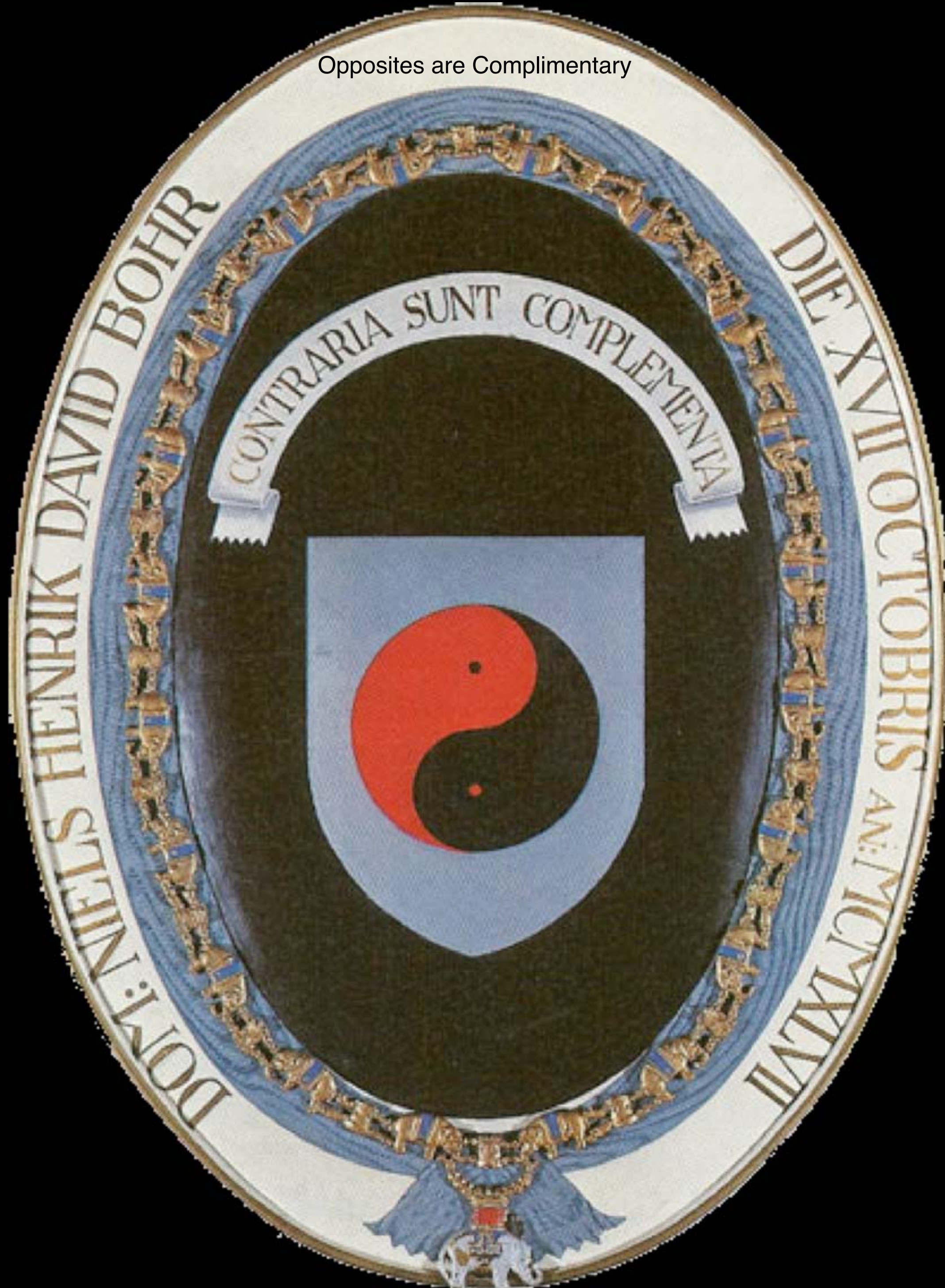


Crest of N. Bohr

The Tao of PHOBOS

Peter Steinberg, for the PHOBOS collaboration
Brookhaven National Laboratory
RHIC/AGS Users Meeting - June 18, 2007

“There is a flow in the universe, and it is called dao...”

Ubiquity of Dynamics

Unity of Opposites

The PHOBOS Collaboration

Burak Alver, Birger Back, Mark Baker, Maarten Ballintijn, Donald Barton, Russell Betts, **Richard Bindel**, Wit Busza (Spokesperson), **Vasundhara Chetluru**, Edmundo García, **Tomasz Gburek**, Joshua Hamblen, Conor Henderson, David Hofman, Richard Hollis, Roman Hołyński, Burt Holzman, Aneta Iordanova, Chia Ming Kuo, **Wei Li**, Willis Lin, Constantin Loizides, Steven Manly, Alice Mignerey, Gerrit van Nieuwenhuizen, Rachid Nouicer, Andrzej Olszewski, Robert Pak, Corey Reed, Christof Roland, Gunther Roland, **Joe Sagerer**, Peter Steinberg, George Stephans, Andrei Sukhanov, Marguerite Belt Tonjes, Adam Trzupek, **Sergei Vaurynovich**, Robin Verdier, Gábor Veres, **Peter Walters**, **Edward Wenger**, Frank Wolfs, Barbara Wosiek, Krzysztof Woźniak, Bolek Wysłouch

argonne national laboratory
brookhaven national laboratory
intsitute of nuclear physics, PAN, krakow
massachusetts institute of technology
national centeral university, taiwan
university of illinois at chicago
university of maryland
university of rochester

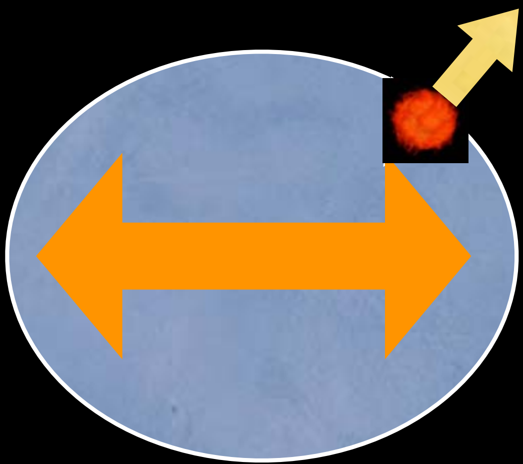
Hydrodynamics

Energy density thermalized in a volume, adjacent cells are in causal contact

Presure gradients develop via adiabatic expansion into vacuum

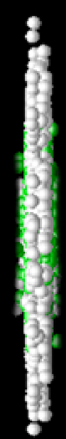
$$\partial_\mu T^{\mu\nu} = 0$$

$$p = f(\epsilon, n)$$

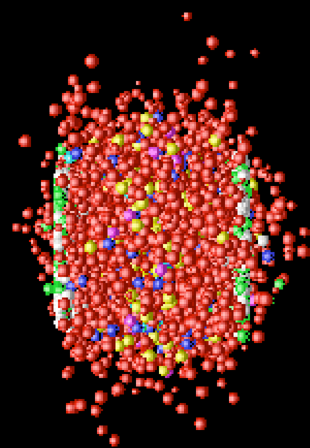


When local temperature falls below some T_c interactions turn off and fluid cells "freeze out" as isotropic fireballs (in fluid rest frame)

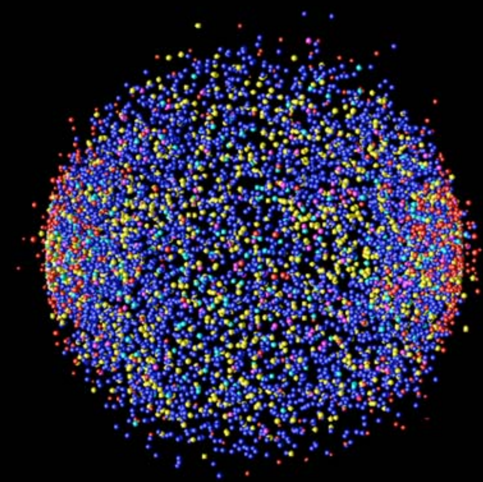
Connection to QCD



Initial interactions, hard and soft, establish initial state



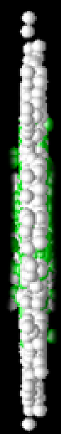
Subsequent interactions, between degrees of freedom, evolve hydrodynamically



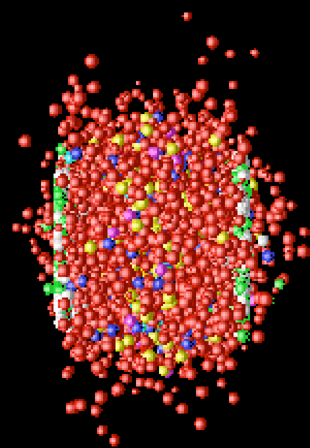
System expands and cools, freezing out into stable hadrons

VNI

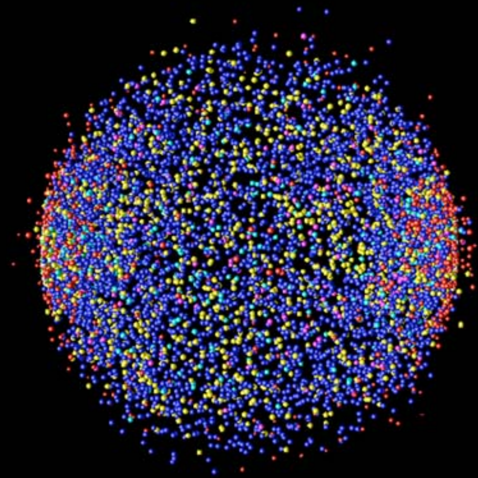
Experimental Questions



What and When
is the initial state?
Is it thermalized?

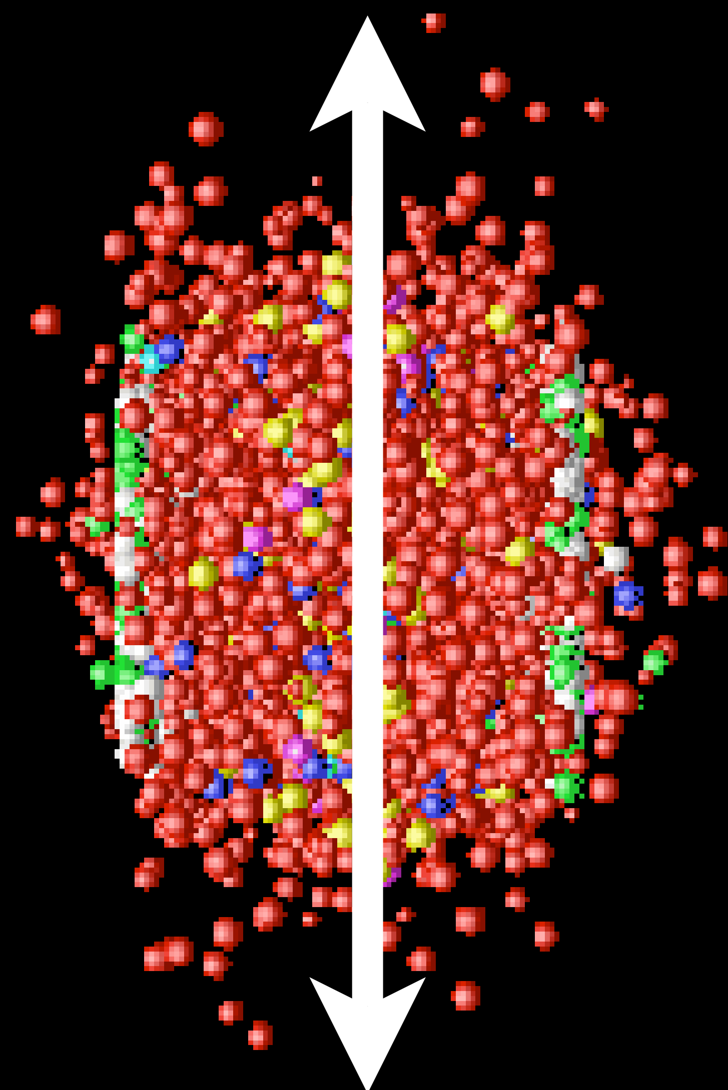


Is hydro ideal
(i.e. isentropic)
everywhere?

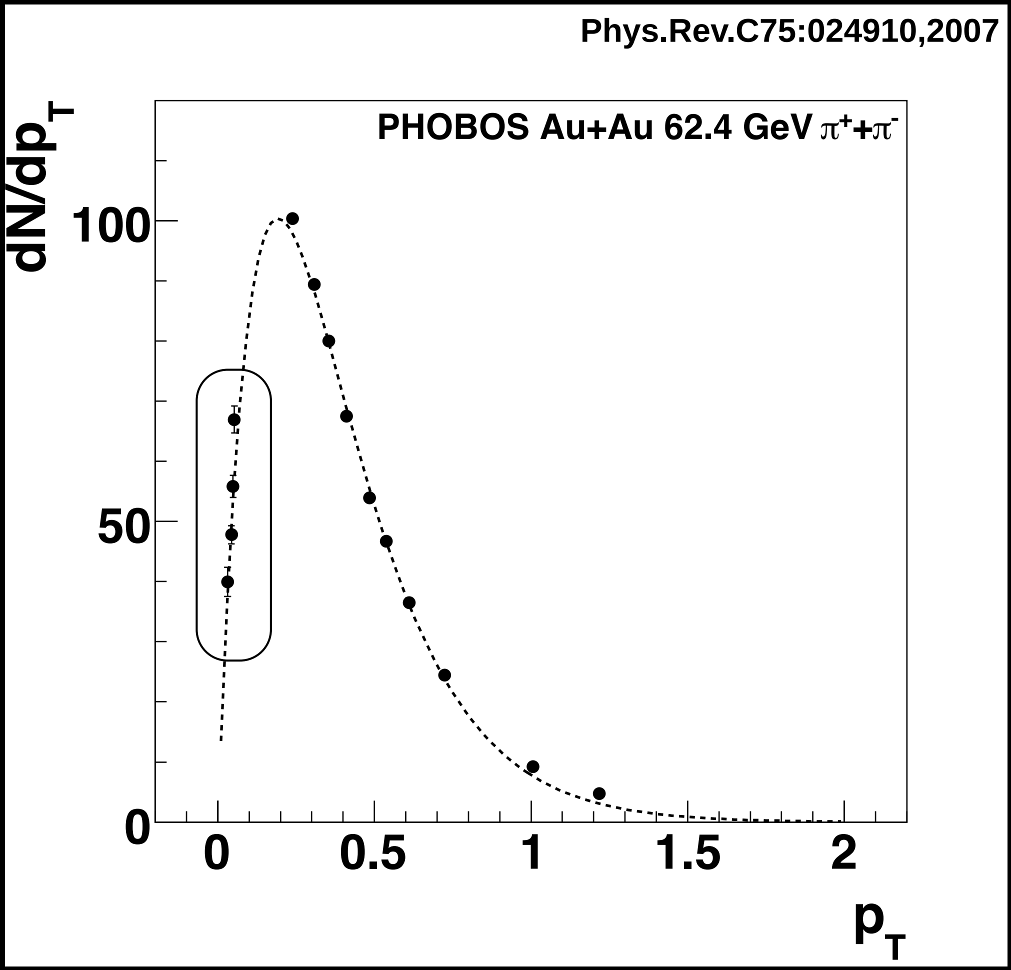


What is produced
at freeze-out?

Mid-rapidity

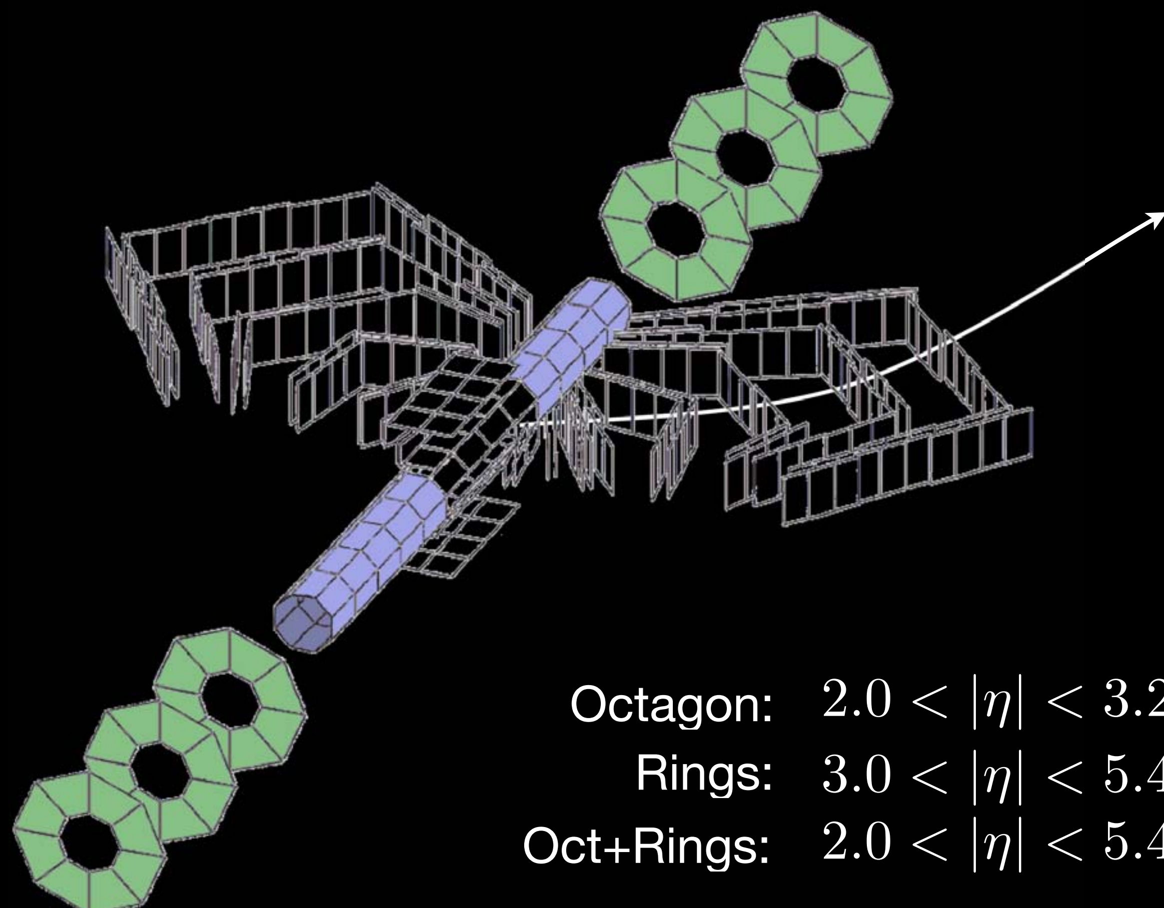


“Strong Blackbody”



PHOBOS measures at *all* p_T, from very low (30 MeV!) to very high (with PID up to 1-2 GeV)

Measuring Flow



Octagon: $2.0 < |\eta| < 3.2$

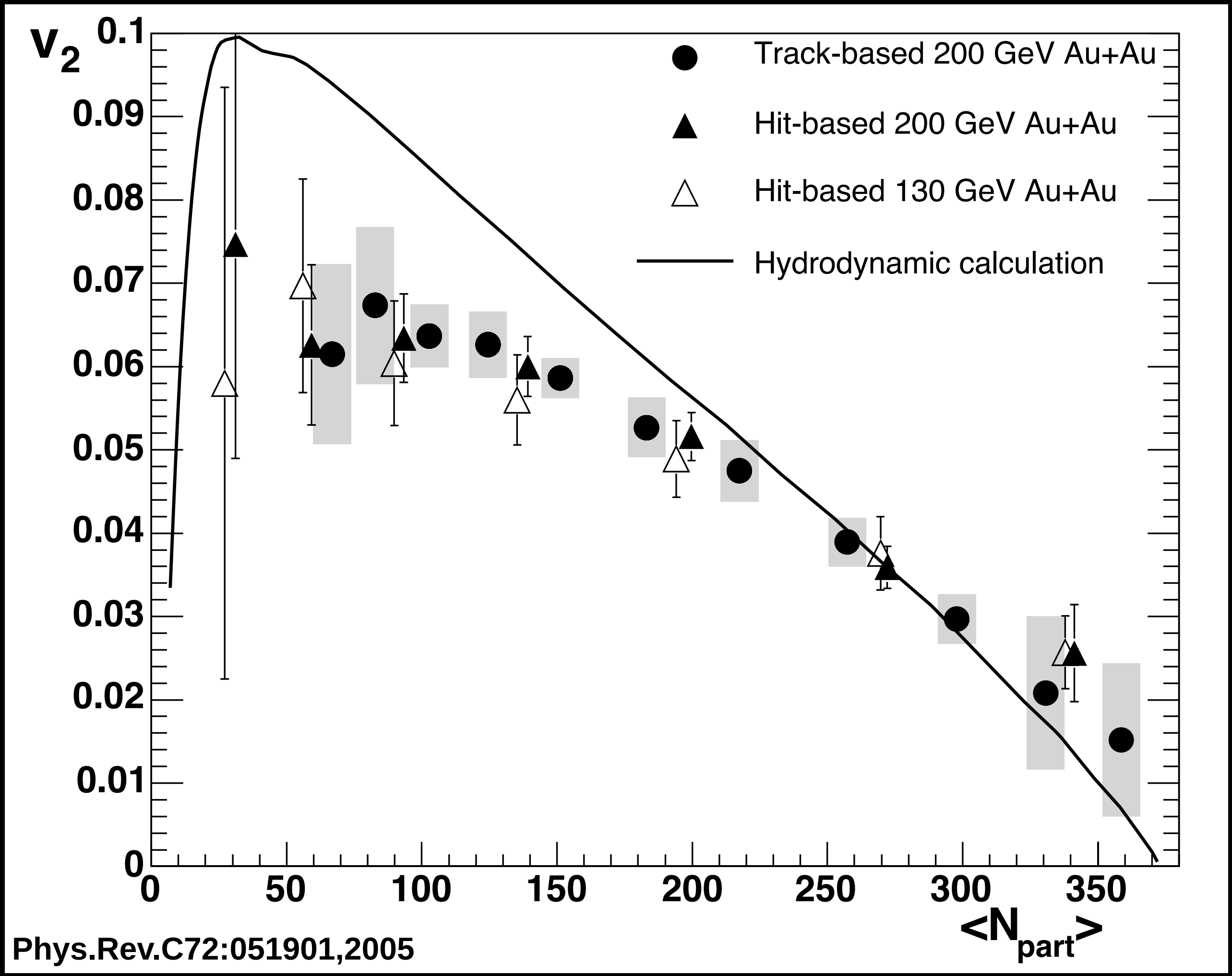
Rings: $3.0 < |\eta| < 5.4$

Oct+Rings: $2.0 < |\eta| < 5.4$

Hit-based:
Track-based:

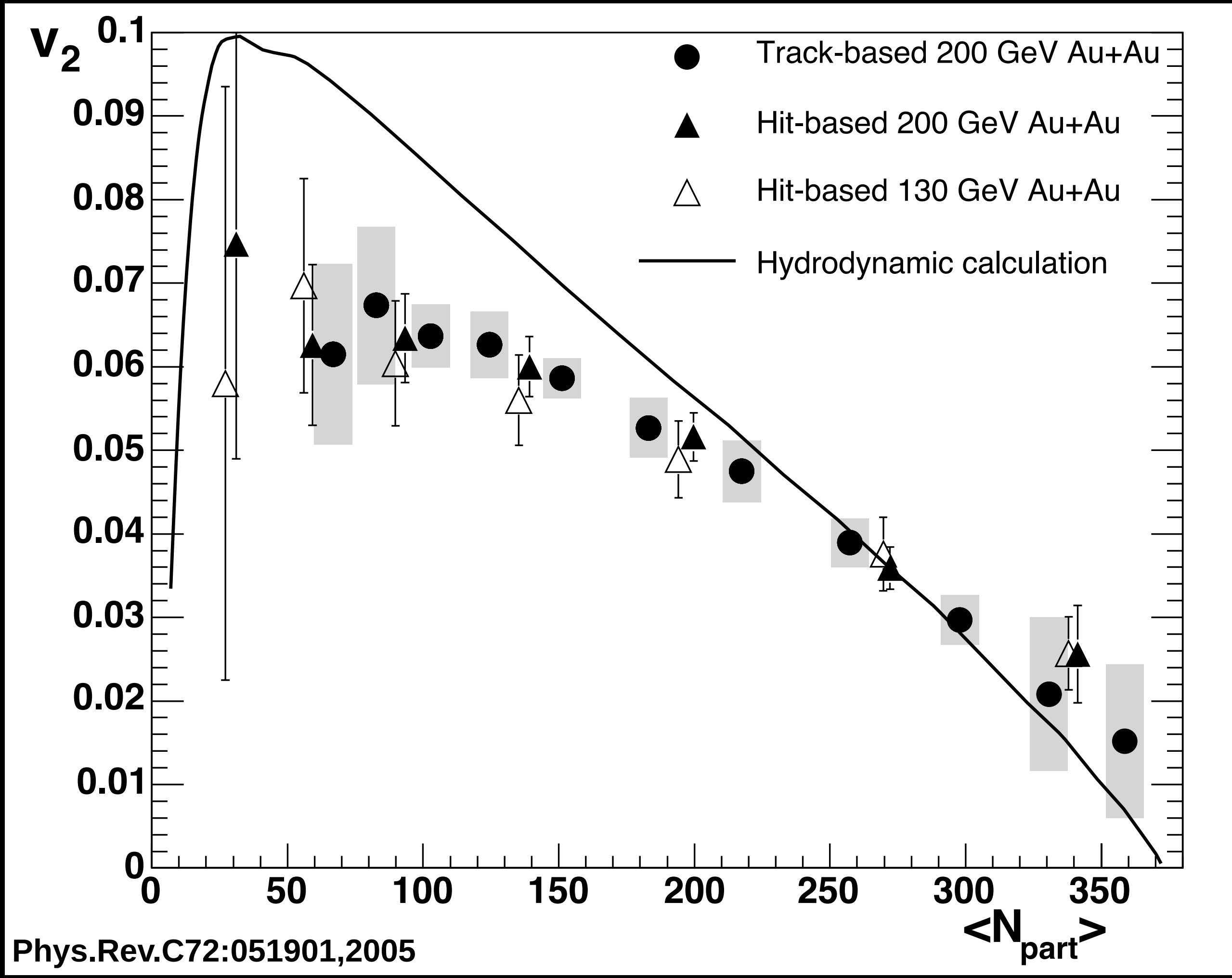
$$v_2 = \frac{\langle \cos(2[\phi_i - \Psi_R]) \rangle}{\sqrt{\langle \cos(2[\Psi_P - \Psi_N]) \rangle}}$$ resolution

Hydro @ RHIC



Hydro calculations agree for semi-central collisions

Hydro @ RHIC



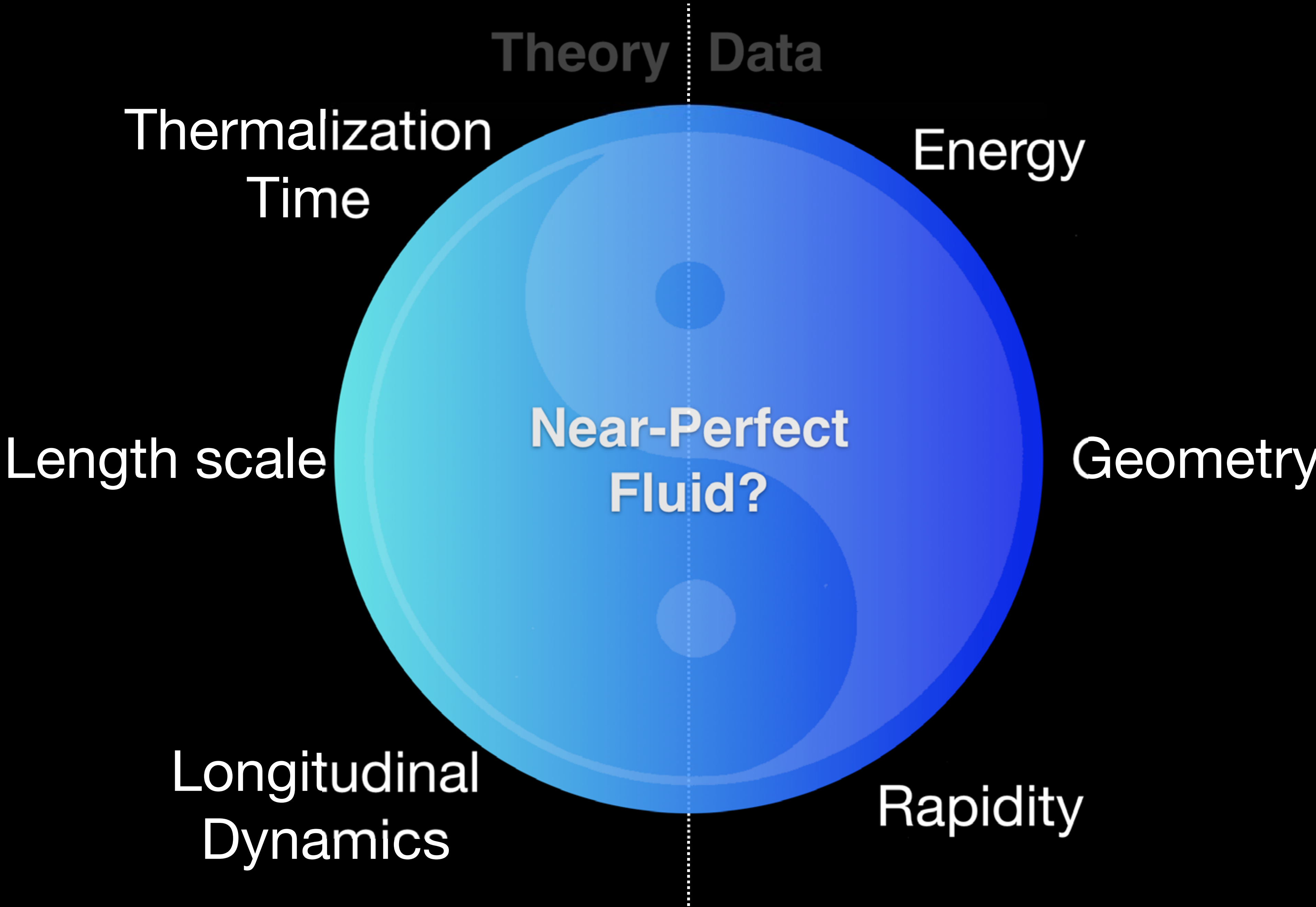
hydro scales $\tau_0 \sim 0.6 fm/c$ $\epsilon \sim 30\ GeV/fm^3$ $\Longleftrightarrow$ $\tau_0 \sim 1\ fm/c$ $\epsilon \sim 500\ MeV/fm^3$ **hadronic scales**

Do we know that it has zero viscosity?

Does it have attractive interactions characteristic of liquids?

Near-Perfect
Fluid?

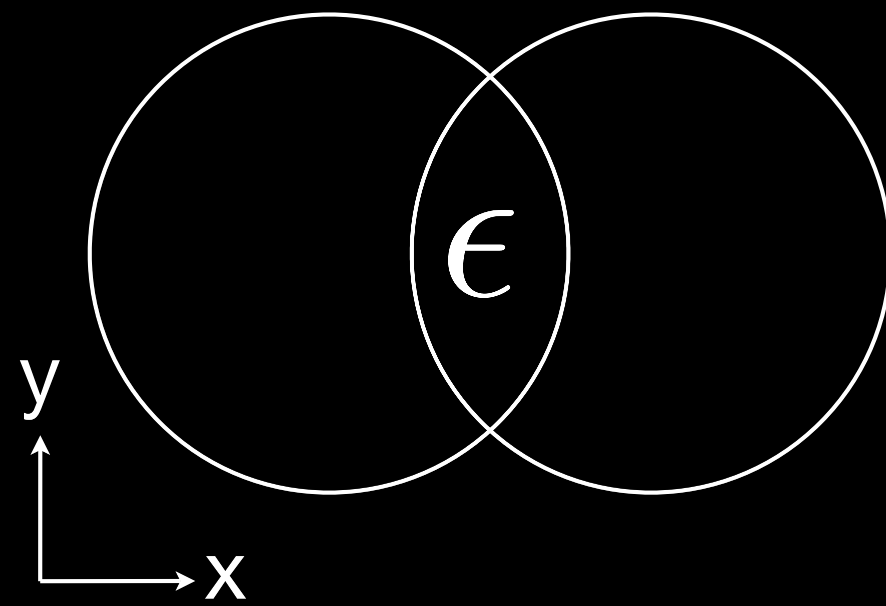
The Edge of Liquidity



Eccentricity

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

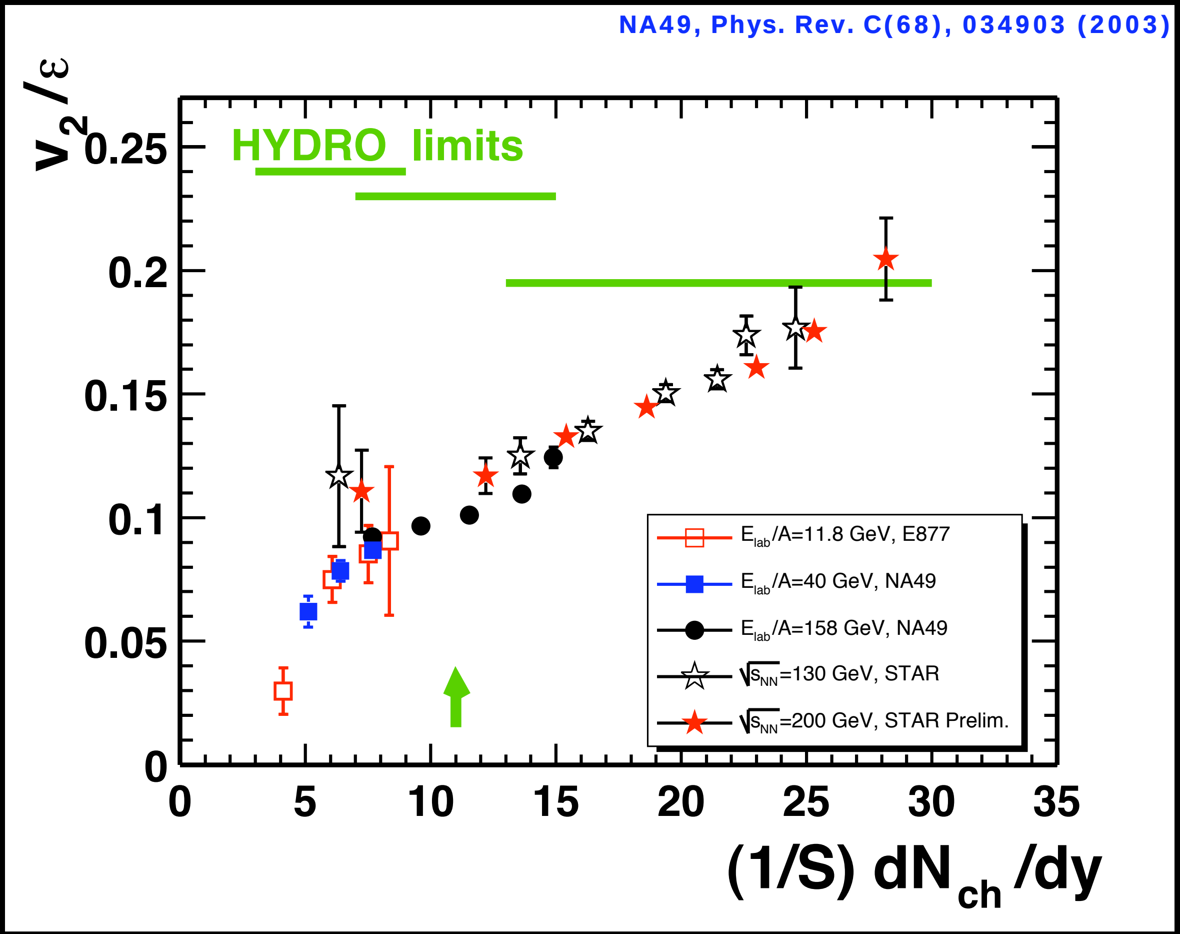
$$\epsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$



Generically, hydro predicts complete transfer of spatial anisotropy into momentum anisotropy!

$$v_2 \propto \epsilon$$

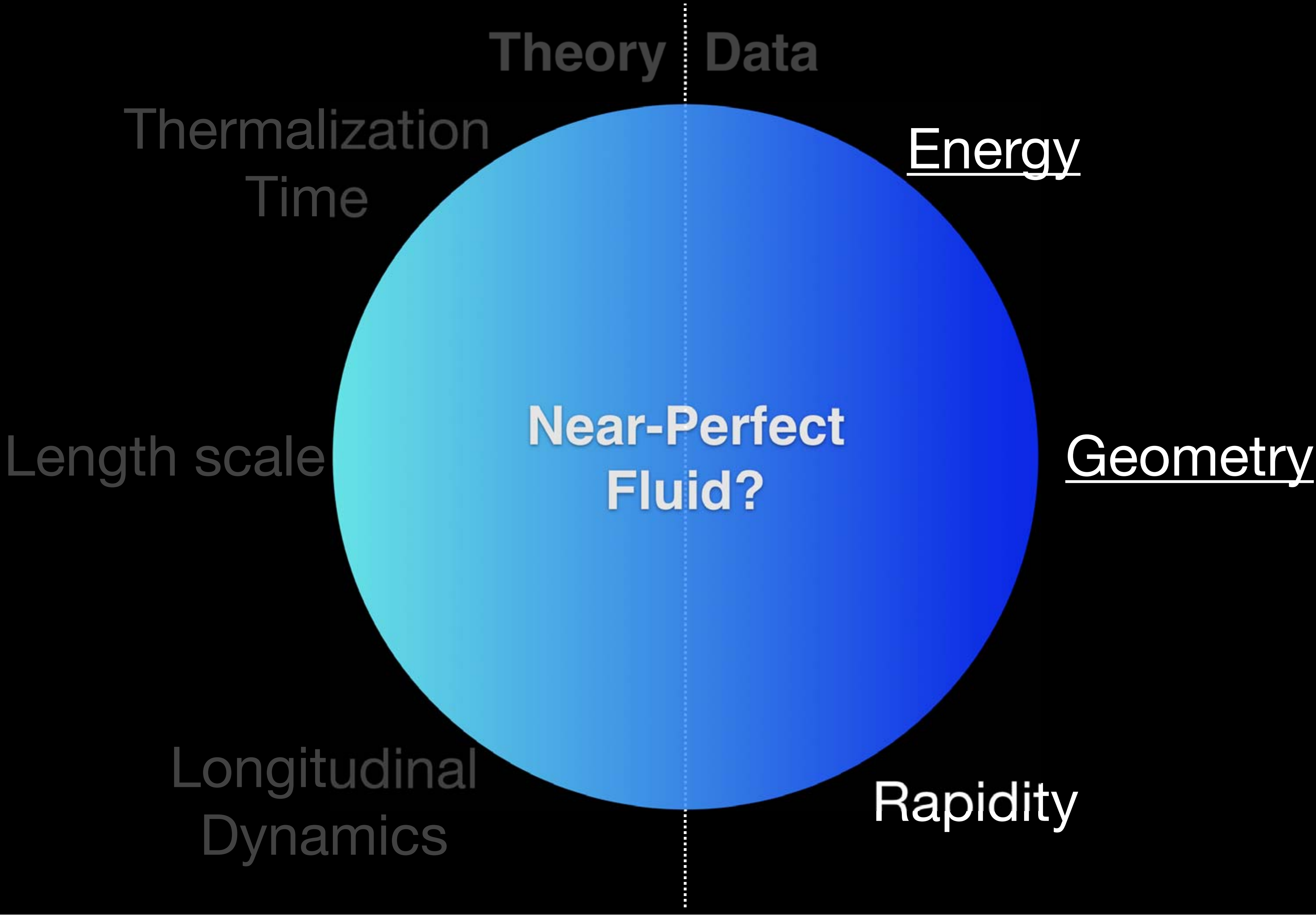
"Scaling Behavior"



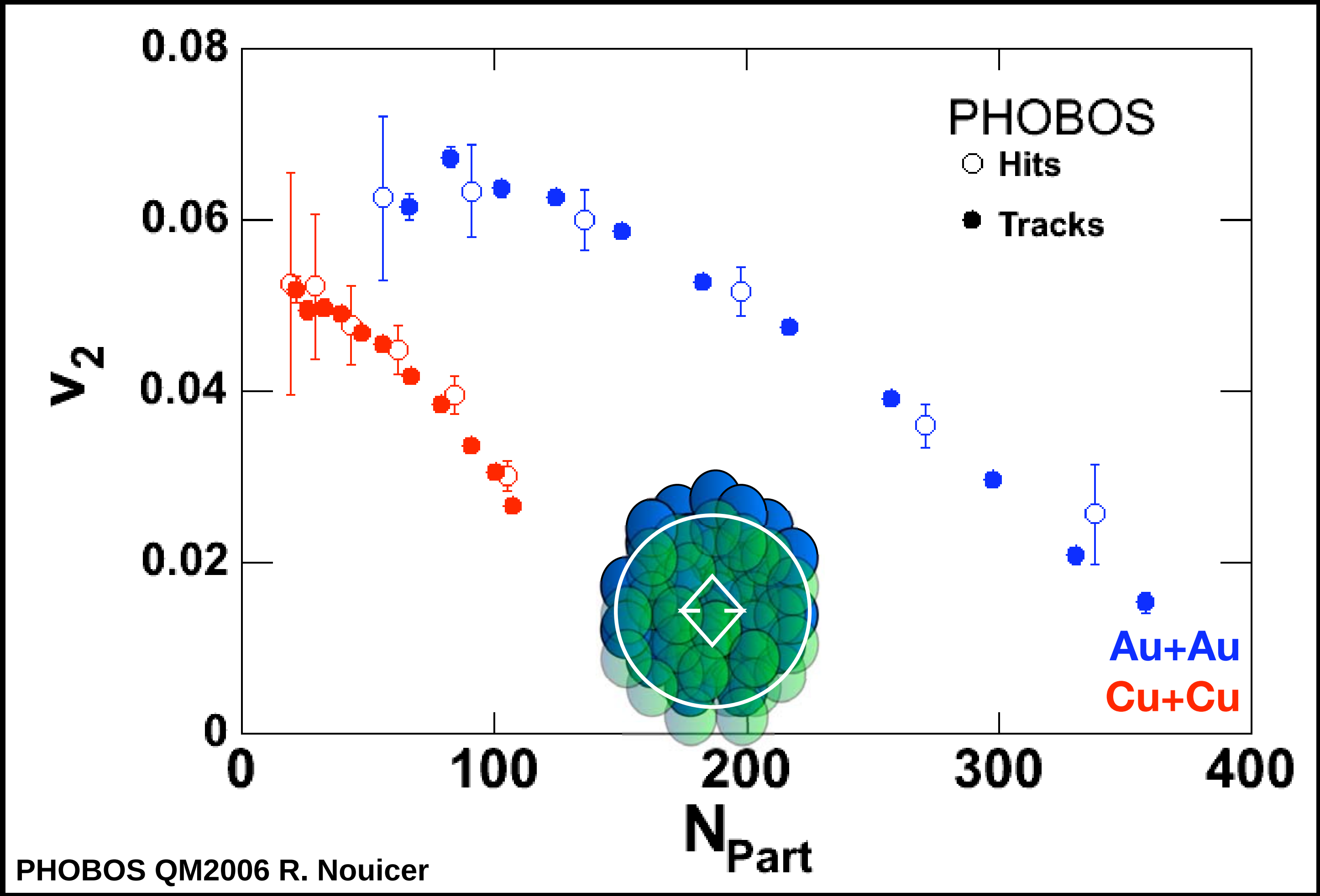
"hydro limit"?

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

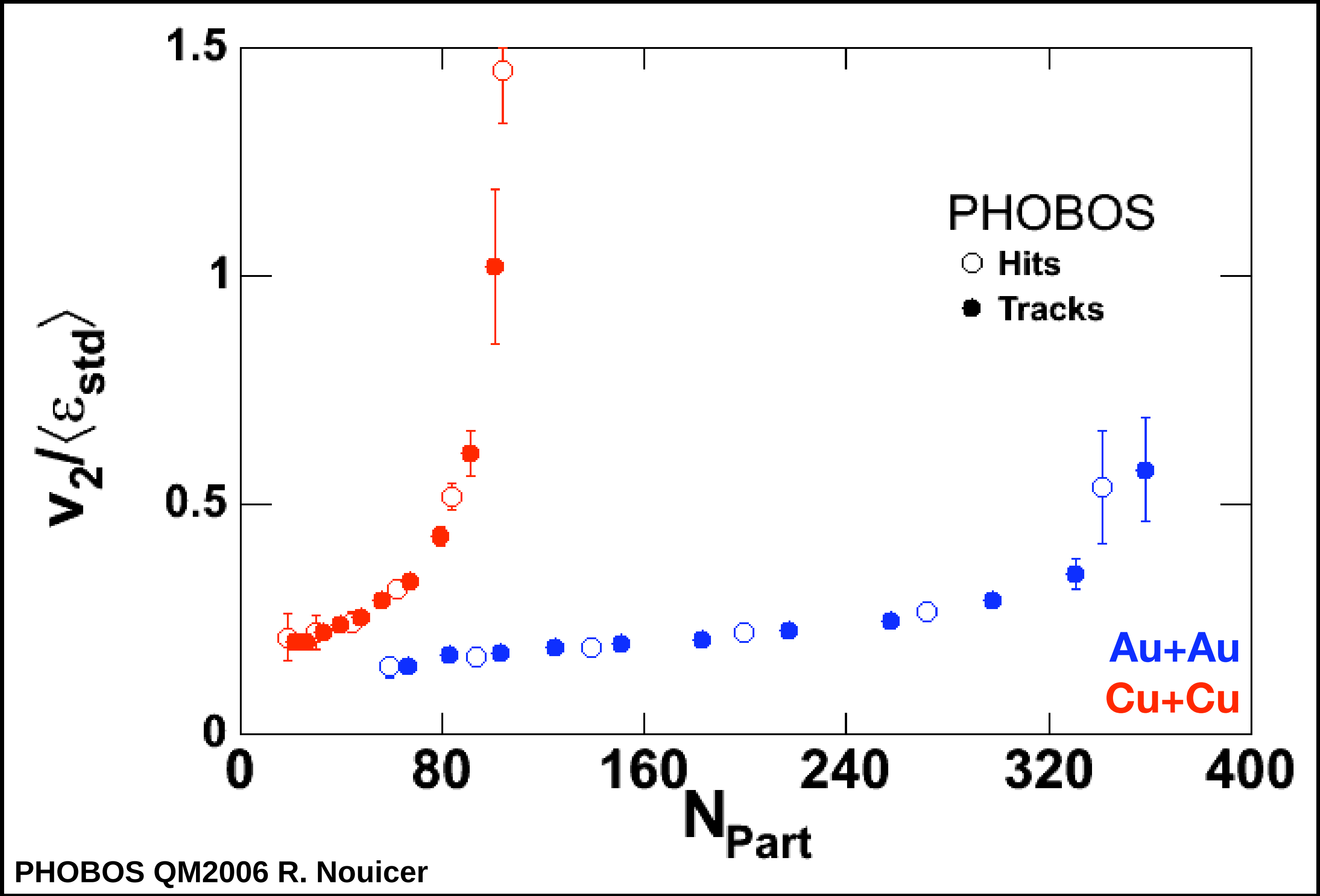
Is this hydrodynamic equilibration, or just the approach to it? In any case, it seems to be <u>universal</u>



Does v_2 follow ϵ?



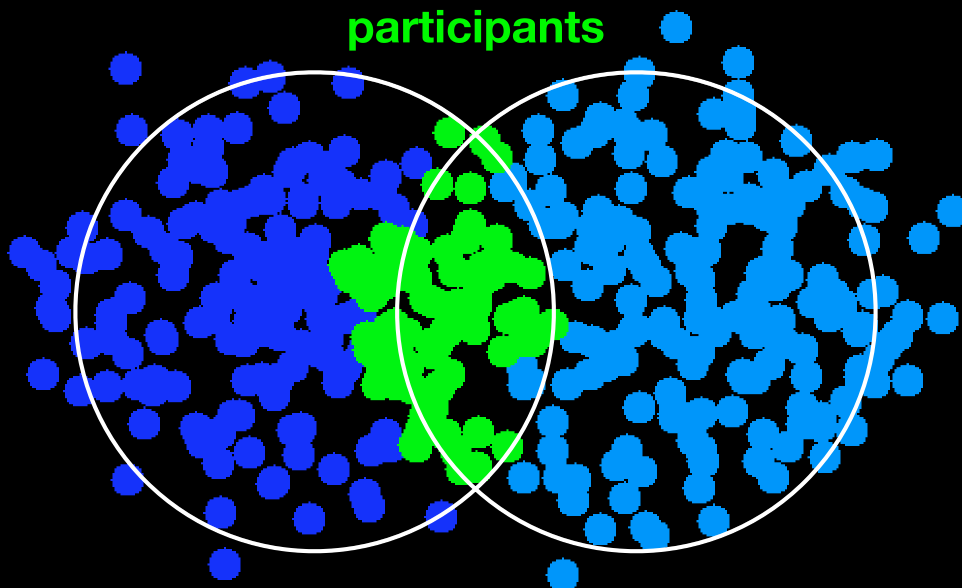
Something wrong...



Eccentricity Fluctuations

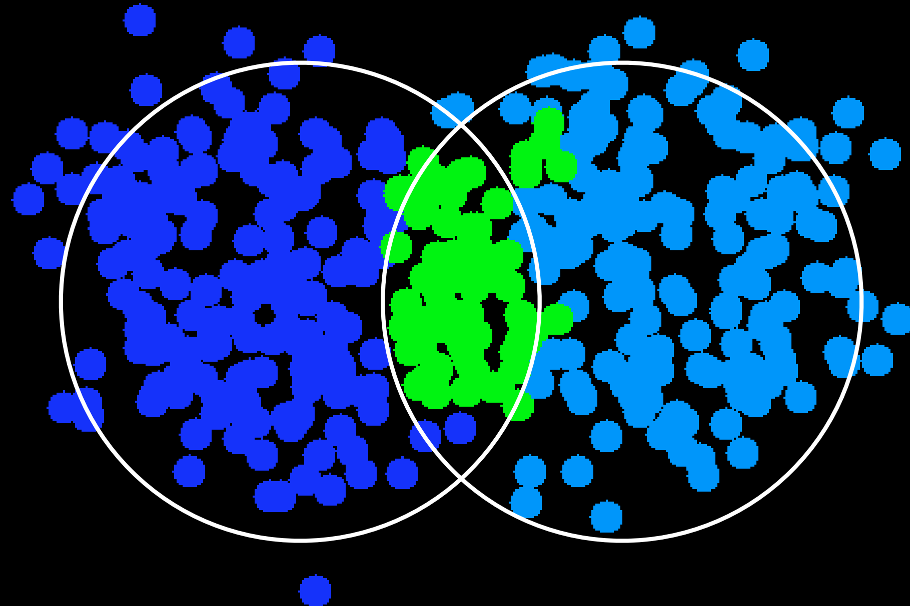
Smooth nuclei

Discrete Nucleons (“Glauber Monte Carlo” approach)

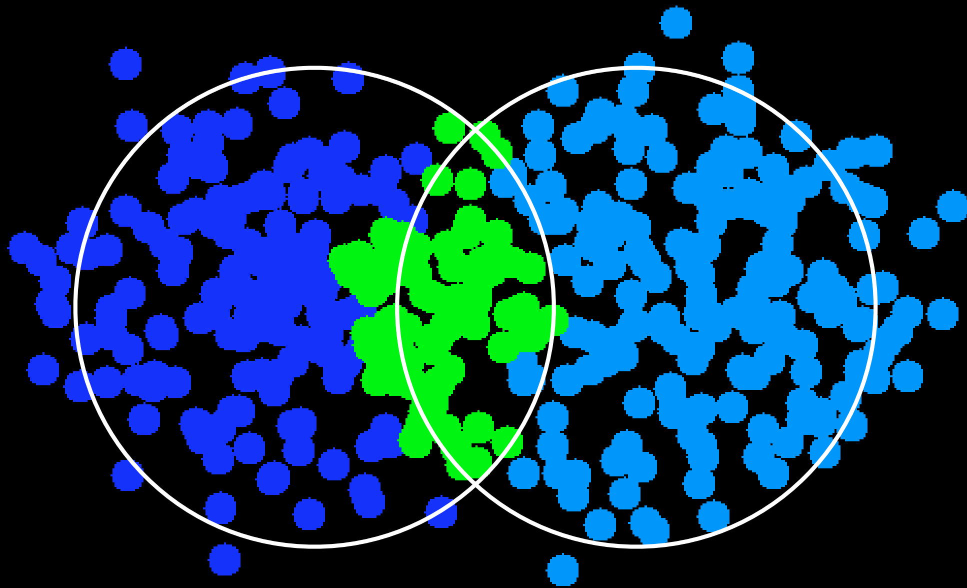


We know nuclei are made of nucleons,
Why “insist” that an average density
matters for flow measurements?

Au+Au



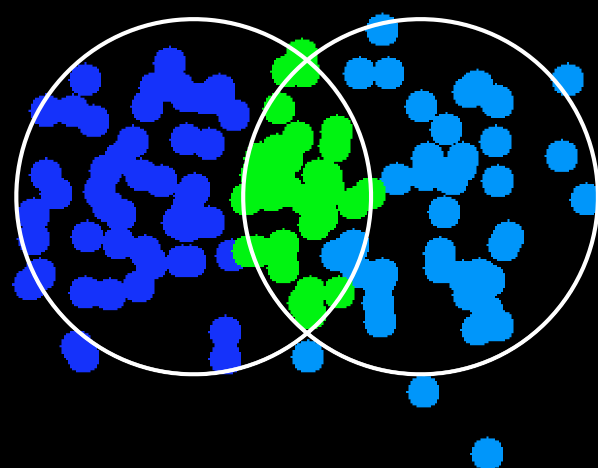
Au+Au



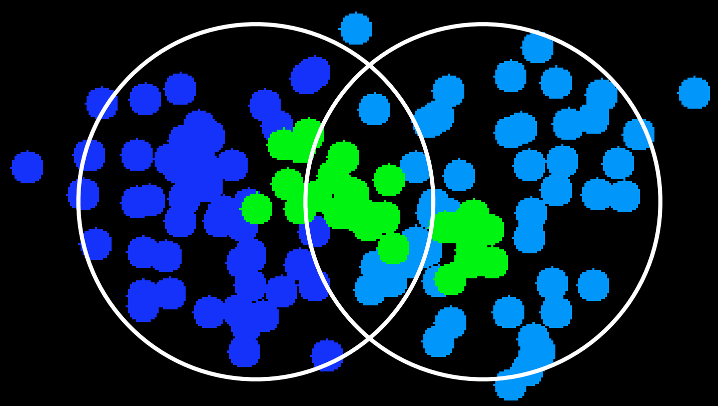
Participants trace out overlap zone, but include

1. Fluctuations (finite number per event)
2. Correlations (it takes two to tango...)

Cu+Cu

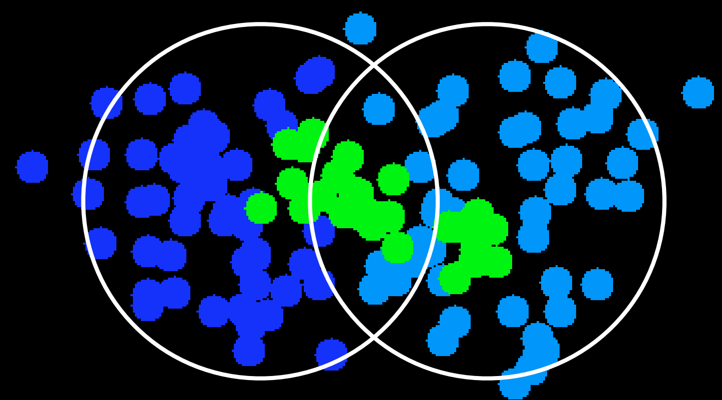


Cu+Cu



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

Cu+Cu

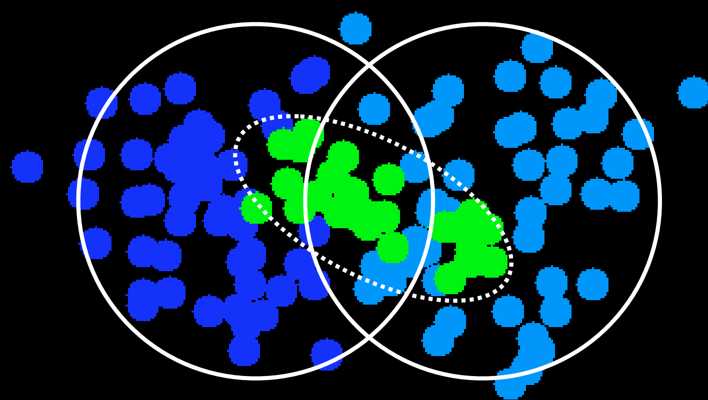


$$\epsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

"Standard eccentricity"

Cu+Cu

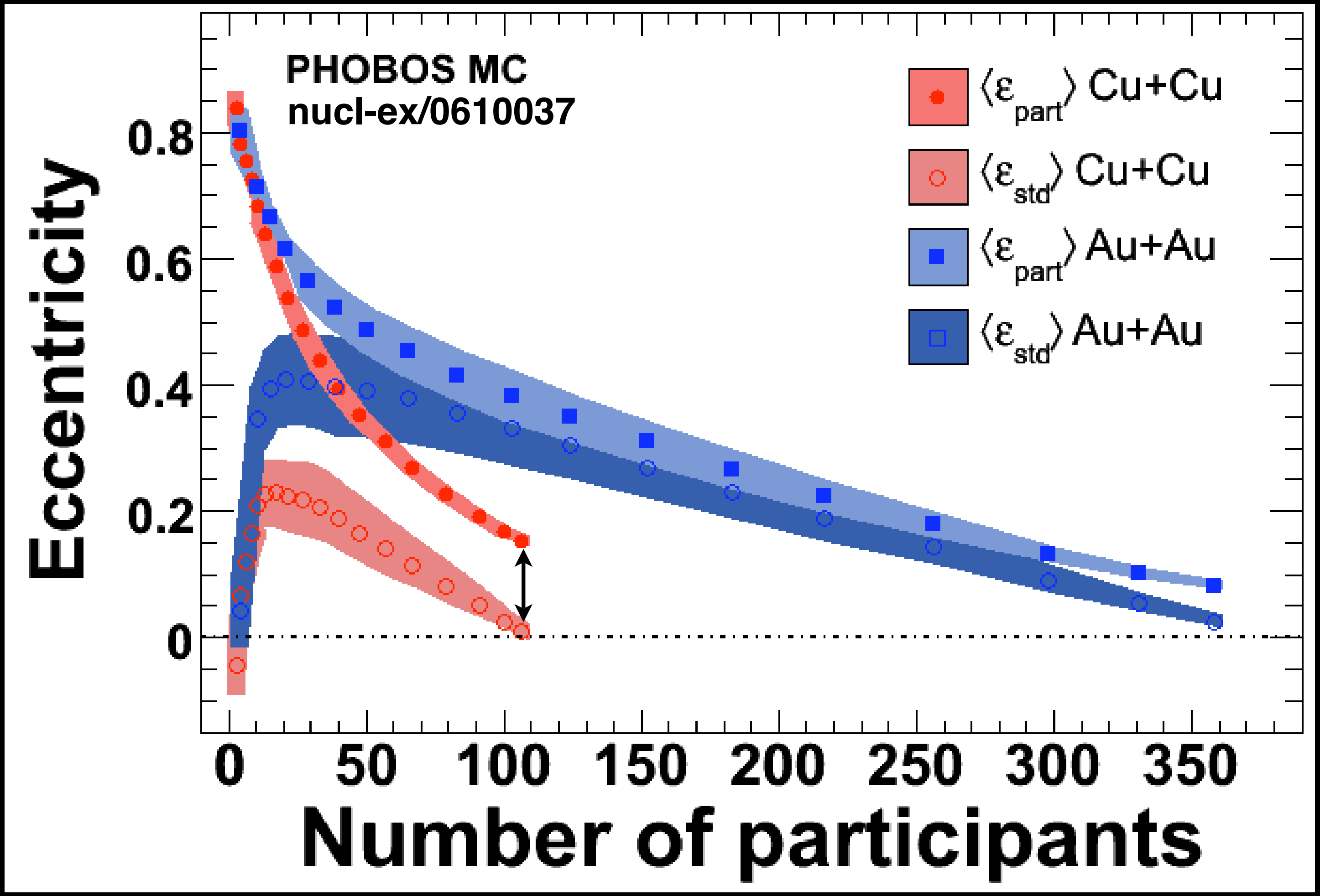
Principal axes make sense if v_2 depends on shape of produced matter, not the reaction plane



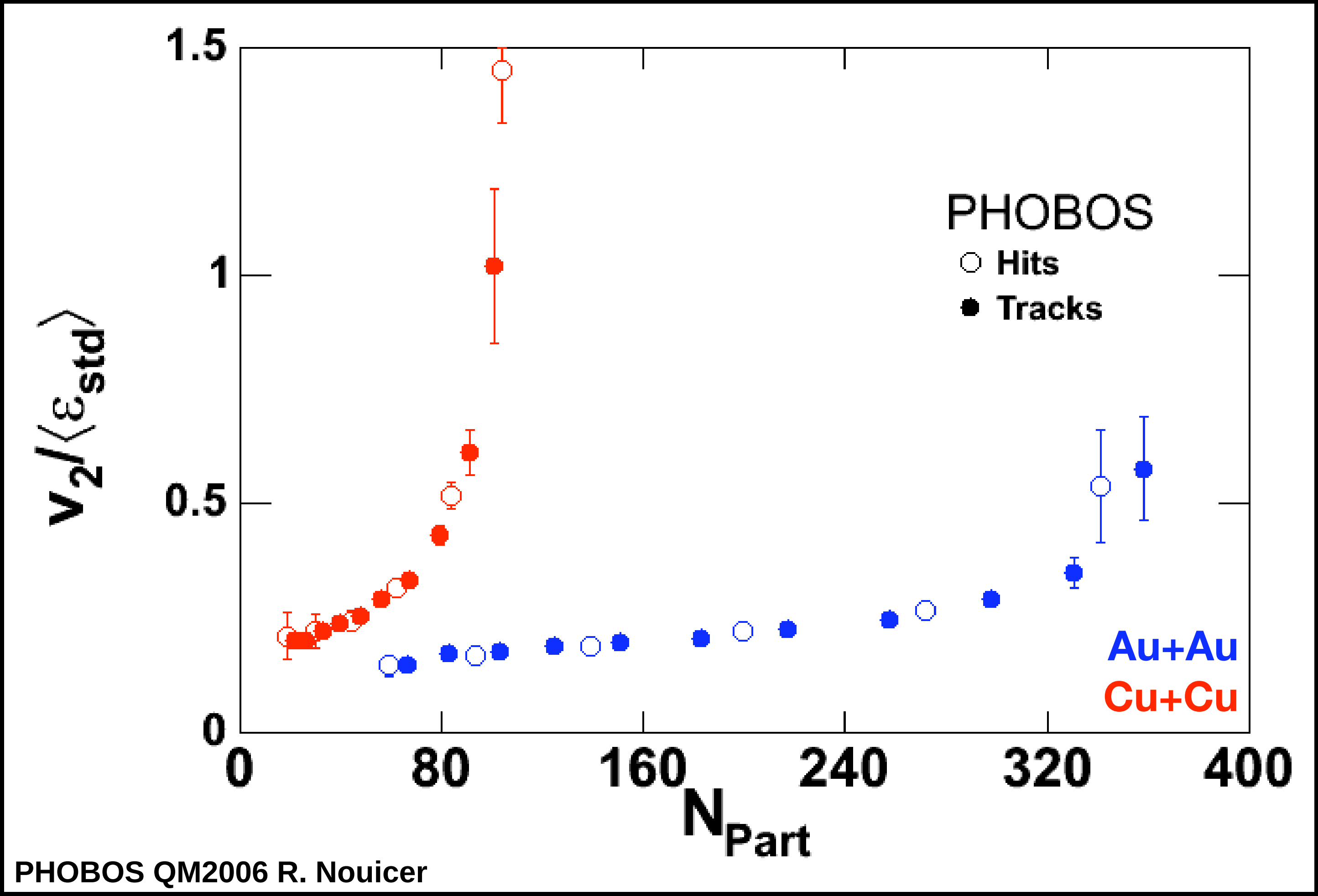
$$\epsilon_{part} = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4(\sigma_{xy}^2)^2}}{\sigma_y^2 + \sigma_x^2}$$

"Participant eccentricity"

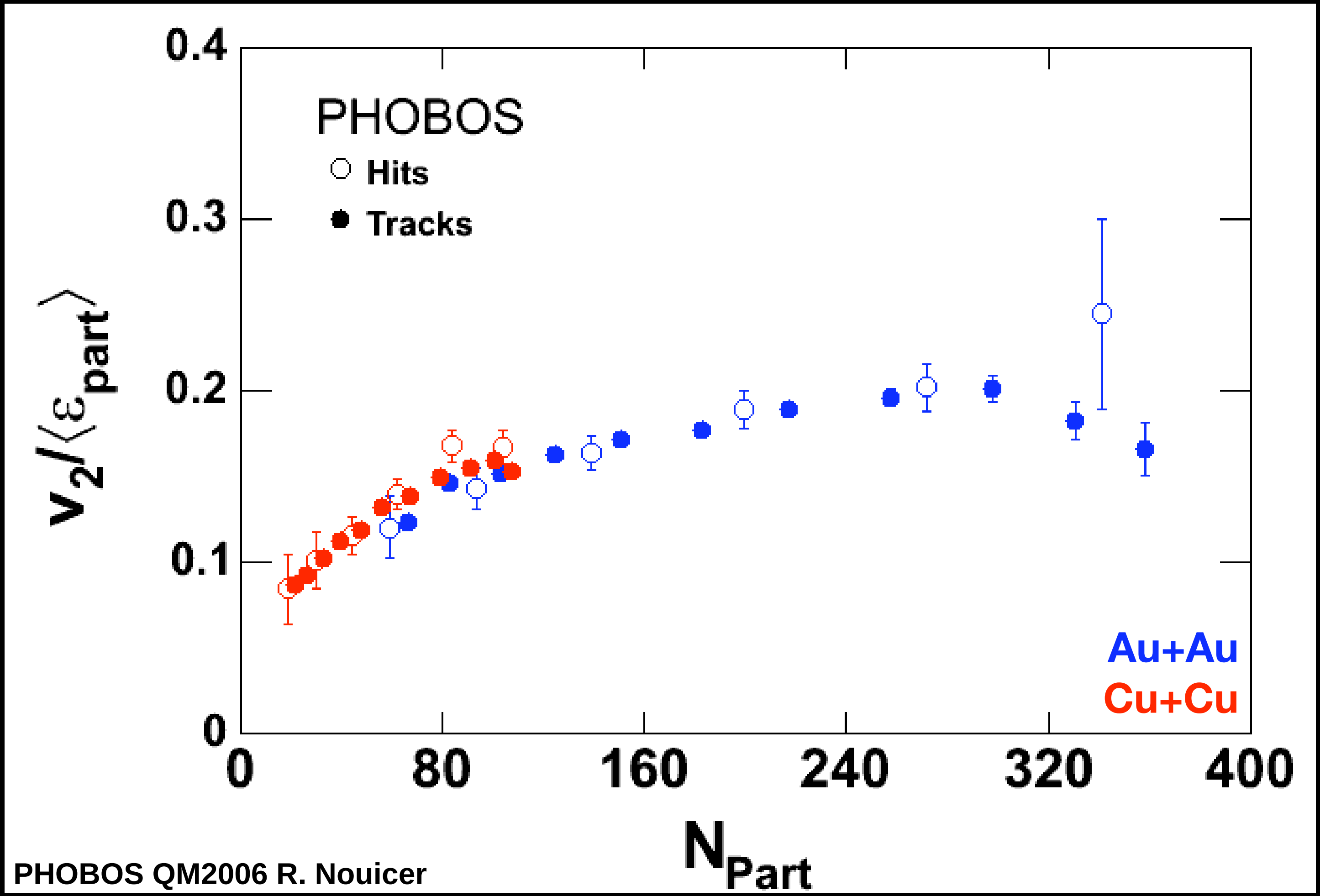
Participant vs. Standard



Something wrong...



...leads to scaling



vs. Areal Density

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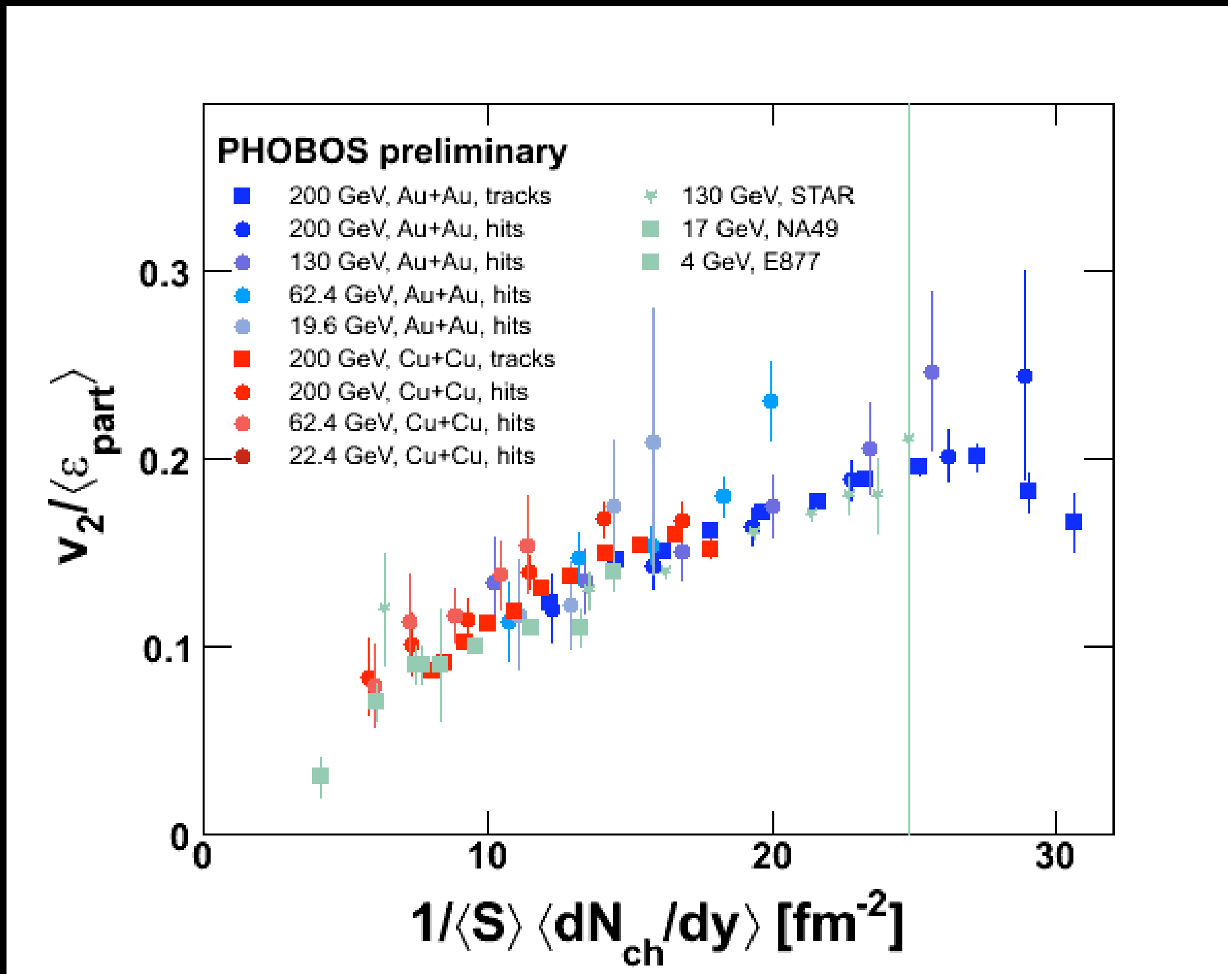
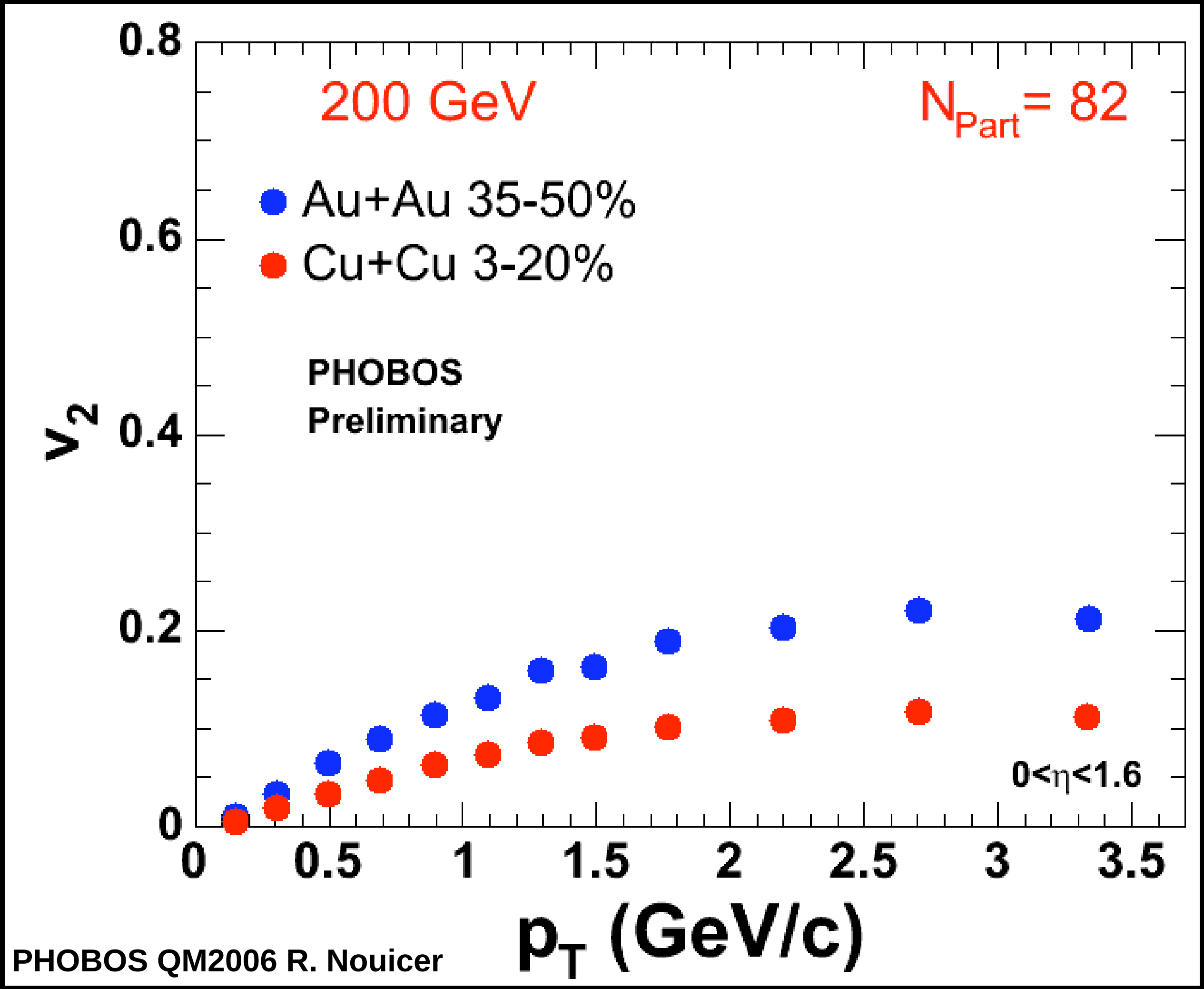


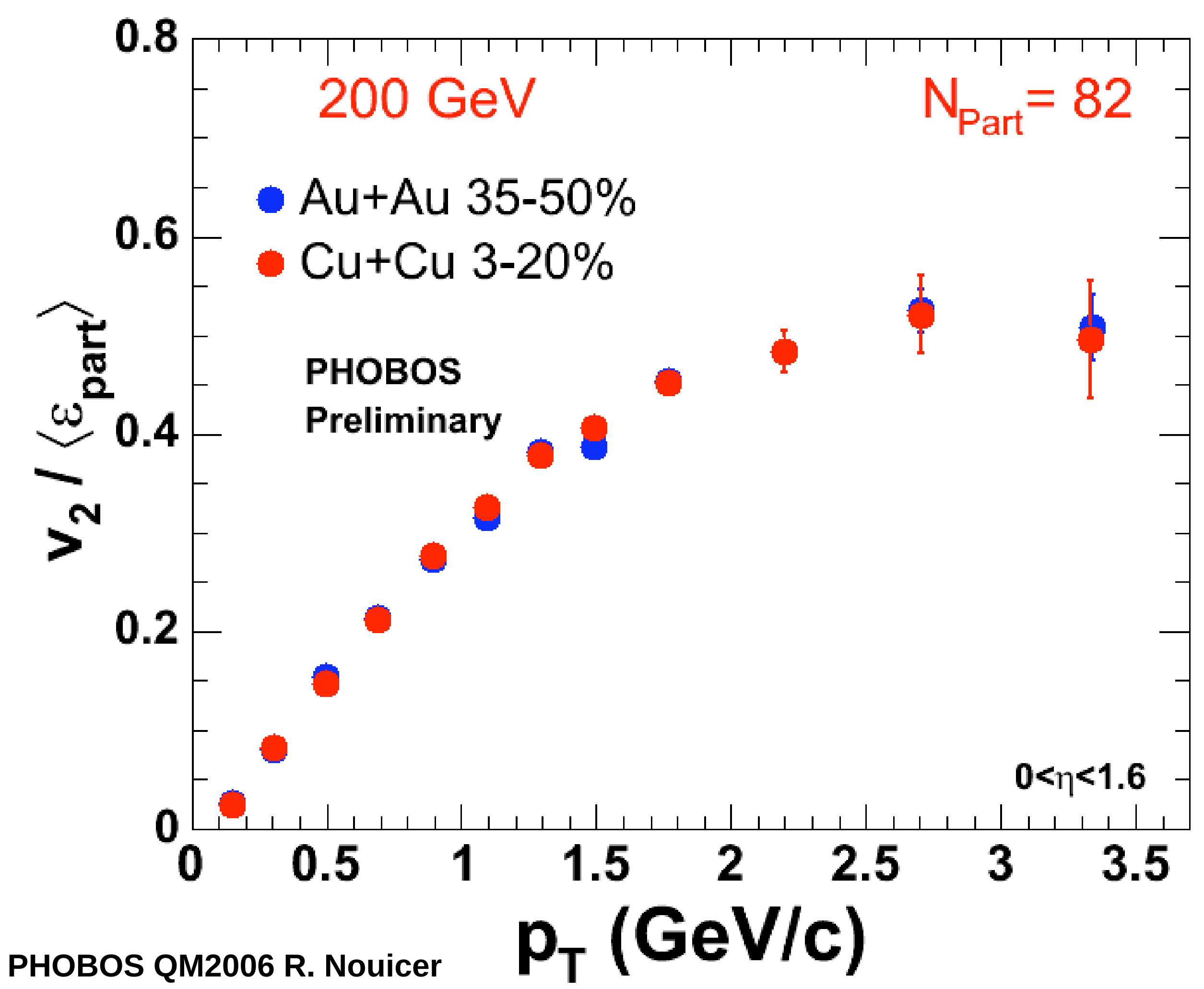
statistical errors only

Transverse Momentum



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

Transverse Momentum

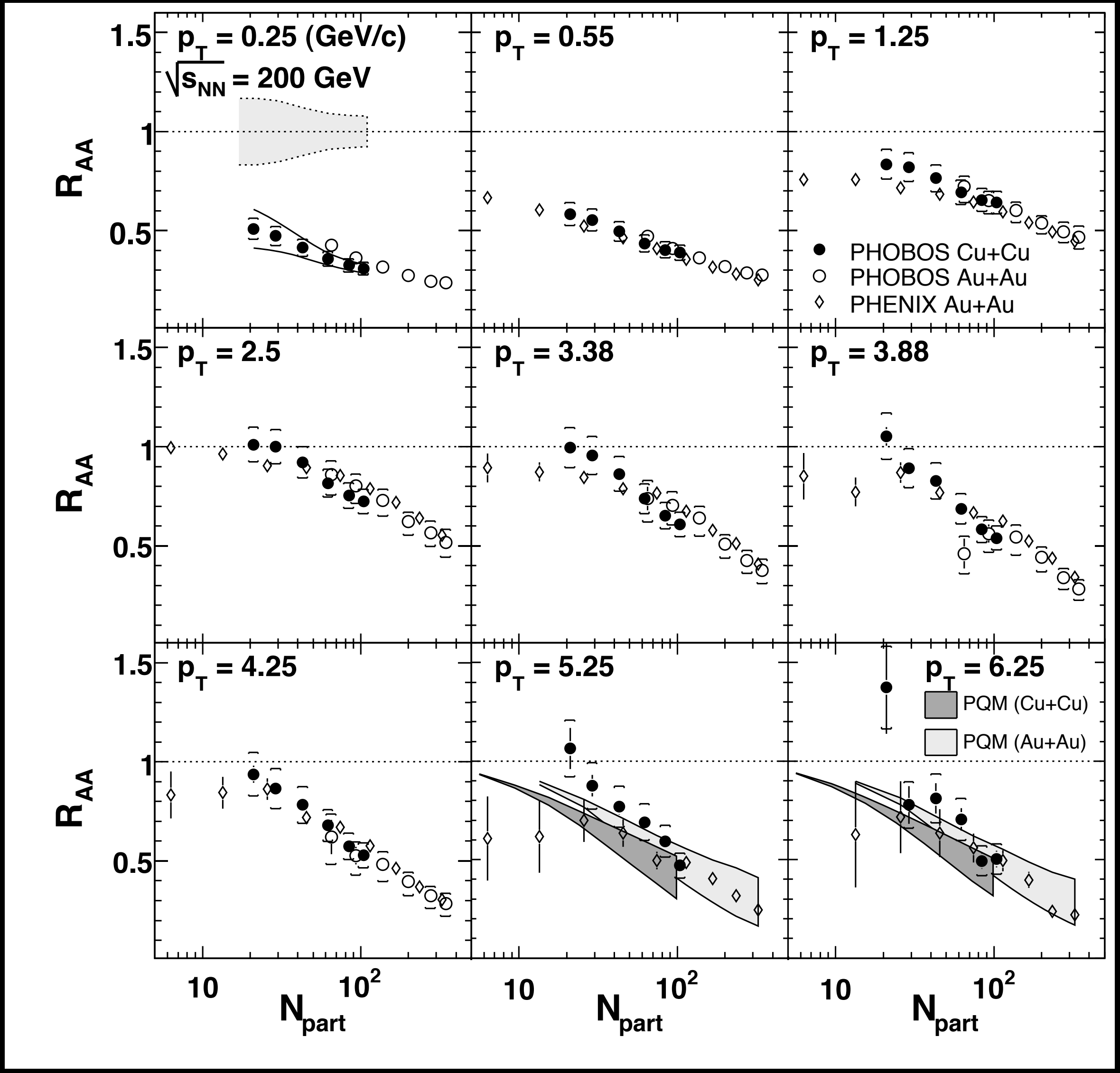


Unity of geometry, system, energy, p_T

at same N_{part}

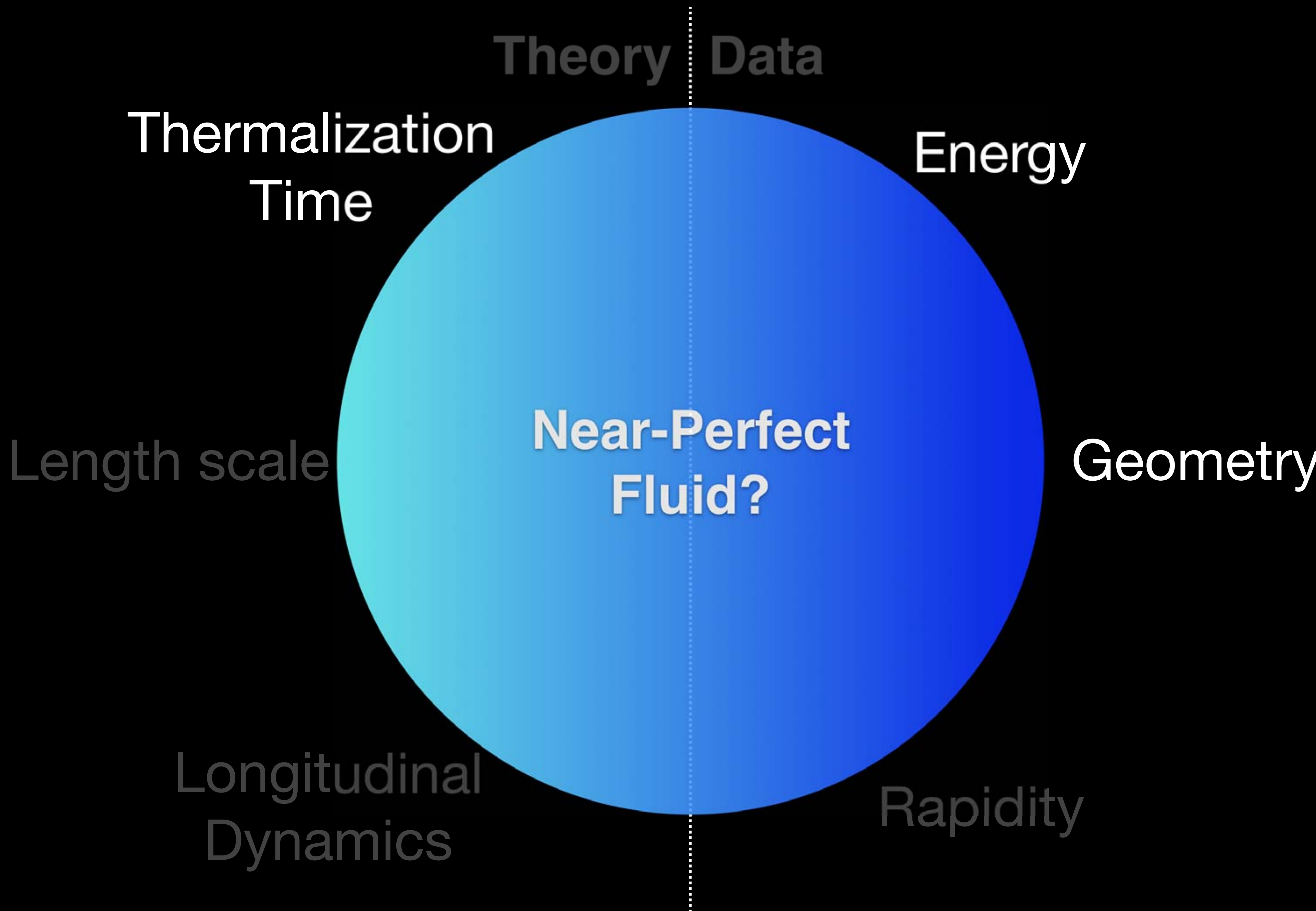
“N_{part} Scaling”

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

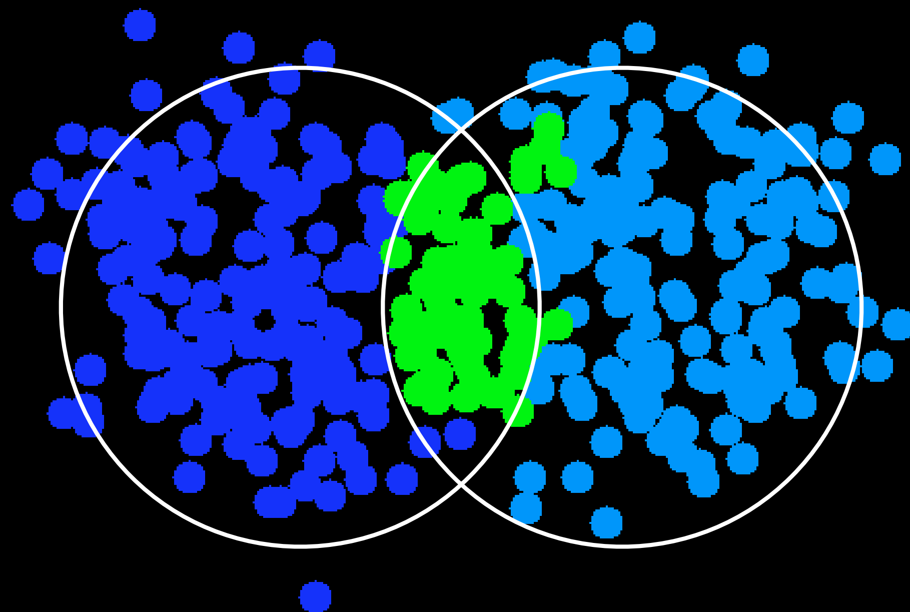


We’ve seen this before, even for R_{AA}

Suggests the geometry is “frozen in” immediately

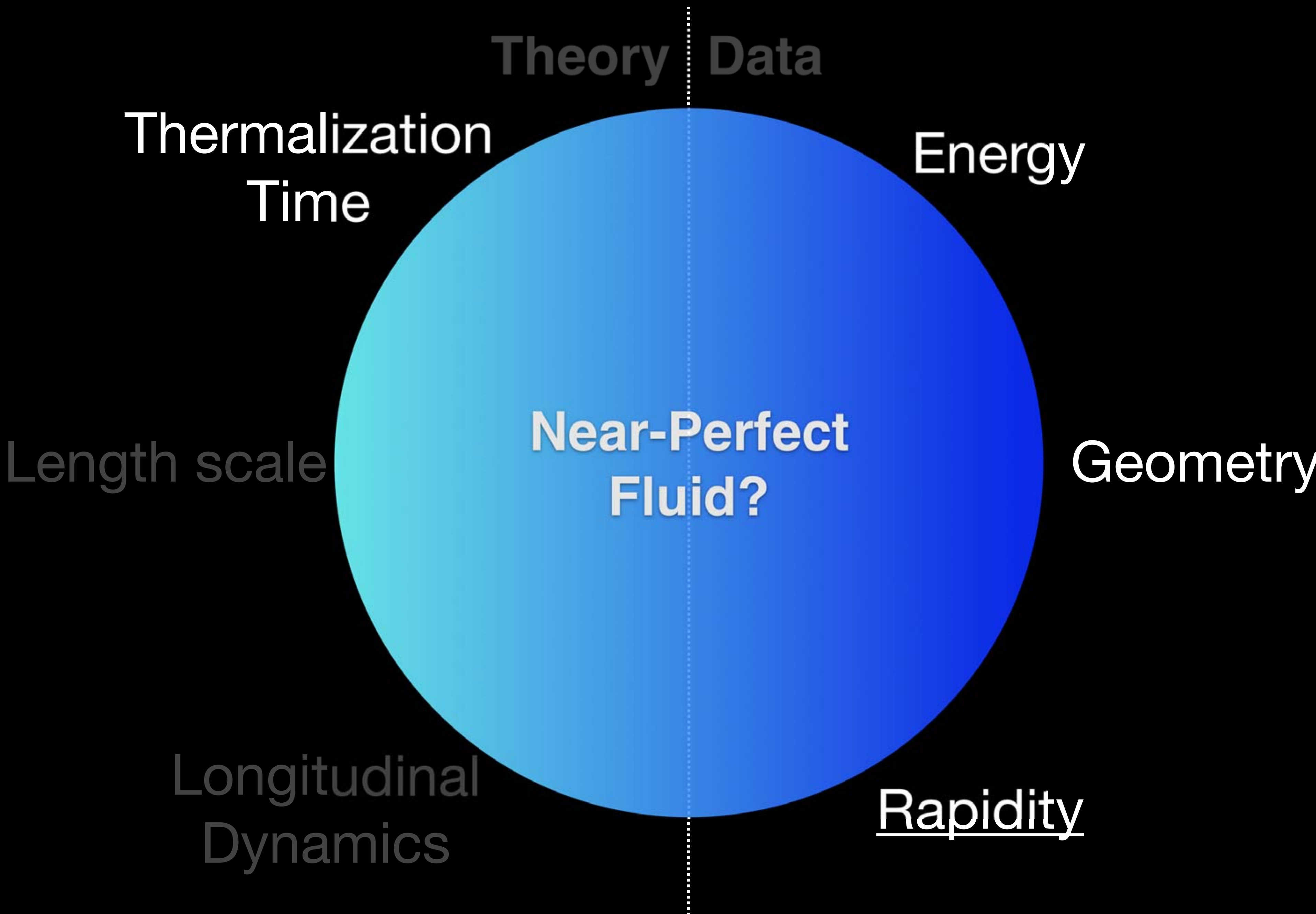


“Freeze-in”

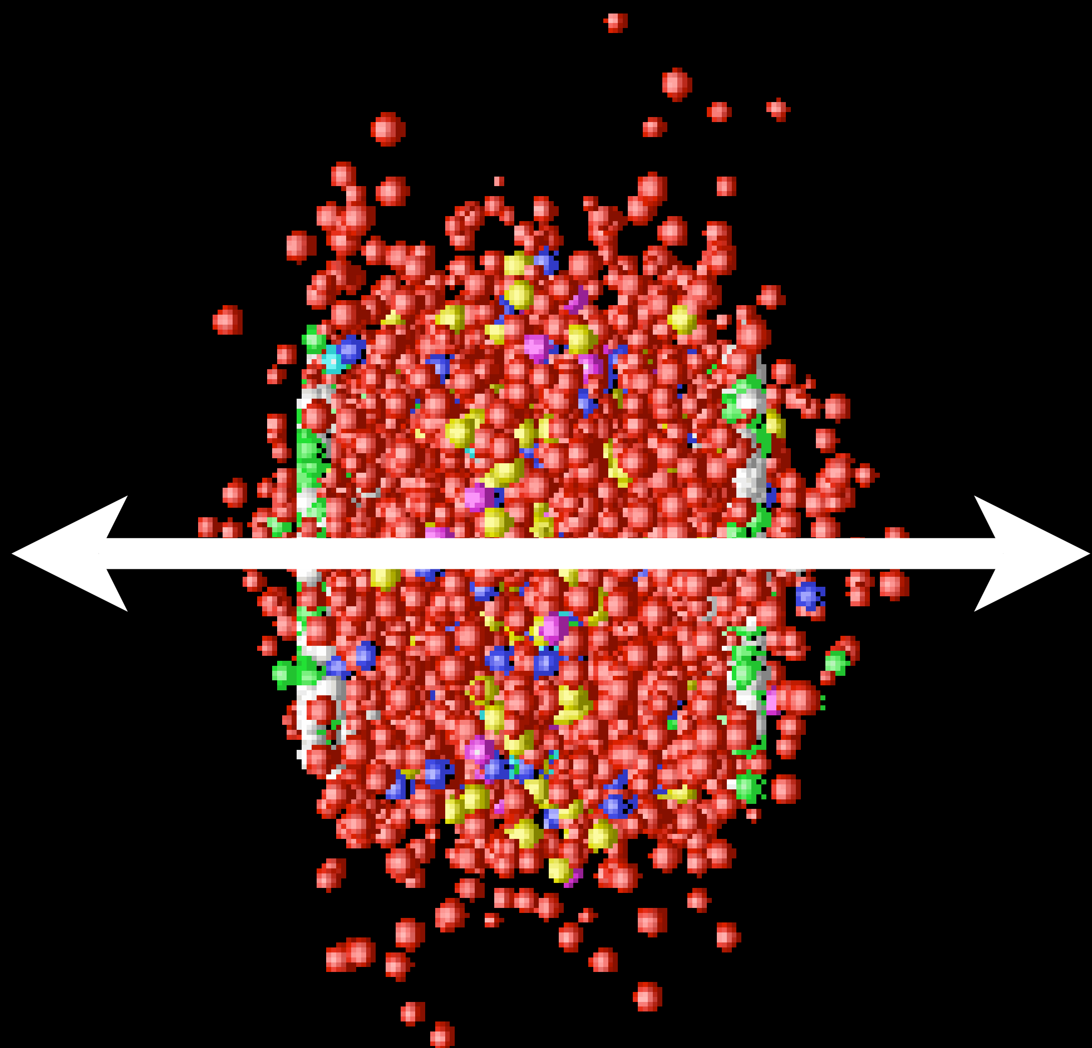


Configuration established early and preserved: substantial viscosity would generate new entropy under different geometric conditions

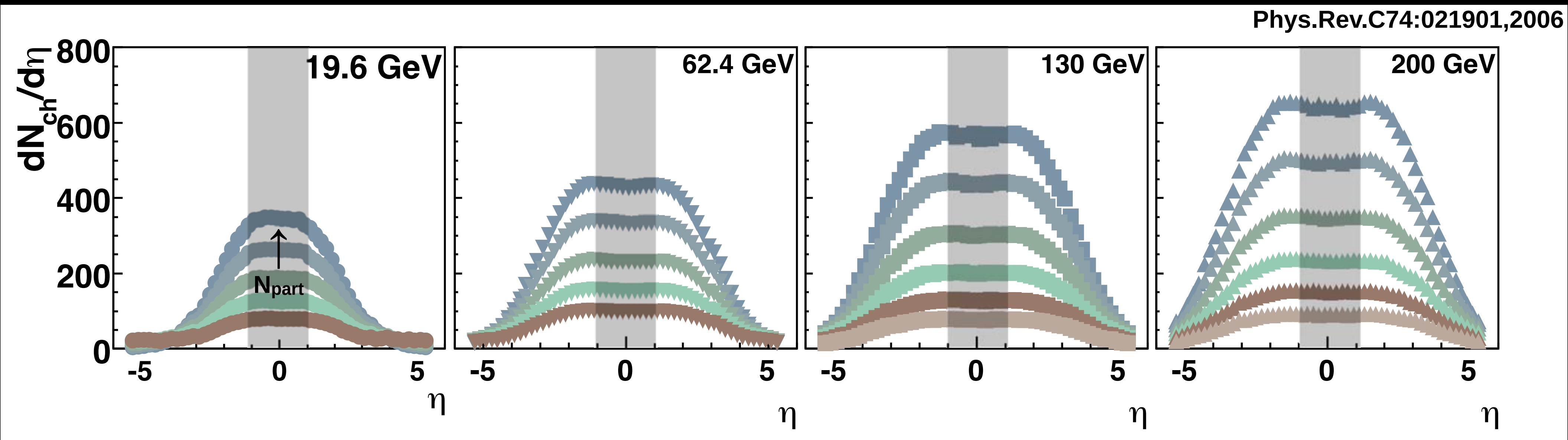
What about “the rest” of particle production?



Longitudinal Distributions



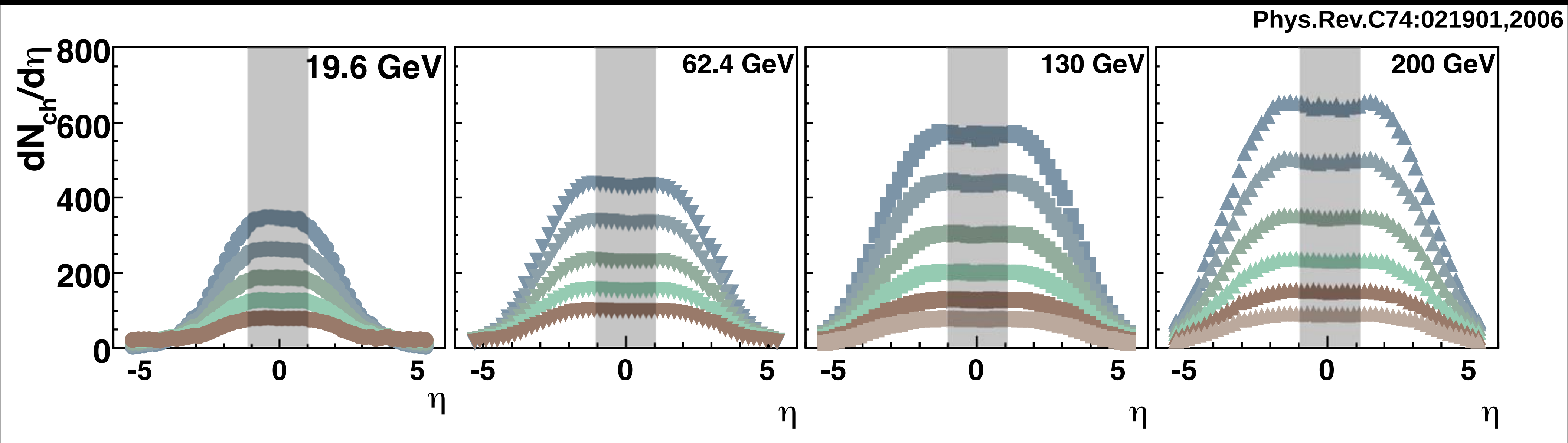
RHIC in 3D

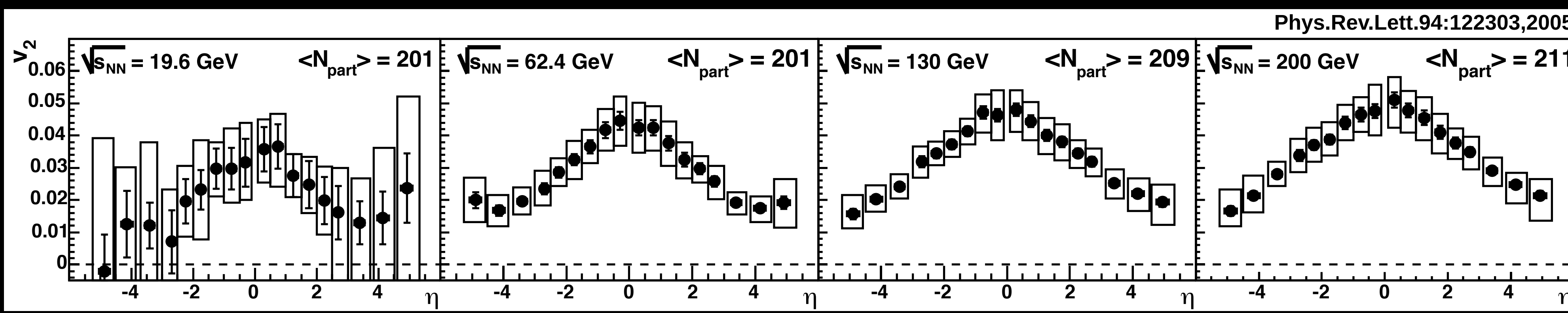


Ignoring rapidity axis
ignores most of the particle production

$$y = tanh^{-1}\beta_z \quad \rightarrow \quad \eta = -\log(\tan(\theta/2))$$

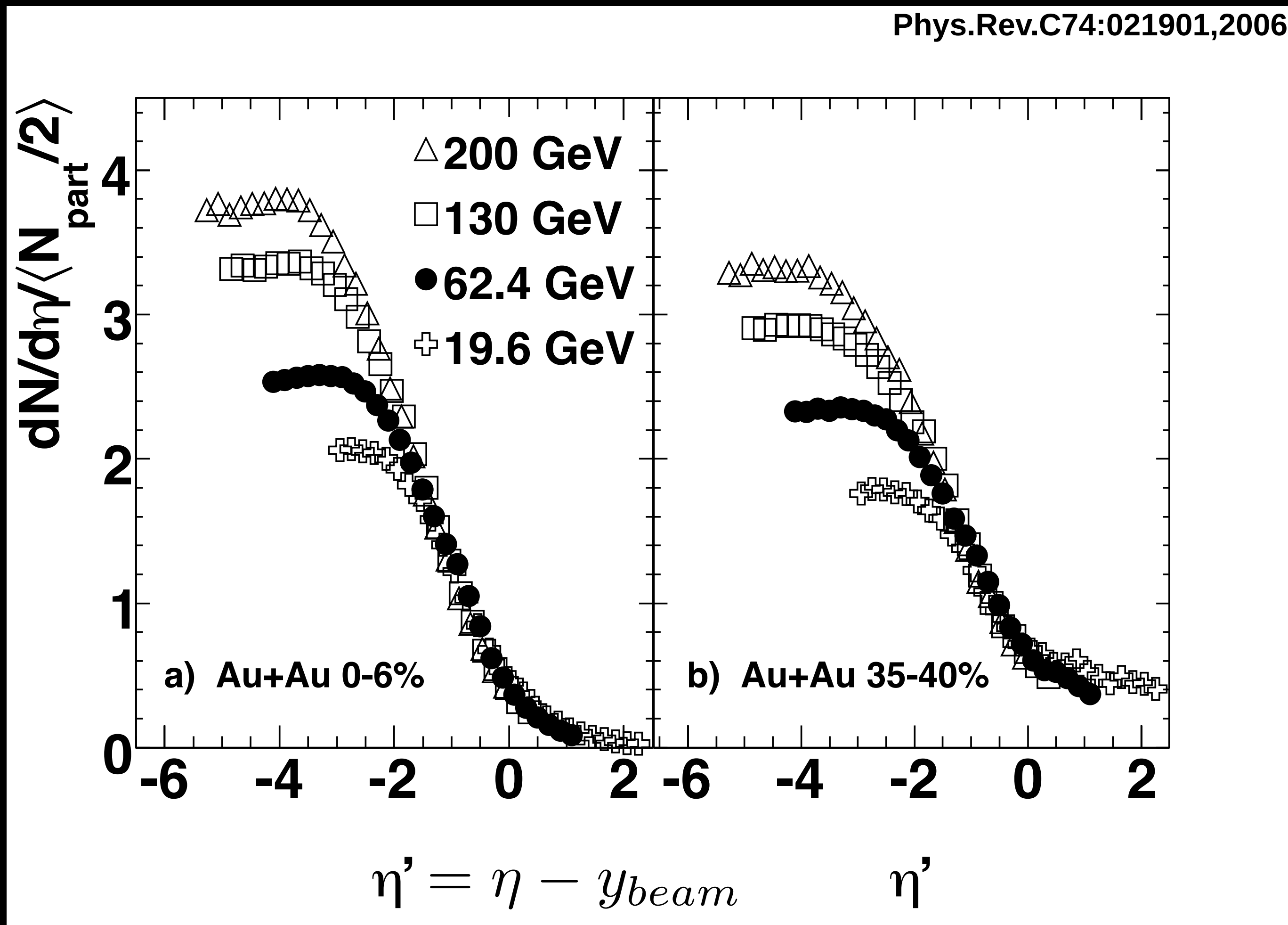
Flow in 3D





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

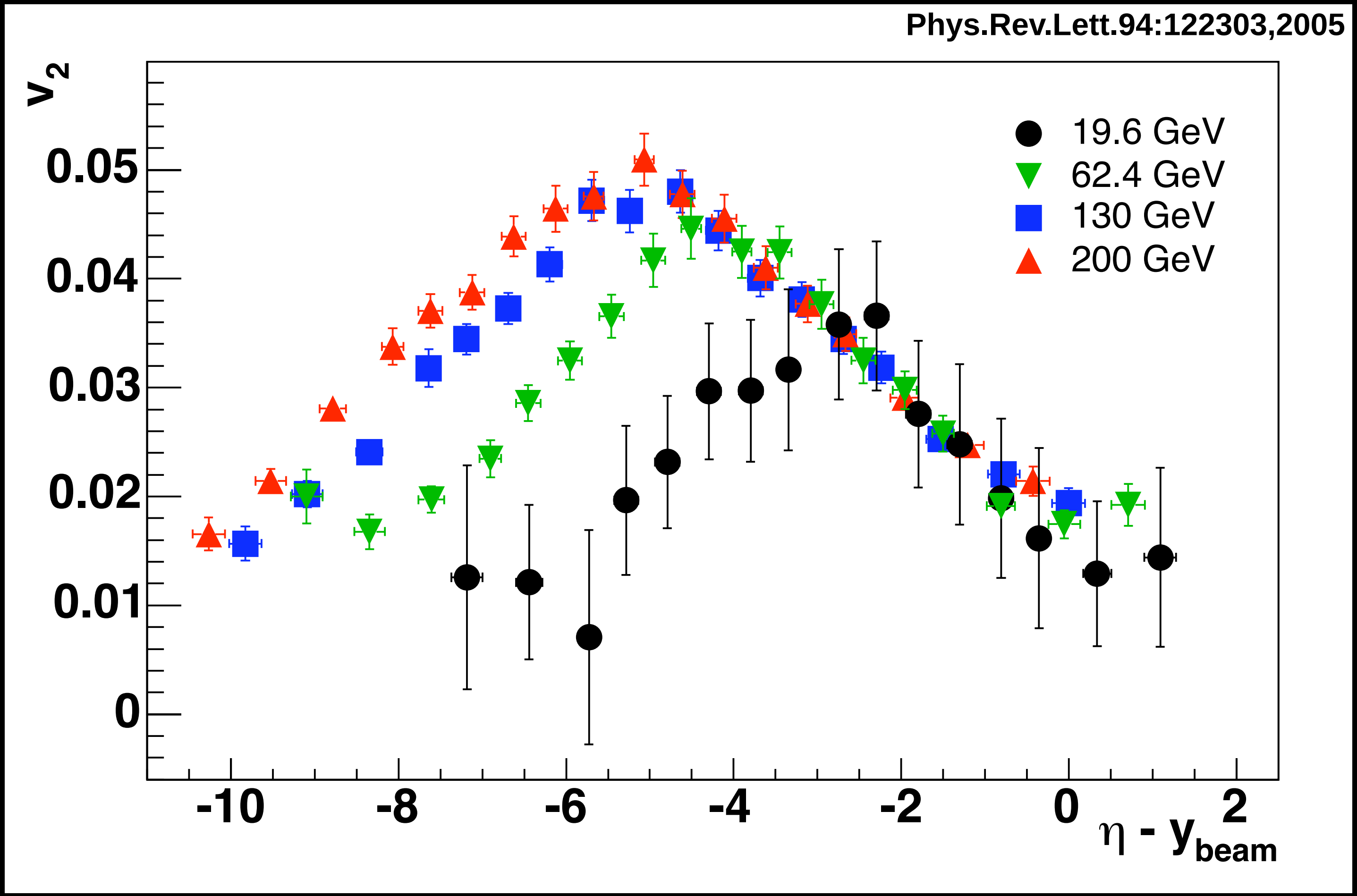
Longitudinal Scaling



Particle densities are invariant when viewed in the rest frame of one of the projectiles

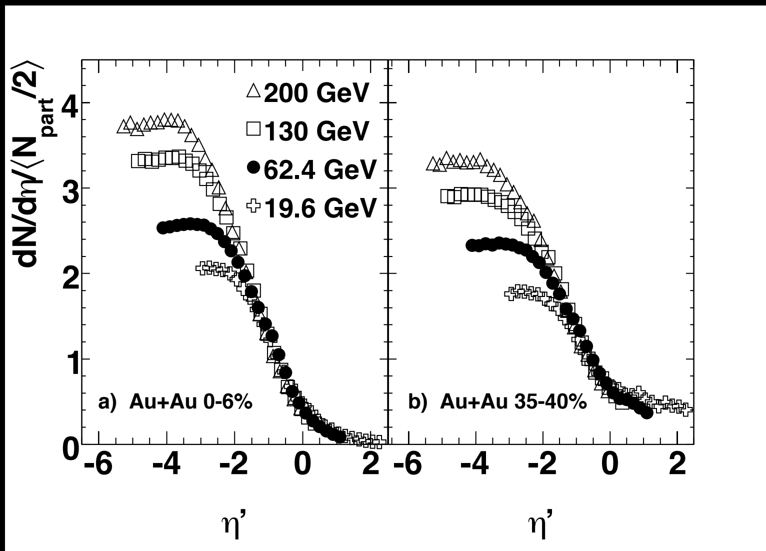
(Entire distribution changes w/ centrality...)

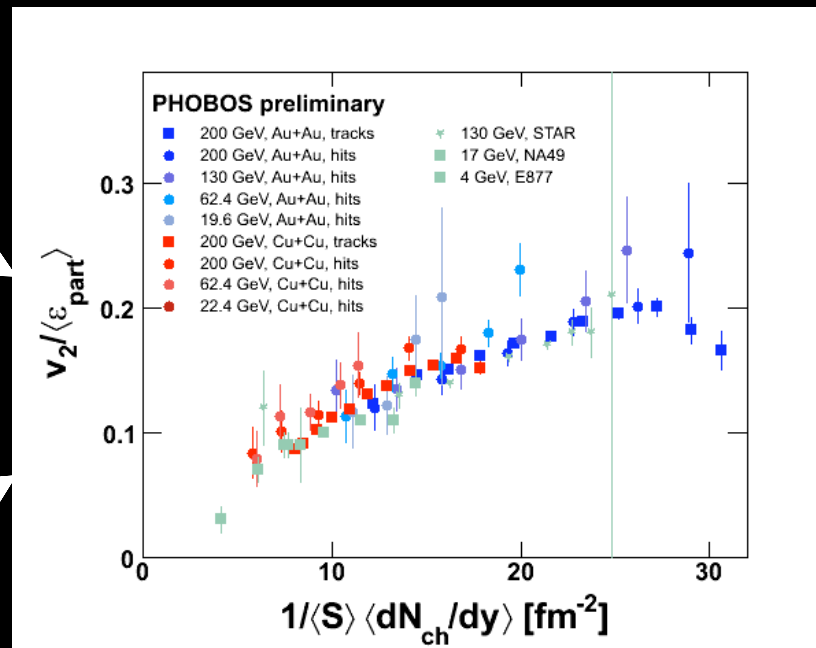
Longitudinal Scaling

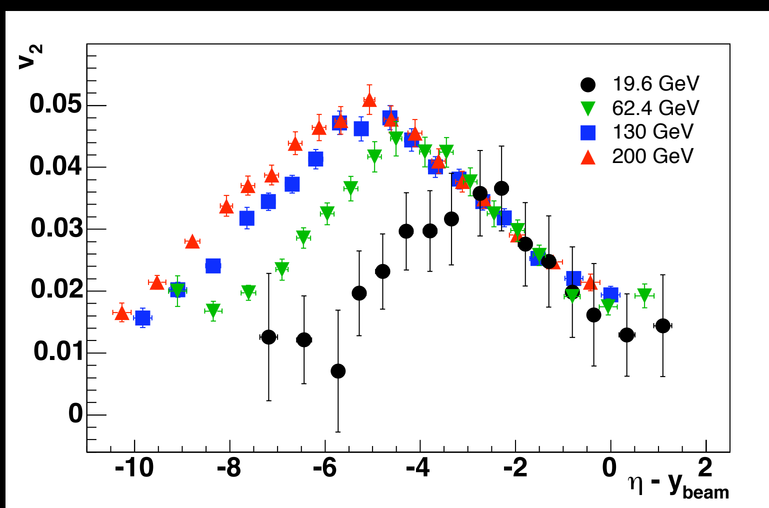


Elliptic flow is invariant when viewed in the rest frame of one of the projectiles

Unity of Response

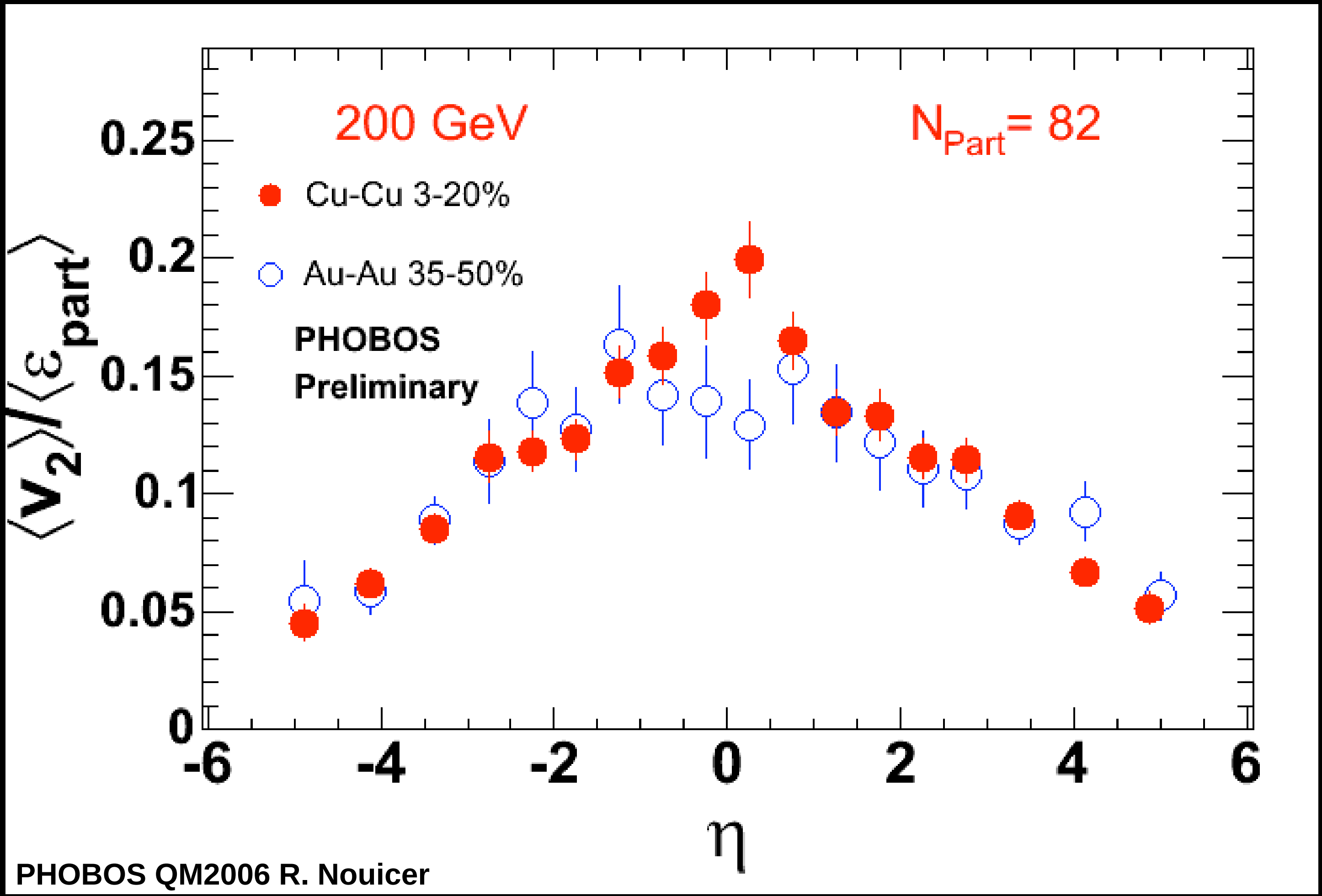






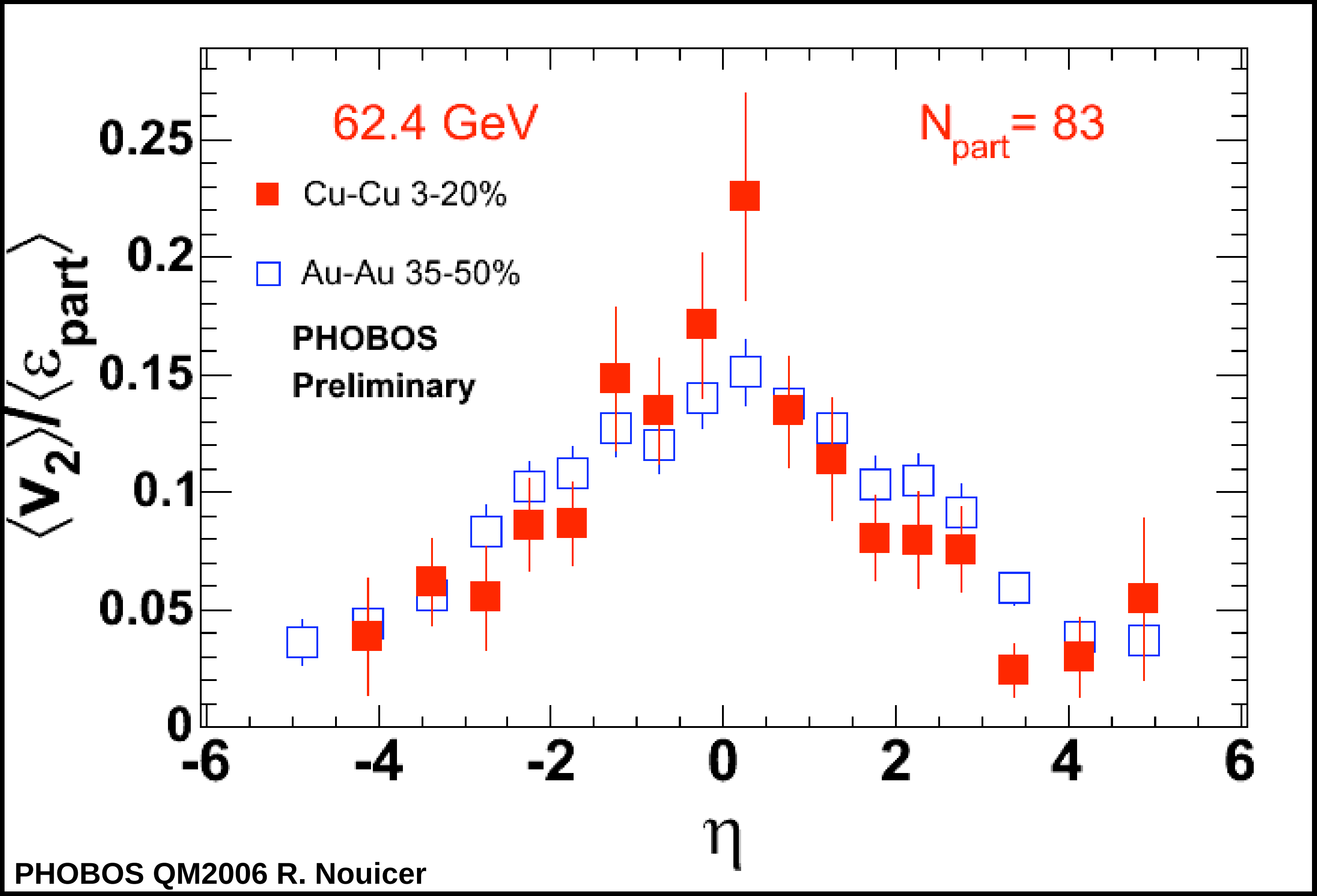
v_2 seems to respond ~linearly to particle density at all energies, rapidities, & centralities

Eccentricity is Global



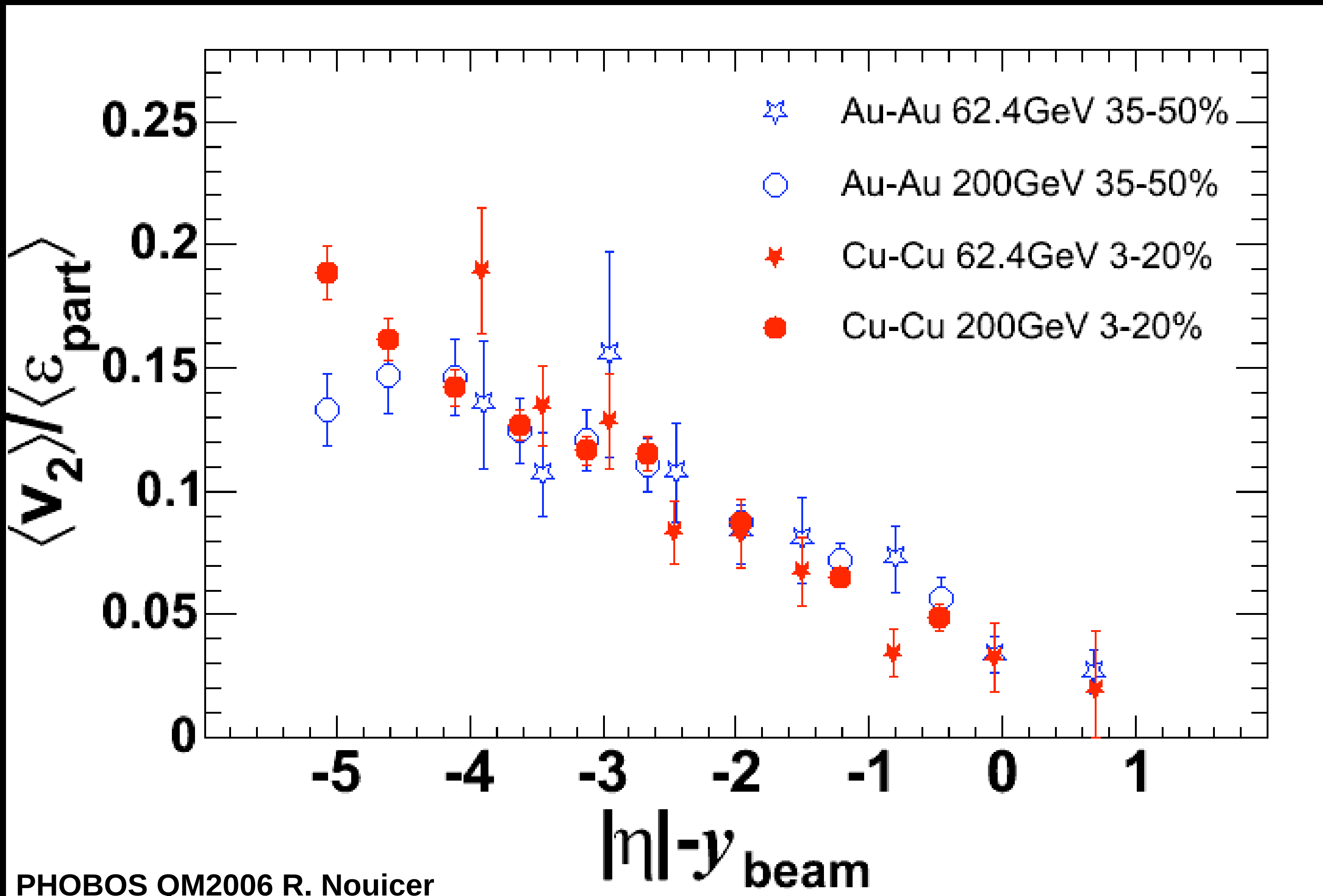
Participant eccentricity unifies different systems
at same N_{part}, at all pseudorapidities:
source shape does not change with η

Eccentricity is Global



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

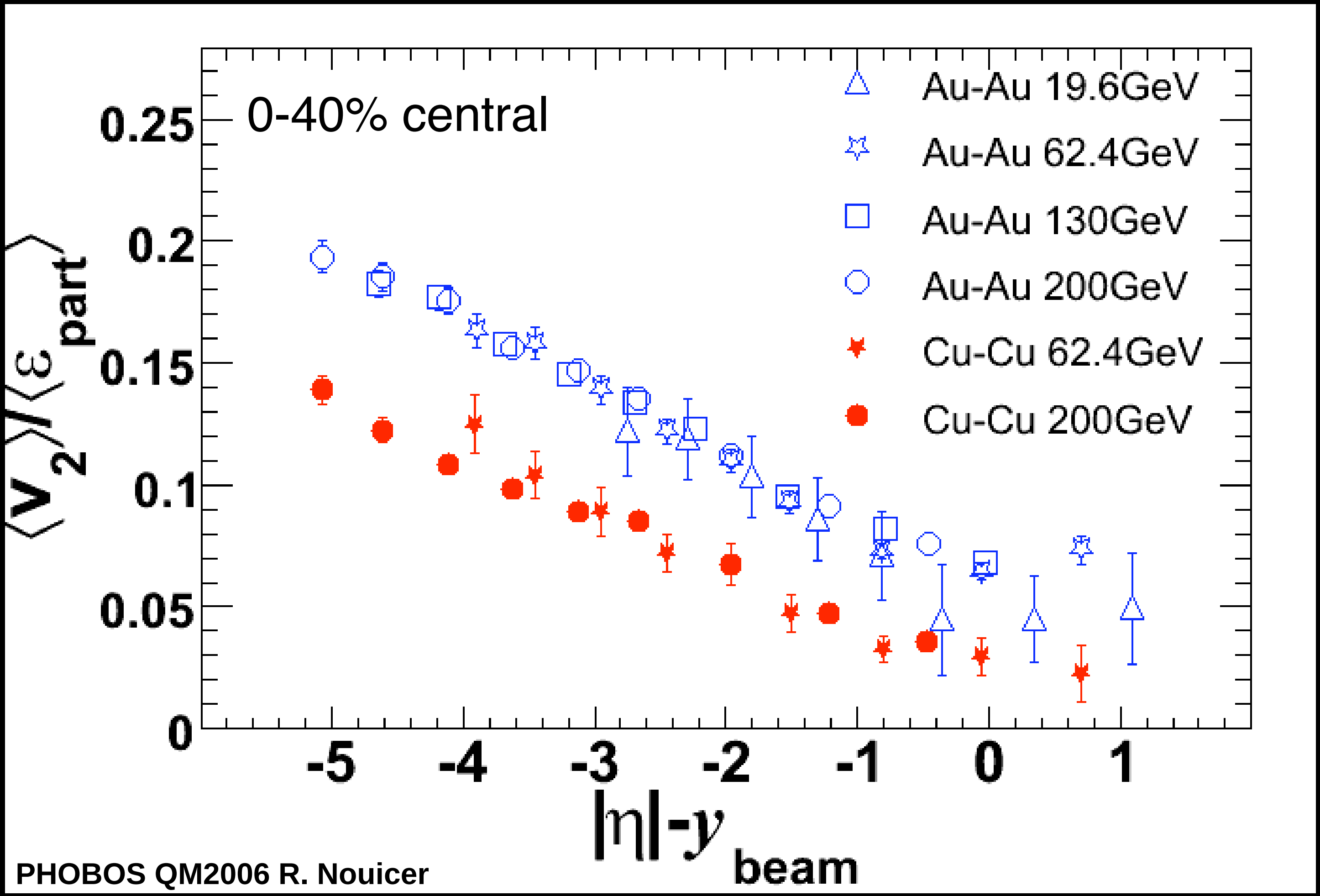
Same N_{part}



Unity of geometry, system, energy, rapidity

at same N_{part}

Different N_{part}



At same fraction of cross section,
observe longitudinal scaling, but system dependence

Cross Section Scaling

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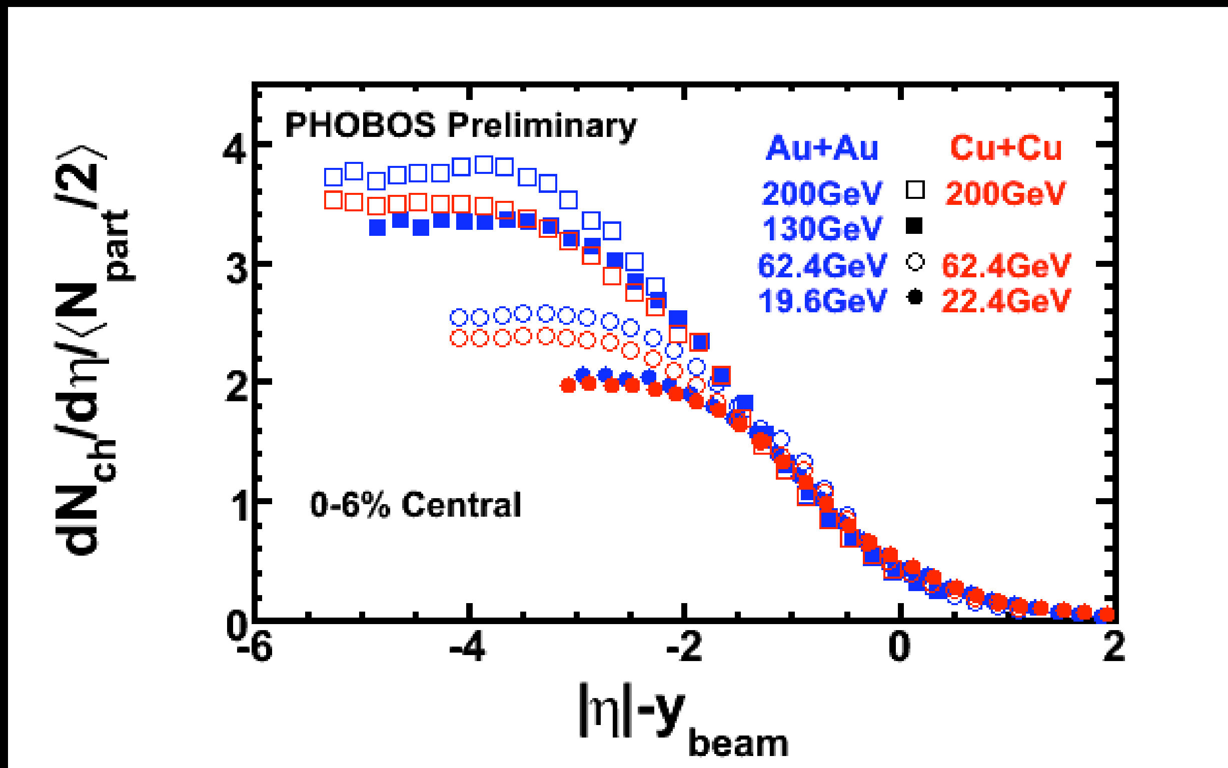
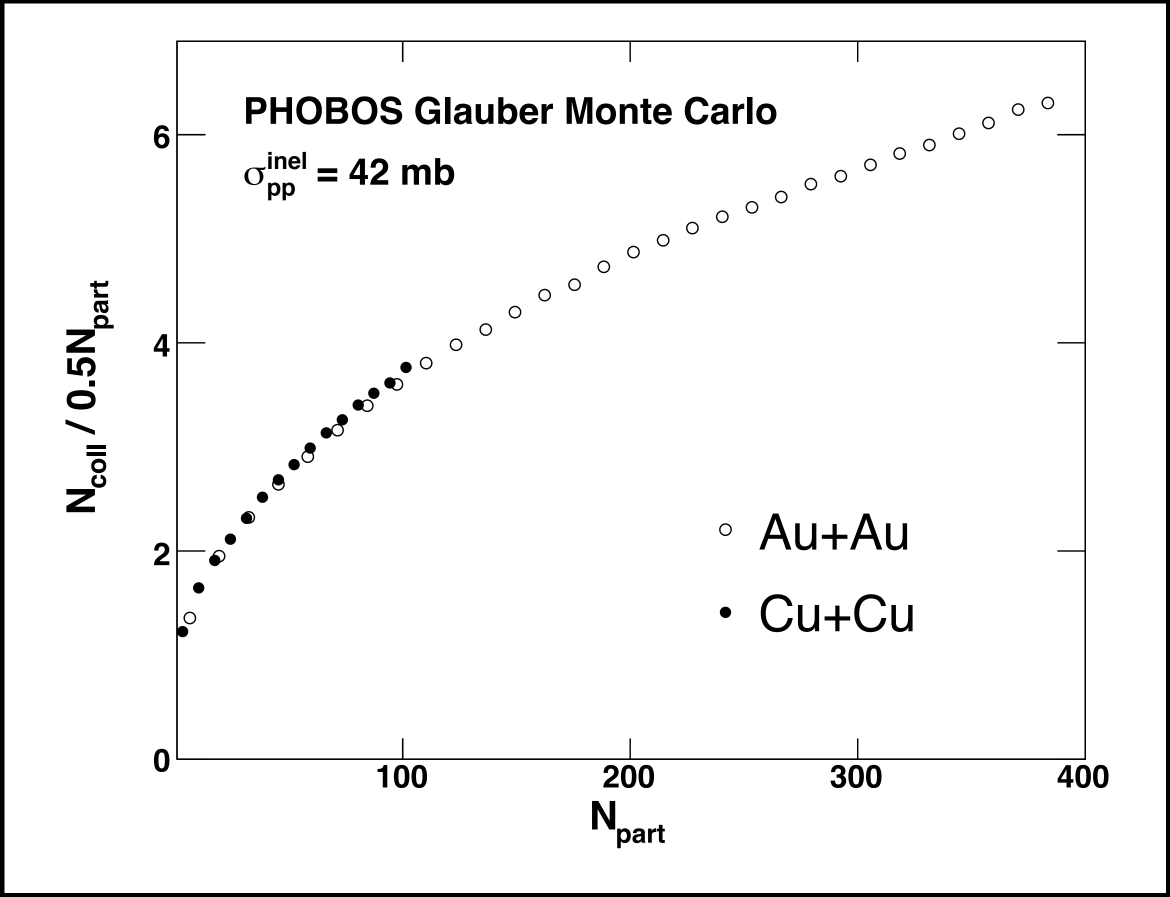


Curious, since longitudinal distributions of particle multiplicities are similar when matching fraction of cross section...

Au+Au vs. Cu+Cu

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

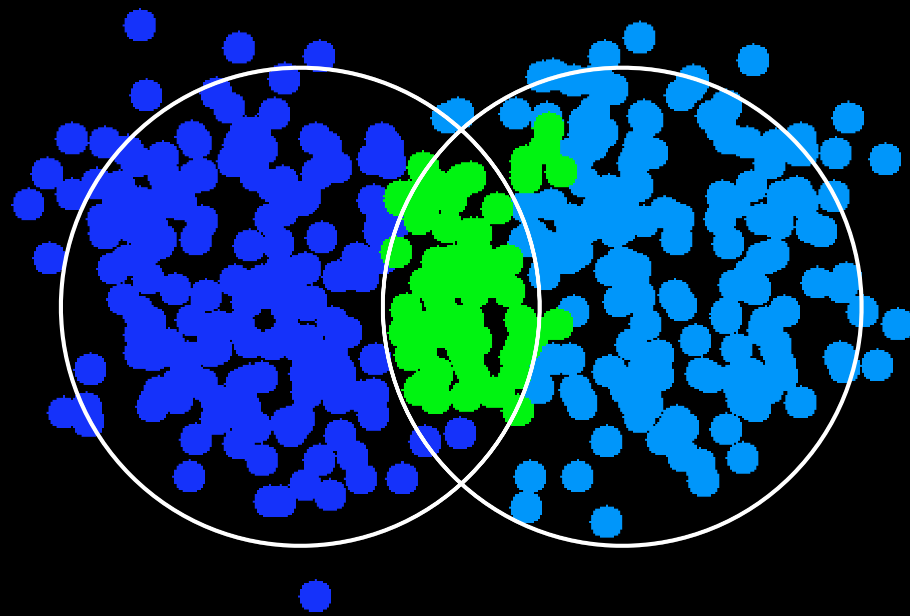


Same nuclear thickness? Same total particle density?

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?

The Strong Assumption

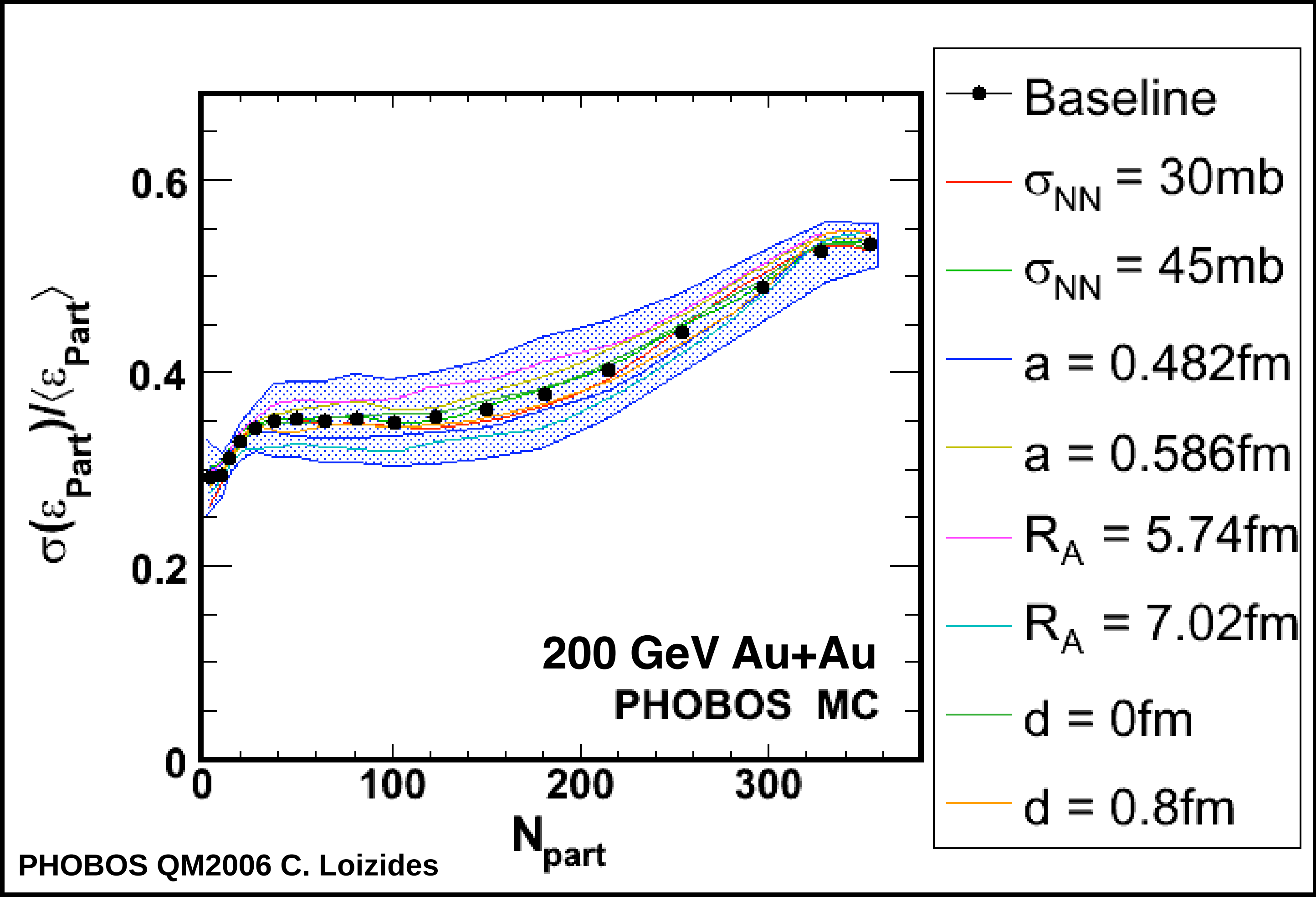
if:

$$v_2 \propto \epsilon_{part}$$

event-by-event, then:

$$\frac{\sigma_{v_2}}{v_2} = \frac{\sigma_{\epsilon_{part}}}{\epsilon_{part}}$$

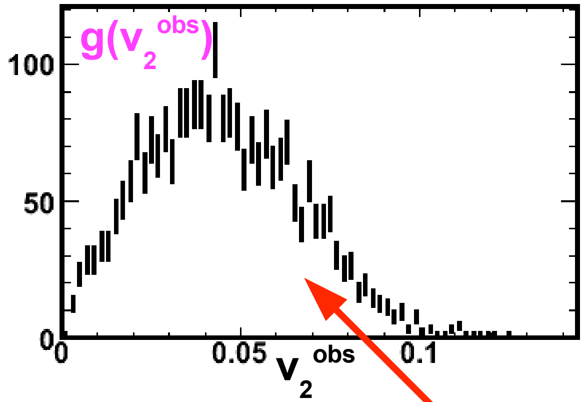
Glauber Monte Carlo



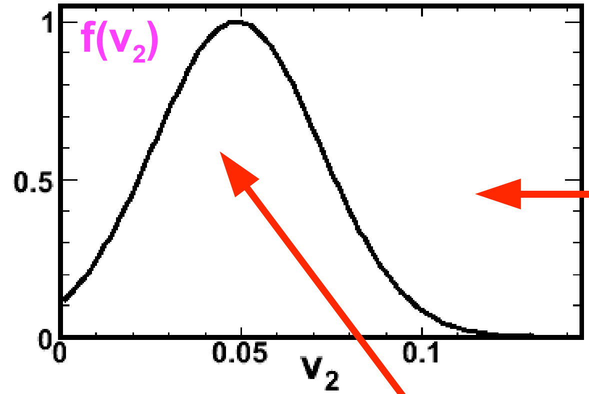
MC approach makes definite prediction for event-by-event fluctuations of ϵ_{part}~40% (robust against variation in Glauber MC parameters)

Measuring elliptic flow fluctuations

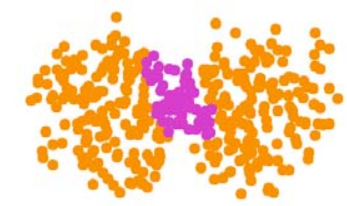
Observed v_2 distribution



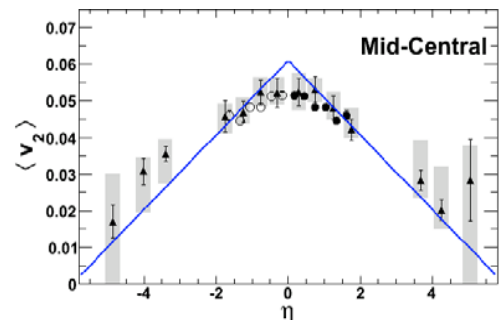
True v_2 distribution



Source of v_2 fluctuation



$$g(v_2^{obs}) = \int_0^1 K(v_2^{obs}, v_2)\, f(v_2)\, dv_2$$

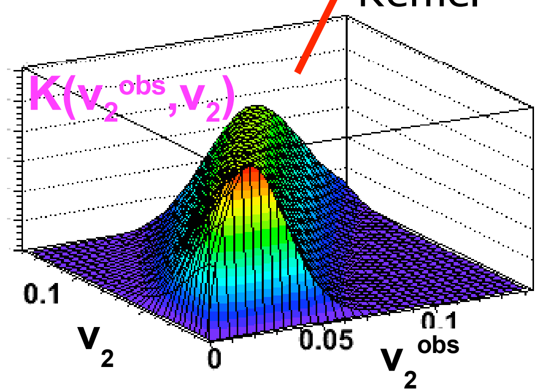


use hits in 4π to calculate event-wise v_2

Kernel

- Detector and acceptance effects
- Finite-number fluctuations
- Multiplicity fluctuations

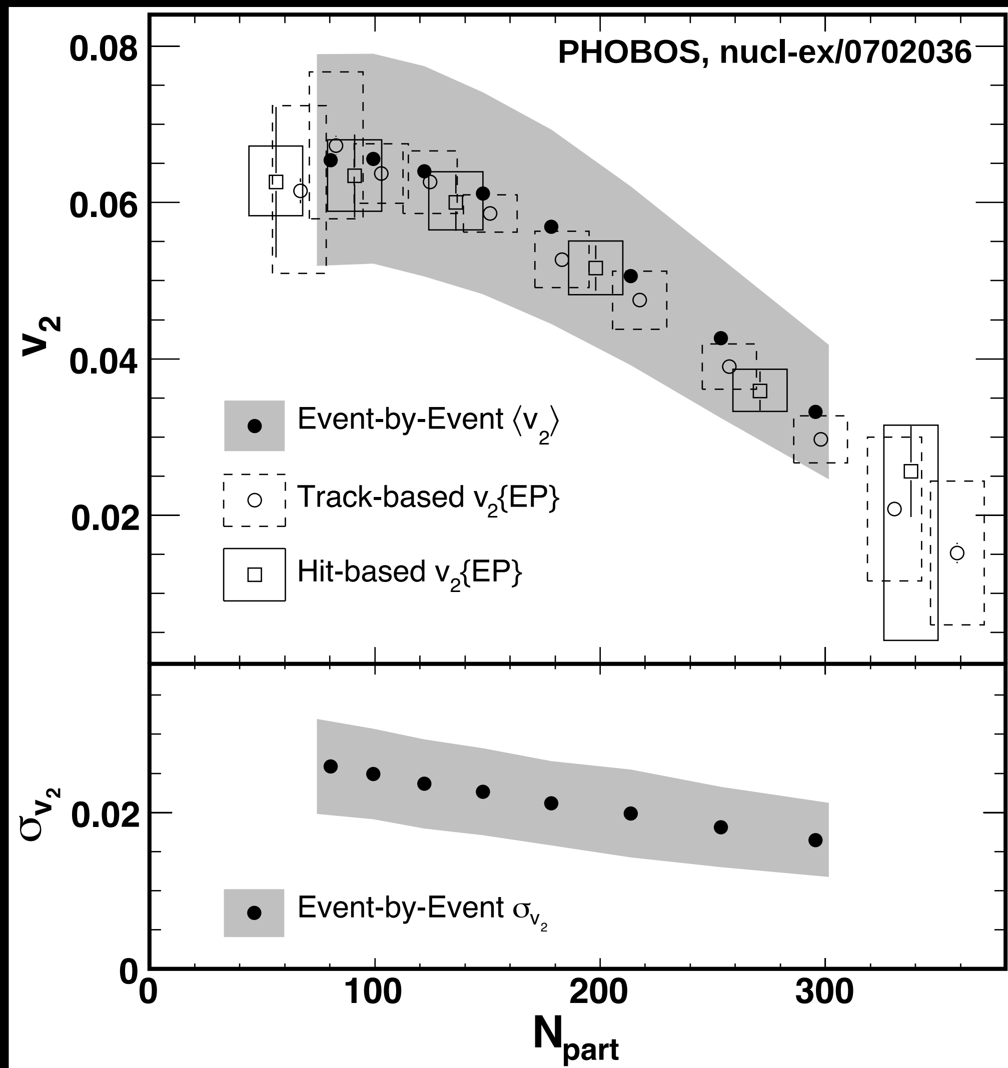
Kernel



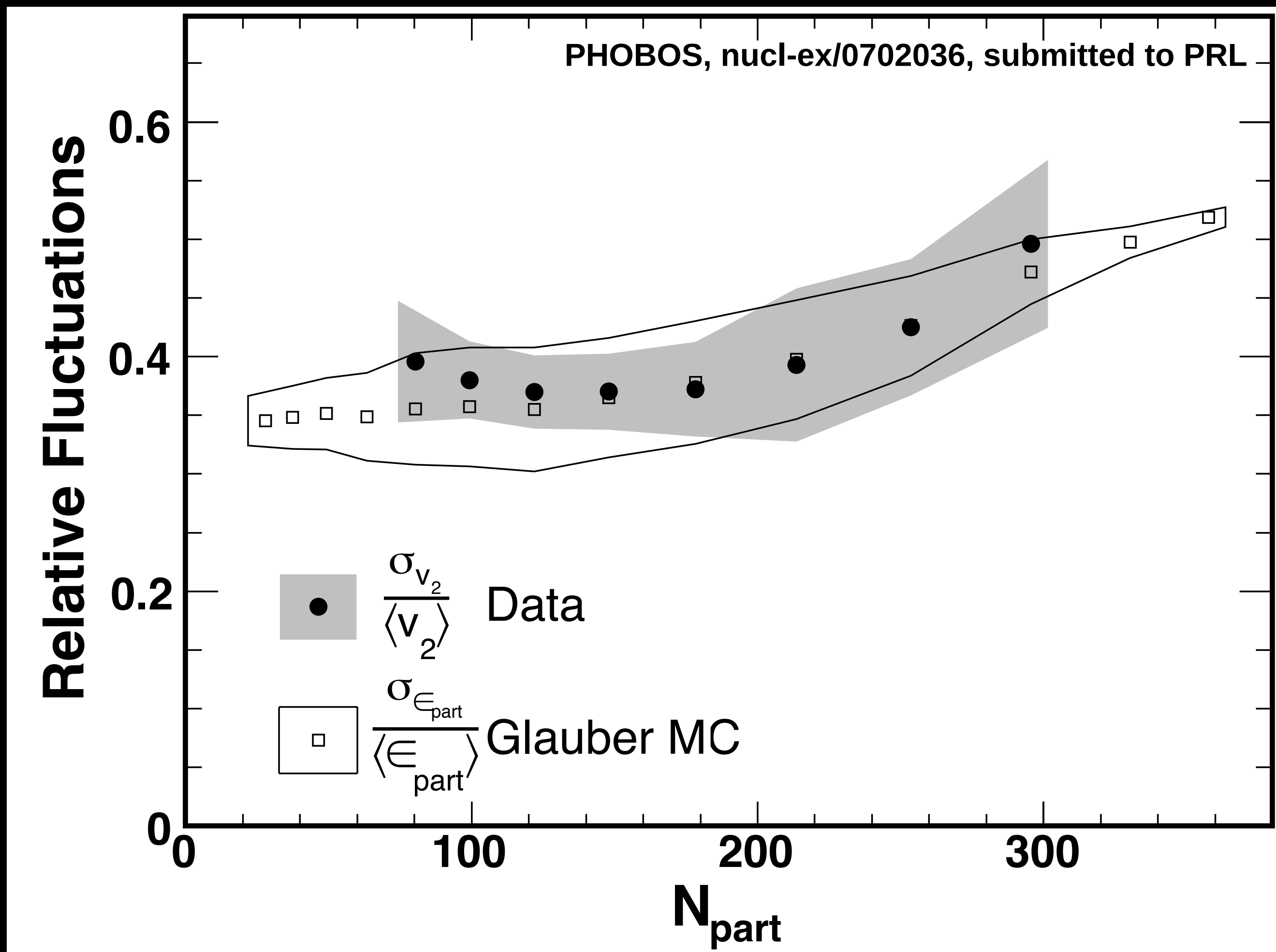
Detector response

see also, nucl-ex/0702036
& PoS CFRNC2006:023,2006 (nucl-ex/0608025)

Test of Method



Flow Fluctuations Result



Flow fluctuations ~ Glauber MC prediction

(peripheral results have better agreement than QM2006!)

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**

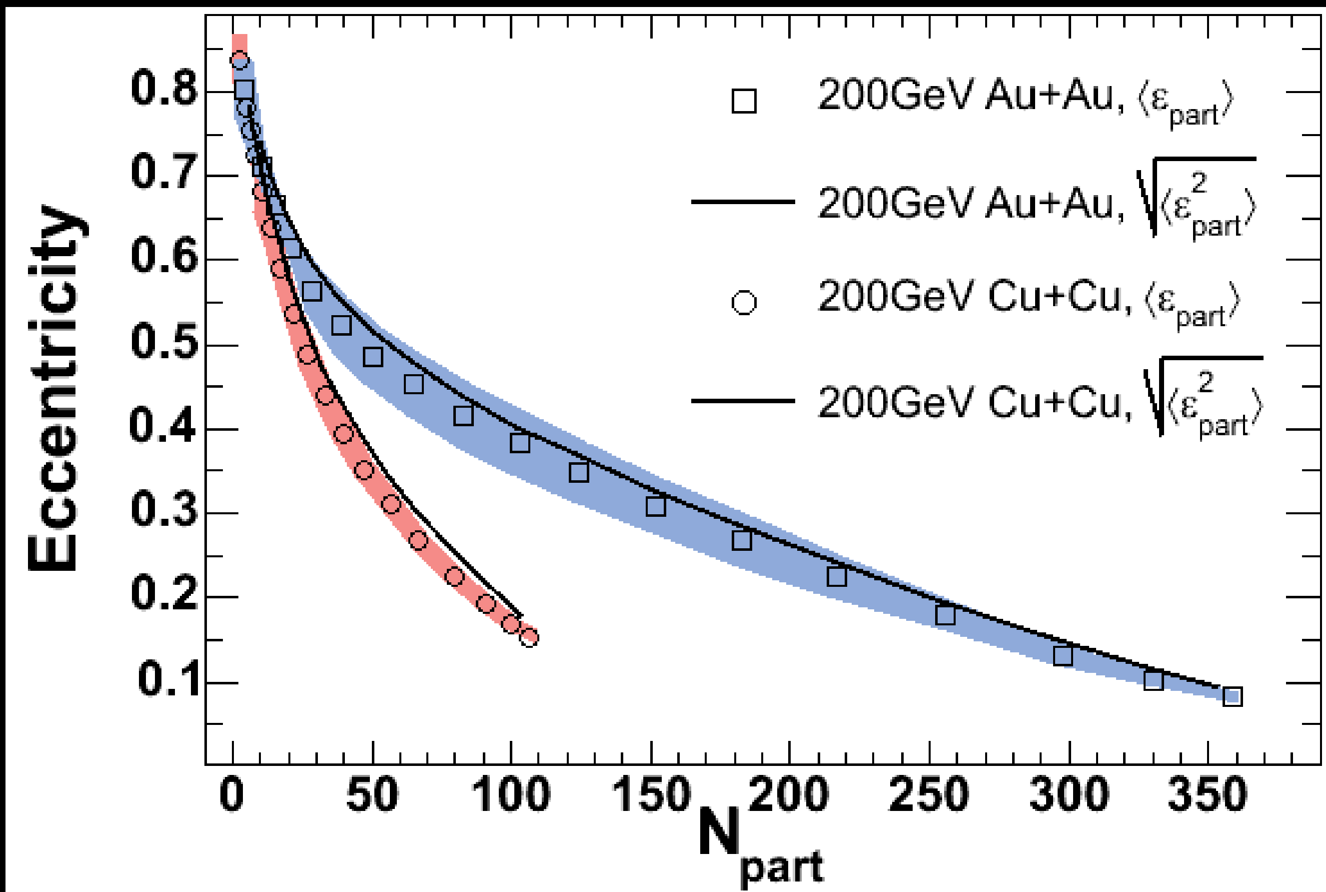
  J.Y. Ollitrault - private communication

  - 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



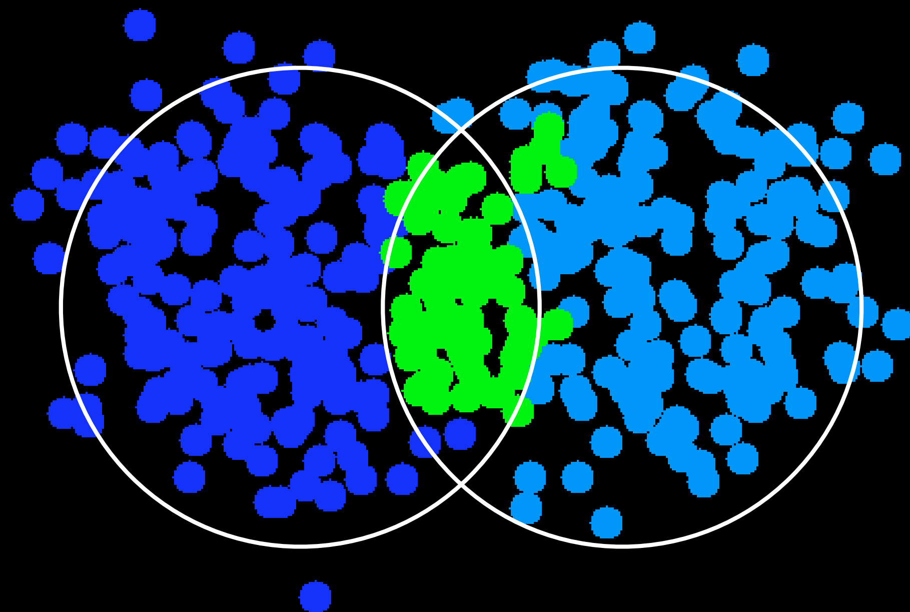
$$\frac{\sigma_\epsilon}{\langle\epsilon\rangle} = \alpha$$

↓

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

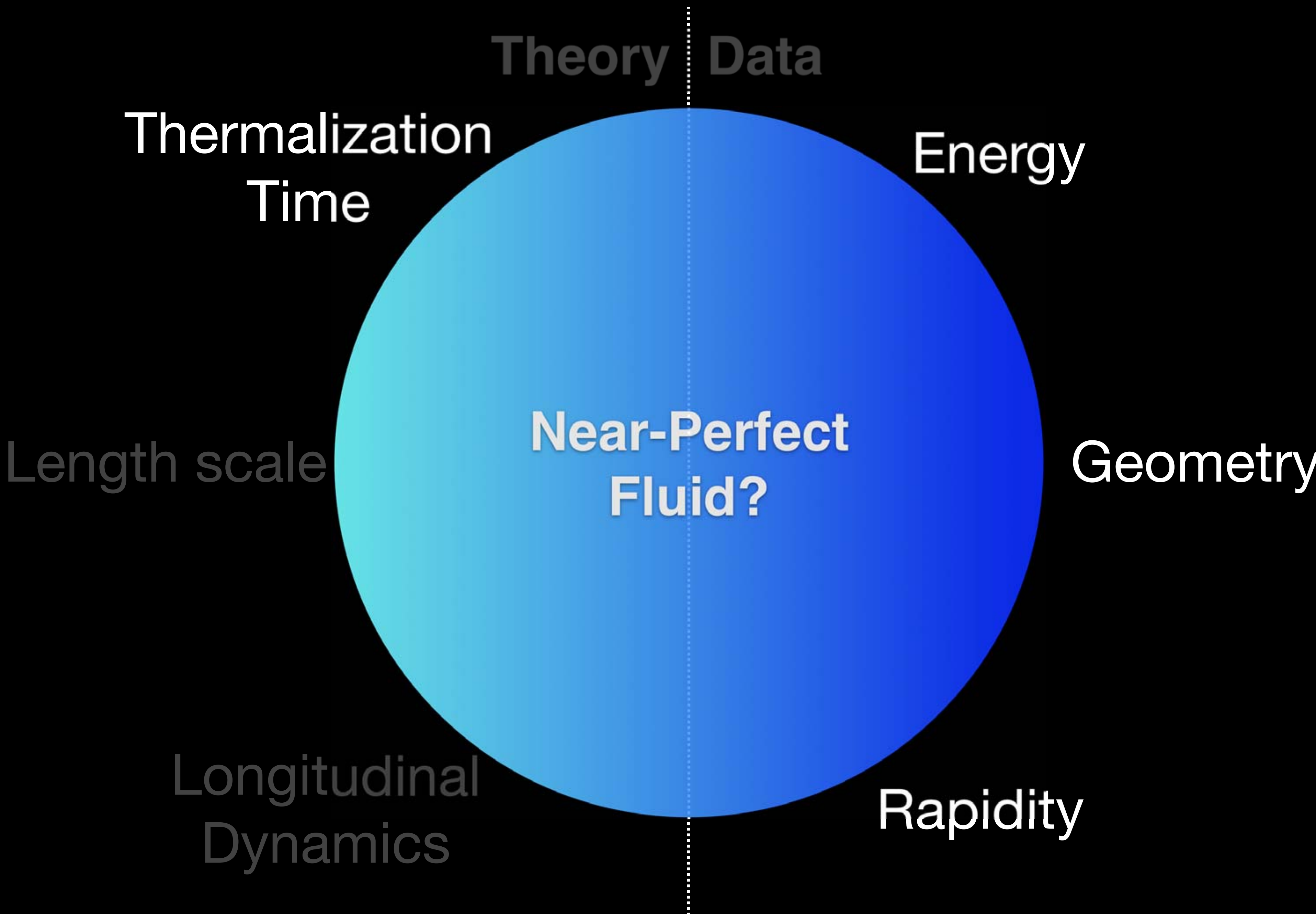
MC calculations suggests that
Mean and RMS of eccentricity differ by ~8%
→ Small effect on areal density plot

Once more, with feeling



Flow fluctuations directly confirm earlier hypothesis: configuration established early and preserved

But is dN/dy just a non-perturbative “fact”, or something generated dynamically?



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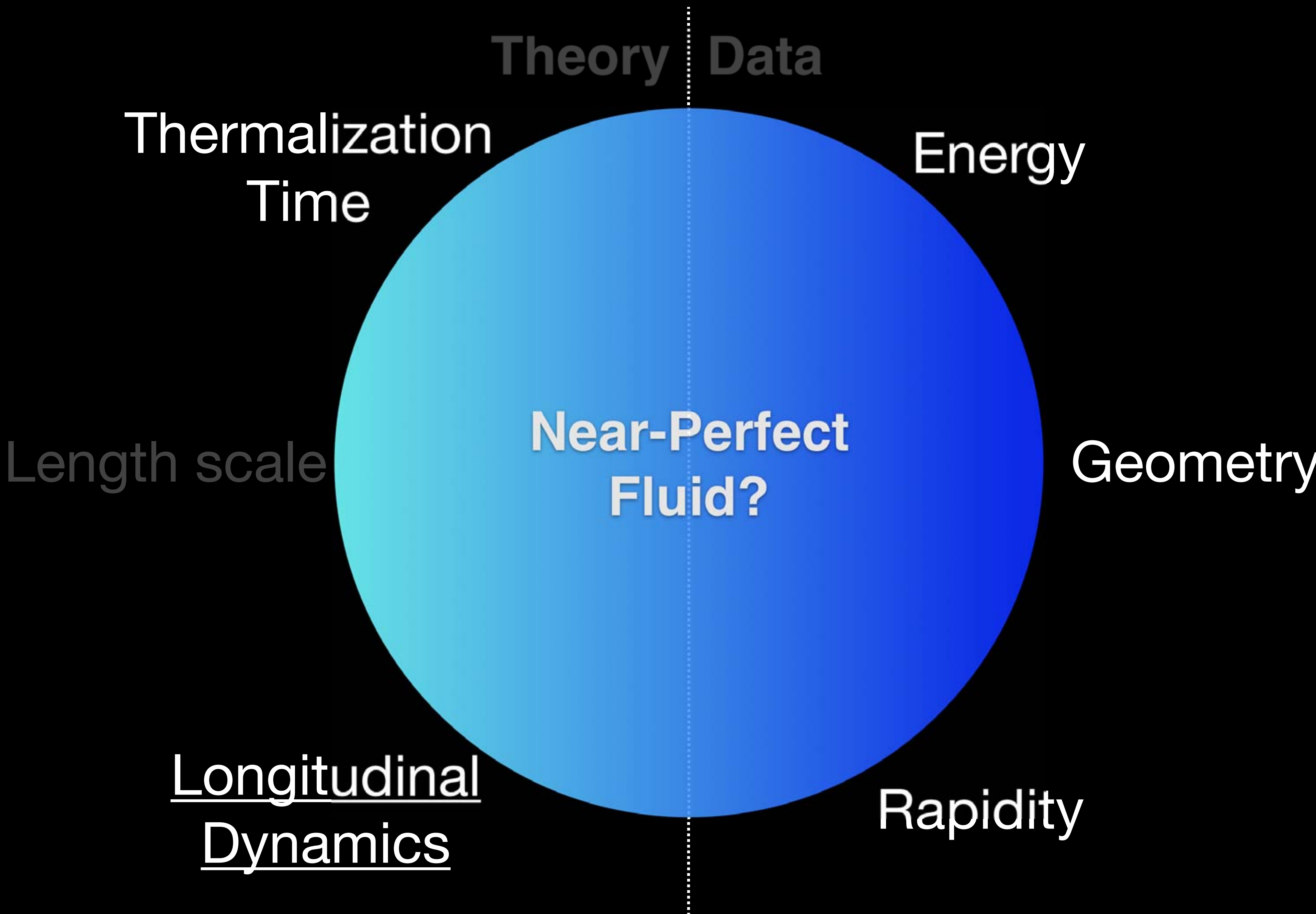
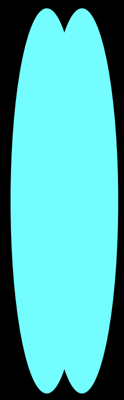


Thermalization Times

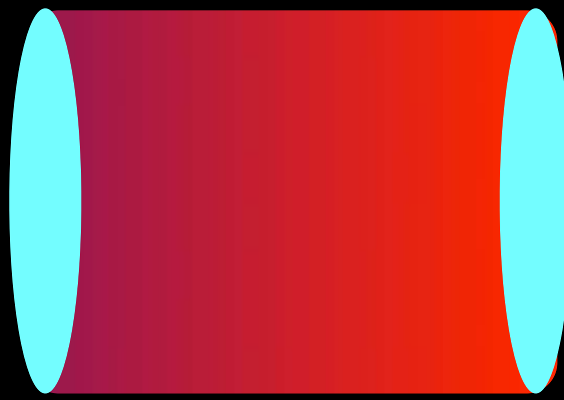
Landau



Total stopping, immediate thermalization & longitudinal re-expansion

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

Bjorken



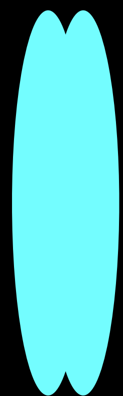
Partial stopping, "boost-invariant" expansion

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

<u>Same</u> hydro, different initial conditions (e.g. very different initial velocity gradients)!

Causal Structure

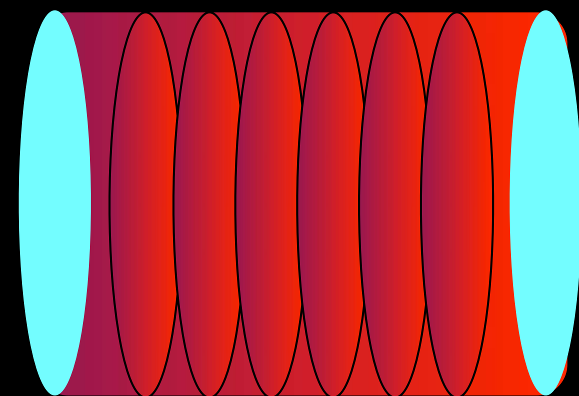
Landau



One object that emits into both hemispheres

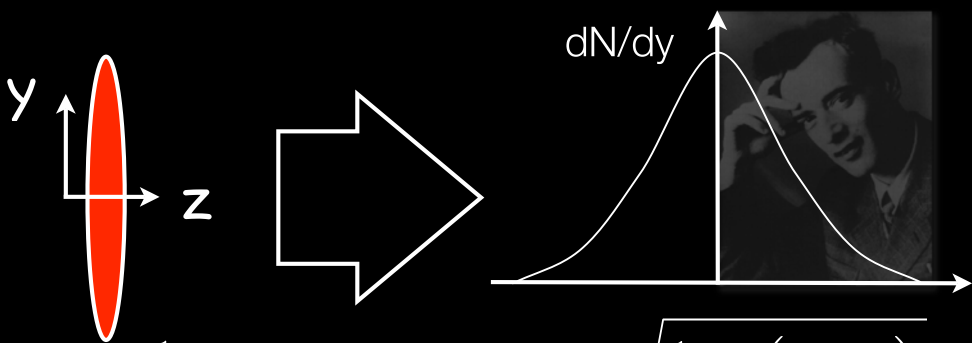
→ **fully 3D dynamics**

Bjorken



Adjacent cells in rapidity space are causally disconnected
→ **2D dynamics**

A Personal Aside:



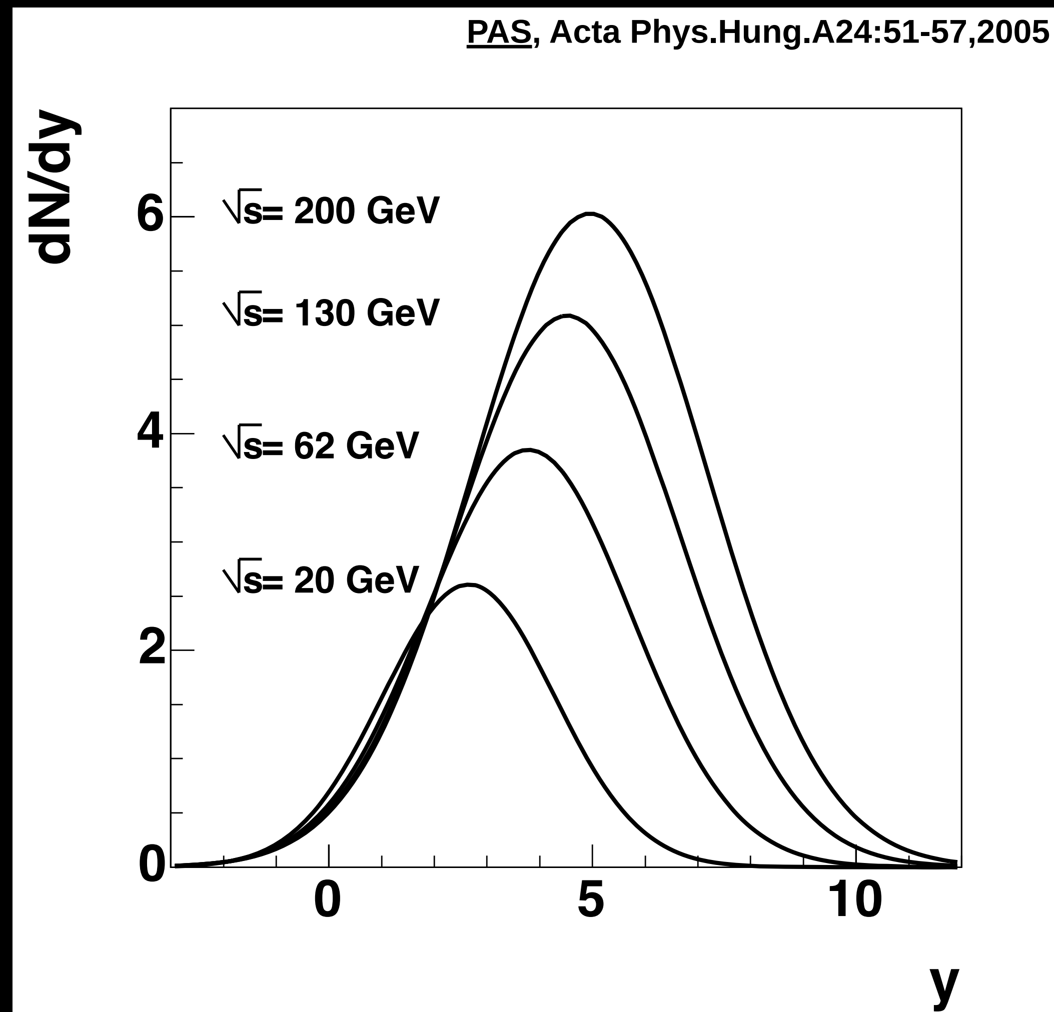
$$\Delta z \sim \frac{1}{\sqrt{s}}$$

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

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

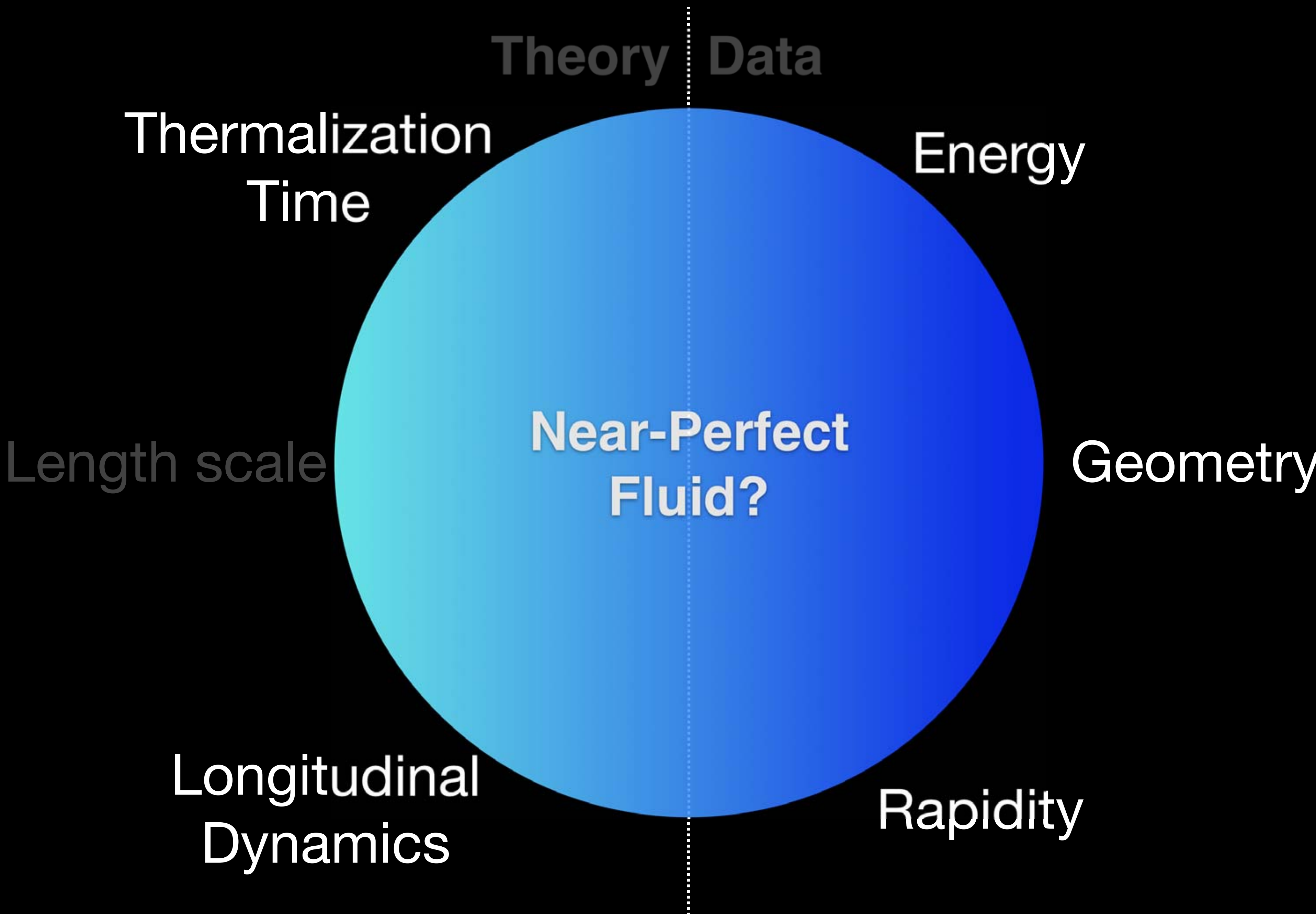
$$L = \ln\left(\frac{\sqrt{s}}{2m_P}\right) \quad y' = y + y_{beam} = y + e^L$$

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



Landau Hydro is an example of Longitudinal Scaling

Do the PHOBOS scaling behaviors suggest a broader validity of hydro over most of the evolution?



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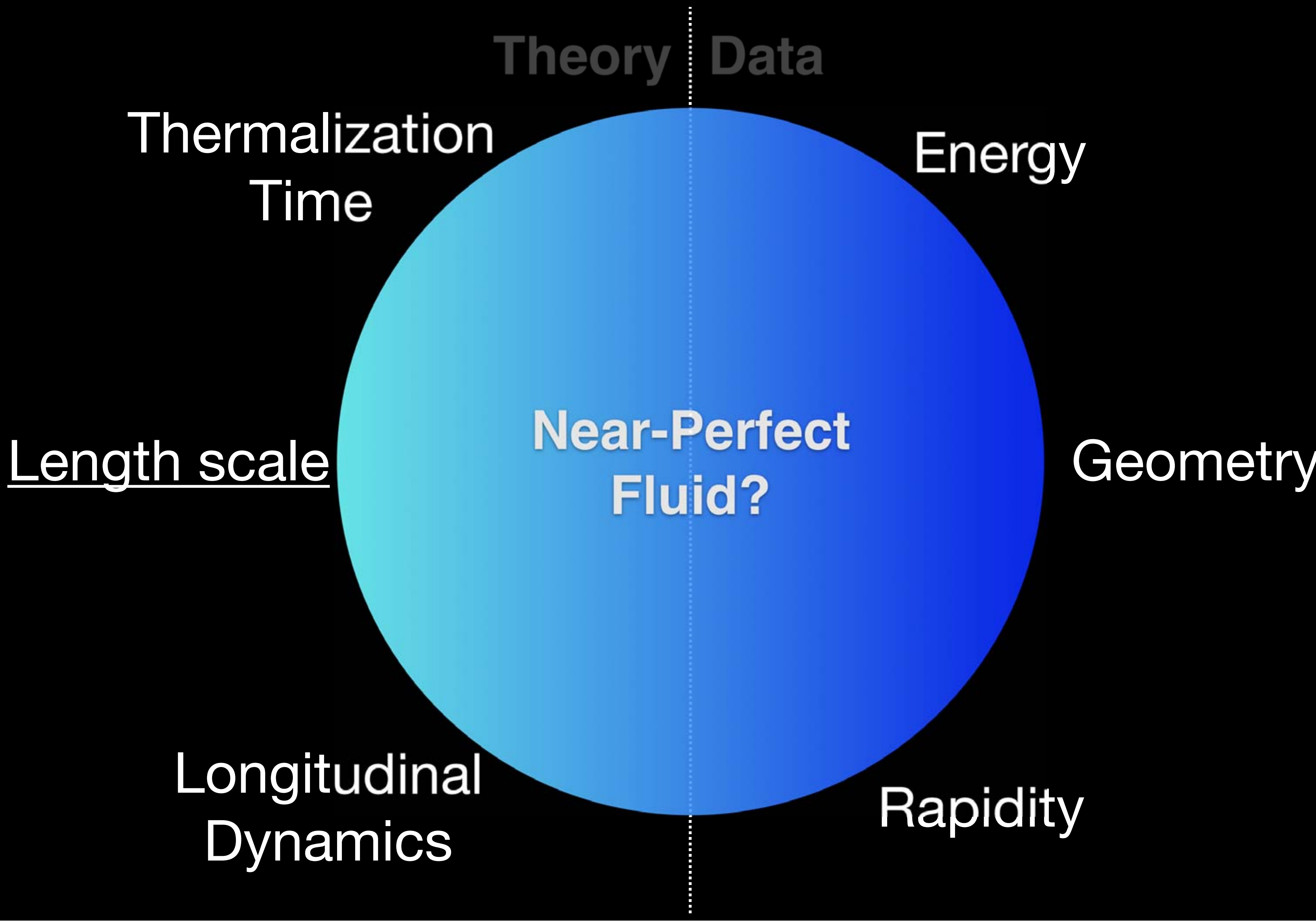
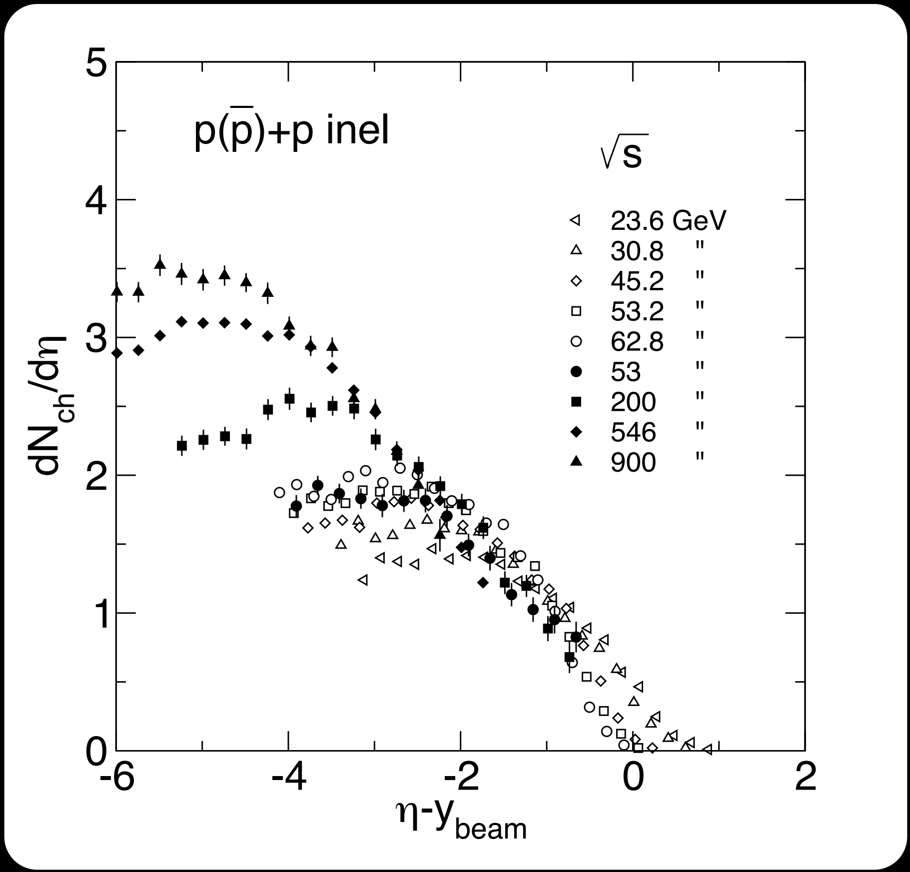
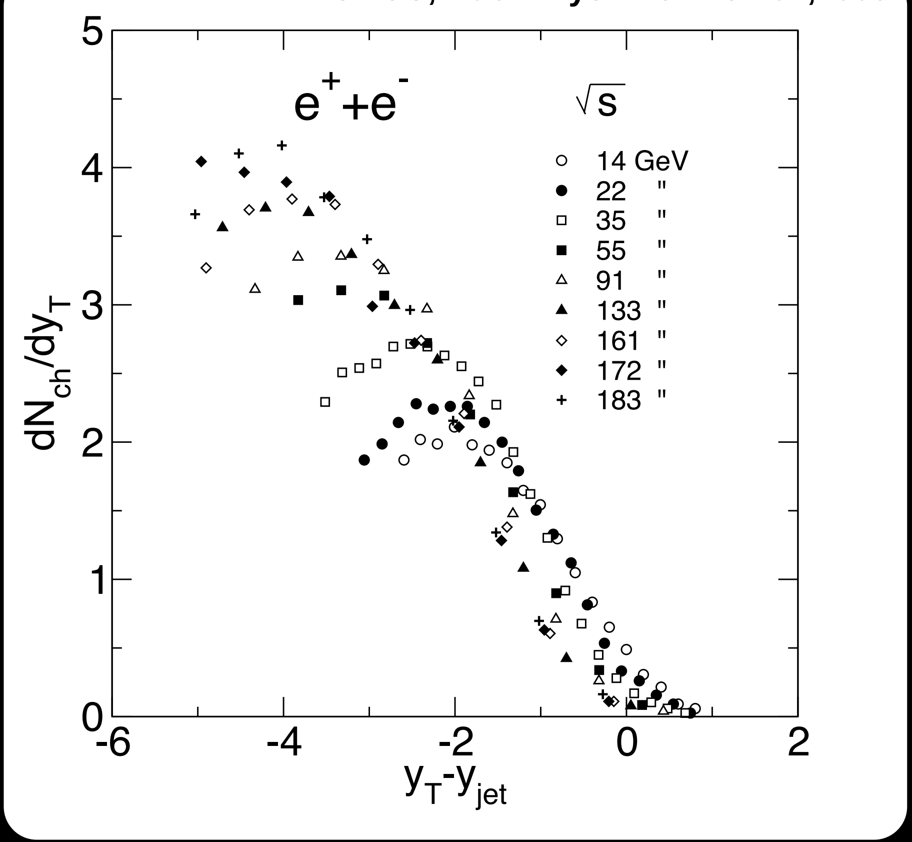
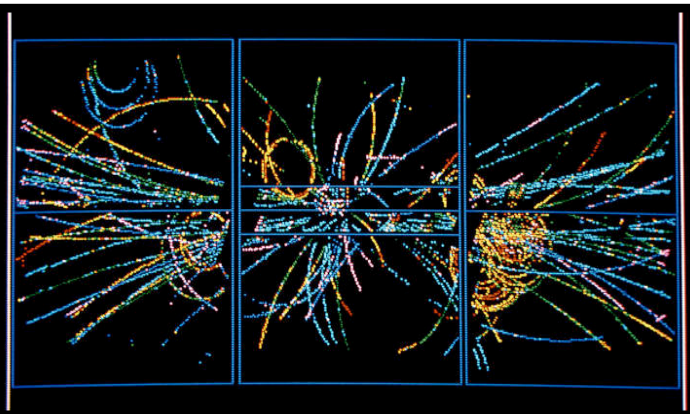


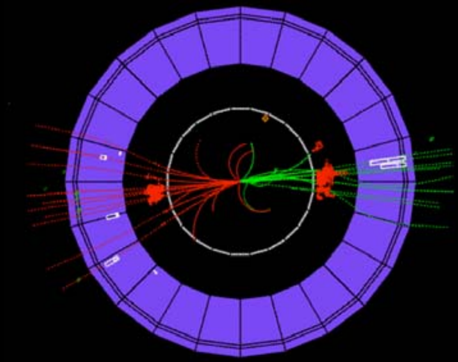
Length Scale?



PHOBOS, Nucl.Phys.A757:28-101,2005

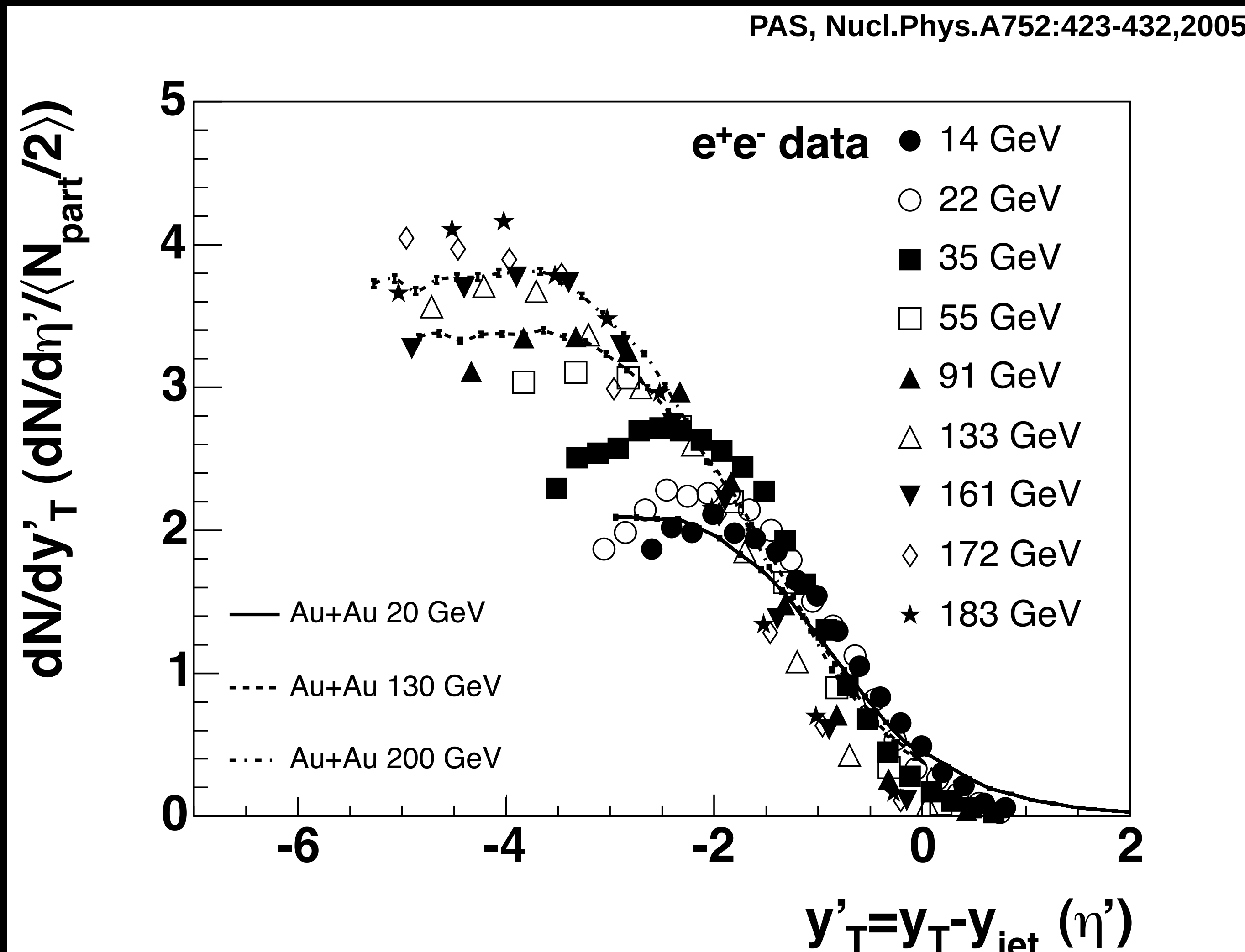






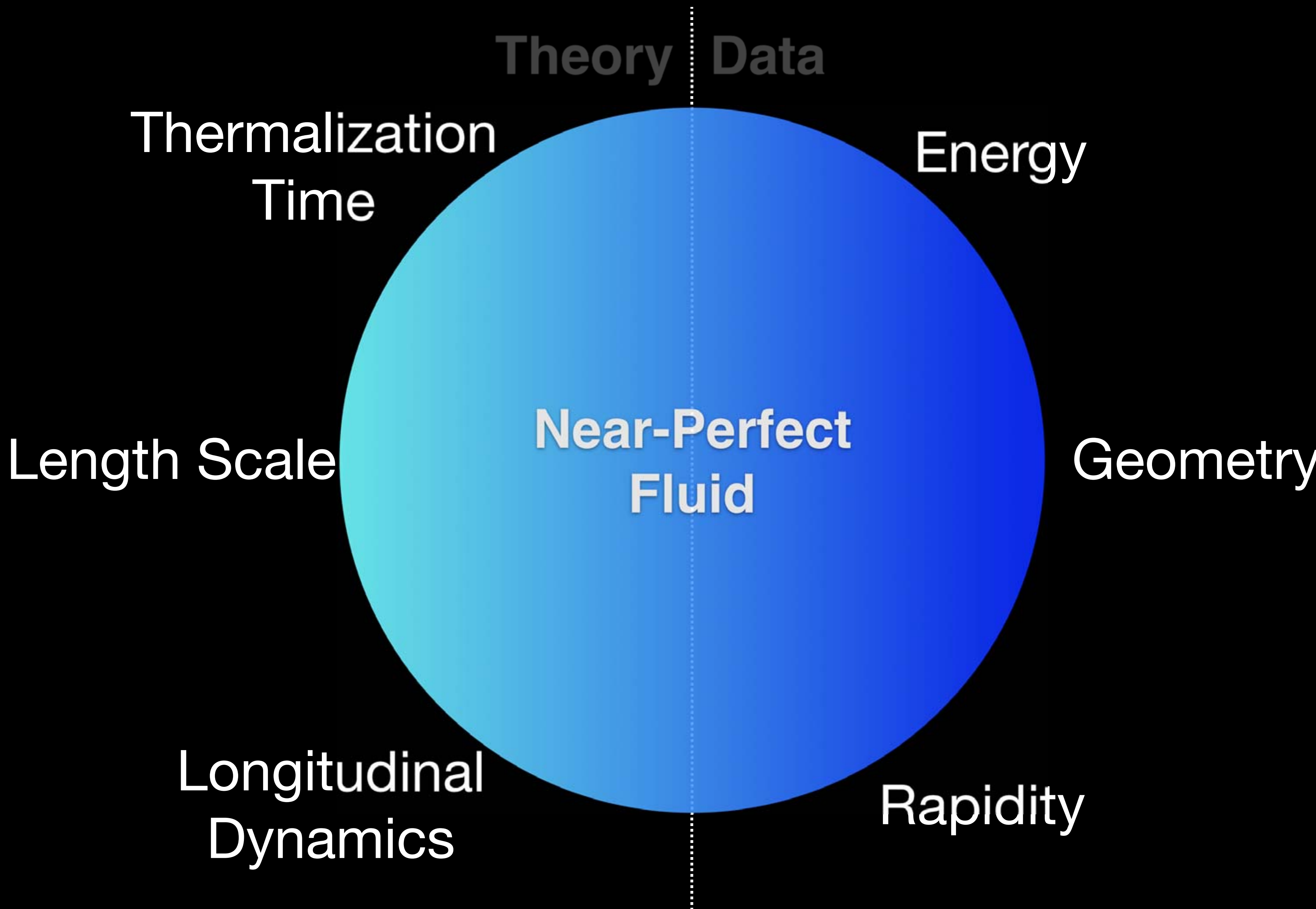
Compiled in PHOBOS White Paper (2004)

How Small is “Small”?



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

Do all of these scaling behaviors indicate a broader validity of hydro in almost all strong reactions?



The Tao of PHOBOS

Initial State ↔ Final State

Midrapidity ↔ Forward rapidity

Large Systems ↔ Small Systems

reconciled by early thermalization and hydrodynamic evolution

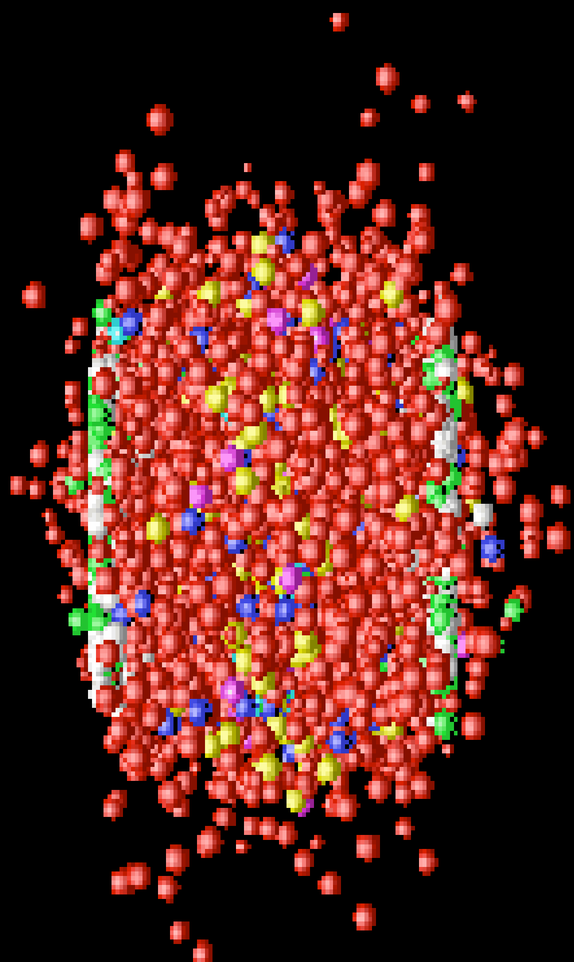
The Tao of PHOBOS

Ubiquity of Dynamics

↕

Unity of Opposites

What is the fluid made of?



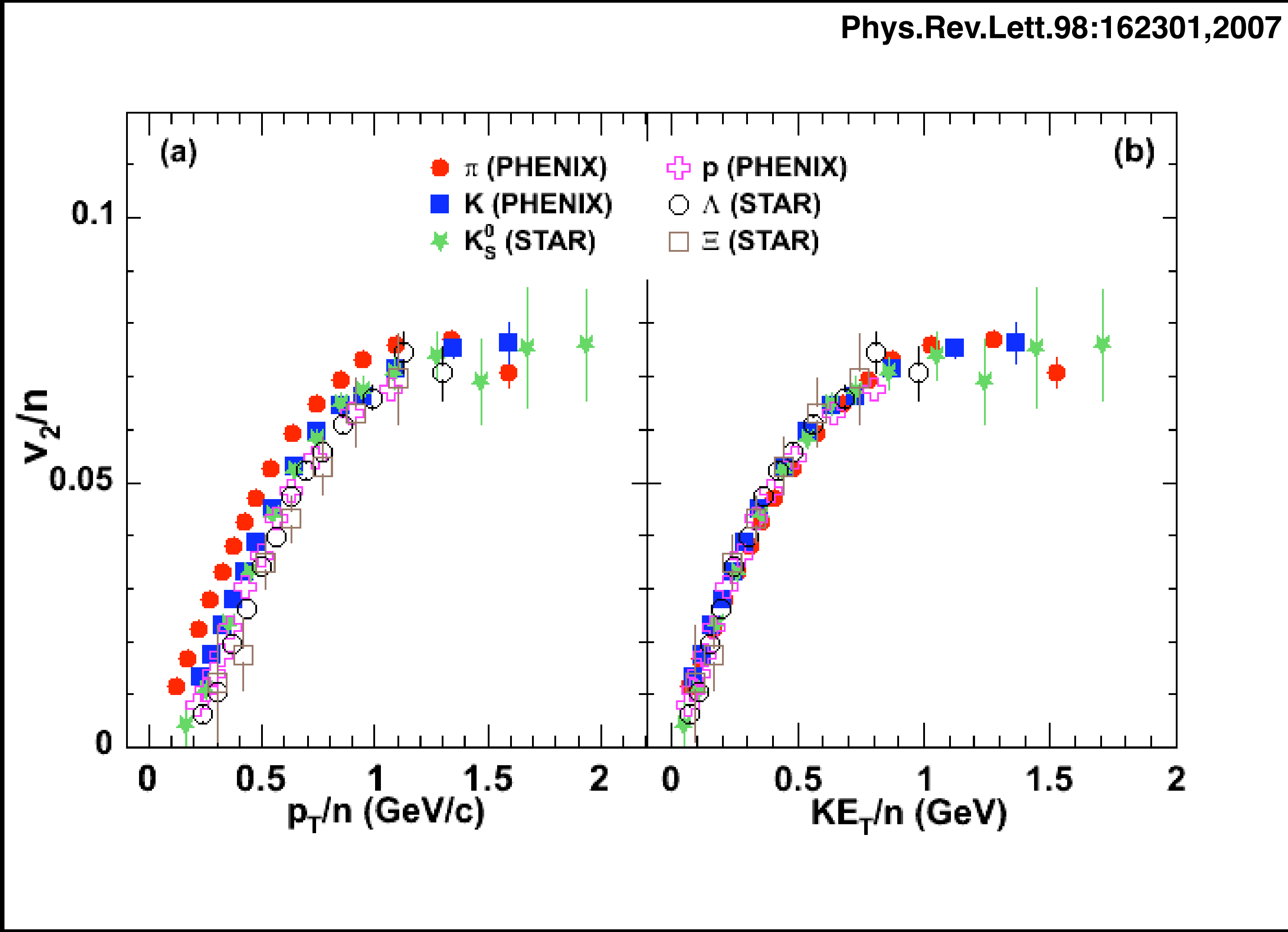
Rapidly thermalized matter

$\tau_0 \ll 1 fm/c$

But of what? and how so fast?

Quarks & gluons?
Is it a real "quark-gluon plasma" (QGP)?

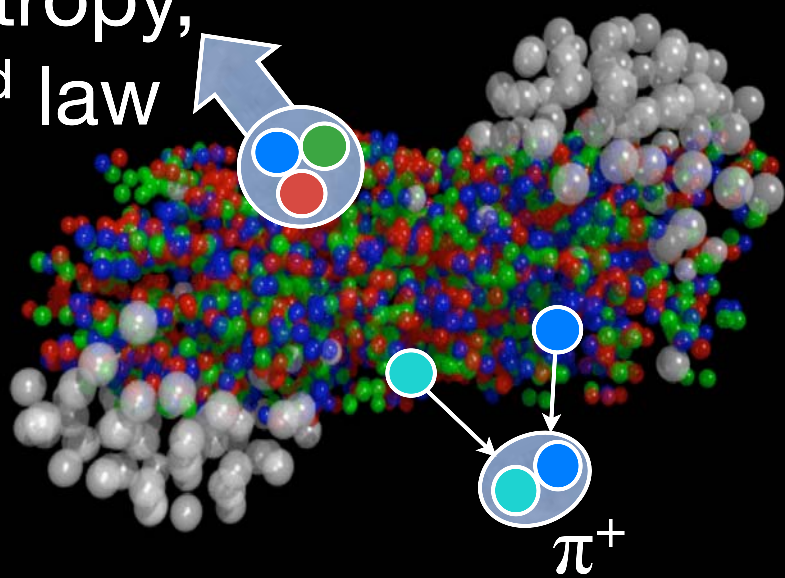
Constituent Quark Scaling?



PID flow is “simple” in “kinetic energy”, especially when dividing by the number of constituent quarks (CQ). Are these the degrees of freedom at early times?

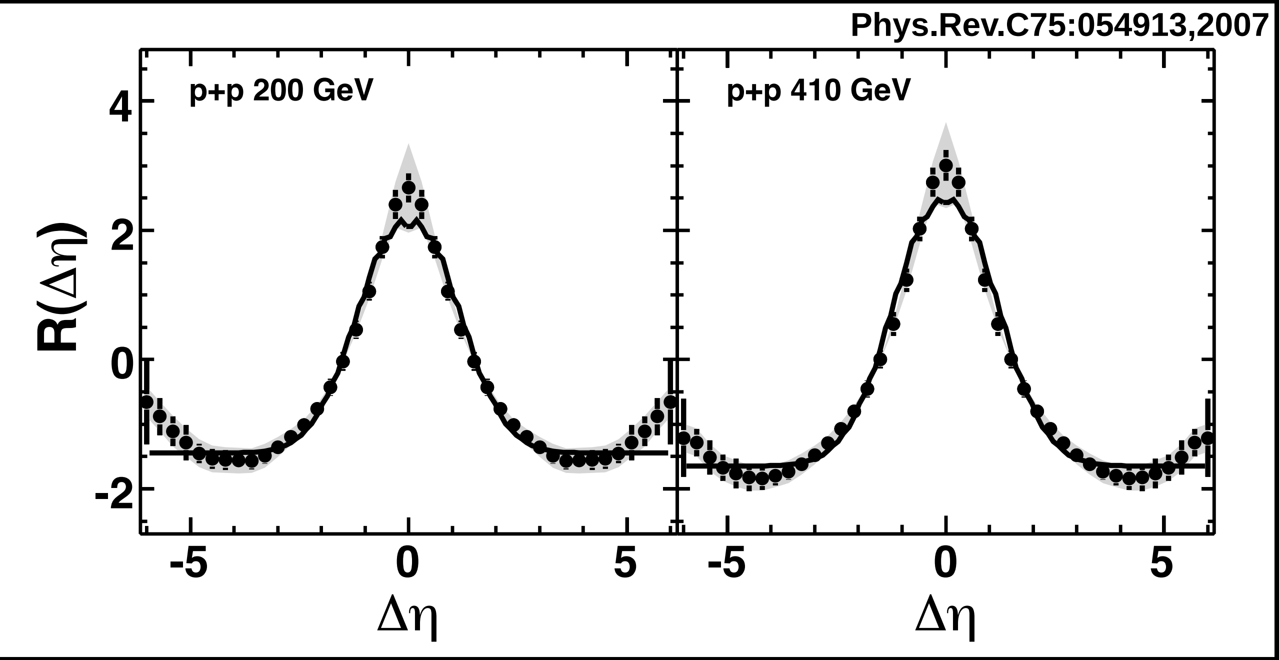
Entropy Problem?

CQ 2→1 processes generally thought to decrease entropy, violating 2nd law



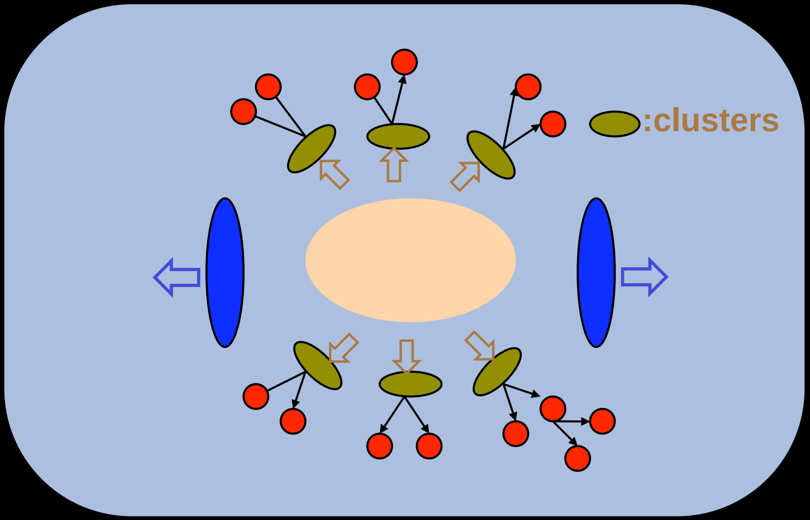
UrQMD

Correlations in p+p

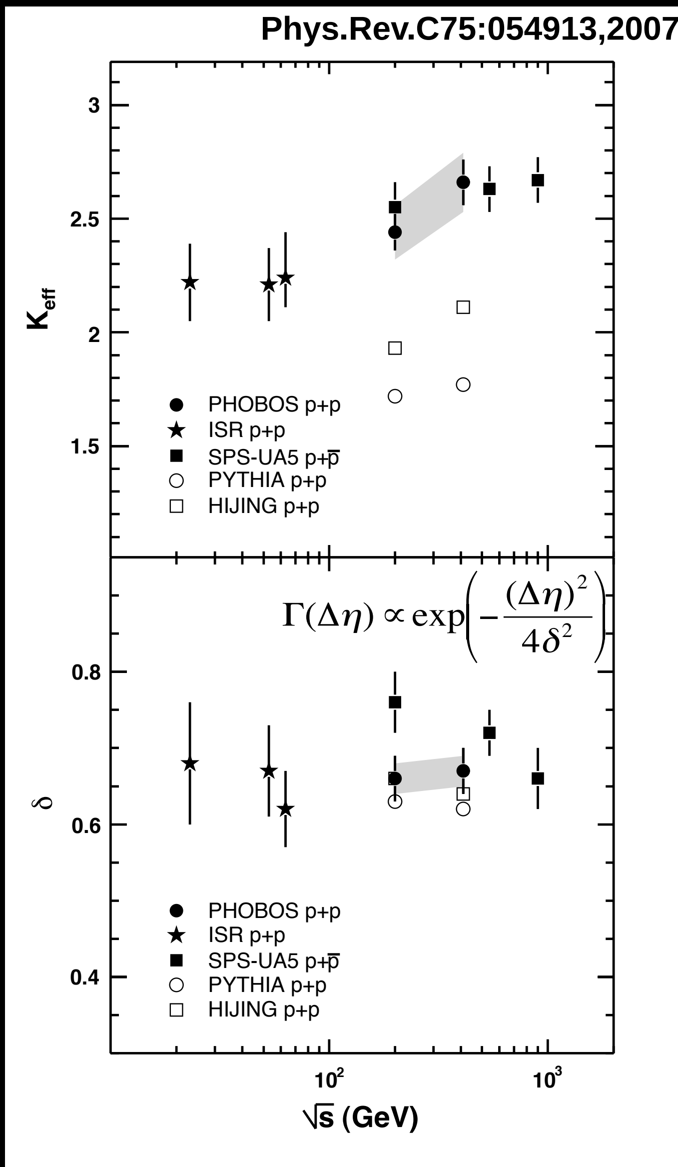


$$R(\Delta\eta) = \langle (n-1)\left(\frac{\rho(\eta_1 - \eta_2)}{\rho_{mix}} - 1\right)\rangle$$

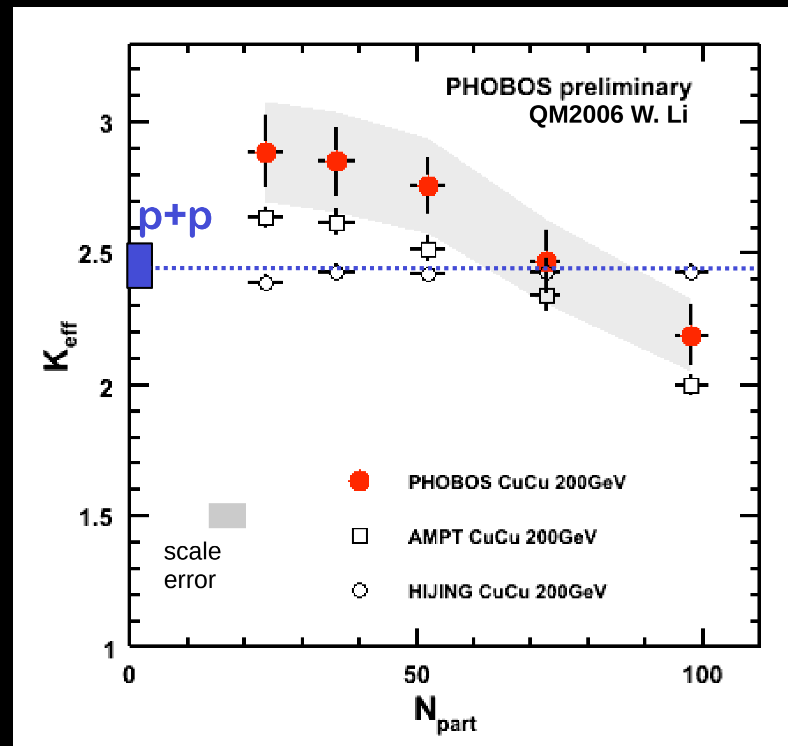
Every particle produced in p+p has >1 associated particles close in η & ϕ: "Cluster models"



Clusters in p+p & A+A



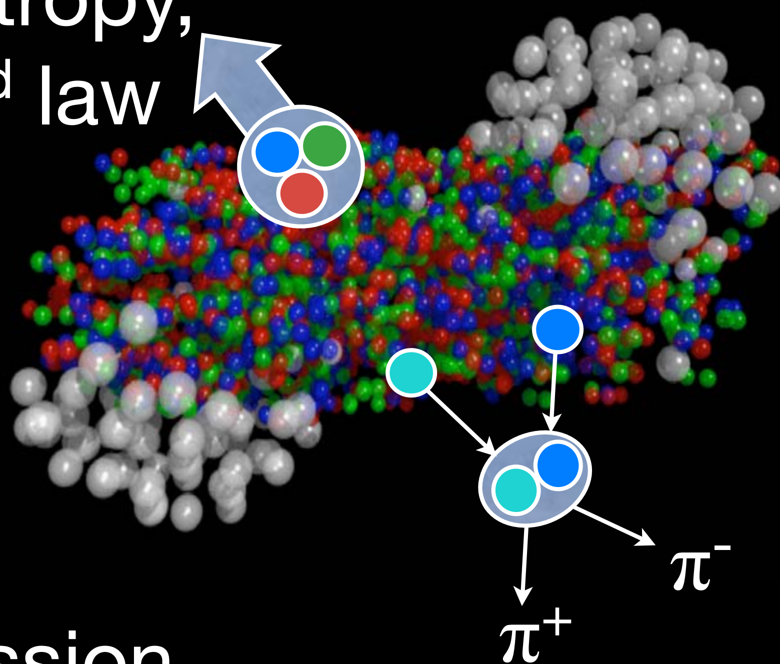
Effective cluster size
& decay width



Cluster "size" (K_{eff}) in peripheral data larger than p+p, drop to level near p+p in central events: clusters still active in A+A!

Entropy Problem?

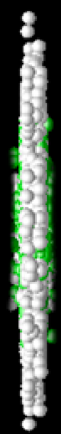
CQ 2→1 processes generally thought to decrease entropy, violating 2nd law

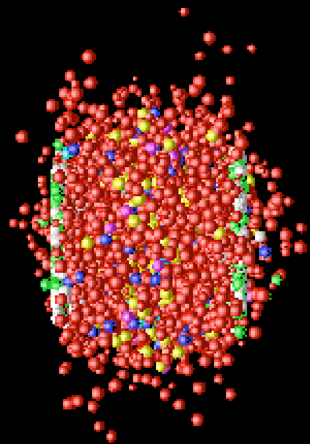


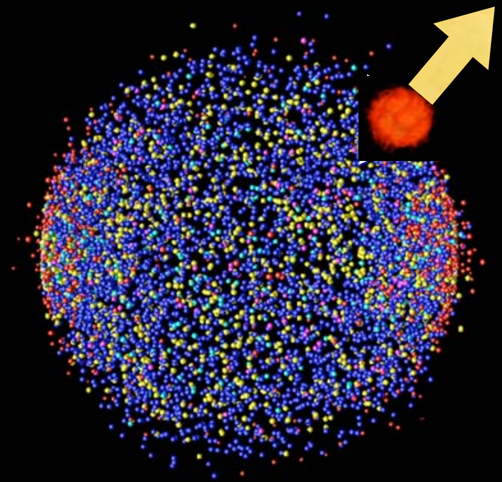
Cluster emission suggests substantial amount of 1→2

Maybe entropy <u>unchanged</u> by hadronization? i.e. quasi “2→2”

Conclusions







What and When
is the initial state?
Is it thermalized?

Is hydro ideal
(i.e. isentropic)
everywhere?

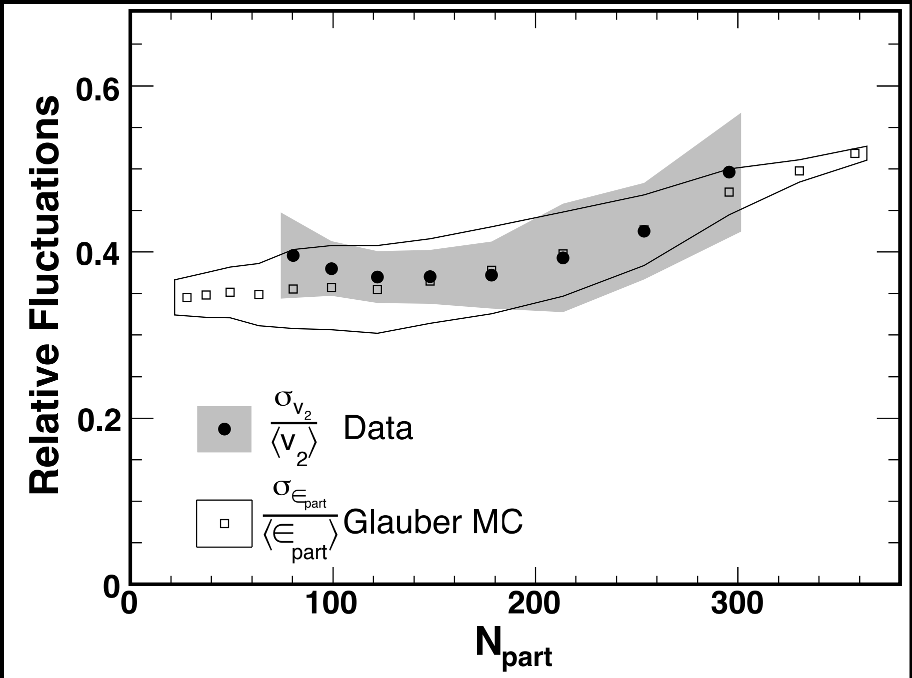
What is produced
at freeze-out?

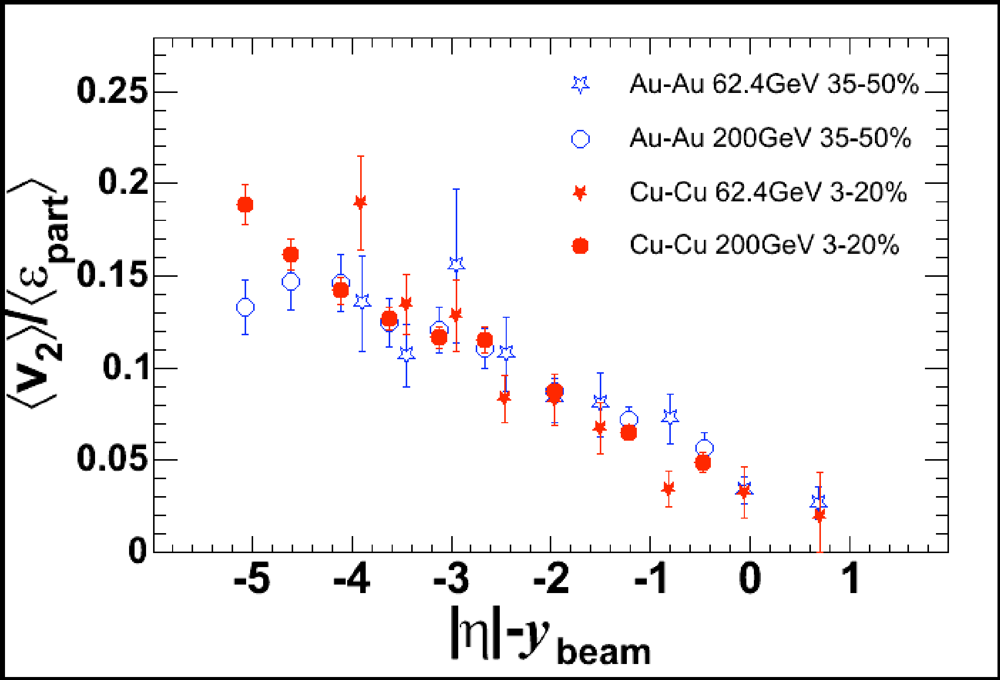
early, if not
~immediately

evolution preserves
initial state:
at observed A,b,η,p_T

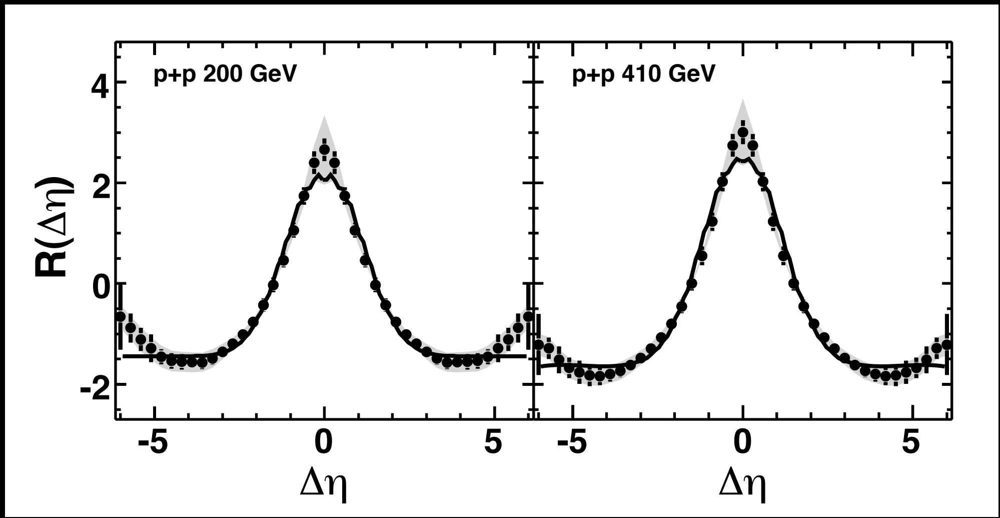
Clusters
(e.g. resonances)
which decay

A request

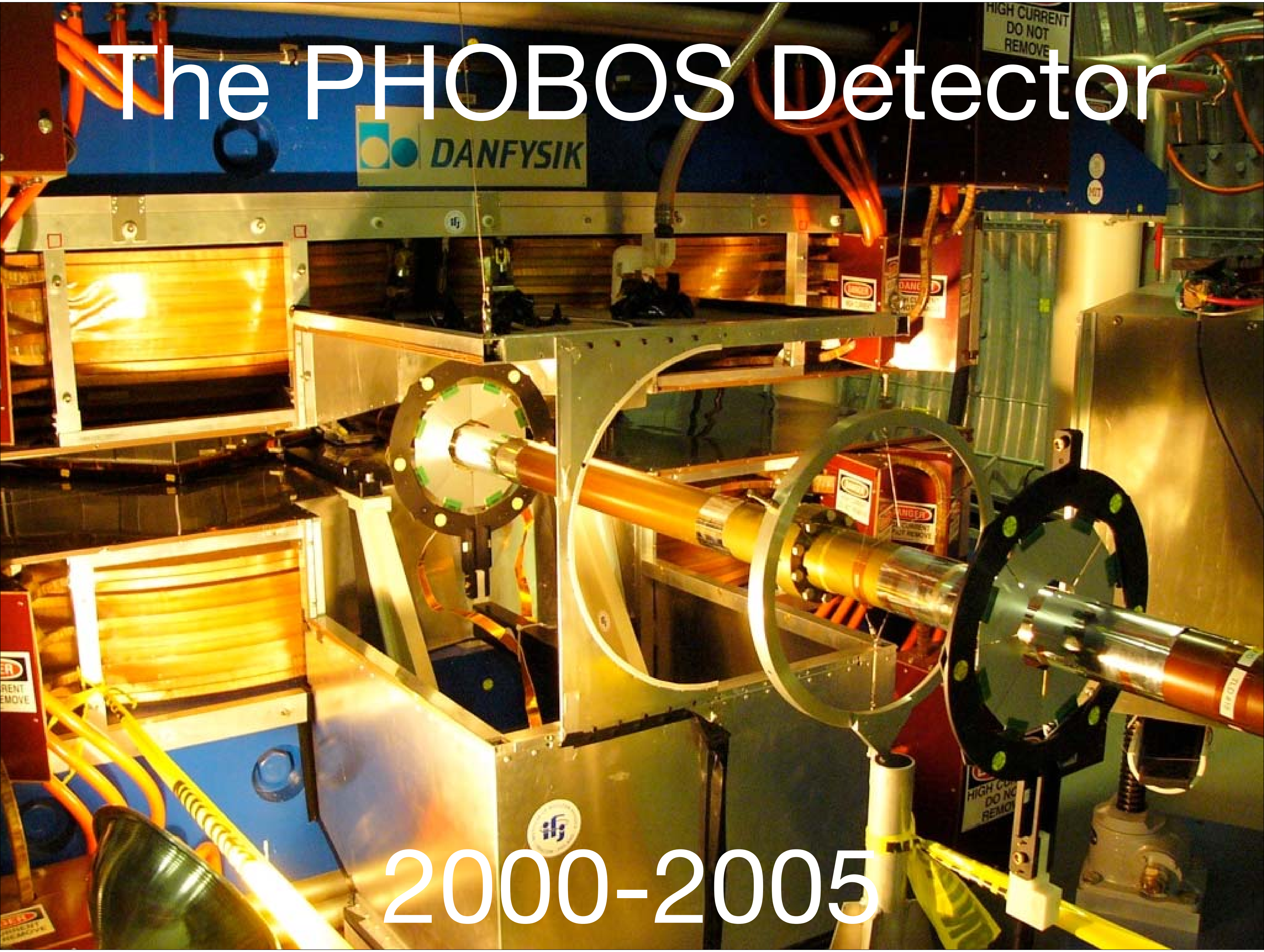




We have a lot of data,
covering a large region
of phase space & geometry:
please try and use all of it,
simultaneously!



The PHOBOS Detector



2000-2005