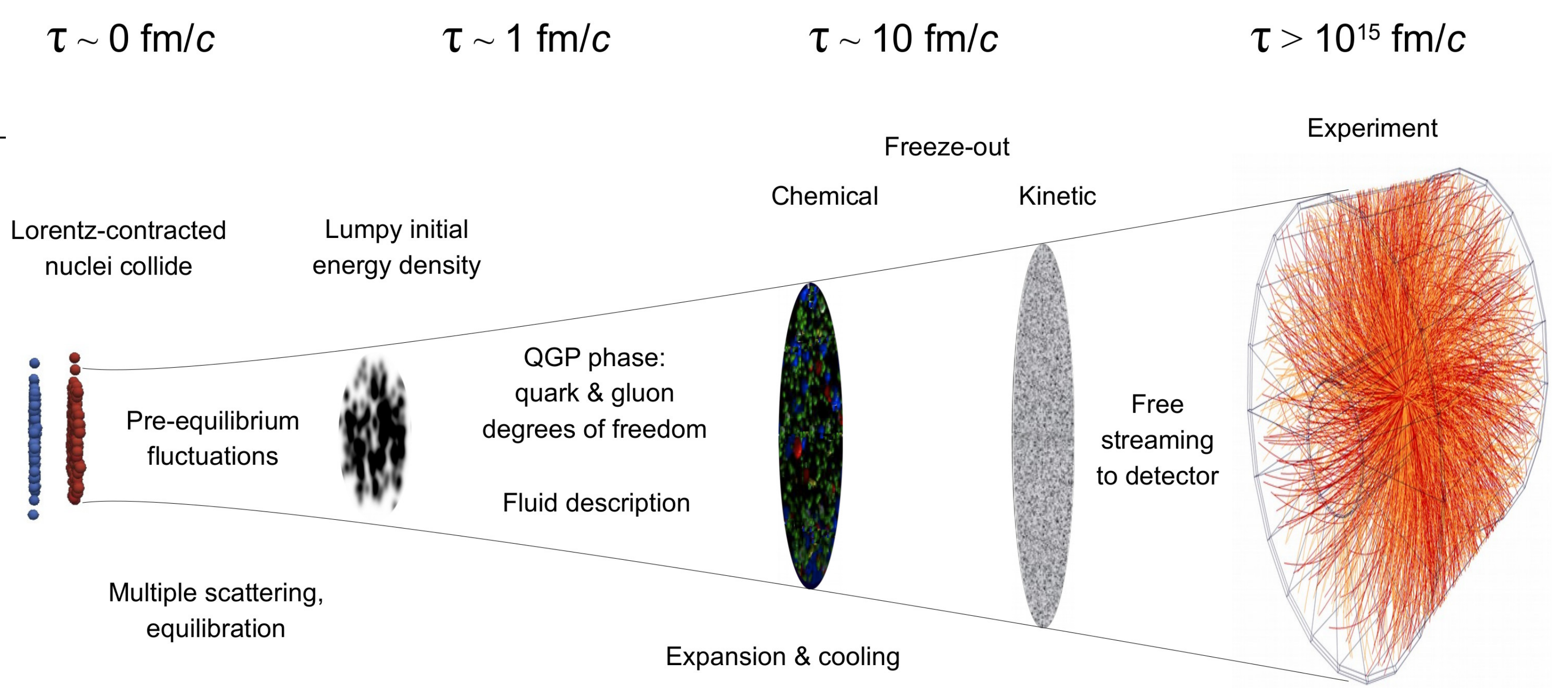
Outline

- Historical view: experimental opportunities, first theoretical ideas
- Thermodynamics of strongly interacting matter and phase diagram
- QCD matter under extreme conditions in nature and in the lab
- Global characteristics: centrality, energy density, multiplicities

- Bulk (soft) particle production
  - Thermal model, particle yields and chemical freeze-out
  - (hyper-)(anti-)nuclei
  - **Hydrodynamics, flow and correlations**
  - Particle spectra, Blast-Wave fits and kinetic freeze-out
  - Small systems

- Hard probes
  - Jets, heavy quarks, heavy quarkonia
- Future

Reminder:

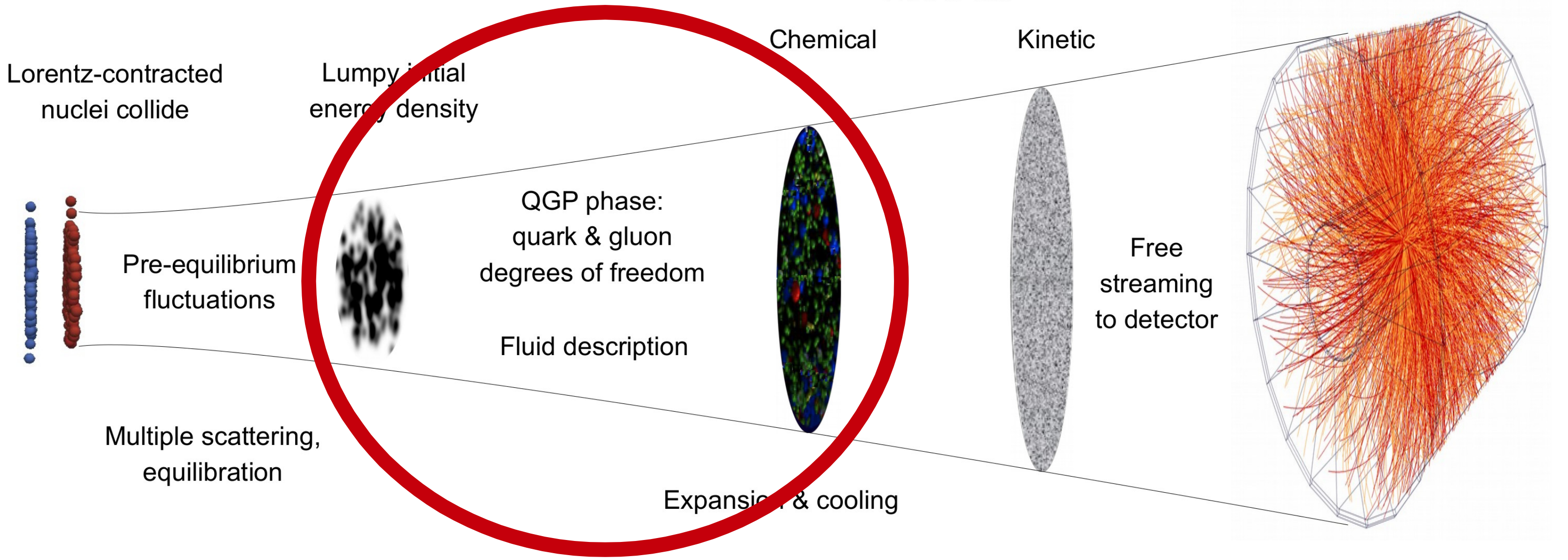


1. Initial conditions, pre-equilibrium, hard scattering processes
2. Thermalization: equilibrium is established ($t_{eq} \leq 1$ fm/c)
3. Expansion and cooling ($t_{QGP} < 10 – 15$ fm/c)
4. Hadronization (quarks and gluons form hadrons)
5. Chemical freeze-out: inelastic collisions cease, yields are defined
6. Kinetic freeze-out: elastic collisions cease, spectra are frozen ($t_{had} \sim 3\text{-}5$ fm/c)

≈ 10^{-22} s

Measurements can only be performed at stages 5 and 6
From those, we want to deduce information on phases 2, 3, 4

Reminder:



1. Initial conditions, pre-equilibrium, hard scattering processes
2. **Thermalization: equilibrium is established ($t_{eq} \leq 1$ fm/c)**
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4. Hadronization (quarks and gluons form hadrons)
5. Chemical freeze-out: inelastic collisions cease, yields are defined
6. Kinetic freeze-out: elastic collisions cease, spectra are frozen (t_{had} ~ 3-5 fm/c)

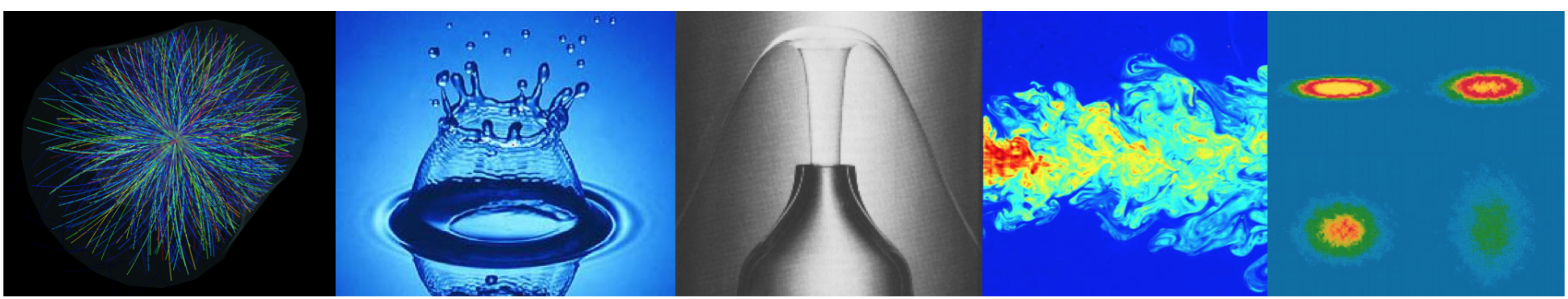
Evolution of system from equilibration to freeze-out can be described as motion and interaction of fluid cells, as collective system

→ **use of fluid dynamics**

Fluid dynamics

Good applicability to large systems, as in heavy-ion collisions:

- Long distances, long times, strong fields
- System described by macroscopic medium properties:
  - Equation of state P(T)
  - Shear viscosity η(T)
  - Bulk viscosity ζ(T)
  - Heat conductivity κ(T)
  - Relaxation times τ_{shear}(T), τ_{bulk}(T), etc



S. Floerchinger

Relativistic fluid dynamics

Assumption: local equilibrium condition

Ingredients:

- Streaming fluid described by velocity field $u^\mu = \frac{dx^\mu}{dt}$
- ε, p: energy and pressure in co-moving frame of fluid cell
- Energy-momentum tensor: $T^{\mu\nu} = (\epsilon + p) u^\mu u^\nu - p g^{\mu\nu}$
- Charge current: $j^\mu = n u^\mu$

  e.g. baryon number $j^{\mu_B} = n_B(x) u^\mu(x)$

- **Equations of relativistic hydrodynamics:**

  Equation of motion from energy-momentum conservation: $\partial_\mu T^{\mu\nu} = 0$

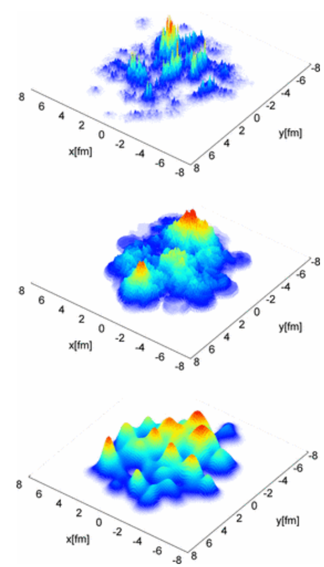
  Charge conservation, e.g. baryon number: $\partial_\mu j^\mu = 0$

Relativistic fluid dynamics

Ingredients

$$\partial_\mu T^{\mu\nu} = 0 \qquad \partial_\mu j^\mu = 0$$

- Equations of relativistic hydrodynamics
  need proper formalism (e.g. Isreal Stewart theory) to have stable and causal equations
- Equation of State (EOS)
  relates thermodynamic variables ε(p,...)
  generally taken from lattice QCD computations
- Transport coefficients: bulk and shear viscosity, their relaxation times, heat conductivity, ...
- Initial conditions: energy density distribution
  MC Glauber, IP Glasma, MC-KLN, TRENTo ...
- Final hadron phase (interactions)
  UrQMD, SMASH



Hydrodynamic frameworks

MODELS
of initial
conditions
Initial energy density

t_0

Hydrodynamic evolution

- Relativistic hydrodynamics equations
- Equation of State
- Transport coefficients

T_{dec}

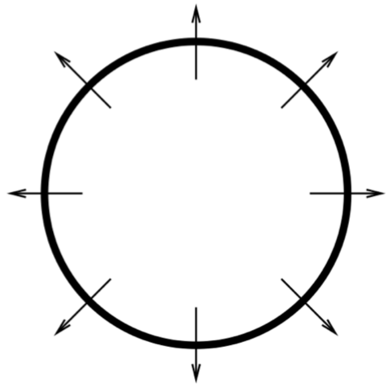
MODELS of final
hadronic phase
(fragmentation,
scattering, decays)

Different realizations:

- Simulation codes (very CPU intensive!):
  VISHNU, MUSIC, ECHO-QGP, etc
- Analytic, mode-by-mode: elegant and fast!
  FLUIDUM (+FastReso for final phase)

Radial expansion

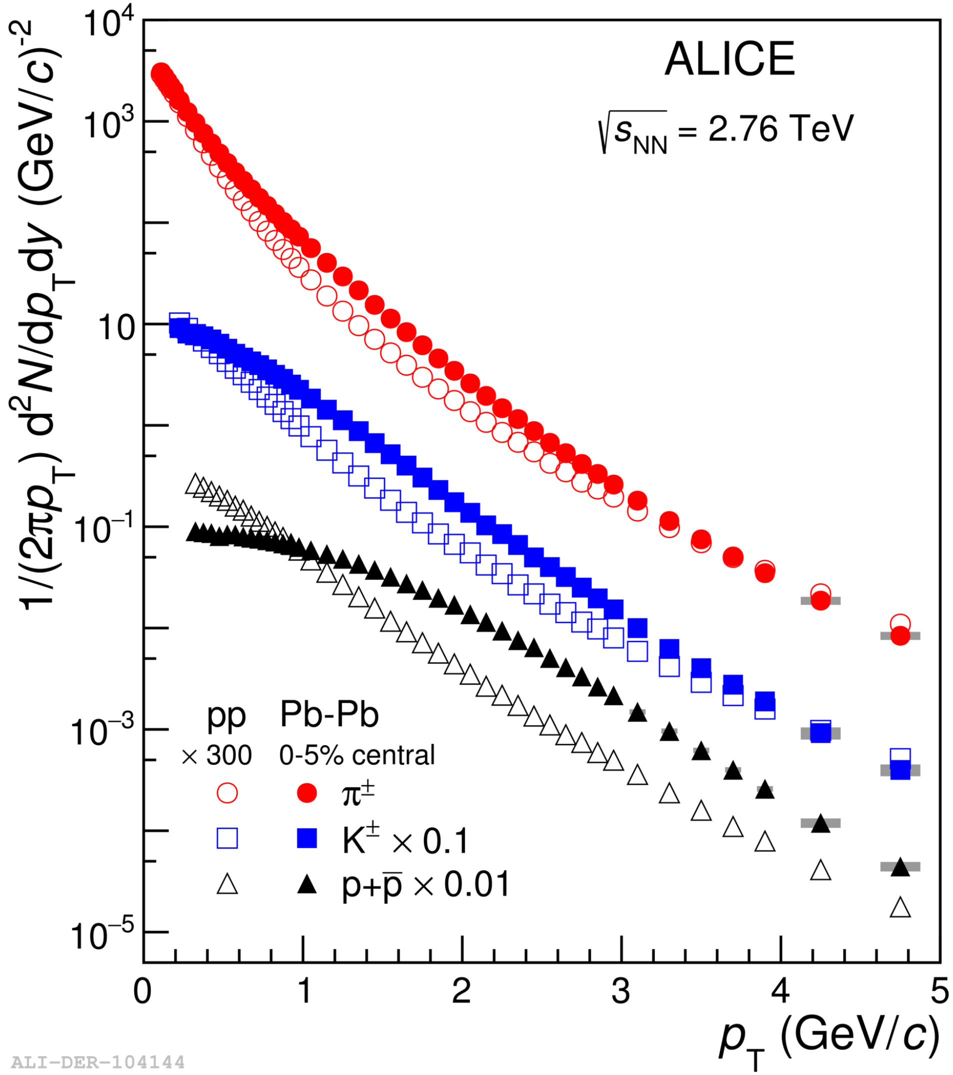
Central collisions, transverse plane



Internal pressure gradient → fluid velocity in radial direction

Depends on bulk viscosity ζ(T)

Demonstrated by particle spectra

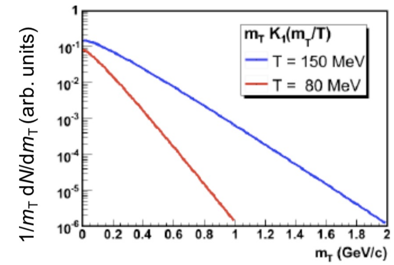


Thermalized source + radial flow boost

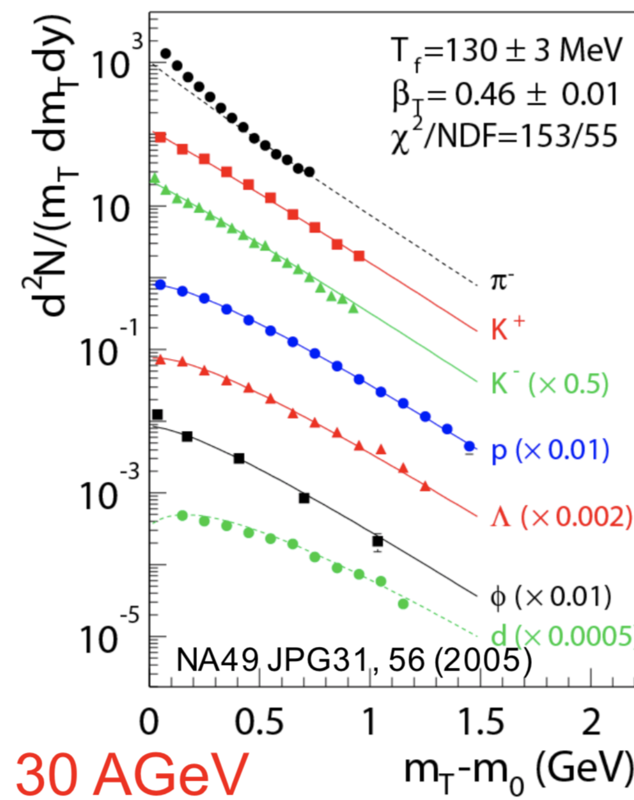
Transverse momentum spectra described as sum of two components:

- Thermal distribution:

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto m_T K_1\left(\frac{m_T}{T}\right) \xrightarrow{m_T \gg T} \sqrt{m_T}\, e^{-m_T/T}$$



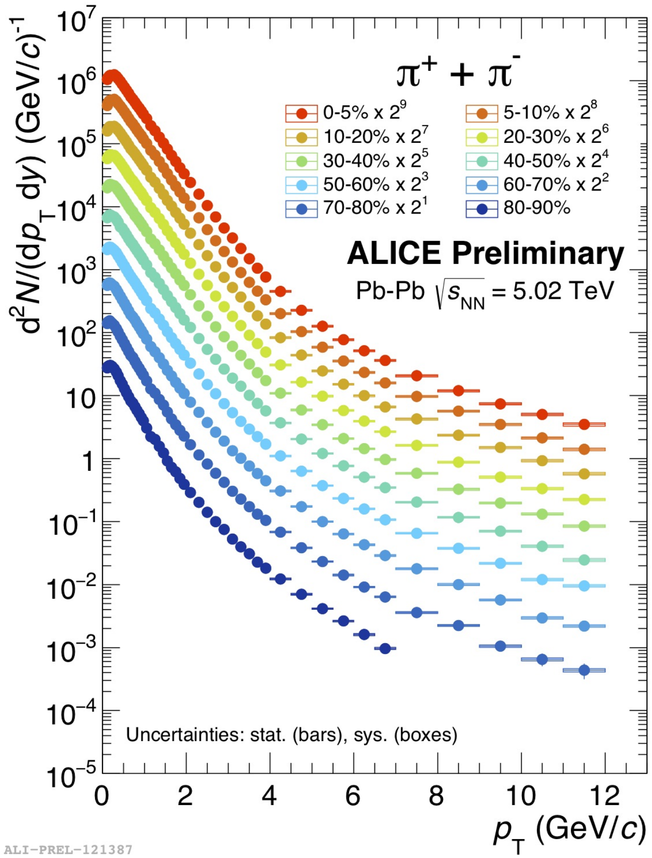
- Additional component due to common transverse velocity from radial expansion Boltzmann-Gibbs **Blast-Wave**: simplified hydro model, with parameters:
  - T_{kin}: kinetic freeze-out temperature
  - $<\beta_T>$: transverse radial flow velocity

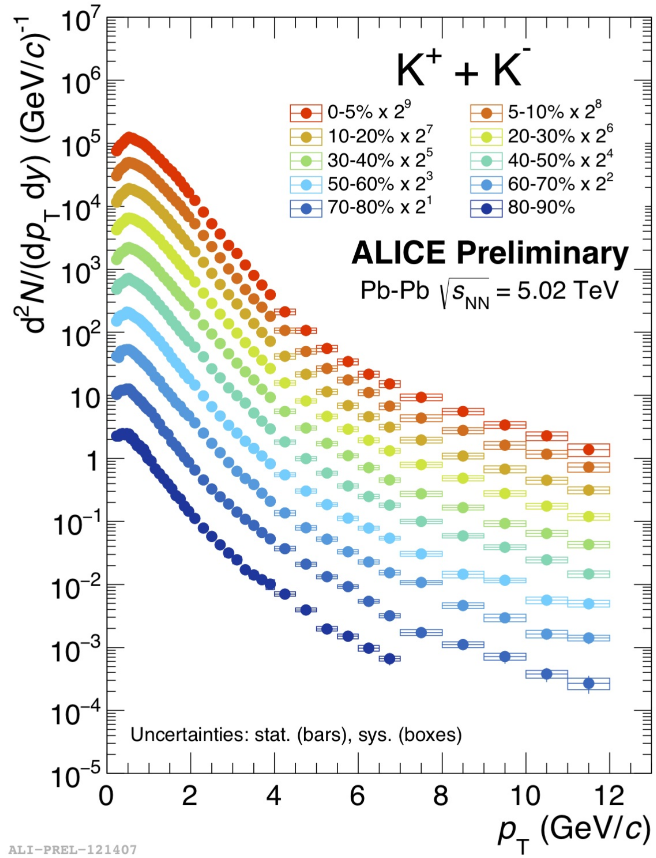


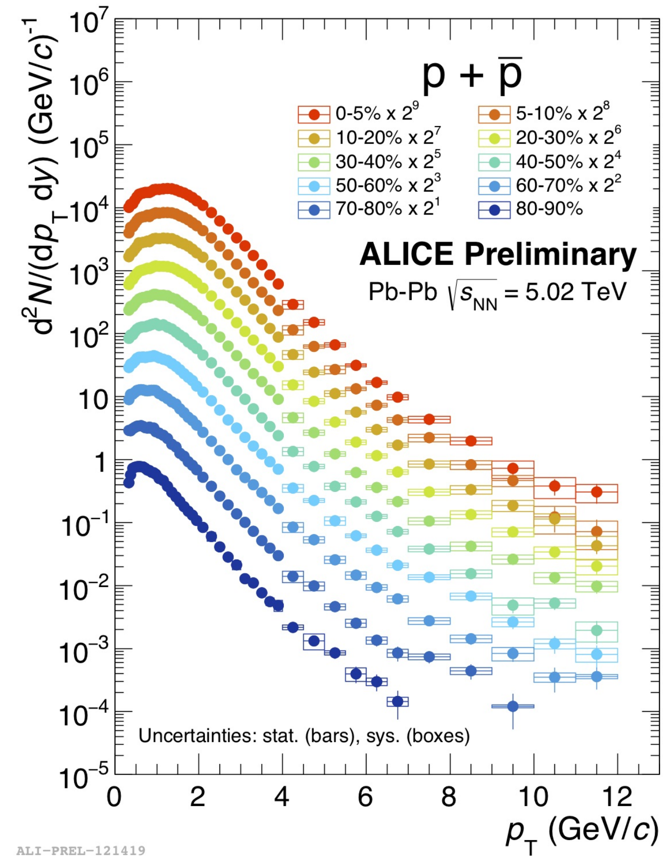
E. Schnedermann et al., Phys. Rev. C48 (1993) 2462

Identified particle spectra at the LHC

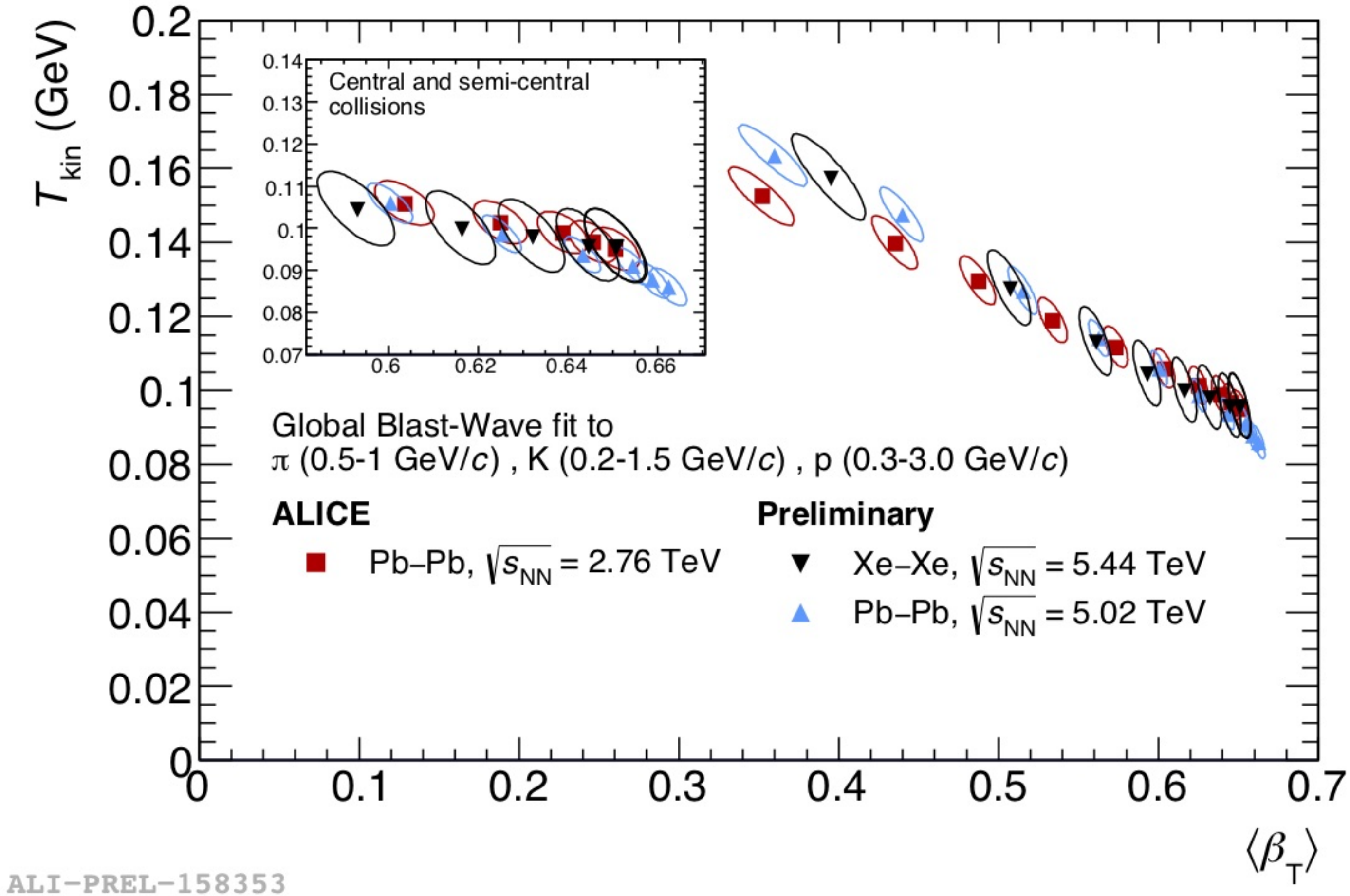
Perform a simultaneous fit of pion, kaon, proton spectra in given centrality range, in the low (hydrodynamic-dominated) region







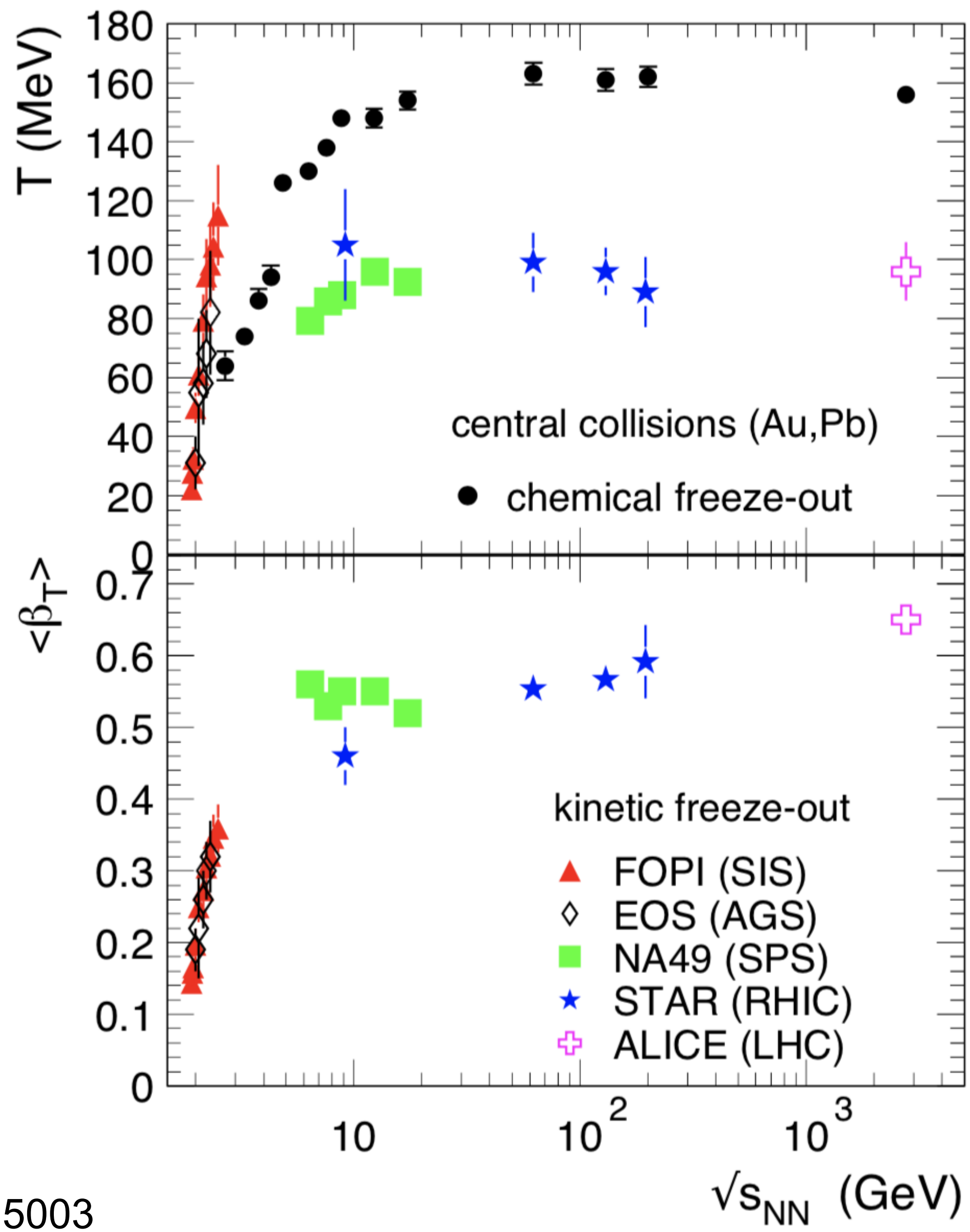
Blast-wave fits: Pb-Pb, Xe-Xe



- $<\beta_T>$: transverse radial flow velocity increasing with centrality

  Order of 0.6 – 0.66 at the LHC
- Pb-Pb and Xe-Xe consistent

Blast-wave fits: all collision systems



A. Andronic, arXiv:1407.5003

Hydro-models

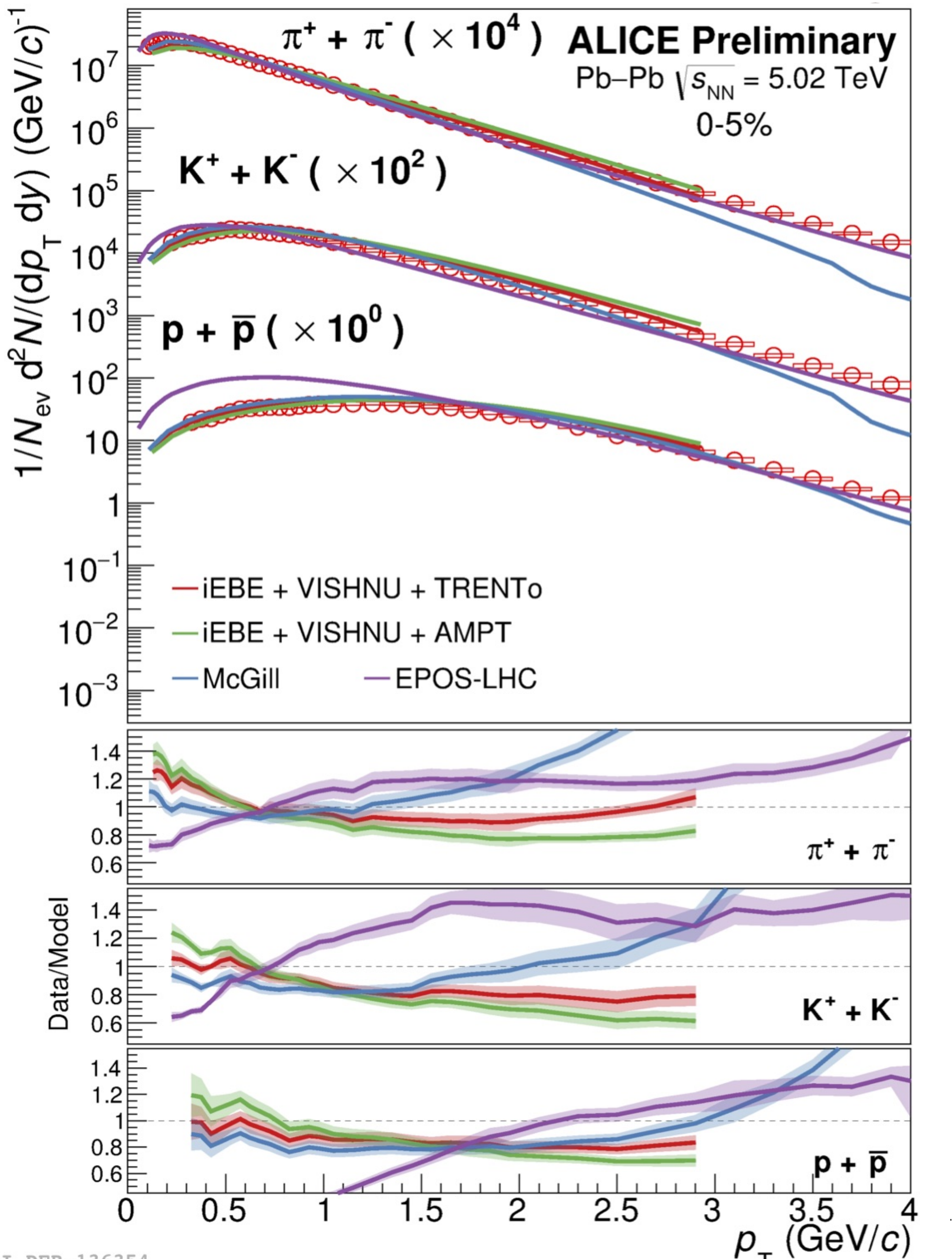
iEbyE + VISHNU + Trento/AMPT: viscous hydro with different initial conditions

[arXiv:1703.10792v1, PRC 92, (2015) 014903, PRC 92 (2015) 011901(R)]

McGill: MUSIC viscous hydro with IP-Glasma initial conditions

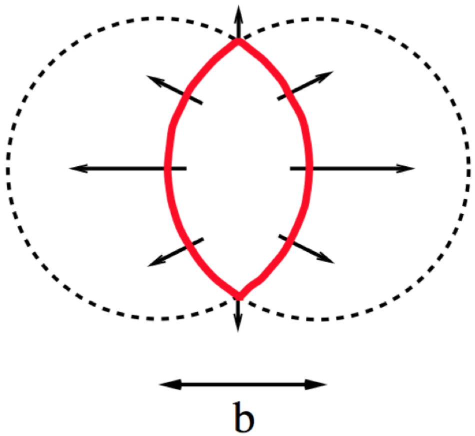
[PRC 95 (2017) 064913]

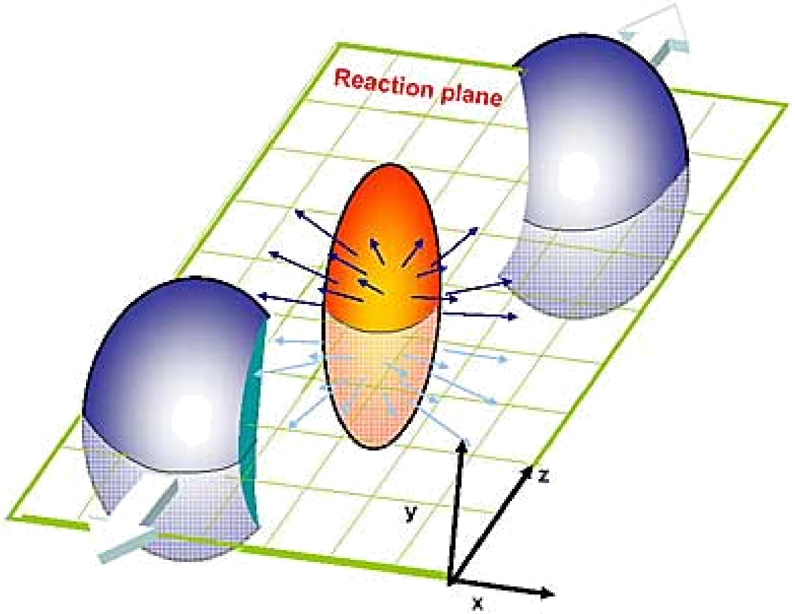
EPOS-LHC: core (hydro) + corona *[PRC 92 (2015) 034906]*



v_n flow coefficients

Non-central collisions





Initial spatial asymmetry
Pressure gradients larger in one direction
→ larger fluid velocity in that direction
→ more particles fly in that direction

Particle distribution:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_n v_n \cos\left(n\left(\phi - \psi_R^n\right)\right)\right]$$

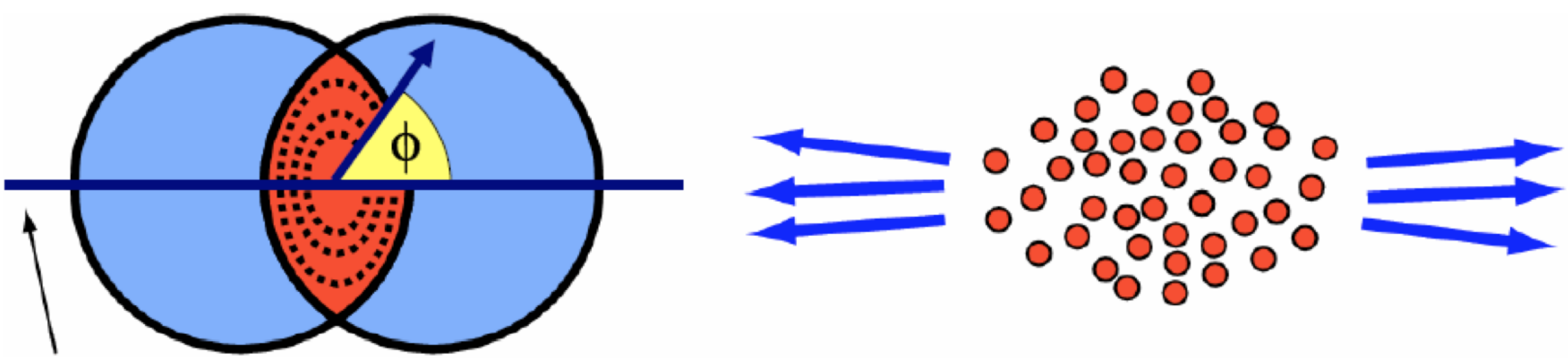
In case of homogeneous initial energy density, for symmetry reasons ($\Phi \rightarrow \Phi+\pi$): $v_1 = v_3 = v_5 = \ldots = 0$

Elliptic flow: v_2 coefficient

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1+2\sum_n v_n \cos\left(n\left(\phi-\psi_R^n\right)\right)\right]$$

In non-central collisions, the second component (coefficient v_2, elliptic flow) is the dominant one

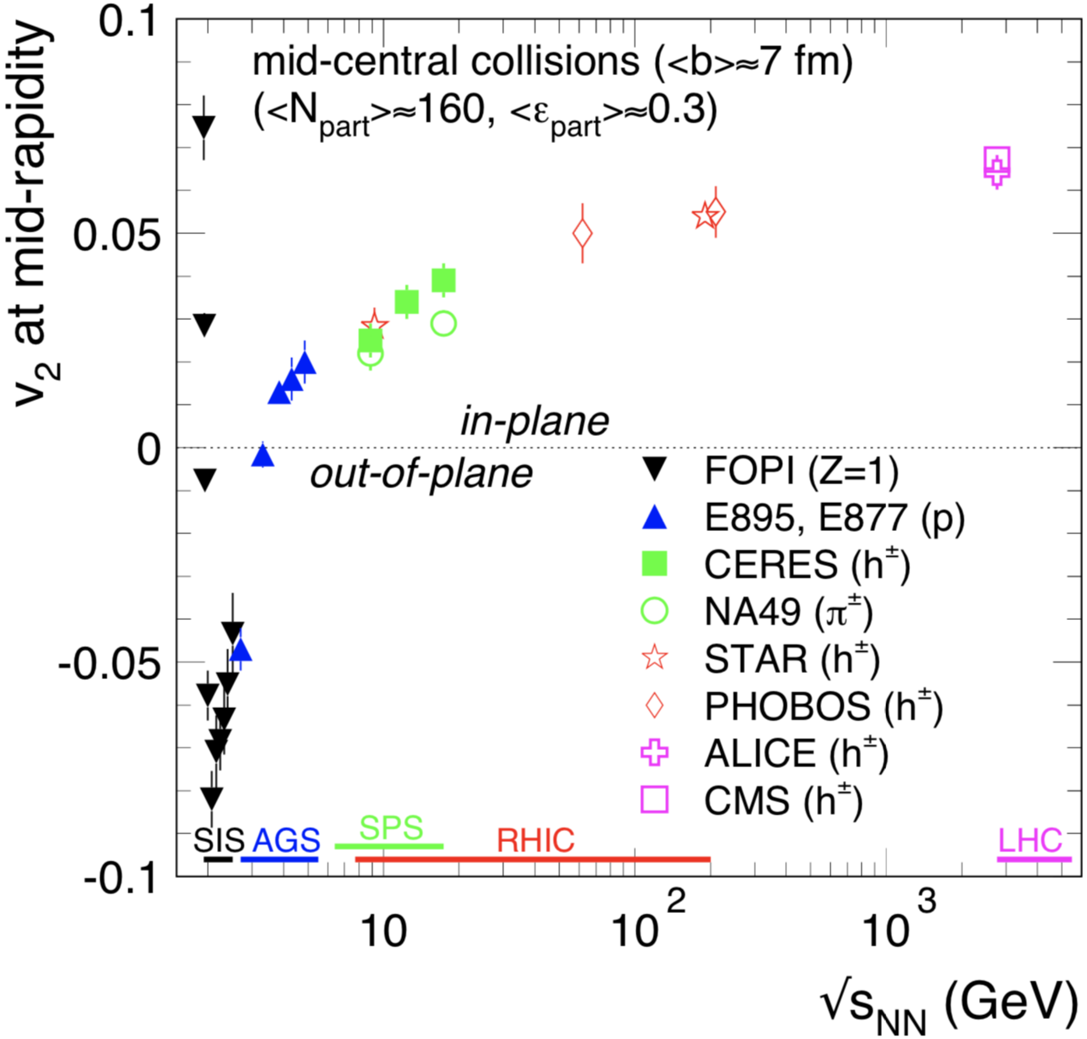
Anisotropy in geometry $\rightarrow$ Anisotropy in momentum space



Reaction plane

Depending on the collision energy, particles prefer to be “in plane” or “out of plane”

Elliptic flow: v_2 coefficient (semi-central collisions)



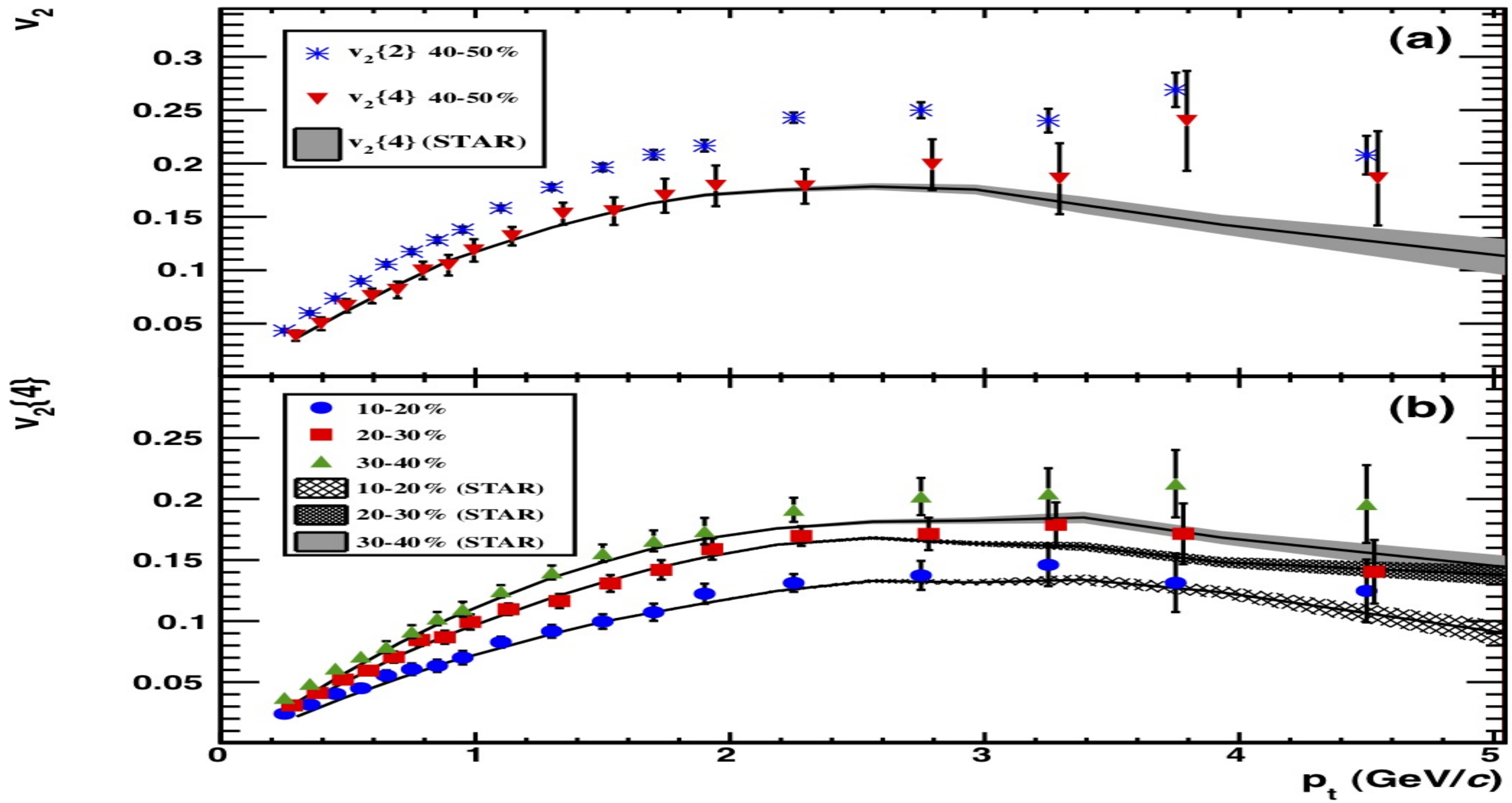
A. Andronic, arXiv:1407.5003

Very low energies: in-plane, rotation like emission. Low energy density and long reaction times.
SIS region: competition between increasing speed of expansion and decreasing passage time of the spectators (hindering expansion in reaction plane) → squeeze-out
High energies: unhindered collective expansion of the initially-anisotropic fireball

Elliptic flow: v_2 coefficient (semi-central collisions)

Comparison between RHIC (200 GeV) and the LHC (2.76 TeV)

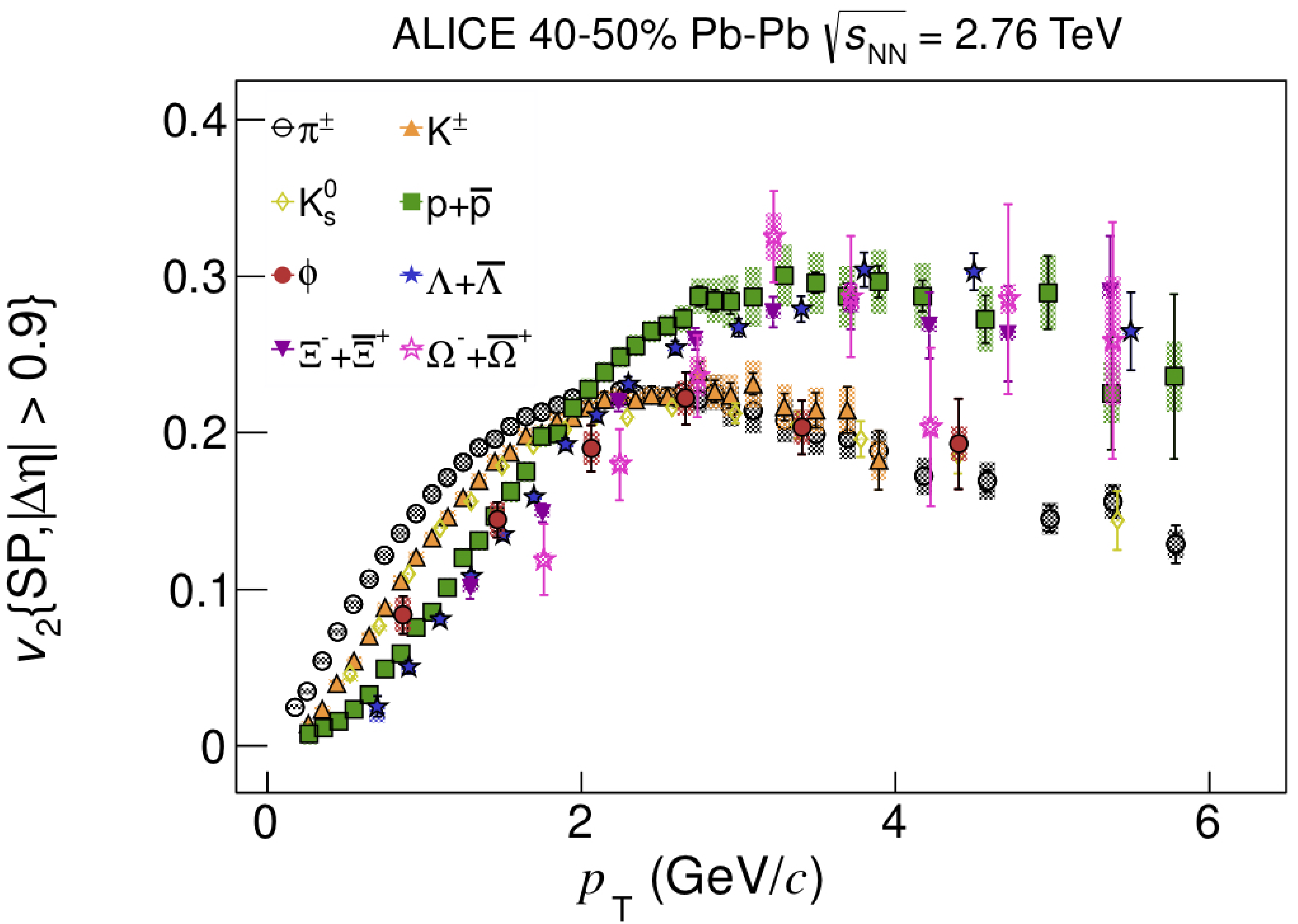
- p_T-integrated v_2 at the LHC ~30% higher than at RHIC
- as a function of the charged-particle p_T: practically identical



PRL 105 (2010) 252302

Elliptic flow: v_2 coefficient (semi-central collisions)

Identified particles: mass dependence and baryon/meson grouping

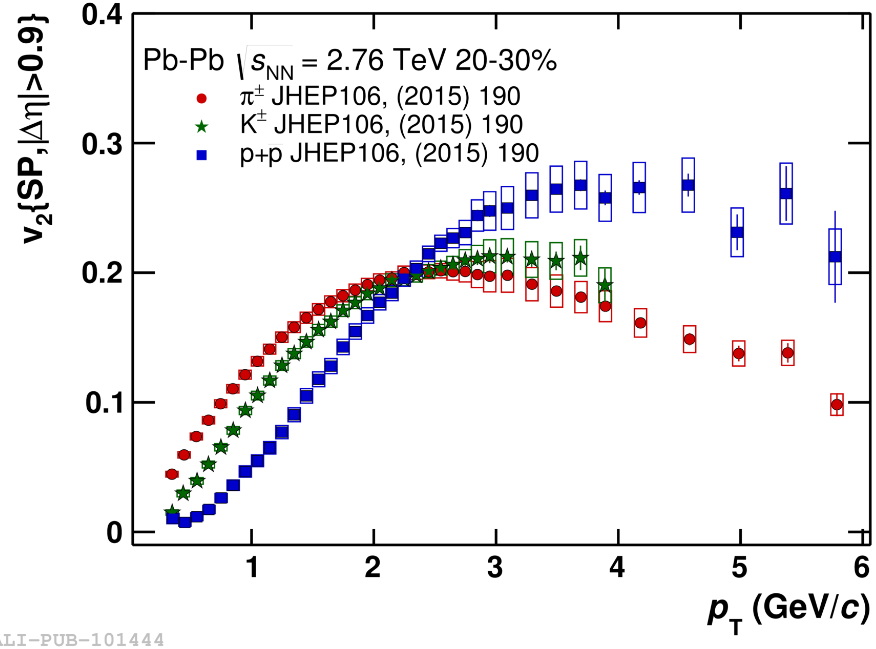


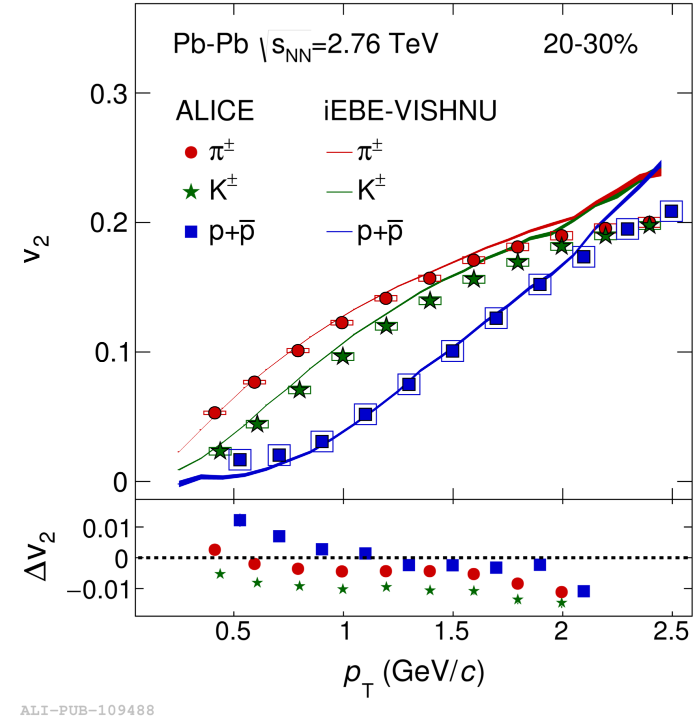
JHEP 06 (2015) 190

Elliptic flow: v_2 coefficient (semi-central collisions)

Identified particles: mass dependence and baryon/meson grouping

Mass ordering of v_2 (combined effect with radial flow)





Comparison to hydro models

Example from 2013

Mass ordering = sign of collectivity

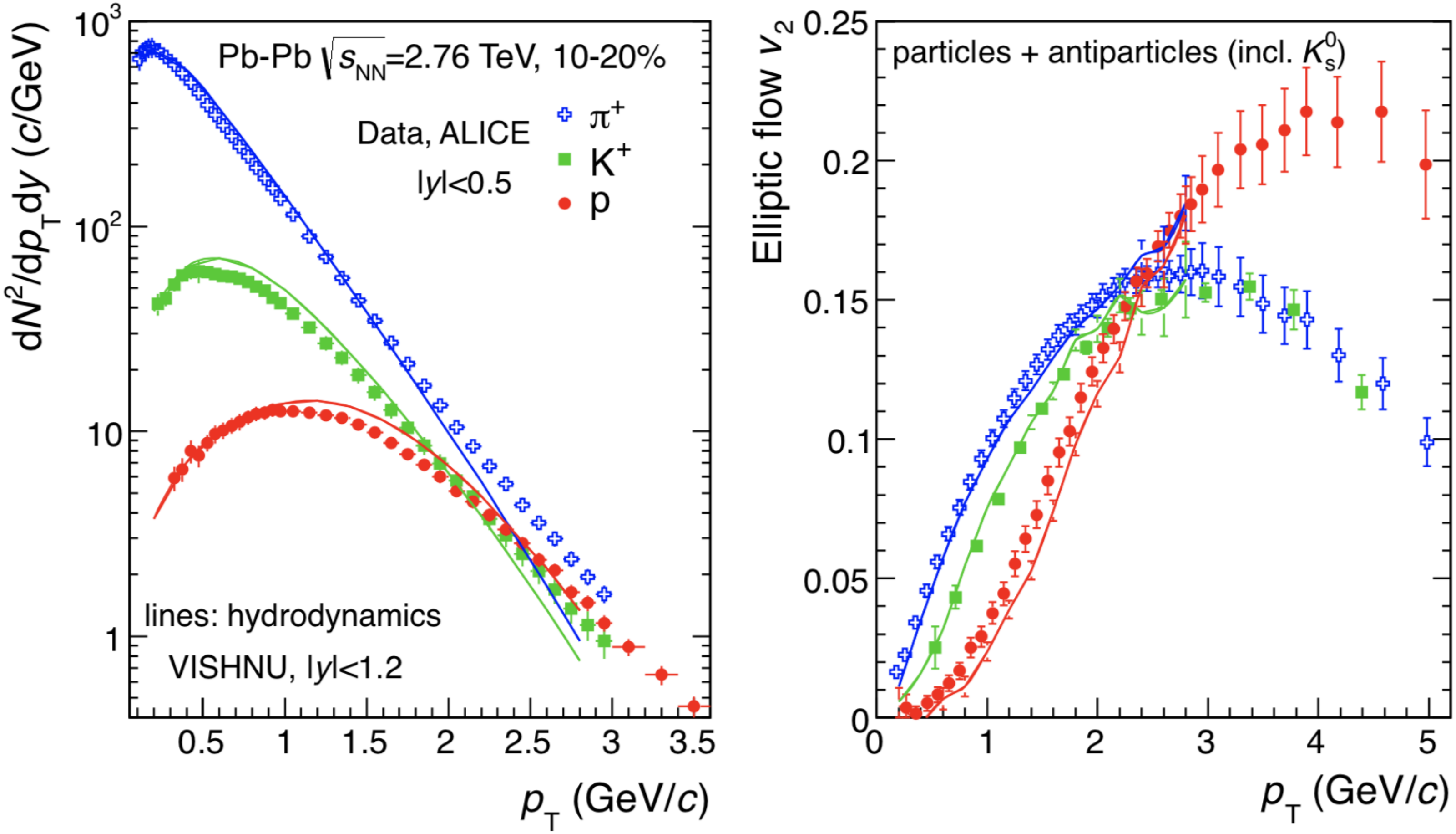


Figure from A. Andronic, arXiv:1407.5003

Hydro: VISHNU, from arXiv:1311.0157

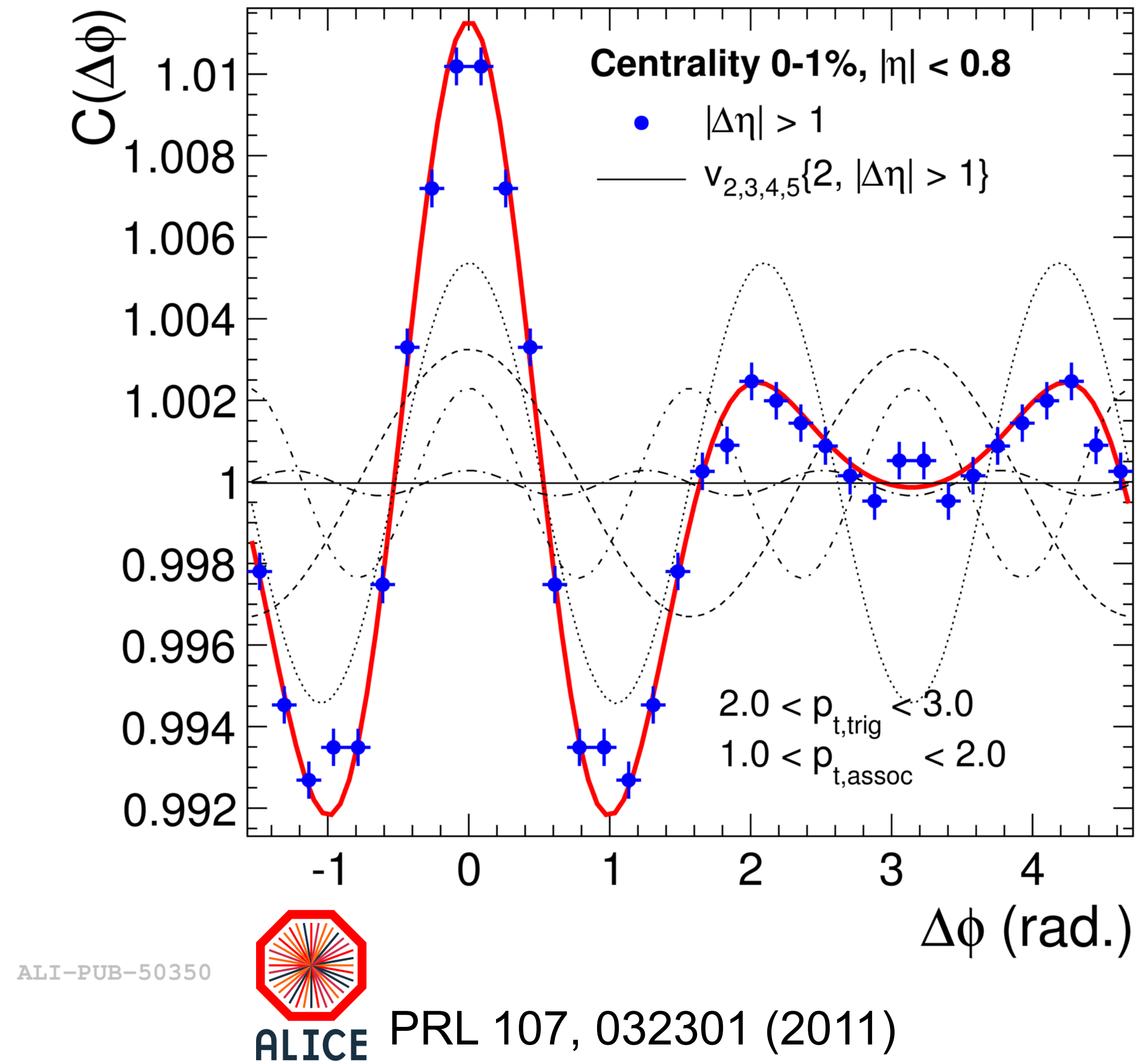
MC-KLN, VISHNU with constant η/s, UrQMD

2-particle correlations

Most central events (0-1%): 2-particle azimuthal correlation

sum of v_2, v_3, v_4, v_5 harmonics

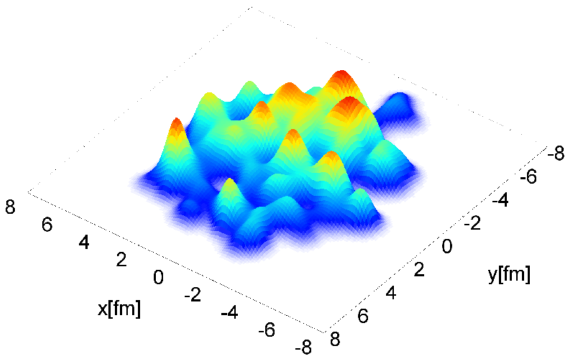
v_3, v_5 non-zero!



PRL 107, 032301 (2011)

Initial state fluctuations

Lumpy energy density profile of initial state



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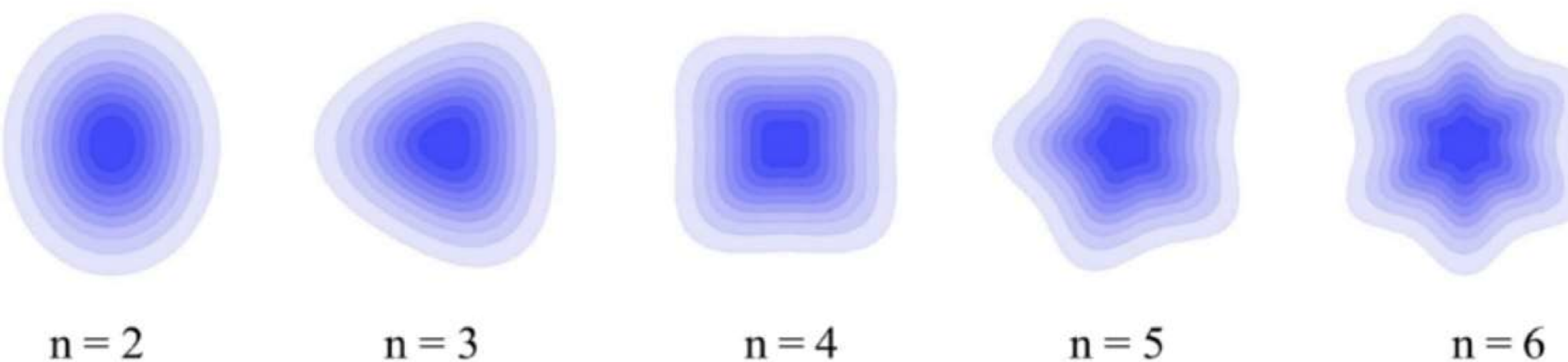
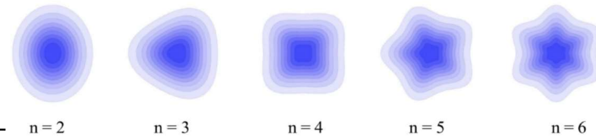
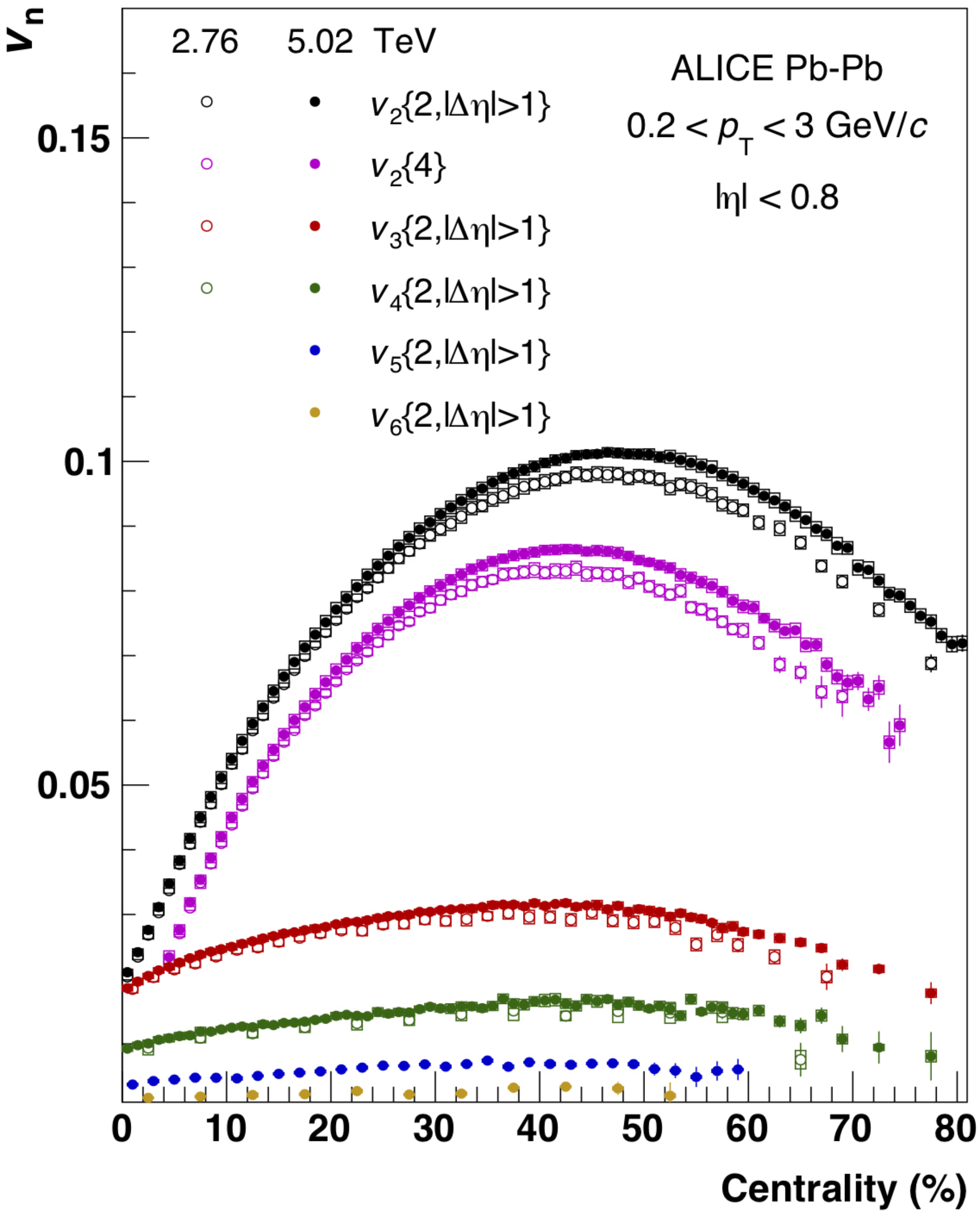
Fluctuations of the complex structure of the energy density profile of the initial state produce non-zero contribution to all harmonics



v_2, v_3, v_4, ...





The energy dependence of anisotropic flow provides additional discriminating power over initial-state models and temperature dependence of transport coefficients.

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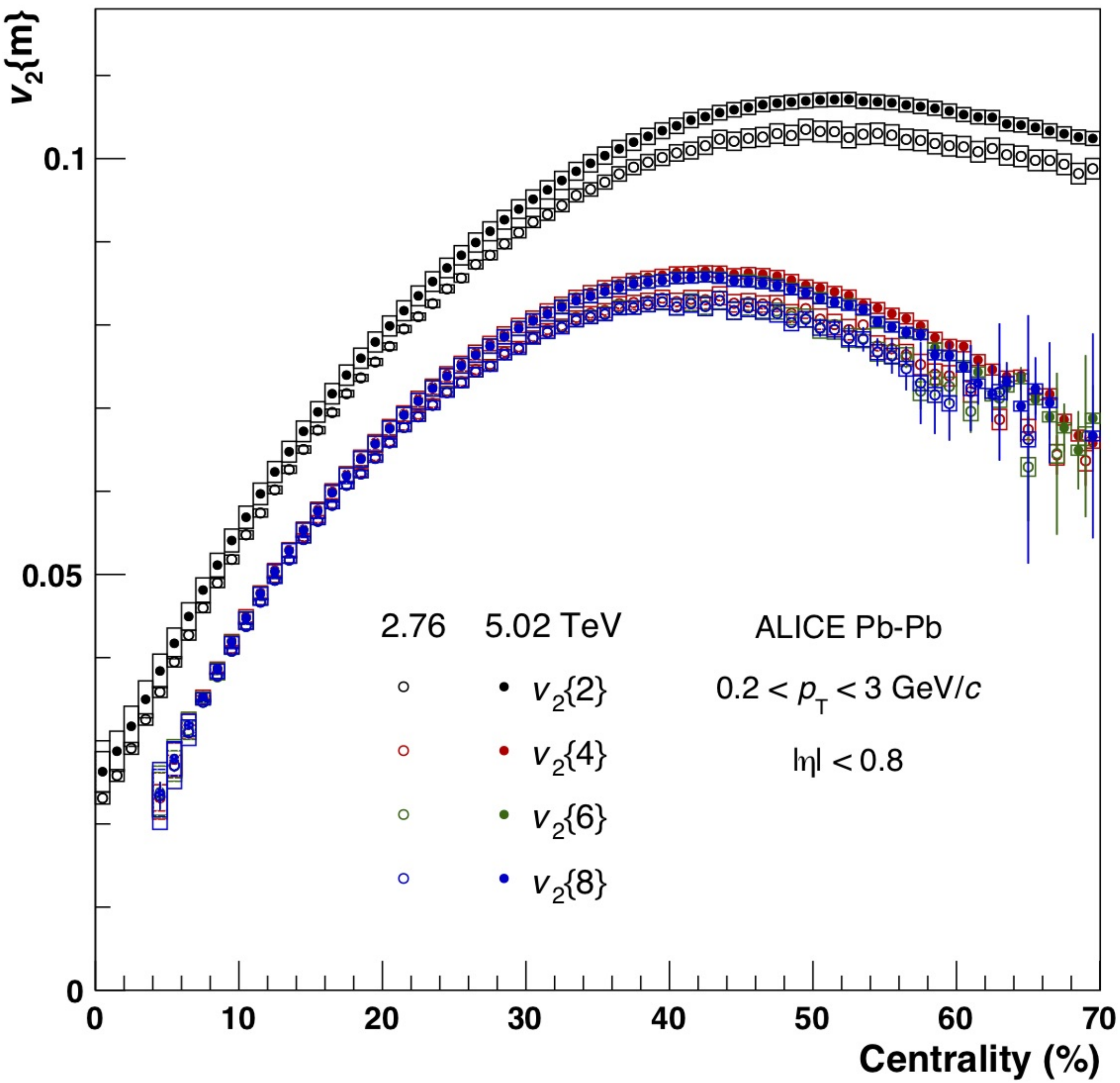
Multi-particle cumulants and flow fluctuations



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$v_2\{2\}$, $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$

The energy dependence of anisotropic flow provides additional discriminating power over initial-state models and temperature dependence of transport coefficients.

Comparison to hydro models

Results: 2018, ALICE and CMS

Charged particles

v_2, ..., v_6 with 2 particle cumulants

Hydro models:

- MUSIC with IP-Glasma initial conditions, UrQMD
- iEbE-VISHNU with initial conditions from either AMPT or Trento, UrQMD
- η/s constant or parametric function

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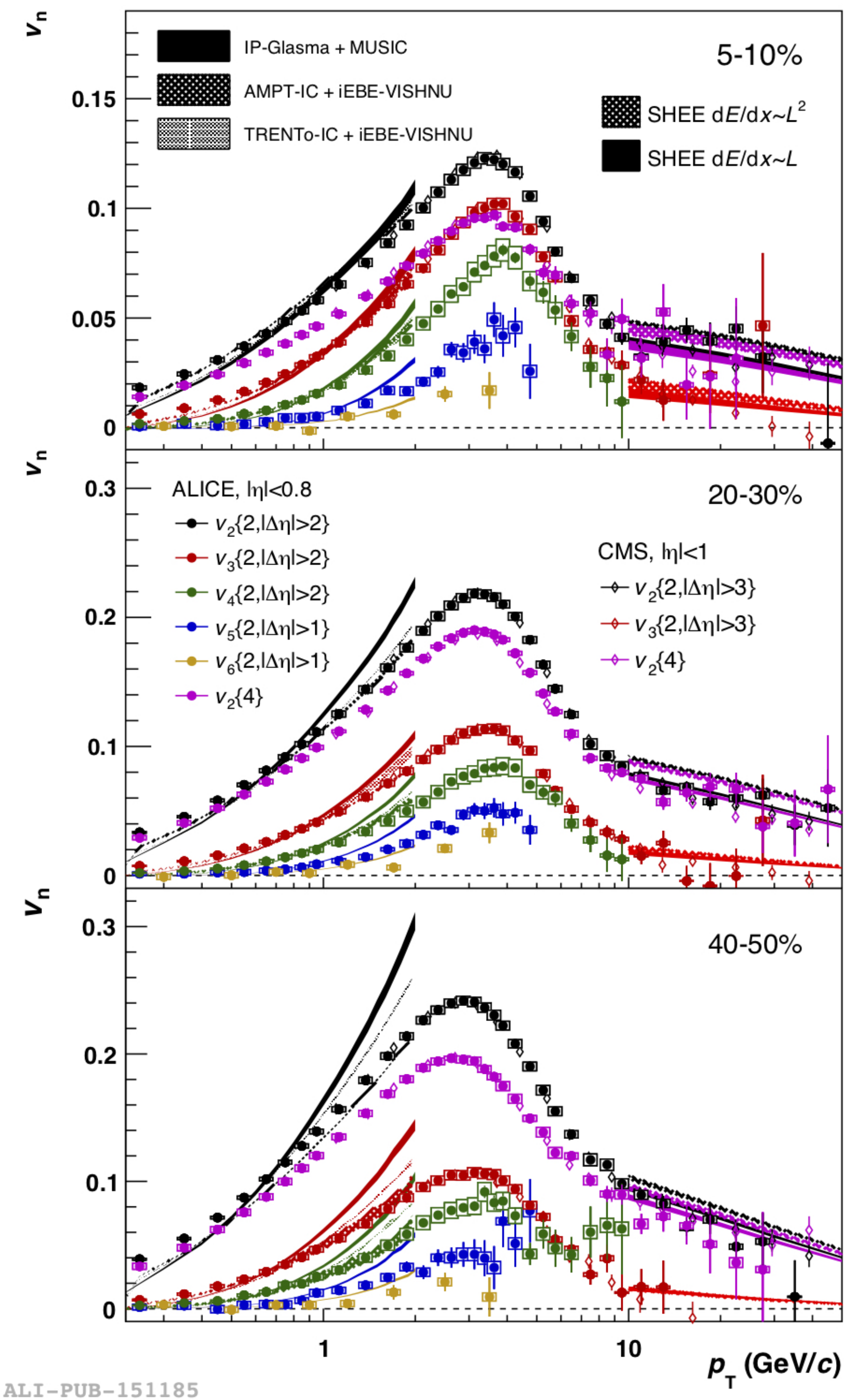
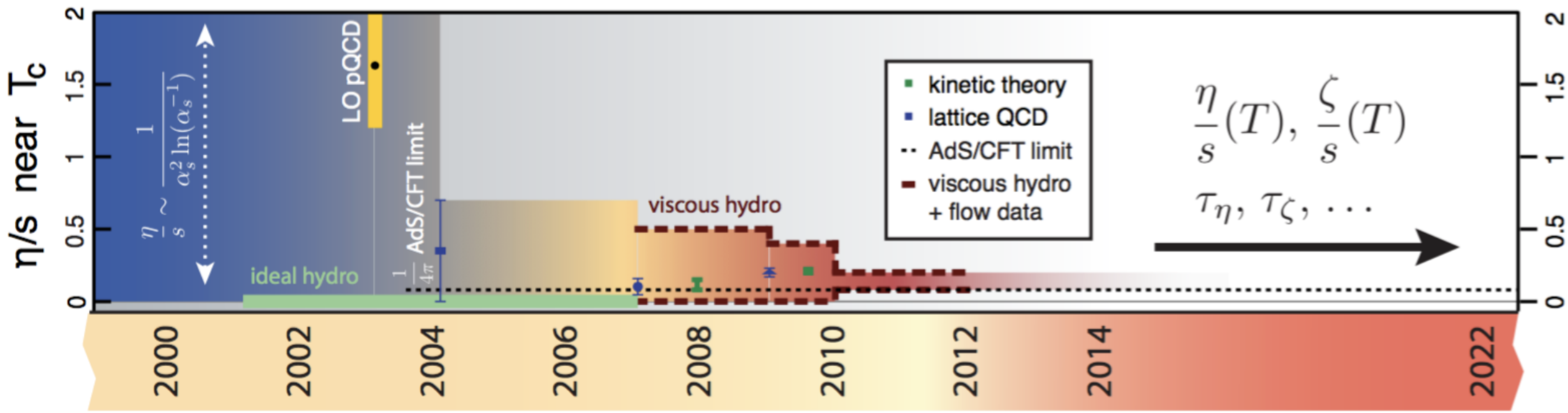


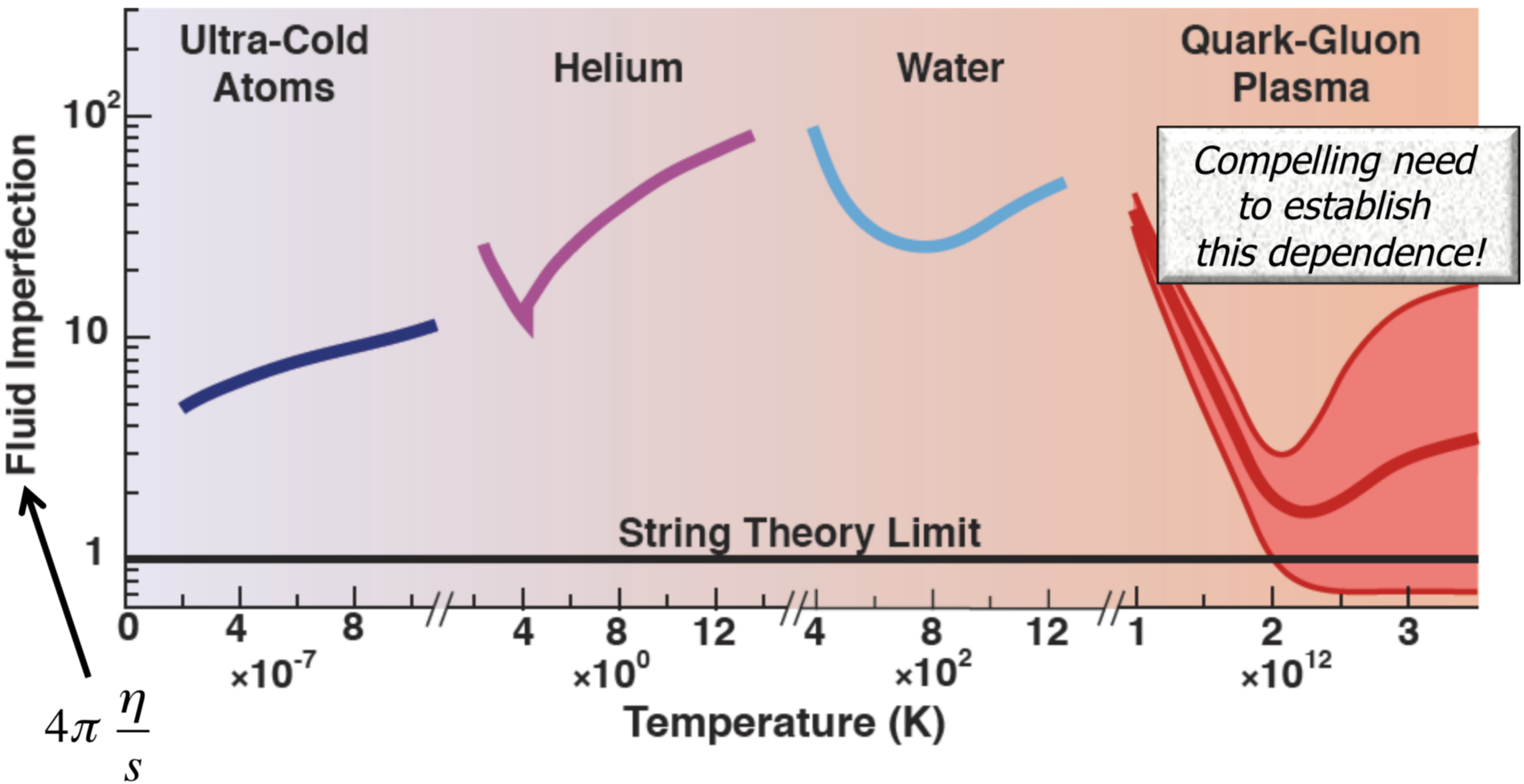
Evolution of the hydro description



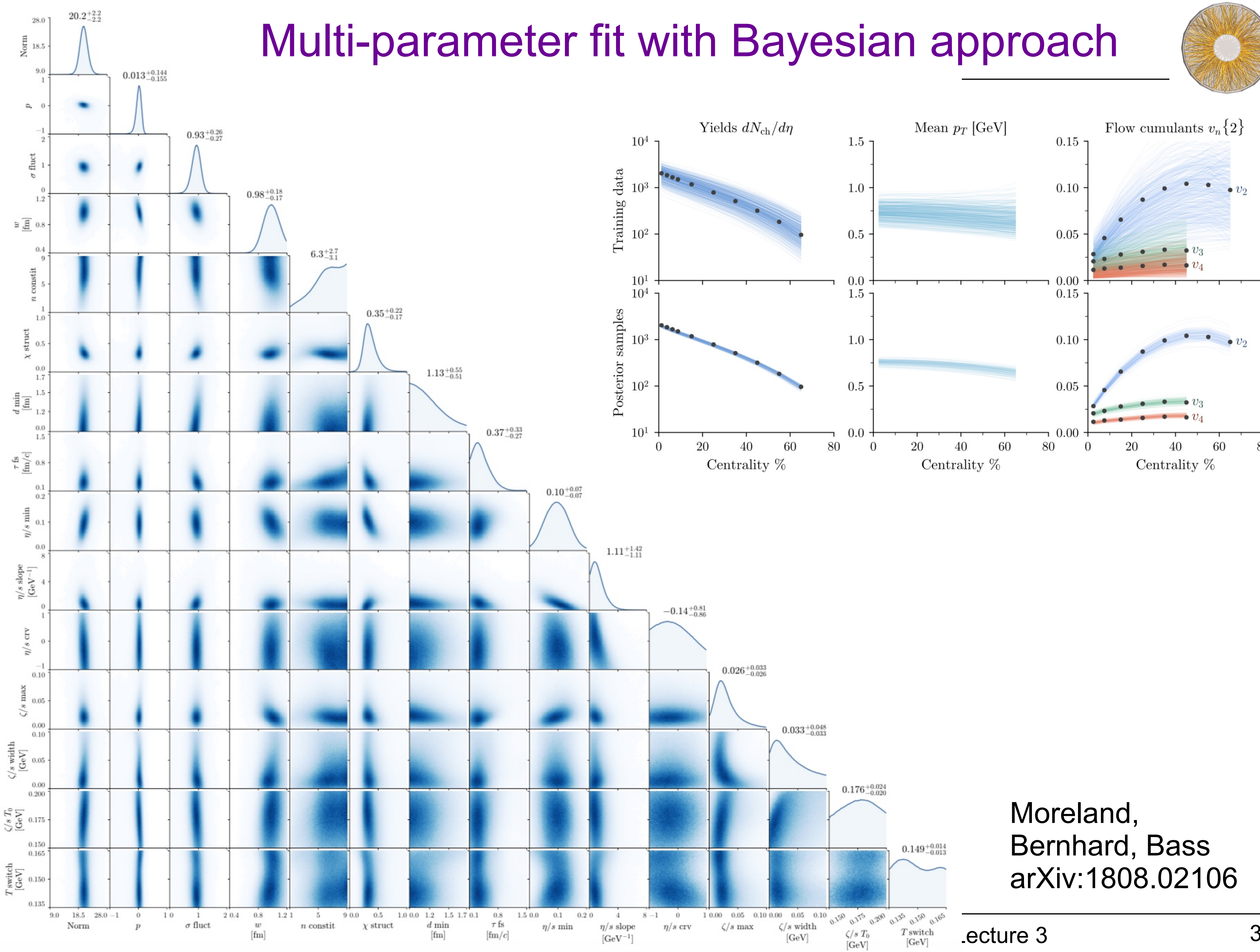
Hot and Dense QCD White Paper (2012)

- Tremendous evolution over the last years
- Hydro implementation more and more refined ...
- ... however still depending on much modeling!!
- High-precision data challenge the hydro computations

The "perfect liquid"



Multi-parameter fit with Bayesian approach

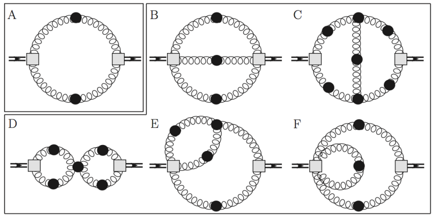


Moreland, Bernhard, Bass
arXiv:1808.02106

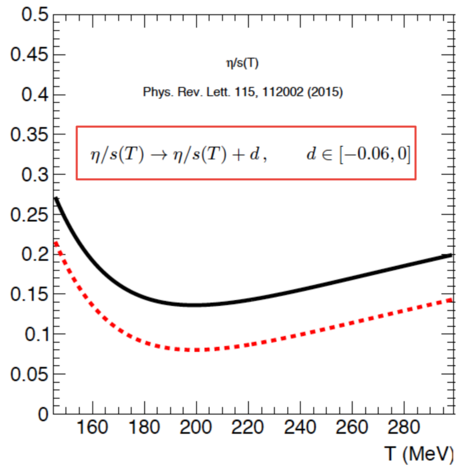
Local contribution within ISOQUANT (SFB1225)

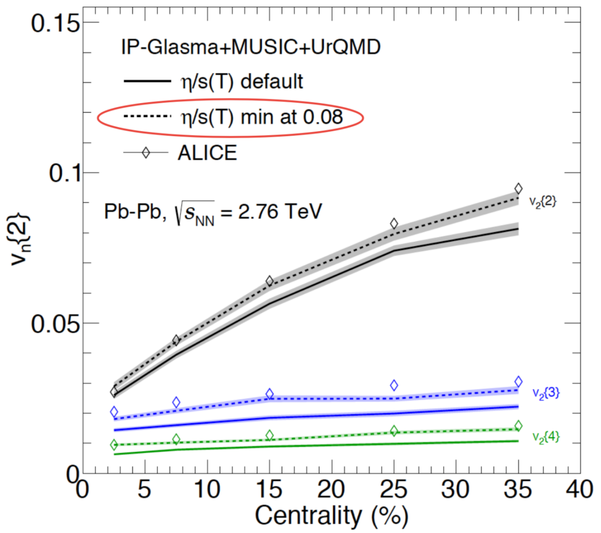
Transport coefficients: compute their temperature and density dependence with first principle QCD

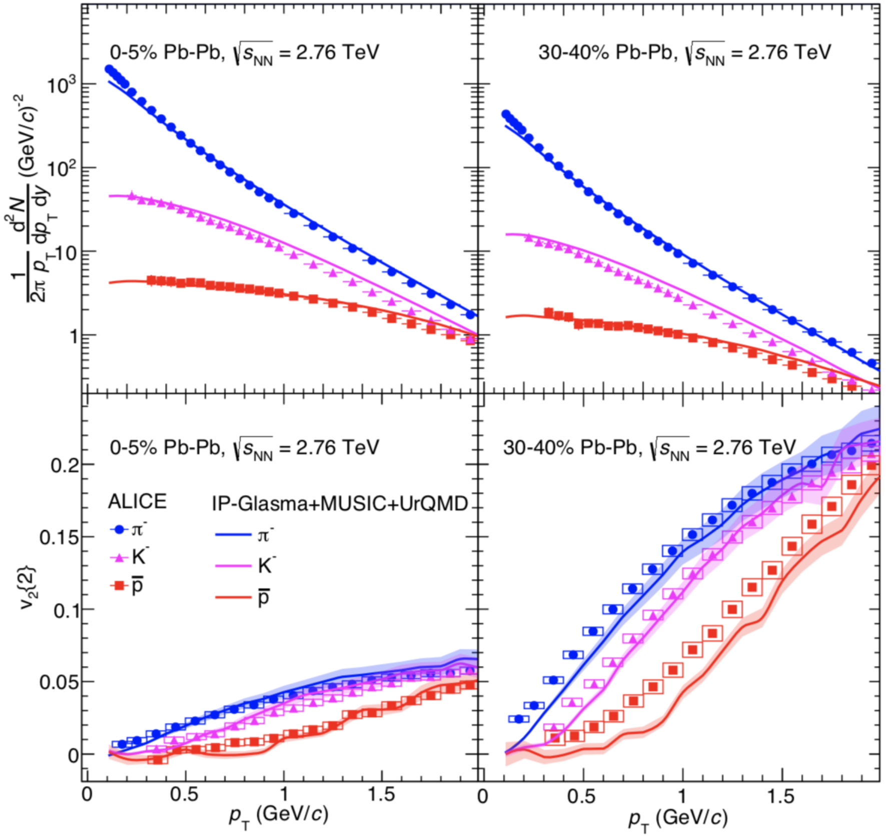
- Functional renormalization group approach
- Lattice QCD



IP-Glasma IC, MUSIC, UrQMD





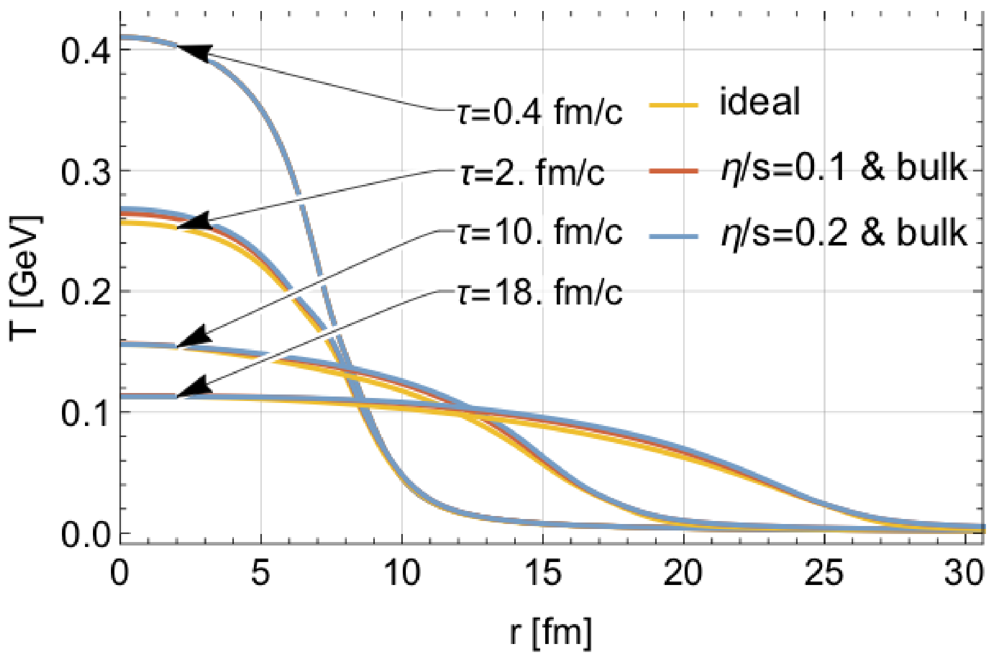


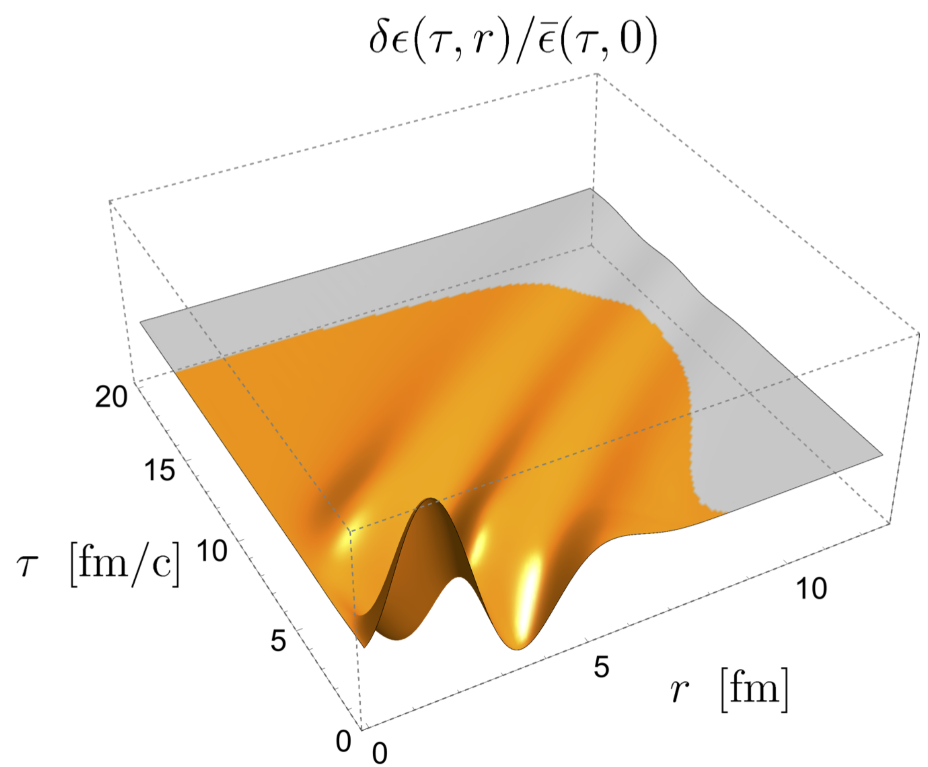
Dubla, S.M., Pawlowski, Schenke, Shen, Stachel, Nucl. Phys. A979 (2018) 251

Local contribution within ISOQUANT (SFB1225)

- Fluid dynamics of heavy ion collisions with Mode expansion (FluiduM)
  Analytic solution of hydrodynamic equations
- Resonance decays (FastReso)

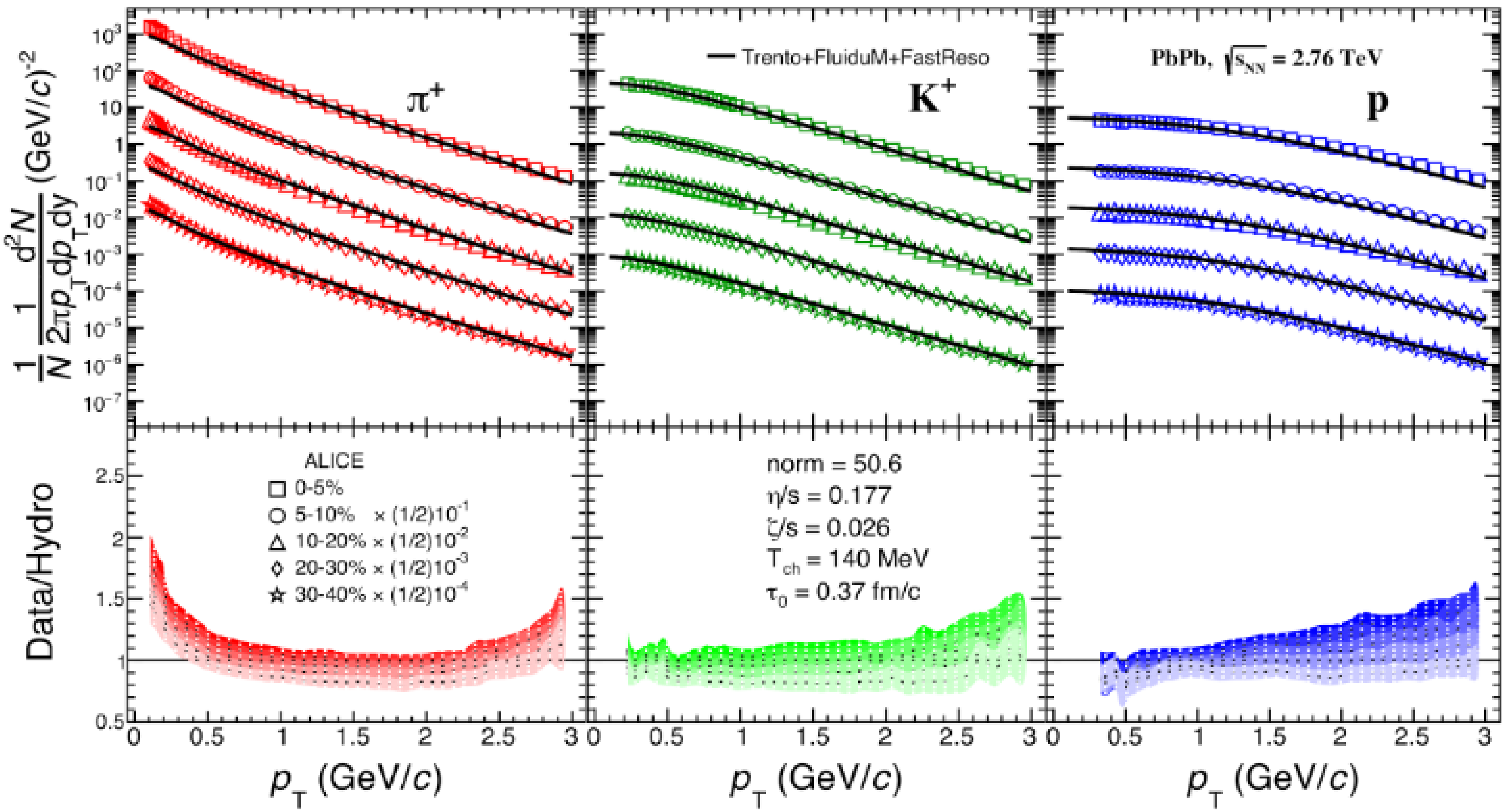
Speed and flexibility: opens new doors and opportunities!





Floerchinger, Grossi, Lion arXiv: 1811.01870

Local contribution within ISOQUANT (SFB1225)

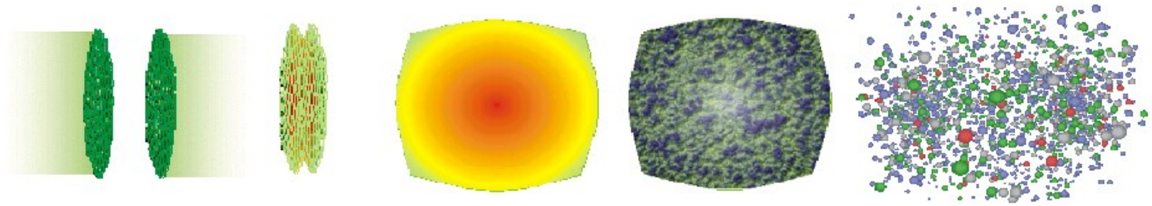


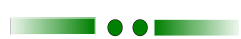
Devetak, Dubla, Floerchinger, Grossi, Masciocchi, Mazeliauskas, Selyuzhenkov, arXiv:1909.10485

Hadrochemistry vs system size

with
a “parenthesis” on “small systems”

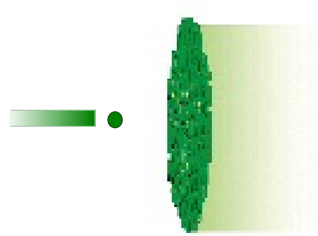
Small systems

Pb - Pb 

proton - proton 

Reference system, normalization

e.g. denominator in the nuclear modification factor R_{AA}

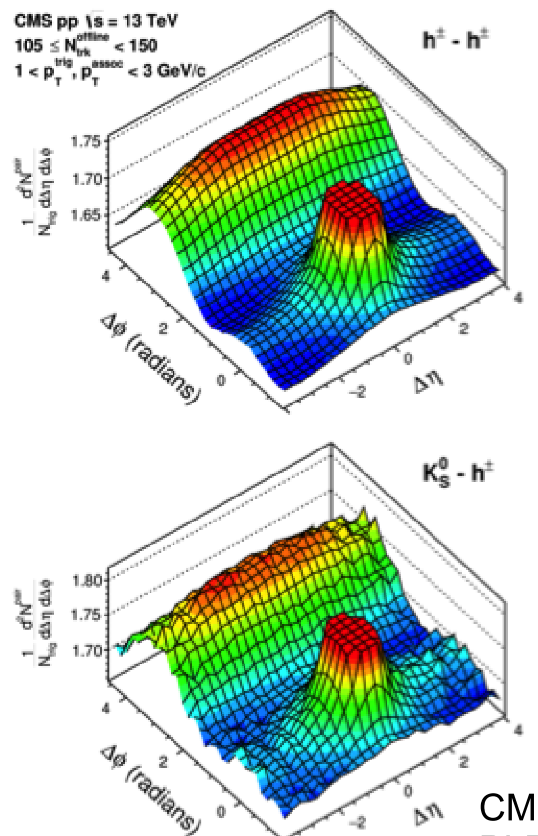
proton - Pb 

Control experiment

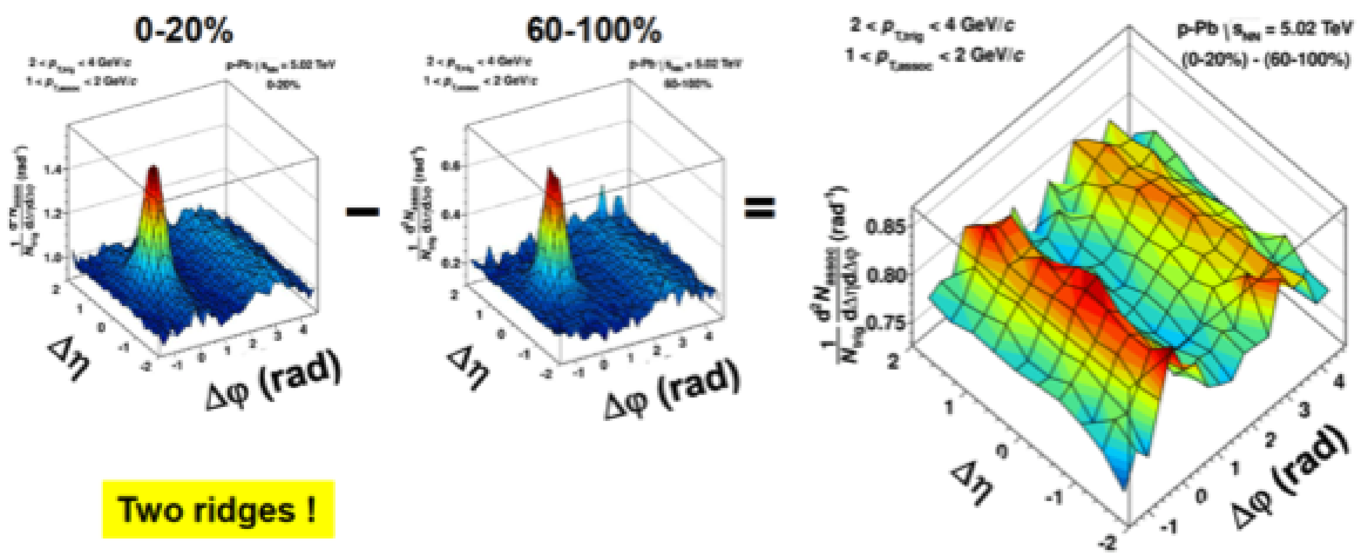
mostly to address cold nuclear matter, initial-state effects (shadowing, gluon saturation, nPDF)

Small systems: signs of collectivity?

New at the LHC: p-Pb and pp collision data (at high multiplicities) show features which are suggestive of the collective behavior known from Pb-Pb



CMS, pp
PLB765(2017)193



ALICE, PLB719 (2013) 29

→ examine evolution vs system size ↔ multiplicity of produced particles

Now: look at hadron yields vs charged-particle multiplicity

Hadro-chemistry vs system size

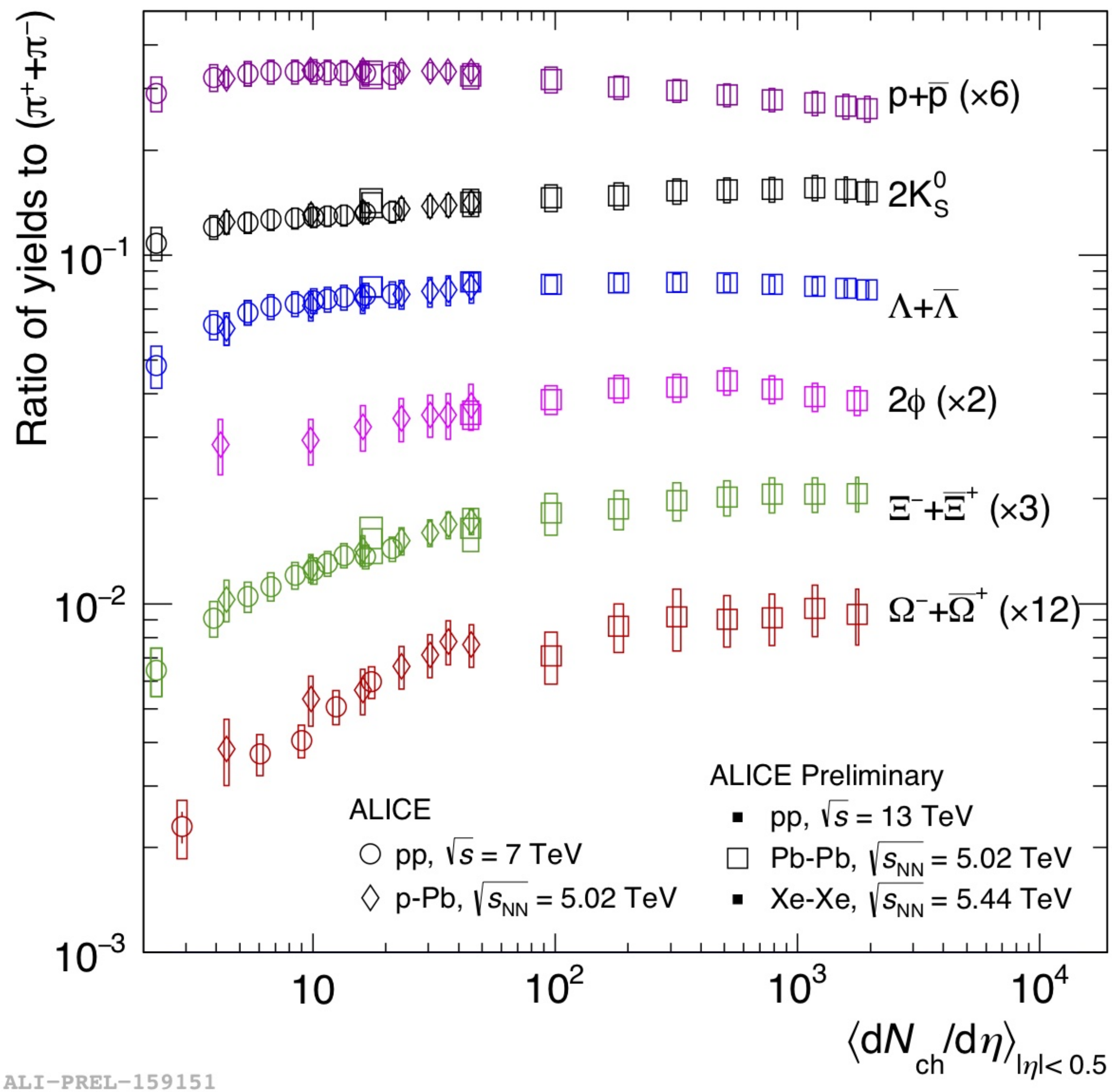
Smooth evolution of particle production yields from small to large systems, as a function of charged particle multiplicity at mid-rapidity

pp $\sqrt{s}$ = 7 TeV

p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

Common hadron production mechanism in all systems, regardless of type and $\sqrt{s}$?



Hadro-chemistry vs system size

Smooth evolution of particle production yields from small to large systems, as a function of charged particle multiplicity at mid-rapidity

pp $\sqrt{s}$ = 7 TeV

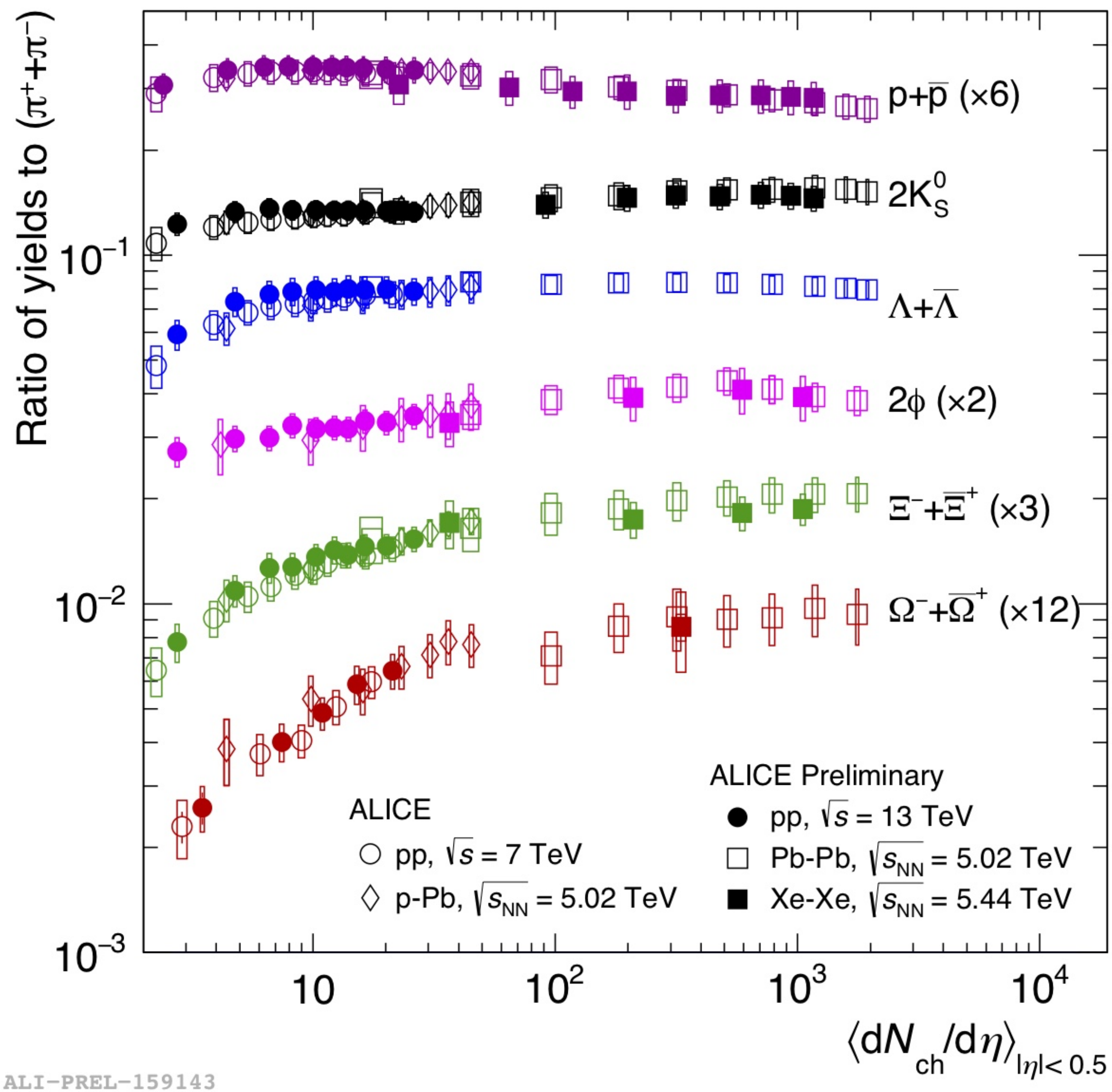
pp $\sqrt{s}$ = 13 TeV

p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

Xe-Xe $\sqrt{s_{NN}}$ = 5.44 TeV

Common hadron production mechanism in all systems, regardless of type and $\sqrt{s}$?



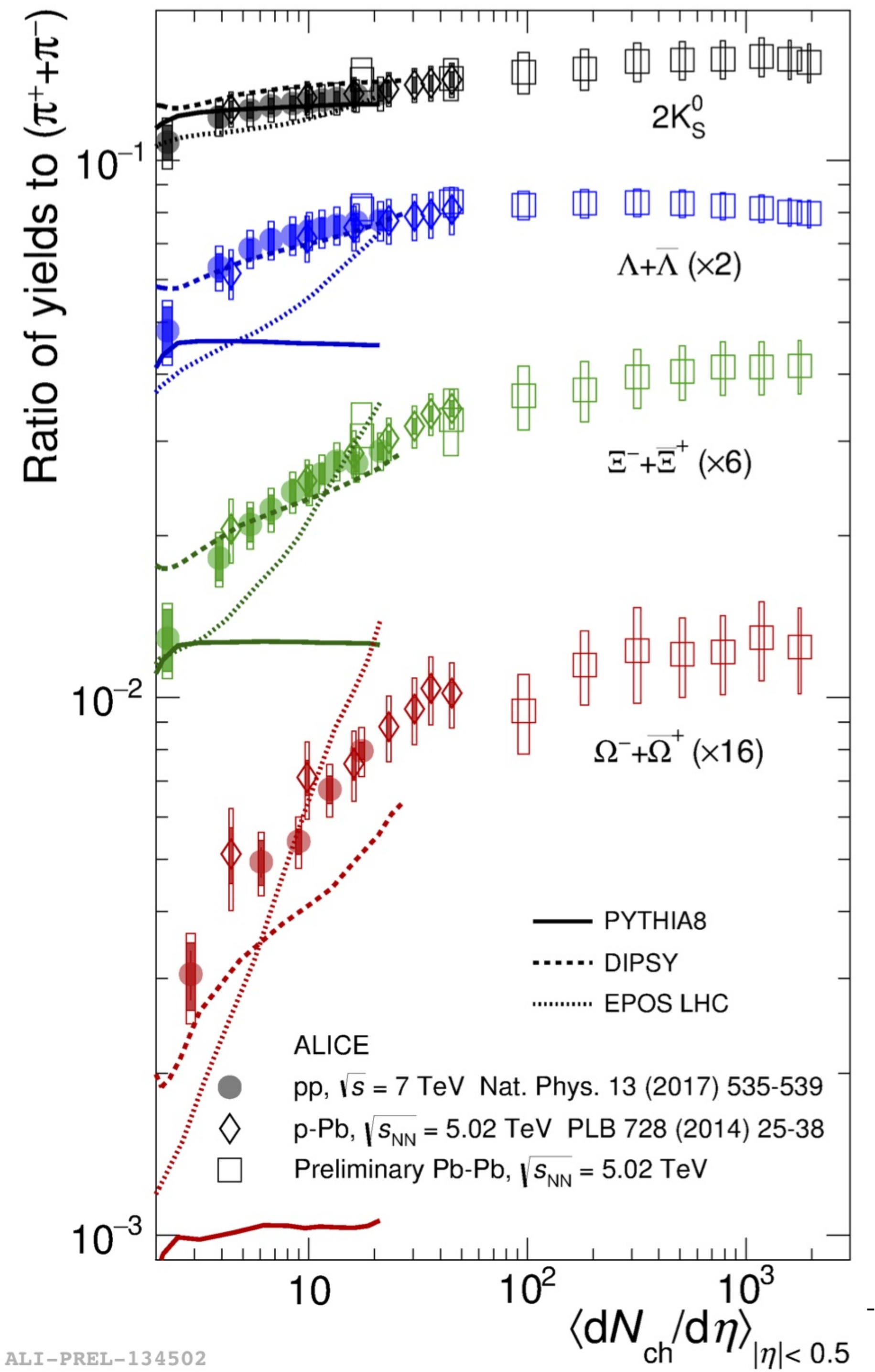
Focus on strageness vs system size

Strong increase of strangeness production with growing charged particle multiplicity at mid-rapidity, until it reaches a saturation

→ gran-canonical plateau

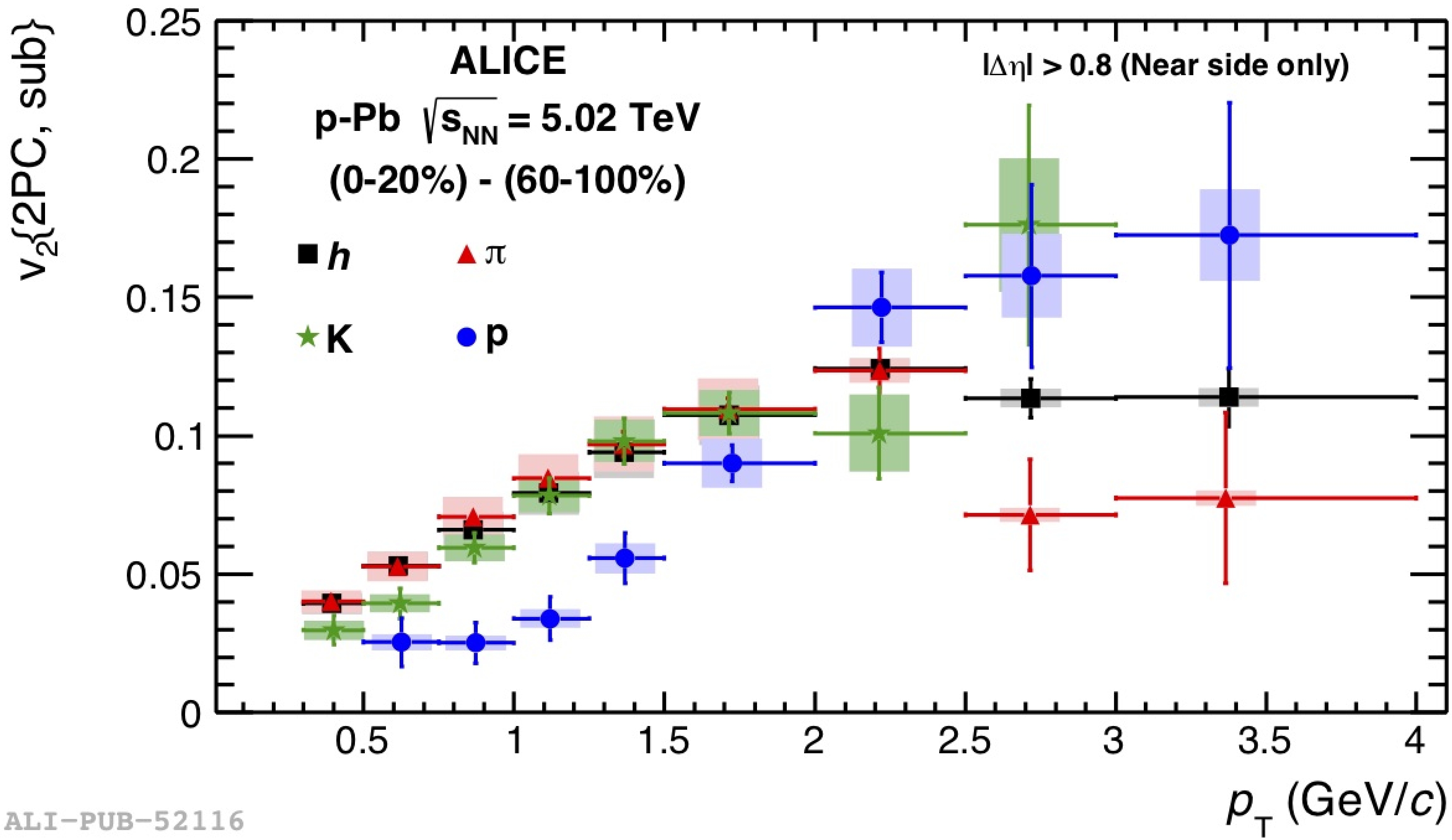
Increasing slope from
s (K_S^0, Λ^0) to ss (Ξ) to sss (Ω)

Clear difficulty of models to describe the data, increasing with S



Small systems

Same mass ordering in the elliptic flow measured:

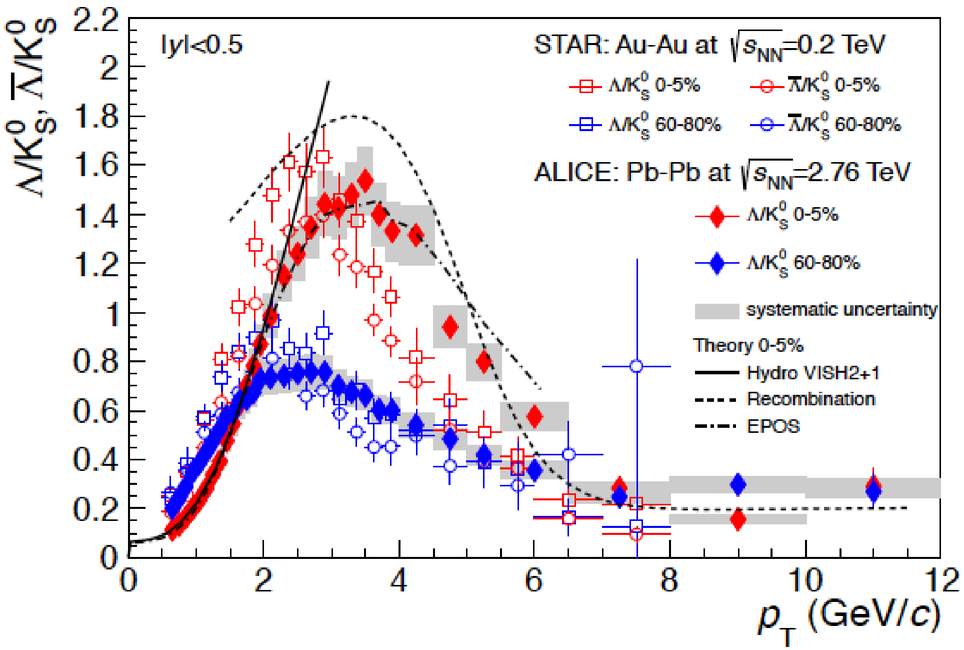


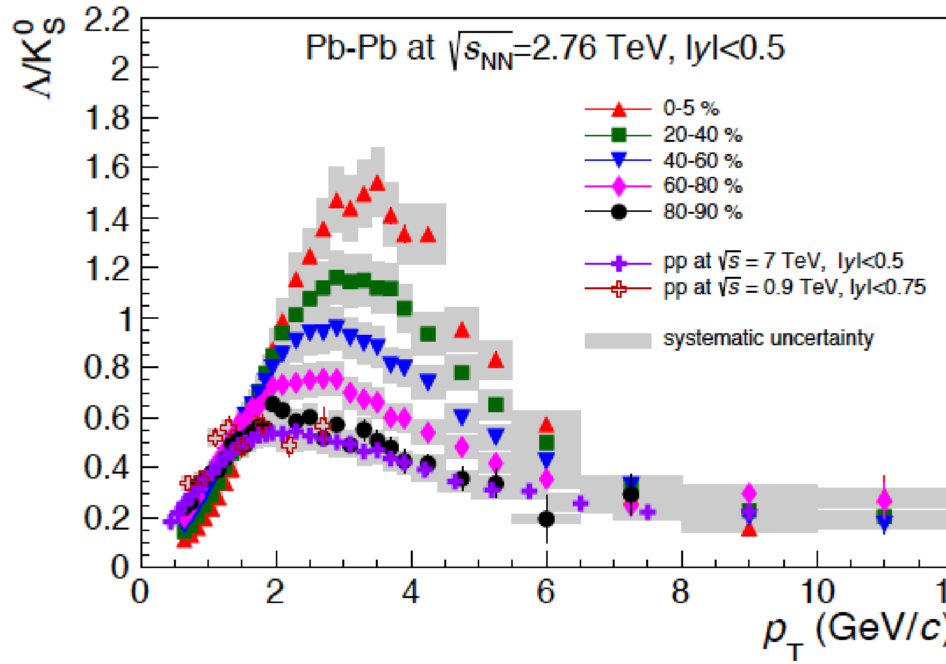
Phys. Lett. B 726 (2013) 164–177

Radial flow: a sign of collectivity

The "baryon anomaly" in Pb-Pb: p_T-dependent distribution of baryons and mesons abundances in different centrality classes:

Λ/K_s ratio





Effect of radial flow, which makes the spectra harder, with a strength proportional to the mass of the particle

arXiv:1307.5530

Small systems: signs of collectivity?

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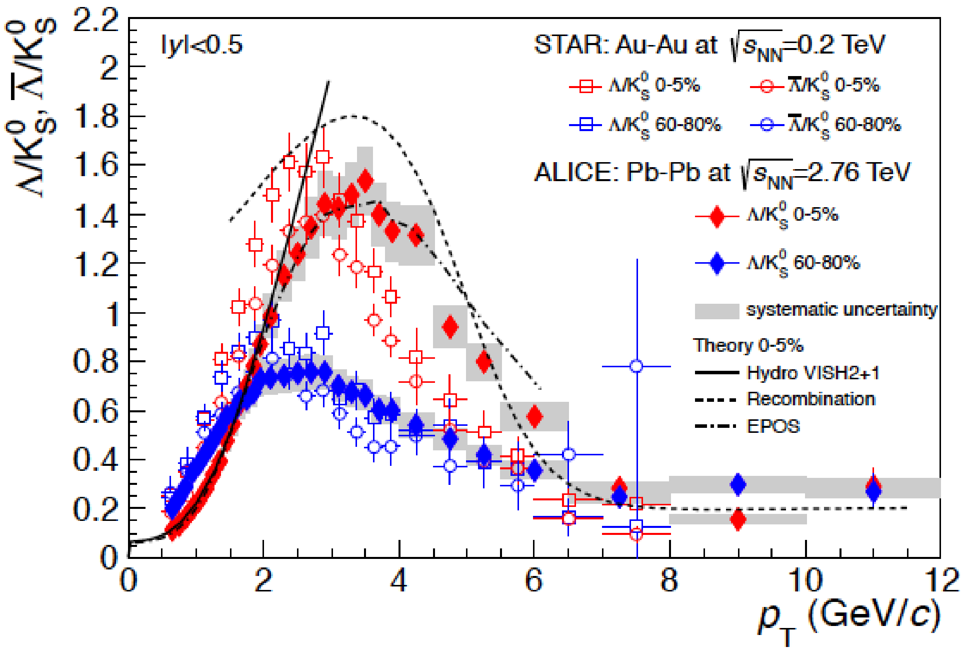
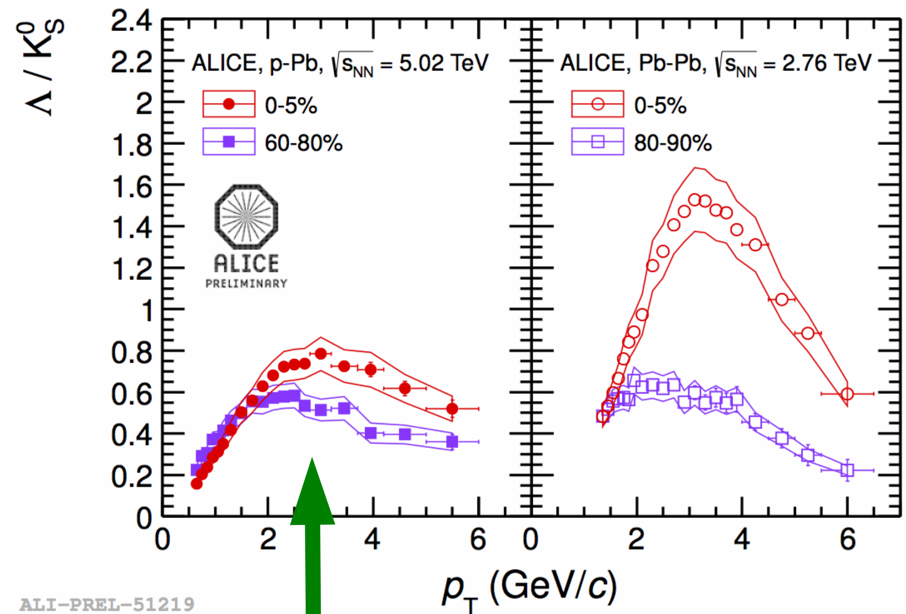
Λ/K_s ratio





Effect of radial flow, which makes the spectra harder, with a strength proportional to the mass of the particle

Also in p-Pb?

Summary

Anisotropic flow is determined by the response of the system to its initial spatial anisotropies. Initial state spatial anisotropies come in turn from both the geometry of the collision and fluctuations in the wave function of the incident nuclei. The significant magnitude of anisotropic flow is interpreted as evidence of the formation of a strongly-coupled system, which can be described as s fluid with very low shear viscosity to entropy density ratio.

- Standard model of heavy-ion collisions
- Provides an overall good description of many features of experimental data
- Relatively many free parameters: important to follow a much more rigorous approach to fix some (e.g. with principle QCD input) and learn about/constrain the others
- Pursue the investigation of small systems to ultimately determine the true driving physics behind the common phenomena

Spares