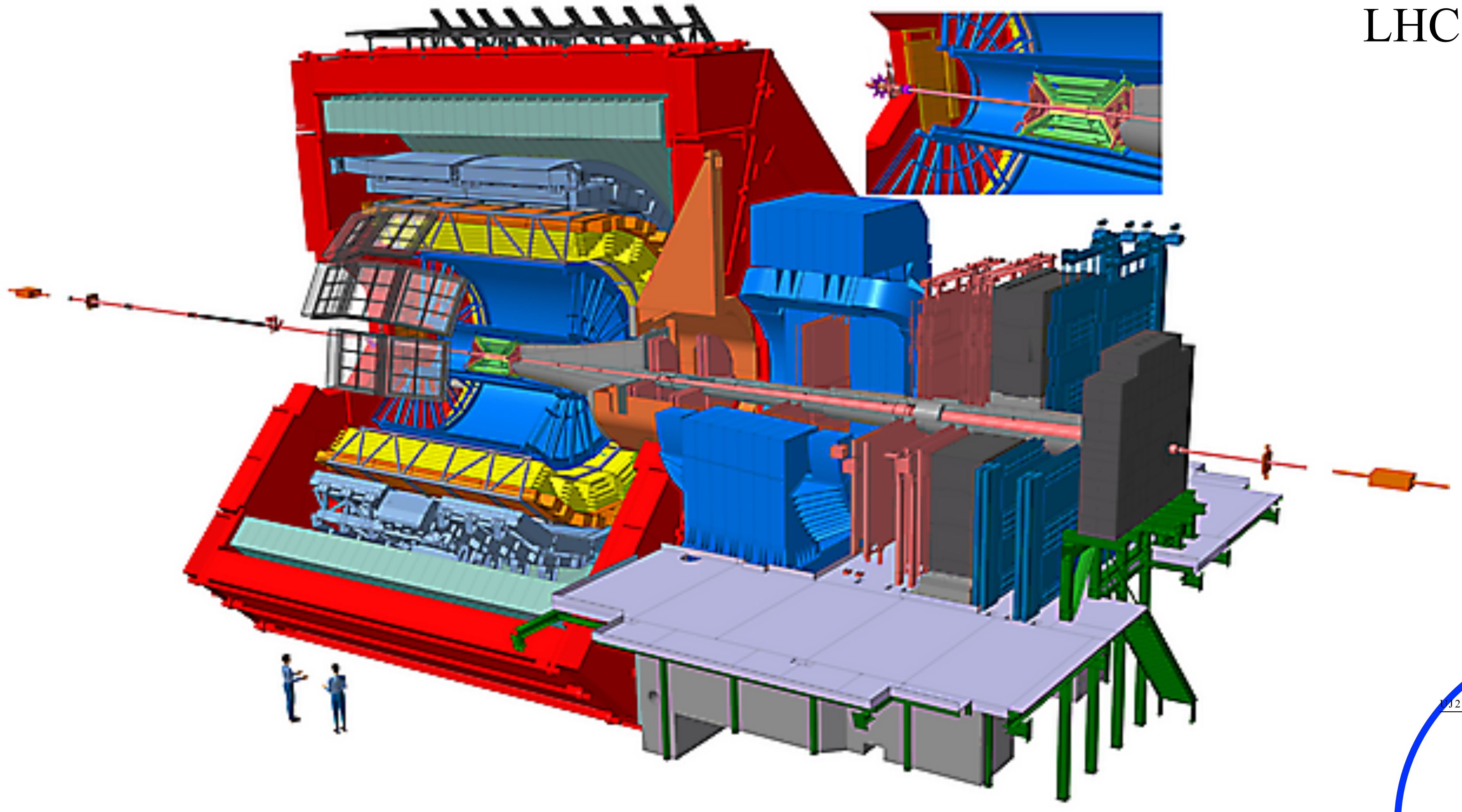
Recent results with ALICE experiment

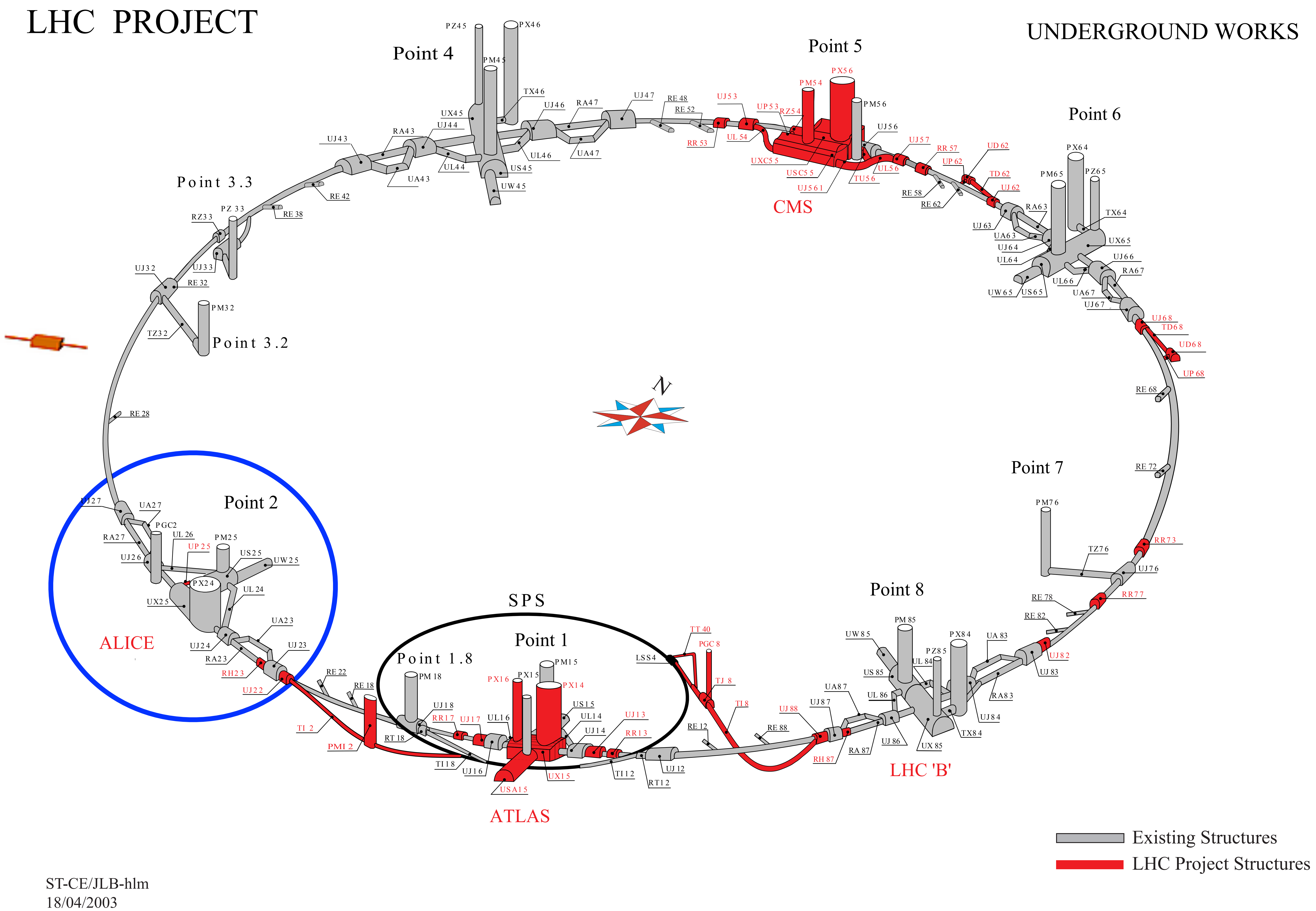
Marek Bombara on behalf of the ALICE Collaboration

(Pavol Jozef Šafárik University, Košice, Slovakia)

New Trends in High-Energy Physics 2018
Budva, Becici, Montenegro
24-30 September 2018

ALICE experiment at the Large Hadron Collider





- dedicated to study hot and dense nuclear matter in heavy ion collisions
- crucial part of the physics programme is to study pp and p−Pb collisions

Why do we study heavy-ion collisions?

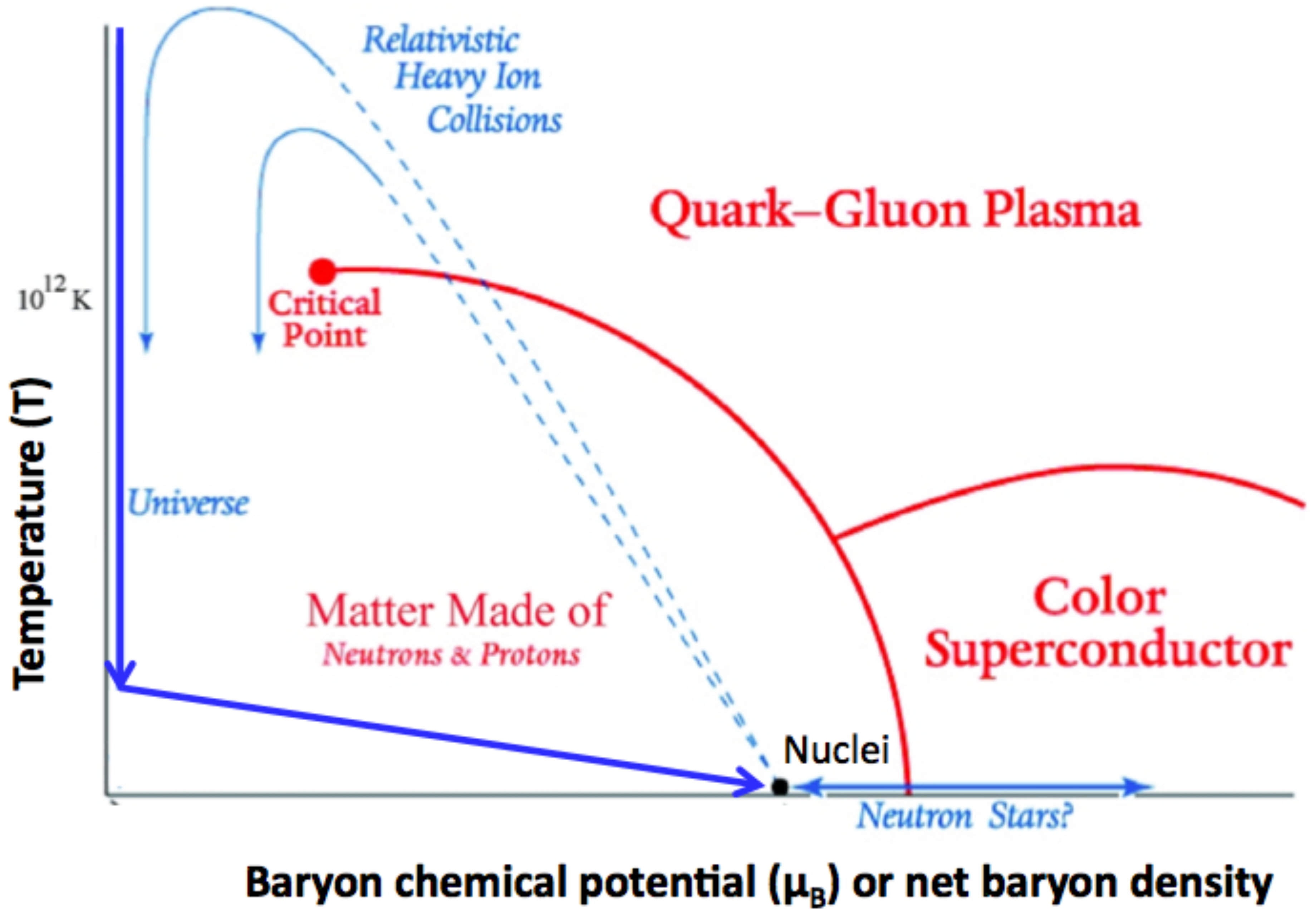
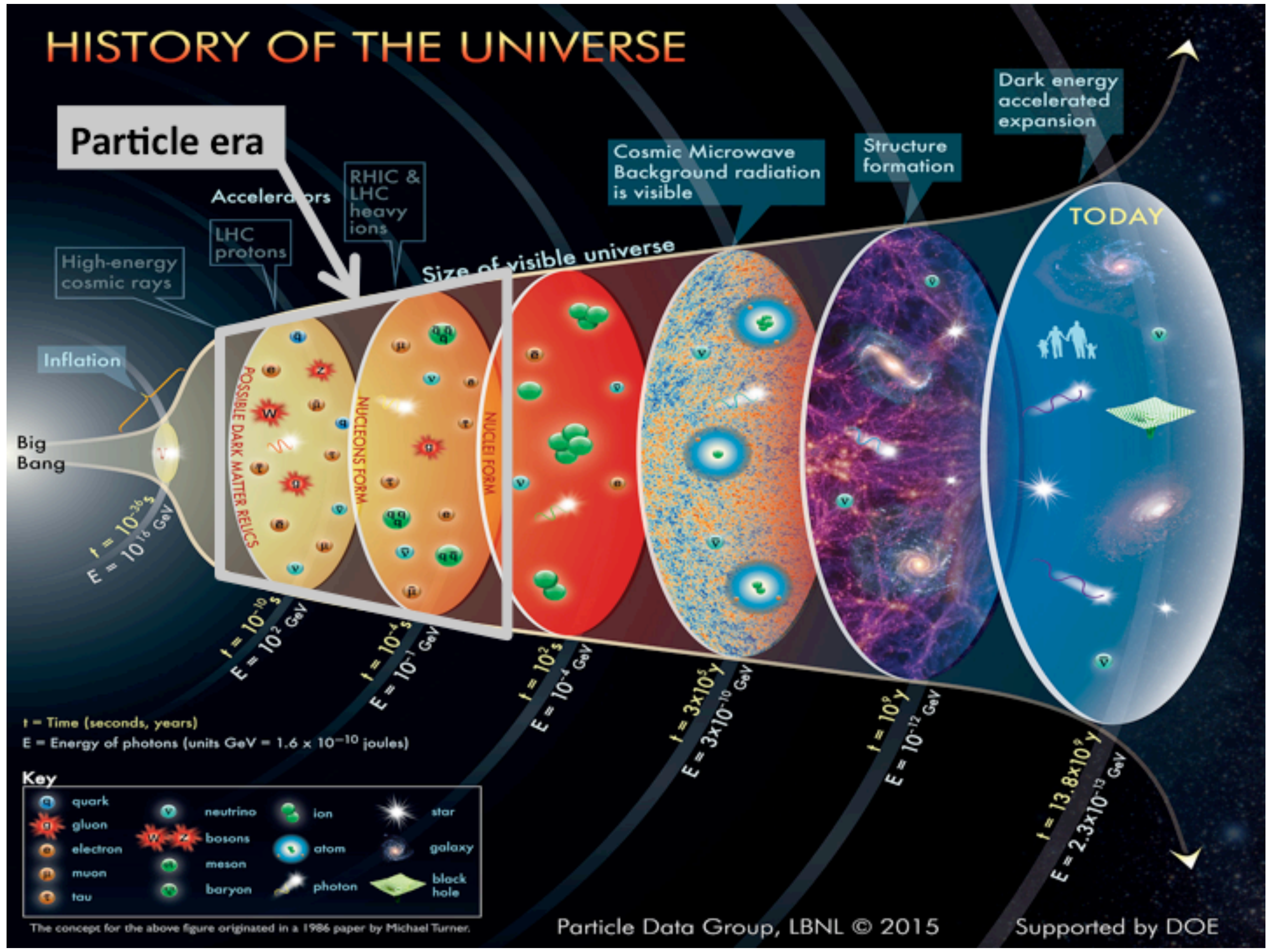
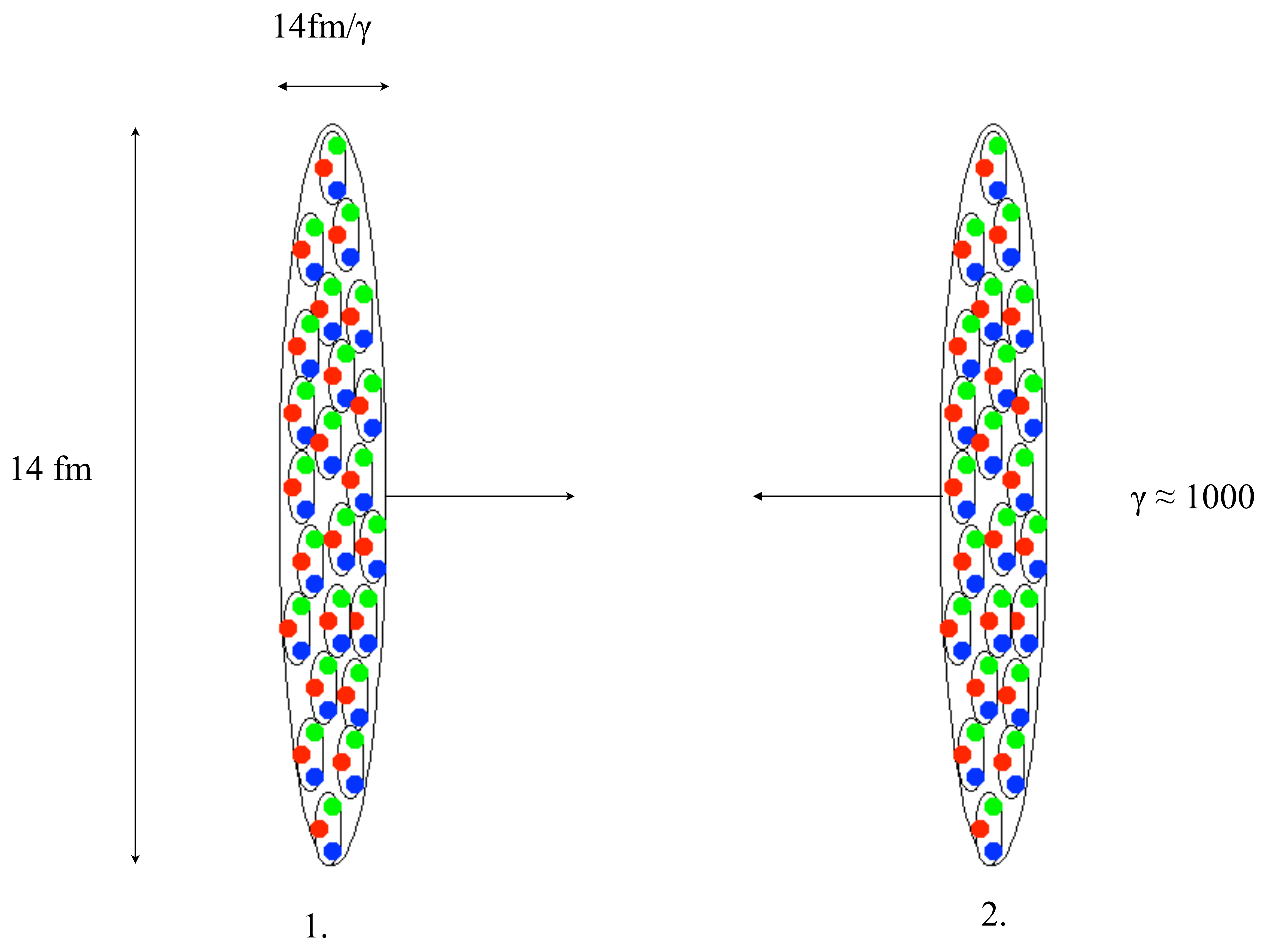


Fig: http://inspirehep.net/record/1397855/plots



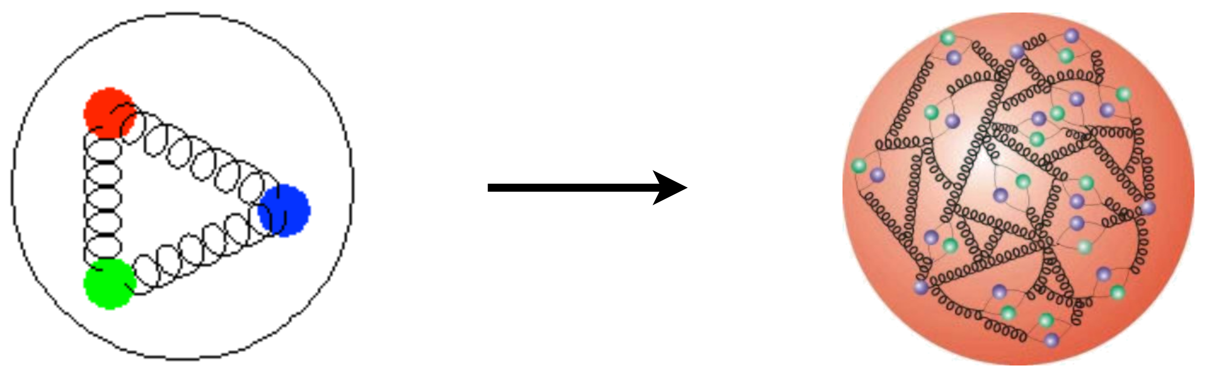
- to explore the QCD matter phase diagram
- unique opportunity to study primordial matter from the Big Bang epoch in the laboratory

Heavy-ion collision at LHC

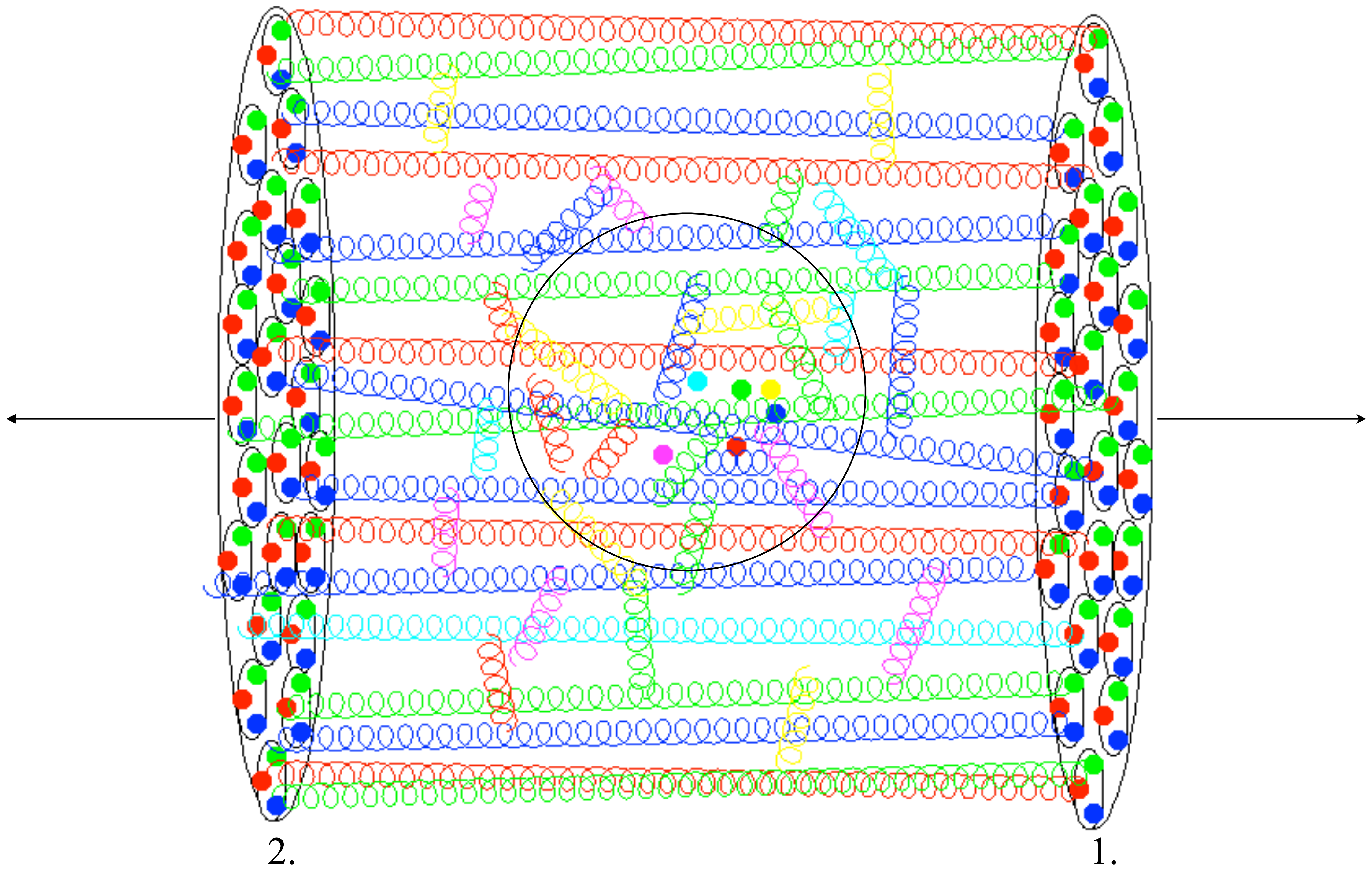


- Pb−Pb@2.76 TeV in 2010 and 2011
- Pb−Pb@5.02 TeV in 2015
- Xe−Xe@5.44 TeV in 2017
- planned this year - Pb−Pb@5.02 TeV
- small collision systems so far: pp and p−Pb

proton at the TeV scale:

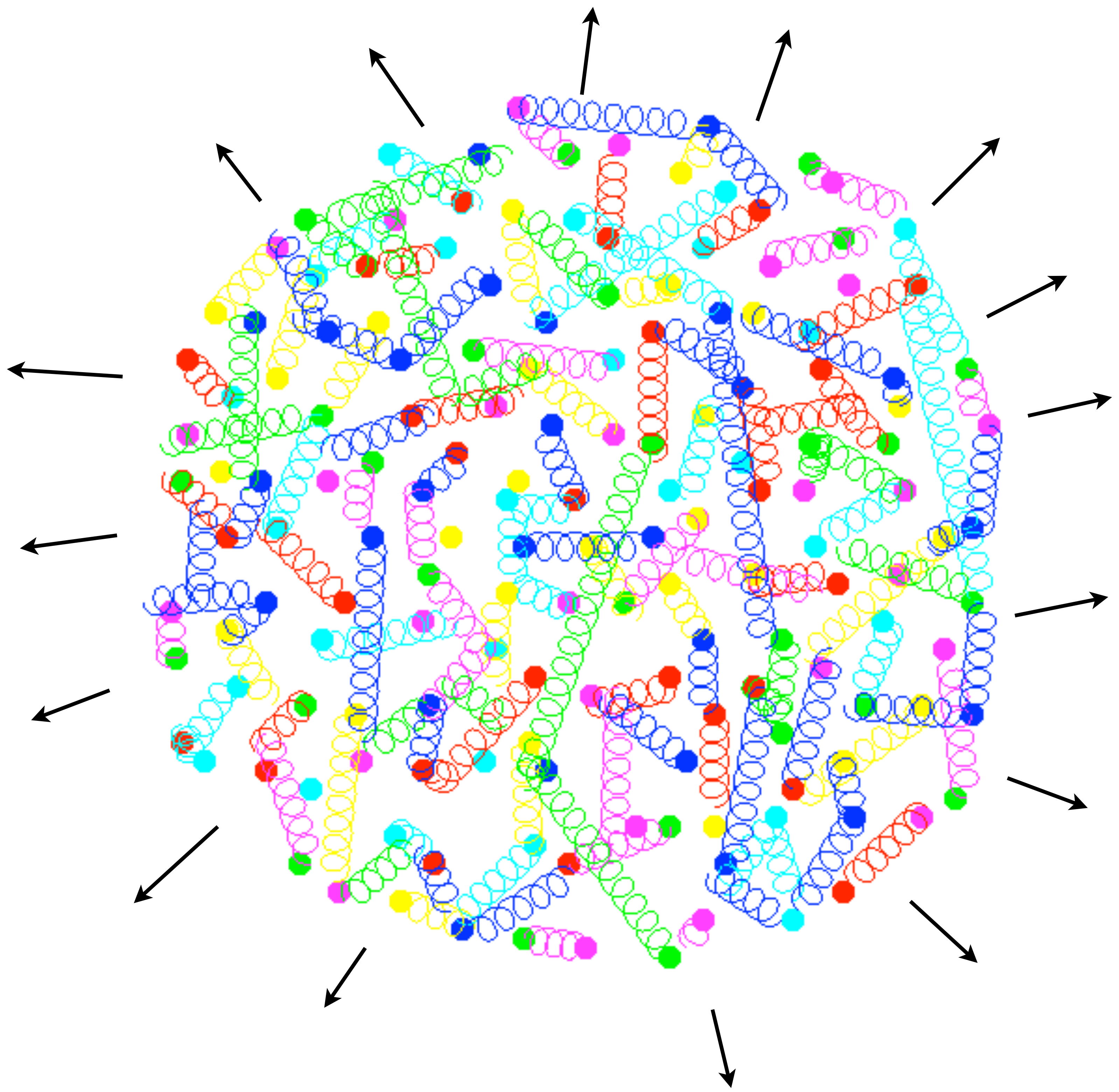


Heavy-ion collision at LHC



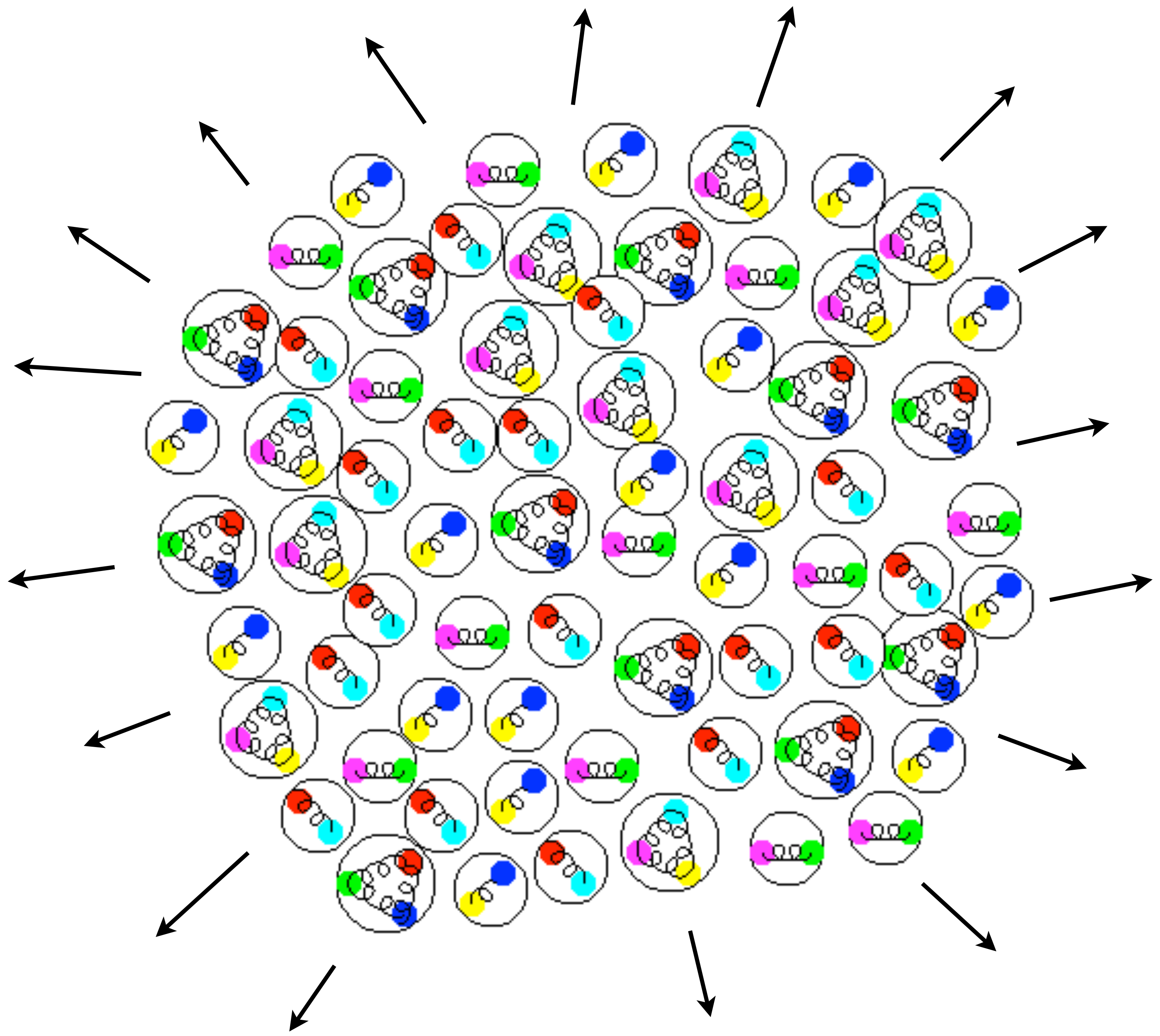
- at the collision - longitudinal colour fields are produced; gradually decaying into gluons, quarks and antiquarks
- large transverse momentum partons or heavy quarks can be created in the first collisions - probes for soon-to-be created quark-gluon plasma (QGP)

Heavy-ion collision at LHC



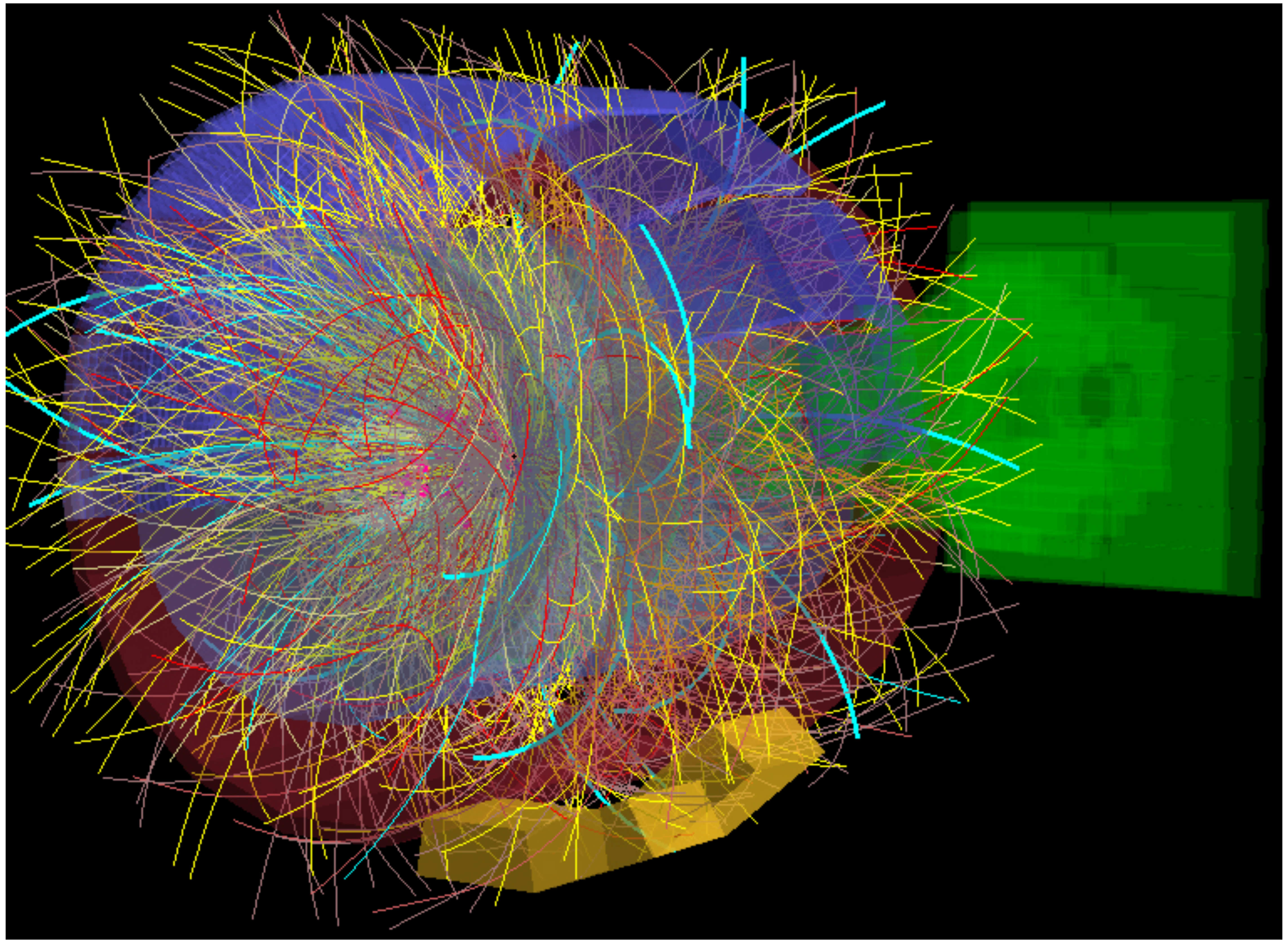
- thermal equilibrium reached after very short time < 1fm/c - QGP created
- energy density just after collision very high: ~12 GeV/fm^3
- quarks and gluons are strongly coupled to their neighbours - relativistic hydrodynamic fluid
- collective expansion of partons until energy density reaches ~1 GeV/fm^3 - the partons convert to hadrons

Heavy-ion collision at LHC



- properties of partons propagated to newly formed hadrons (composition, flow, ..)
- hadron chemical composition fixed at T_{chem} (~160 MeV)
- elastic collisions stop at T_{kin} (~120 MeV)
- most of the signatures are indirect - studying QGP via hadron properties

Heavy-ion collision in ALICE



Example of Pb−Pb collision seen by ALICE detector

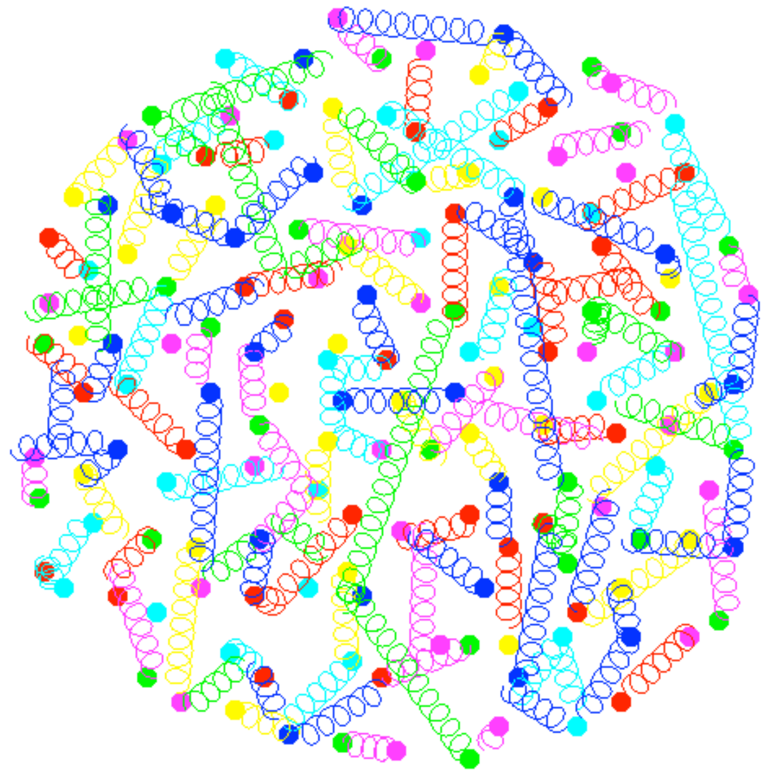
- hadrons created in the collision leave traces in the detector
- many properties of the fireball can be studied like e.g.:
  - chemical composition - hadrochemistry, **strangeness enhancement**
  - collectivity - p_T spectra, **azimutal anisotropy**
  - density - **nuclear modification factor** for hard probes
  - temperature - p_T spectra

Strangeness enhancement

- Originally proposed as a signature of QGP [J. Rafelski, B. Müller, Phys. Rev. Lett. 48 (1982) 1066–1069]

- Production of strange quarks in QGP should be energetically favoured and faster than production in hadron gas

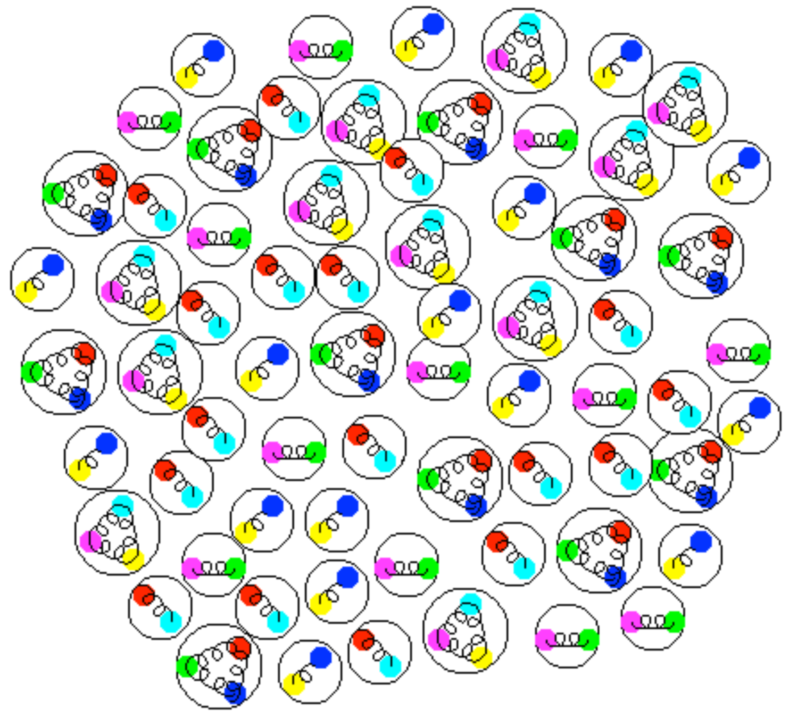
quark-gluon plasma



$$g + g \rightarrow s + \bar{s}$$
$$g + g \rightarrow s + \bar{s}$$
$$q + \bar{q} \rightarrow s + \bar{s}$$

$$\Omega^-(sss)$$

hadron gas



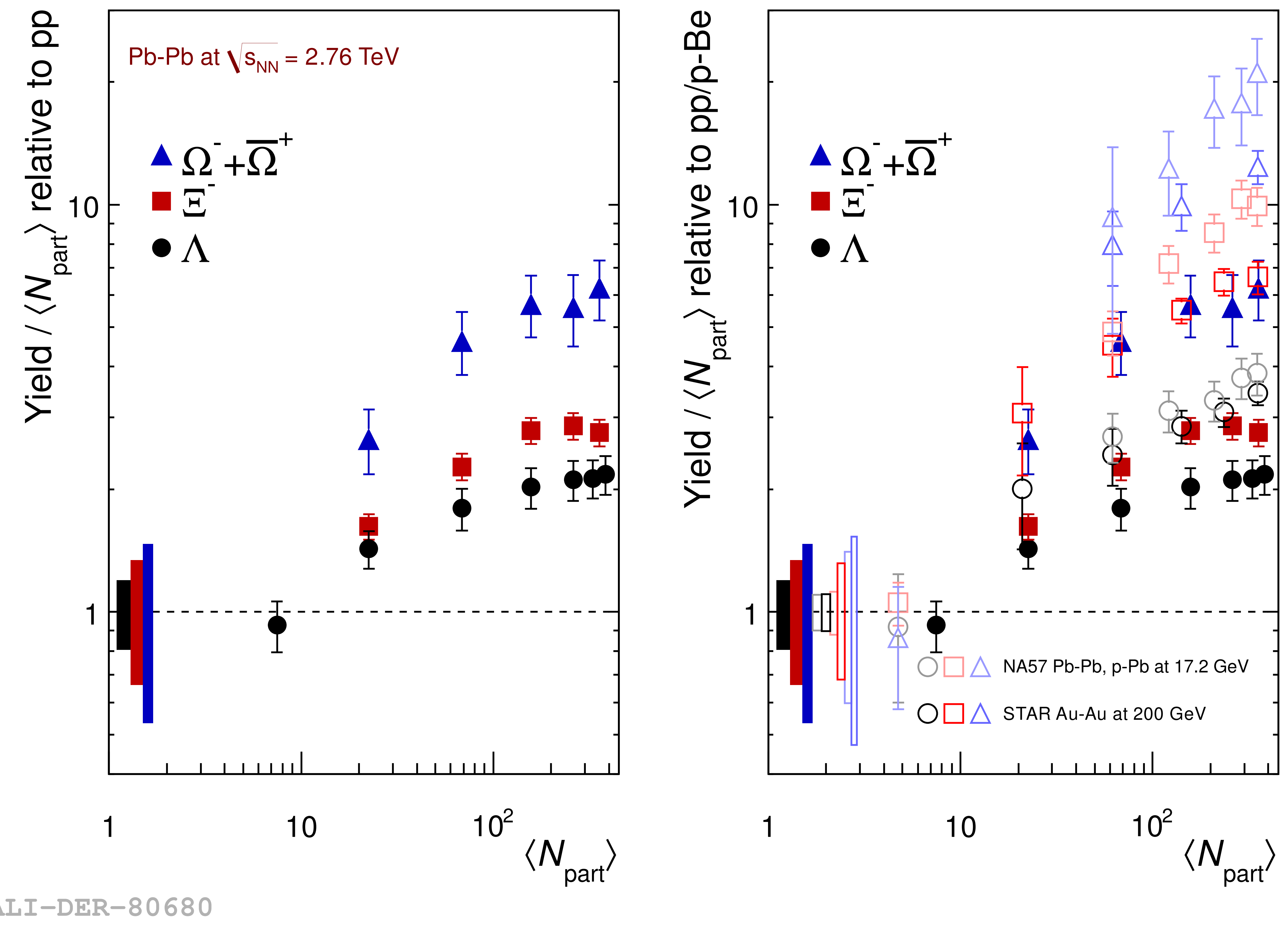
$$p + \pi^- \rightarrow \Lambda^0 + K^0$$
$$\Lambda^0 + \pi^- \rightarrow \Xi^- + K^0$$
$$\Xi^- + \pi^0 \rightarrow \Omega^- + K^0$$

$$\Omega^-$$

Strangeness enhancement

- Originally proposed as a signature of QGP [J. Rafelski, B. Müller, Phys. Rev. Lett. 48 (1982) 1066–1069]
- Production of strange quarks in QGP should be energetically favoured and faster than production in hadron gas
- Experimental variable based on comparison of strange hadron production in nucleus-nucleus collision with nucleon-nucleon (or nucleon-nucleus) collision ⇒ strangeness enhancement confirmed.

ALICE, Phys. Lett. B 728 (2014) 216

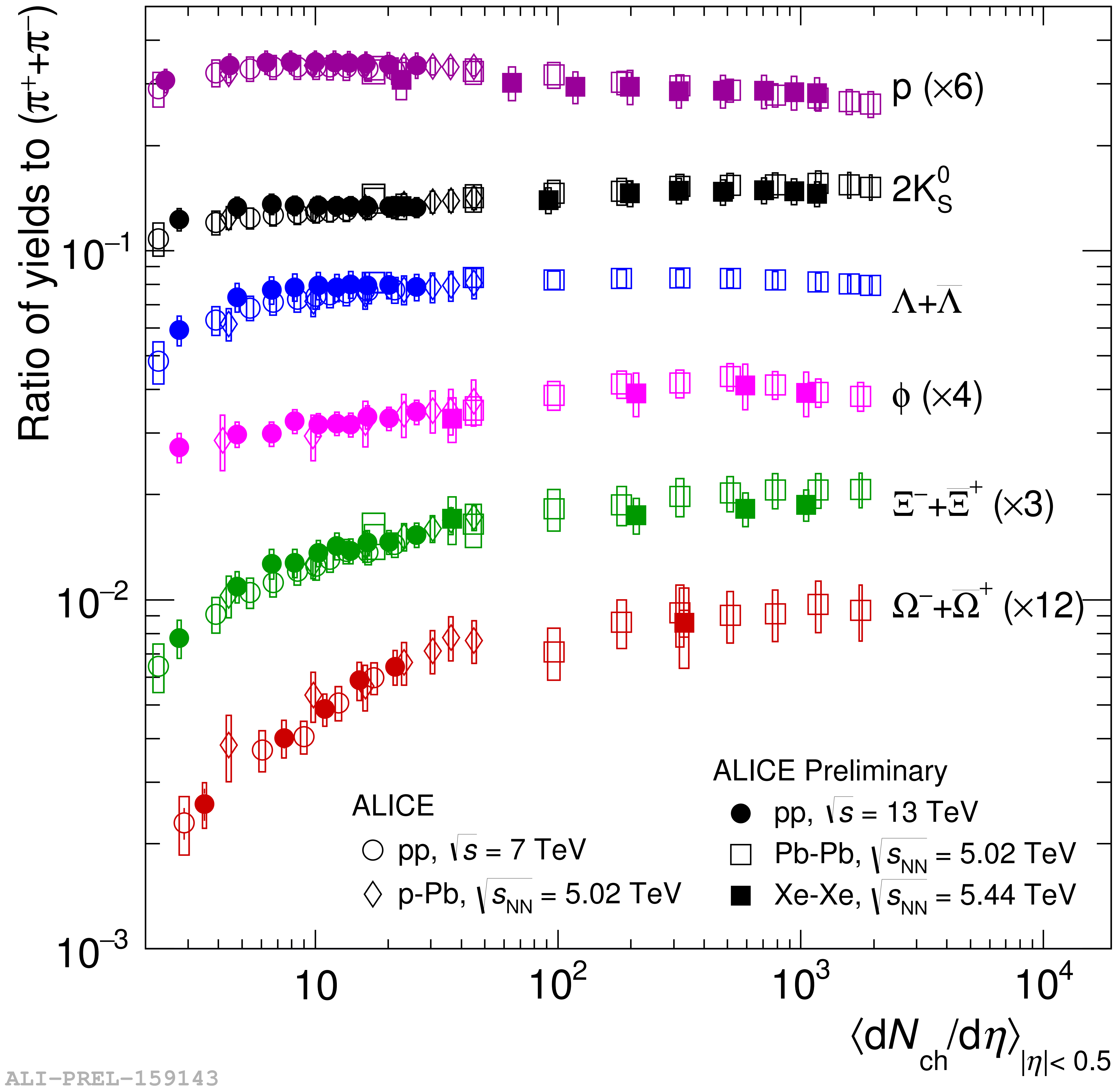


N_{part} - number of nucleons participating in the collision

Strangeness enhancement

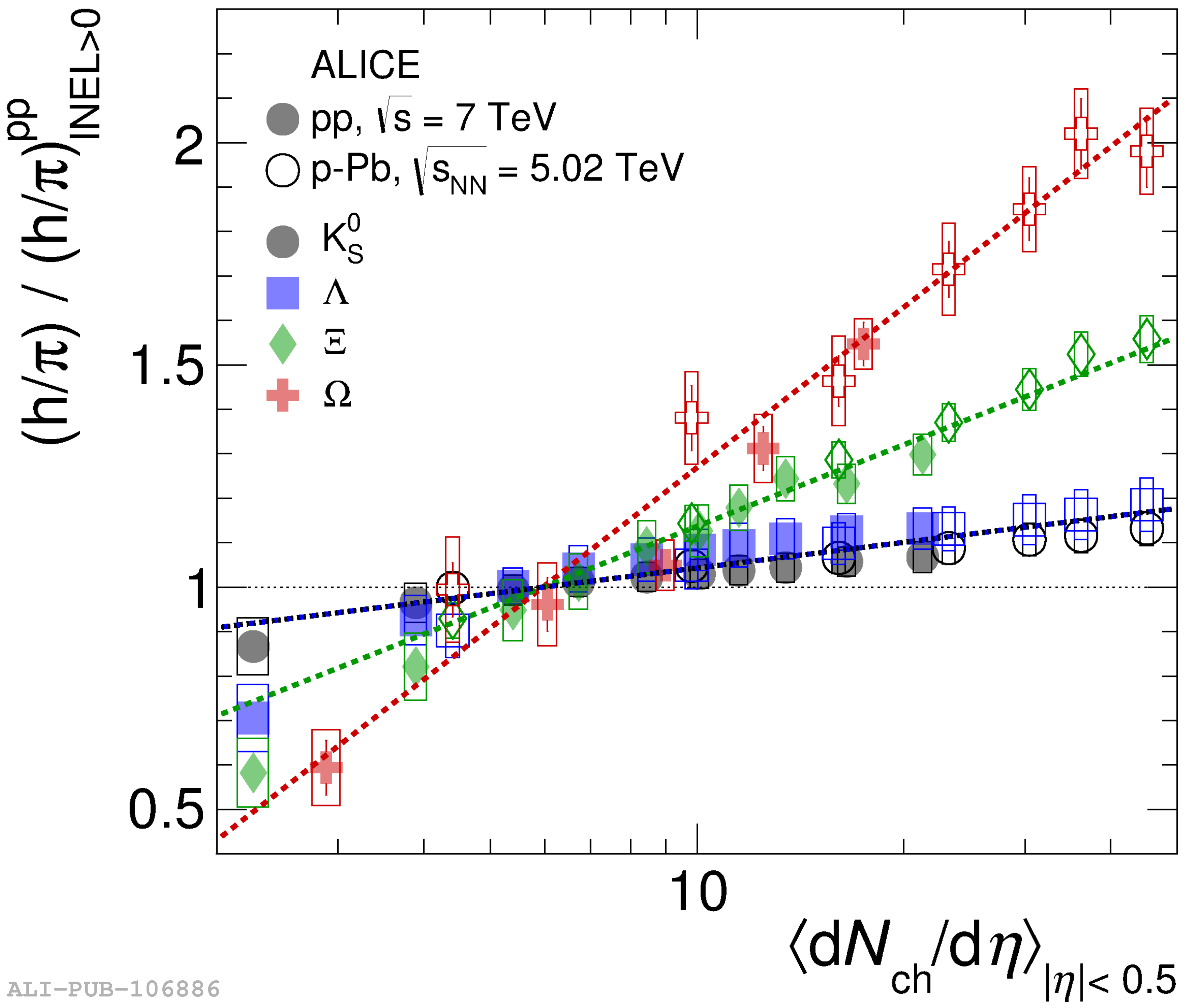
LHC: large statistics for small systems ⇒ study multiplicity (density?) dependence.

- N_{part}-scaling does not hold at LHC energies - a different experimental variable is used: **ratio to pion production** as a function of multiplicity
- remarkable overlap of pp, p–Pb and peripheral Pb–Pb at various energies - seems the only parameter needed to estimate strangeness production is **multiplicity**



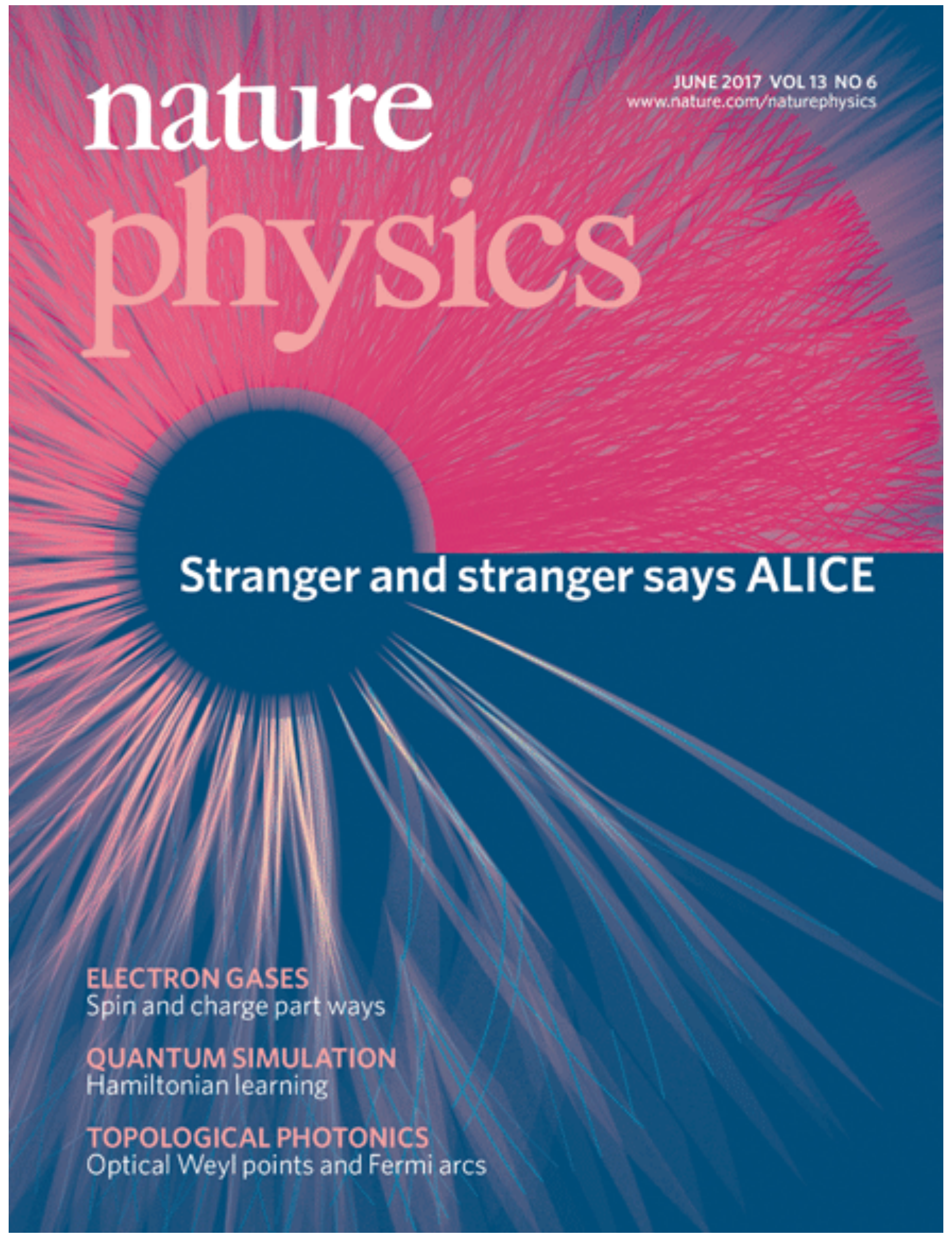
Strangeness enhancement

ALICE, Nature Physics 13 (2017) 535

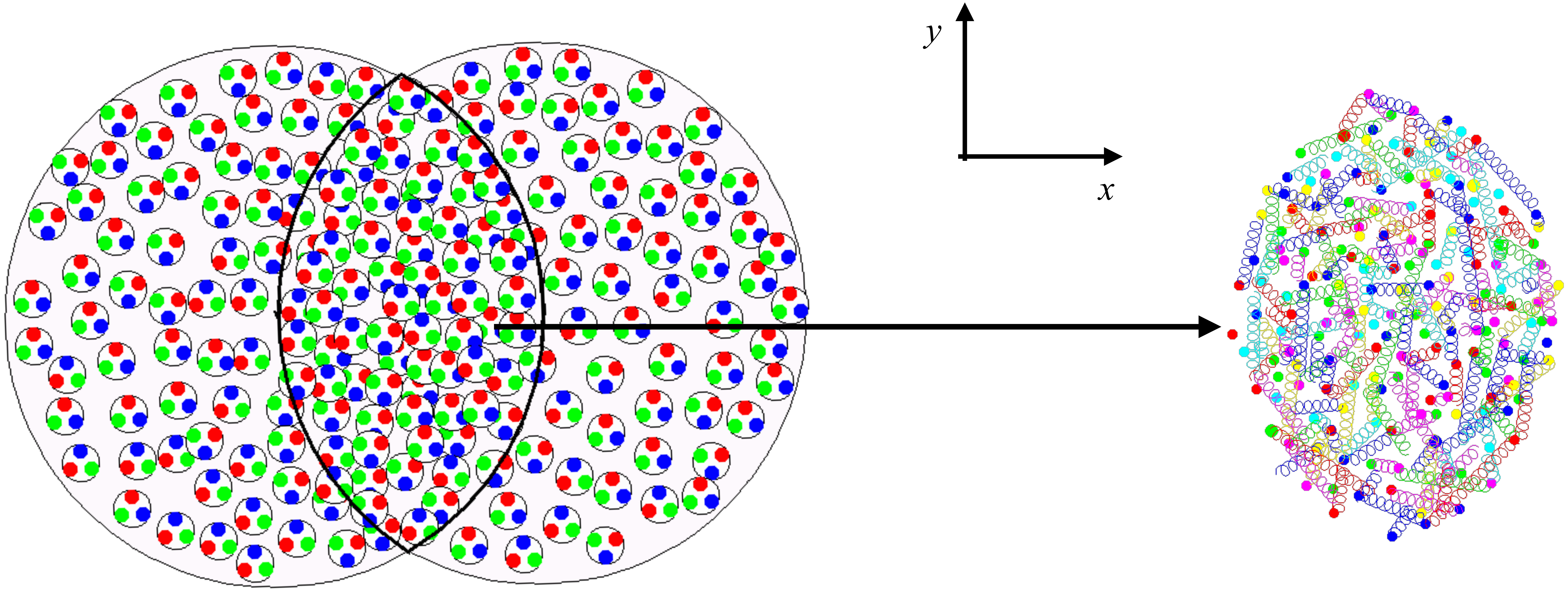


Hierarchy of the enhancement determined by the hadron strangeness

- strangeness enhancement clearly visible for high multiplicity pp and p–Pb collisions



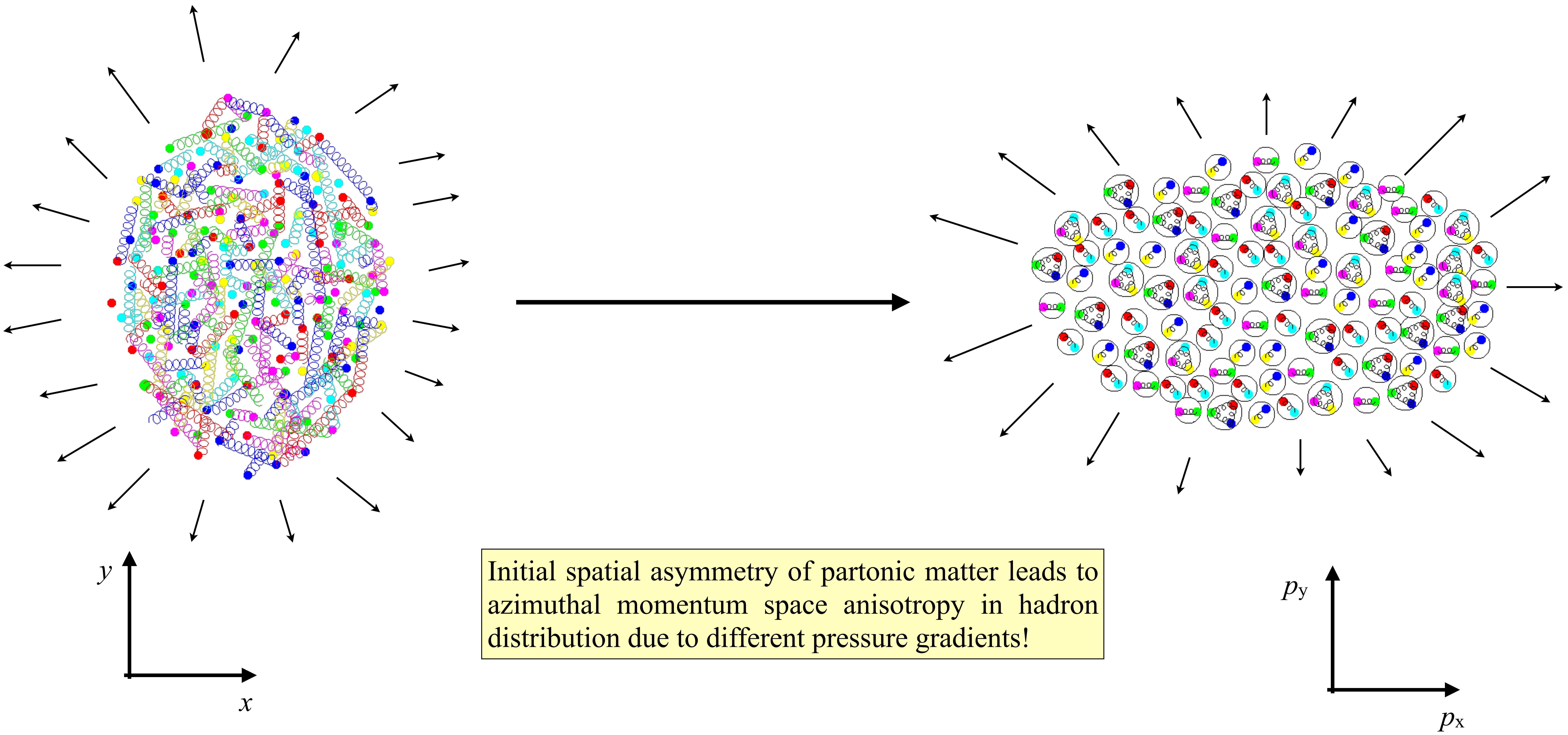
Azimuthal anisotropy



not fully overlapped nuclei at collision ⇒ almond shaped fireball of QGP

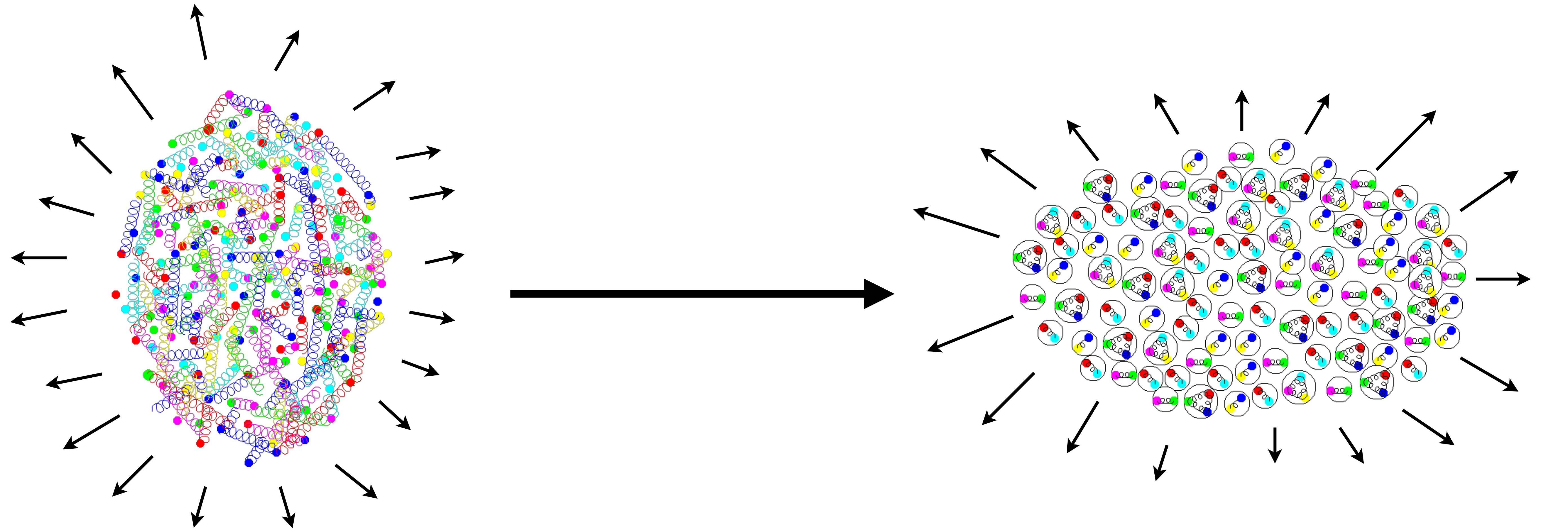
higher pressure gradient in horizontal (in plane) direction than in vertical (out-of-plane) direction

Azimuthal anisotropy



Initial spatial asymmetry of partonic matter leads to azimuthal momentum space anisotropy in hadron distribution due to different pressure gradients!

Azimuthal anisotropy



- anisotropy can be quantified by second Fourier coefficient of the particle distribution (v_2 a.k.a. elliptic flow)
- "Lumpiness" of the fireball (due to fluctuations of the initial energy density profile of the colliding nucleons) can give rise to higher harmonics (v_n, n=3,4,..)

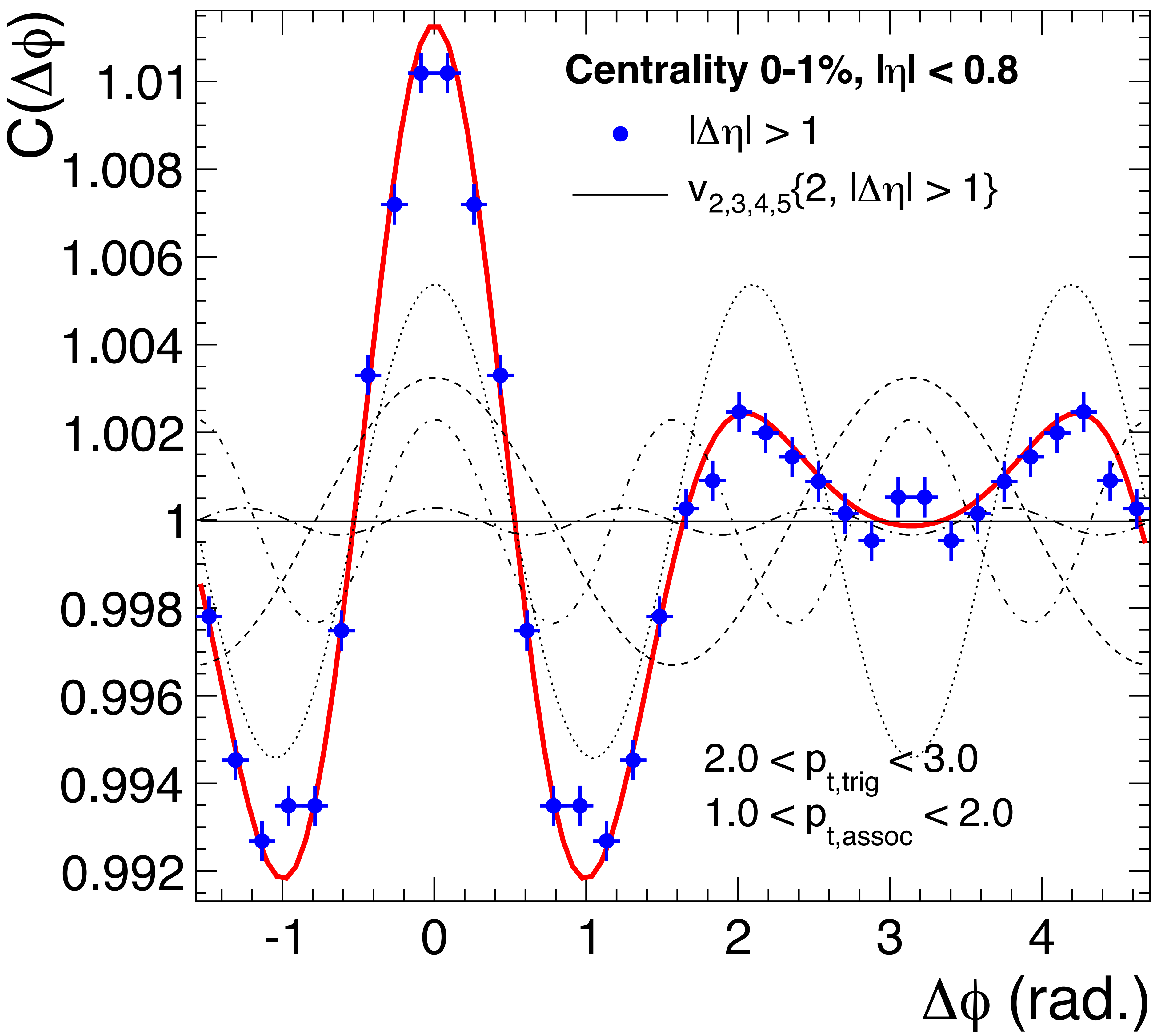
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n(p_T, y)\cos[n(\phi - \Psi_R)]\right)$$

$$v_n(p_T, y) = \langle\cos[n(\phi - \Psi_R)]\rangle$$

Ψ_R - reaction plane angle

Flow in Pb–Pb collisions

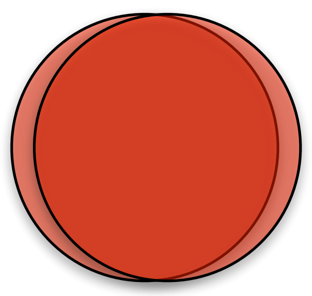
ALICE, Phys. Rev. Lett. 107 (2011) 032301

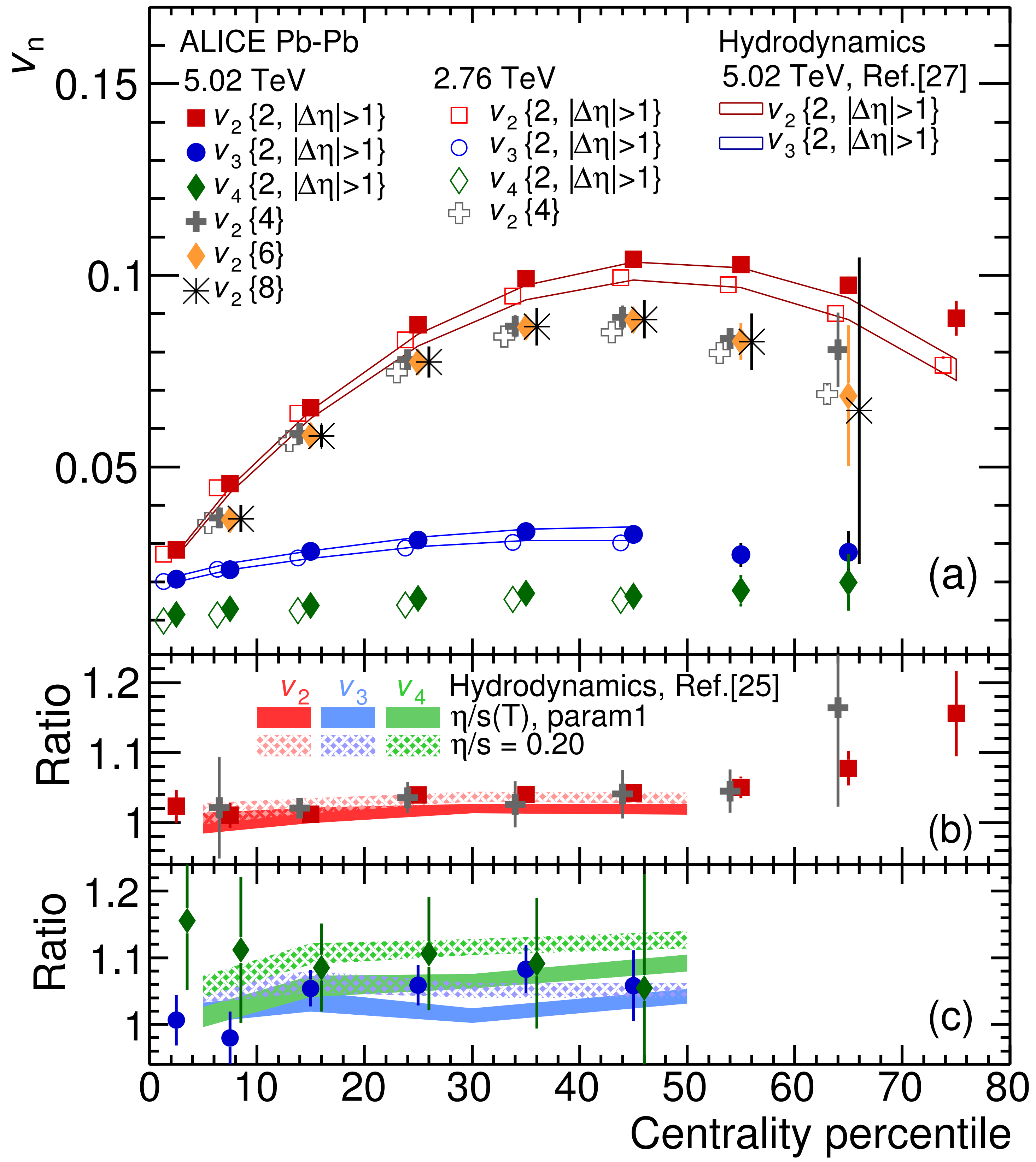


Two particle angular correlation function in good agreement with azimuthal correlation shape expected from v_2, v_3, v_4 and v_5

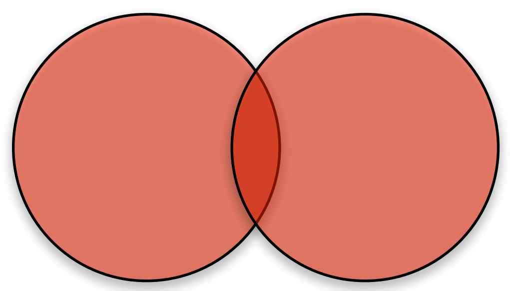
ALICE, Phys. Rev. Lett. 116 (2016) 132302

central



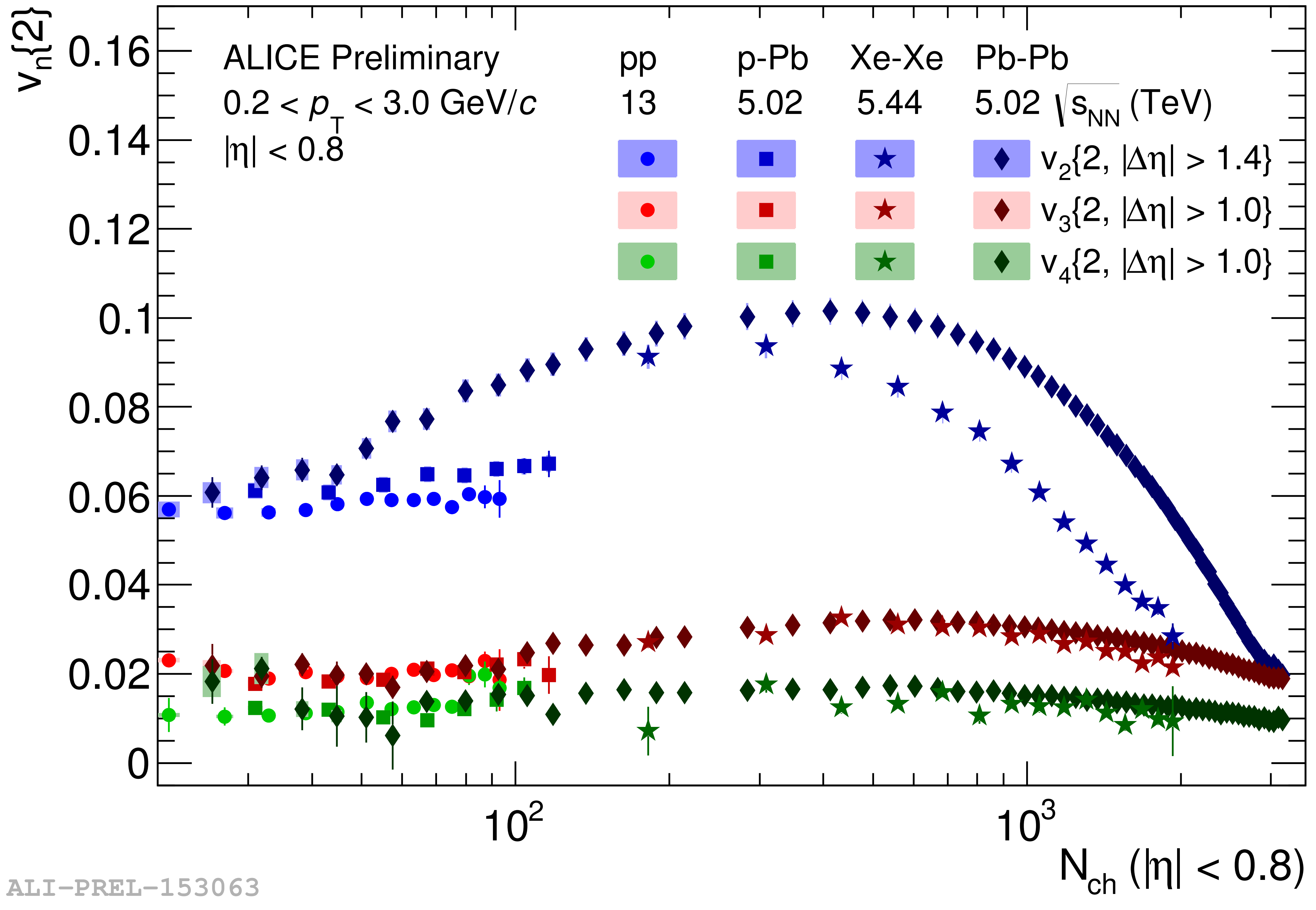


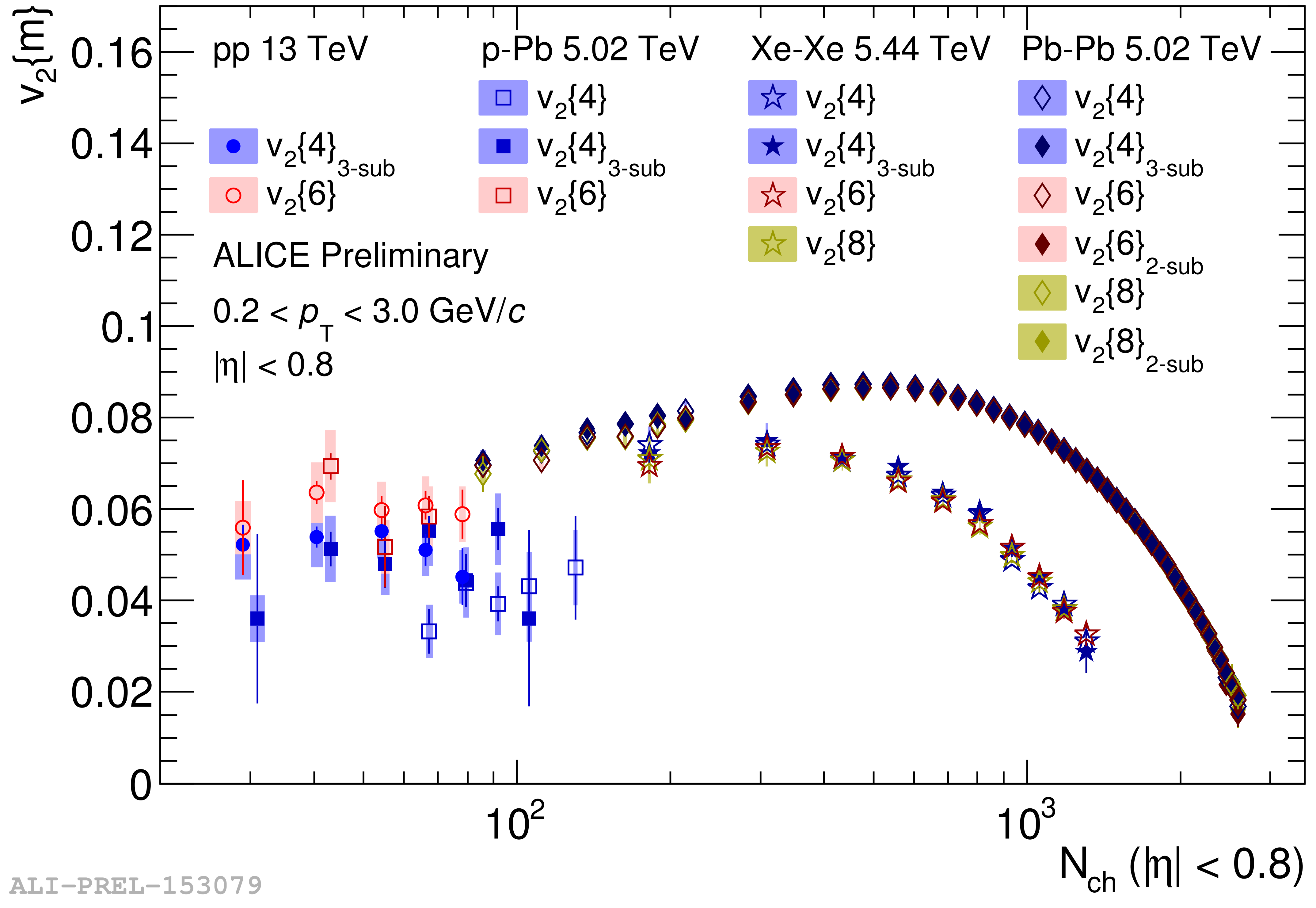
peripheral



Measured azimuthal anisotropy as a function of system size in a very good agreement with corresponding predictions from hydrodynamic models - indication of strongly coupled matter

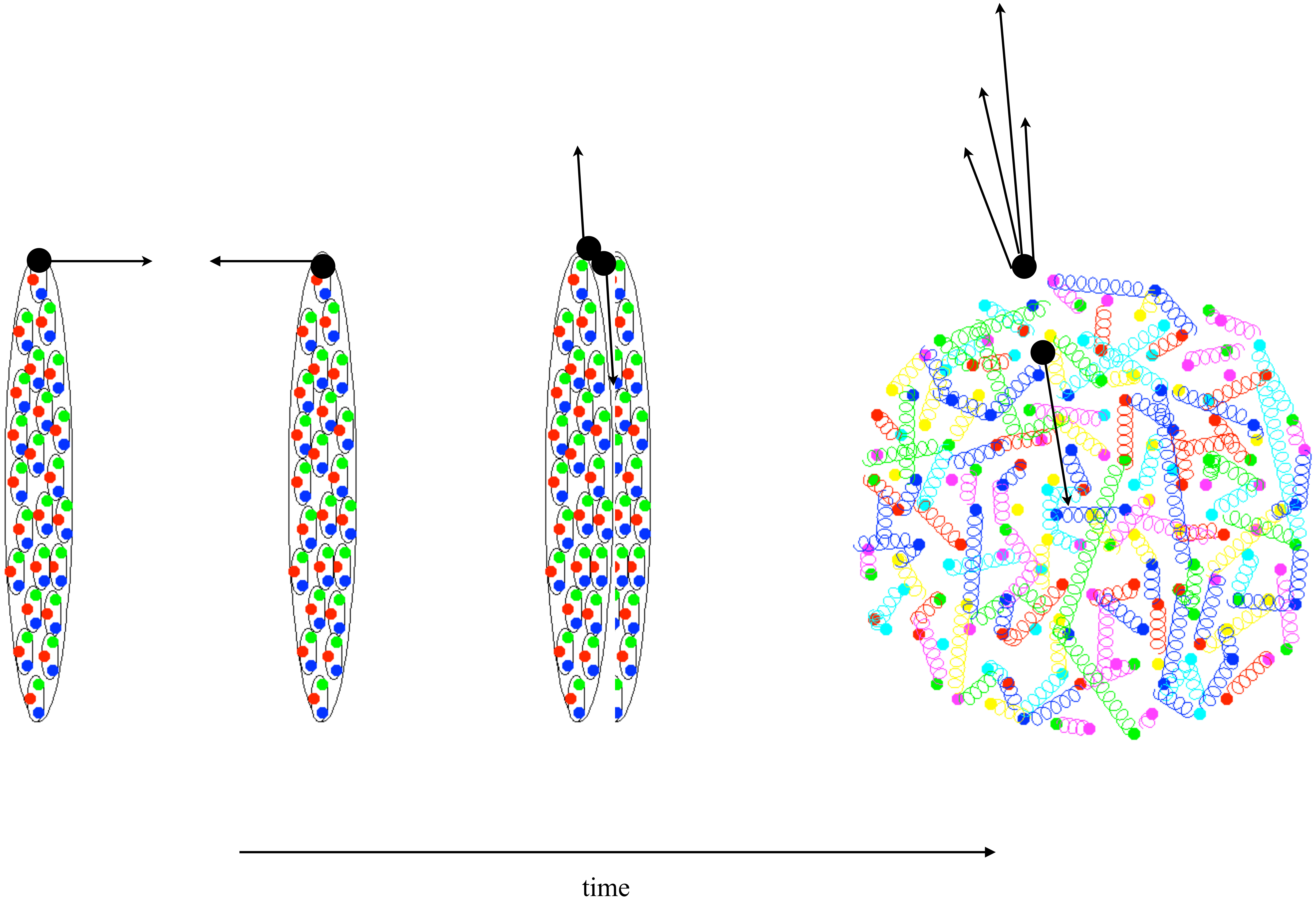
Flow in small systems?





Collectivity persists also in pp and p−Pb collisions!

Hard probes



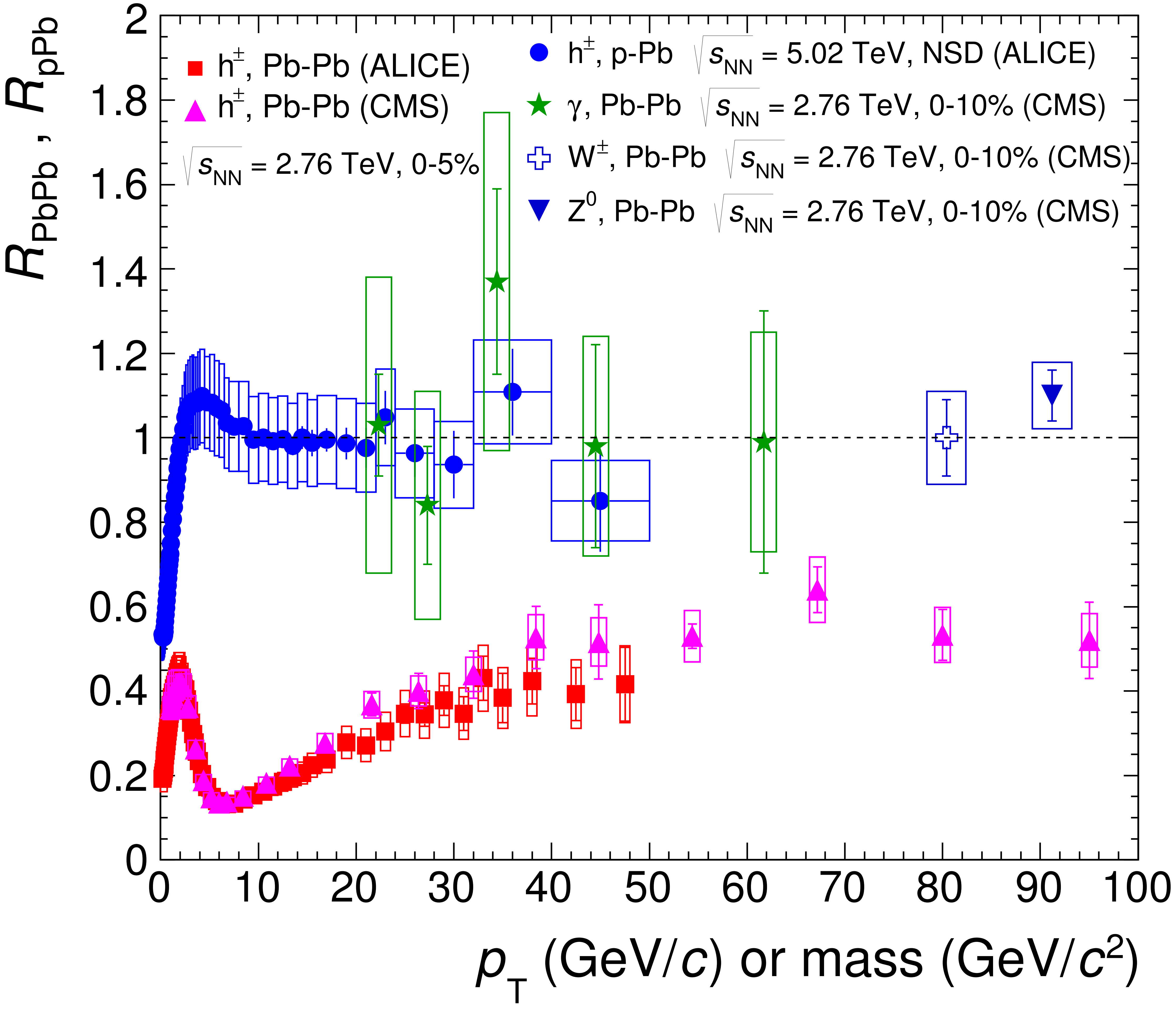
- high p_T partons produced by hard scattering at early times
- can probe all stages of collision
- measurements suggest enormous energy losses at the LHC ~10 GeV per 1 fm - independent (from flow) observation of strongly coupled matter!

Nuclear modification factor (R_{AA})

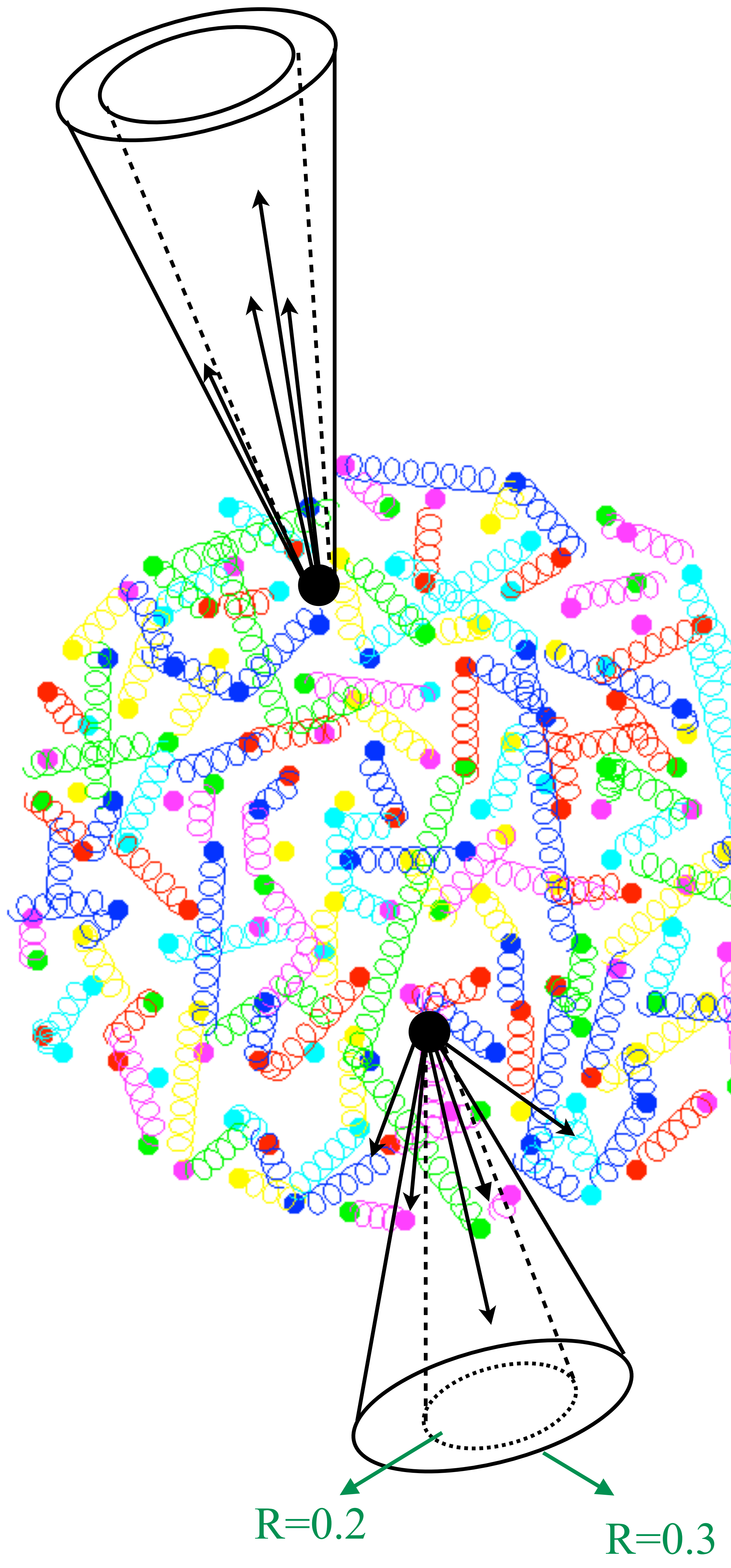
$$R_{AA}(p_T) = \frac{d^2N_{AA}/dydp_T}{\langle N_{coll}\rangle \, . \, d^2N_{pp}/dydp_T}$$

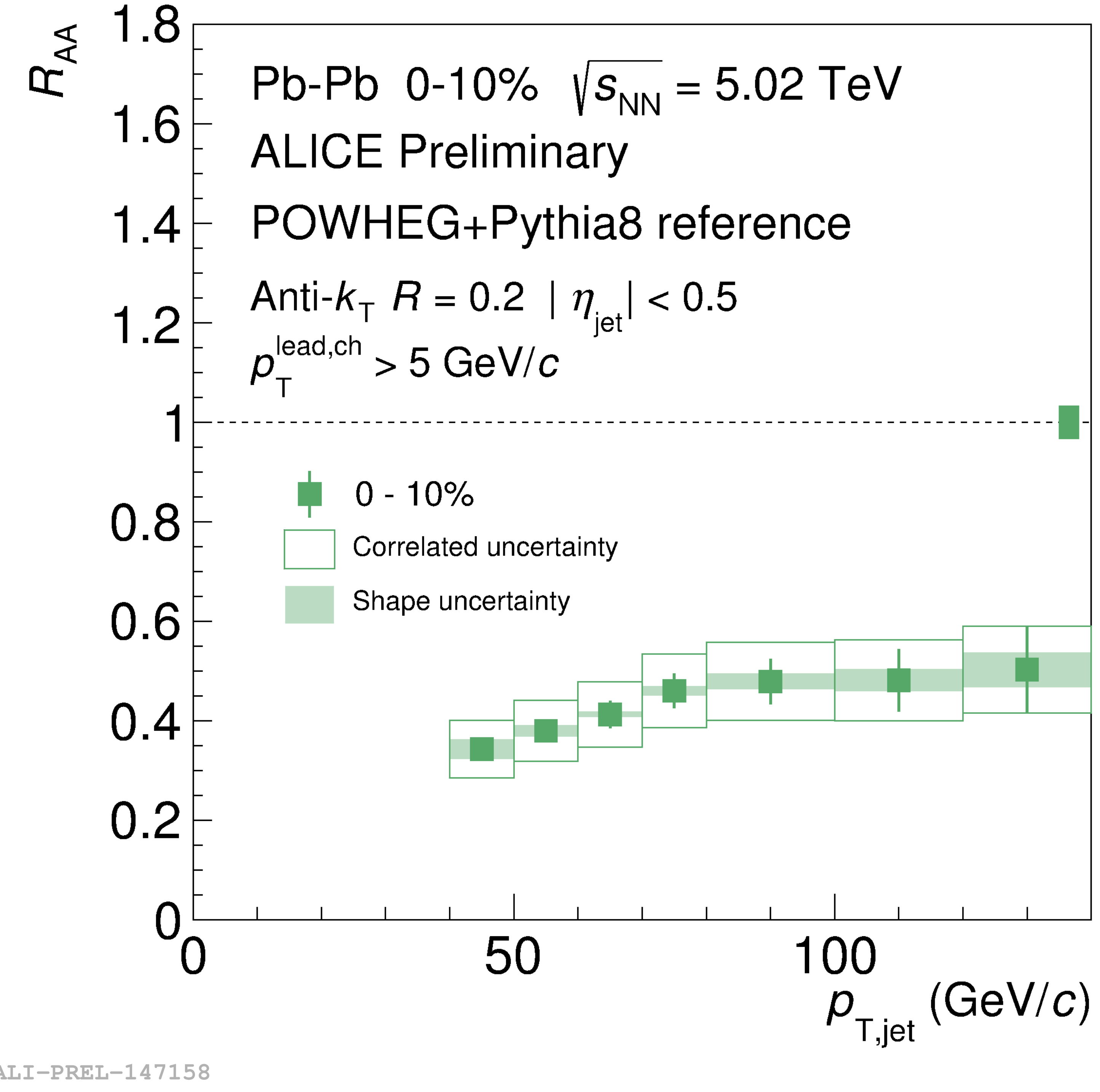
- N could be particles or jets
- $\langle N_{coll}\rangle$ (number of binary collisions) calculated by Glauber model ("volume factor")
- should be 1 for colourless object in QGP (mean free path bigger than system size)

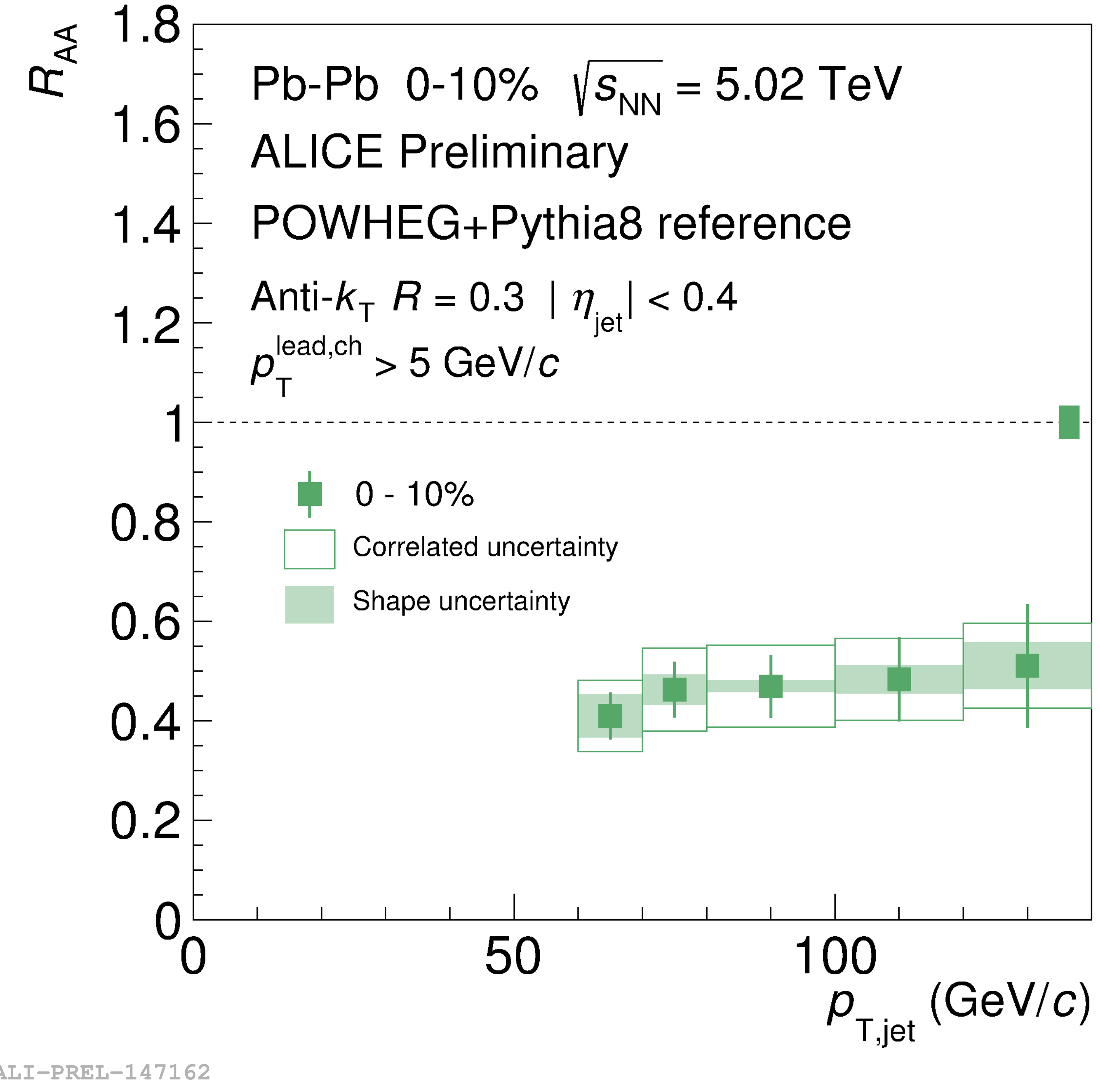
Strong suppression of high p_T hadrons measured in central Pb−Pb collision ⇒ parton energy loss!



Nuclear modification factor (R_{AA})

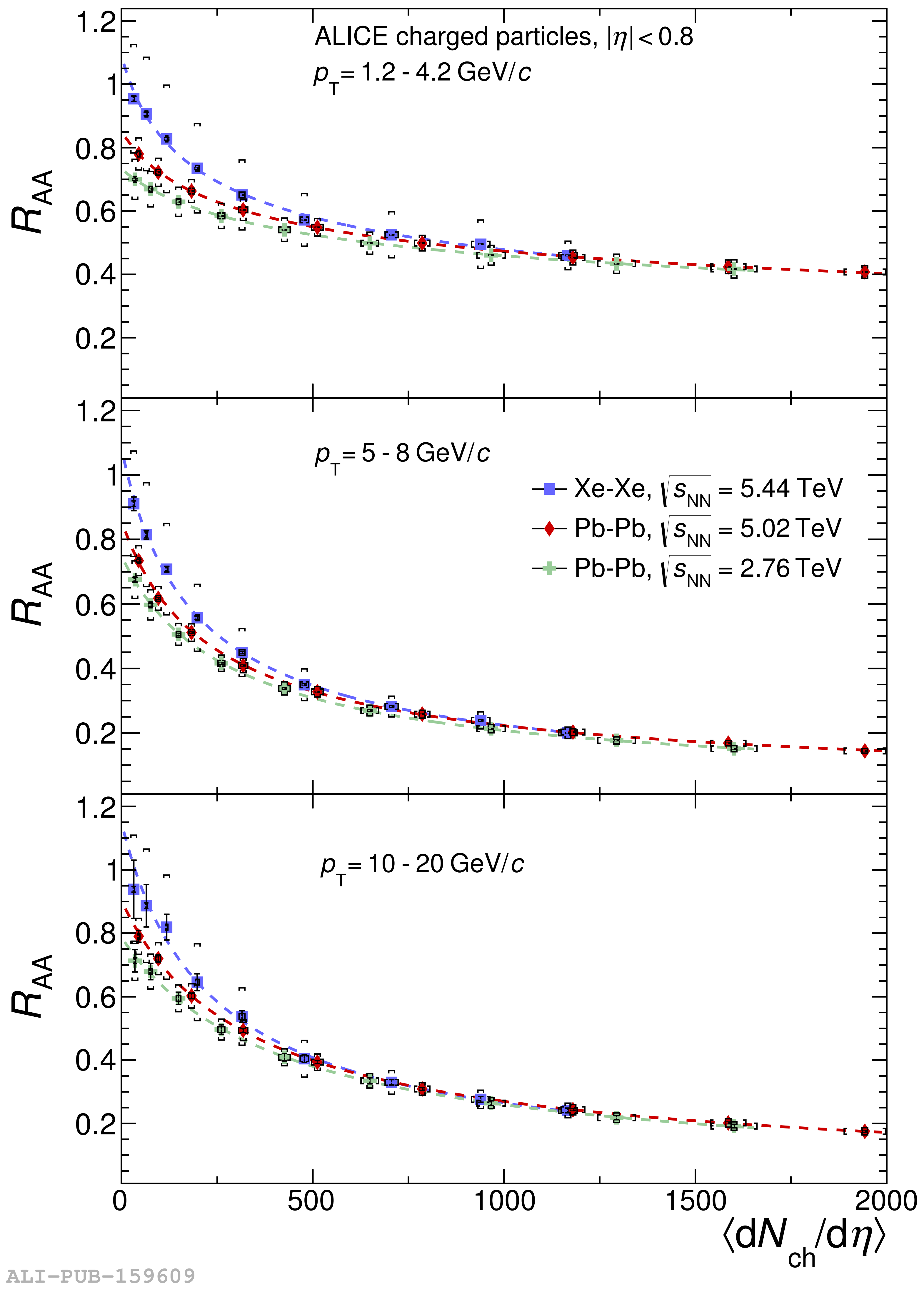


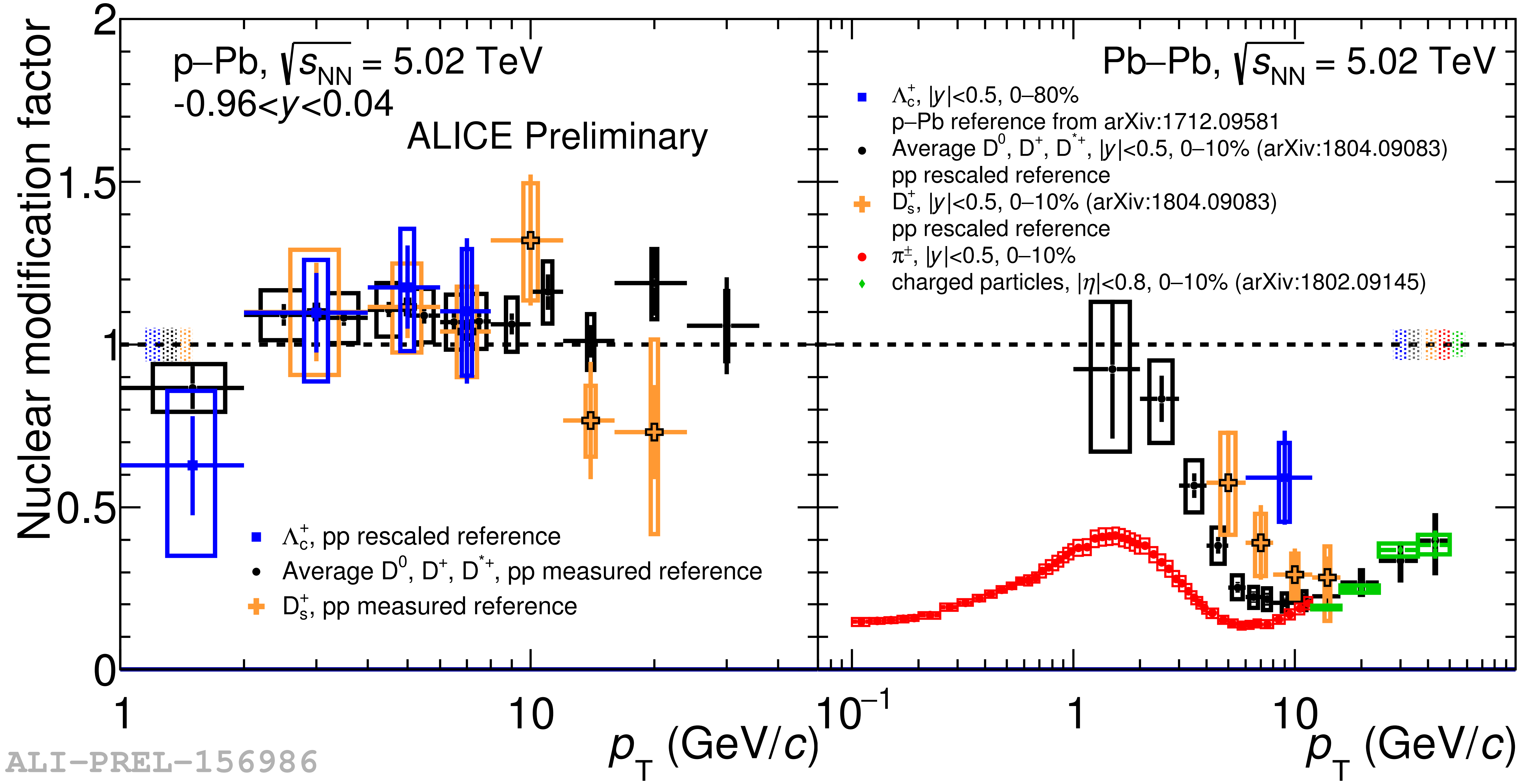




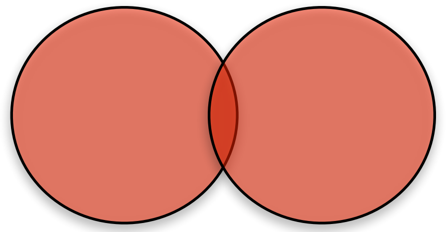
With jet reconstruction we can look at distributions of the radiated energy (in-cone vs out-of-cone) ⇒ a more differential view of parton energy loss!

Nuclear modification factor

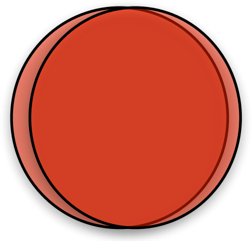




peripheral



central



- high p_T hadrons suppressed in similar way for most central events in different systems and energies
- charmed hadrons also suppressed in heavy ion collisions
- no suppression seen in p–Pb collisions

Summary

- the ALICE experiment studies properties of QGP in nucleus-nucleus (A−A) collisions
- studying pp and p−Pb collisions is important in order to disentangle effects not related to QGP
- strangeness enhancement, as one of the original proposed signature of QGP, also seen in high multiplicity pp and p−Pb collisions
- elliptic flow in A−A and suppression of R_{AA} confirm an existence of dense and strongly coupled plasma of quarks and gluons
- non-zero flow and strangeness enhancement observation in pp and p−Pb collisions brings questions: Is high multiplicity pp (p−Pb) collision a small droplet of QGP? If yes, why there is no suppression in R_{pPb}?