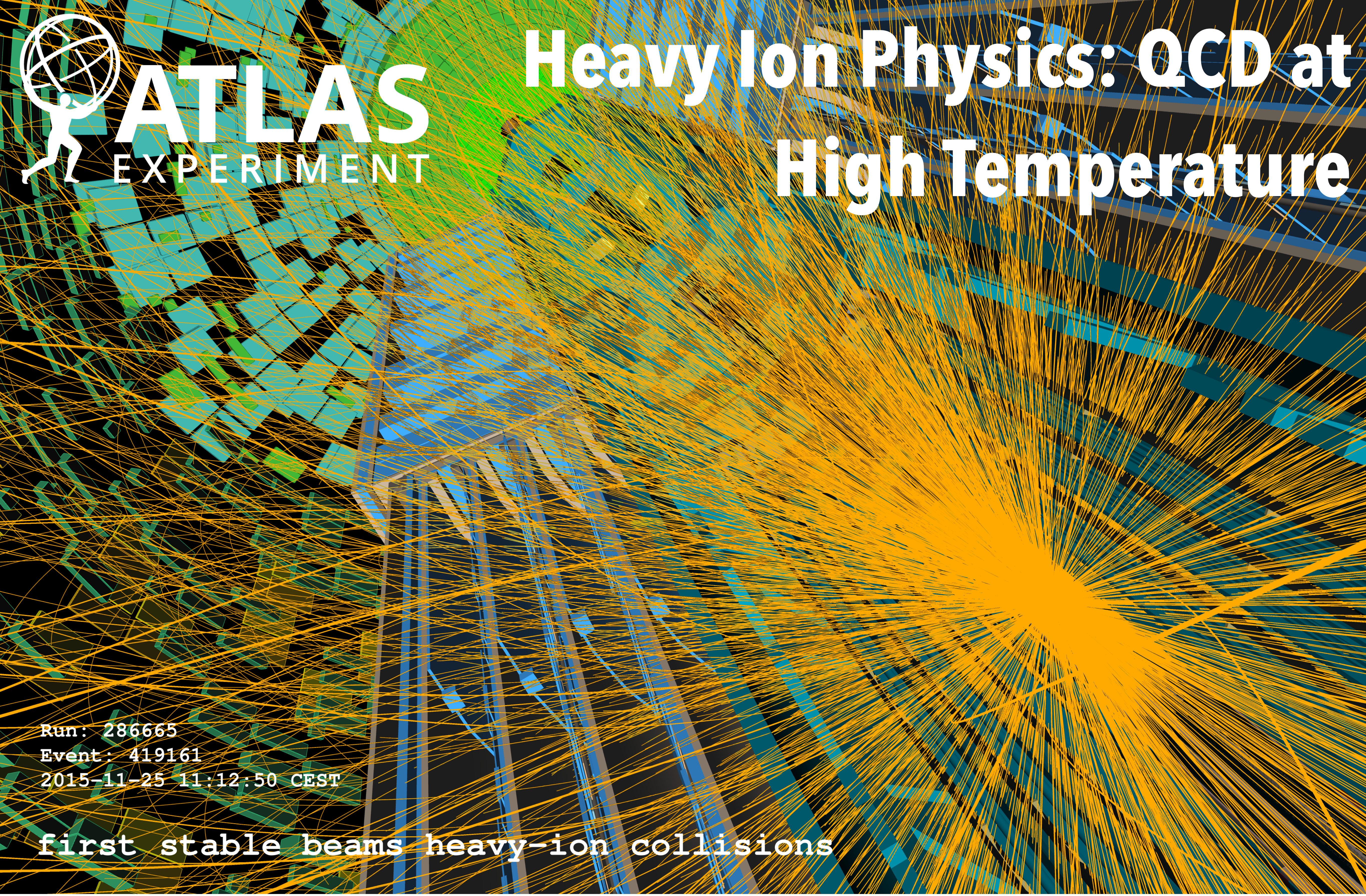
ATLAS EXPERIMENT

Heavy Ion Physics: QCD at High Temperature

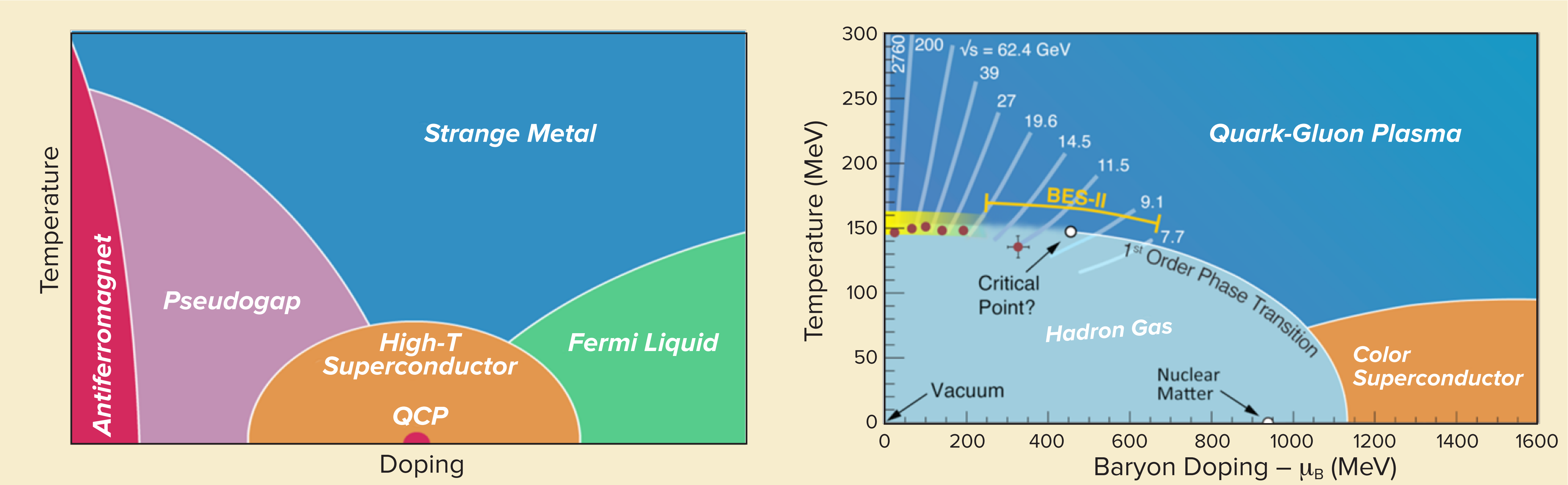


ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Anne M. Sickles
August 23/24, 2018

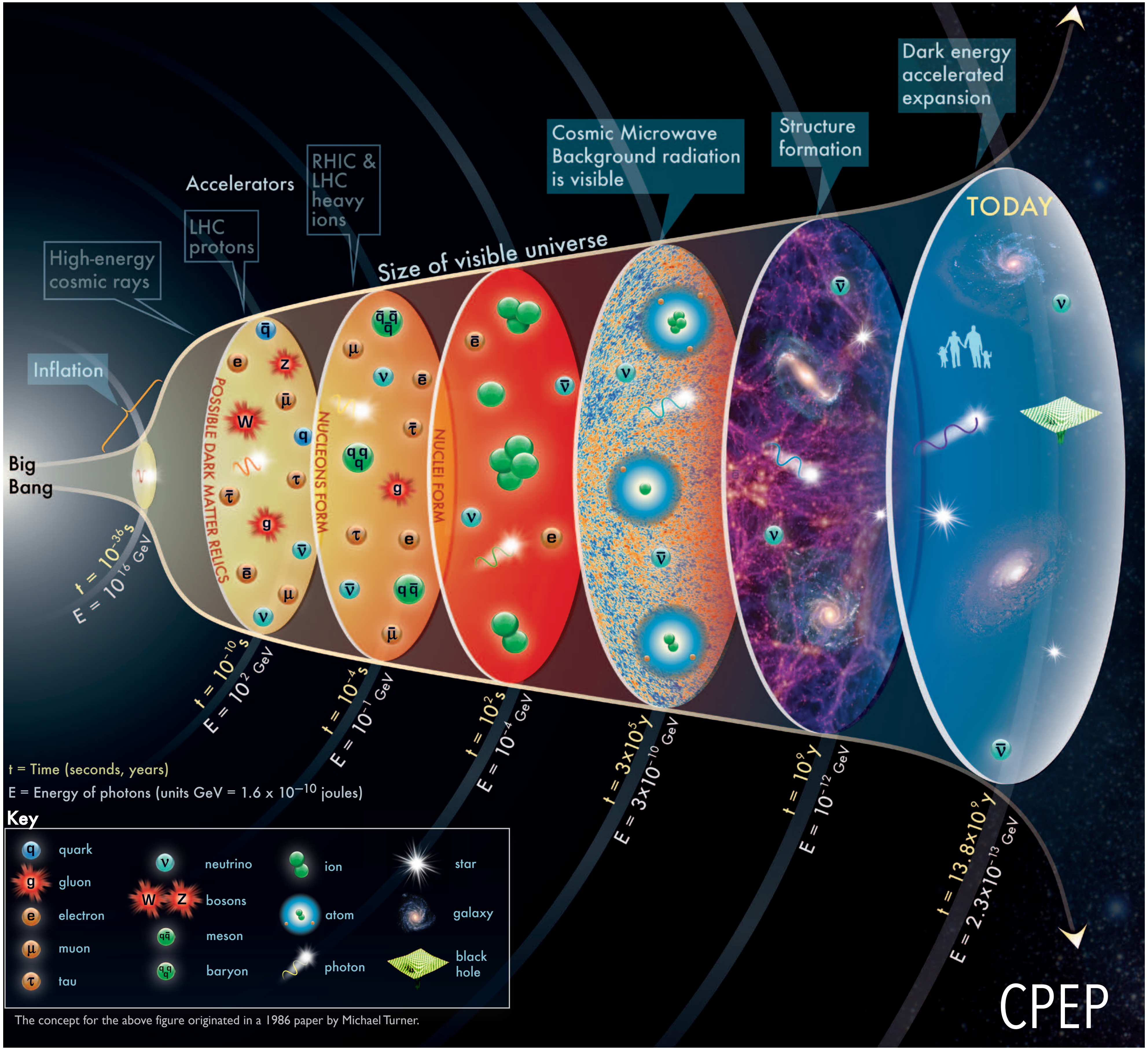
phase structure of QCD

Nuclear Physics 2015 Long Range Plan



what does QCD matter look like away from the nucleus?

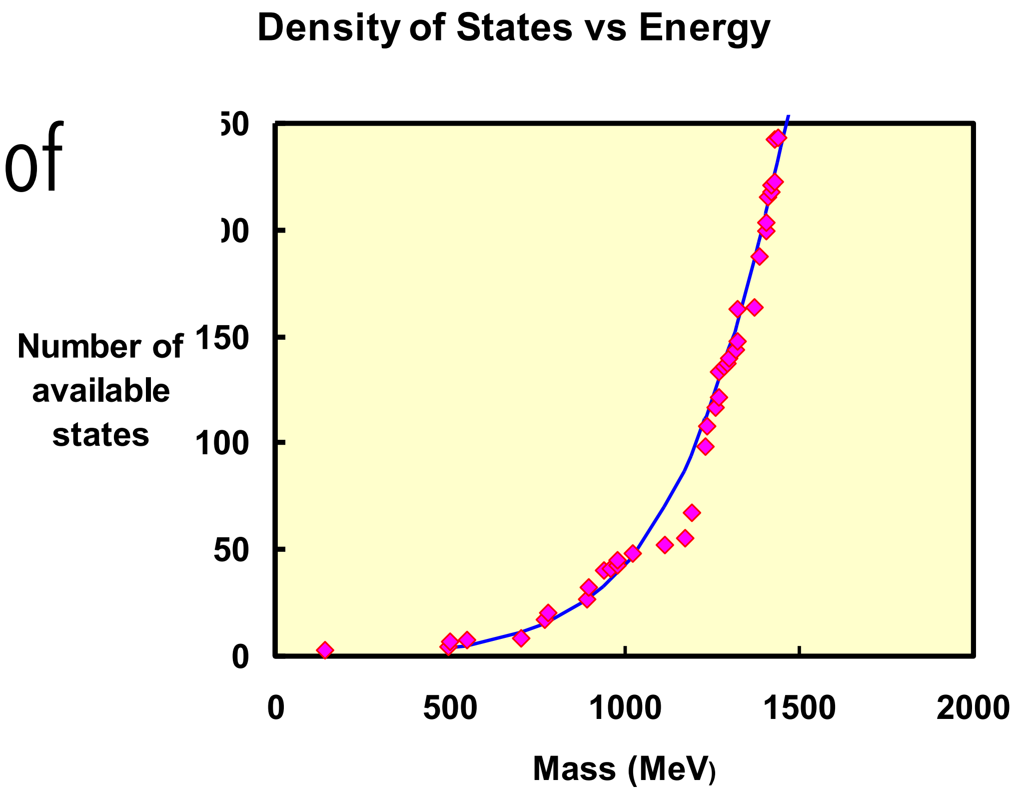
a window into the early universe



The concept for the above figure originated in a 1986 paper by Michael Turner.

an ultimate temperature for a system of hadrons

- pre-QCD (1965!) observation that the number of hadrons increased exponentially with mass
- if that continued, heating a hadron system beyond some T_0 would not be possible
  - $T_0 \sim 170$ MeV



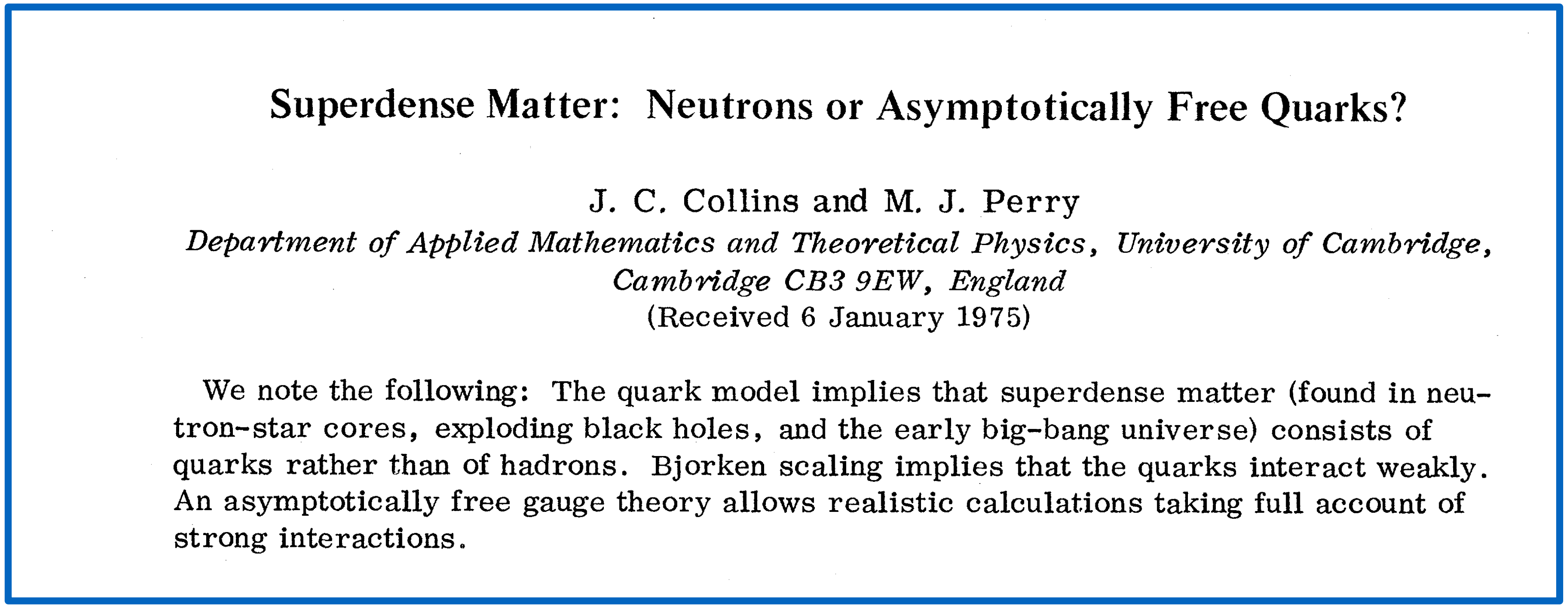
compilation: Bill Zajc

> It then happens that for an exponential growth of $\rho(m)$ the system uses up the energy to increase the temperature and the number of particles only up to some temperature $\approx T_o$; but when T_o is approached it becomes easier to create new particles than to increase the temperature; $\rho(m)$

http://cds.cern.ch/record/346206

QCD and the possibility of free quarks

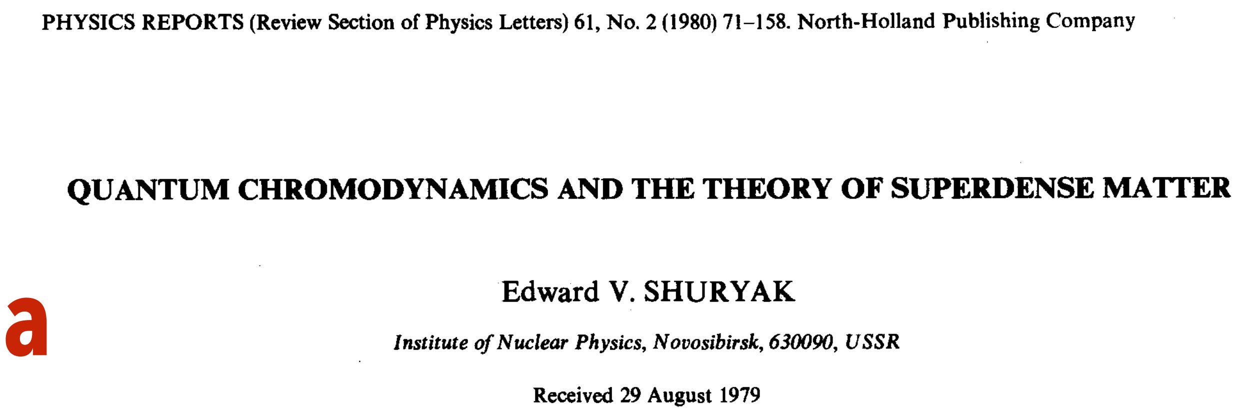
PRL 34 (1974)1353



Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge,
Cambridge CB3 9EW, England
(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.



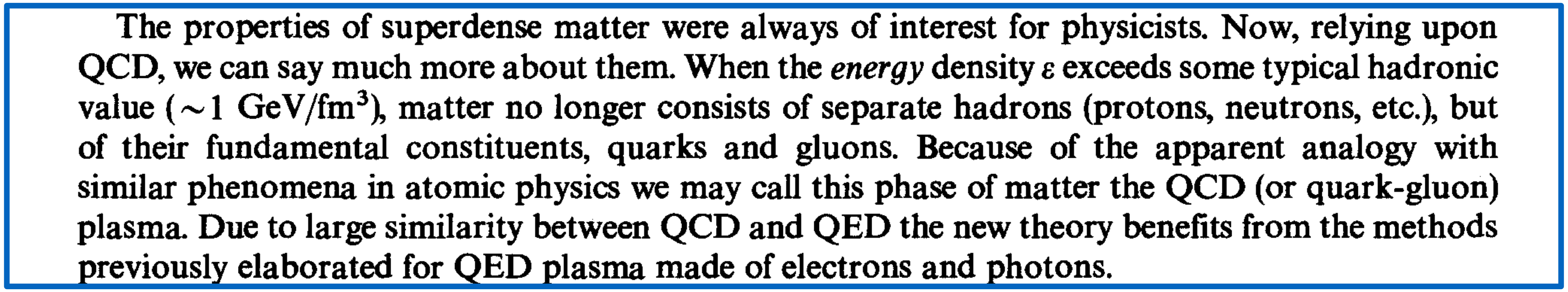
PHYSICS REPORTS (Review Section of Physics Letters) 61, No. 2 (1980) 71–158. North-Holland Publishing Company

QUANTUM CHROMODYNAMICS AND THE THEORY OF SUPERDENSE MATTER

Edward V. SHURYAK
Institute of Nuclear Physics, Novosibirsk, 630090, USSR

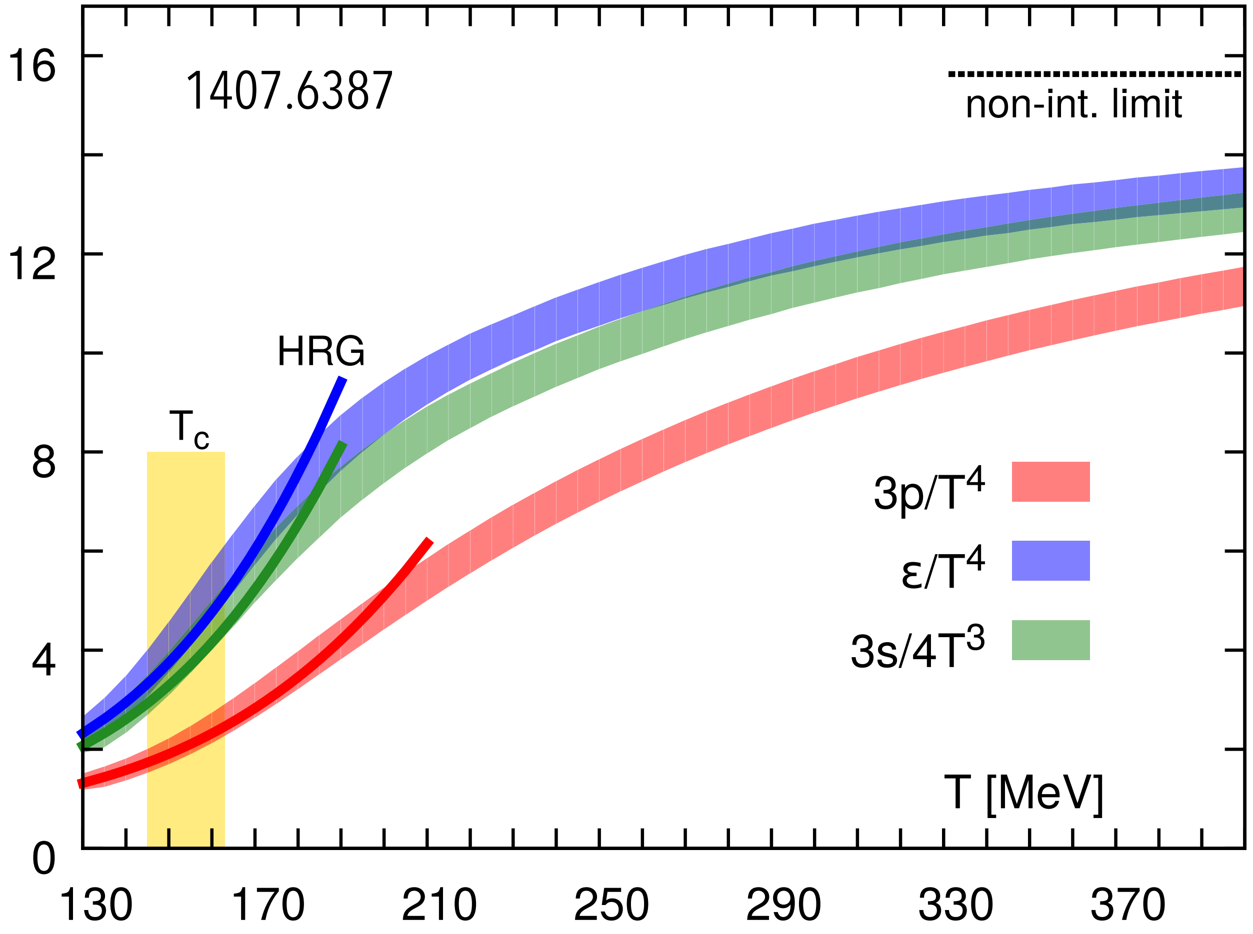
Received 29 August 1979

coining of **quark-gluon plasma**

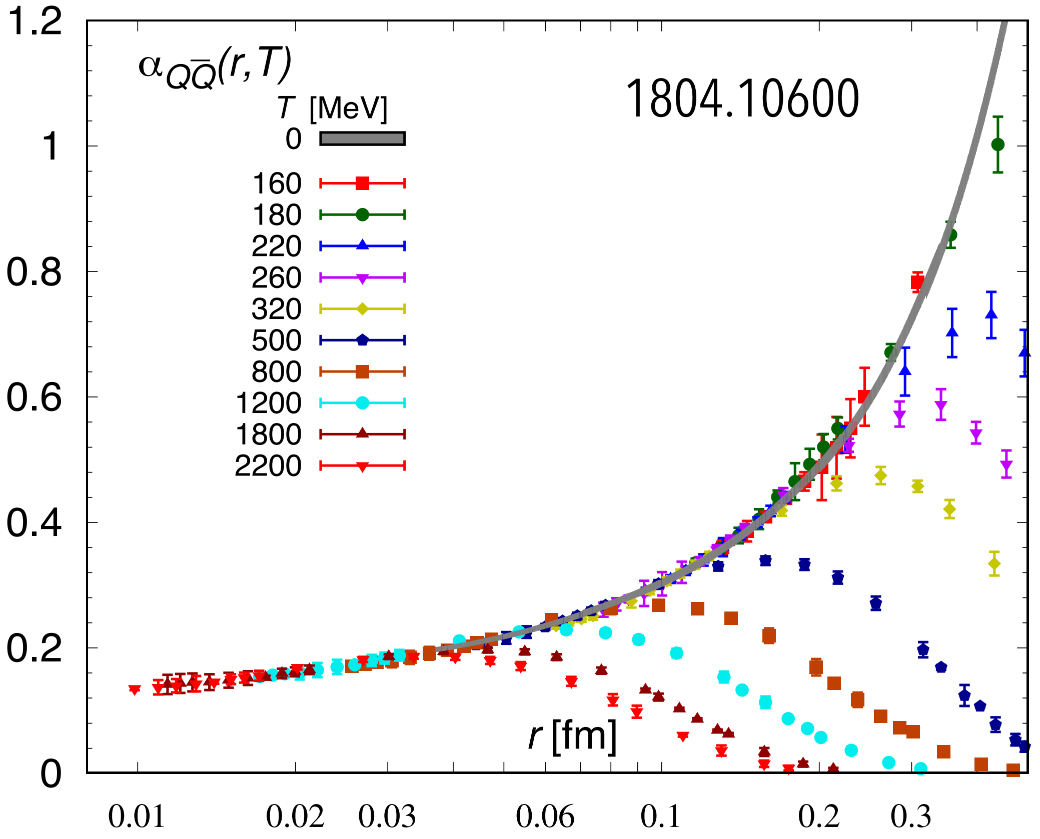


The properties of superdense matter were always of interest for physicists. Now, relying upon QCD, we can say much more about them. When the *energy* density ε exceeds some typical hadronic value ($\sim$1 GeV/fm^3), matter no longer consists of separate hadrons (protons, neutrons, etc.), but of their fundamental constituents, quarks and gluons. Because of the apparent analogy with similar phenomena in atomic physics we may call this phase of matter the QCD (or quark-gluon) plasma. Due to large similarity between QCD and QED the new theory benefits from the methods previously elaborated for QED plasma made of electrons and photons.

modern lattice QCD at T > 0

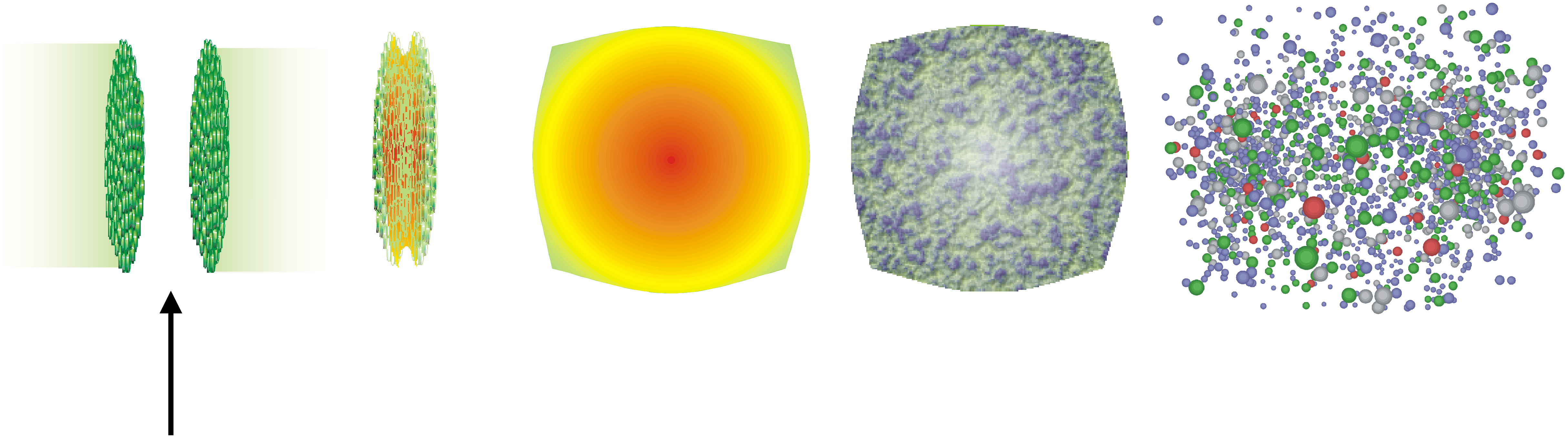


crossover @ ~150 MeV



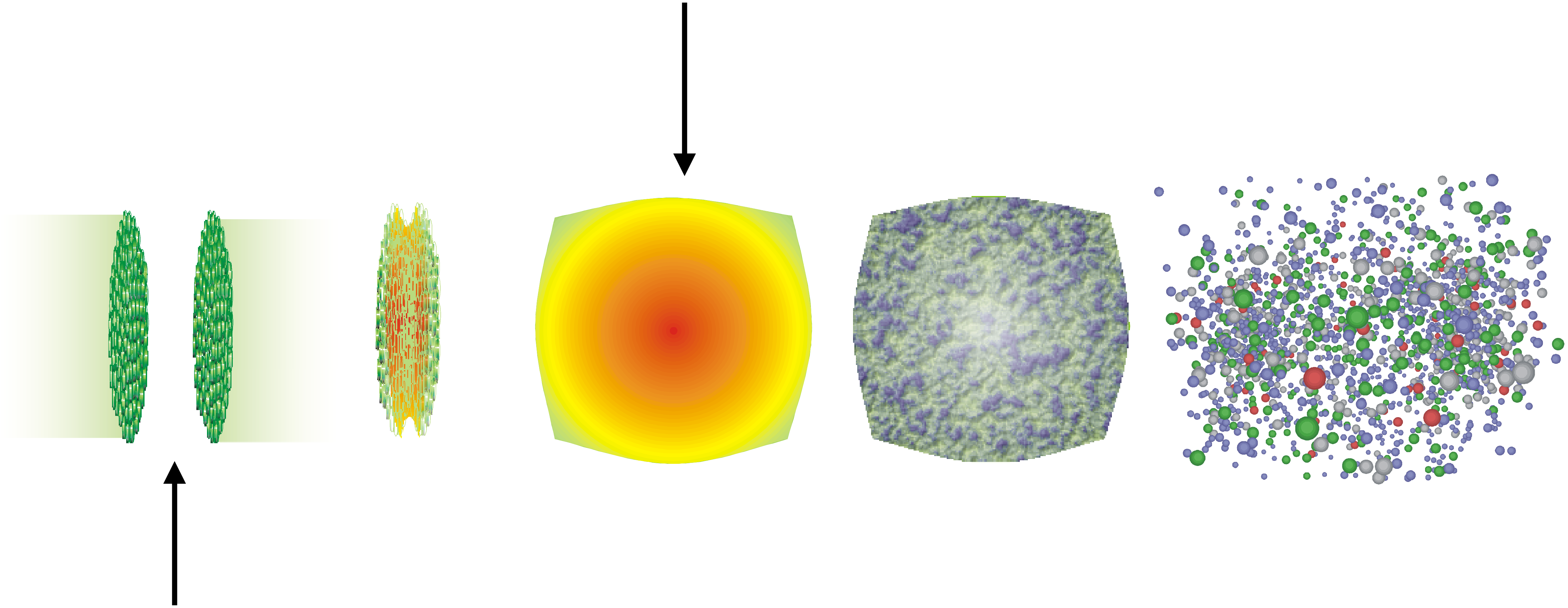
screening at large r
with increasing T

QCD at T > 0 at colliders



incoming Lorentz
contracted nuclei

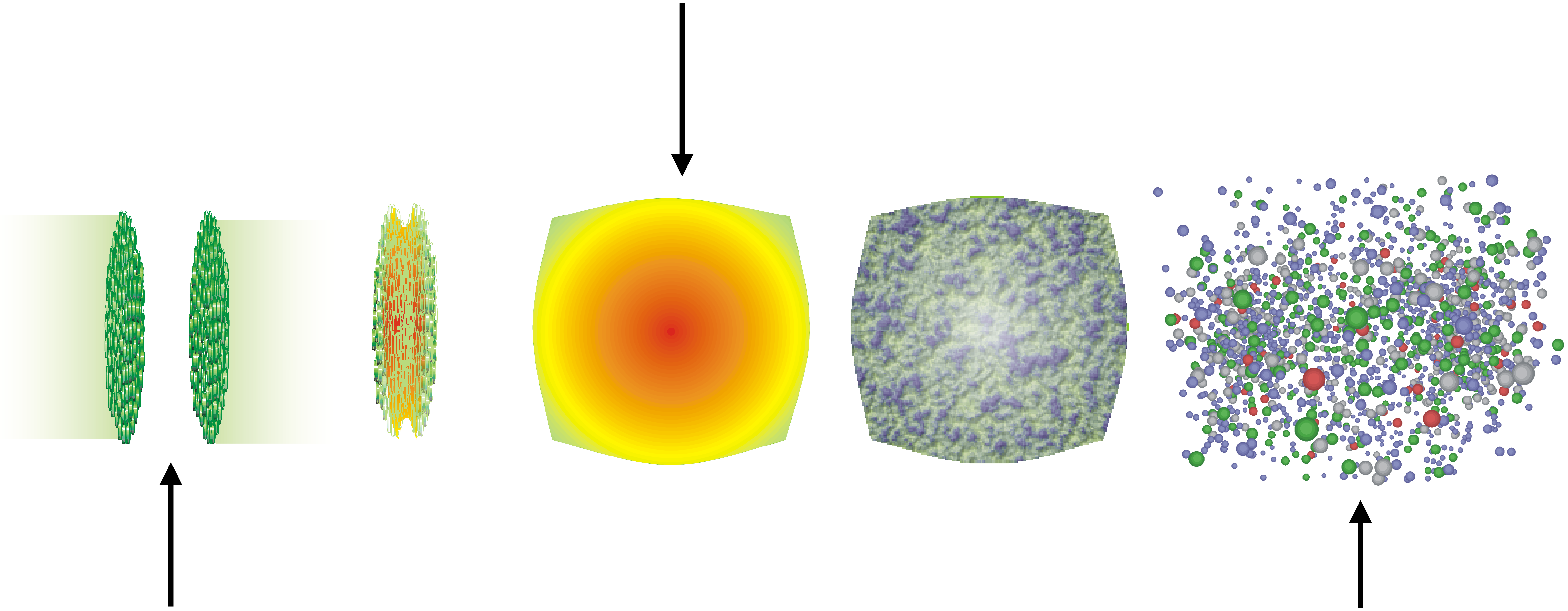
QCD at T > 0 at colliders



quark gluon plasma

incoming Lorentz contracted nuclei

QCD at T > 0 at colliders

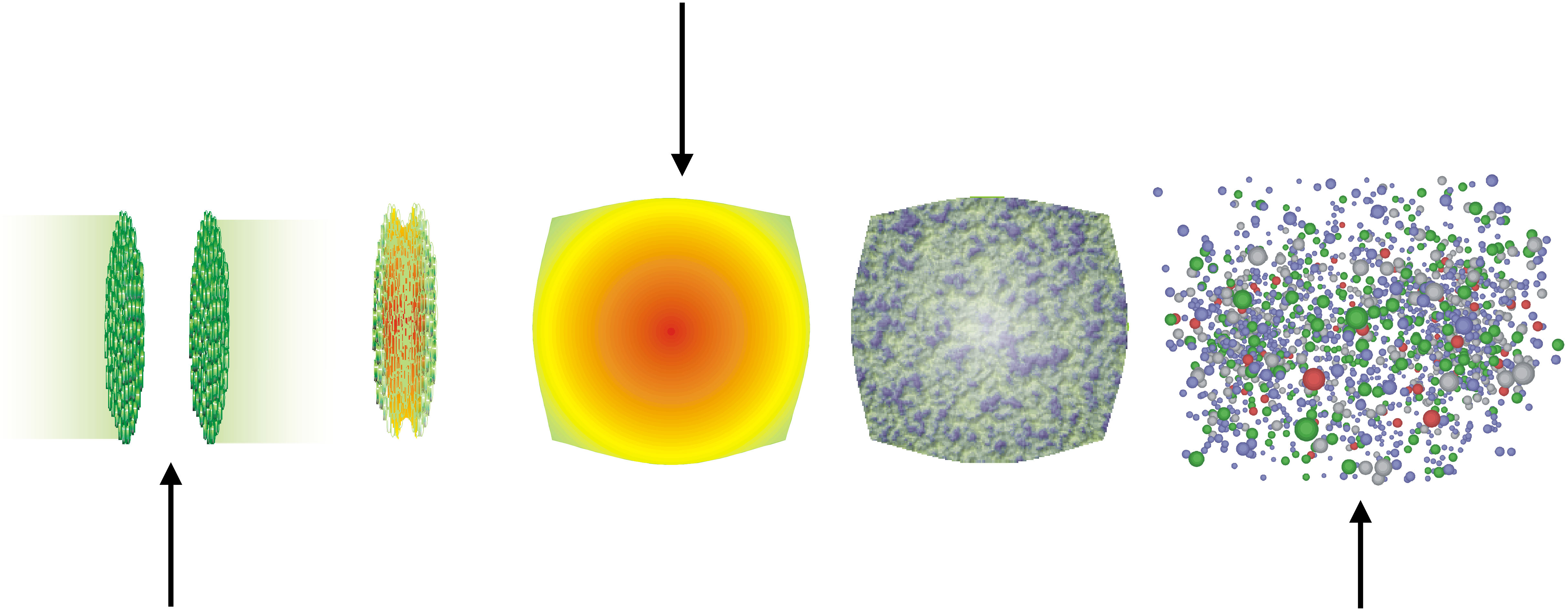


quark gluon plasma

incoming Lorentz contracted nuclei

hadrons headed toward detector

QCD at T > 0 at colliders



quark gluon plasma

incoming Lorentz contracted nuclei

hadrons headed toward detector

$\Delta t \sim 10\ \text{fm}/c \sim 10^{-22}\ \text{s}$

heavy ion physics

- goals of these lectures:
  - what do we know about QCD at high temperature?
  - what are the limits of our understanding
- since the system created in heavy ion collisions is necessarily short lived and governed by the color charge, this is complicated, both experimentally and theoretically
- disclaimers:
  - I am an experimentalist with the ATLAS and sPHENIX collaborations

Large Hadron Collider @ CERN

collide pairs of lead nuclei at 5 TeV / nucleon pair center of mass collision energy

different data than the high energy LHC program but the same experiments are used

~1 month / year of data

~100 of the 3000 ATLAS authors work directly on this physics

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collide pairs of lead nuclei at 5 TeV / nucleon pair center of mass collision energy

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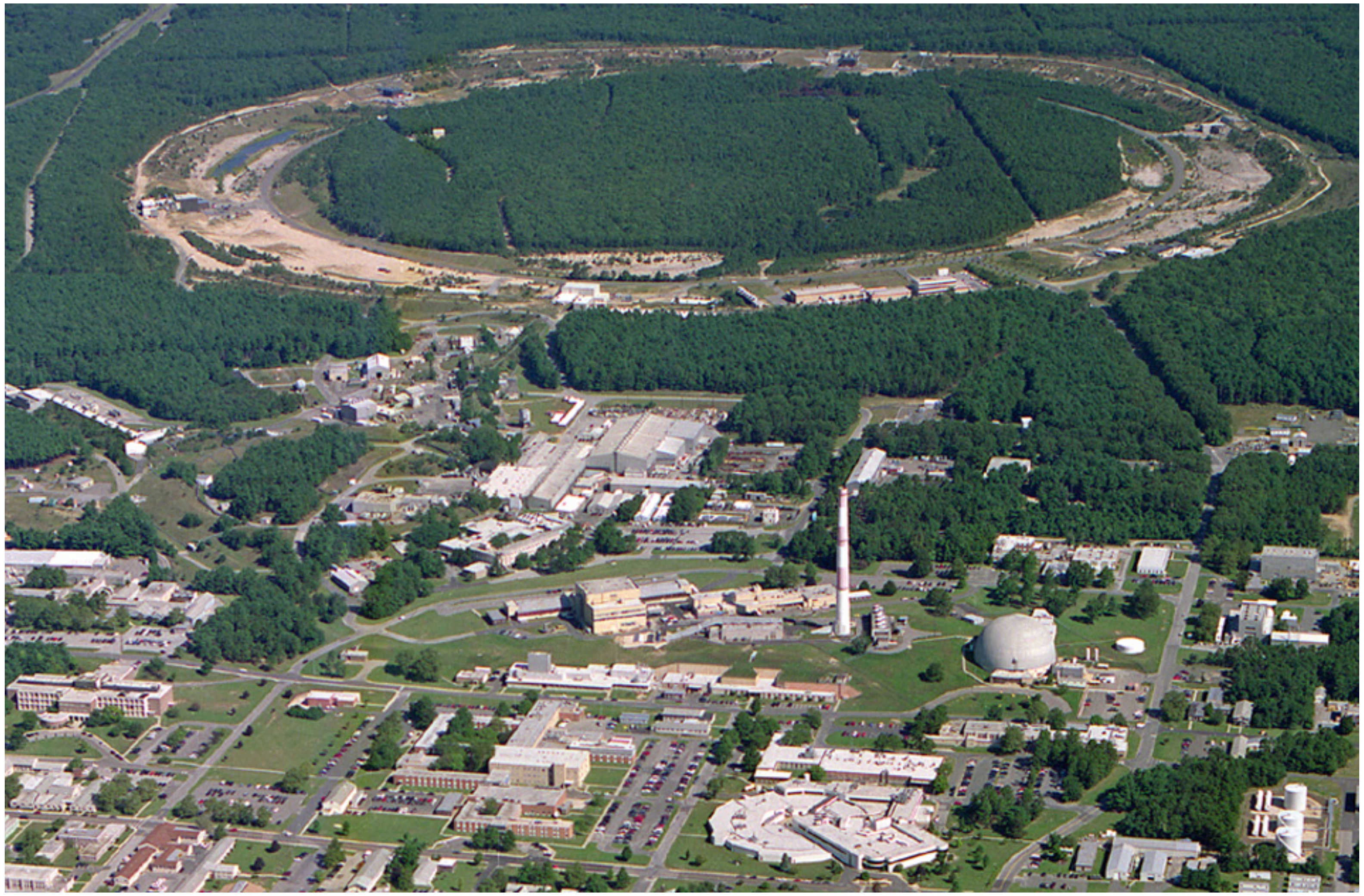
the resulting QGP:

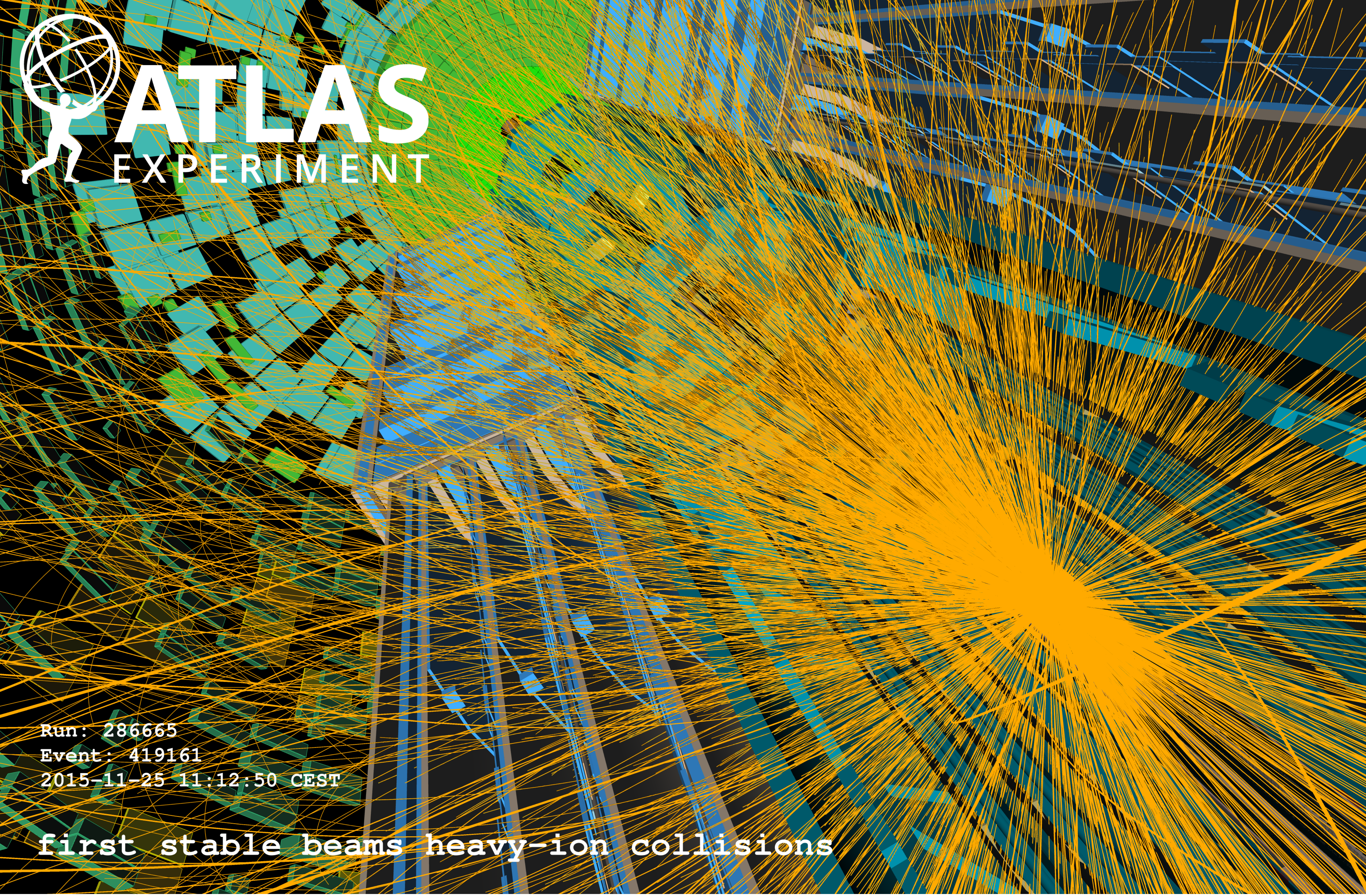
collision energy sets maximum temperature

colliding nuclei set maximum size

Relativistic Heavy Ion Collider @ BNL



- 200 GeV collision energy
- long HI running times
- flexible collision species
- 2 experiments:
  - STAR: large acceptance
  - PHENIX (2001-2016) → sPHENIX new rare probes / large acceptance detector (2023-)

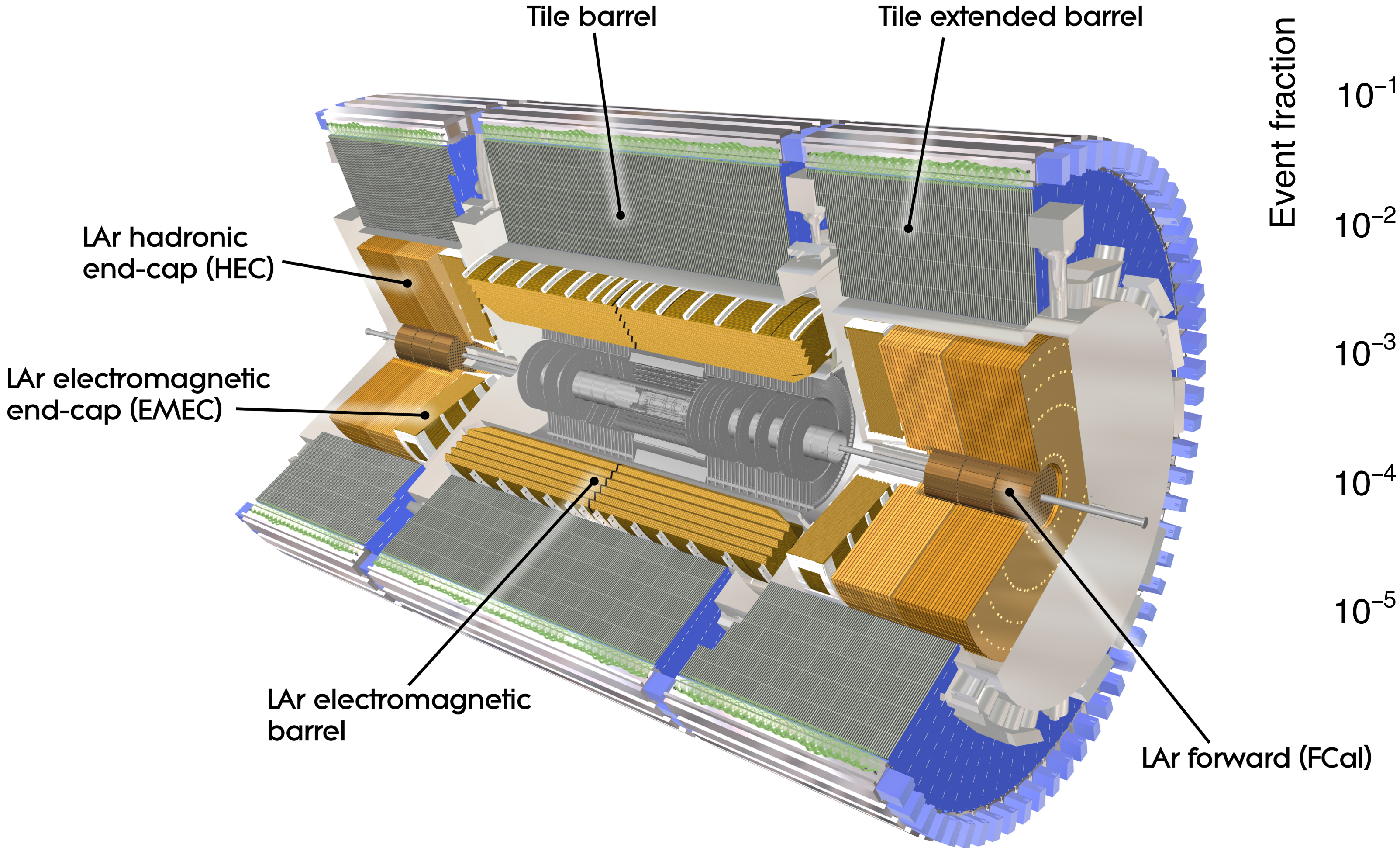


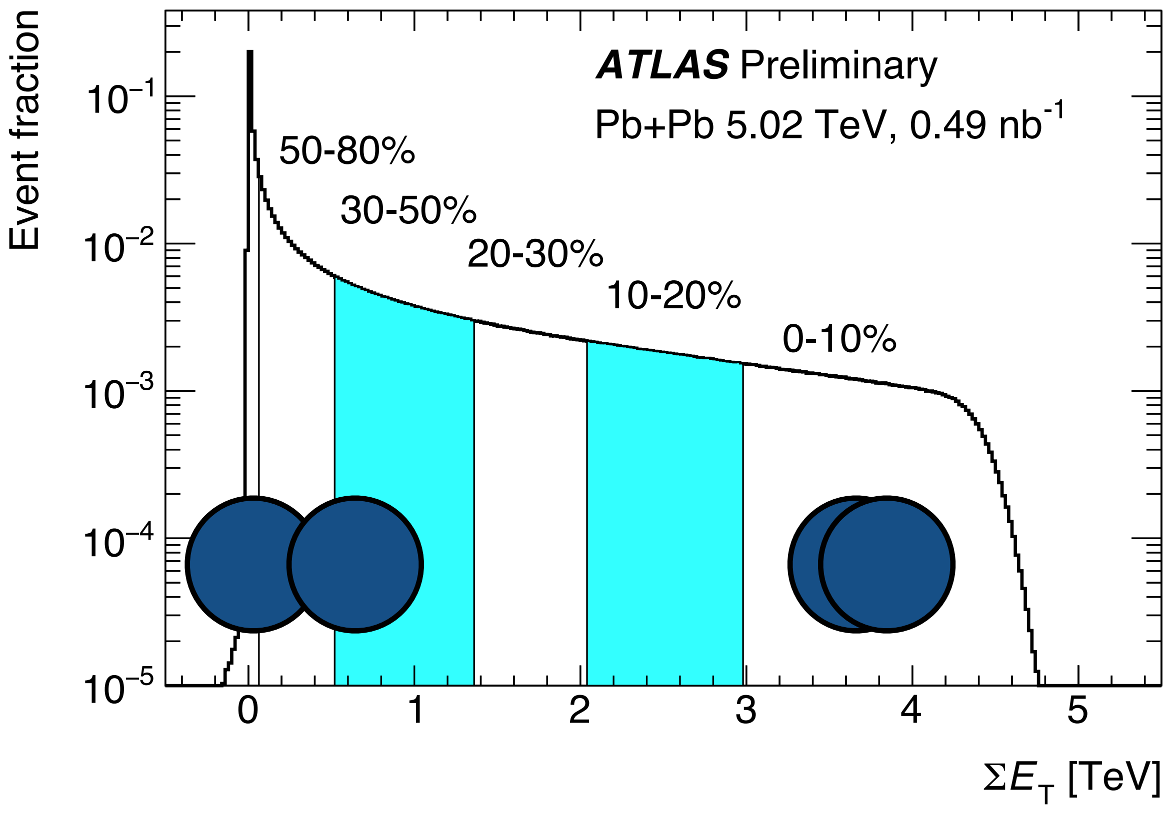
~10^4 particles created in the most head on collisions

equivalent of ~10^3 pp collisions at once

event classification: centrality

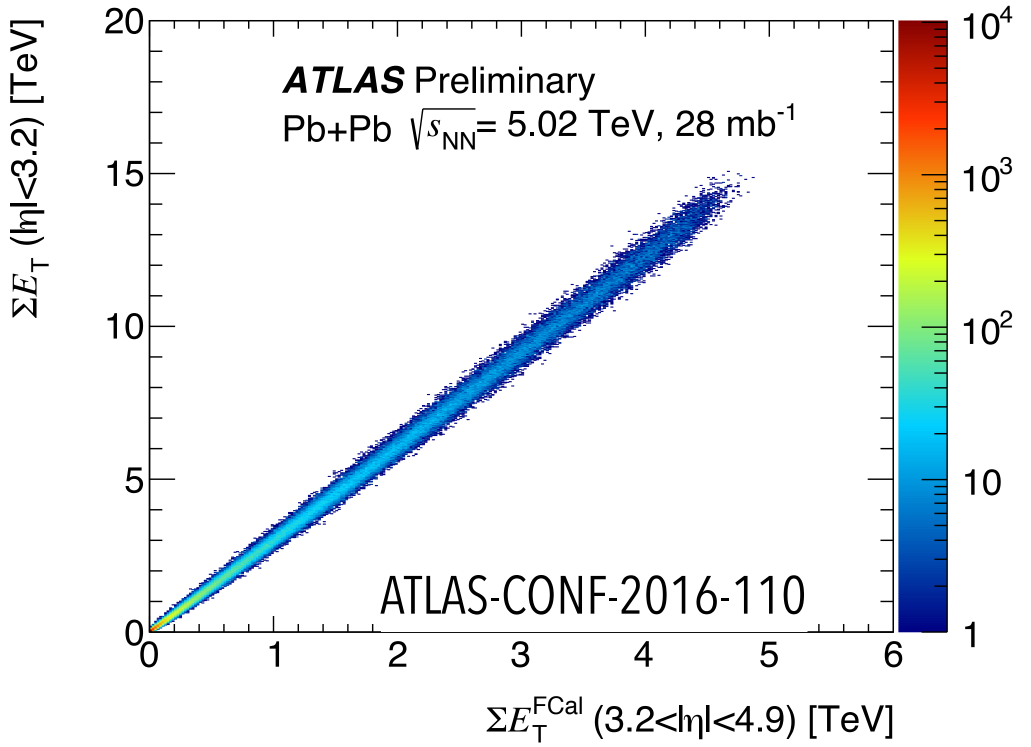
ATLAS Calorimeters





idea: FCal ΣE_T is correlated with collision impact parameter

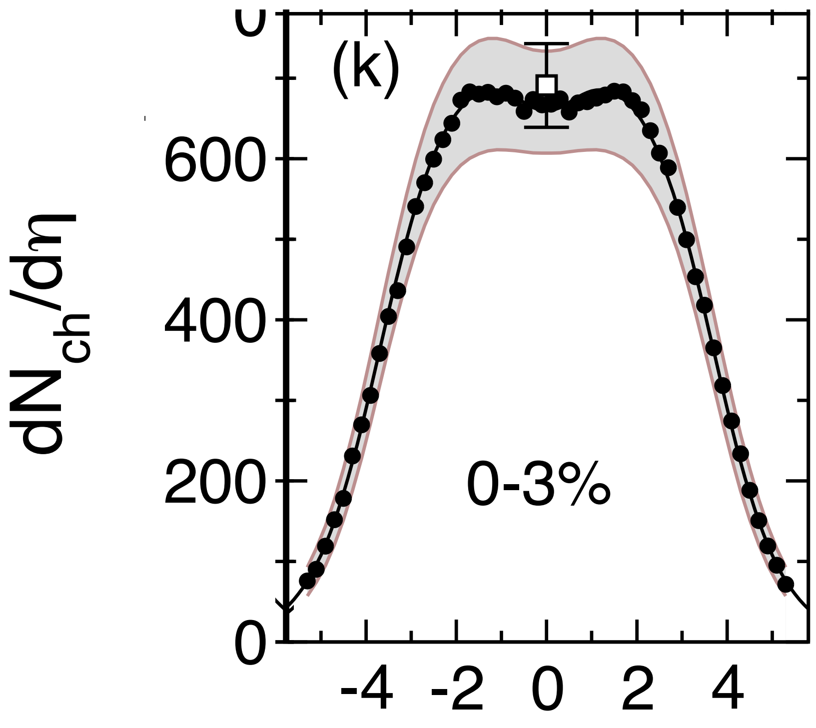
(other experiments use slightly different quantities, but the idea is the same)

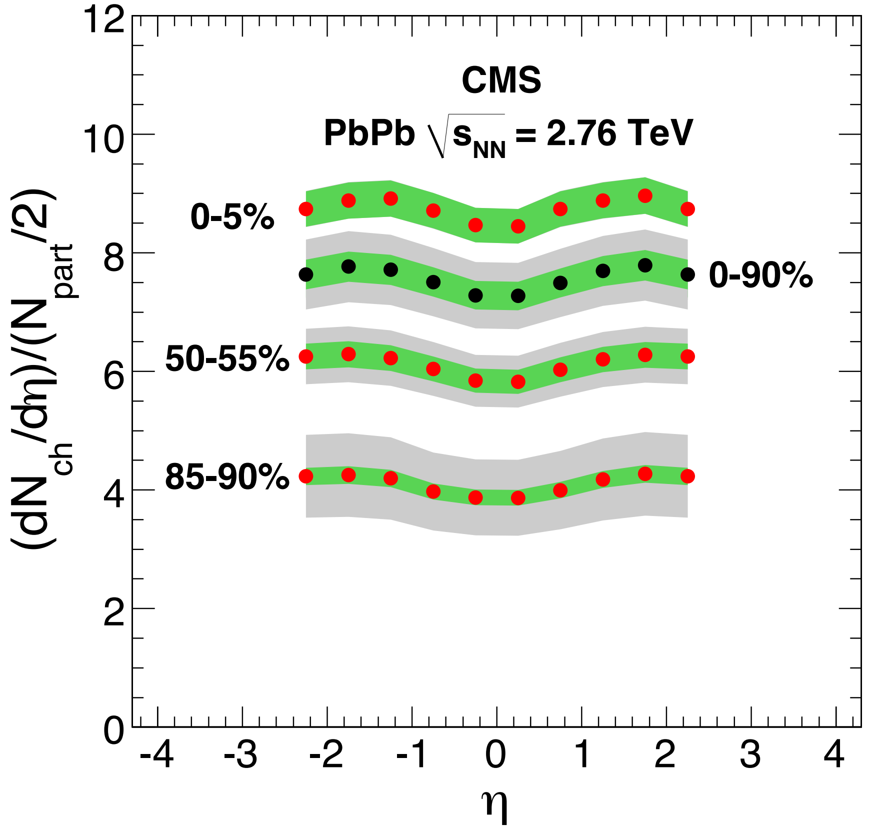


ATLAS-CONF-2016-110

multiplicity of charged particles

central AuAu collisions at RHIC

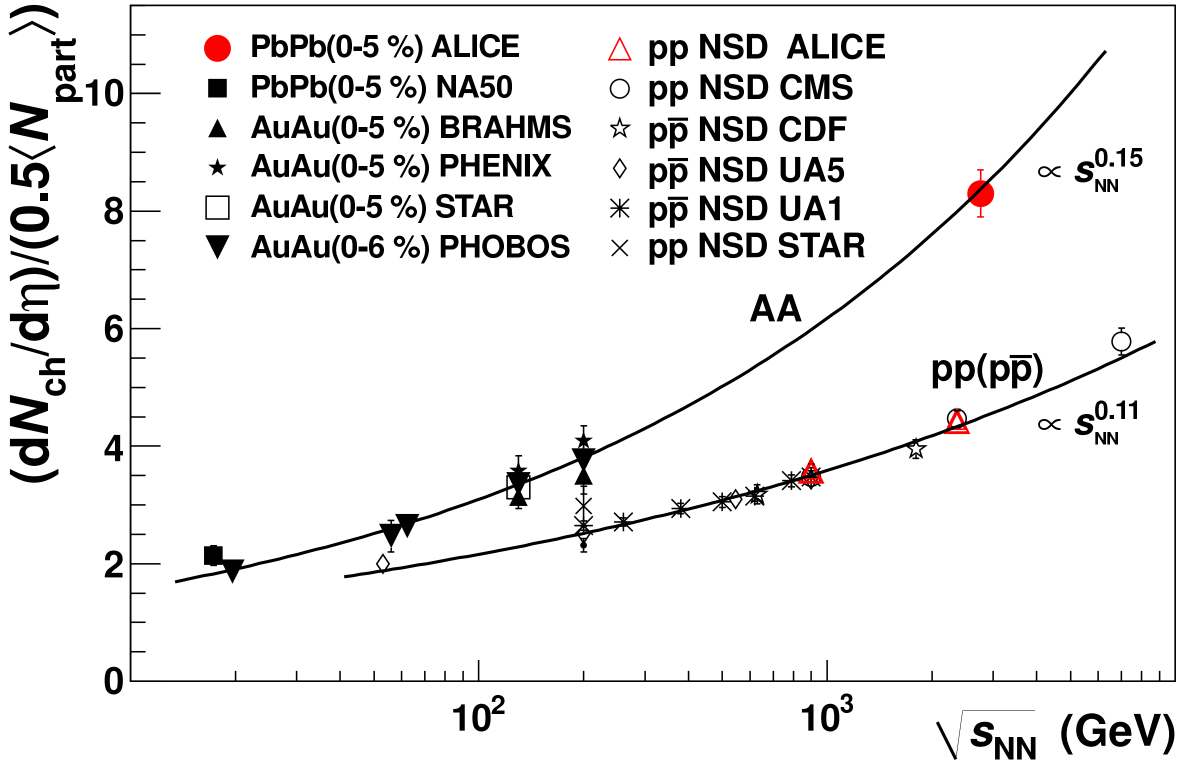




$0.5*N_{part,max}(\sim208) \times 8 \rightarrow$

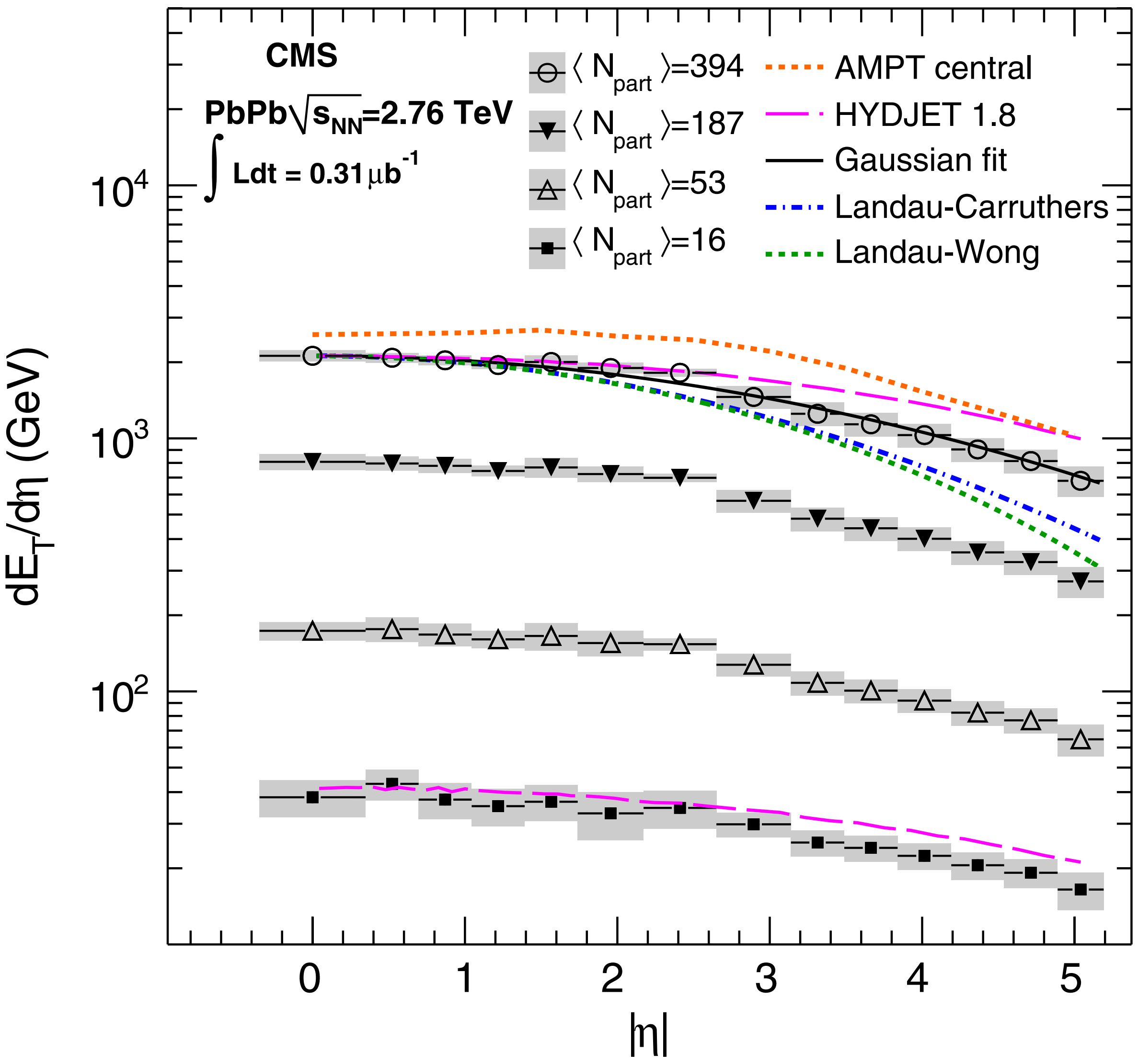
$dN_{ch} / d\eta \sim 1700$

different behavior than pp collisions

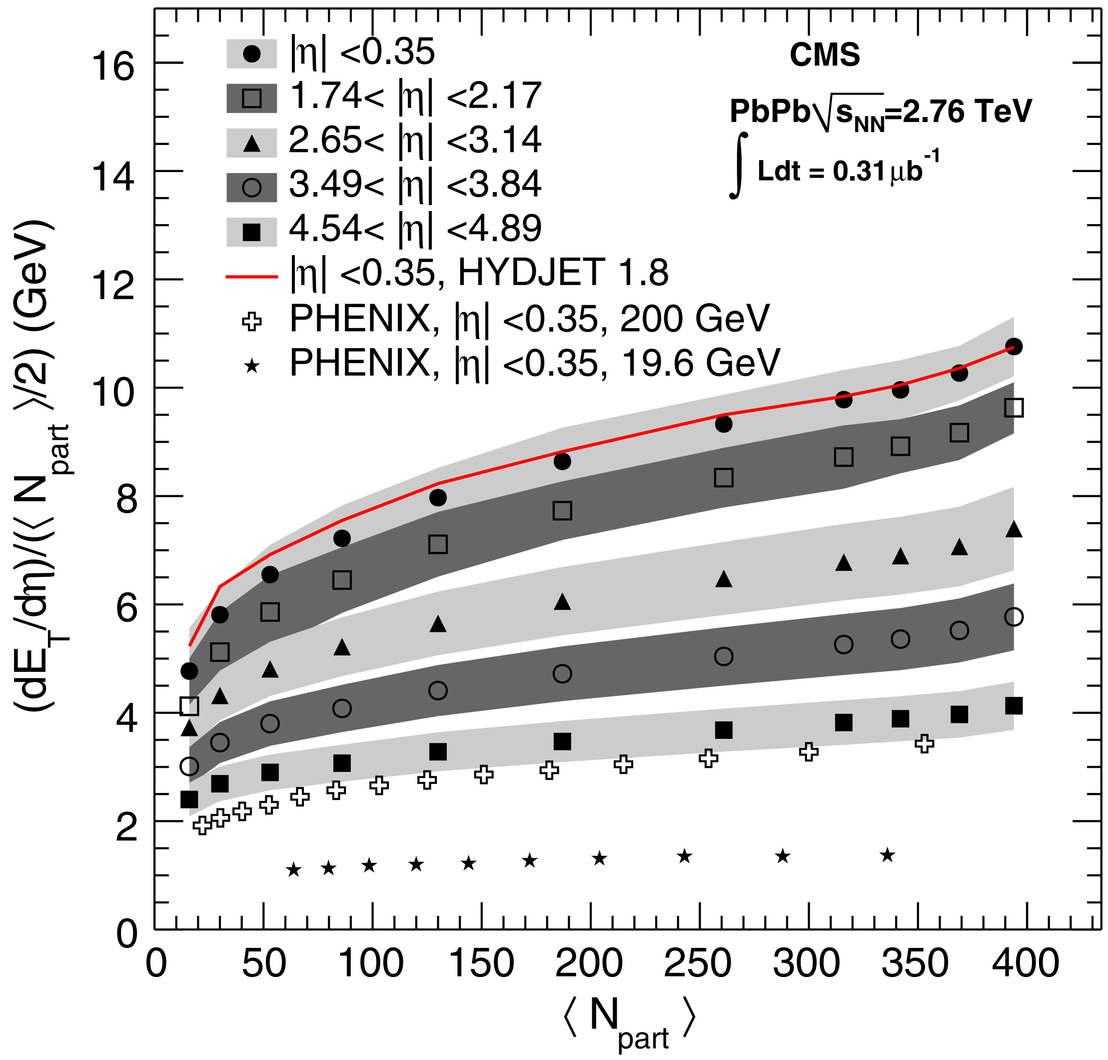


Phys.Rev. C83 (2011) 024913, CMS JHEP 08 (2011) 141, ALICE Phys. Rev. Lett. 105 (2010) 252301

transverse energy



increase in transverse energy with centrality



increase in transverse energy per participant pair with centrality

PRL 109 152303

Glauber model

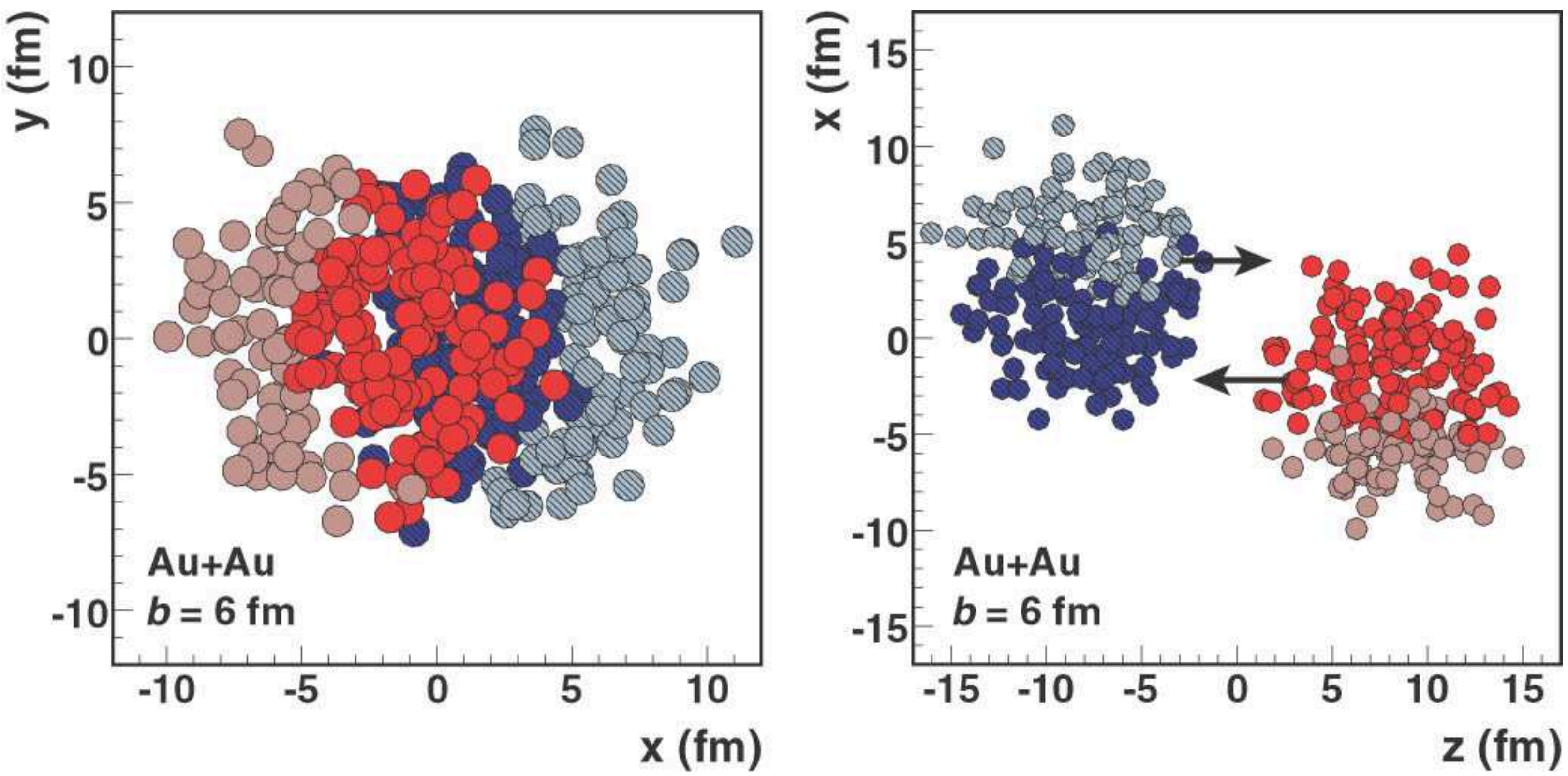
model the distributions of nucleons in nucleus
(Woods-Saxon for spherical nuclei)

$$\rho(r) \propto \frac{1}{1 + exp(\frac{r-R}{a})}$$

sample from that distribution to get a unique distribution of nucleons for each nucleus

for each nucleon in nucleus A ask if it hits a nucleon from nucleus B

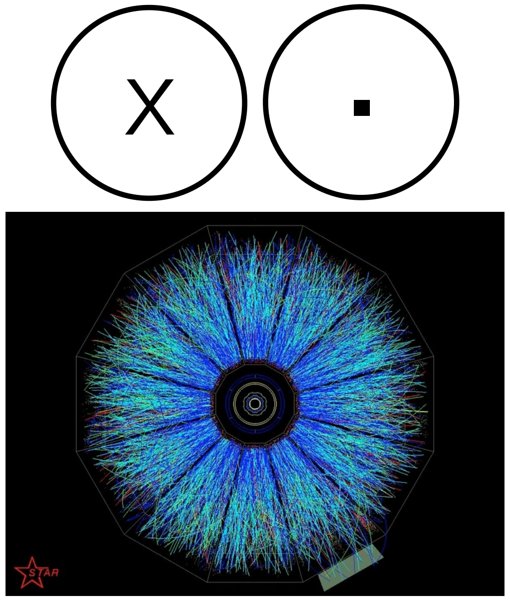
if so, that is a "binary collision" and the nucleons are "**participants**"



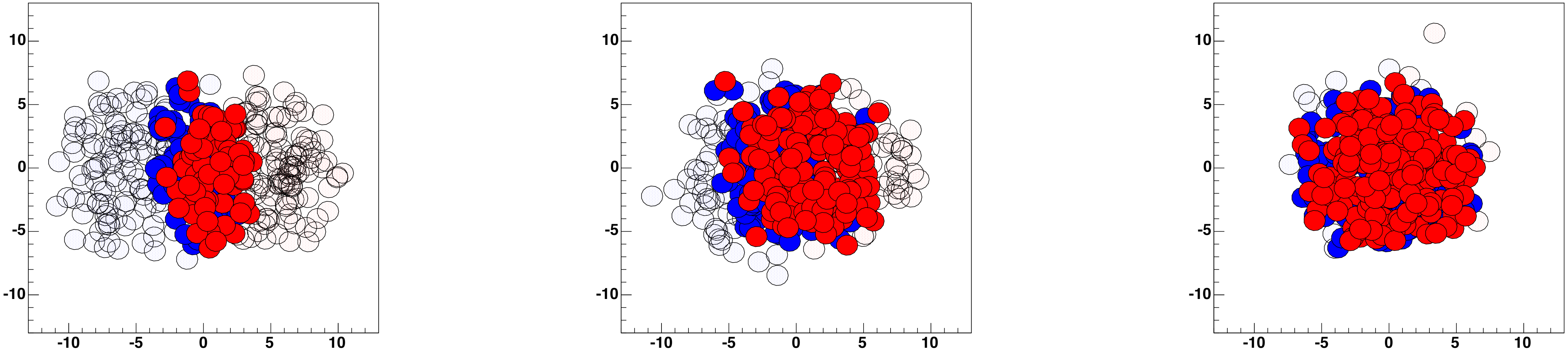
assume monotonic relationship between impact parameter and multiplicity

Miller, et al, Ann Rev Nuc Part 57 (2007) 205
C. Loizides, et al Software X 1-2 (2015) 13
C. Loizides, et al PRC 97 054910

collision geometry

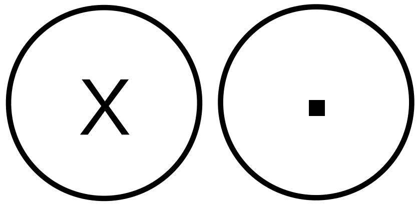


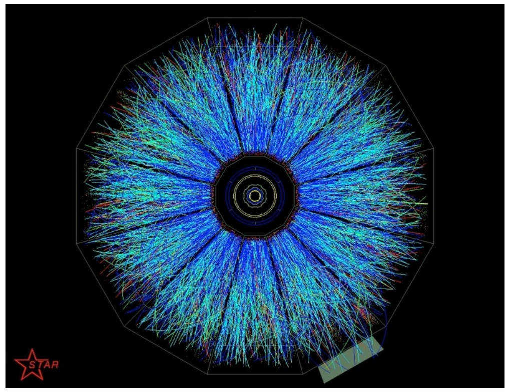
nucleon positions for the colliding nuclei for three different simulated collisions



varying the impact parameter, changes the shape and size of the region where the nuclei overlap

collision geometry





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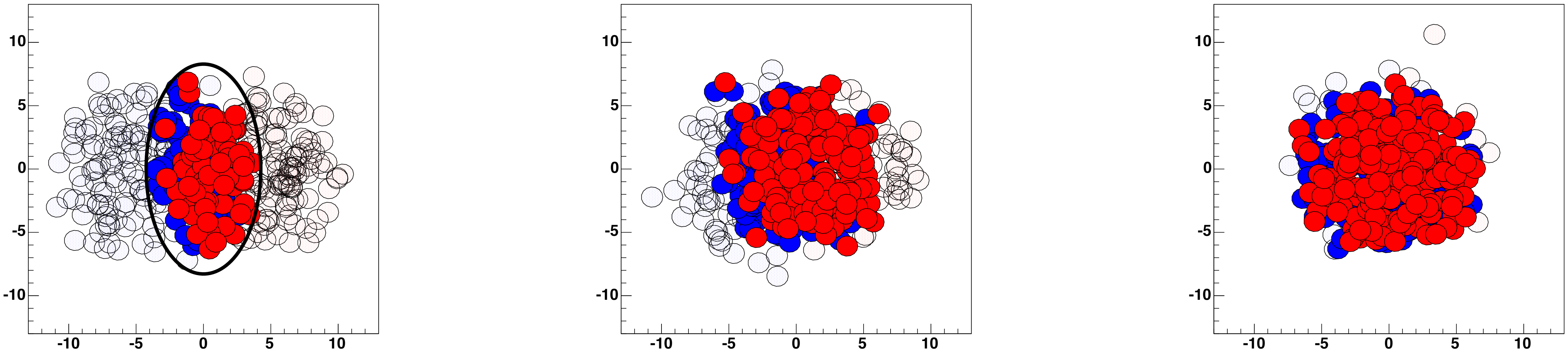

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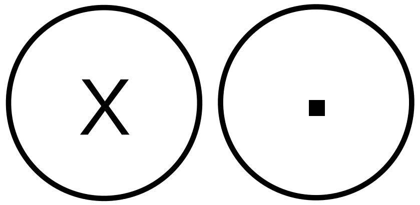

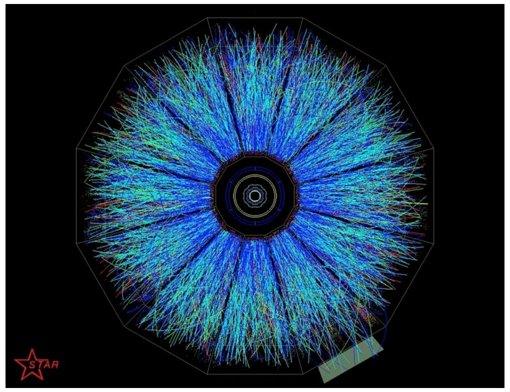

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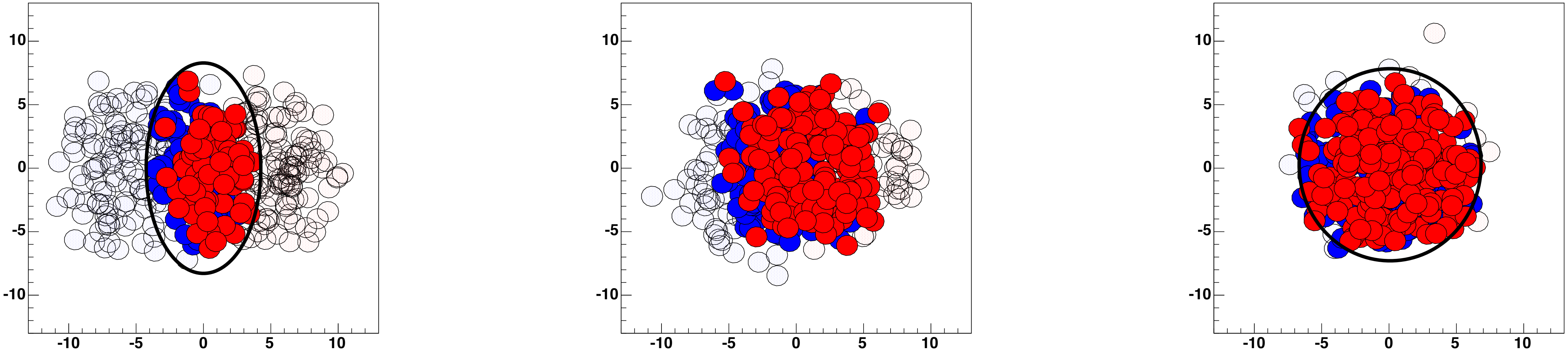
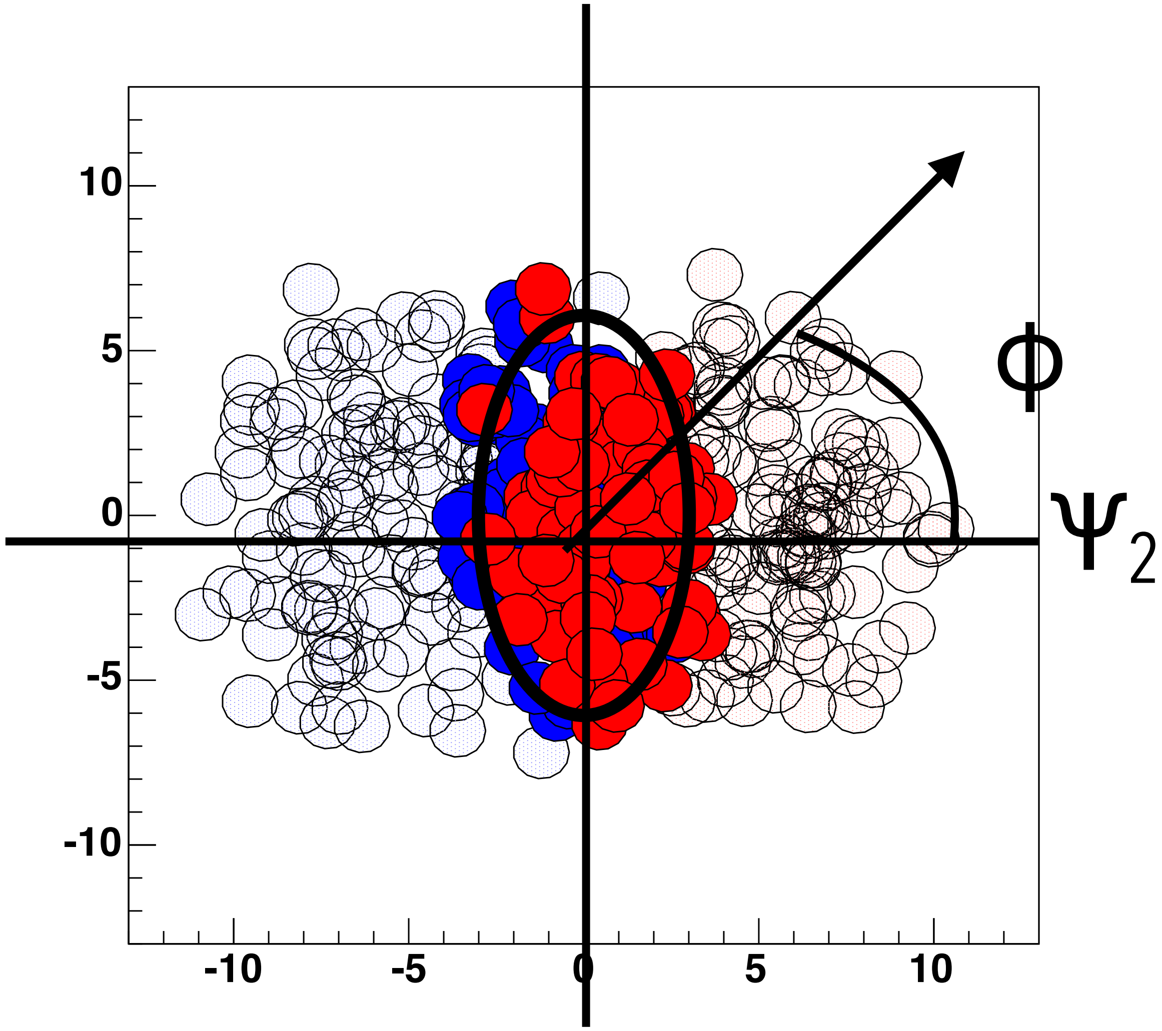


varying the impact parameter, changes the shape and size of the region where the nuclei overlap

counting particles

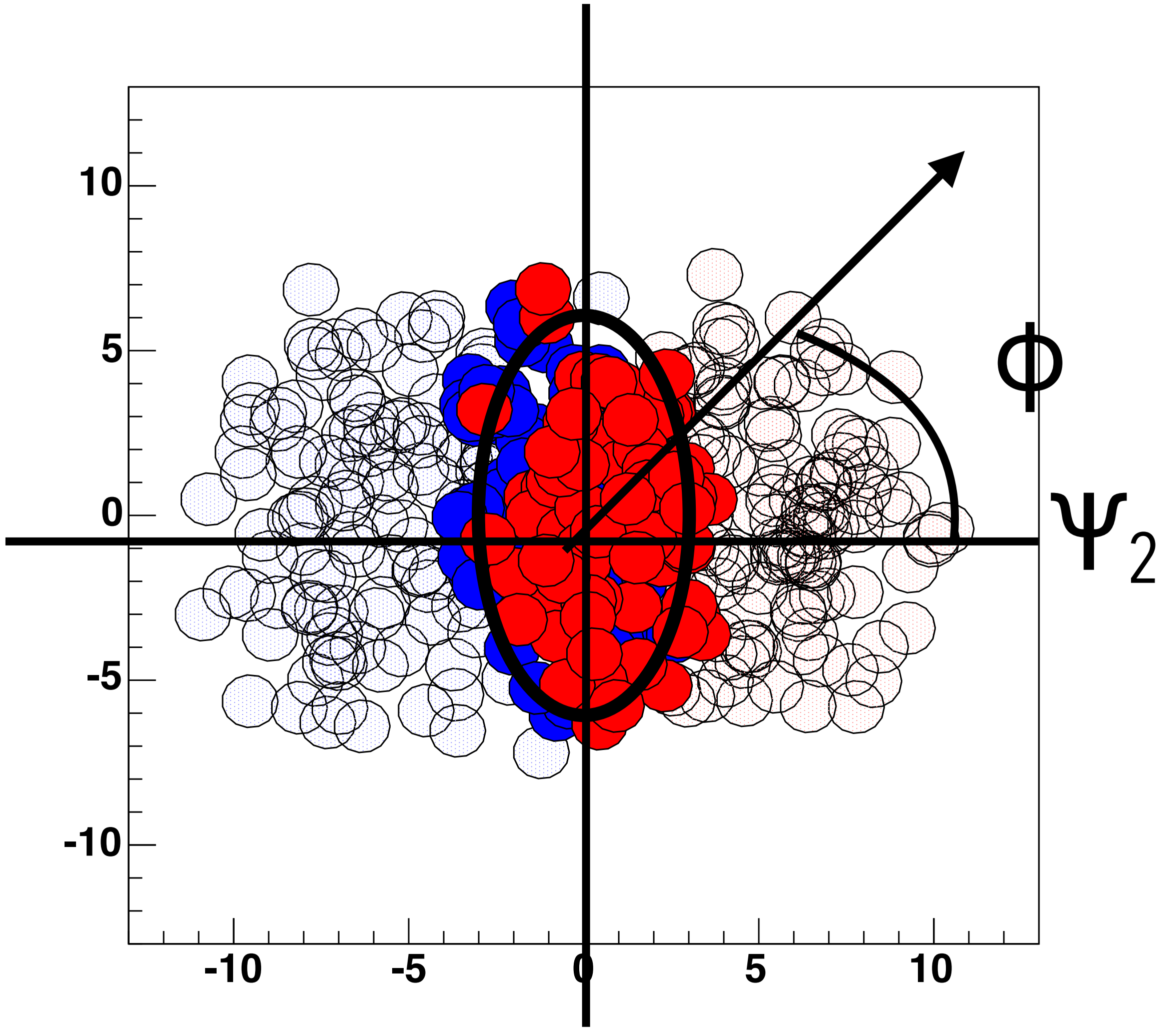
before the collision: orientation of the nuclei



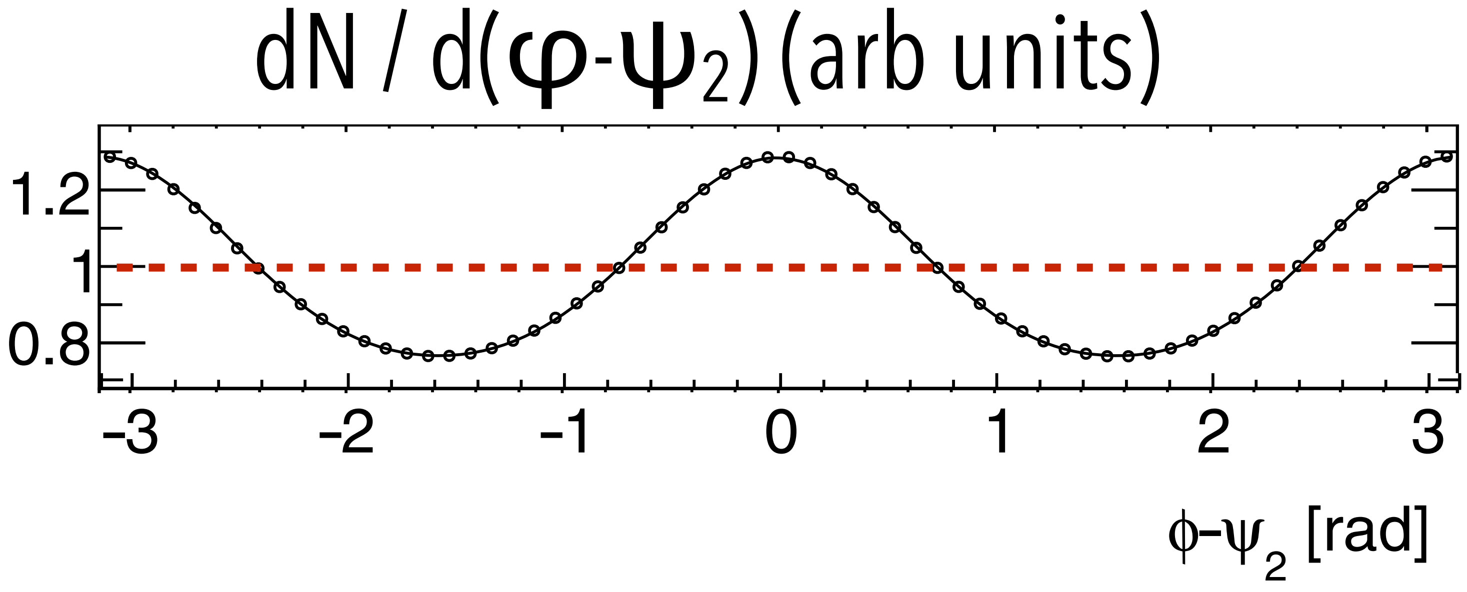
PLB 707 330 (2012)

counting particles

before the collision: orientation of the nuclei



after the collision: angular distribution of particles

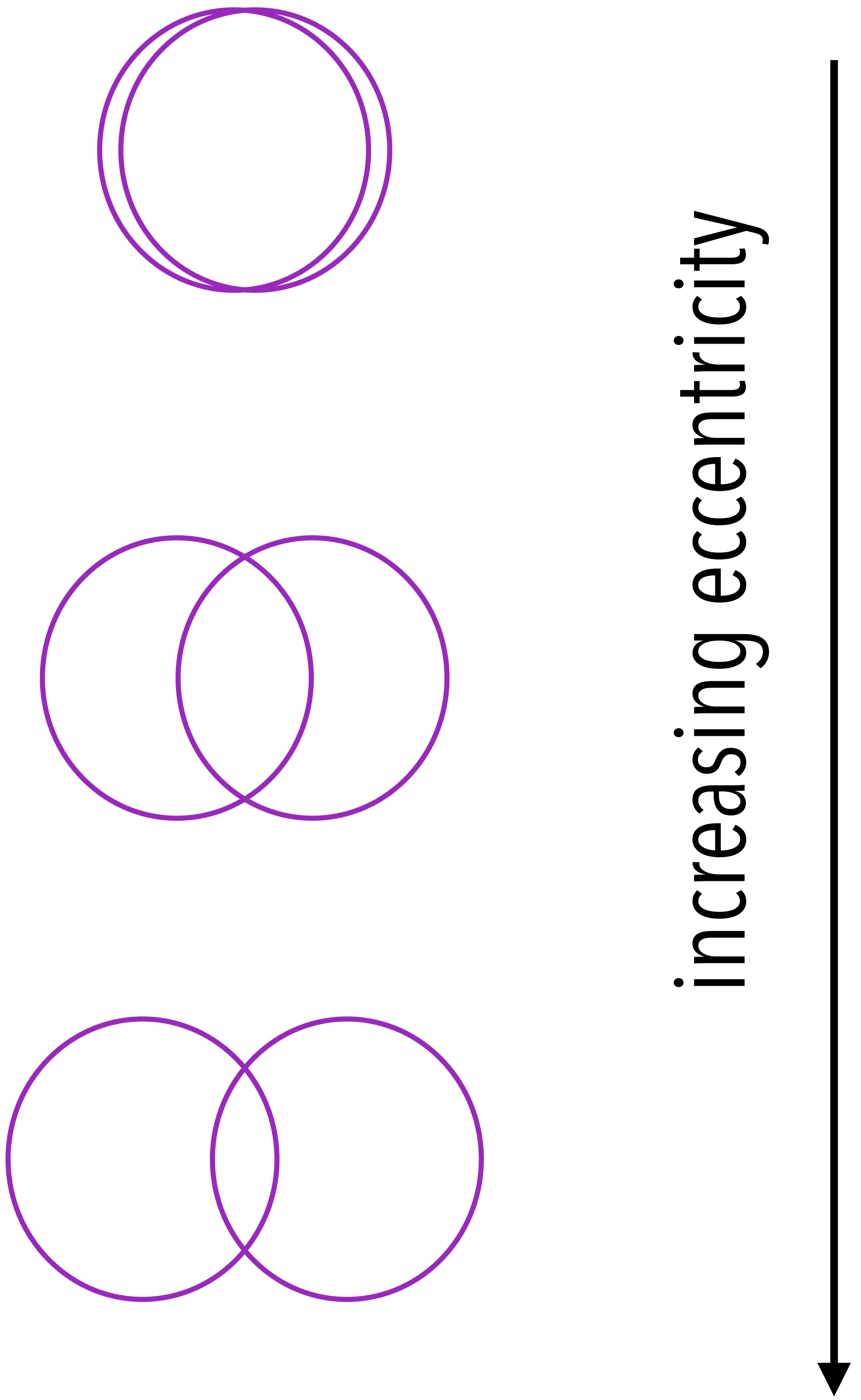


thousands of events with approximately the same impact parameter

PLB 707 330 (2012)

collision geometry

PLB 707 330 (2012)

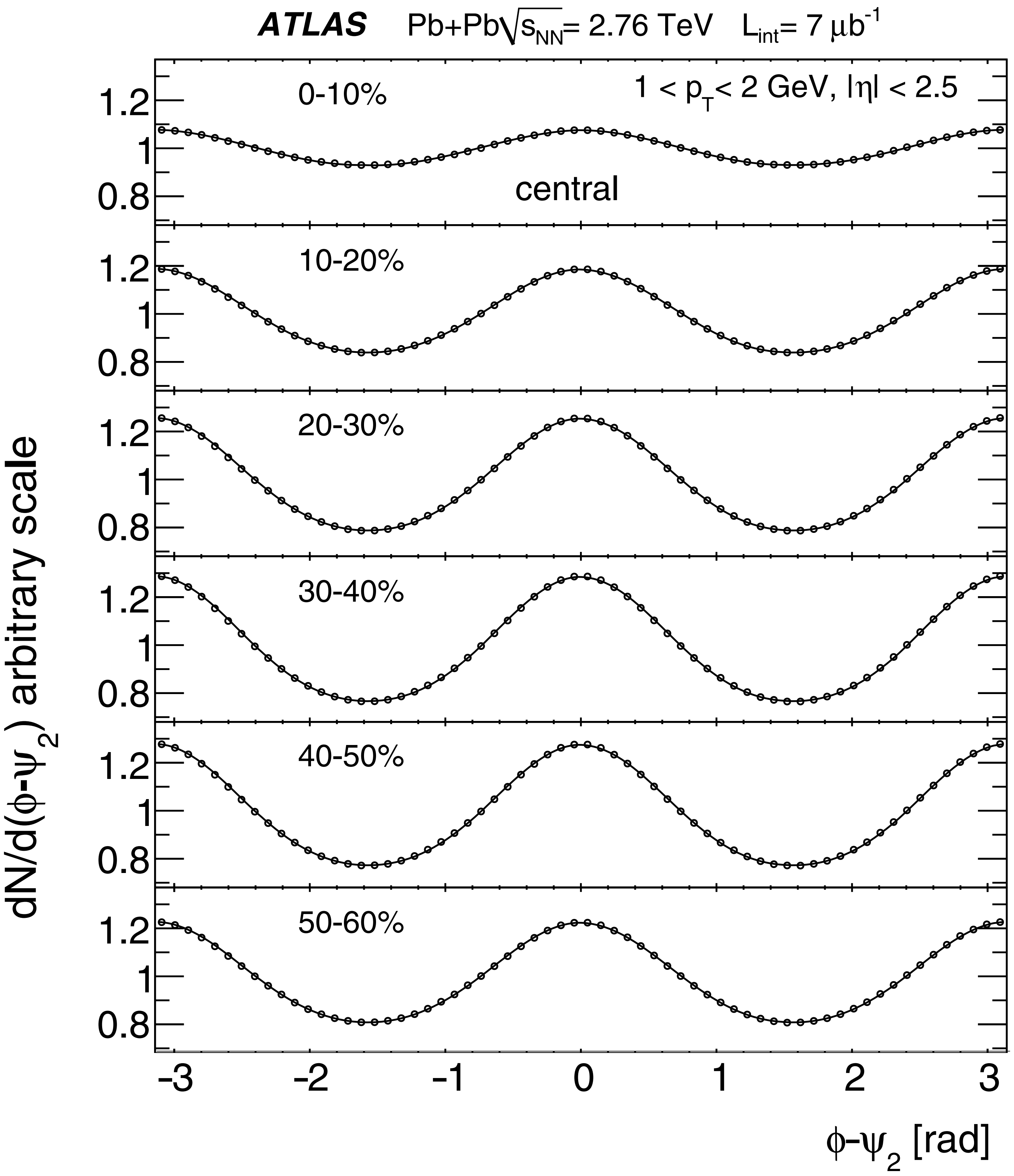


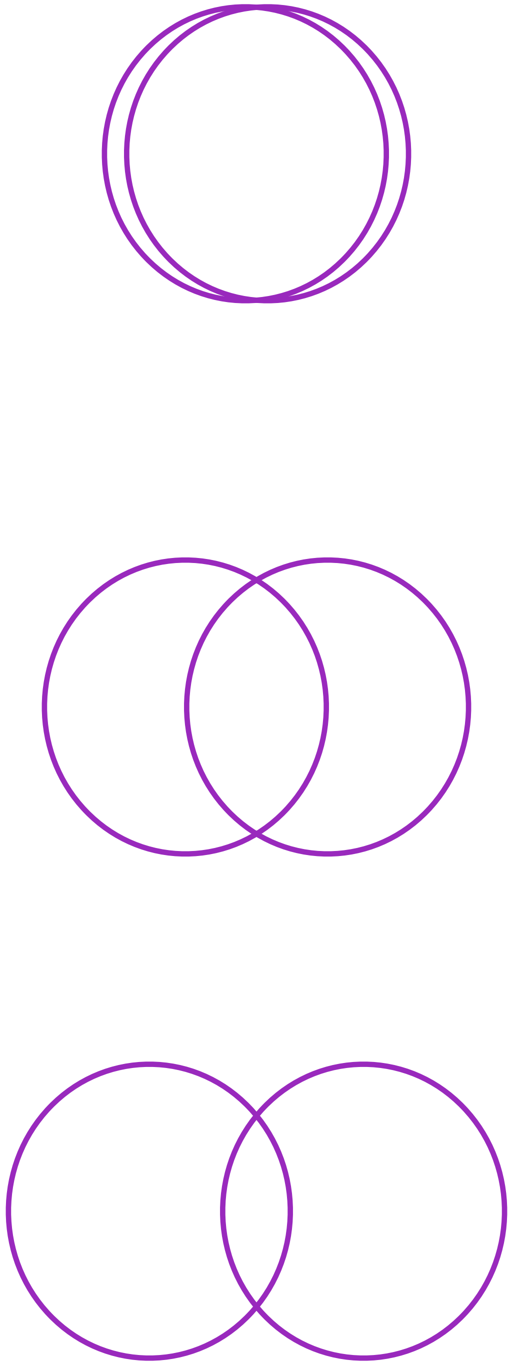
increasing eccentricity

collision geometry

PLB 707 330 (2012)

increasing modulation



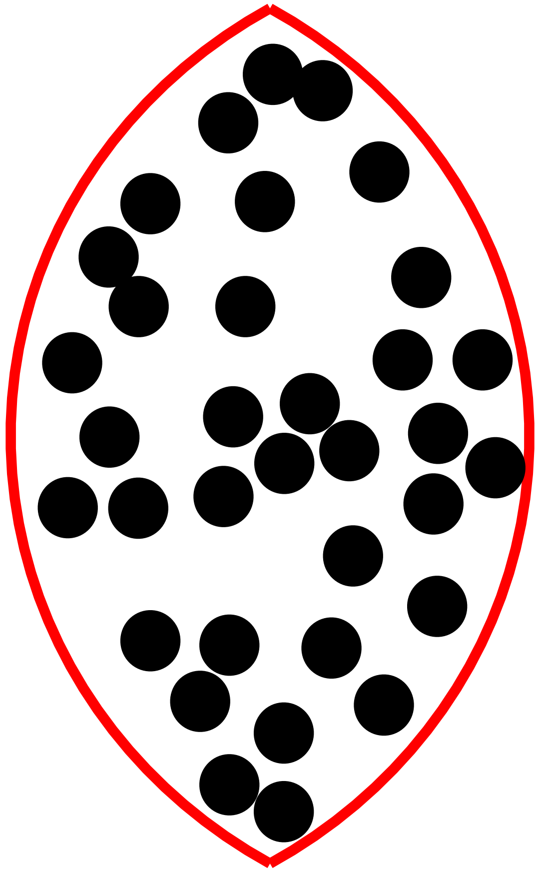


increasing eccentricity

role of interactions

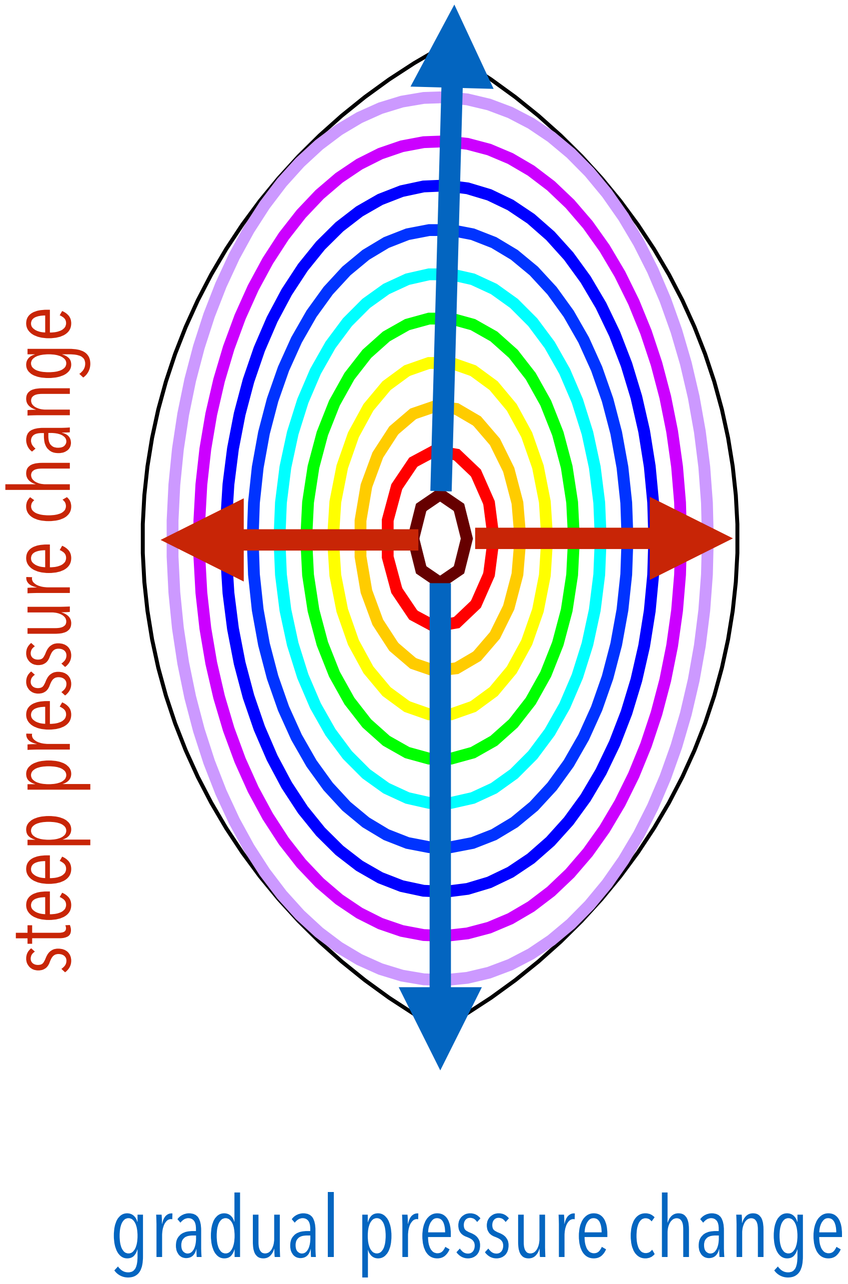
gas: minimal interactions

isotropic expansion



fluid: lots of interactions

anisotropic expansion



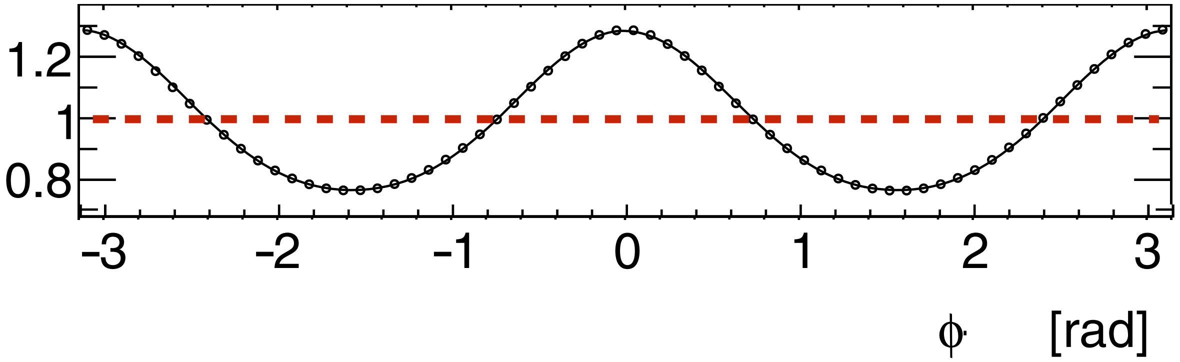
hydrodynamics

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$$ stress energy tensor

$$\partial_\mu T^{\mu\nu} = 0$$ local energy/momentum conservation

- also need
  - relation between ε and P: equation of state, calculated in lattice QCD
  - initial conditions of the system: geometry of the the nucleus
  - any conserved quantities
- ideal hydrodynamics:
  - no viscosity and no dissipation

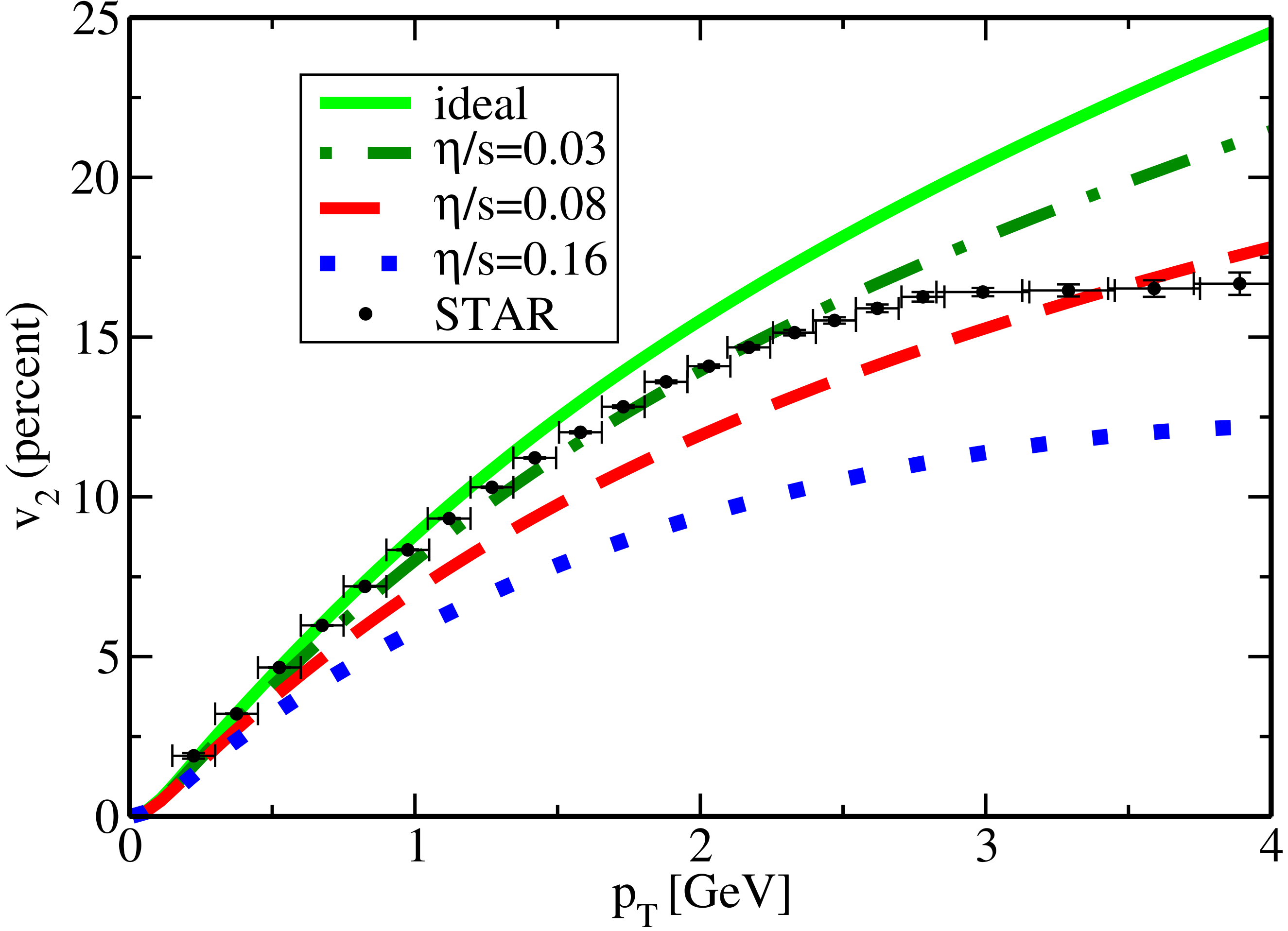
hydrodynamics with viscosity



$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos[2(\phi - \Psi_2)]$$

v_2 → amplitude of modulation

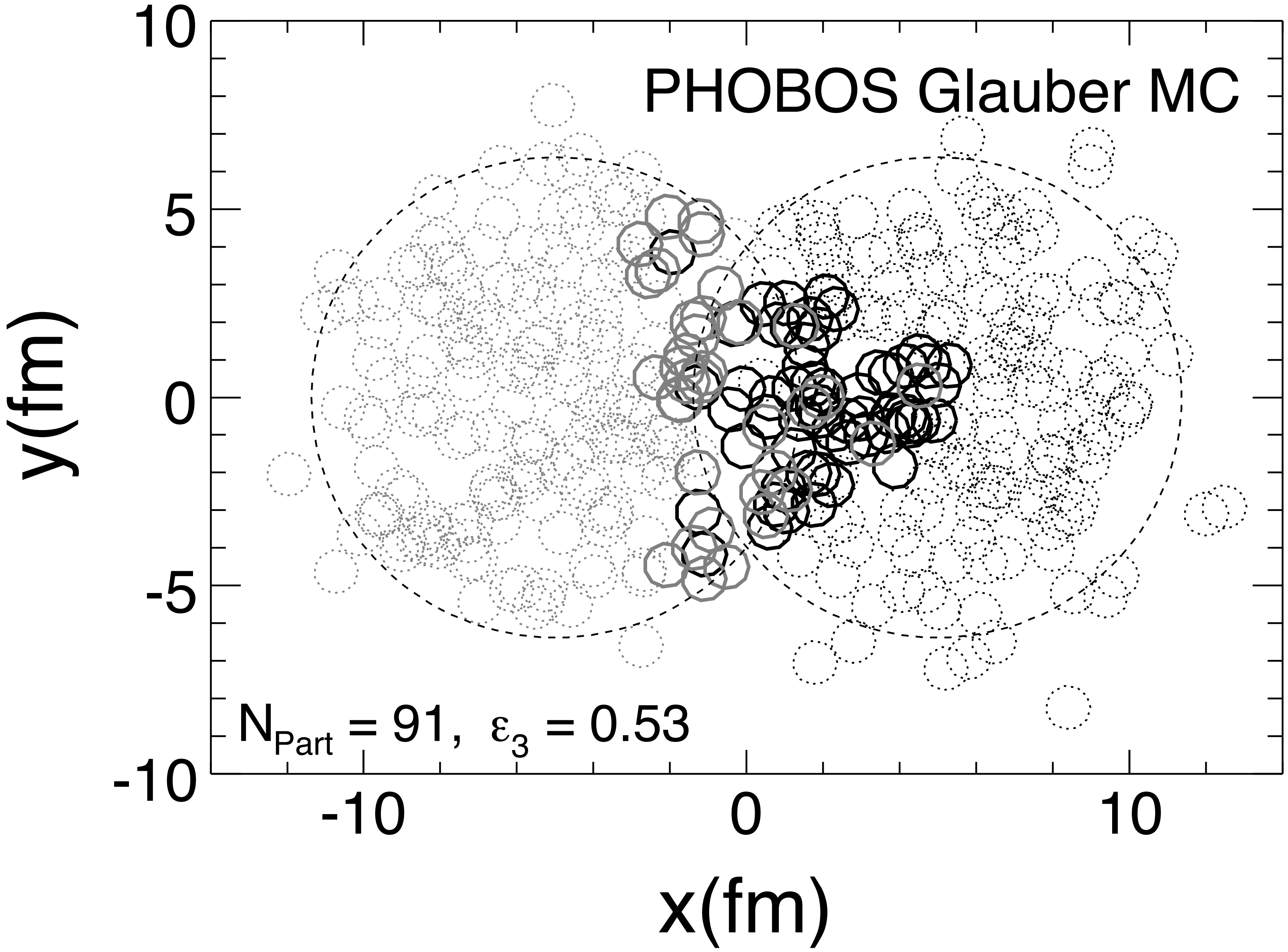
Romatschke & Romatschke PRL 99 172301



- observations:
  - shows that v_2 measurements can be used to constrain η/s (viscosity / entropy density)
  - however, no one η/s value describes the data perfectly
    - η/s ought to depend on temperature and thus one value is an oversimplification
  - correlation between the geometry of the initial state and the η/s
    - need to constrain geometry to measure η/s

role of fluctuations

Alver & Roland, Phys.Rev. C81 (2010) 054905

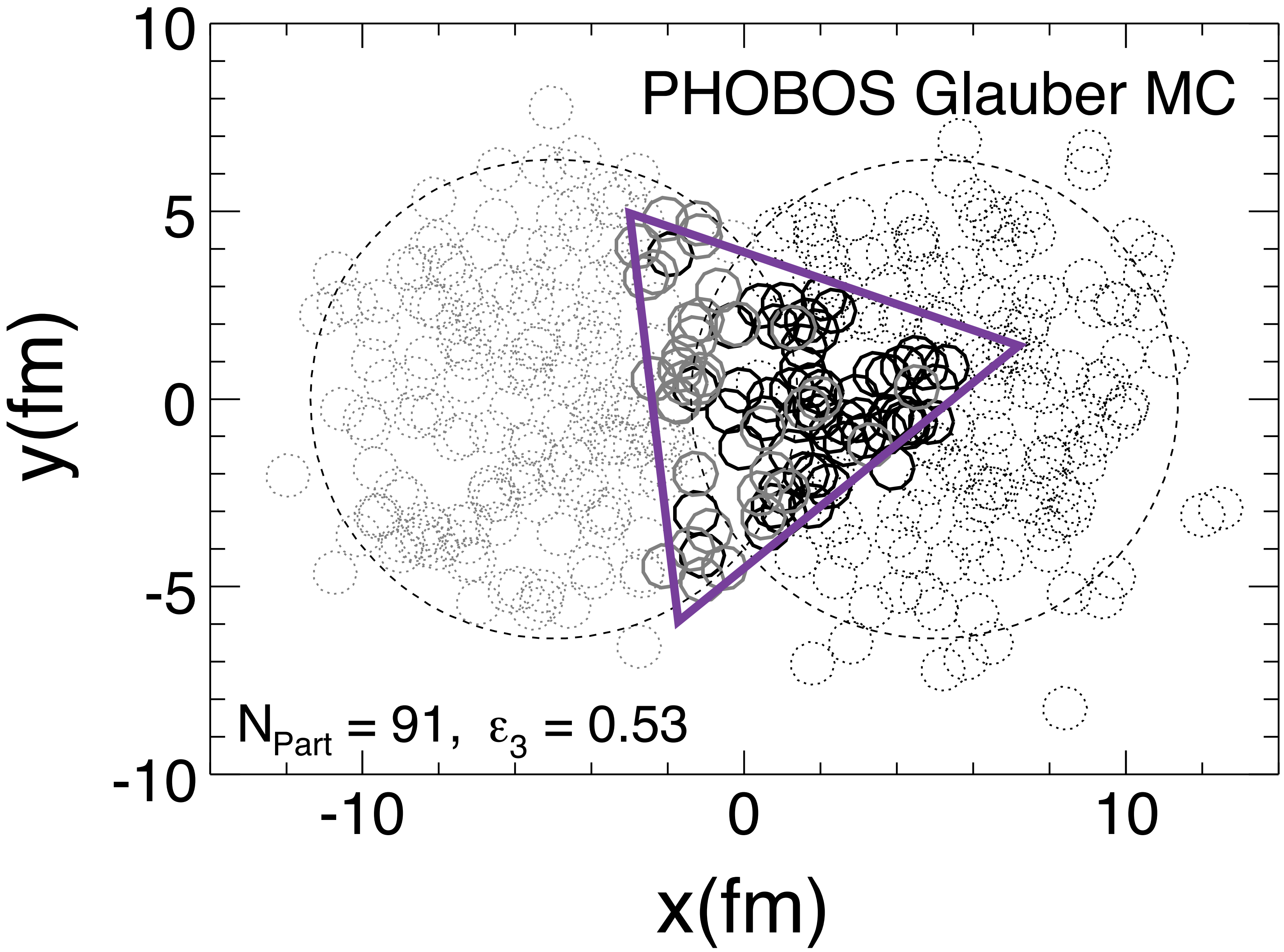


fluctuations in the nucleon position can create shapes any shape of the initial nucleon positions

→not just v_2, but v_3, v_4, v_5…can be measured

role of fluctuations

Alver & Roland, Phys.Rev. C81 (2010) 054905



fluctuations in the nucleon position can create shapes any shape of the initial nucleon positions

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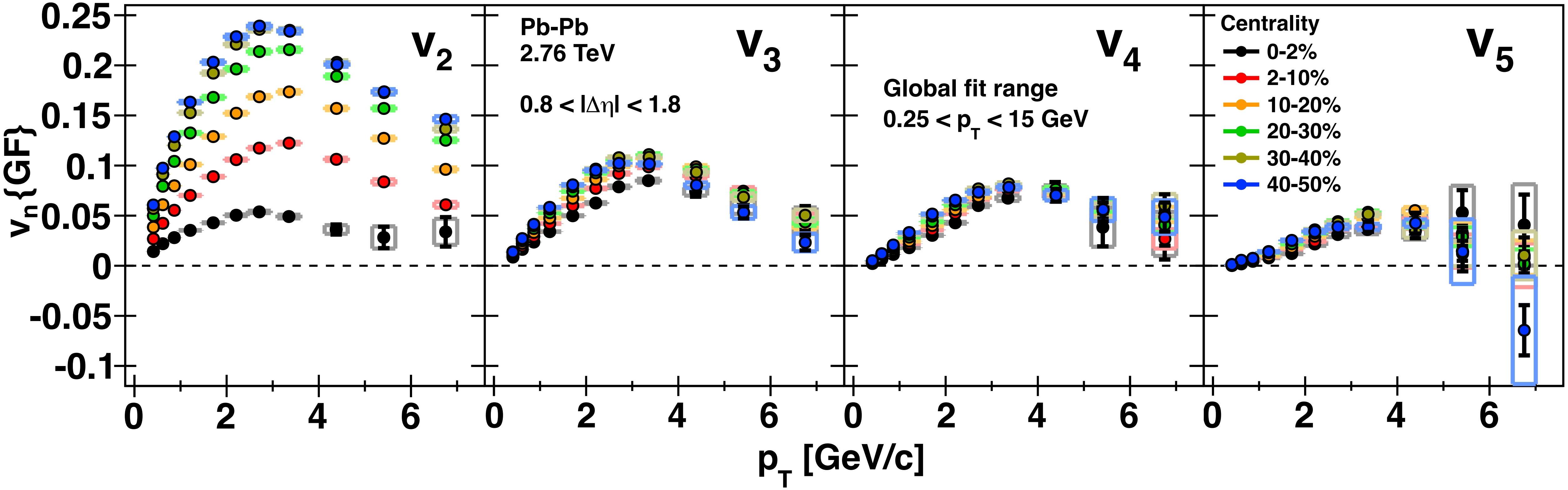
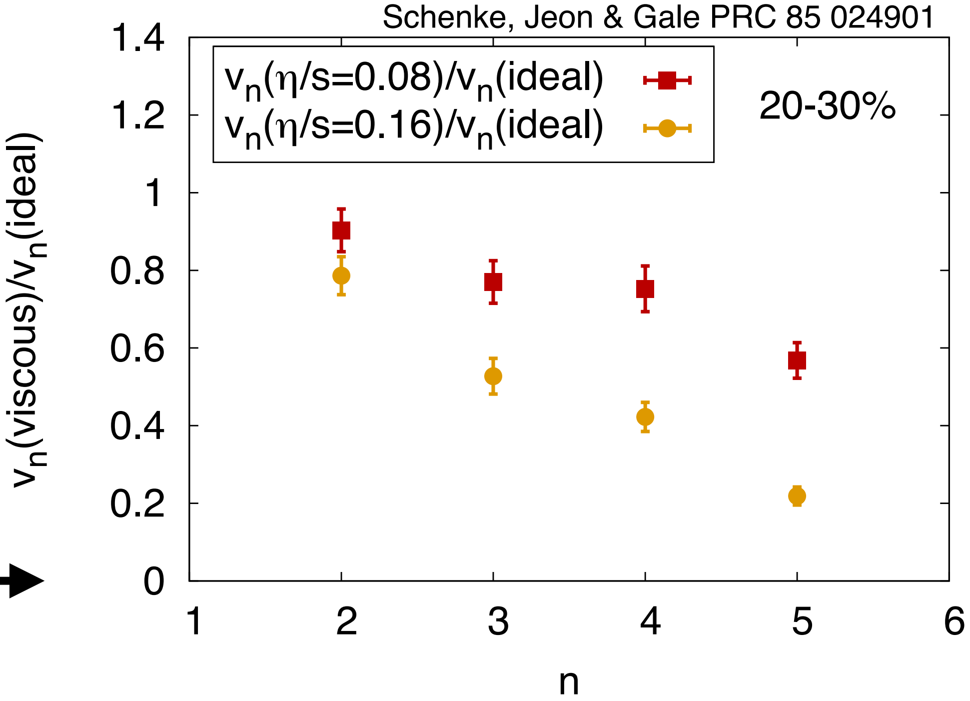
v_N & viscosity

ALICE: 1109.2501



- v_2: overlap geometry (centrality dependent) & fluctuations
- $v_{N>2}$: fluctuations only
- sensitivity to viscosity increases with N

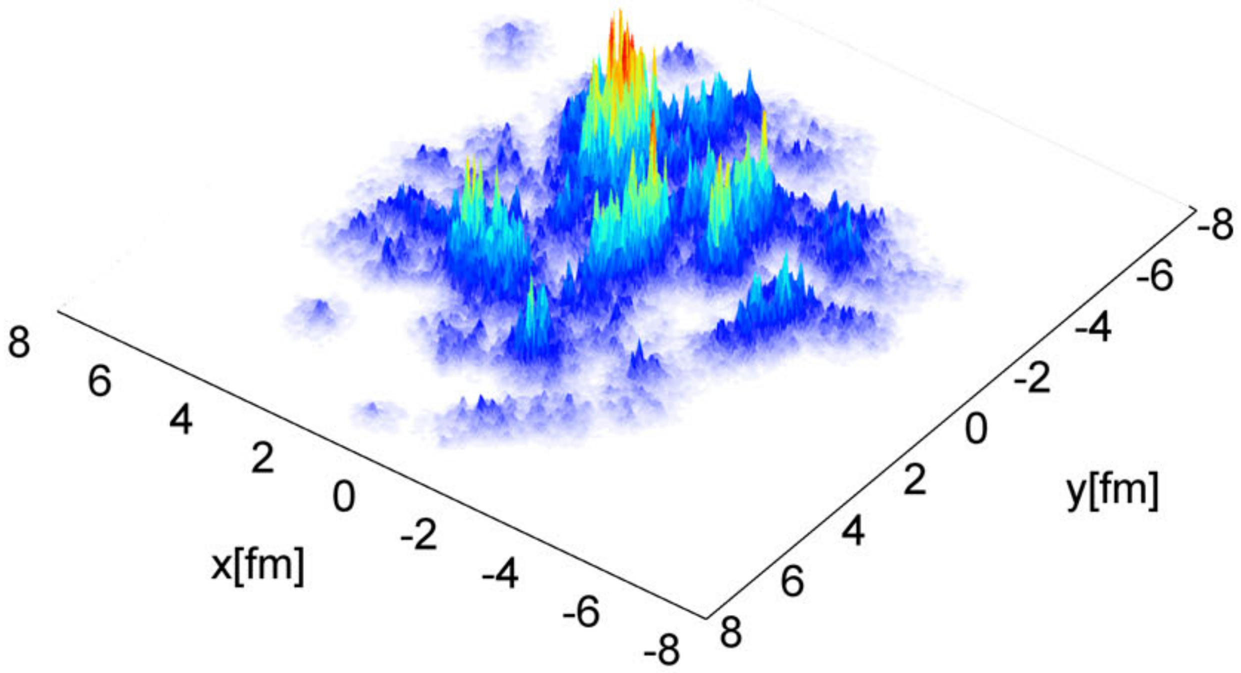
Schenke, Jeon & Gale PRC 85 024901



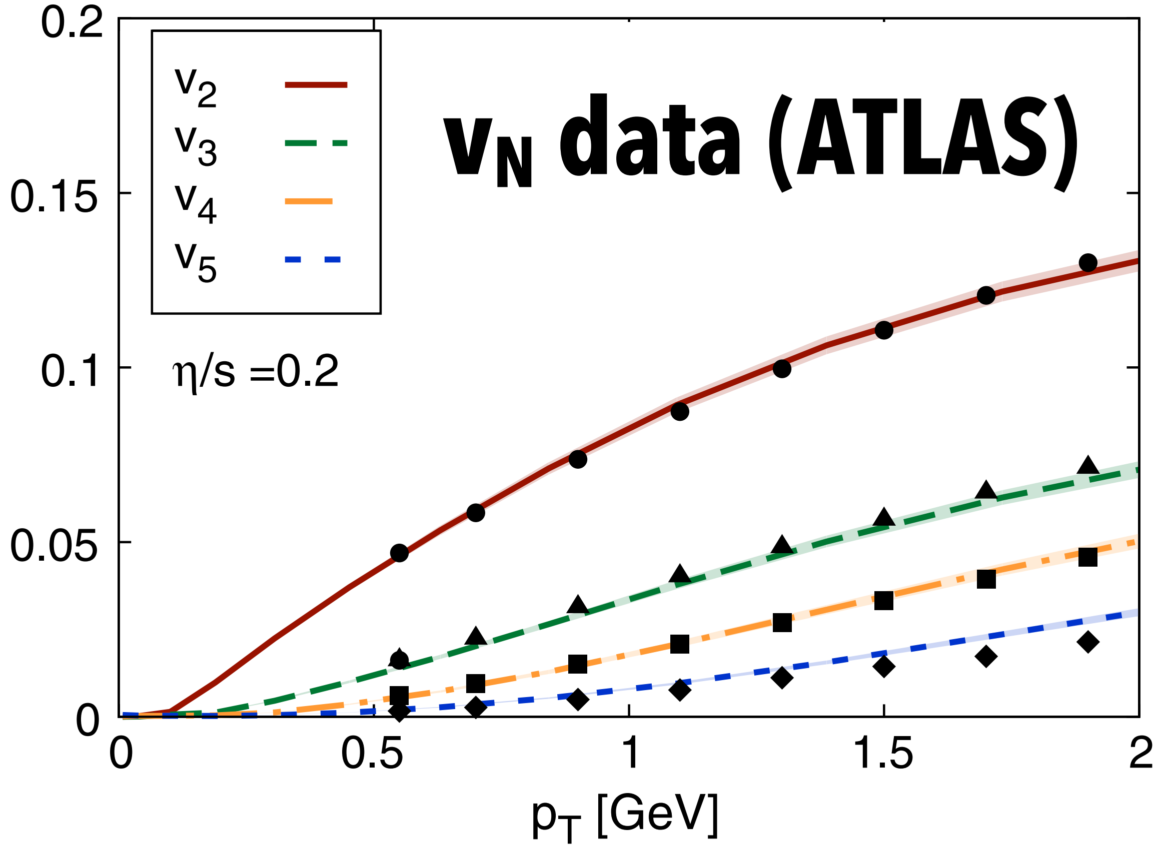
hydrodynamic modeling (II)

initial energy density calculation: one collision including nucleon fluctuations and fluctuations within the nucleon

Schenke, PRL 108 252301



Gale, et al PRL 110 012302

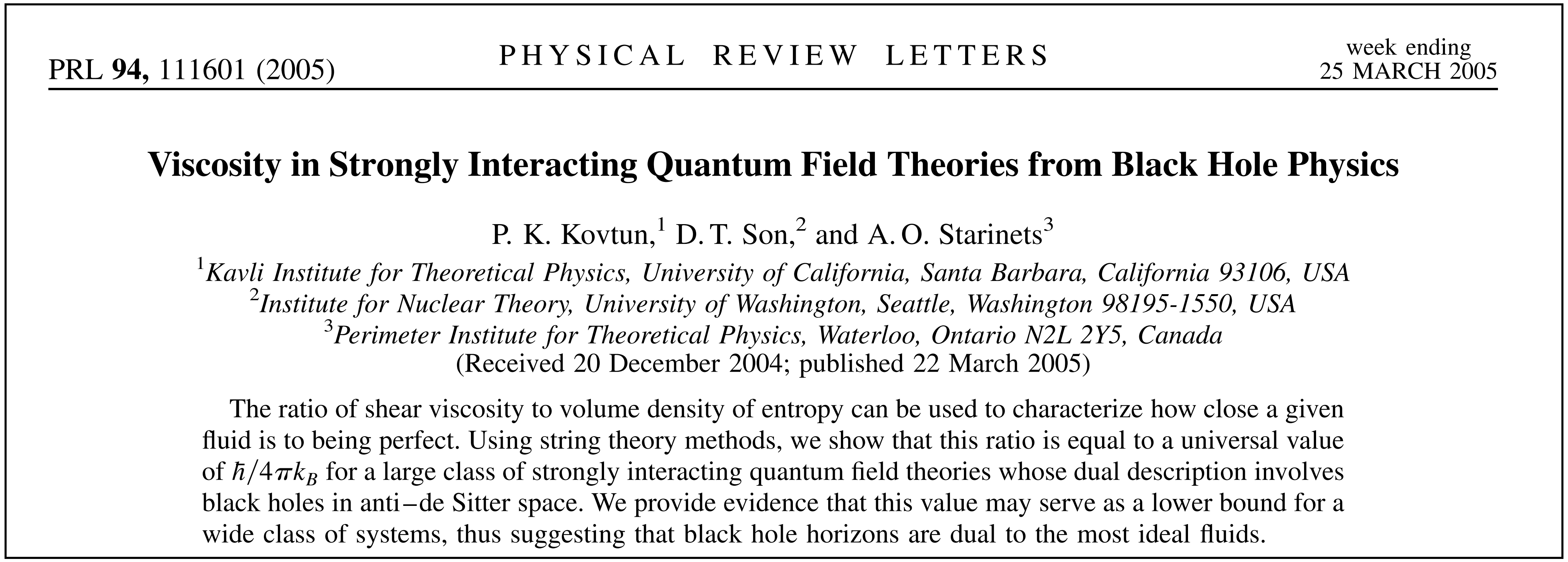


$$\frac{dN}{d\phi} \propto 1 + 2v_N \cos[N(\phi - \Psi_N)]$$

these calculations sensitive to *nuclear geometry* and *shear viscosity / entropy density* ratio (η/s)

liquid QGP

- why does QCD matter at extremely high temperature behave like a fluid?
    - interactions between quarks and gluons drive fluid behavior but QCD known for asymptotic freedom at short distances
- η / s needed to describe QGP viscosity within a factor of a 2-3 of conjectured theoretical bound of η / s =1/4π



PRL **94,** 111601 (2005) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2005

Viscosity in Strongly Interacting Quantum Field Theories from Black Hole Physics

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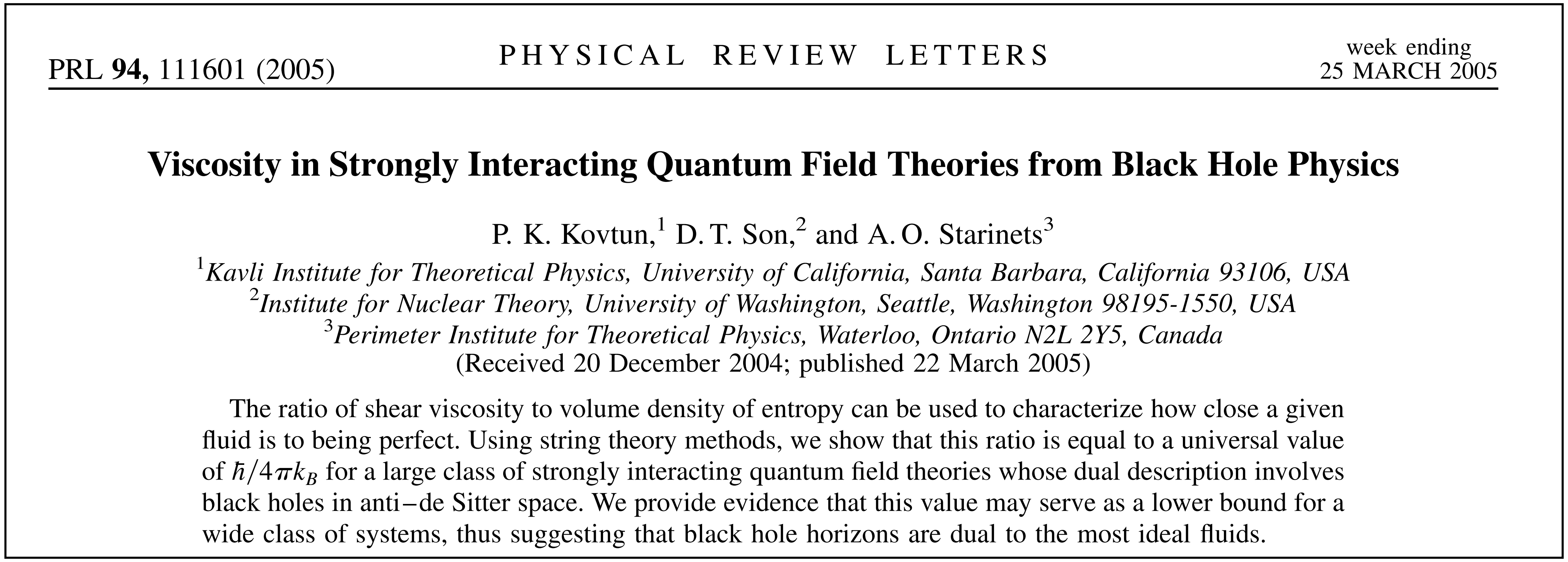
[2] *Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195-1550, USA*
[3] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*

(Received 20 December 2004; published 22 March 2005)

The ratio of shear viscosity to volume density of entropy can be used to characterize how close a given fluid is to being perfect. Using string theory methods, we show that this ratio is equal to a universal value of $\hbar/4\pi k_B$ for a large class of strongly interacting quantum field theories whose dual description involves black holes in anti–de Sitter space. We provide evidence that this value may serve as a lower bound for a wide class of systems, thus suggesting that black hole horizons are dual to the most ideal fluids.

liquid QGP



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[2]*Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195-1550, USA*
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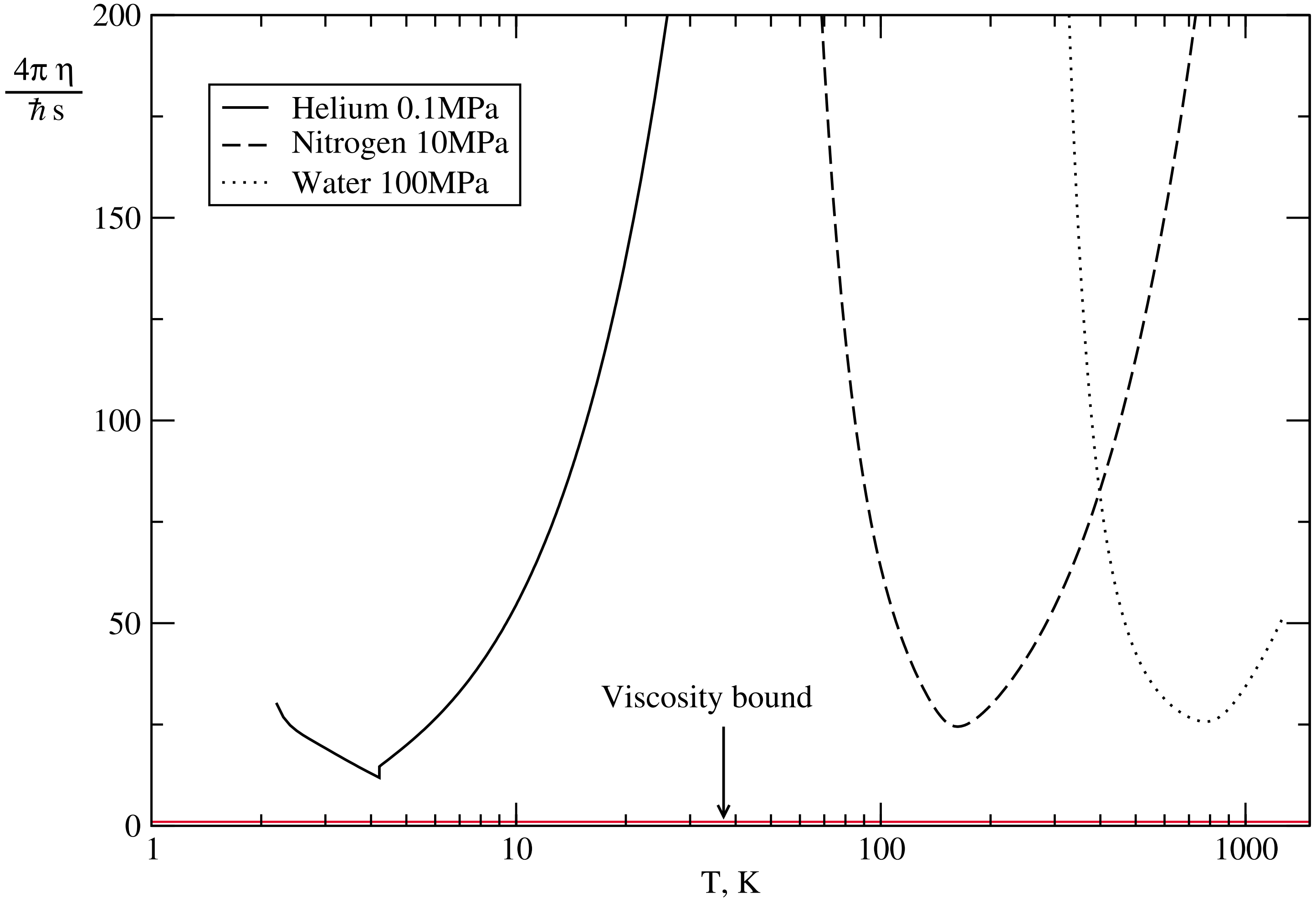
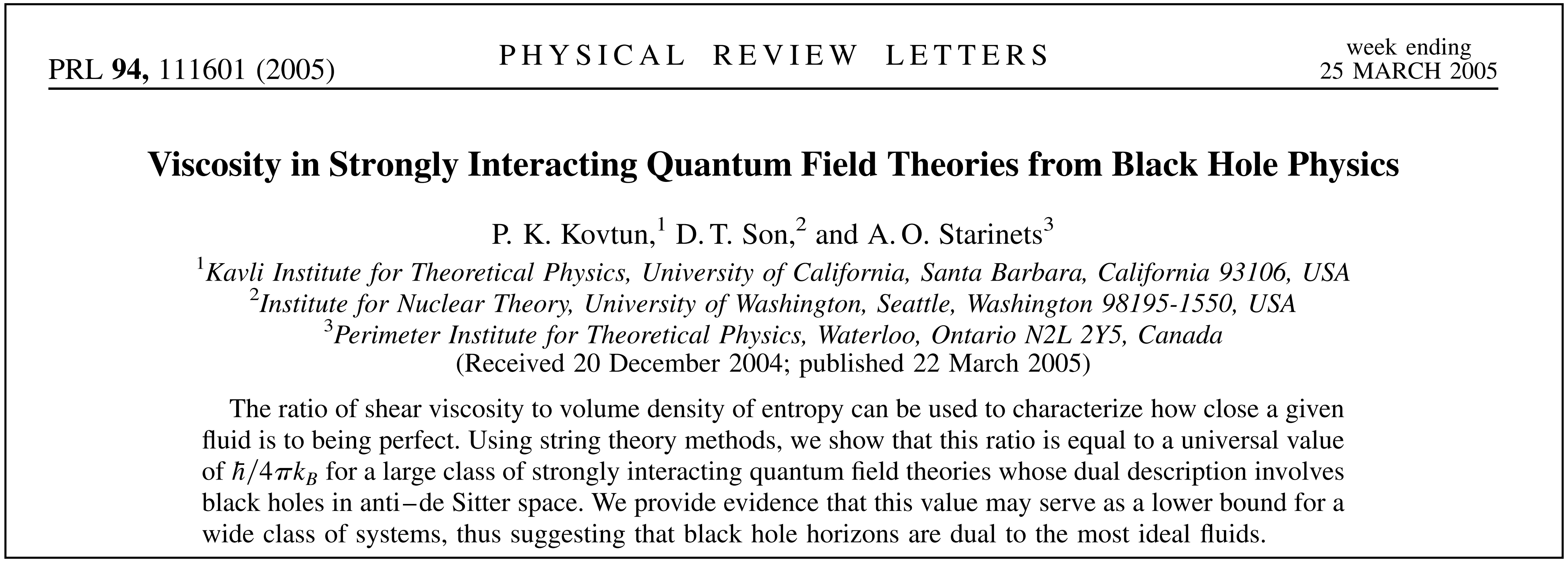
(Received 20 December 2004; published 22 March 2005)

The ratio of shear viscosity to volume density of entropy can be used to characterize how close a given fluid is to being perfect. Using string theory methods, we show that this ratio is equal to a universal value of $\hbar/4\pi k_B$ for a large class of strongly interacting quantum field theories whose dual description involves black holes in anti–de Sitter space. We provide evidence that this value may serve as a lower bound for a wide class of systems, thus suggesting that black hole horizons are dual to the most ideal fluids.



liquid QGP



PRL **94,** 111601 (2005) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2005

Viscosity in Strongly Interacting Quantum Field Theories from Black Hole Physics

P. K. Kovtun,[1] D. T. Son,[2] and A. O. Starinets[3]

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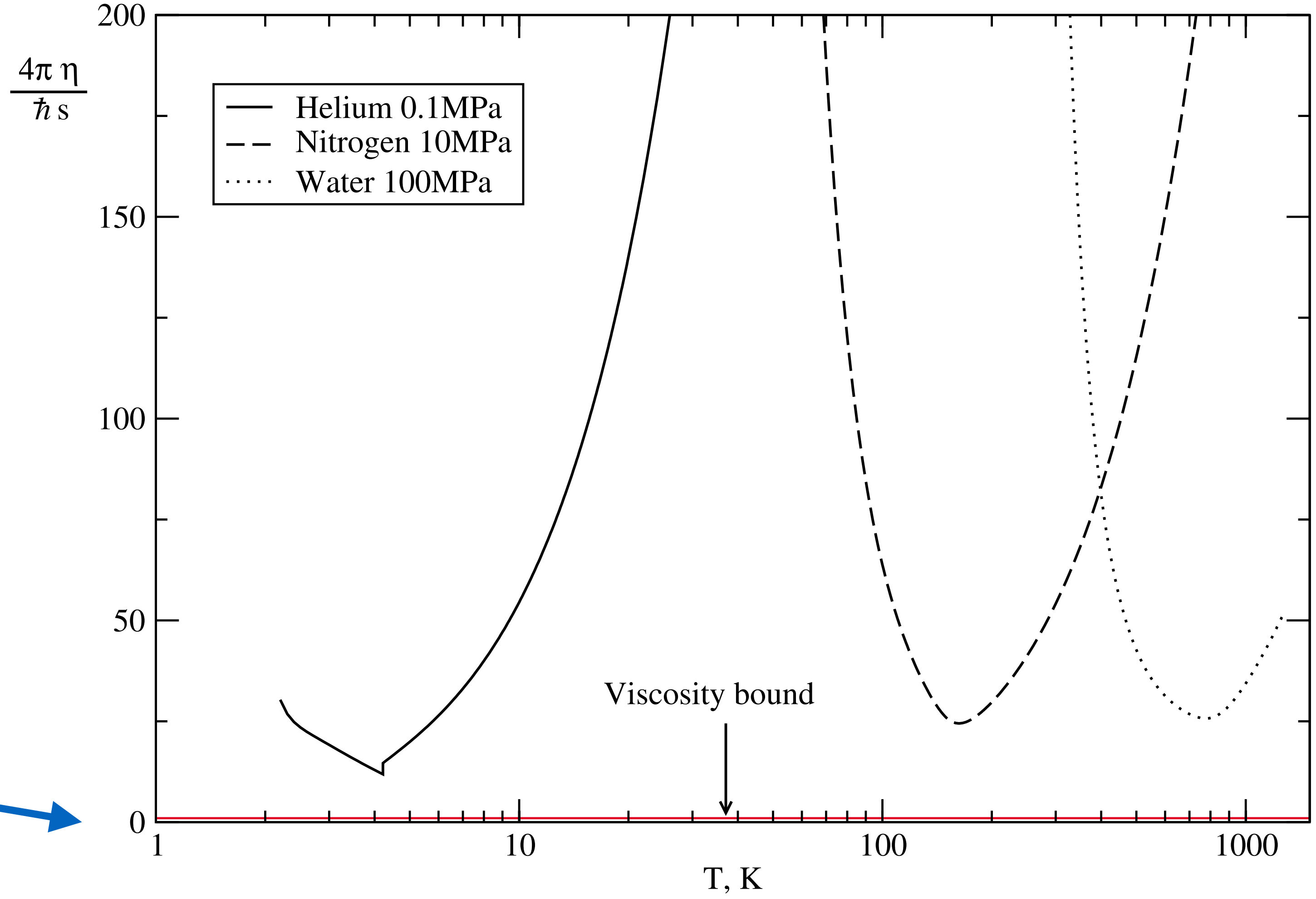
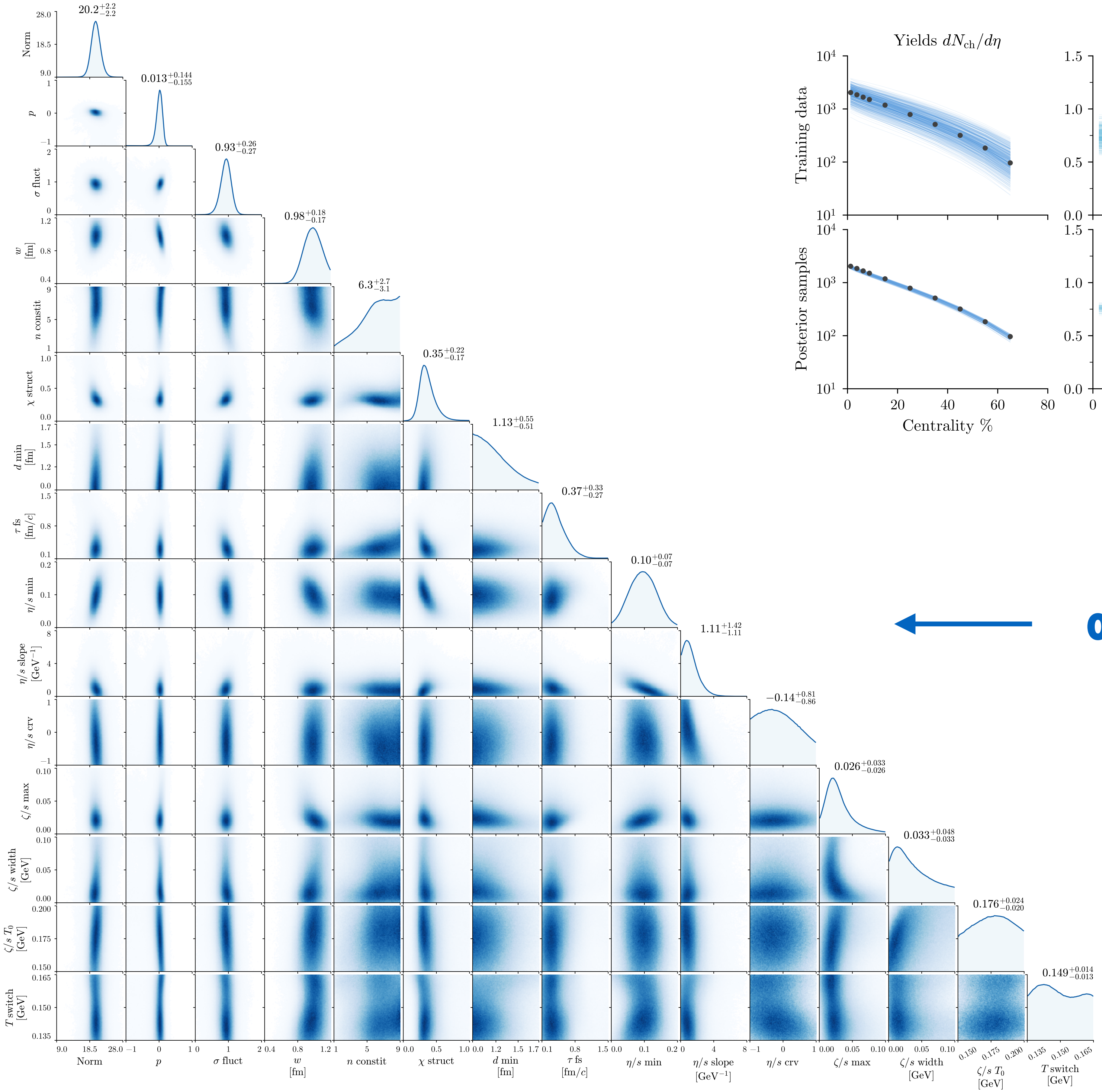
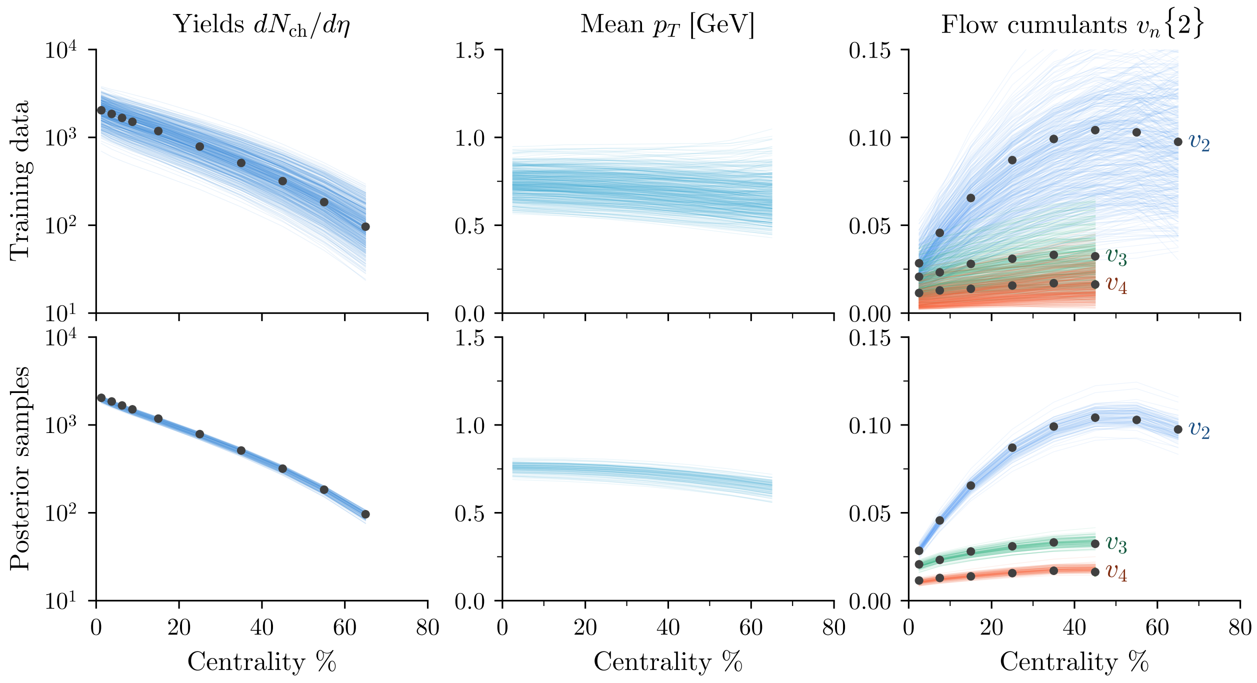


QGP?

using computing to constrain η/s from data





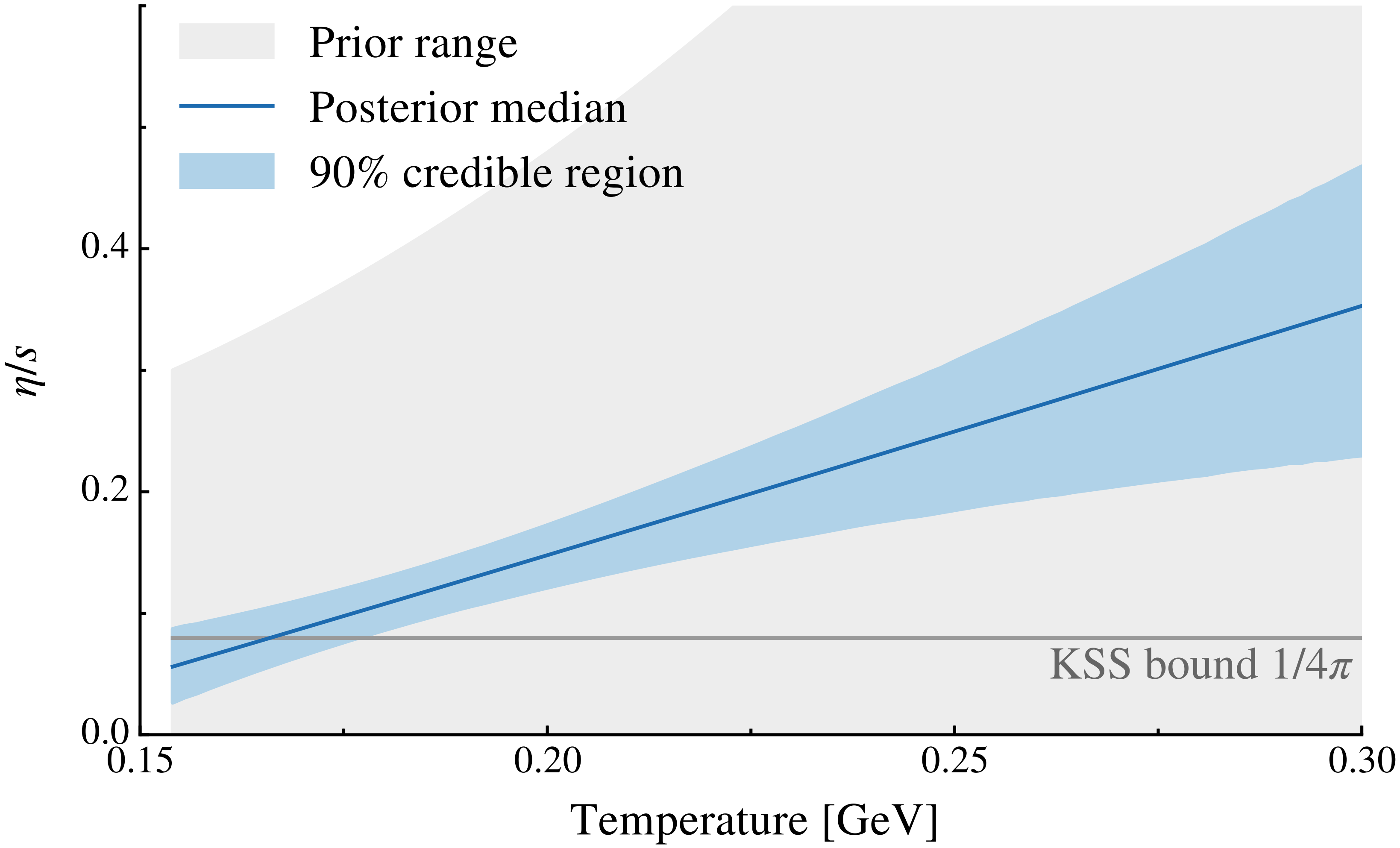
inputs: data from ALICE

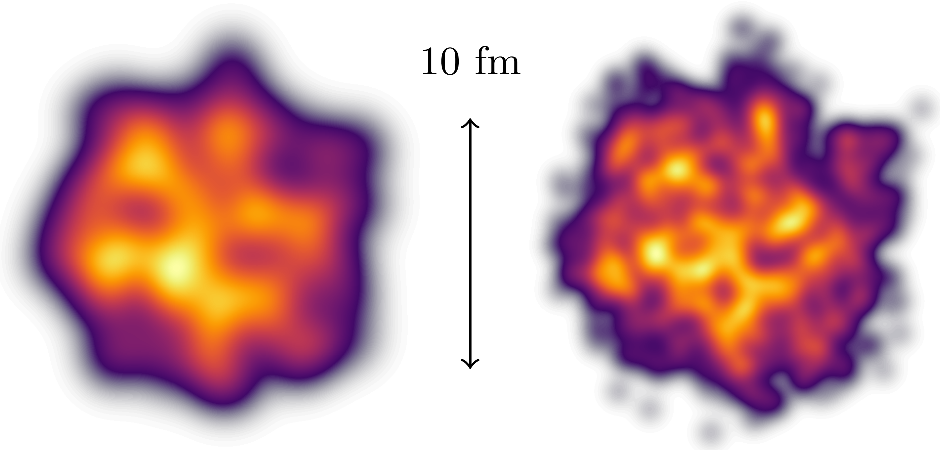
outputs: parameters in the hydrodynamic simulation

Moreland, Bass, Bernhard:
1808.02106,1704.07671

finding the viscosity

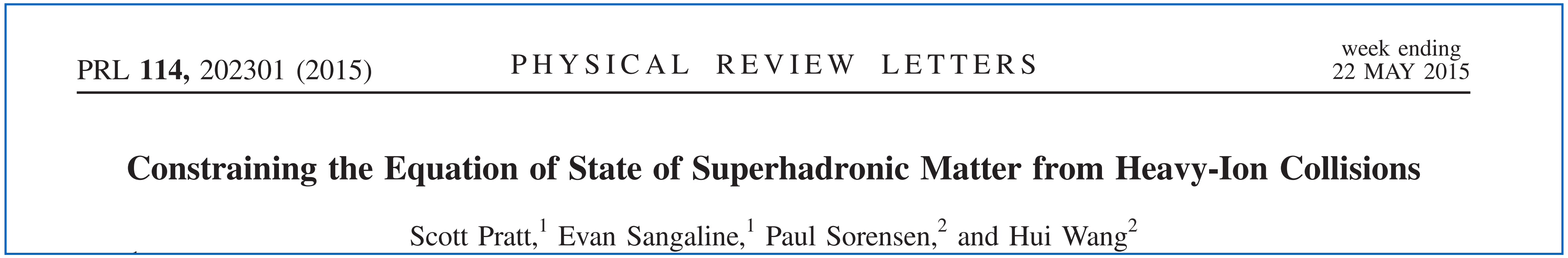
- constraints on visocosity from a Bayasian analysis of data from the LHC
- one of the main sources of uncertainty is the geometry of the initial state and the size of the hot spots created from a nucleon-nucleon collision





Bass et al, 1704.07671, 1808.02106

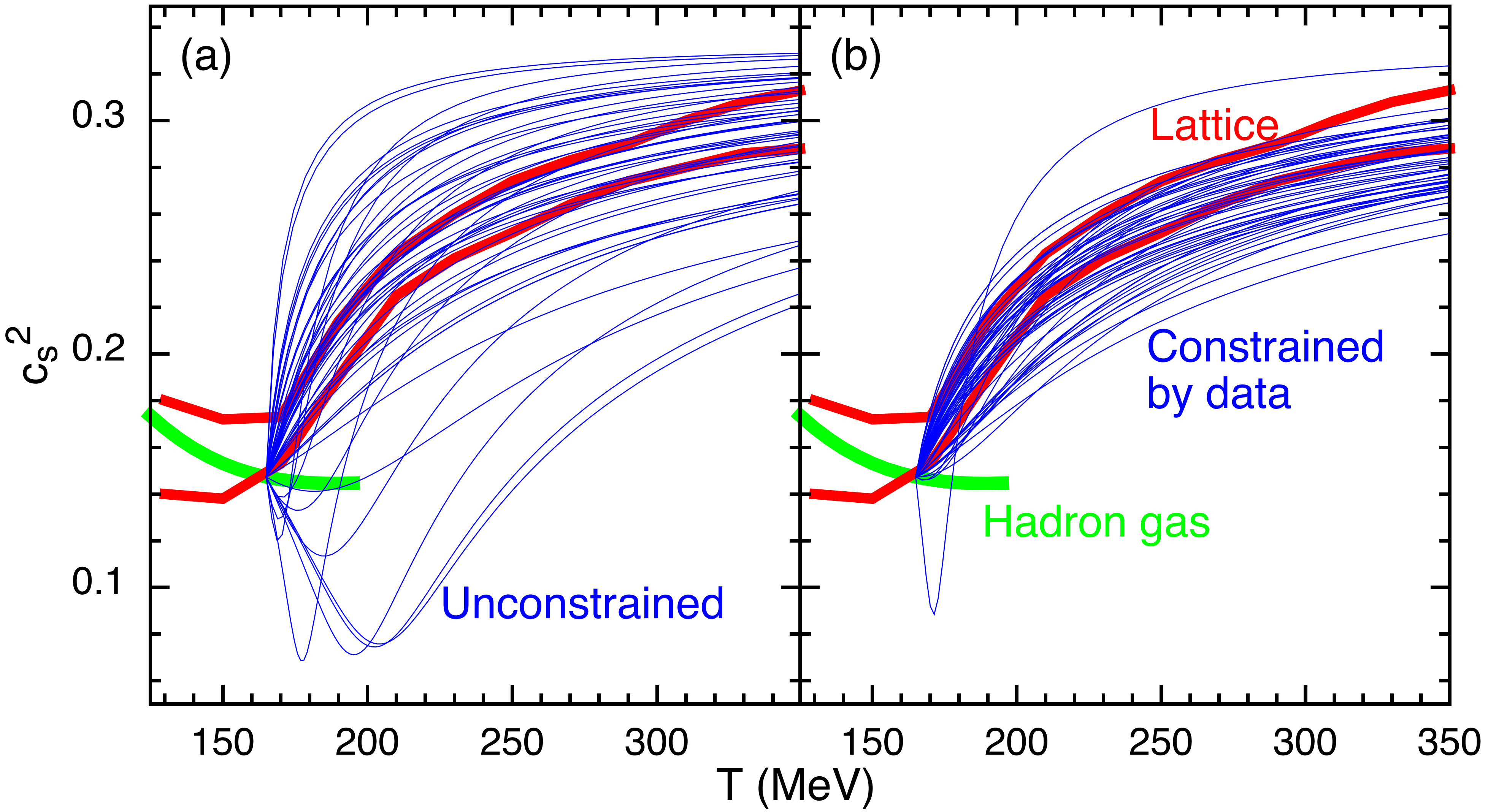
equation of state



PRL **114,** 202301 (2015) PHYSICAL REVIEW LETTERS week ending 22 MAY 2015

Constraining the Equation of State of Superhadronic Matter from Heavy-Ion Collisions

Scott Pratt,[1] Evan Sangaline,[1] Paul Sorensen,[2] and Hui Wang[2]



- really amazing to recover the lattice results from data

two big questions

- where does this behavior break down in T (and collision energy) and size

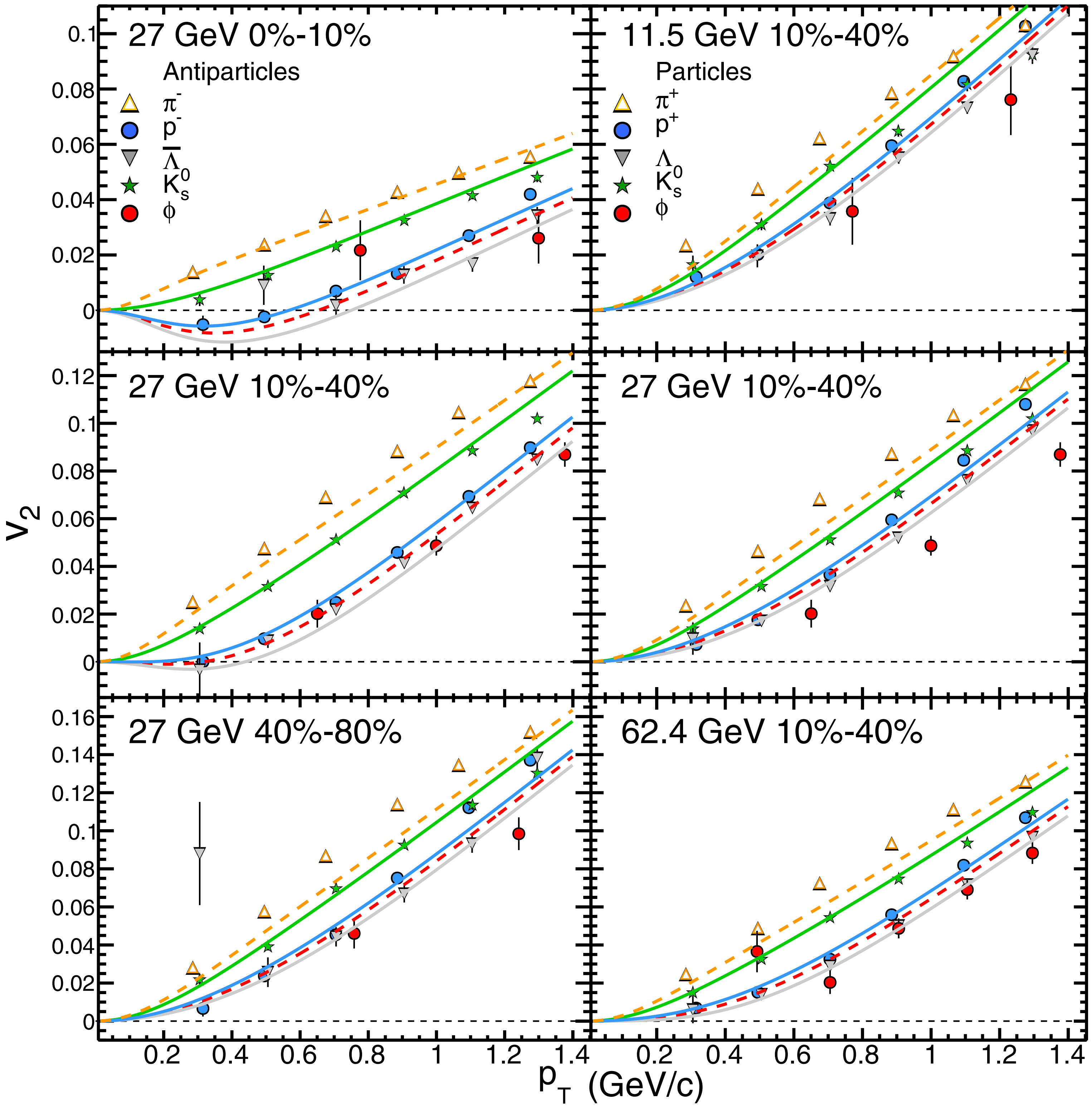
- why does QCD lead to a low viscosity liquid?

two big questions

- where does this behavior break down in T (and collision energy) and size
  - the rest of this lecture
- why does QCD lead to a low viscosity liquid?
  - the next lecture

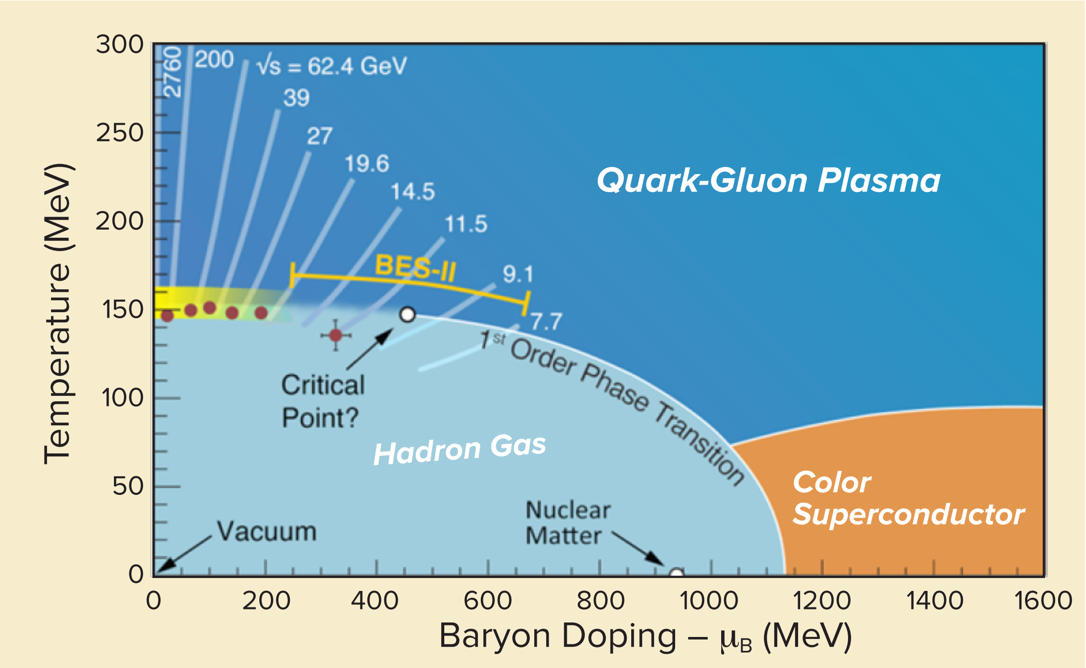
RHIC Beam Energy Scan

STAR PRC 93 014907 (2016)

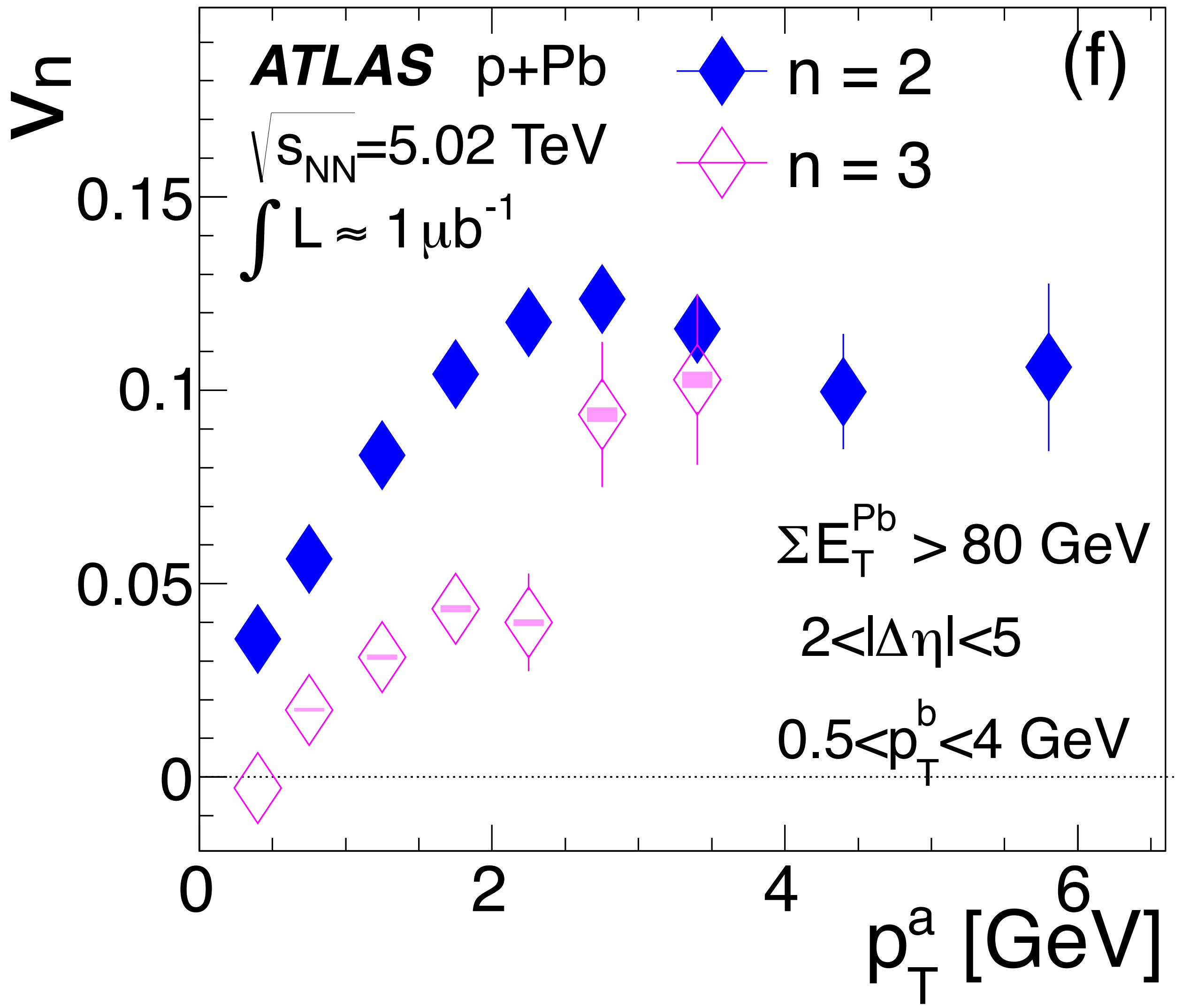


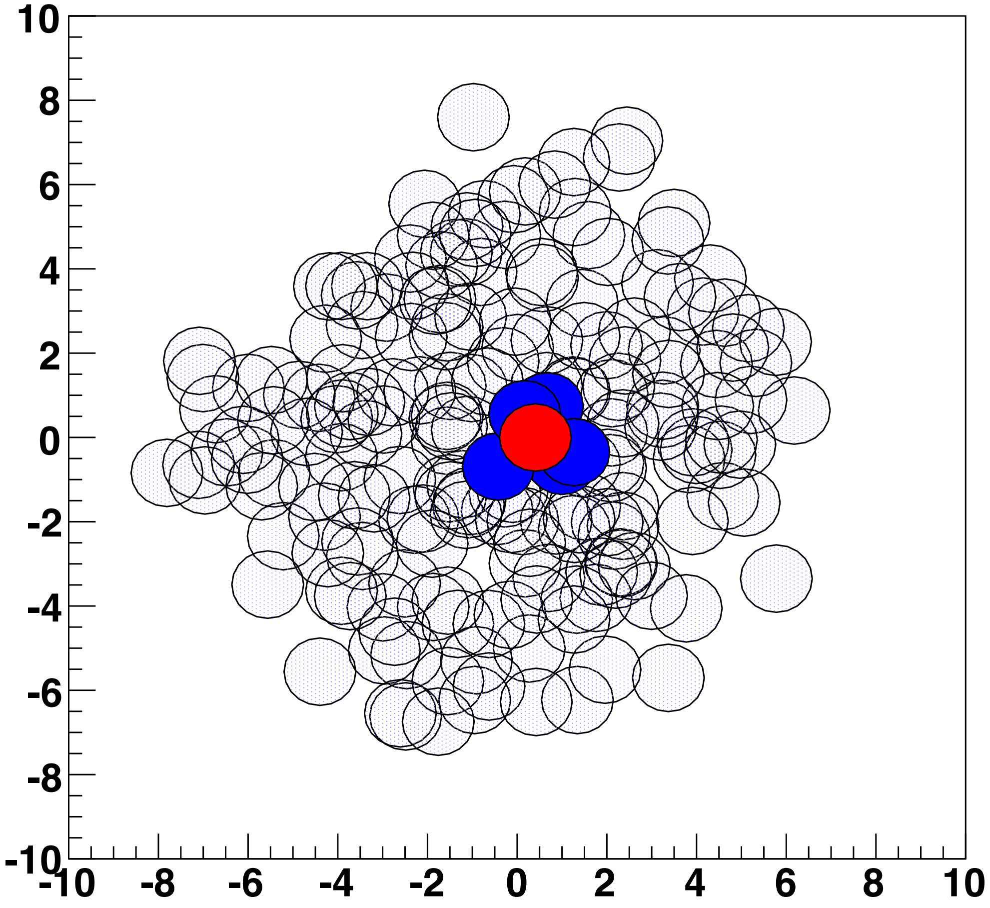
at lower collision energies do QGP signals turn off?

is there evidence for a critical endpoint and 1st order phase transition?



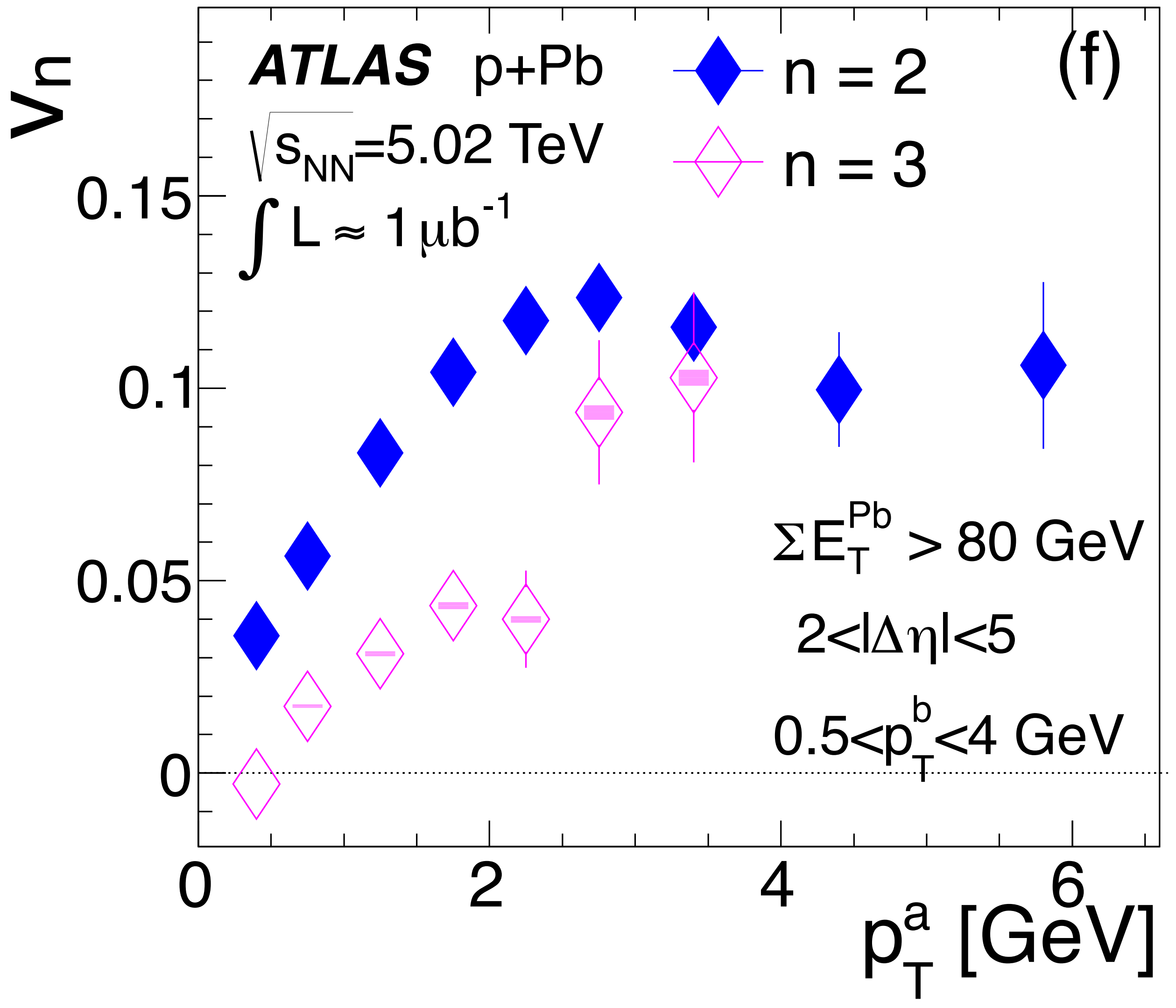
v_2 & v_3 in pPb collisions





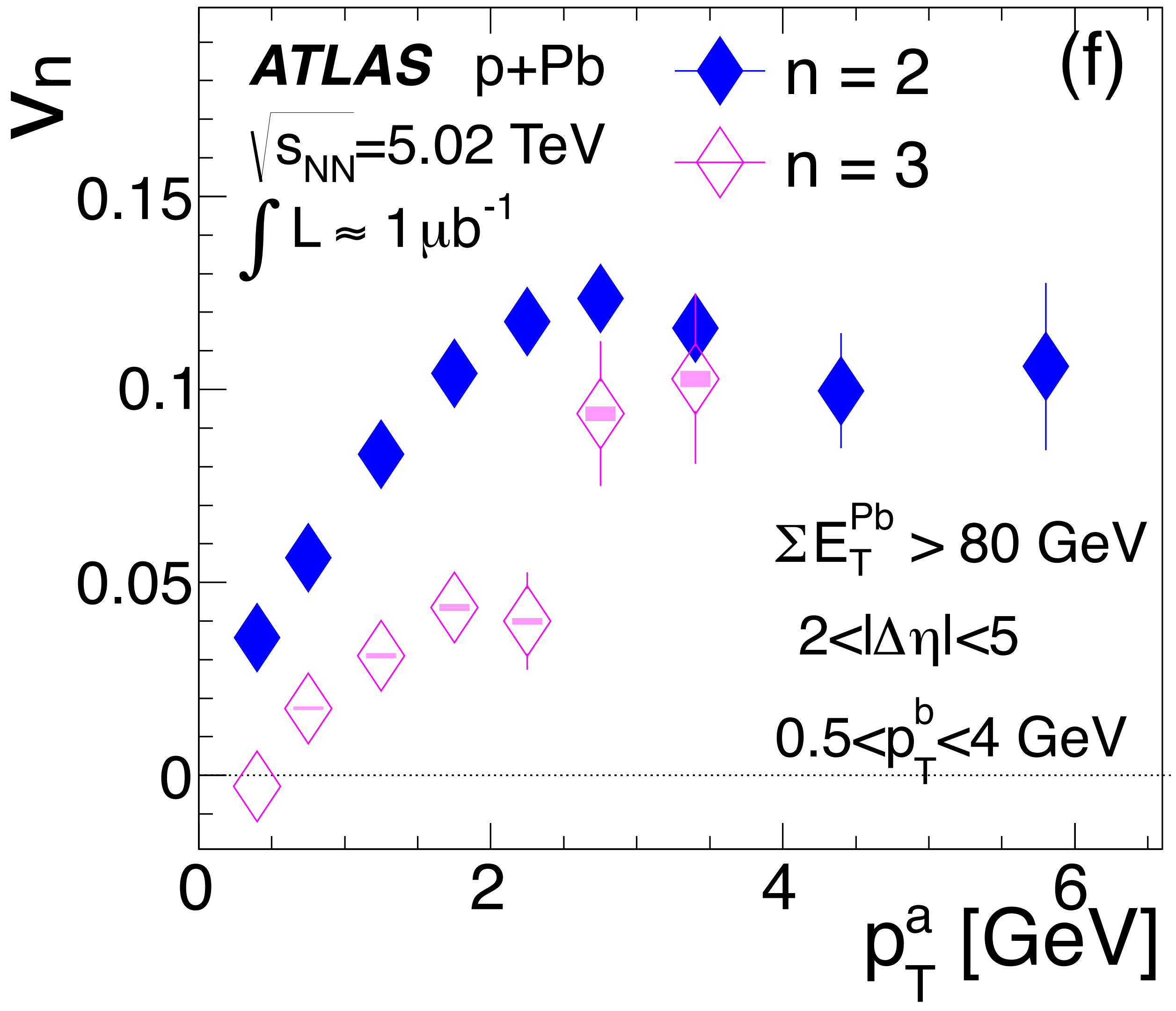
ATLAS PRL 110 102303

v_2 & v_3 in pPb collisions

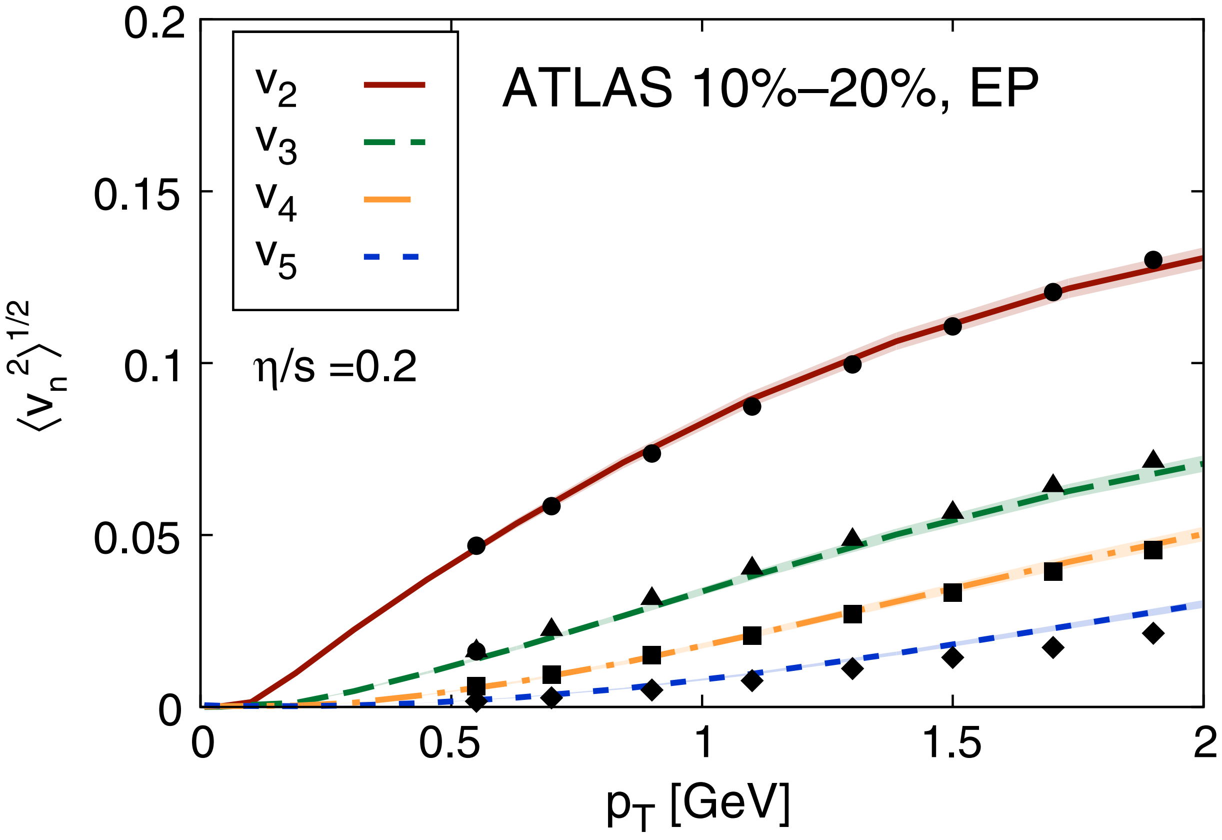


ATLAS PRL 110 102303

v_2 & v_3 in pPb collisions



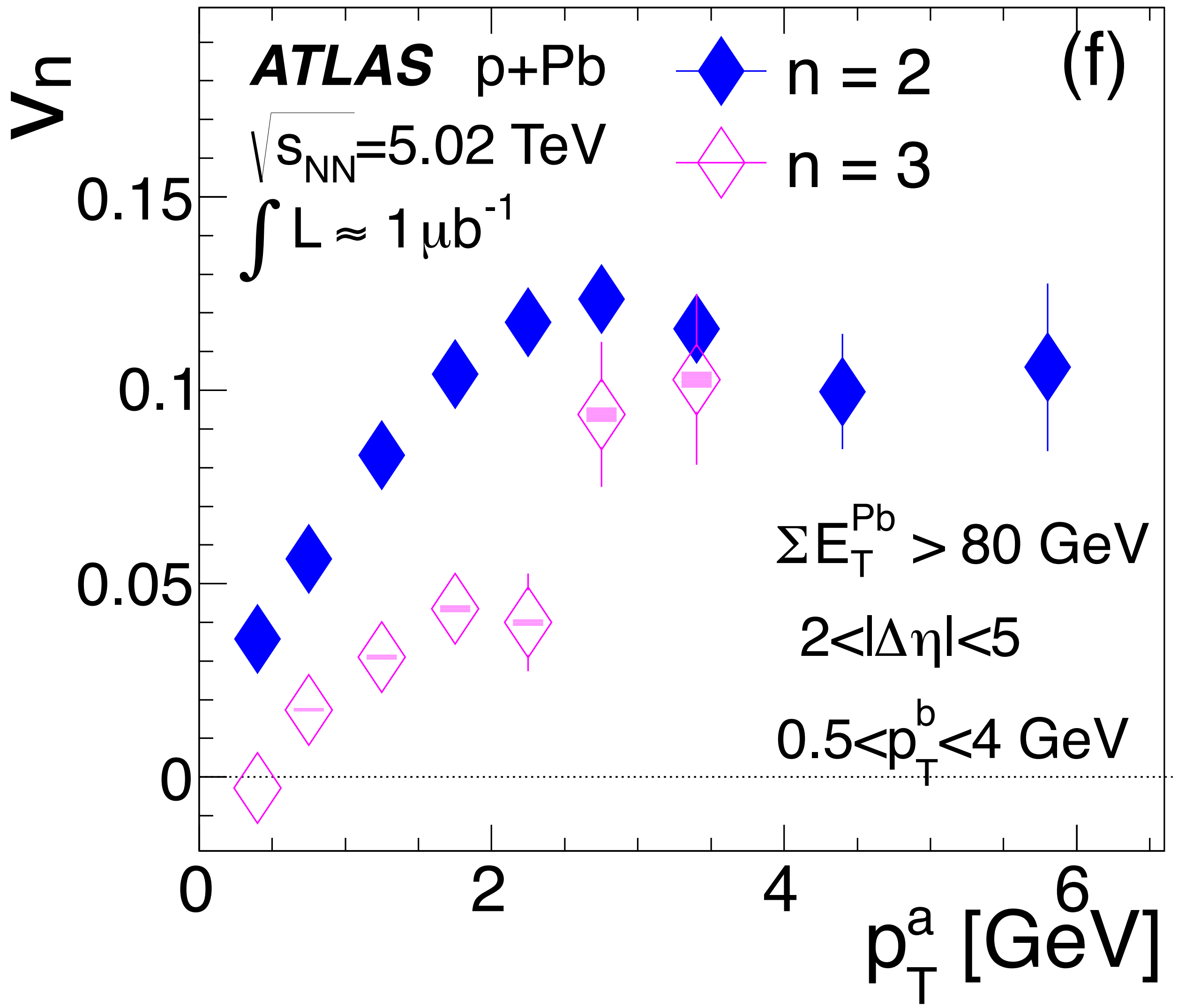
very similar to AA results



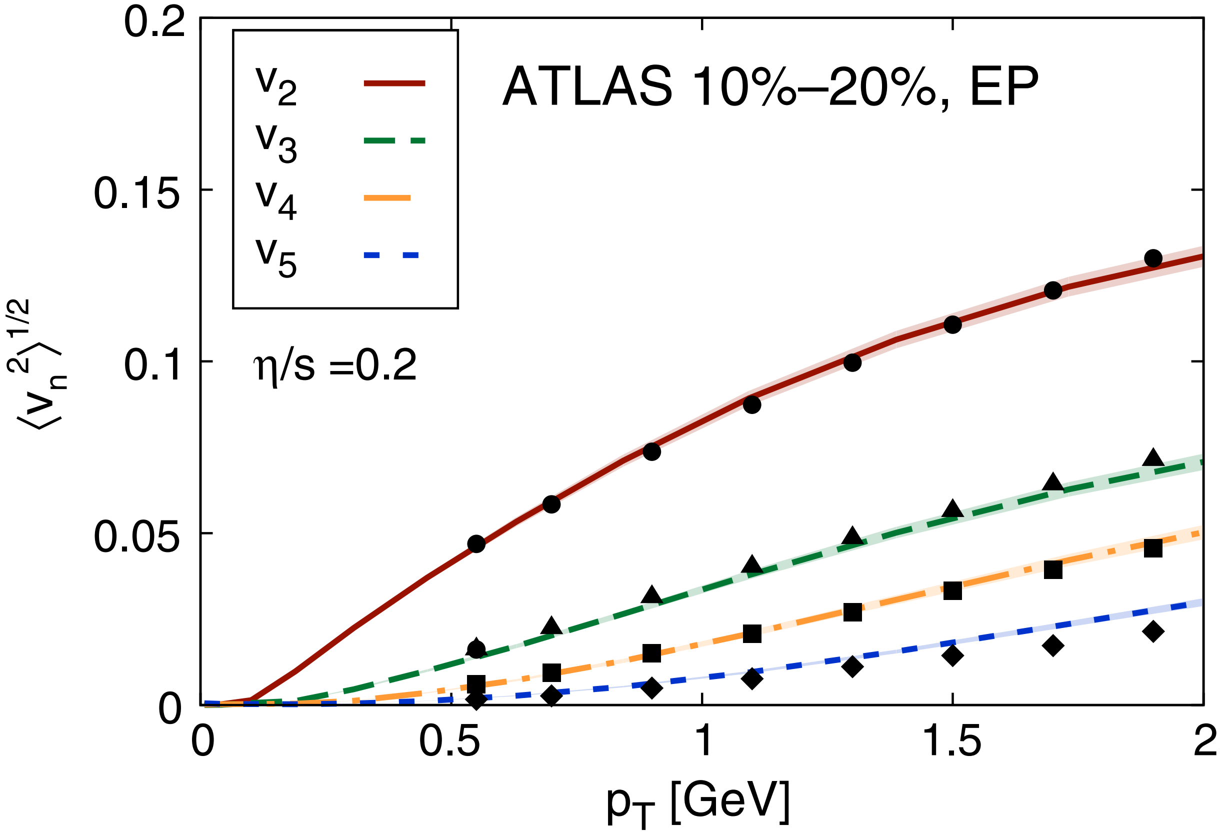
ATLAS PRL 110 102303

v_2 & v_3 in pPb collisions

are the pA and AA v_N related to the same physics?

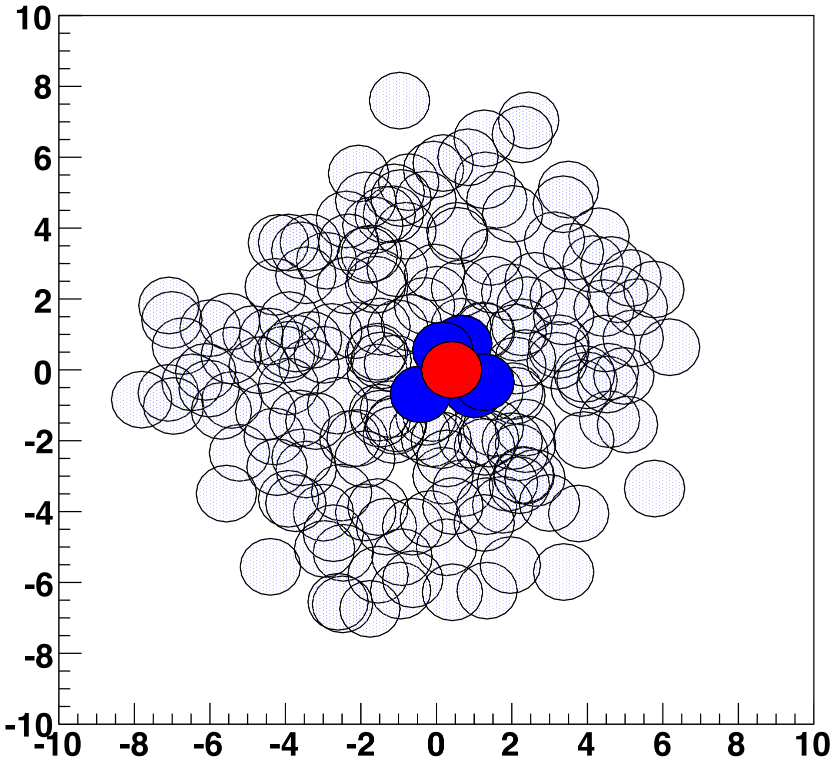


very similar to AA results

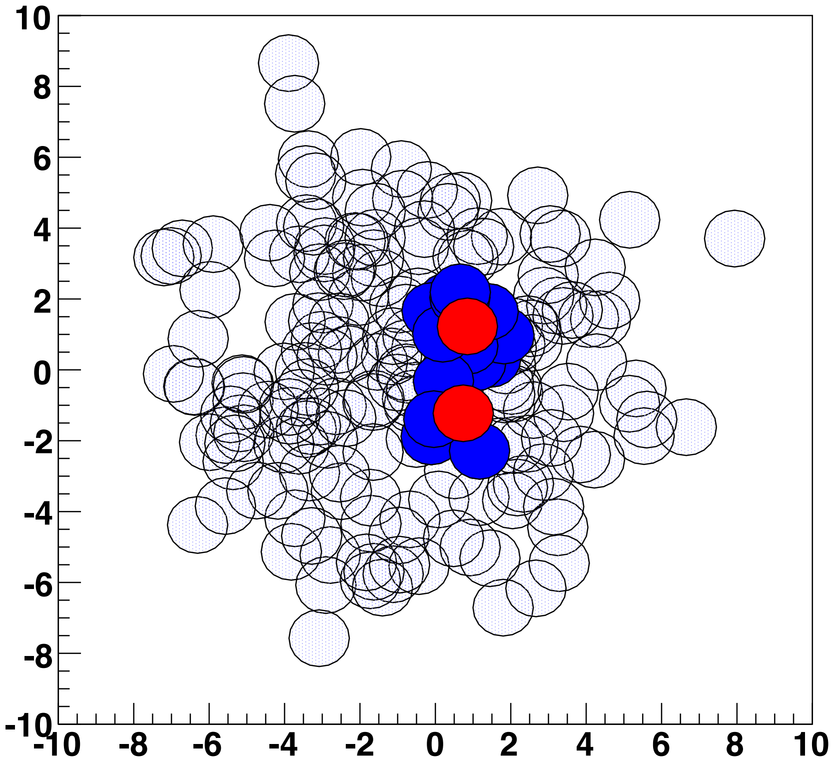


ATLAS PRL 110 102303

variation of the small nucleus



pA

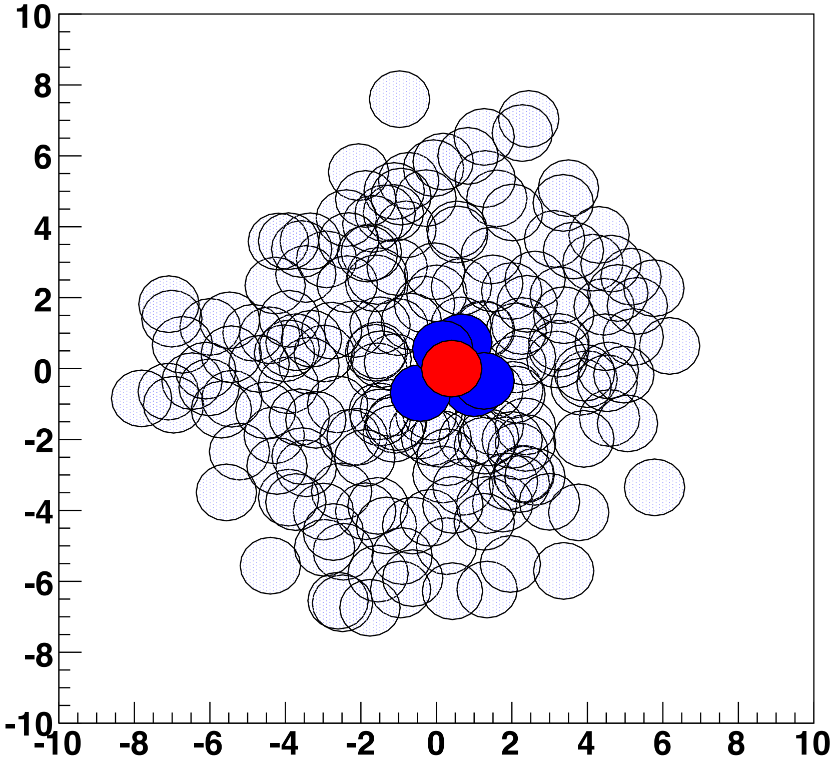


dA

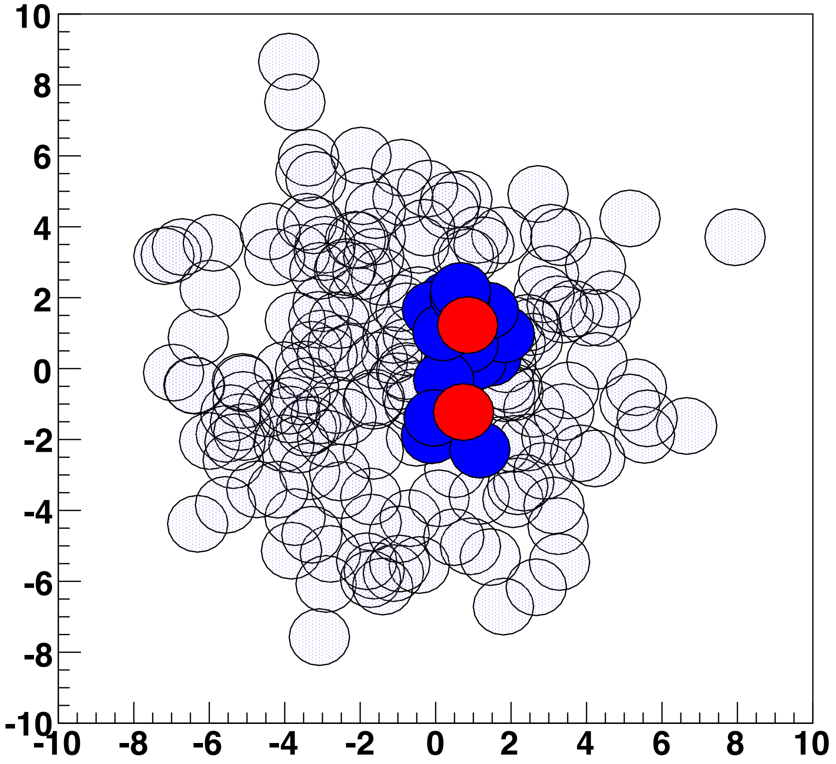
control the collision geometry by varying the small nucleus

variation of the small nucleus

pA



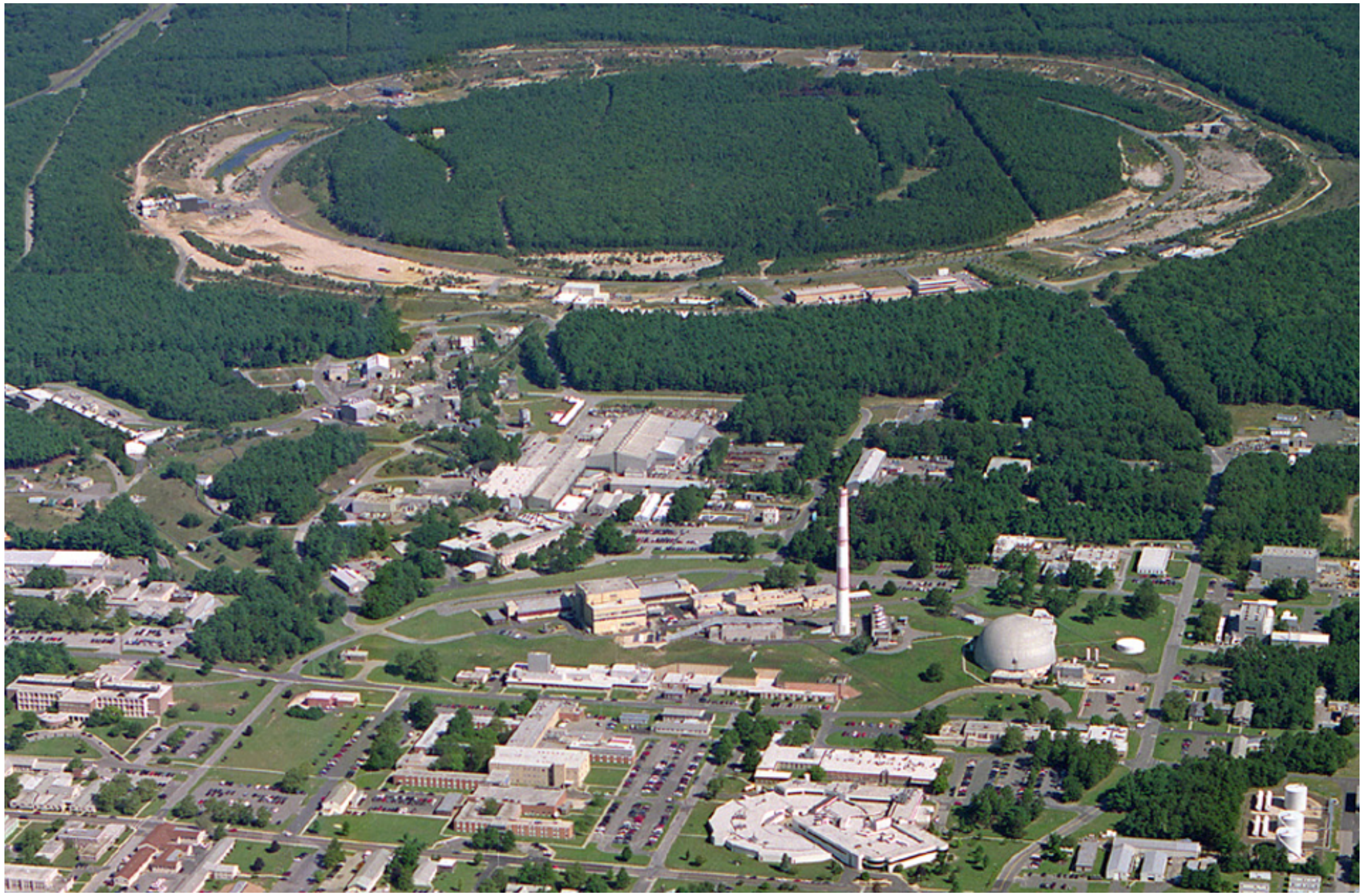
dA



control the collision geometry by varying the small nucleus

does v2 reflect the geometry of the initial state in p/d+A as in A+A?

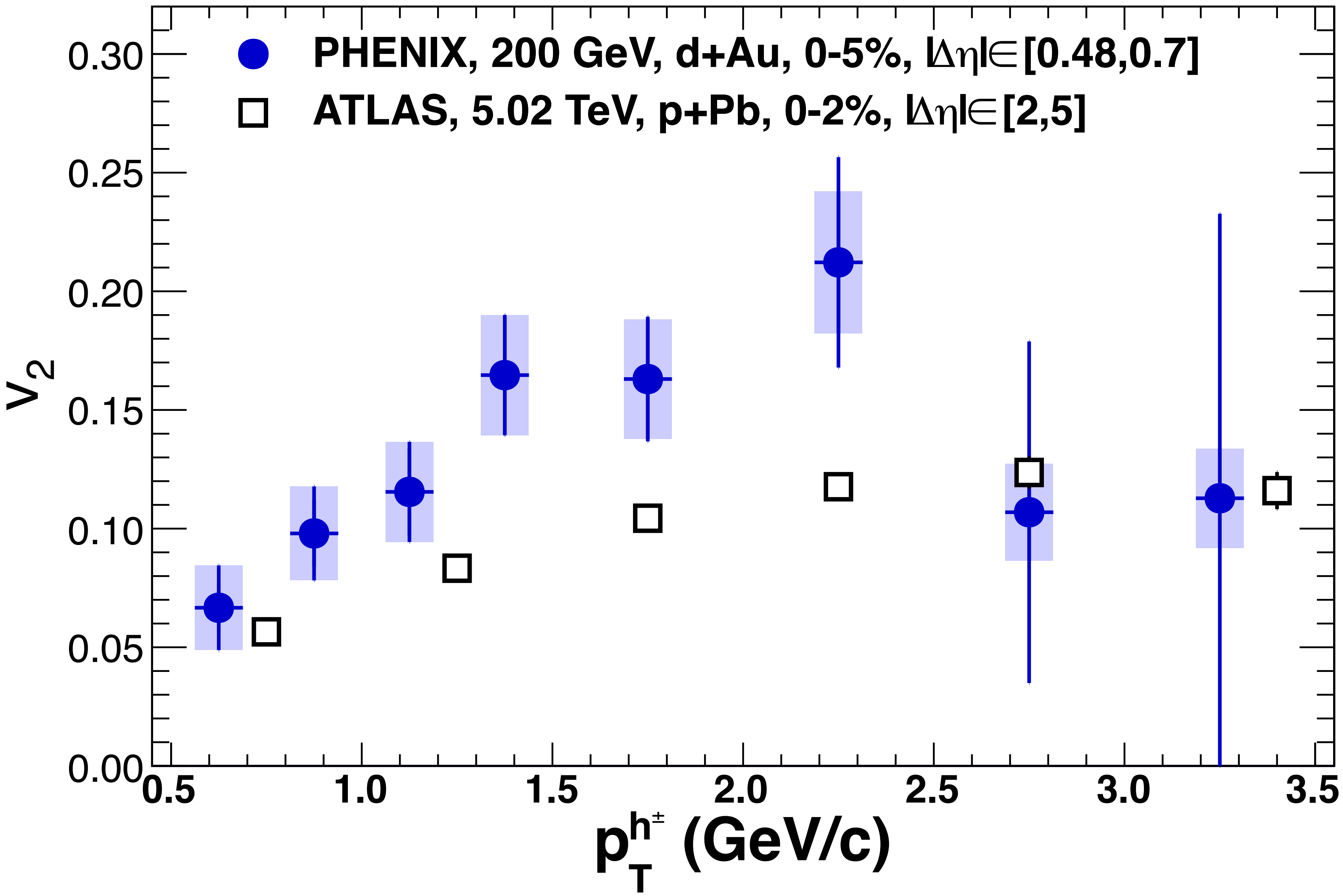
what can RHIC add?

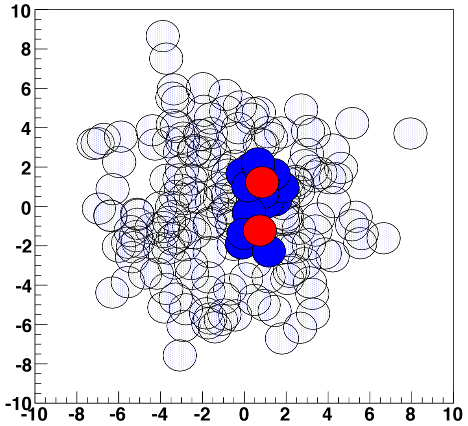


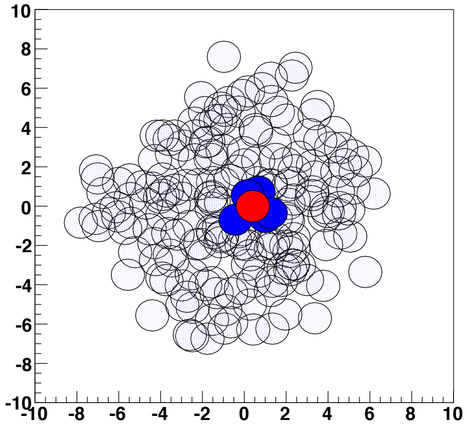
RHIC had huge d+Au sample

25x smaller collision energy than the LHC

v2: pPb & dAu



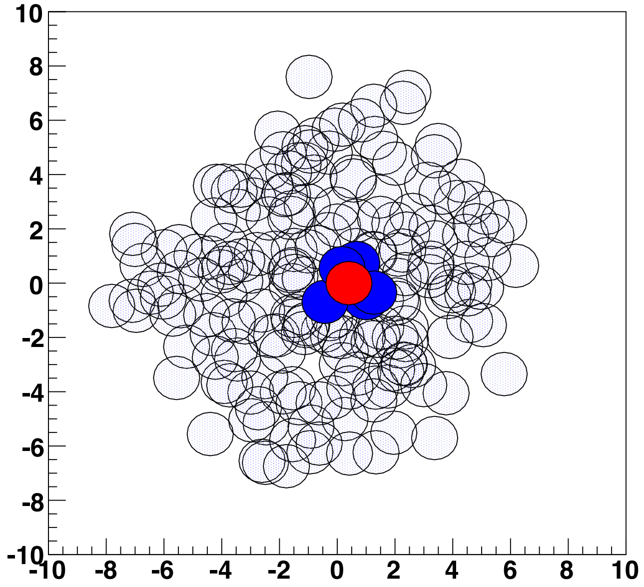




PHENIX PRL 111 212301 (2013)
ATLAS PRL 110 182302 (2013)

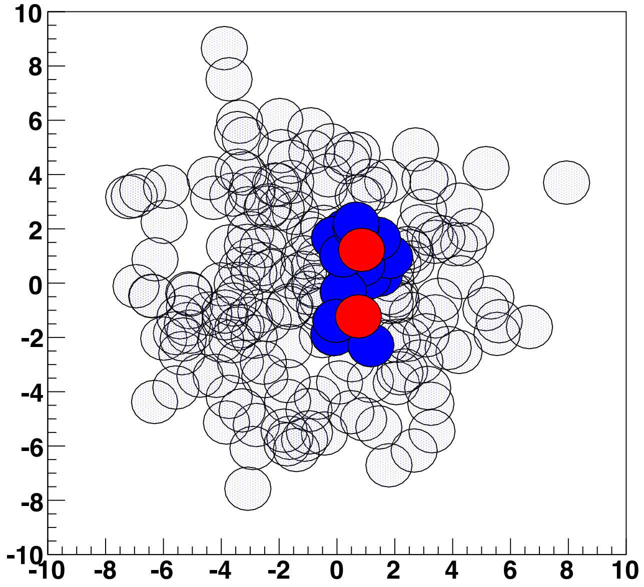
a small QGP?

pA



small ε2

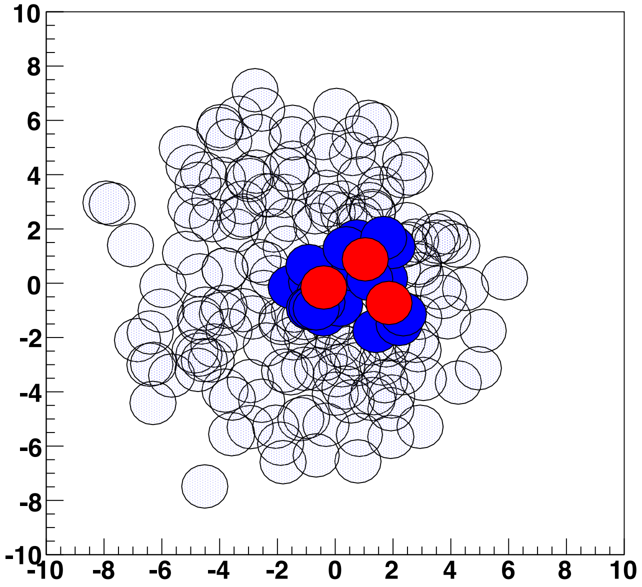
dA



large ε2

small ε3

^{3}HeA



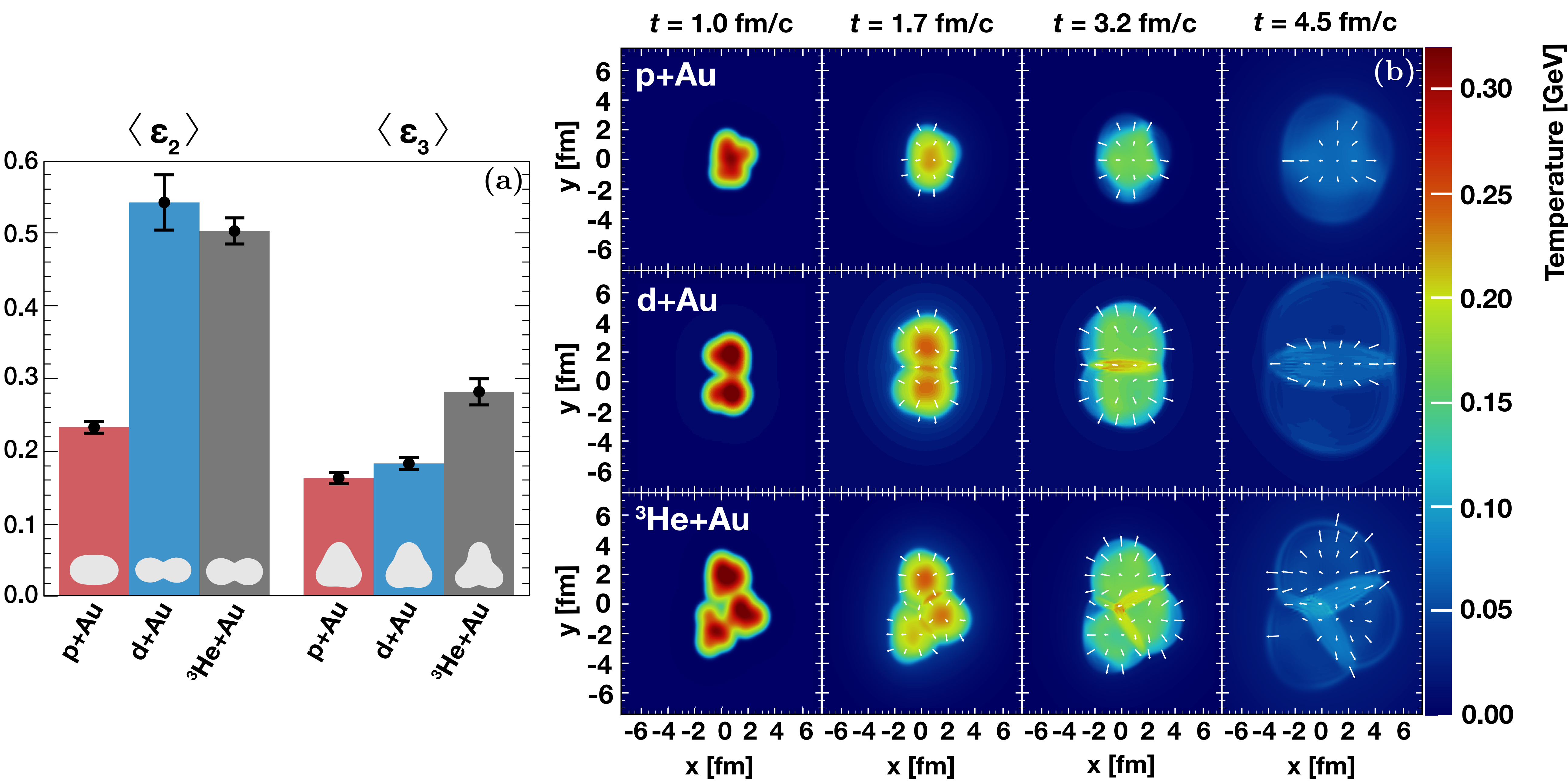
large ε3

$$\varepsilon_n = \frac{\sqrt{\langle r^2 \cos n\phi \rangle^2 + \langle r^2 \sin n\phi \rangle^2}}{\langle r^2 \rangle}$$

control the collision geometry by varying the small nucleus

geometry and hydrodynamics in small systems

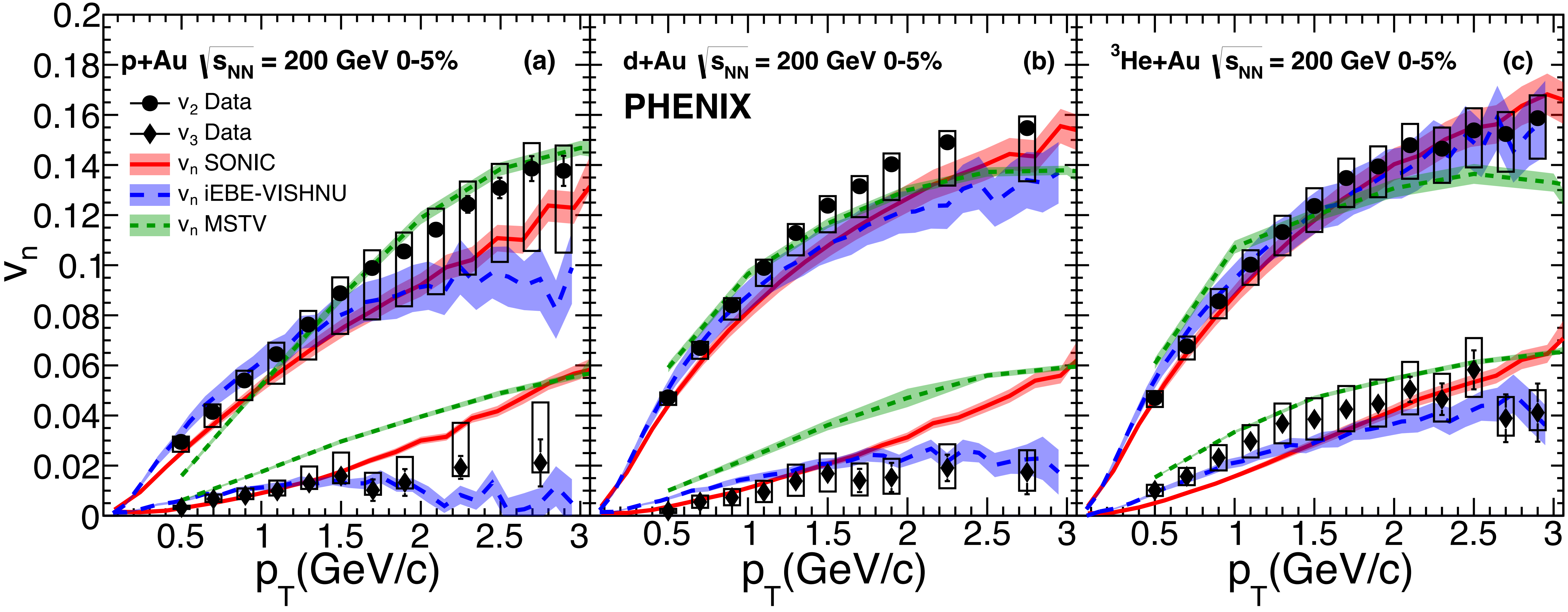
hydrodynamic evolution of pAu, dAu and 3HeAu collisions



PHENIX, 1805.02973

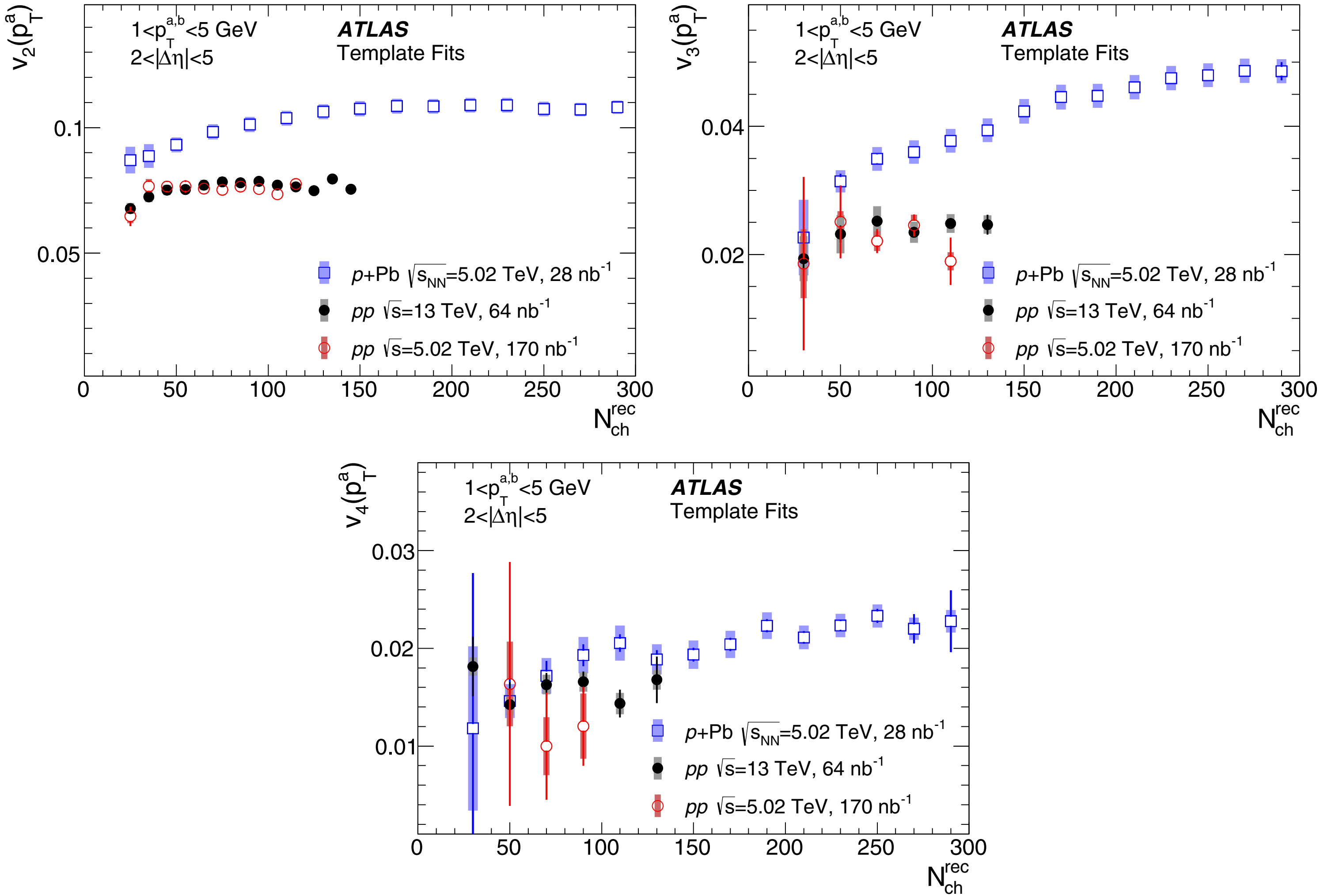
geometry and hydrodynamics in small systems

v_2, v_3 from pAu, dAu, ^{3}HeAu compared to two hydrodynamic models (SONIC & iEBE-VISHNU)



PHENIX, 1805.02973

pp collisions?



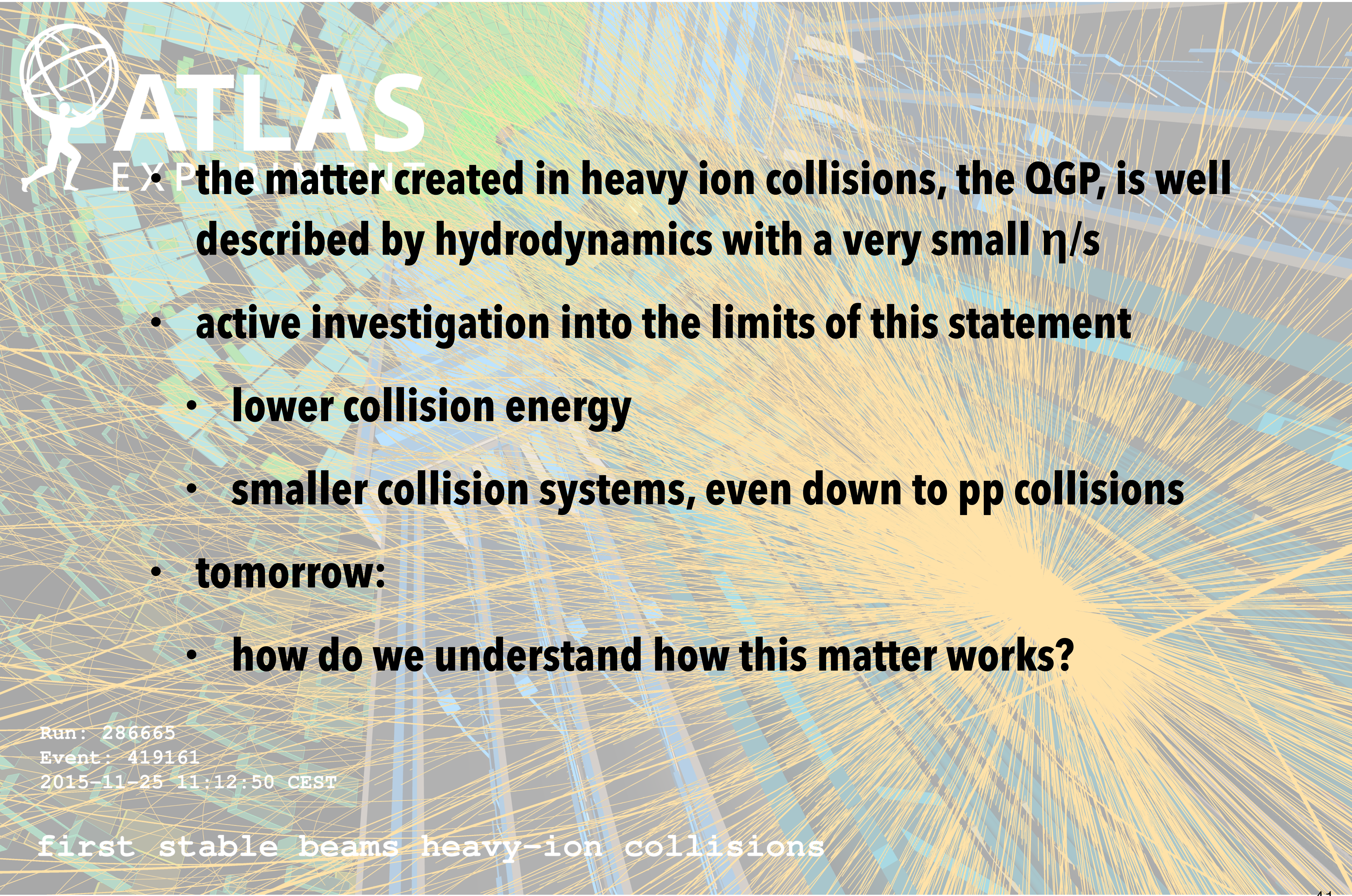
ATLAS, PRC 96 024908 (2016)

- evidence for similar v_N signals in pp collisions as well
- does that mean:
  - QGP in pp collisions?
  - vN is not evidence for hydrodynamics in AA collisions?
  - something else?
- what is the smallest size QGP you could make?

this is an area of very active discussion

Weller & Romatschke, PLB 774 351
Mace et al PRL 121 052301
Nagle & Zajc, 1808.01276
M. Strikland, Quark Matter 2018
…
plus many experimental papers

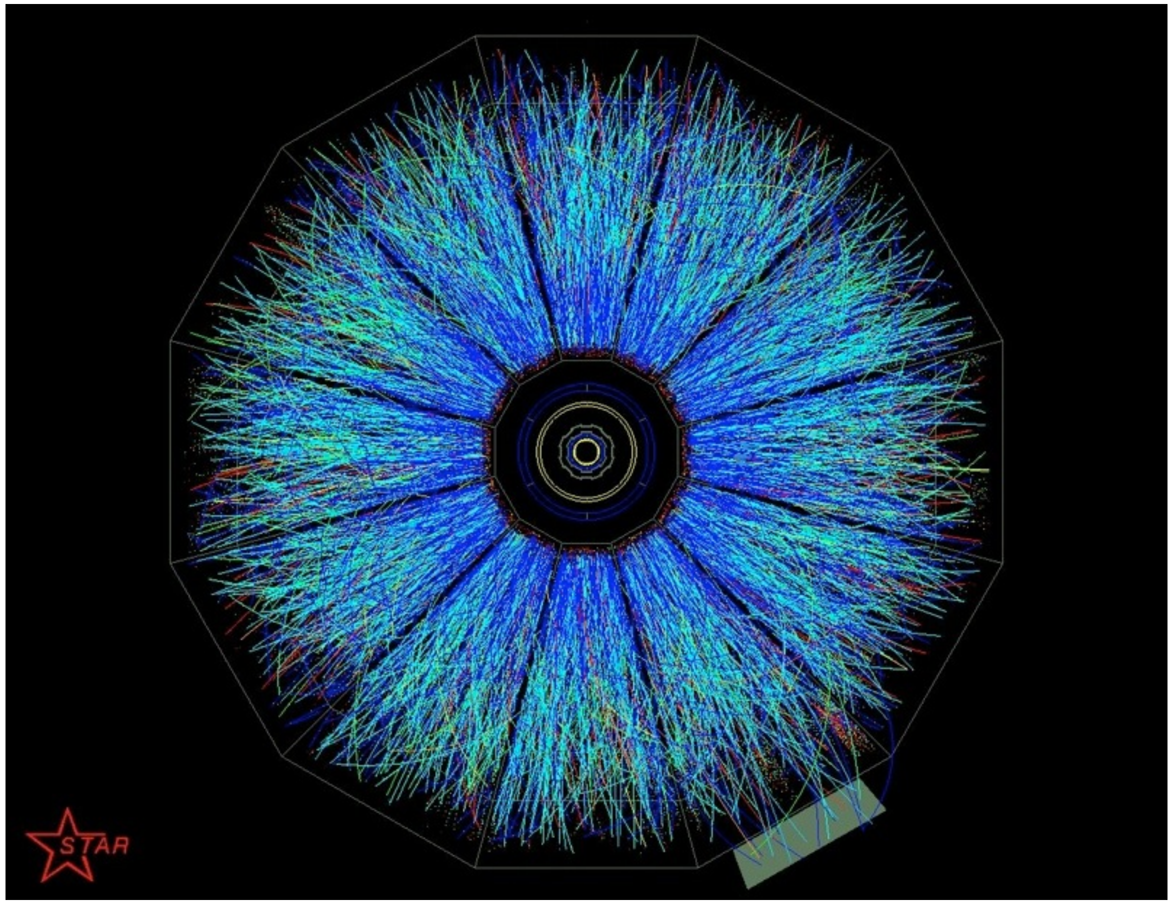
summary of part 1



- **the matter created in heavy ion collisions, the QGP, is well described by hydrodynamics with a very small η/s**
- **active investigation into the limits of this statement**
  - **lower collision energy**
  - **smaller collision systems, even down to pp collisions**
- **tomorrow:**
  - **how do we understand how this matter works?**

extras

two particle correlations



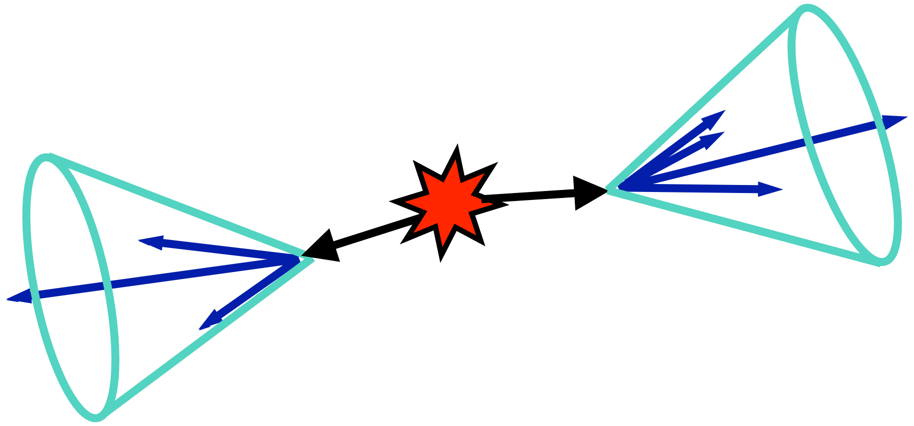
$$\frac{dN}{d\phi} \propto 1 + \sum^{n} 2v_n \cos n\left(\phi - \Psi_n\right)$$

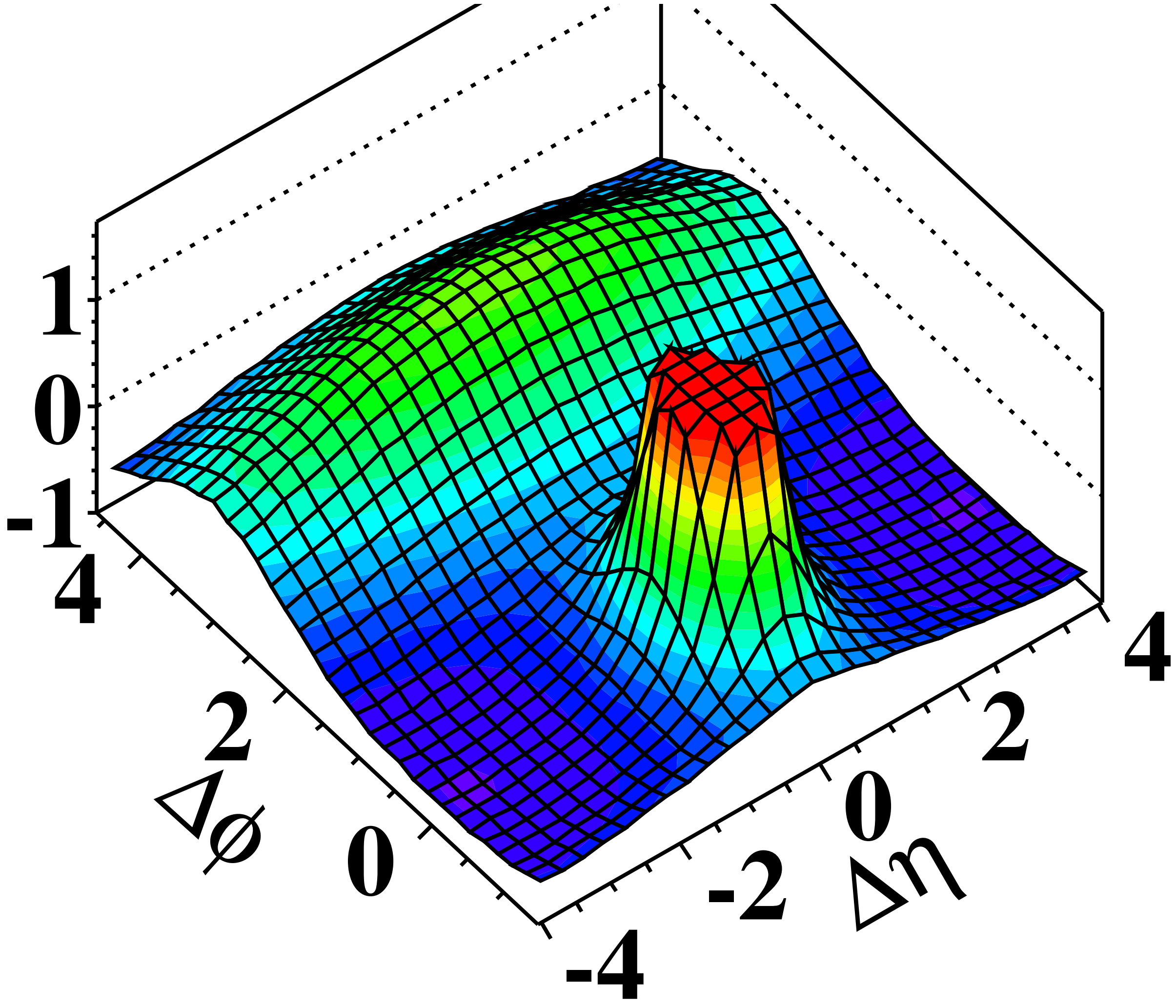
$$\Big\downarrow$$

$$\frac{dN_{AB}}{d\Delta\phi} \propto 1 + \sum^{n} 2v_{n,A}v_{n,B} \cos\left(n\Delta\phi\right)$$

two particle correlations

jets in pp collisions





flow

single particles

$$\frac{dN}{d\phi} \propto 1 + \sum^{n} 2v_n \cos n\left(\phi - \Psi_n\right)$$

$$\downarrow$$

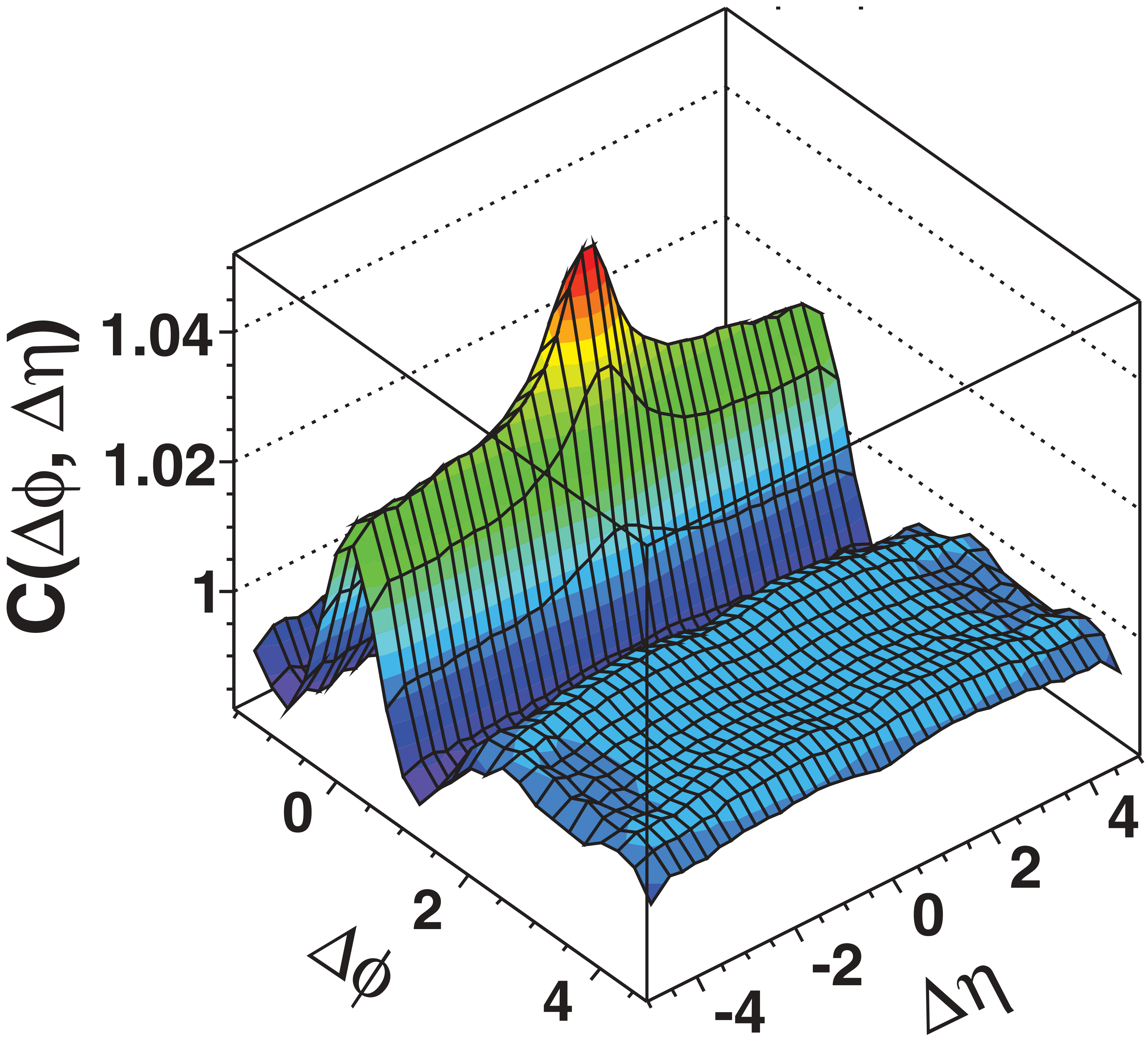
pairs of particles

$$\frac{dN_{AB}}{d\Delta\phi} \propto 1 + \sum^{n} 2v_{n,A}v_{n,B} \cos\left(n\Delta\phi\right)$$

flow correlations should be long range η

CMS JHEP 1009 (2010) 091

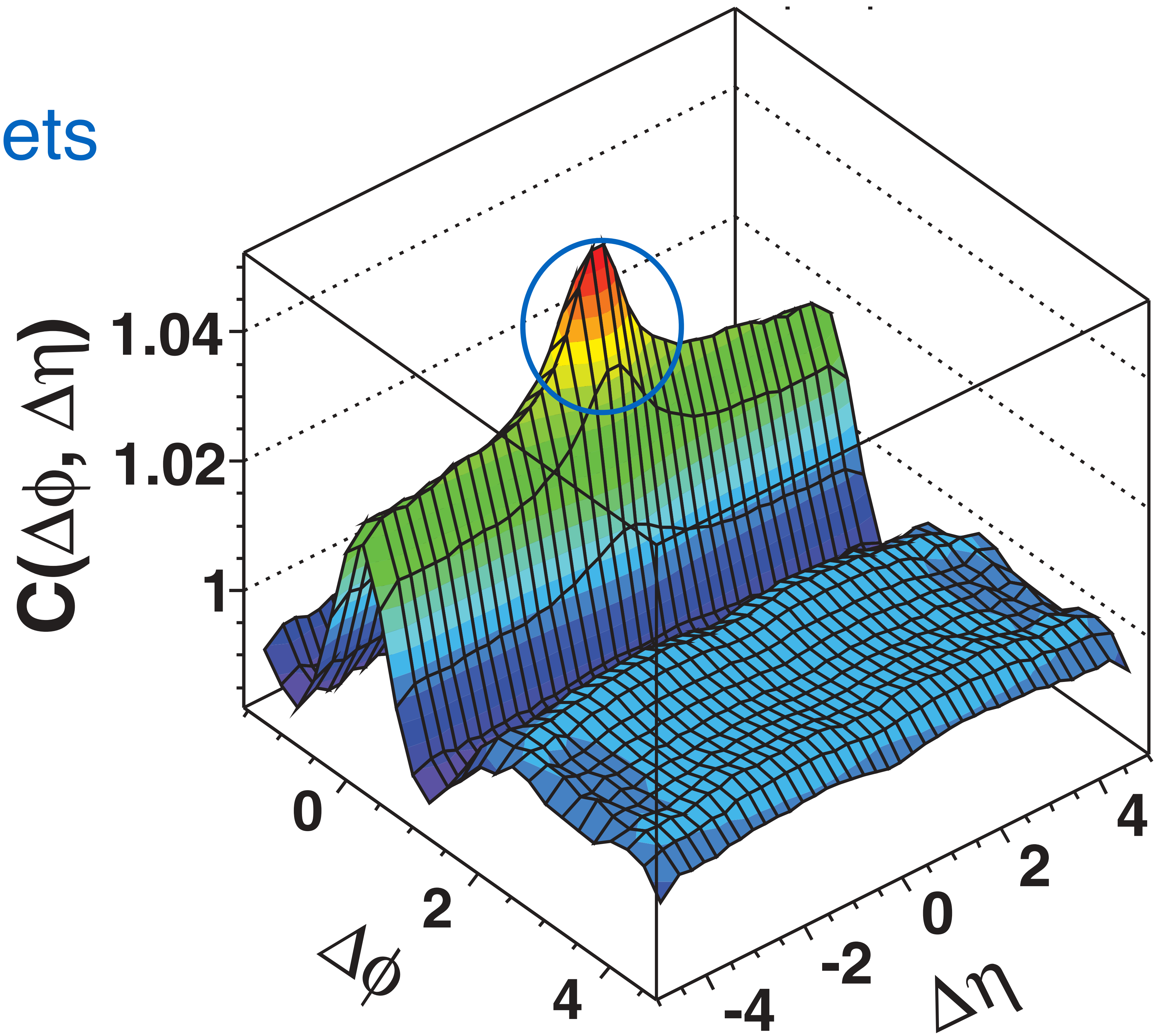
correlations in PbPb



ATLAS PRC 86 014907

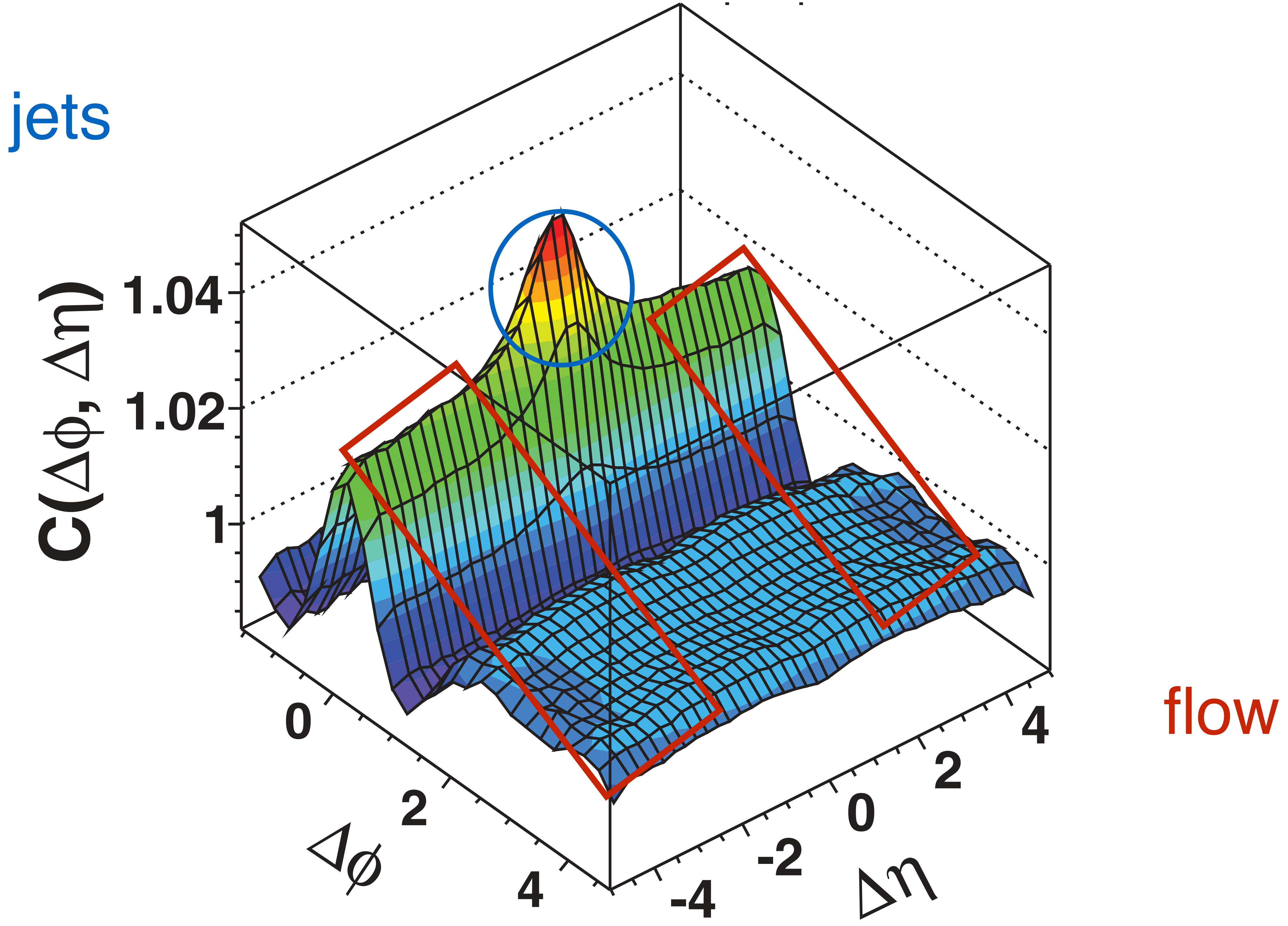
correlations in PbPb

jets



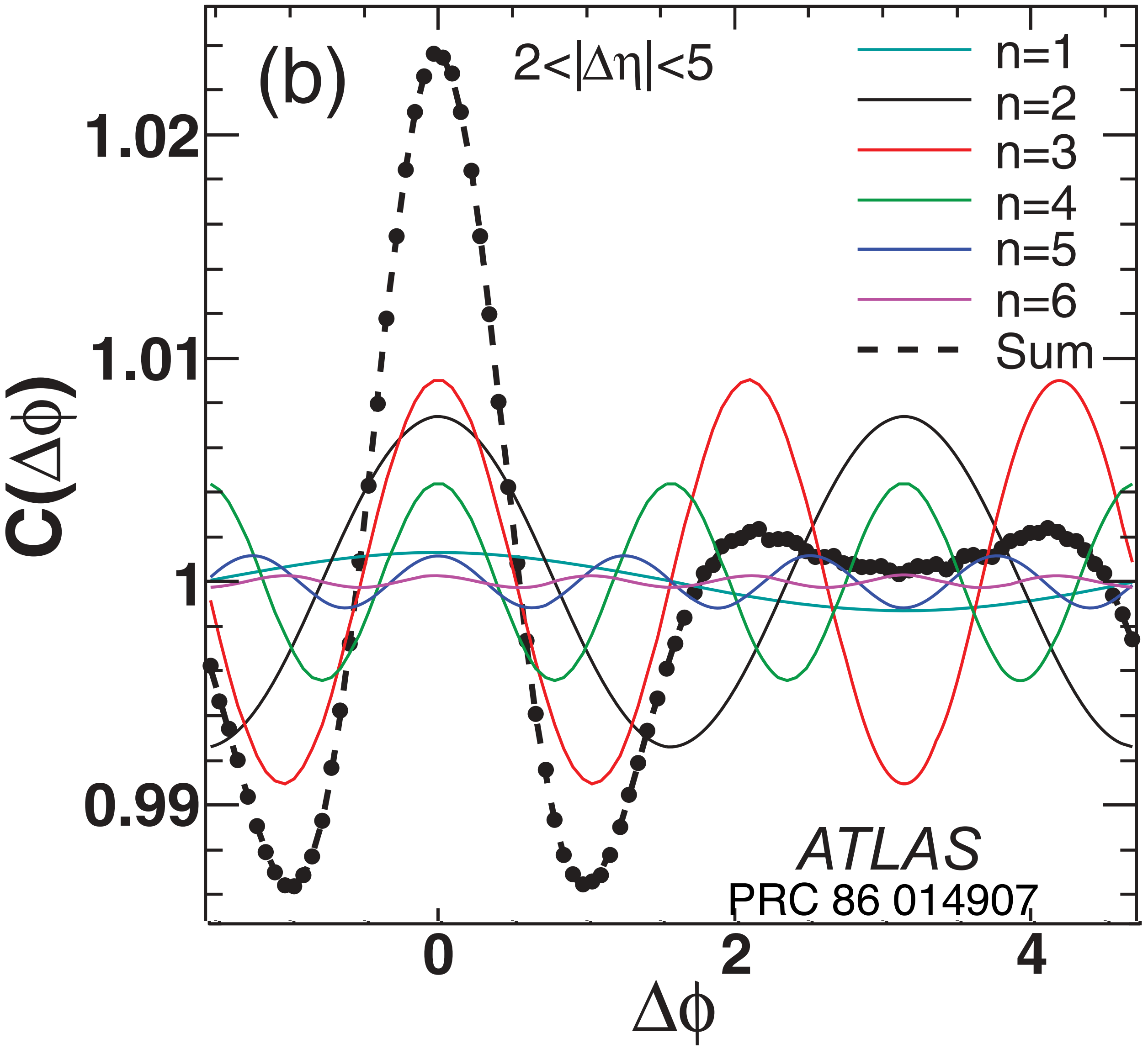
ATLAS PRC 86 014907

correlations in PbPb



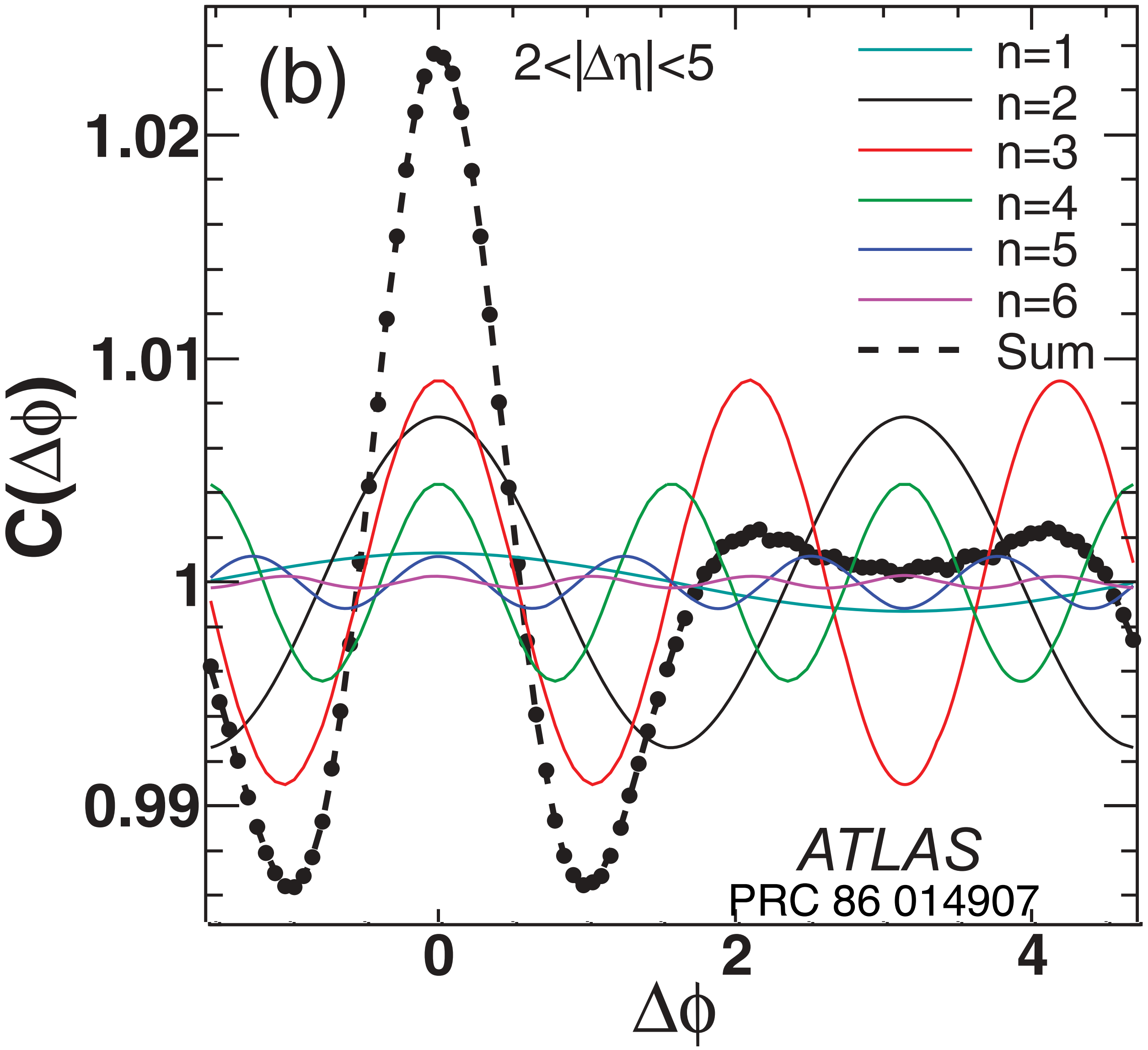
ATLAS PRC 86 014907

ridge: v_N & two particle correlations



$$\frac{dN_{AB}}{d\Delta\phi} \propto 1 + \sum^{n} 2v_{n,A}v_{n,B}\cos\left(n\Delta\phi\right)$$

ridge: v_N & two particle correlations



$$\frac{dN_{AB}}{d\Delta\phi} \propto 1 + \sum^{n} 2v_{n,A}v_{n,B}\cos\left(n\Delta\phi\right)$$

evidence for many higher order terms in particle correlations