# Collective Effects in p-A & A-A collisions

Anne M. Sickles
9/19/14

ILLINOIS

# outline

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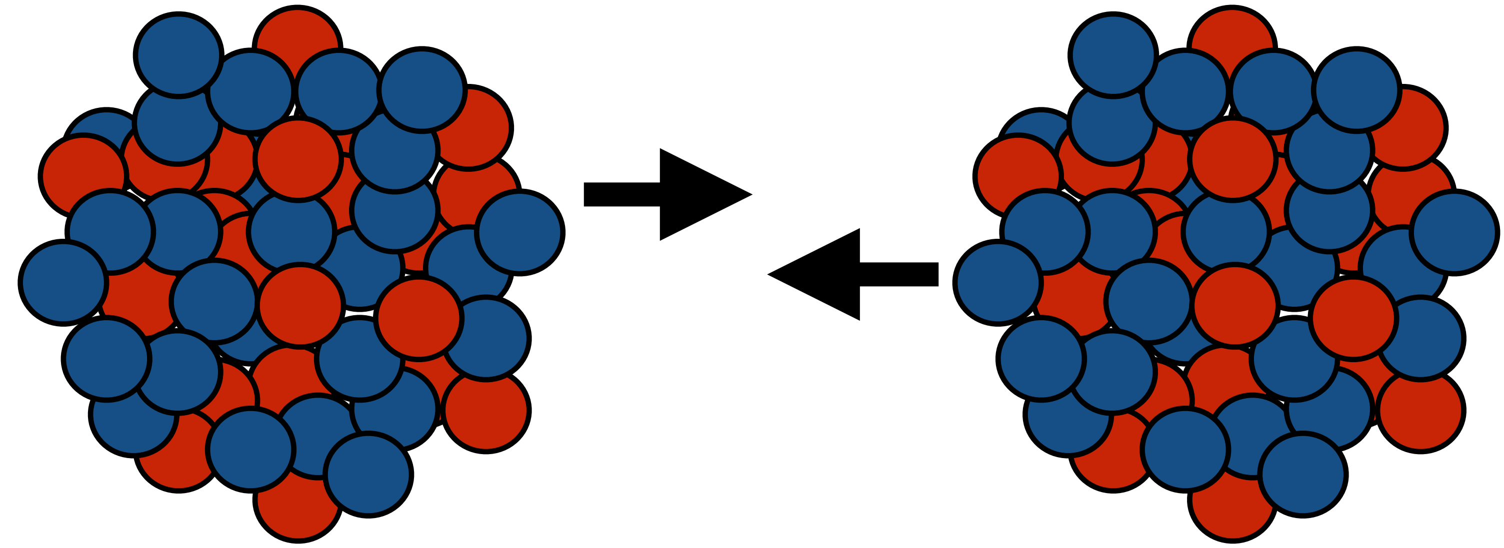
collide heavy nuclei: create & study hot deconfined QCD: the quark gluon plasma



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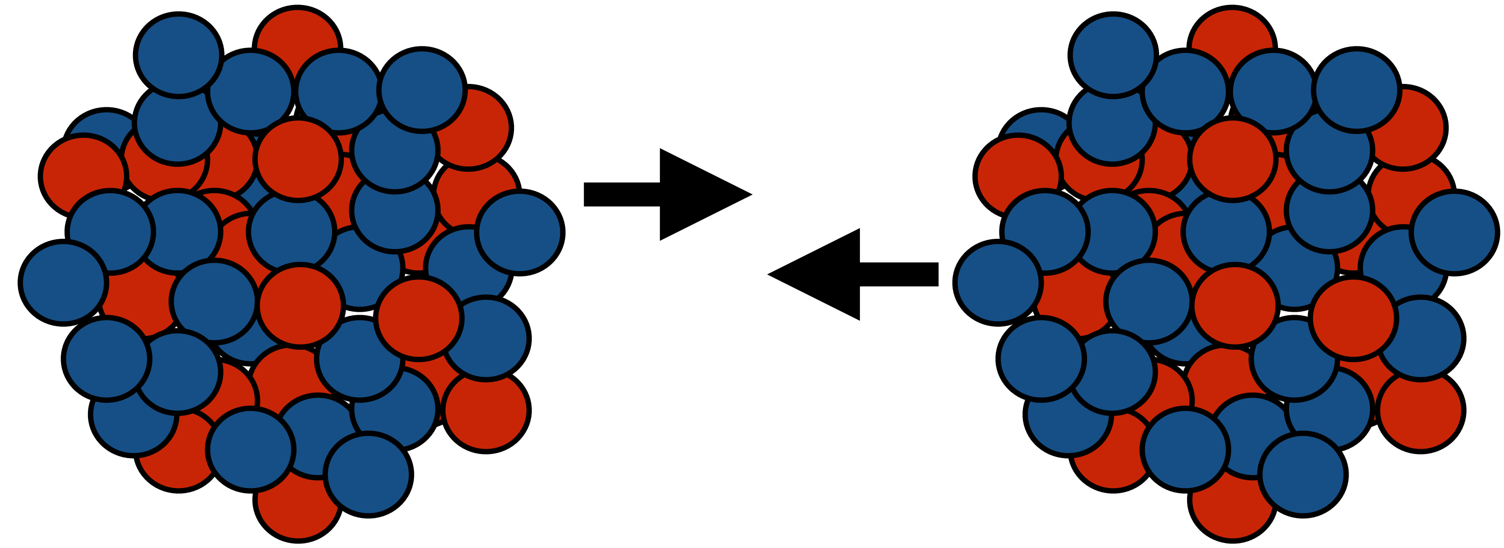
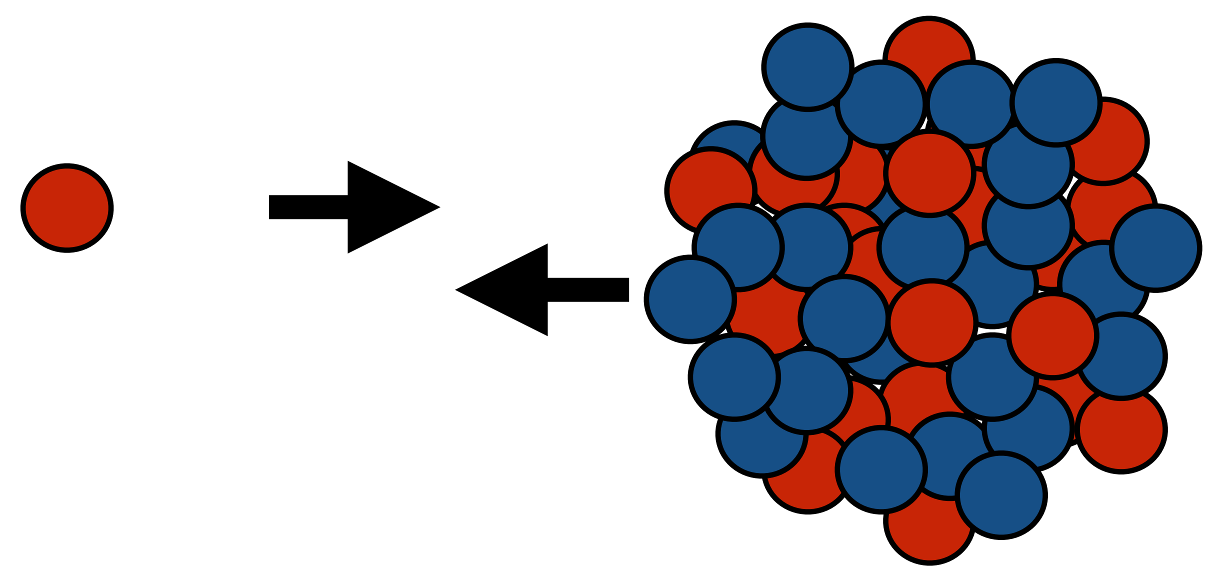


highly asymmetric collisions: turn off the plasma, study the nucleus



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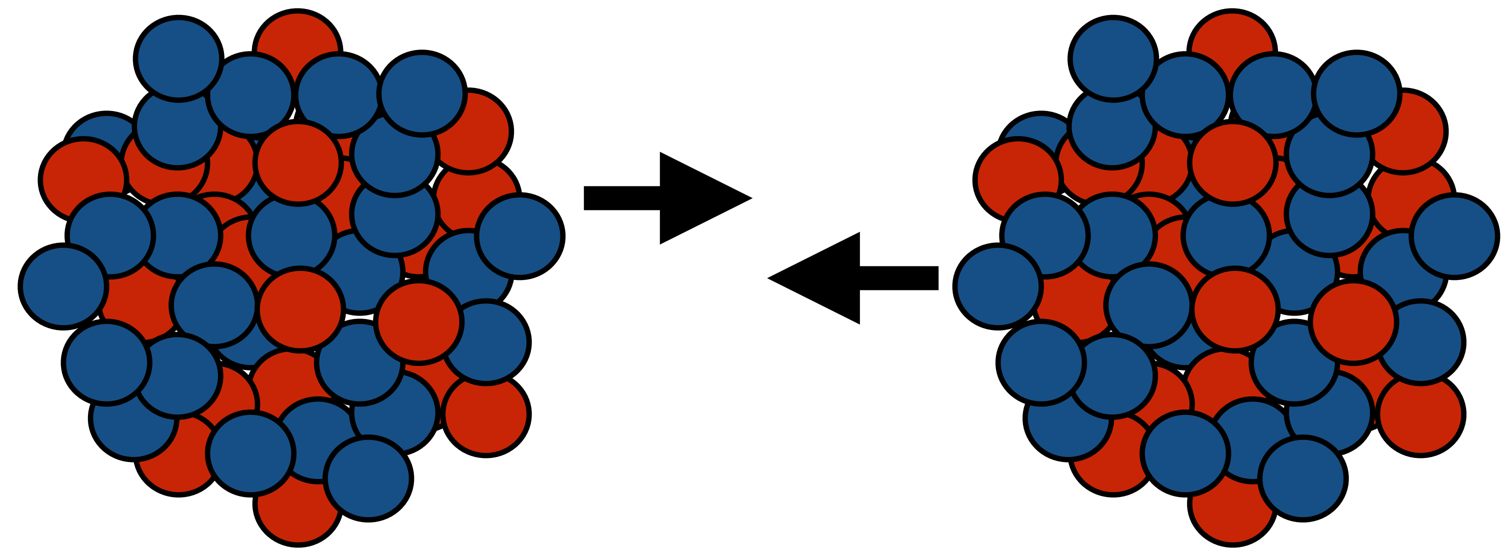

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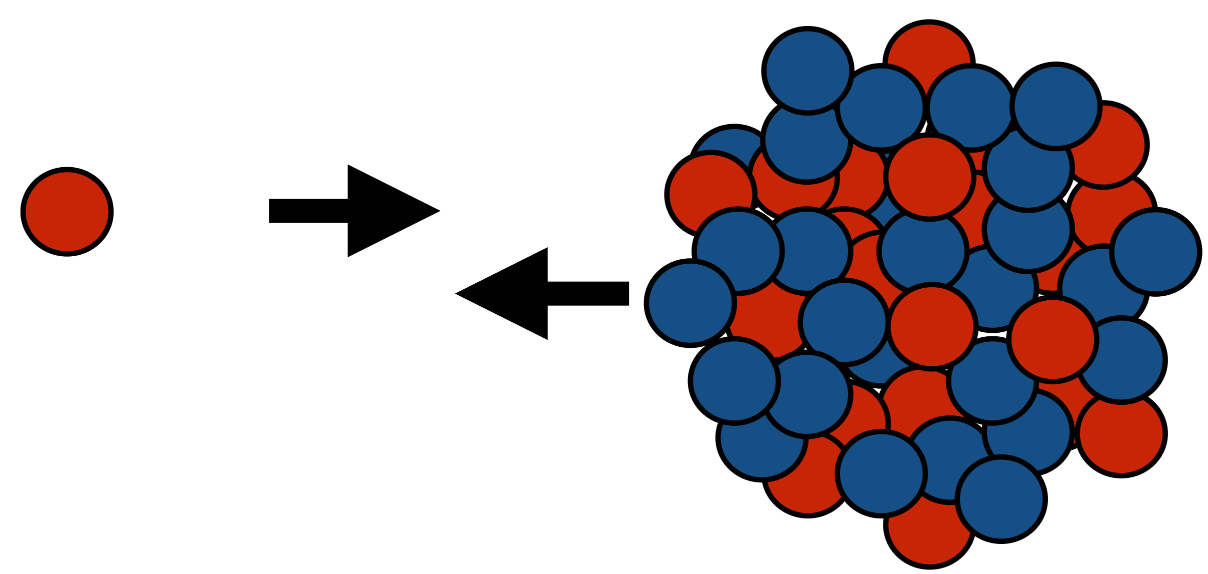
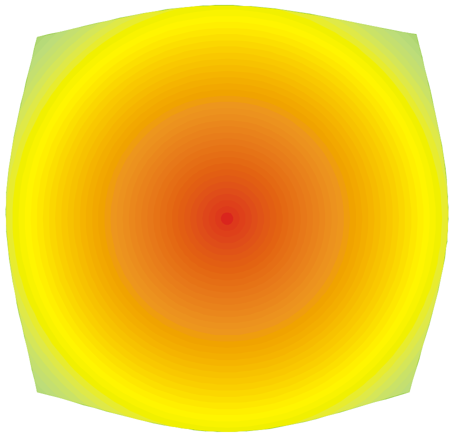


or maybe not…

# relativistic **heavy** ion collisions

**quark gluon plasma**



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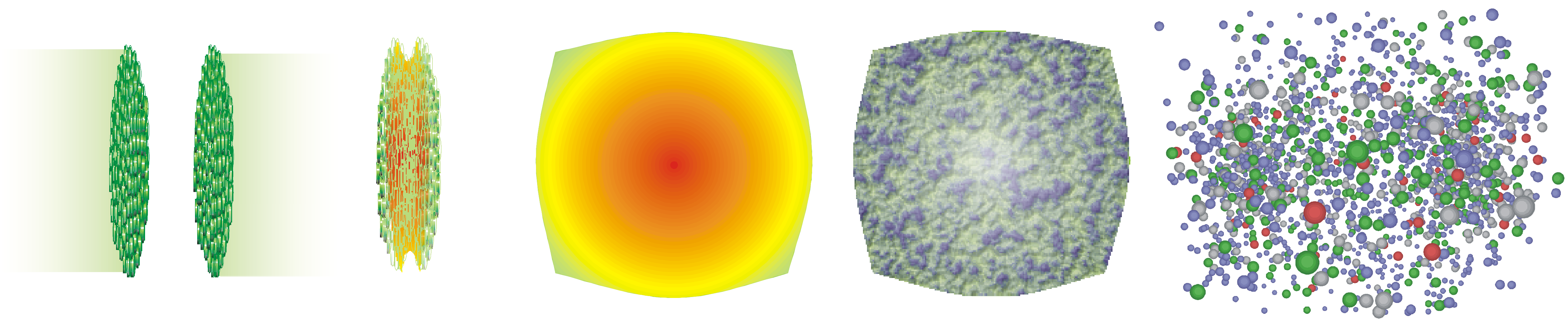

# relativistic **heavy** ion collisions

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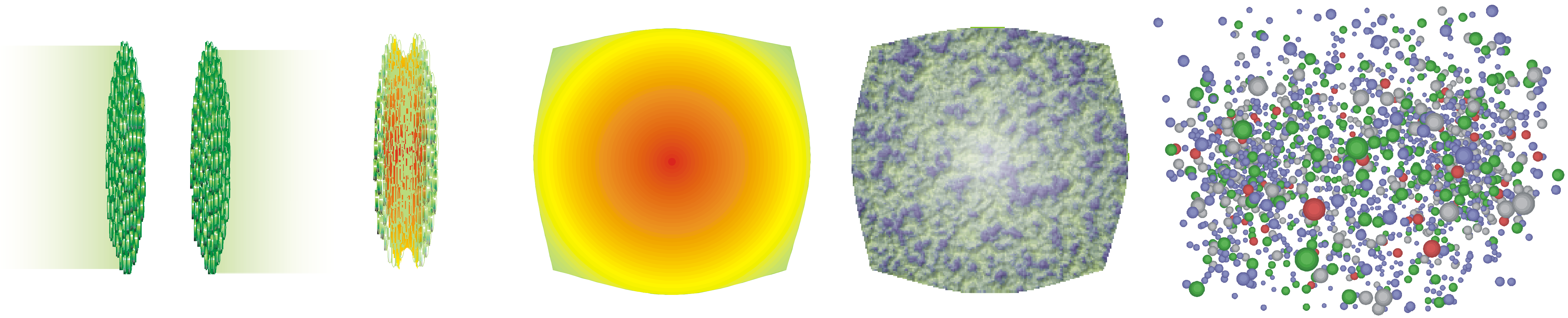
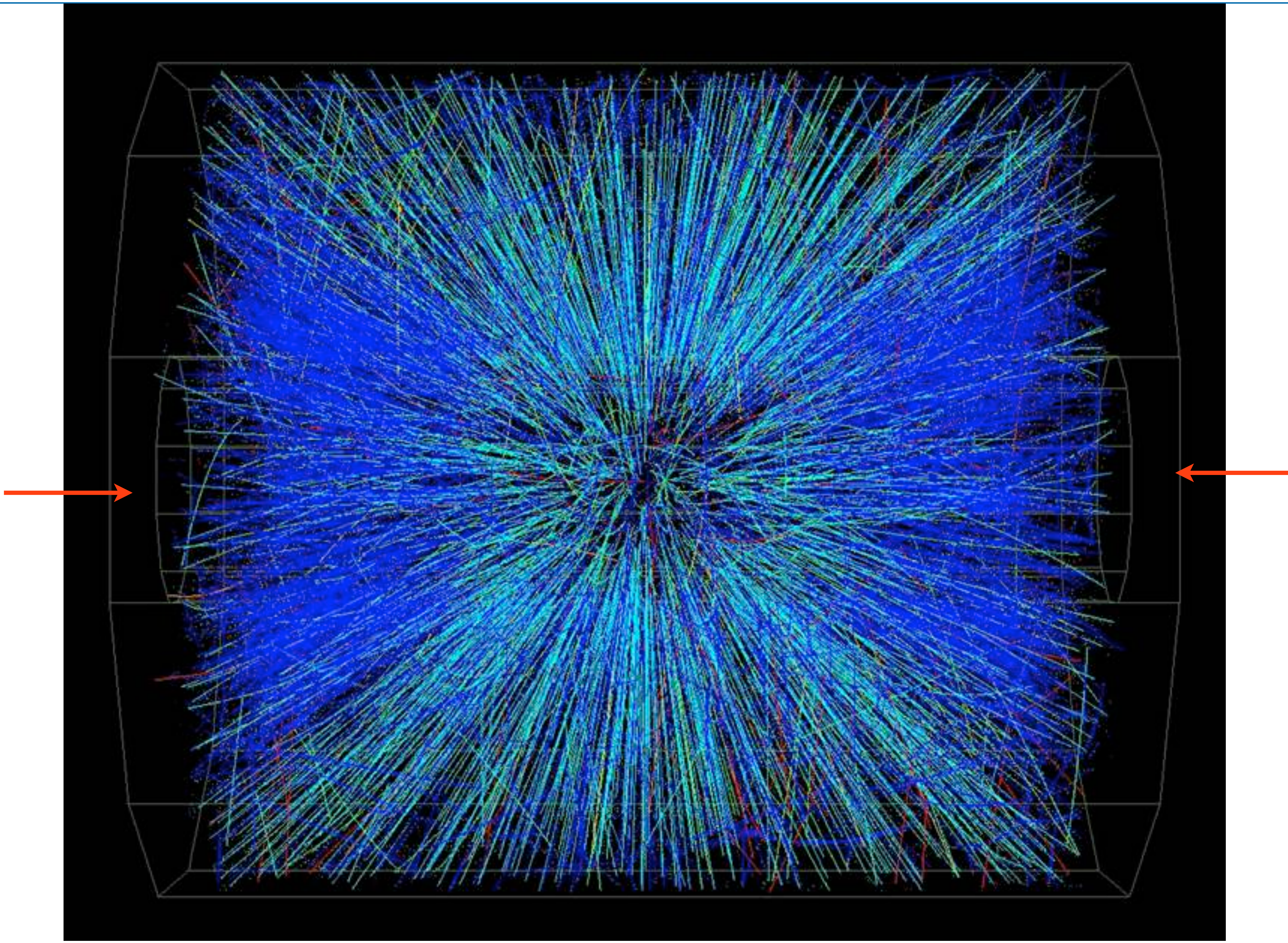
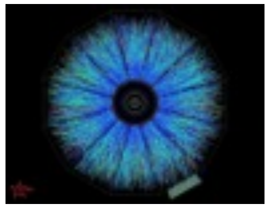


want to untangle QGP effects from effects of initial nucleus and hadronic matter

# the aftermath

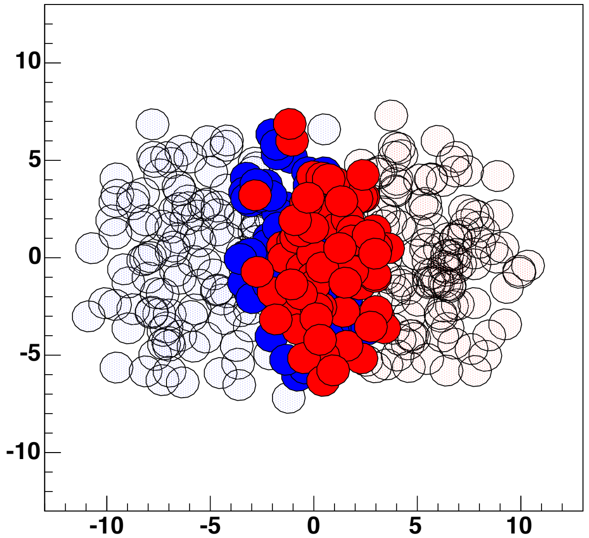


# collision geometry



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

nucleon positions for the colliding nuclei for three different collisions



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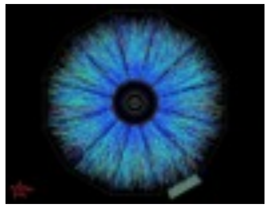

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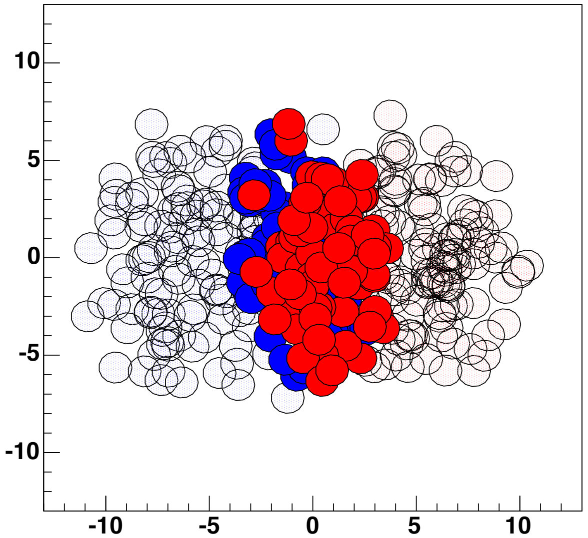


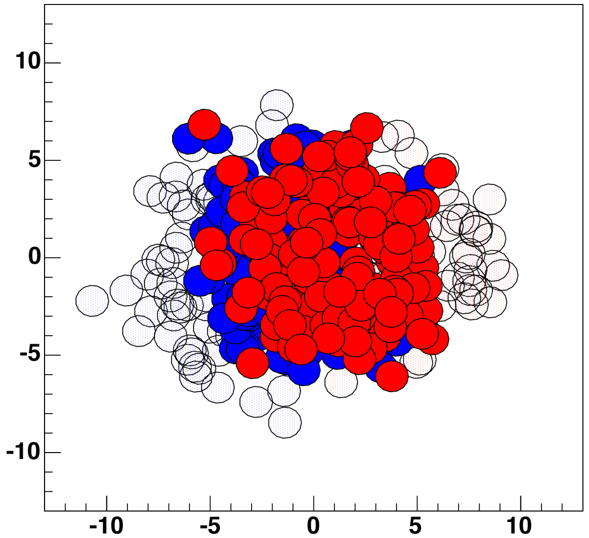

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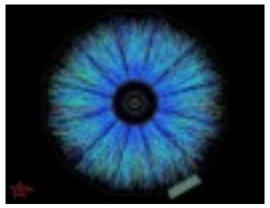

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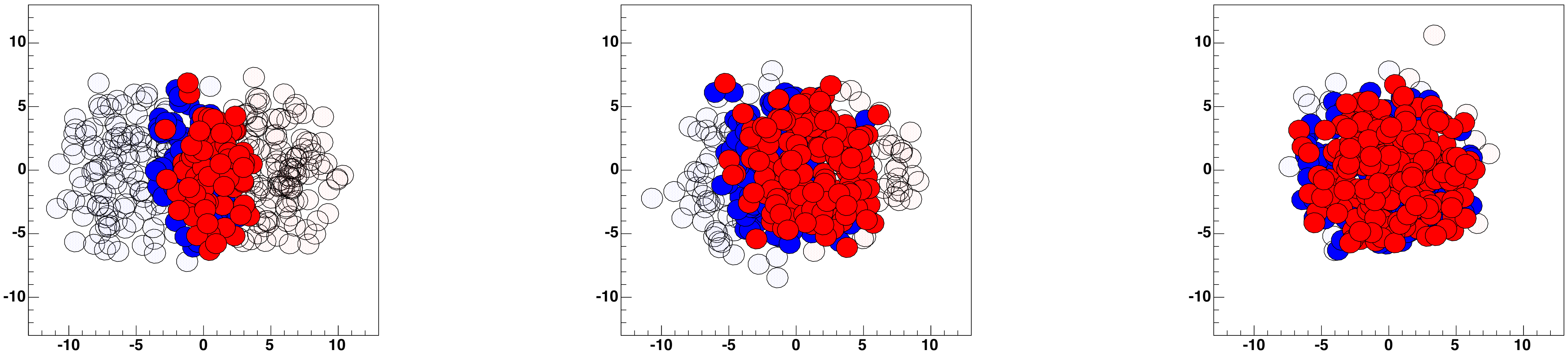

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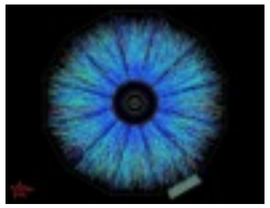

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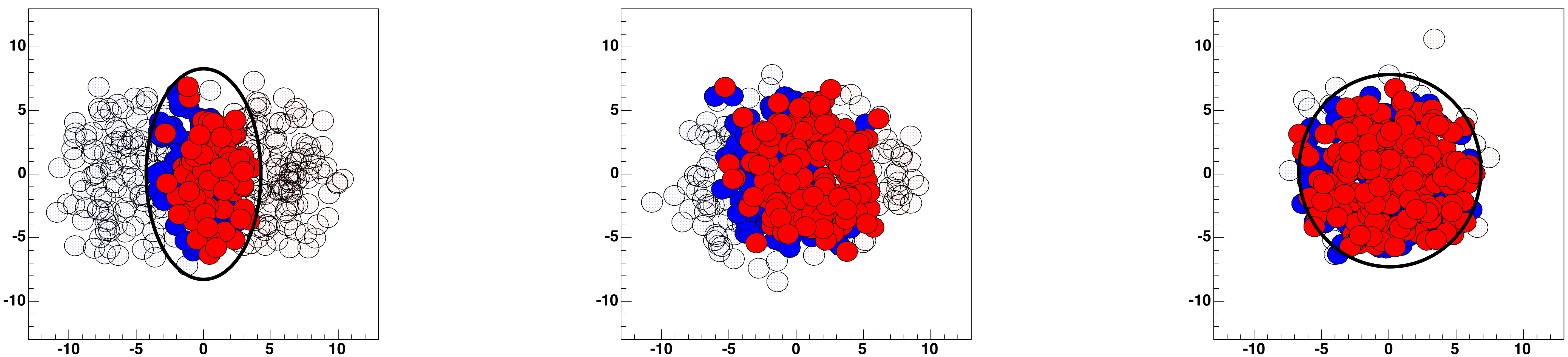
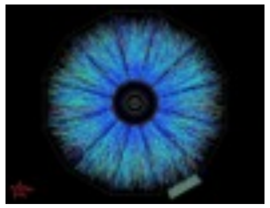



decreasing impact parameter

# collision geometry



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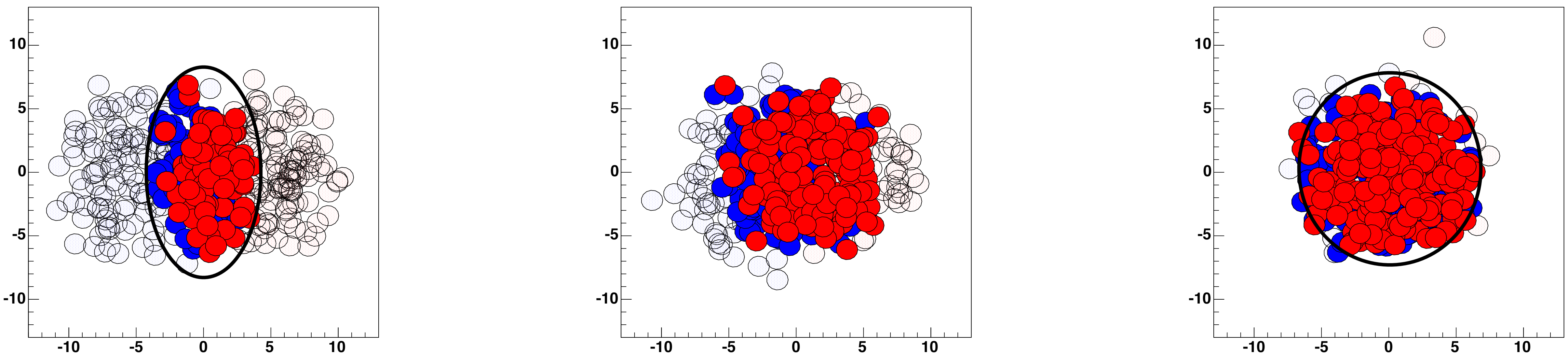
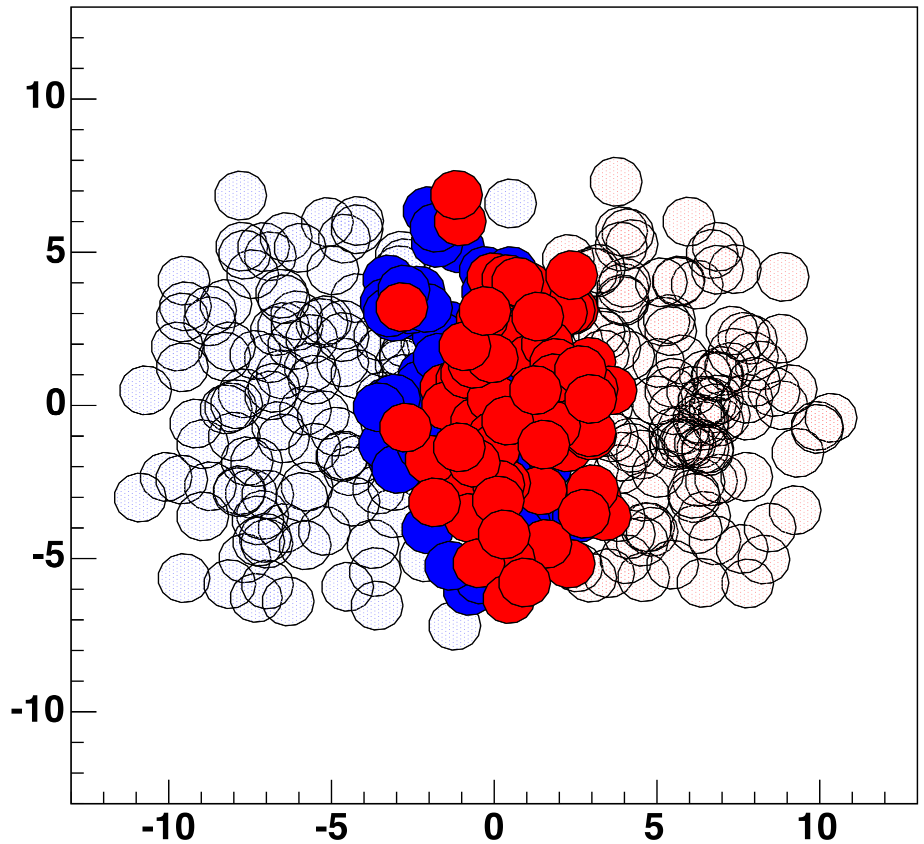



decreasing impact parameter

the overlap of the nuclei changes shape with impact parameter

# collision geometry → measured particles

initial collision geometry




PLB 707 330 (2012)

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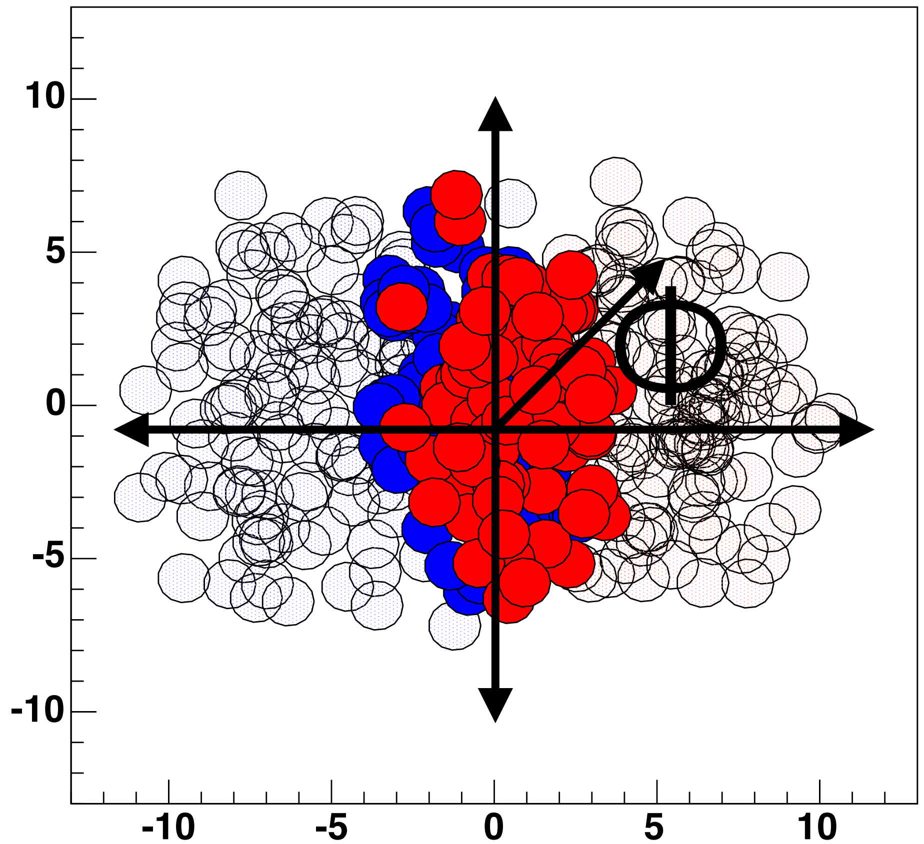


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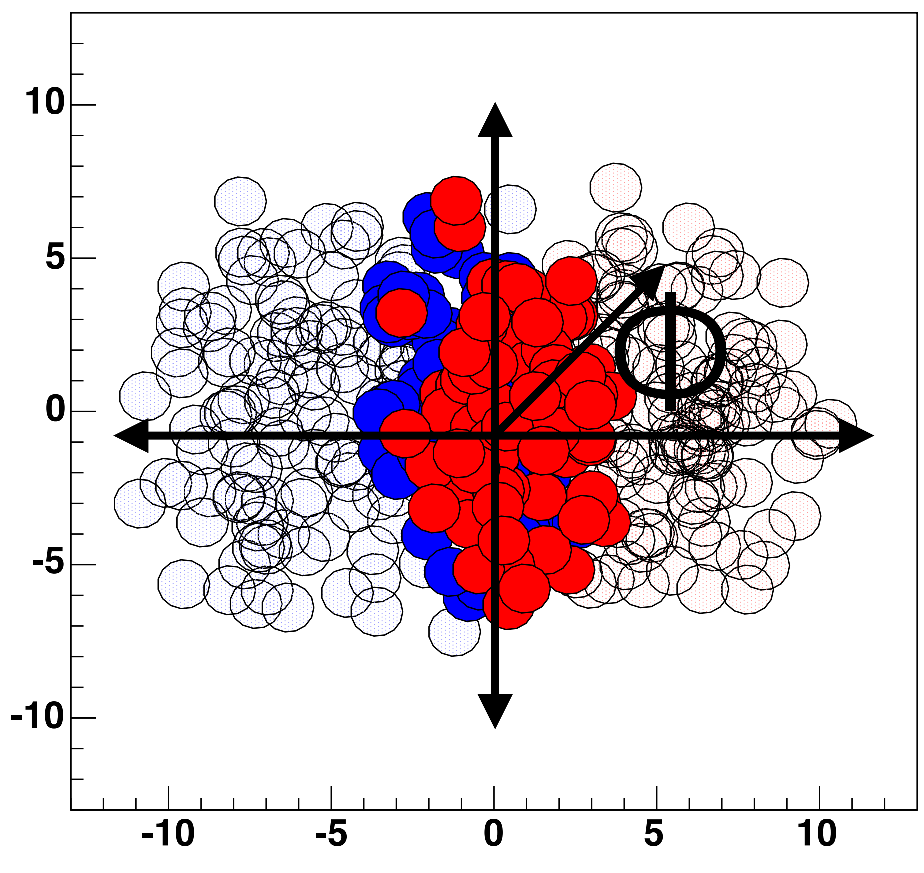
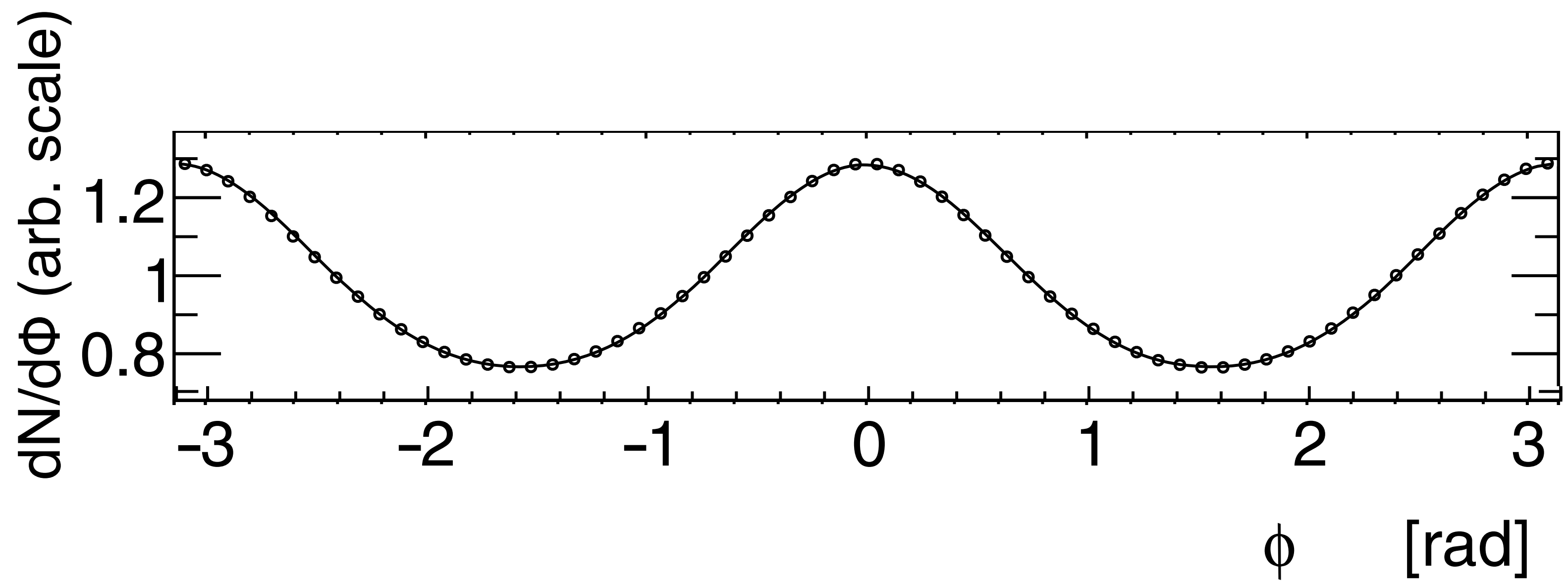



## measured hadron distributions

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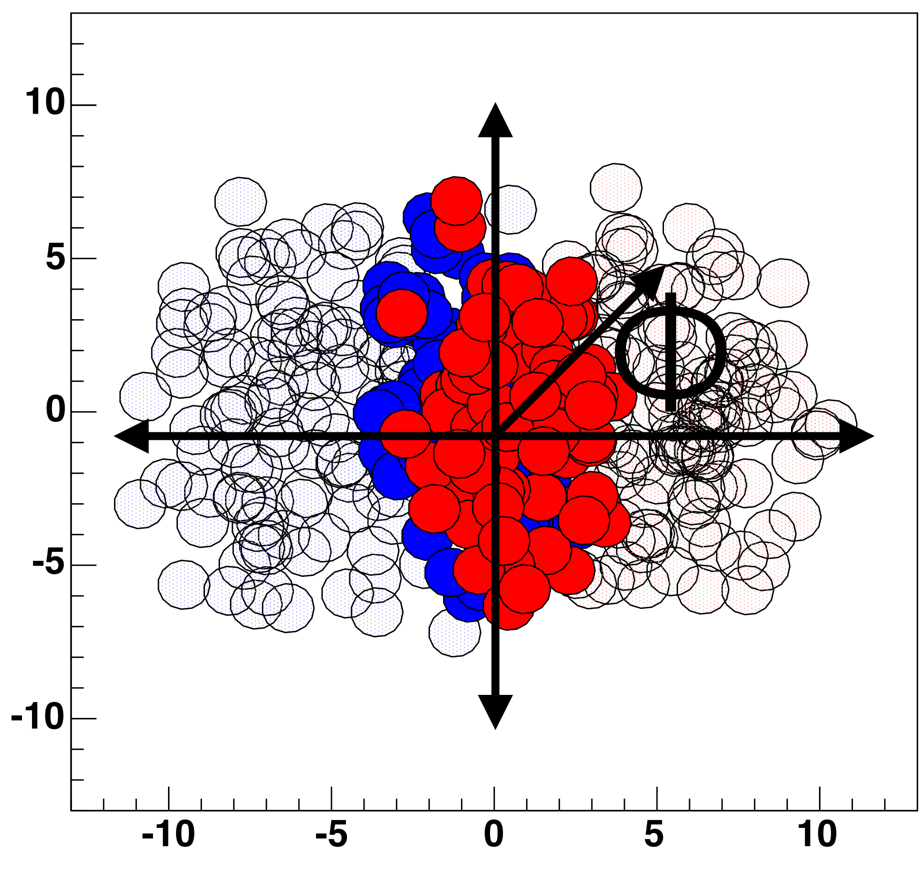


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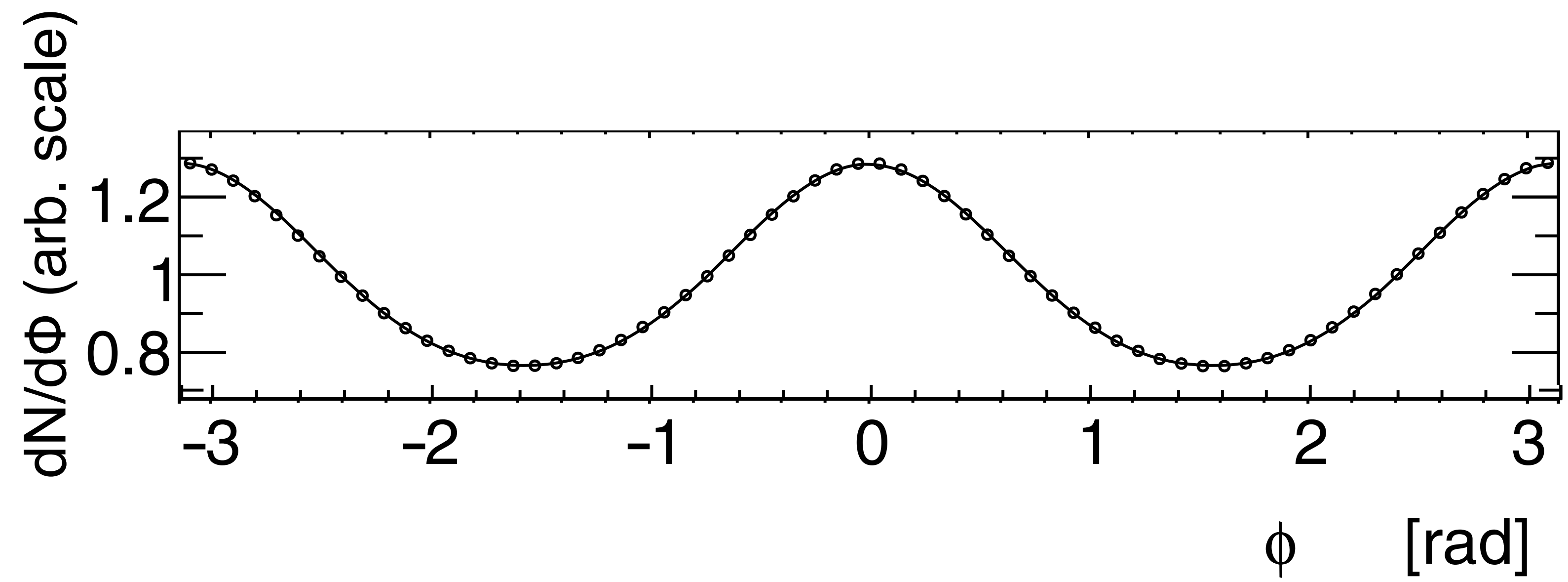


the shape of the collisions is accessible in the particle distributions

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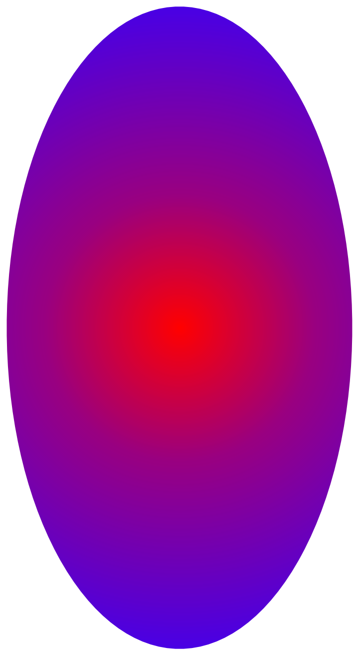
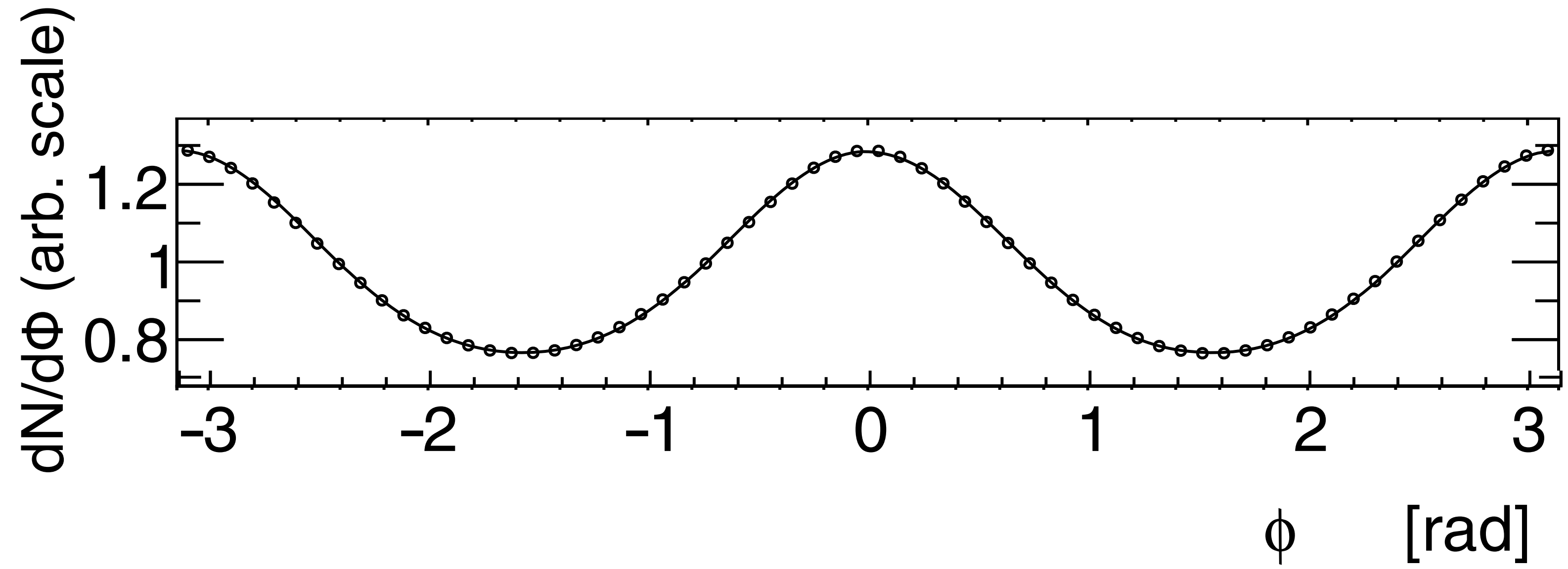
# strong interactions






- large observed anisotropies → strong interactions:
  - **fluid behavior, hydrodynamics**
- larger pressure gradients push more particles out in the x direction than in y

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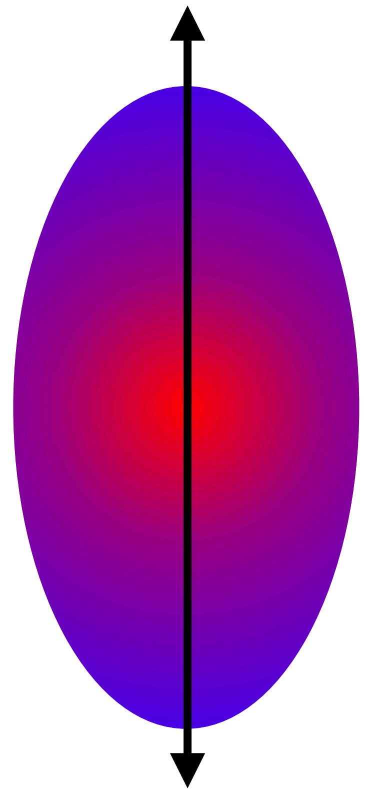
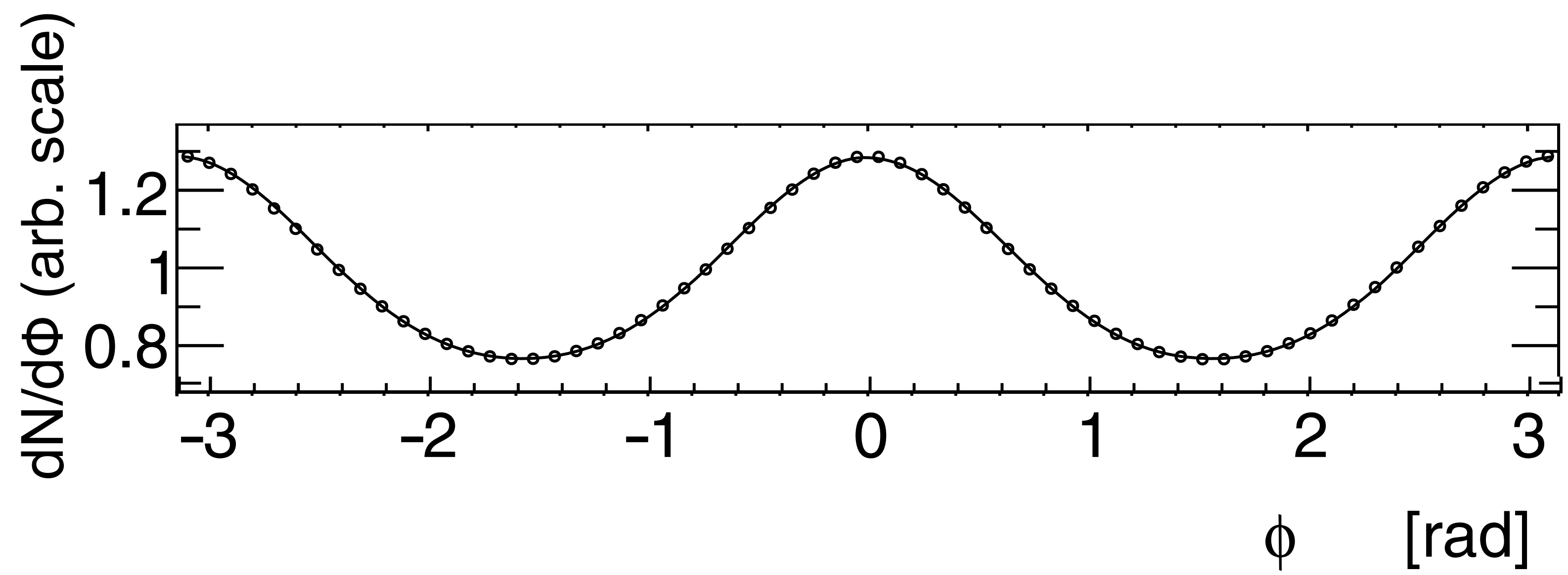


gradual
pressure
change

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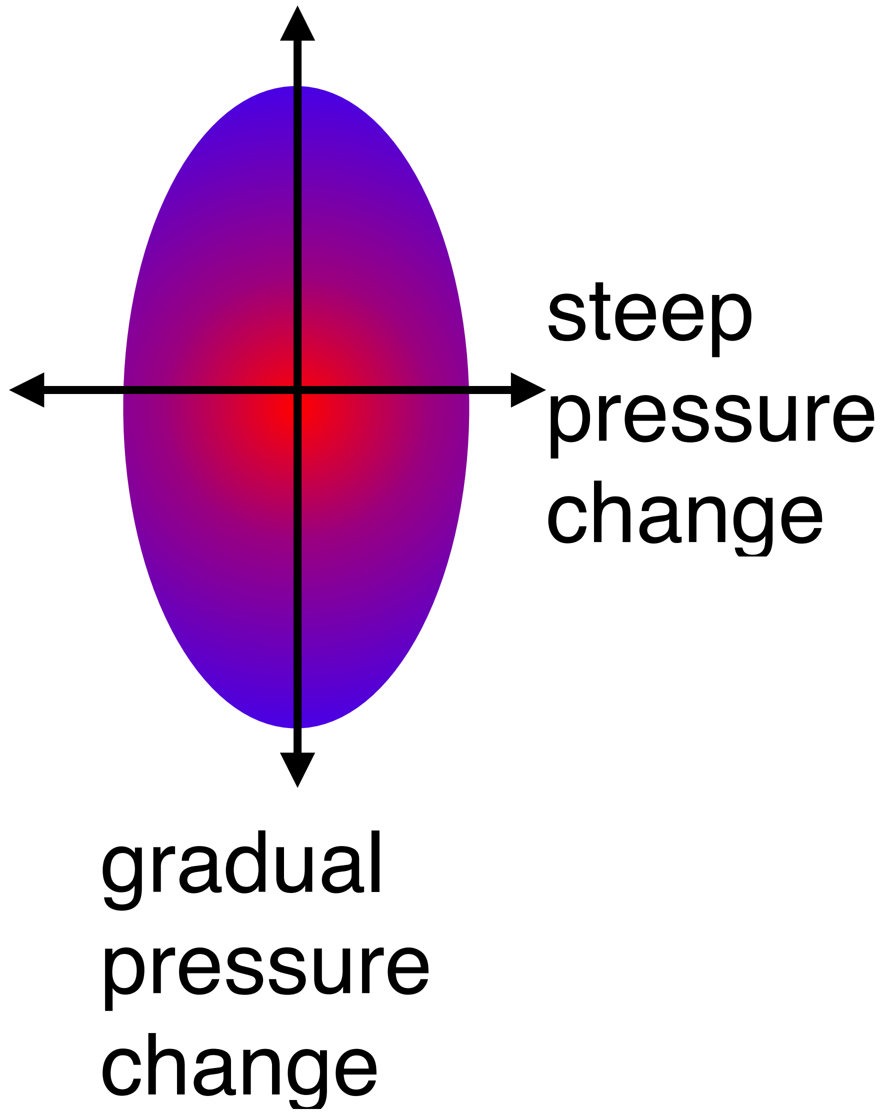


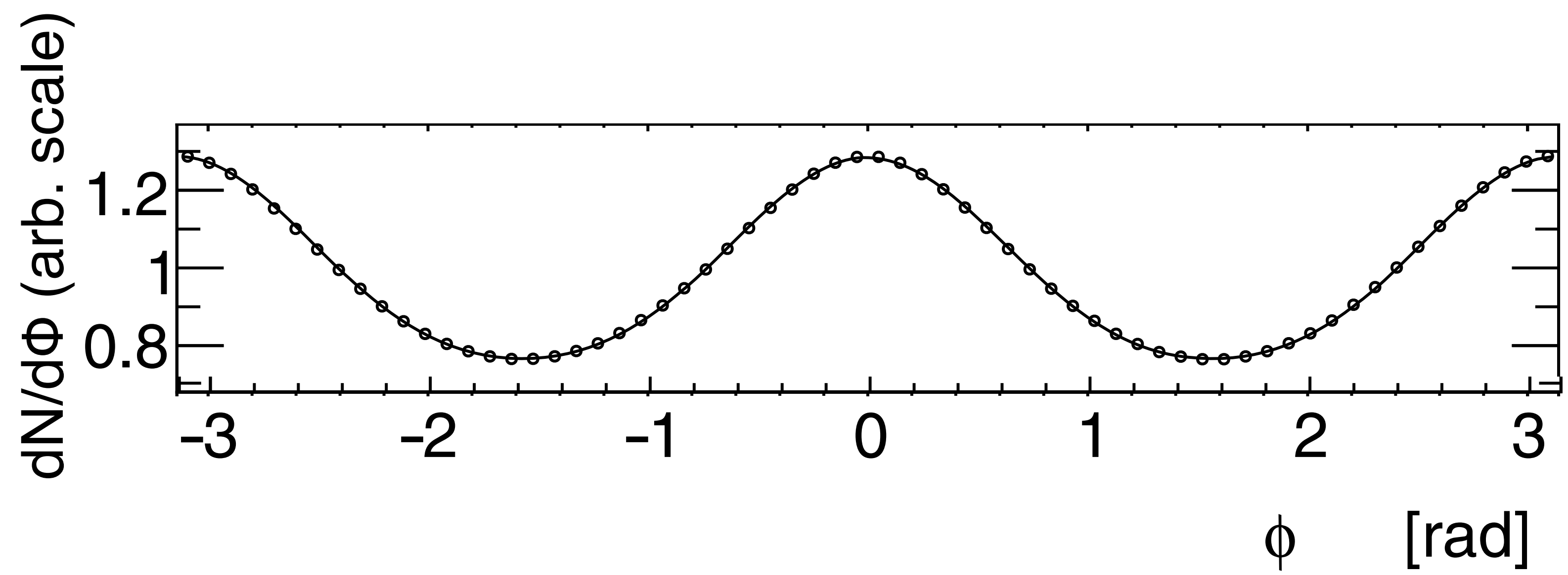


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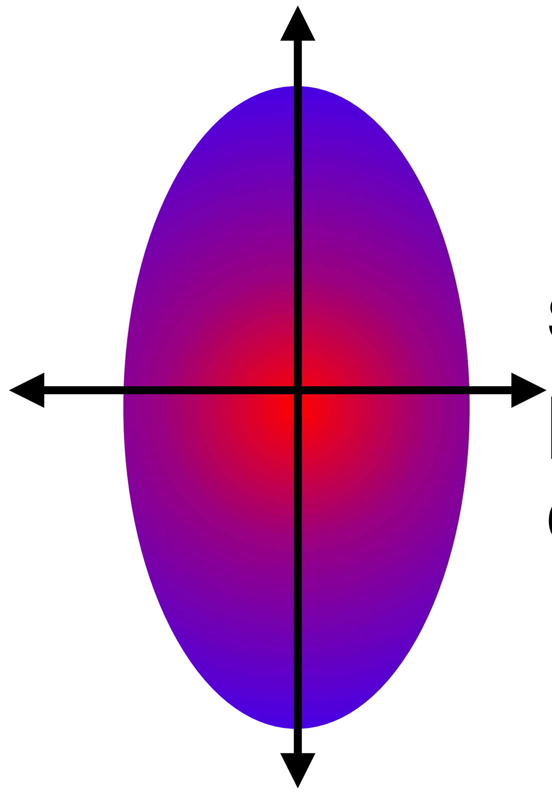
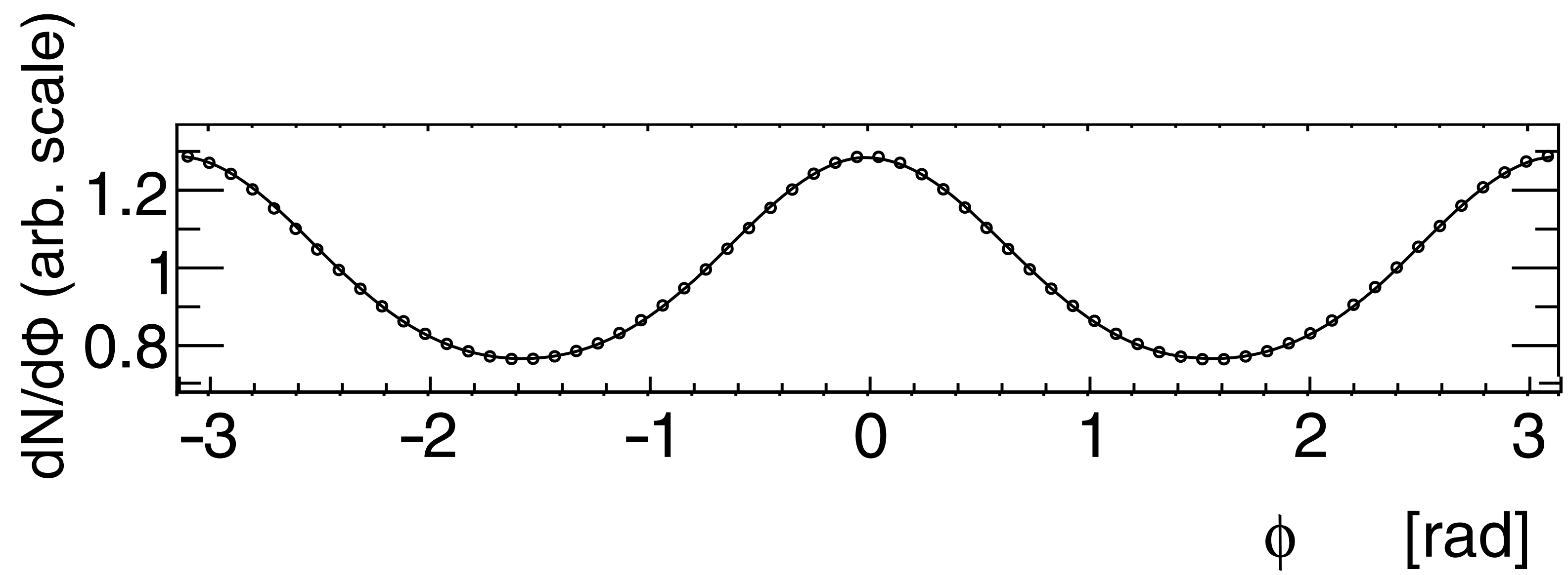


steep
pressure
change

gradual
pressure
change




$$\frac{dN}{d\phi} = 1 + 2v_2 \cos 2\phi$$

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  - **fluid behavior, hydrodynamics**
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# characterizing the fluid

- large $v_2$ → viscosity is small

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]

conjectured lower bound on
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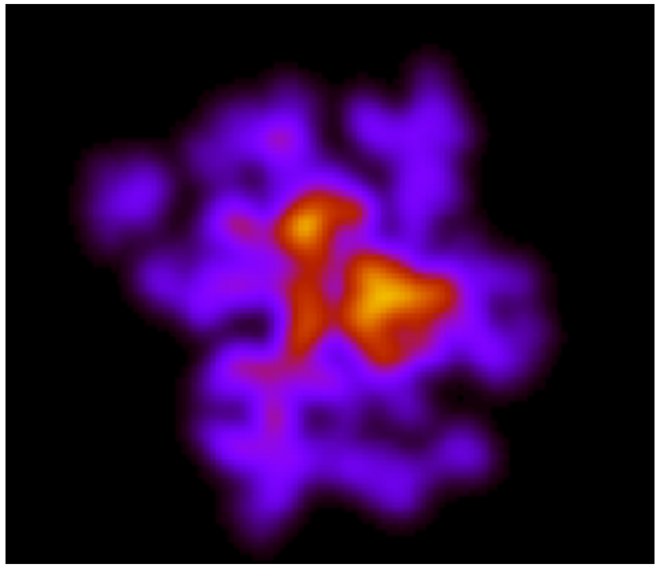
conjectured lower bound on viscosity / entropy density: $\eta/s > 1/4\pi$

question: how does the QGP $\eta/s$ compare to this bound?

# viscometer: fine scale structure

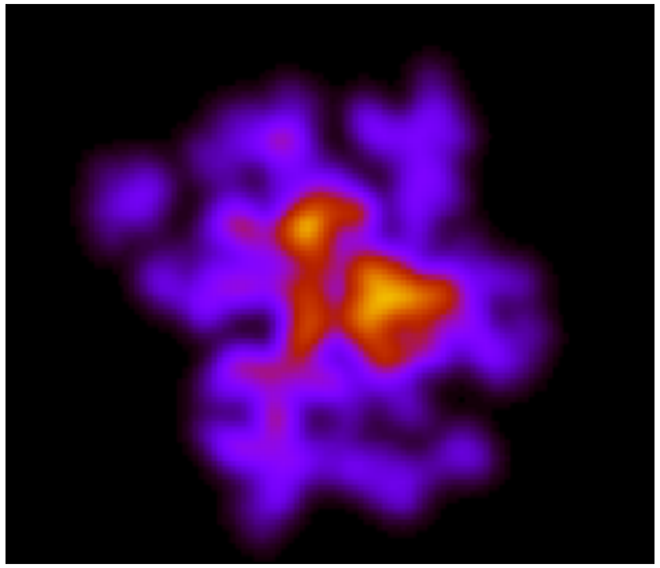
t = 0.5 fm/c

η/s = 0



t = 0.5 fm/c

η/s = 2/4π



calculation: 1109.6289, images B. Schenke

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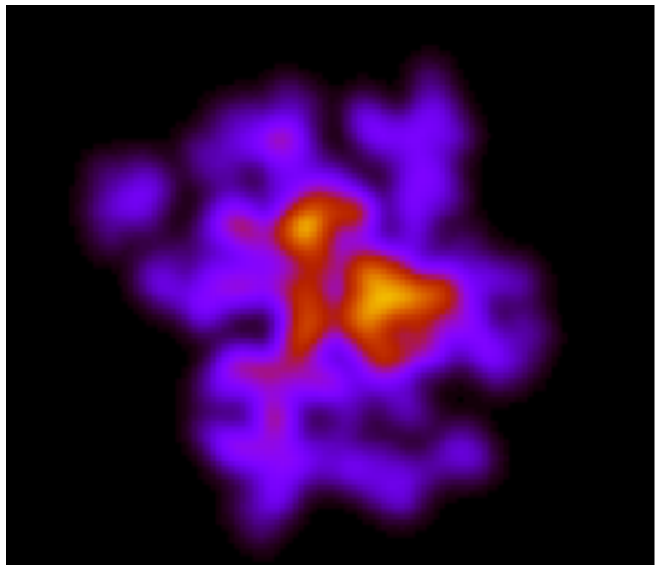
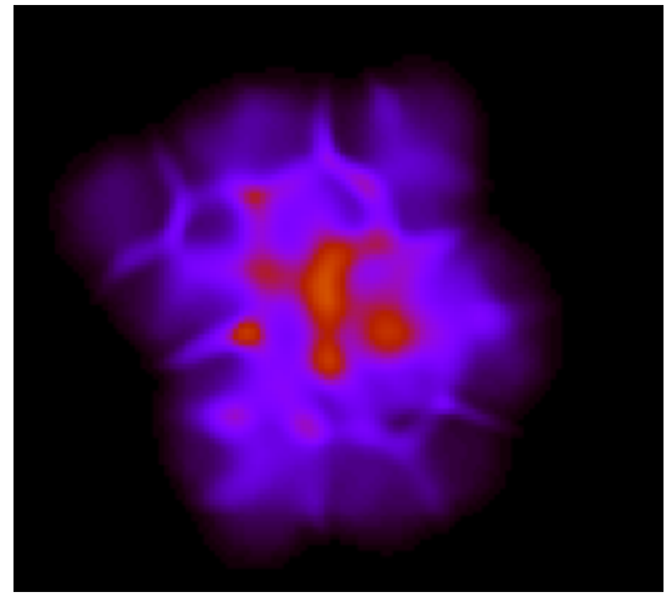


t = 2.1 fm/c



$\eta/s = 2/4\pi$

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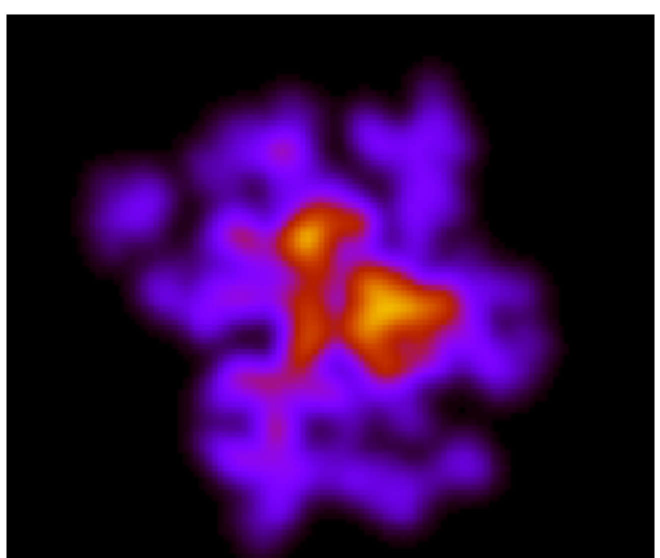

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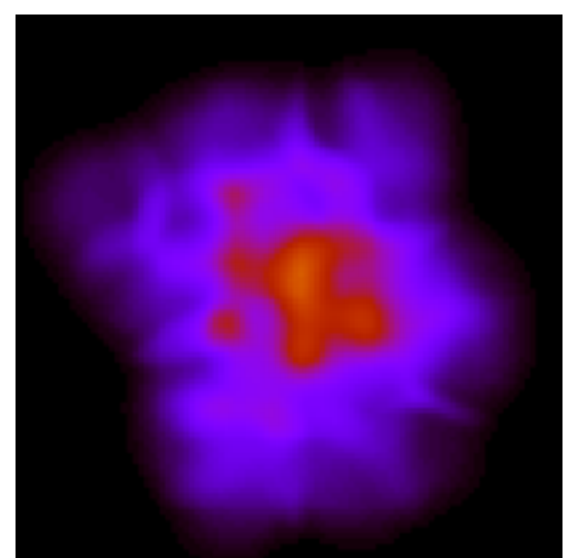

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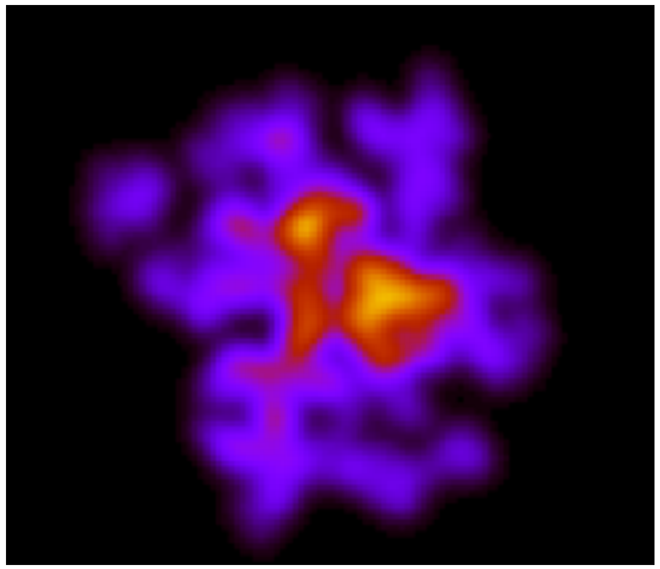

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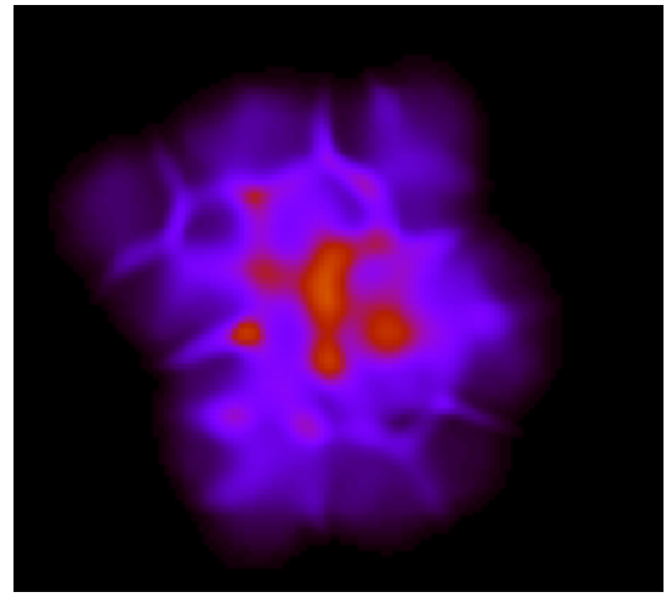
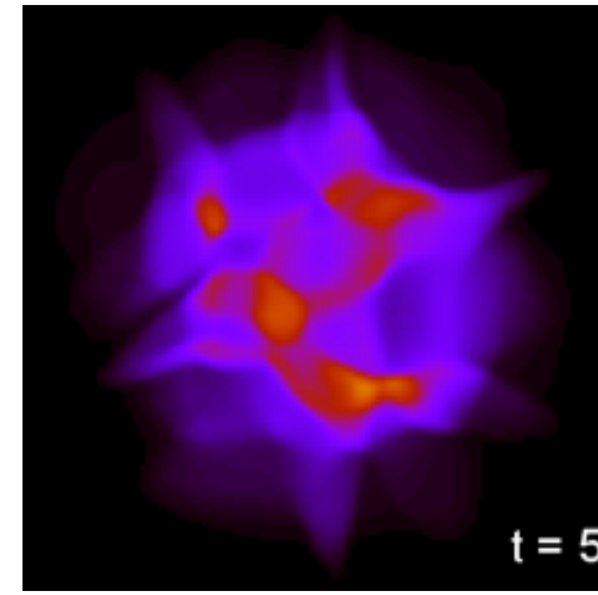
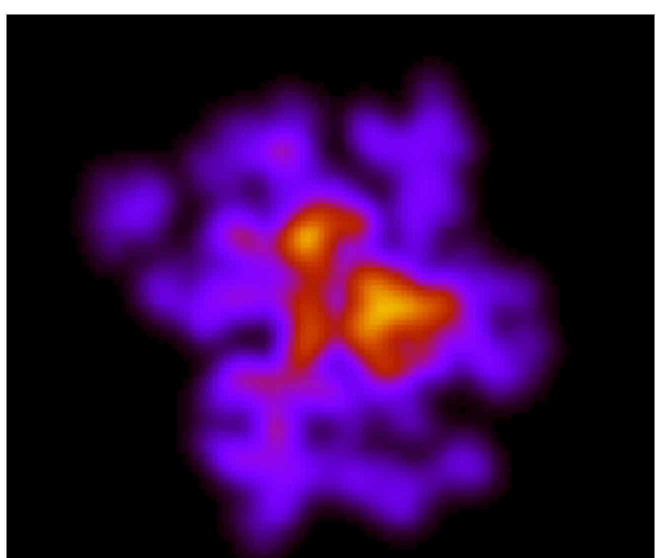


t = 5.1 fm/c




$\eta/s = 2/4\pi$

t = 0.5 fm/c



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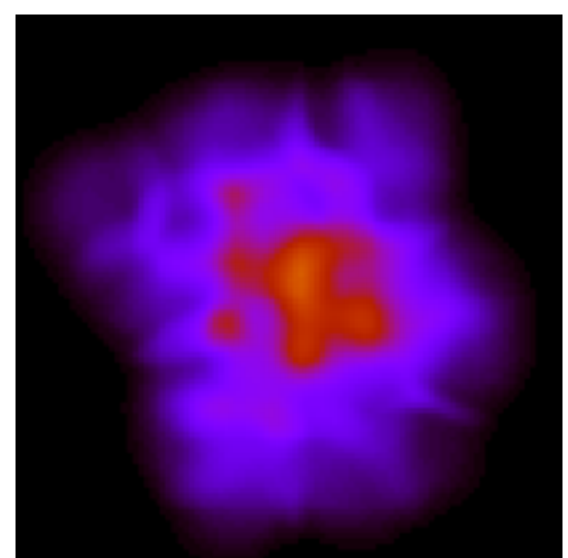

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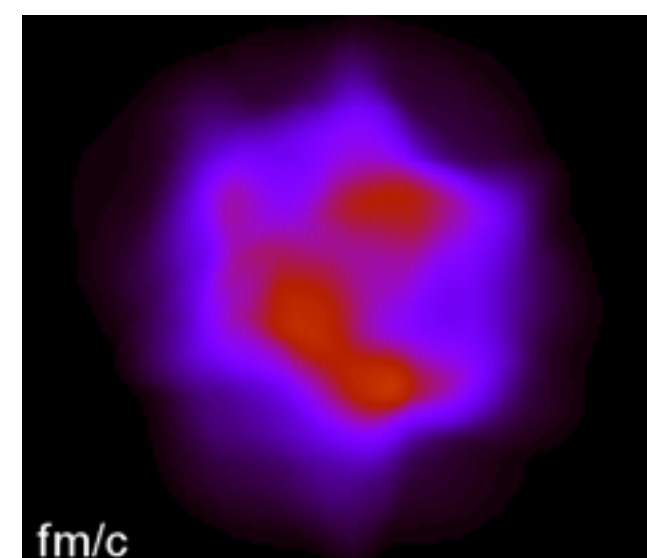


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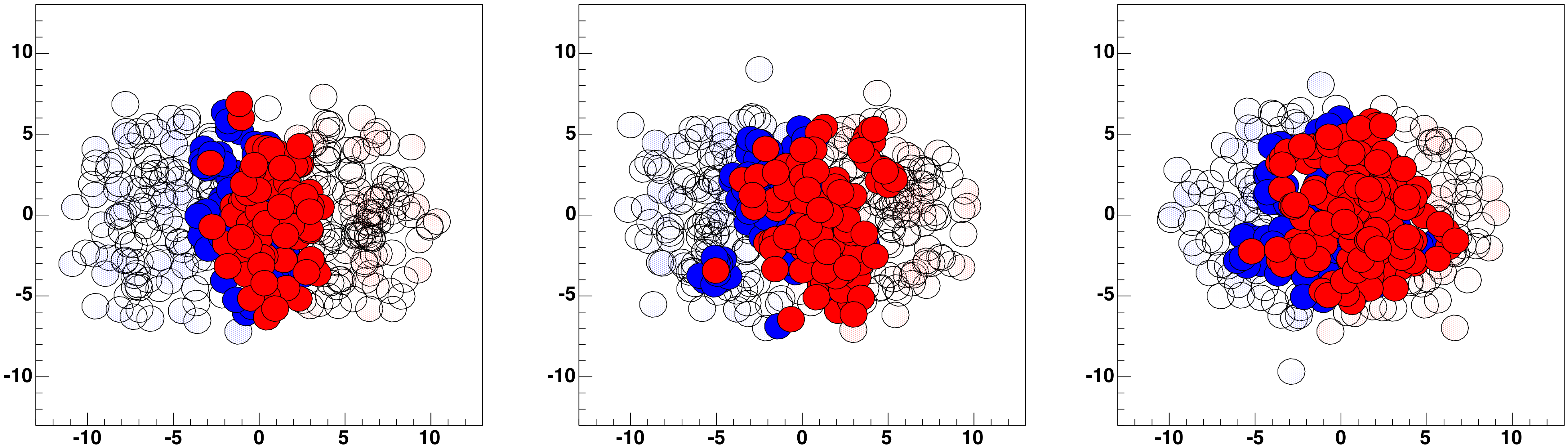
# each event is unique

nucleon distributions for 3 single collisions (xy-plane)

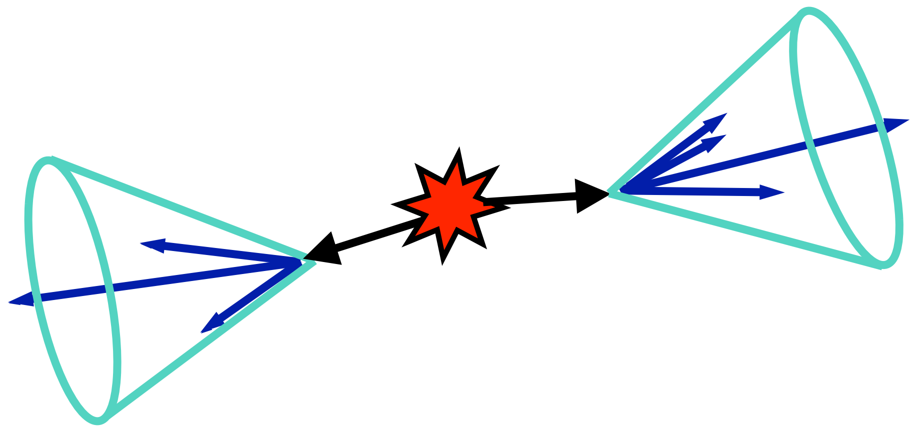


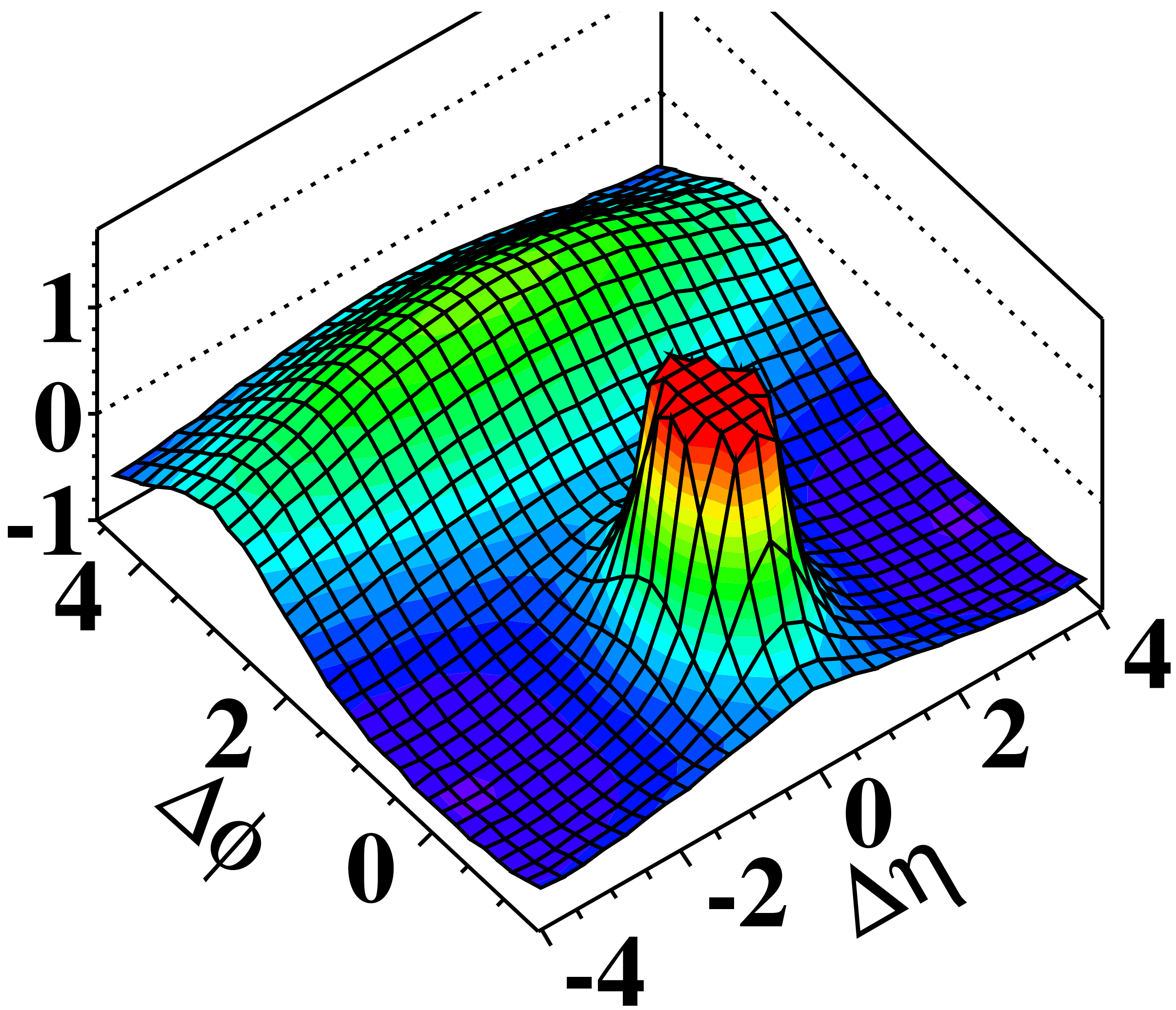

not just $v_2$ describing cos2Φ, but $v_n$:

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

# two particle correlations

jets in pp collisions






CMS JHEP 1009 (2010) 091

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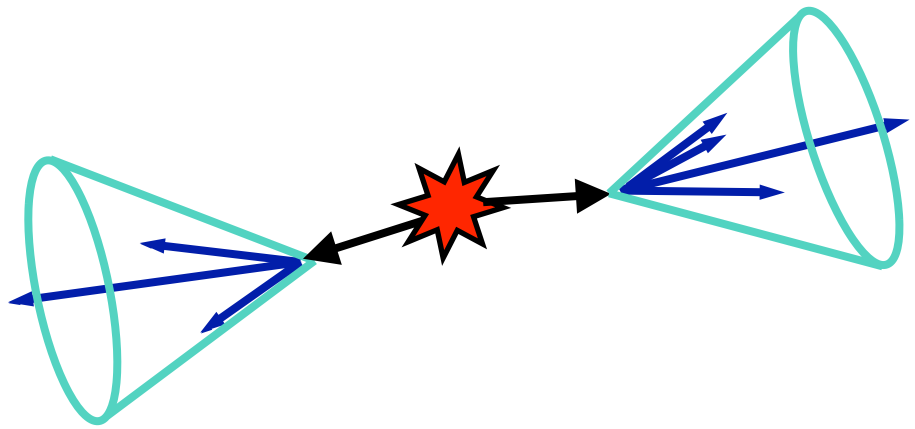

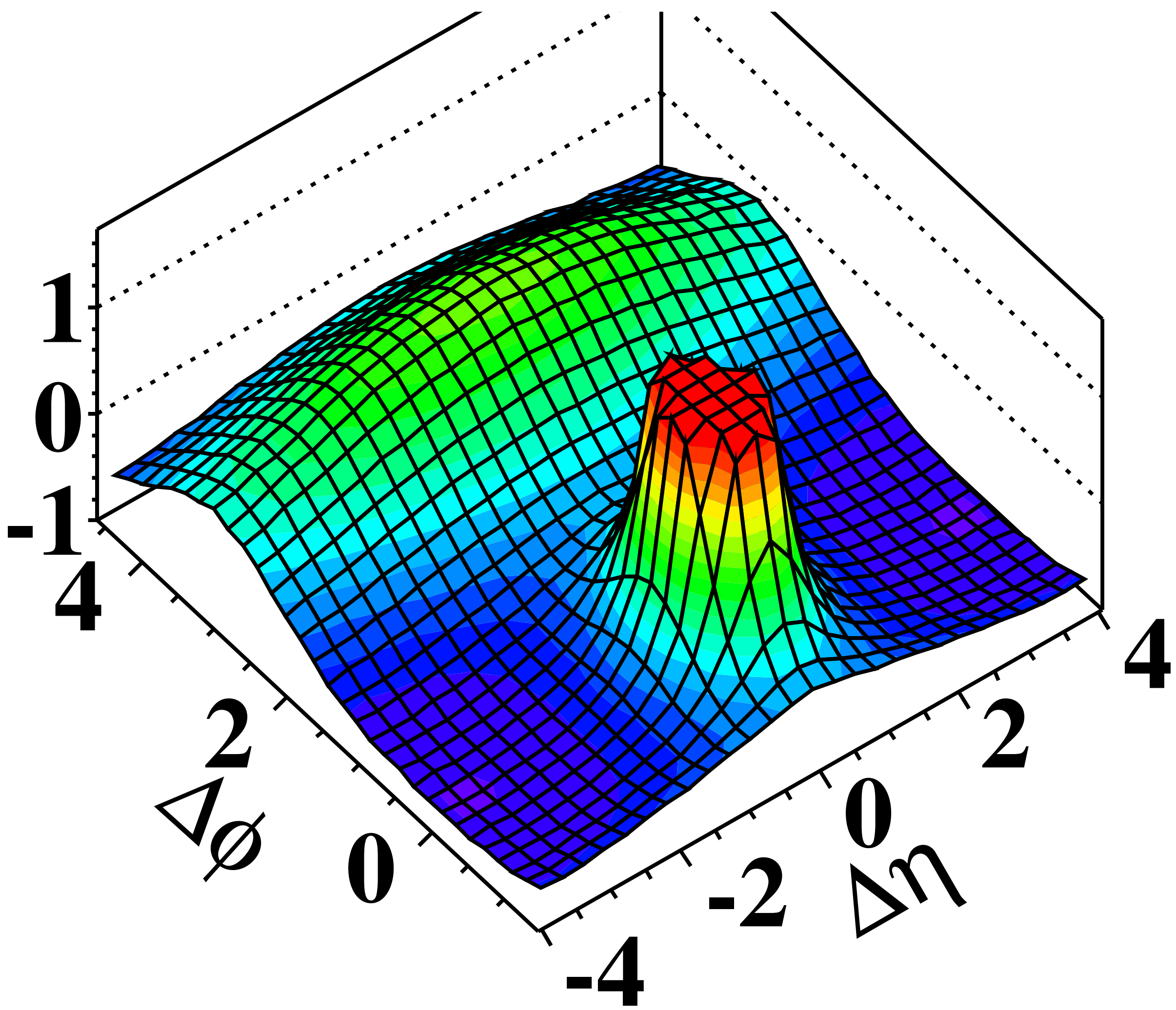


hydrodynamics

single particles

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

pairs of particles

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

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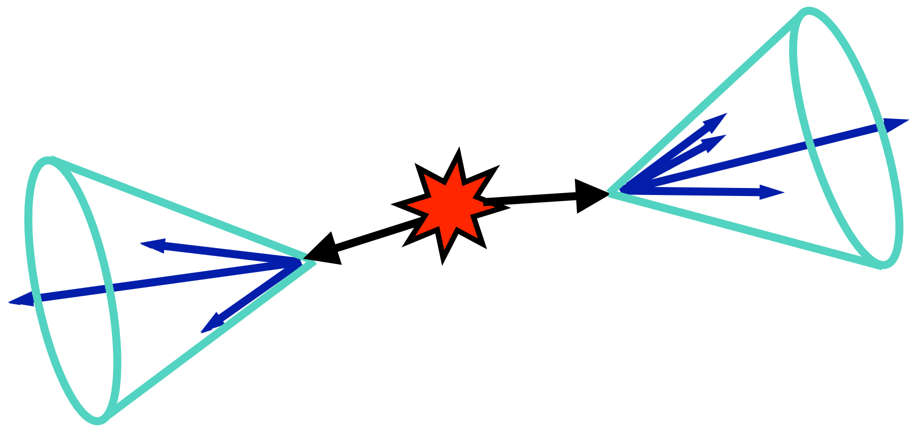

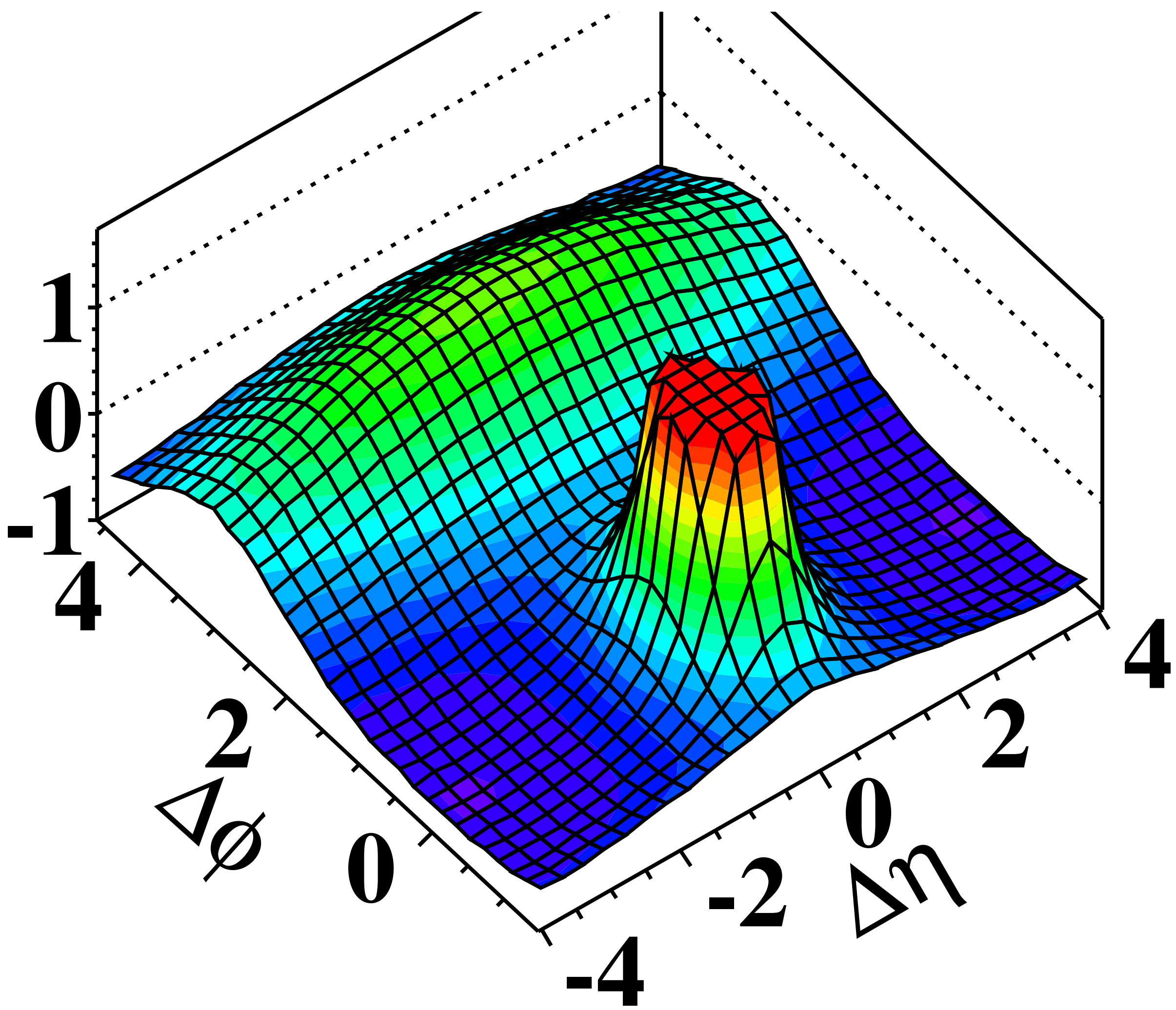


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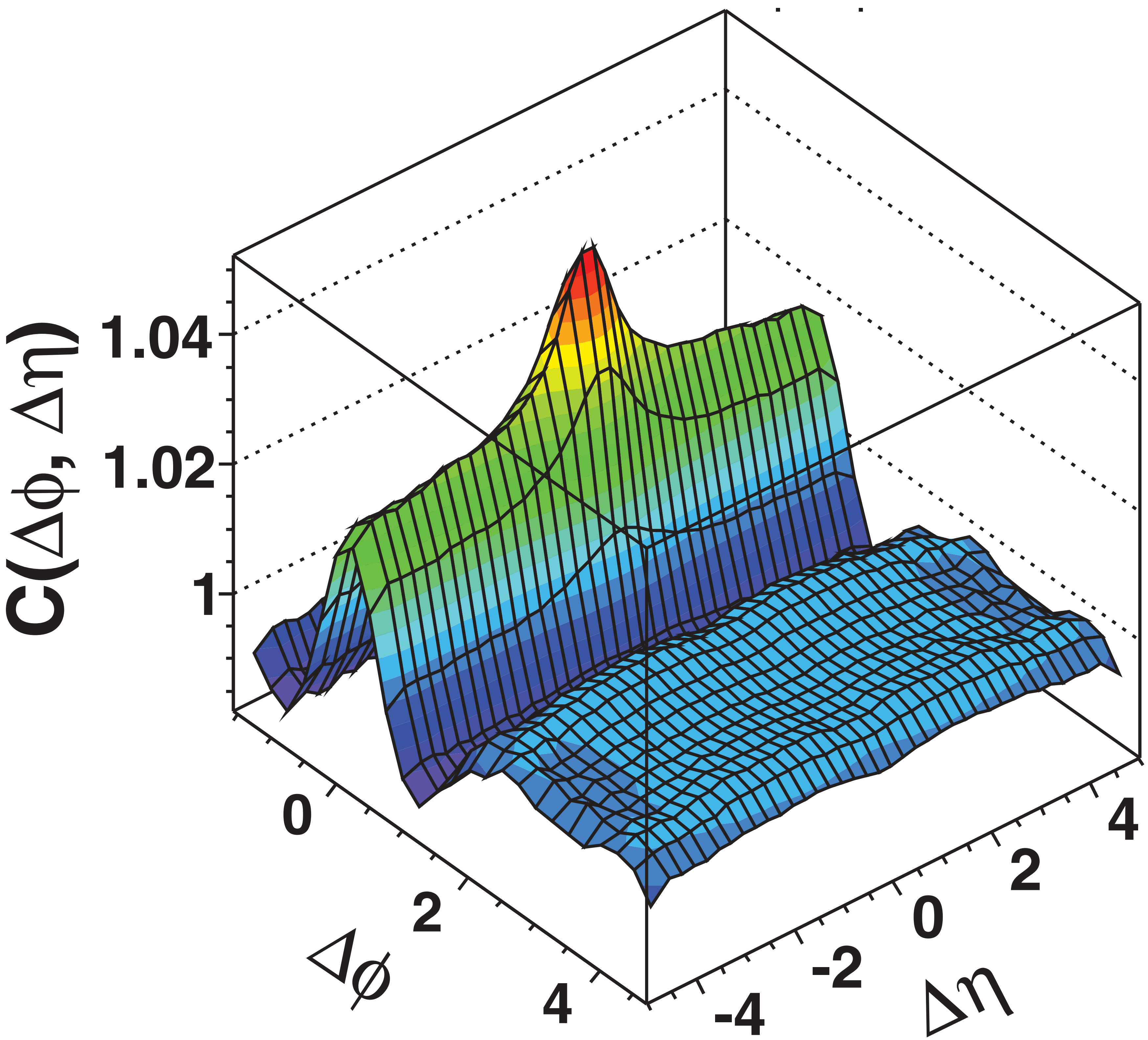
**smoking gun**: hydrodynamic correlations are long range η

CMS JHEP 1009 (2010) 091

# correlations in PbPb




ATLAS PRC 86 014907

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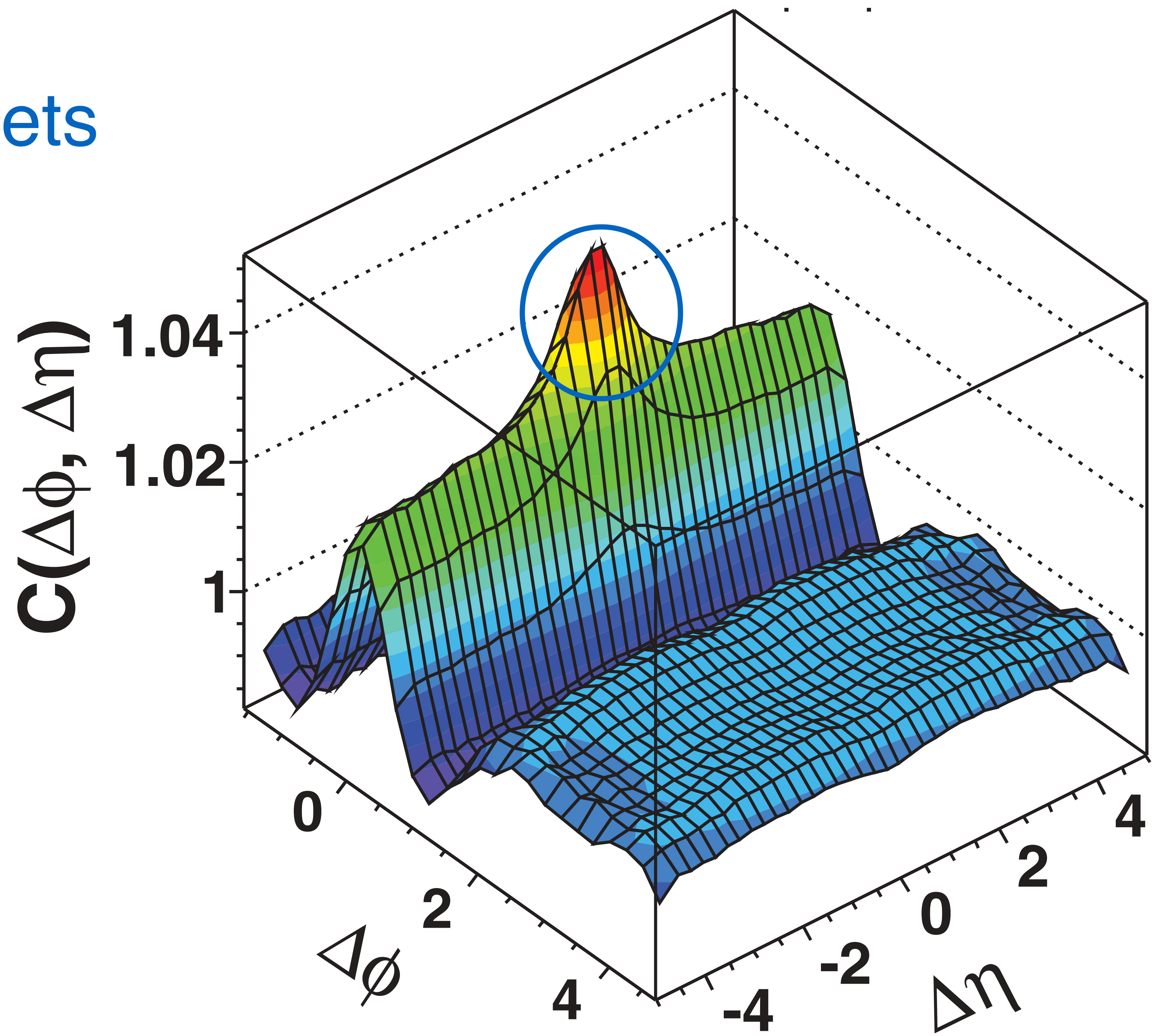
jets



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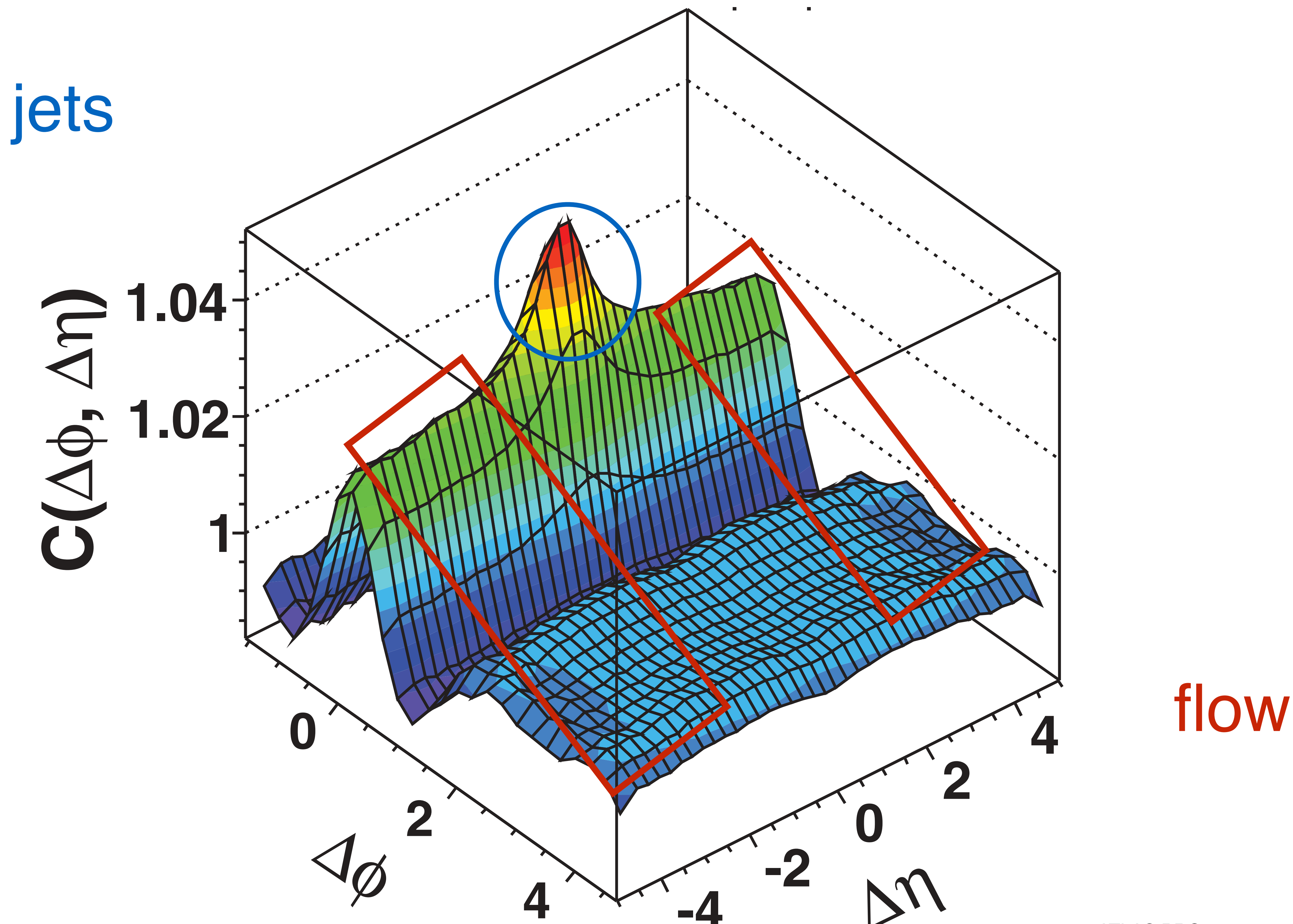
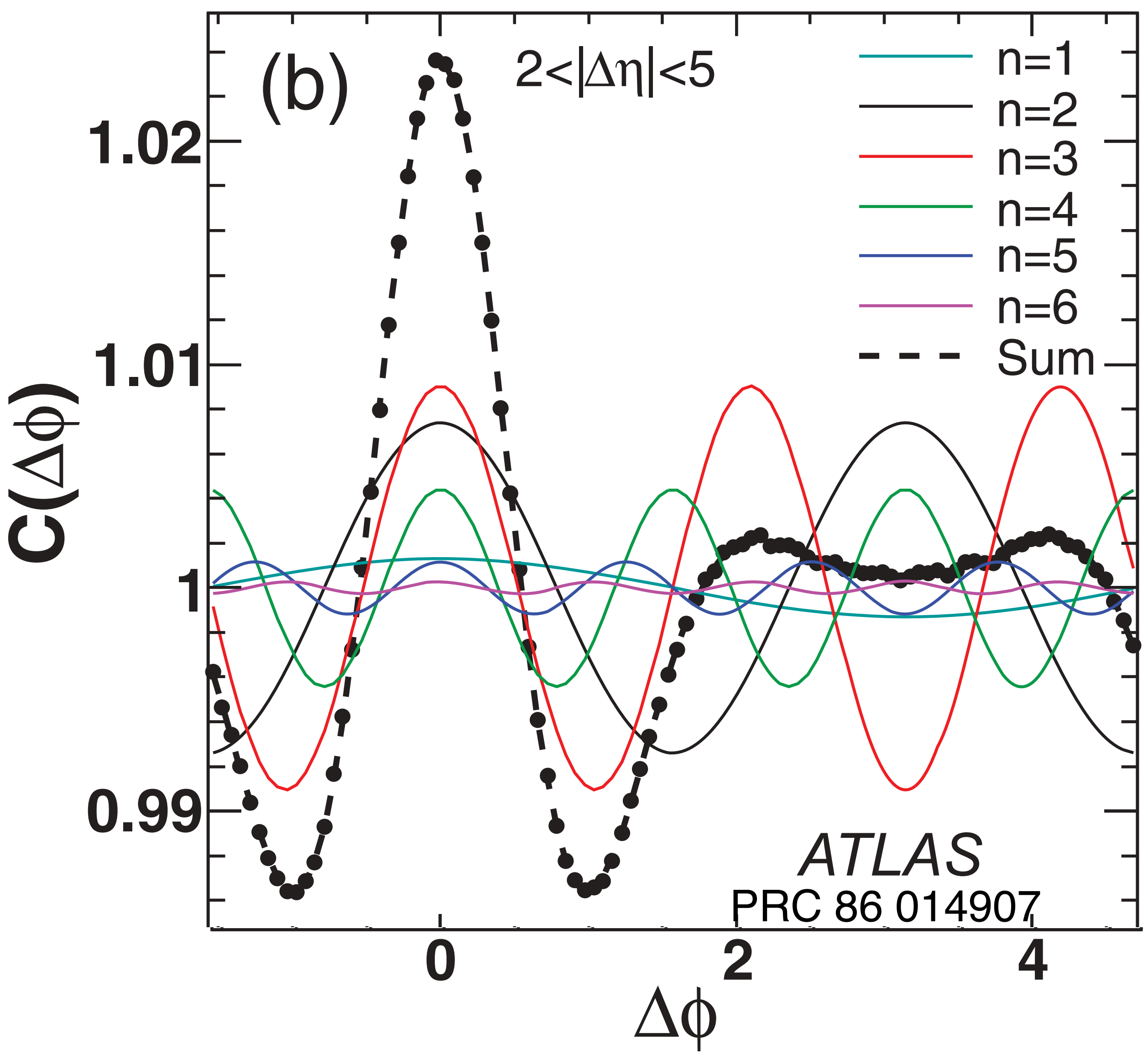



ATLAS PRC 86 014907

# $v_2$, $v_3$, $v_4$… → $\eta/s$




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

calc: Gale, et al. PRL 110 012302 (2013)

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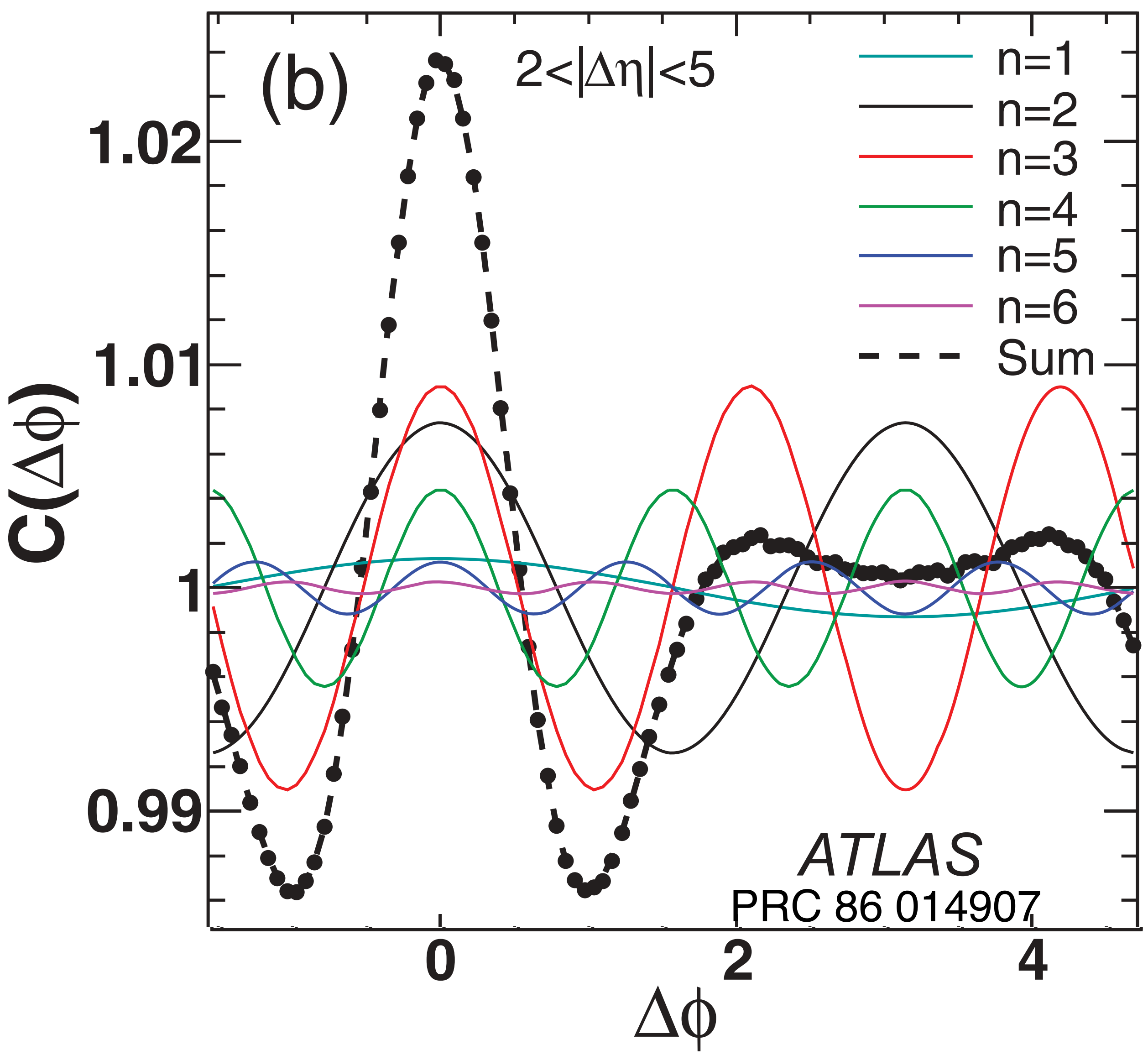


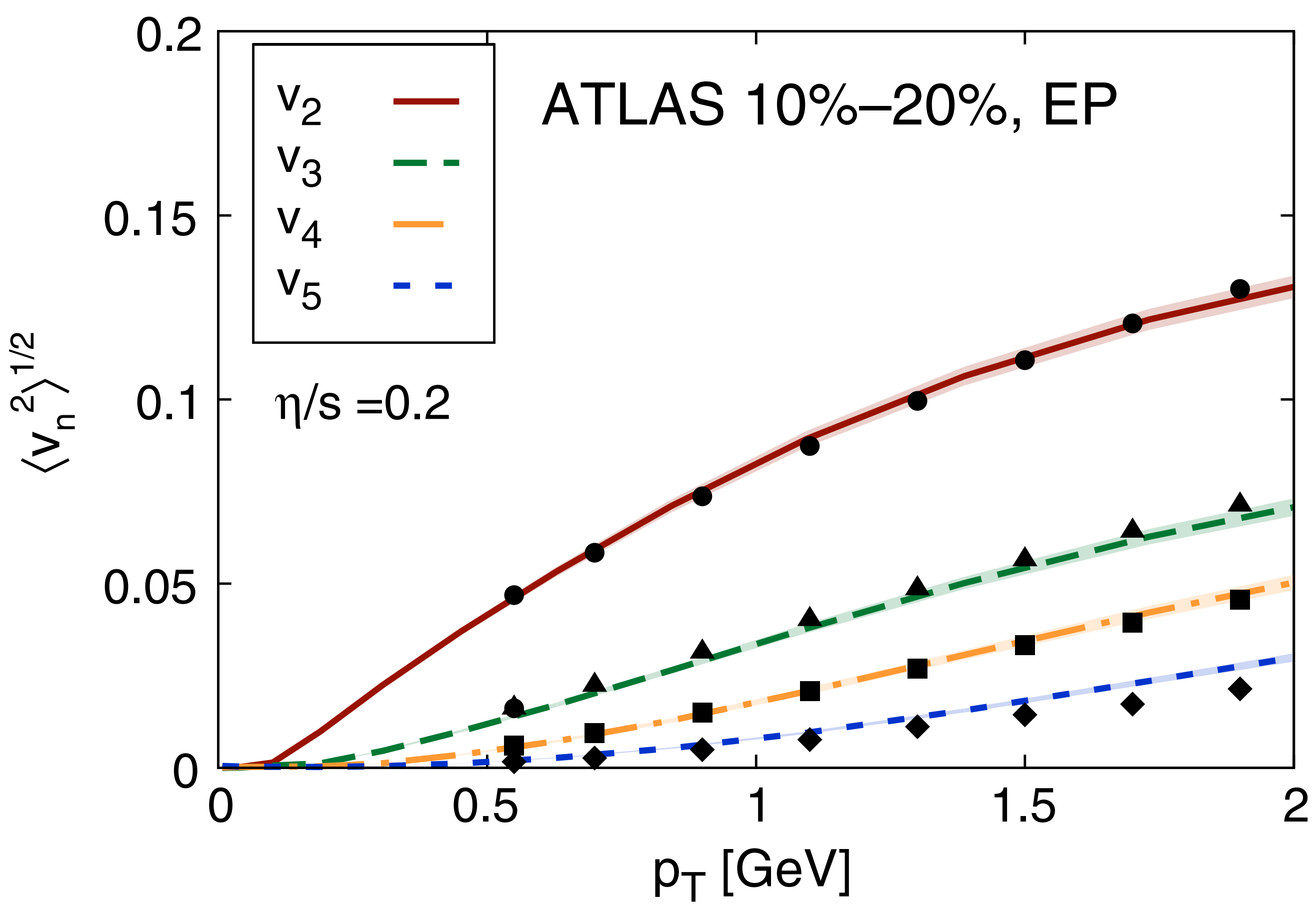


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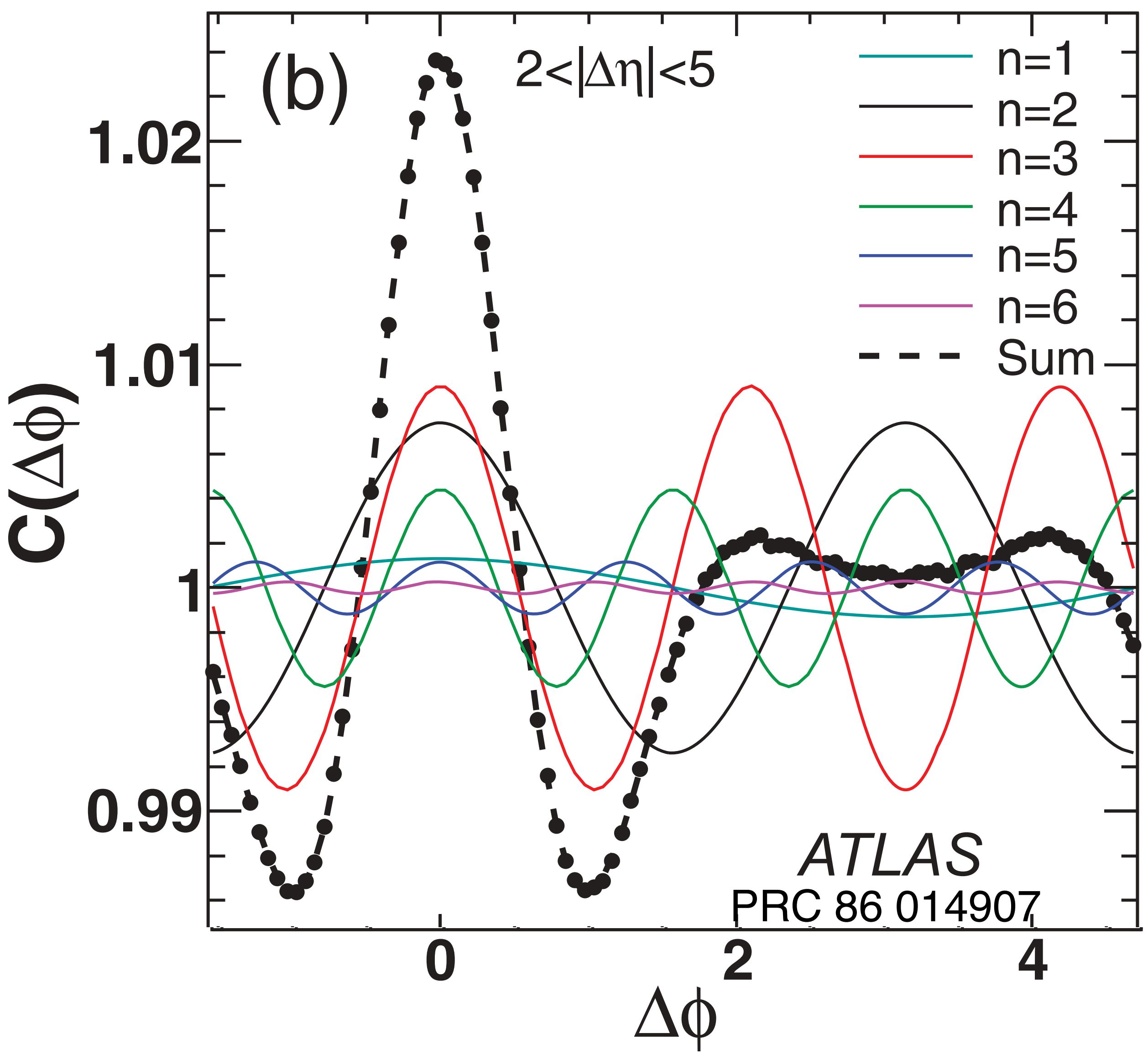
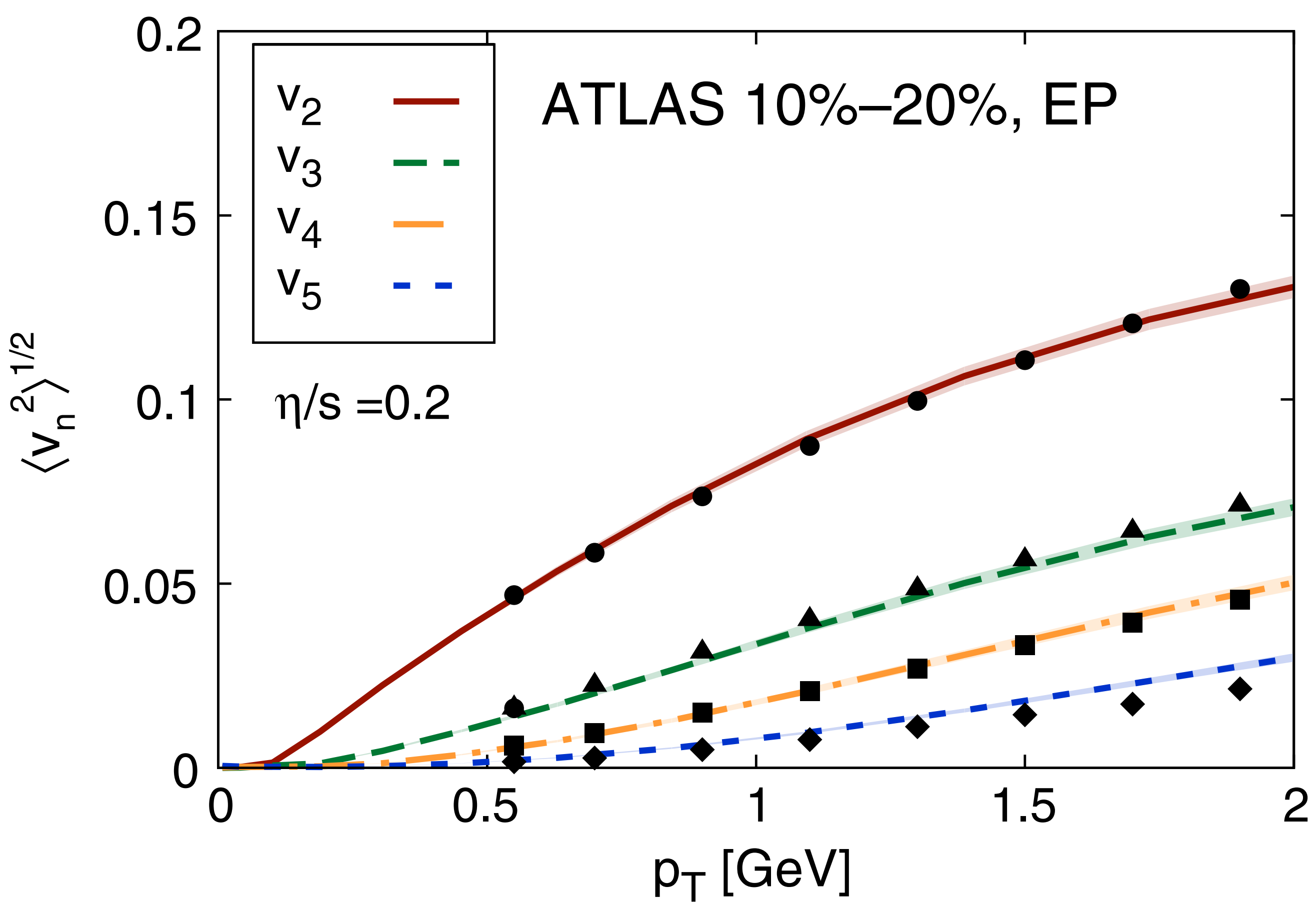
calc: Gale, et al. PRL 110 012302 (2013)

# $v_2$, $v_3$, $v_4$… → $\eta/s$




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




$\eta/s = 2.5/4\pi$

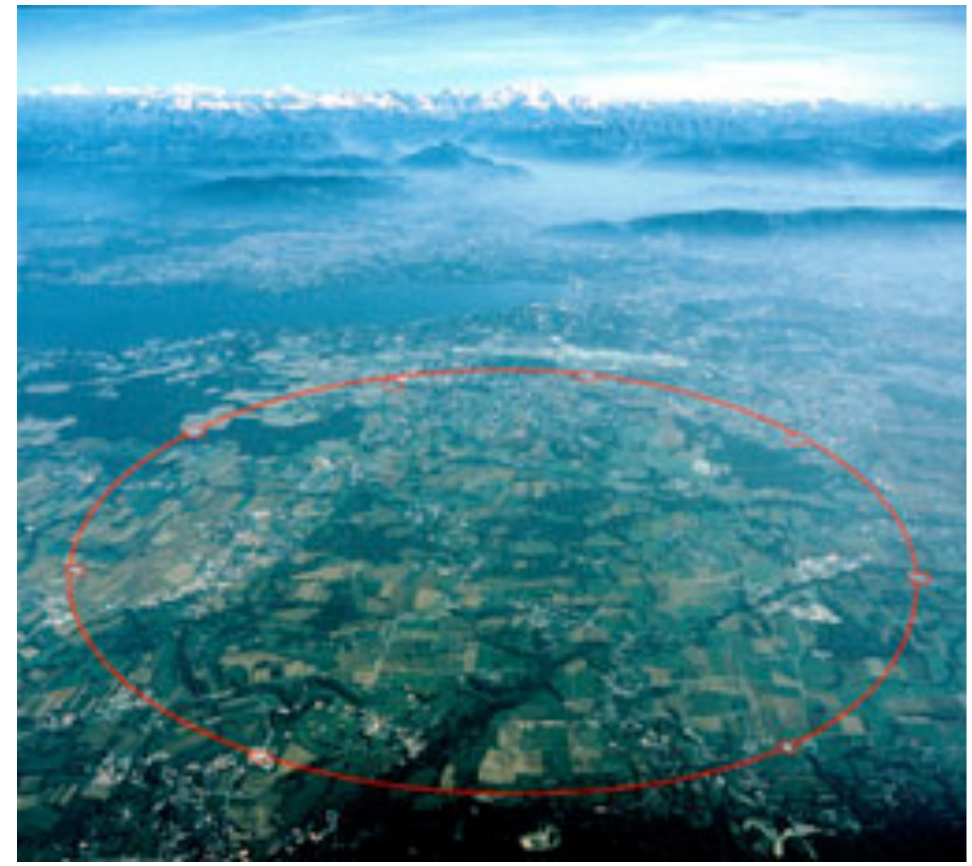
calc: Gale, et al. PRL 110 012302 (2013)

# Heavy Ions @ RHIC & the LHC

RHIC

200 GeV max collision energy

LHC



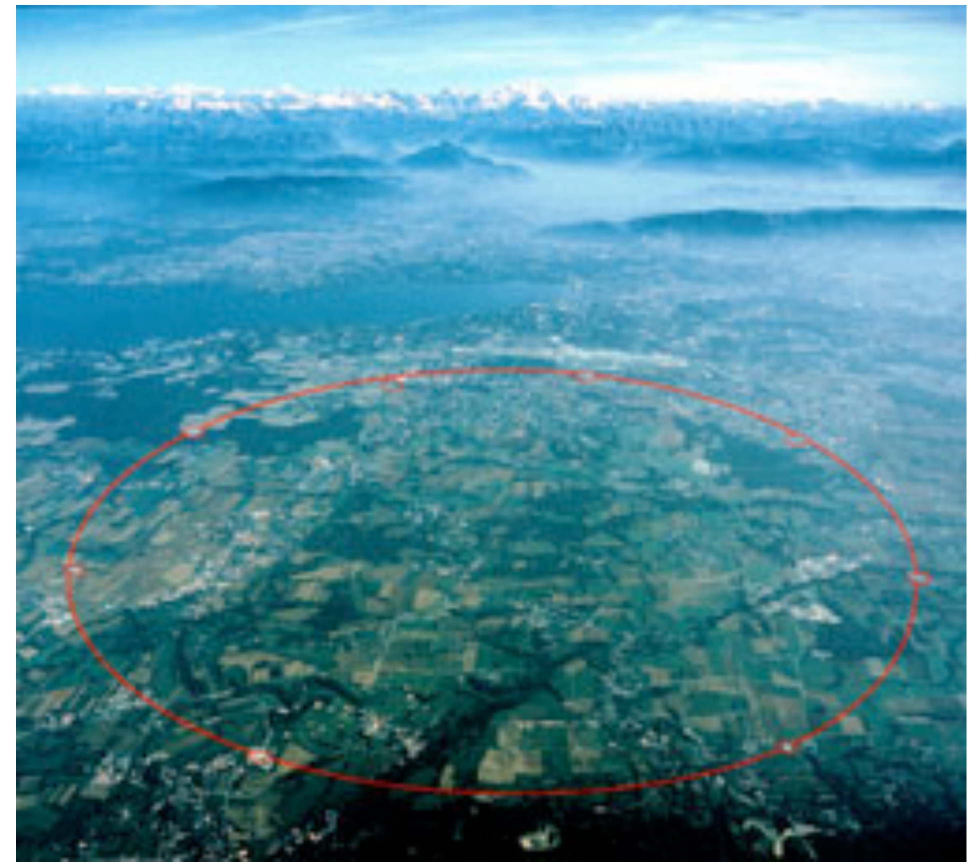
2.76 TeV max collision energy

# Heavy Ions @ RHIC & the LHC

RHIC

200 GeV max collision energy

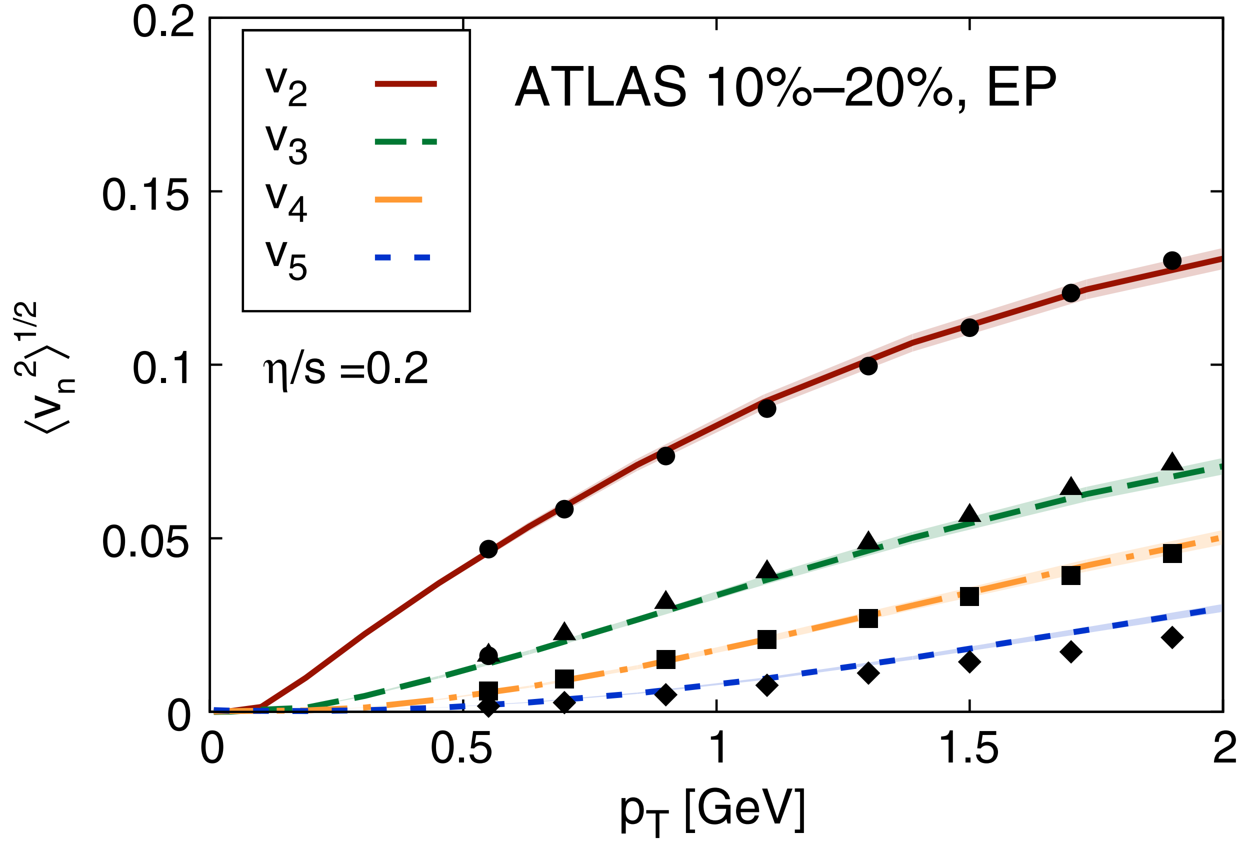
LHC



2.76 TeV max collision energy

question: how does $\eta/s$ change with temperature?

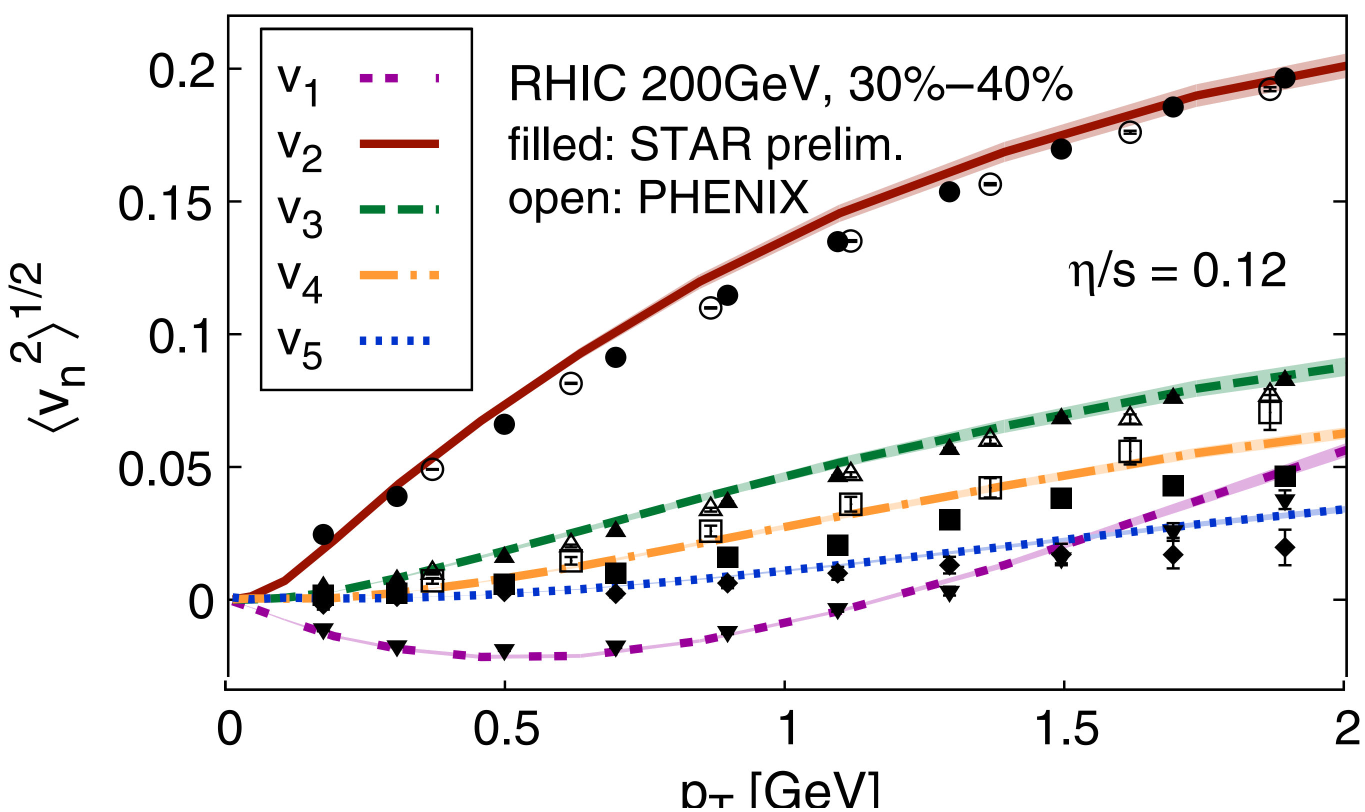
# state of the art hydrodynamic calculations

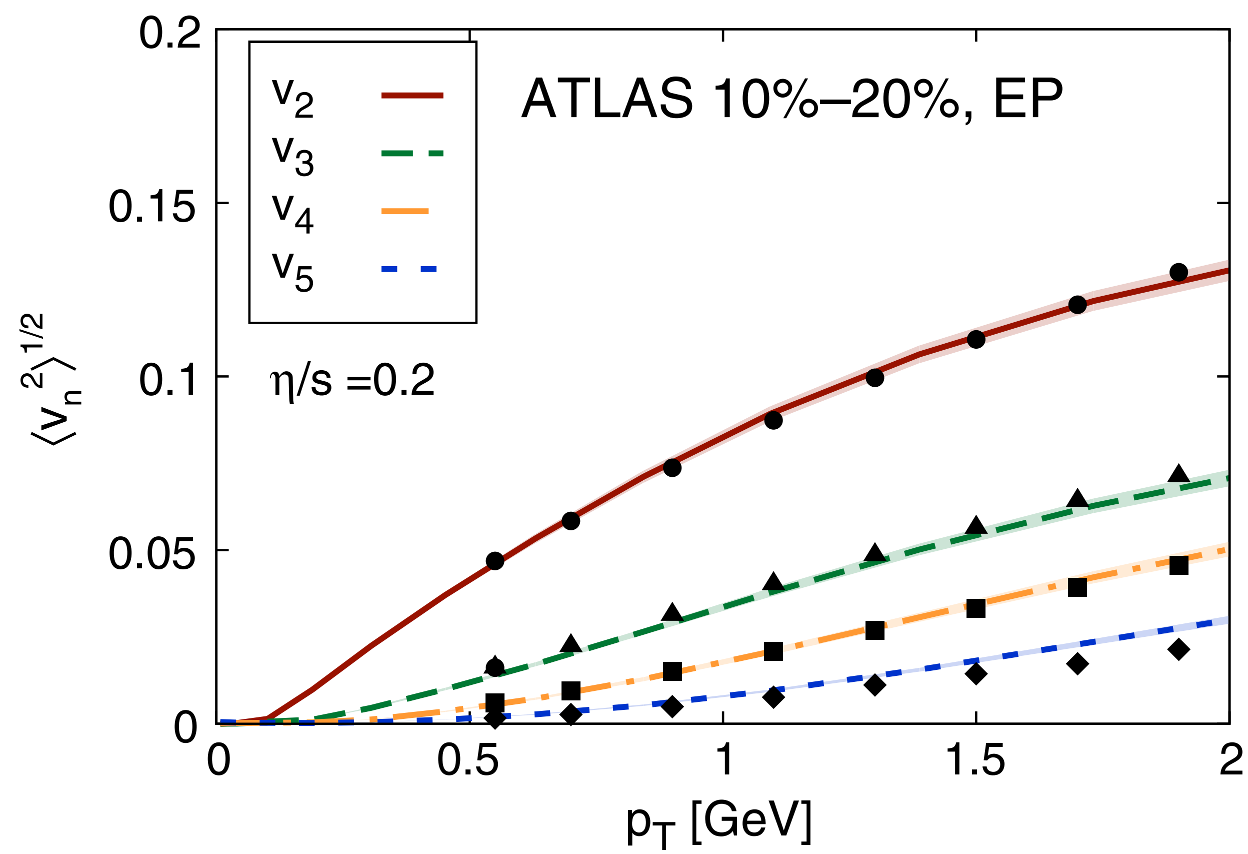



LHC: $\eta/s = 2.5 / 4\pi$

Gale, Jeon, Schenke, Tribedy, Venugopalan PRL 110 012302

# state of the art hydrodynamic calculations



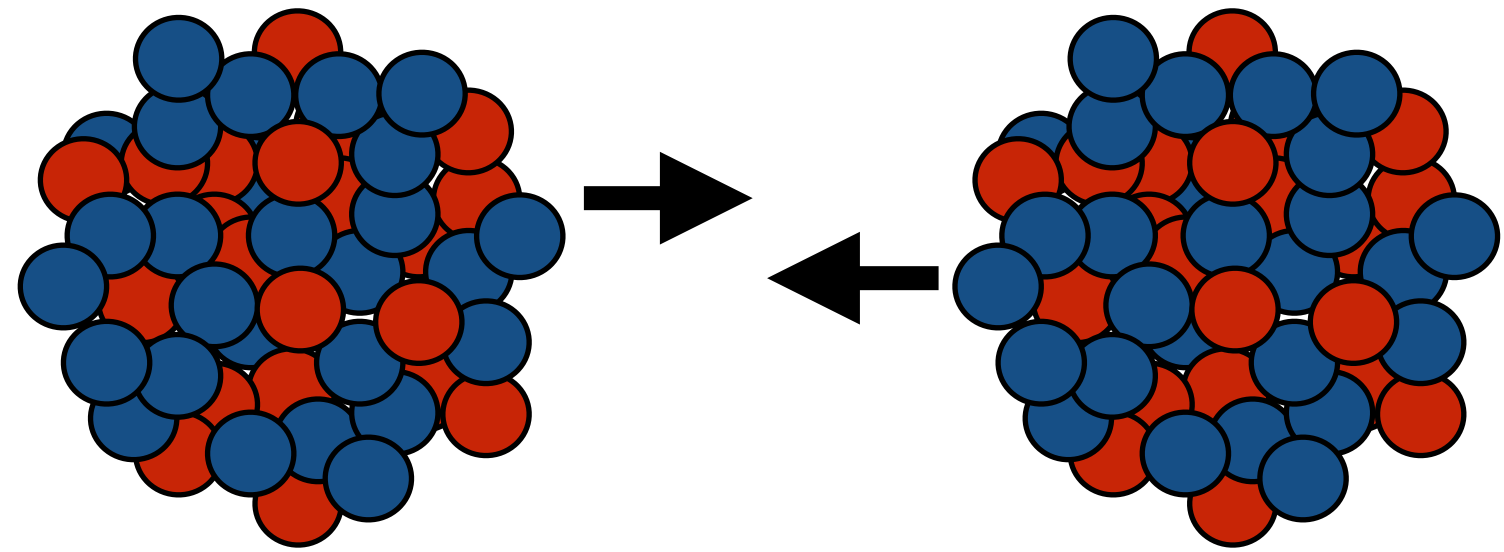




RHIC: $\eta/s = 1.5 / 4\pi$ LHC: $\eta/s = 2.5 / 4\pi$

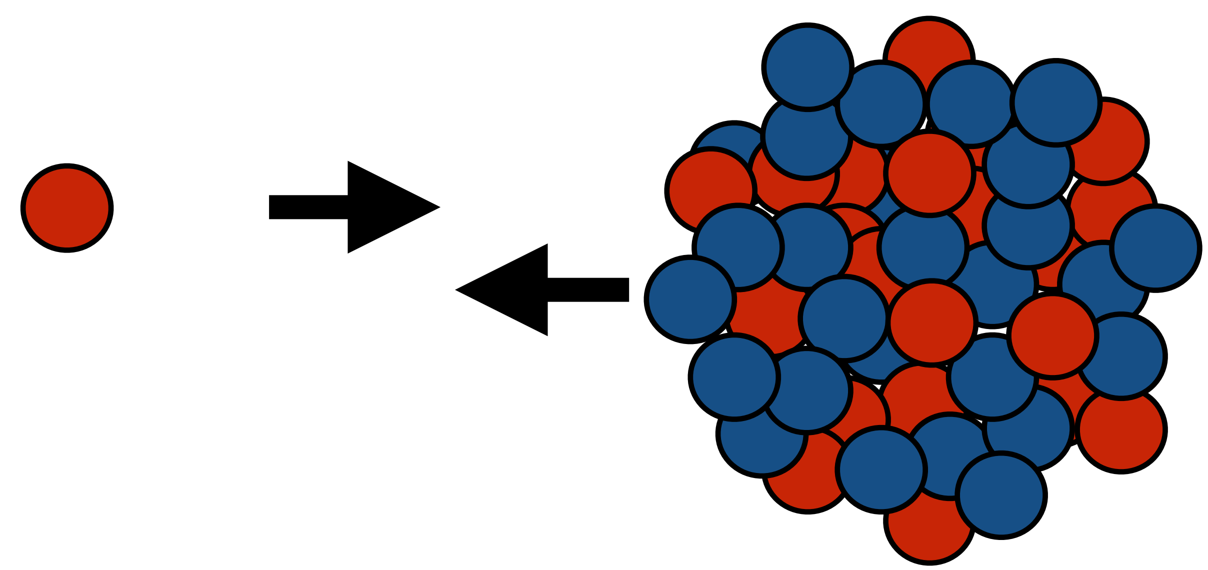
Gale, Jeon, Schenke, Tribedy, Venugopalan PRL 110 012302

# outline

collide heavy nuclei: create & study hot deconfined QCD: the quark gluon plasma



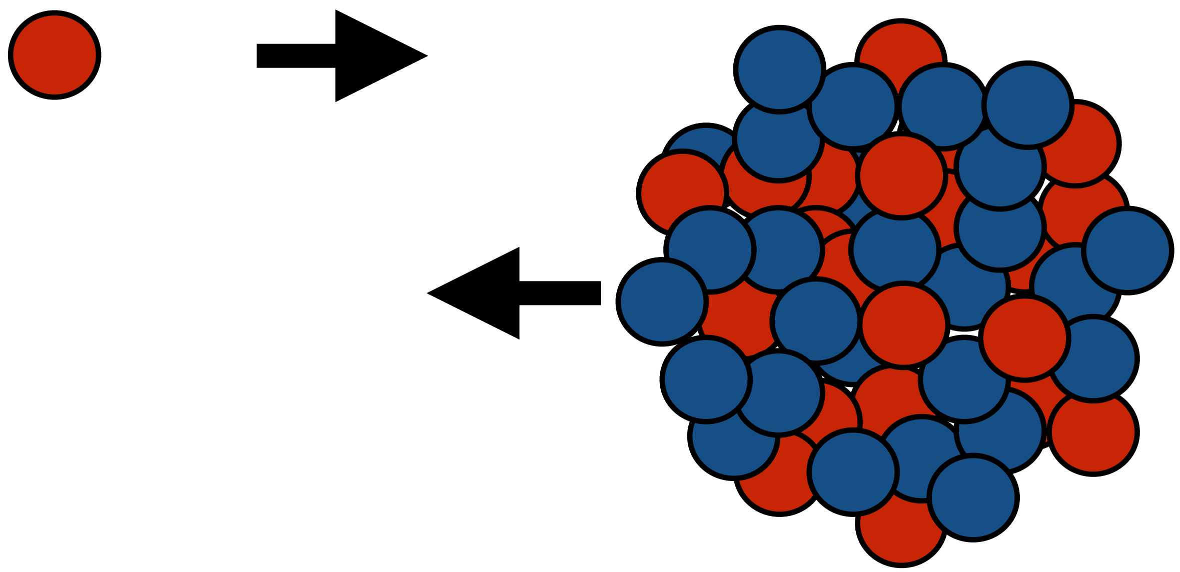
highly asymmetric collisions: turn off the plasma, study the nucleus

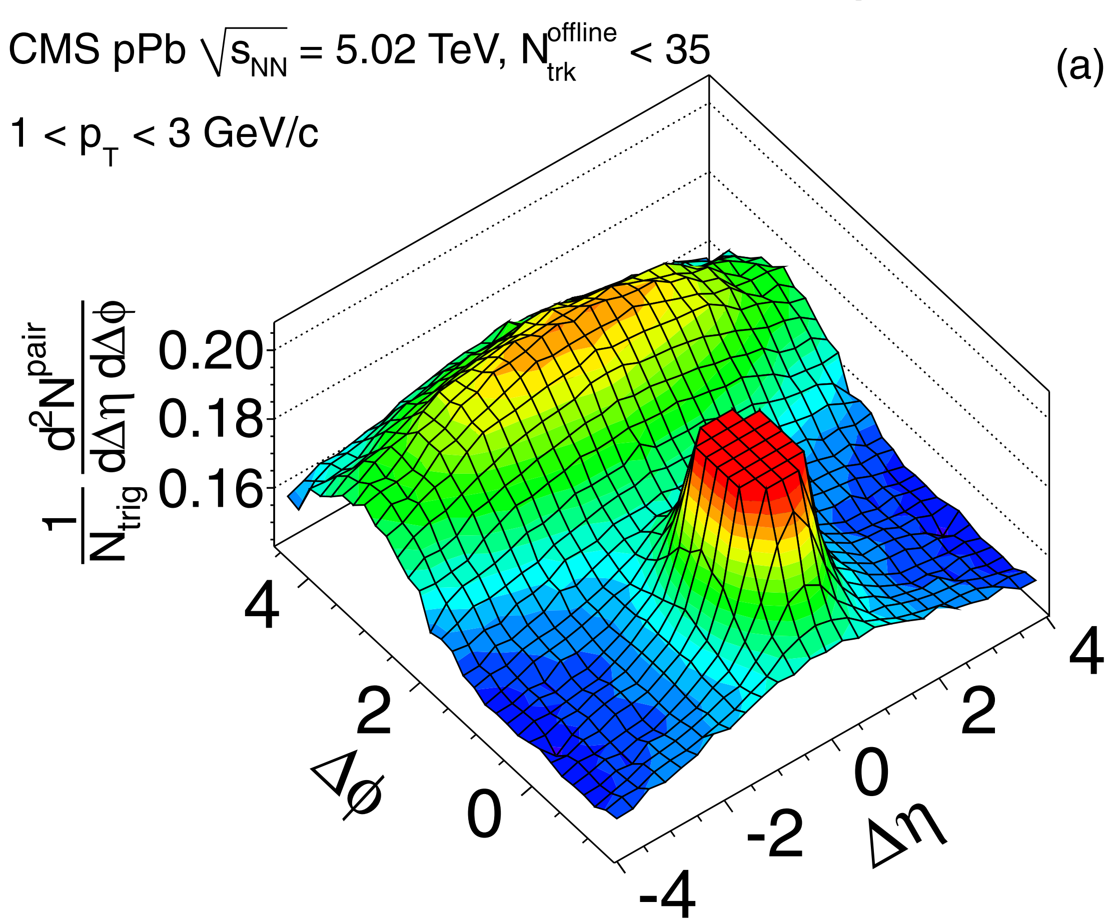


or maybe not…

# p-A collisions

peripheral collisions



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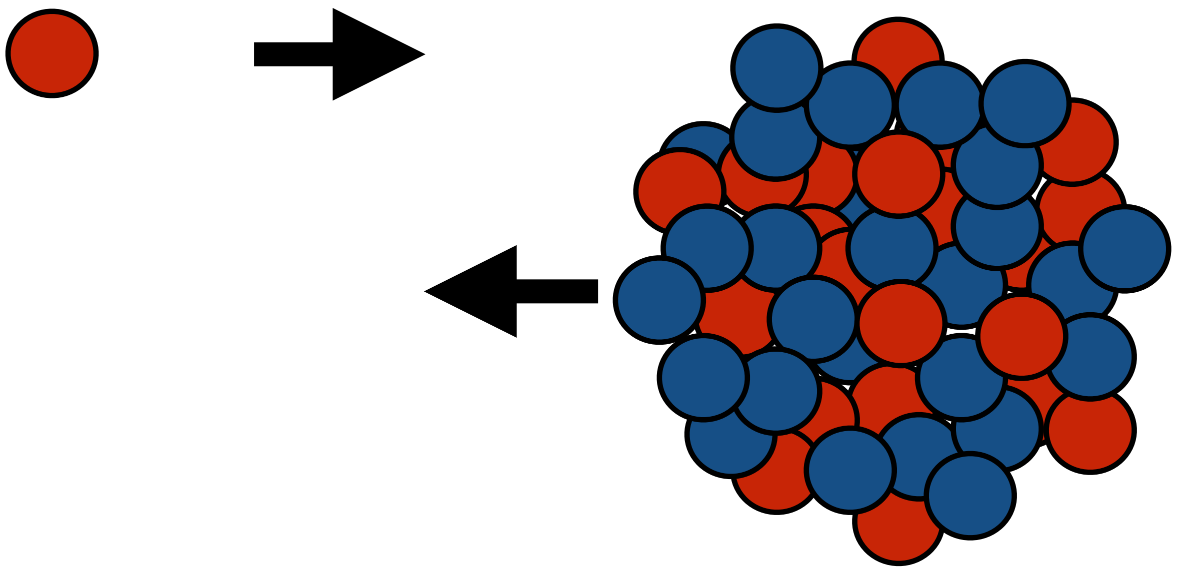
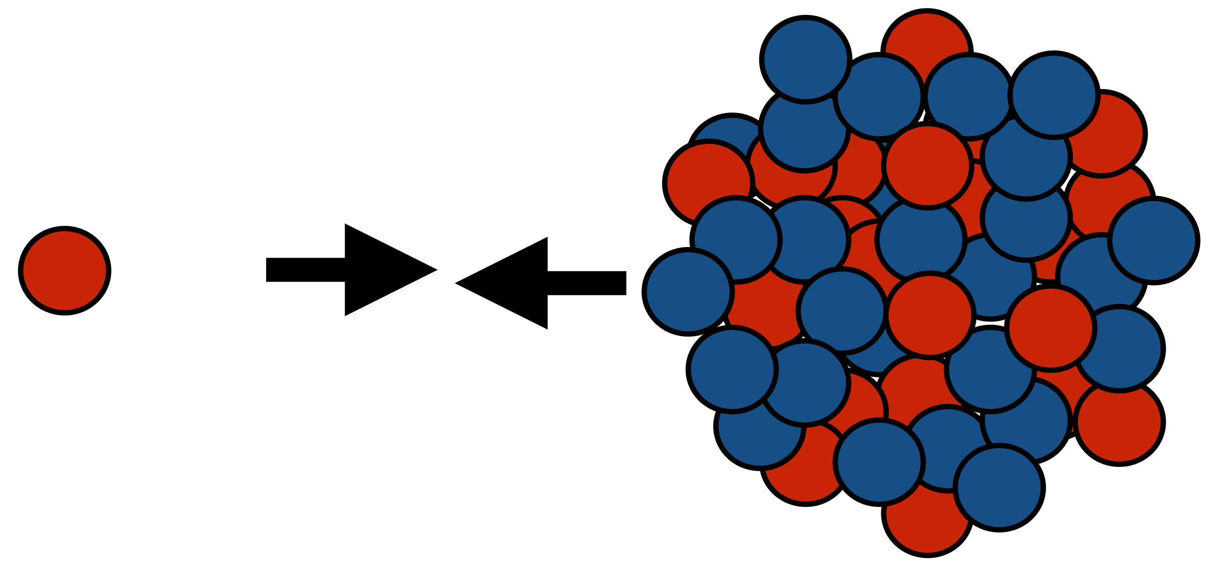
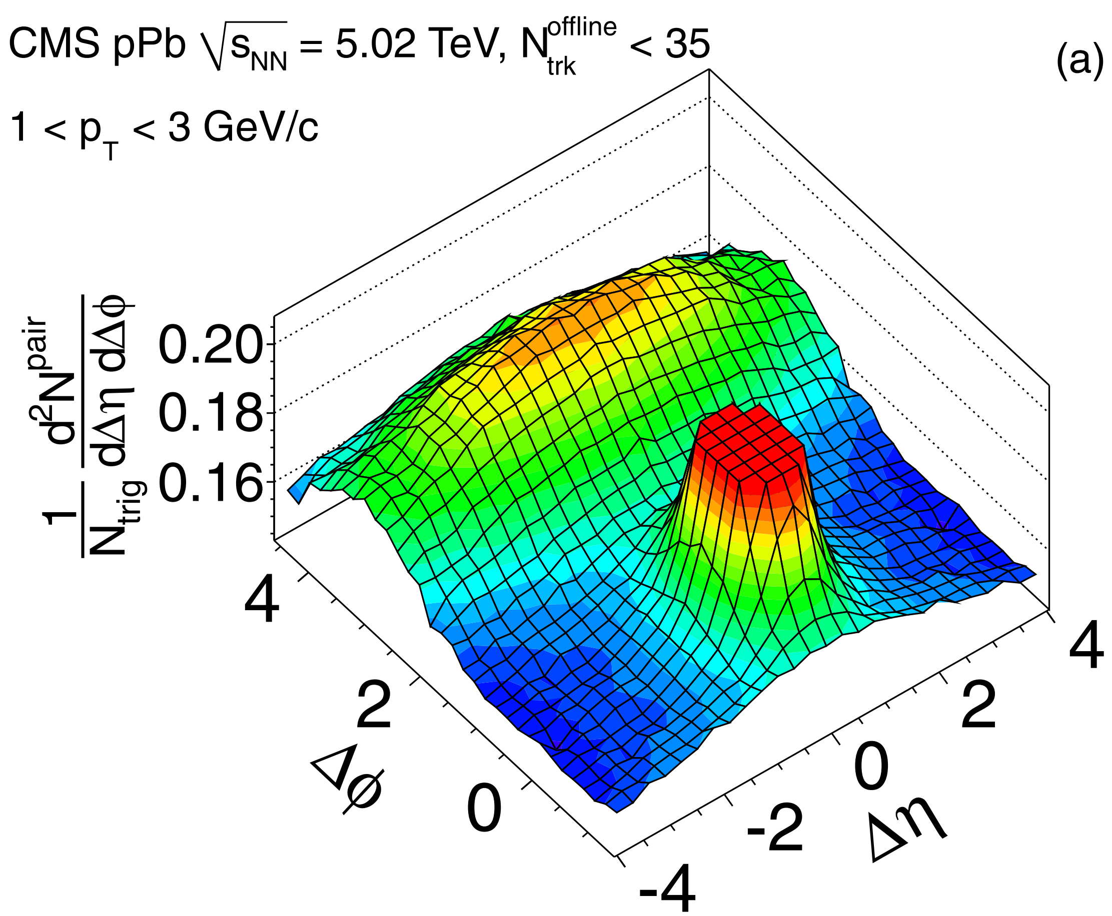
# p-A collisions

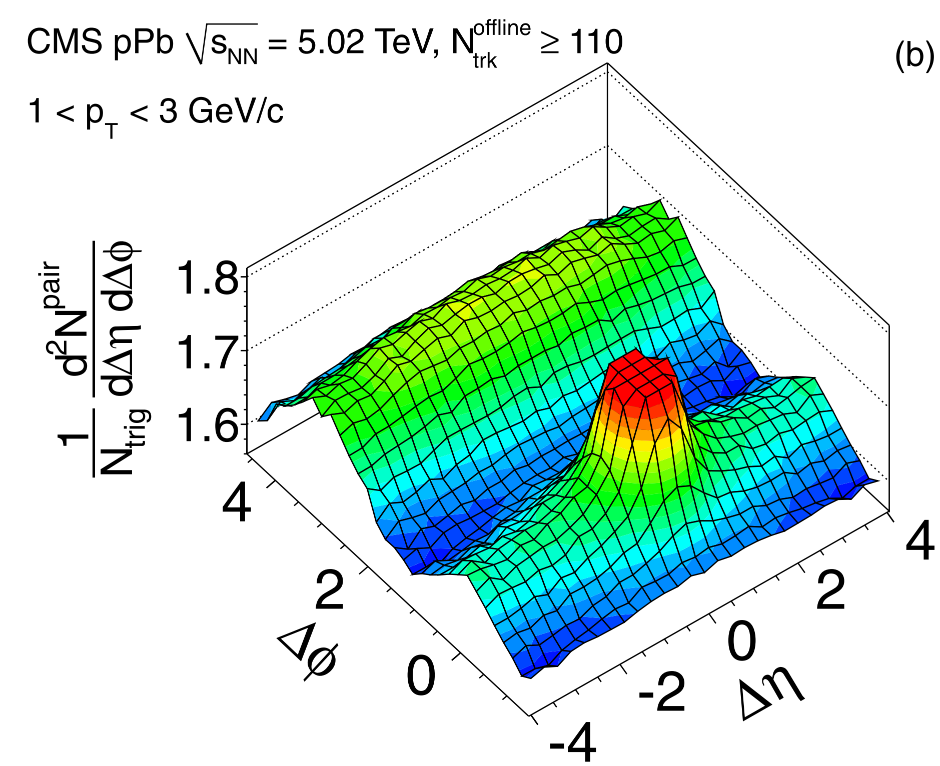
## peripheral collisions



## central collisions



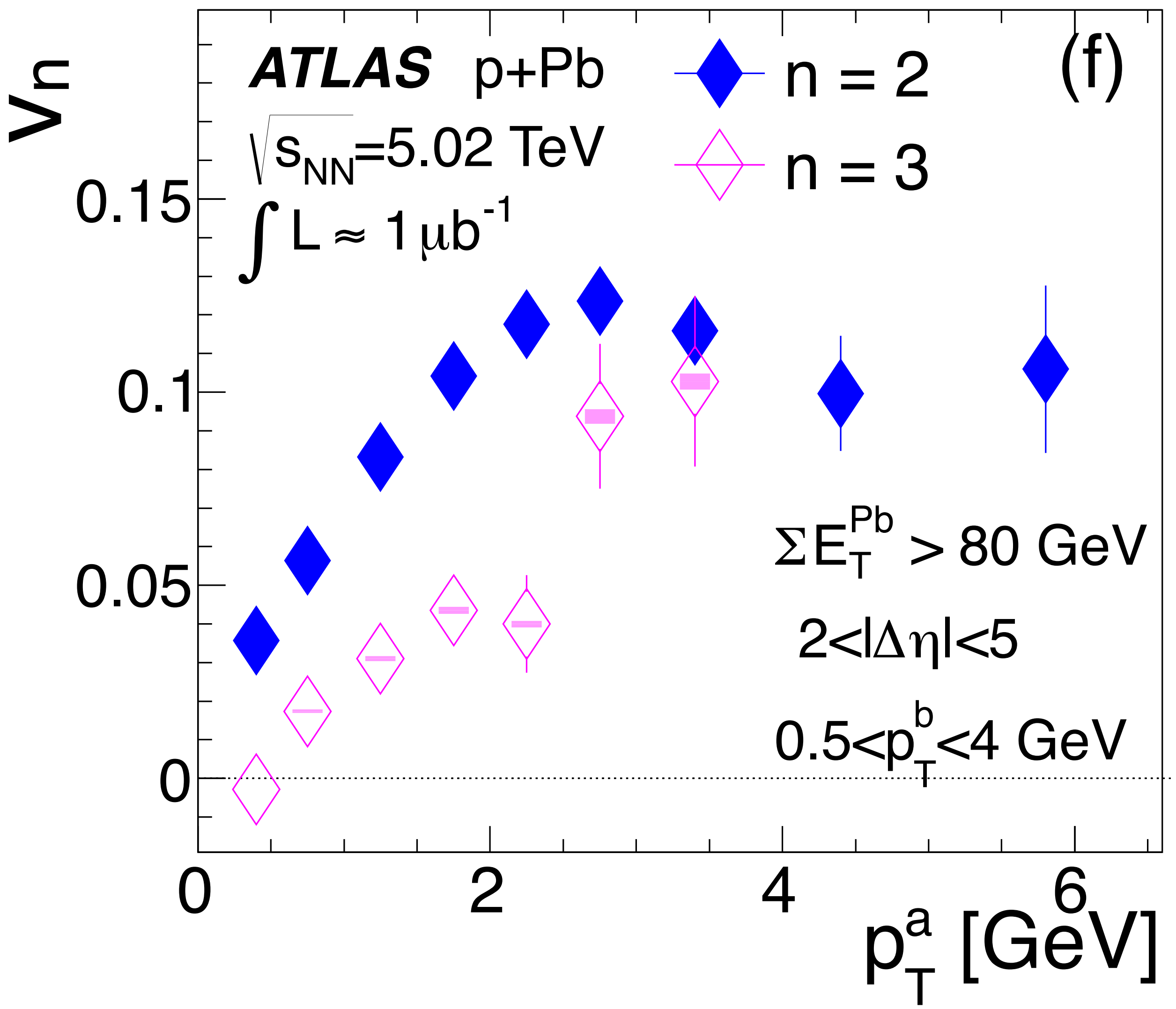



CMS PLB 718 795 (2013)

# $v_2$ & v3 in pPb collisions

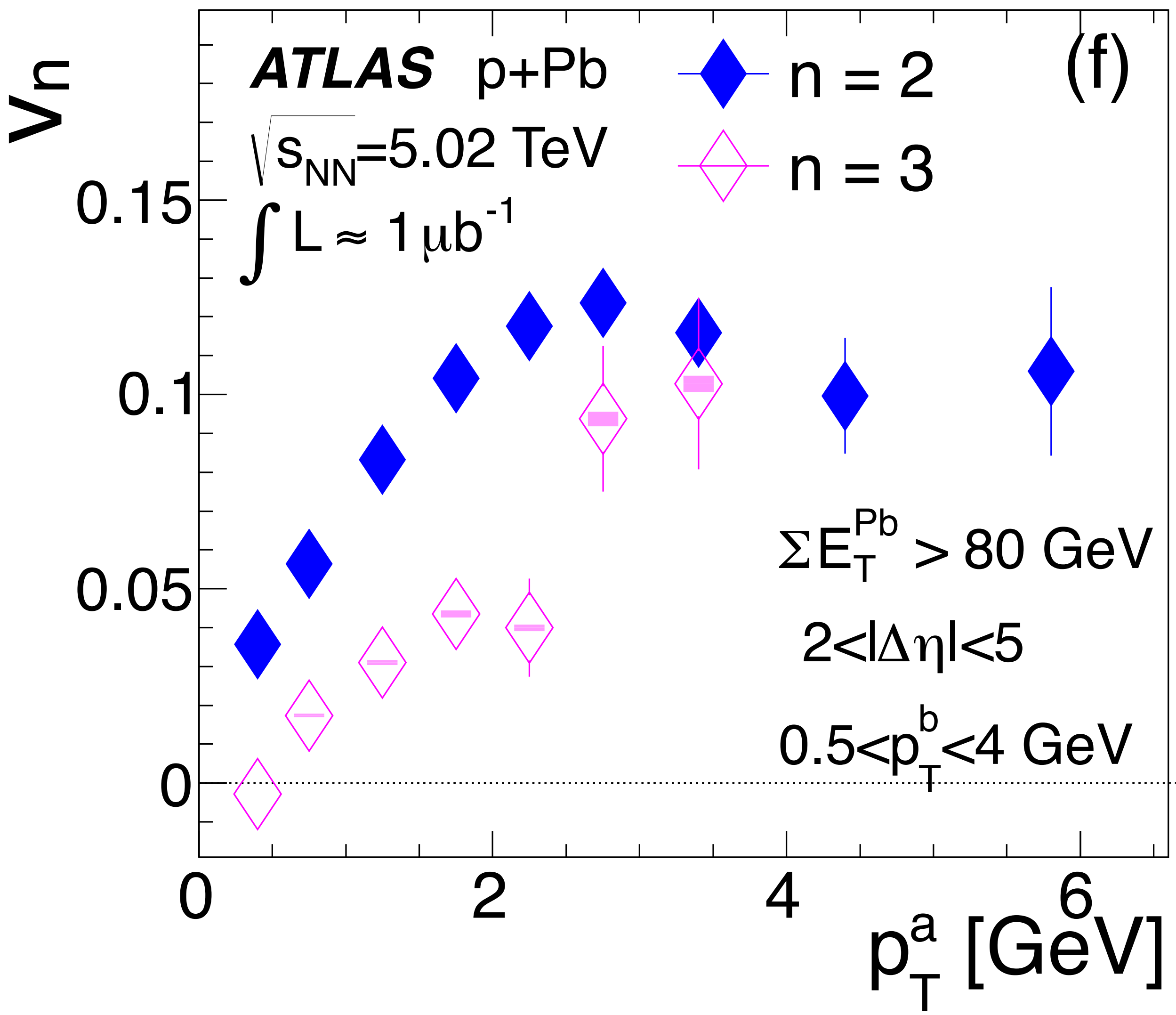
pPb



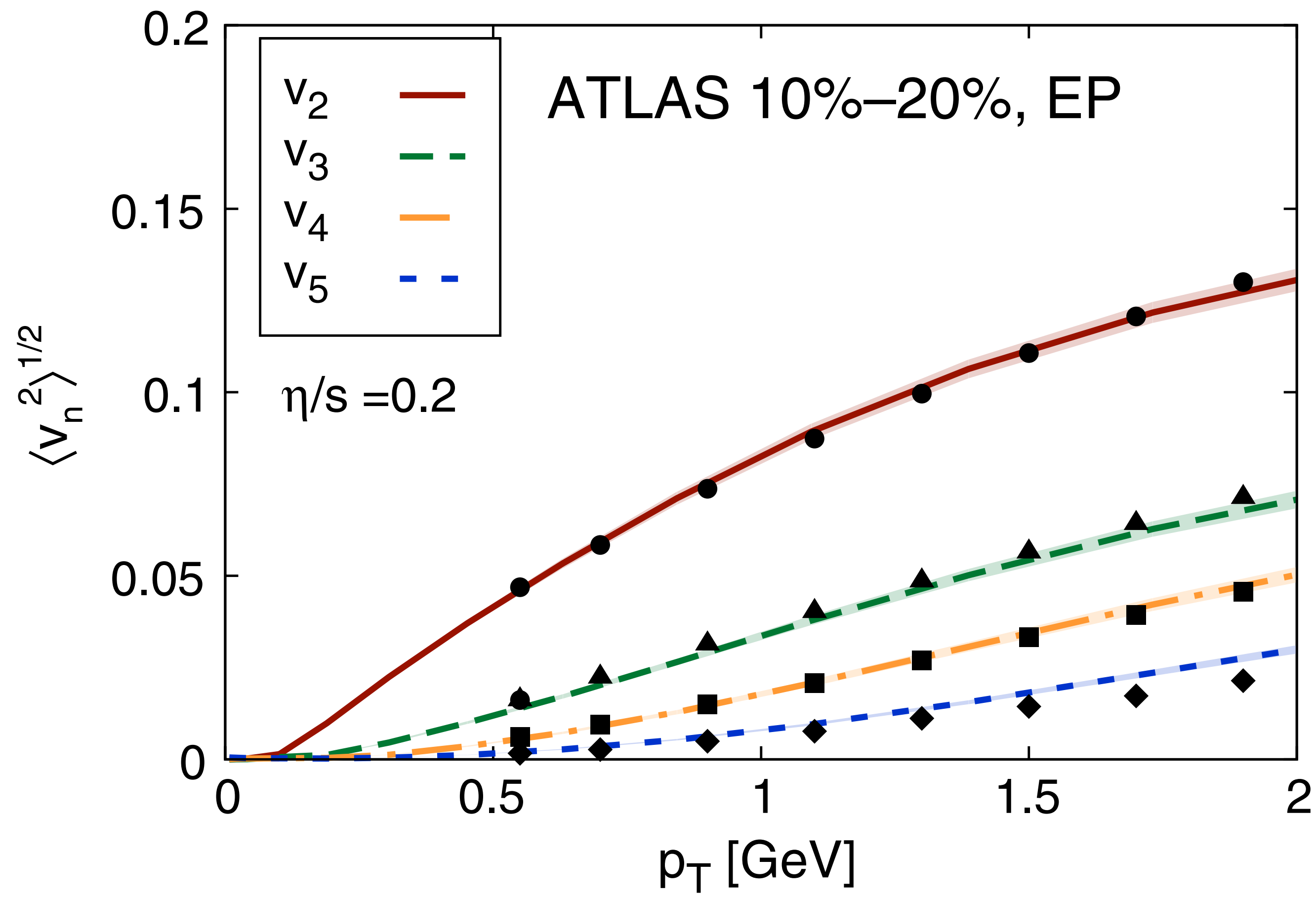

ATLAS PRL 110 102303

# $v_2$ & v3 in pPb collisions

pPb




PbPb

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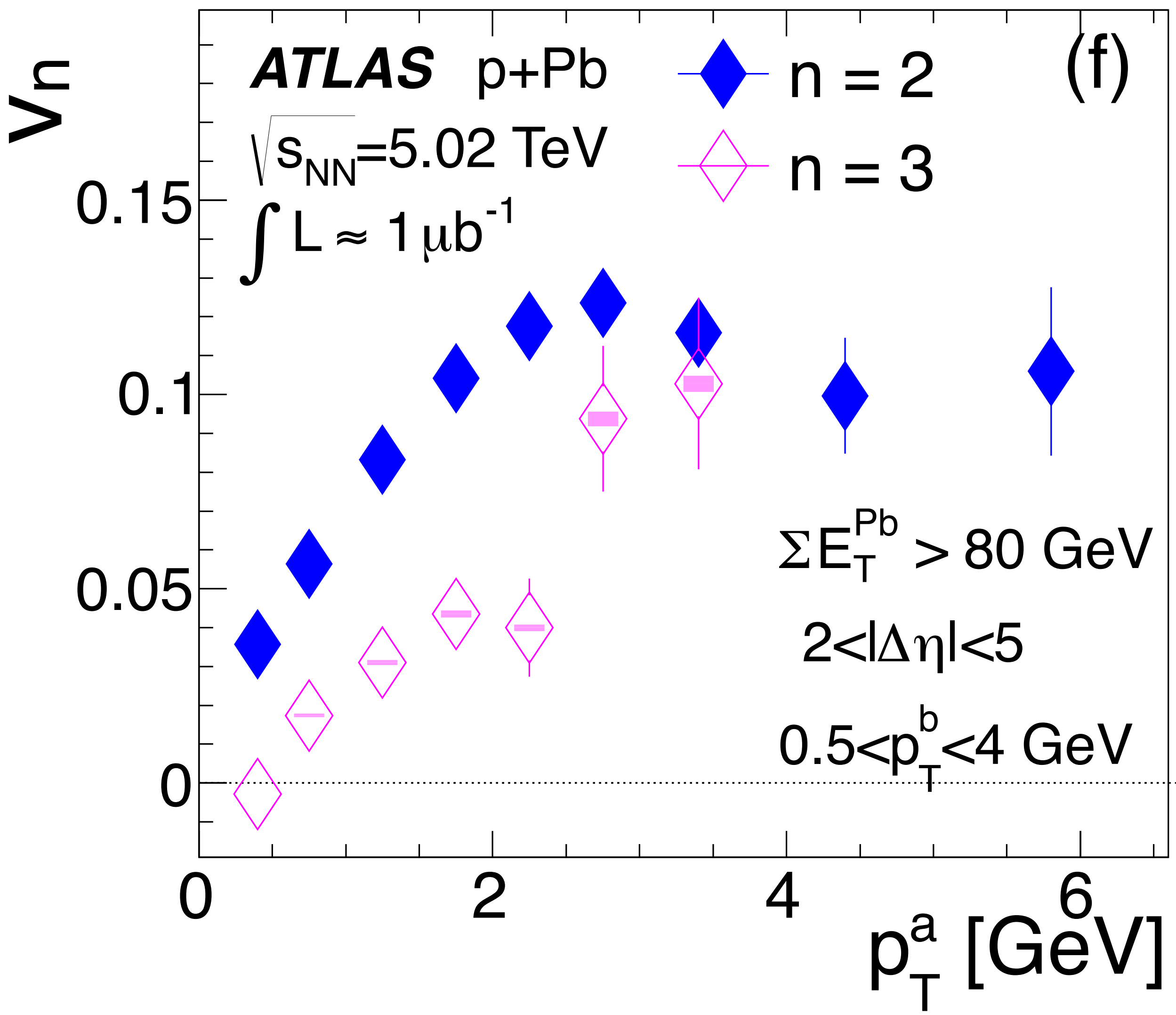
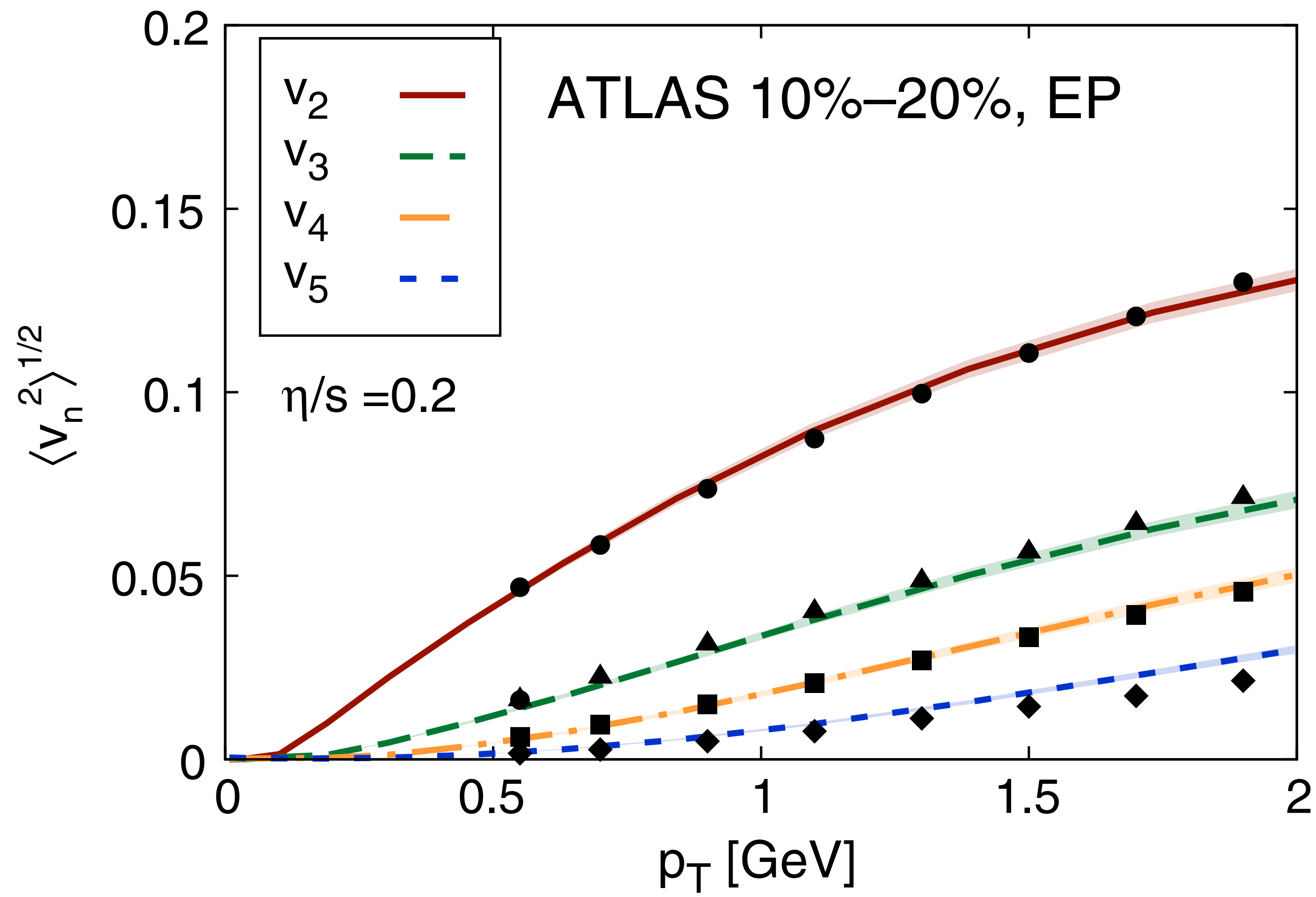
# $v_2$ & v3 in pPb collisions

## pPb




## PbPb




$v_2$ & $v_3$ very similar between pPb & PbPb! do they have a common origin?

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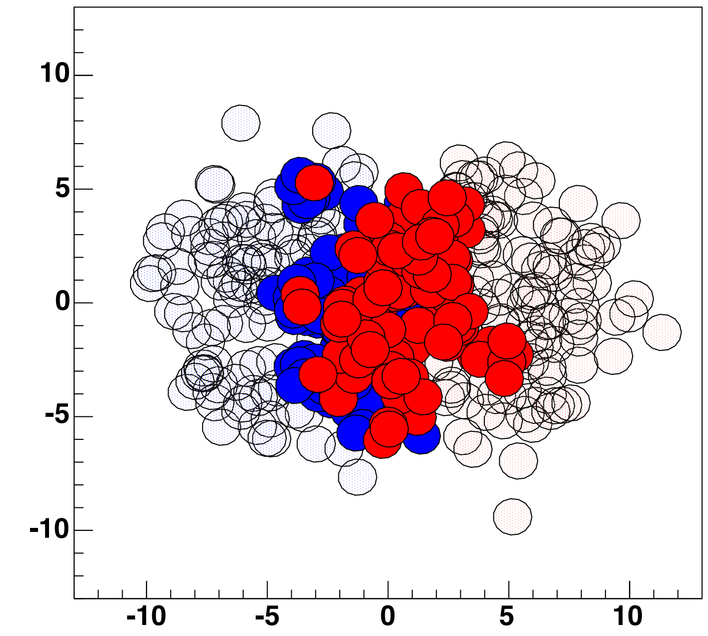
# geometry in AA & pA

AA

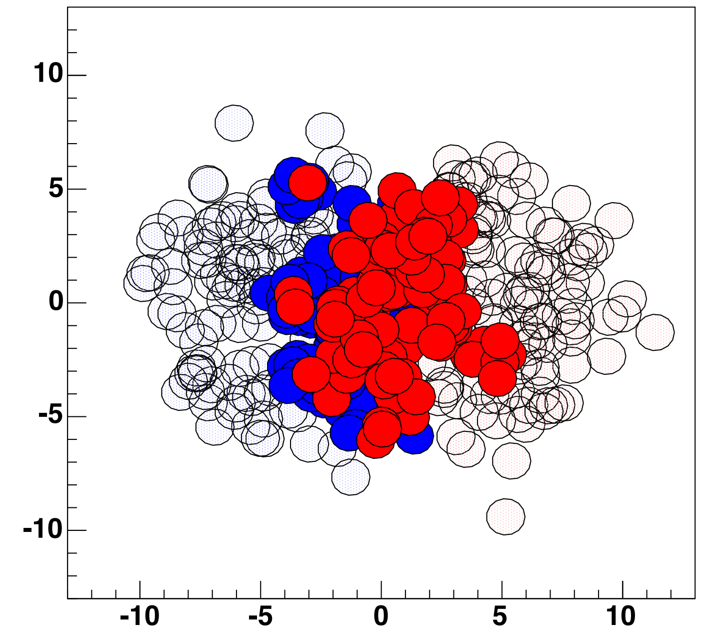
geometry
& fluctuations



# geometry in AA & pA

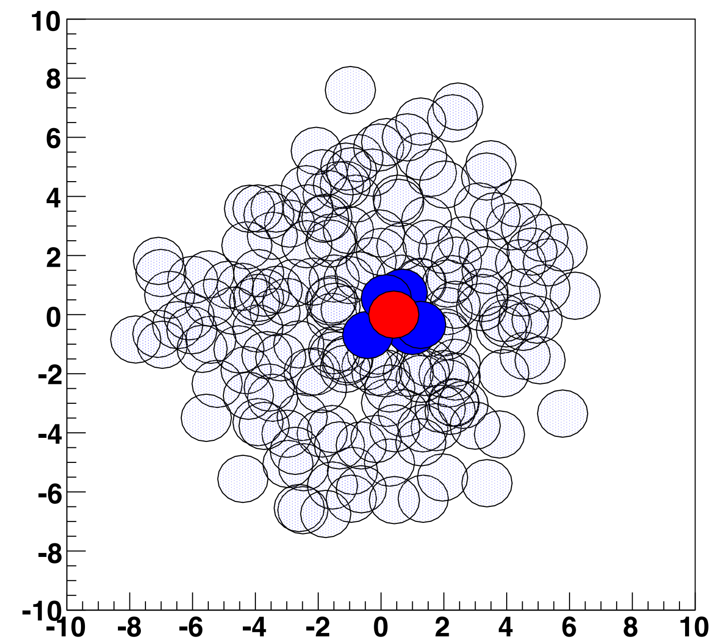
AA

geometry
& fluctuations

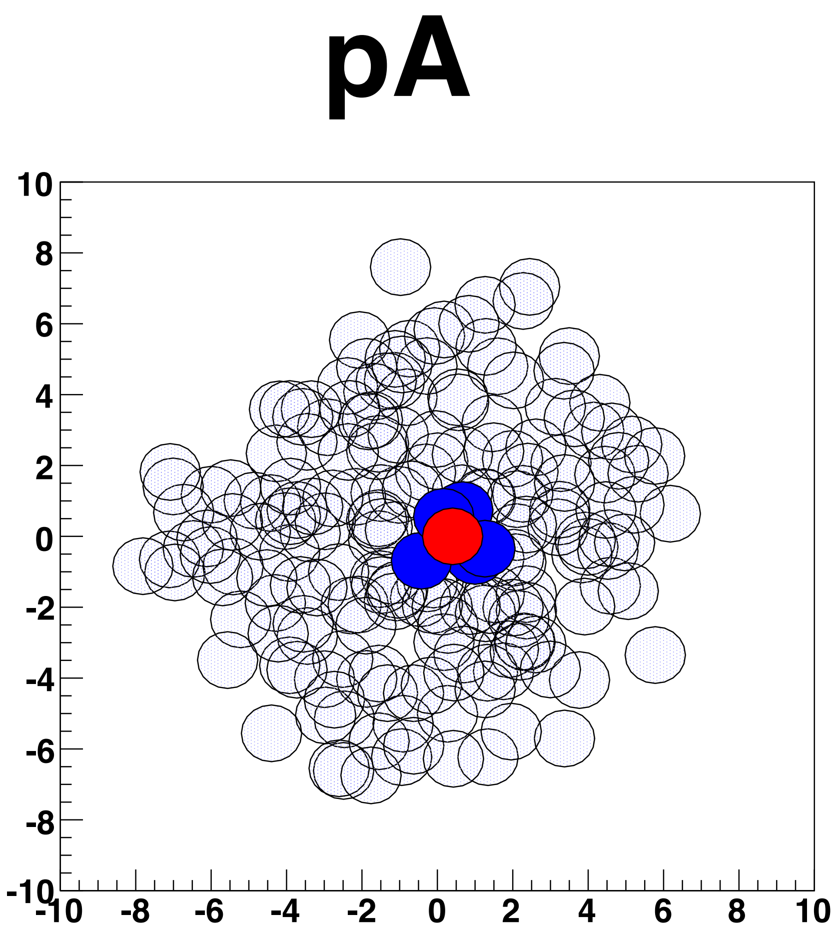


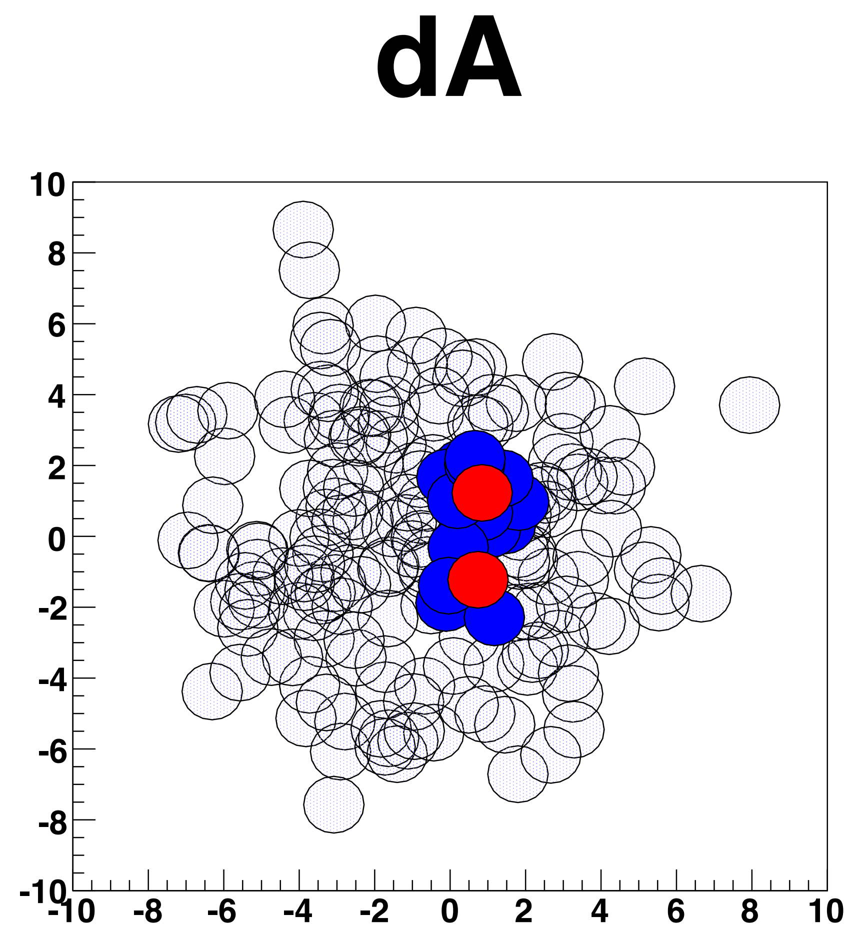

pA

fluctuations

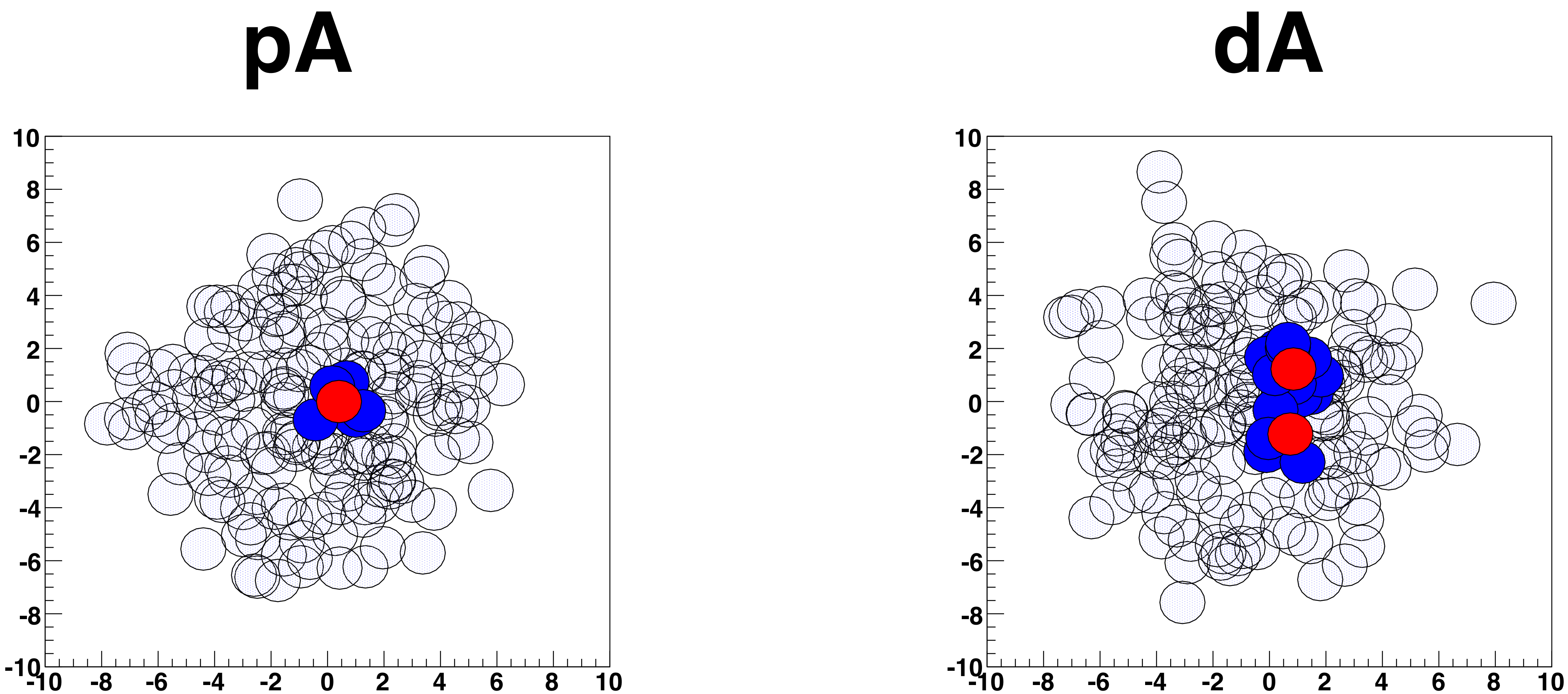


# adding geometry to pA



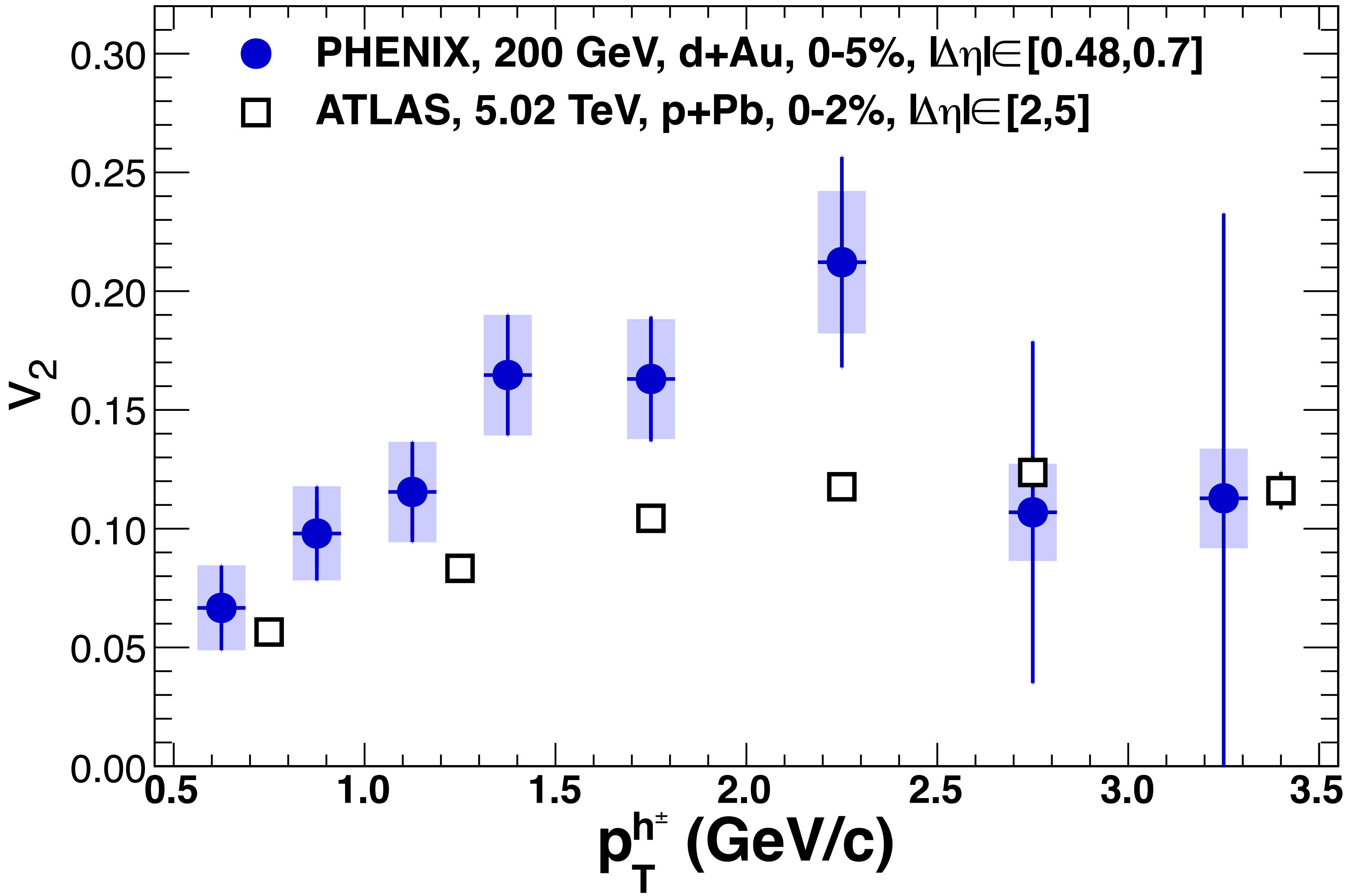



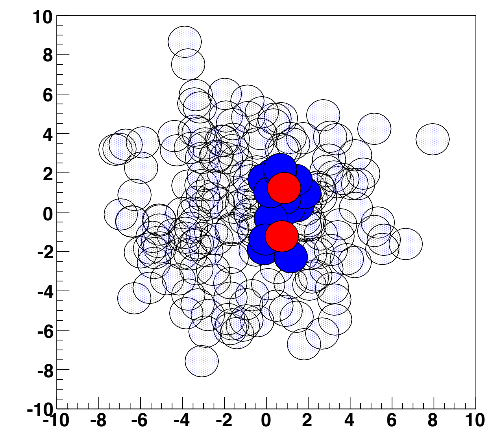
# adding geometry to pA

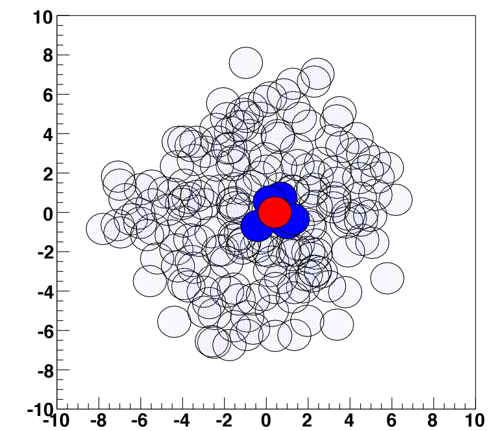



now test whether the $v_2$ observed is related to geometry

# v2: pPb & dAu

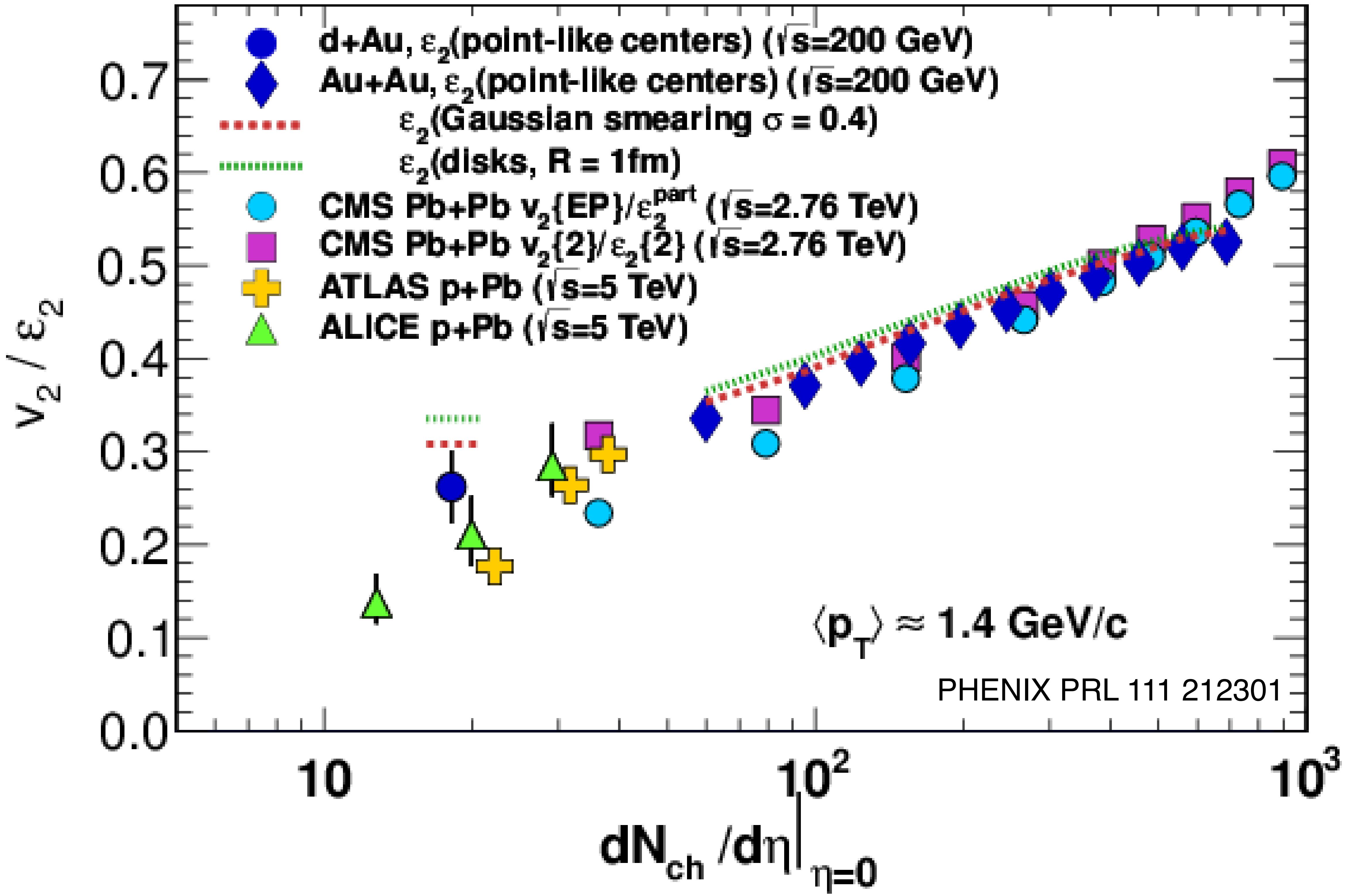




PHENIX PRL 111 212301 (2013)
ATLAS PRL 110 182302 (2013)

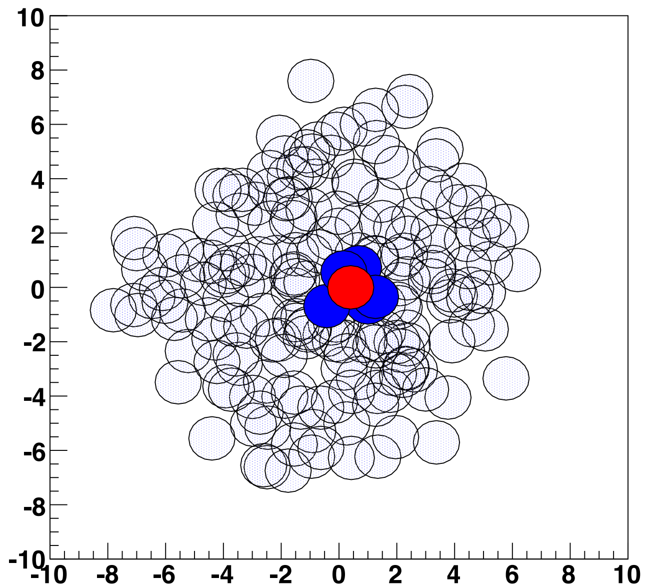
# dAu, pPb, AuAu & PbPb



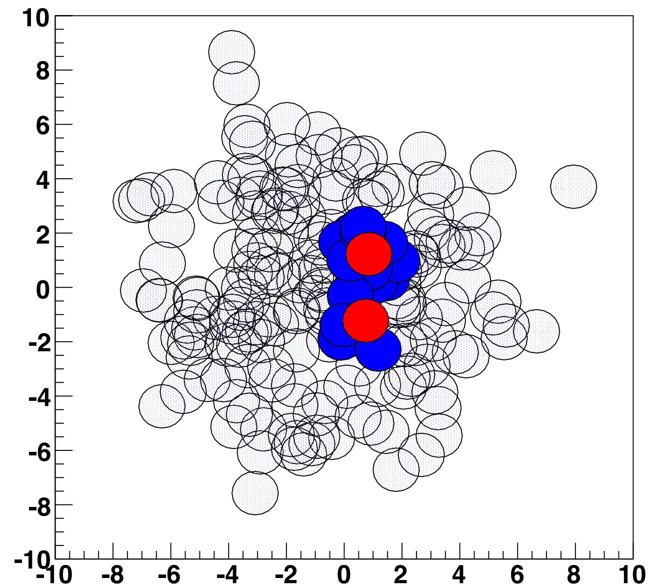

single trend, AA data understood as initial geometry + hydrodynamics

# variation of the small nucleus

pA

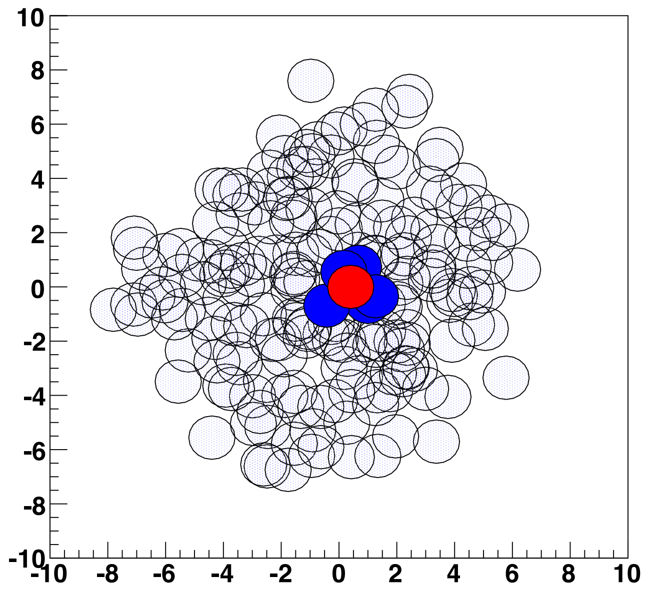



dA

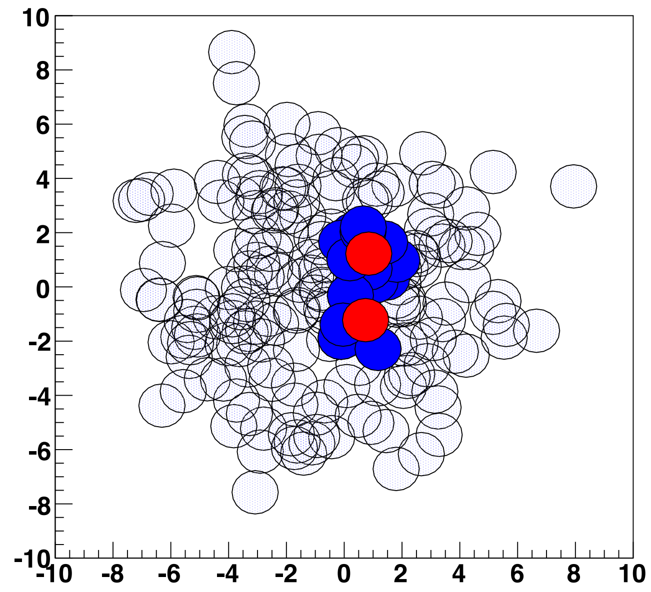


# variation of the small nucleus

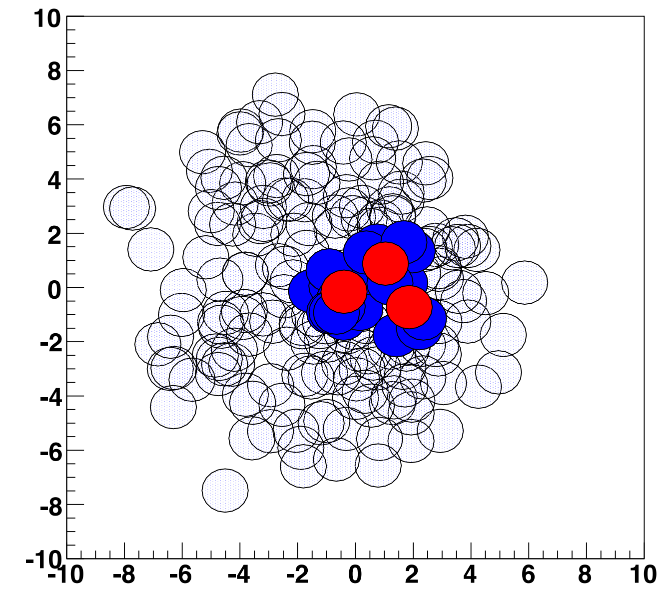
pA




dA




$^3$HeA



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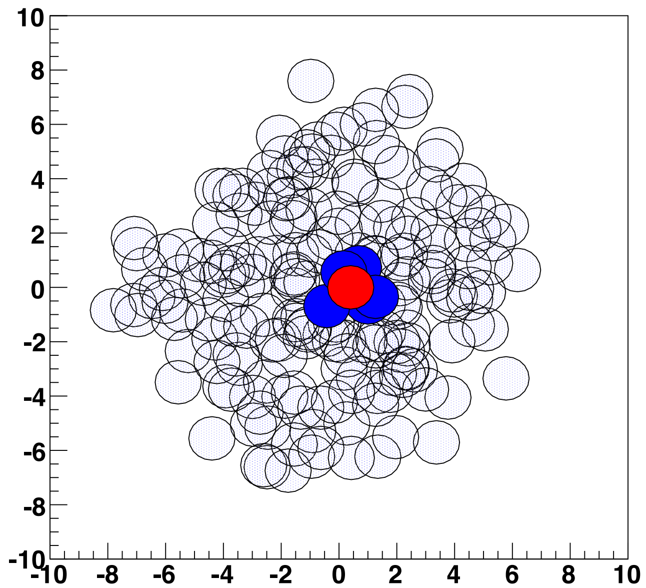
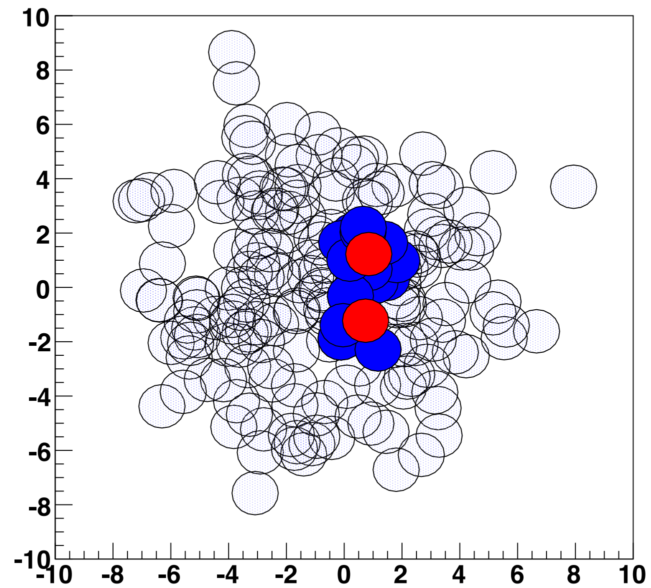
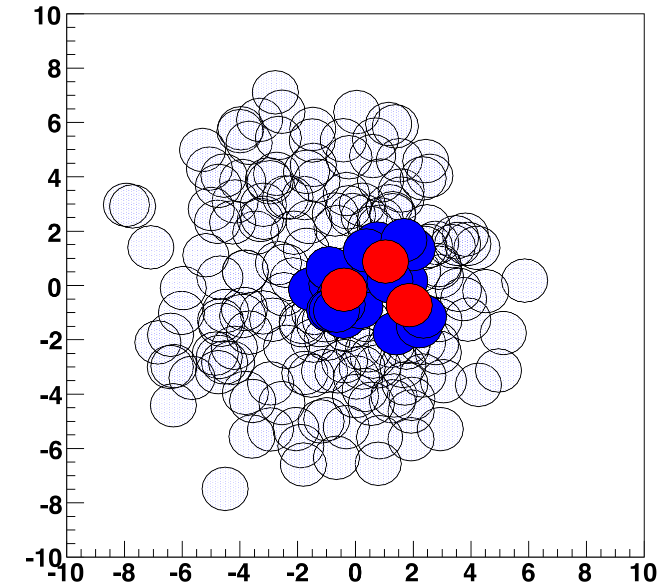
pA




dA



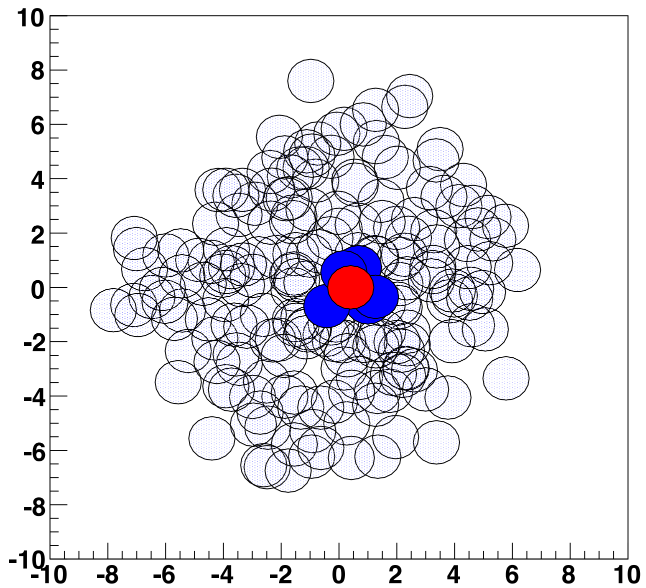

$^{3}$HeA



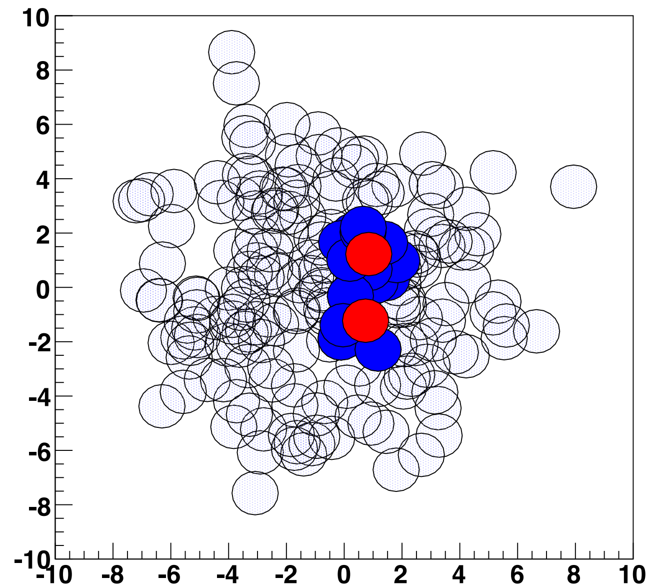

LHC

# variation of the small nucleus

pA




dA

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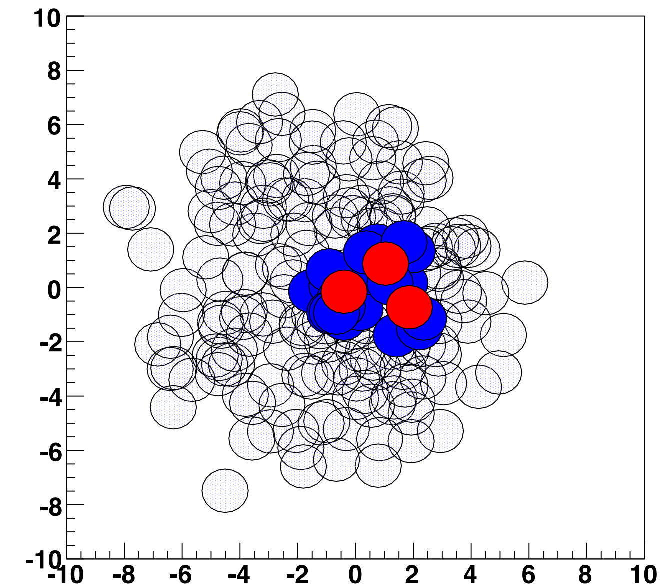
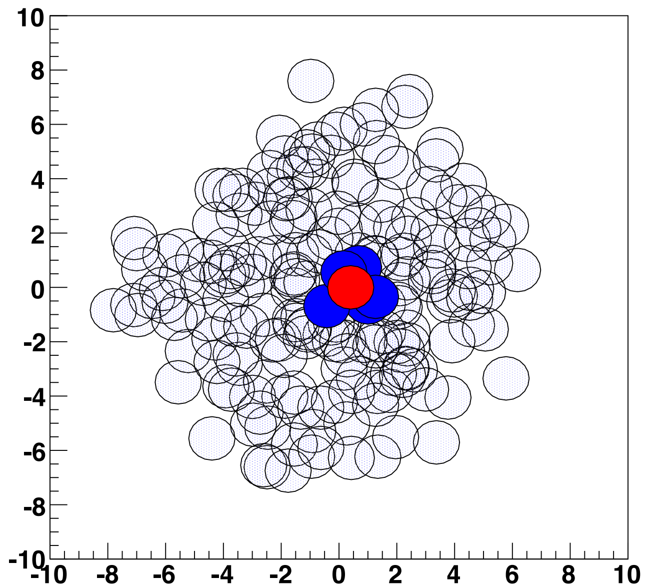



LHC

RHIC

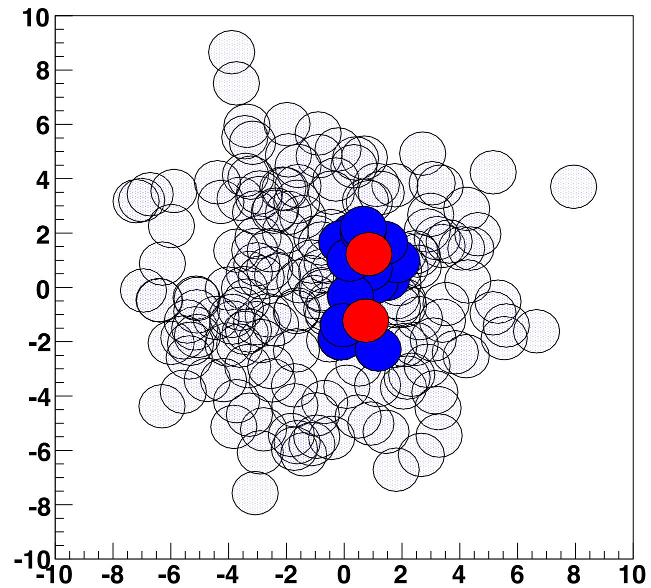
# variation of the small nucleus

pA



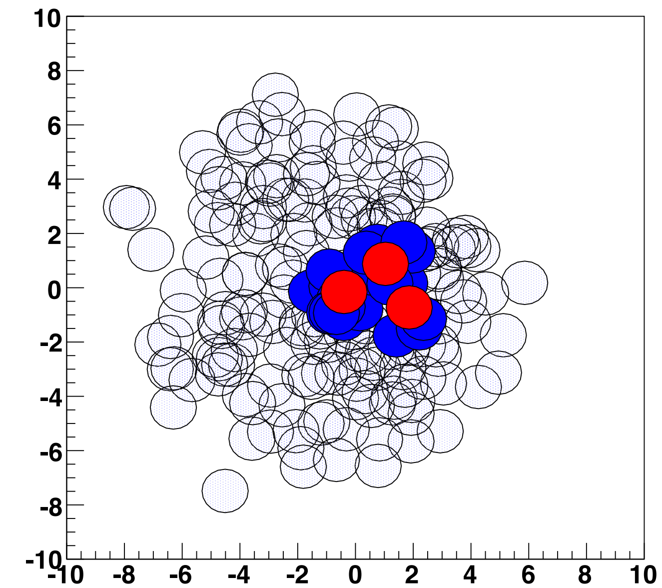

LHC

dA




RHIC

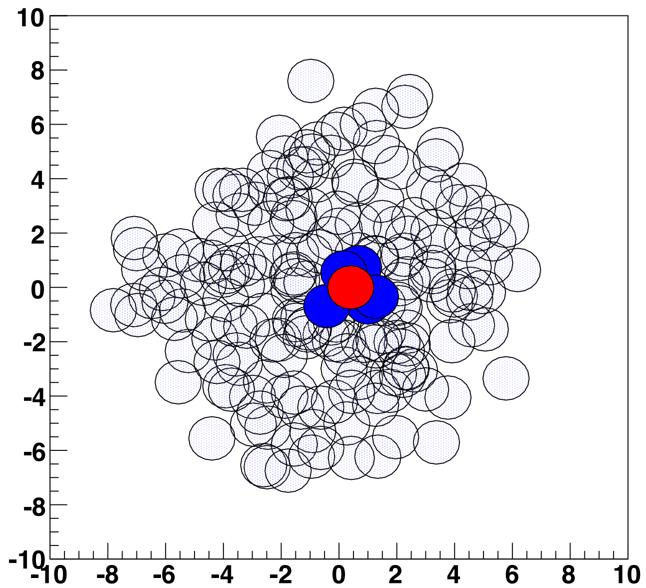
$^3$HeA



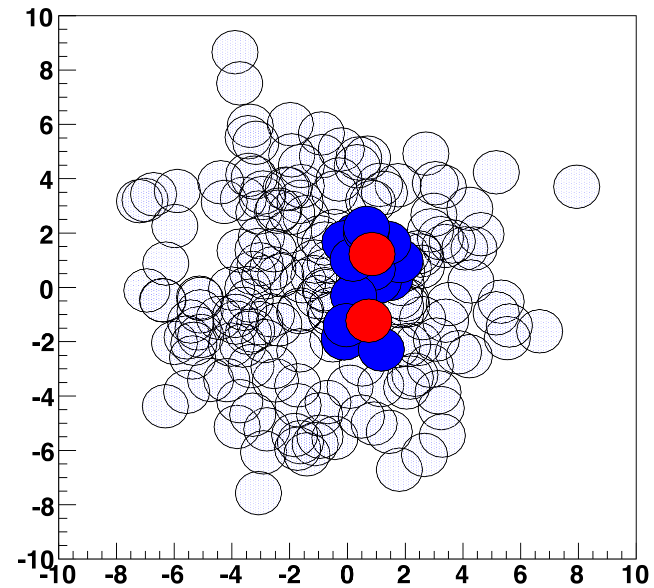

RHIC (6/14)

# variation of the small nucleus

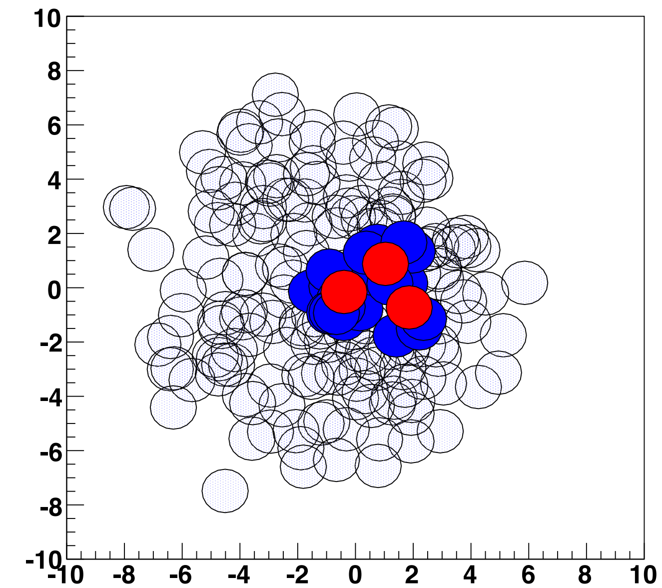
pA




dA




$^3$HeA




LHC

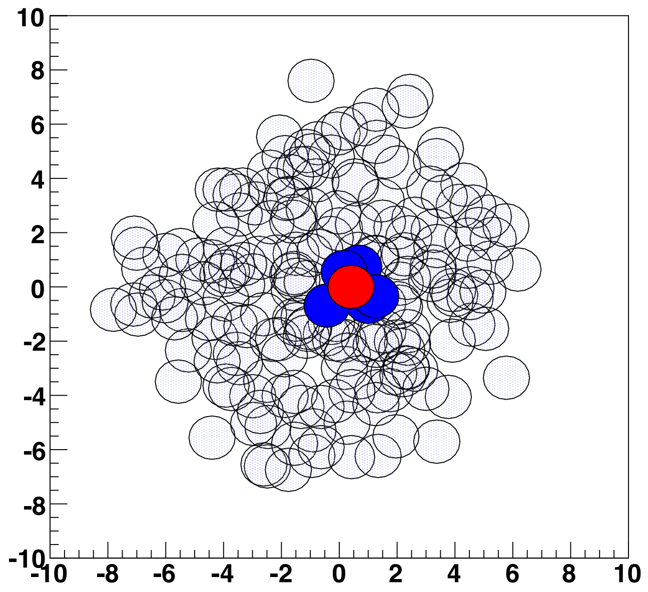
RHIC (1/15)

RHIC

RHIC (6/14)

# variation of the small nucleus

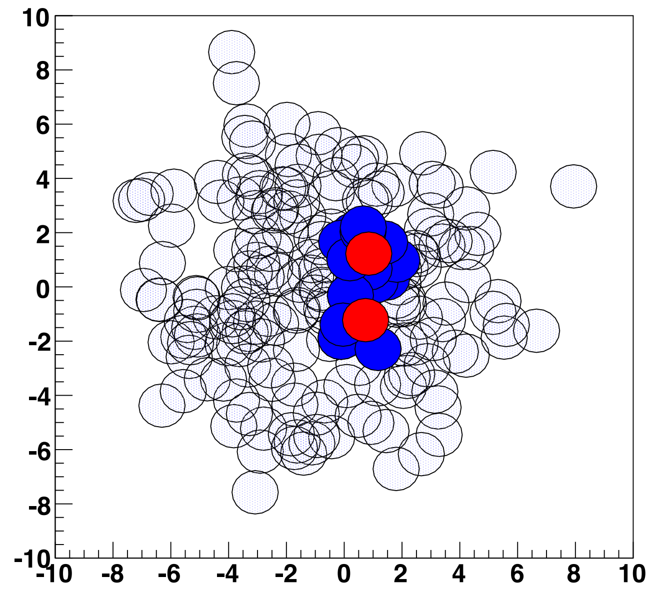
pA




LHC

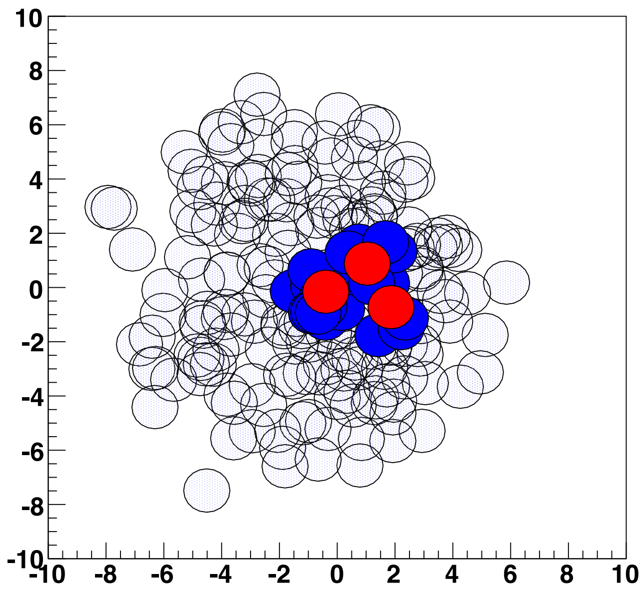
RHIC (1/15)

dA




RHIC

$^3$HeA




RHIC (6/14)

very exciting to engineer the collision geometry in small systems at RHIC in the next few months!

# why is this so important?

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- small scale structures are the most sensitive to viscosity

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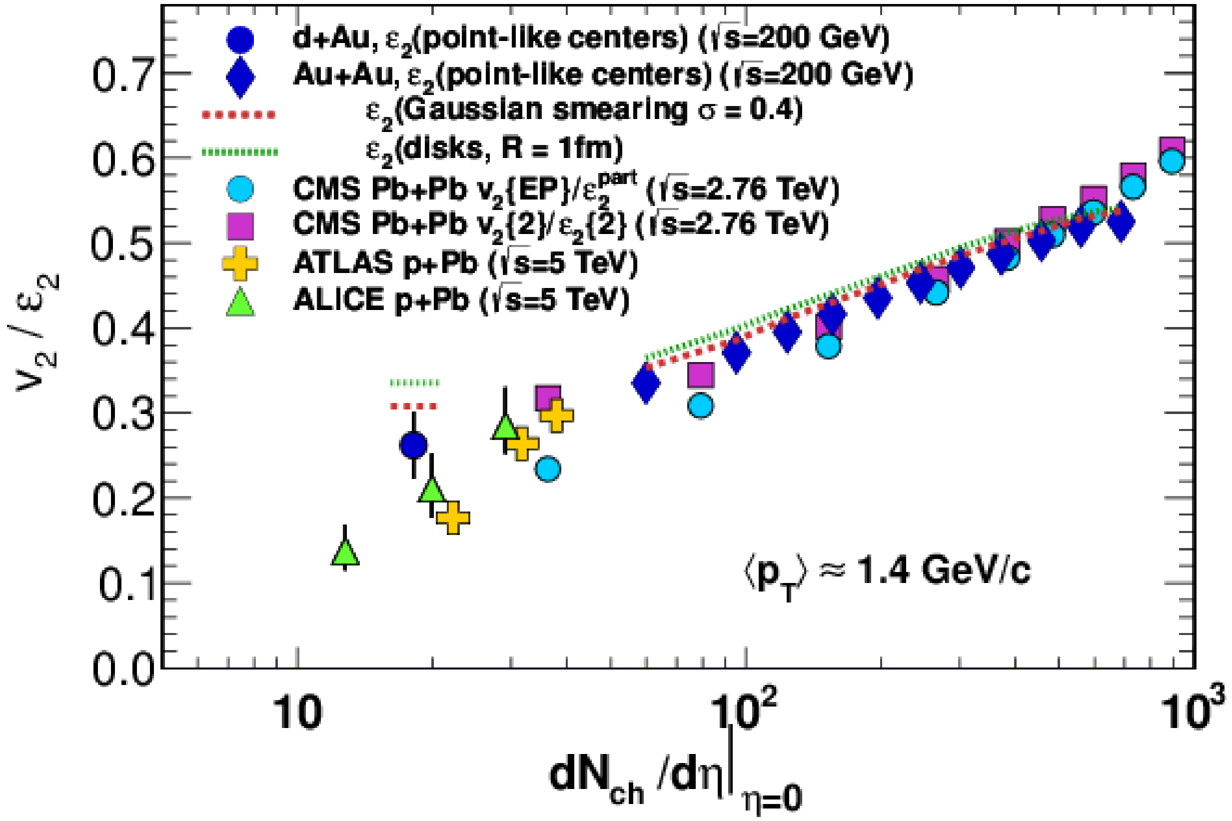
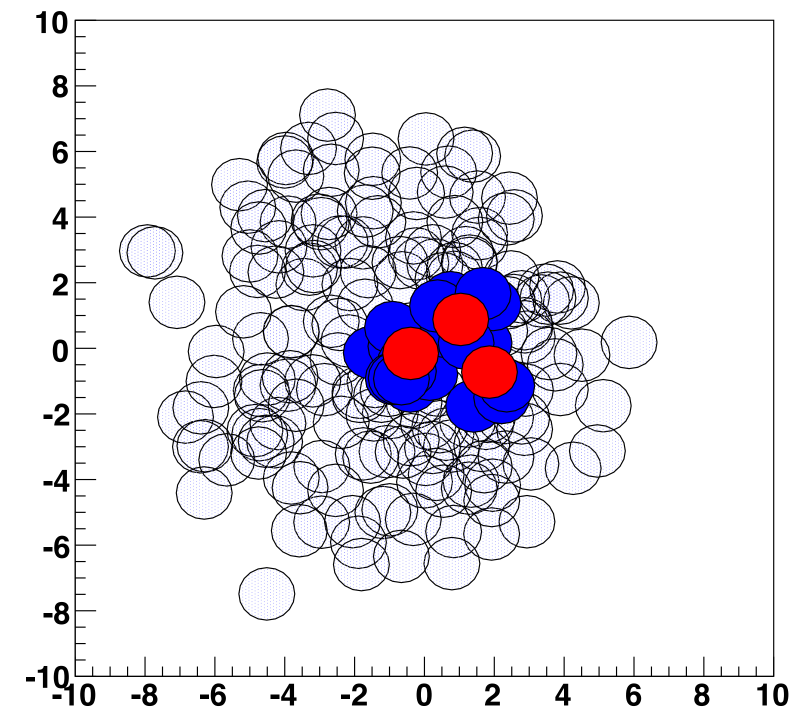
# why is this so important?

- small scale structures are the most sensitive to viscosity
- one of the biggest uncertainties on η/s is how the energy density is distributed in the initial state, pA, dA, He3A provide a new, powerful test of those models
- more fundamentally, we are interested in **how** the QGP forms and **why** it behaves as it does;
  - any pA QGP will have a shorter lifetime, potentially more sensitive to how it is formed
  - hydrodynamic models are pushed to their limit for such small systems why do the data still look fluid-like?
  - if it's not a QGP, what is going on and how does that impact understanding AA?

# conclusions




$^{3}$HeA



- many advances in determining the viscosity of the QGP
- new surprises from pA collisions
- new data very soon to test whether we are forming a very small QGP or something else…