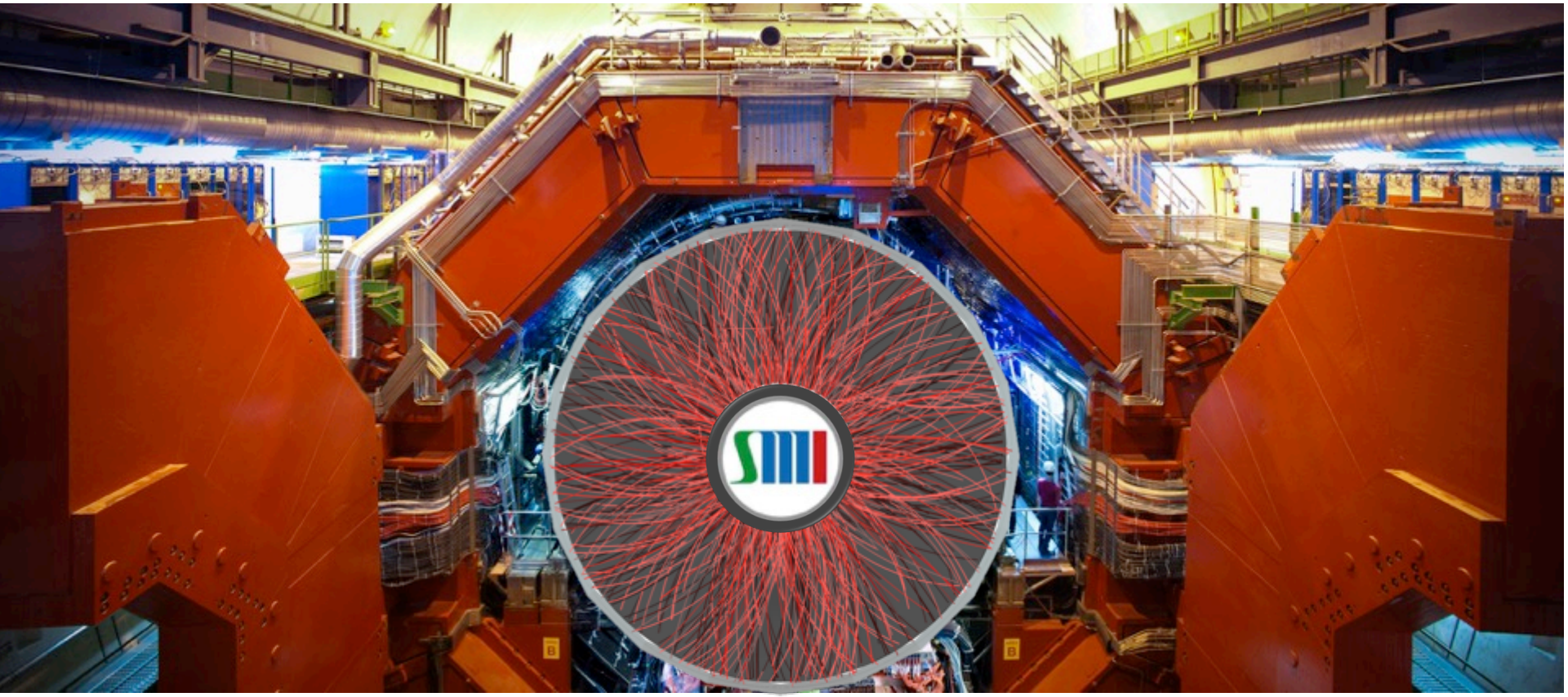
A Large Ion Collider Experiment

ALICE: SOFT QCD PROBES



MICHAEL WEBER (SMI, VIENNA)

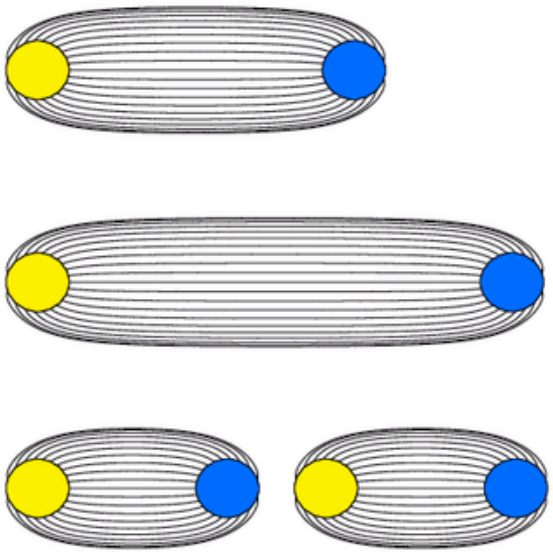
WE HERAEUS PHSYICS SCHOOL

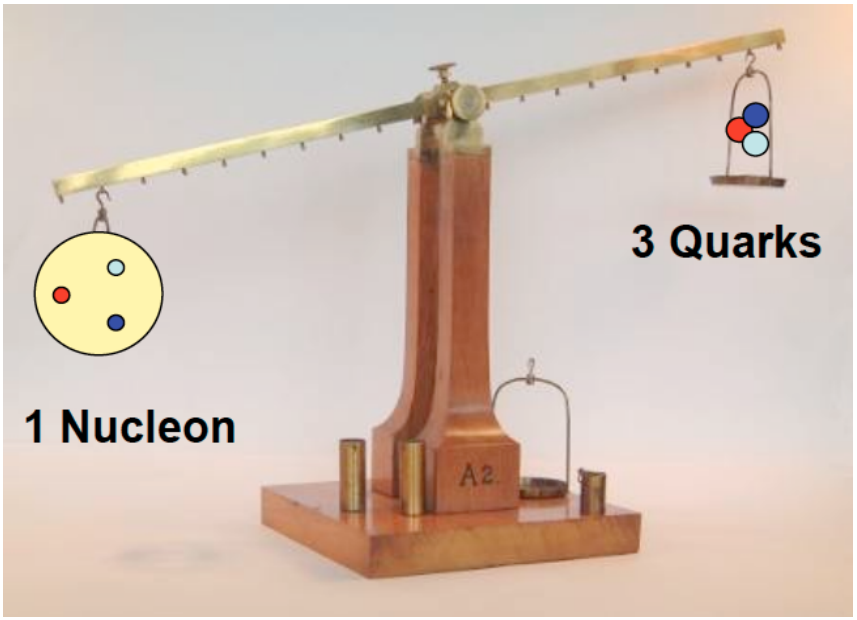
24.-30.09.2017

OUTLINE

- **Introduction**
  - QCD at extreme conditions
  - Heavy Ion collisions
- **Soft probes**
  - Initial energy density
  - Chemical freeze-out
  - Kinetic freeze-out
  - Radial flow
  - Anisotropic flow
  - Small systems

CHALLENGES IN QCD





Confinement

Generation of hadron masses

Non-perturbative QCD / dynamics

QCD AT EXTREME CONDITIONS

- Interactions between quarks and gluons become weaker at small distances and for large momentum transfers → **"deconfined" phase of QCD matter** by creating a **high density/temperature extended system** composed by quarks and gluons

Weakly coupled Quark-Gluon Plasma

E.V. Shuryak, Phys. Lett. B, vol. 78, page 150, 1978.

- **First sketch of phase diagram** in that sense date back to the '70s
- But ideas of critical densities are even older (Pomeranchuk '50s, Hagedorn '60s)

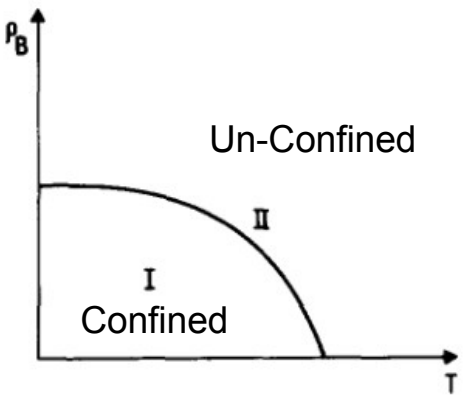
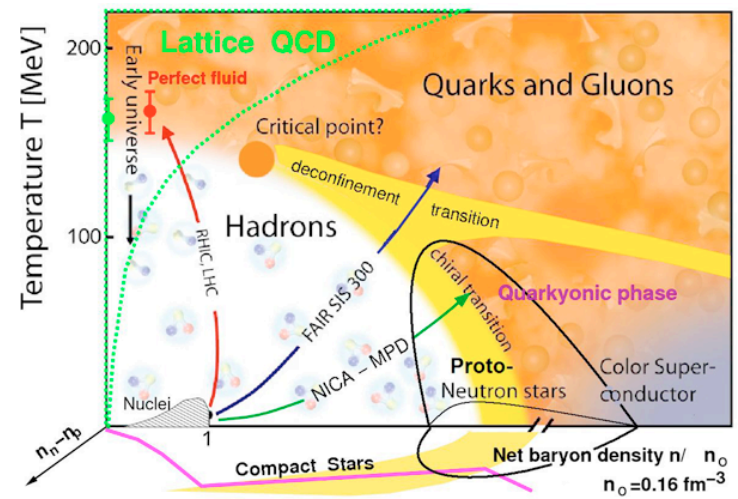
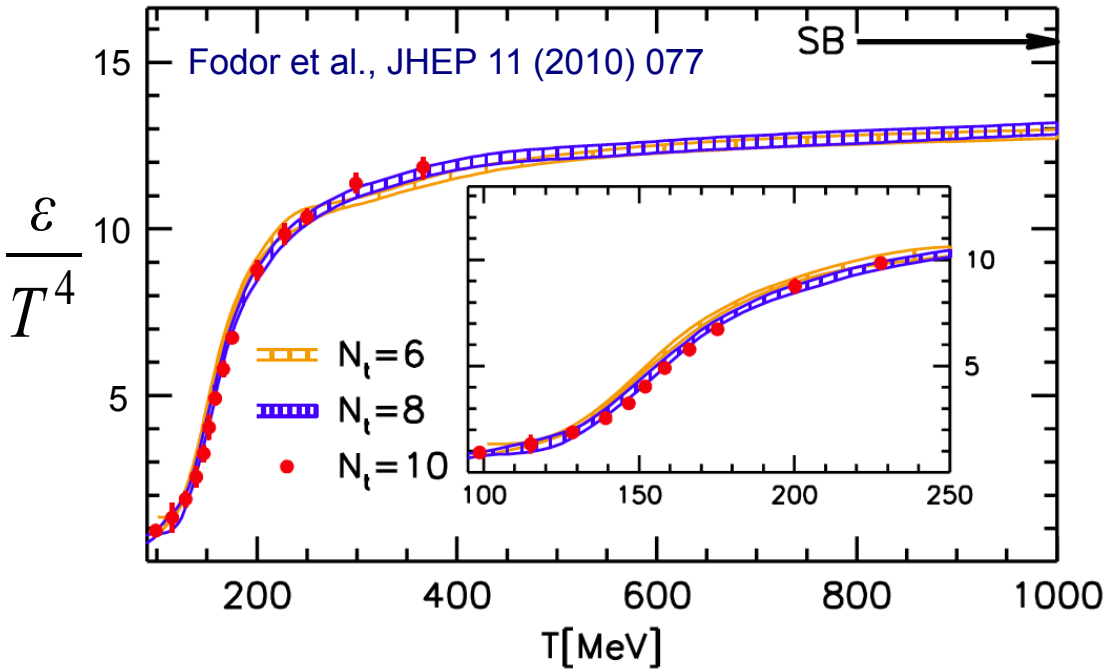


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.



"Experimental hadronic spectrum and quark liberation"
Cabibbo and Parisi *Phys.Lett.* **59 B**,67(1975)
→ **Phase transition at large T and/or ρ_B**

LATTICE QCD – PHASE TRANSITION

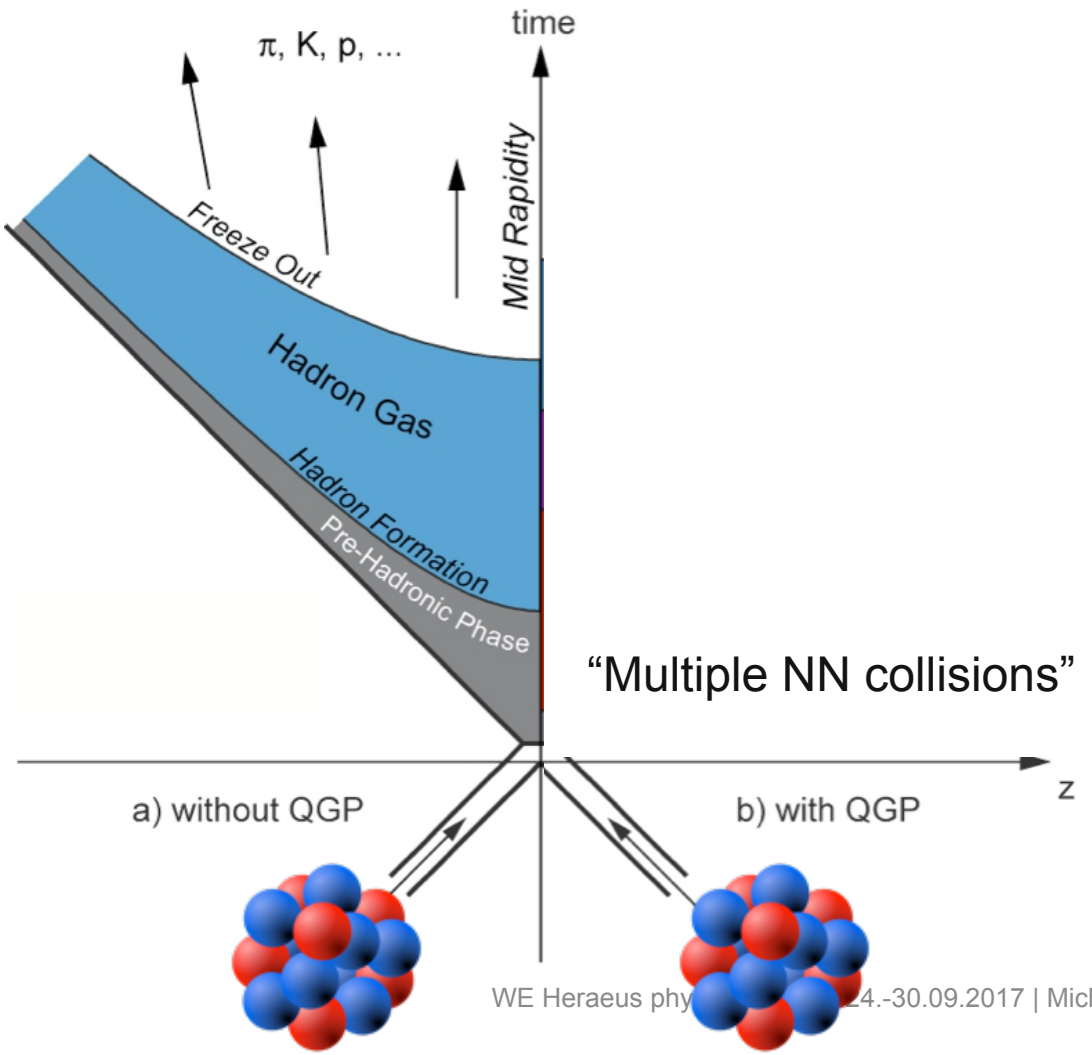


- increase in the number of d.o.f. from pion gas (3 d.o.f., corresponding to π^+, π^-, π^0) to deconfined phase leads to increase in energy density
- no sharp phase transition but **cross-over**
- **Critical temperature** T_c between 140 and 200 MeV (energy density between 0.2 and 1.8 GeV/fm^3), compare to MIT bag model: $T_c \approx 150$ MeV and $\varepsilon_c \approx 0.6$ GeV/fm^3

Heavy Ion collisions

A laboratory to test QCD at extreme conditions

HEAVY ION COLLISIONS

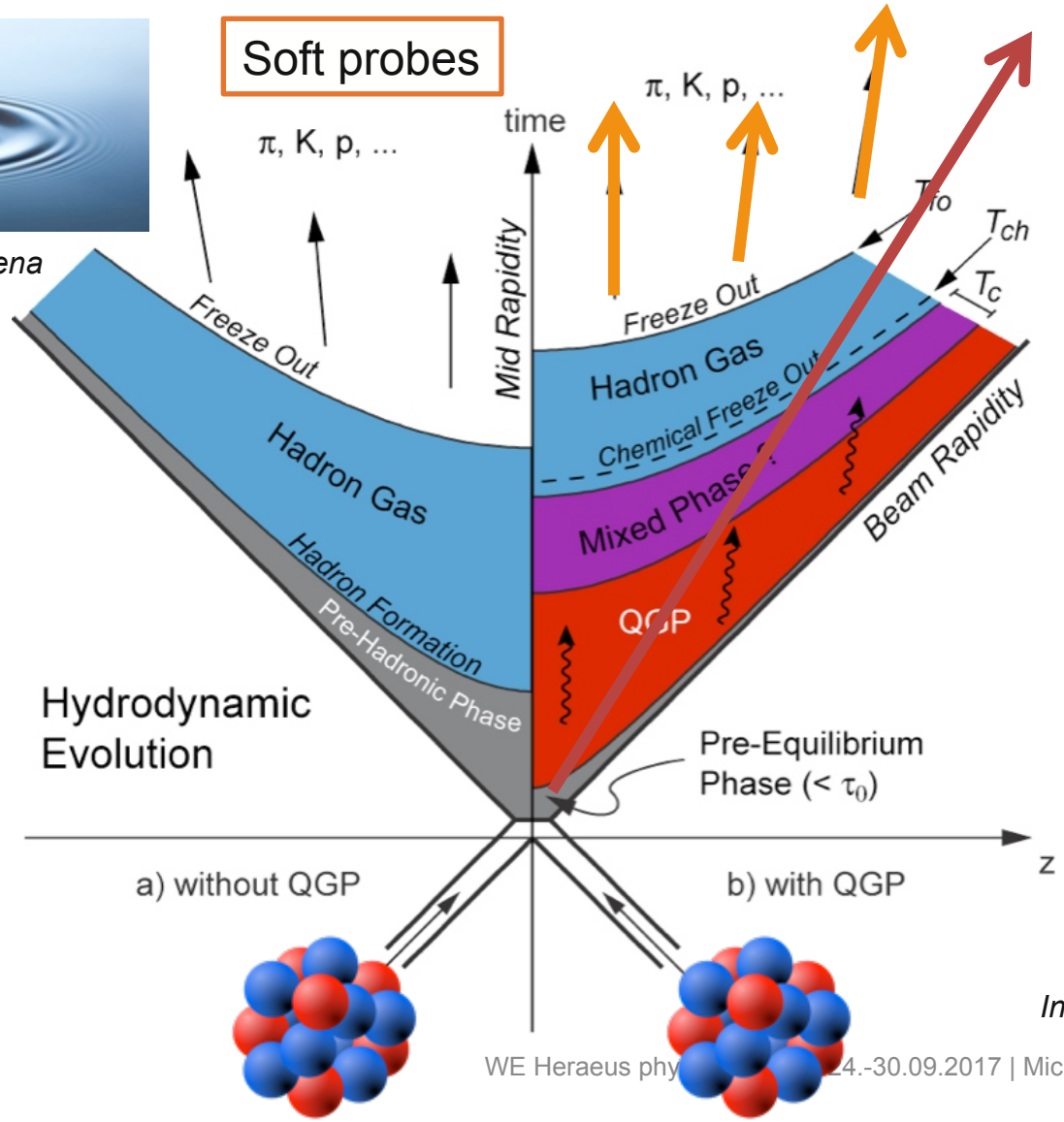


"Multiple NN collisions"

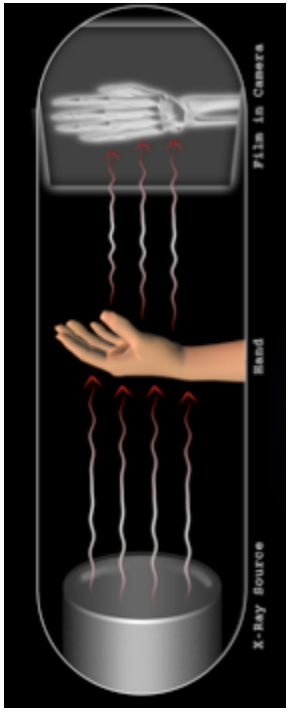
HEAVY ION COLLISIONS

Collective phenomena

Soft probes



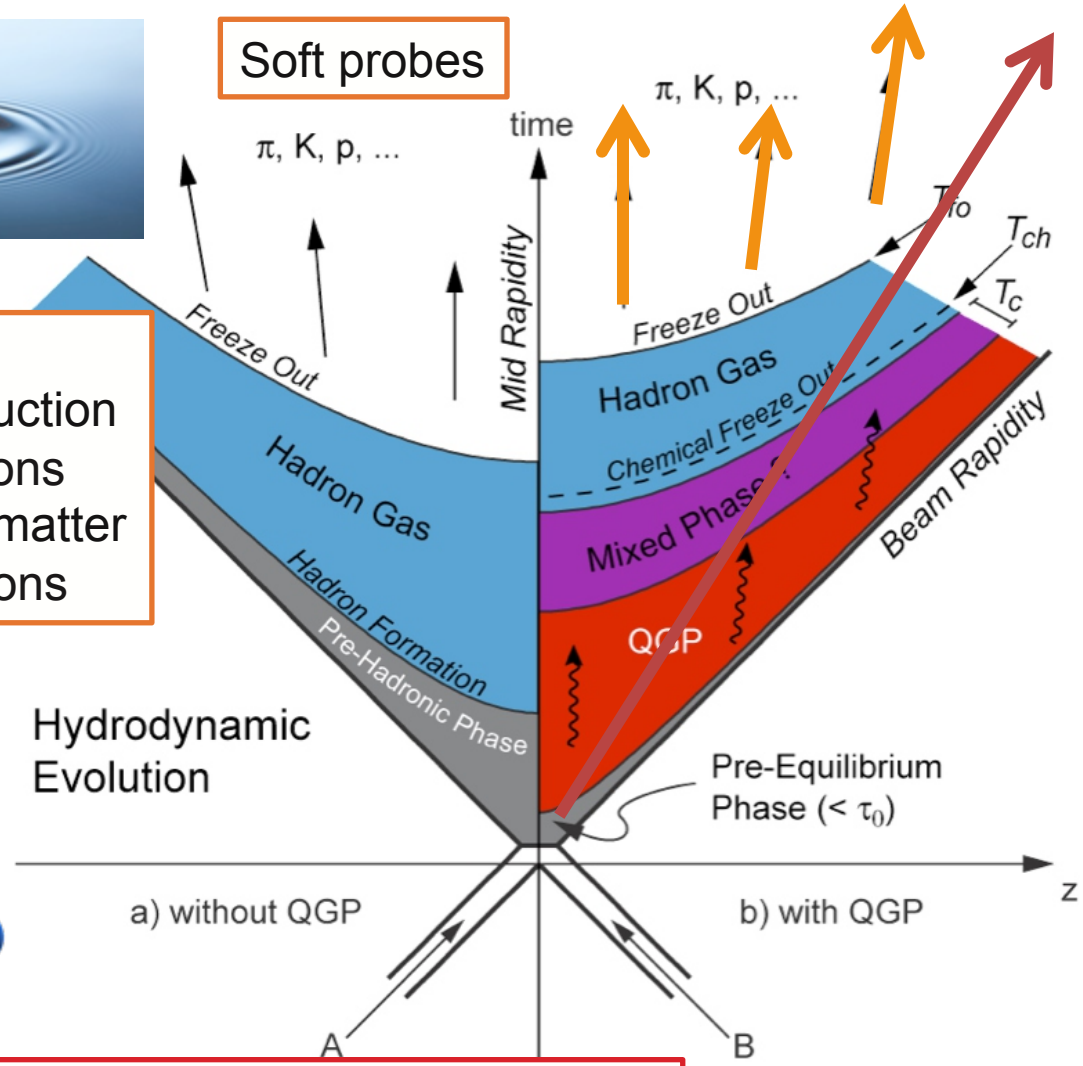
Hard probes
- c, b quarks
- Jets
- (Photons)



Interaction with matter

HEAVY ION COLLISIONS

Soft probes



Hard probes
- c, b quarks
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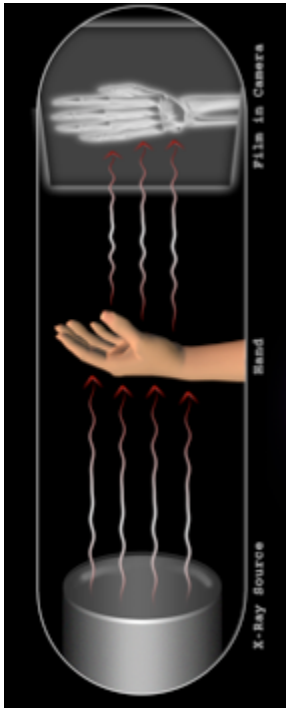
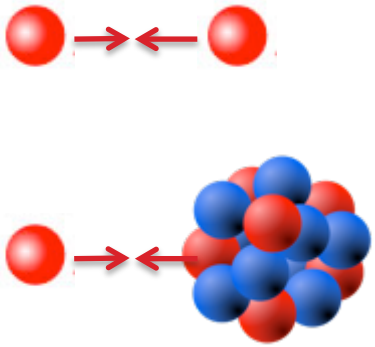


Reference:
- Vacuum production
  → pp collisions
- Cold nuclear matter
  → pA collisions



Studied at various laboratories around the world

HEAVY ION COLLISIONS

Collective phenomena

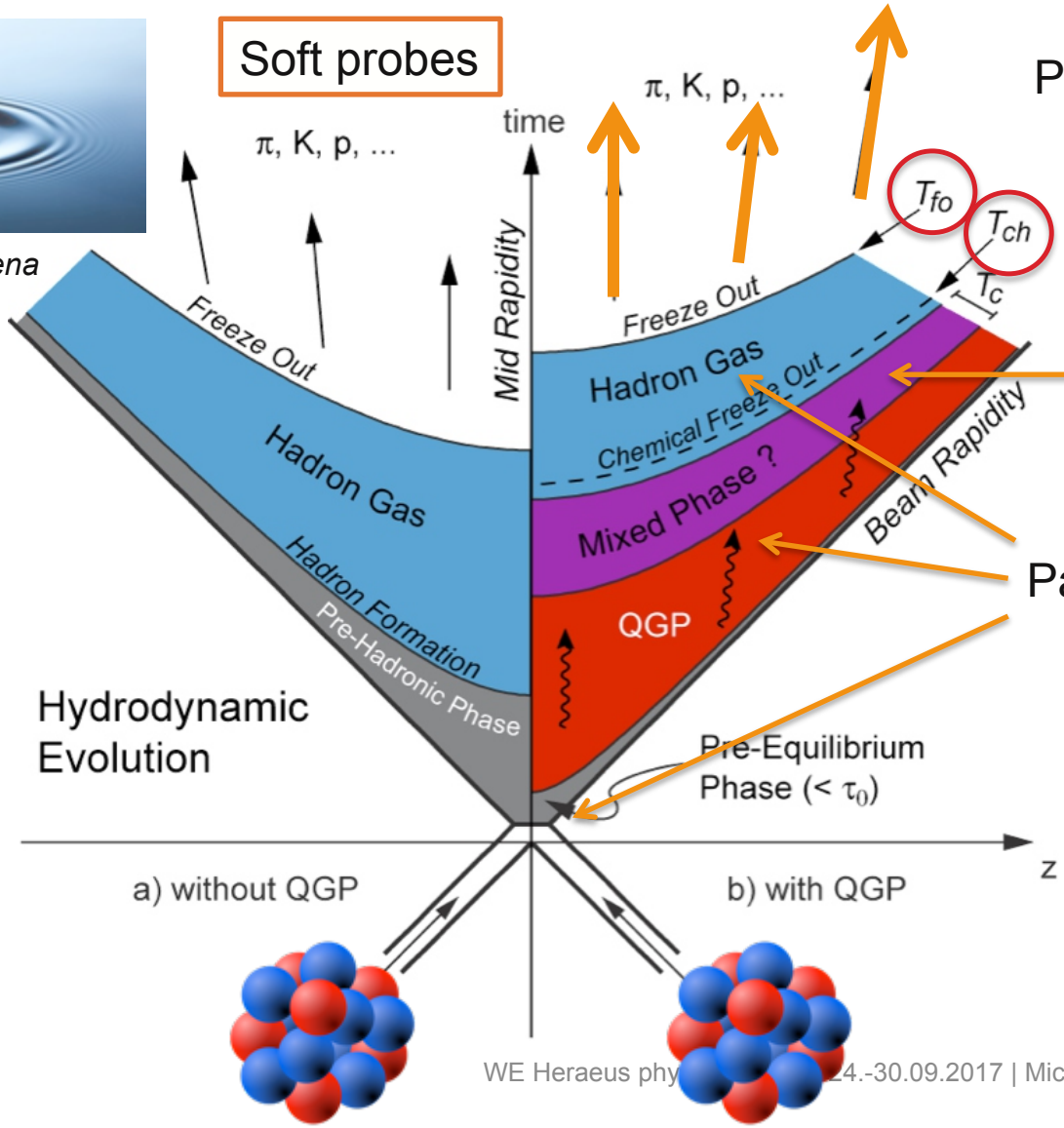
Soft probes

Particle spectra

Particle yields

(Fluctuations)

Particle anisotropy



ALICE (A LARGE ION COLLIDER EXPERIMENT)

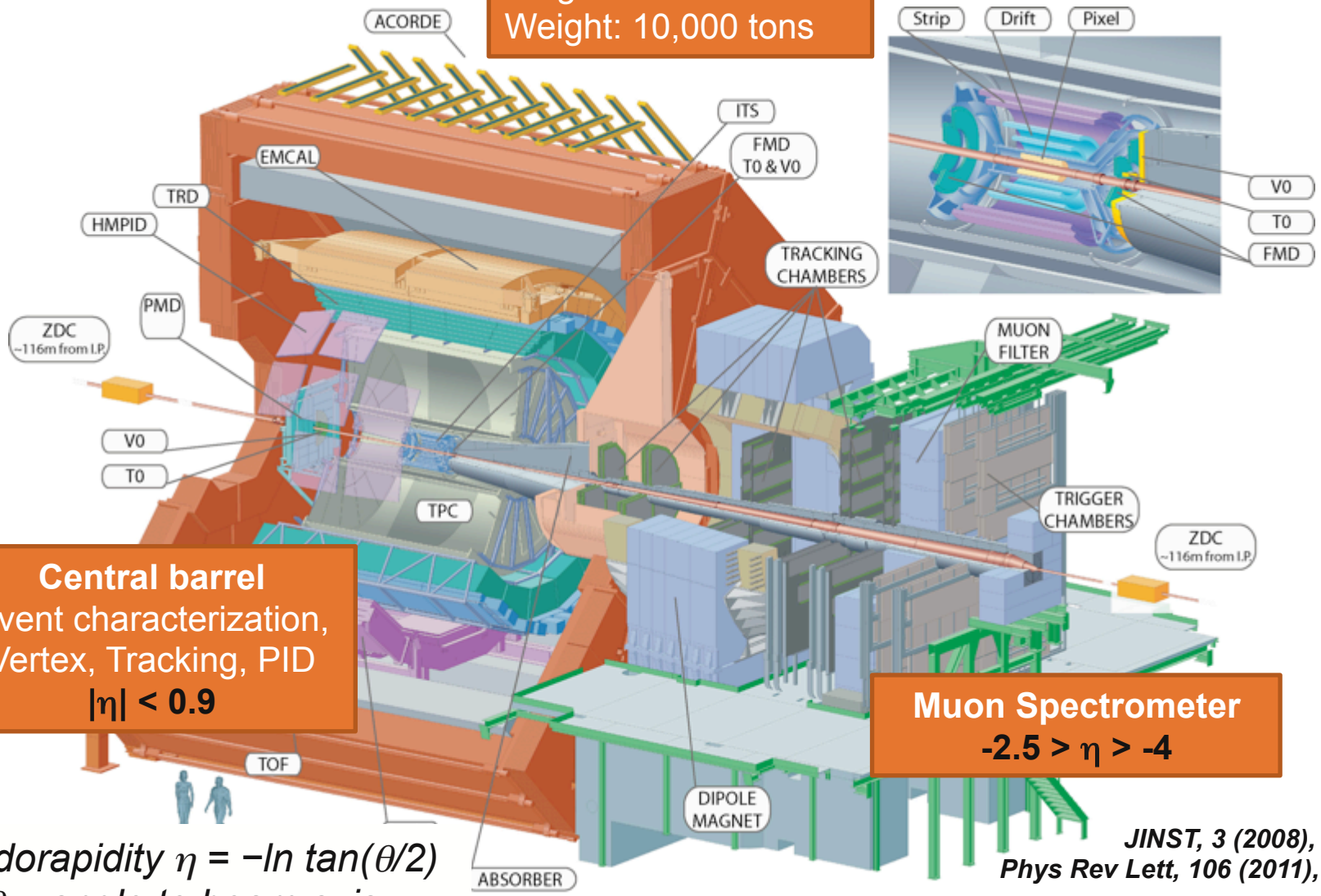
42 countries, 176 institutes, 1800 members

AUSTRIA
VIENNA, Stefan Meyer Institute

GERMANY
BONN, Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische F-W.-Universität Bonn
DARMSTADT, GSI Helmholtzzentrum fur Schwerionenforschung GmbH
DARMSTADT, Technische Universität Darmstadt
FRANKFURT, Institut für Kernphysik, Johann-Wolfgang-Goethe Universität
FRANKFURT, Johann-Wolfgang-Goethe Universitat, Institut fur Informatik
FRANKFURT, Frankfurt Institute for Computer Science
HEIDELBERG, Physikalisches Institut, Ruprecht-Karls-Universität
KOELN, Fachhochschule Köln
MUNICH, Technische Universitat Muchen
MUENSTER, Institut für Kernphysik, Westfälische Wilhelms-Universität
TUEBINGEN, Eberhard-Karls-Universitat Tubingen
WORMS, Fachhochschule Worms, ZTT,

ALICE

Detector:
Length: 26 meters
Height: 16 meters
Weight: 10,000 tons



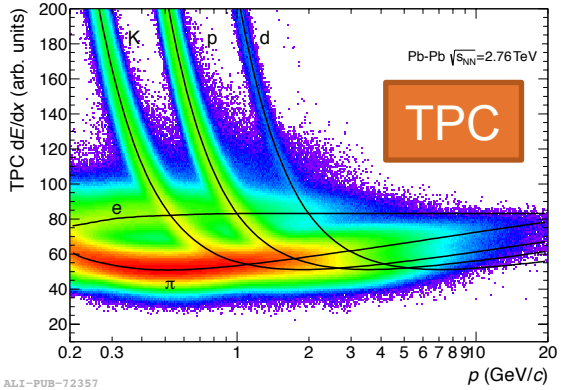
Central barrel
Event characterization,
Vertex, Tracking, PID
$|\eta| < 0.9$

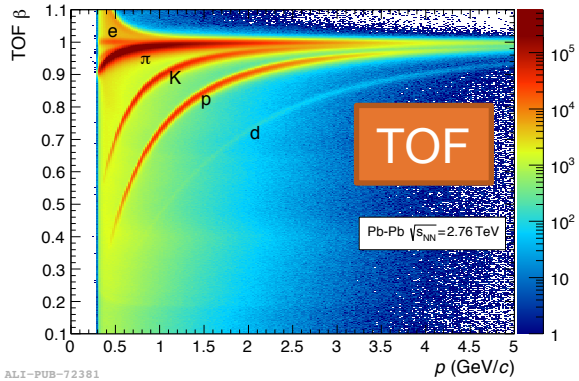
Muon Spectrometer
$-2.5 > \eta > -4$

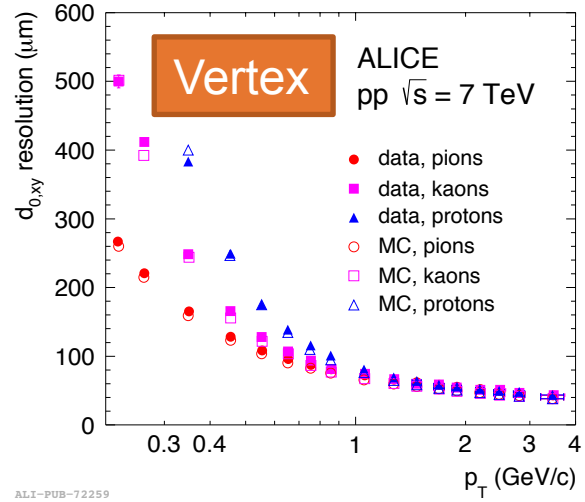
Pseudorapidity $\eta = -\ln \tan(\theta/2)$
with θ = angle to beam axis;
additive in relativity

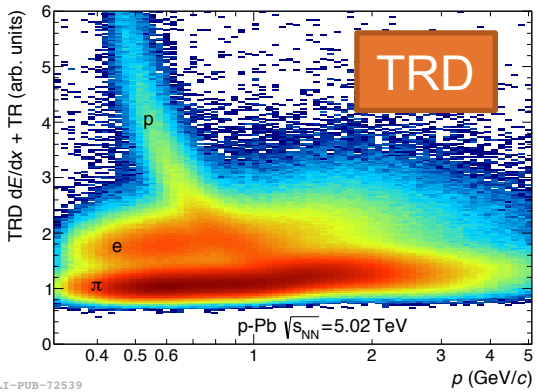
JINST, 3 (2008), S08002
Phys Rev Lett, 106 (2011), 032301

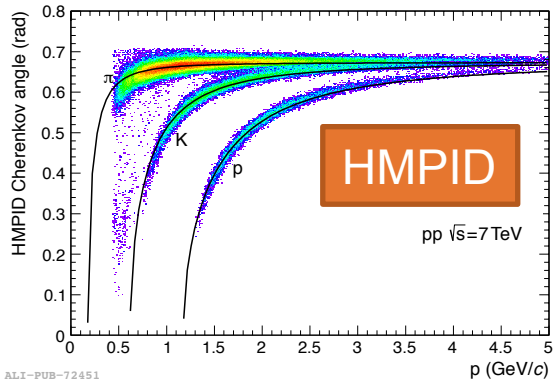
ALICE PERFORMANCE

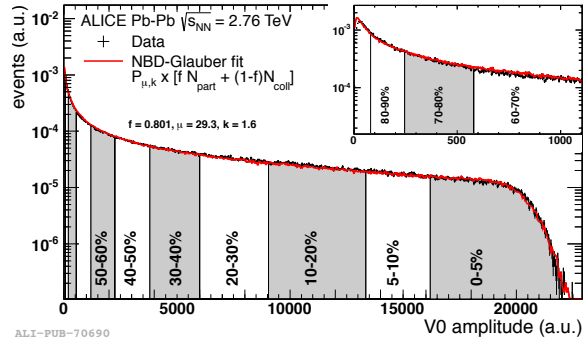


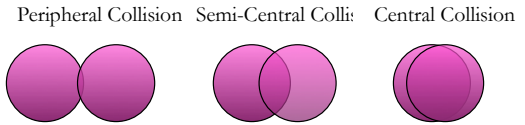












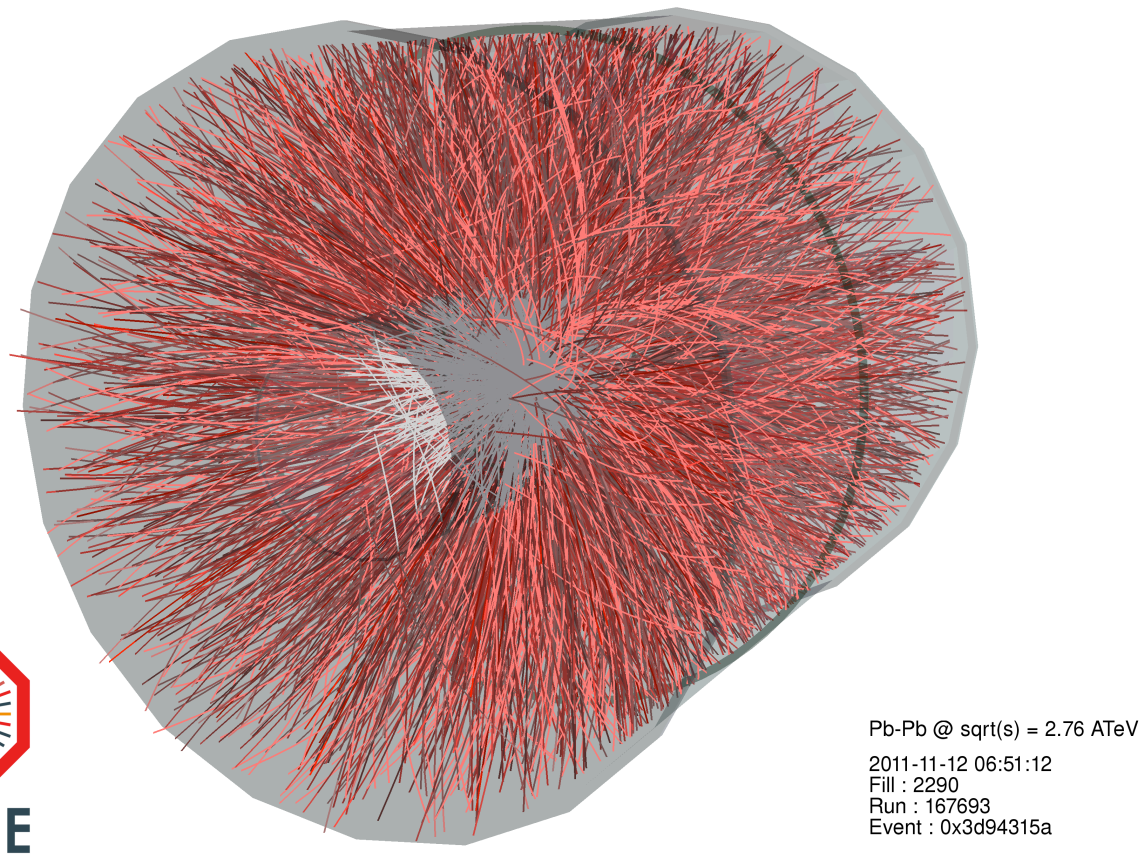
Centrality

- extremely low-mass tracker ~ 10% of X_0
- efficient low-momentum tracking, down to ~100 MeV/*c*
- particle identification (practically all known techniques)
- excellent vertexing capability

Int. J. Mod.Phys. A29 (2014) 1430044

ONE HEAVY ION COLLISION

= several 1000 charged particles in the detector in central collisions!



ALICE
A JOURNEY OF DISCOVERY

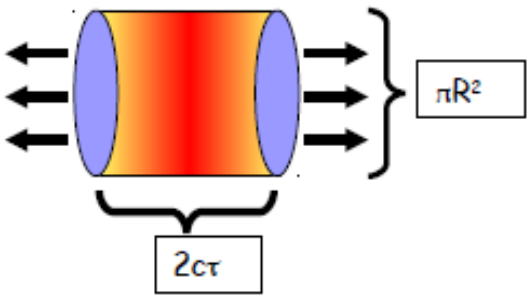
Particle multiplicity

Estimate of energy density

ENERGY DENSITY

- Can we estimate **the energy density** reached in the collision ?
- Important quantity: directly related to the possibility of **observing the deconfinement transition** (foreseen for $\varepsilon \geq 1$ GeV/fm^3)
- Consider colliding nuclei as thin pancakes (Lorentz-contraction) which, after crossing, leave an initial volume with a limited longitudinal extension, where the secondary particles are produced

Bjorken estimate:



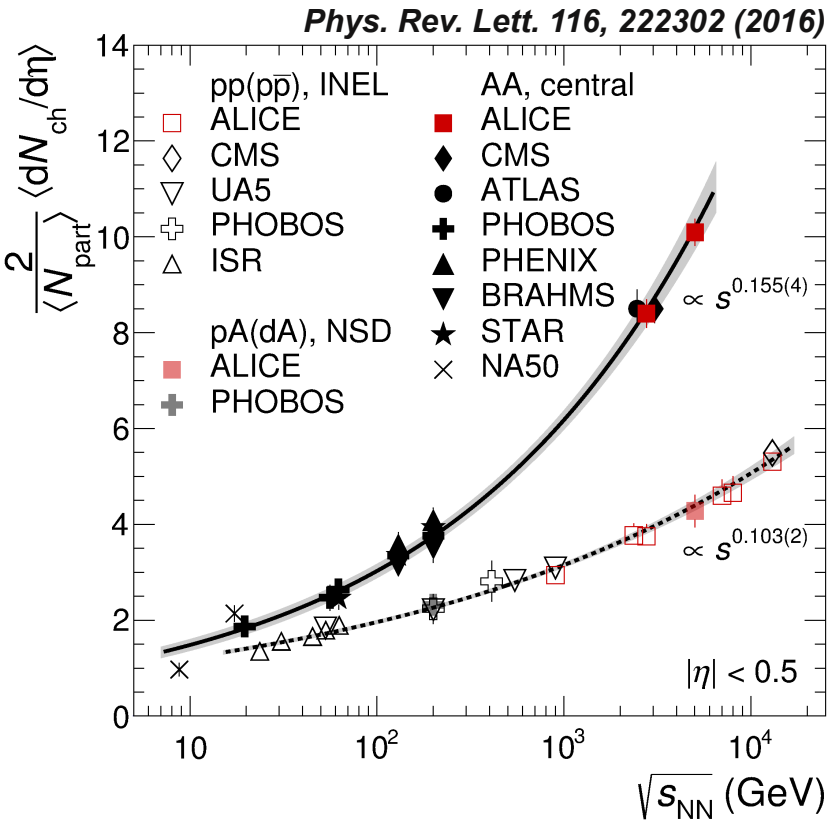
$$\langle \varepsilon \rangle (\tau) = \frac{1}{\tau \pi R^2} \frac{\mathrm{d}E_\mathrm{T}}{\mathrm{d}y}$$

Bjorken, PRD 27 (1983) 140

- System undergoes rapid evolution, use 1 fm/c as an upper limit for the time needed for "thermalisation"
- $R^2 = r_0^2 A^{2/3} = (1.25\ \mathrm{fm})^2 * 208^{2/3}$ for Pb
- $E_T = m_T \cosh y \sim m_T$ (for $y \sim 0$)
- Assume $\langle m_T \rangle \sim 0.5$ GeV (see later)

- **$dE_T/dy \sim \langle m_T \rangle\ dN/dy$**

MEASURE PARTICLE MULTIPLICITY DENSITY



Centrality	$\langle dN_{ch}/d\eta \rangle$	$\langle N_{part} \rangle$	$\frac{2}{\langle N_{part} \rangle} \langle dN_{ch}/d\eta \rangle$
0–2.5%	2035 ± 52	398 ± 2	10.2 ± 0.3
2.5–5.0%	1850 ± 55	372 ± 3	9.9 ± 0.3
5.0–7.5%	1666 ± 48	346 ± 4	9.6 ± 0.3
7.5–10%	1505 ± 44	320 ± 4	9.4 ± 0.3
10–20%	1180 ± 31	263 ± 4	9.0 ± 0.3
20–30%	786 ± 20	188 ± 3	8.4 ± 0.3
30–40%	512 ± 15	131 ± 2	7.8 ± 0.3
40–50%	318 ± 12	86.3 ± 1.7	7.4 ± 0.3
50–60%	183 ± 8	53.6 ± 1.2	6.8 ± 0.3
60–70%	96.3 ± 5.8	30.4 ± 0.8	6.3 ± 0.4
70–80%	44.9 ± 3.4	15.6 ± 0.5	5.8 ± 0.5

- With LHC data one gets $\varepsilon \sim 18$ GeV/fm^3
- Leads to densities above deconfinement transition (also at AGS)
- **Caveat**: only necessary not sufficient condition for QPG
- **Warning**: τ_f is expected to decrease when increasing $\sqrt{s}$

$$\text{AGS (Au - Au)}: \quad \sqrt{s_{NN}} = 5 \quad \text{GeV} \quad \Rightarrow \quad \varepsilon_{Bj} = 1.5 \quad \text{GeV/fm}^3$$

$$\text{SPS (Pb - Pb)}: \quad \sqrt{s_{NN}} = 17 \quad \text{GeV} \quad \Rightarrow \quad \varepsilon_{Bj} = 2.9 \quad \text{GeV/fm}^3$$

$$\text{RHIC (Au - Au)}: \quad \sqrt{s_{NN}} = 200 \quad \text{GeV} \quad \Rightarrow \quad \varepsilon_{Bj} = 5.4 \quad \text{GeV/fm}^3$$

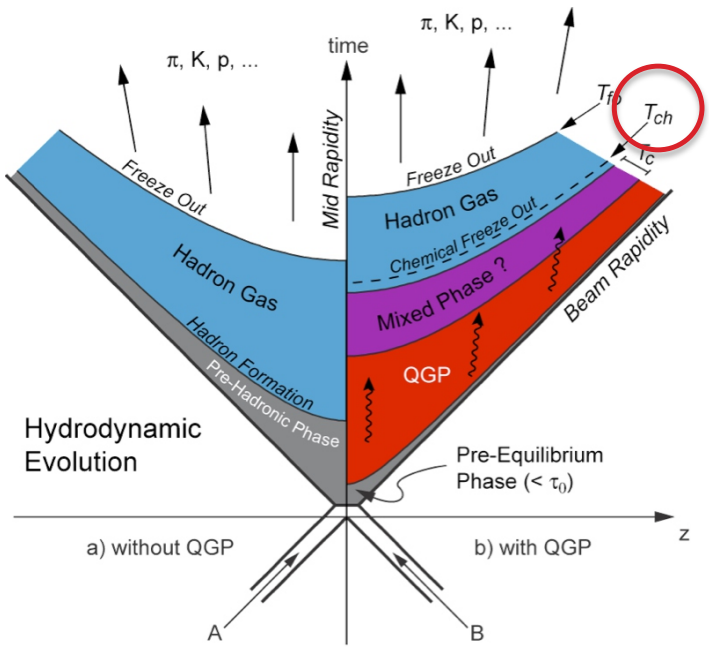
Particle yields

Are particles produced as expected from a grand canonical system in chemical equilibrium?

CHEMICAL COMPOSITION OF THE FIREBALL

- measure the multiplicity of the various particles produced in the collision
  → **chemical composition**

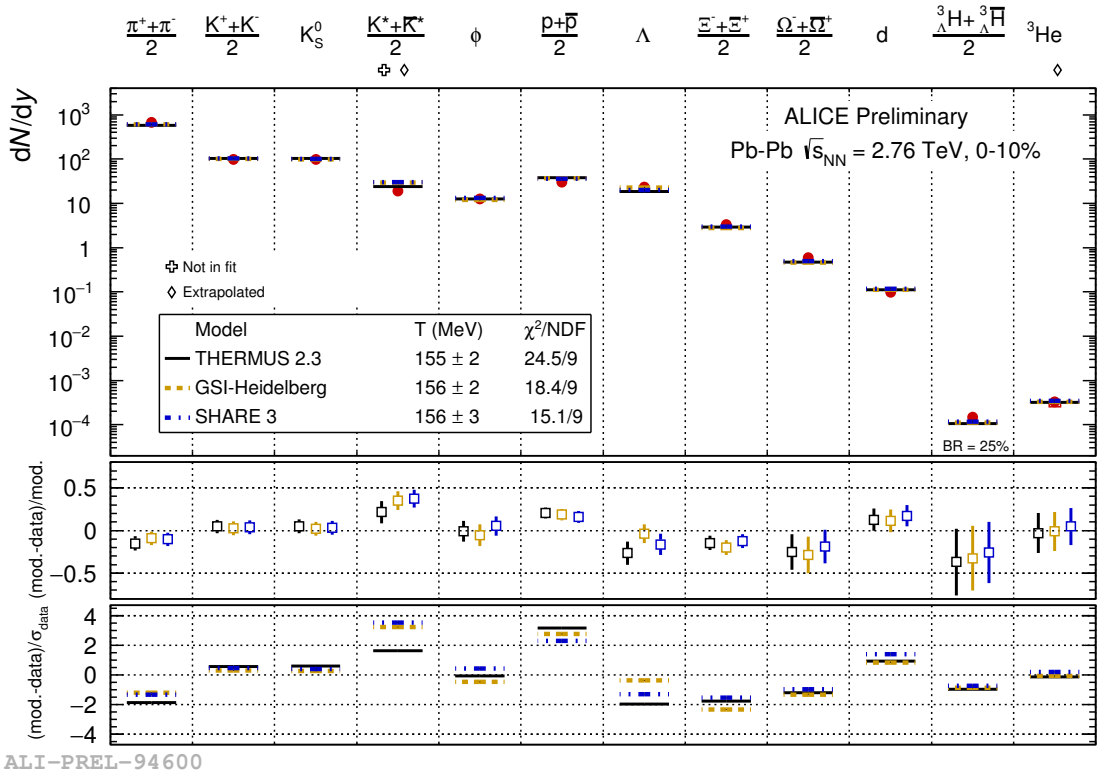
- The chemical composition of the fireball is sensitive to
  - Degree of equilibrium of the fireball at (chemical) freeze-out
  - Temperature T_{ch} at chemical freeze-out
  - Net-Baryonic content of the fireball



- This information is obtained through the use of **statistical models**
  - Thermal and chemical equilibrium at chemical freeze-out assumed
  - Write partition function and use statistical mechanics (grand-canonical ensemble) → assume hadron production is a statistical process
  - System described as an ideal gas of hadrons and resonances
  - Follows original ideas by Fermi (1950s) and Hagedorn (1960s)

Hagedorn temperature:
R. Hagedorn, Nuovo Cim. Suppl. 3, 147 (1965)

PARTICLE RATIOS AT LHC



- Ratios well described over **7 orders of magnitude**
- Small disagreement for p/π (only 2.8 σ) may point to the relevance of other effects at LHC like:
  - Rescattering in hadronic phase
  - Non-equilibrium effects
  - Flavor-dependent freeze-out

Minimum χ^2 for : T_{ch} = 156±2 MeV and μ_B = 0 MeV (fixed)

Wheaton et al, Comput.Phys.Commun, 180 84
Petran et al, arXiv:1310.5108
Andronic et al, PLB 673 142

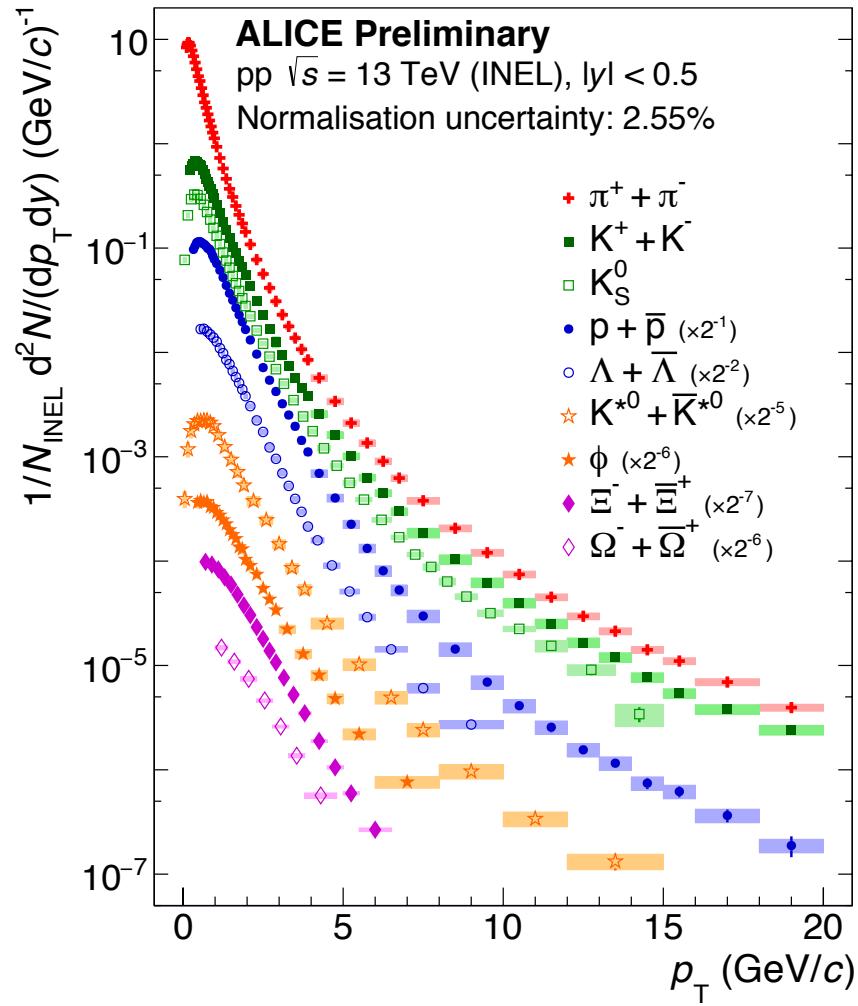
Radial flow

Are the particle p_T distributions as expected from a thermal source in kinetic equilibrium?

PARTICLE SPECTRA

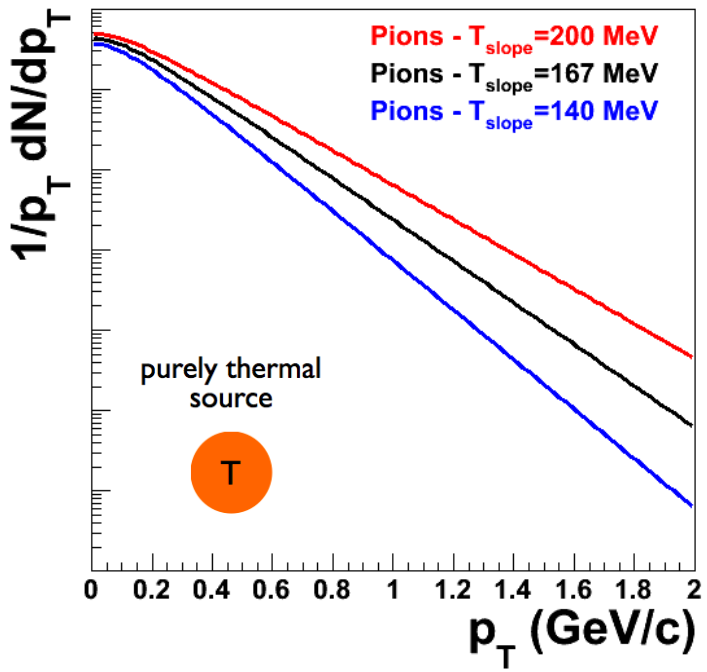
- Exponential behavior at low p_T, in pp collisions
  - ~ Identical for all hadrons
  - Transverse mass (m_T) scaling

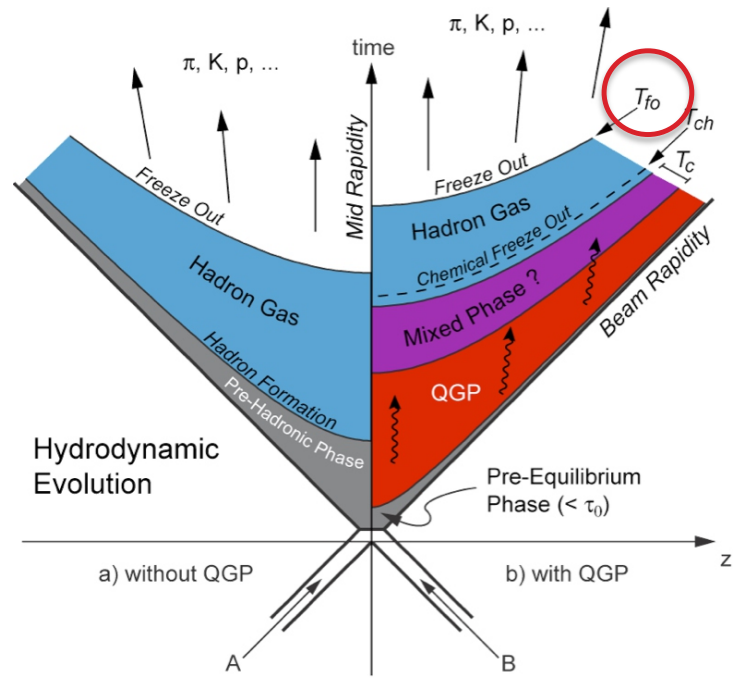
$$\frac{\mathrm{d}N}{m_\mathrm{T}\mathrm{d}m_\mathrm{T}} \propto e^{-\frac{m_\mathrm{T}}{T_\mathrm{slope}}} \quad (m_\mathrm{T}^2 = m_0^2 + p_\mathrm{T}^2)$$



THERMAL SOURCE

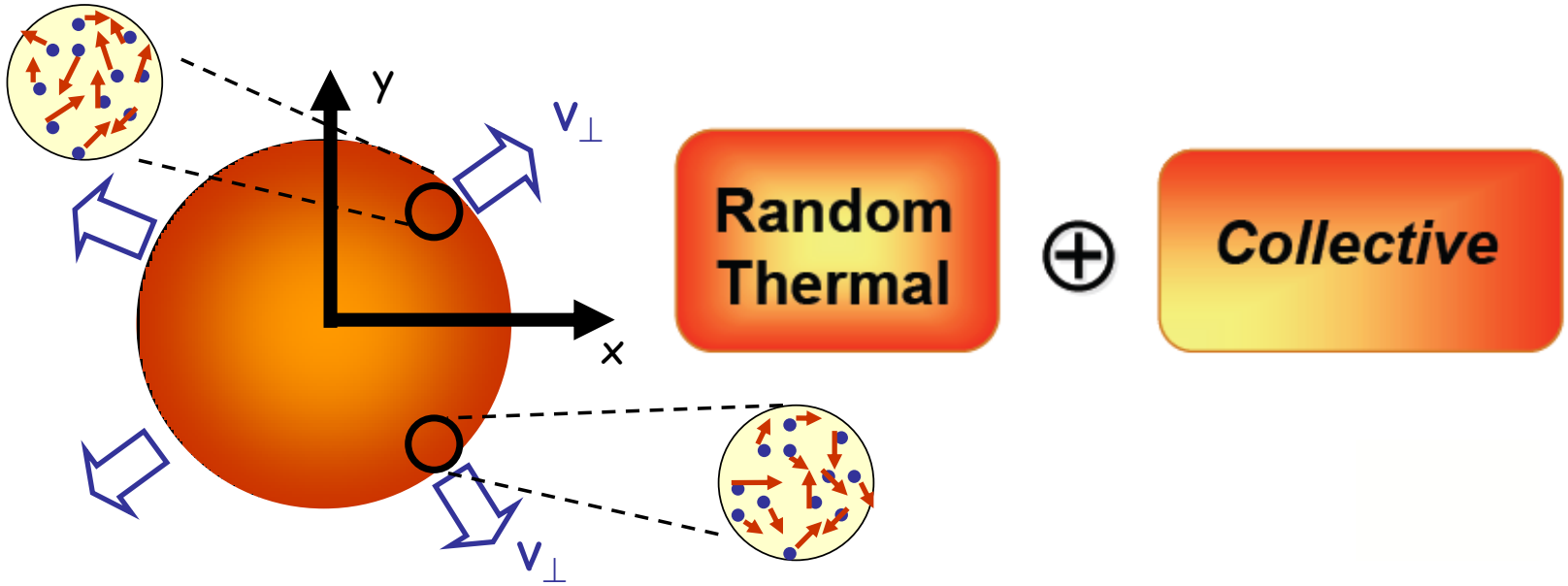
Small shape difference when plotting vs. p_T instead of m_T





- Evolution of p_T spectra vs T_{slope}, higher T implies “flatter” spectra
- T_{slope} can be interpreted as the temperature at the time when kinetic interactions between particles ended
- Kinetic freeze-out temperature (T_{fo})

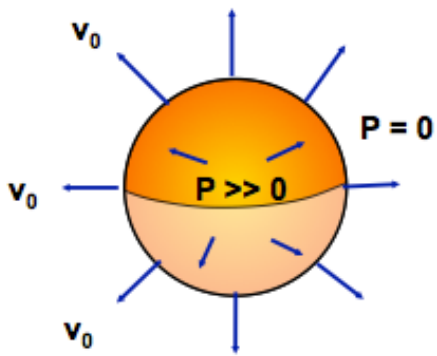
COLLECTIVE RADIAL EXPANSION

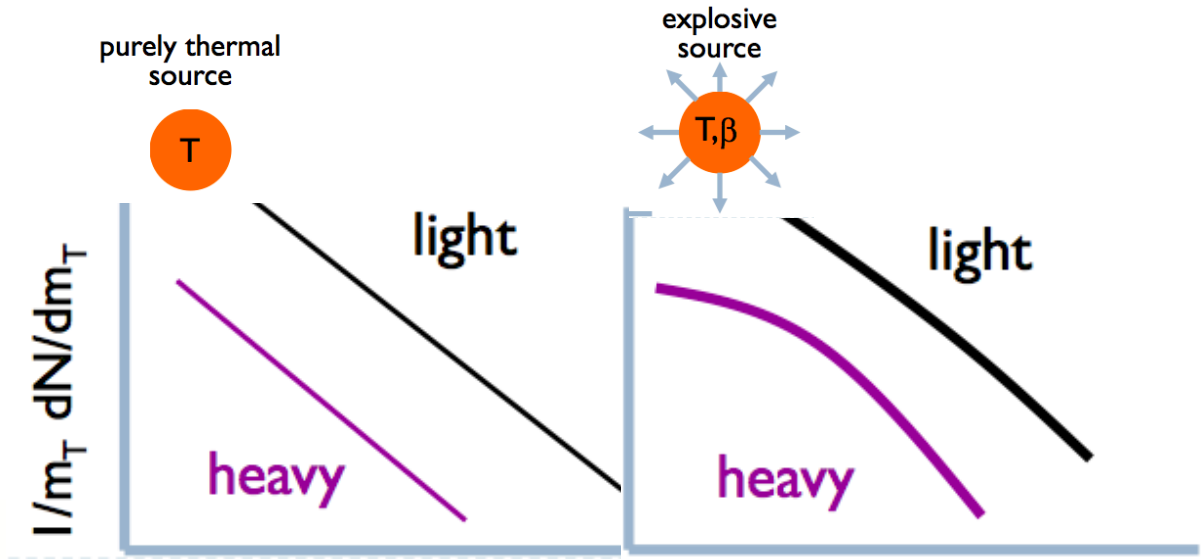


- high pressures generated when nuclear matter is heated and compressed
  → Flow: collective motion of particles superimposed to thermal motion

- Due to the Flux velocity of an element of the system is given by the sum of the velocities of the particles in that element
- Collective flow is a correlation between the velocity v of a volume element and its space-time position

COLLECTIVE RADIAL EXPANSION



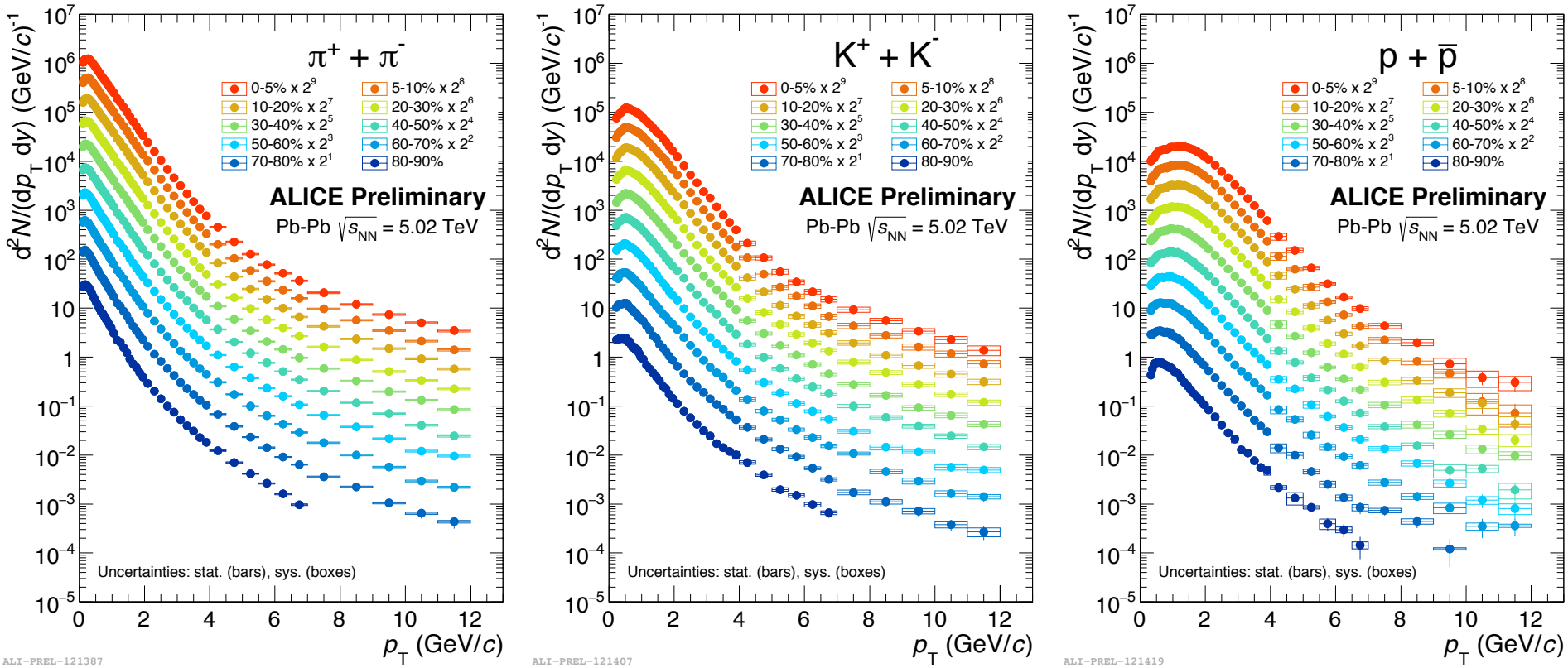


Pressure gradient in transverse plane leads to collective **radial** expansion

Mass dependent hardening of spectrum
Transverse mass (m_T) **scaling broken**

$$T_{slope} \sim T_{fo} + \tfrac{1}{2} m v_T^2$$

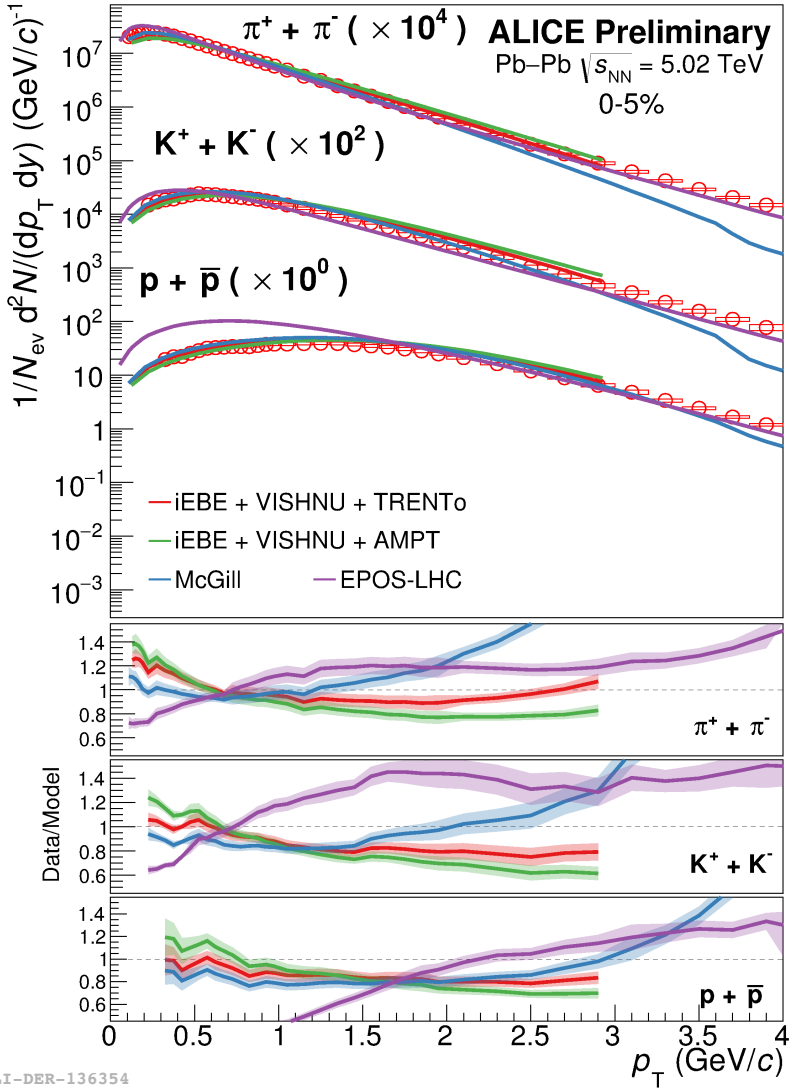
RADIAL FLOW AT LHC



- hardening of the spectrum with increasing centrality
- more pronounced for the heavier protons than for pions.

→ **Radial Flow observed**

RADIAL FLOW AT LHC

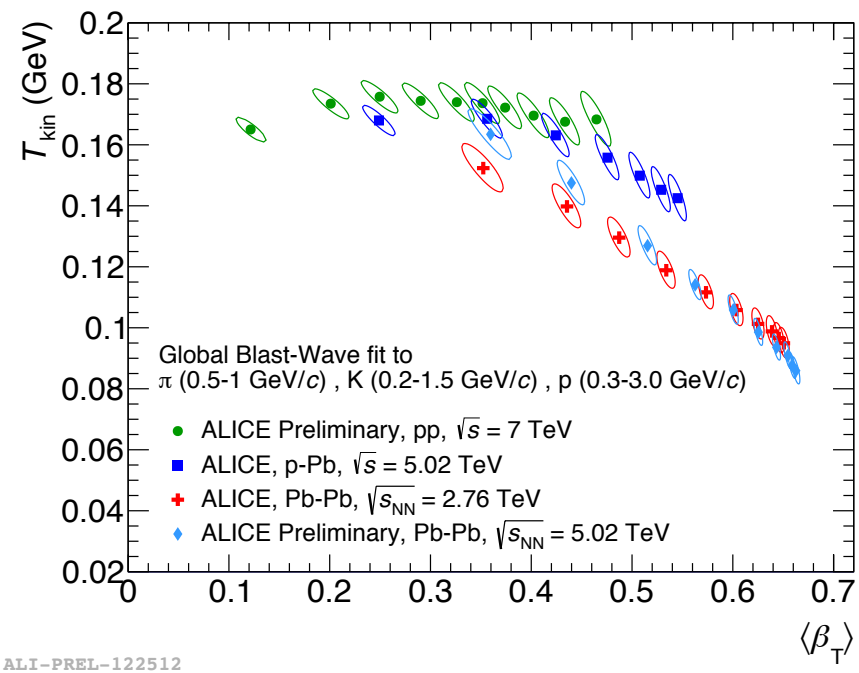


ALI-DER-136354

- Hydro models work reasonably well
- Blast-Wave fits ("simplified hydro model") to p_T spectra, parameters:

→ **Radial flow velocity <β> ≈ 0.65**

→ **Kinetic freeze-out temp. T_{fo} ≈ 90 MeV**



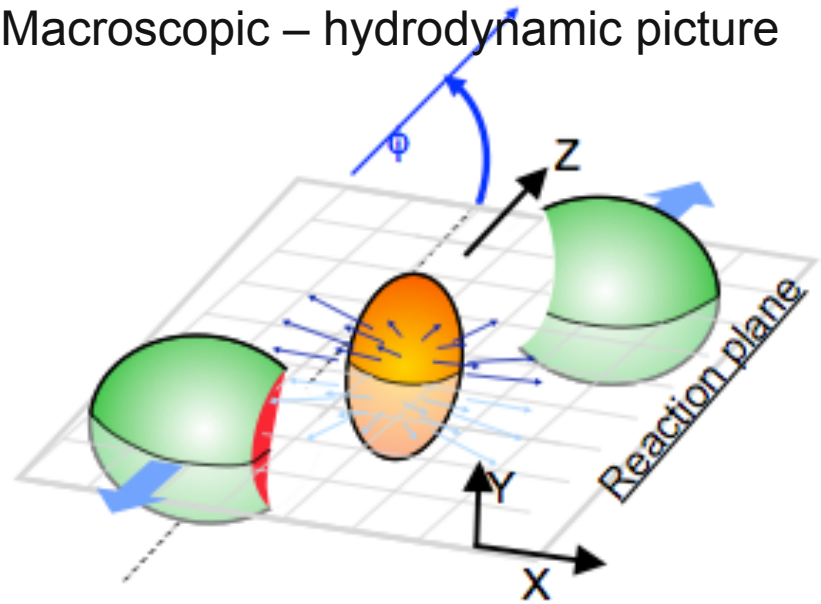
ALI-PREL-122512

Anisotropic flow

Did we create “matter” (collectivity)?
What are its properties?

COLLECTIVE EXPANSION

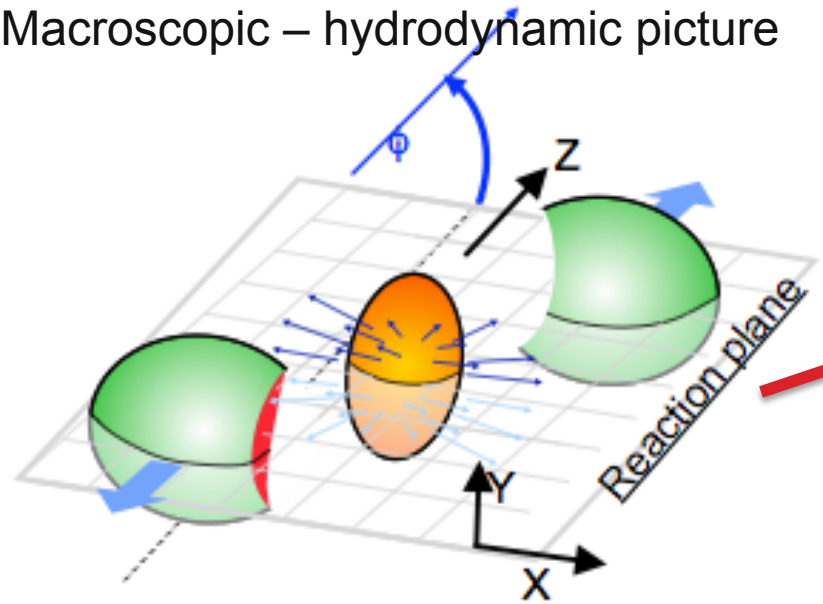
Macroscopic – hydrodynamic picture



Spatial anisotropy (eccentricity)
of nuclear overlap zone

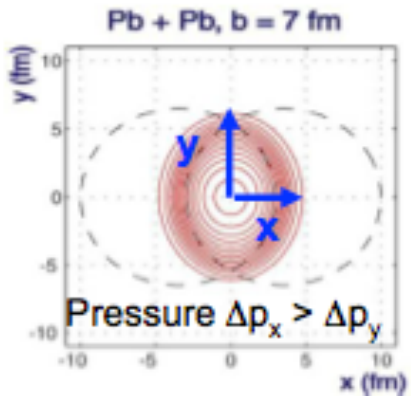
COLLECTIVE EXPANSION

Macroscopic – hydrodynamic picture

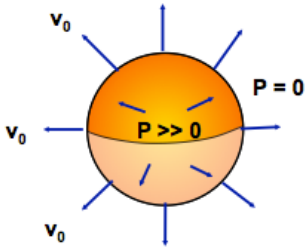


Spatial anisotropy (eccentricity) of nuclear overlap zone

Azimuthal pressure gradients (w.r.t. reaction plane)

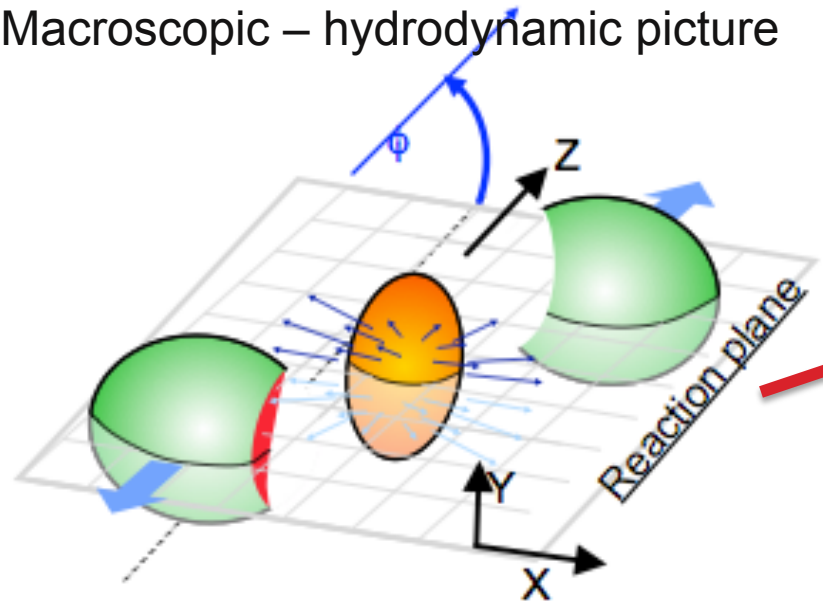


Instead of:

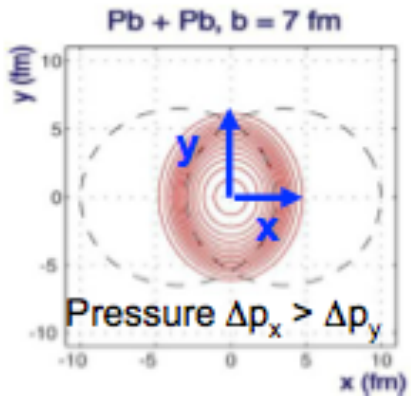


COLLECTIVE EXPANSION

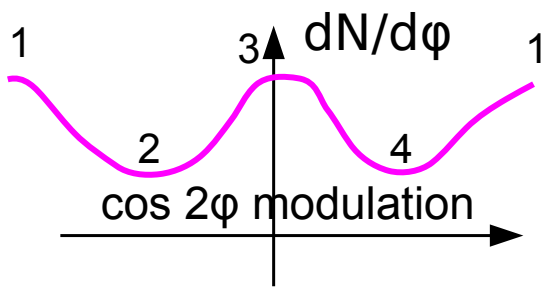
Macroscopic – hydrodynamic picture

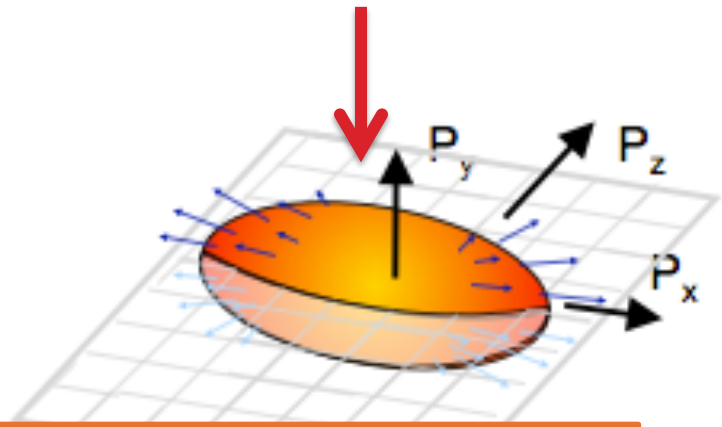


Azimuthal pressure gradients
(w.r.t. reaction plane)



Spatial anisotropy (eccentricity)
of nuclear overlap zone

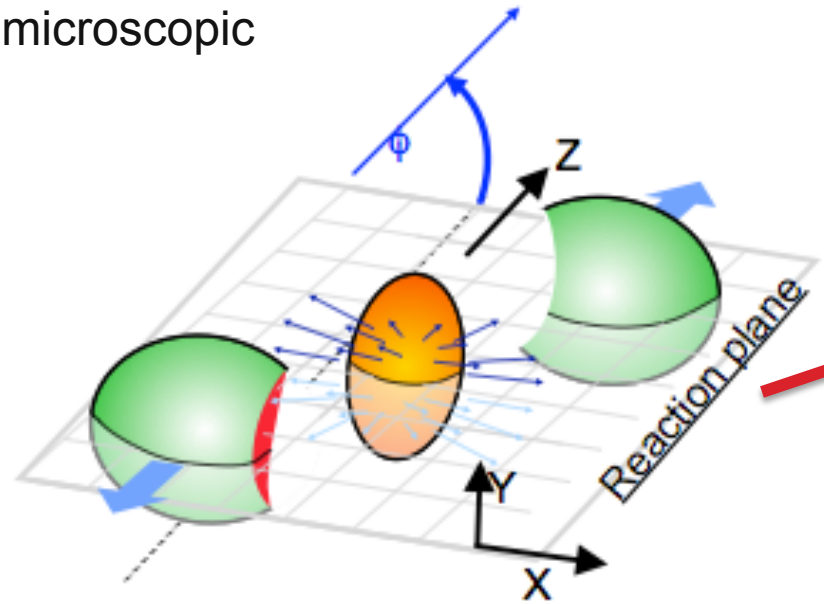




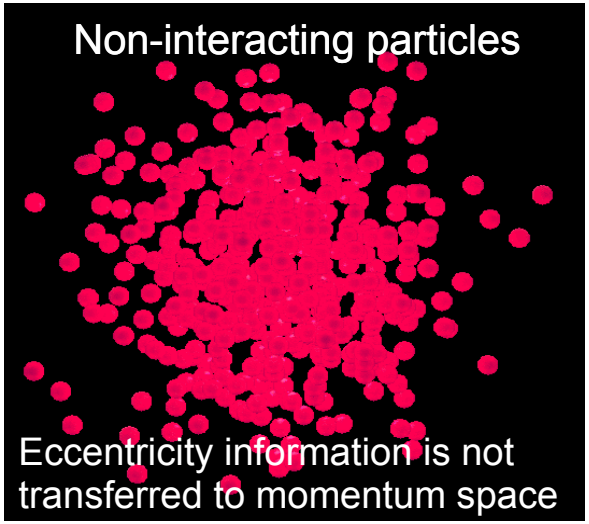
Momentum space anisotropy

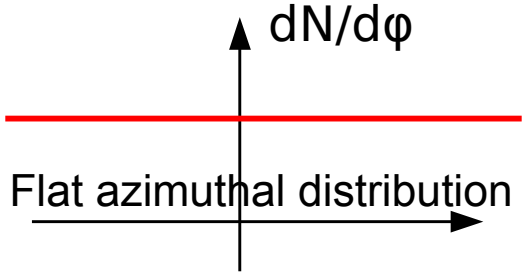
NULL HYPOTHESIS: NON INTERACTING PARTICLES

microscopic



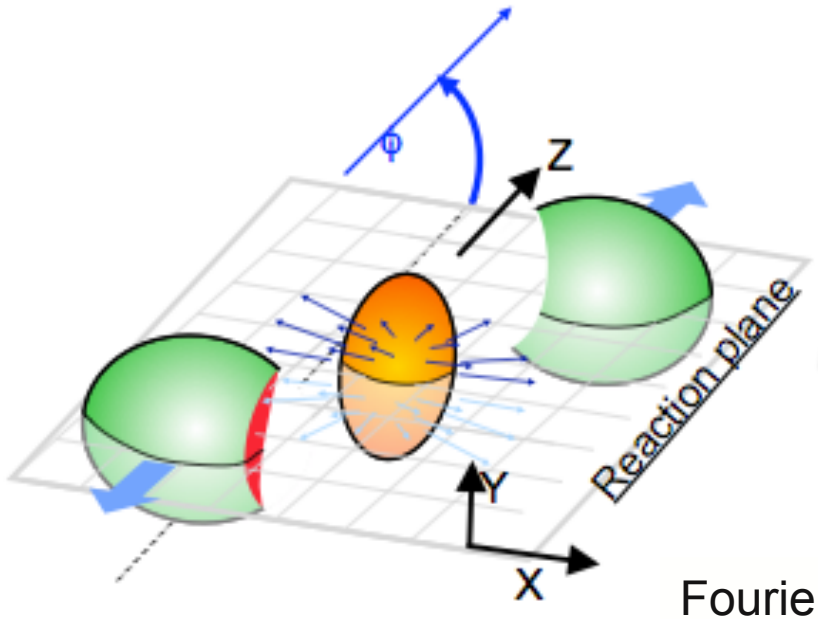
Spatial anisotropy (eccentricity) of nuclear overlap zone





Uniform particle density

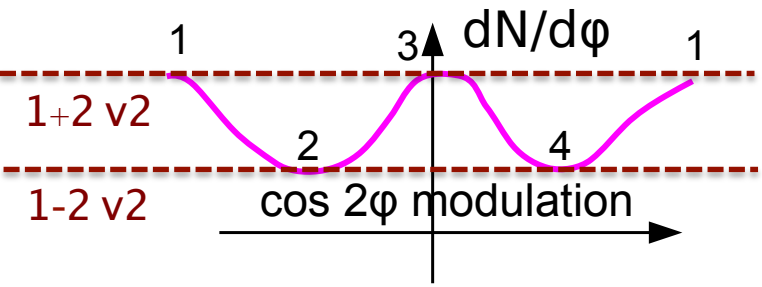
ANISOTROPIC FLOW



Eccentricity $\epsilon_{\mathrm{std}} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$

Fourier decomposition:

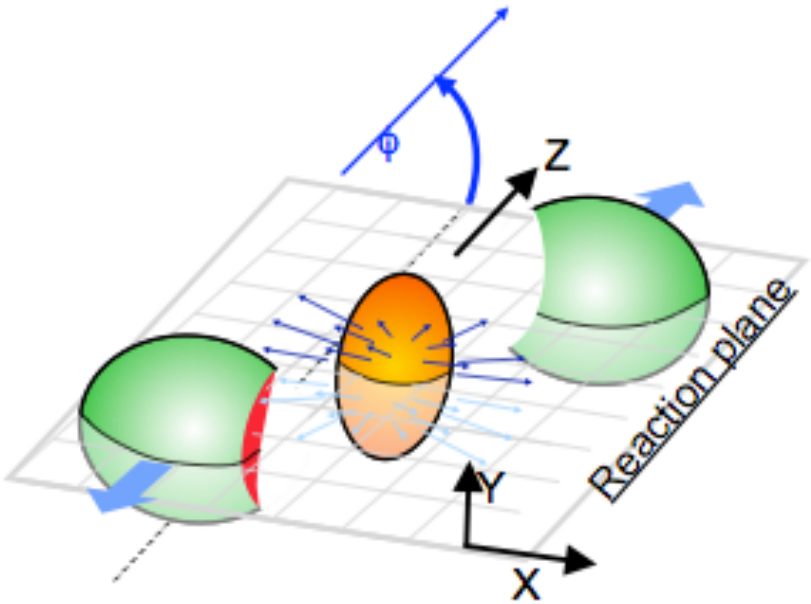
$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + ..$$



Elliptic flow parameter:

$$v_2 = \langle \cos(2\varphi - 2\Psi_R) \rangle$$

ANISOTROPIC FLOW

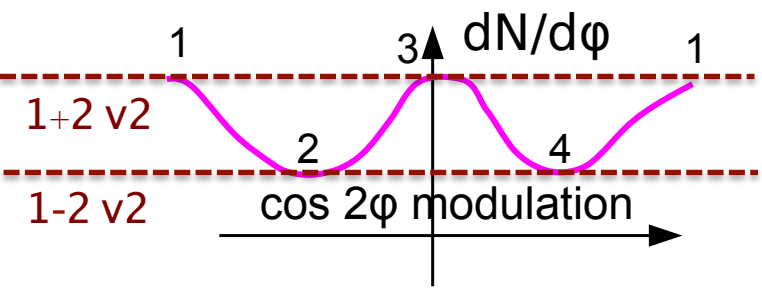


Eccentricity?

Initial energy density?
Event-by-event fluctuations?

Medium transport parameters?

Hadronic phase?

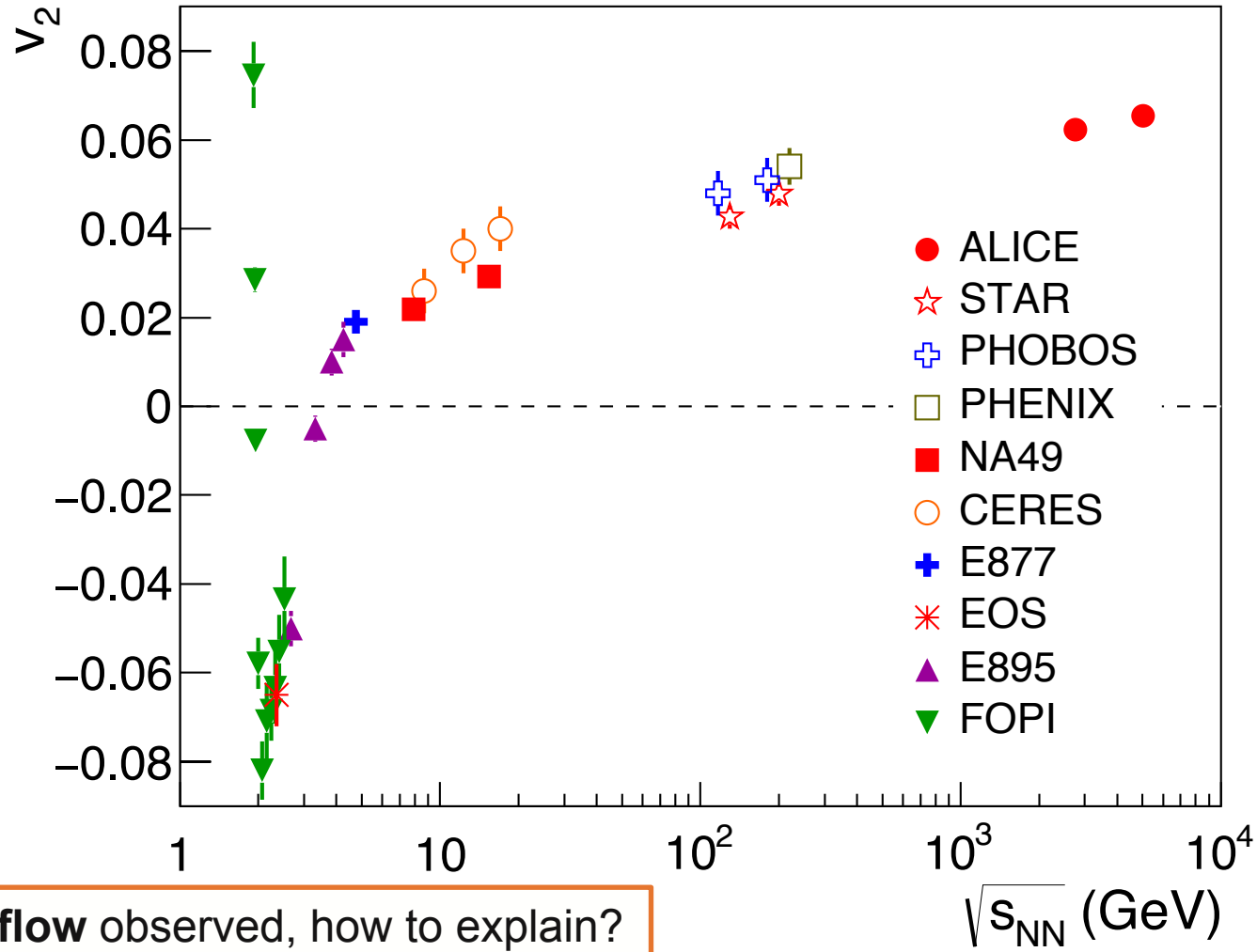


Elliptic flow parameter:

$$v_2 = \langle \cos(2\varphi - 2\Psi_R) \rangle$$

ANISOTROPIC FLOW IN HEAVY ION EXPERIMENTS

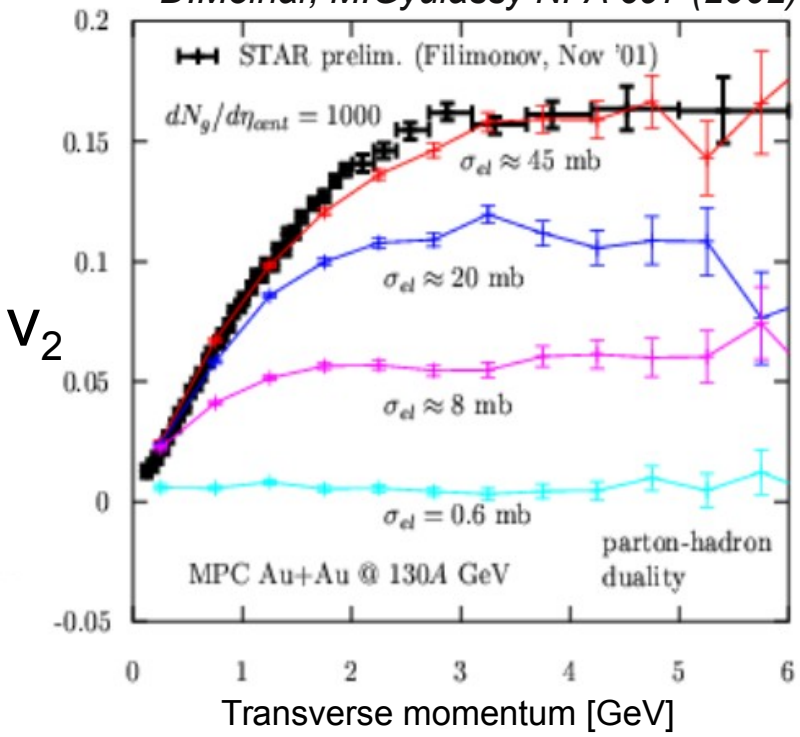
ALICE, Phys Rev Lett 116 (2016) 132302



Large **elliptic flow** observed, how to explain?

MICROSCOPIC PICTURE

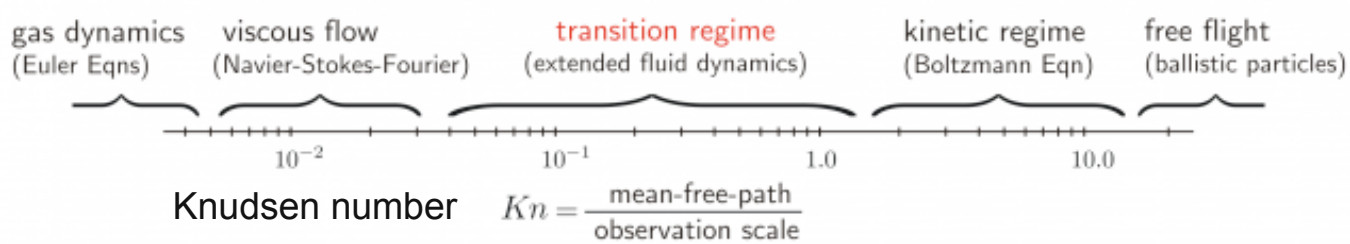
D.Molnar, M.Gyulassy NPA 697 (2002)



Parton transport model:
Boltzmann equation with 2-to-2 gluon processes

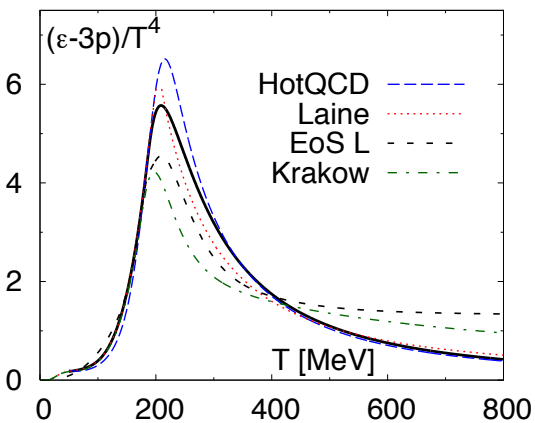
- HUGE (hadronic) cross sections needed to describe v_2
- Macroscopic description possible?

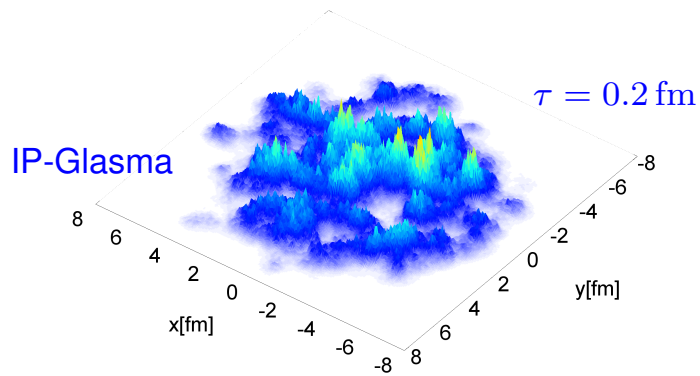
$$1/\lambda = n\sigma$$
$$Kn = \lambda/L \ll 1$$



MACROSCOPIC: HYDRODYNAMIC MODELS

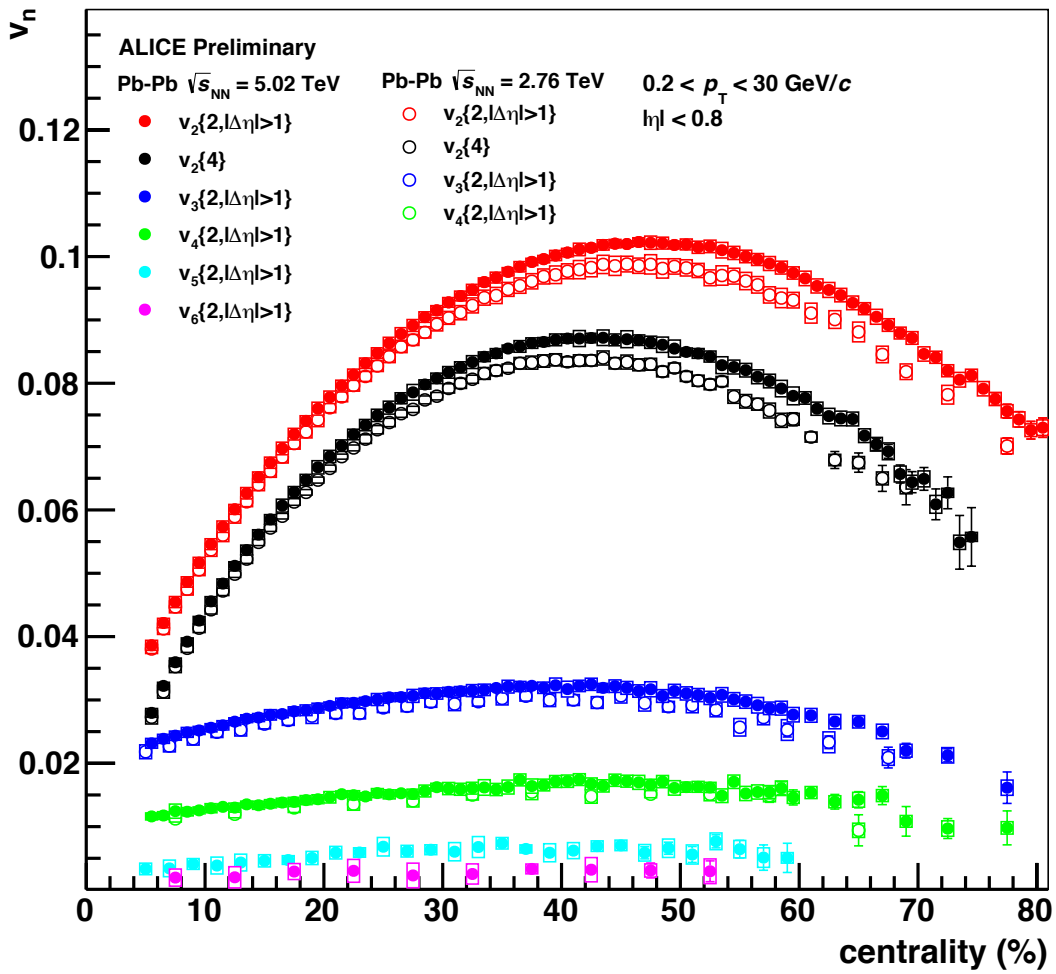
- Hydrodynamics works for all systems with short mean free path (compared to size scales of interest)





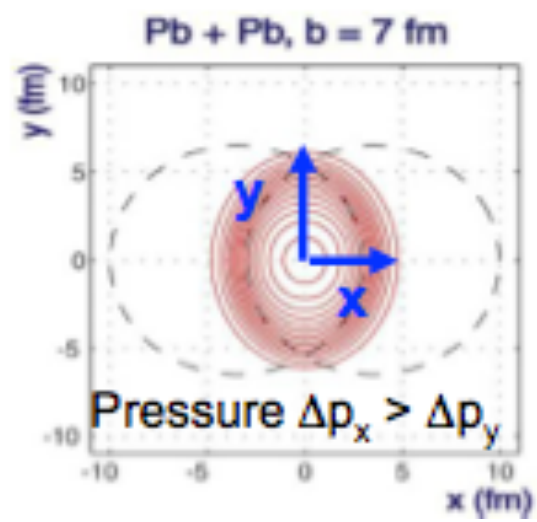
- Ingredients:
  - **Equation of state** $p(\varepsilon, \rho_B)$: from lattice QCD
  - **Initial conditions** (energy density in fluid cells): e.g. taking into account gluon saturation
  - Values of **transport coefficients of QCD**: e.g. shear viscosity
  - **Freeze-out** and conversion of energy densities into particles (after hydrodynamic evolution)

BACK TO THE MEASUREMENT



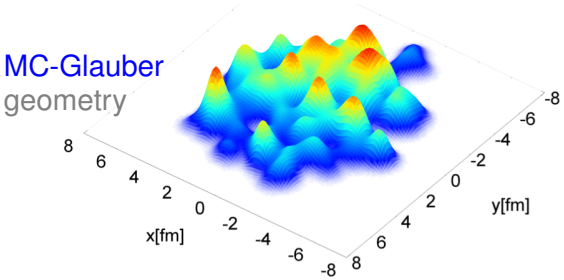
Integrated v_n measured up to v_6 using cumulants

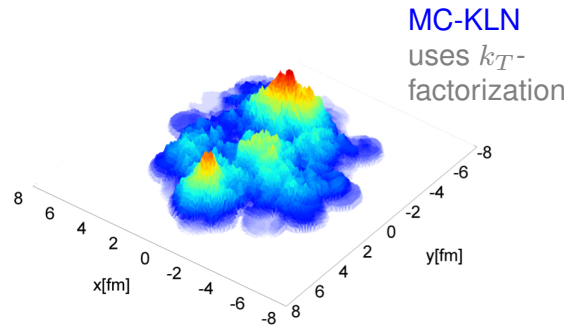
Not only large v_2,
but also odd harmonics
(in a symmetric system?)

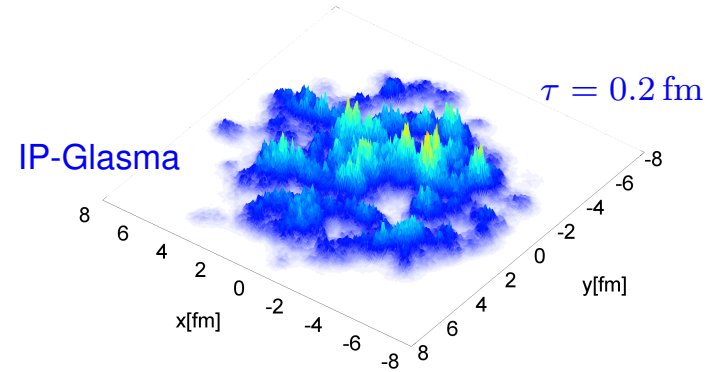


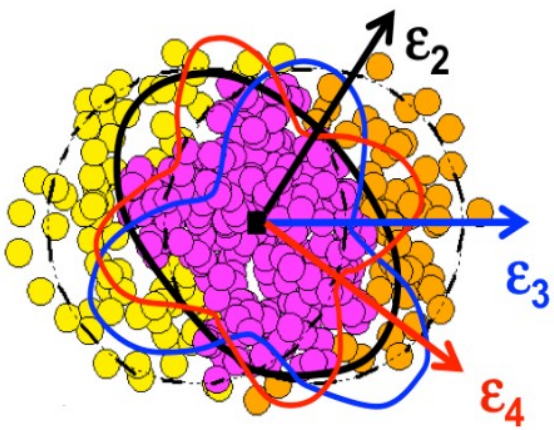
$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + ..$$

THE ROLE OF INITIAL ENERGY DISTRIBUTION









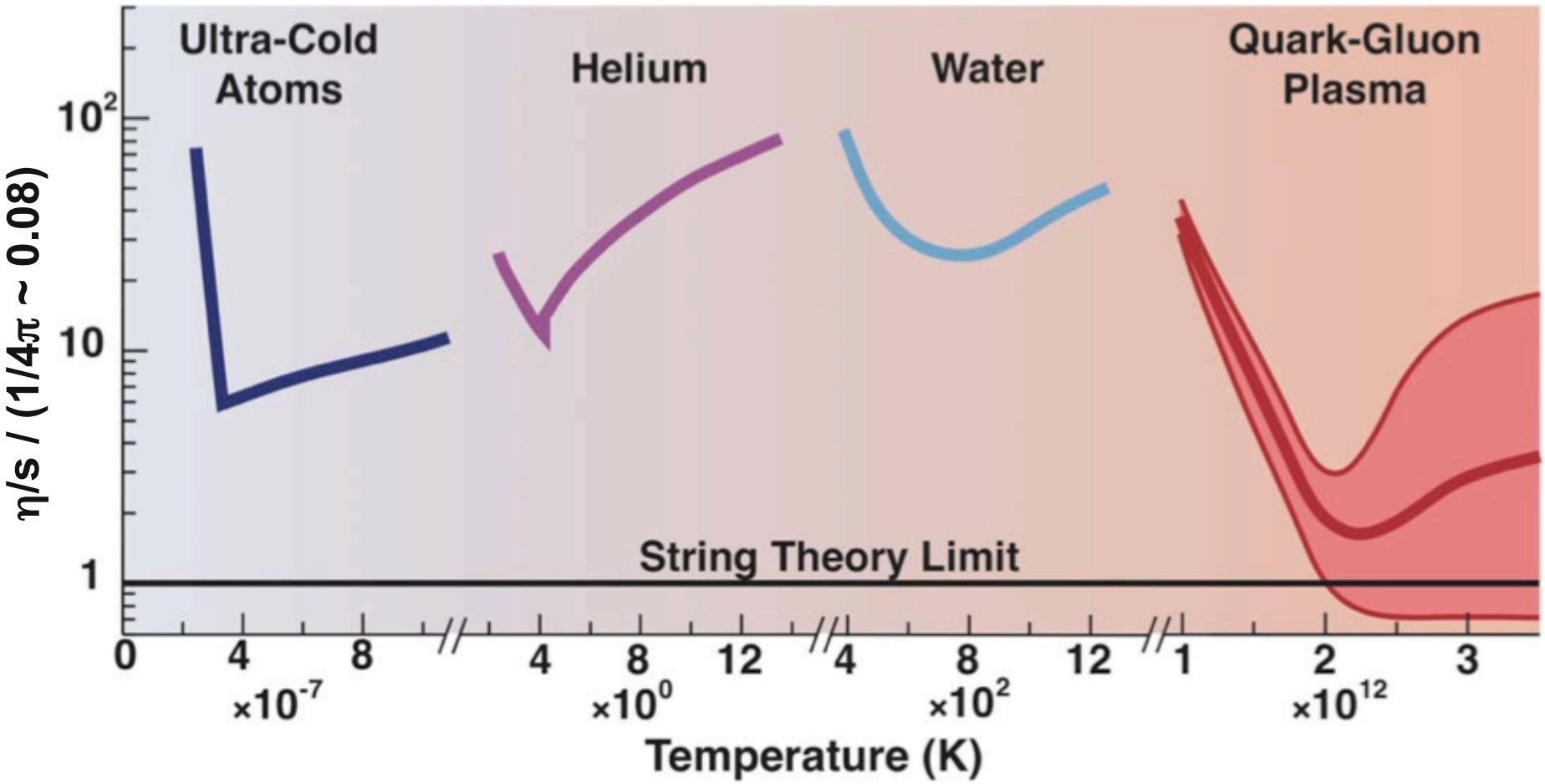
Alver, Roland

Initial spatial anisotropy not smooth, leads to higher harmonics / symmetry planes.

$$\frac{dN}{d\varphi} \sim 1 + 2v_2 \cos[2(\varphi - \psi_2)] + 2v_3 \cos[3(\varphi - \psi_3)] + 2v_4 \cos[4(\varphi - \psi_4)] + 2v_5 \cos[5(\varphi - \psi_5)] + \ldots$$

CONSTRAINING VISCOSITY OF QCD MATTER

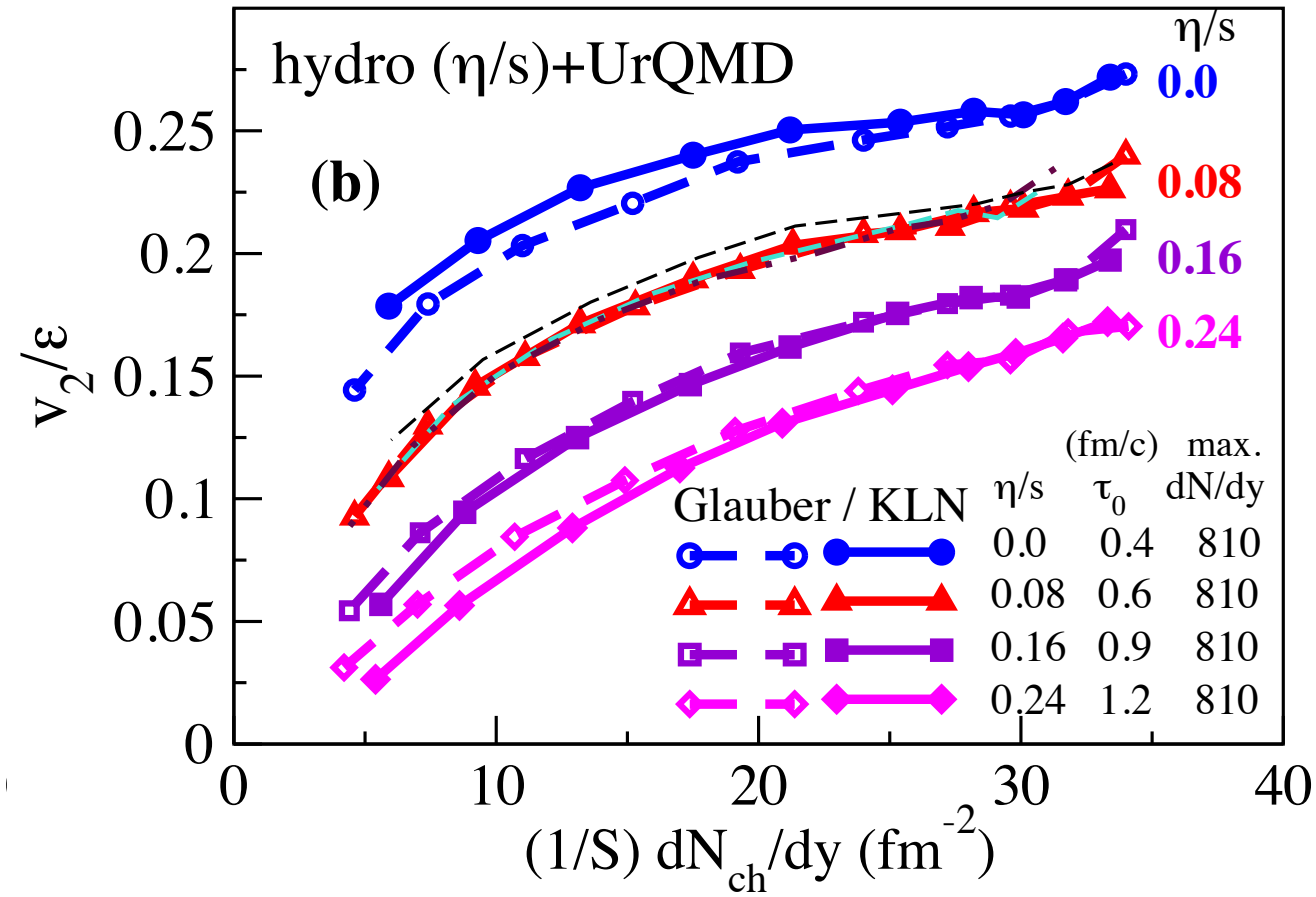
Observable: Shear viscosity over entropy η/s



C. Shen, U. Heinz, Nucl.Phys.News 25 (2015) no.2, 6-11

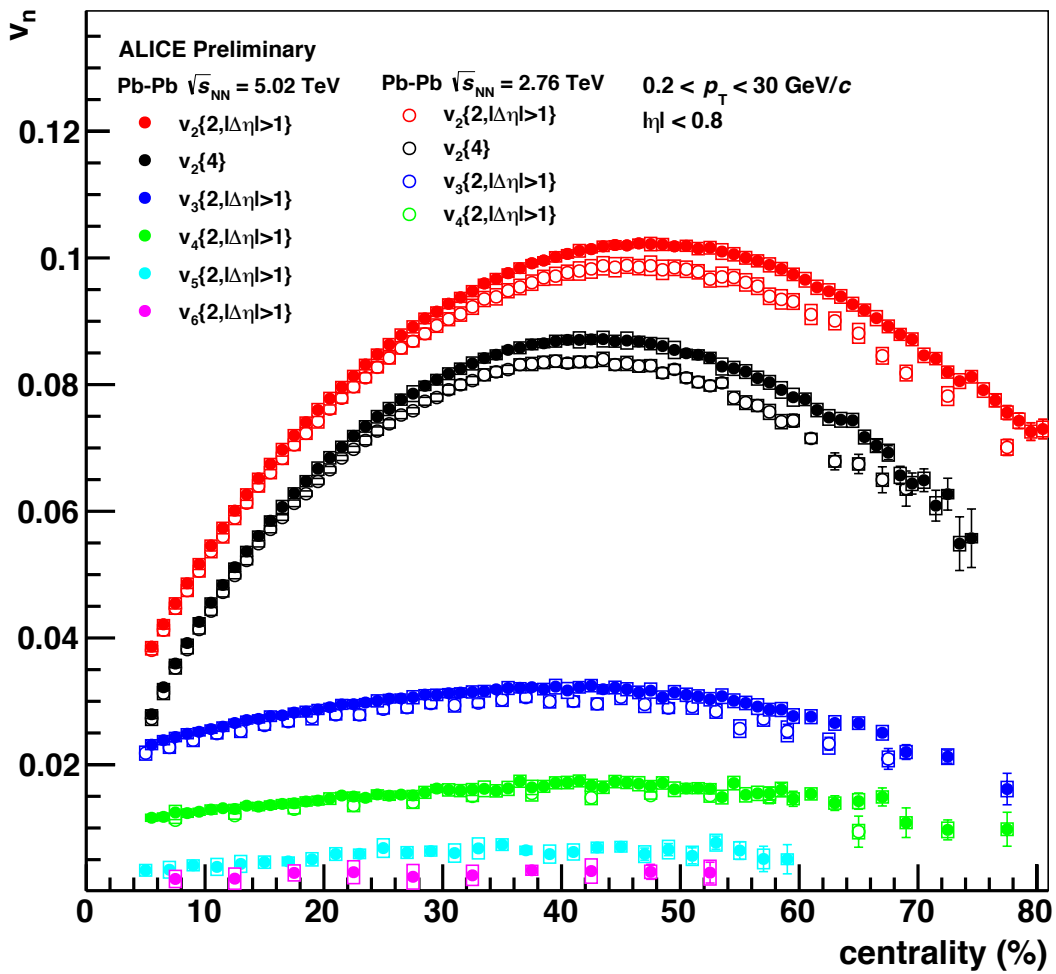
CONSTRAINING VISCOSITY OF QCD MATTER

Observable: Shear viscosity over entropy η/s



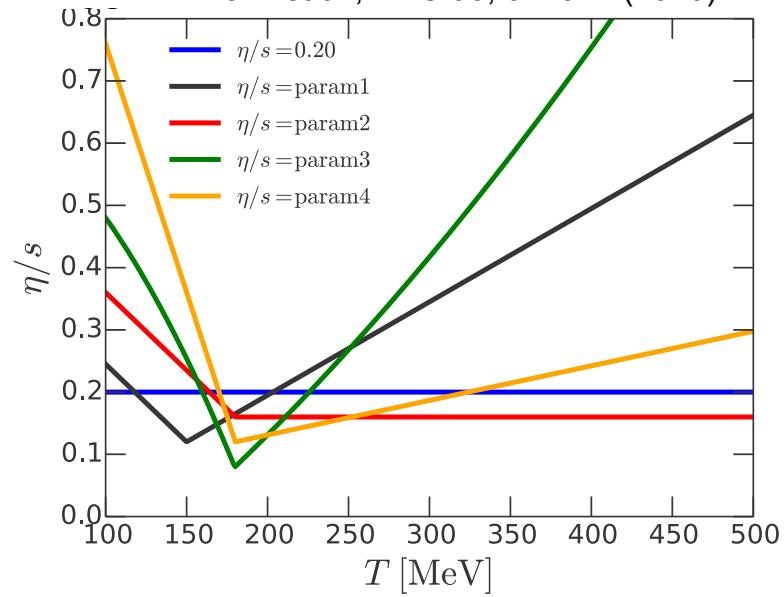
H. Song, S. A. Bass, U. Heinz, T. Hirano and C. Shen, Phys. Rev. Lett. ***106****, 192301 (2011).*

CONSTRAINING VISCOSITY OF QCD MATTER



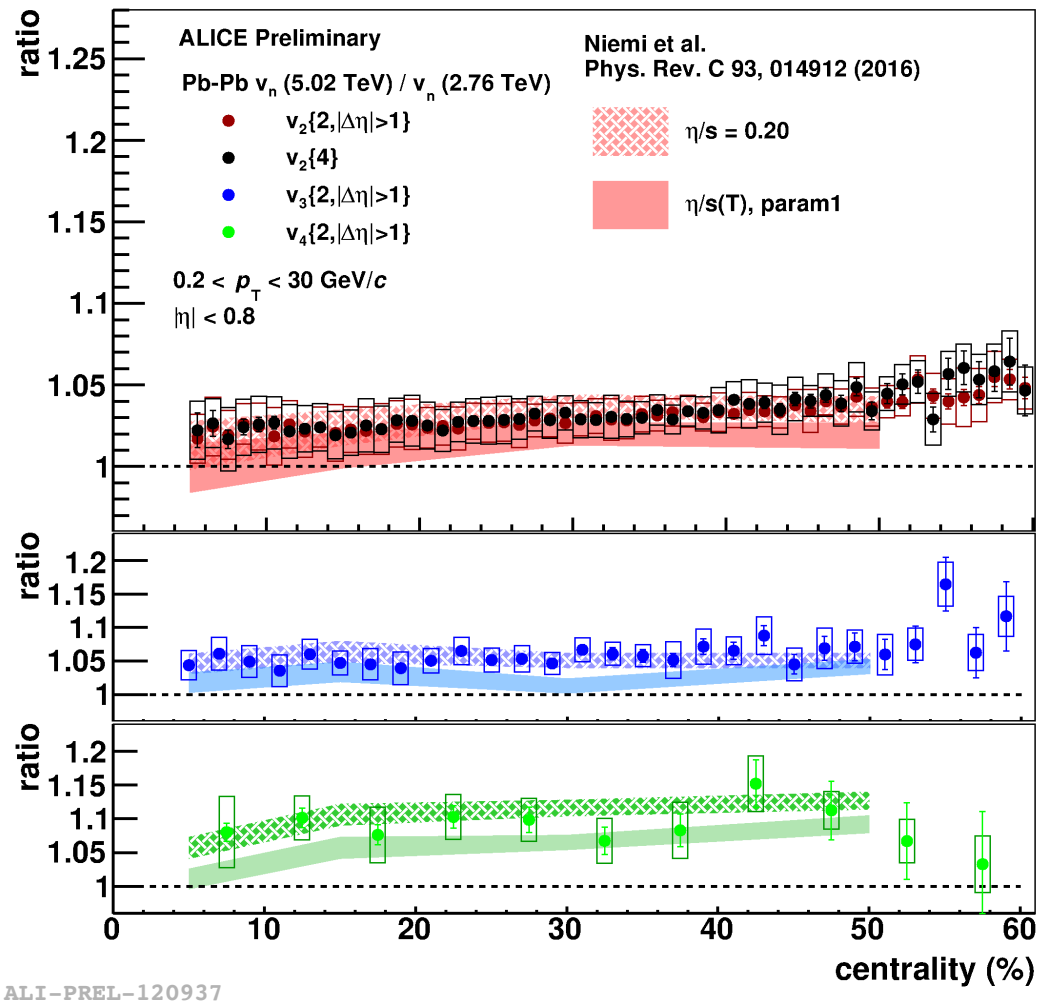
ALI-PREL-118603

H. Niemi et al., PRC 93, 014912 (2016)



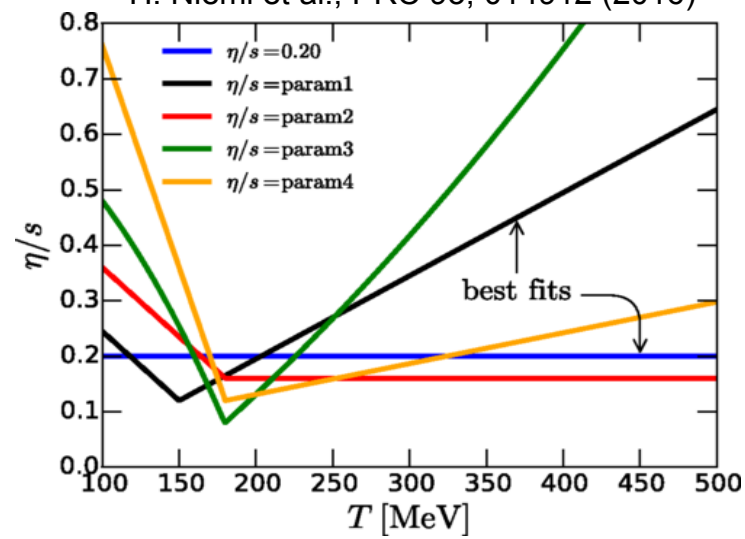
Collision energy dependence of η/s?

CONSTRAINING VISCOSITY OF QCD MATTER



ALI-PREL-120937

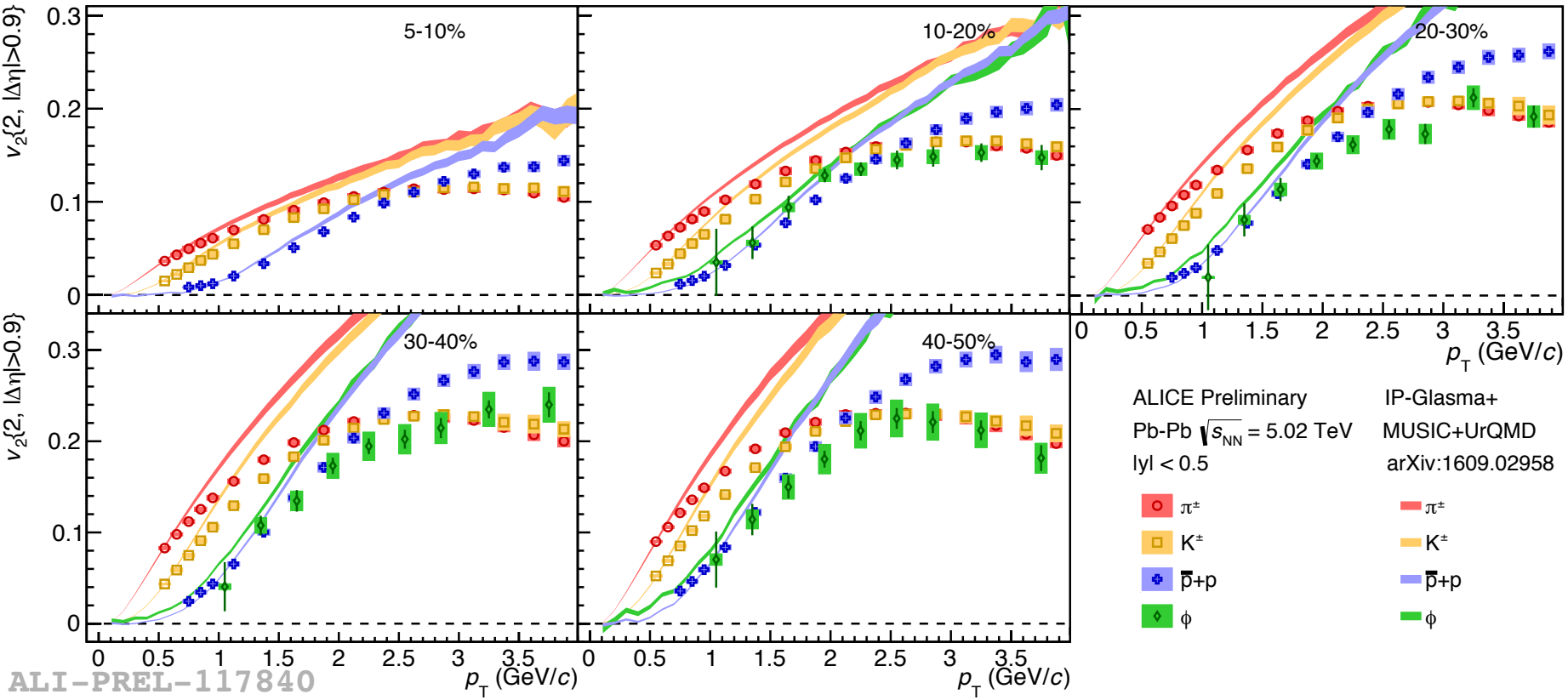
H. Niemi et al., PRC 93, 014912 (2016)



Collision energy dependence of η/s? → Ratio comparison

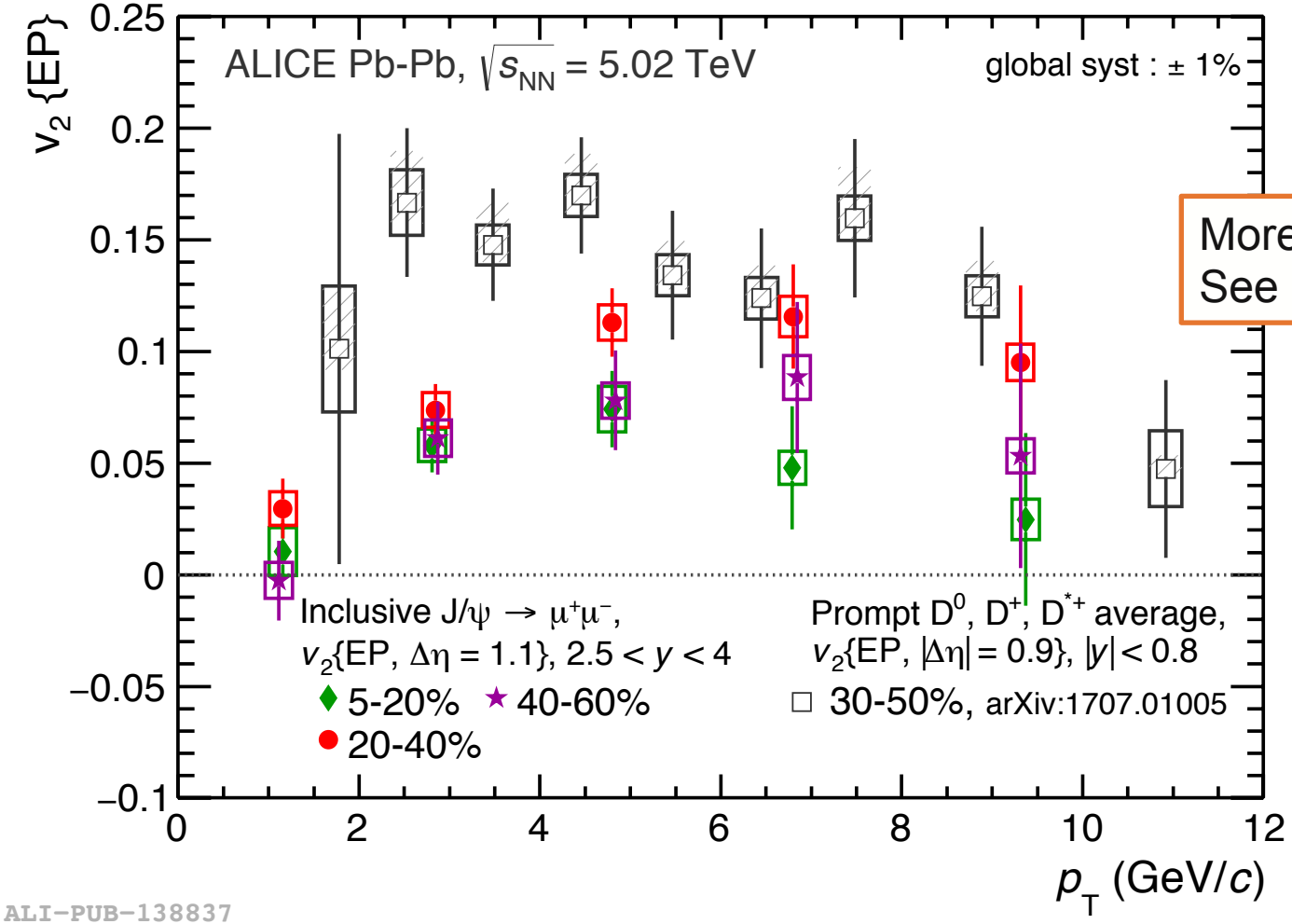
Perfect liquid (RHIC, 2005): Strongly coupled Quark-Gluon Plasma

IDENTIFIED PARTICLES V_2



- Low p_T (p_T < 2 GeV/c): mass ordering ➜ elliptic/radial flow interplay
- Well described by hydrodynamic models
- ϕ meson different ➜ importance of hadronic rescattering phase?

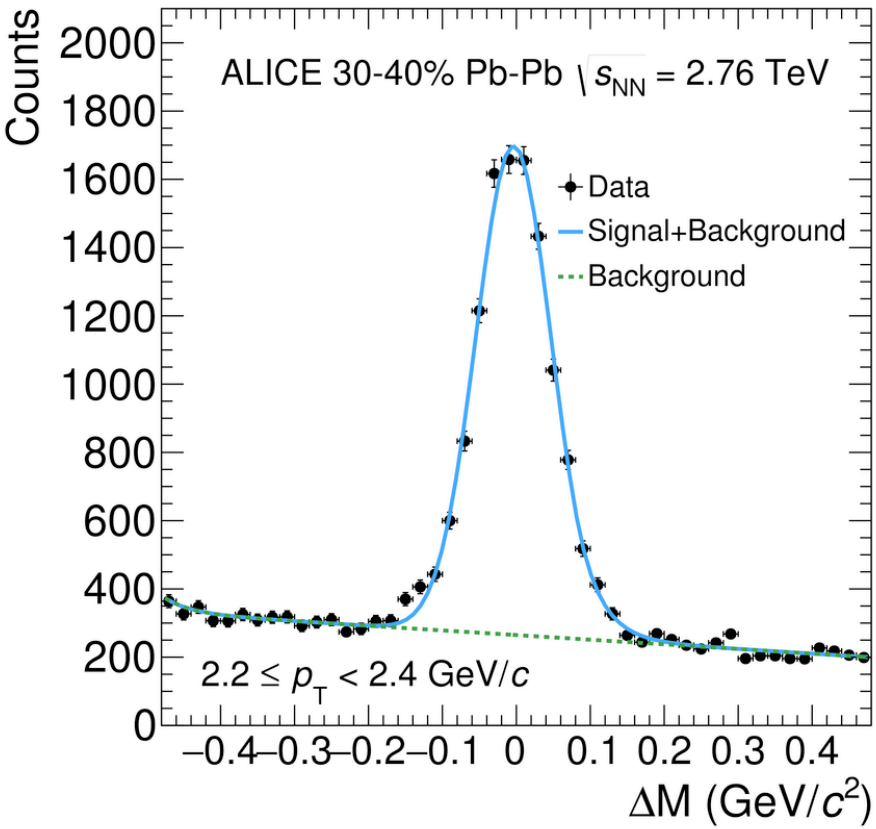
HEAVY QUARKS FLOW

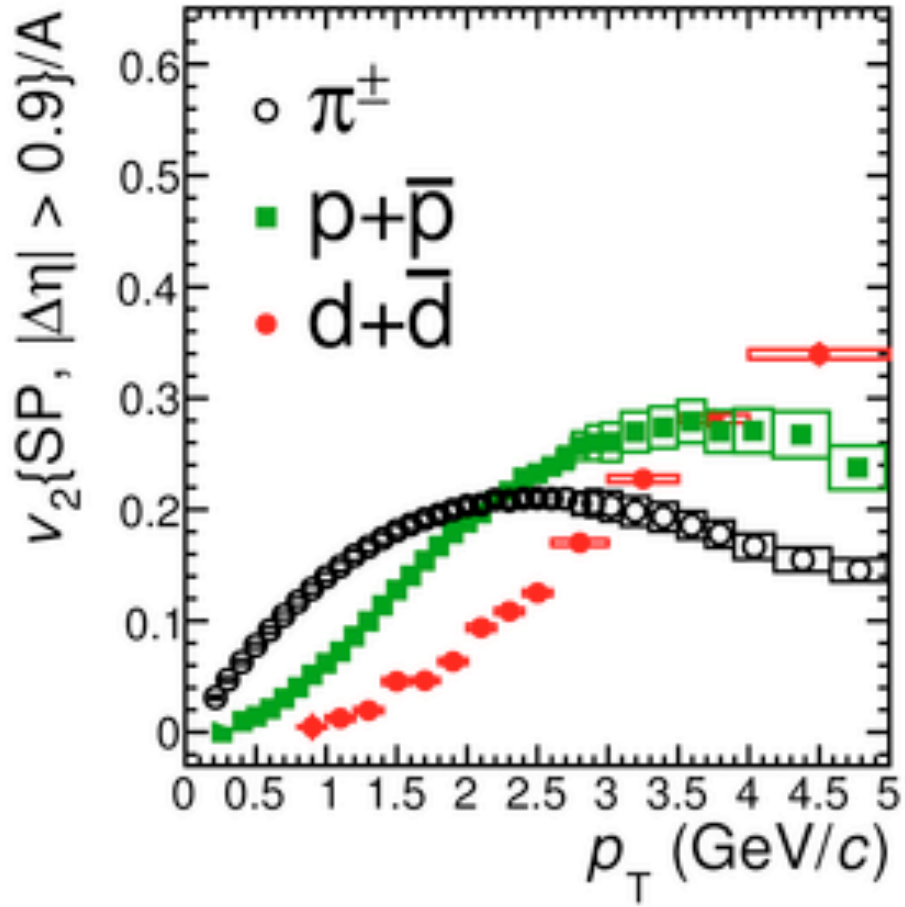


More on heavy quarks:
See next talk

***ALICE**, arXiv:1709.05260 [nucl_ex]*

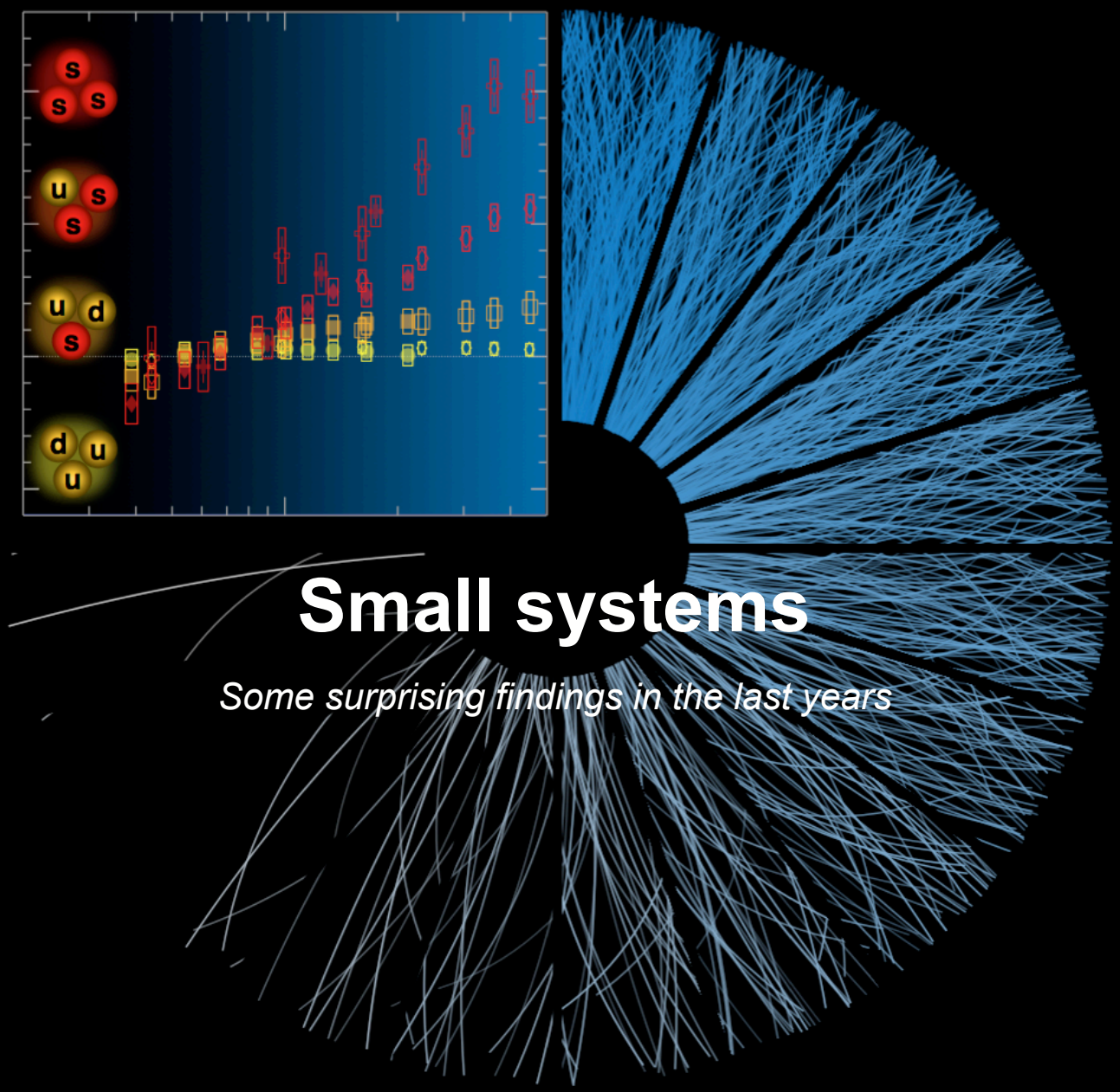
AND EVEN LIGHT NUCLEI FLOW





Deuterons follow the expected mass ordering

***ALICE**, arXiv:1707.07304 [nucl-ex]*



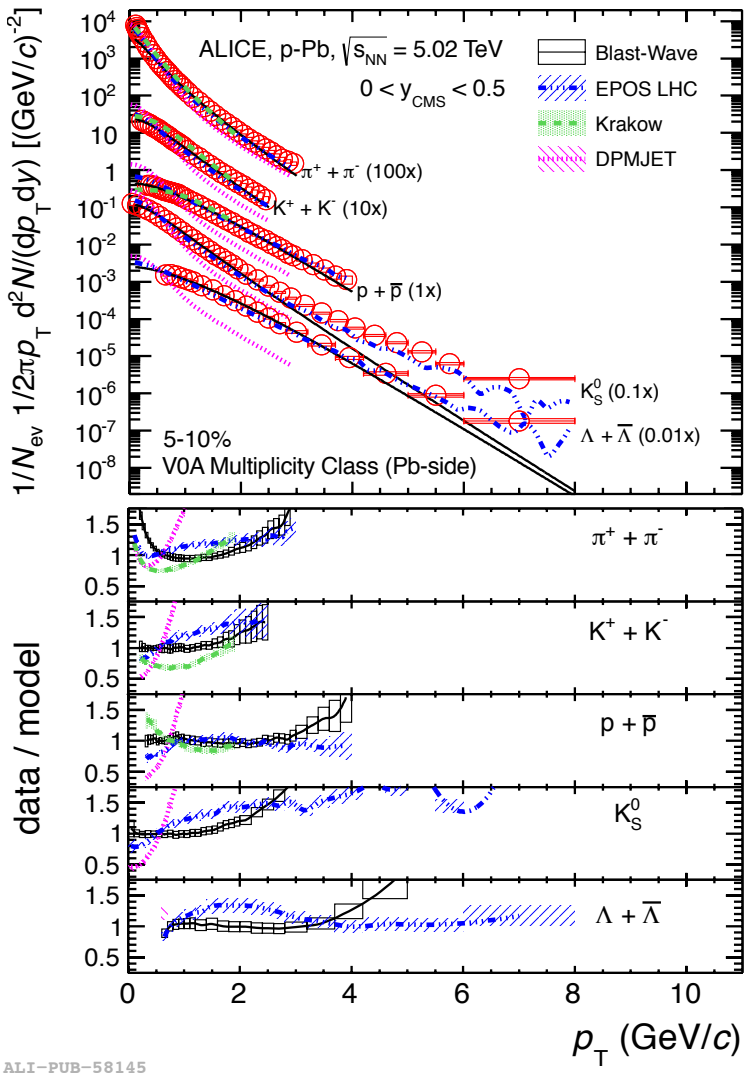
Small systems

Some surprising findings in the last years

ALICE, *Nature Physics 13 (2017) 535-539*

TRANSVERSE MOMENTUM SPECTRA

ALICE, Phys. Lett. B 728 (2014) 25-38



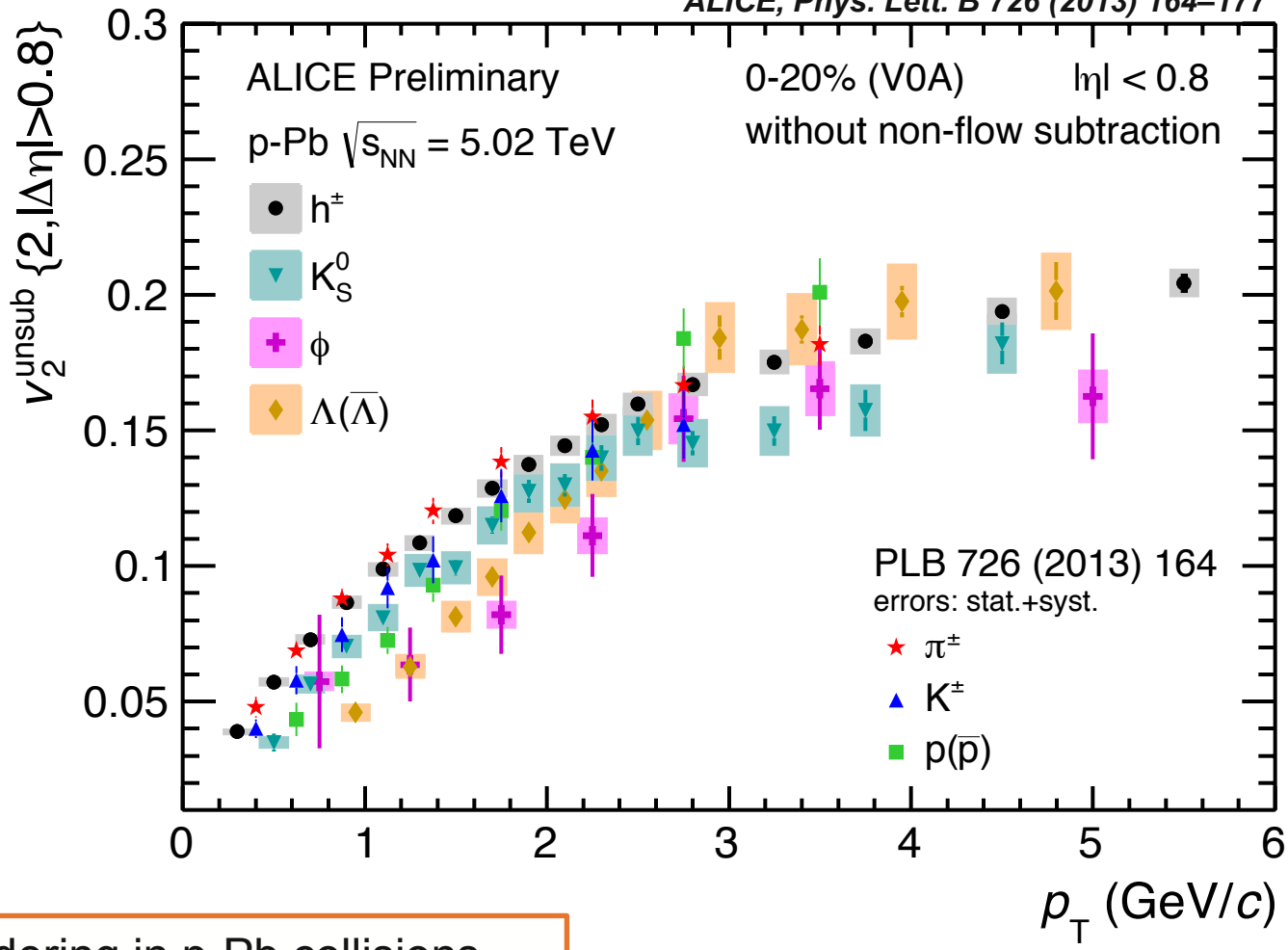
In **high multiplicity** p-Pb collisions at LHC (also in d-Au at RHIC)

- Hardening of spectra
- Mass ordering
- Hydrodynamic models (EPOS, Krakow) show a better agreement than QCD inspired models (DPMJET)
- Blast wave fits describes spectra reasonably well → radial flow velocity **<β> ≈ 0.55**

Radial Flow in p-Pb collisions?

ANISOTROPIC FLOW

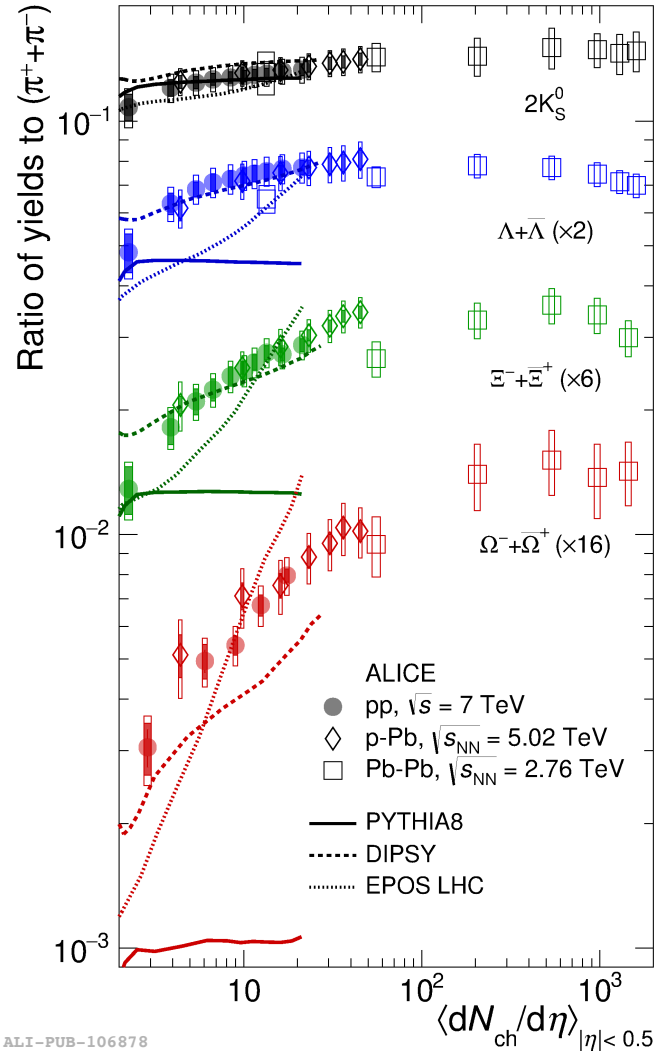
ALICE, Phys. Lett. B 726 (2013) 164–177

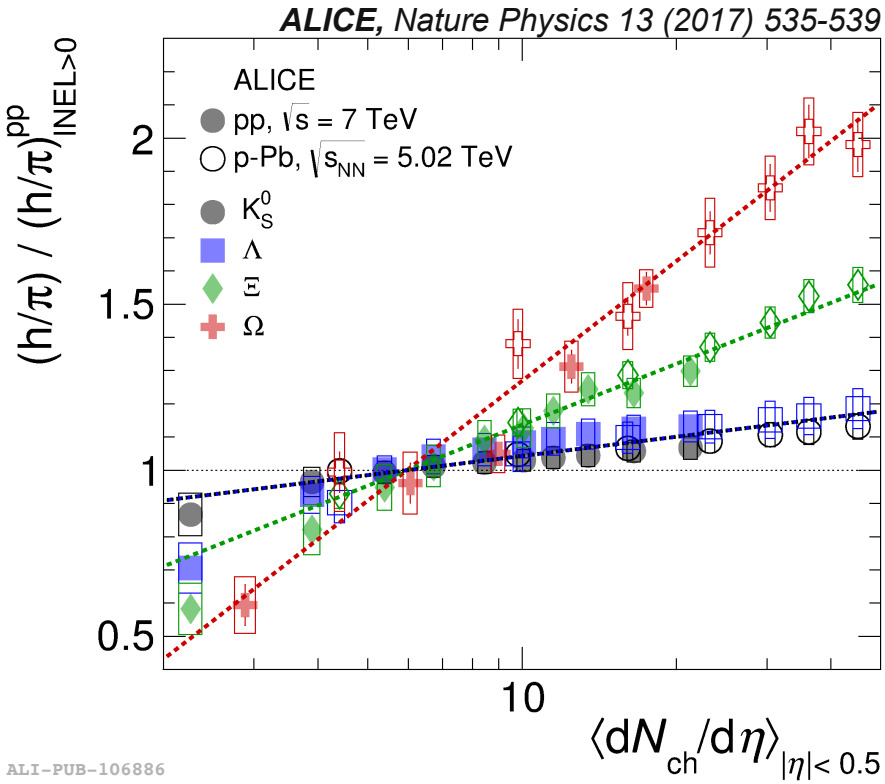


Mass ordering in p-Pb collisions
Qualitative similar picture of v_2 for identified particles as in Pb-Pb

Elliptic Flow in p-Pb collisions?

STRANGENESS





- **Strangeness enhancement** thought to be signature of **deconfined matter**
- **BUT:** smooth evolution with increasing multiplicity
- Slope depends on **strangeness content**

SUMMARY

Collective phenomena

Soft probes

$dN/d\eta \approx 2000$
(central PbPb at 5 TeV)

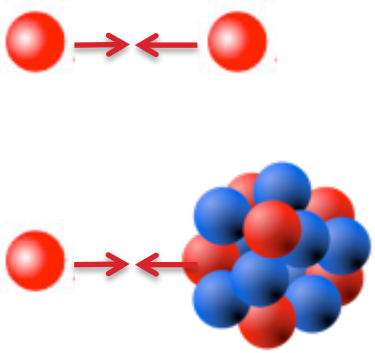
Kinetic freeze-out ~ 90 MeV
Radial flow velocity ~ 0.65 c

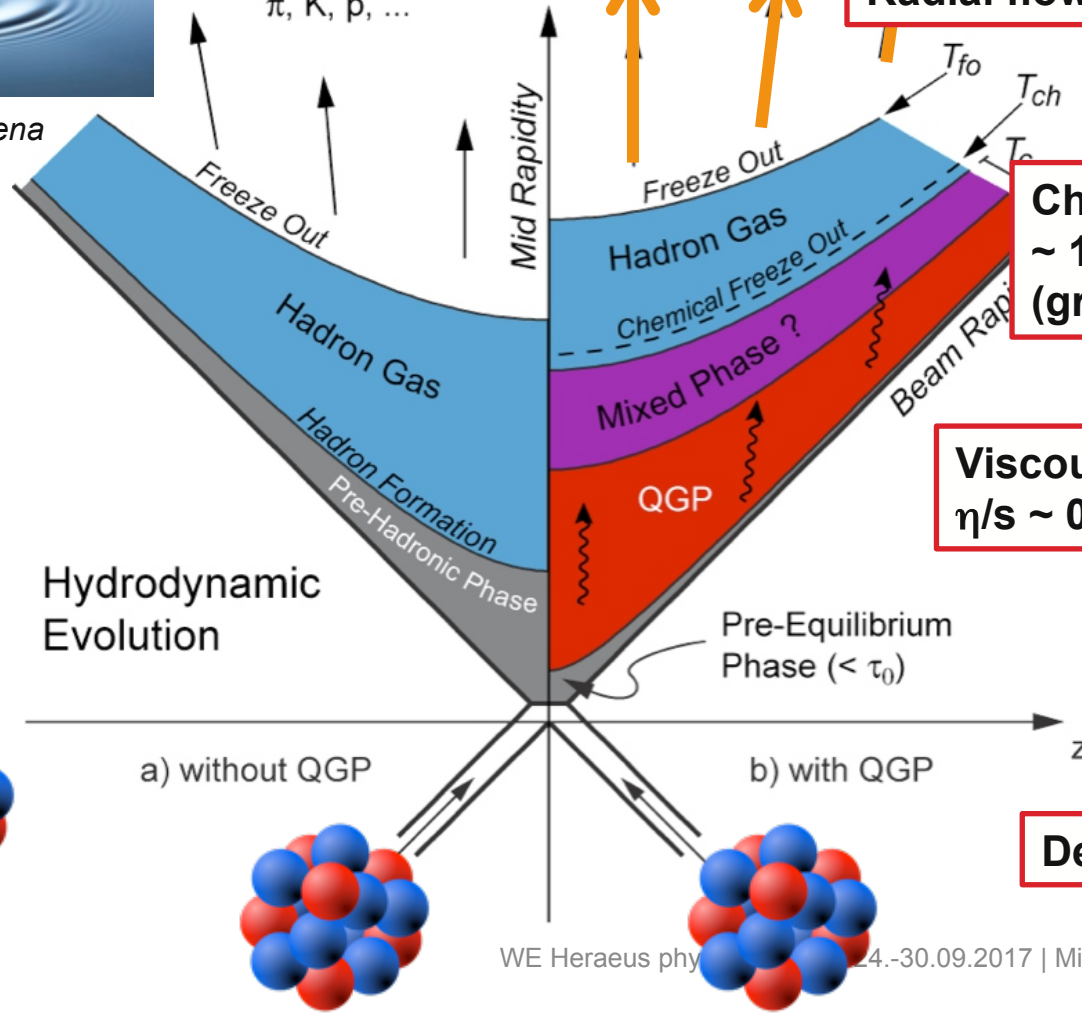
Chemical freeze-out ~ 160 MeV (grand-canonical)

Viscous hydrodynamics $\eta/s \sim 0.2$

Density fluctuations

Reference?

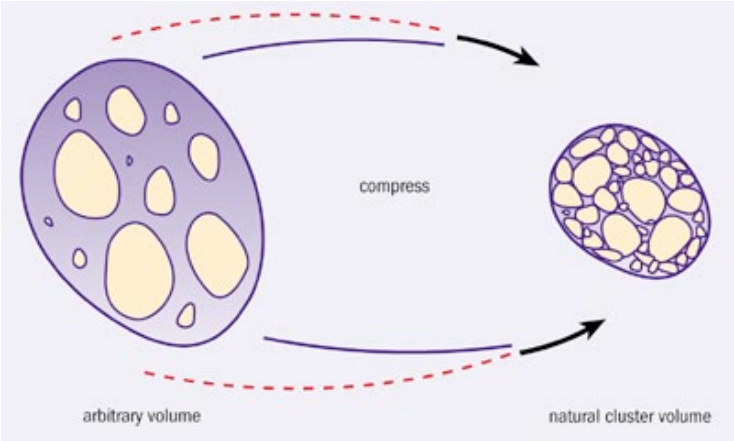




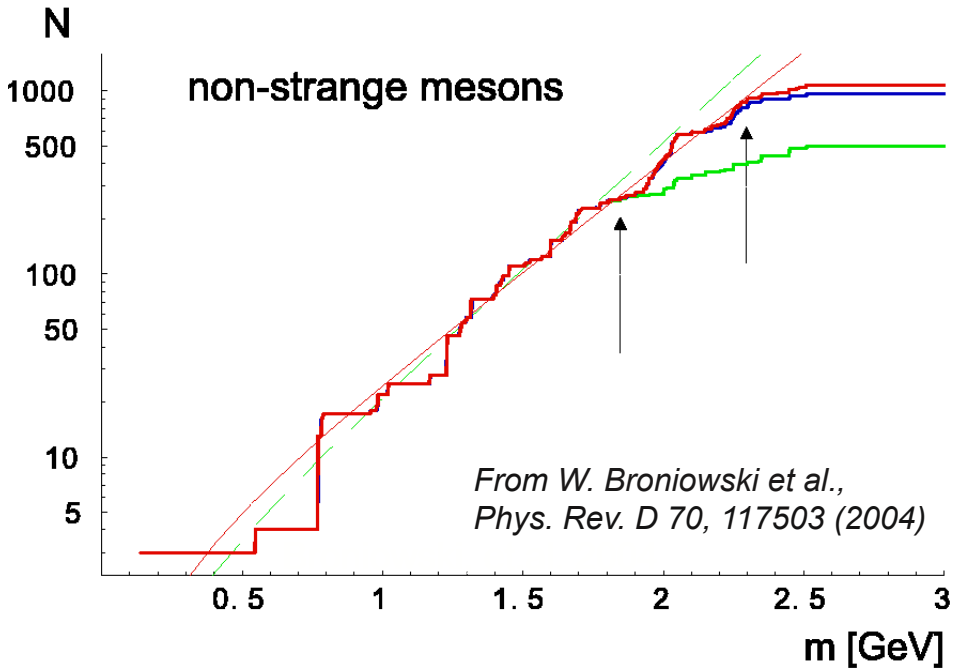

Thank you

BACKUP

HAGEDORN PICTURE



From CERN Courier, Sep 2003



From W. Broniowski et al., Phys. Rev. D 70, 117503 (2004)

Statistical Bootstrap model:
Number of hadronic resonances increases exponentially with the mass m of the resonances

$$\frac{dN_{\text{Particles}}}{dM} \sim \exp\left(M / T_{\text{H}} \right)$$

R. Hagedorn, Nuovo Cim. Suppl. 3, 147 (1965)

HAGEDORN PICTURE

K. Redlich, H. Satz, arXiv: 1501.07523 [hep_ph]

Consider an interacting gas of resonances, partition function:

$$\ln \mathscr{Z}(T,V) = \sum_i \frac{VTm_i^2}{2\pi^2}\,\rho(m_i)\,K_2\left(\frac{m_i}{T}\right)$$

With exponential behaviour (see previous slide):

$$\ln \mathscr{Z}(T,V) \simeq \frac{VT}{2\pi^2}\int dm\, m^2 \rho(m_i)\,K_2\left(\frac{m_i}{T}\right)$$

$$\sim V\left[\frac{T}{2\pi}\right]^{3/2}\int dm\, m^{-3/2}\exp\{-m\left[\frac{1}{T}-\frac{1}{T_H}\right]\}.$$

Divergent, for $T > T_H$:
→ **Limiting "Hagedorn temperature"**
→ **T_H ~ 150 MeV**

R. Hagedorn, Nuovo Cim. Suppl. 3, 147 (1965)

STATISTICAL MODEL

- Statistical models of hadronization
  - Use hadron resonance gas with masses < 2 GeV/c

- Yield per species for a grand-canonical ensemble:

$$N_i = V \frac{g_i}{2\pi^2} \int \frac{p^2 \, \mathrm{d}p}{e^{(E_i - \mu_\mathrm{B} B_i - \mu_\mathrm{s} S_i - \mu_3 I_{3i})/T} \pm 1}$$

- Here, E_i is the energy and g_i is the degeneracy of the species i, and μ_B, μ_S, μ_3 are baryon, strangeness and isospin chemical potentials, respectively
- In principle, 5 unknowns but also have information from initial state about Ns neutron and Zs stopped protons

$$V \sum n_i I_{3i} = \frac{Z_\mathrm{S} - N_\mathrm{S}}{2}$$
$$V \sum n_i B_i = Z_\mathrm{S} + N_\mathrm{S}$$
$$V \sum n_i S_i = 0$$

- Only three parameters remain: V, μ_B and T
- Typically use ratio of particle yields between various species to determine μ_B and T

BLAST WAVE MODEL

- Consider a thermal Boltzman source

$$E\frac{\mathrm{d}^3N}{\mathrm{d}p^3} \propto E\,e^{-E/T} \qquad E = m_\mathrm{T}\cosh(y)$$

- Boost source radially with a velocity β and evaluate at y=0

$$\frac{1}{m_\mathrm{T}}\frac{\mathrm{d}N}{\mathrm{d}m_\mathrm{T}} \propto m_\mathrm{T}\, I_0\left(\frac{p_\mathrm{T}\sinh(\rho)}{T}\right) K_1\left(\frac{m_\mathrm{T}\cosh(\rho)}{T}\right)$$

with $\rho = \tanh^{-1}(\beta)$

- Simple assumption: Consider uniform sphere of radius R

$$\frac{1}{m_\mathrm{T}}\frac{\mathrm{d}N}{\mathrm{d}m_\mathrm{T}} \propto \int_0^R r\mathrm{d}r\, m_\mathrm{T}\, I_0\left(\frac{p_\mathrm{T}\sinh(\rho(r))}{T}\right) K_1\left(\frac{m_\mathrm{T}\cosh(\rho(r))}{T}\right)$$

and parametrize surface velocity as

$$\beta(r) = \beta_\mathrm{s}\,(r/R)^n$$

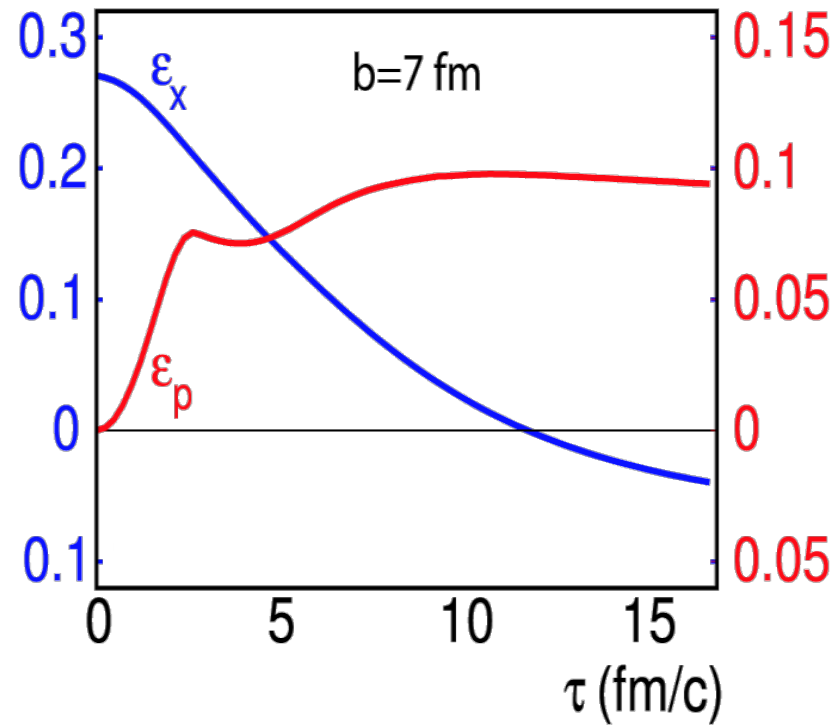
Three parameters: T,β_s and n
(sometimes n=2 is fixed)

Schnedermann et al., PRC 48 (1993) 2462

GEOMETRIC AND MOMENTUM ANISOTROPY

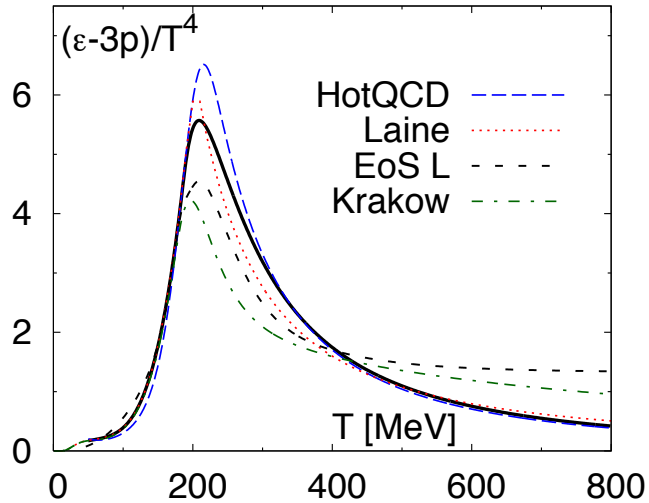
From hydrodynamic models:

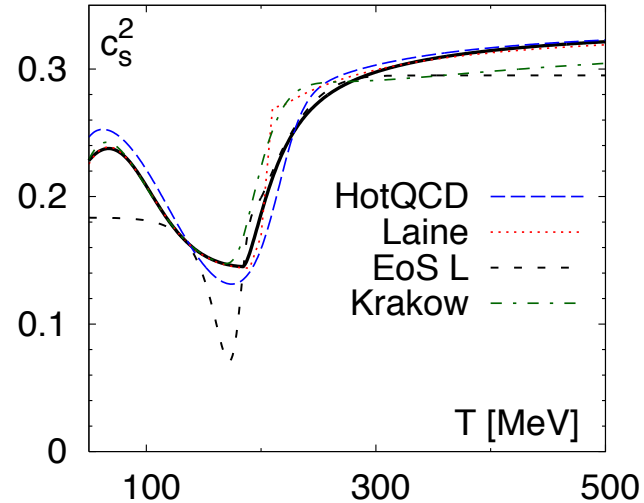
- Geometric anisotropy (ε_X= elliptic deformation of the fireball) decreases with time
- Momentum anisotropy (ε_p, actual observable):
  - grows quickly in the QGP state (τ < 2-3 fm/c)
  - remains constant during the phase transition (2<τ<5 fm/c), which in the models is assumed to be first-order
  - Increases slightly in the hadronic phase (τ > 5 fm/c)



How can we measure this?

EQUATION OF STATE

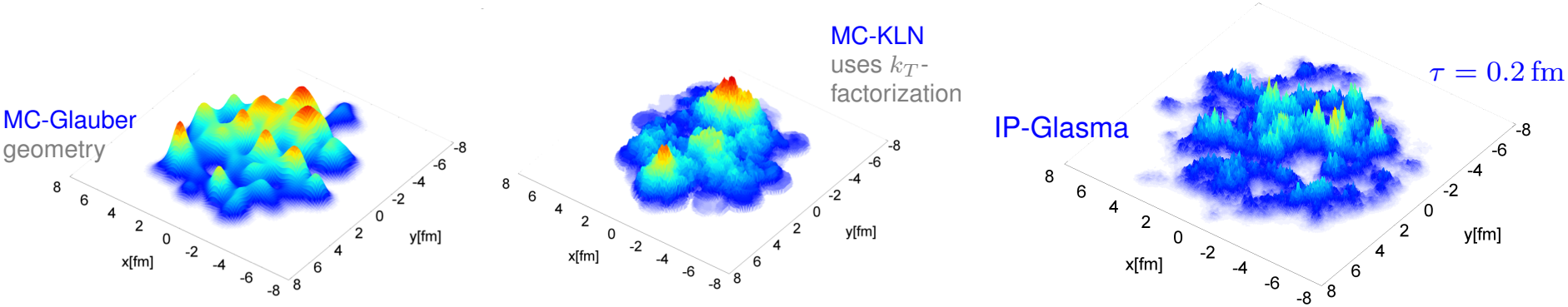




Need an equation of state p(ε) to close the set of hydro equations:

- Early days: 1st order phase transition EoS from MIT bag model
- Today: EoS from lattice QCD + hadron resonance gas model

INITIAL CONDITIONS

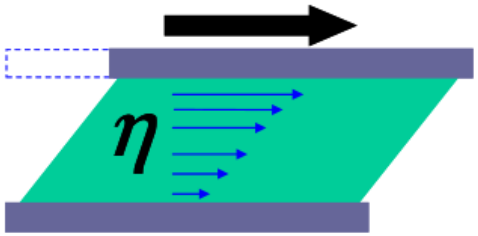


- **MC-Glauber**: geometric model determining wounded nucleons based on the inelastic cross section (different implementations)
- **MC-KLN**: Color-Glass-Condensate (CGC) based model using kT –factorization
- **IP-Glasma**: Recent CGC based model using classical Yang-Mills evolution of early-time gluon fields, including additional fluctuations in the particle production

- Also hadronic cascades UrQMD or NEXUS and partonic cascades (e.g. BAMPS) can provide initial conditions

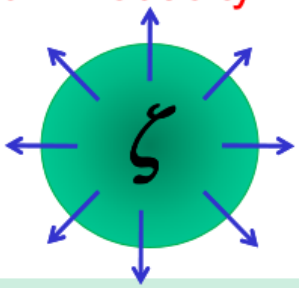
TRANSPORT COEFFICIENTS

Shear viscosity – measures the resistance to flow gradients

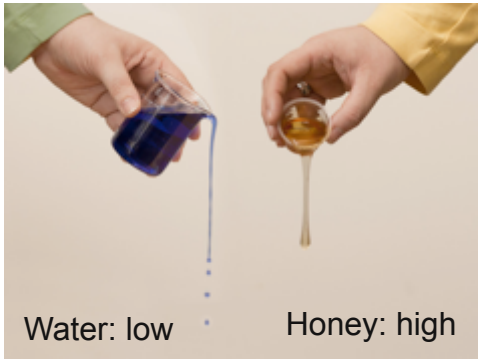


acts against the buildup of **flow anisotropy**

Bulk viscosity – measures the resistance to expansion

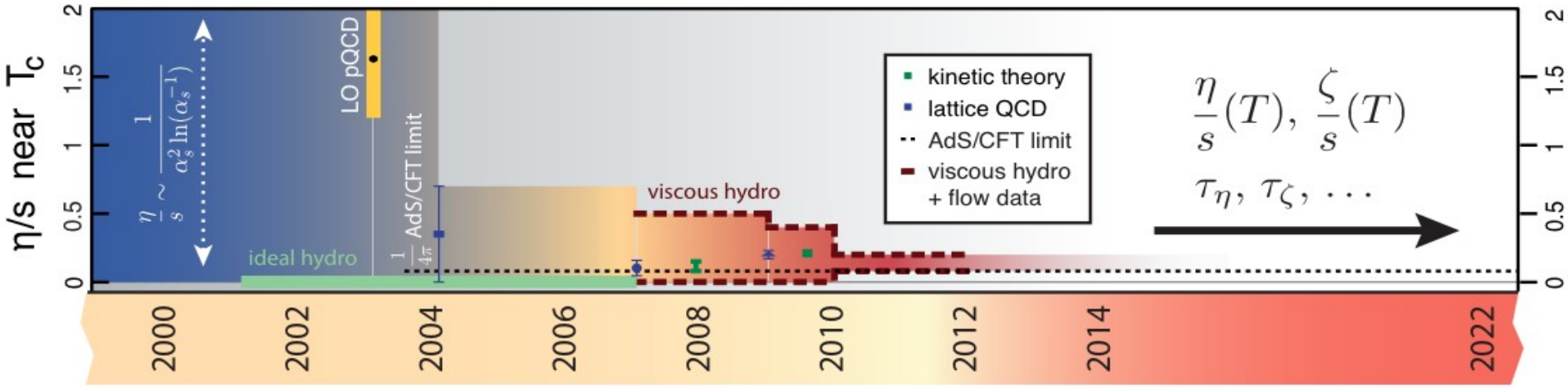


acts against the buildup of **radial flow**



- Usually divided by entropy: η/s
- Early hydro models (at RHIC) were done with $\eta/s=0$. Today small values between (1-3)/4π used.

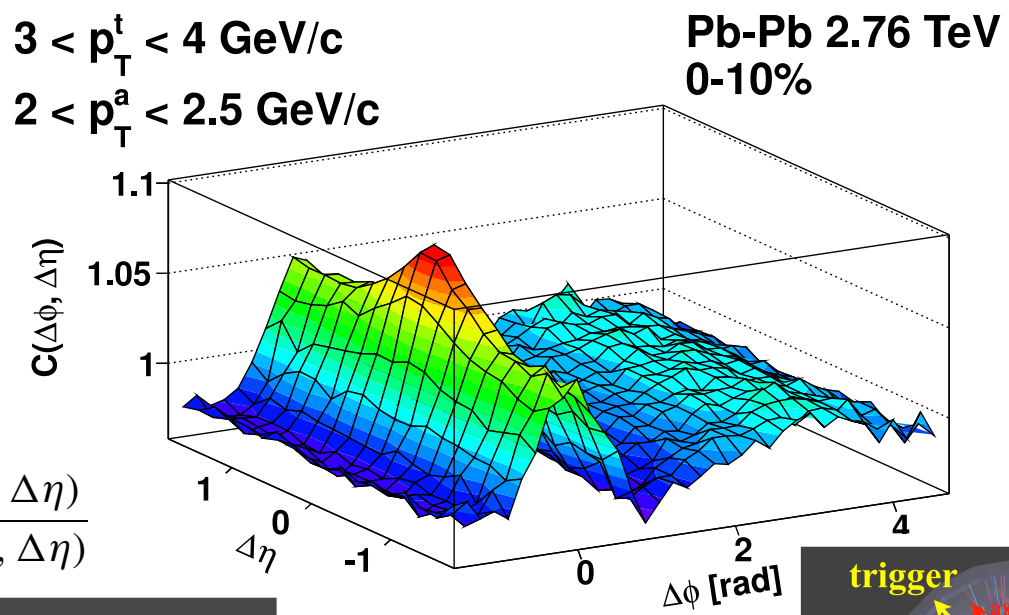
HYDRO TIMELINE



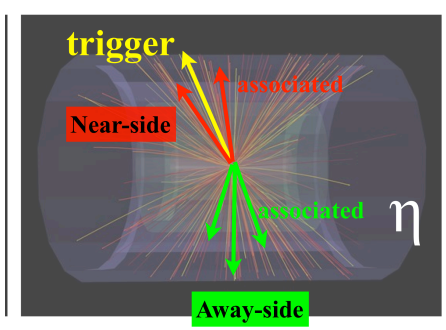
EXPERIMENTAL FLOW METHODS

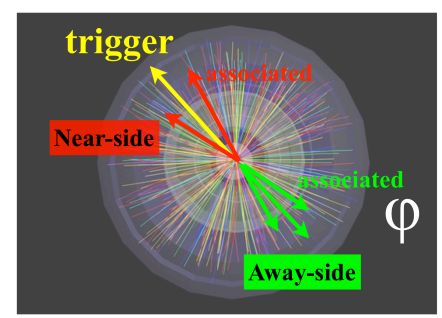
- Usage of two-particle azimuthal correlations instead of event plane:

ALICE, Phys Lett B 708 (2012) 249–264



$$C(\Delta\phi, \Delta\eta) \equiv \frac{N_{\text{mixed}}}{N_{\text{same}}} \times \frac{N_{\text{same}}(\Delta\phi, \Delta\eta)}{N_{\text{mixed}}(\Delta\phi, \Delta\eta)}$$

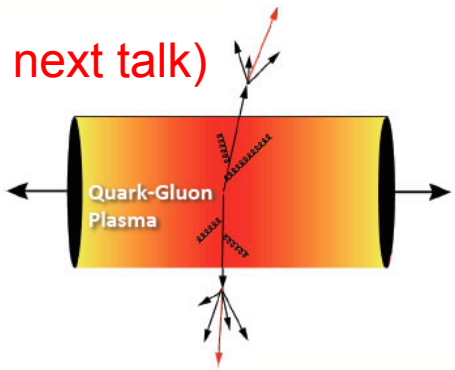




EXPERIMENTAL FLOW METHODS

- Usage of two-particle azimuthal correlations instead of event plane:

(see next talk)



ALICE, Phys Lett B 708 (2012) 249–264

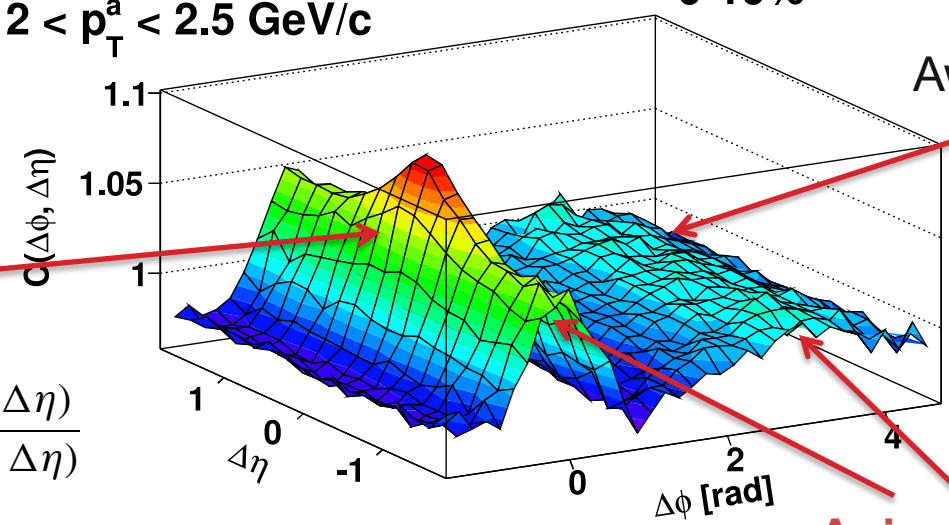
$3 < p_T^t < 4$ GeV/c

$2 < p_T^a < 2.5$ GeV/c

Pb-Pb 2.76 TeV
0-10%

Away-side jet

Near-side jet peak



$$C(\Delta\phi, \Delta\eta) \equiv \frac{N_{\text{mixed}}}{N_{\text{same}}} \times \frac{N_{\text{same}}(\Delta\phi, \Delta\eta)}{N_{\text{mixed}}(\Delta\phi, \Delta\eta)}$$

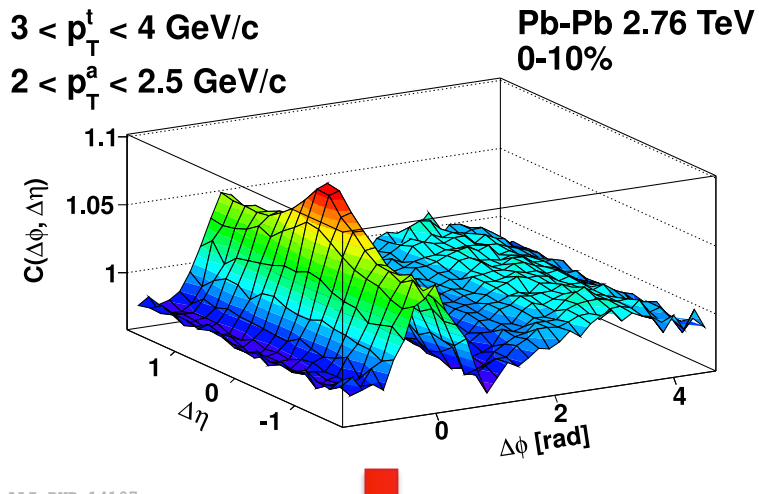
ALI-PUB-14107

Anisotropic flow (“Ridge”)

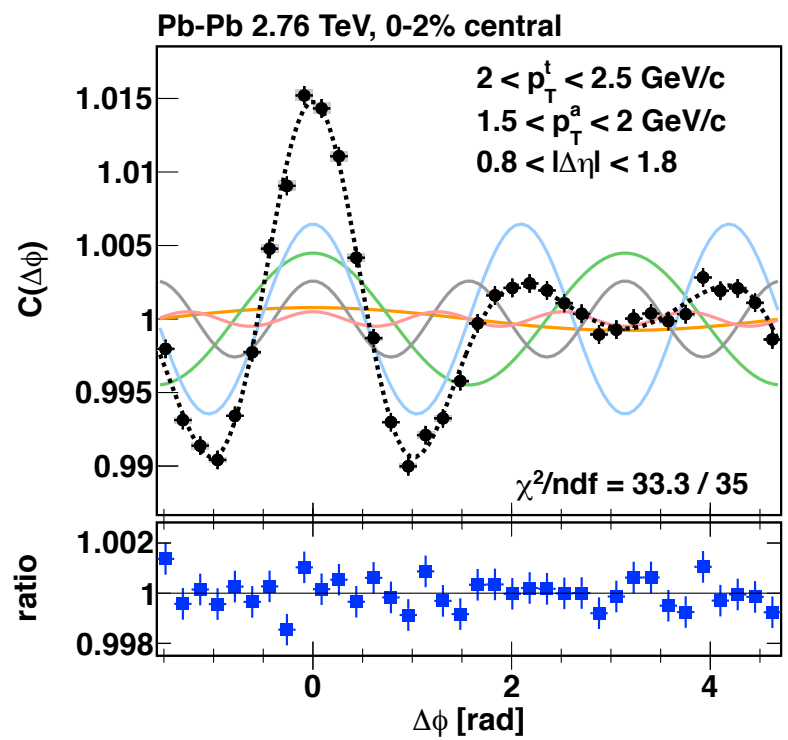
Remove **non-flow** by **projecting at large Δη**

EXPERIMENTAL FLOW METHODS

- Usage of two-particle azimuthal correlations instead of event plane:



ALICE, Phys Lett B 708 (2012) 249–264



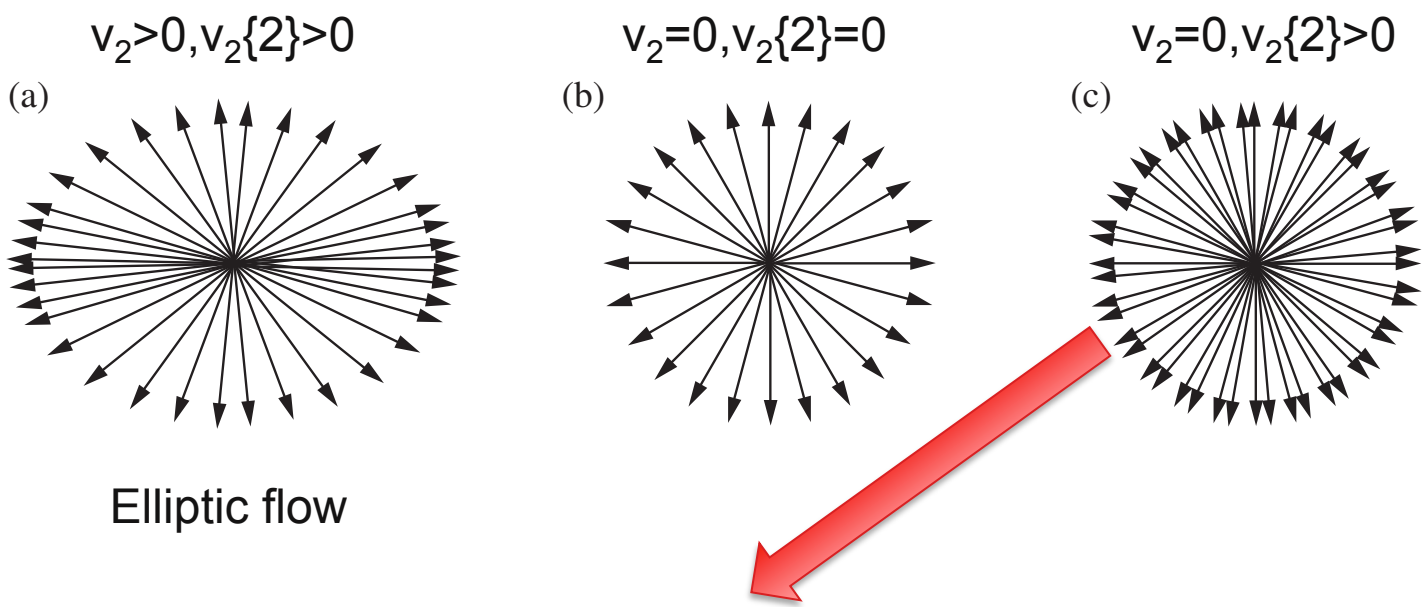
Calculate Fourier coefficients

$$V_{n\Delta} = \langle \cos n\Delta\varphi \rangle = \frac{\int d\Delta\varphi C(\Delta\varphi)\cos n\Delta\varphi}{\int d\Delta\varphi C(\Delta\varphi)}$$

EXPERIMENTAL FLOW METHODS

- Usage of two-particle azimuthal correlations instead of event plane:

Snellings, New Jour Phys 13 (2011) 055008



Elliptic flow

Reduce contribution from **non-flow** effects by using **4- and more particle correlations** $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$…