Anisotropic flow measurements at RHIC and LHC

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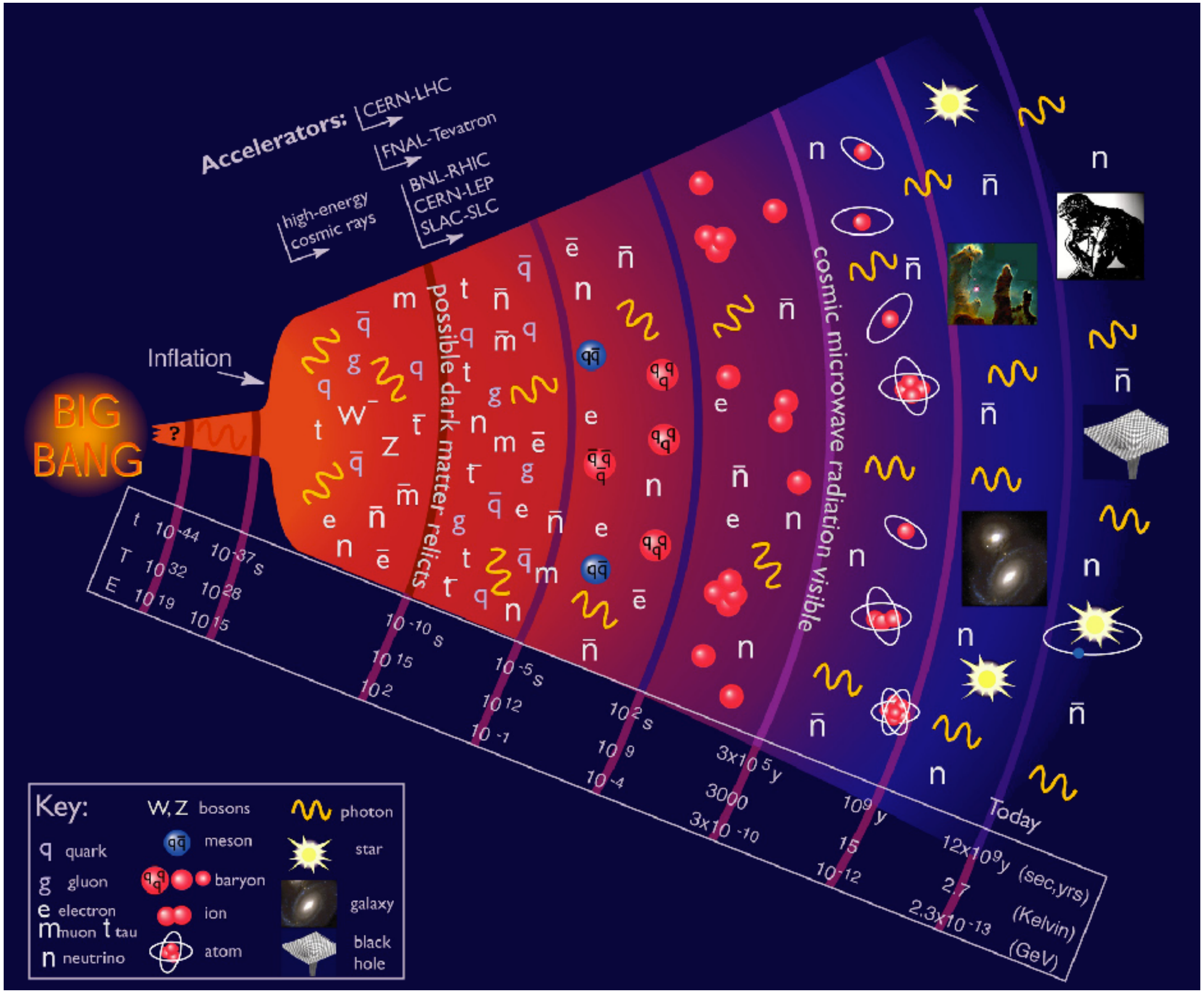
(EMMI, GSI & FIAS)

EMMI Days

GSI, November 07, 2011

Introduction to the heavy-ion physics

History of the universe



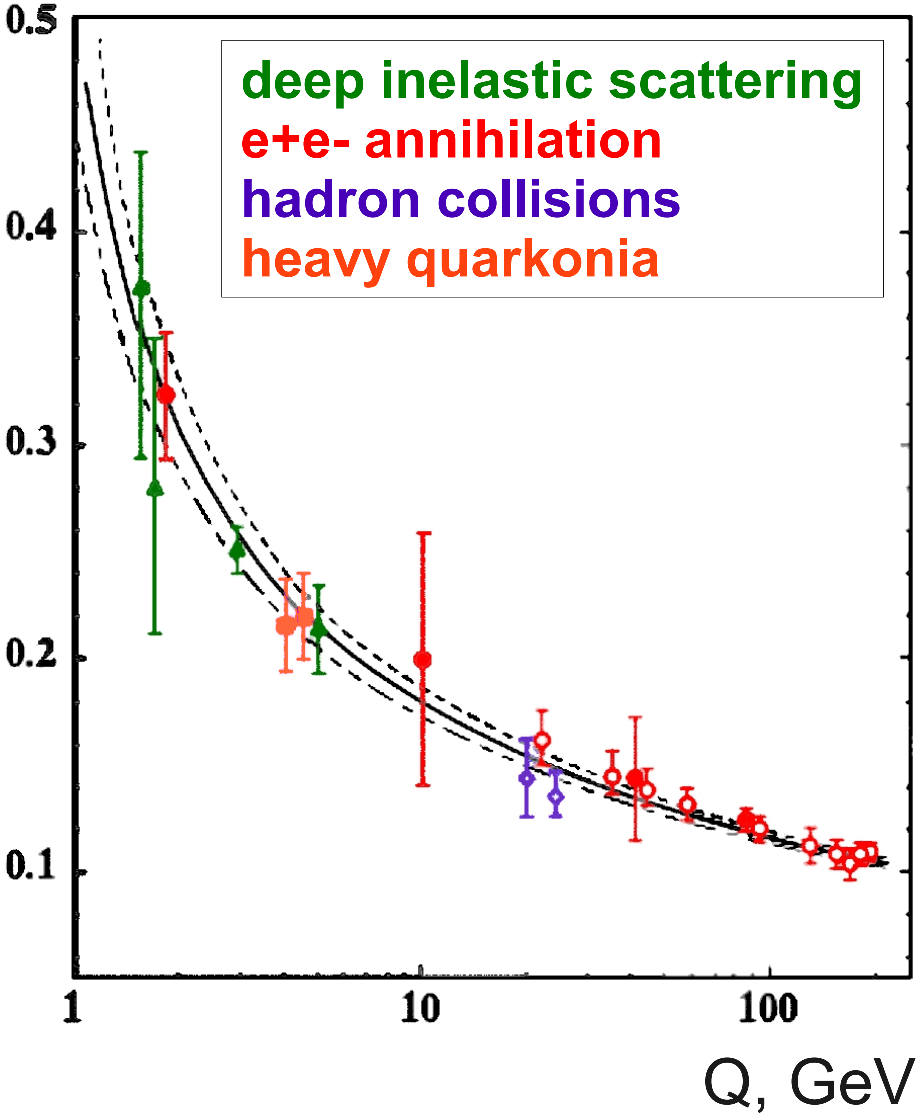
Age ~ 13 billion years

Properties of matter during the 1st second are not well known

Early times ↔ short distances: interaction governed by QCD

Quantum Chromo-Dynamics (QCD)

α_s, strong coupling constant



QCD is a theory of strong interactions

- Chiral symmetry:
  identical left & right handed quarks
- Asymptotic freedom & running coupling.
  Renormalization scale:

  $\Lambda_{QCD} \sim$ 200MeV
- Perturbative regime: $Q^2 \gg \Lambda_{QCD}$

  Deconfined state of quark & gluons
- Non-perturbative regime: $Q^2 \sim \Lambda_{QCD}$

  Quark & gluons confined in hadrons

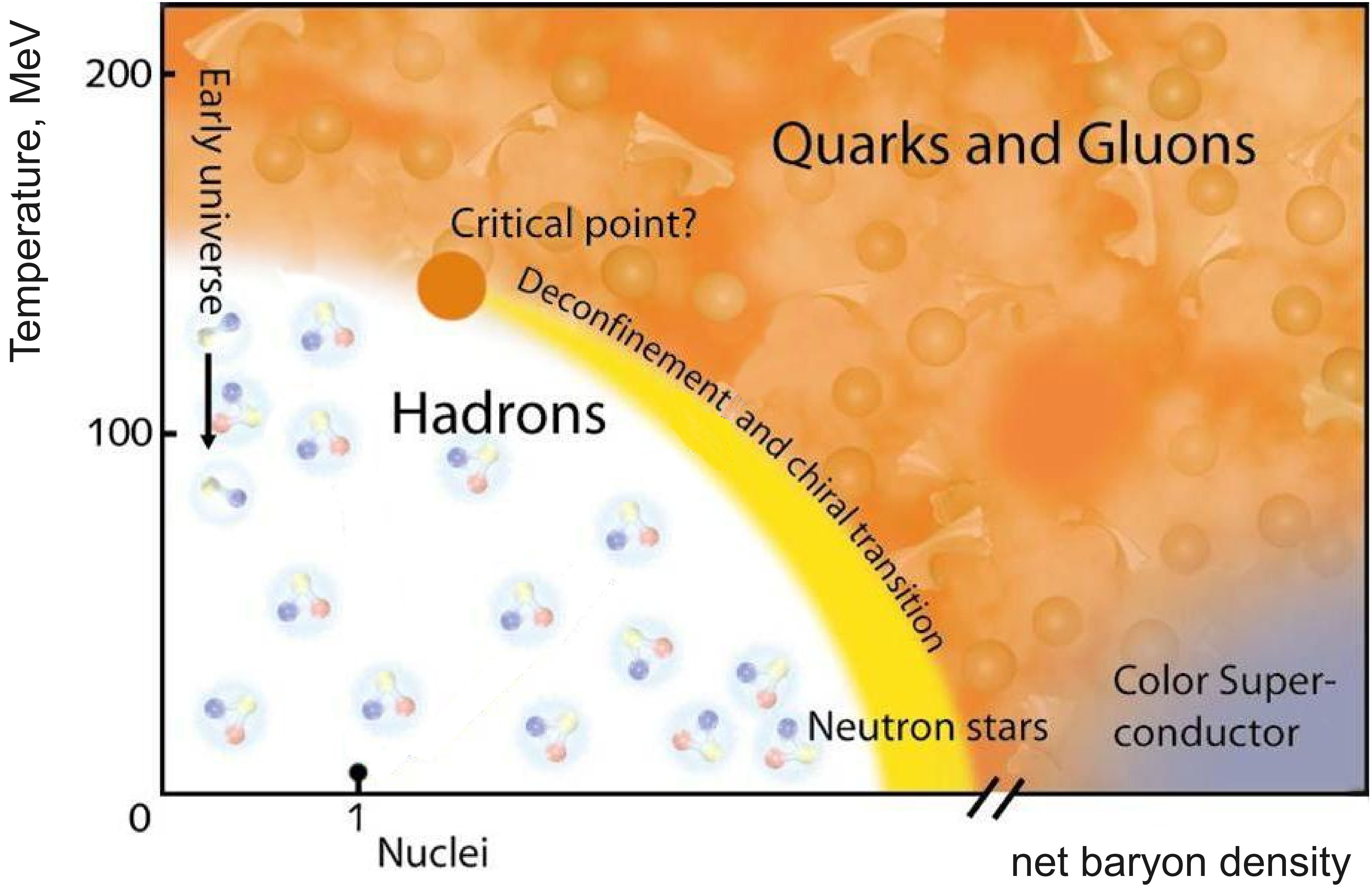
Main questions about QCD

- What are the forms of extended QCD matter?
  - Properties of hadrons (confined quarks)
  - Properties of deconfined quarks and gluons
  - Relevant degrees of freedom for those states

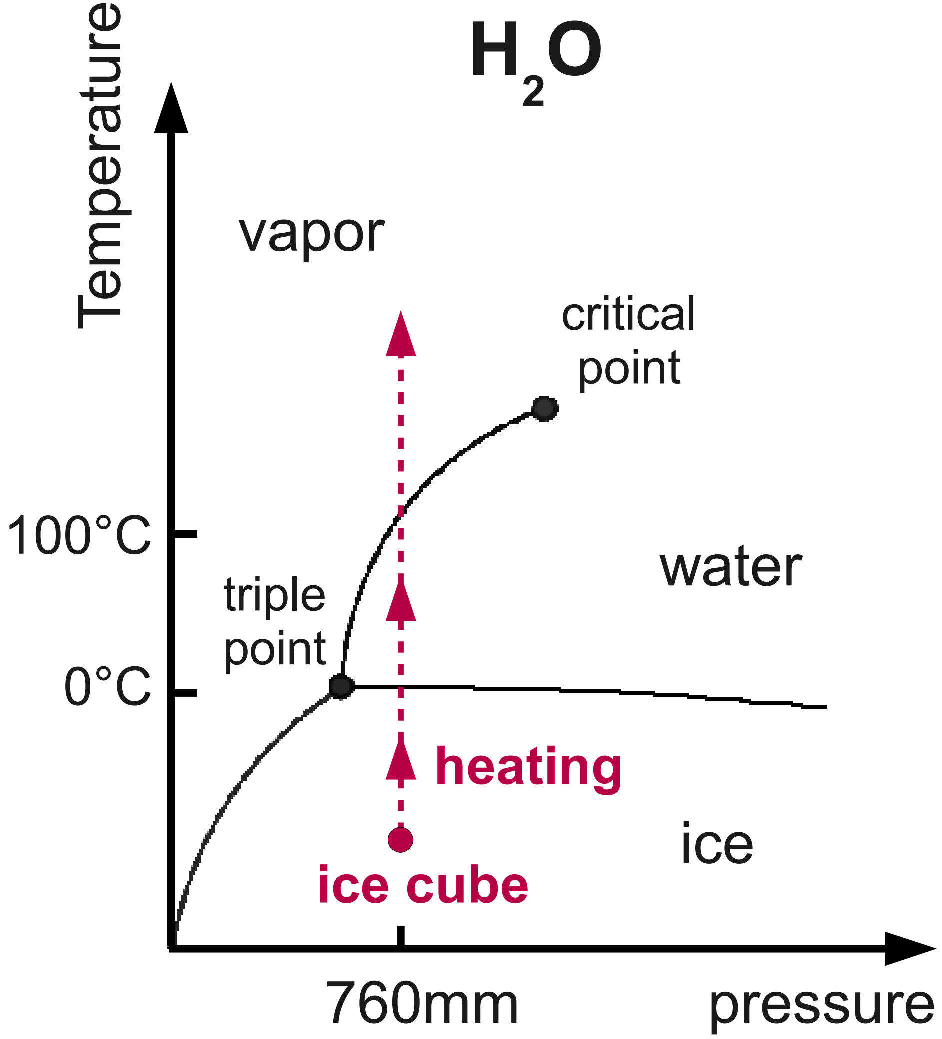
- How & when the transition between different states of matter happens?

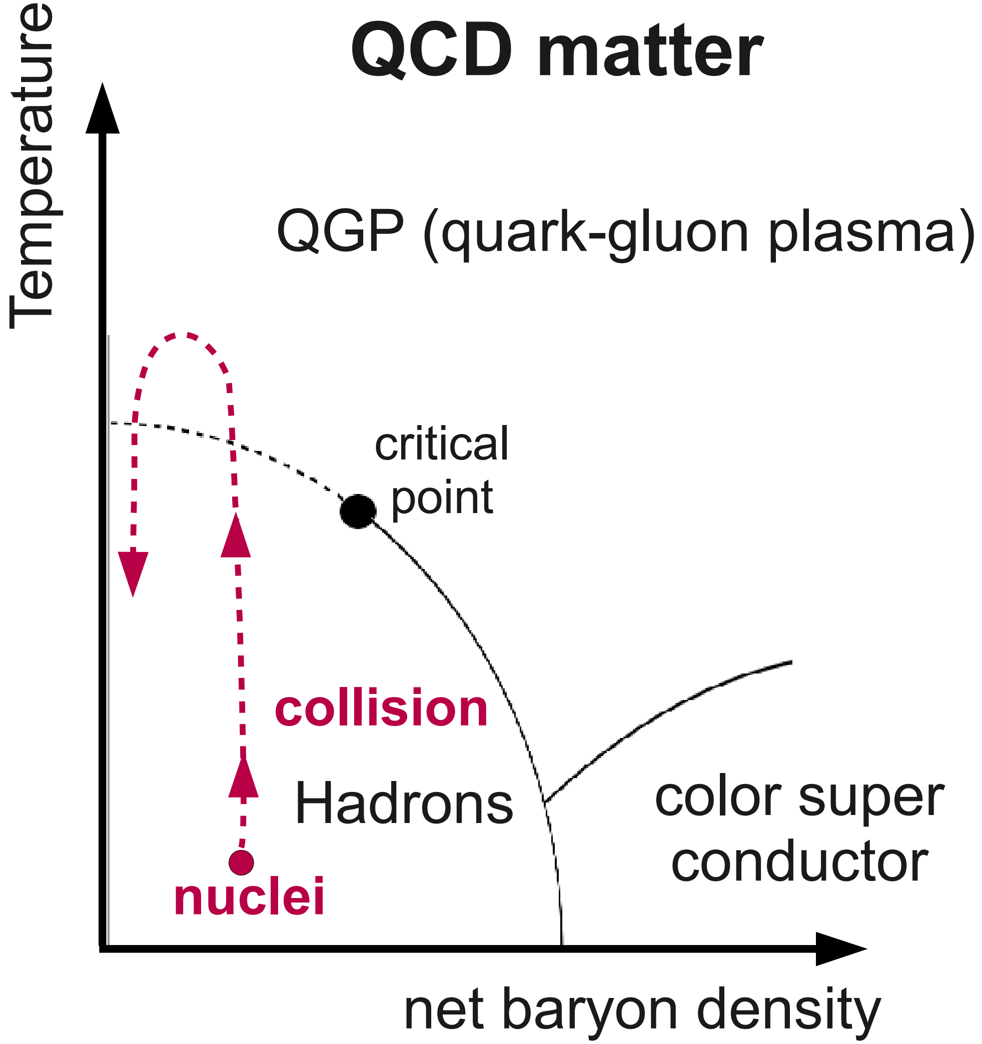
- What symmetries are preserved by QCD (chirality, Time, Parity, and C)
  Under what conditions they can be broken/restored?

Phase diagram: map of states and phase transitions



Experimental study of the phase diagram

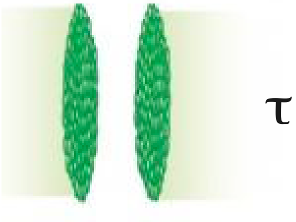




Experimental study of QGP phase diagram by:
smashing nuclei in head-on collision and
converting cold nuclear matter into a fireball of partons

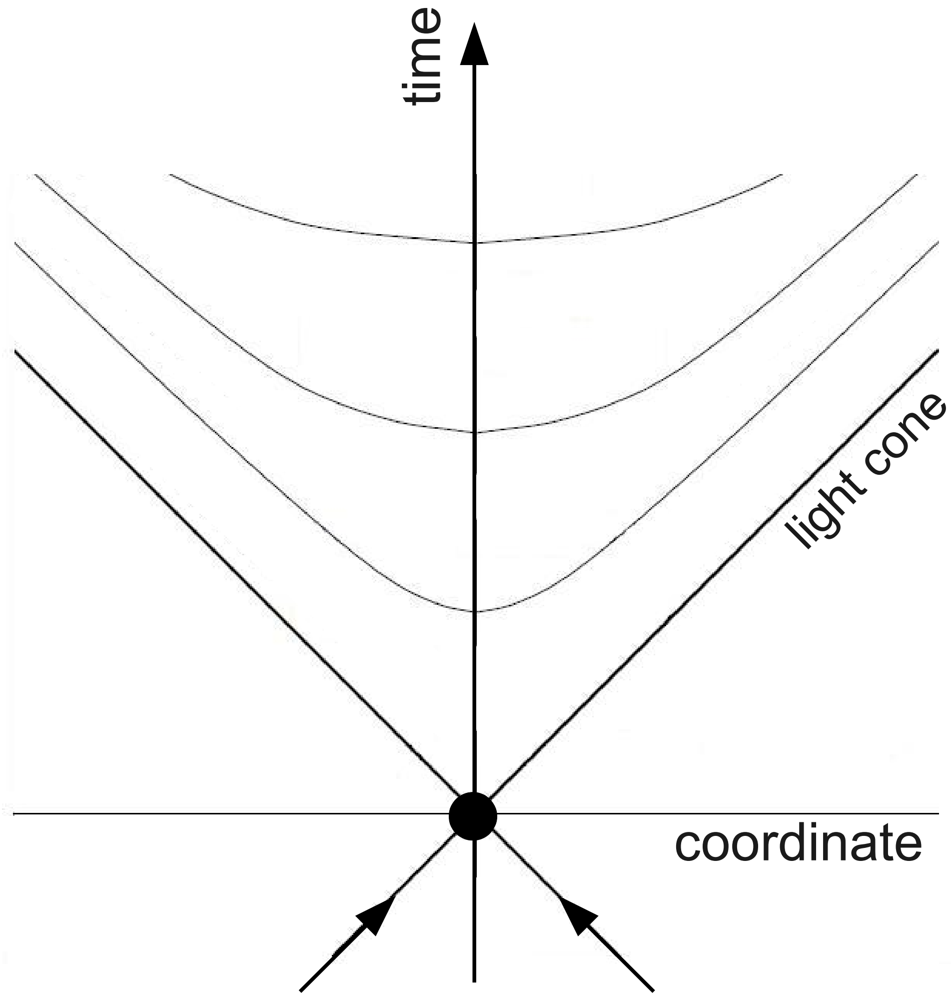
Evolution of the system created in HIC

time



$\tau \sim 0$

- Nuclei just before collision



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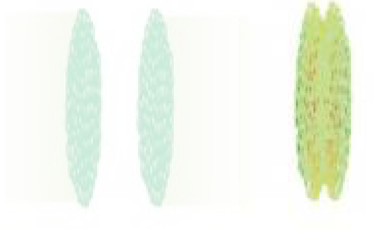
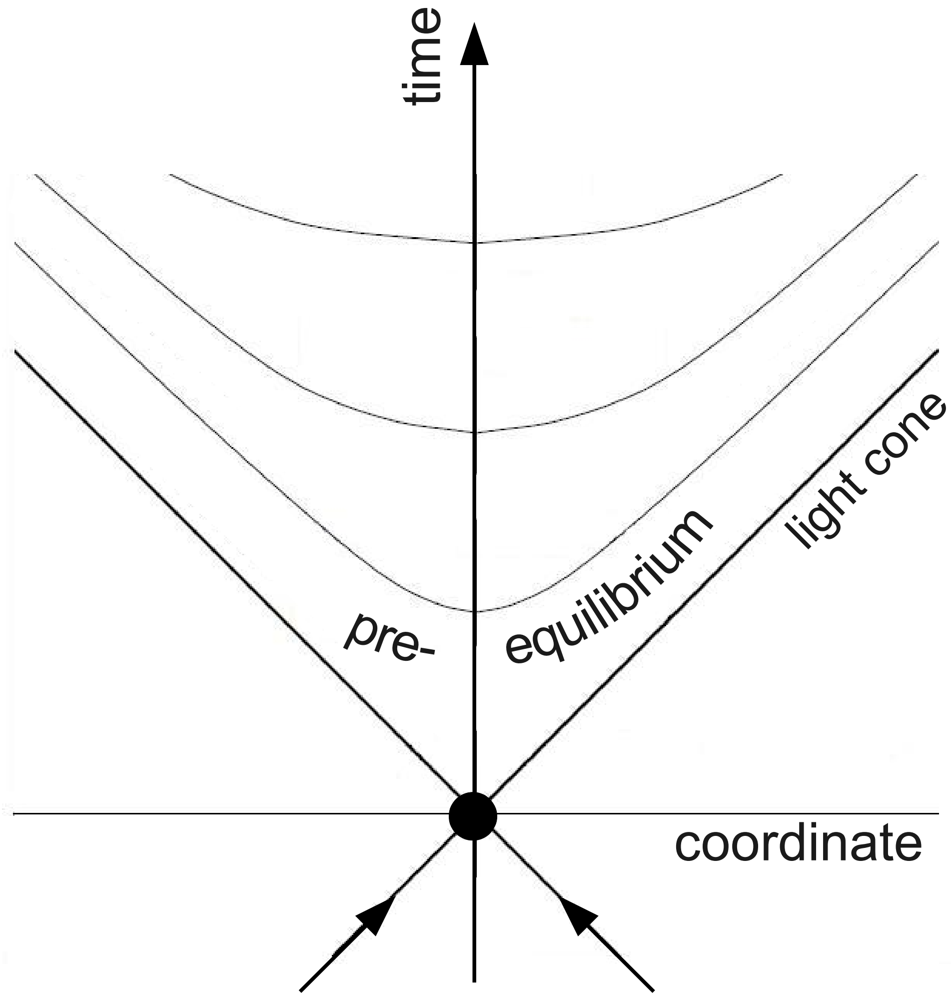


$\tau < 1\ fm/c$

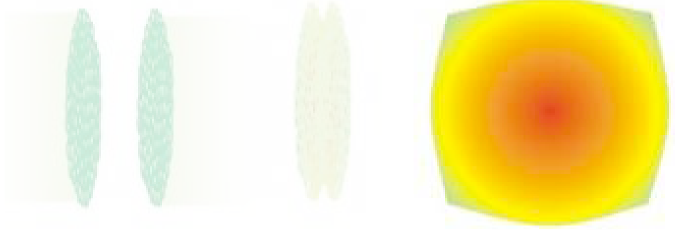


- Initial pre-equilibrium state

  hard parton scattering & jet production
  gluonic fields (Color Glass Condensate)

Nuclei just before collision

Evolution of the system created in HIC



time

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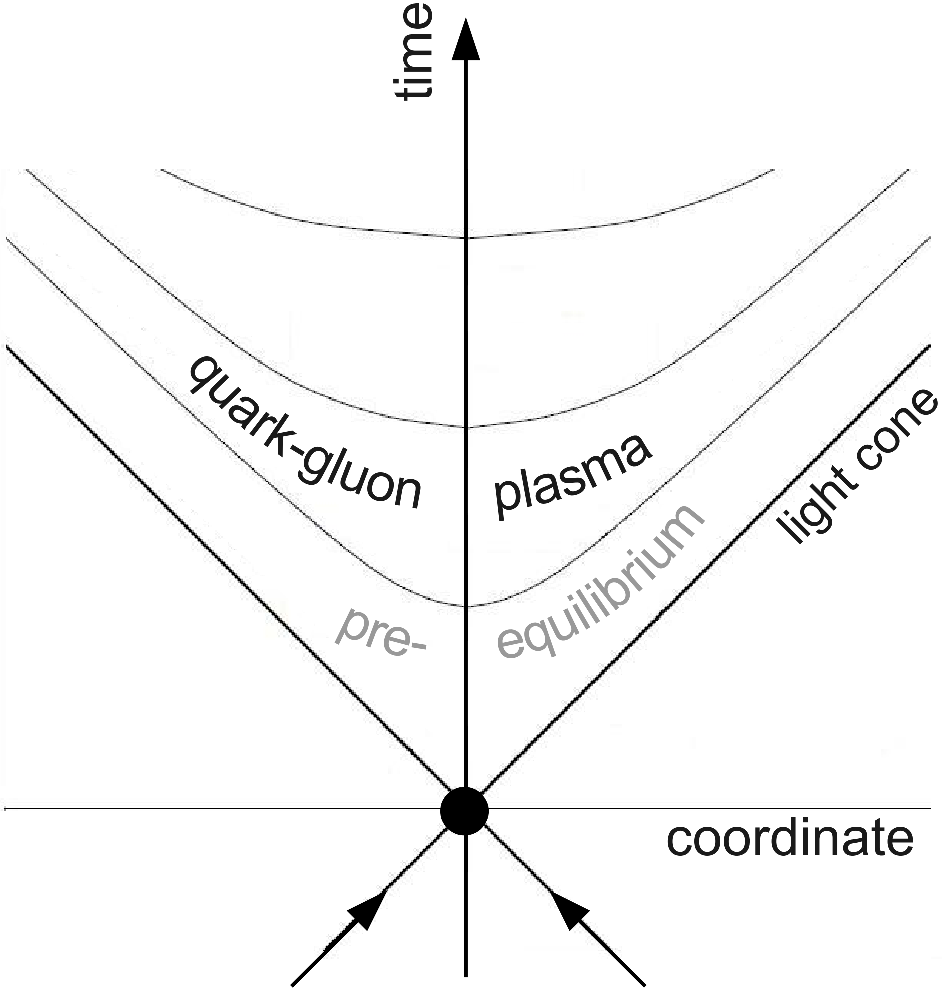

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- Quark-gluon plasma formation

  thermalization (hydrodynamics)

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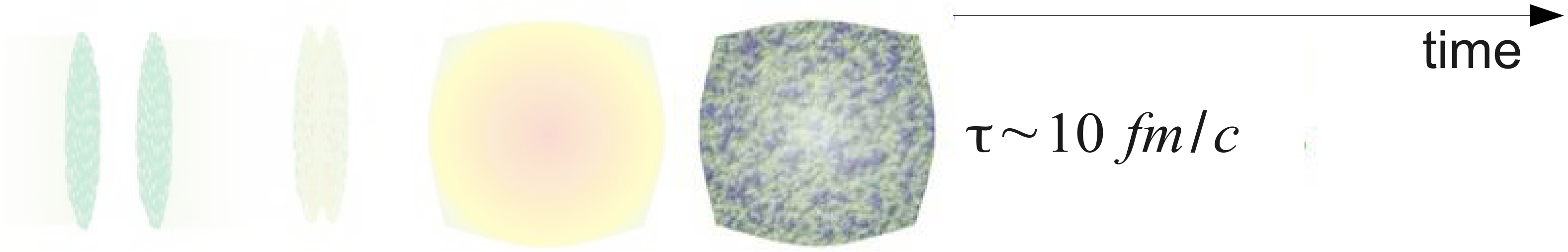

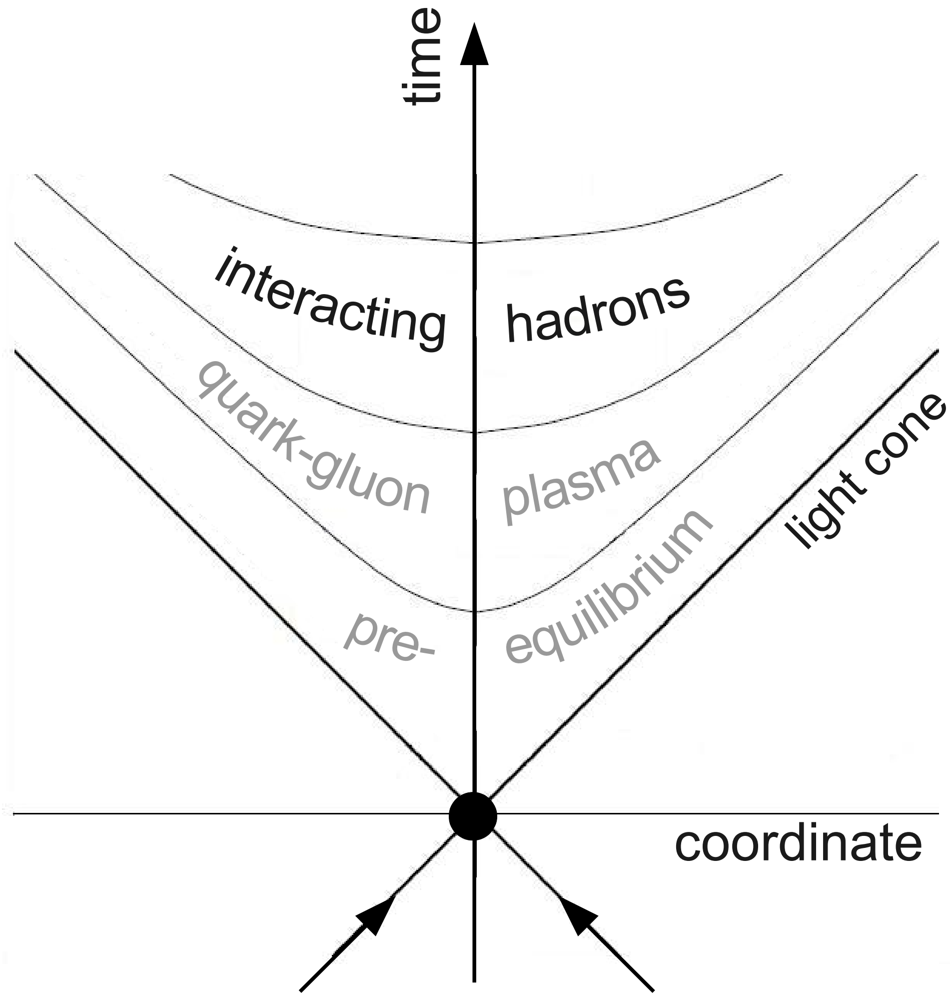

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  phase transition of partons into hadrons

  - Hadronization

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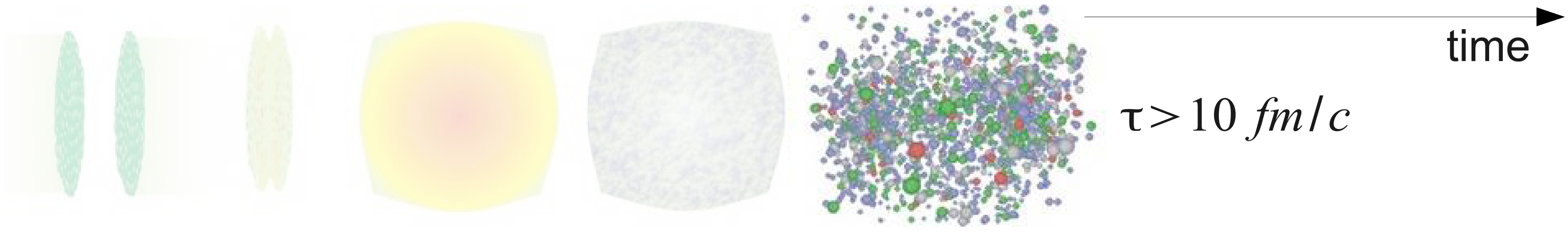
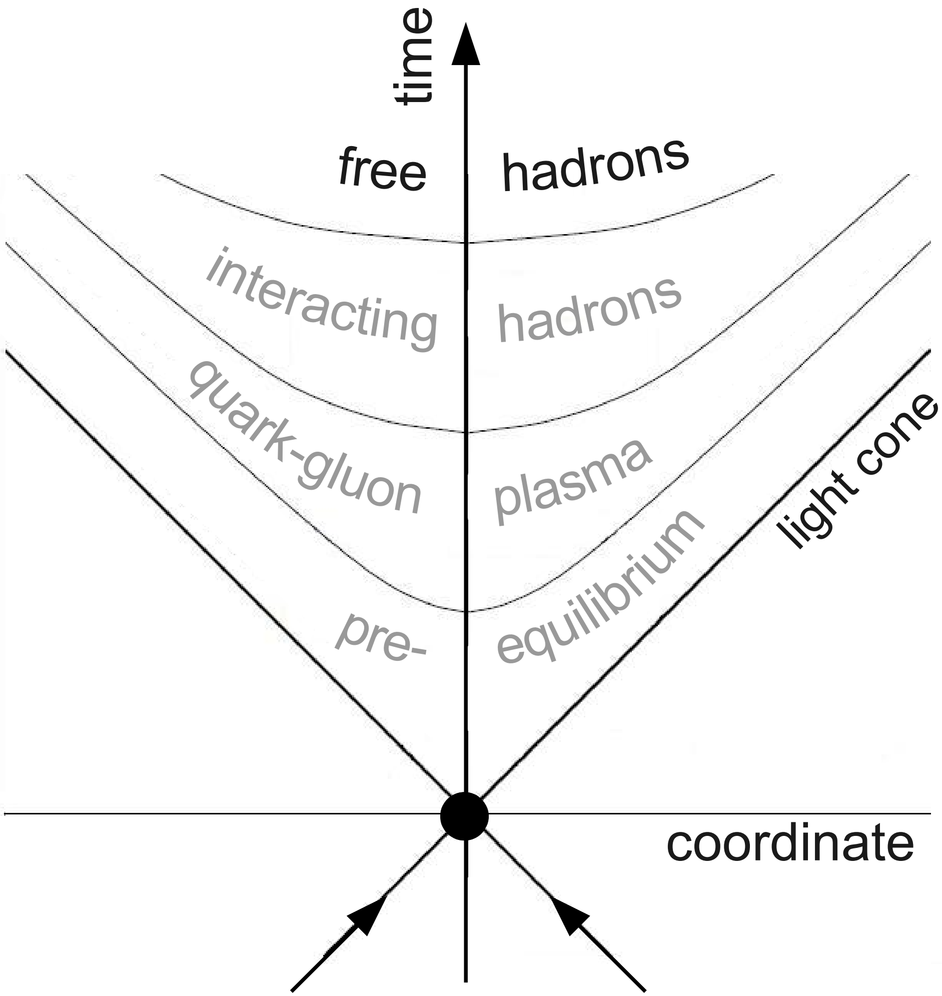


$\tau > 10\ fm/c$



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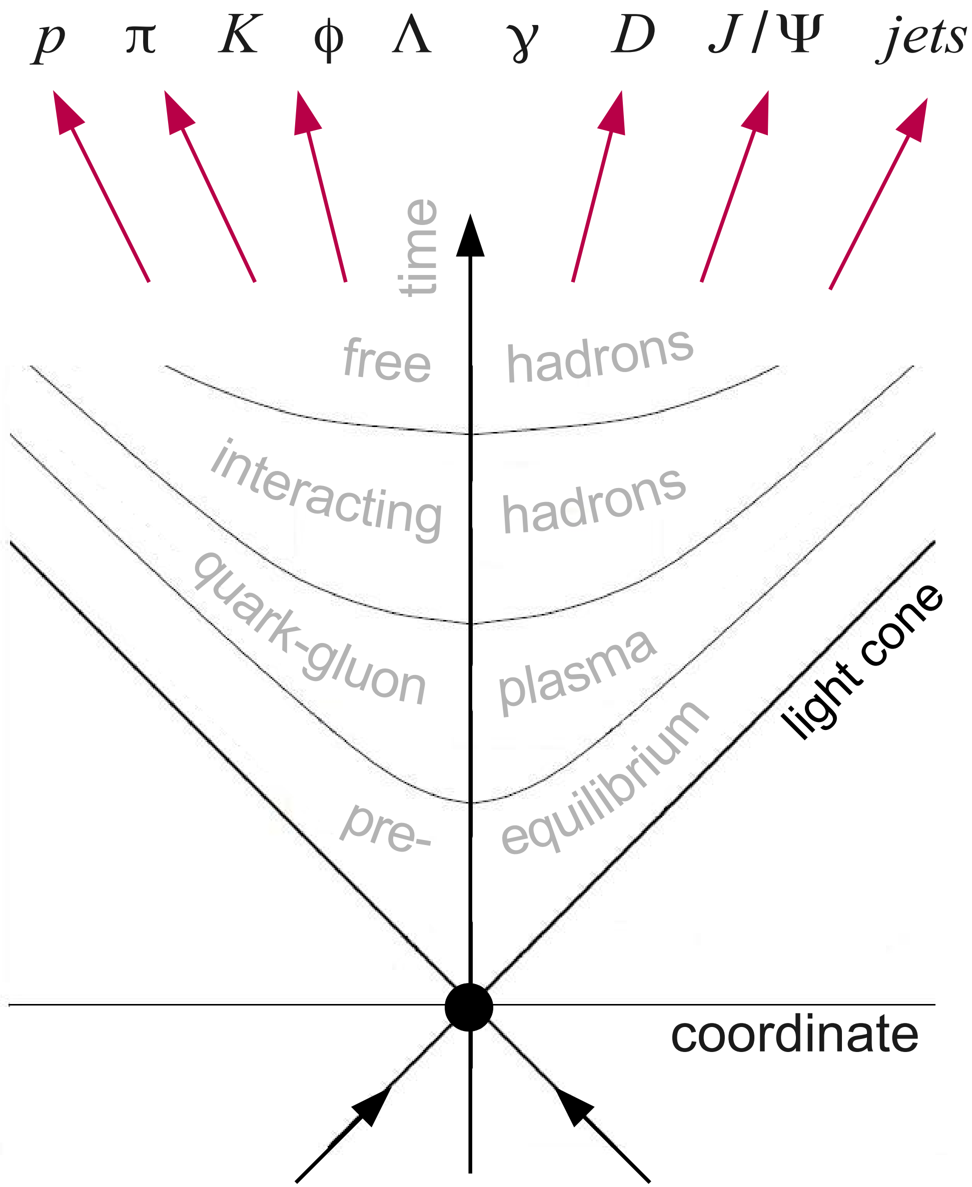
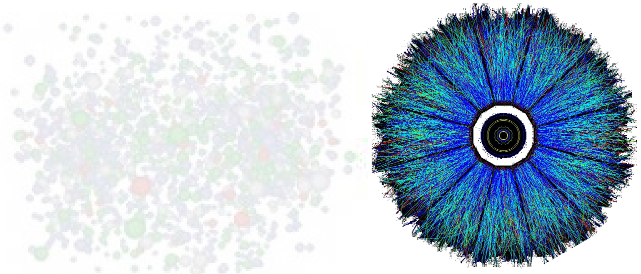
  - Rescattering & chemical freeze out
  - Kinetic freeze out (stop interacting)

Evolution of the system created in HIC

produced particles:



Nuclei just before collision



time

$\tau \sim 10^{15}\ fm/c$

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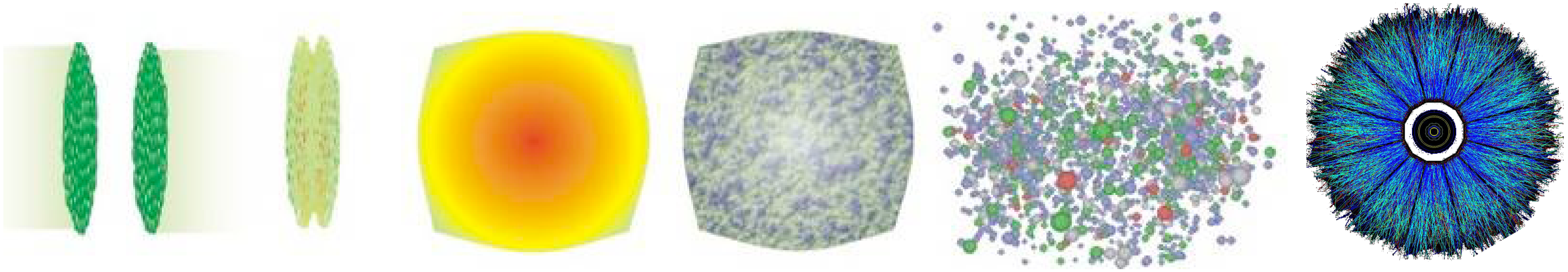
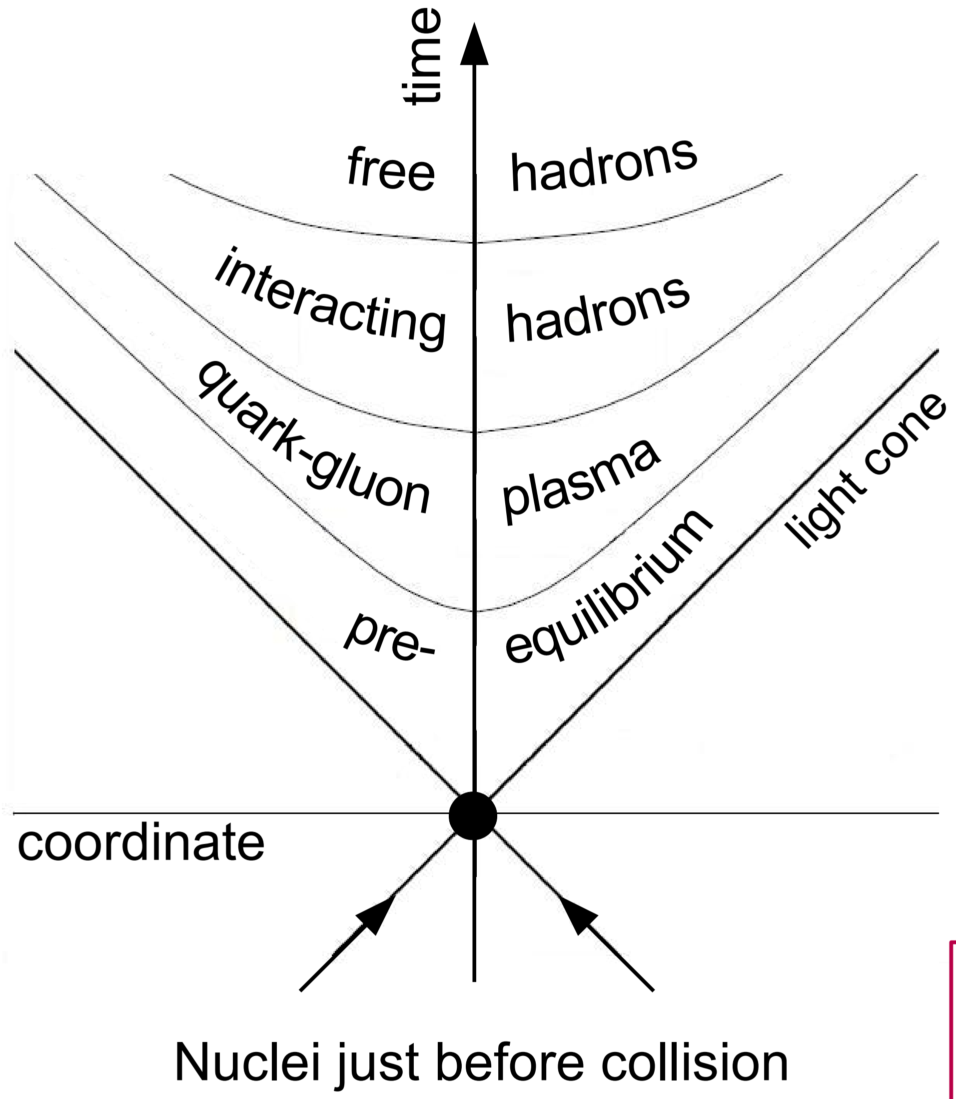
- Experimentally access only hadronic state

Evolution of the system created in HIC





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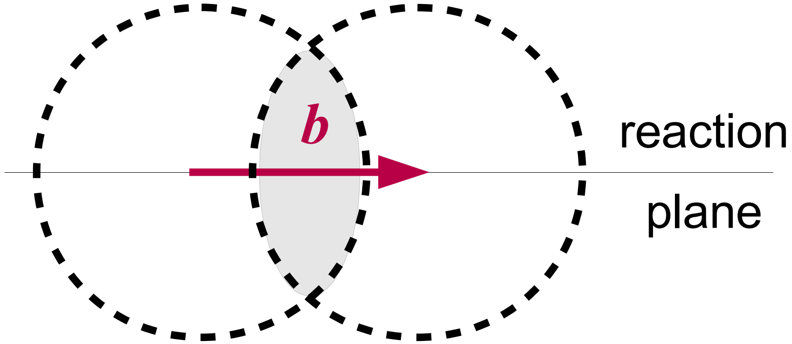
Many observables need to be studied
to establish the properties of QGP

Anisotropic transverse flow

- ✓ Why measure flow?
- ✓ Measurement techniques: correlations and non-flow
- ✓ Elliptic flow at RHIC and LHC
- ✓ Flow fluctuations and higher harmonics

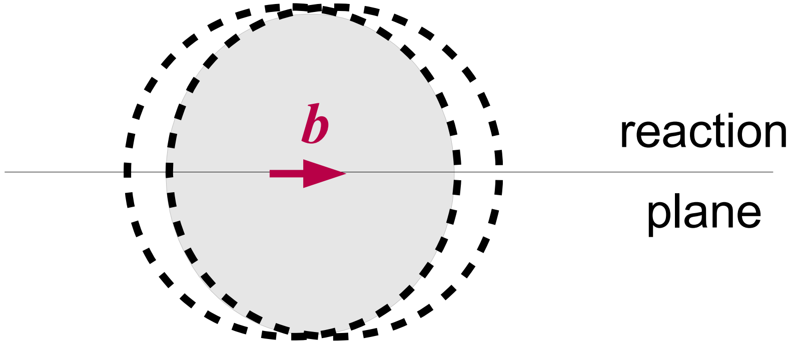
Colliding nuclei has a finite size

Peripheral collision (large ***b***)



Overap region is strongly asymmetric in the transverse plane

Central collision (small ***b***)



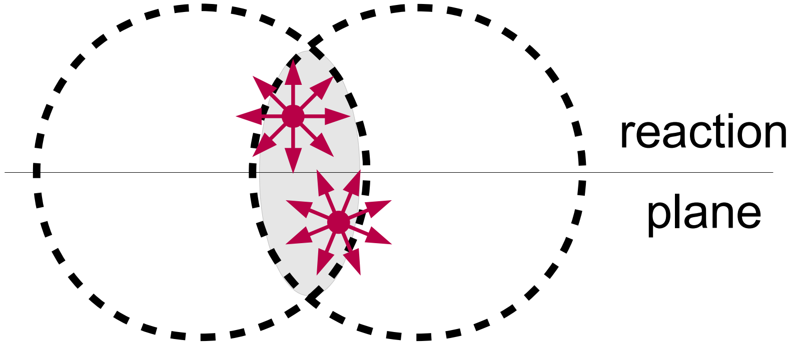
Overap region is close to be symmetric in the transverse plane

Asymmetry of the overlap region depends on the impact parameter

b - impact parameter

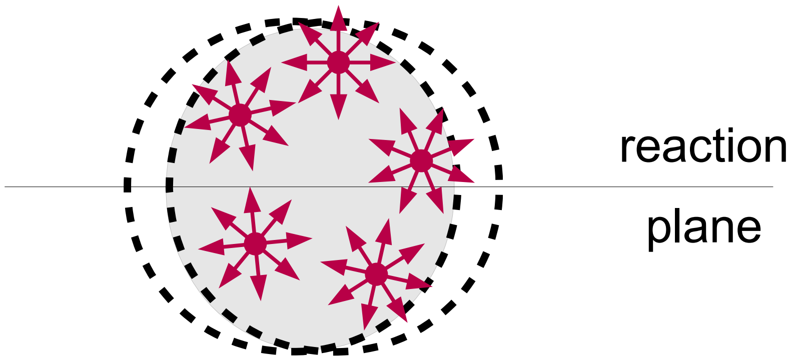
Nucleon-nucleon collisions in the overlap region

Peripheral collision



Small number of nucleon-nucleon collisions:
few particles produced

Central collision



Large number of NN collisions:
abundant particle production

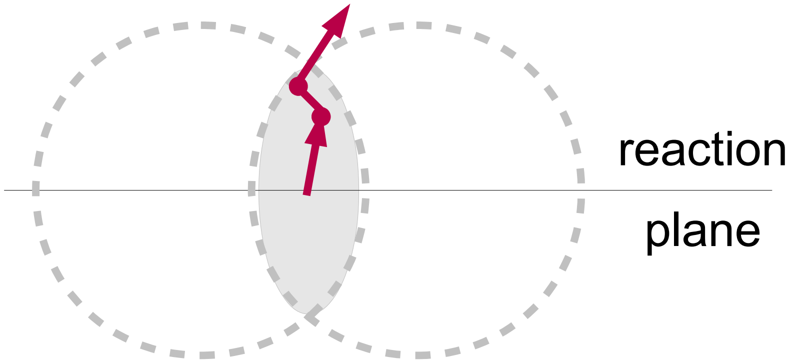
Number of produced particles
is correlated with the impact parameter

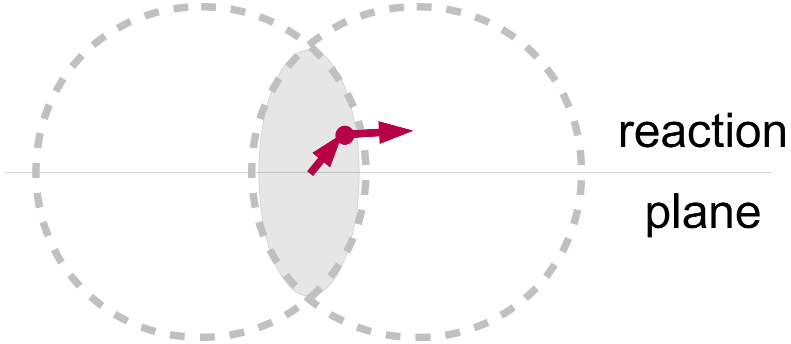
✸ - elementary
nucleon-nucleon (NN) collision

Produced particles interact with each other

Particle emitted out-of-plane

Emitted in-plane



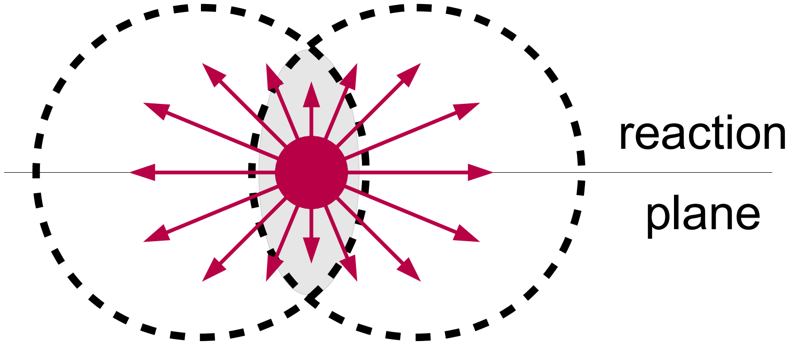


Multiple interaction with medium

Less interaction - small modification

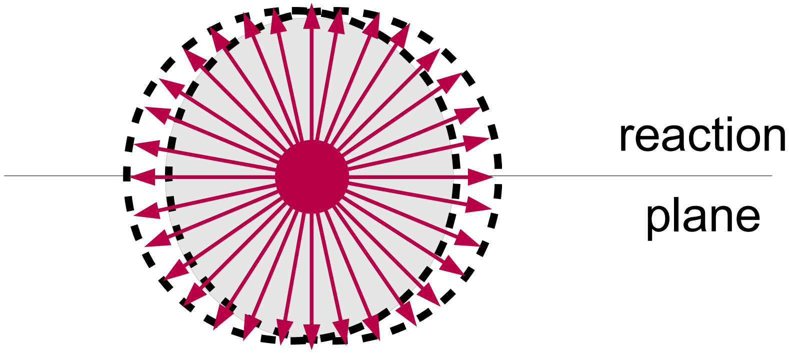
Particle collectivity

Peripheral collision



Strong coordinate space asymmetry transforms into the azimuthal asymmetry in the momentum space

Central collision



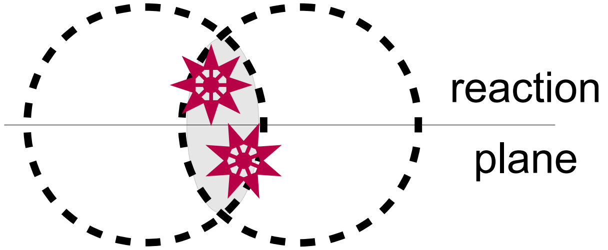
Multiple interaction with medium but small initial spacial asymmetry:
small asymmetry in the momentum space

Correlated particle production
wrt. the collision plane of symmetry

Quantifying azimuthal asymmetry

Coordinate space asymmetry is ~ ellipsoidal
quantified by eccentricity:

$$\epsilon_s = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



x, y - position of each elementary NN interaction

Quantifying azimuthal asymmetry

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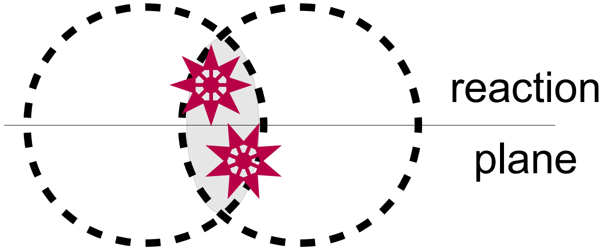
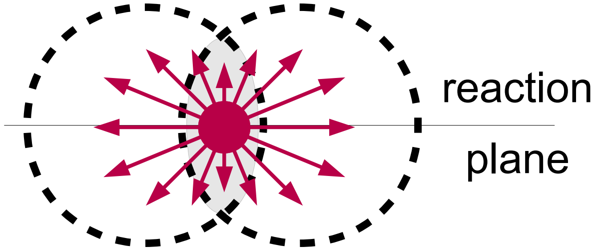


x, y - position of each elementary NN interaction

Momentum space asymmetry:

$$e_p \sim \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_y^2 + p_x^2 \rangle} \rightarrow \langle \cos(2\Delta\phi) \rangle$$



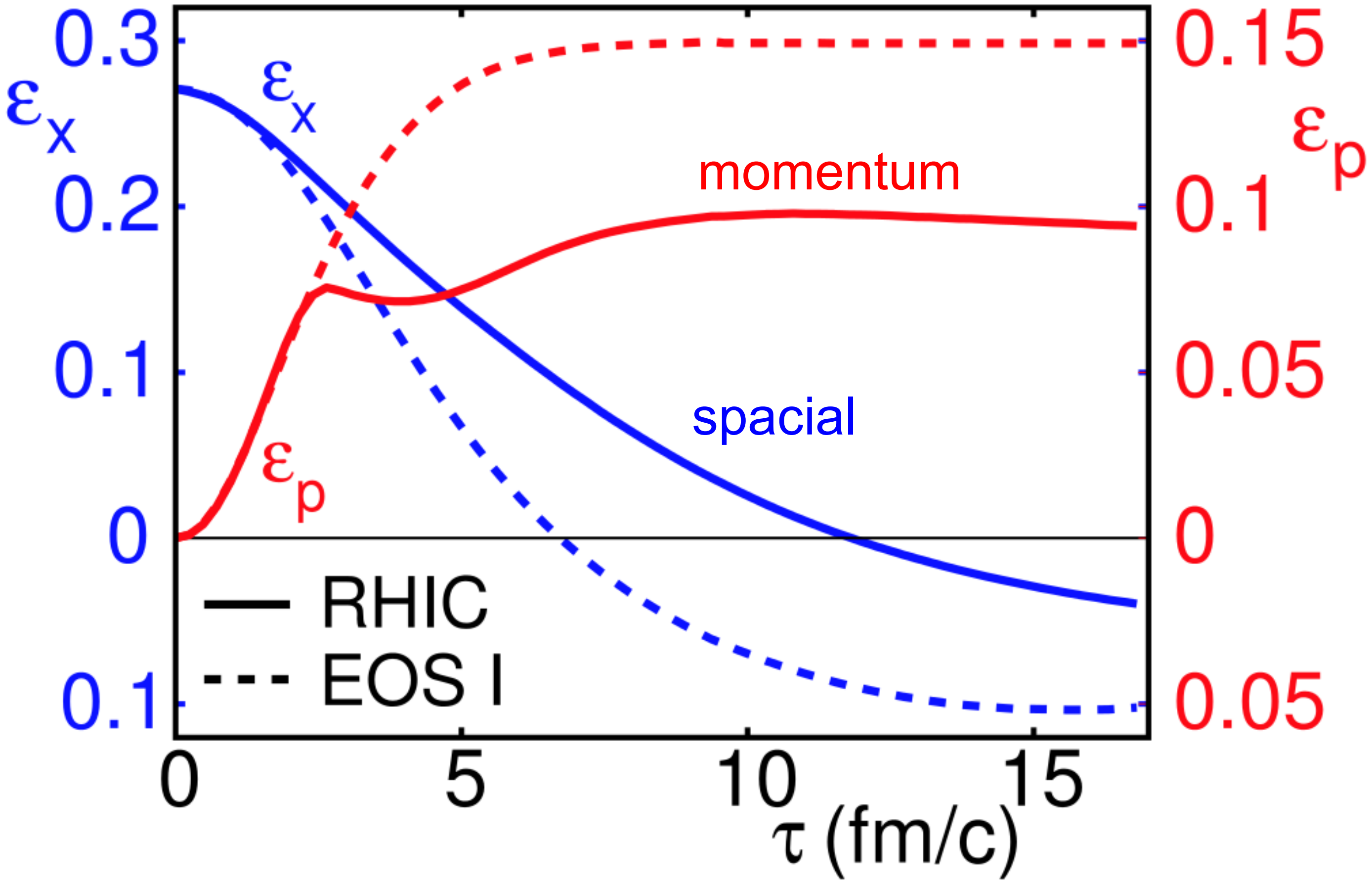
Second Fourier harmonic in momentum space

p_t - particle transverse momentum

$\Delta\phi$ - azimuthal angle relative to the reaction plane

Time evolution of the spacial and momentum asymmetries

arXiv:0901.4355



Spacial asymmetry drops very fast

Momentum asymmetry develops very early

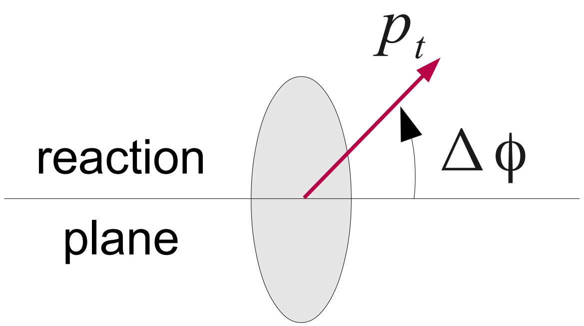
EoS I: massless ideal gas
EoS RHIC: matching Lattice QCD

Momentum asymmetry is sensitive to:

- Early times of the system evolution
- Equation of State

Anisotropic transverse flow: Fourier harmonics

Fourier decomposition of the particles azimuthal distribution wrt. the reaction plane:



$$\frac{dN}{d(\Delta\phi)} \sim 1 + 2\sum_{n=1} v_n(p_t,\eta)\ \cos(n\Delta\phi)$$

No “sin” terms because of the collision symmetry

$v_n(p_t,\eta)$ – anisotropic transverse flow coefficients

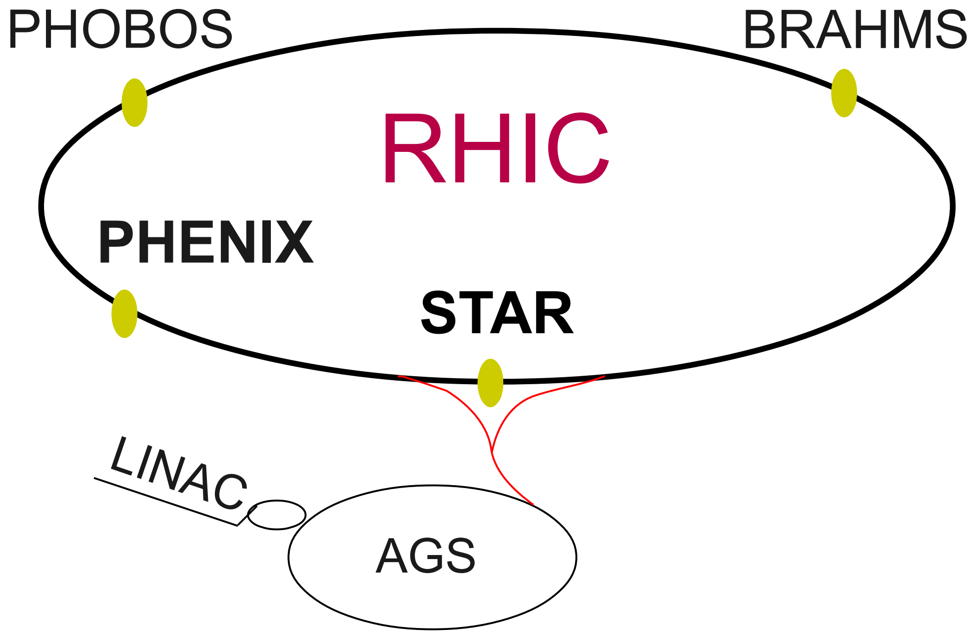
v_1 - directed flow

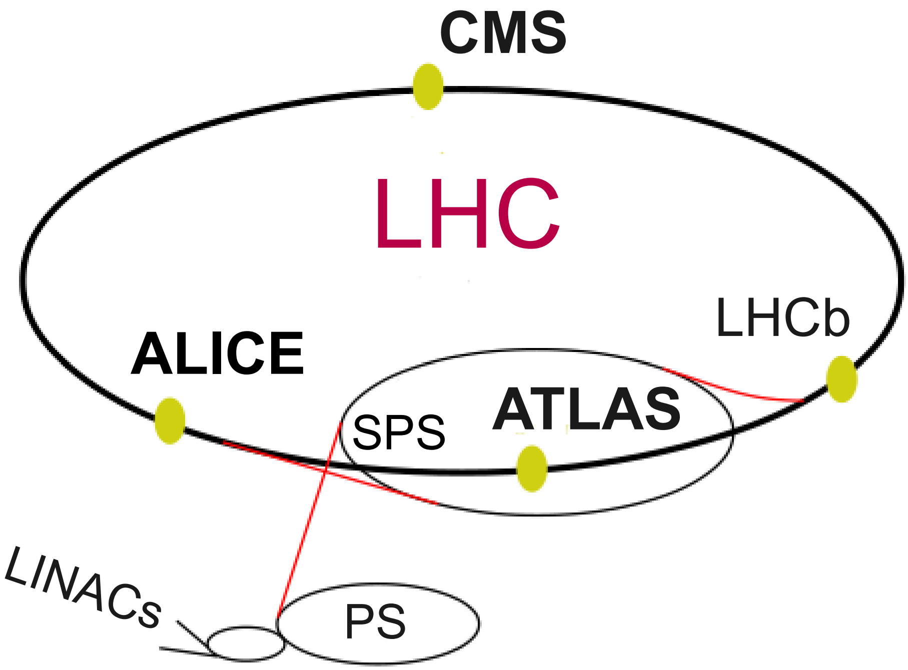
v_2 - elliptic flow

v_3 - triangular flow

Experimental measurements of the anisotropic flow

Modern ultra-relativistic HI colliders

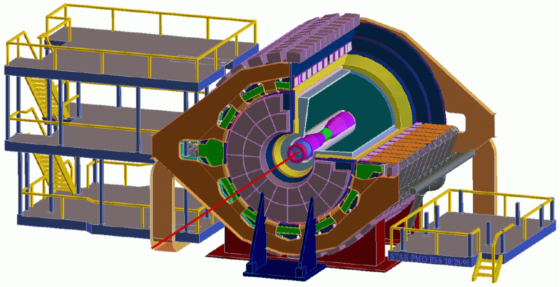




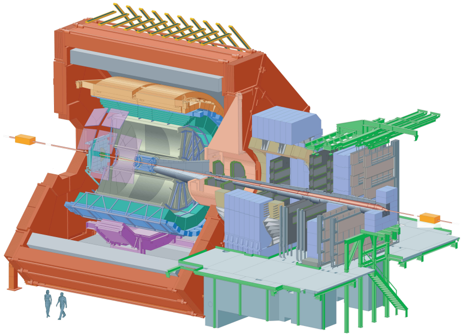
	RHIC	**LHC**
Location	BNL (USA)	CERN (Europe)
Circumference	3.8 km	27 km
Species	p, d, Cu, Au, U polarized protons	p, Pb
Center of mass energy per nucleon pair	in GeV 7.7-38, 62, 200 500 (pp only)	in TeV 0.9, 2.76, 7 (pp) 2.76 (Pb)

Current heavy-ion experiments at RHIC and LHC

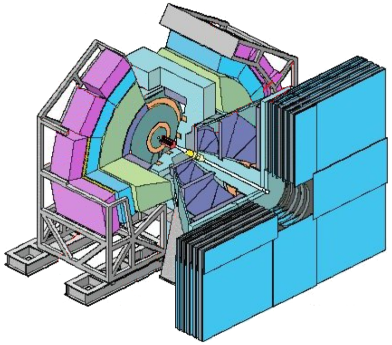
STAR (Solenoidal Tracker At RHIC)



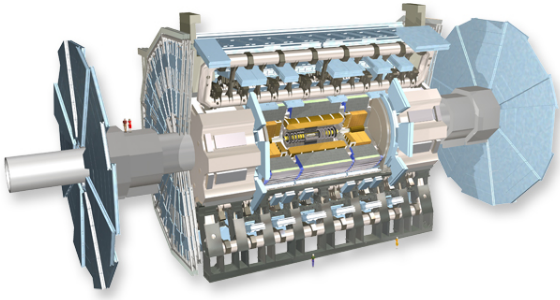
ALICE (A Large Ion Collider Experiment)



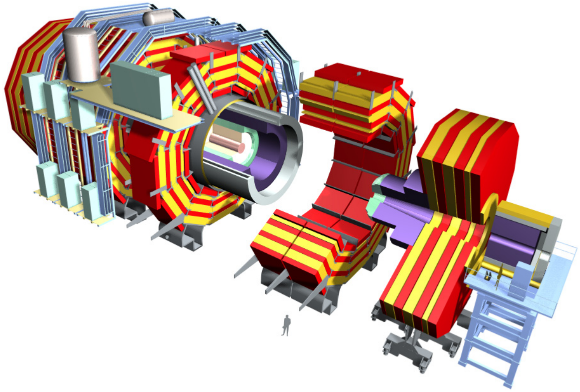
PHENIX (Pioneering High Energy Nuclear Ion Experiment)



ATLAS (A Toroidal LHC Apparatus)



CMS (Compact Muon Solenoid)



Main capabilities for heavy-ion studies:

Charge particle tracking and identification:
full azimuth, large rapidity coverage
wide p_t range: ~ 100 MeV/c to ~ 100 GeV/c

Calorimetry and rare probes:
neutral particles, photons, jets, heavy flavor

Anisotropic flow measurement techniques

$$\frac{dN}{d(\phi_i - \Psi_{RP})} \sim 1 + 2 \sum_{n=1} v_n \cos[n(\phi_i - \Psi_{RP})]$$

$$v_n = \langle \cos[n(\phi_i - \Psi_{RP})] \rangle$$

- directly calculable only in theory when the reaction plane orientation is known

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---

Event plane angle - experimental estimate of the reaction plane angle based on the measured azimuthal distribution of particles:

$$\Psi_{RP} \rightarrow \Psi_{EP}\left\{ \sum_{\phi_j} g(\phi_j) \right\}$$

$$v_n^{obs} = \langle \cos[n(\phi_i - \Psi_{EP})] \rangle \sim \langle \sum_{\phi_j \neq \phi_i} \cos n(\phi_i - \phi_j) \rangle$$

$$c_n\{2\} = \langle \cos n(\phi_i - \phi_j) \rangle$$

- two particle correlations

Measure anisotropic flow with azimuthal correlations

Non-flow correlations

Non-flow: correlations among the particles unrelated to the reaction plane

In case of two particle correlations: $\langle \cos[n(\phi_i - \phi_j)] \rangle = \langle v_n^2 \rangle + \delta_{2,n}$

Sources of non-flow correlations:

- Resonance decay
- Jet production
- In general - any cluster production

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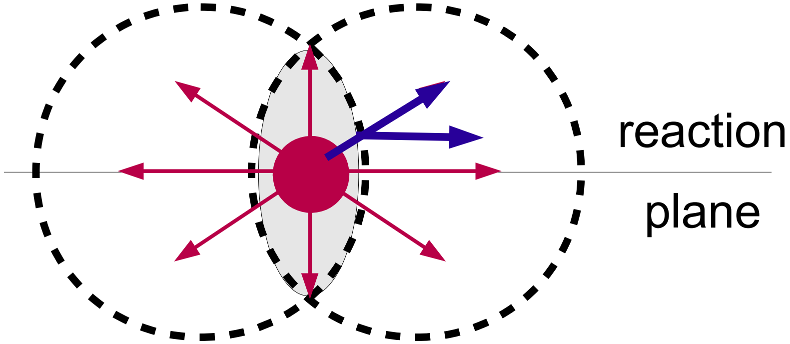
Example: 2-particle decay



Probability to be correlated for one particle with another out of *M*-particles is *1/(M-1)*:

$$\delta_2 \sim \frac{1}{M-1}$$

To measure flow with 2-particle correlations:

$$\boxed{v_n \gg 1/\sqrt{M}}$$

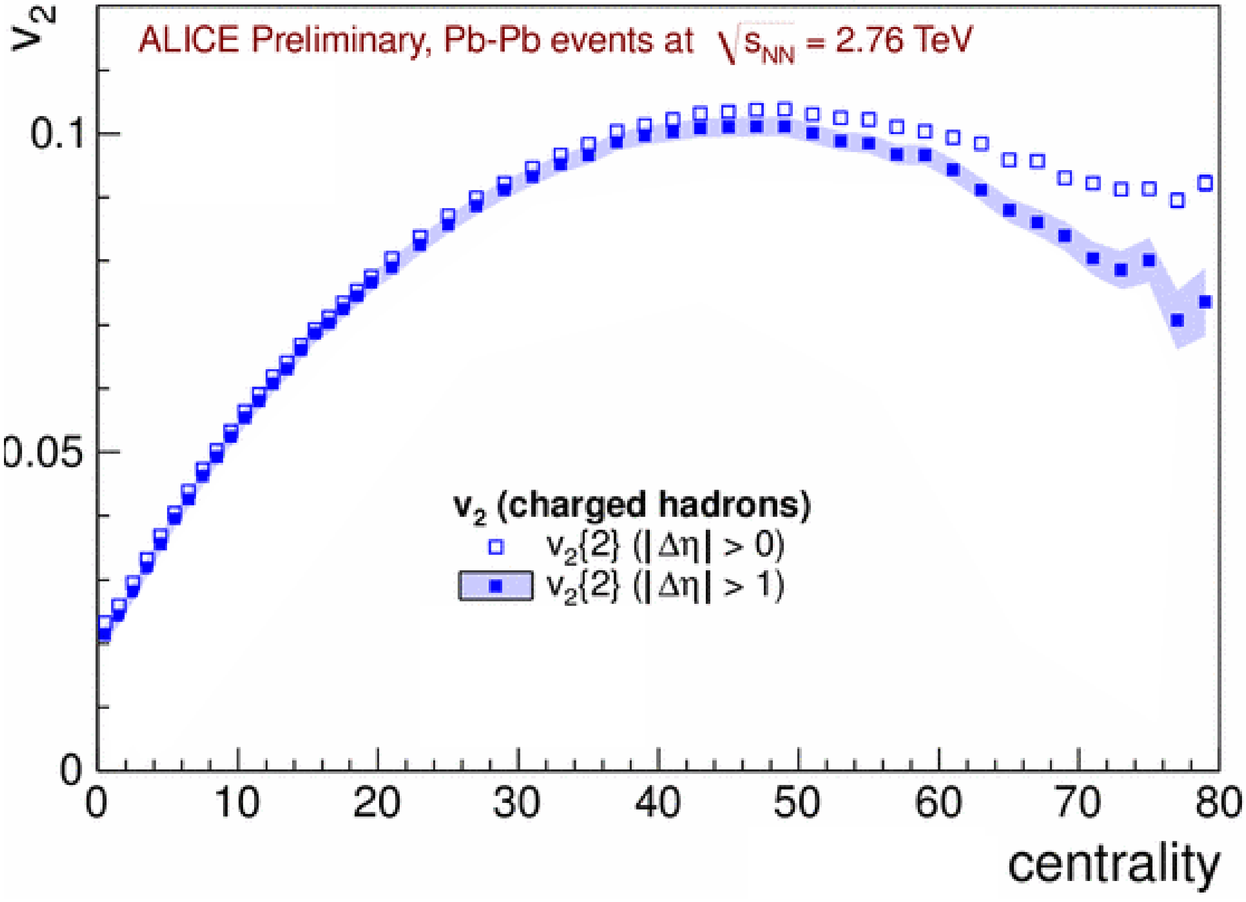
Collective flow:
correlations between particles through the common plane of symmetry

$$M = 200 \rightarrow v_n \gg 0.07$$

For RHIC/LHC: $v_n \approx 0.04 - 0.07$

Estimating flow with multi-particle cumulants

elliptic flow vs. centrality



Rapidity separation between correlated particles suppress short-range non-flow:

$$v_2\{2\} > v_2\{2,|\Delta\eta|\}$$

Large non-flow in peripheral collisions

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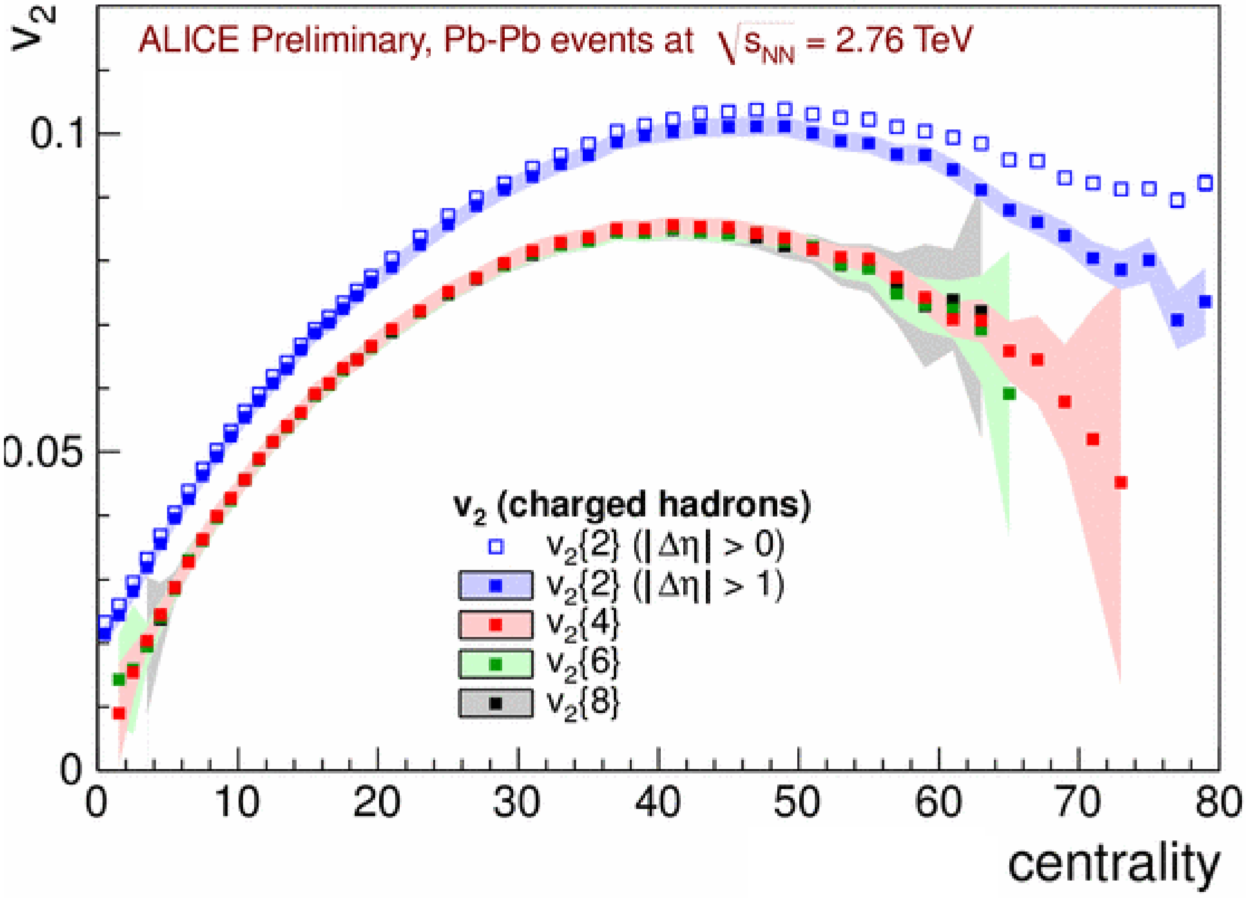


Rapidity separation between correlated particles suppress short-range non-flow:

$$v_2\{2\} > v_2\{2, |\Delta\eta|\}$$

Large non-flow in peripheral collisions

Note:

$v_2\{2\}$ and $v_2\{4\}$ differ not only because of non-flow, but also due to flow fluctuations (discussed later)

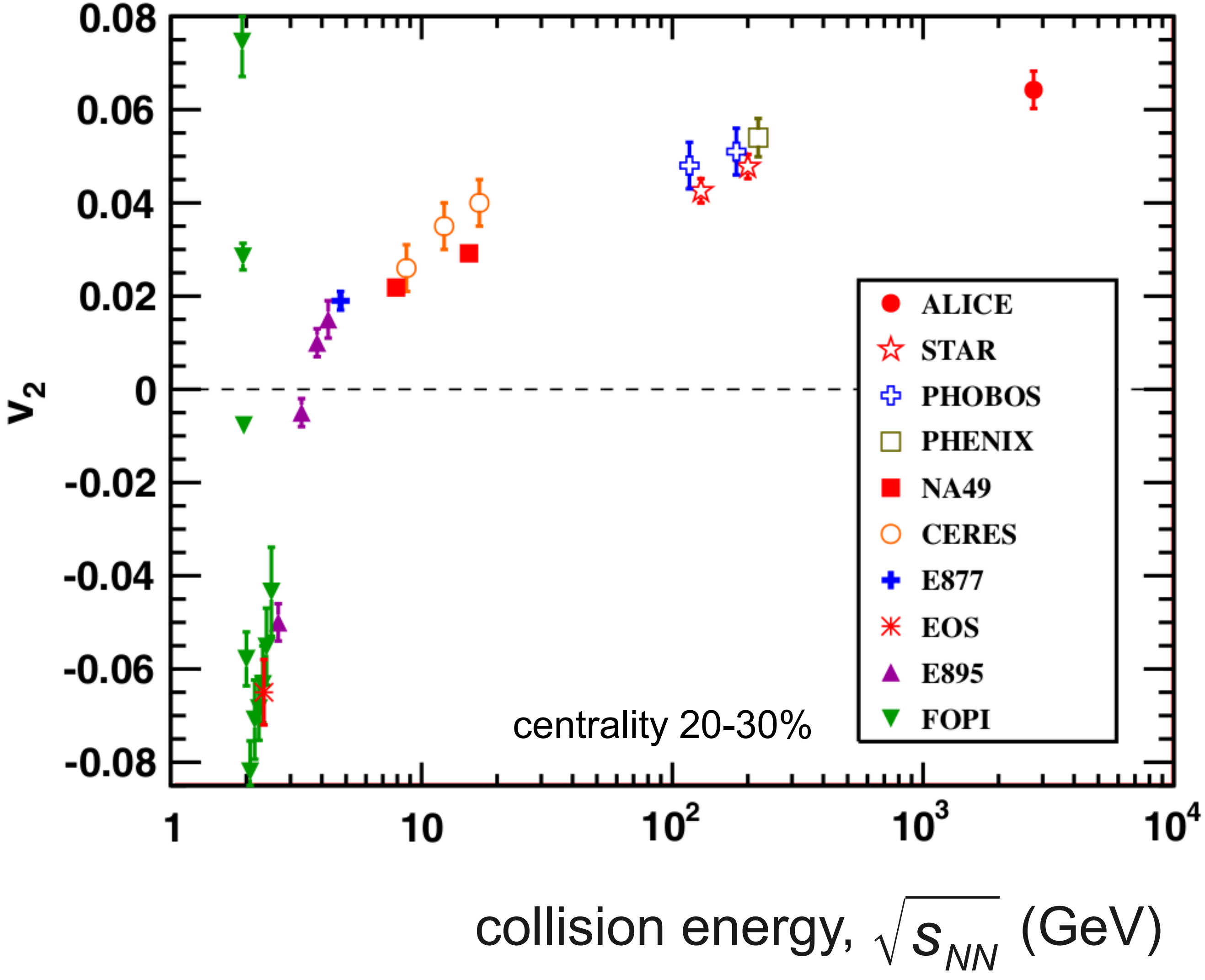
Multi-particle cumulants remove residual non-flow:

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

Elliptic flow:

the dominant flow component at the relativistic energies

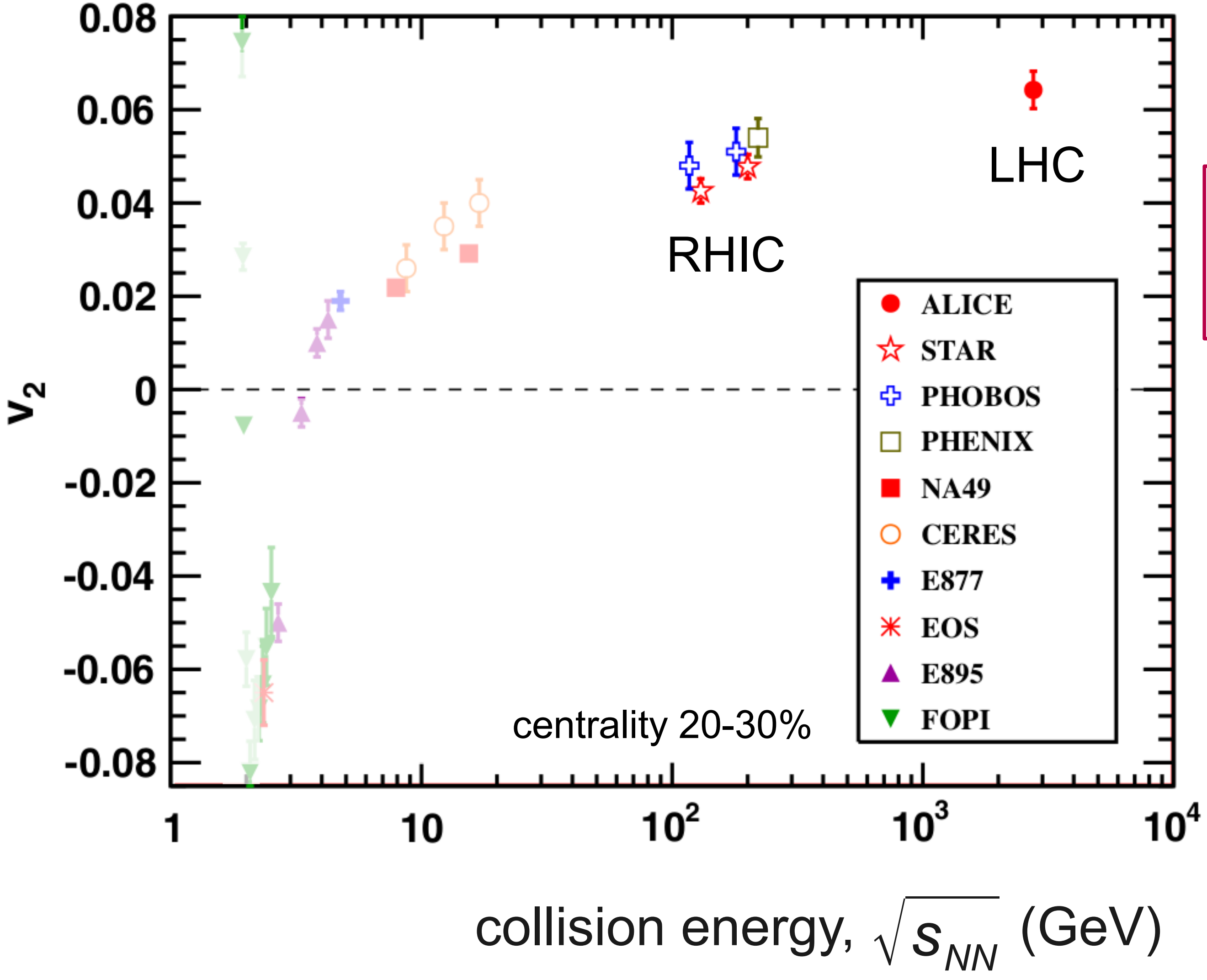
Elliptic flow vs. collision energy



Experimental results covers about 4 decades of the collision energy

Data from GSI, AGS, SPS, RHIC, and LHC experiments

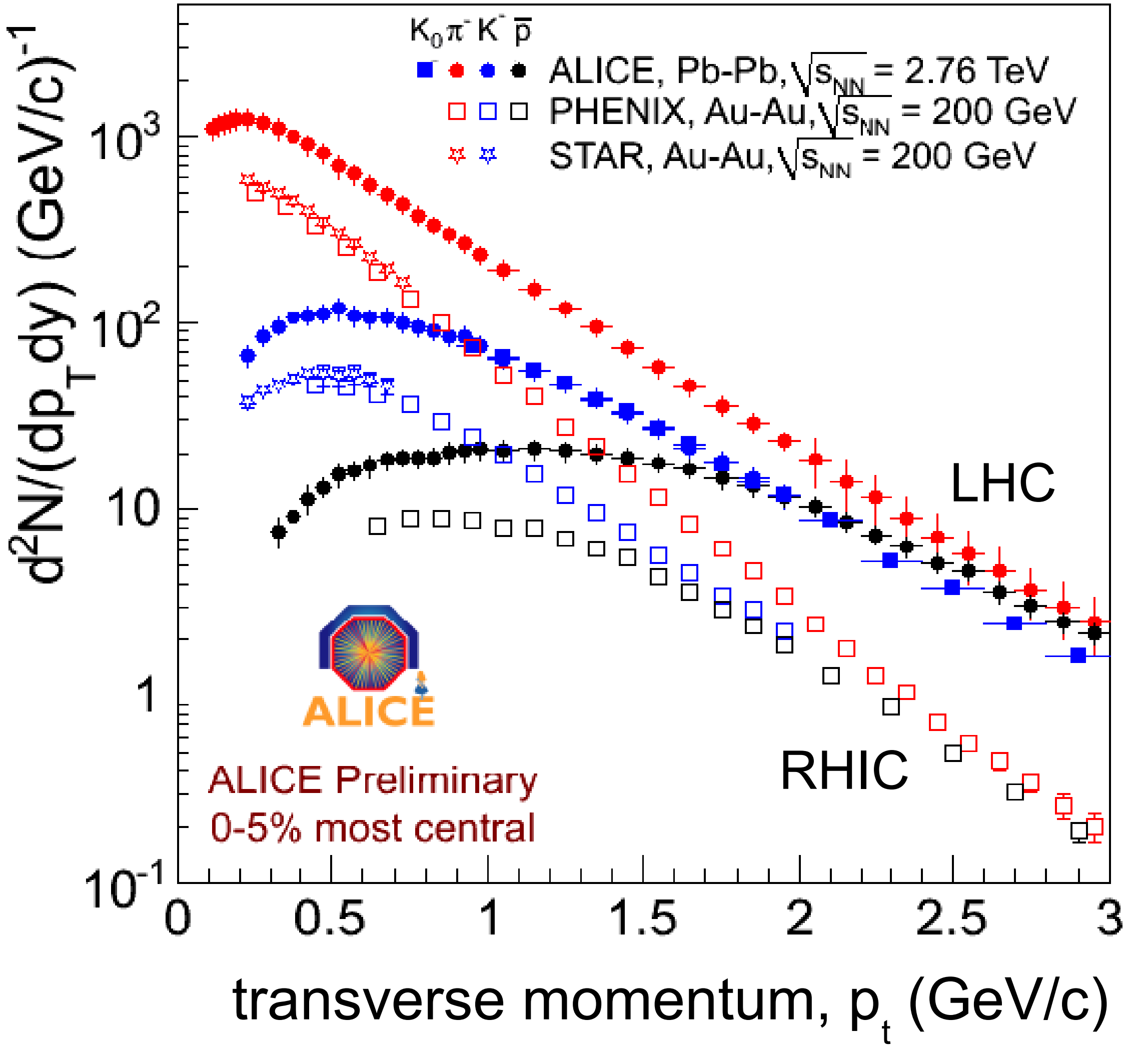
Elliptic flow: RHIC vs. LHC



30% increase of v_2 from RHIC: stronger collectivity at LHC

But: measured v_2 vs. transverse momenta has similar shape and magnitude at RHIC and LHC

Identified particle spectra: LHC vs. RHIC



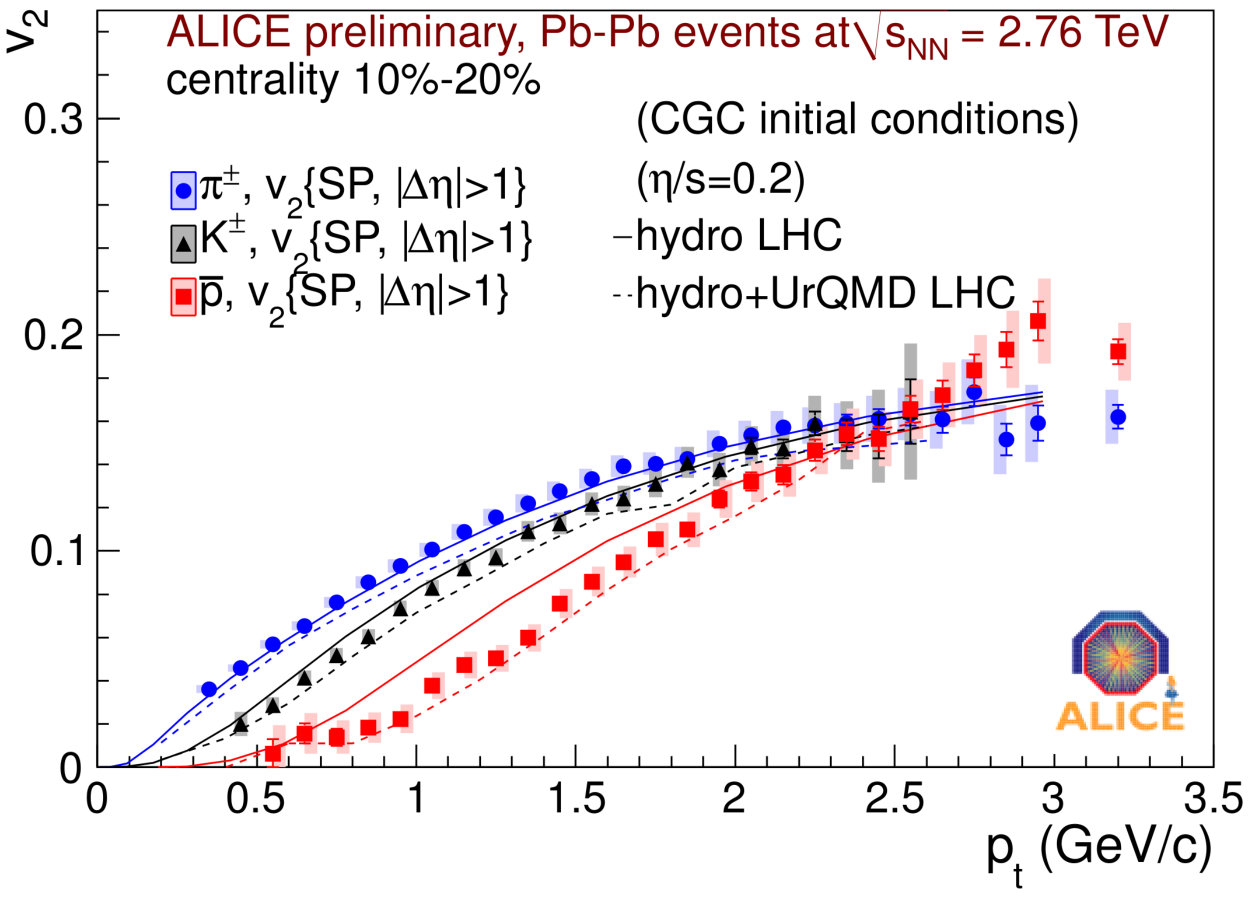
Spectra shapes changed significantly from RHIC to LHC

Radial expansion (flow):

Boost particles to higher p_t
(particles gain extra radial velocity)

From Blast wave spectra fits:
20% stronger radial flow at LHC
→ increase of integral v_2

Elliptic flow mass splitting



VISHNU: Heinz et. al, arxiv:1108.5323

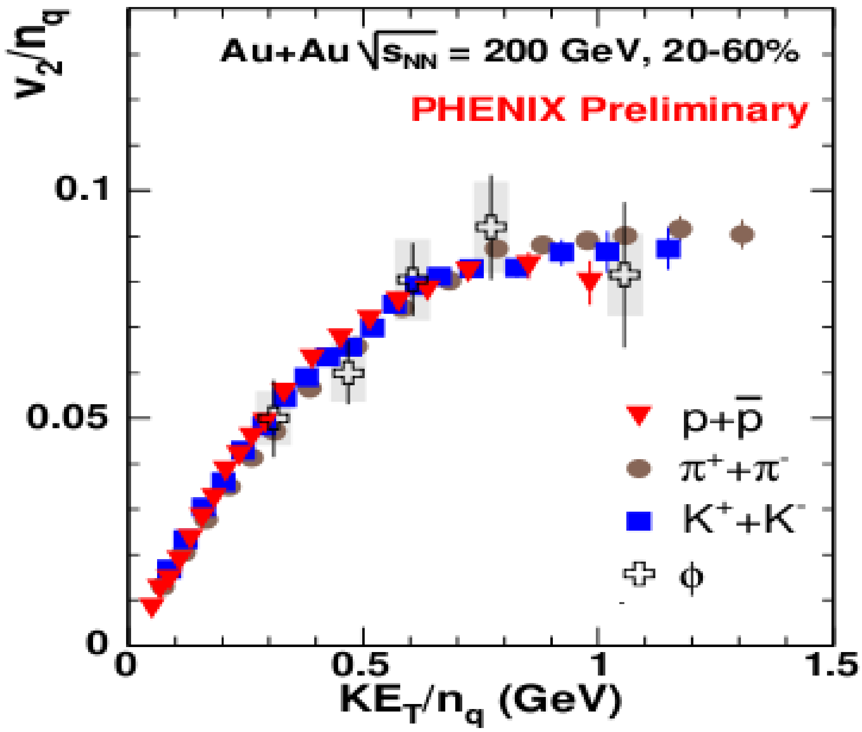
Similar to spectra:
v_2 of heavier particles
is pushed to higher p_t

Viscous hydrodynamics
well describe flow of π± and K±:
→ sensitivity to QGP viscosity

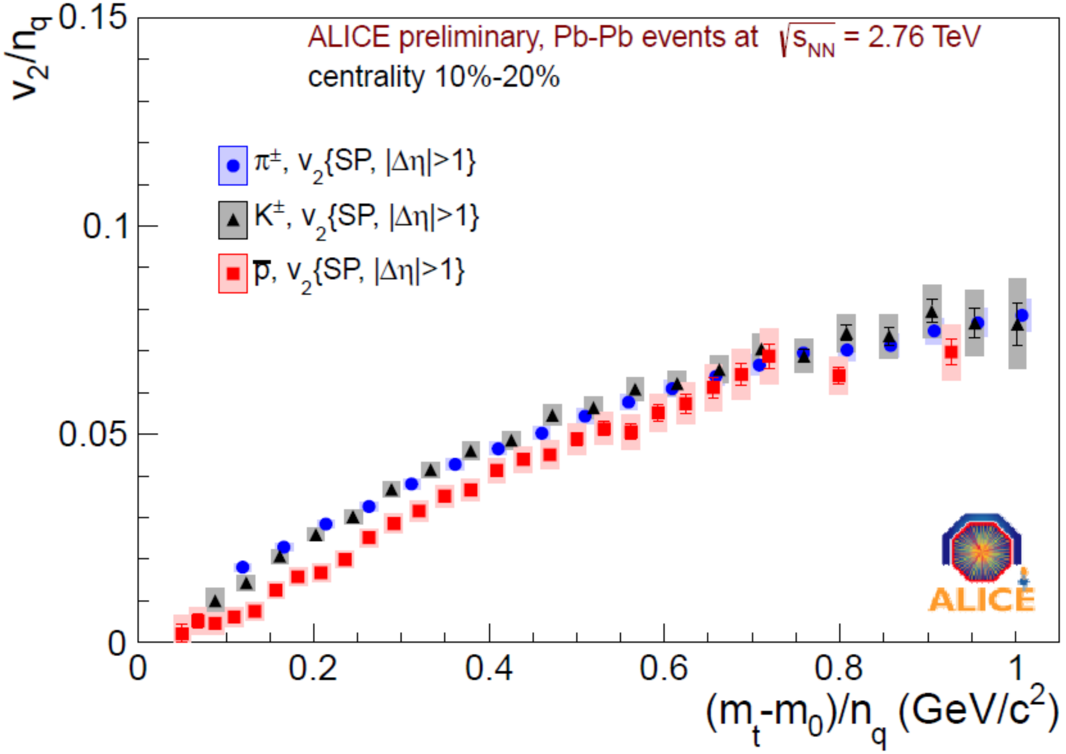
Including hadronic rescattering
with UrQMD model allows
better reproduce proton v_2:
→ sensitivity to the evolution

Constituent number of quarks scaling

RHIC



LHC



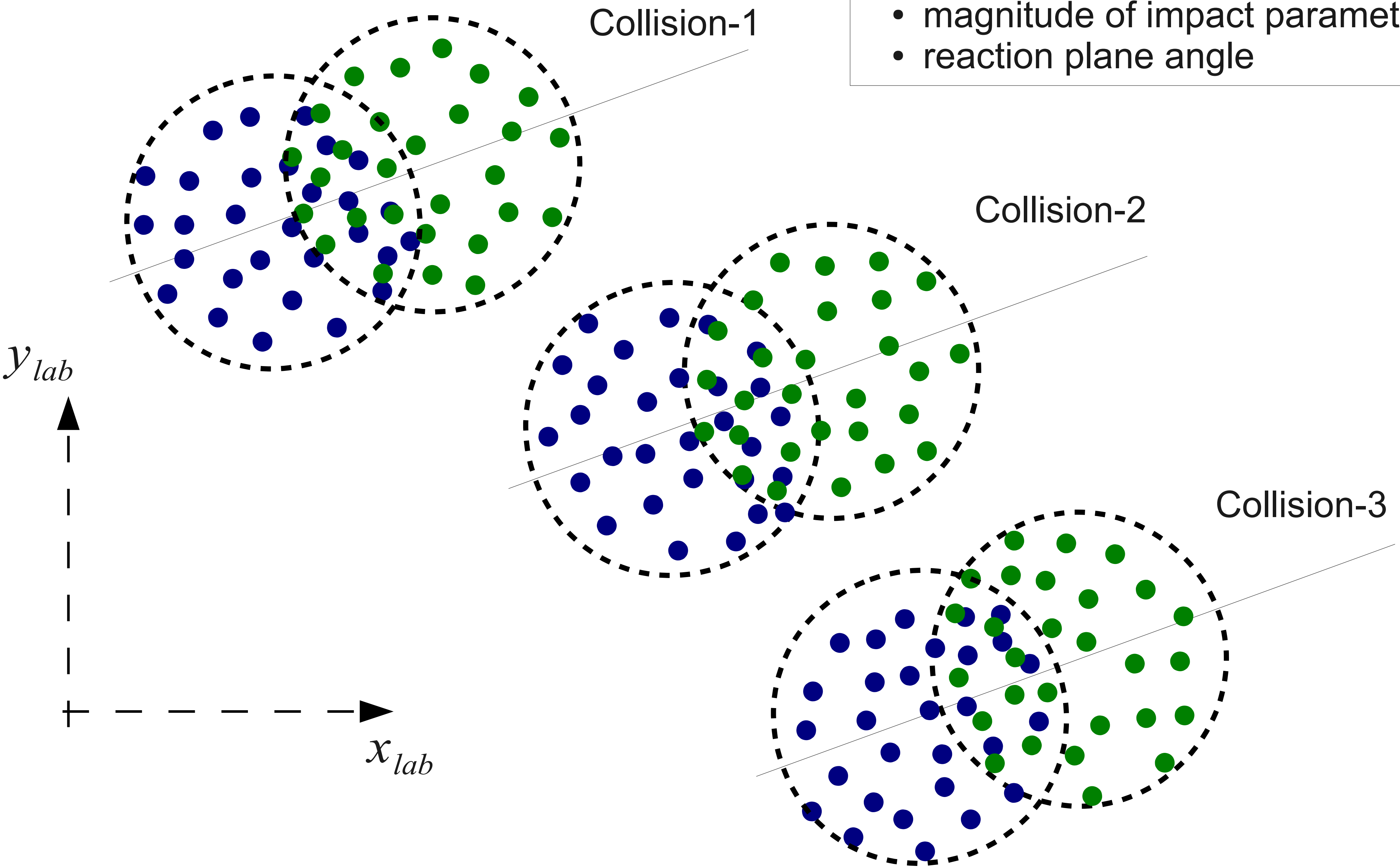
Observe approximate number of quark scaling:

Strong indication that system evolved through deconfined (QGP)phase

Flow fluctuations

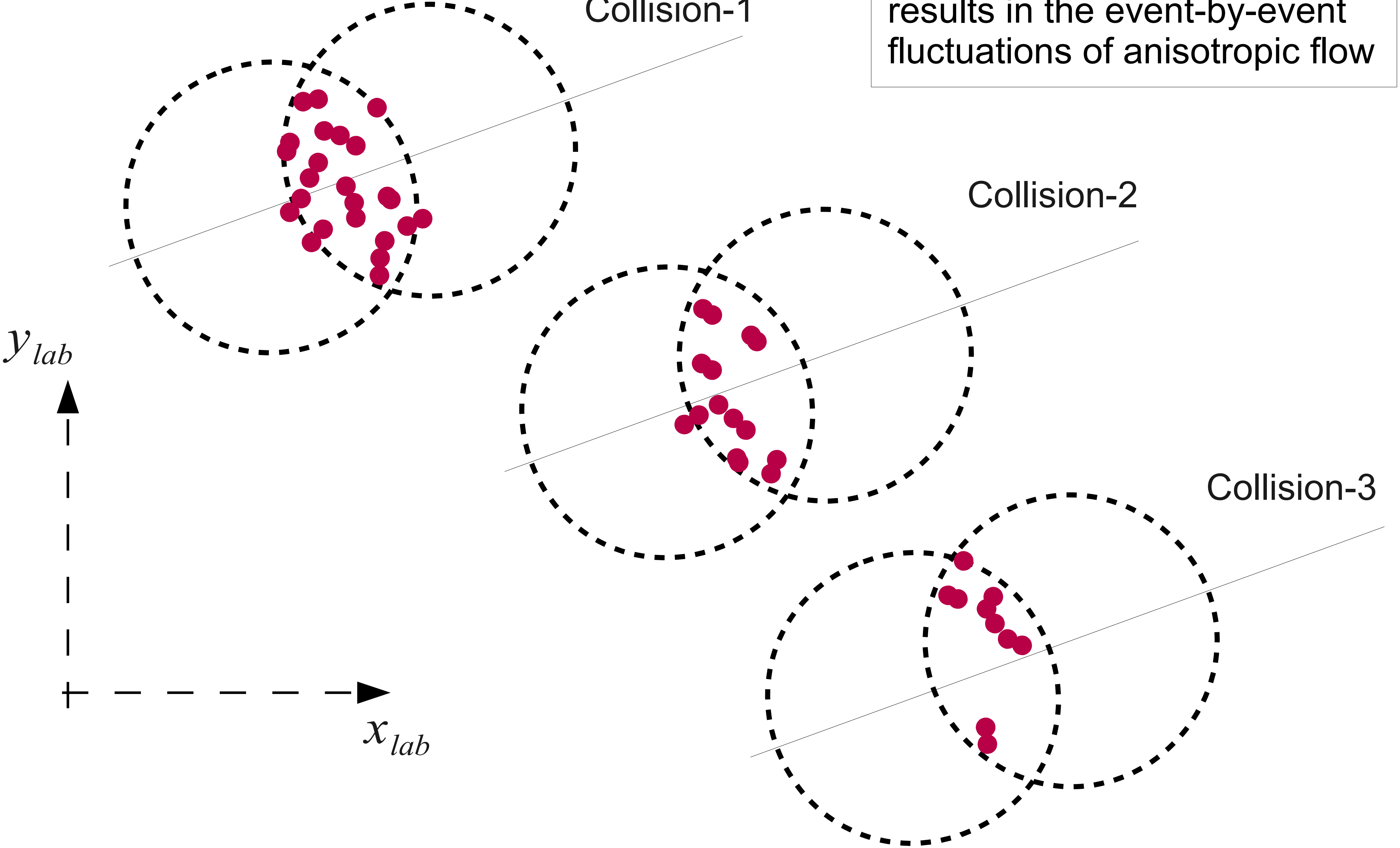
Experimentally study many collisions

Three collisions with the same:
- magnitude of impact parameter
- reaction plane angle



Fluctuating initial energy density

Fluctuating spacial asymmetry results in the event-by-event fluctuations of anisotropic flow



How fluctuations affect the measured flow?

2-particle azimuthal correlation:

$$c_n\{2\} = \langle \cos[2(\phi_i - \phi_j)] \rangle = \langle v_n^2 \rangle + \delta_{n,2}$$

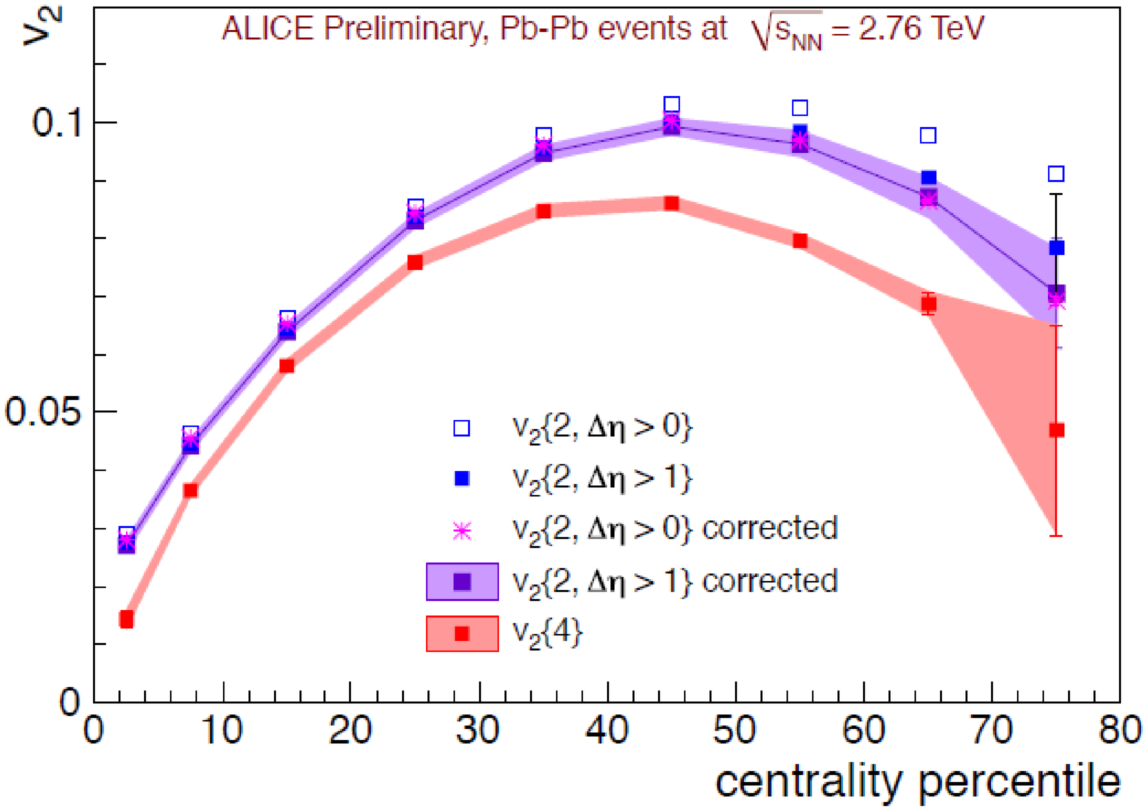
$$\boxed{\langle v_n^2 \rangle \neq \langle v_n \rangle^2}$$

$$\langle v_n^2 \rangle = \langle v_n \rangle^2 + \sigma_n^2$$

$$\boxed{\langle \cos[n(\phi_i - \phi_j)] \rangle = \underbrace{\langle v_n \rangle^2}_{\text{flow}} + \underbrace{\sigma_n^2}_{\text{fluctuations}} + \underbrace{\delta_{n,2}}_{\text{non-flow}}}$$

Elliptic flow fluctuations

2-particle correlations affected by 3 effects: $v_2\{2\} = \sqrt{\langle v_2 \rangle^2 + \sigma_2^2 + \delta_2}$



Residual non-flow subtracted based on HIJING Monte-Carlo:

$$v_2^{corr}\{2\} \approx \langle v_2 \rangle + \frac{\sigma_2^2}{2\langle v_2 \rangle}$$

Many-particle correlations free of non-flow:

$$v_2\{4\} \approx \langle v_2 \rangle - \frac{\sigma_2^2}{2\langle v_2 \rangle}$$

Fluctuations set the difference

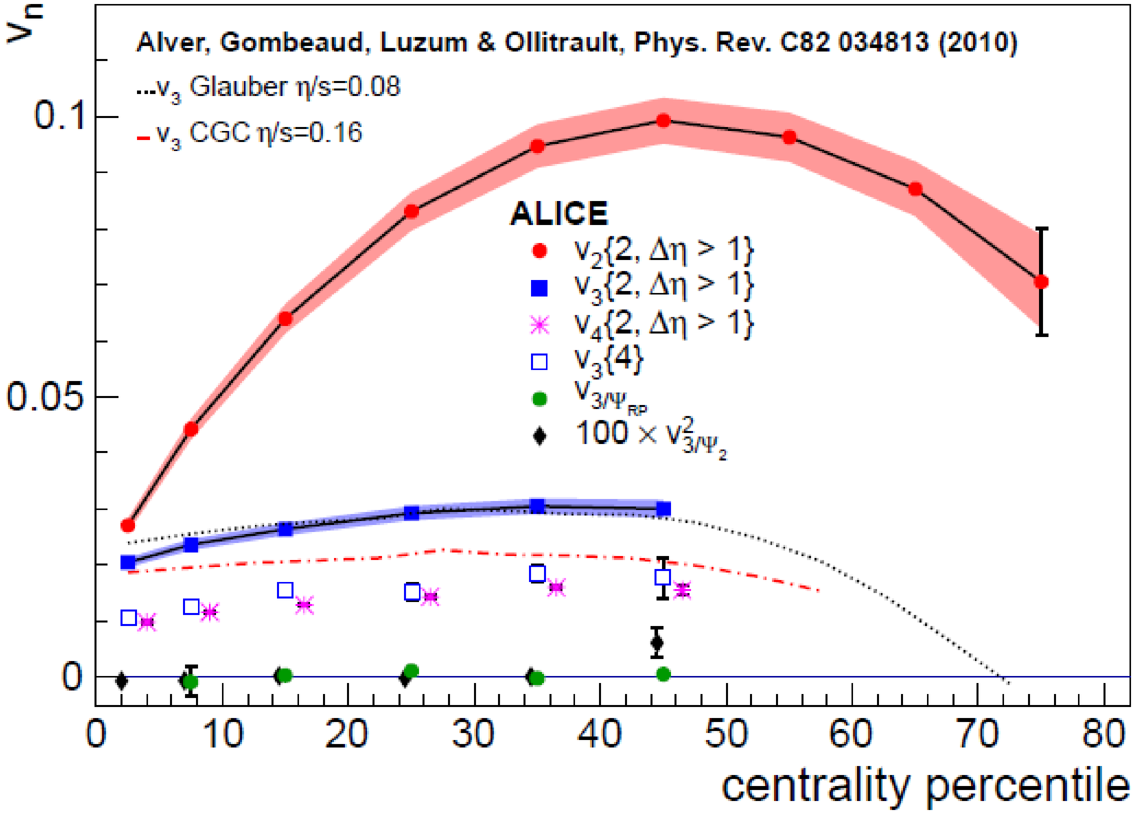
between $v_2^{corr}\{2\}$ and $v_2\{4\}$

Flow fluctuations are significant

Additional constraint on the initial condition

Triangular flow, v_3 - pure fluctuations

Non-zero correlations observed for $v_3^{corr}\{2\}$ and $v_3\{4\}$!



$$v_3^{corr}\{2\} = \sqrt{\langle v_3\rangle^2 + \sigma_3^2} \neq 0$$

Due to collision symmetry the odd harmonic flow is asymmetric:

$$v_{2n+1}(-\eta) = -v_{2n+1}(\eta)$$

In the symmetric rapidity range:

$$\langle v_3\rangle = 0$$

$$v_3^{corr}\{2\} = \sigma_3$$

Together with fluctuations in the 2nd harmonic provides strong constraints on the initial condition

Summary

- Relativistic heavy-ion collisions provide a unique way to study the properties of the quark-gluon plasma (QGP) which is believed to be existed a few microseconds after the Big-Bang

- Anisotropic flow is a key experimental observable to study the evolution of a heavy-ion collision. It provides constraints on:
  - ✓ Equation of state of the created matter
  - ✓ Transport properties (i.e. viscosity) of the QGP matter
  - ✓ Shape of the initial conditions in a heavy-ion collision

- Other important observables:
  - ✓ Hard probes – see talk by Henner Büsching
  - ✓ Heavy quarks – see talk by Yvonne Pachmayer

Looking forward for the upcoming heavy-ion run at LHC!