(Unintended) Consequences of the Glauber Initial State

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ETD-HIC - July 17, 2007

July 2007 Early Time Dynamics Montreal

Acknowledgments

Glauber Modeling in High-Energy Nuclear Collisions

Michael L. Miller,[1] Klaus Reygers,[2] Stephen J. Sanders,[3] and Peter Steinberg[4]

online now! annualreviews.org

nucl-ex/0701025

The PHOBOS+ Glauber Working Group:

Mark Baker, Constantin Loizides, Steve Manly, PAS, Uli Heinz

Additional discussions:

W. Busza, G. Roland, A. Dumitru

Geometric properties of nuclear collision (what could involve earlier times?...)

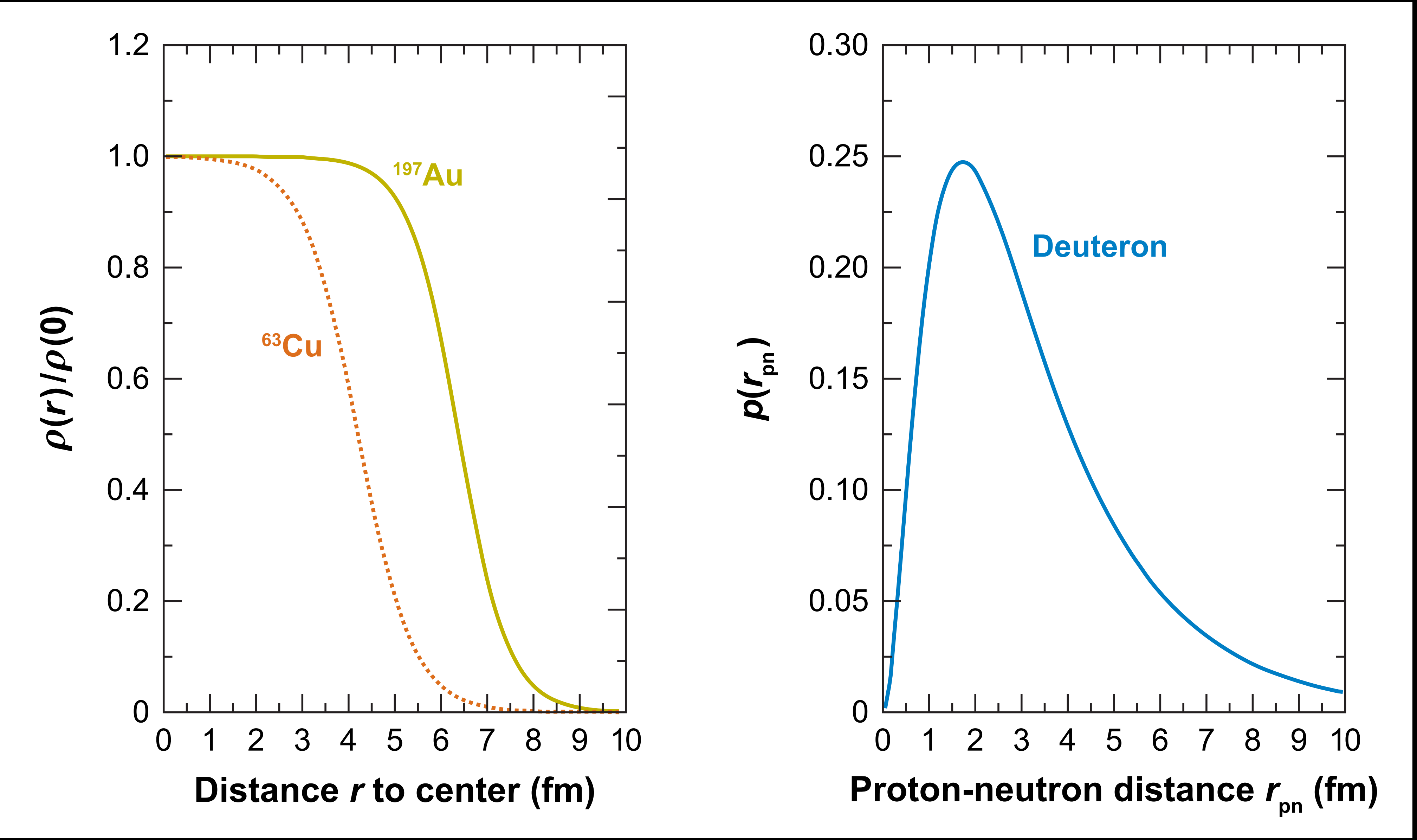
Simple model of matter creation

What is a Nucleus?

An average density distribution of nucleon positions

Nuclear Distributions

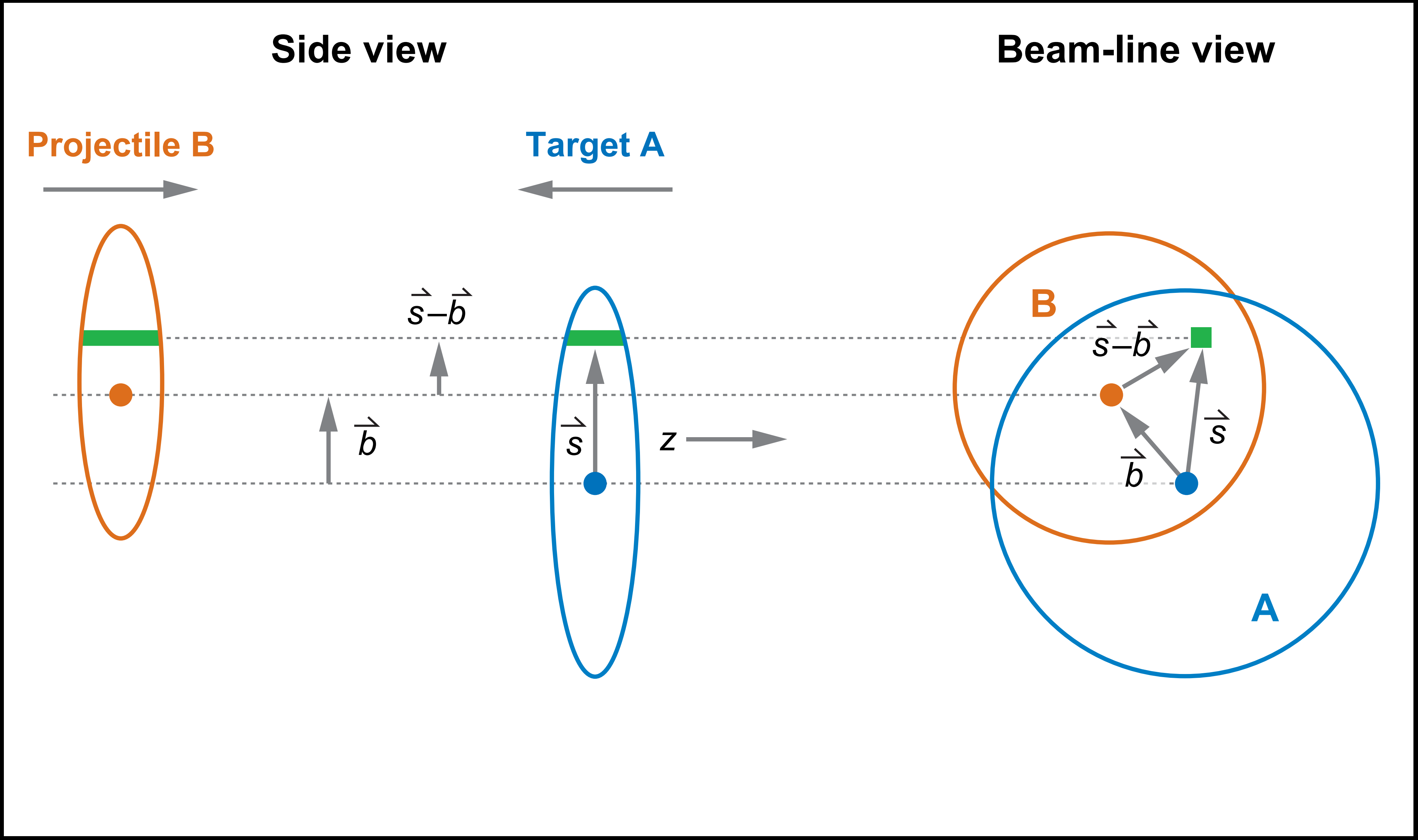
nucl-ex/0701025



Distributed according to a Fermi distribution
(or Hulthen, for d+Au)

Optical Limit Approach

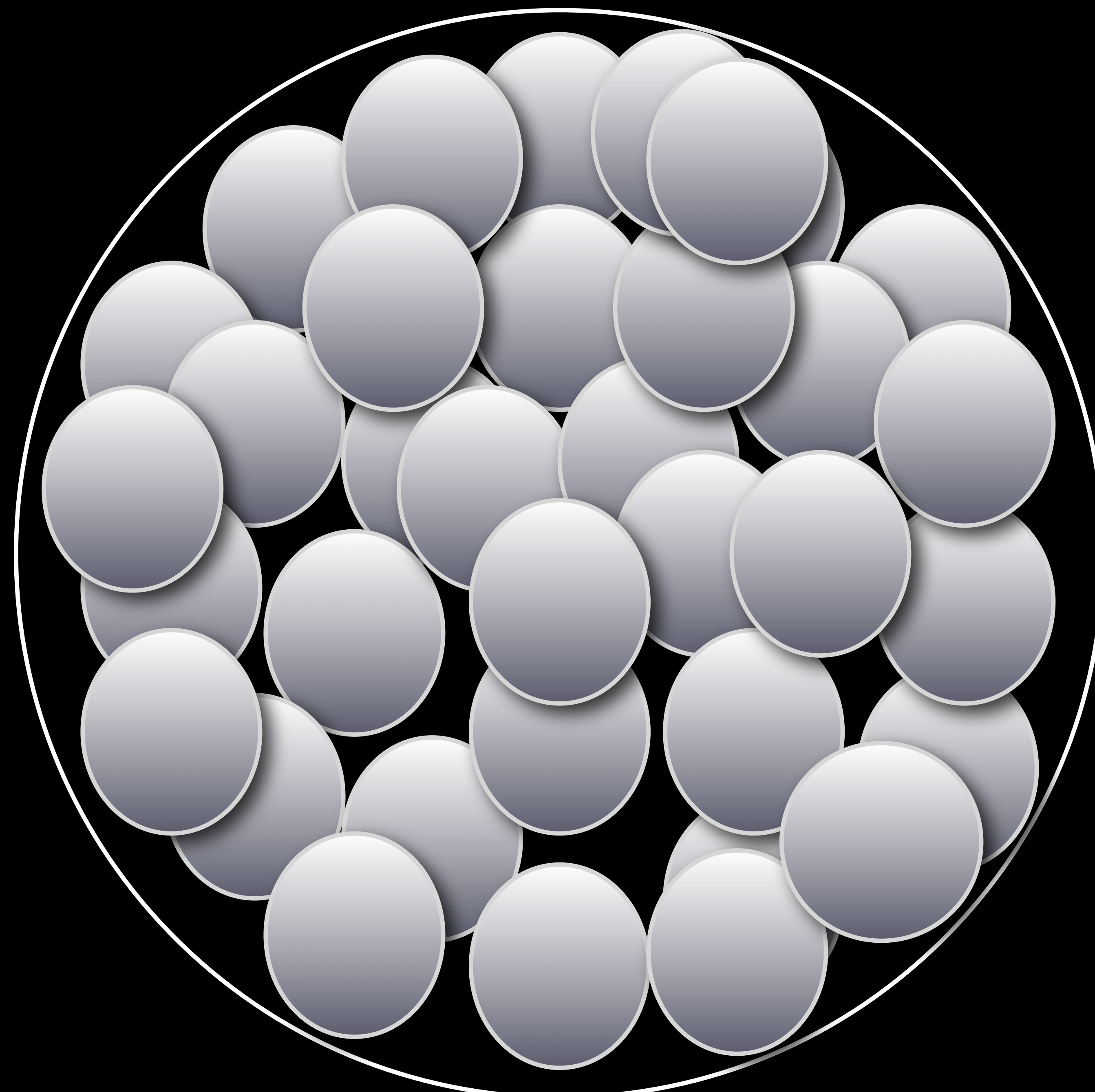
nucl-ex/0701025



$$\sigma_{AB} = \int d^2b \left\{1 - [1 - \sigma_{inel}^{NN} T_{AB}(b)]^{AB}\right\}$$

everything based on smooth, averaged densities

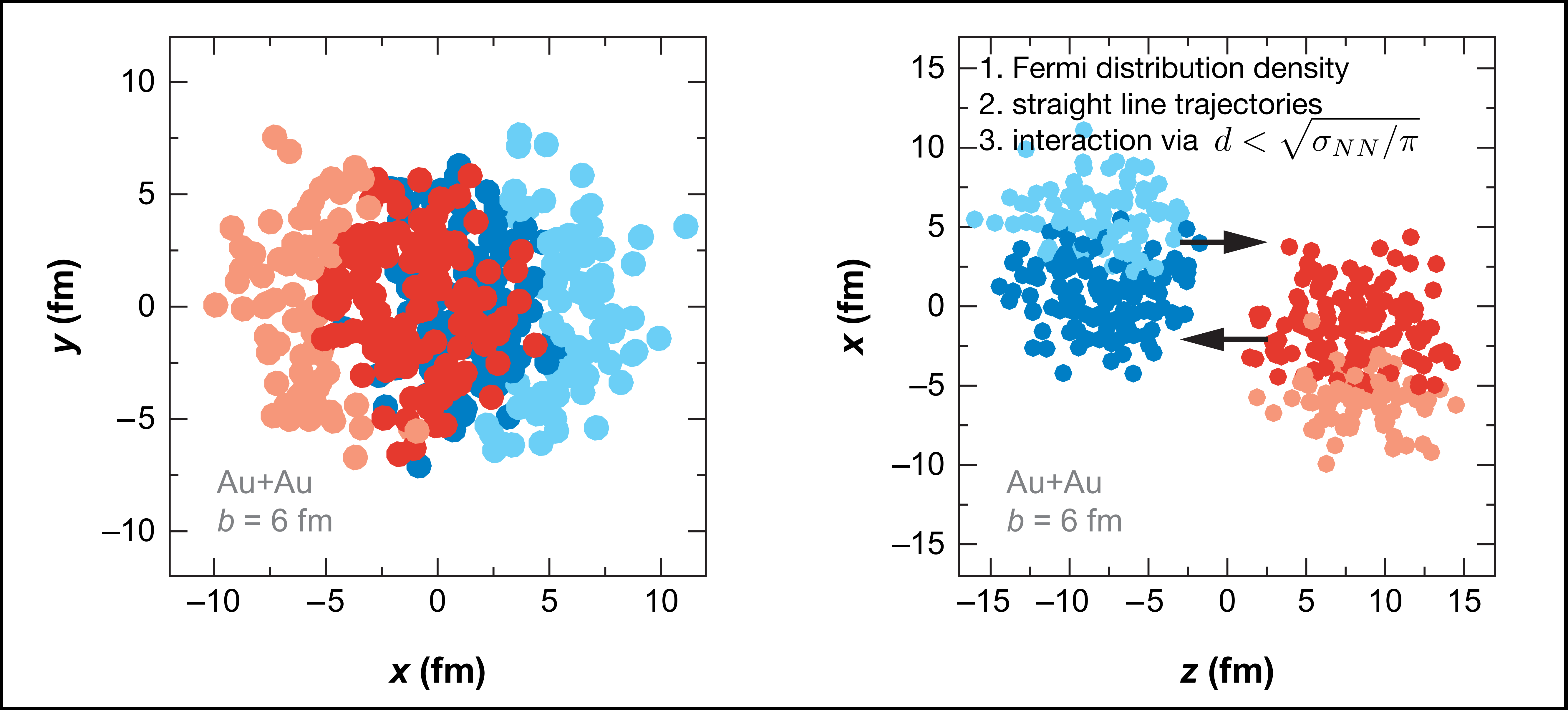
What is a Nucleus?



A bound state of nucleons, with positions chosen according to the Fermi distribution

Glauber Monte Carlo (GMC)

nucl-ex/0701025

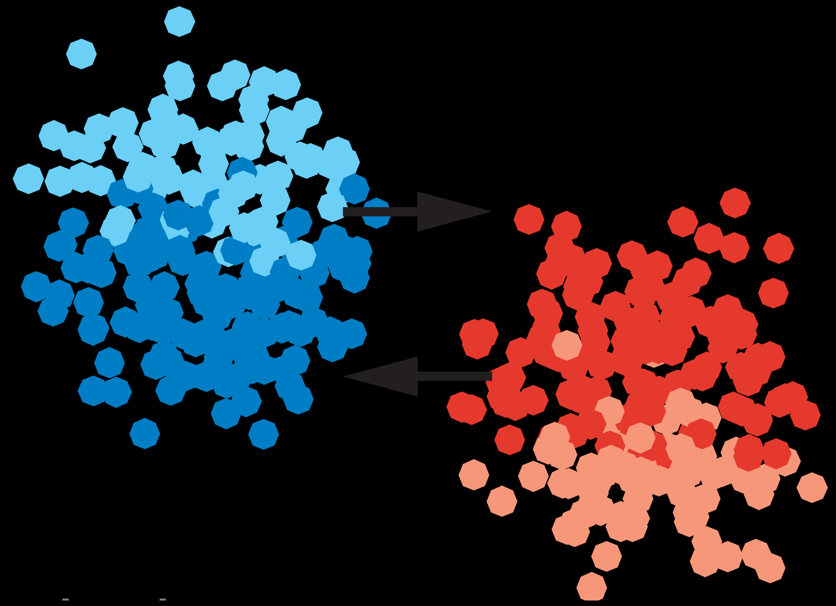


$$\sigma_{inel}^{AB} = \int d^2b \int d^2s_1^A \cdots d^2s_A^A d^2s_1^B \cdots d^2s_B^B \times$$
$$\hat{T}_A(\mathbf{s_1^A}) \cdots \hat{T}_A(\mathbf{s_A^A}) \hat{T}_B(\mathbf{s_1^B}) \cdots \hat{T}_B(\mathbf{s_B^B}) \times$$
$$\left\{ 1 - \prod_{j=1}^{B} \prod_{i=1}^{A} [1 - \hat{\sigma}(\mathbf{b} - \mathbf{s_i^A} + \mathbf{s_j^B})] \right\}$$

800 dimensional integral w/ 20 lines of code.

Glauber Monte Carlo (GMC)

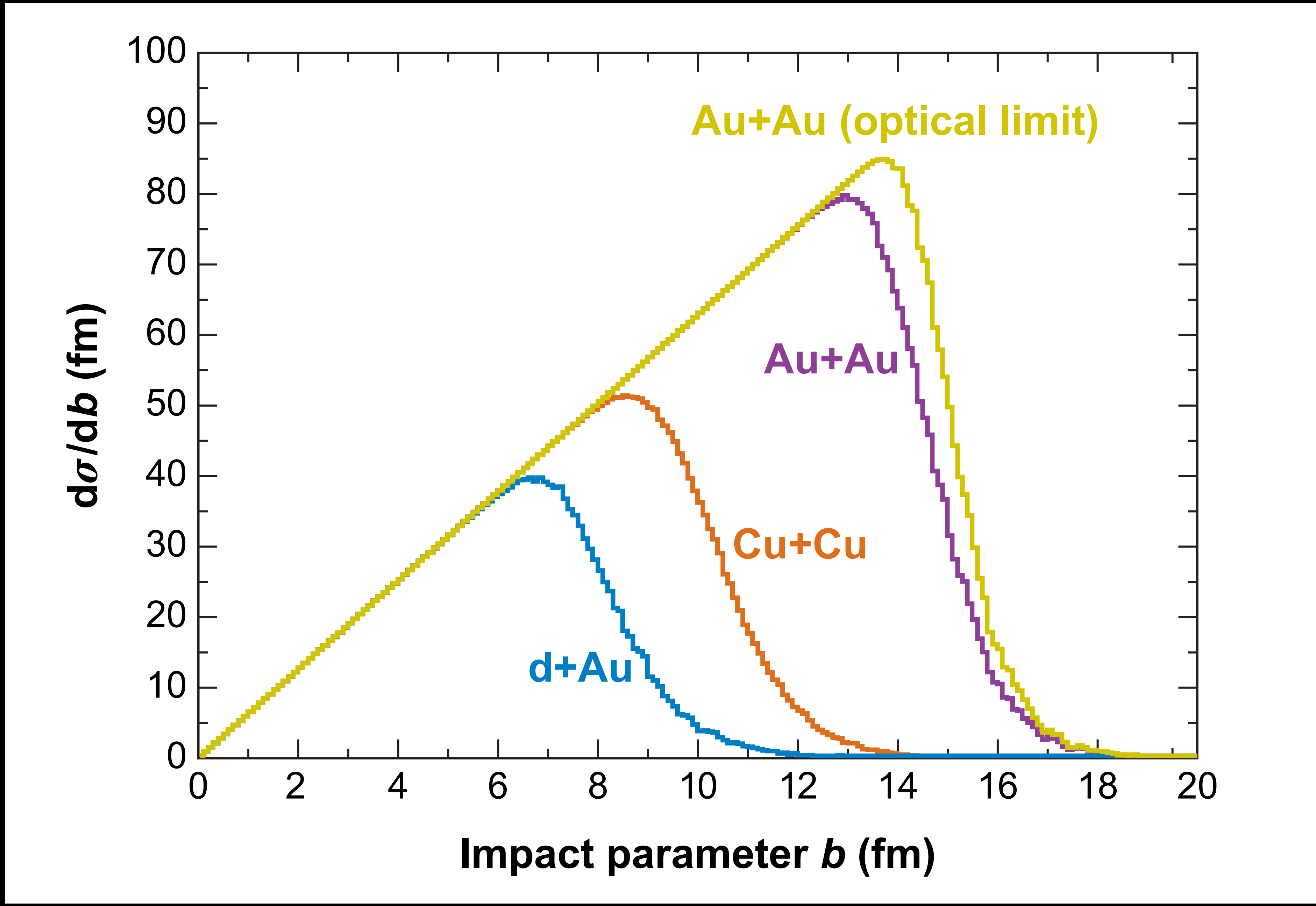
- **Can calculate geometric features event-by-event (and nucleon-by-nucleon)**
  - Participants, collisions
  - Collisions *per* participant (e.g. nuclear thickness)
  - Eccentricity
  - Cold nuclear effects (onia suppression)



Collisions on “surface” are quasi-p+p. How can R_{AA} go below geometric limit?

Effect on Total Cross Section

nucl-ex/0701025



Total cross section systematically <u>larger</u> in optical approach

"Eclipsing" (Shadowing)

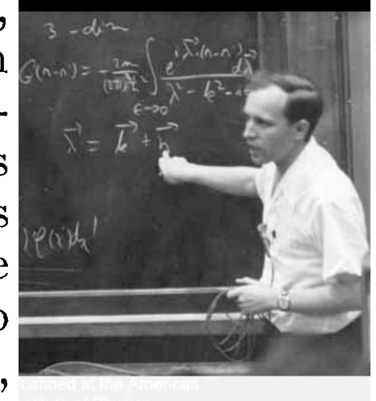
PHYSICAL REVIEW VOLUME 100, NUMBER 1 OCTOBER 1, 1955

Cross Sections in Deuterium at High Energies

R. J. GLAUBER
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts

(Received May 27, 1955)

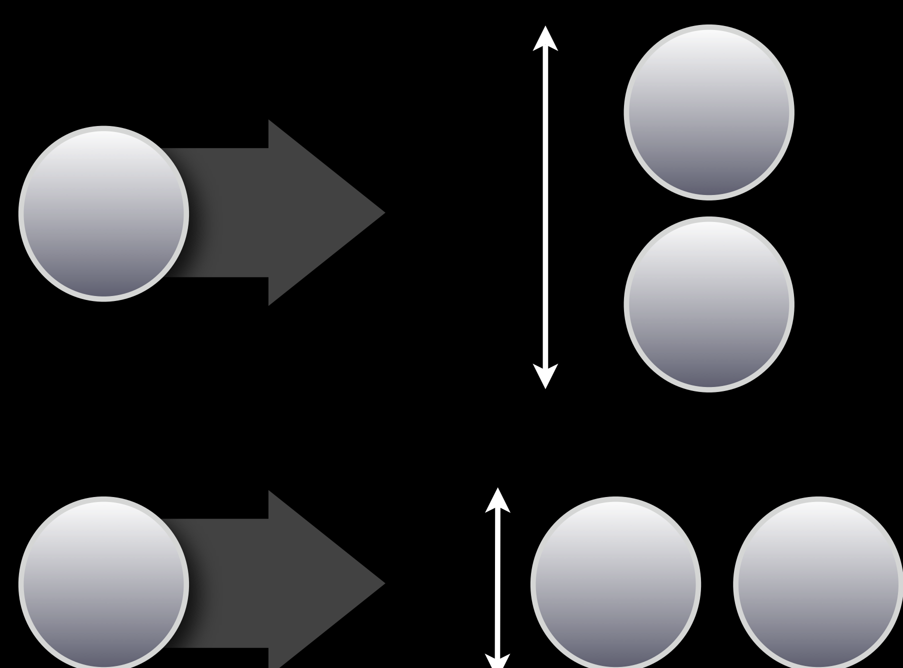
Recent measurements of nucleon attenuation at 1.4 Bev (where $\bar{\lambda}=0.1\times10^{-13}$ cm) seem, on the contrary, to reveal a substantial lack of additivity of the neutron and proton cross sections, in deuterium.[1,2] Measurements with incident protons and incident neutrons both indicate that the deuteron cross section is less than the sum of the free-particle cross sections. The measured differences, although obviously subject to uncertainty, amount to 9 mb and 6 mb respectively, values to be compared with $\sigma(n,p)=42$ mb and $\sigma(p,p)=48$ mb.



Some simple considerations may be of help in indicating the nature of the effect. At these energies the attenuation of the incident amplitude by incoherent processes such as meson production may be schematically represented as due to a certain amount of absorption of the incident wave by the nucleons. Since the incident wavelengths in these cases are evidently much smaller than the ranges of interaction, the nucleons may be thought of as casting fairly well-defined shadows. It is then clear that absorption or scattering by either nucleon is reduced when it enters the shadow of the other. Astronomers have long been familiar with a time-reversed analog of this effect; the decrease in luminosity of binary star systems during eclipses.

a)

b)



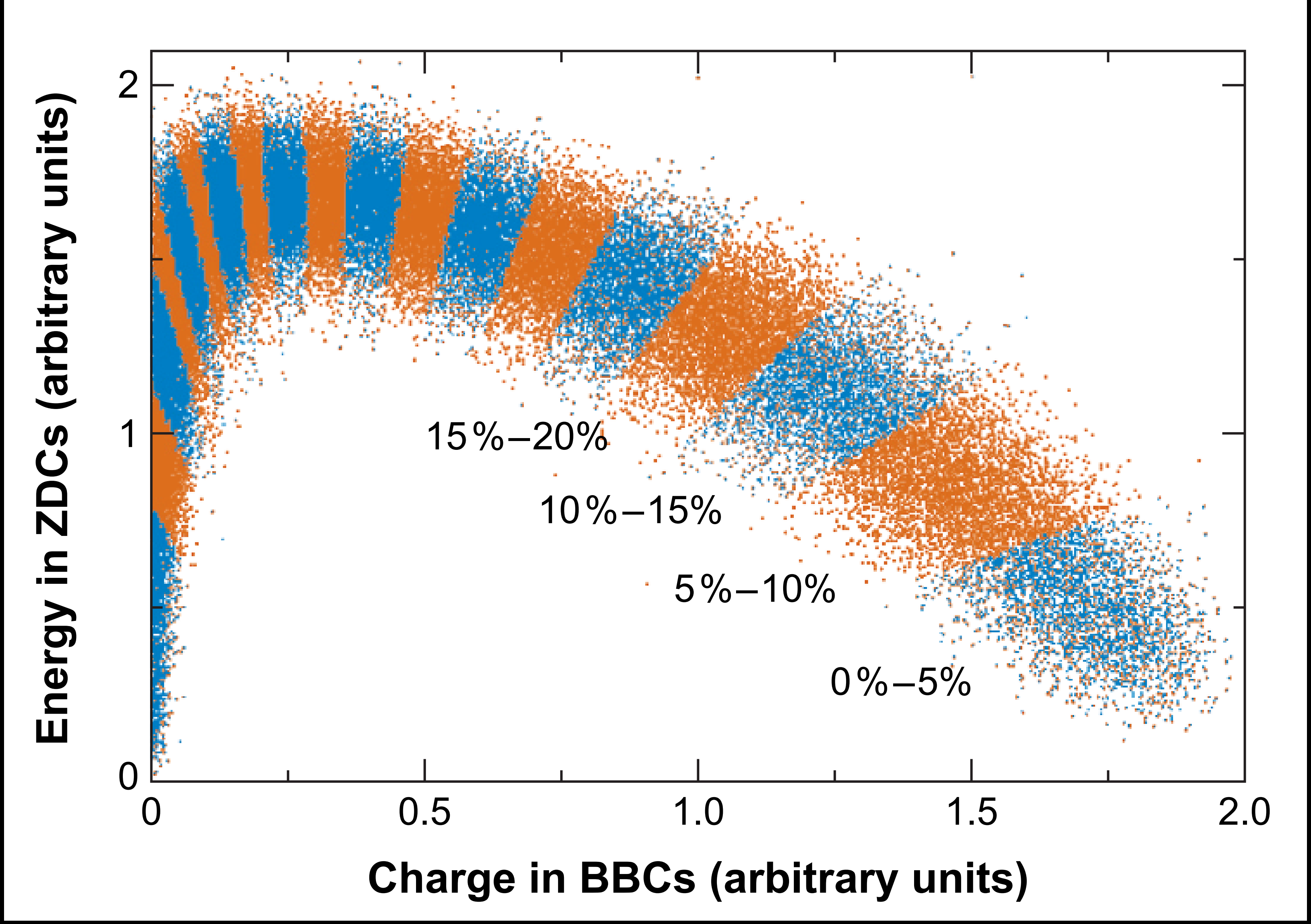
eclipsing gives

$$\sigma_b < \sigma_a$$

only in MC approach

Effect on Centrality

nucl-ex/0701025



Centrality bins are relative to <u>total</u> cross section:
even with a few % difference, expect systematic effects

Optical vs. MC

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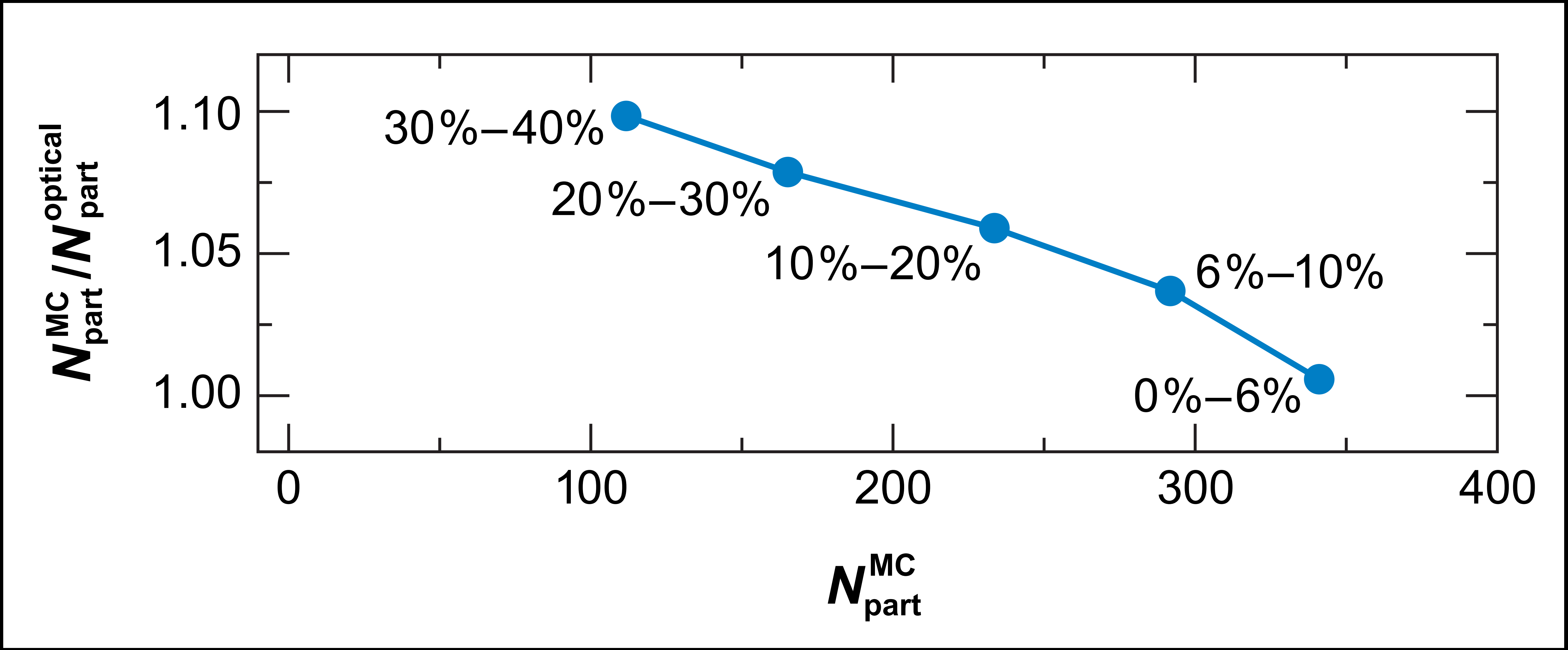

Generically, optical limit (no fluctuations) leads to underestimating N_{part} in peripheral events

Effect on Observables

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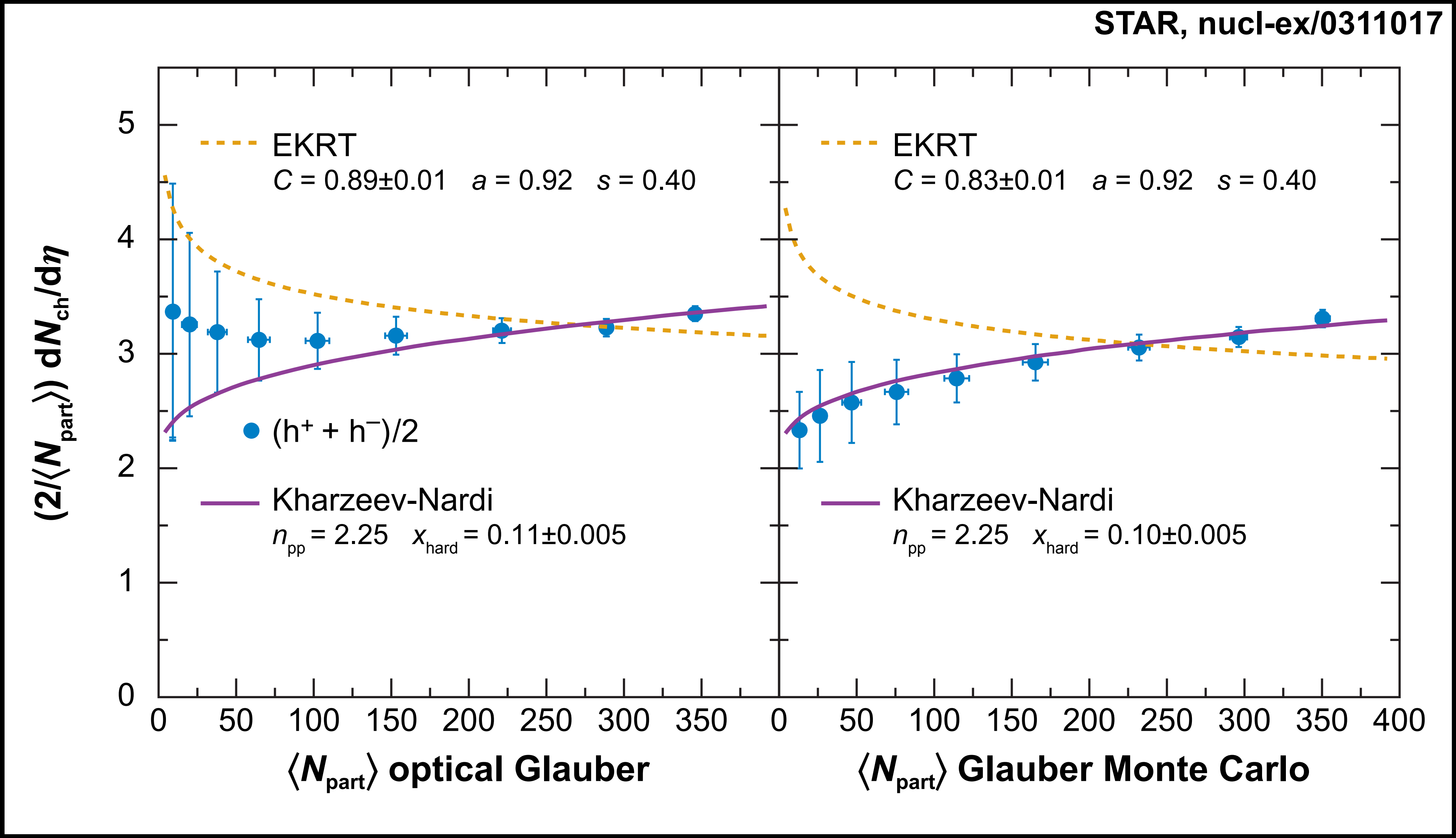


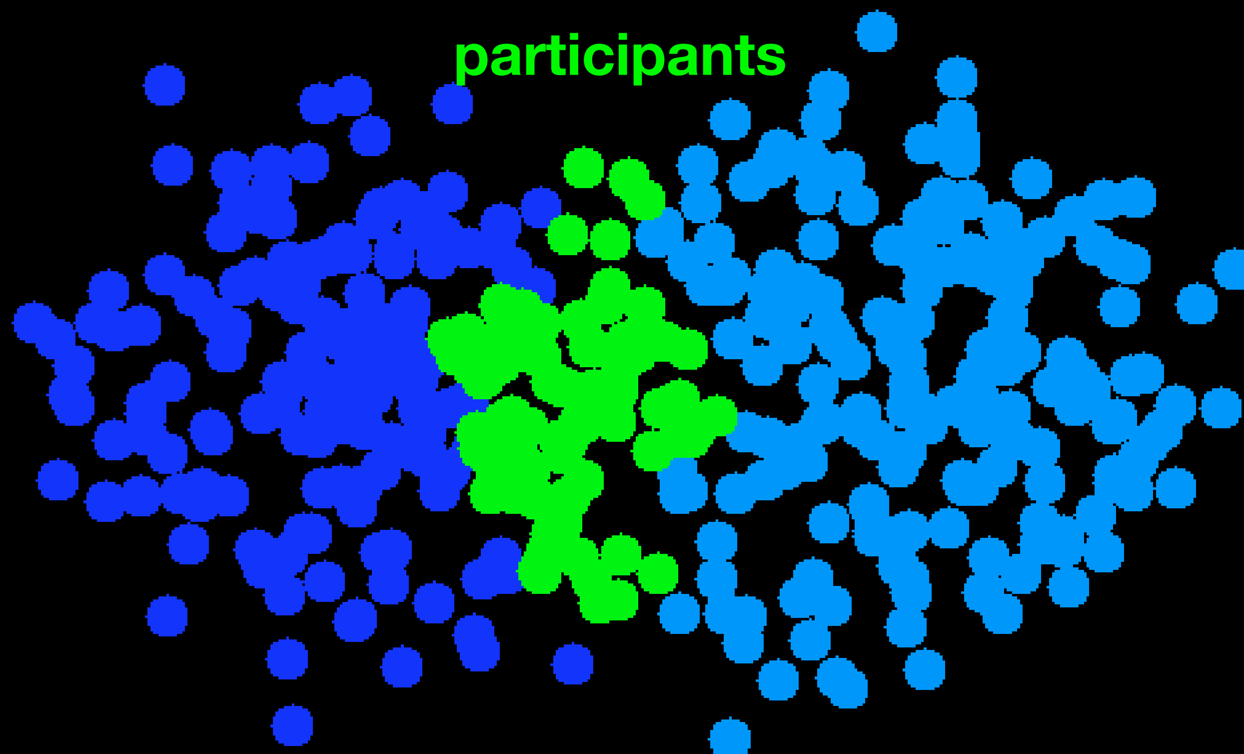
Interpretation of data can be changed by using optical (wrong!) or MC Glauber approach

Role of Glauber @ Early Times

- **The inelastic cross section shows that Glauber matters as to whether anything happens at all!**
  - Do CGC-shadowed calculations give σ_{tot}?
- **It can also give us a hint as to how and where matter was produced**
  - No longer a means to do an integral, but a quasi-“model”

SLP

Sudden Localized Participants



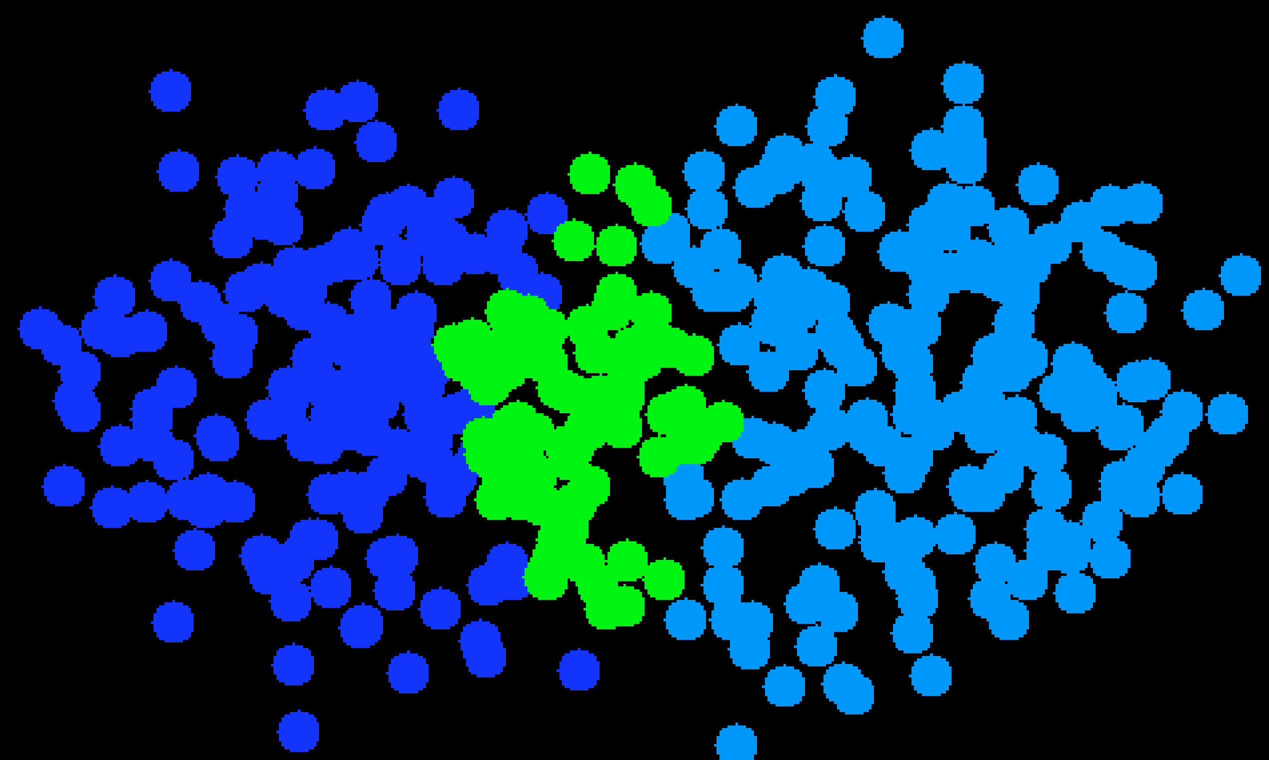
Glauber images from
PHOBOS MC, R. Bindel

let us also assume that the matter is created
where the interactions occur, following the participants

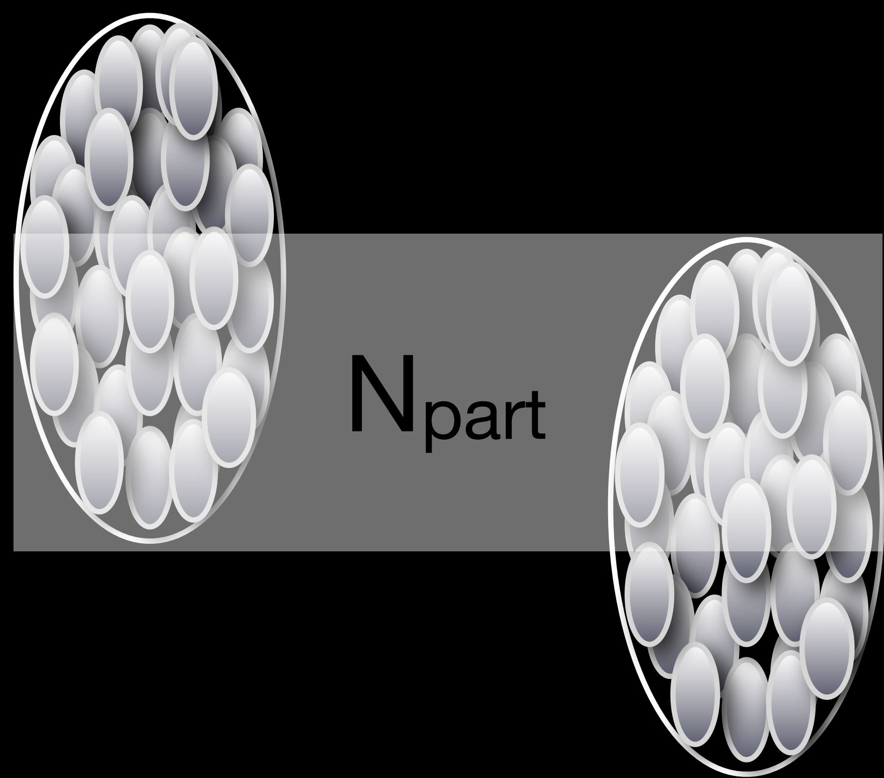
If it thermalizes suddenly, then this is the initial state
for hydrodynamic evolution (less sudden→less local)

SPLAT

Sources are **P**articipants, **L**ocalized **A**t **T**hermalization



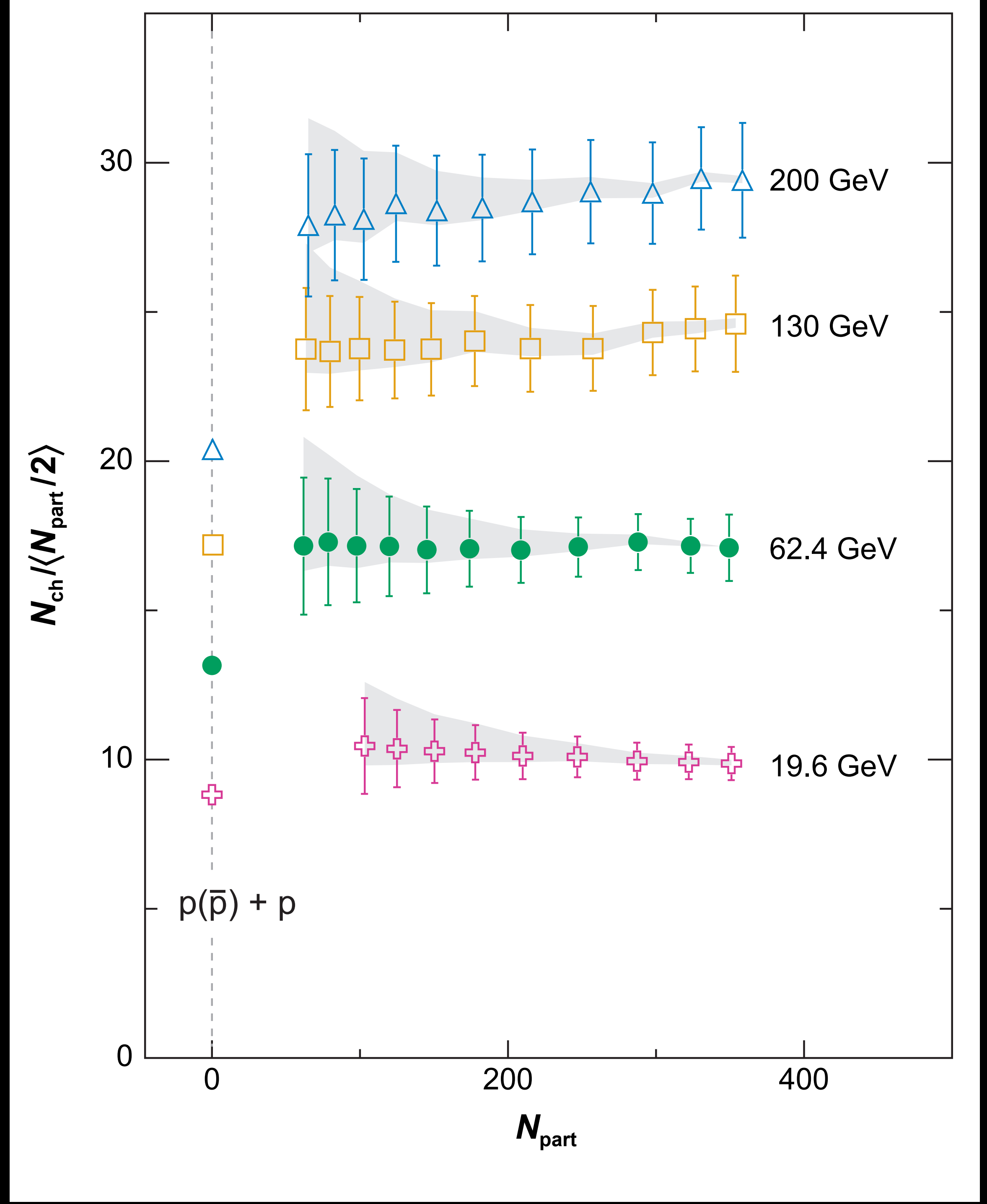
Total Multiplicity



Total produced entropy scales <u>linearly</u> with N_{part}

No information on where matter was created

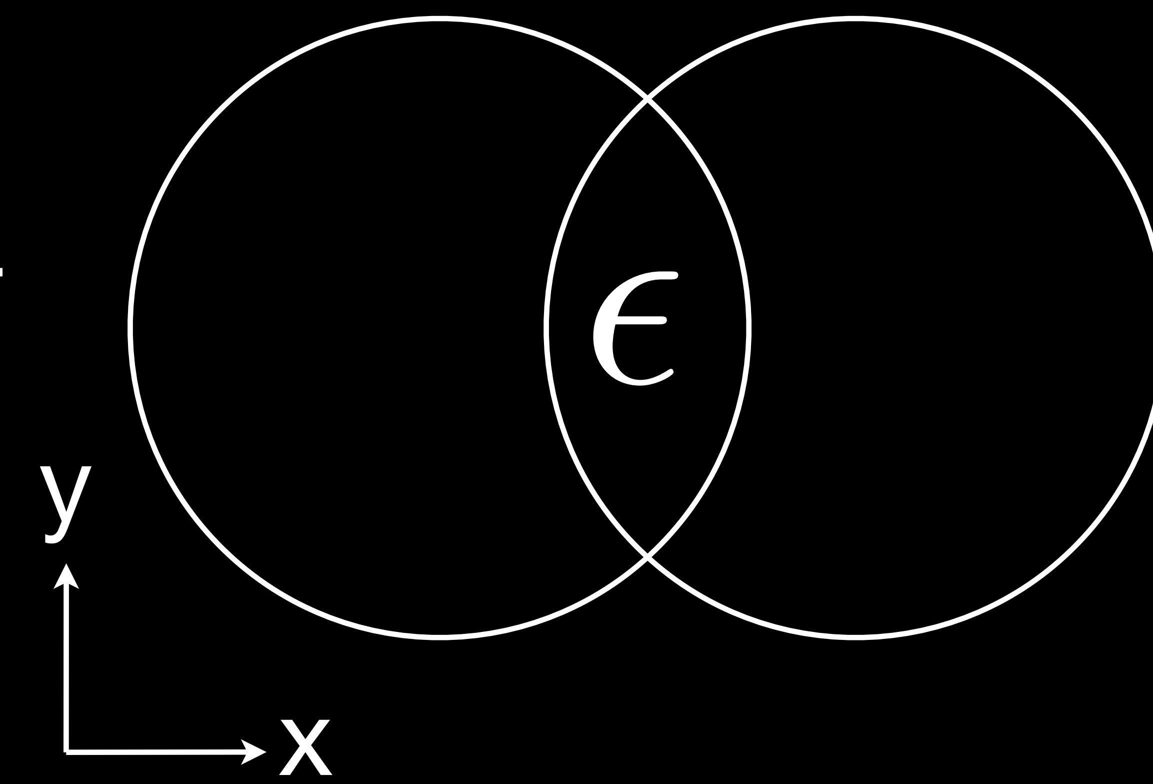
nucl-ex/0701025
Phys.Rev.C74:021901,2006



Eccentricity

Overlap zone where matter thermalizes has a particular "shape" vs. impact parameter

$$\epsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

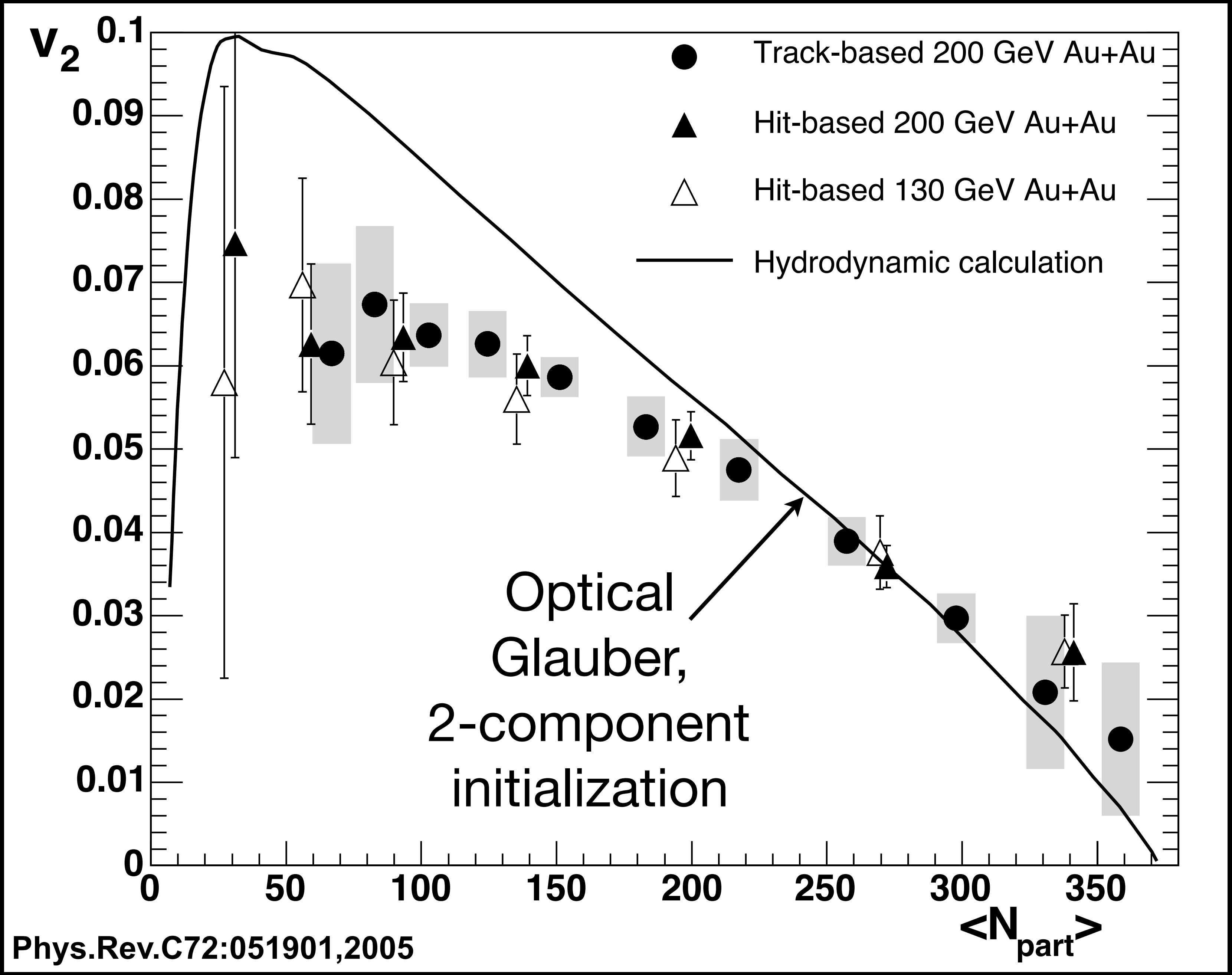


Generically, hydro predicts complete transfer of spatial anisotropy into momentum anisotropy! (Heinz, Ollitrault,)

$$v_2 \propto \epsilon$$

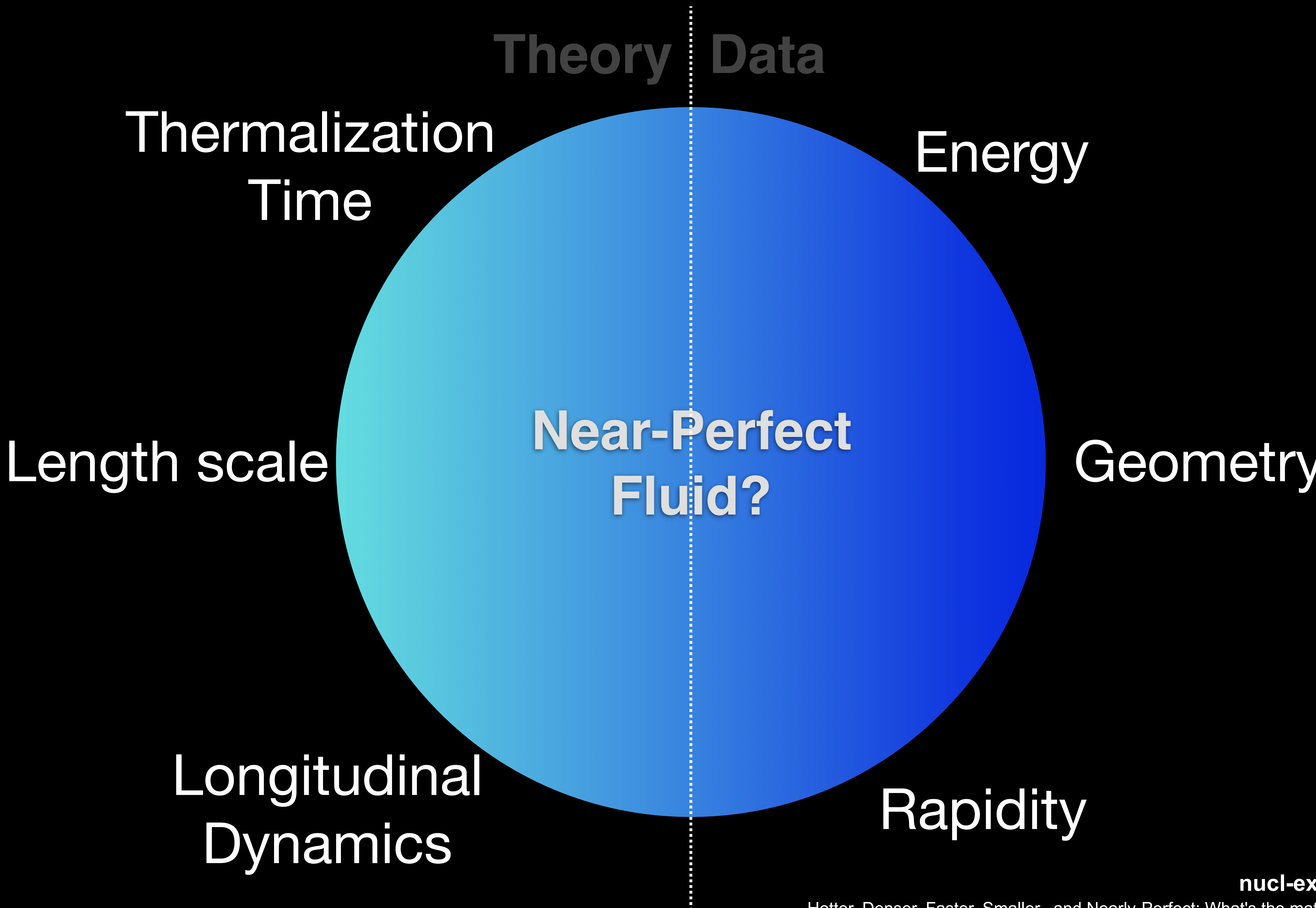
Hydro is sensitive to <u>where</u> the matter was (and not what!)

Hydro @ RHIC



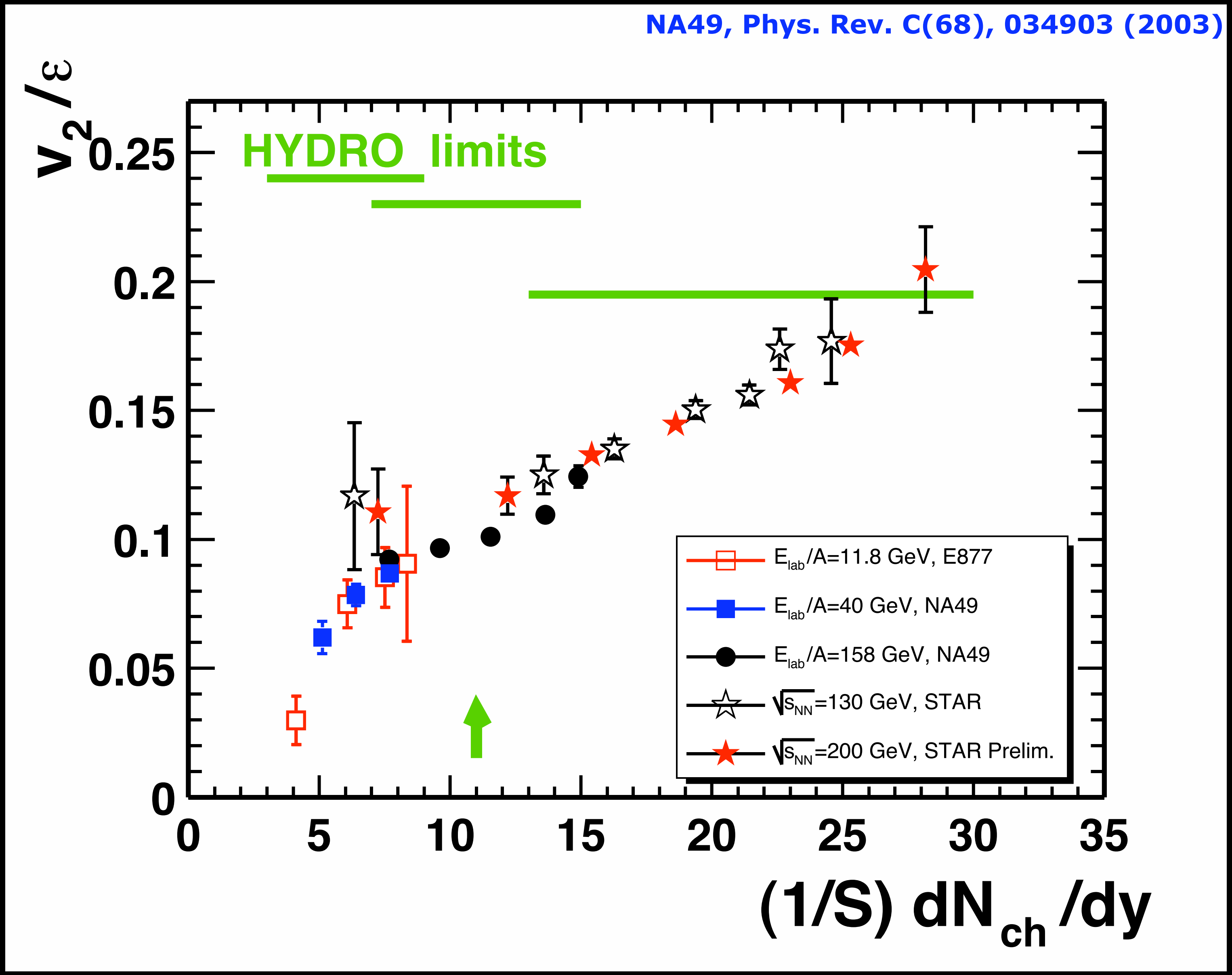
hydro scales $\tau_0 \sim 0.6 fm/c$ $\quad \epsilon \sim 30\ GeV/fm^3$ $\Longleftrightarrow$ $\tau_0 \sim 1\ fm/c$ $\quad \epsilon \sim 500\ MeV/fm^3$ **hadronic scales**

The Edge of Liquidity



nucl-ex/0702020
Hotter, Denser, Faster, Smaller...and Nearly-Perfect: What's the matter at RHIC?

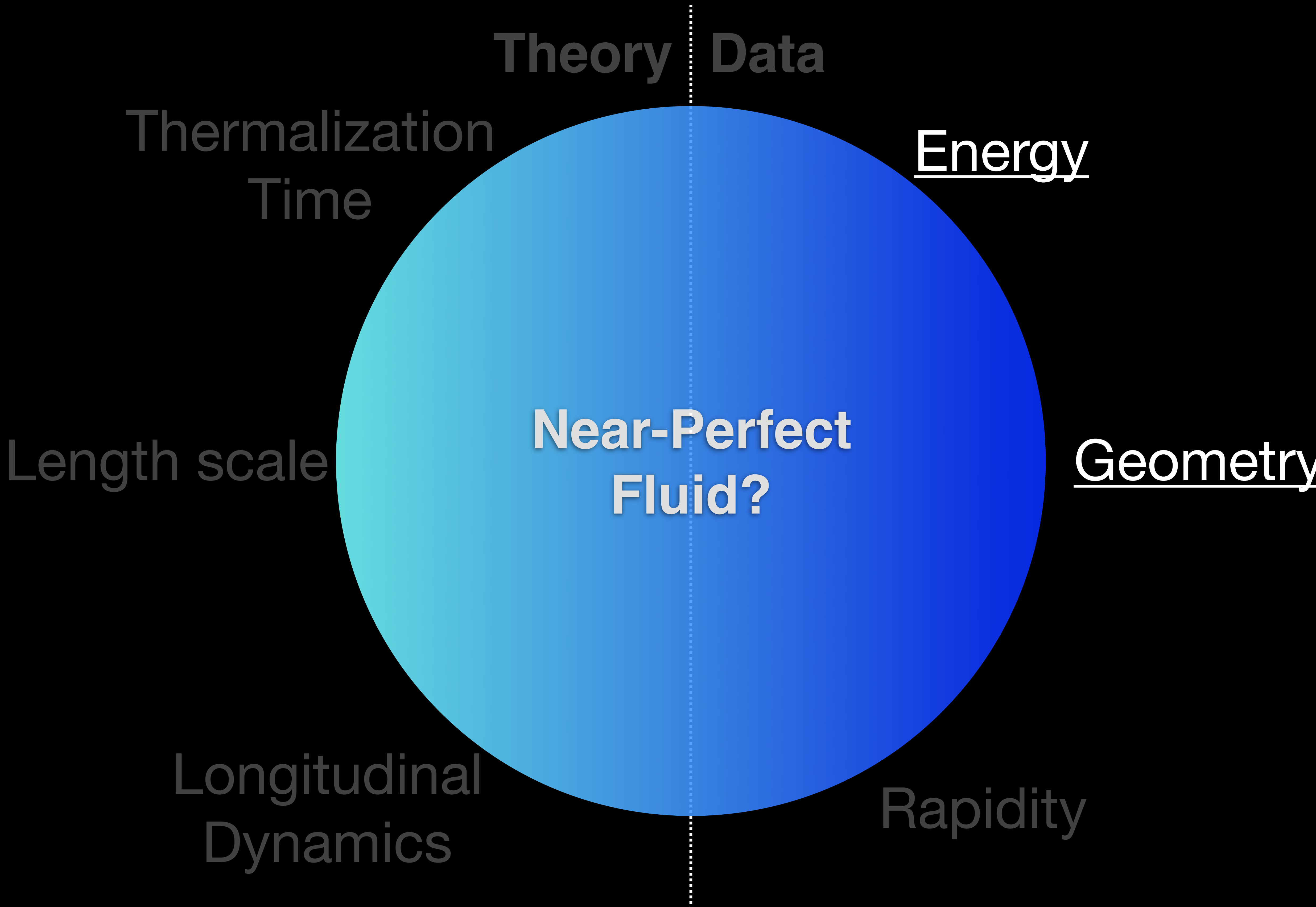
"Scaling Behavior"



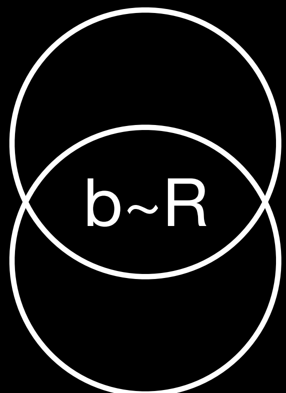
"hydro limit"?

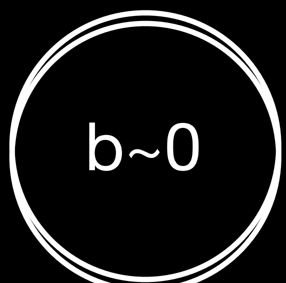
integrated "pressure" $\frac{v_2}{\epsilon}$ is a simple function of $\frac{dN/dy}{S}$ "transverse density"

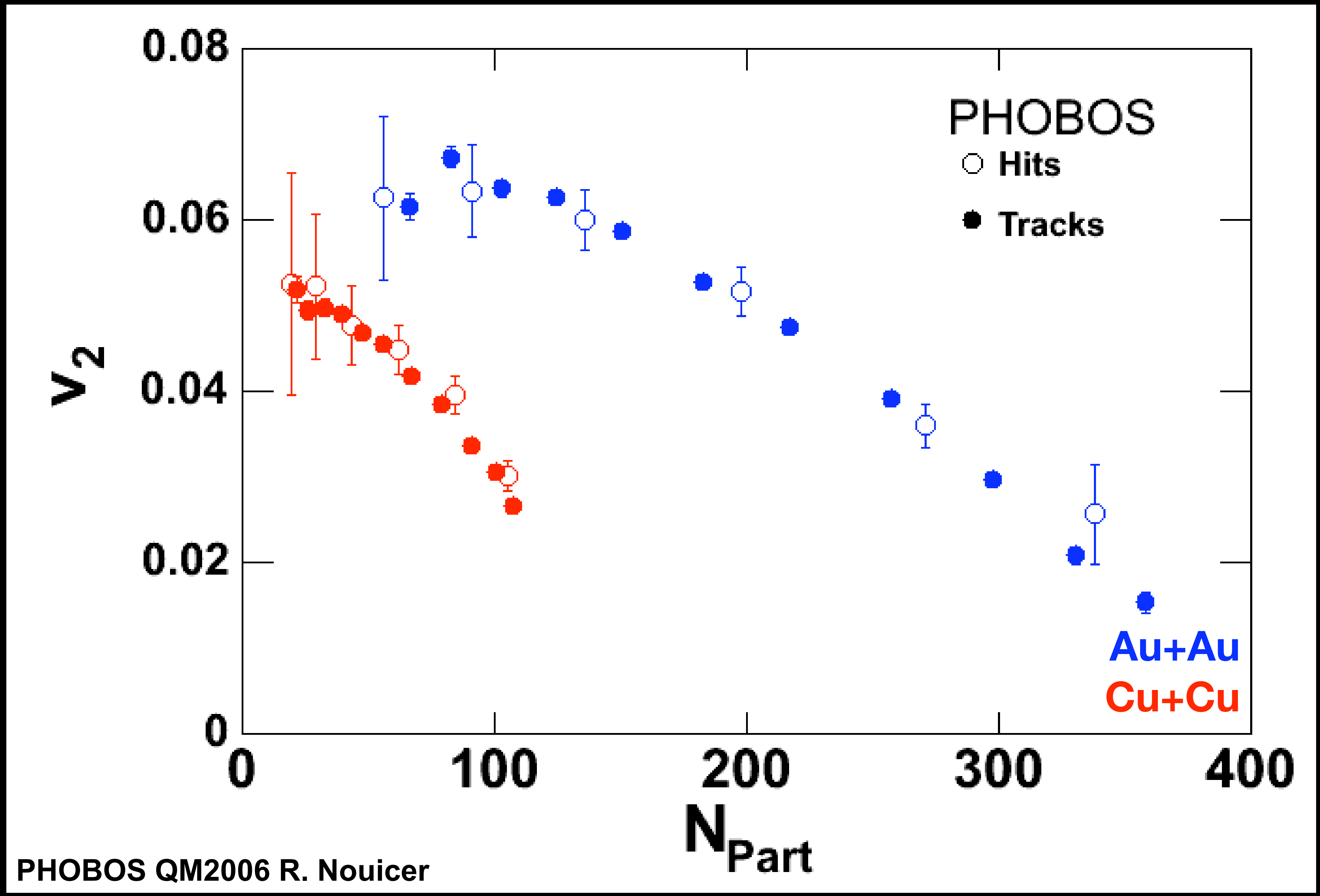
Is this hydrodynamic equilibration, or just the approach to it? In any case, it seems to be <u>universal</u>



Does v_2 follow ϵ?

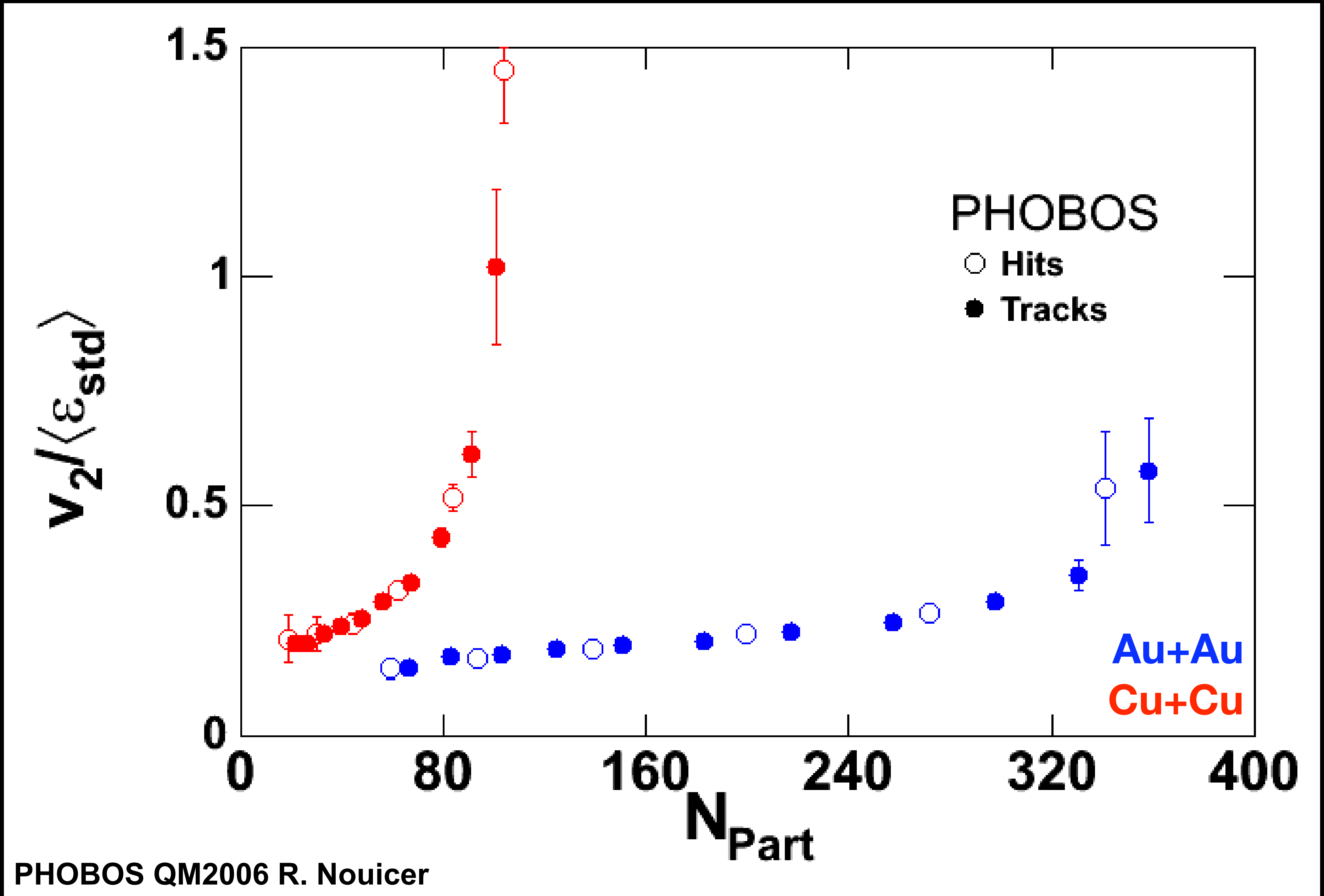




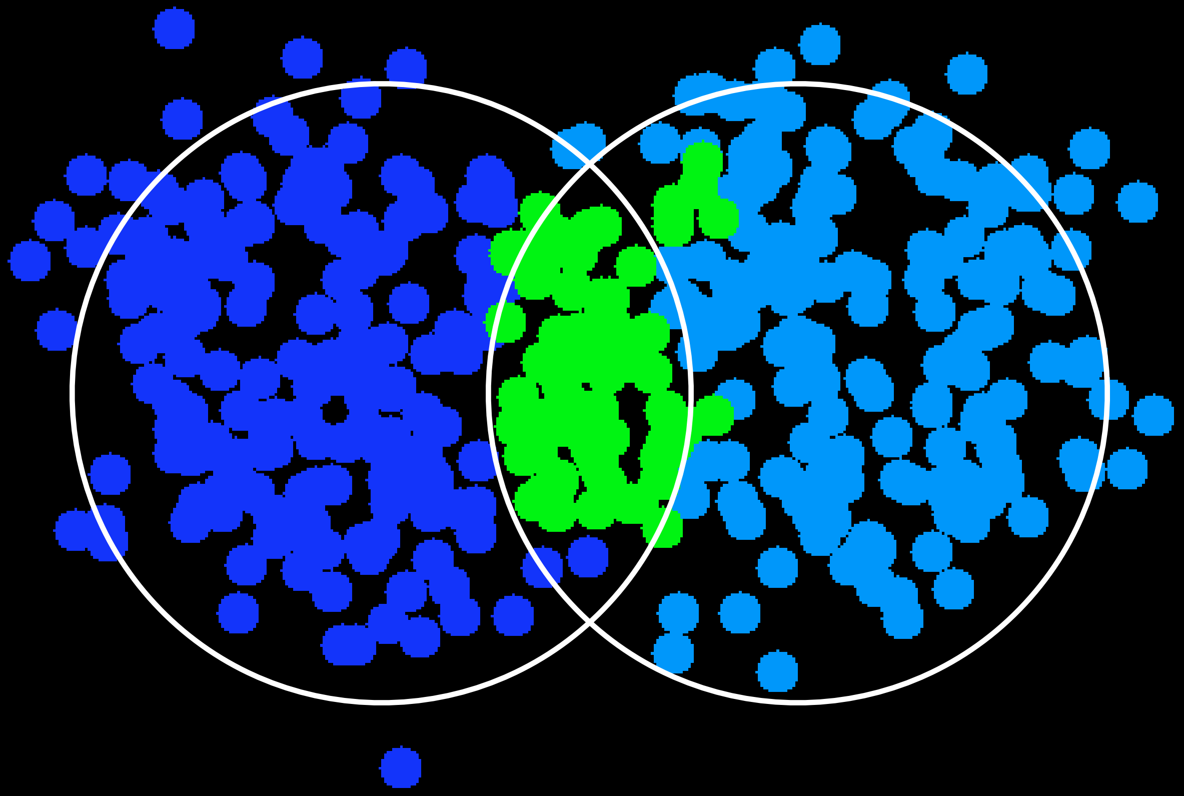


v_2 does not go to zero when eccentricity should (b~0)

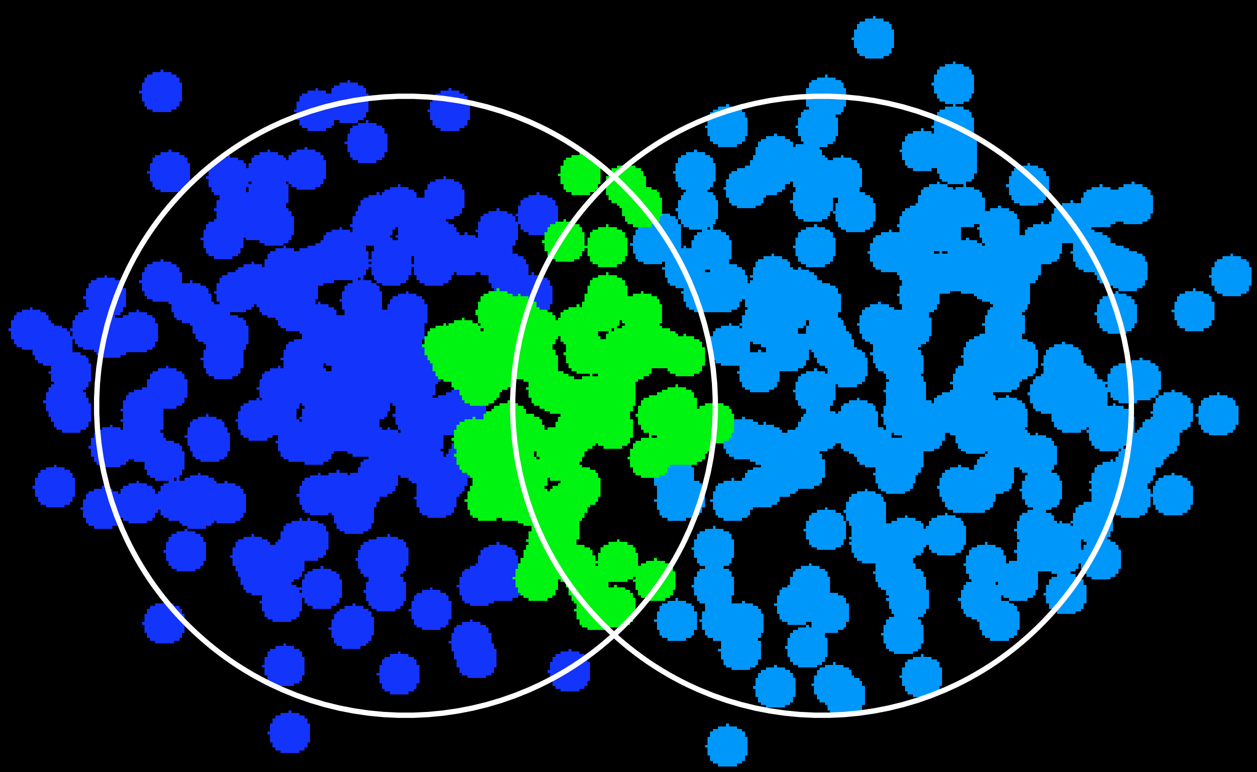
Something wrong...



Au+Au



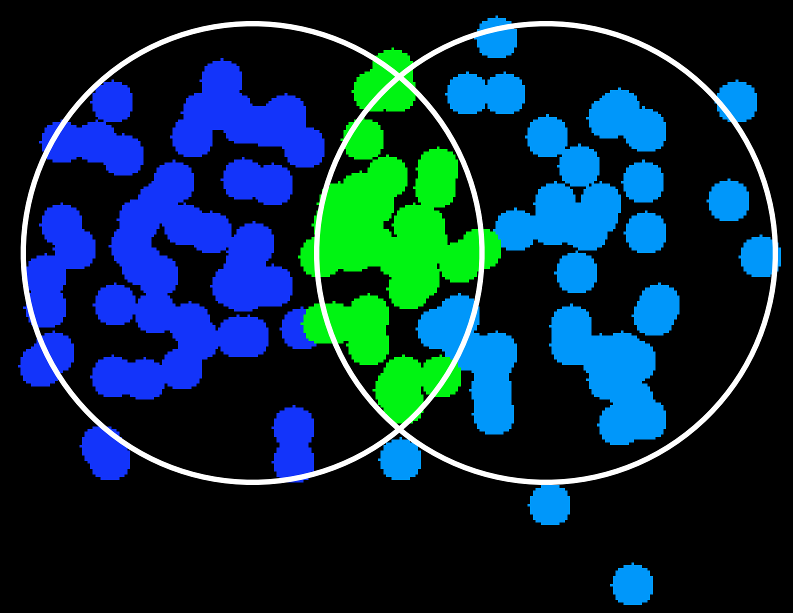
Au+Au



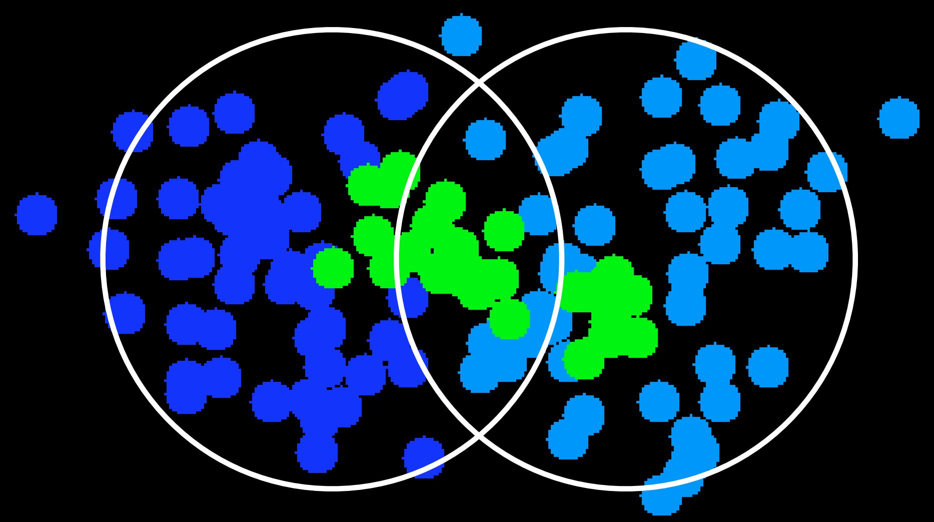
Participants trace out overlap zone, but include
1. Fluctuations (finite number per event)
2. Correlations (it takes two to tango...)

(NB: these are snapshots of nucleon configurations, not stable nuclear states!)

Cu+Cu

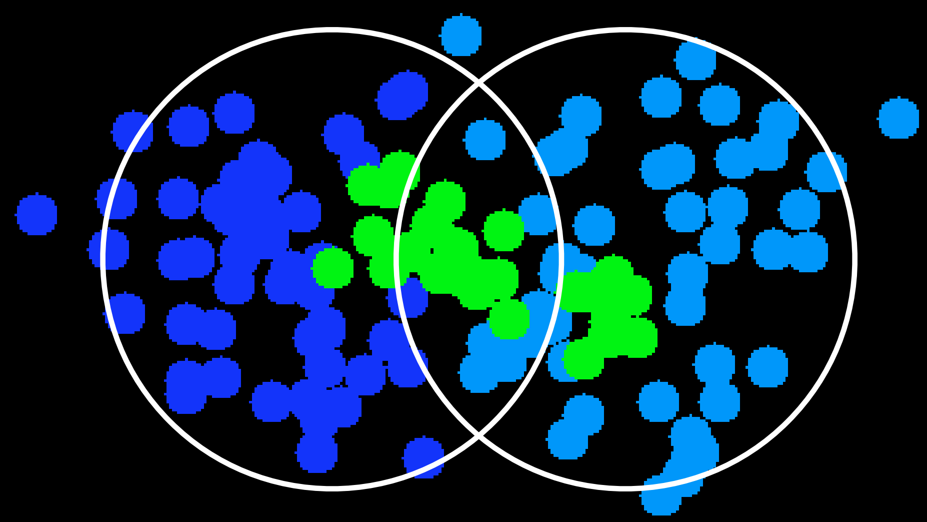


Cu+Cu



Fluctuations can significantly deviate from nominal overlap zone for small numbers of nucleons

Cu+Cu

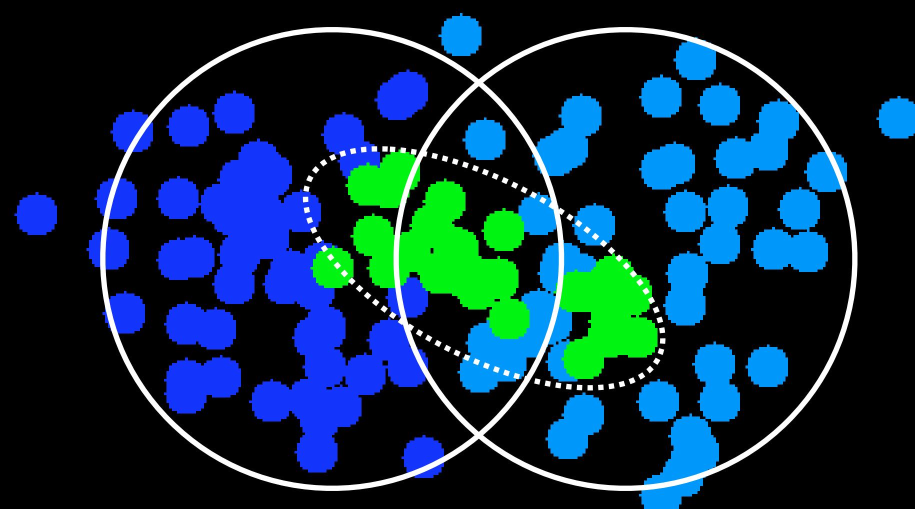


$$\epsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

“Standard eccentricity”

Cu+Cu

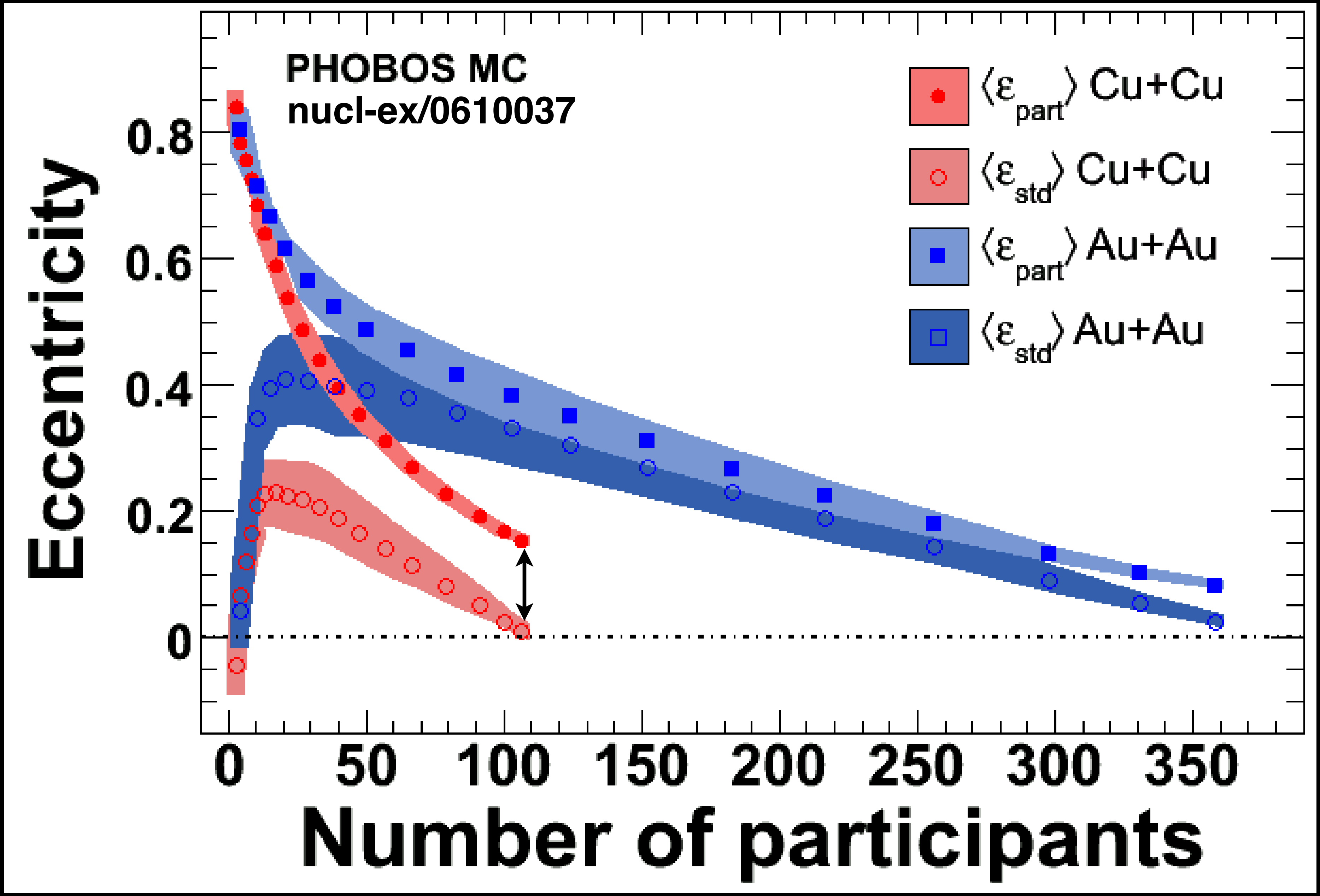
Principal axes make sense if v_2 depends on shape of produced matter (in SLP), not the reaction plane



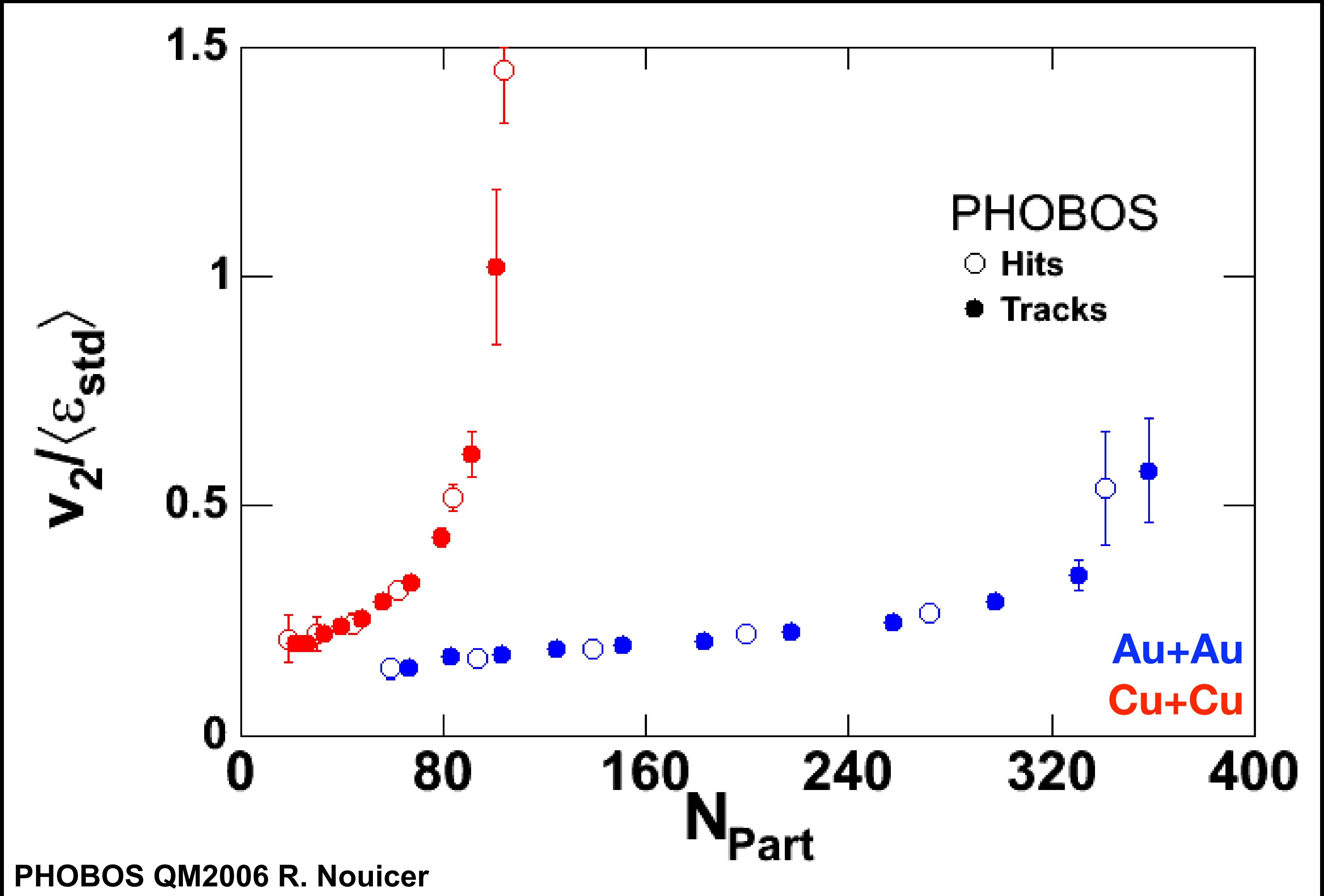
$$\epsilon_{part} = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4(\sigma_{xy}^2)^2}}{\sigma_y^2 + \sigma_x^2}$$

"Participant eccentricity"

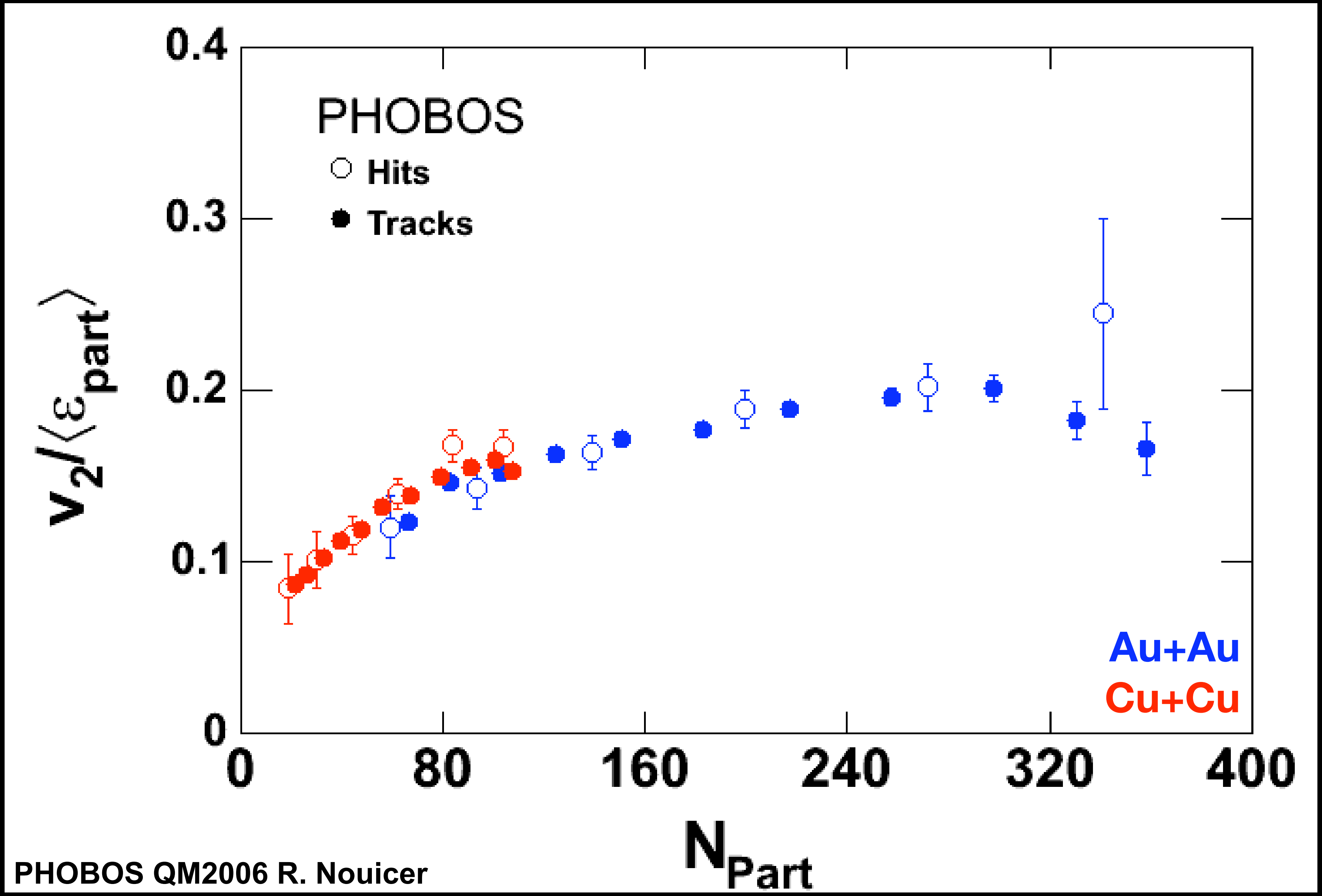
Participant vs. Standard



Something wrong...

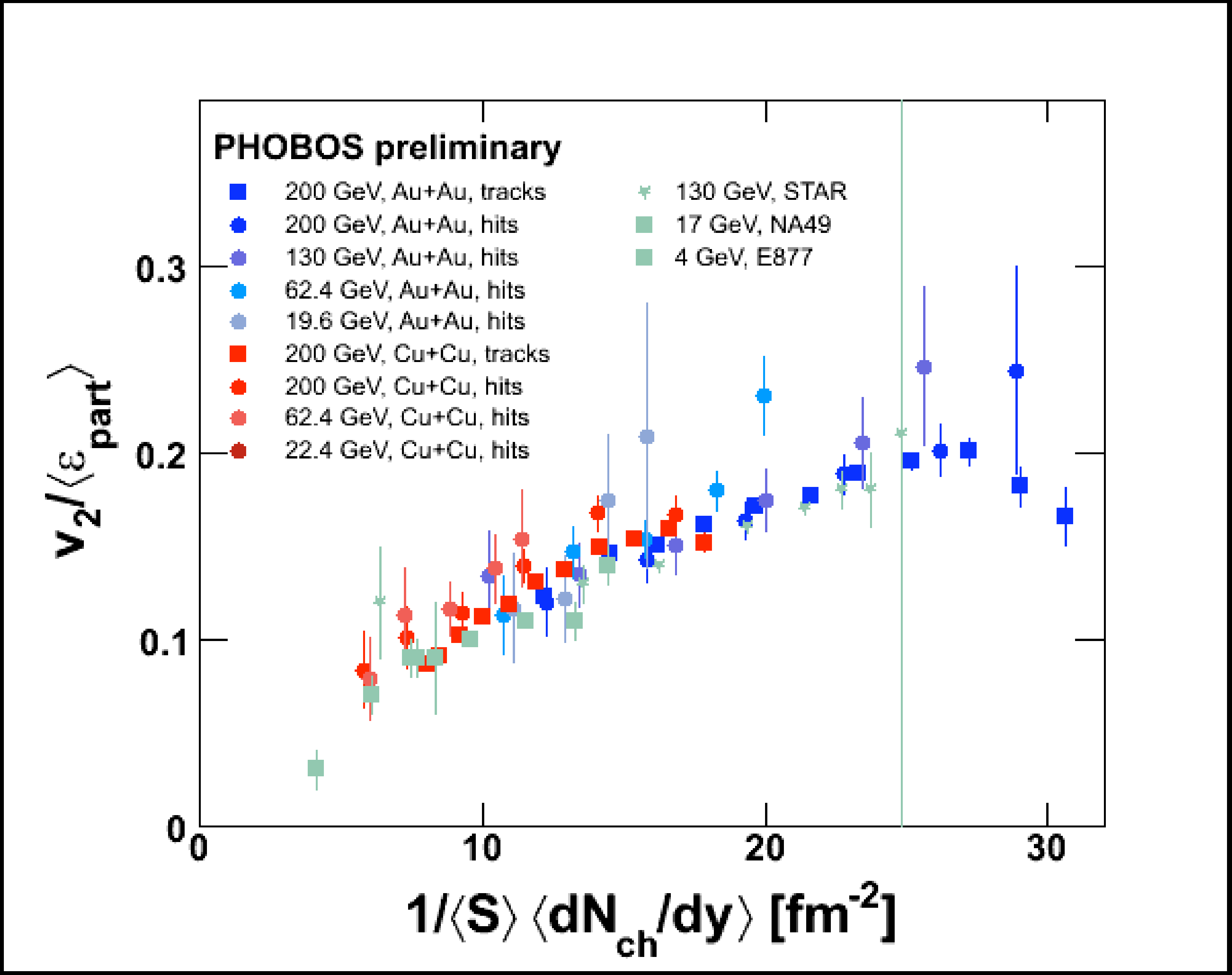


...leads to scaling



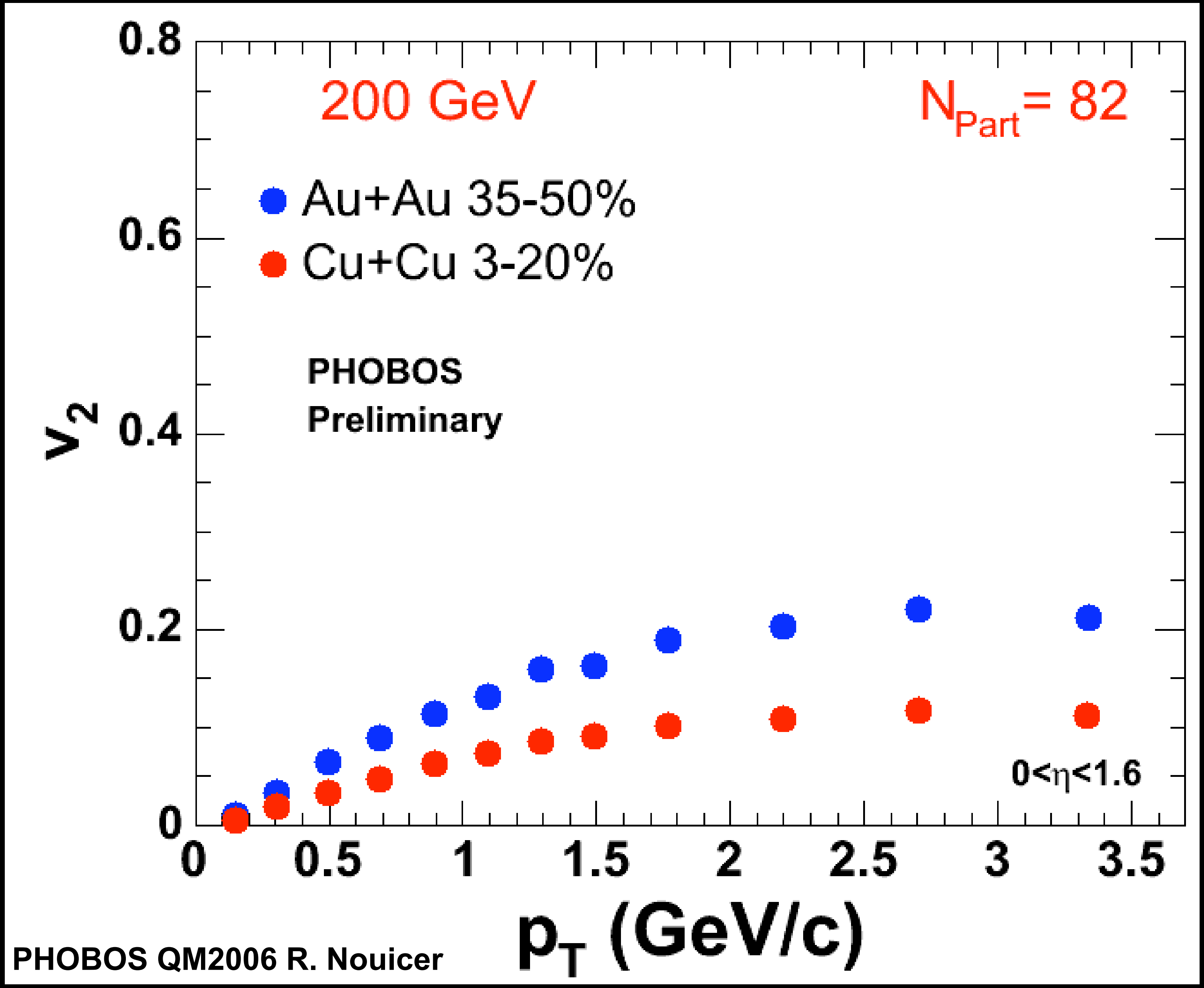
vs. Areal Density

PHOBOS QM2006



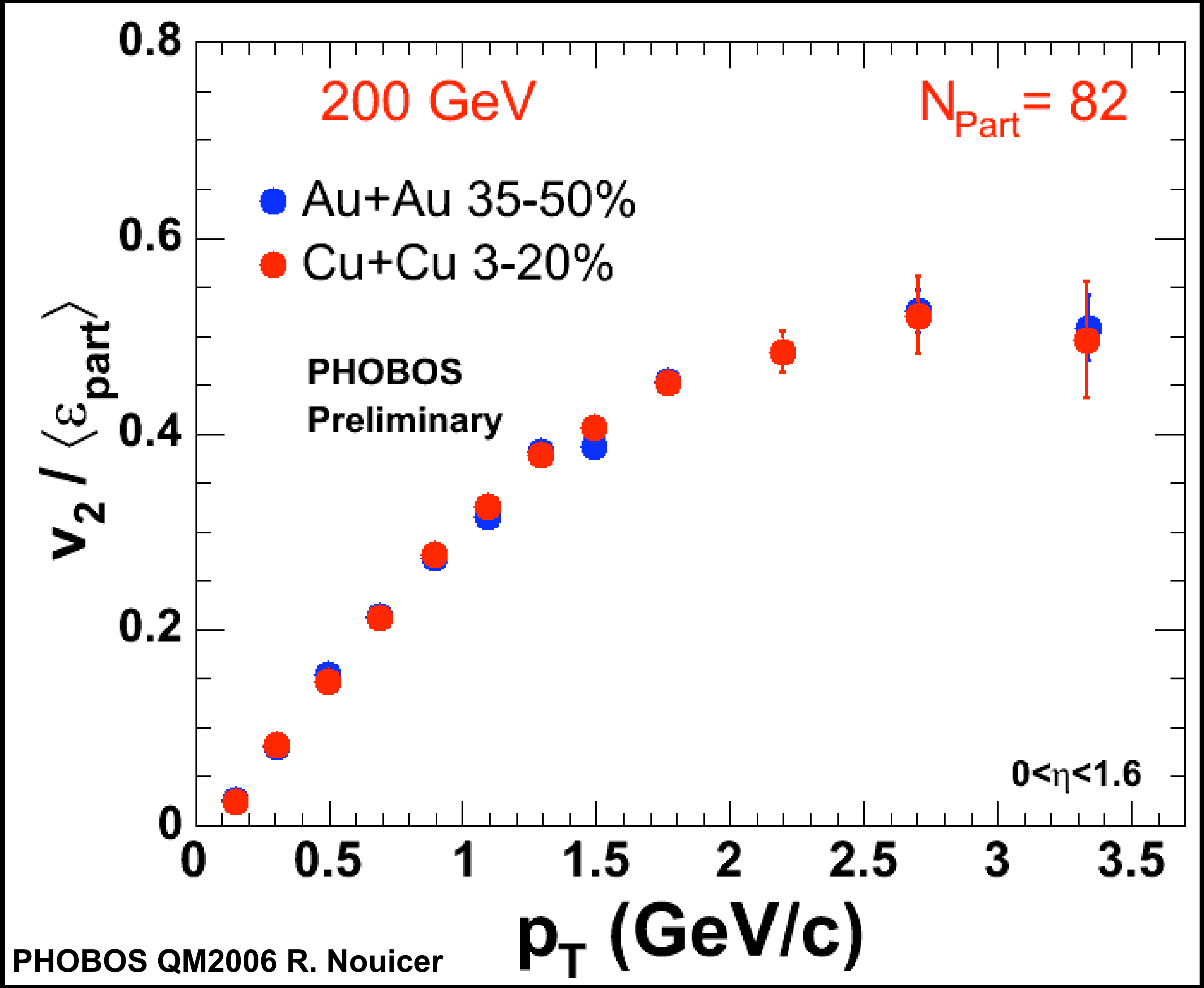
statistical errors only

Transverse Momentum



Choose two bins with same N_{part} (~same density)

Transverse Momentum

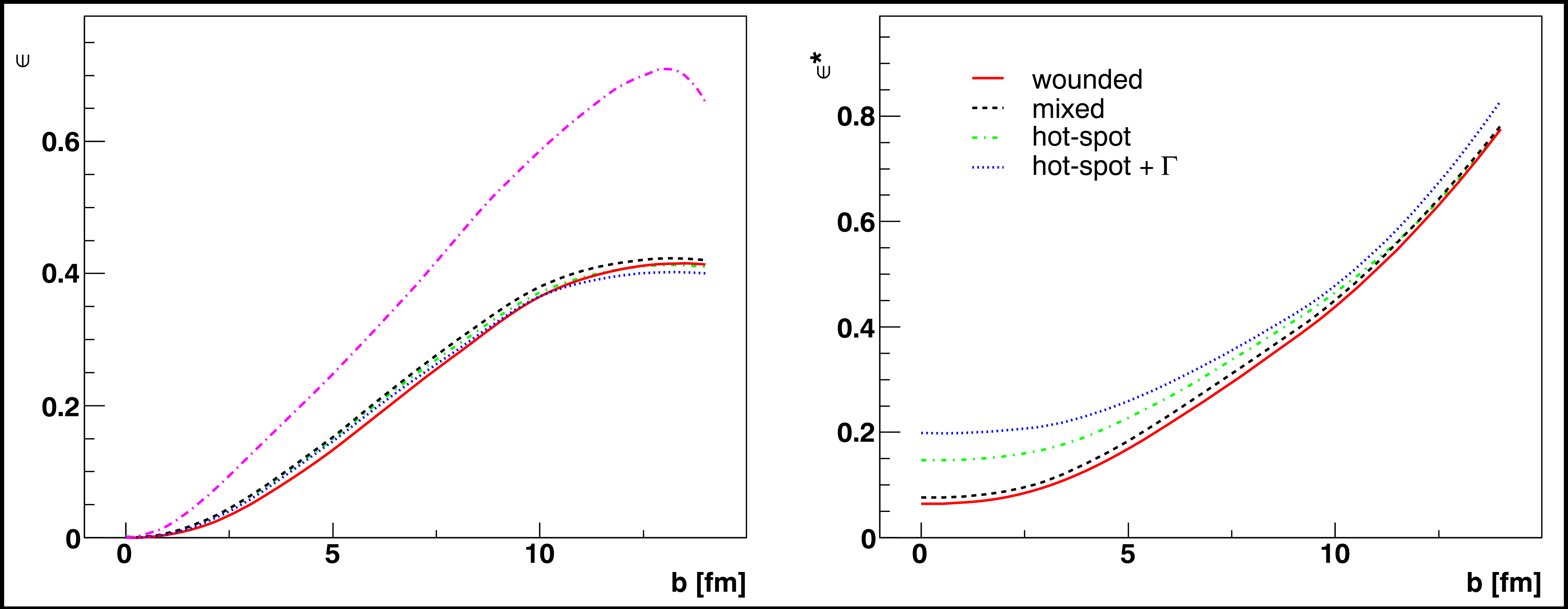


Unity of geometry, system, energy, p_T

at same N_{part}

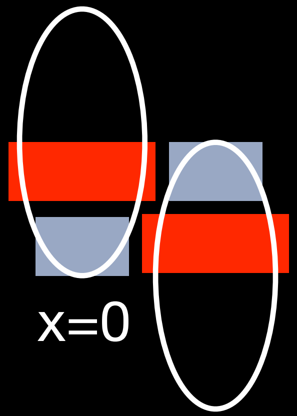
Production Model

Broniowski et al



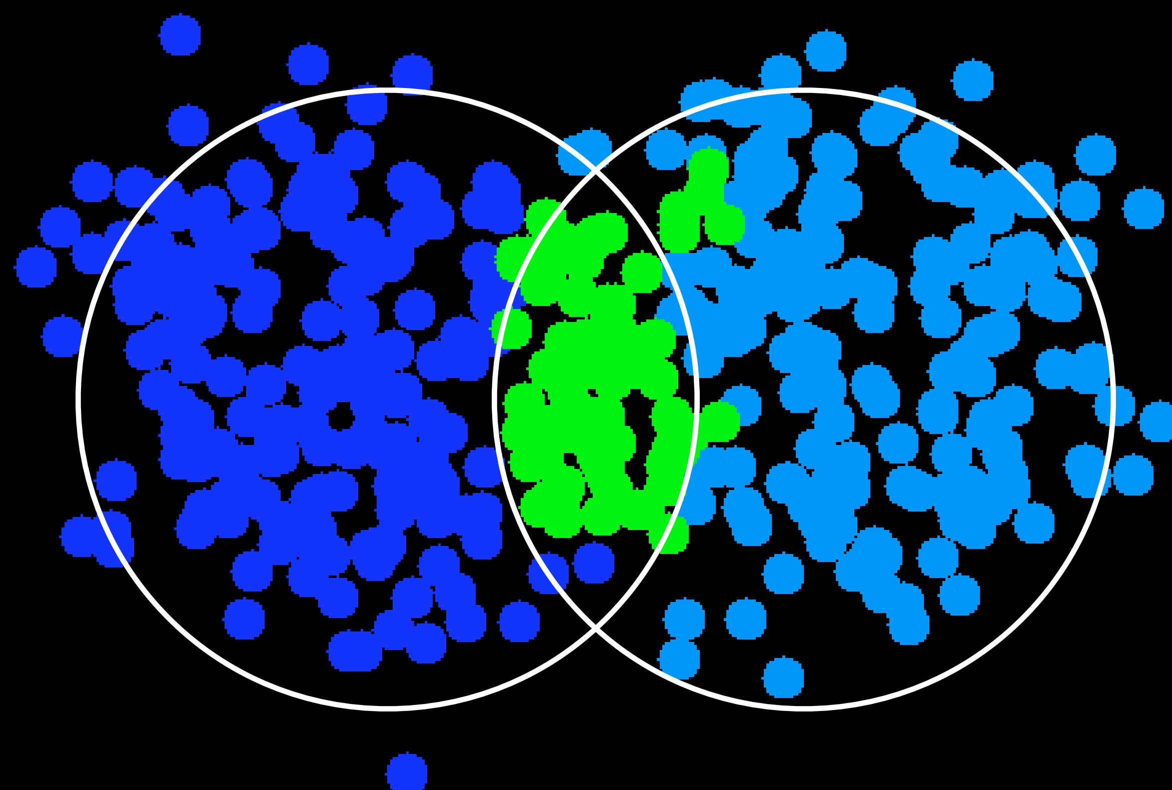
Generally, ϵ not sensitive to (N_{part}, N_{coll}) if variable is <u>local</u>

(smear matter by 1-2fm to mock-up thermalization time?...TBD)



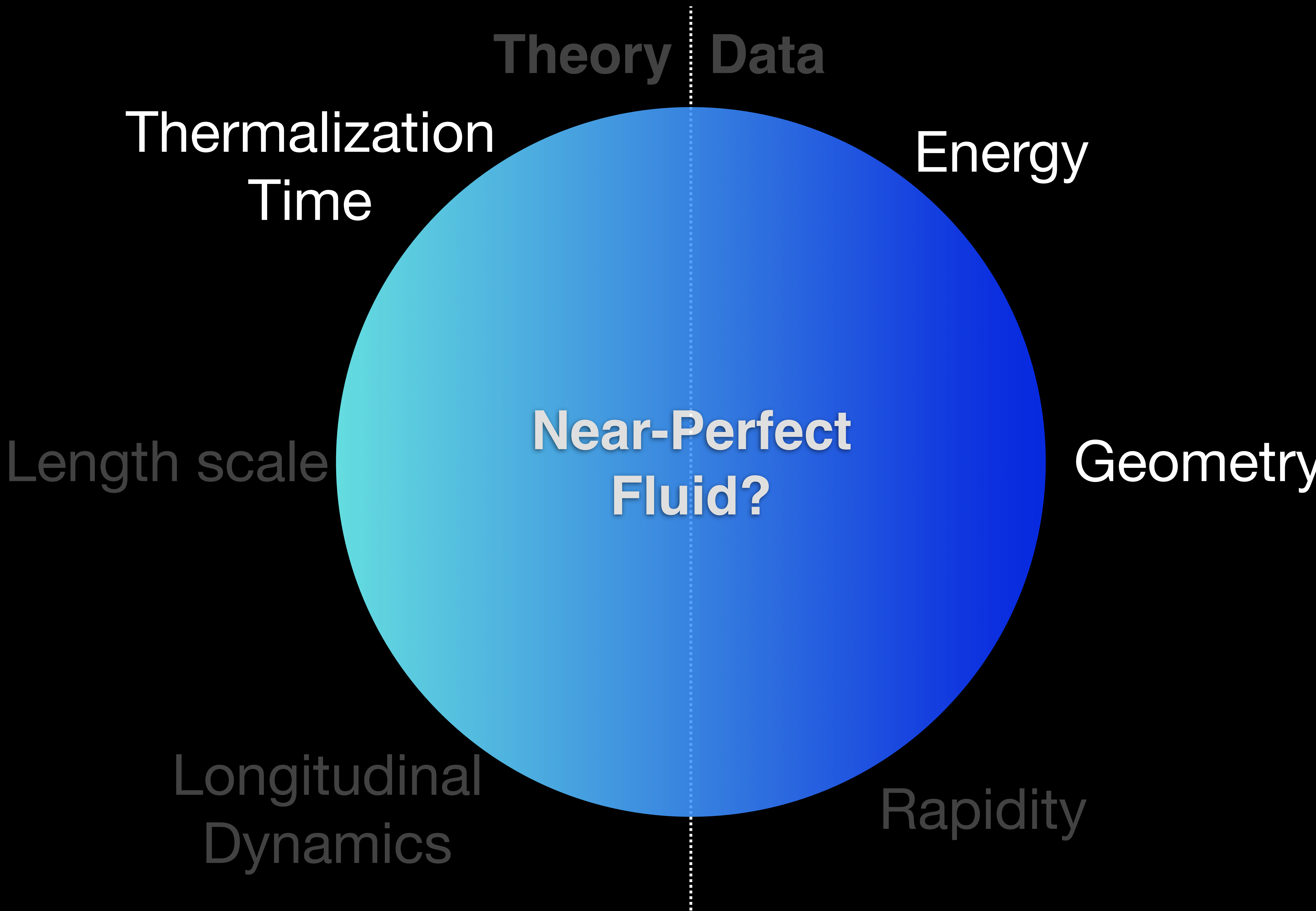
CGC models “throw away” information and get large eccentricities (Adil, et al)

“Freeze-in”

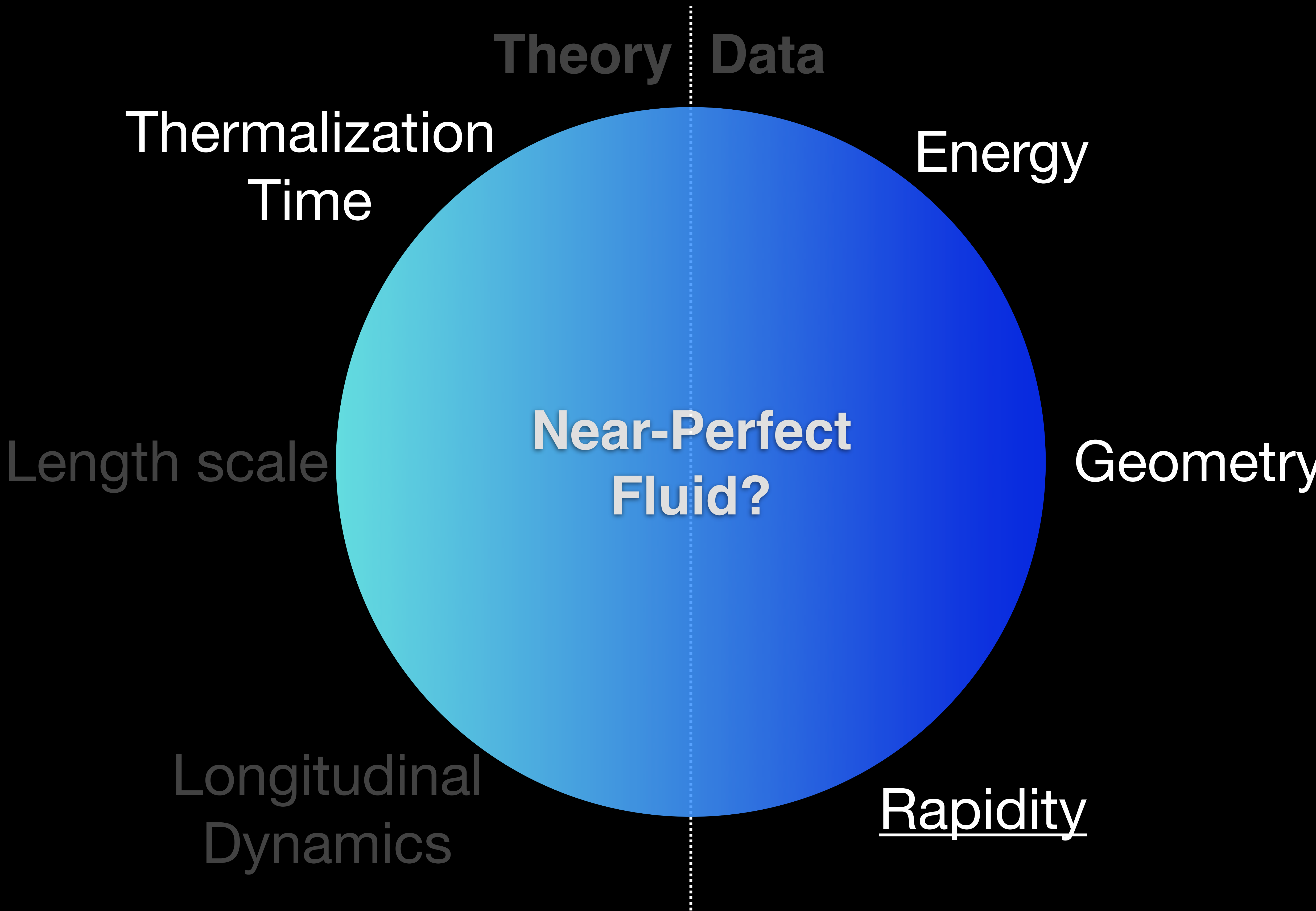


Configuration established <u>early</u> and <u>preserved</u>:
<u>substantial viscosity</u> or <u>long thermalization times</u>
generates entropy under different geometric conditions

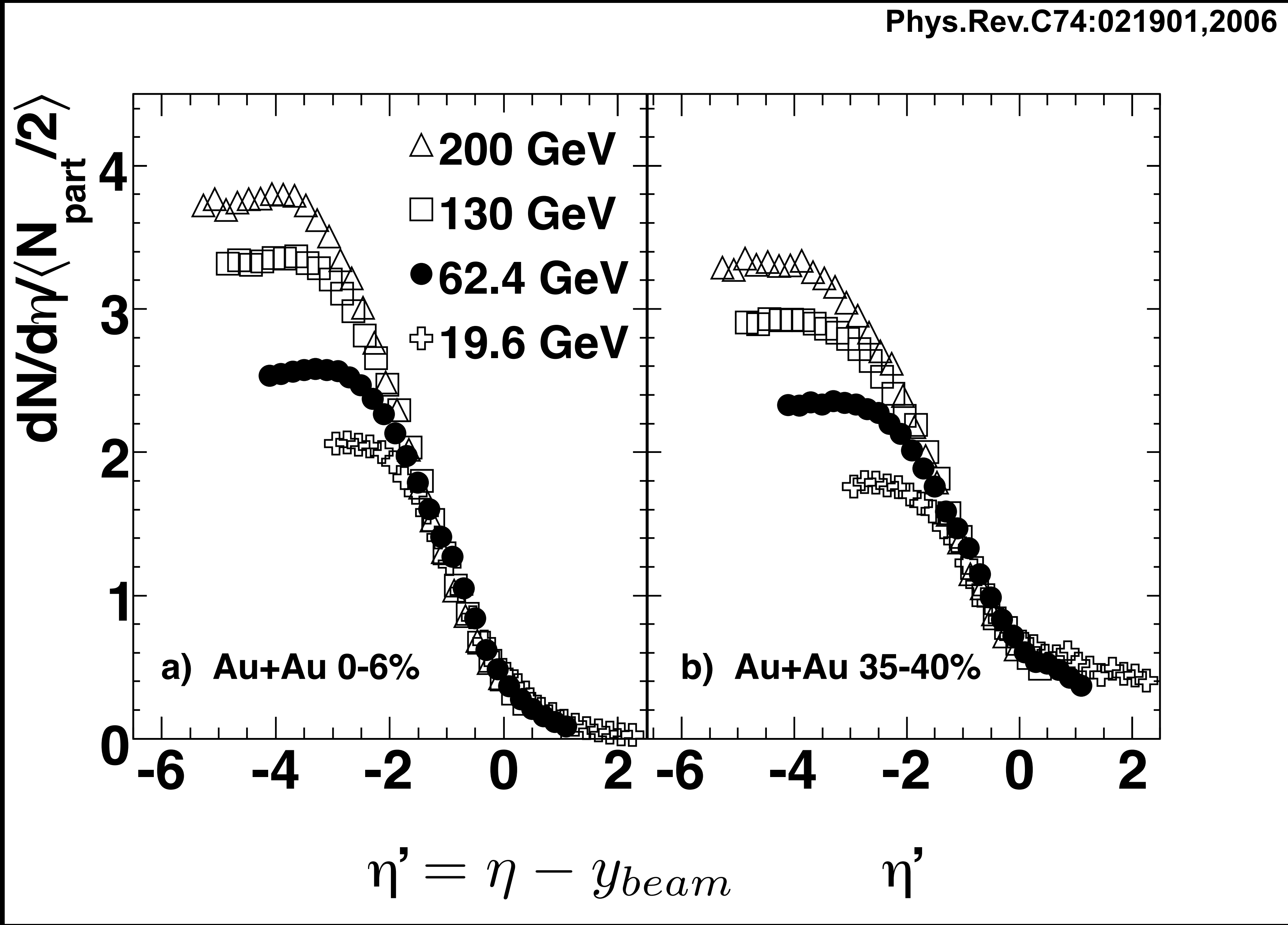
Energy/geometry systematics at $\eta=0$ suggest small τ_0



What about “the rest” of particle production, η≠0?



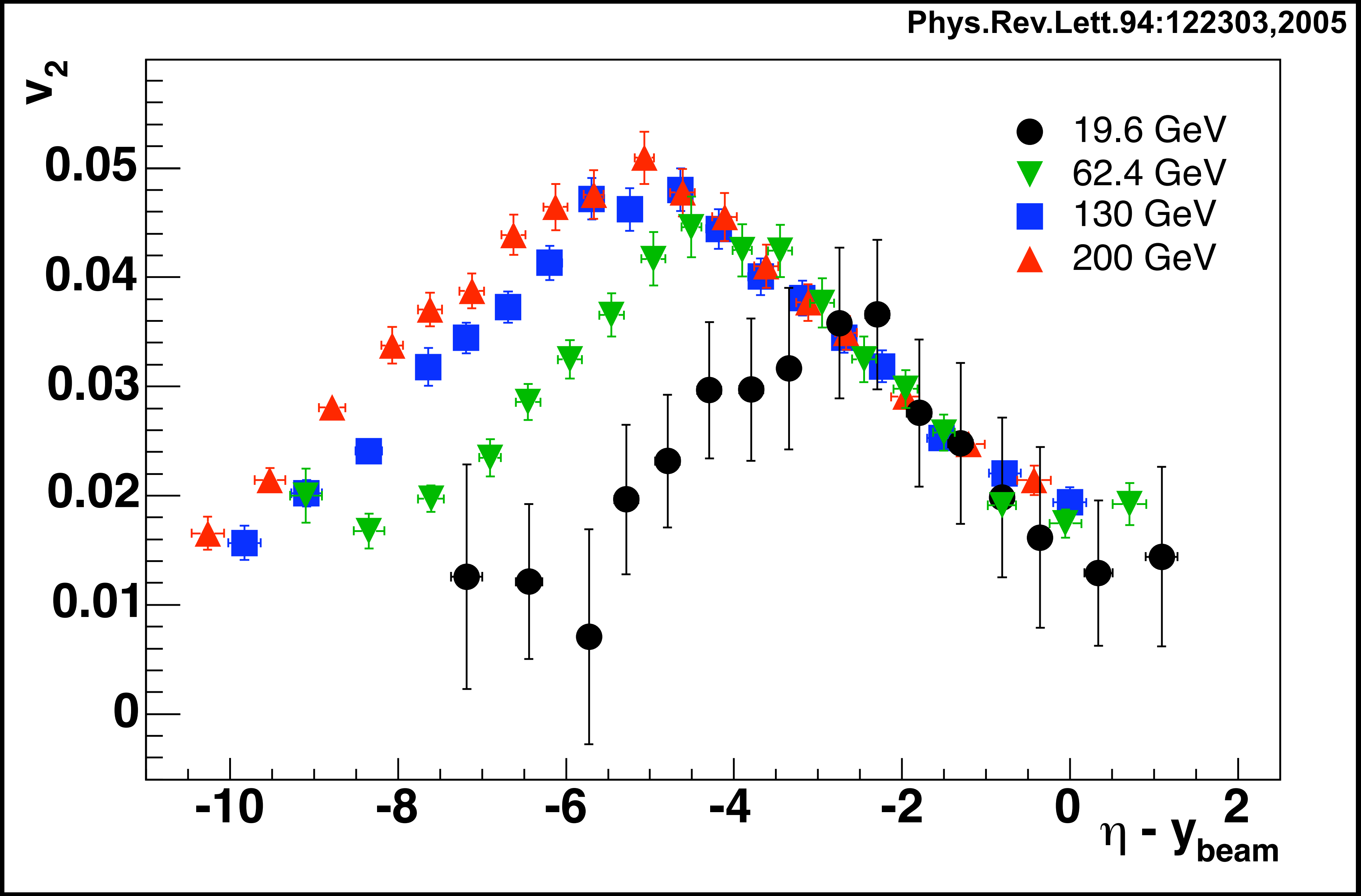
Longitudinal Scaling



N.B.
N_{part} scaling
of total mult.
from <u>global</u>
modification
of dN/dη'

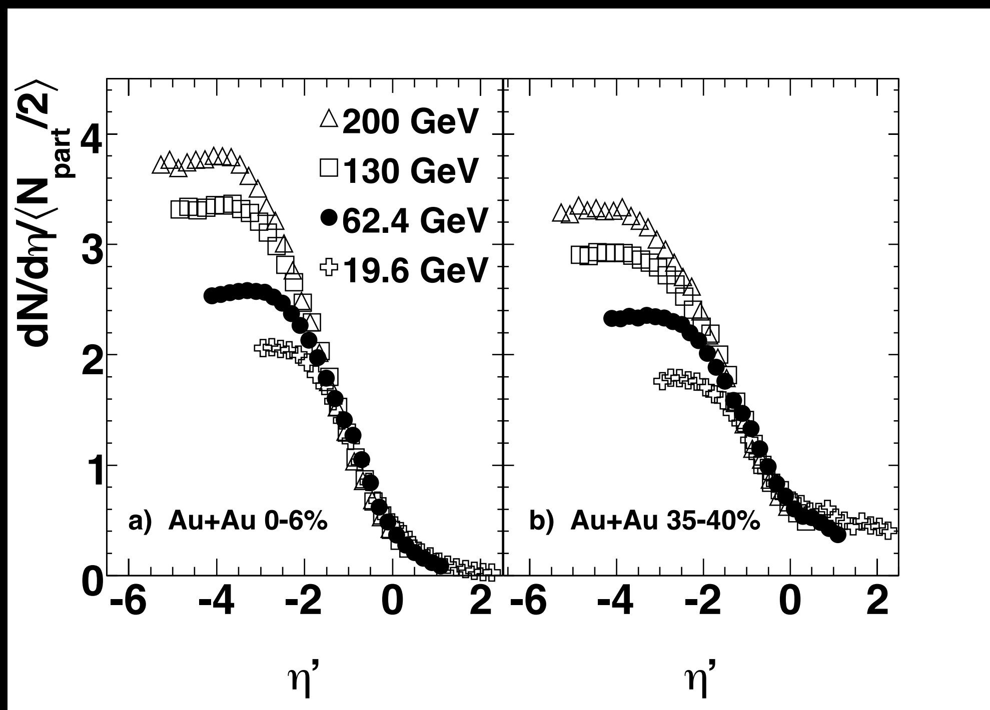
In "limiting fragmentation" frame, one sees that <u>entire angular distribution</u> changes with centrality, in an <u>energy-independent</u> way

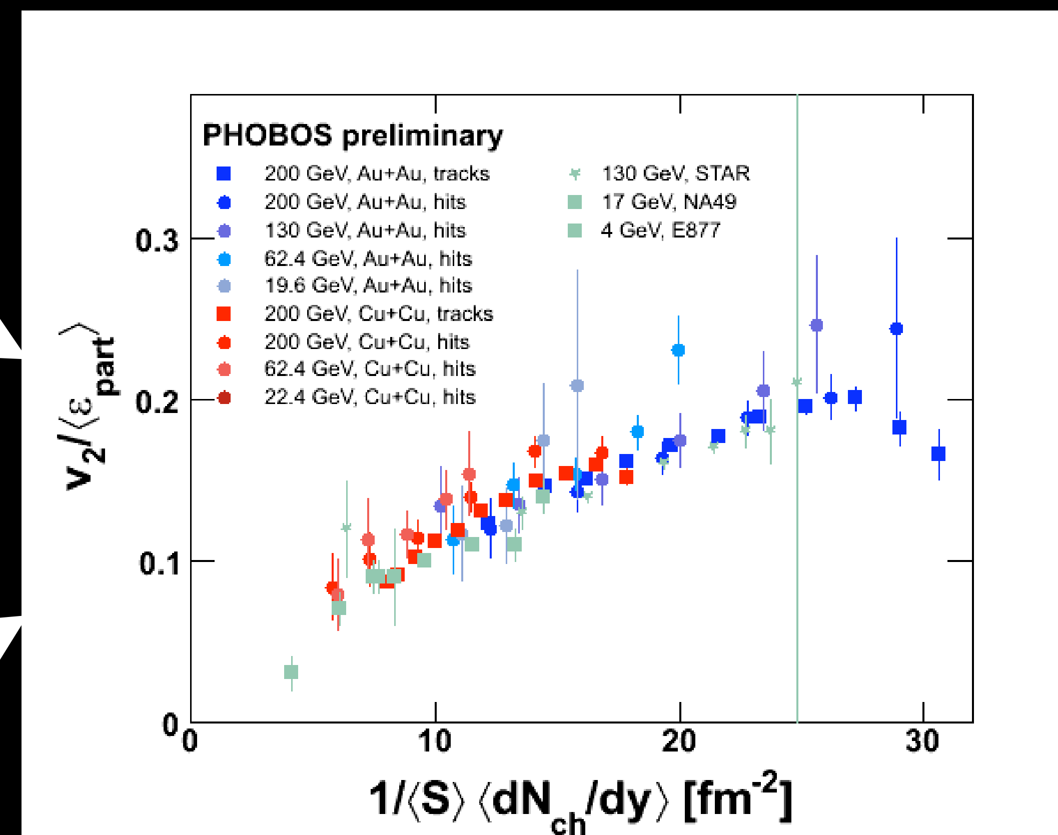
Longitudinal Scaling

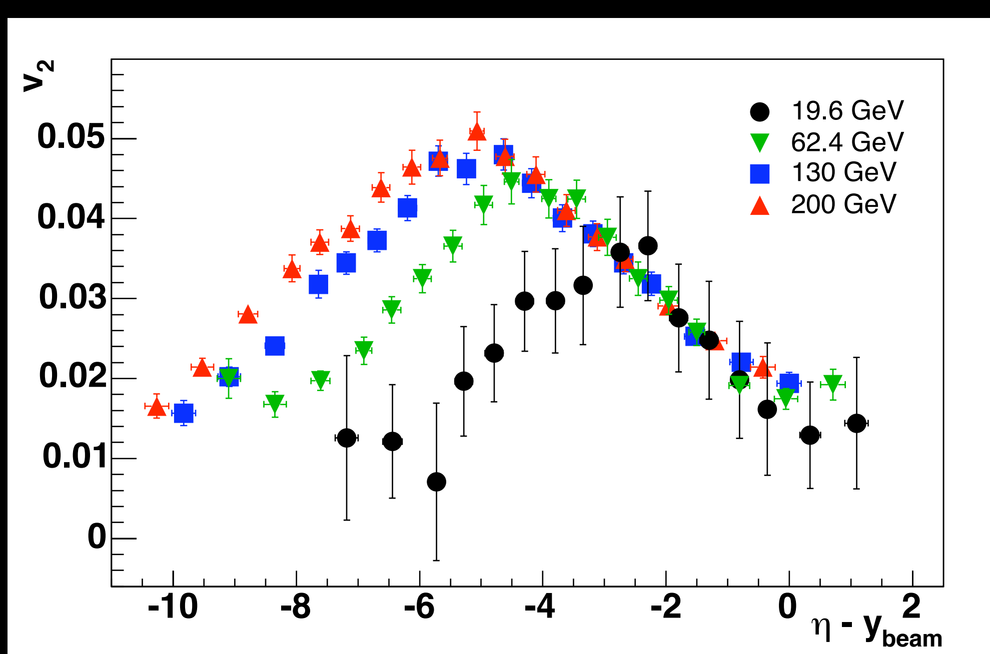


Elliptic flow is invariant when viewed in the same “limiting fragmentation” frame

Unity of Response

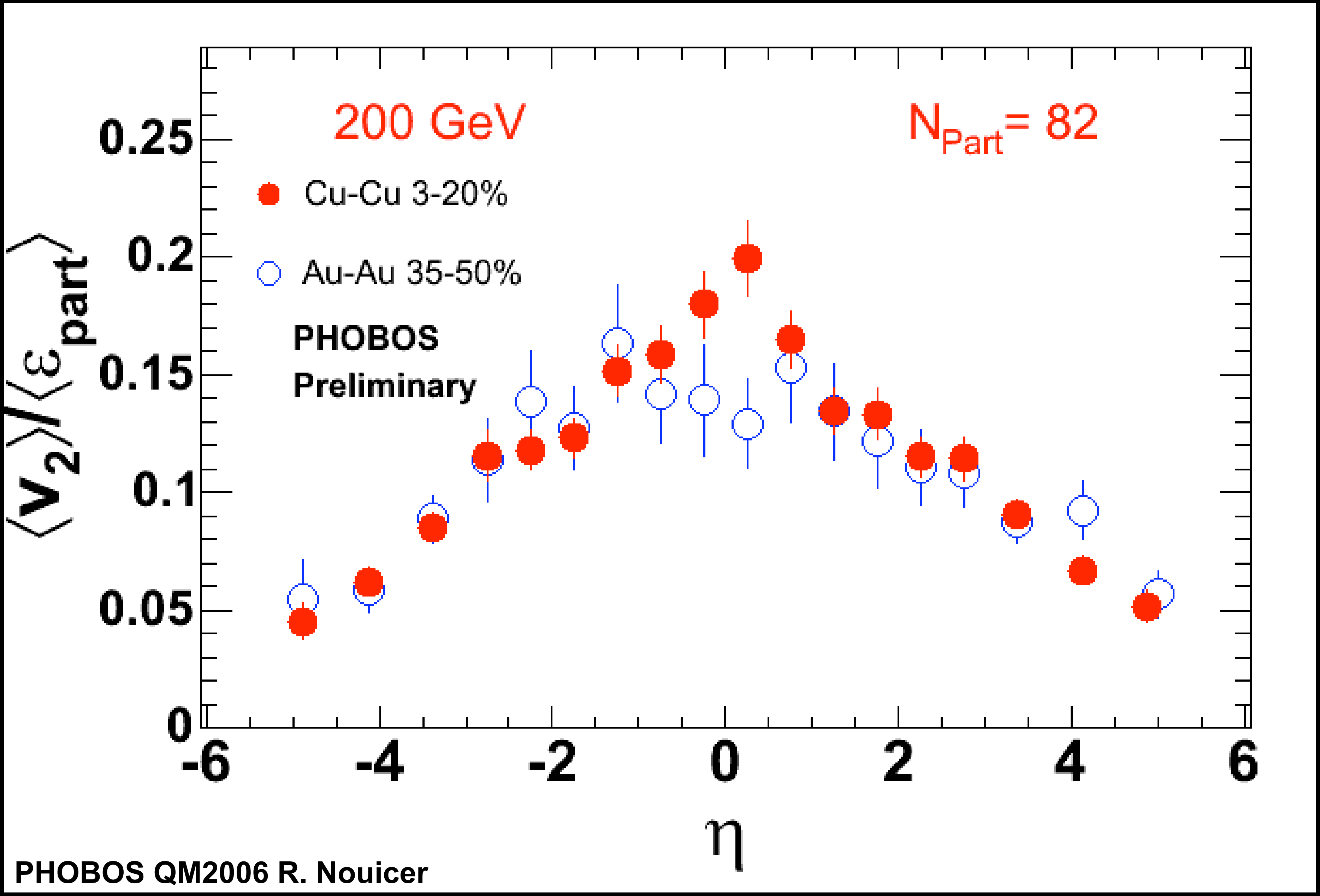






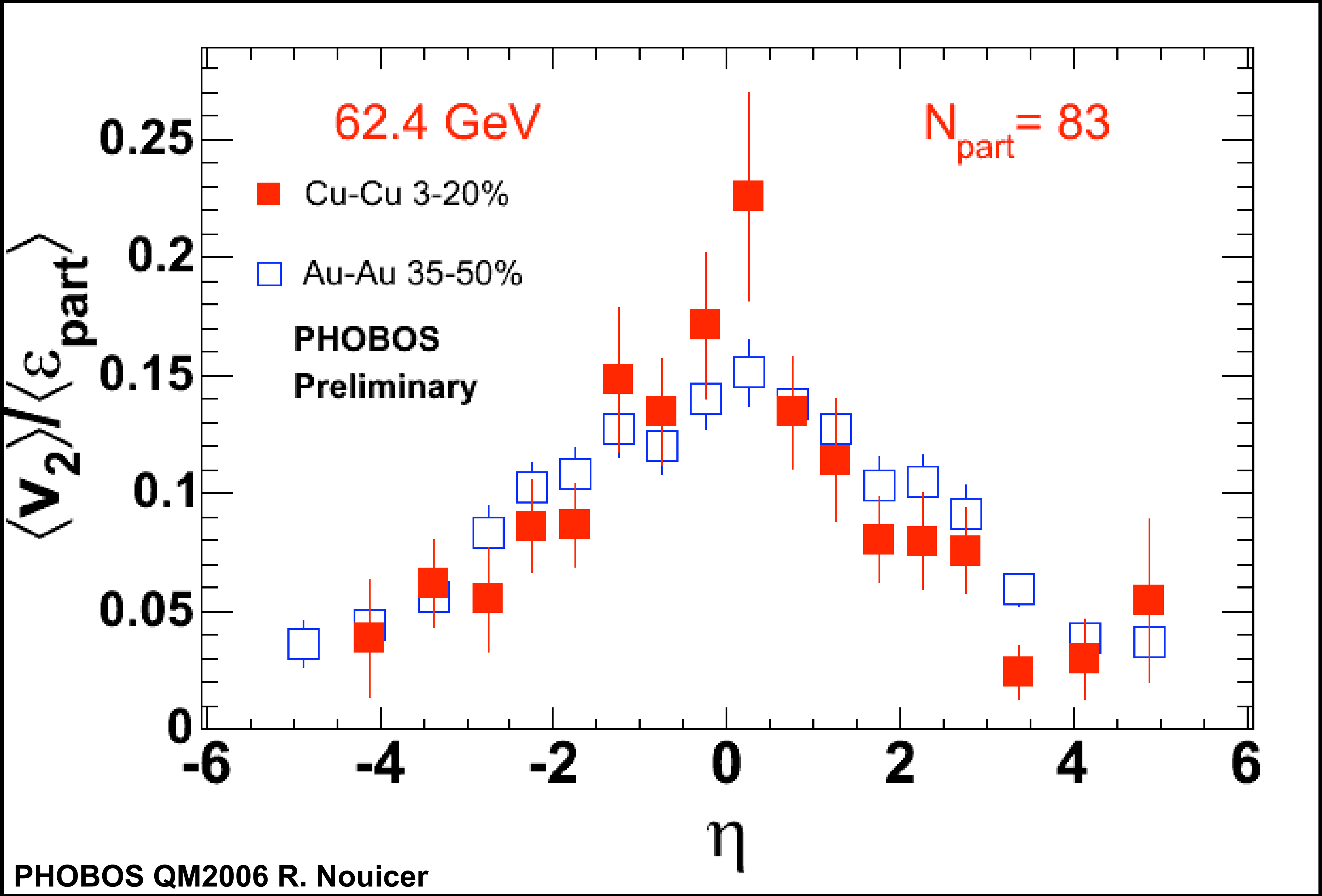
v_2 seems to respond ~linearly to particle density at all energies, rapidities, & centralities

Eccentricity is Global



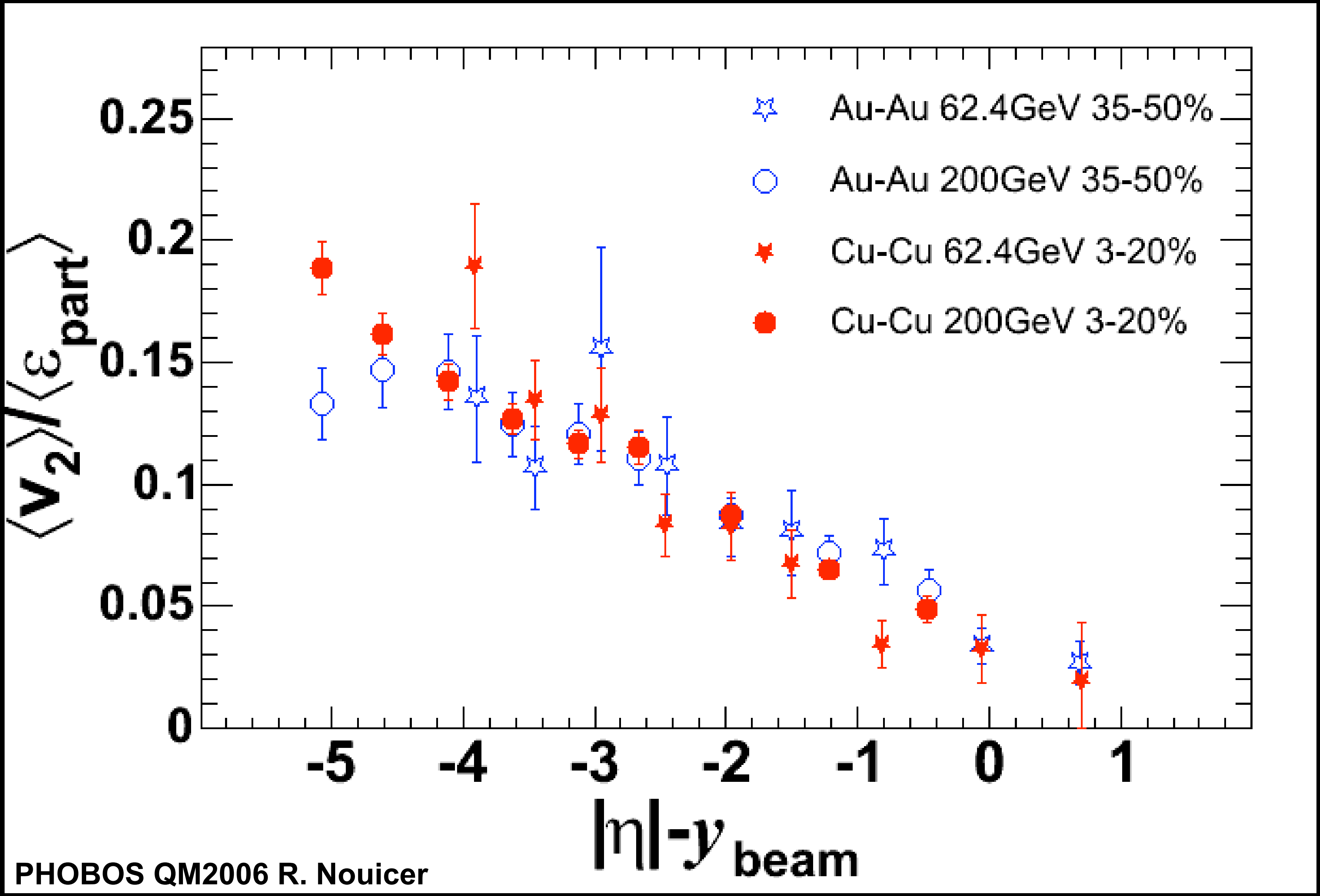
Participant eccentricity unifies different systems
at same N_{part}, at all pseudorapidities:
source shape does not change with η

Eccentricity is Global



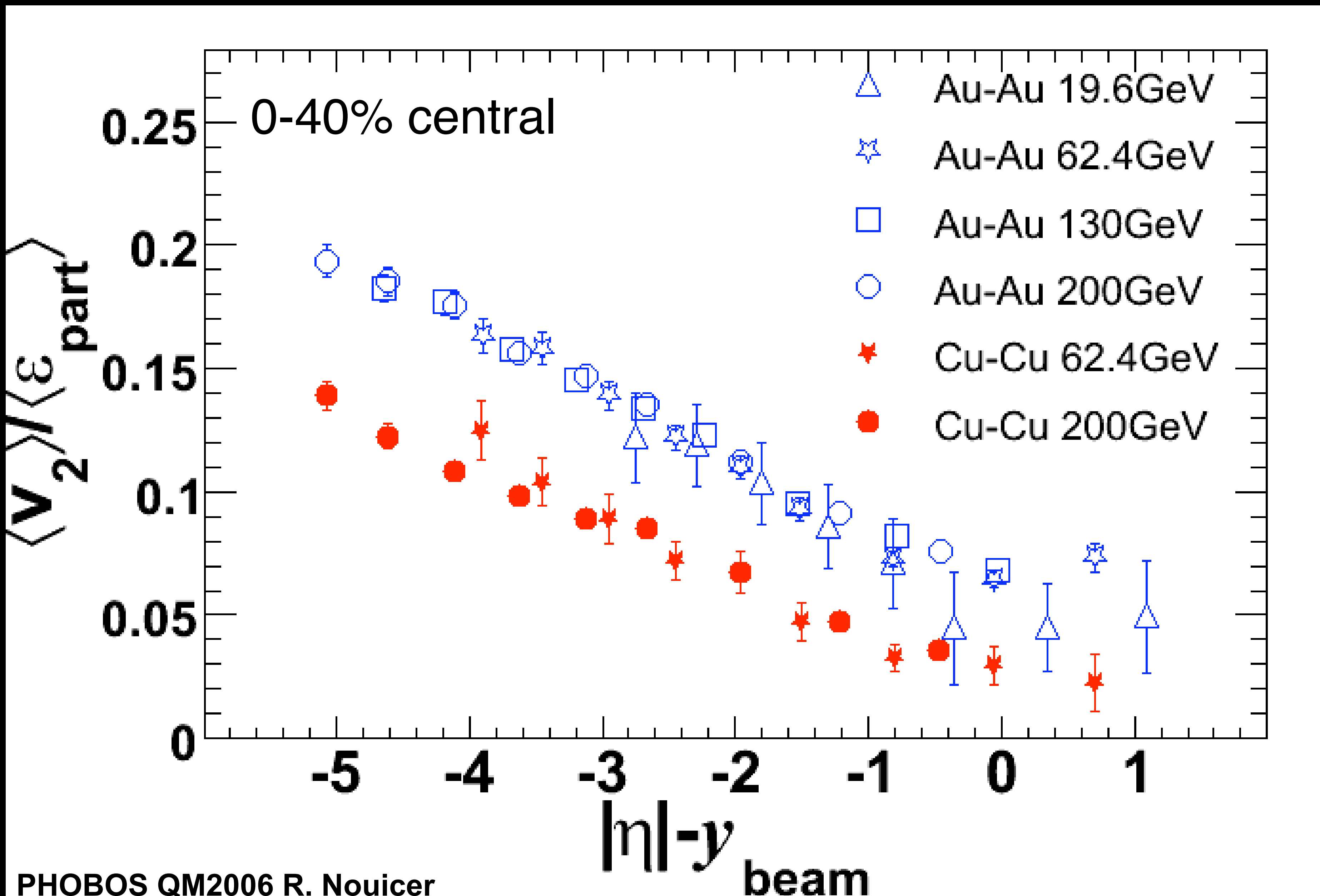
Participant eccentricity unifies different systems
at same N_{part}, at all pseudorapidities:
source shape does not change with η

Same N_{part}



Unity of geometry, system, energy, rapidity
<u>at same N_{part}</u>

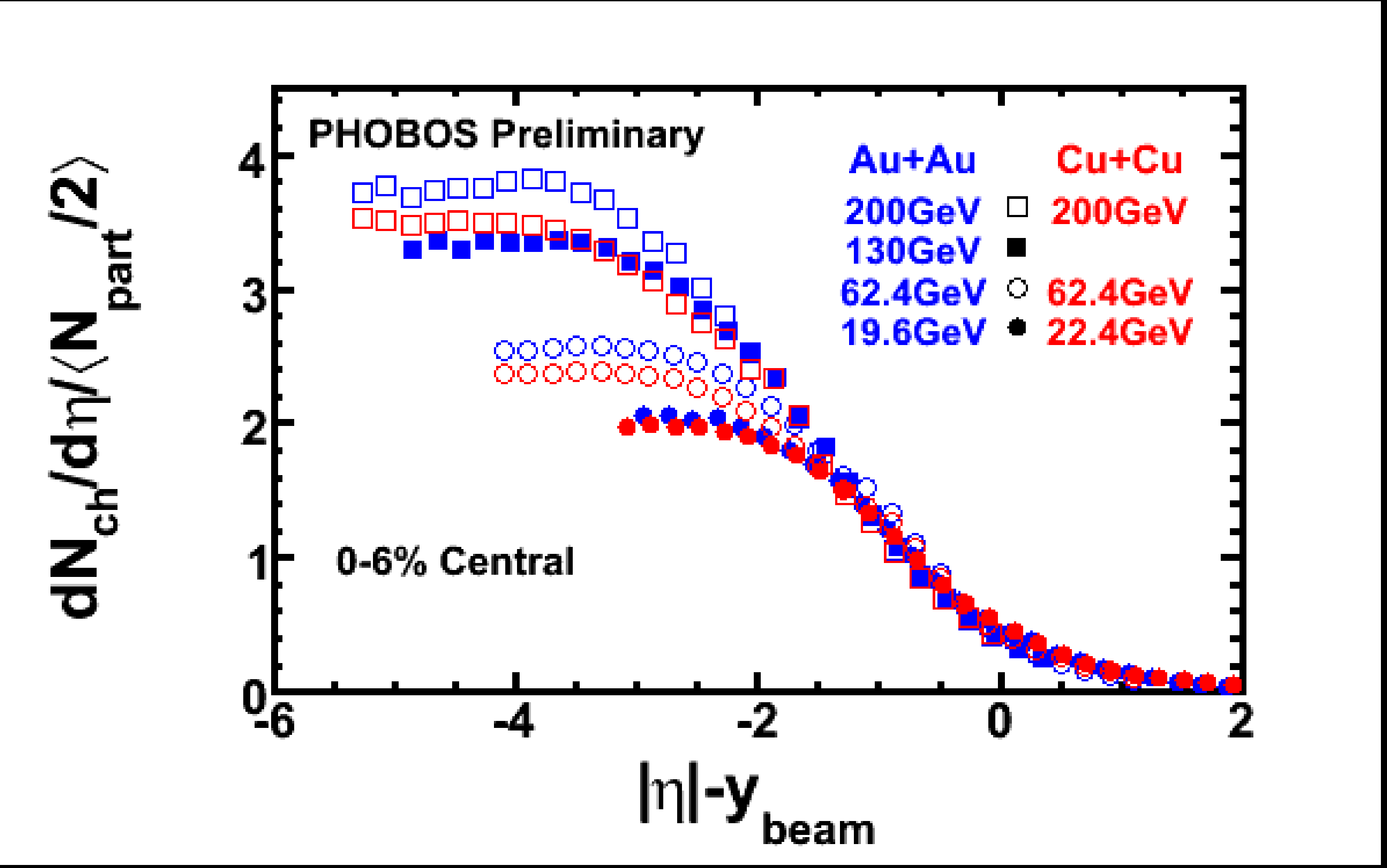
Different N_{part}



At same fraction of cross section (~b/2R),
observe longitudinal scaling, but system dependence

Cross Section Scaling

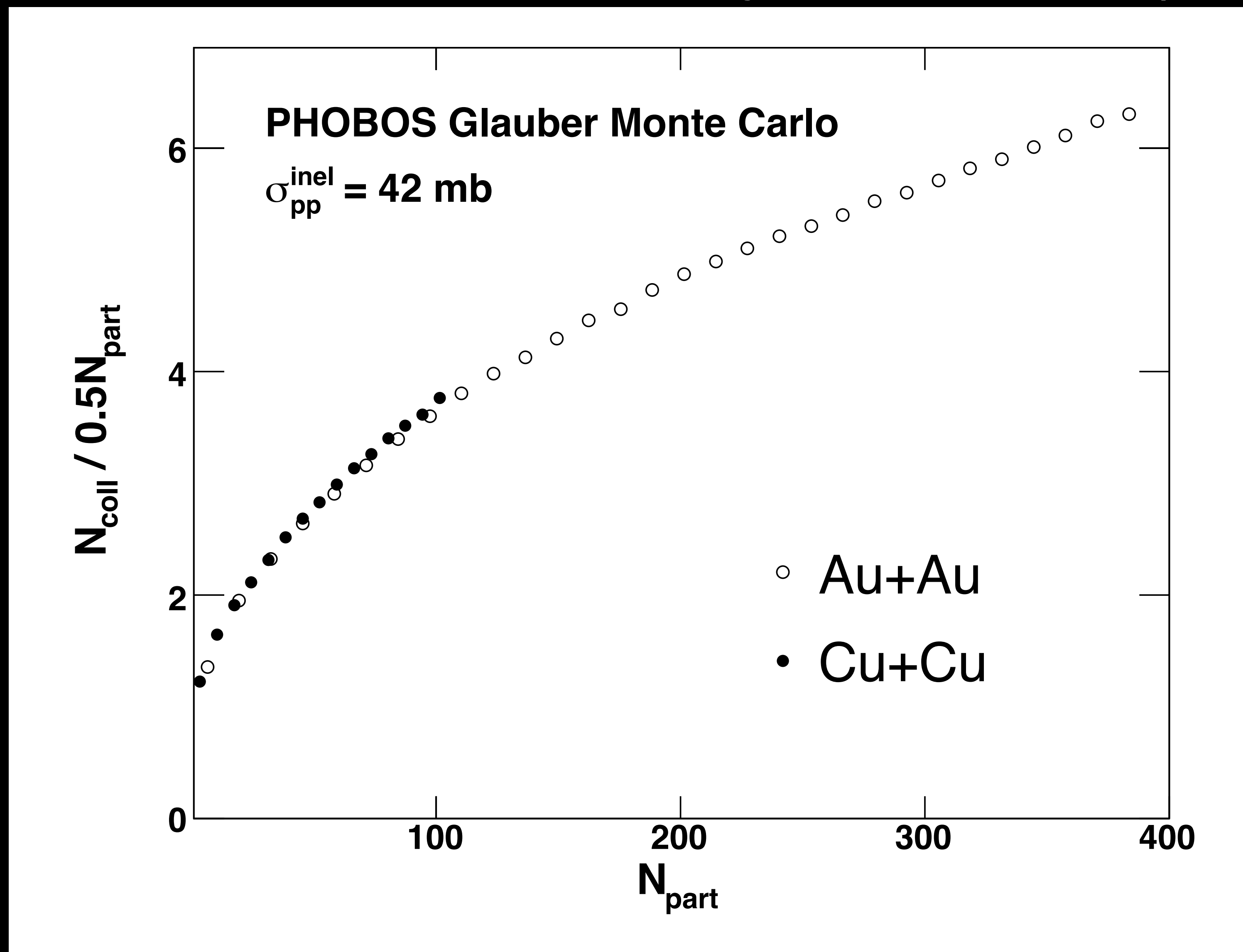
PHOBOS QM2006



Curious, since longitudinal distributions of particle multiplicities are similar when matching fraction of cross section...

Au+Au vs. Cu+Cu

Phys. Rev. Lett. 96, 212301 (2006)

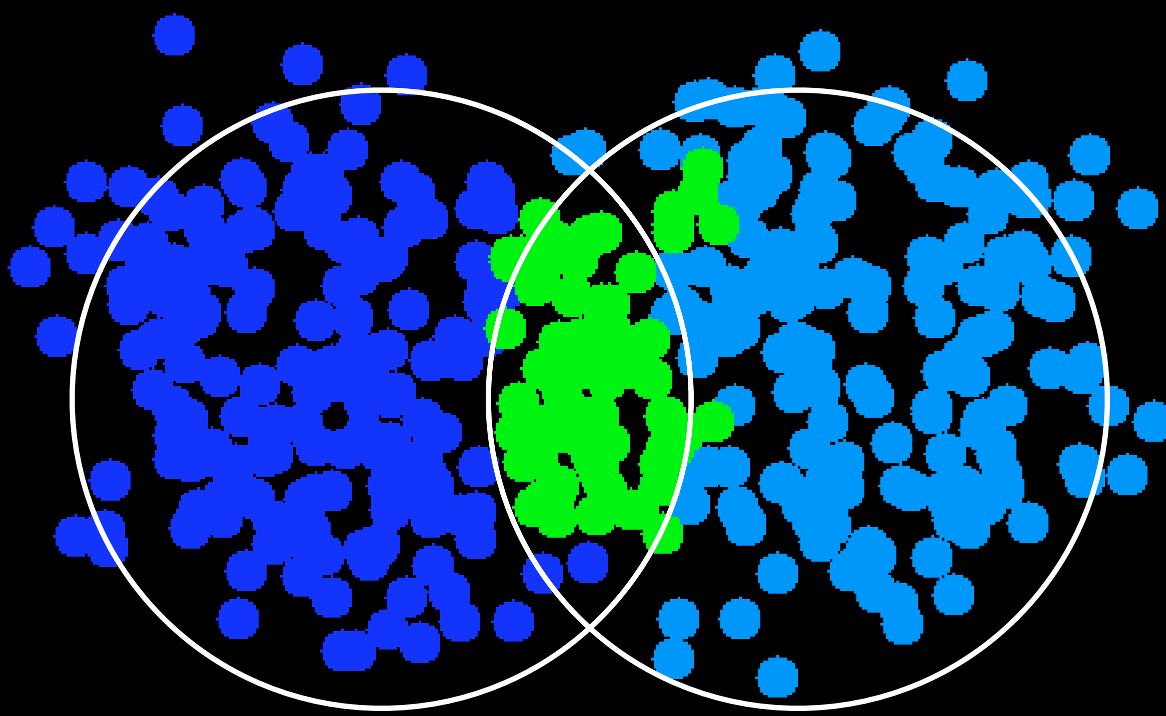


Same nuclear thickness? Same total particle density?

or, transverse observables: N_{part}

longitudinal observables: cross section?

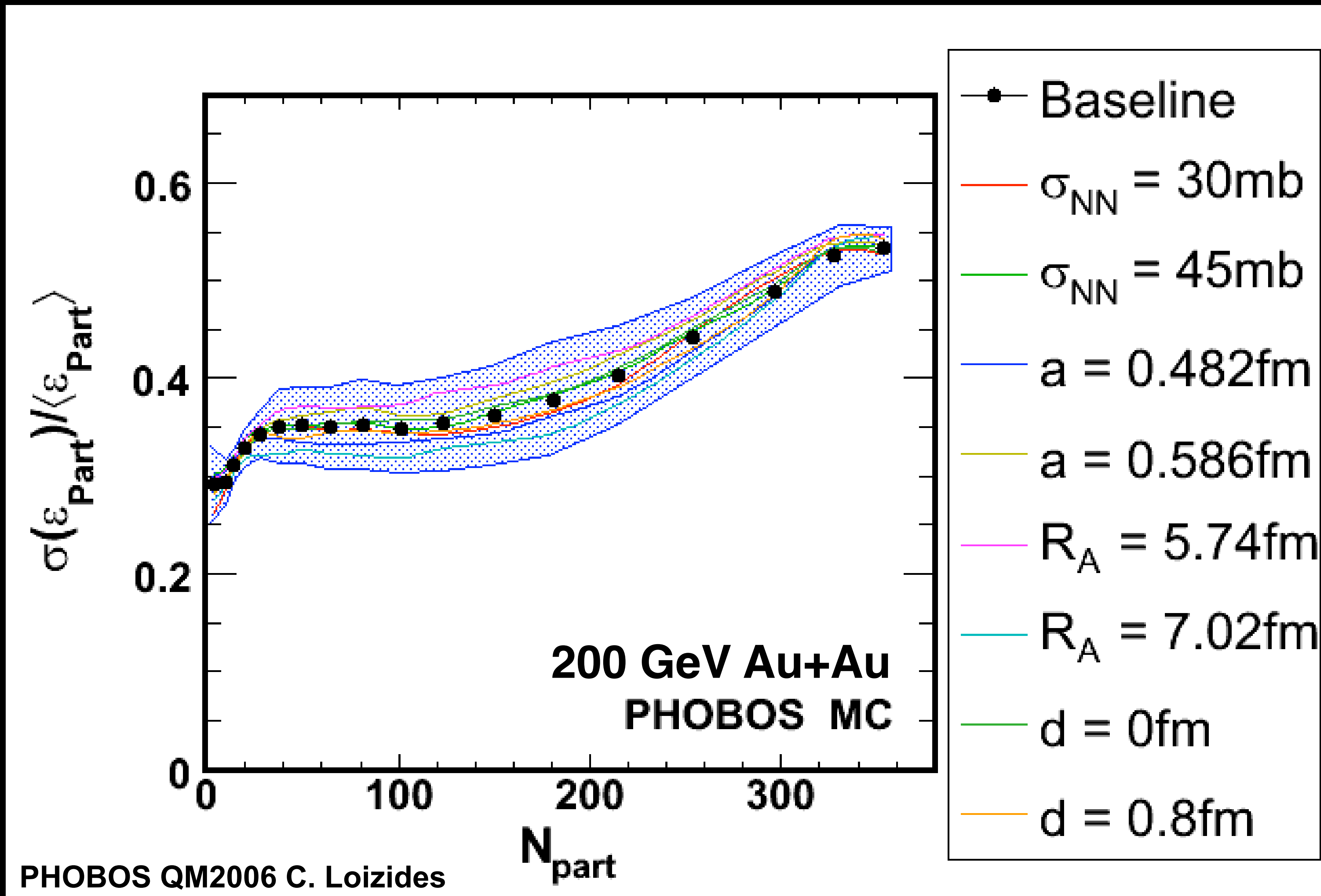
Flow Fluctuations



Configuration is transmitted to particles at all rapidities and (observed) p_T.
Does this hold event-by-event?

strong assumption: $v_2 \propto \epsilon_{part}$ ➡ $\frac{\sigma_{v_2}}{v_2} = \frac{\sigma_{\epsilon_{part}}}{\epsilon_{part}}$ B. Alver Wednesday

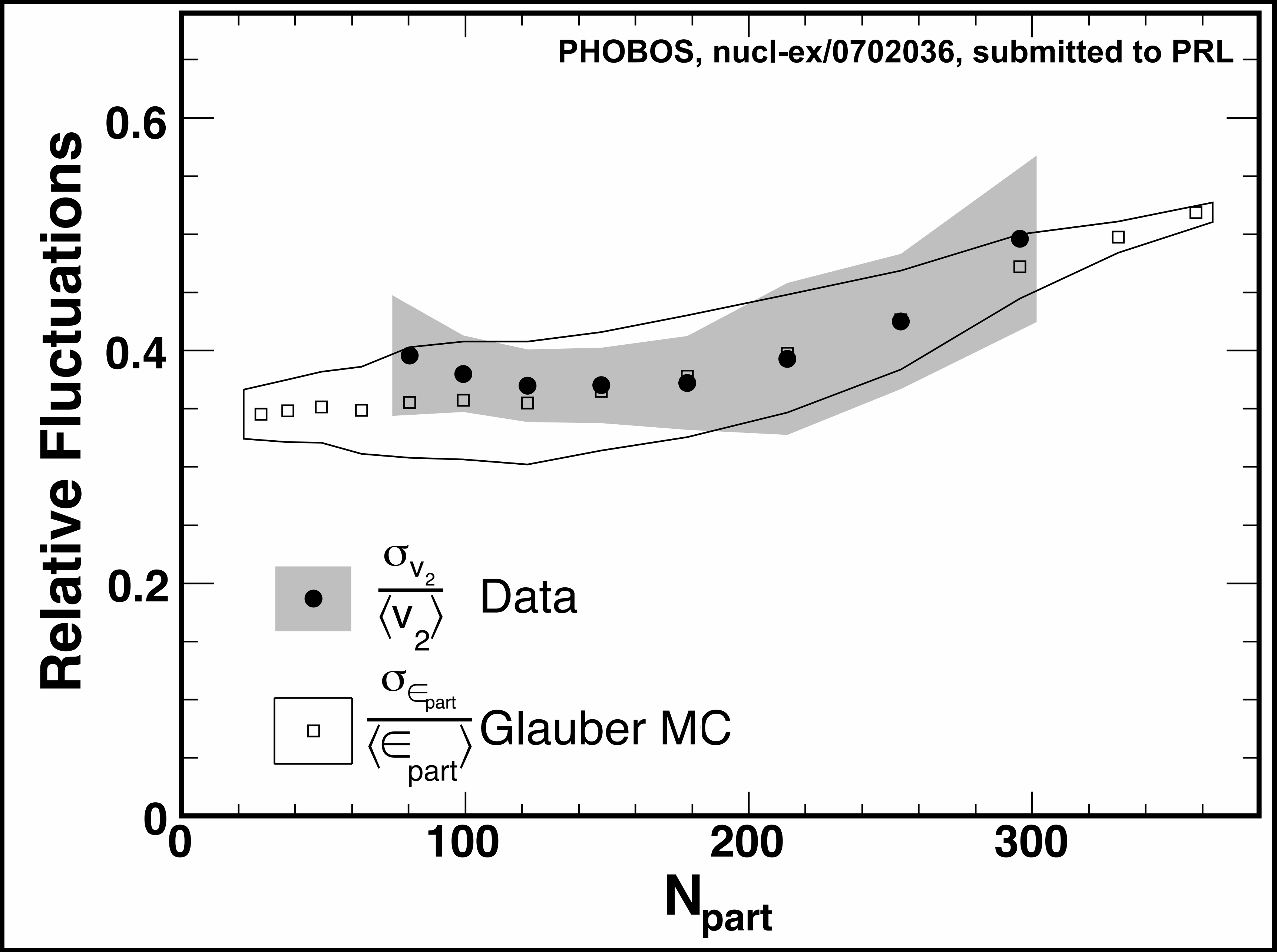
v_2 Fluctuations in GMC



MC approach makes definite prediction for event-by-event fluctuations of ϵ_{part}~40%
(robust against variation in Glauber MC parameters)

Flow Fluctuations Result

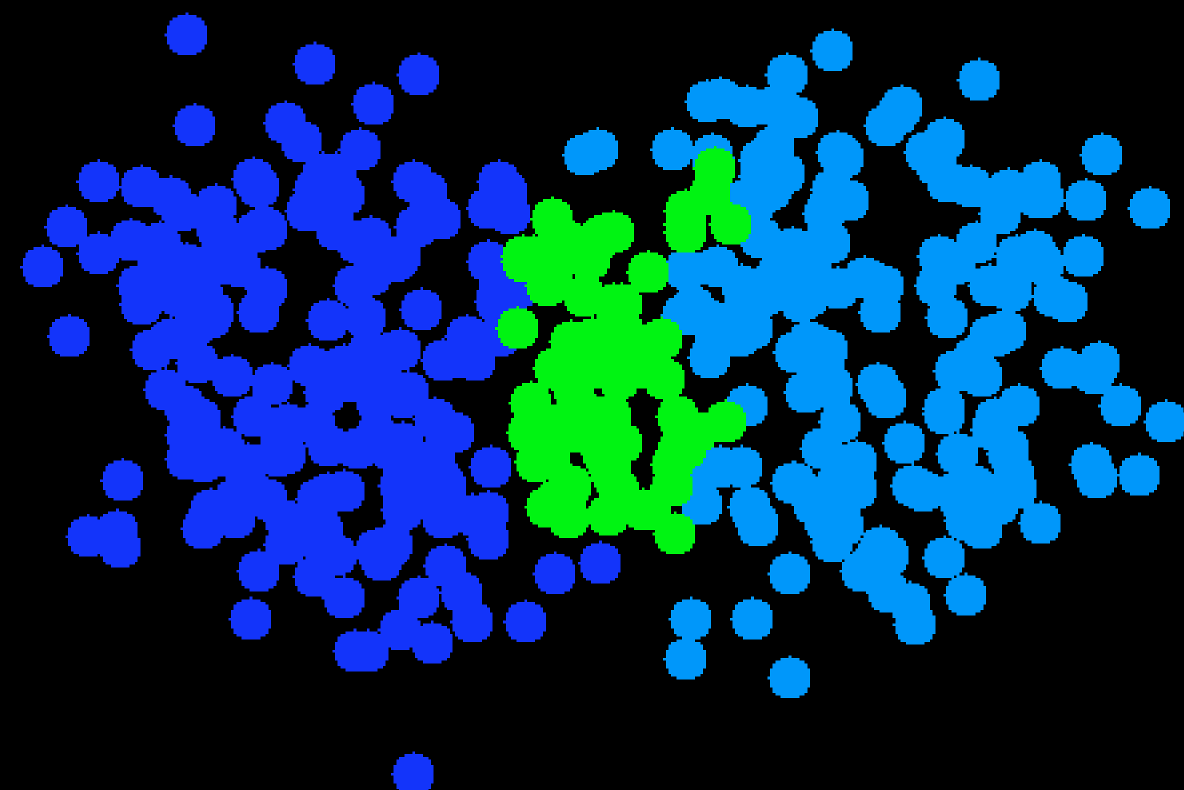
B. Alver
Wednesday



Flow fluctuations directly suggest SLP approach: configuration established <u>early</u> by <u>participants</u>, and <u>preserved</u>

Conclusions

Sudden, localized participant (SLP) matter unifies a substantial amount of experimental data.

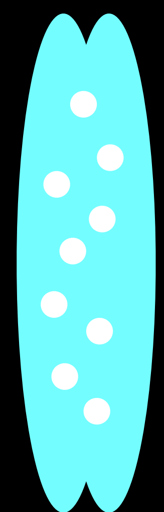


What does this imply about early time dynamics in H:IC ?

thermalization time? viscosity (dynamical length scales)?
2+1D vs. 3+1D? initial velocity gradients?
long-range rapidity correlations?

Thermalization Scenarios

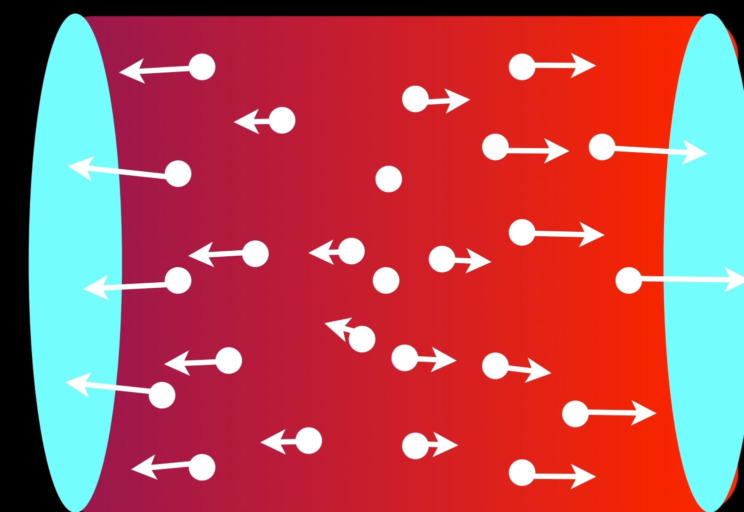
Landau



Total stopping, immediate thermalization & longitudinal re-expansion

$$\tau_0 \sim \frac{1}{\sqrt{s}} fm/c$$

Bjorken



Partial stopping, "boost-invariant" expansion

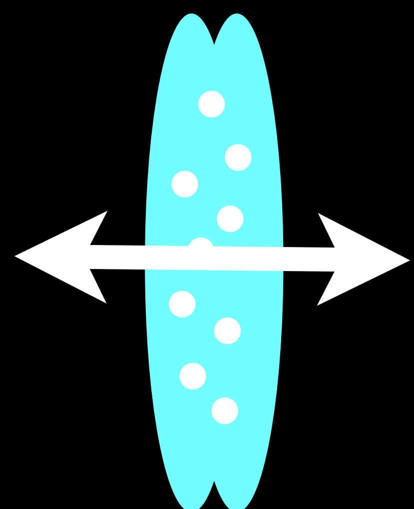
$$v = z/t$$

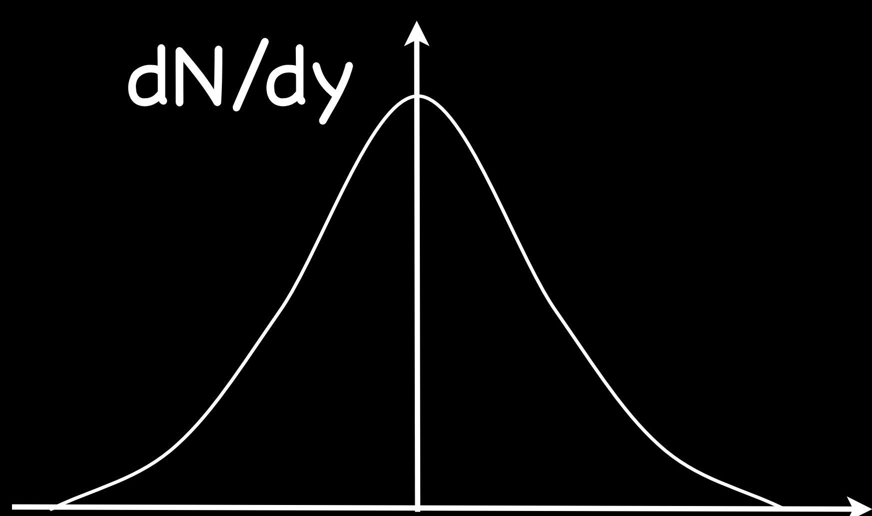
$$\tau_0 \sim 1 fm/c$$

Same hydro, different initial conditions (e.g. very different initial velocity gradients)!

Longitudinal Physics

Landau





$$\sigma_y \sim \sqrt{\log(E_{NN})}$$

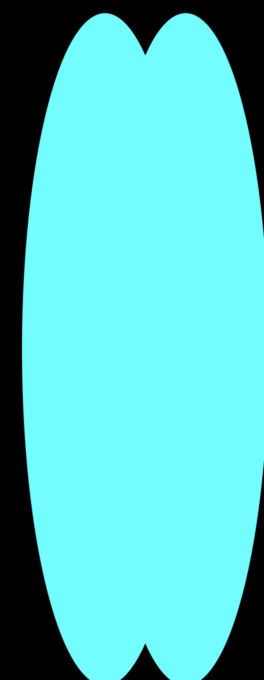
Complete stopping
in initial state
(local “freeze-in”)

These initial conditions
naturally (& rapidly) propagate
initial configuration to large y
(explains N_{ch}, dN/dy,
limiting fragmentation):

→long-range rapidity correlations

Separation of Scales

Landau

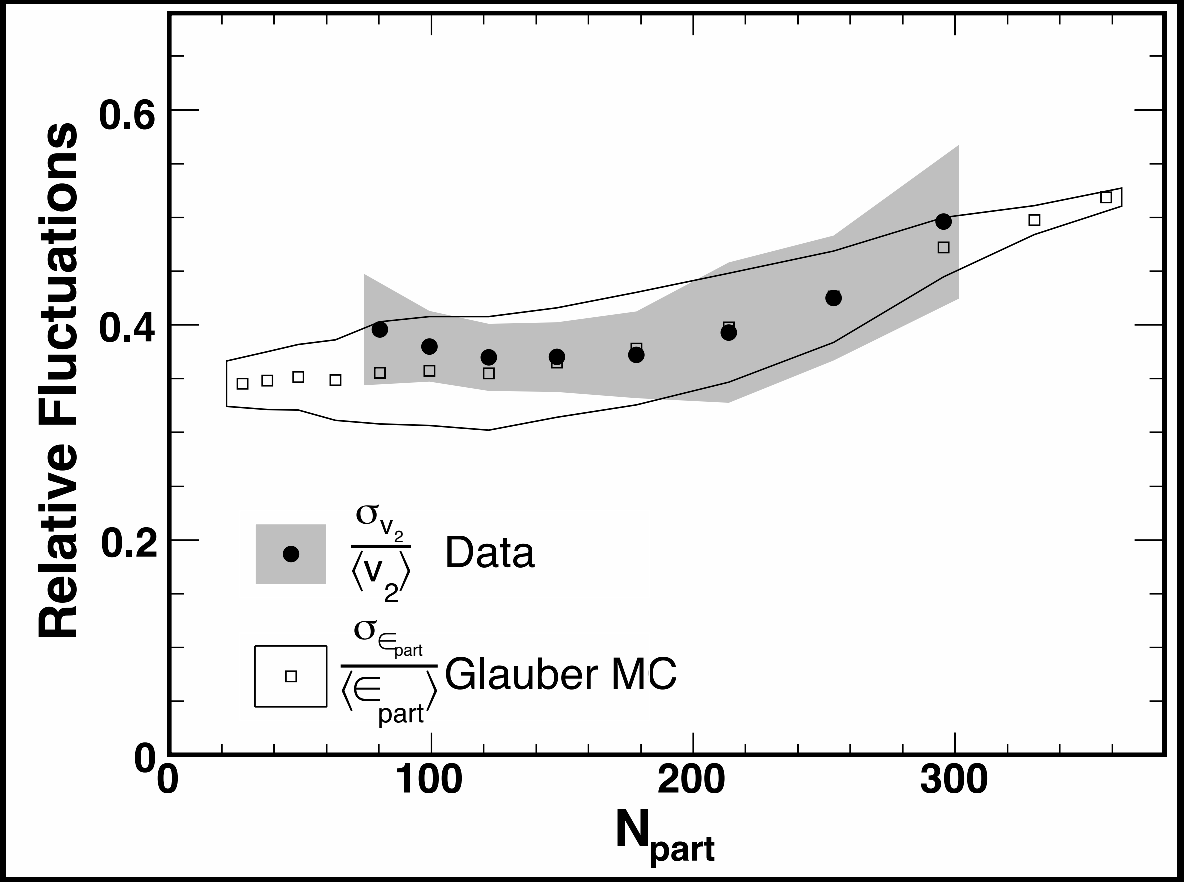


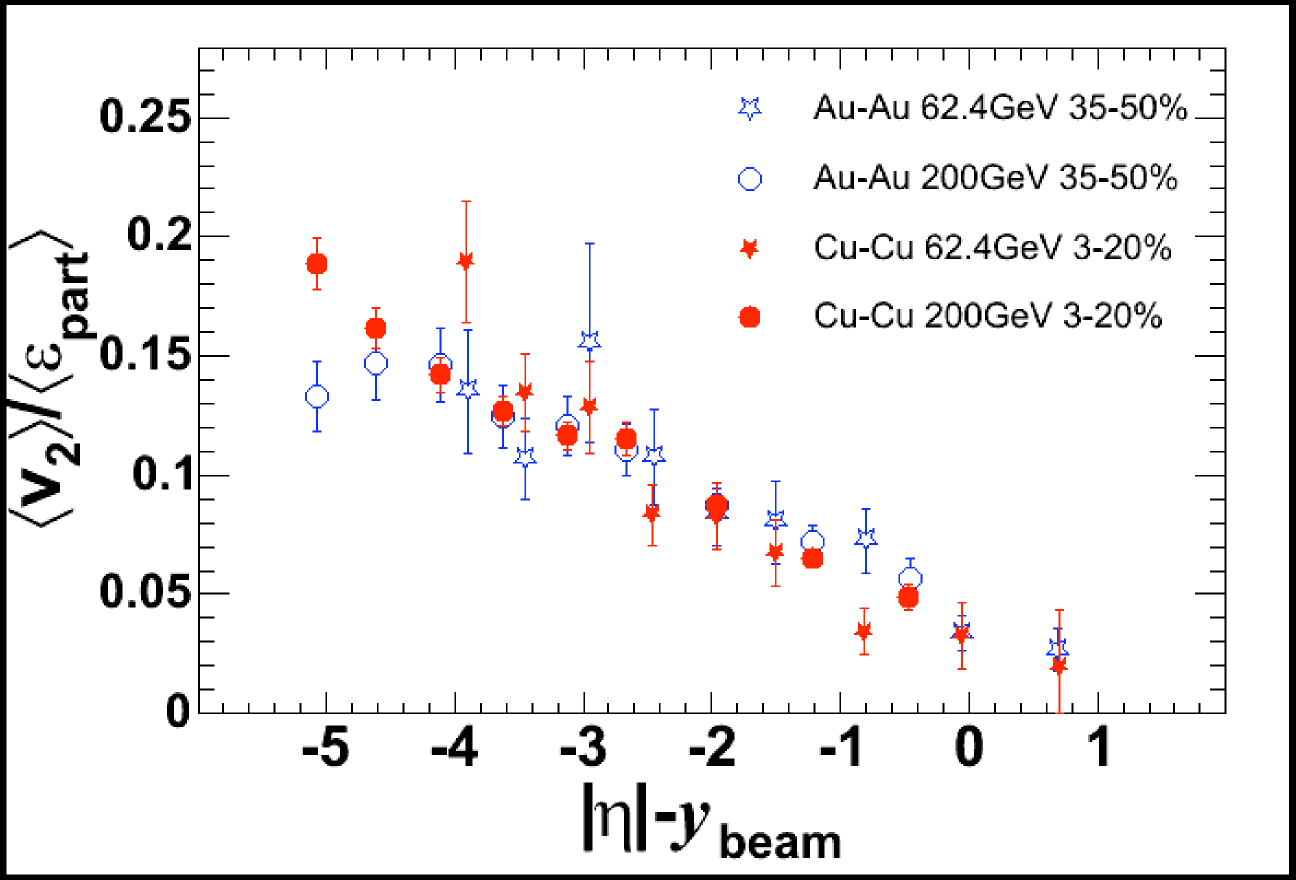
$$\Delta r \sim O(R)$$

$$\Delta z \sim O(1/\sqrt{s})$$

Longitudinal physics (dN/dy) develops on much shorter time scales than transverse physics (dN/dp_T, v_2): τ_0=0.1 fm/c is “initial conditions” to τ_0=0.6 fm/c

A request





RHIC has a lot of data, covering a large region of phase space & geometry:

please try and use all of it, and simultaneously!

“Hello, Nobel Prize Committee?
No...it’s not for the initial state at RHIC...”

Extra Slides

Just a Moment

If:

$$v_2 \propto \epsilon$$

then an n-particle v_2 measurement is really measuring a higher moment of the eccentricity distribution

$$v_2\{n\} \sim \langle \epsilon^n \rangle^{1/n}$$

(argument applies to moments & cumulants)

Which Moment?

- **Moment of event-plane (EP) method depends on v_2 resolution**

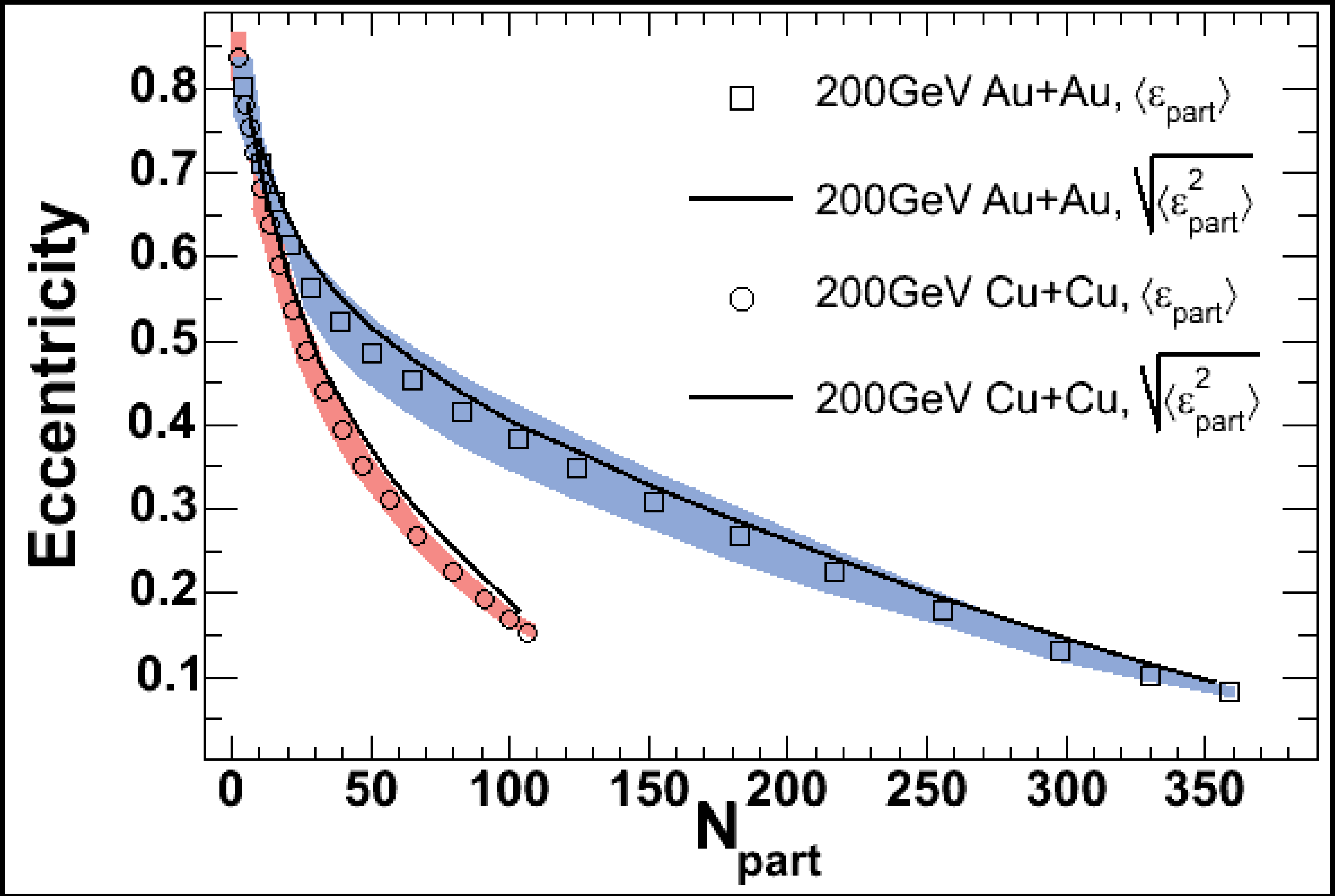
J.Y. Ollitrault - private communication

  - Good resolution: $\langle v_2 \rangle$
  - Poor resolution: $\sqrt{\langle v_2^2 \rangle}$

- **Experiment-dependent**
  - Different resolutions, different moment!

Mean vs. RMS vs. Fluctuations

PHOBOS QM2006



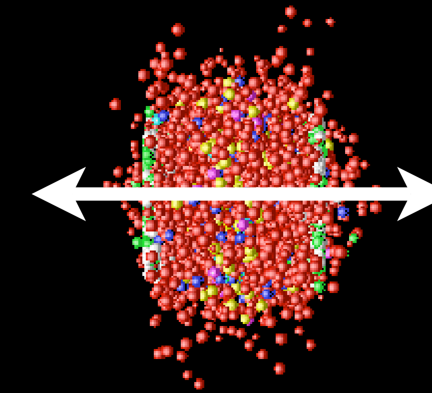
$$\frac{\sigma_\epsilon}{\langle \epsilon \rangle} = \alpha$$

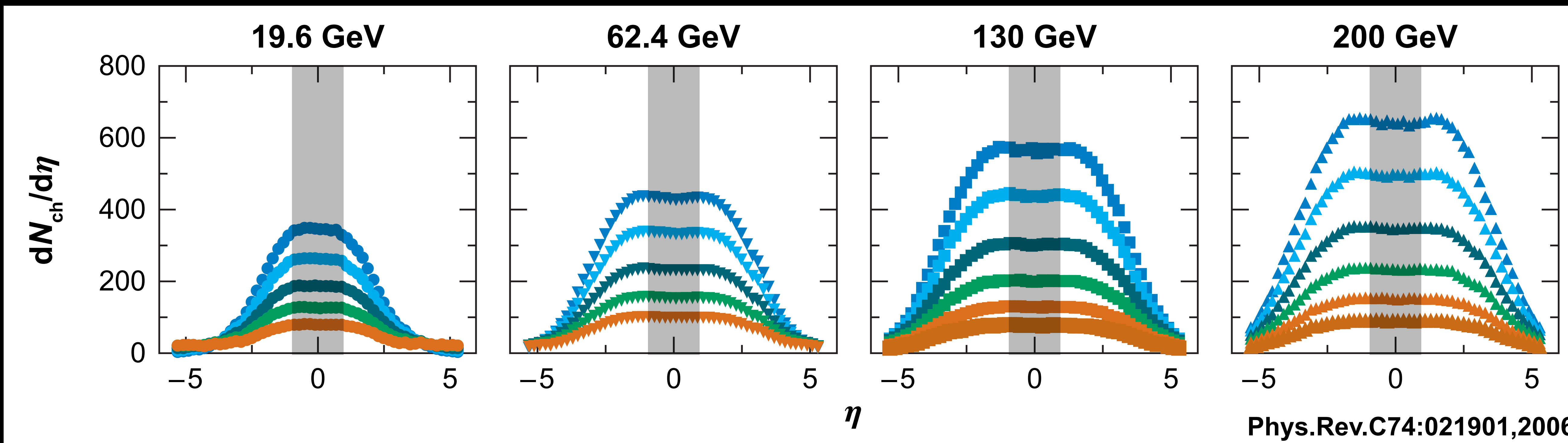
↓

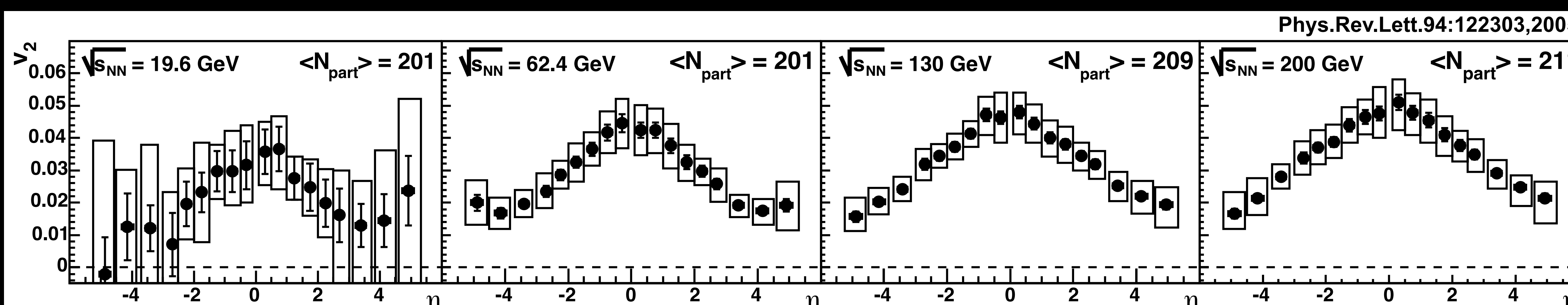
$$\langle \epsilon^2 \rangle = (1 + \alpha^2) \langle \epsilon \rangle^2$$

MC calculations suggests that
Mean and RMS of eccentricity differ by ~8%
→ Small effect on areal density plot

Longitudinal Distributions

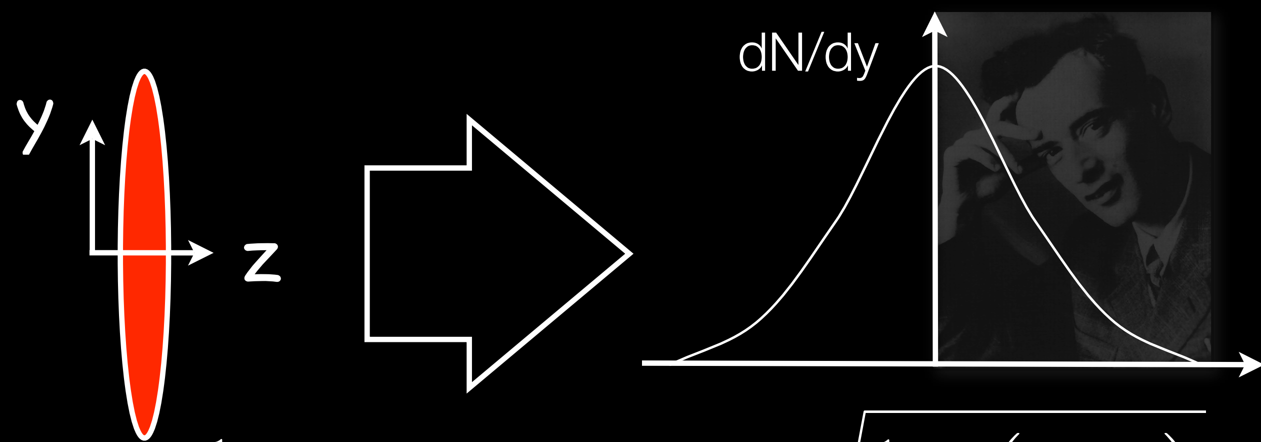






Elliptic flow shows strong pseudorapidity dependence, not entirely dissimilar to particle density

Longitudinal Scaling



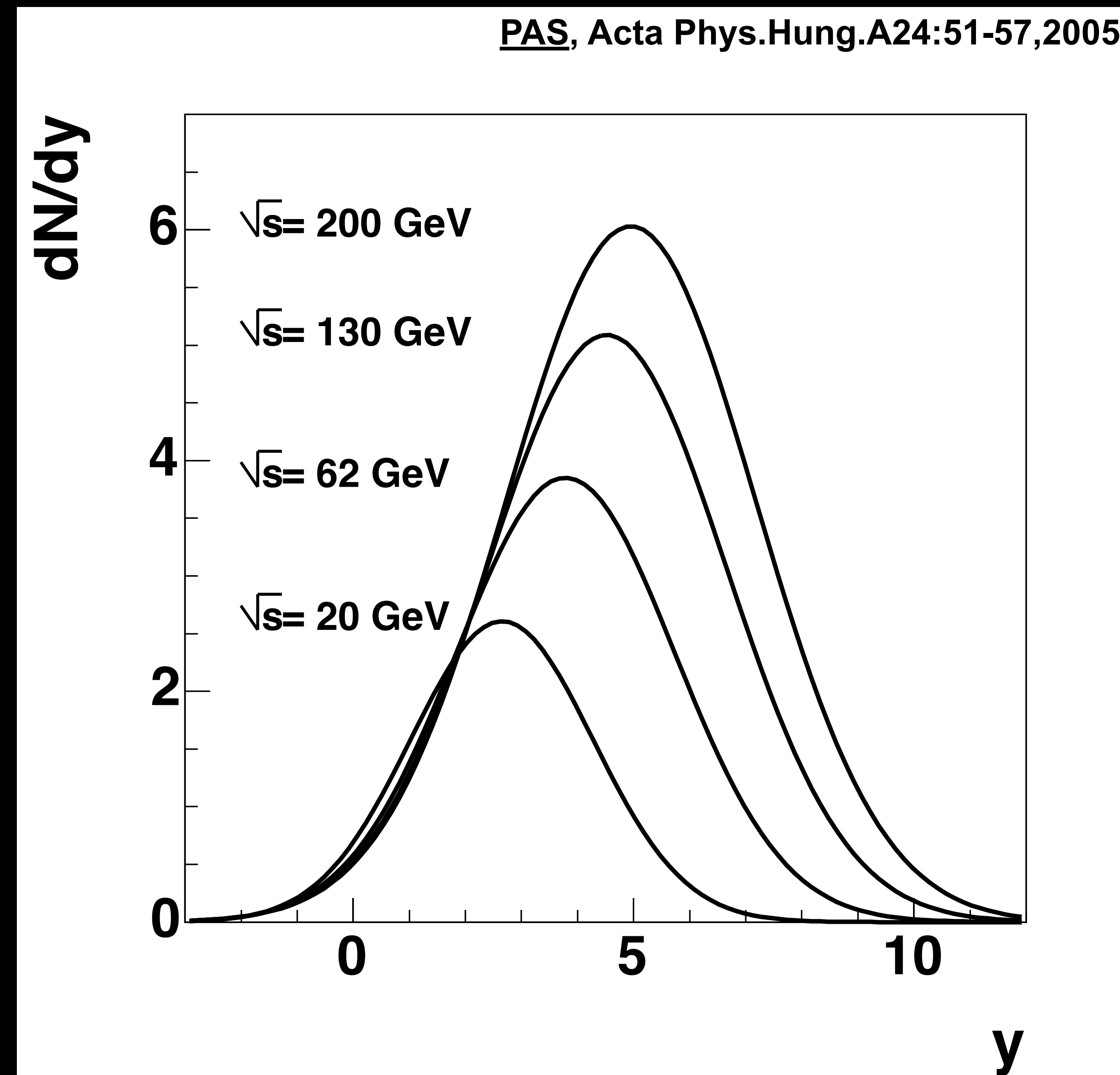
$$\Delta z \sim \frac{1}{\sqrt{s}}$$

$$\sigma_y = \sqrt{\frac{1}{2}\ln\left(\frac{s}{4M_P^2}\right)}$$

$$\frac{dN}{dy} = K s^{1/4} \frac{1}{\sqrt{2\pi L}} \exp\left(-\frac{y^2}{2L}\right)$$

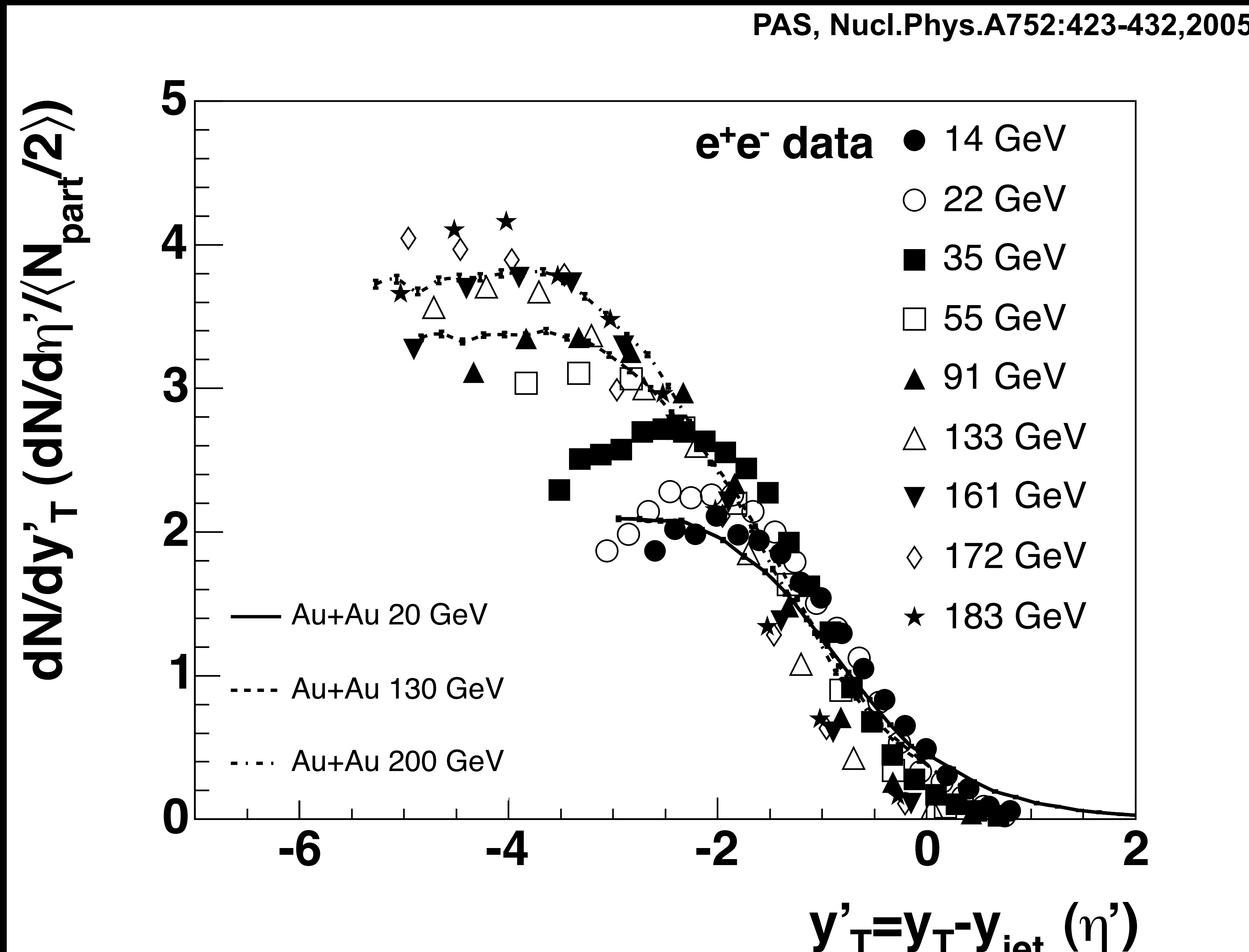
$$L = \ln\left(\frac{\sqrt{s}}{2m_P}\right) \quad y' = y + y_{beam} = y + e^L$$

$$\frac{dN}{dy'} \sim \frac{1}{\sqrt{L}} \exp\left(-\frac{y'^2}{2L} - y'\right)$$



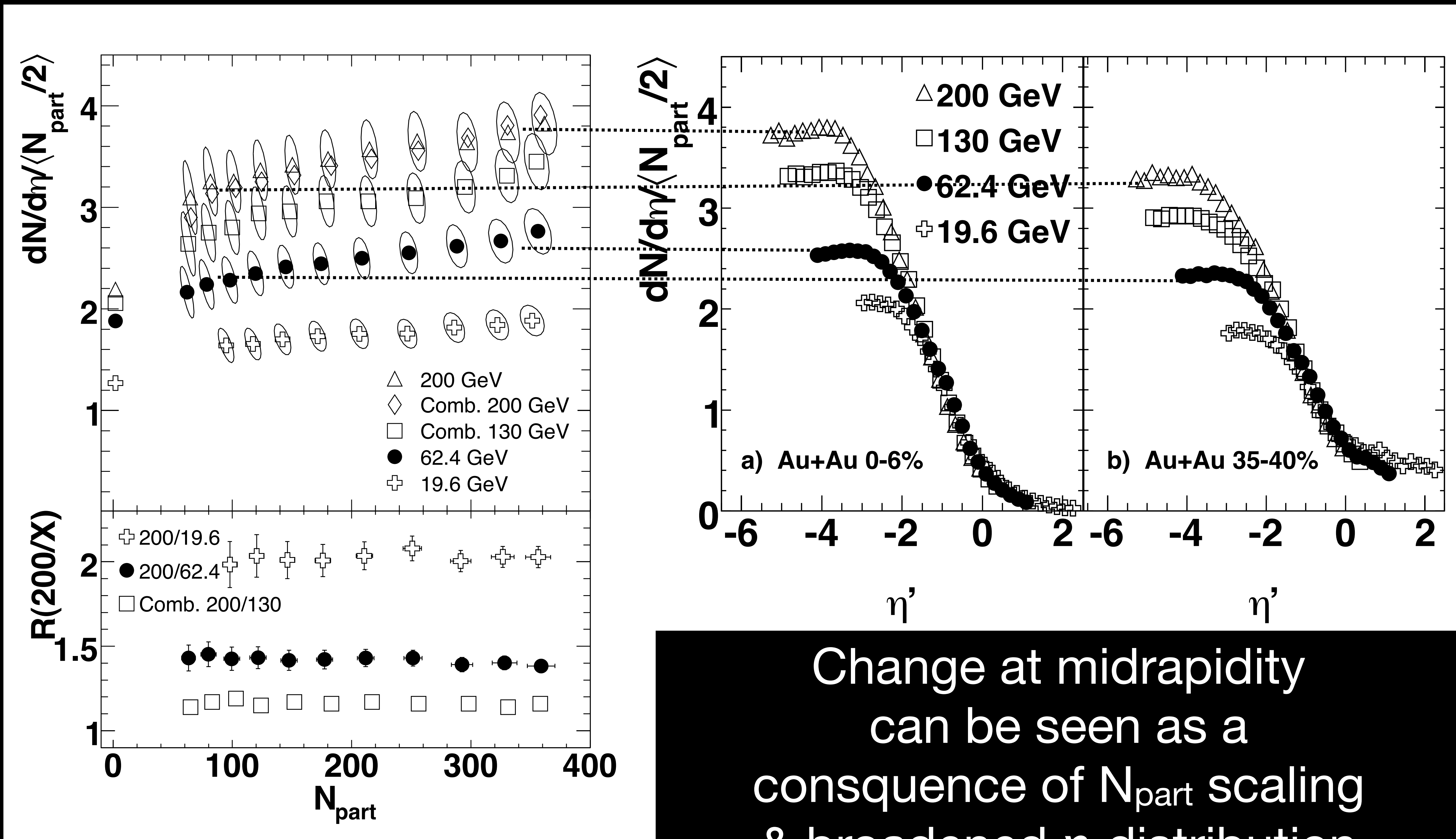
Landau Hydro is an example of Longitudinal Scaling

How Small is "Small"?



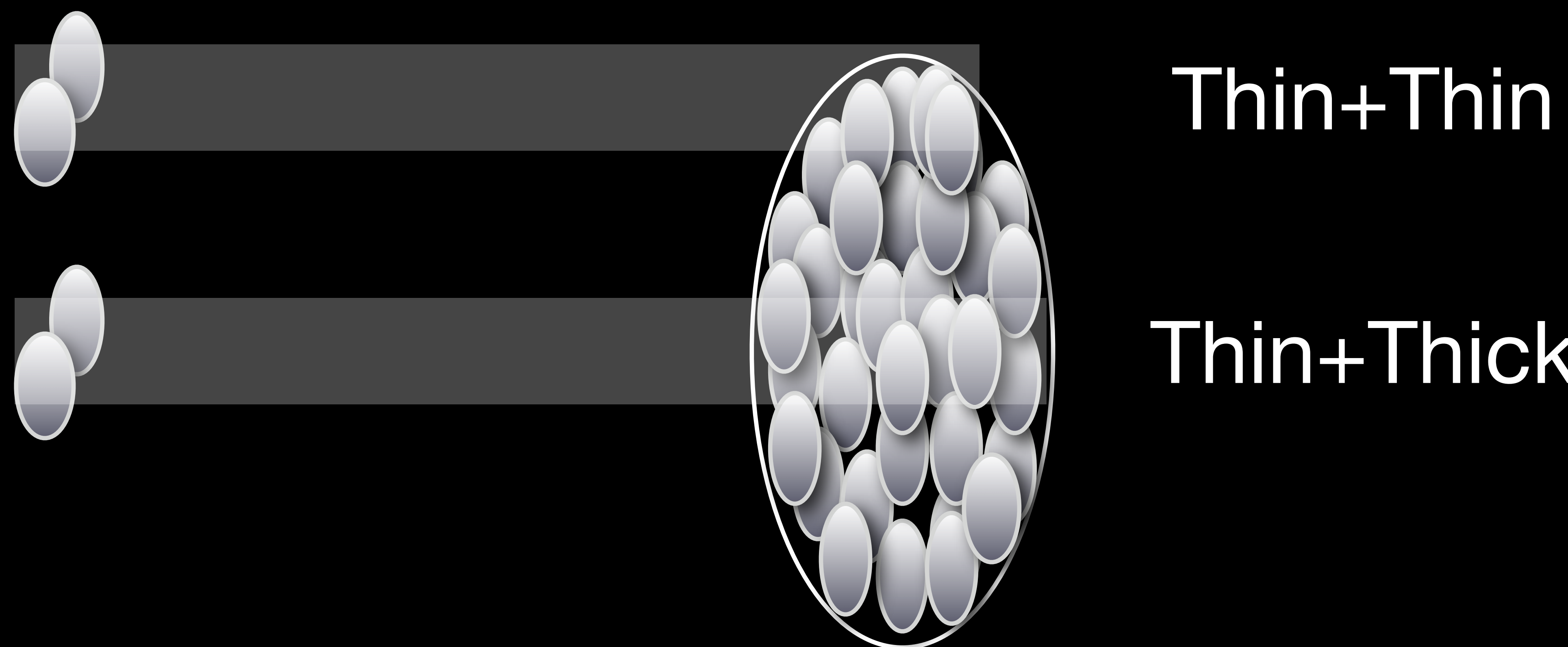
A+A: Large, hydrodynamic ↔ e^+e^-: small, perturbative

Rethink 2-component model



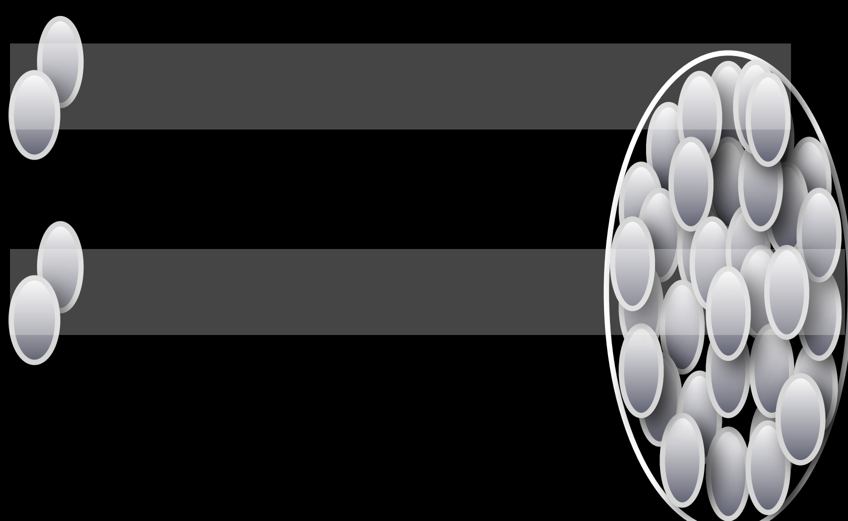
Change at midrapidity can be seen as a consquence of N_{part} scaling & broadened η distribution

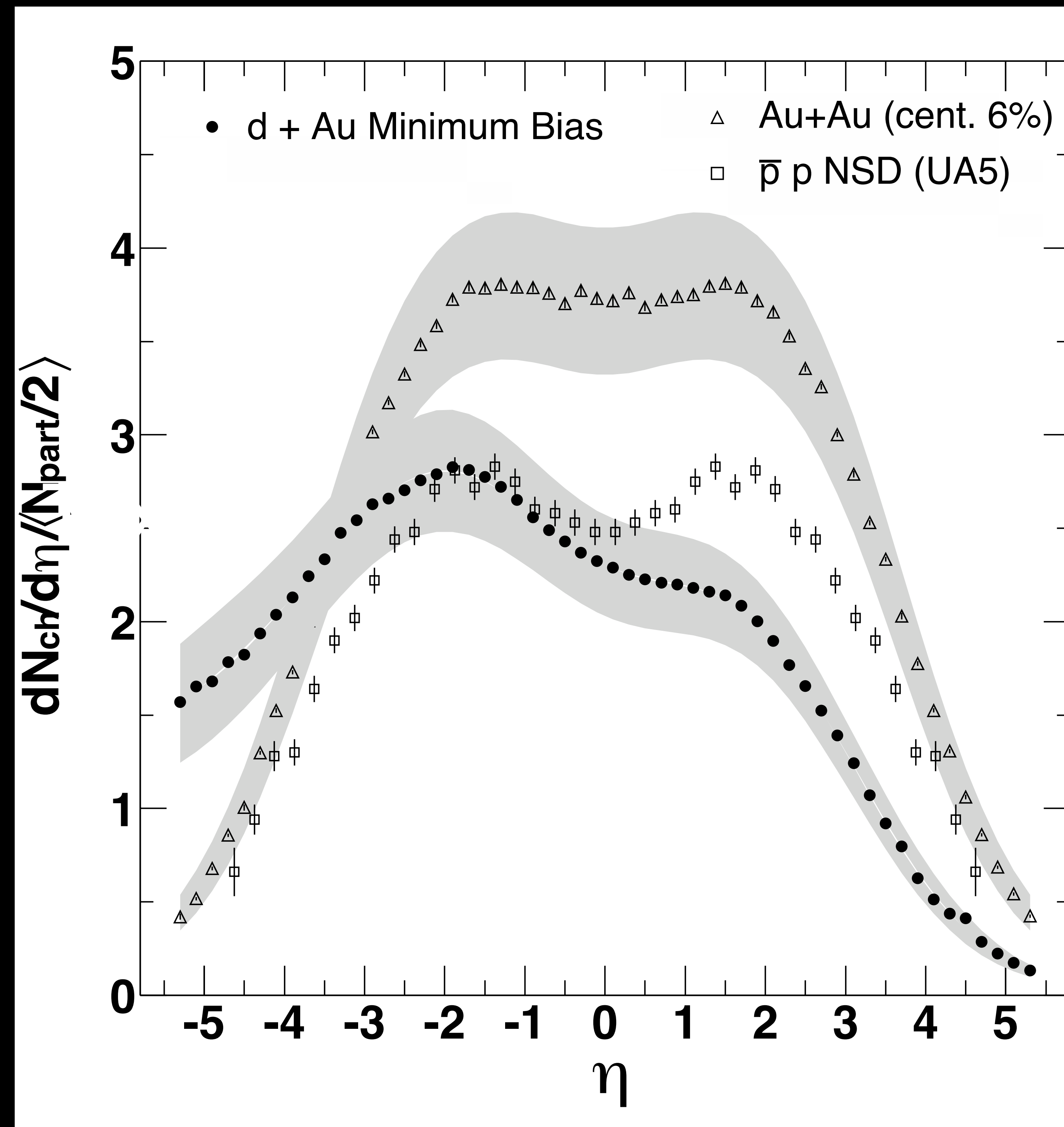
d+Au Distributions



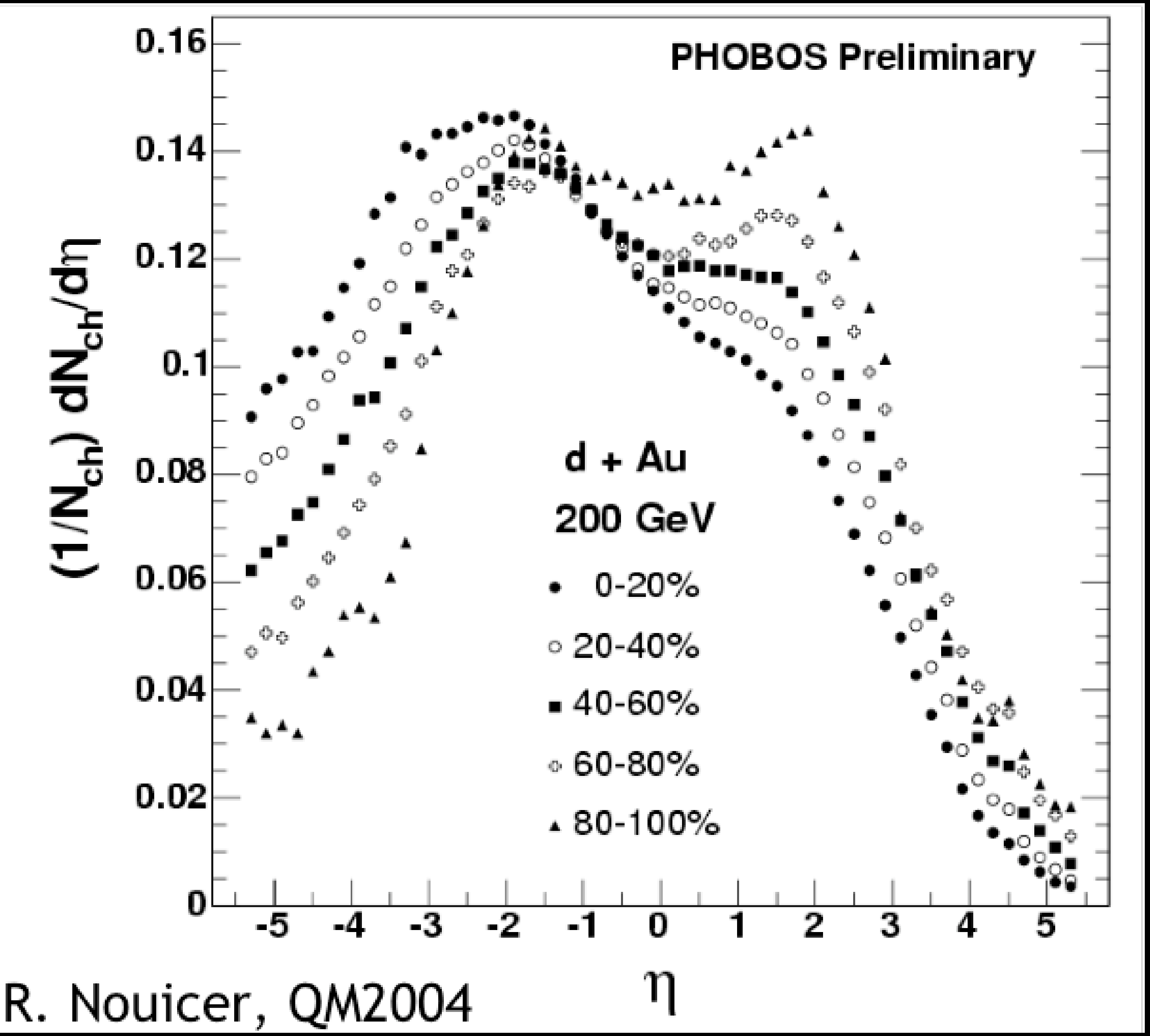
Thin+Thin ~ several p+p collisions
Thin+Thick ~ minbias p+A

Longitudinal Asymmetry



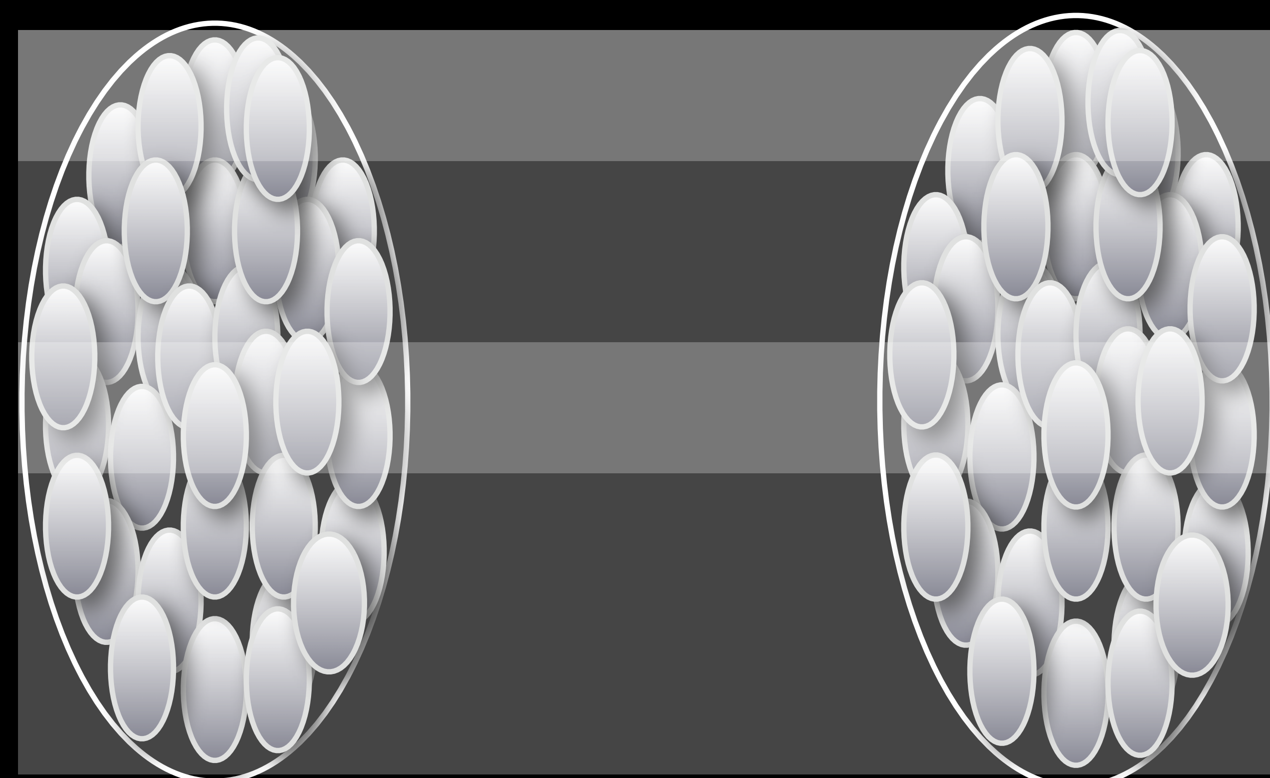


Shifting CM in d+Au



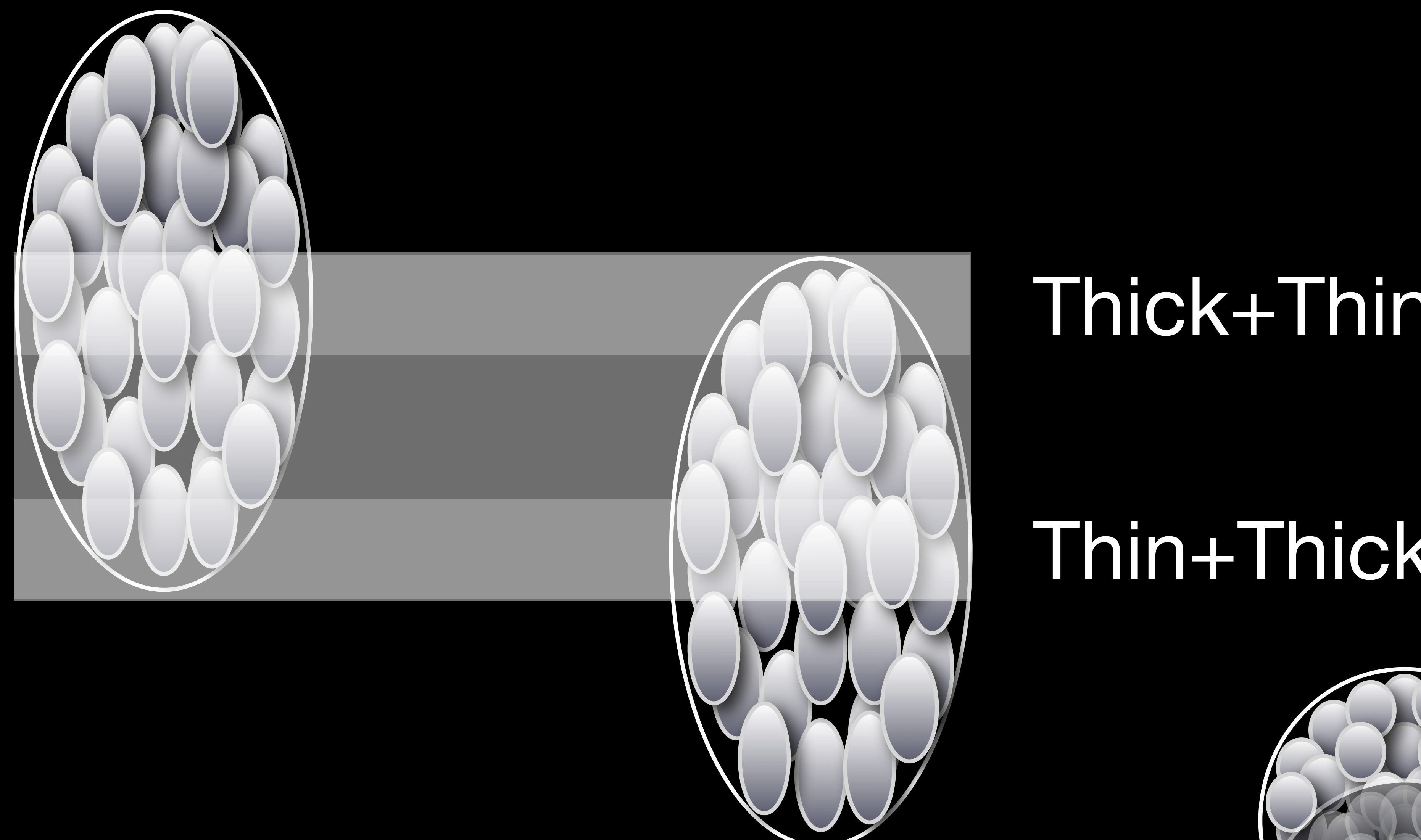
Dividing by N_{part} shows distributions “shift” backwards

Central Events

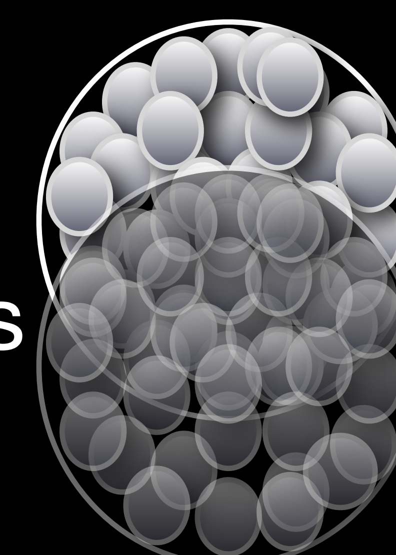


Central collisions involve highly symmetric longitudinal configurations

Peripheral Events



Peripheral events involve asymmetric collisions in local regions of transverse overlap.



Convolution of local “d+Au” collisions will widen integrated dN/dη