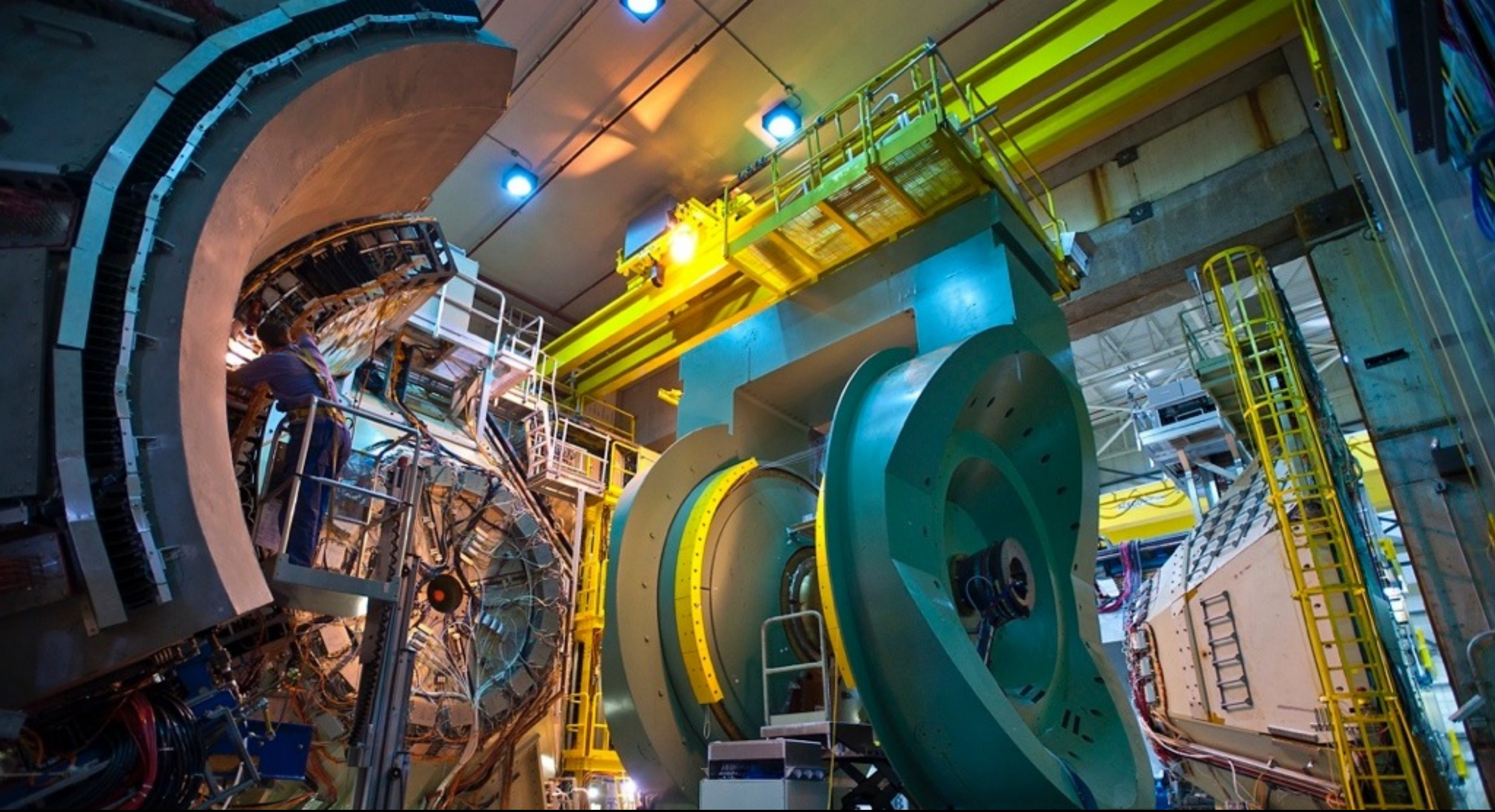


The Smallest Drops of the Hottest Matter? New Investigations at the Relativistic Heavy Ion Collider

Anne M. Sickles

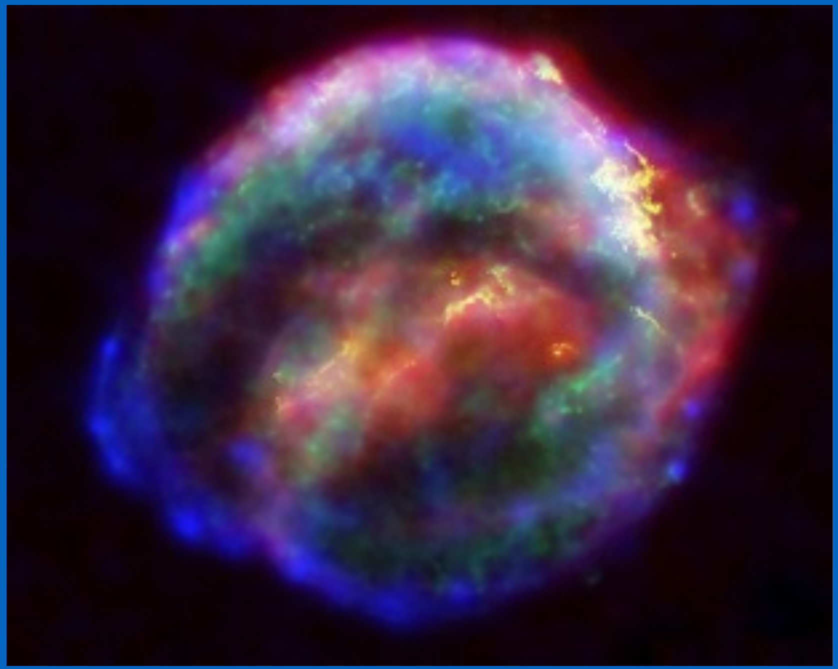
Brookhaven Lecture, March 19, 2014

how hot?

80 ° F

2000 ° F

28M ° F



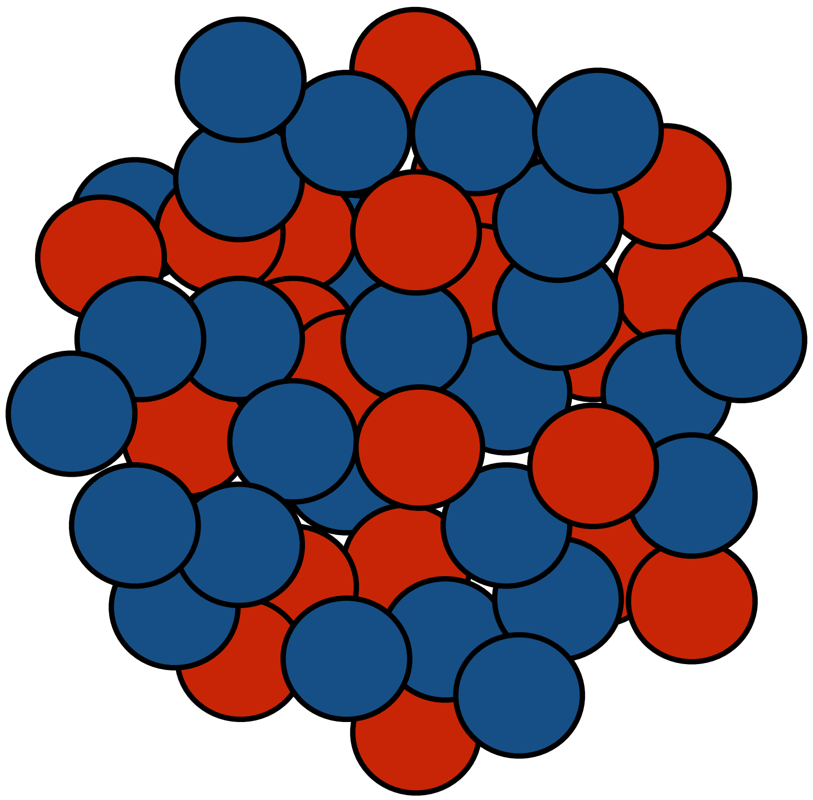
150B ° F

quark-gluon plasma

no photo available

5T ° F

The nucleus



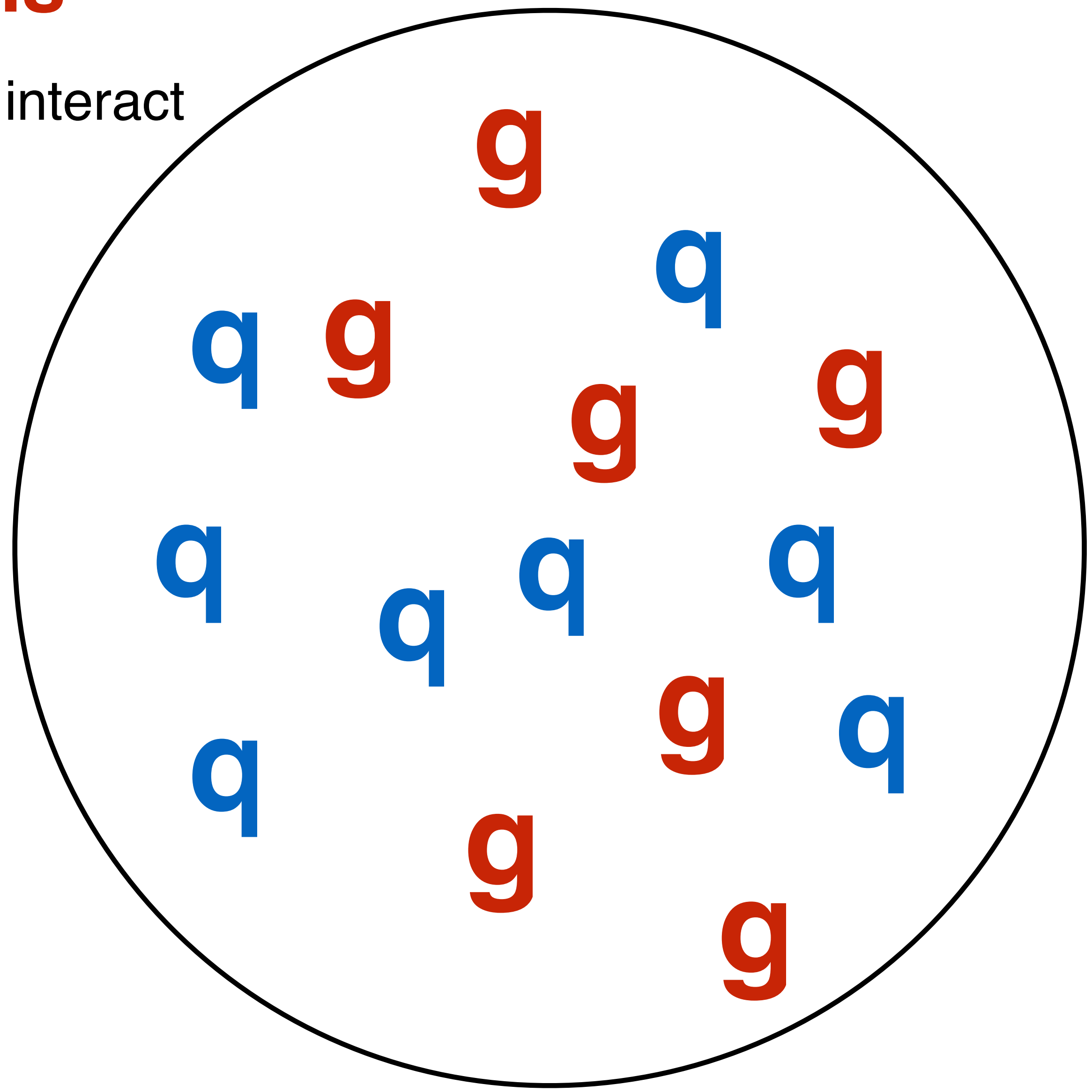
- >99% of the mass of atoms, and thus normal matter, is in the nucleus
- composed of protons and neutrons
- the nucleus is held together by the strong force
  - one of the 4 fundamental forces
  - very strong short range interactions

and what's inside protons and neutrons?

quarks and gluons

fundamental particles which interact via the strong force

confinement

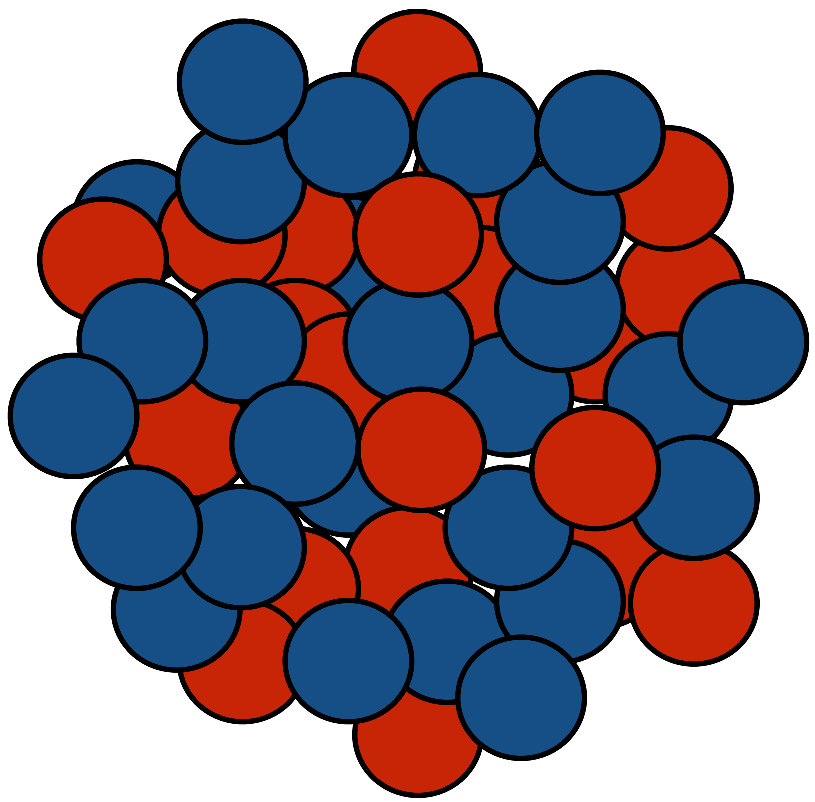


confinement makes the strong force hard to study because the details are locked inside the protons and neutrons

strong force at high temperature

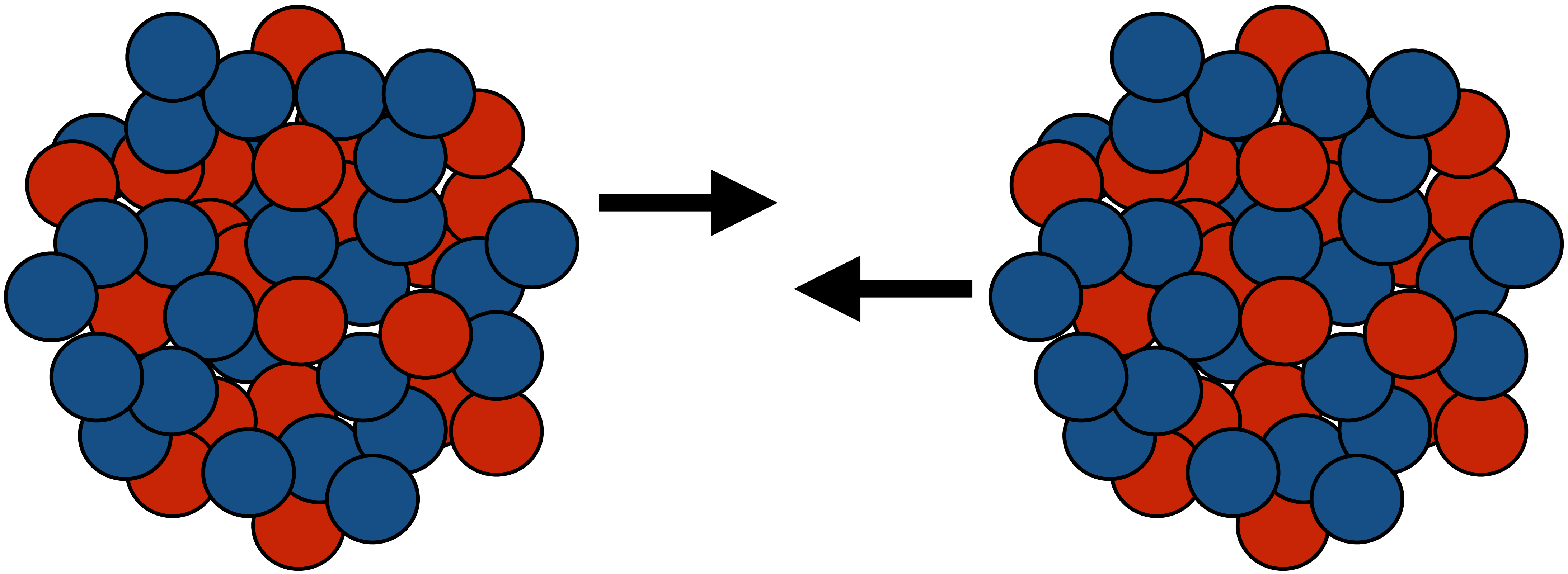
a system that's hot and dense enough for the quarks and gluons to not be confined anymore

nucleus
(many protons & neutrons)



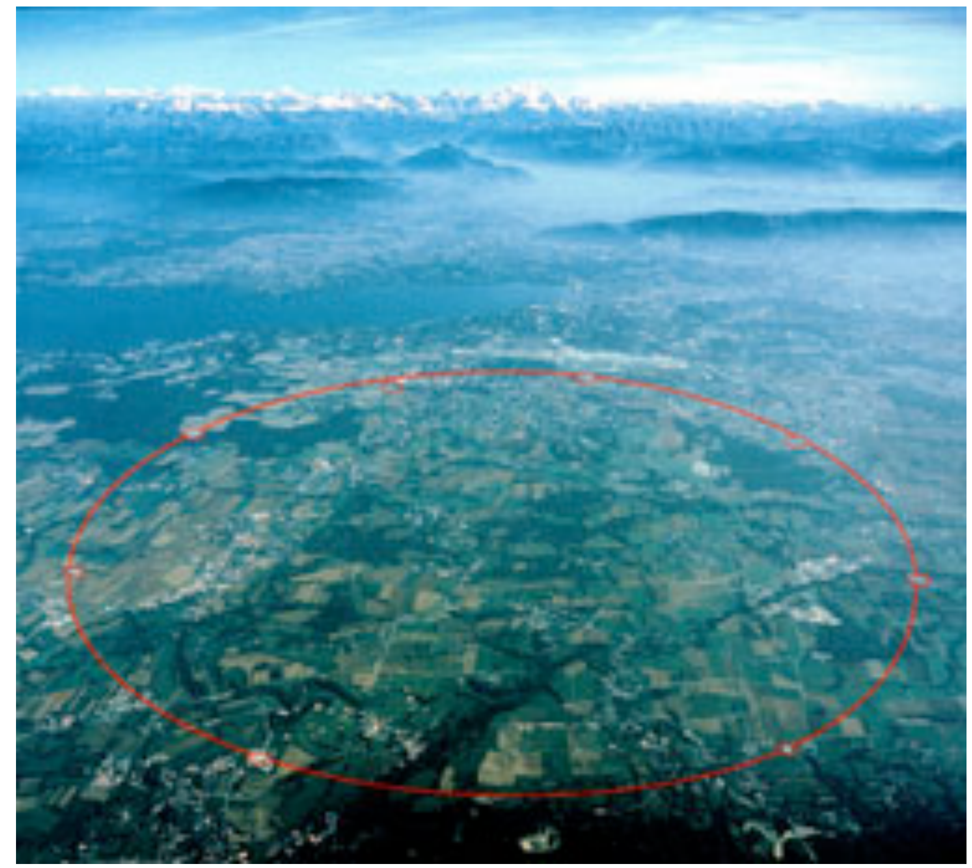
+ energy

strong force at high temperature



to create a system that's hot and dense enough for the quarks and gluons to not be confined anymore: the **quark gluon plasma**

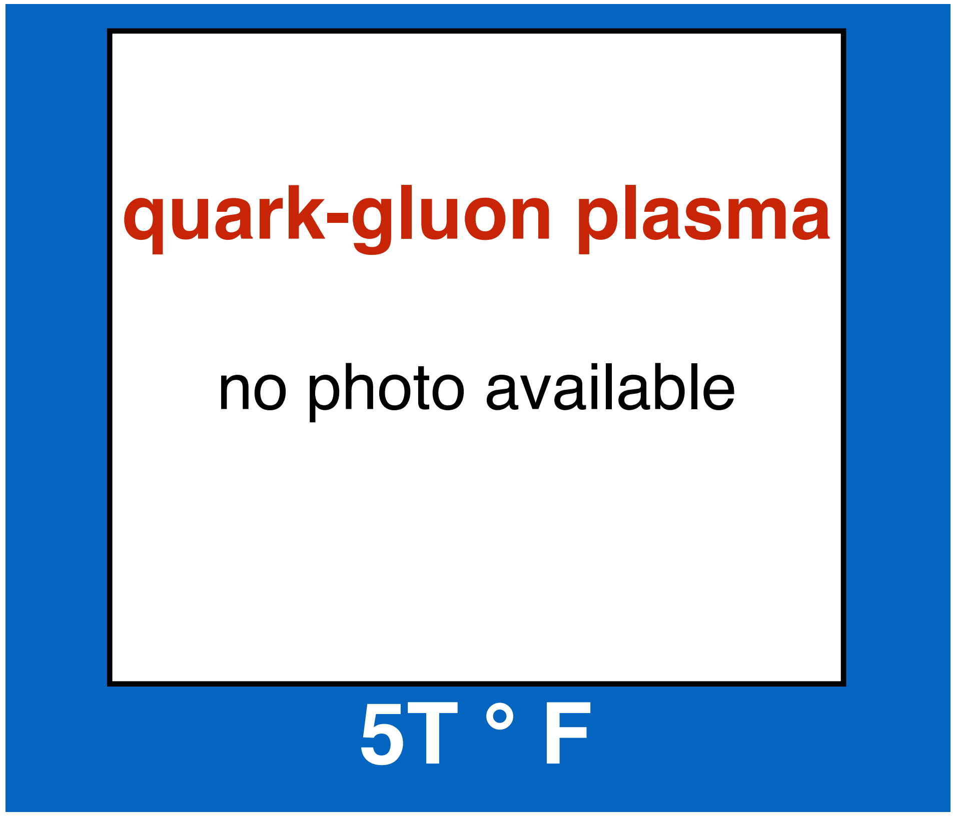
Colliders at BNL and CERN

RHIC	LHC
	
0.200 TeV collision energy Au+Au	2.76 TeV collision energy Pb+Pb

relativistic **heavy** ion collisions

Quark Gluon Plasma

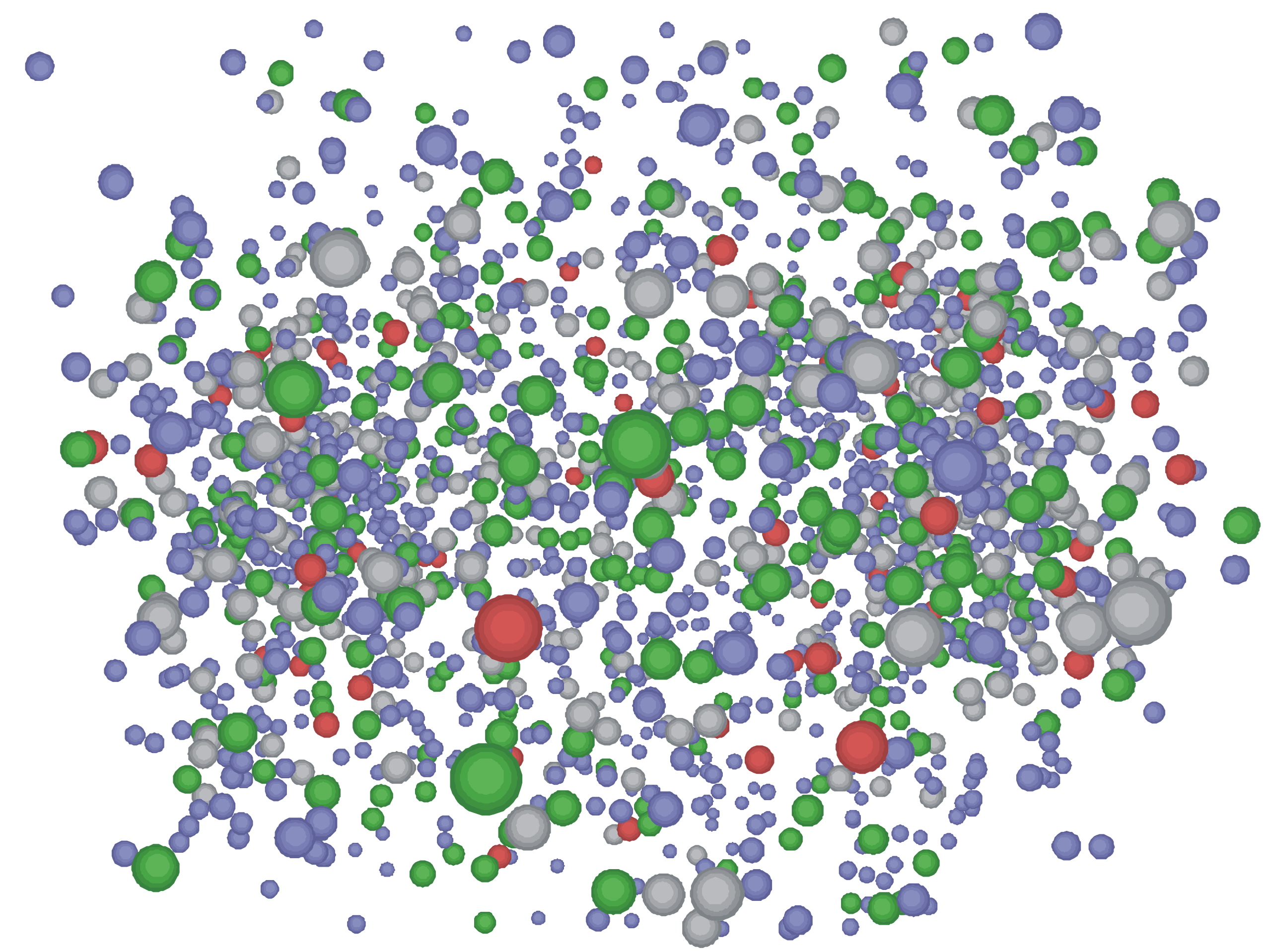
lasts for a billionth of a trillionth of a second
and billion times smaller than a pixel on an iPhone display



what do we see?

hundreds or thousands of **new** particles are created in each collision

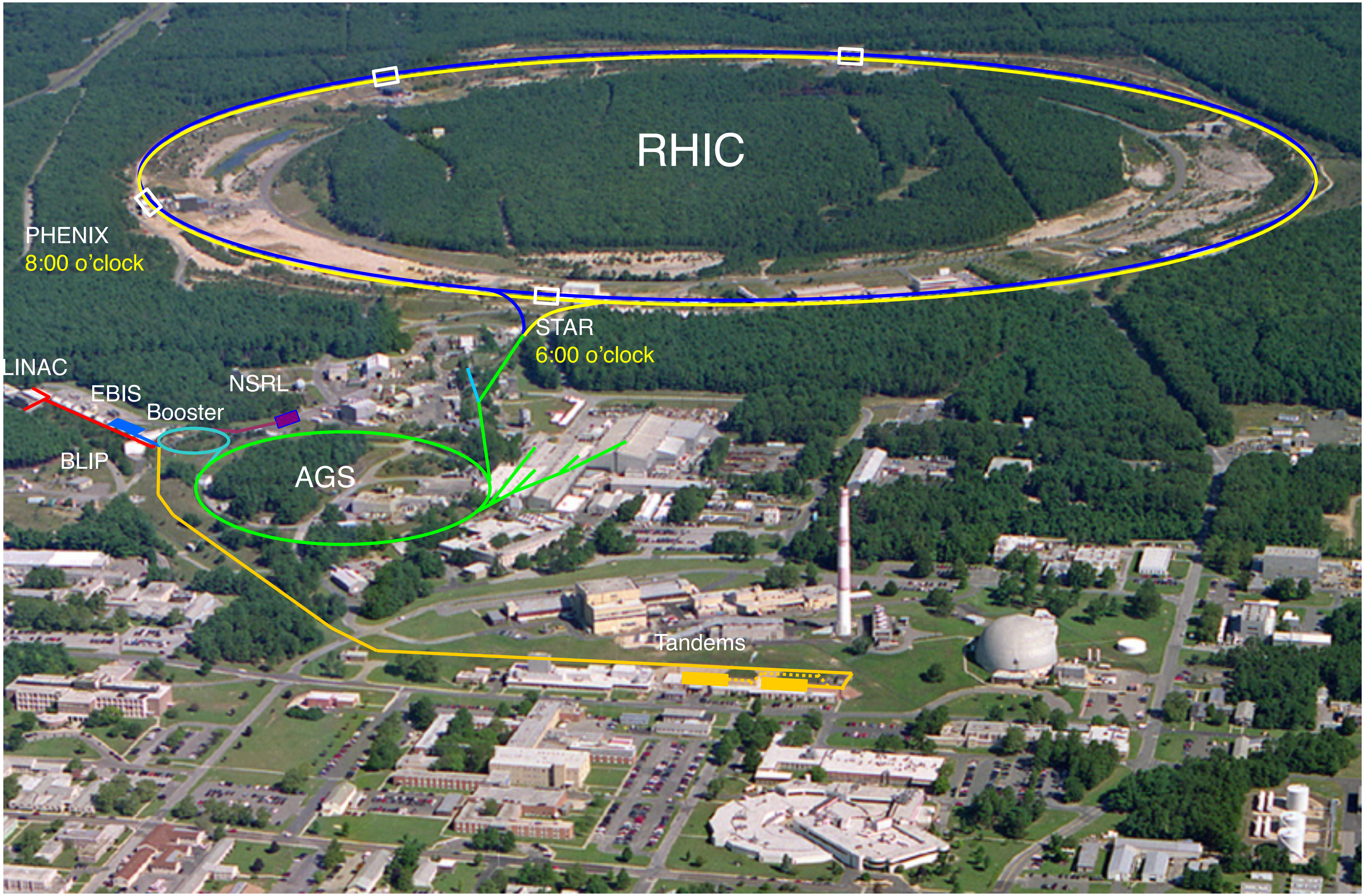
$E = mc^2$



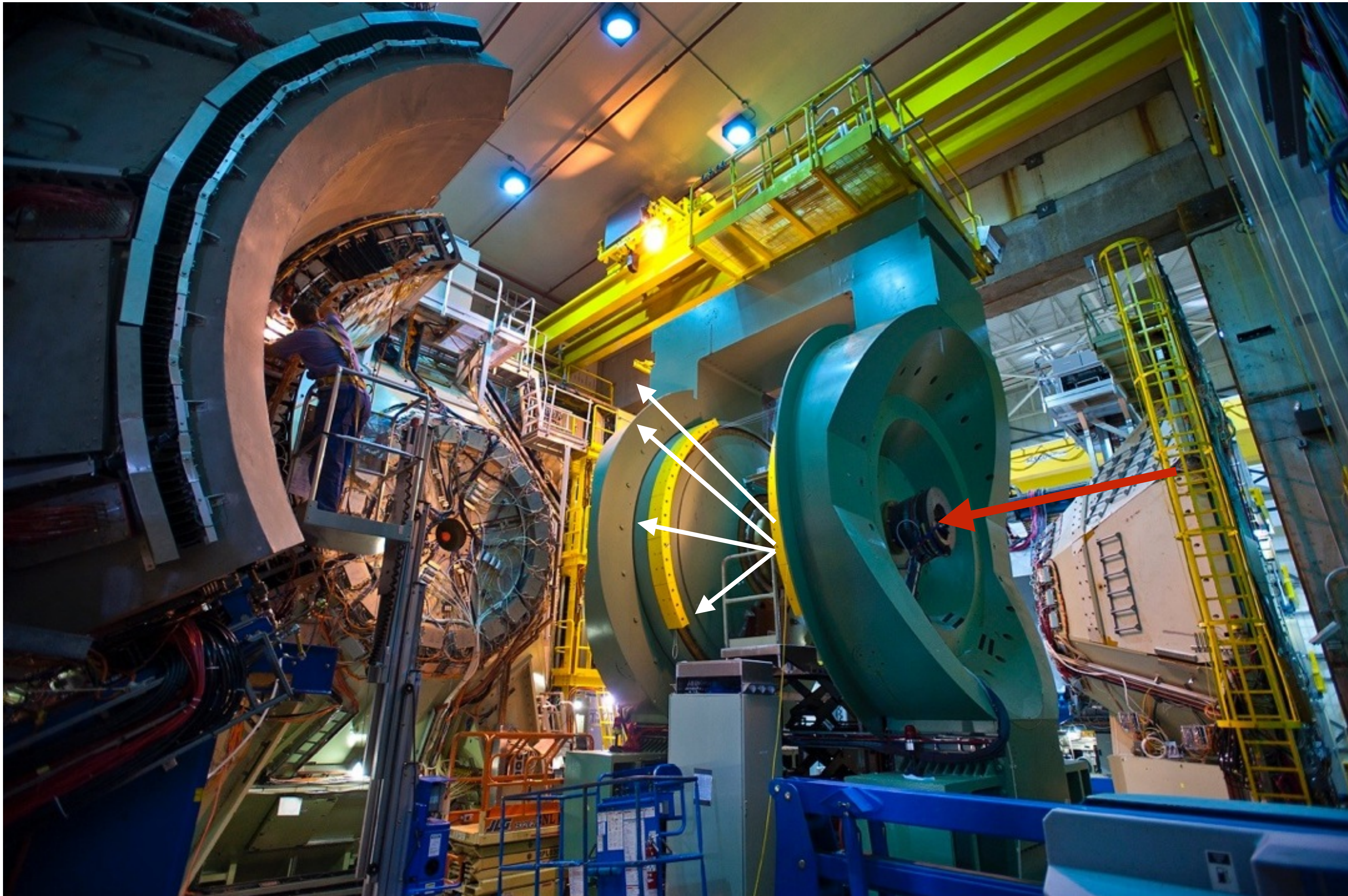
these particles provide the only window into the earlier stages of the collision

we look at each collision individually, but measure billions of collisions!

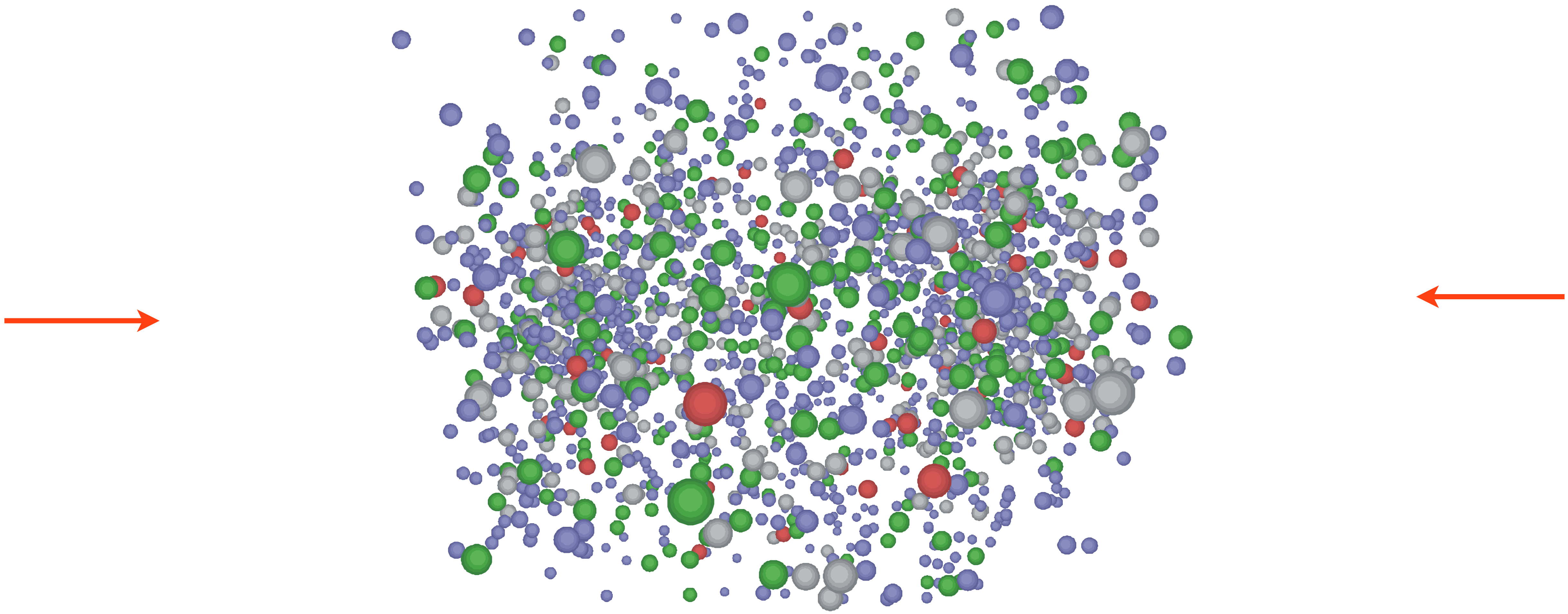
RHIC @ Brookhaven



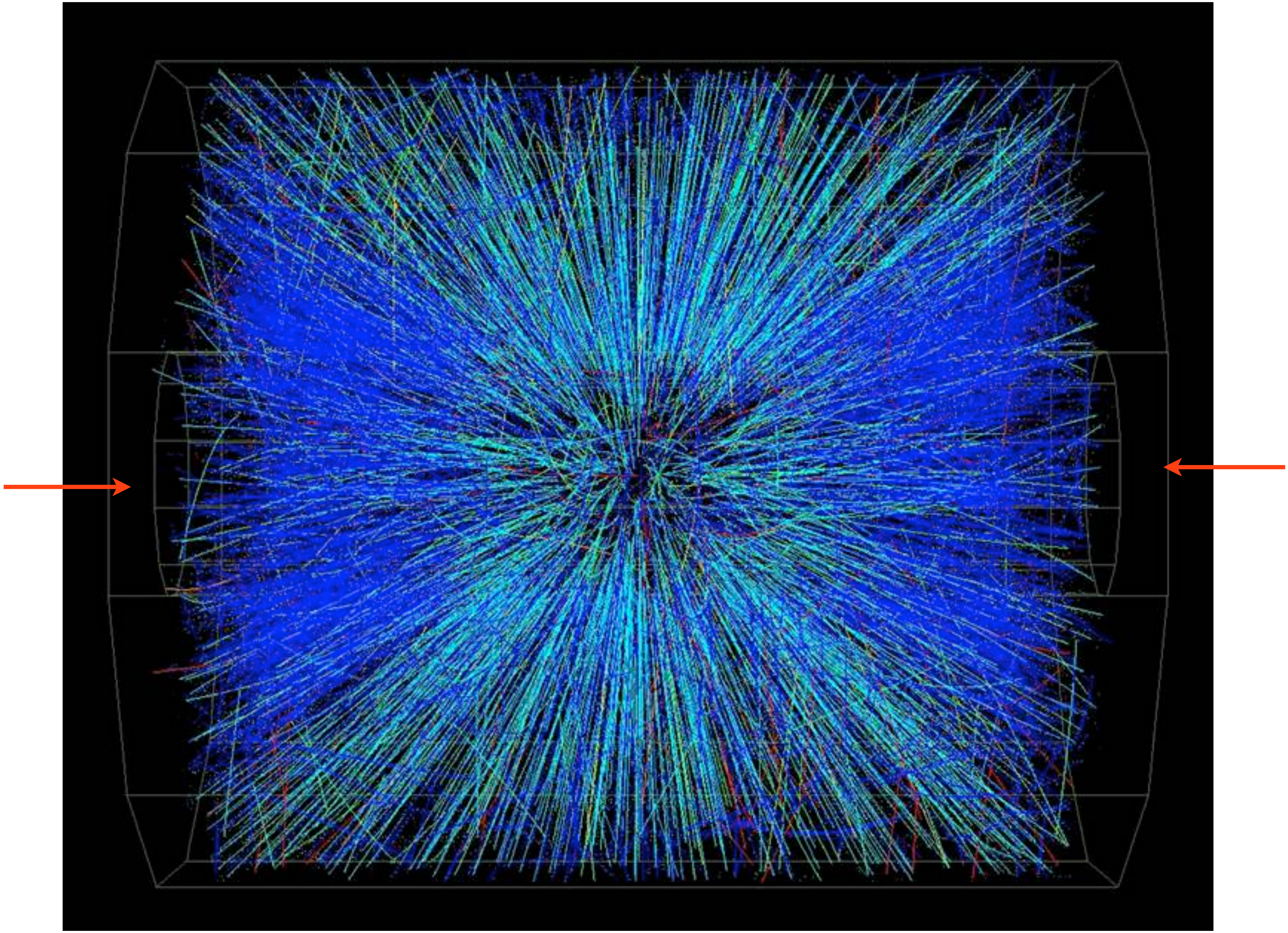
PHENIX Detector

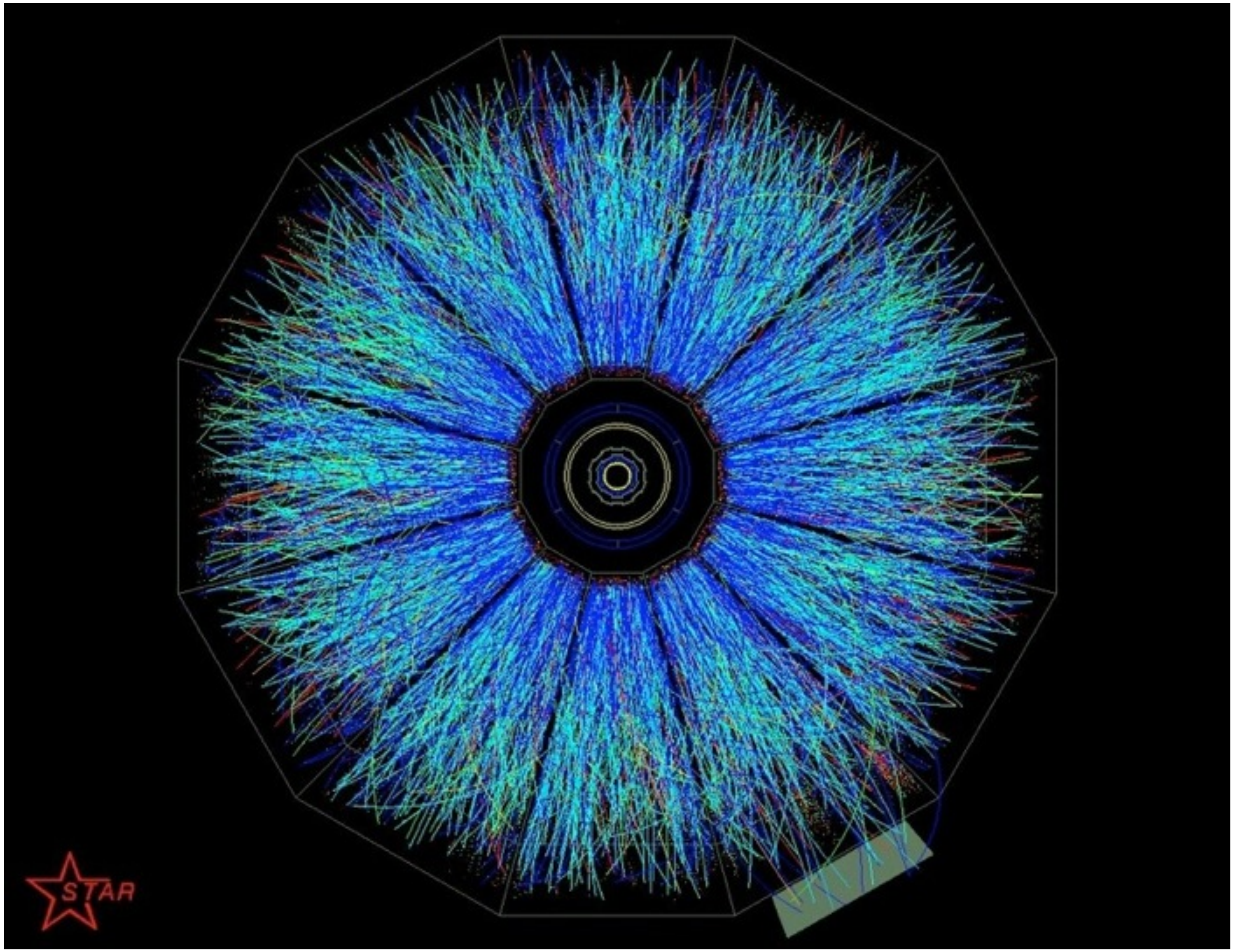


the aftermath of a collision

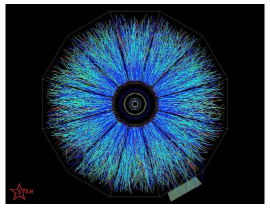


the aftermath of a single collision



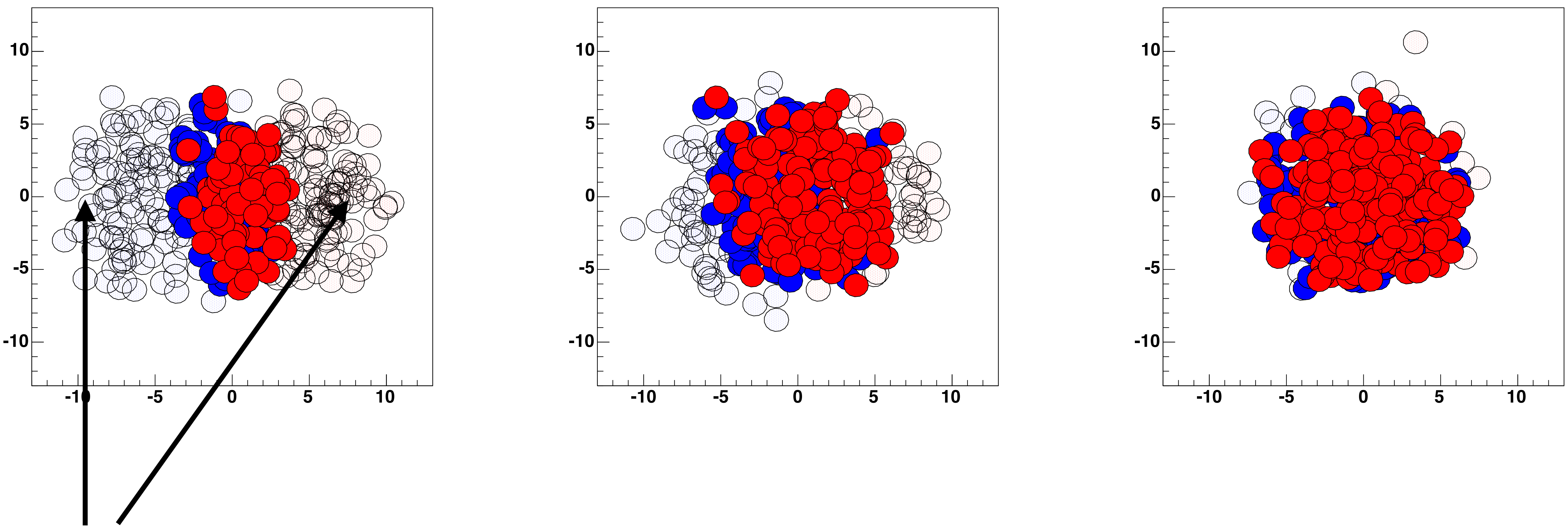

STAR

collision geometry



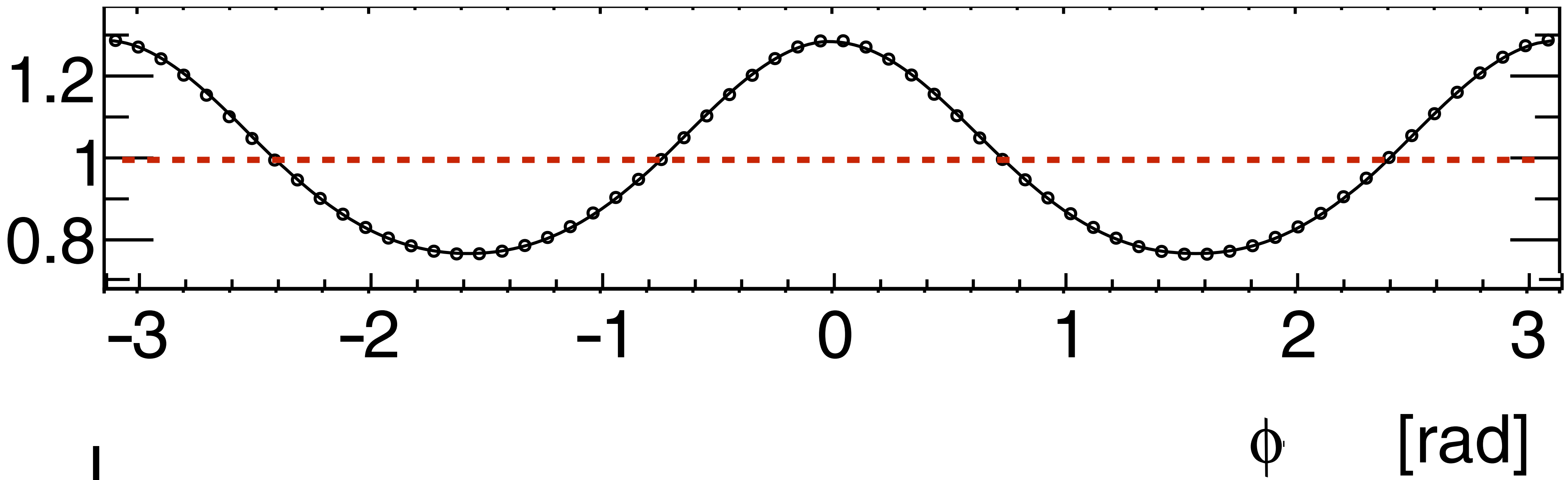
view: one nuclei going into the screen and one coming out

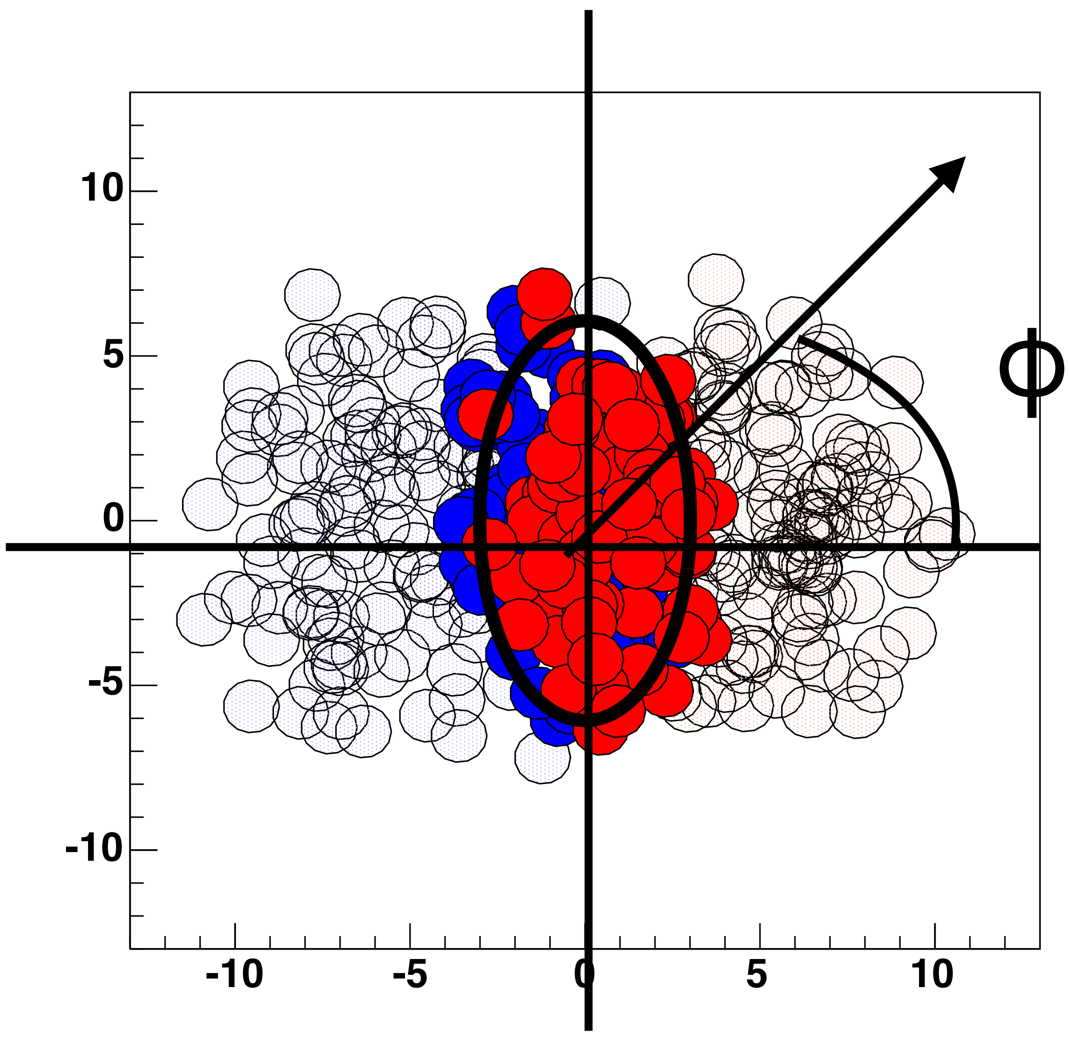
varying the distance between the nuclei, changes the shape and size of the region where the nuclei overlap



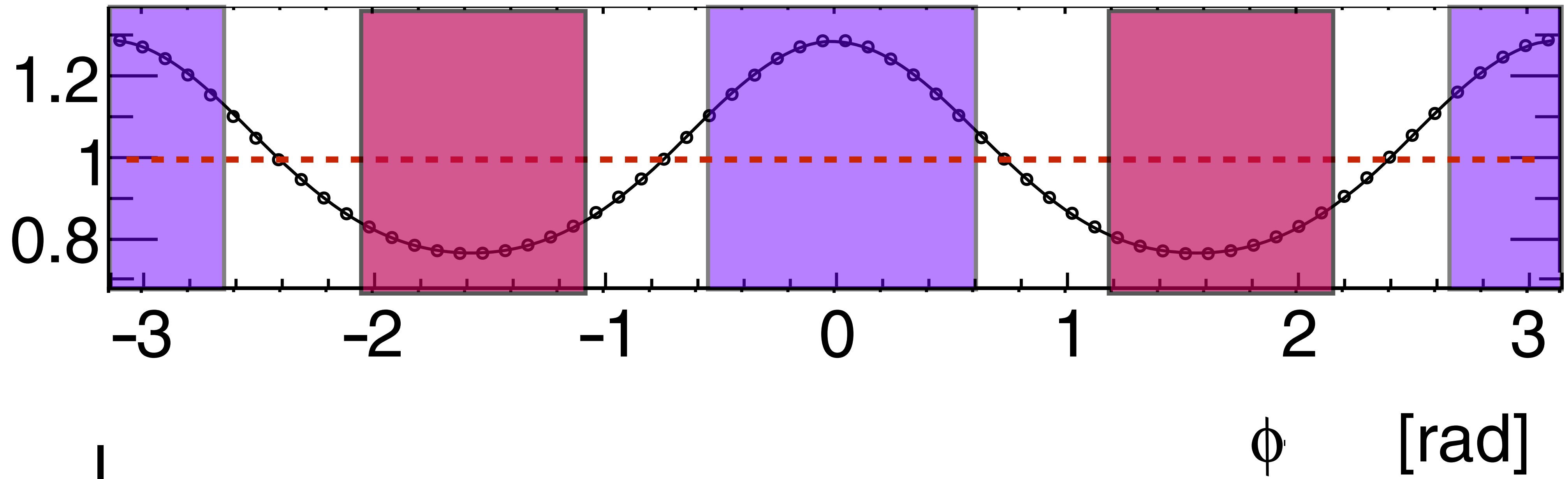
the parts of the nuclei that don't overlap continue on and don't play a role

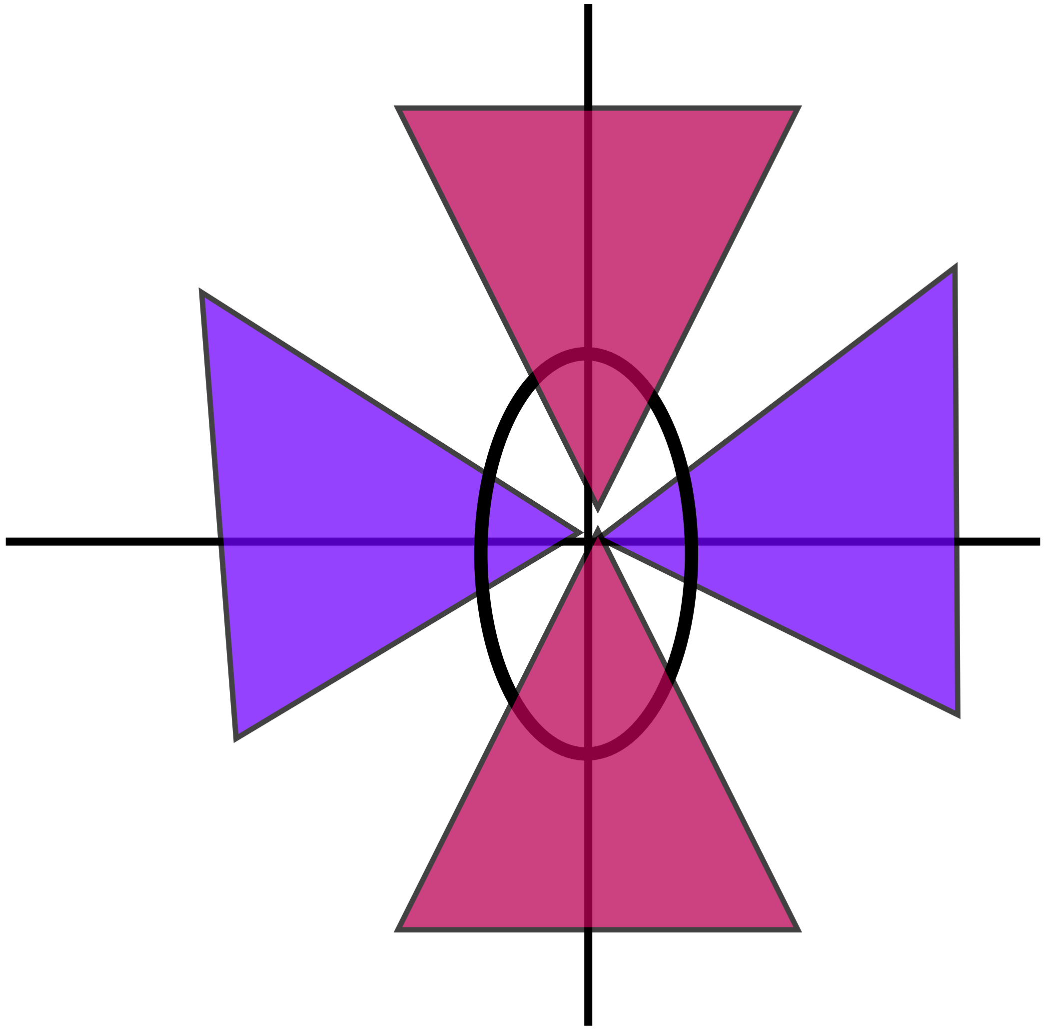
counting particles





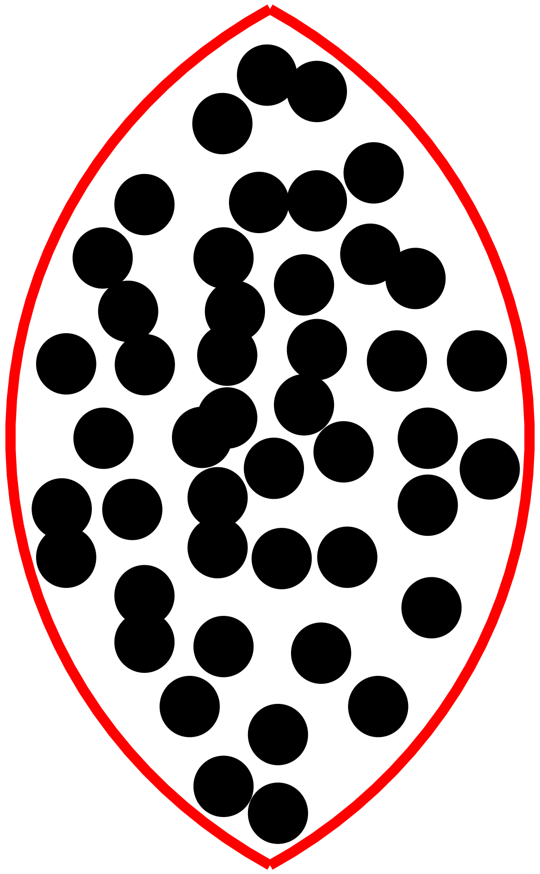
collision geometry





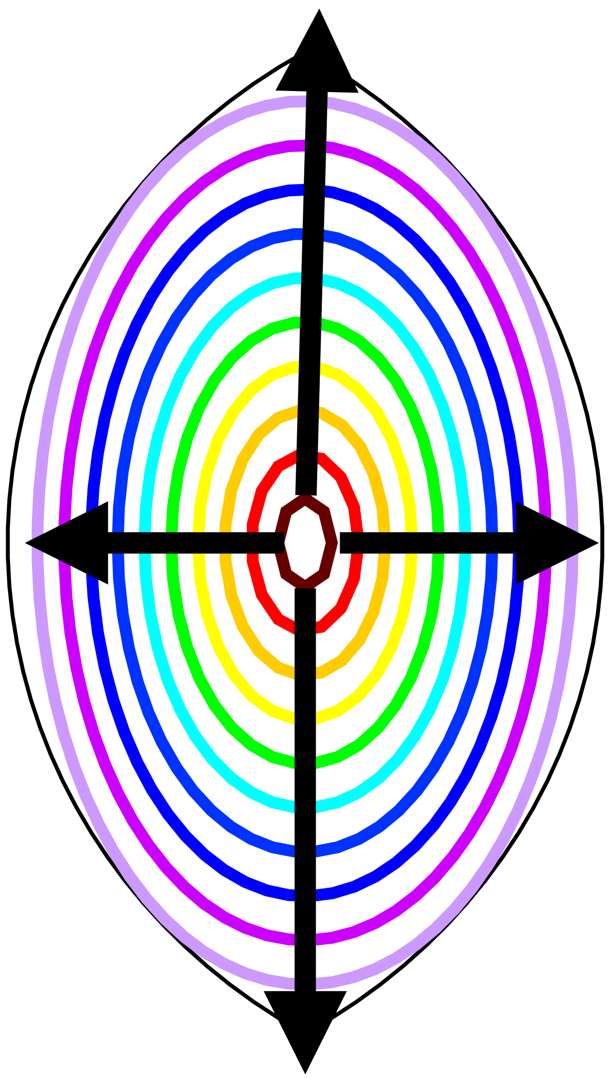
more particles come out the long side than the short side!

interactions are important



liquid rather than a gas

gradual pressure change



steep pressure change

characterizing a liquid

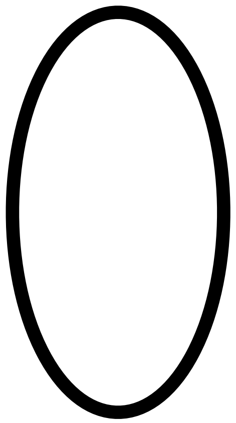
- liquids flow

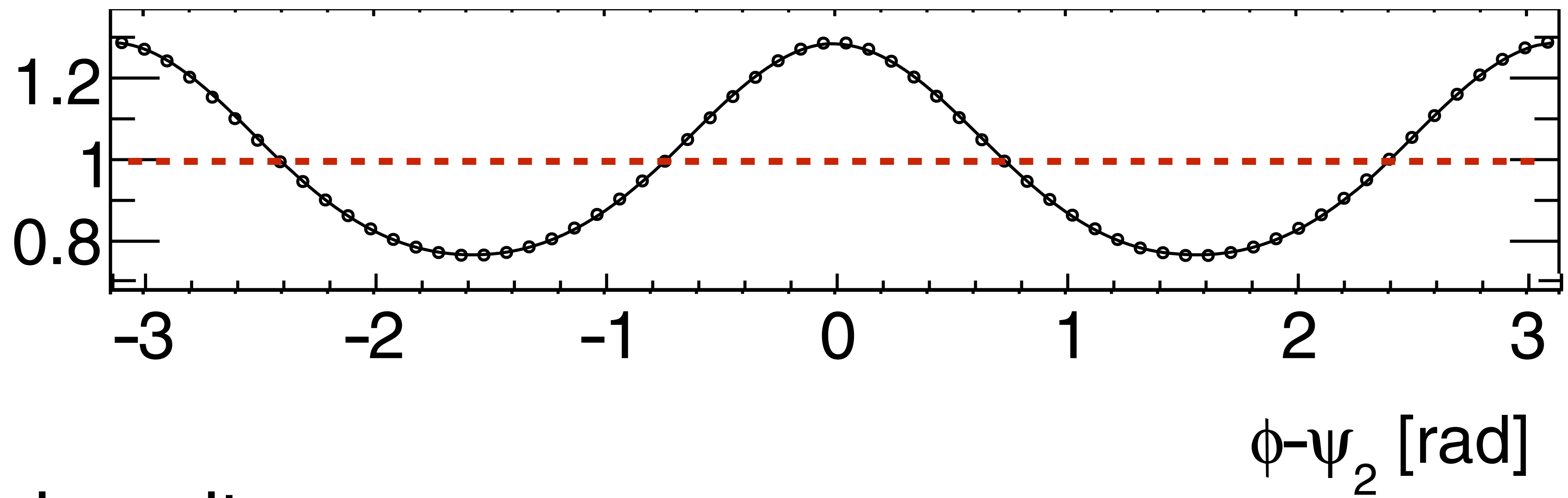
low viscosity

high viscosity

liquid QGP

QGP flows well!





low viscosity

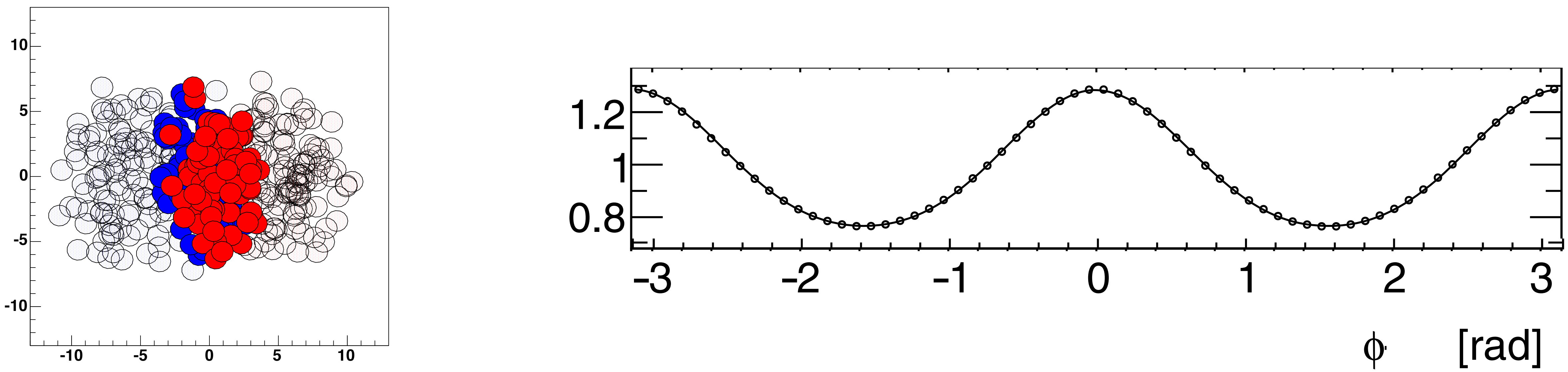
$\eta/s > 25\ (1/4\pi)$

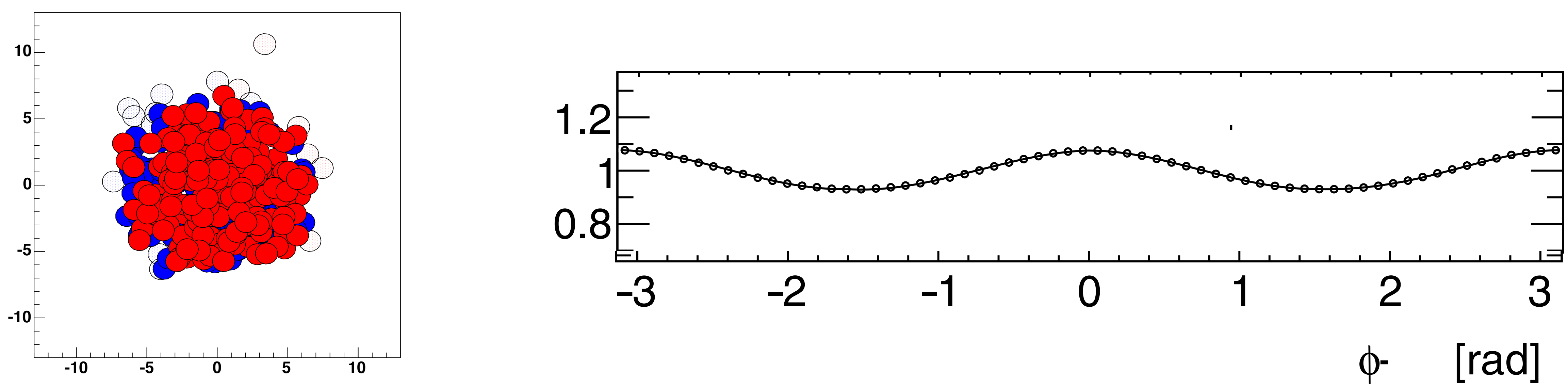
$\eta/s(\mathrm{QGP}) < 5\ (1/4\pi)$

string theory calculation:
universal minimum
$\eta/s > 1/4\pi$

determining $\eta/s(\mathrm{QGP})$
is very important

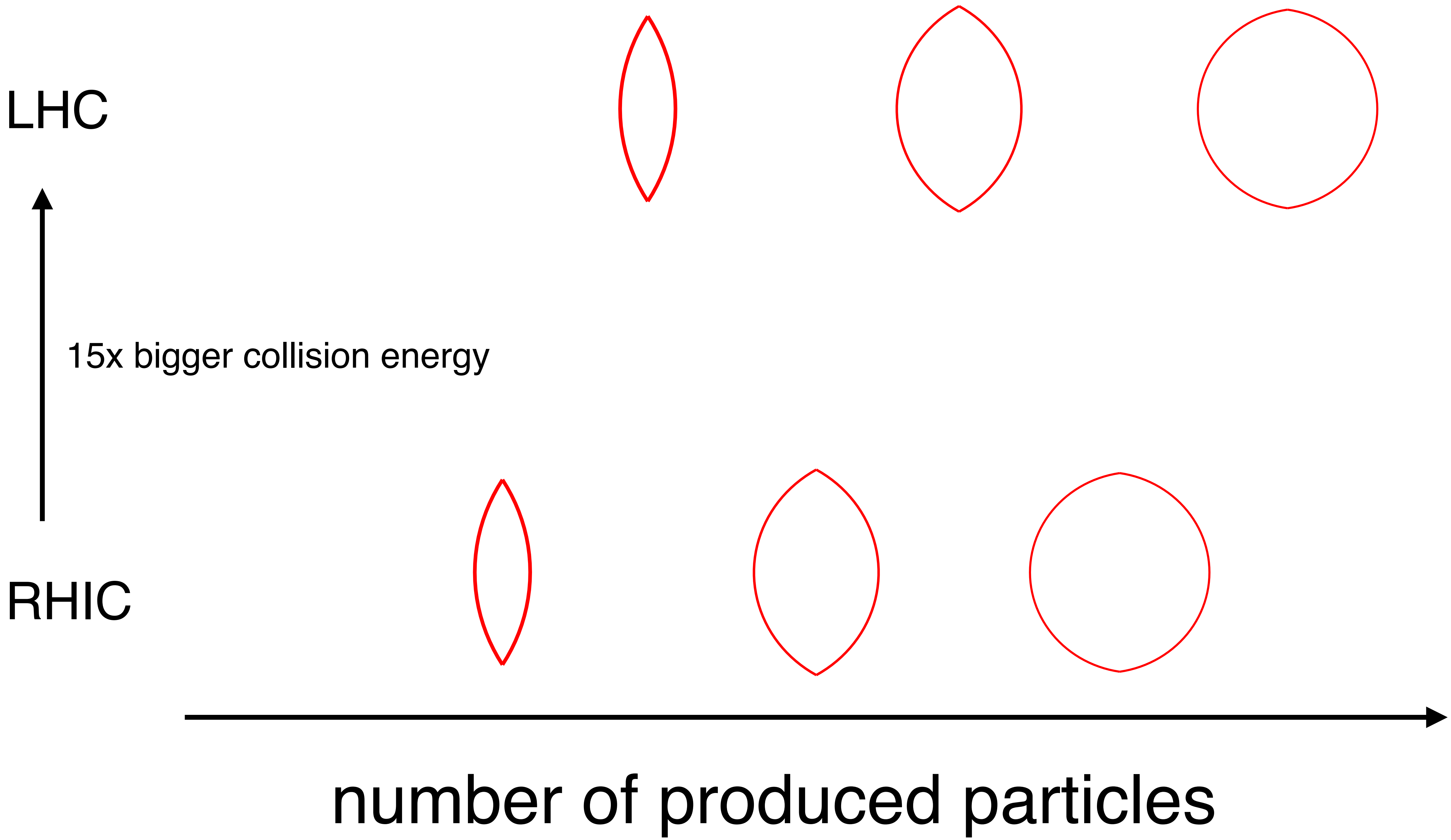
shape changes and particle distributions



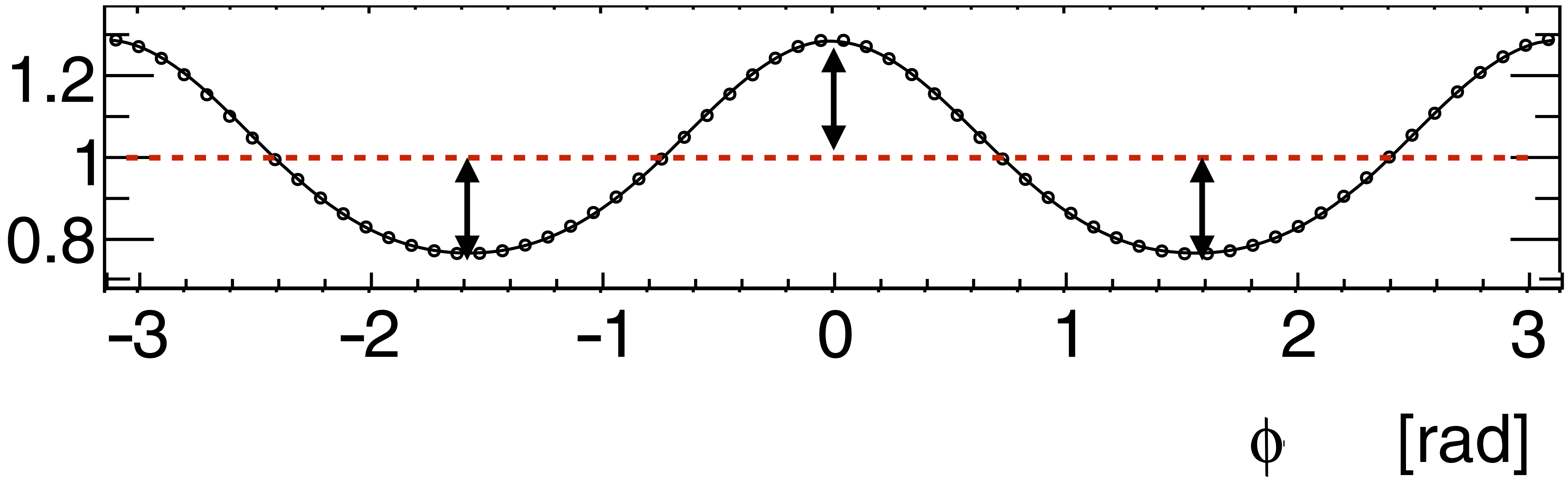


ATLAS PLB 707 330 (2012)

isolating shape effects

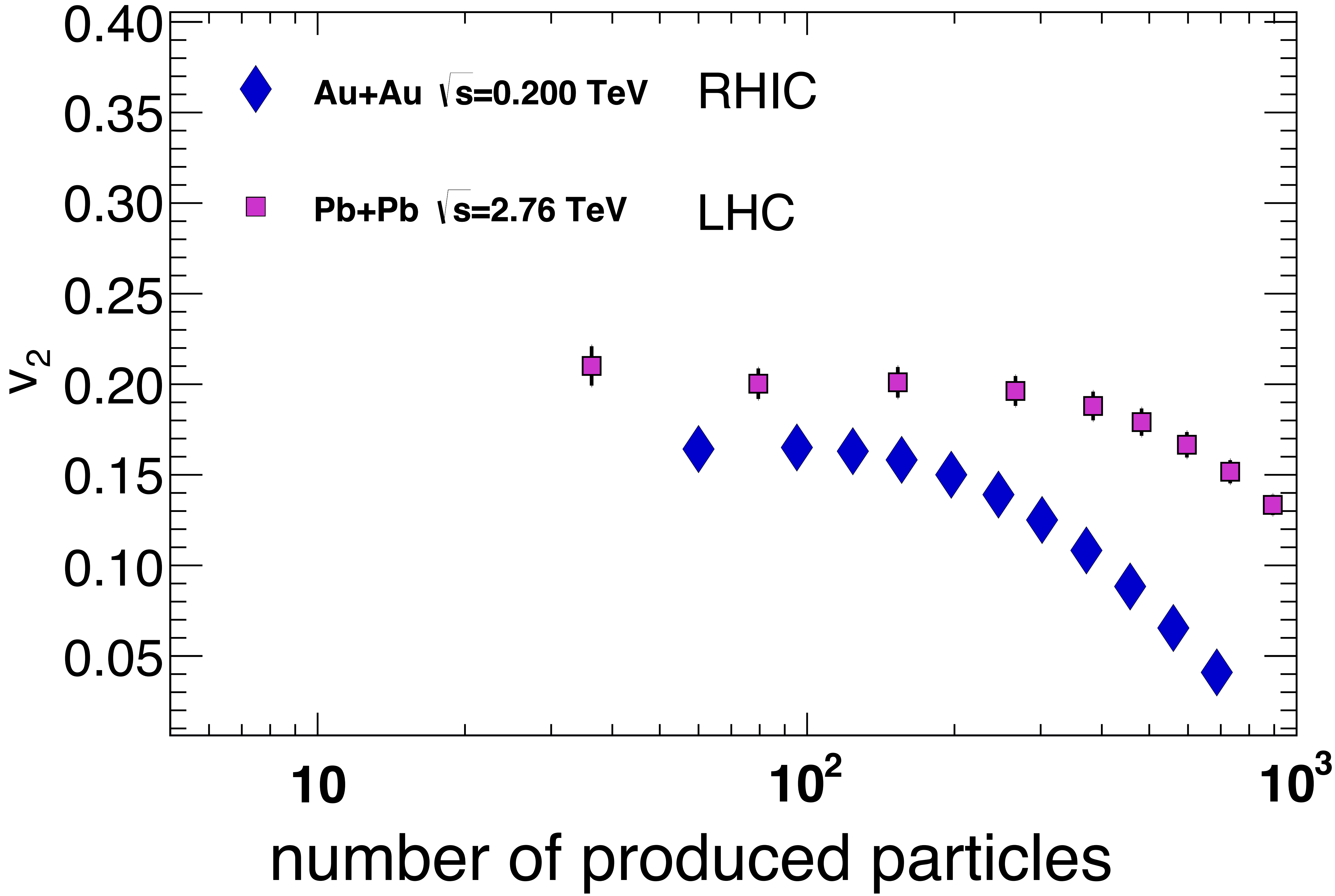


characterizing particle distributions



v_2 is the strength of the modulation

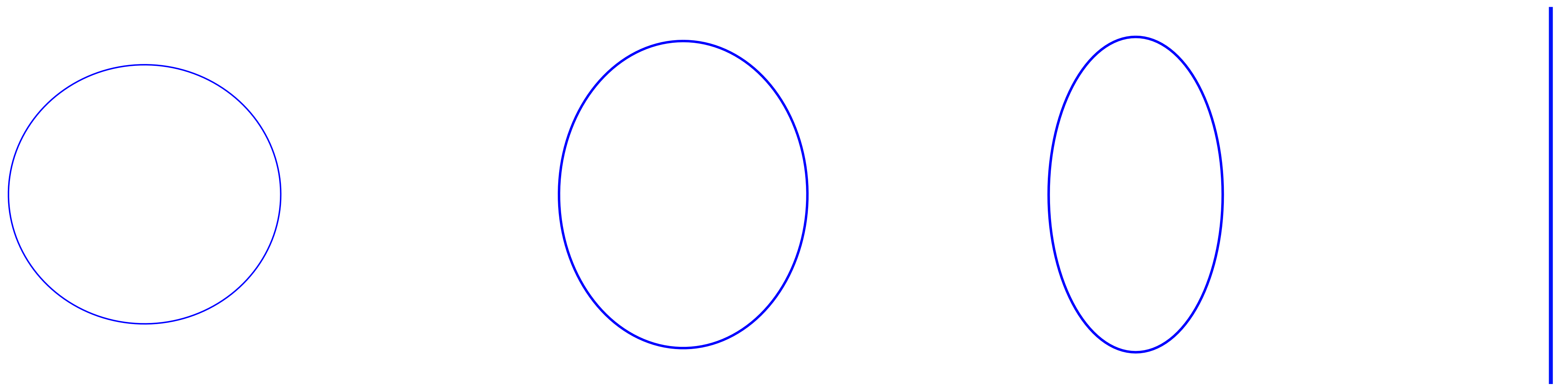
v_2 in heavy ion collisions



PHENIX PRL 105 062301
CMS PRC 87 014902

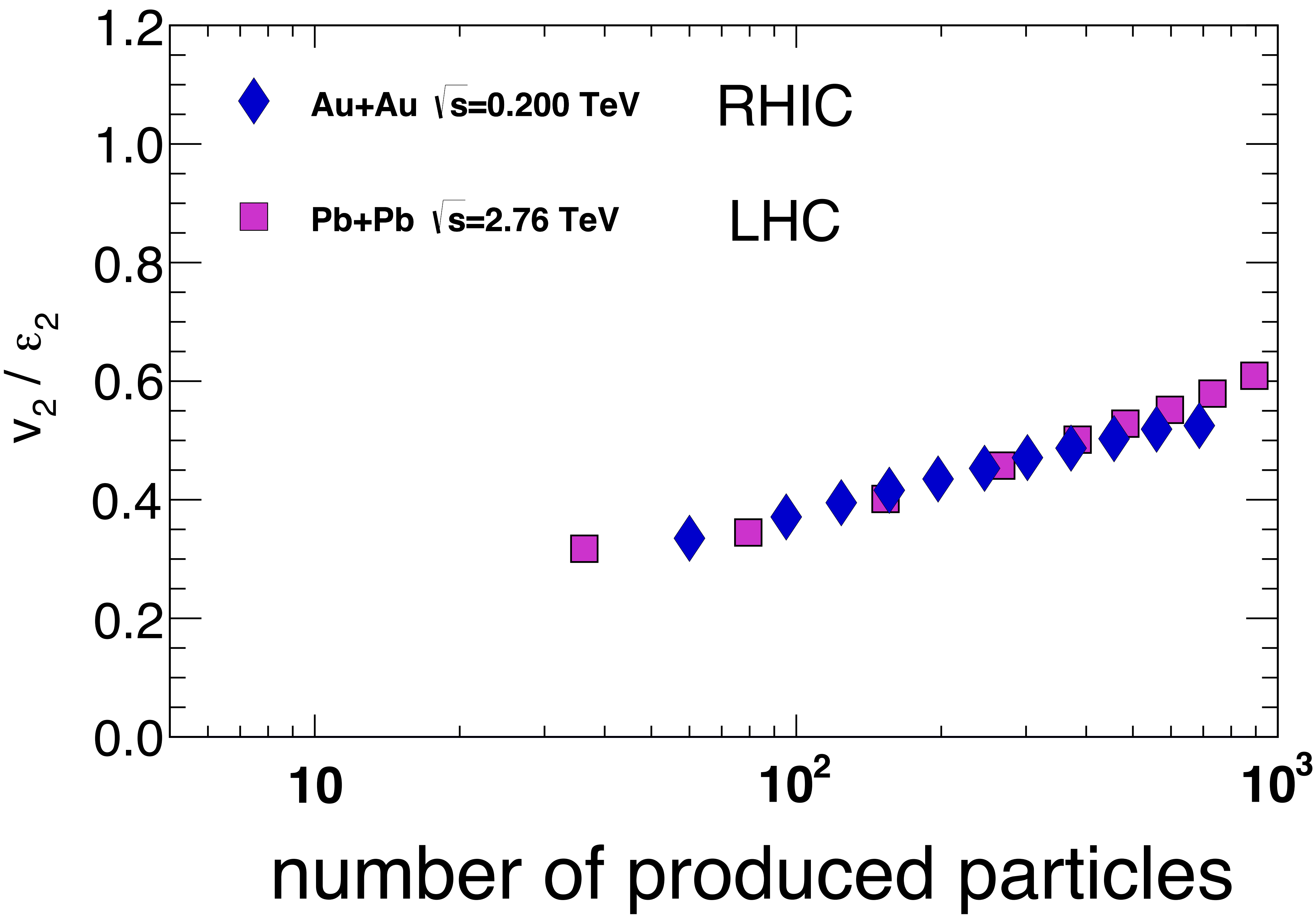
quantifying shapes

eccentricity (ε_2) is related to how elongated any shape is



$\varepsilon_2 = 0$ $\varepsilon_2 = 0.17$ $\varepsilon_2 = 0.50$ $\varepsilon_2 = 1$

ratio: v_2 / ε_2

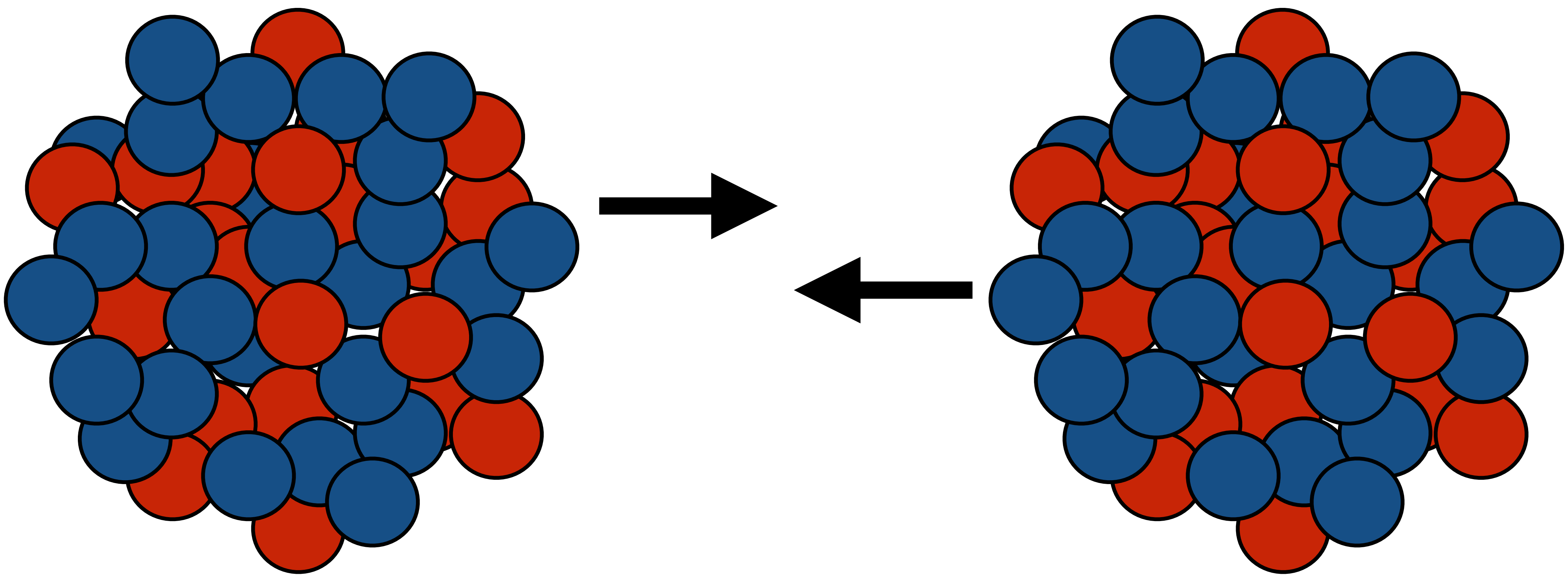


relationship between geometry (ε_2) and v_2 is a signature of small viscosity QGP

How Small can the Quark Gluon Plasma Be?

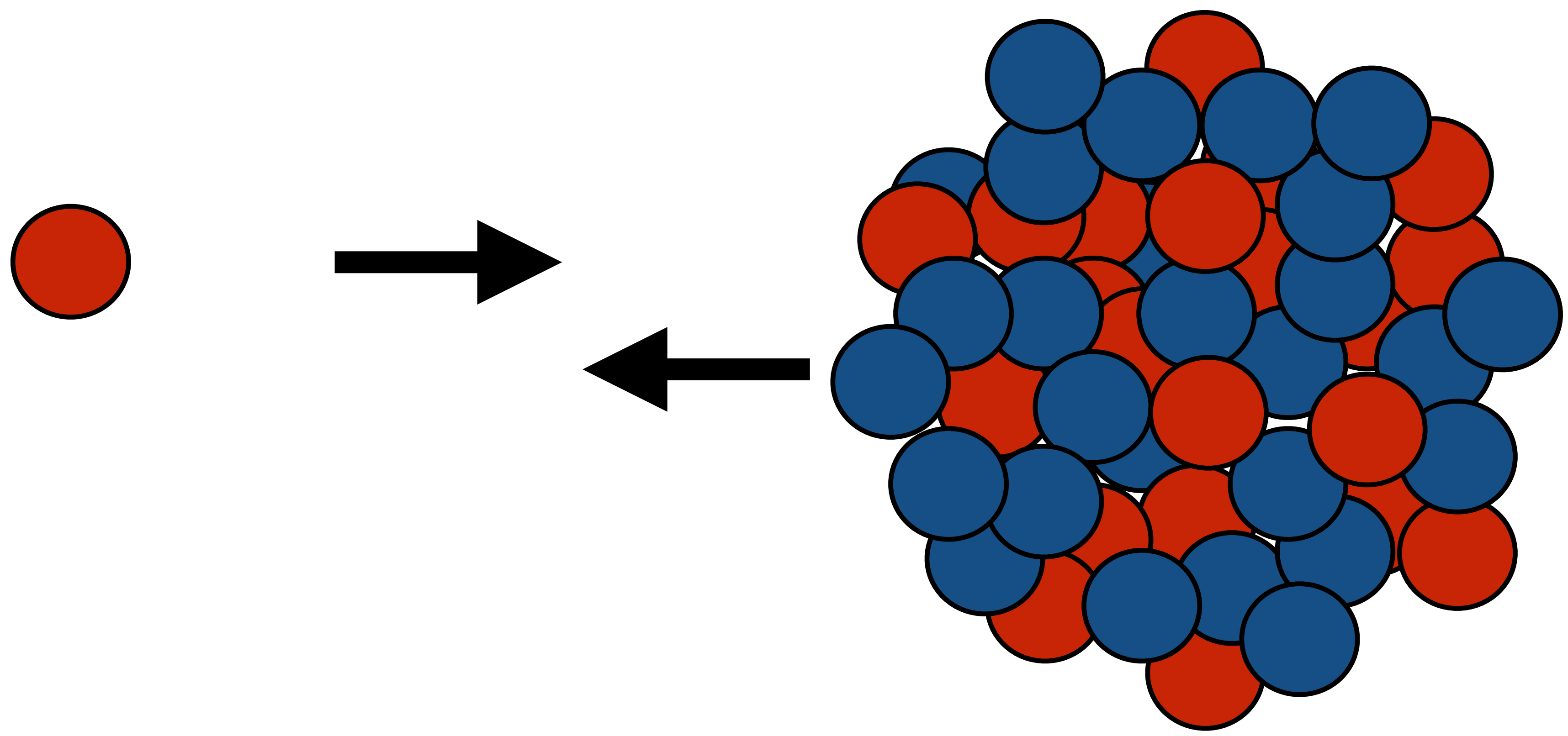
why take something so small and make it smaller?

- changing the shape and size of the QGP help to measure the viscosity

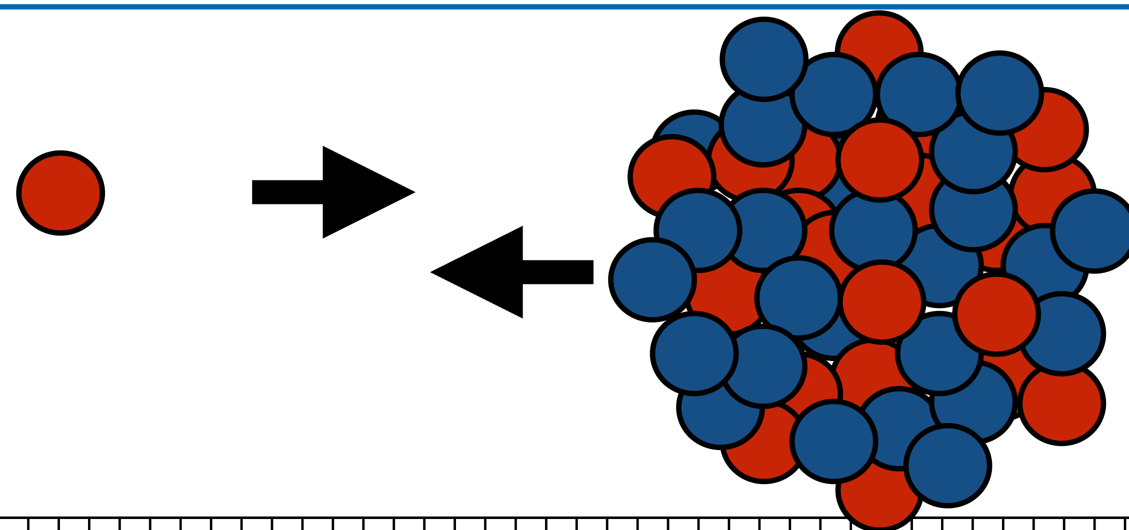


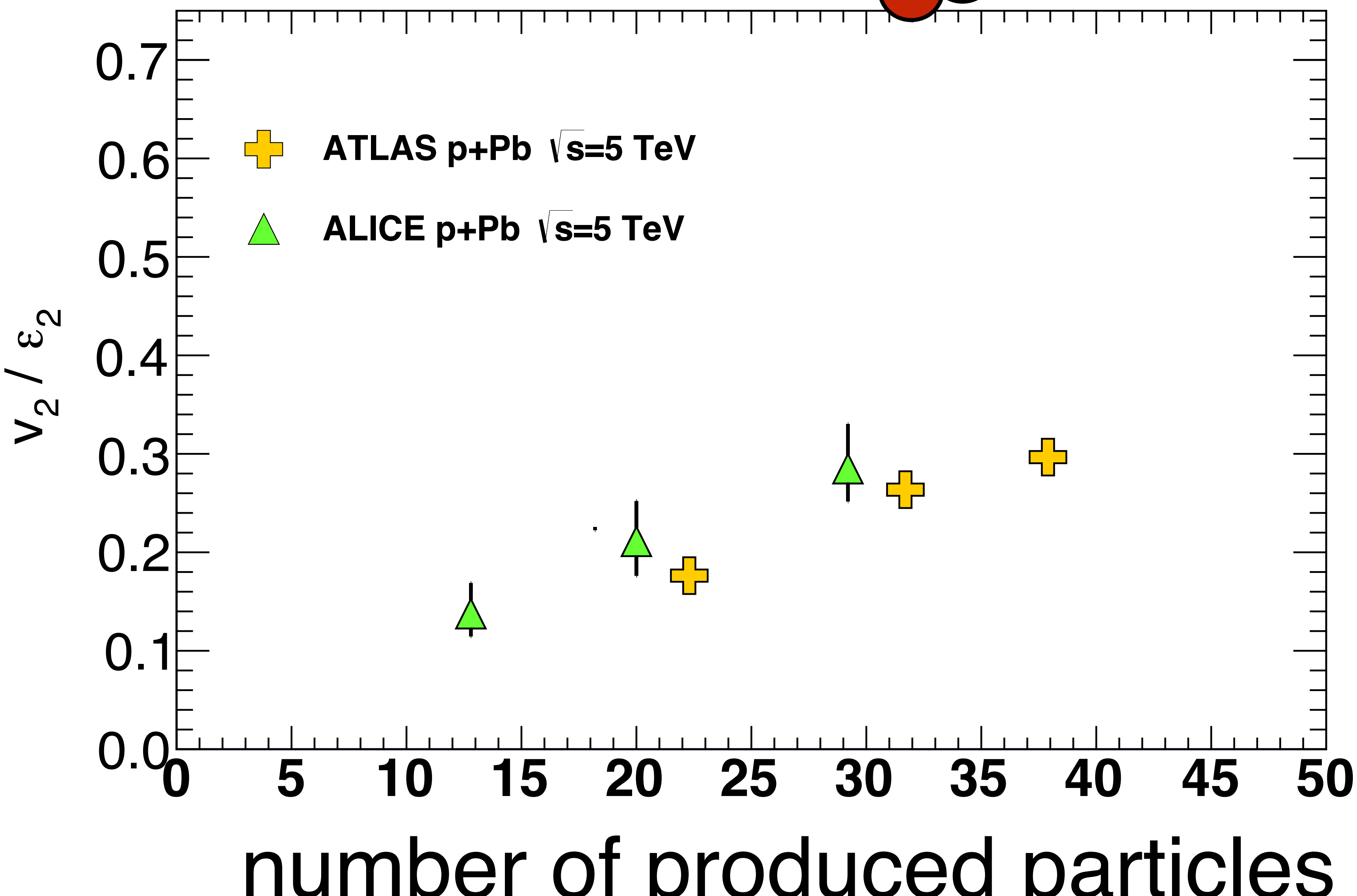
why take something so small and make it smaller?

- changing the shape and size of the QGP help to measure the viscosity



v2 in p+Pb collisions @ the LHC

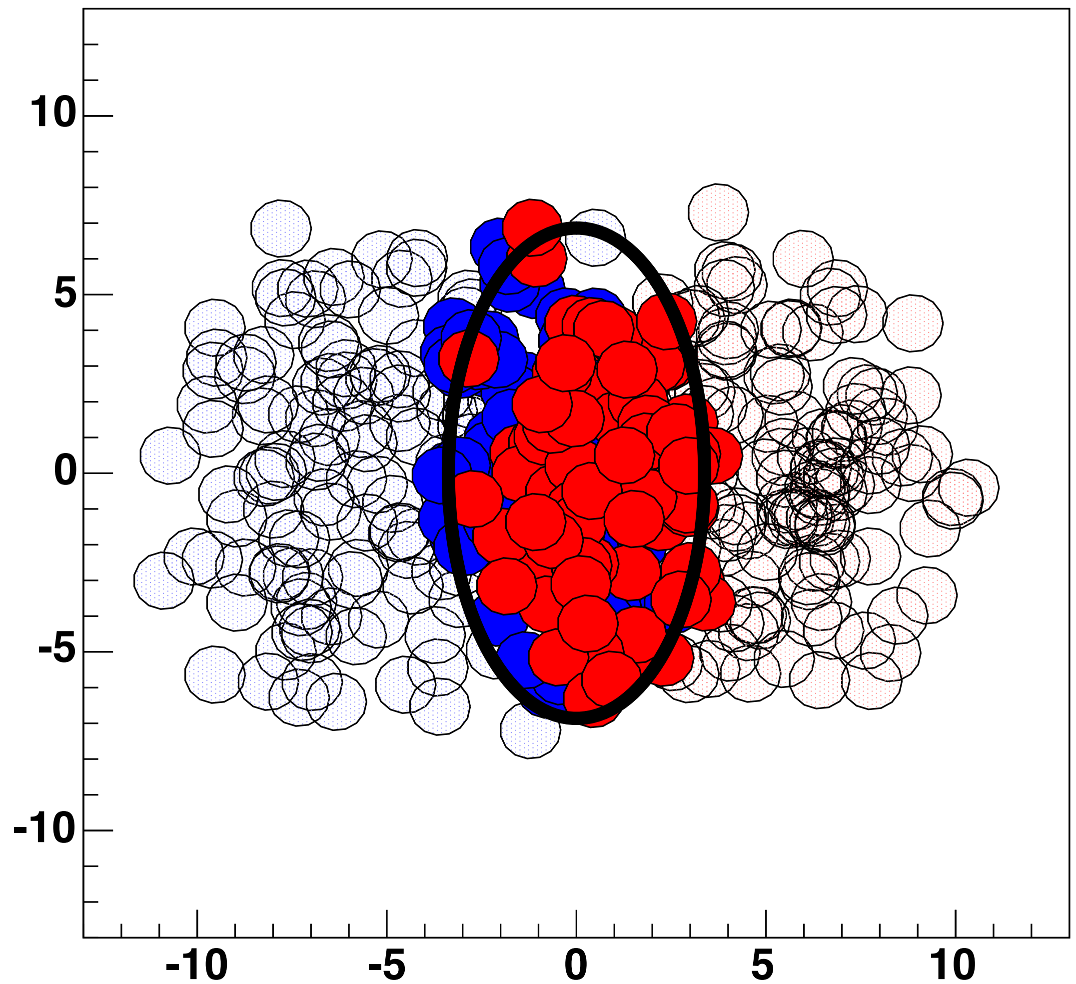




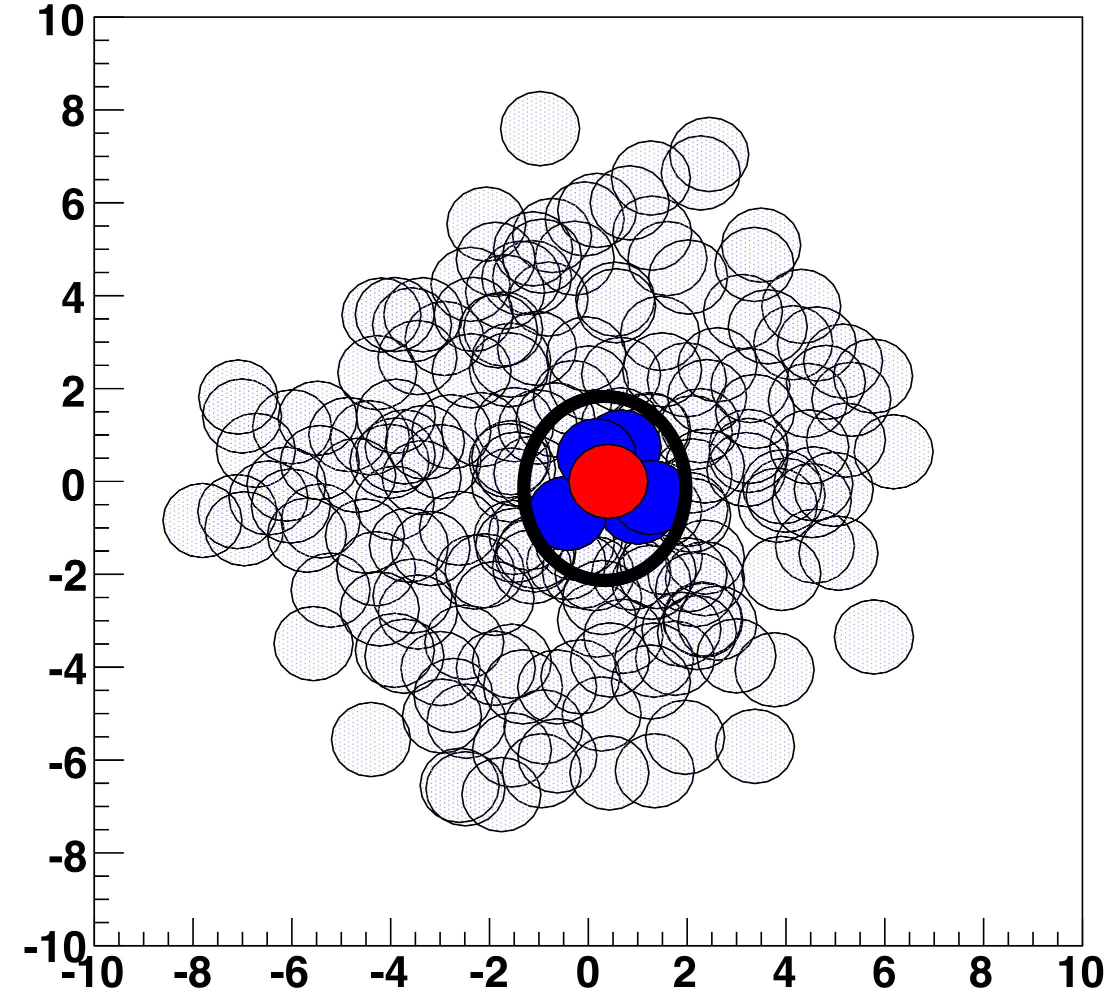
ALICE PLB 719 29 (2013)
ATLAS PRL 110 182302 (2013)

big vs small collisions

large ε_2



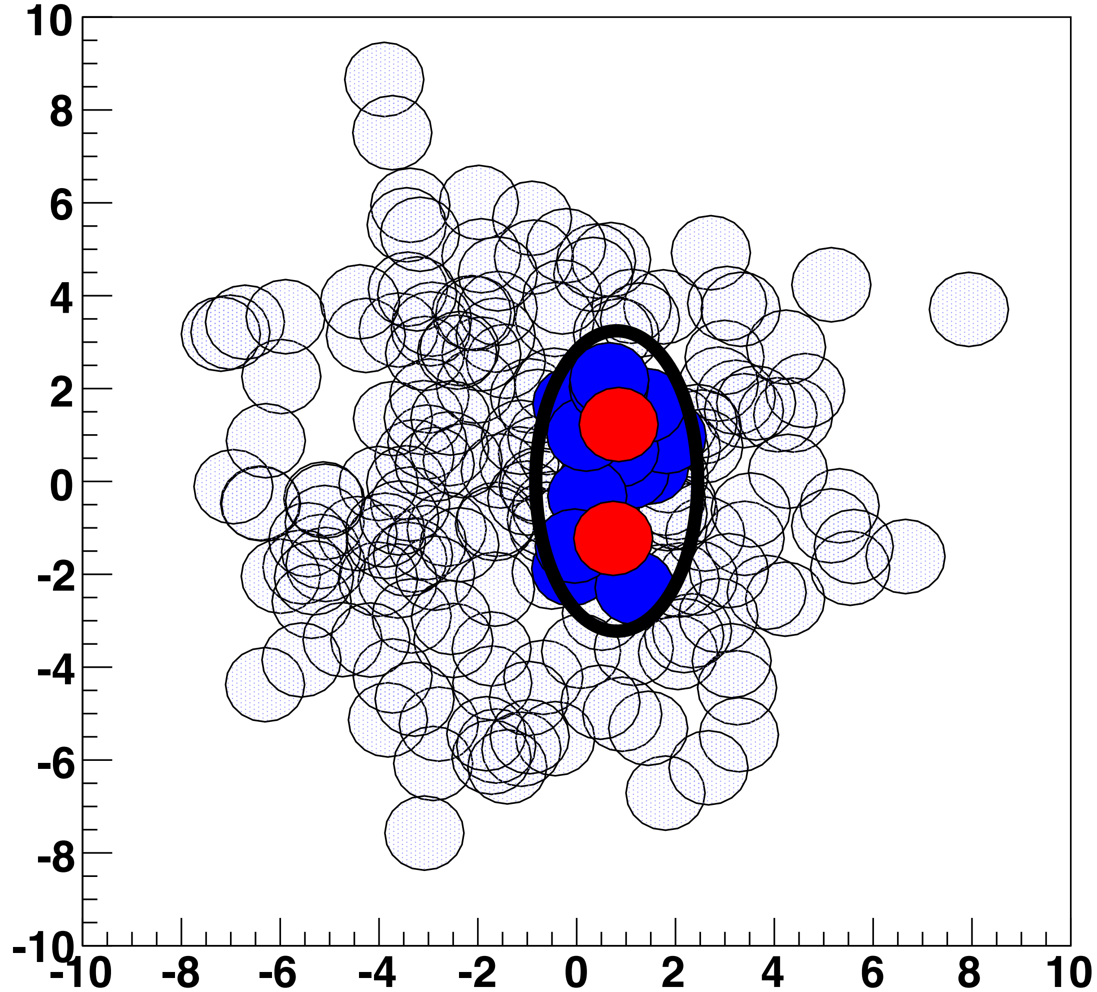
small ε_2



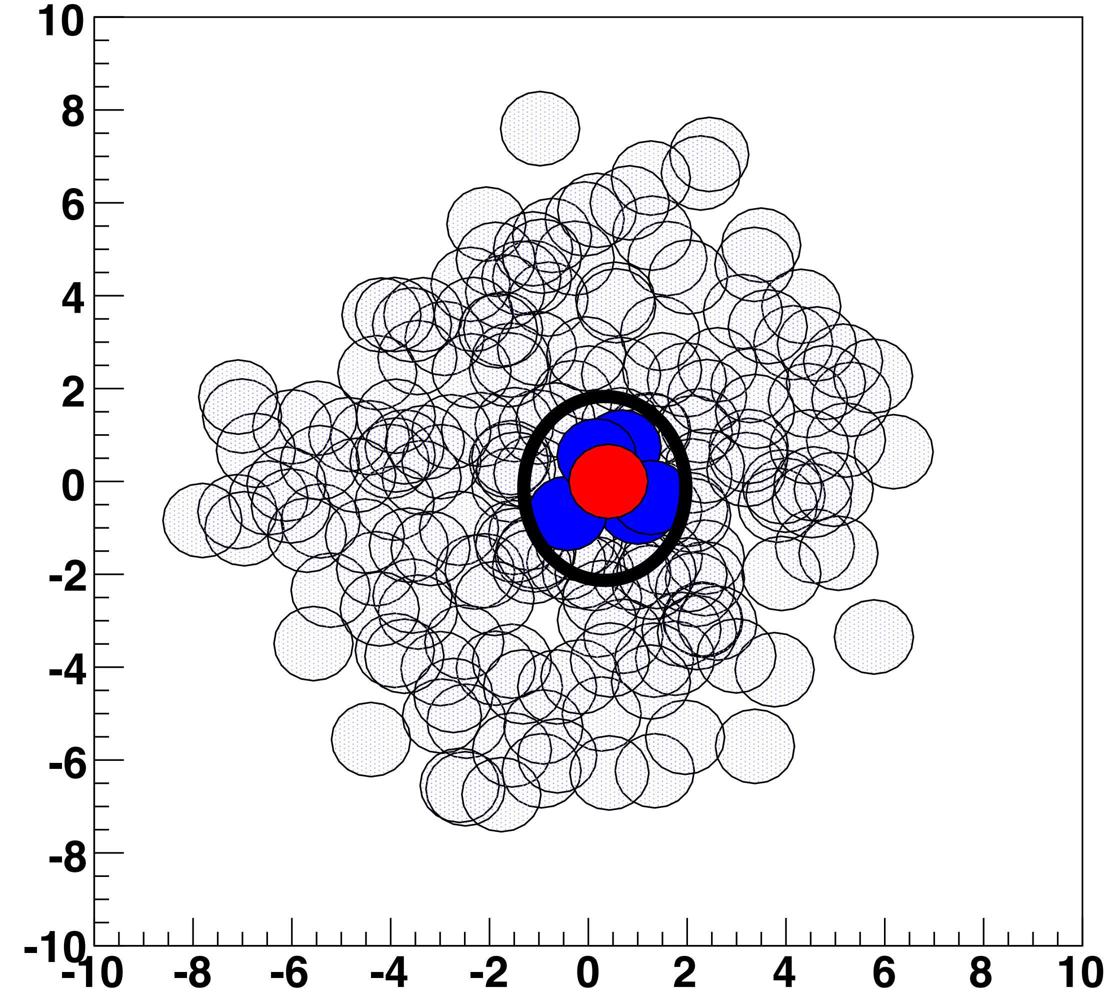
can we have a collision with large eccentricity, but similar size to p+Pb?

varying the small nucleus

d+Au
large ε_2

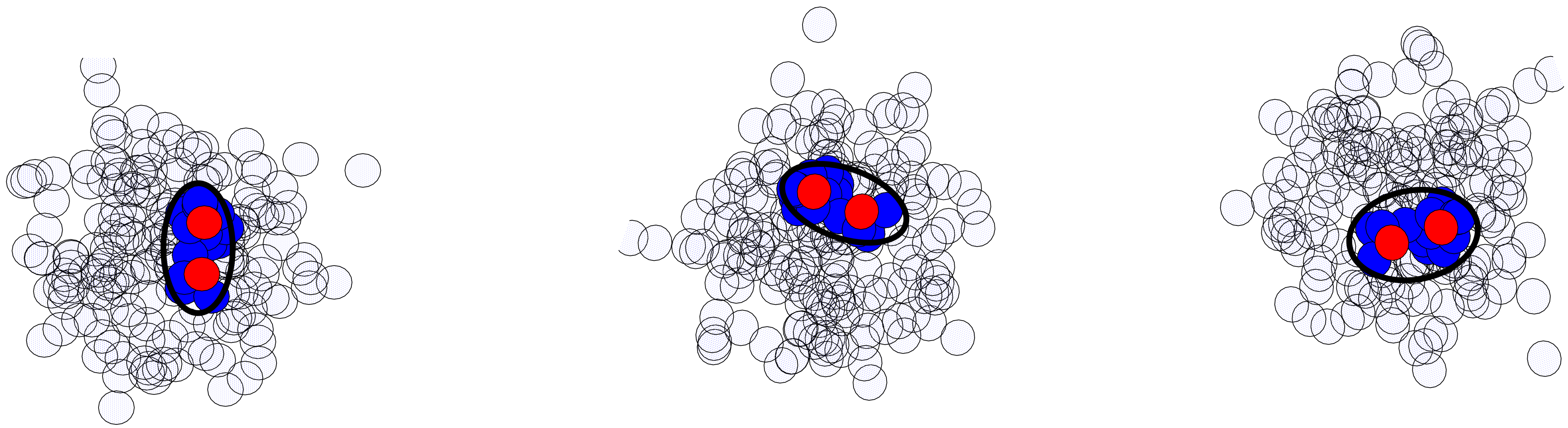


p+Pb
small ε_2



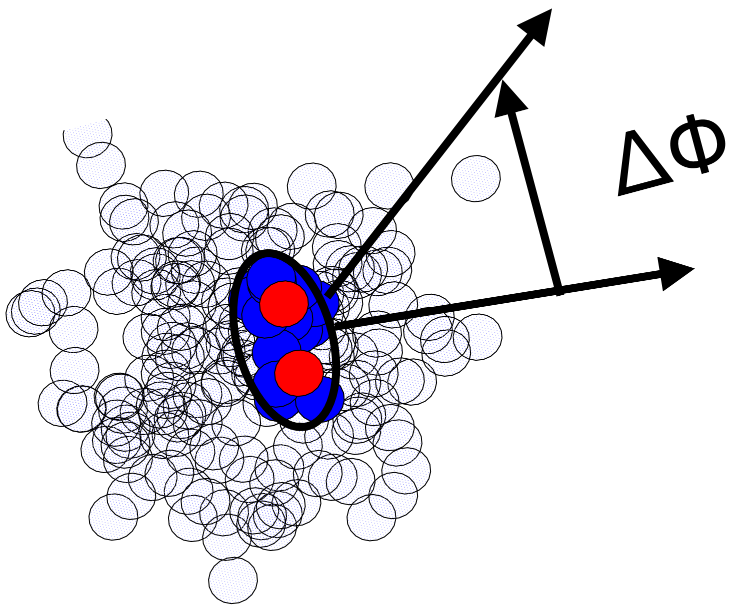
deuteron (d): 1 proton and 1 neutron

which way does the ellipse go?



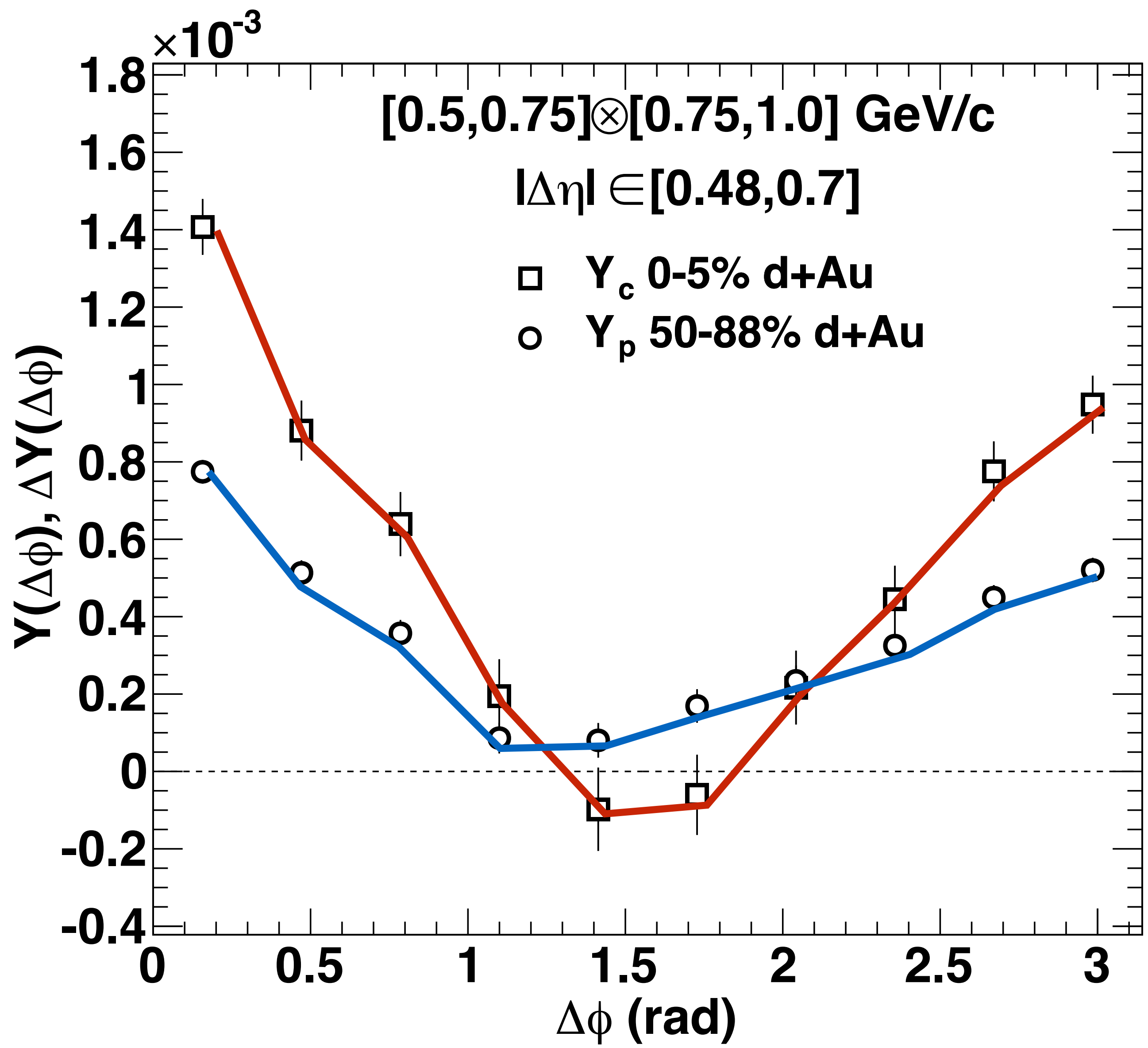
in any given event, we can’t control it and it’s hard to measure for these small systems

looking for v2 in d+Au



correlations between pairs of particles
each particle knows something about the collision orientation, but the precision is low

also, there are lots of reasons for particles to be correlated



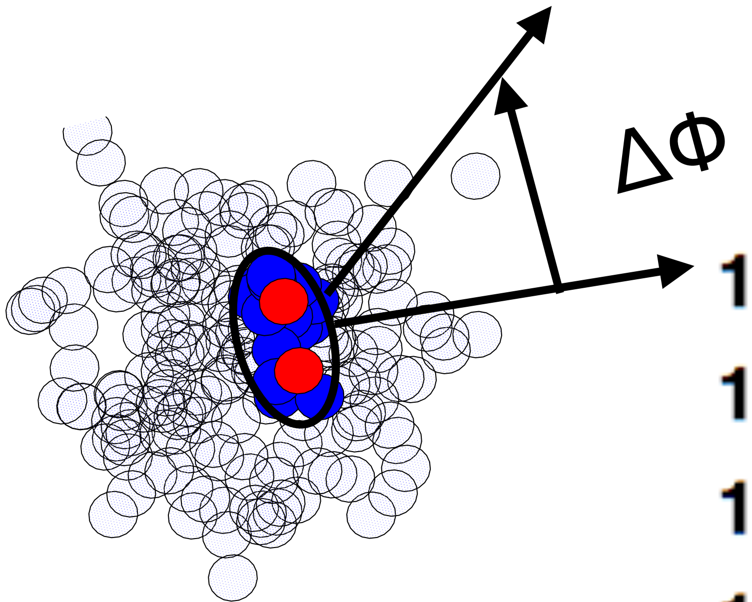
signal + background

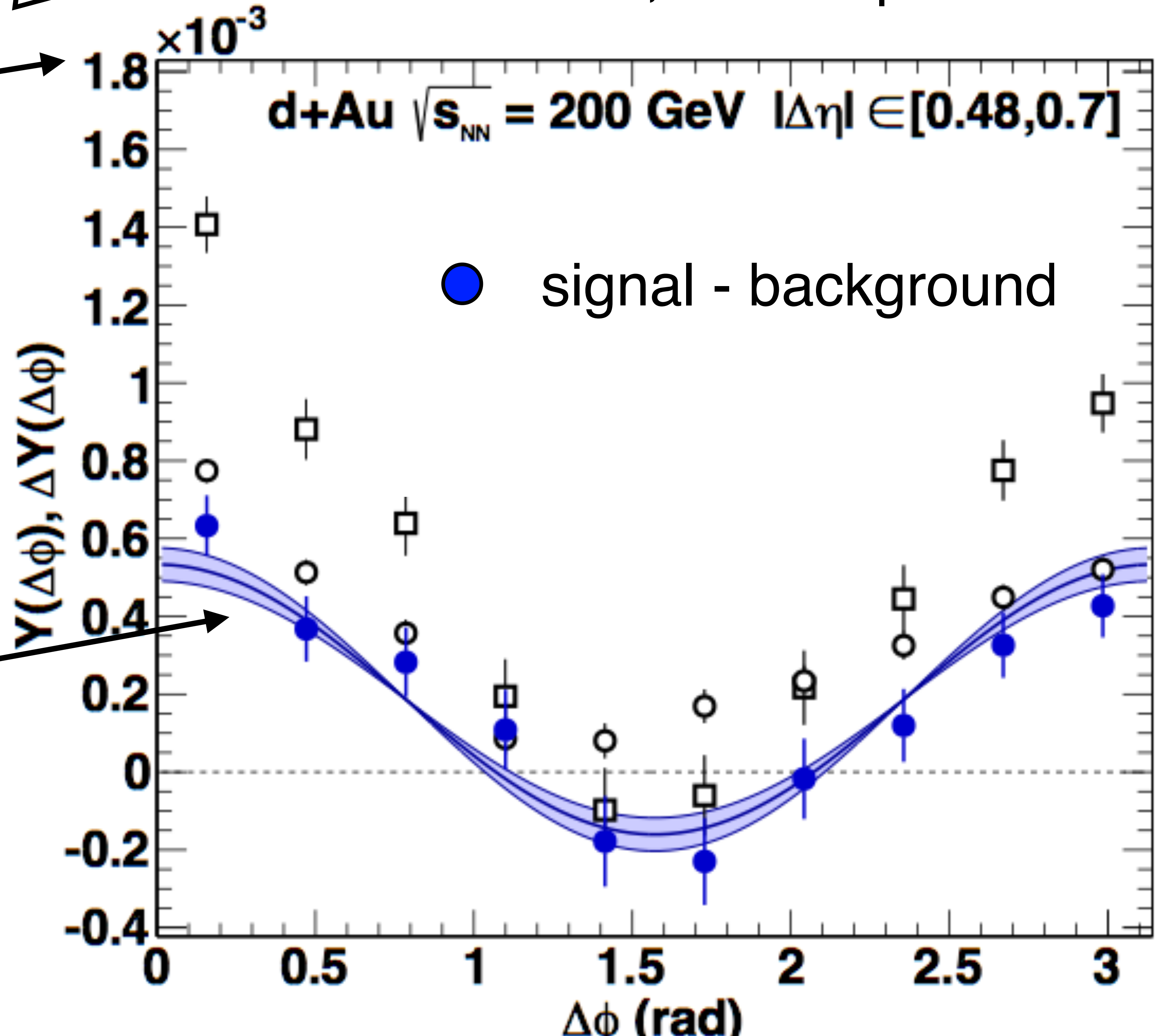
background

hunting down the signal

correlations between pairs of particles

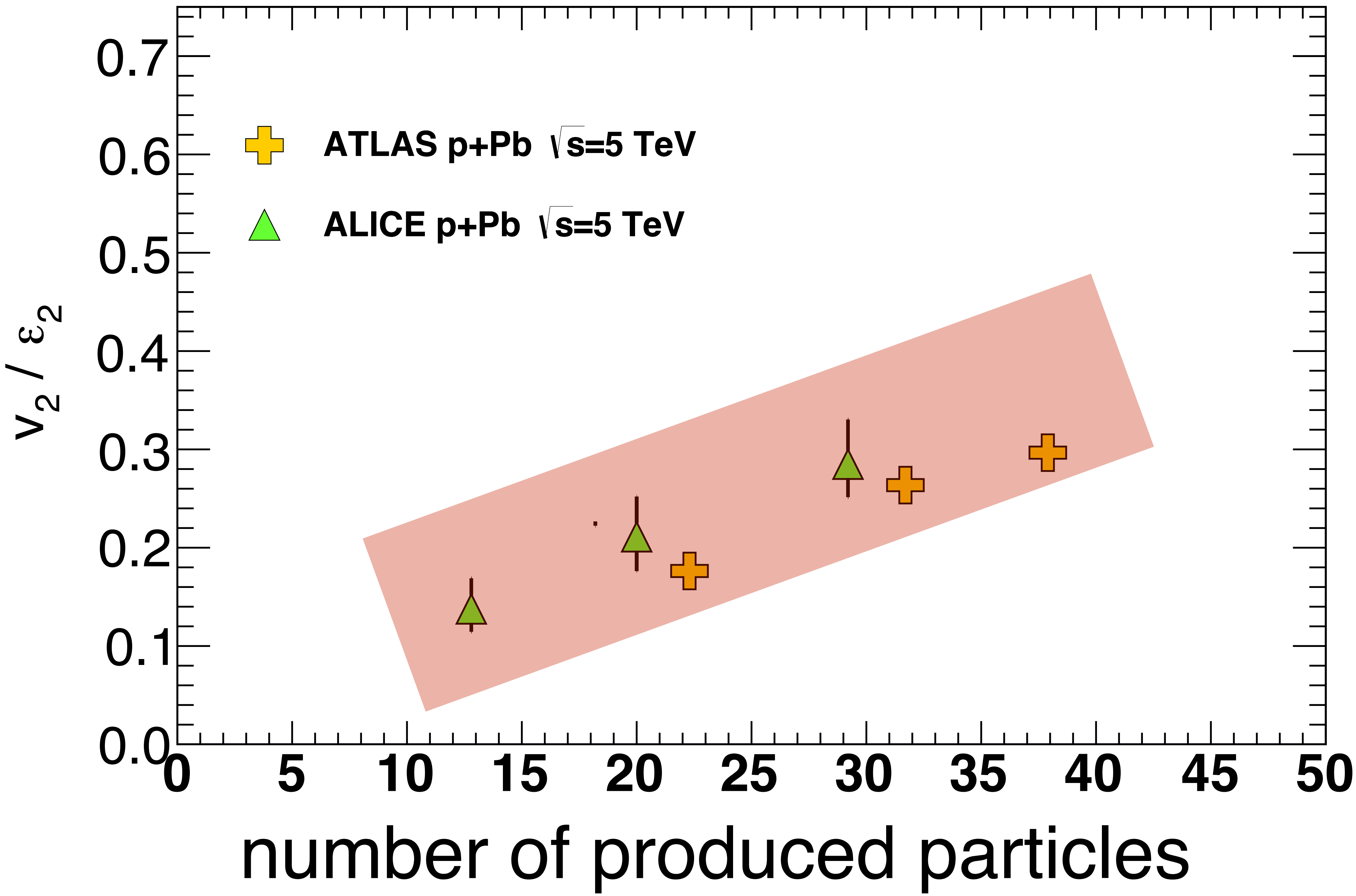
each particle knows something about the collision orientation, but the precision is low





$v_2^2\cos2\Delta\phi$

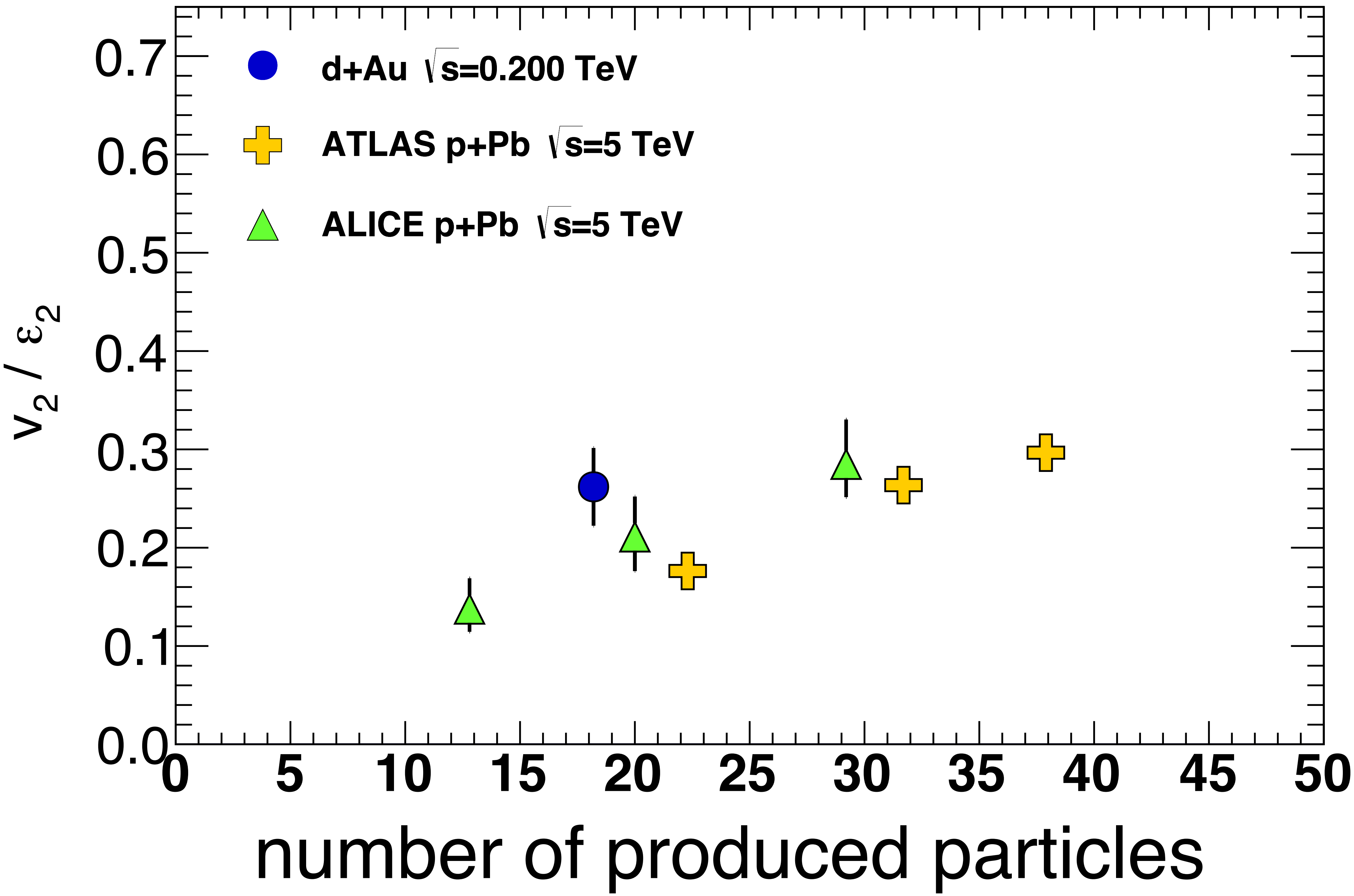
v_2 / ε_2, expectations in d+Au



QGP

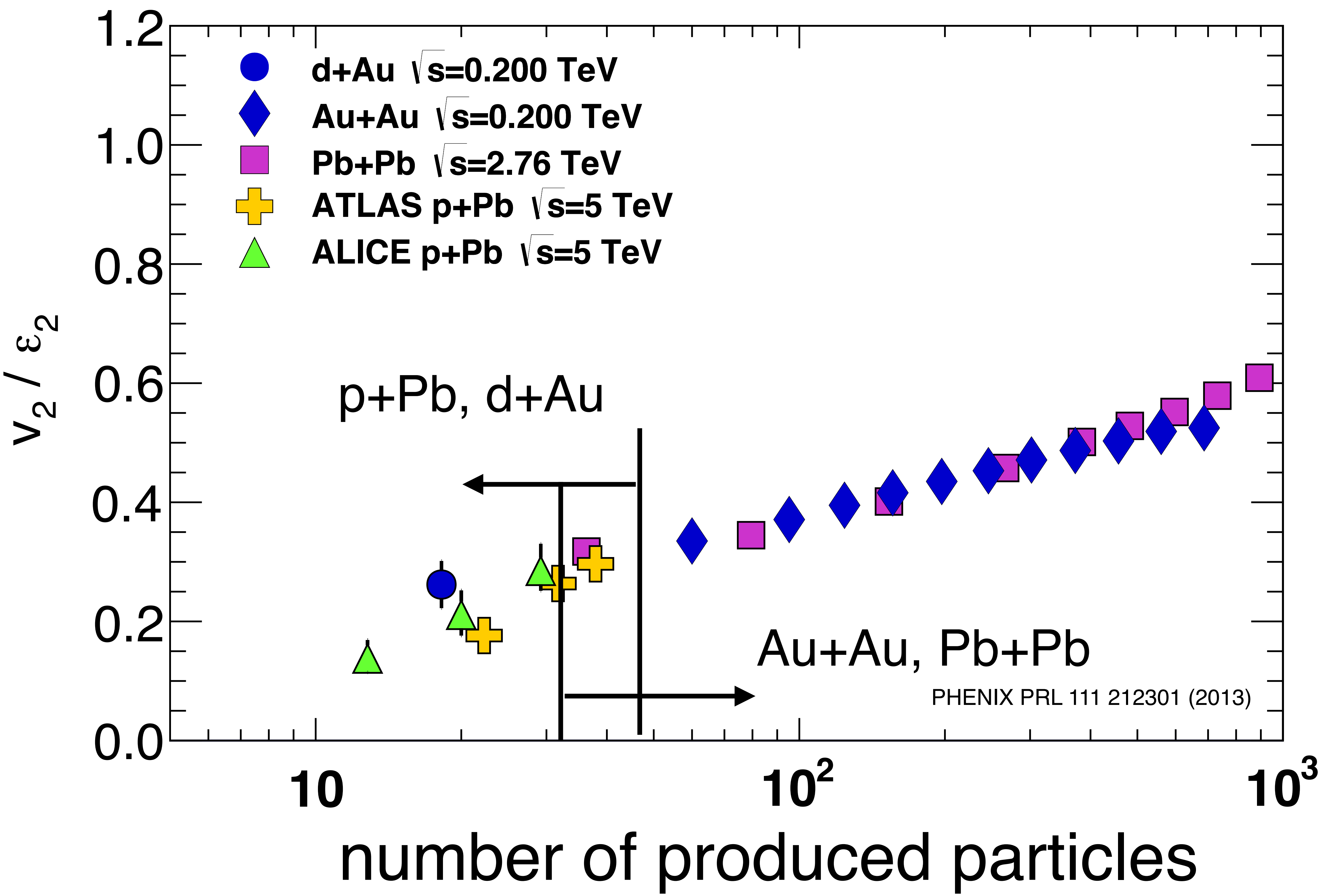
ALICE PLB 719 29 (2013)
ATLAS PRL 110 182302 (2013)

v_2 / ε_2



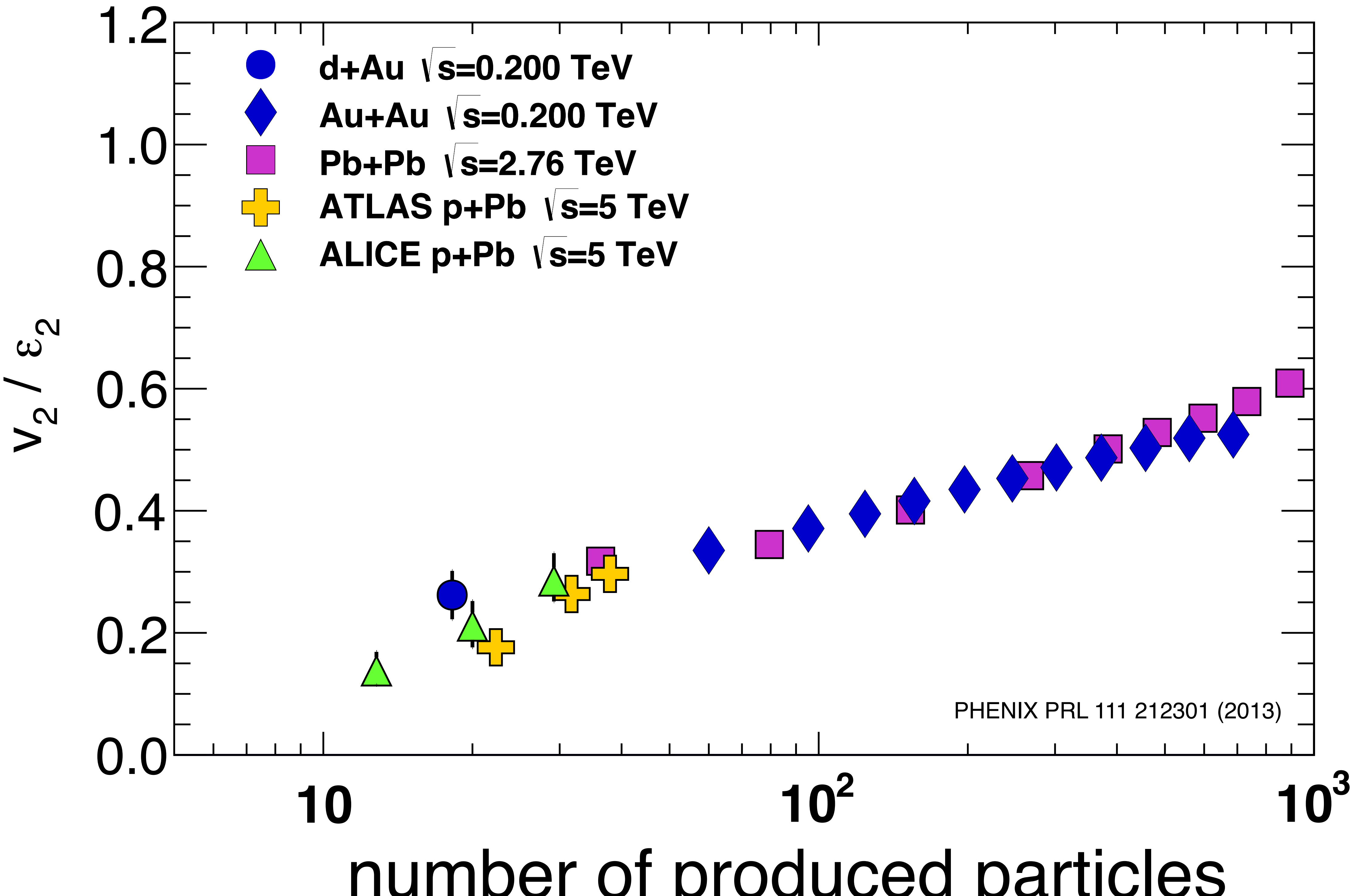
PHENIX PRL 111 212301 (2013)
ALICE PLB 719 29 (2013)
ATLAS PRL 110 182302 (2013)

a small QGP?



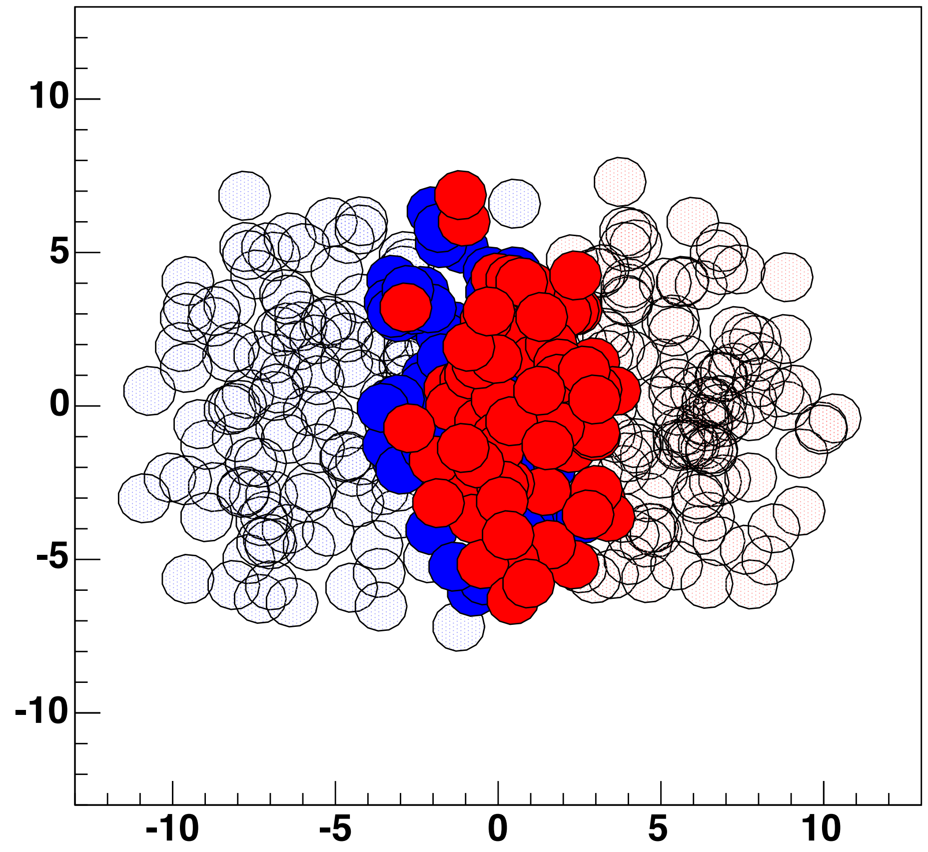
continuous behavior from big to small collisions

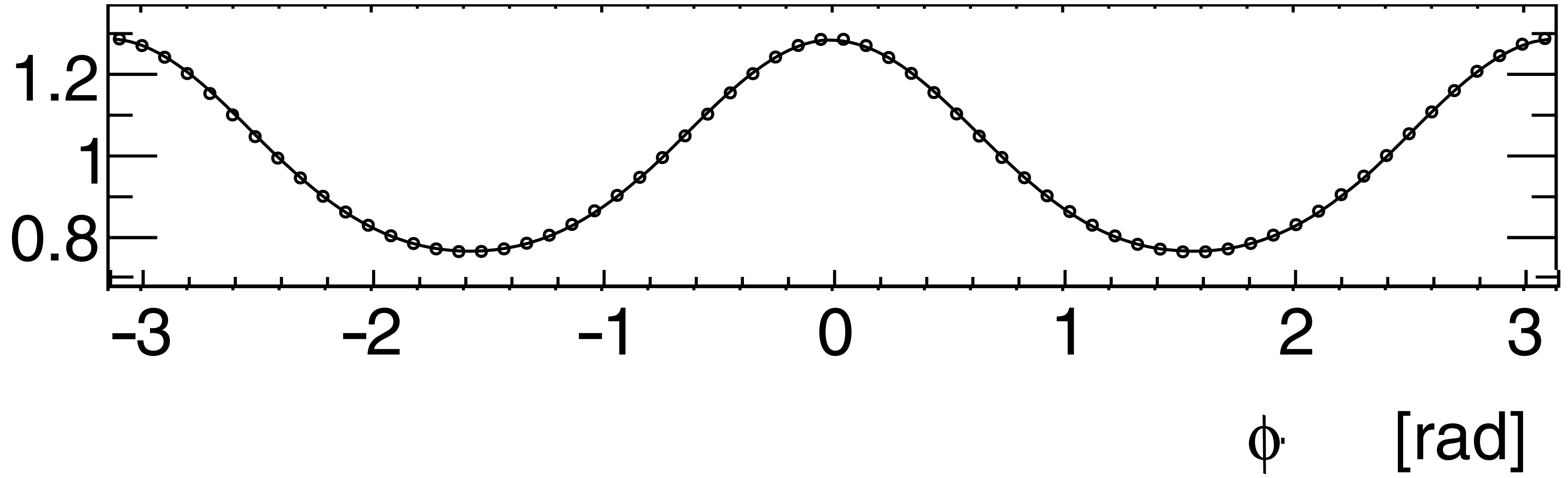
a small QGP?



continuous behavior from big to small collisions

particle distributions reflect initial shape

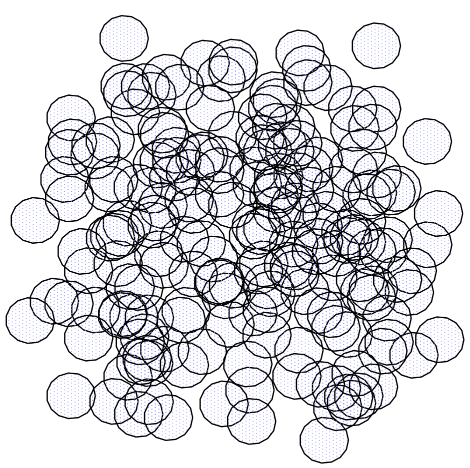


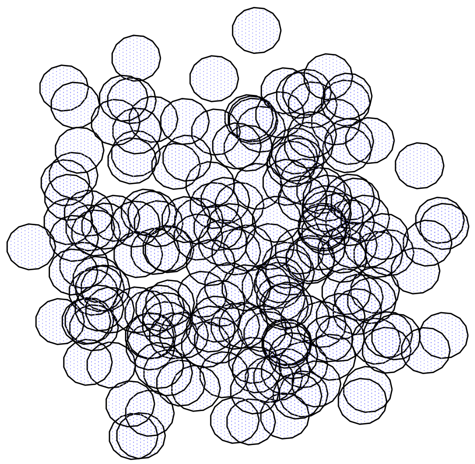


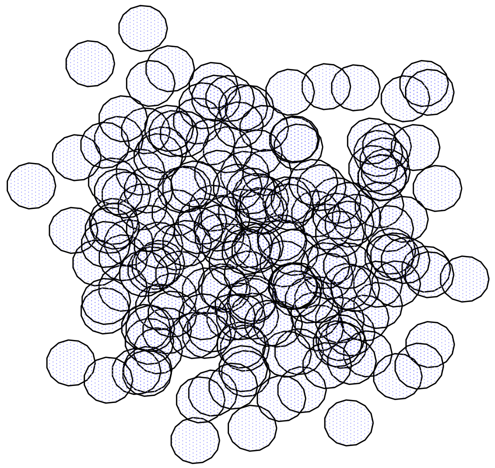
in big & small collisions…

each nucleus is a little different

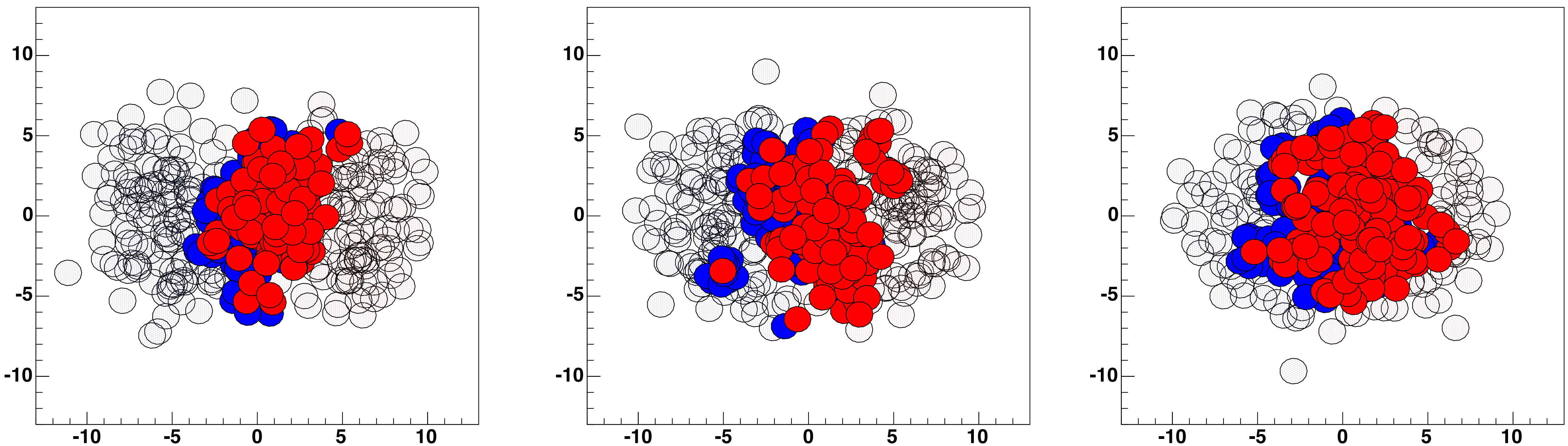
- 200 protons and neutrons move around within the nucleus

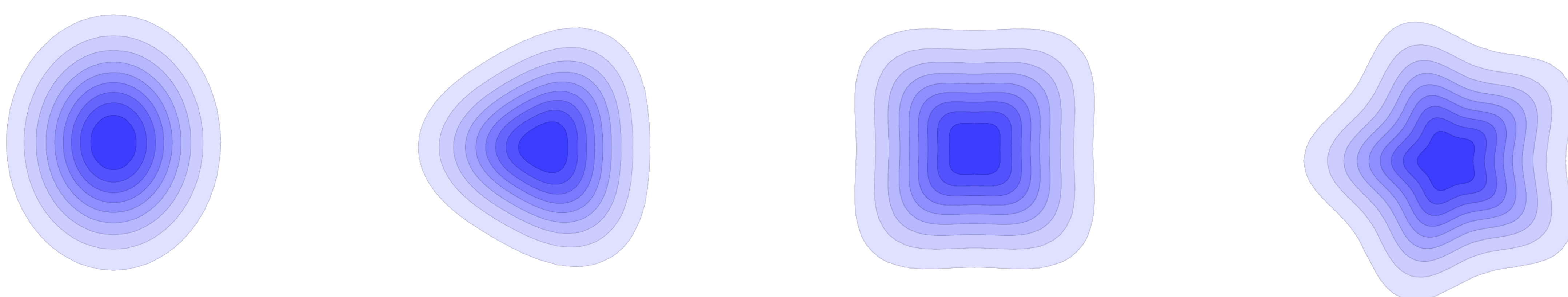






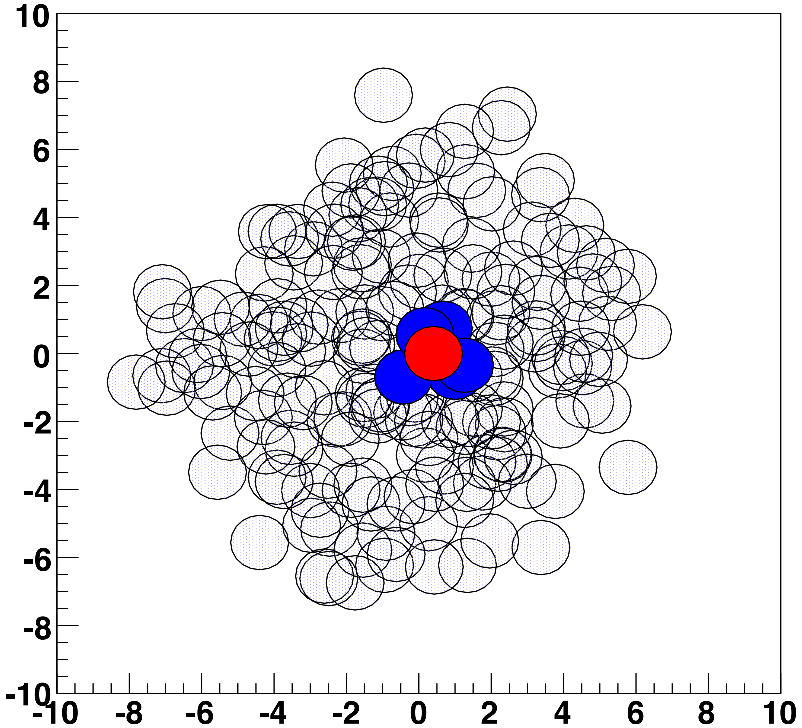
each collision is unique

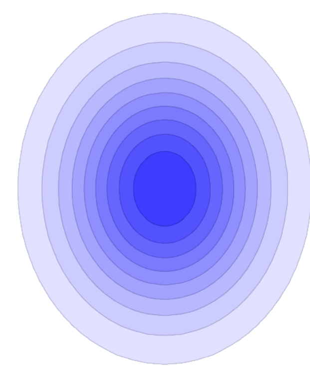




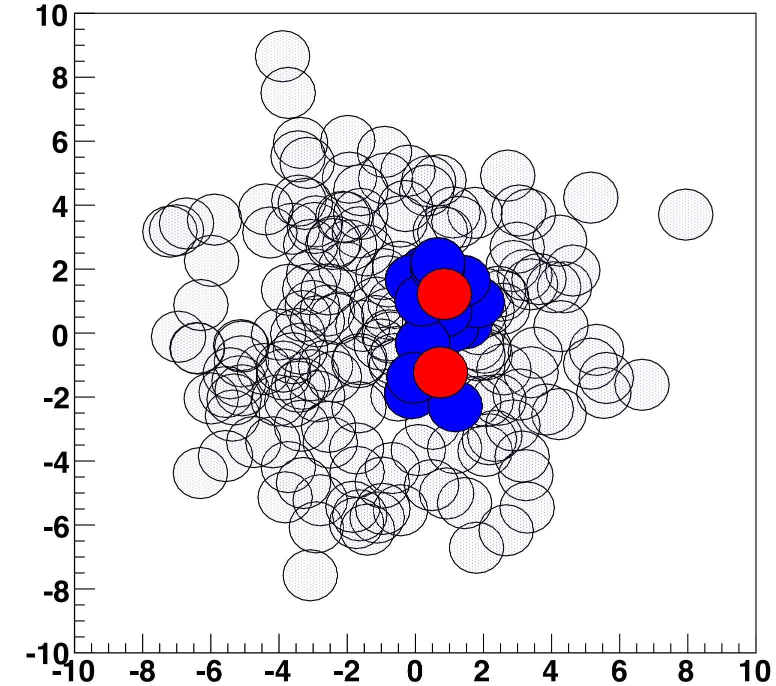
shape control

small ε_2

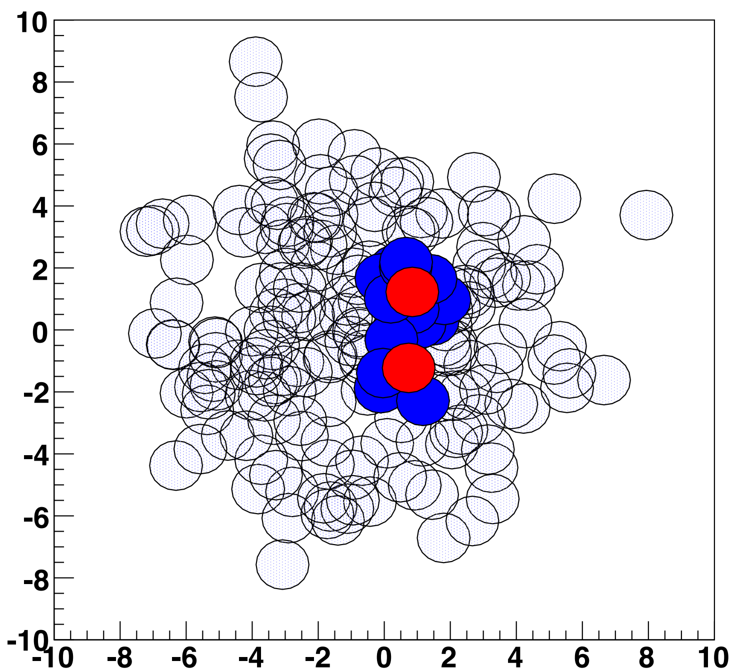


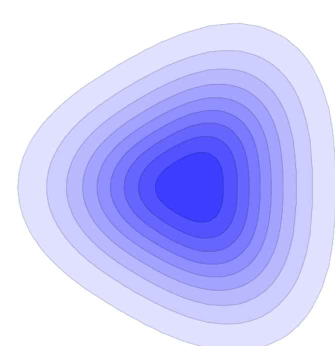


large ε_2

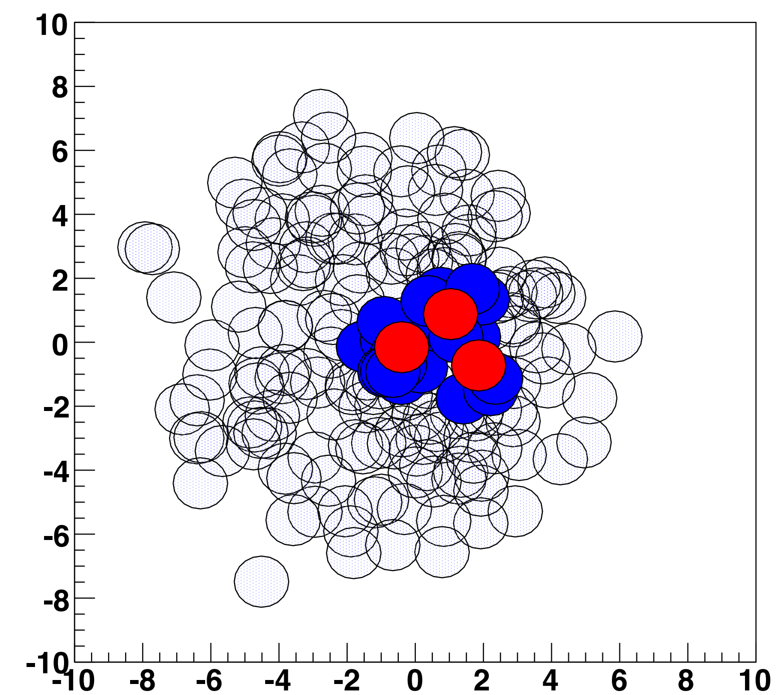


small ε_3



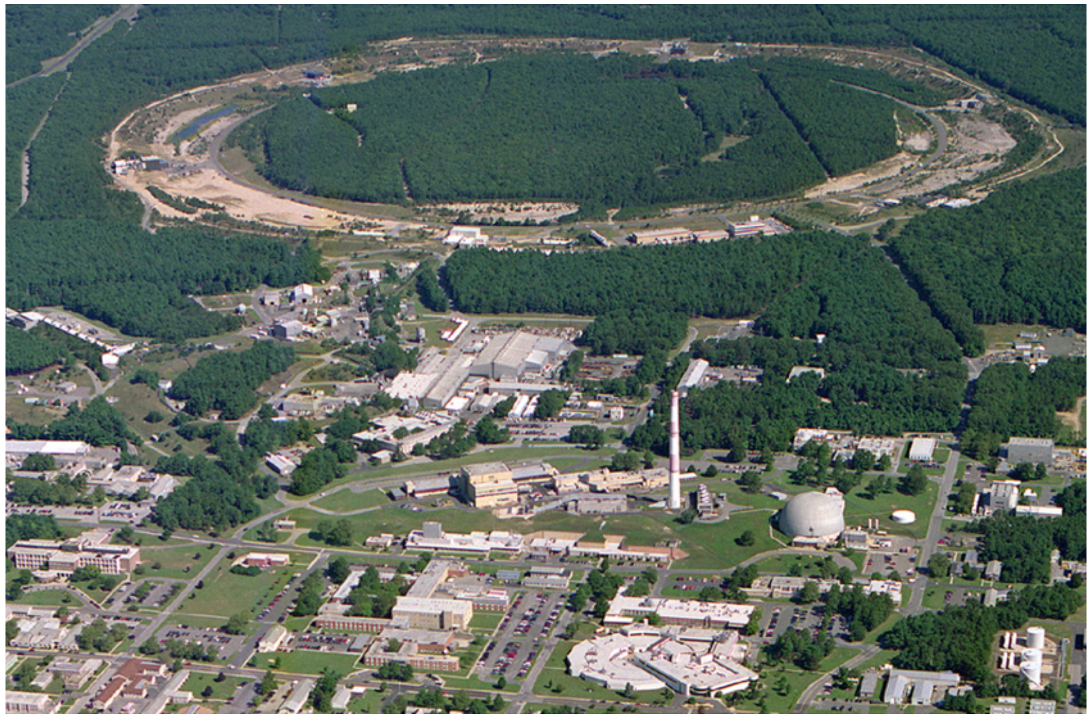


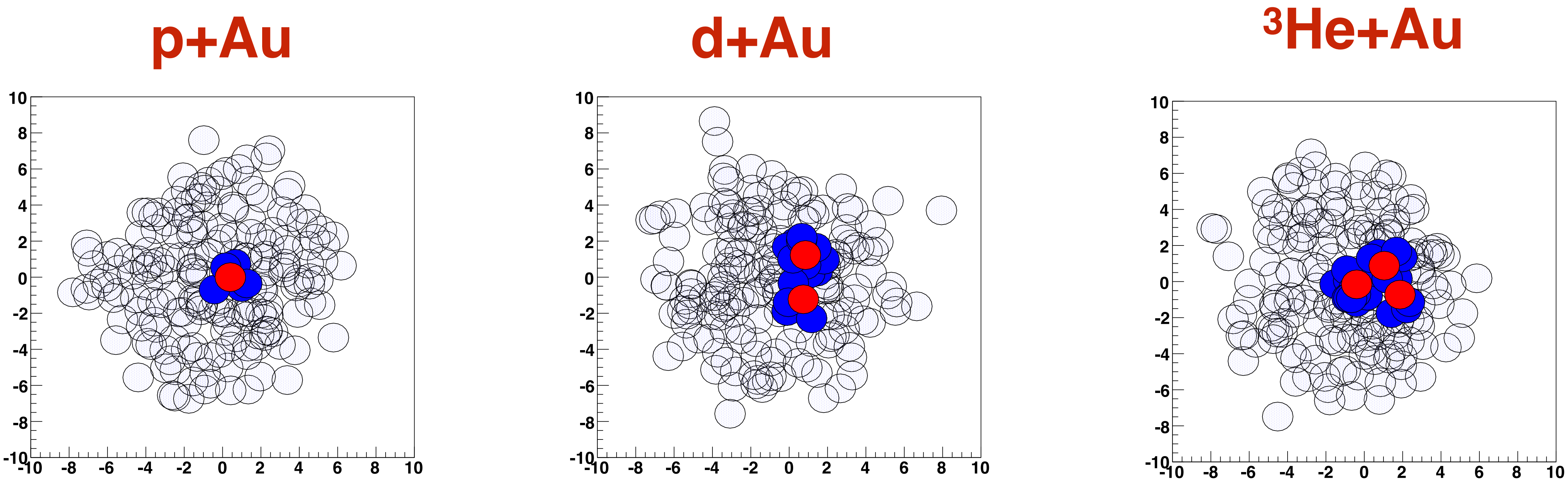
large ε_3



a triangular nucleus?

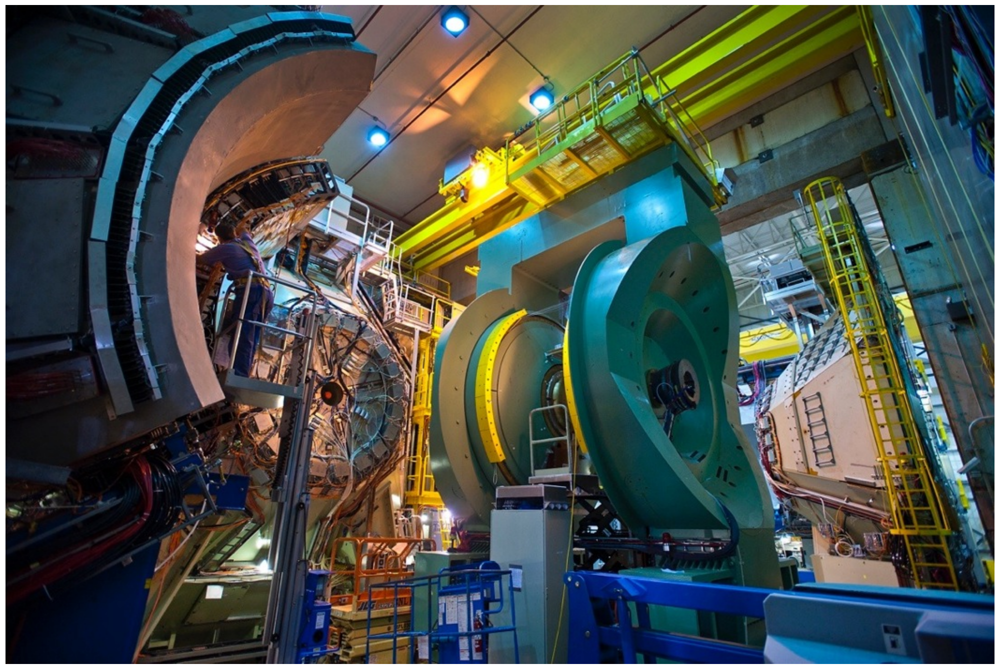
deuteron: 1 proton, 1 neutron
helium 3 (^3He): 2 protons, 1 neutron



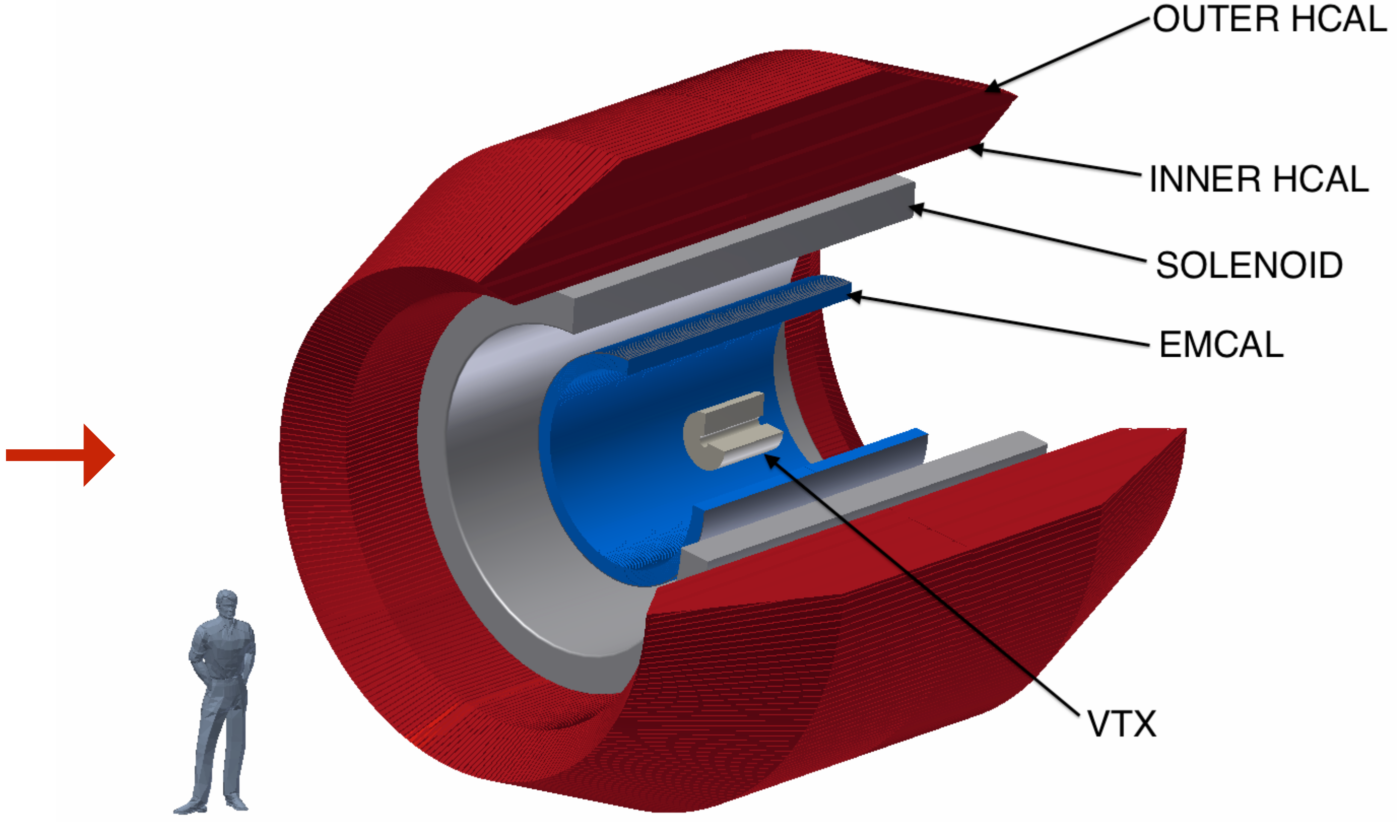


another view of the QGP

PHENIX

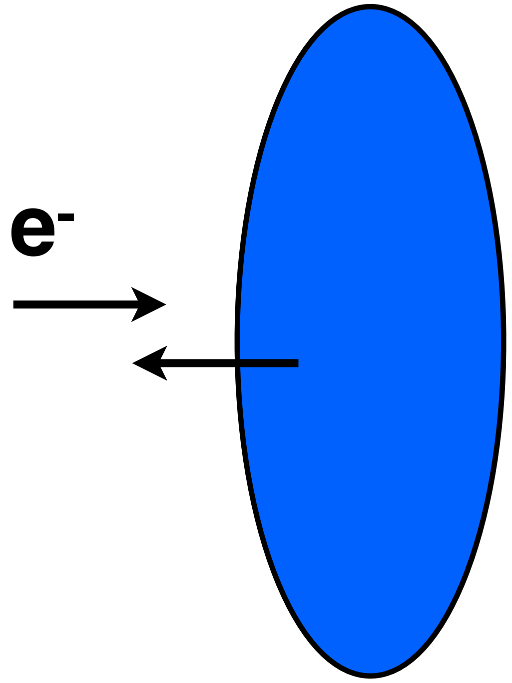


sPHENIX (coming in 2020)

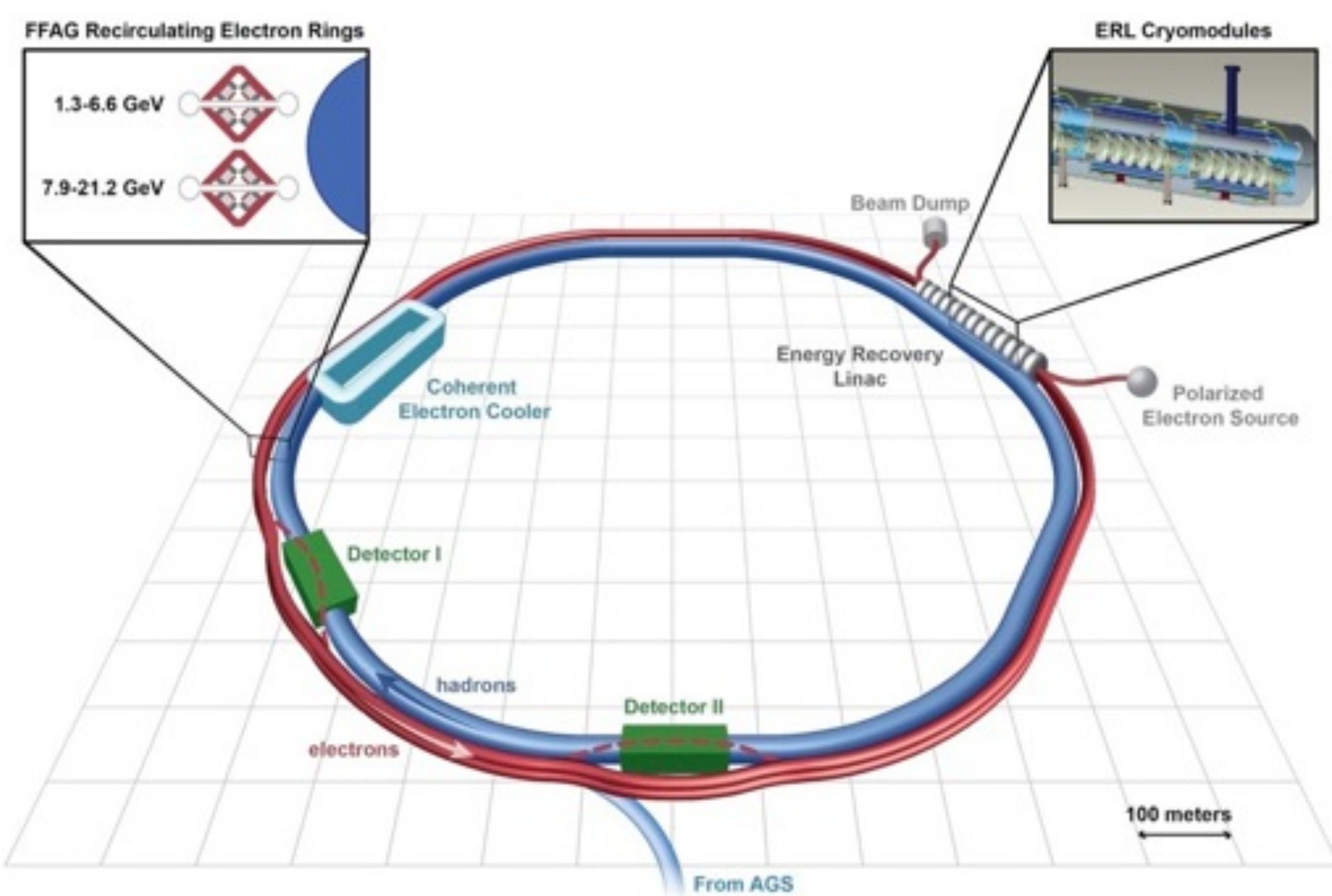


- what happens to very high energy quarks and gluons (jets) as they pass through the QGP?
- **what does the combination of flow and jets tell us about how the QGP works?**

investigating initial state of the nucleus?



- electrons are point-like particles

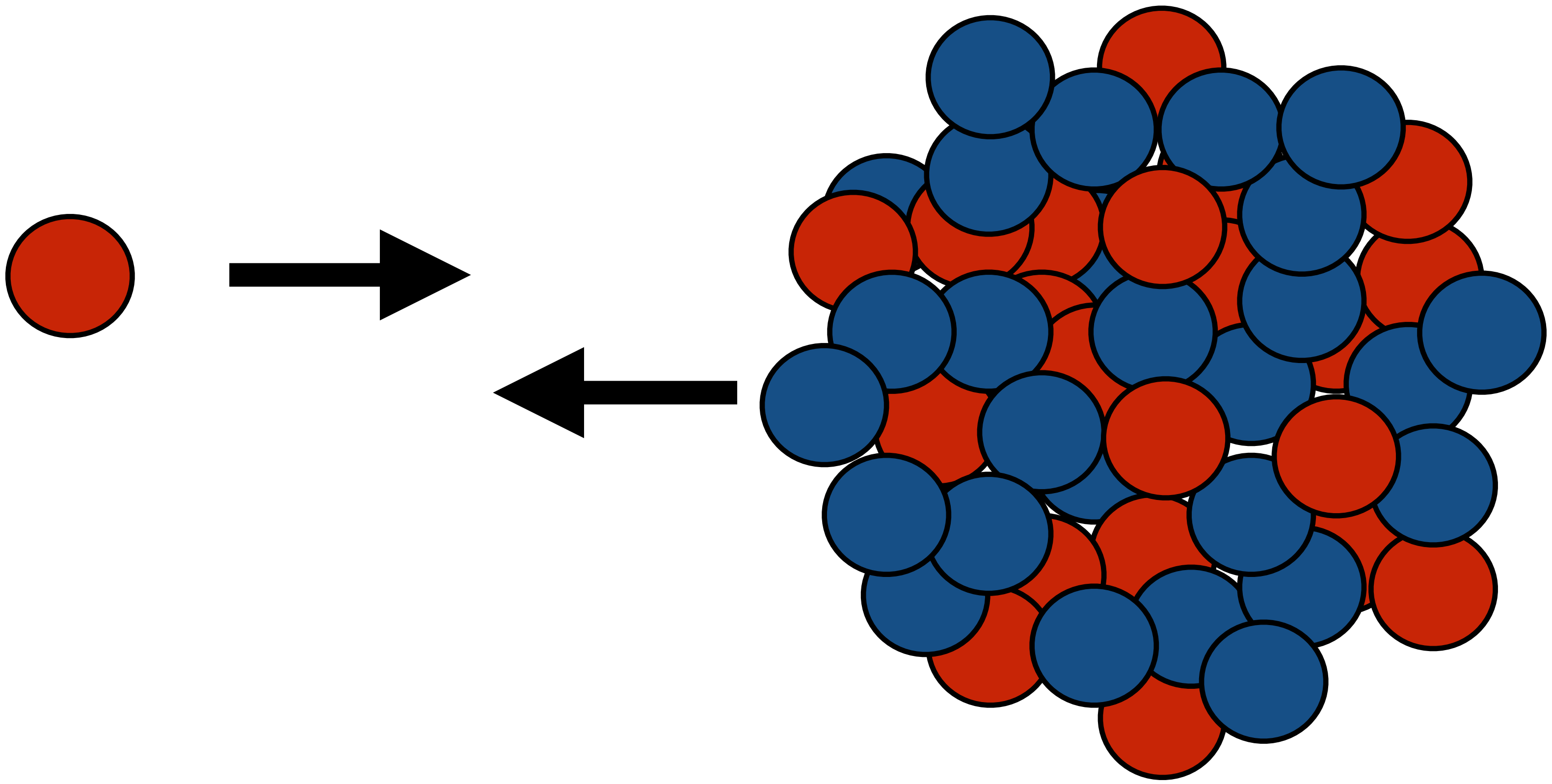


eRHIC

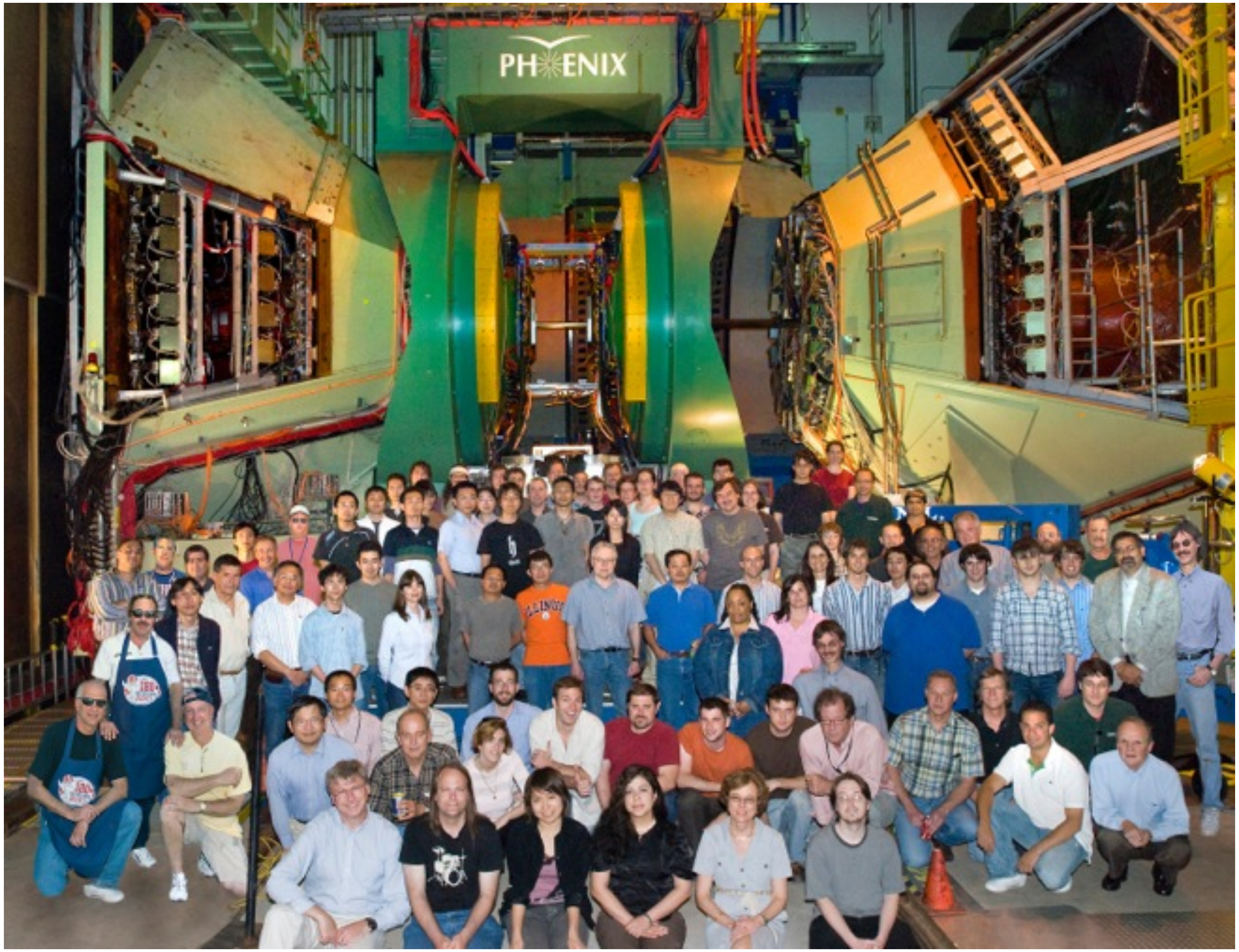
upgrade to allow electrons at RHIC
timescale ~ 2025

exploring the strong force

- creating a picture of the quark-gluon plasma by using the geometry and variations of the nuclei collided at RHIC and the LHC
  - very small nuclei are providing a unique control of the geometry
  - excited to be able to fully exploit this technique at RHIC with p+Au, d+Au, and 3He+Au collisions soon!



acknowledgements



- all the members of the PHENIX Collaboration
- my colleagues at BNL
- funded through DOE Office of Science