Elliptic Flow at PHOBOS and the Eccentricity Conundrum

Richard Bindel

For the PHOBOS Collaboration

Collaboration (June 2006)

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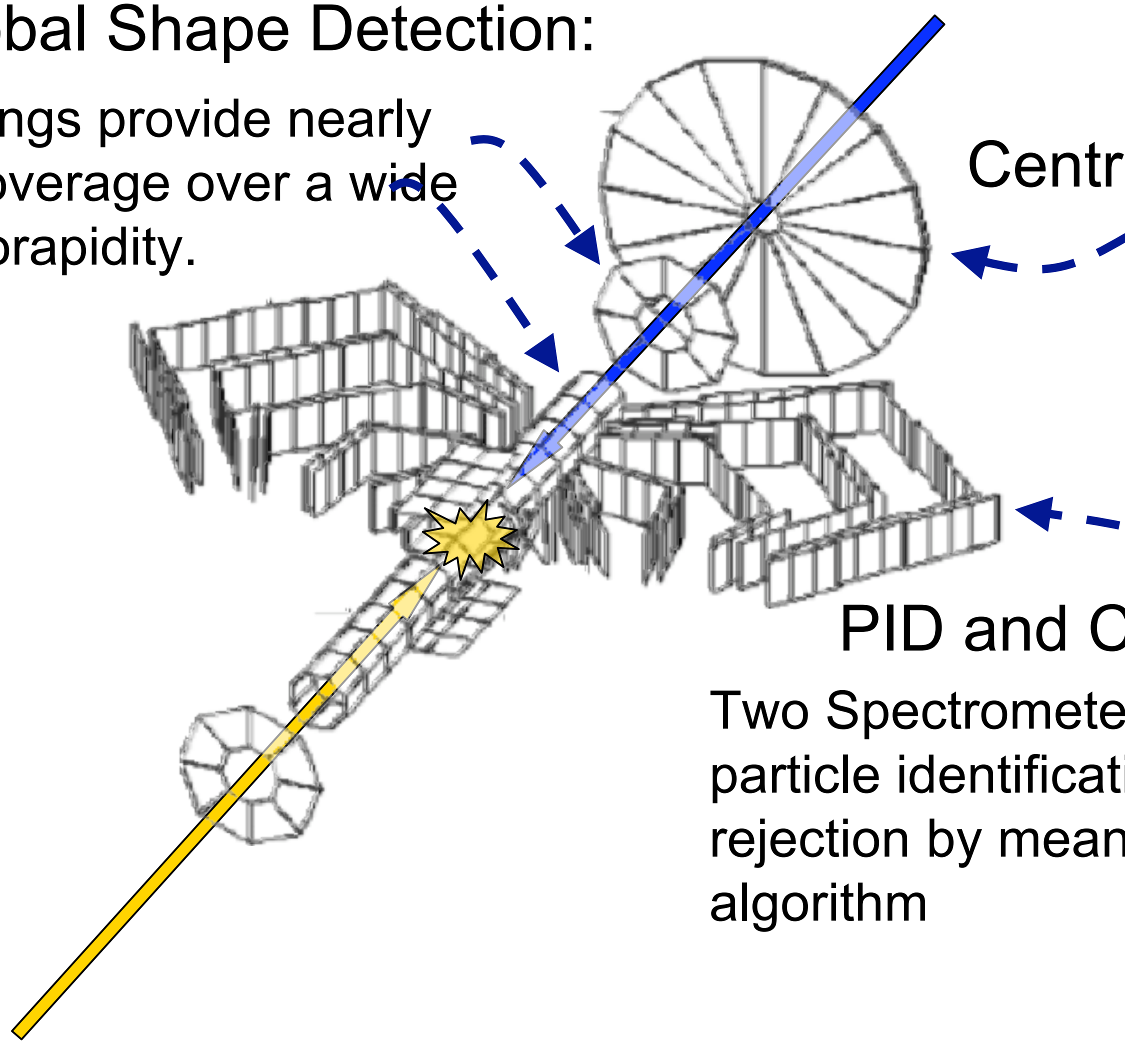
UNIVERSITY OF ILLINOIS AT CHICAGO
UNIVERSITY OF ROCHESTER

Measurement of elliptic flow at PHOBOS

Advantages of the PHOBOS detector:

Excellent Global Shape Detection:

Octagon and Rings provide nearly full azimuthal coverage over a wide range of pseudorapidity.



Centrality Measure

PID and Clean Signal:

Two Spectrometer Arms provide particle identification and noise rejection by means of tracking algorithm

Measurement of elliptic flow at PHOBOS

Two Analysis Techniques are used at PHOBOS:

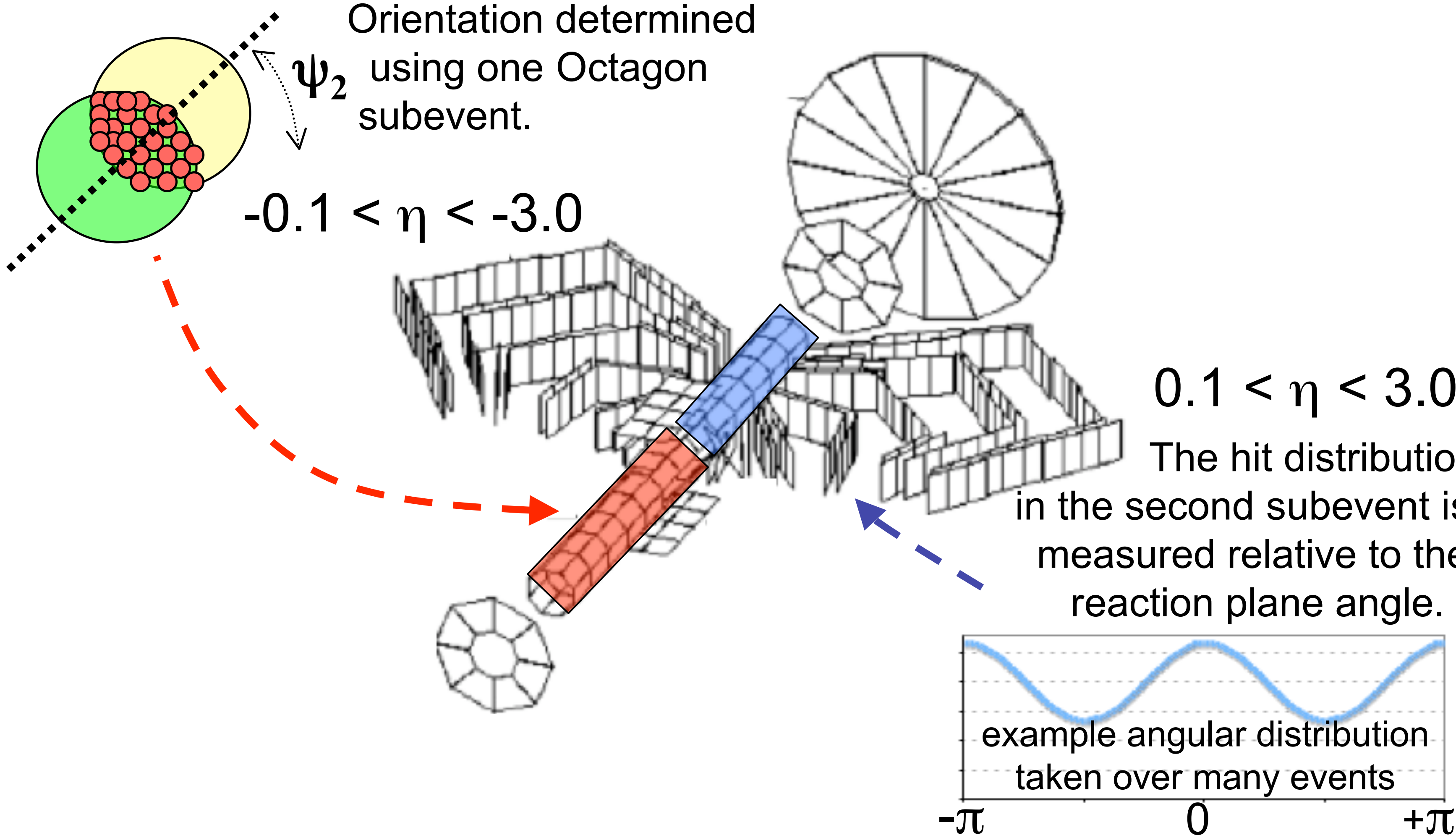
Hit Based Method (Hits in the octagon and rings)

Track Based Method (Tracks in the spectrometer also)

Both employ the reaction plane / subevent technique, in which the orientation of the reaction is found in one portion of the detector, while another detector region is subsequently correlated to it.

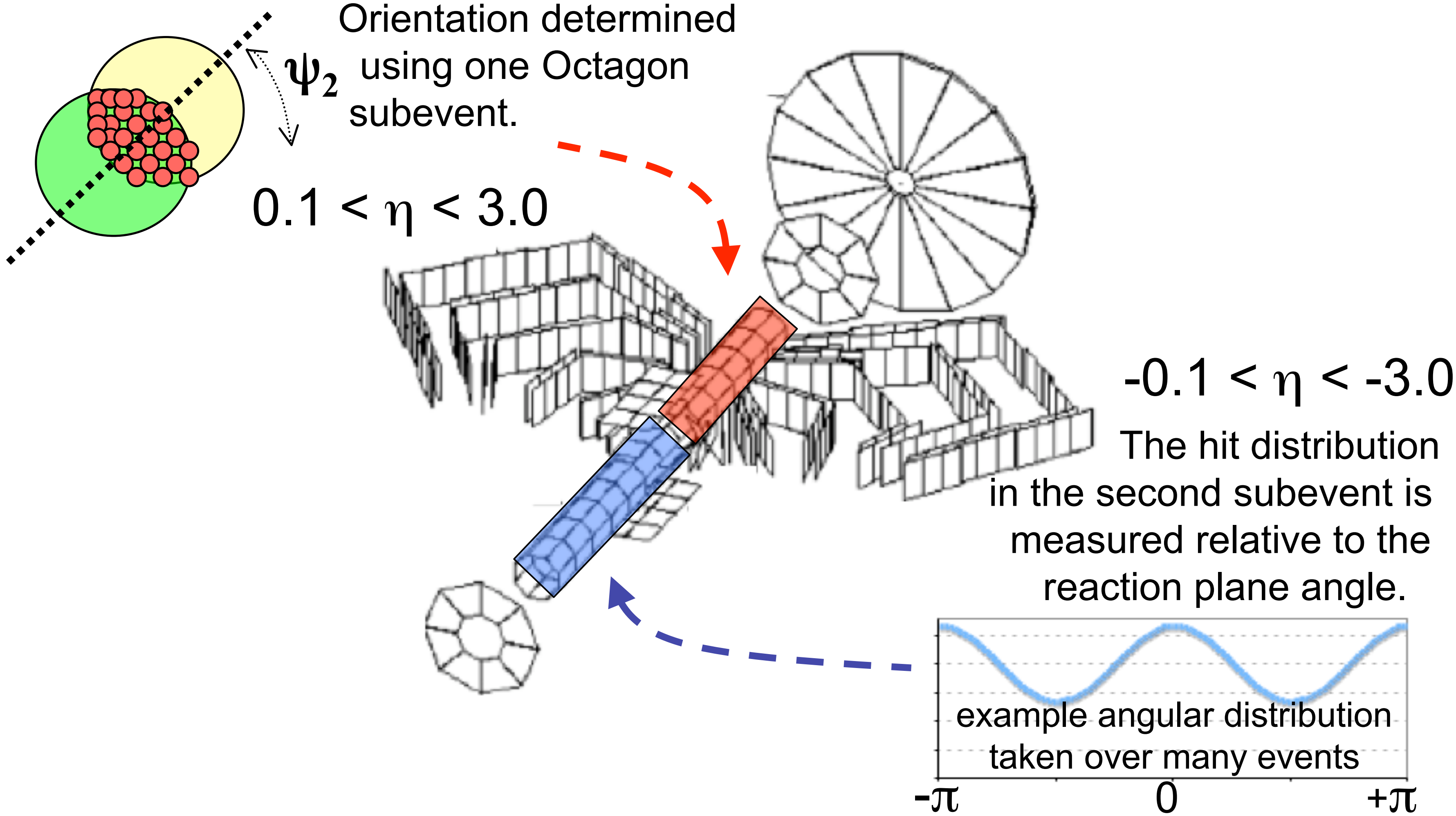
Measurement of elliptic flow at PHOBOS

Hit Based Method



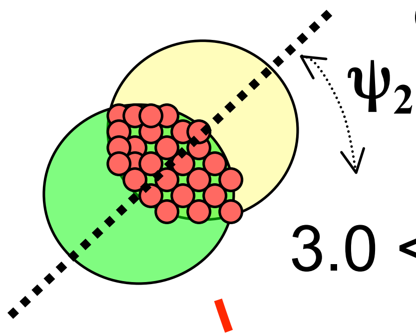
Measurement of elliptic flow at PHOBOS

Hit Based Method



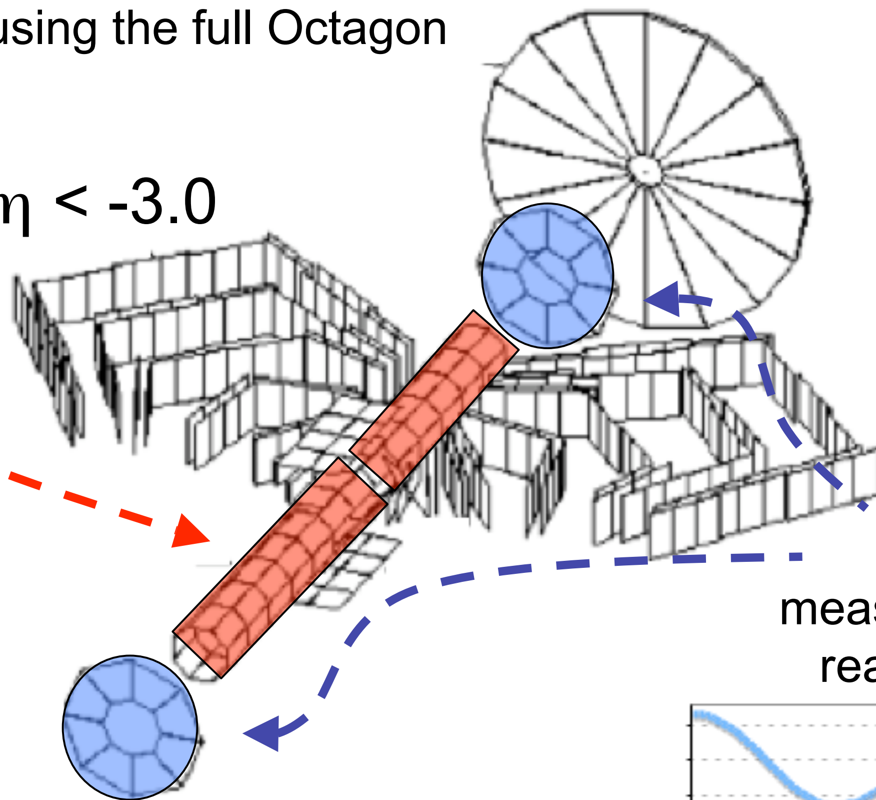
Measurement of elliptic flow at PHOBOS

Hit Based Method



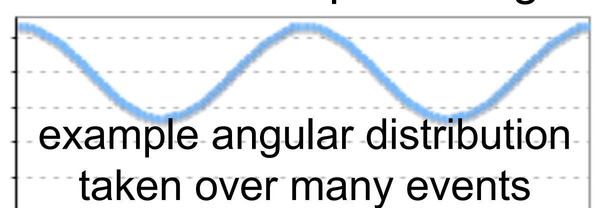
Orientation determined using the full Octagon

$3.0 < \eta < -3.0$



$\pm 3.0 < \eta < \pm 5.4$

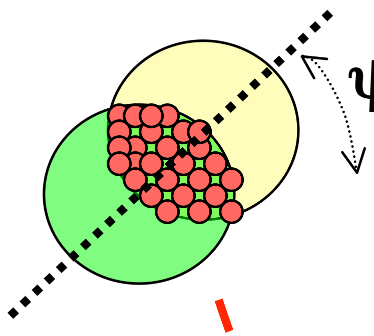
The hit distribution in the rings is measured relative to the reaction plane angle.



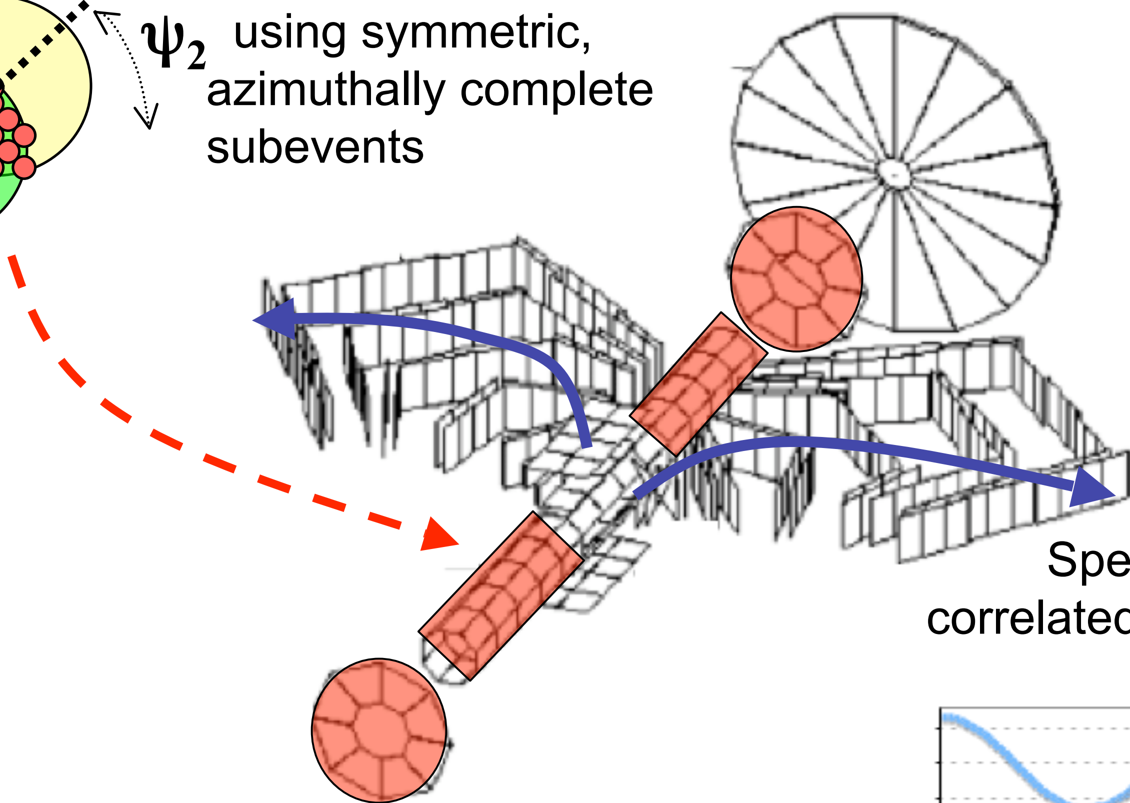
the combination of these measurements spans $-5.4 < \eta < +5.4$

Measurement of elliptic flow at PHOBOS

Track Based Method

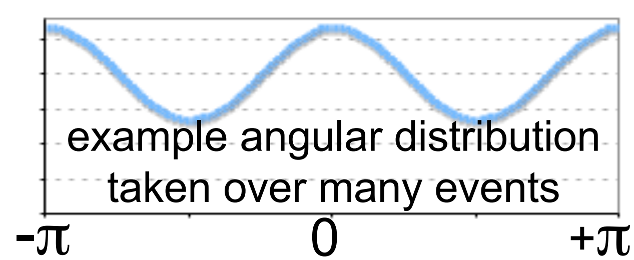


Orientation determined using symmetric, azimuthally complete subevents



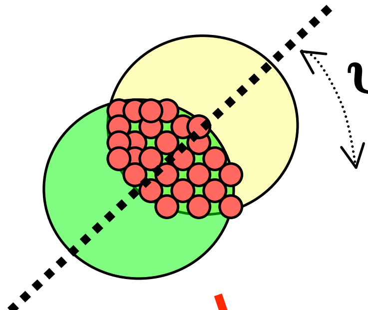
$0 < \eta < 1$

Tracks in the Spectrometer arms are correlated to the reaction plane

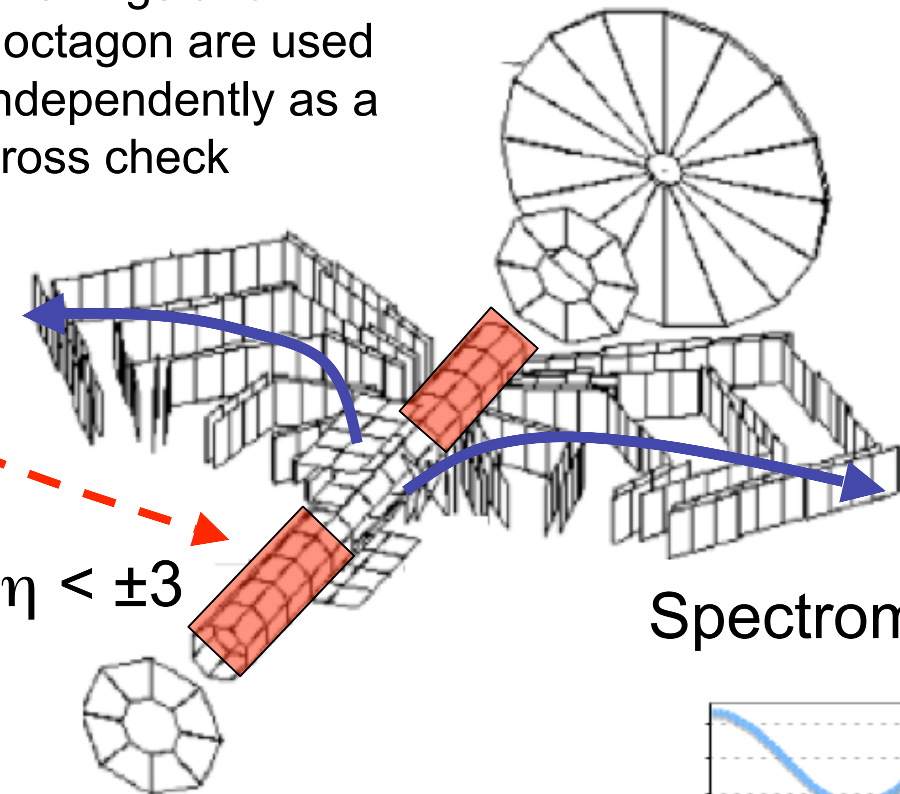


Measurement of elliptic flow at PHOBOS

Track Based Method

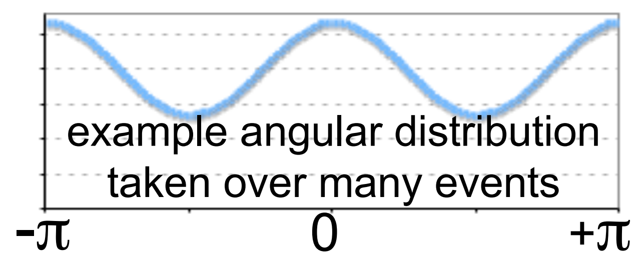


The rings and octagon are used independently as a cross check



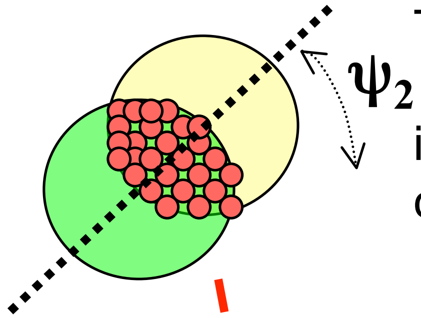
Restricted to the
Octagon: $\approx\pm2 < \eta < \pm3$

Spectrometer: $0 < \eta < 1$



Measurement of elliptic flow at PHOBOS

Track Based Method



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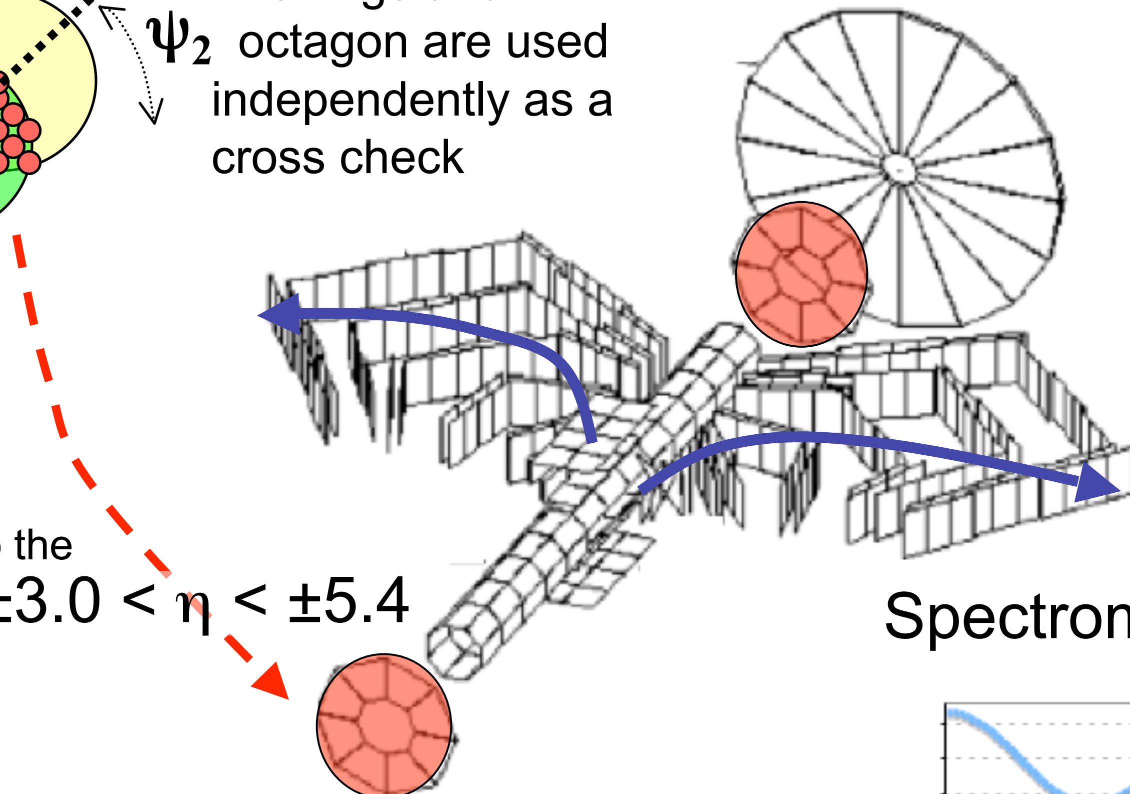
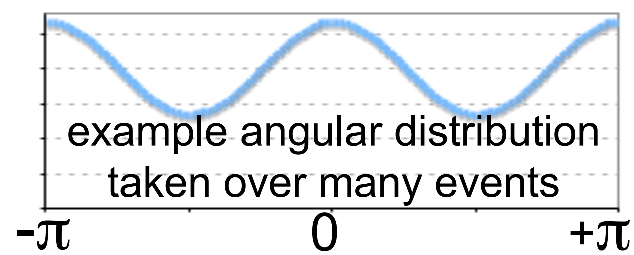


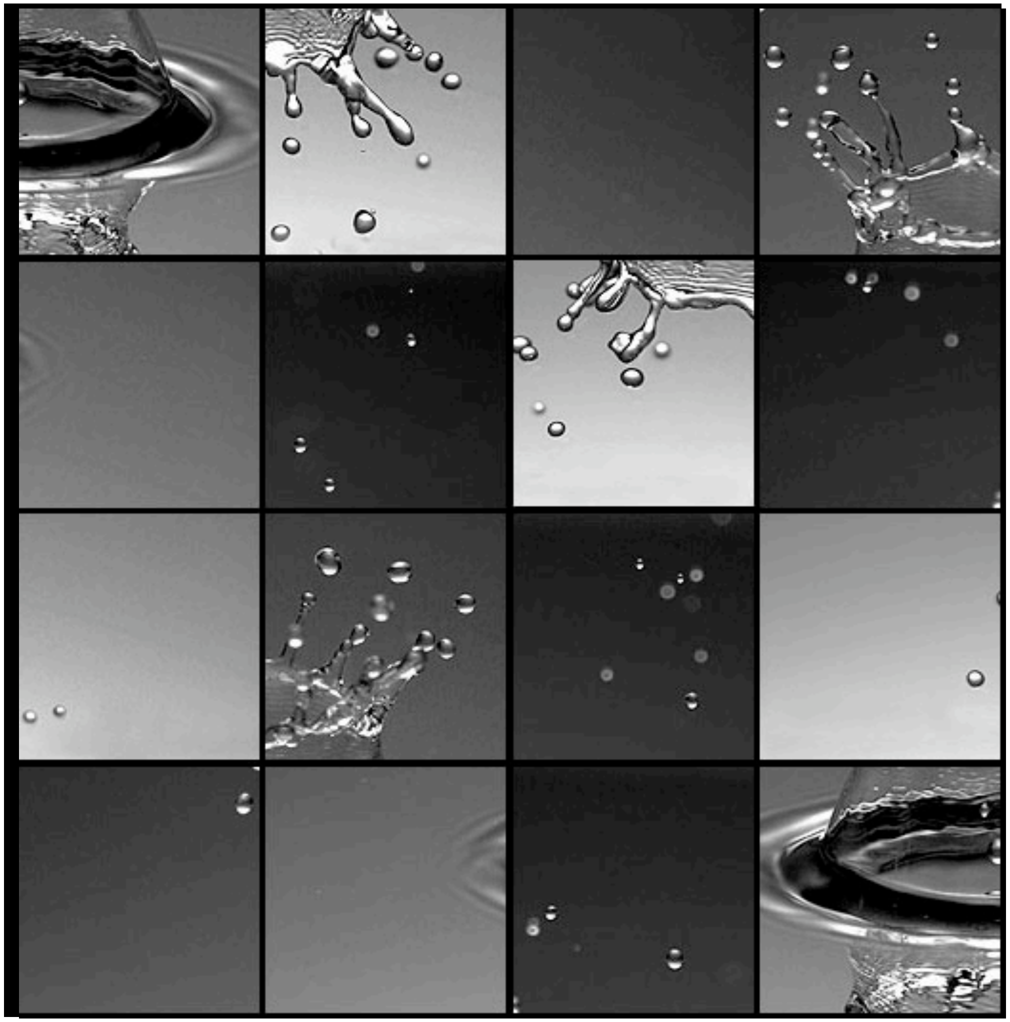
Restricted to the
Rings: $\pm 3.0 < \eta < \pm 5.4$

Spectrometer: $0 < \eta < 1$



Measurement of elliptic flow at PHOBOS

An event at PHOBOS can be divided many ways…



Measurement of elliptic flow at PHOBOS

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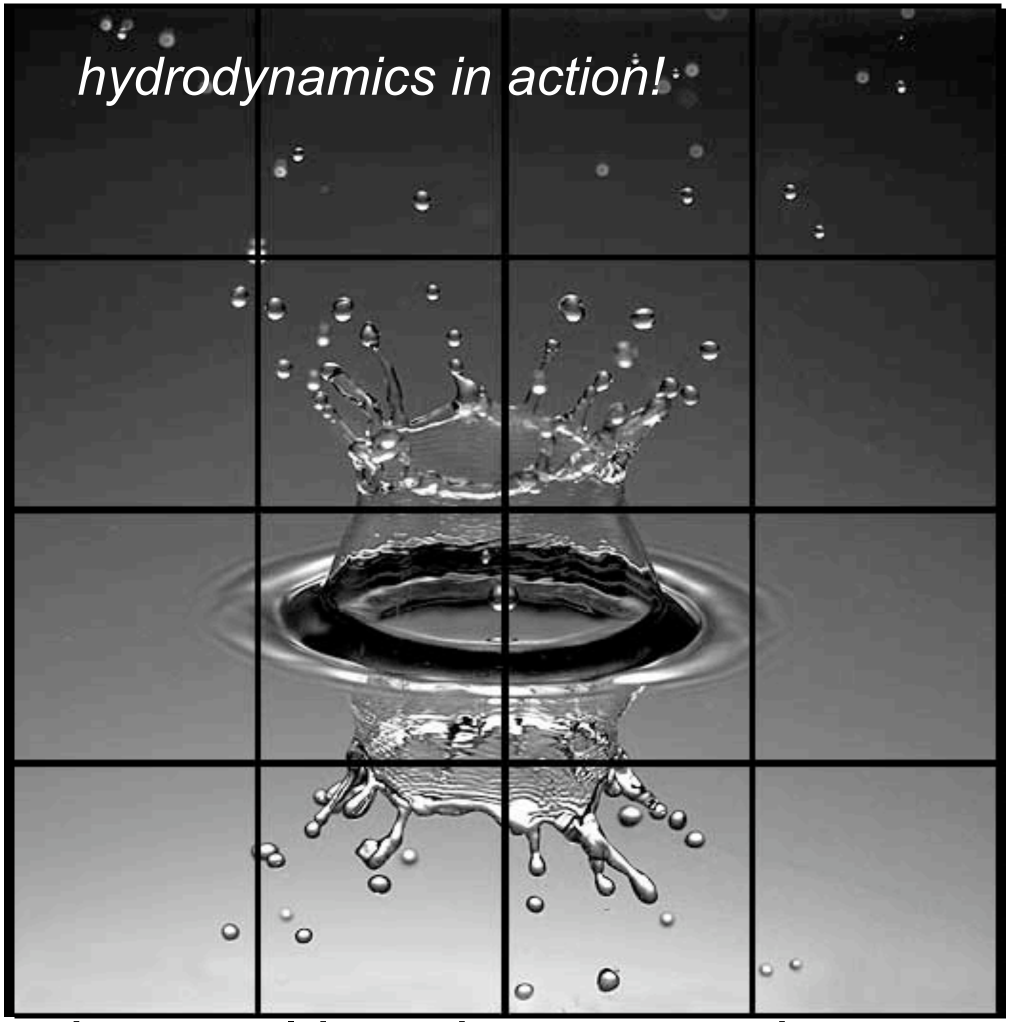
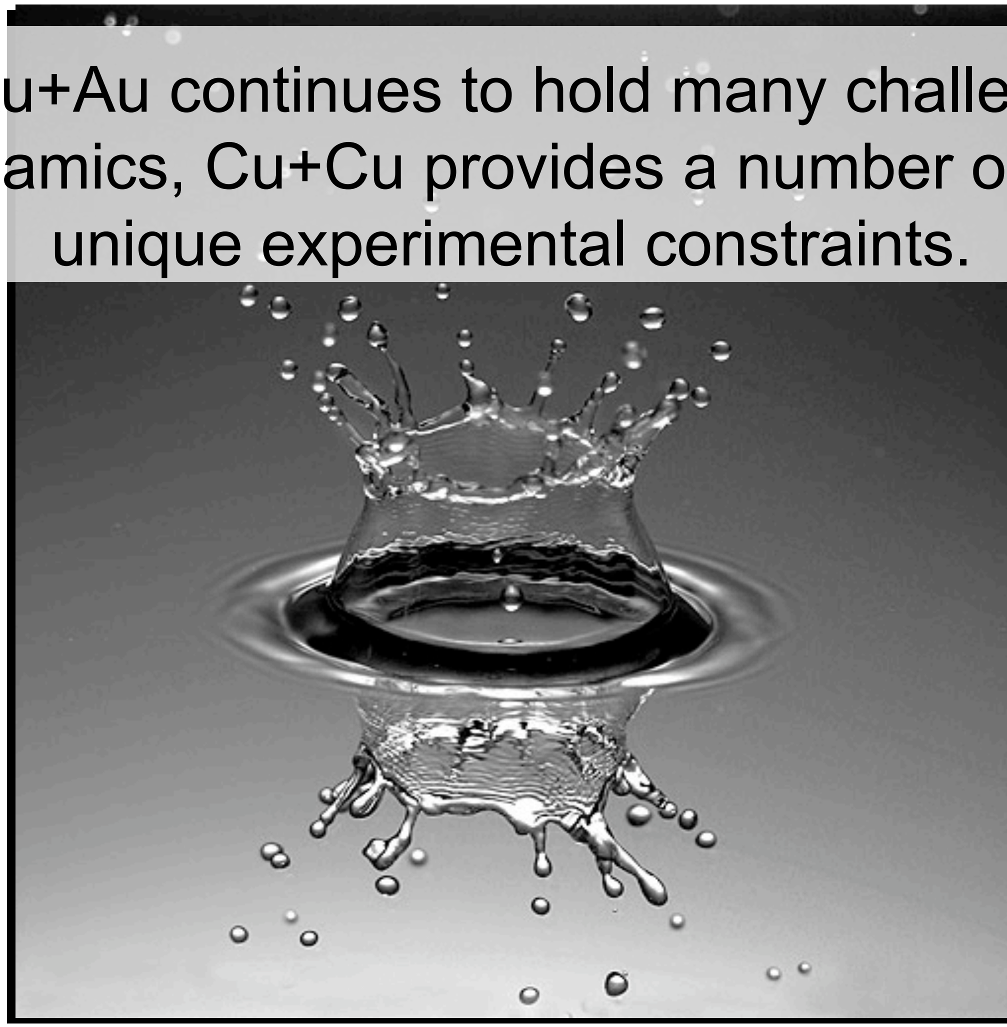


…but the resulting picture remains consistent

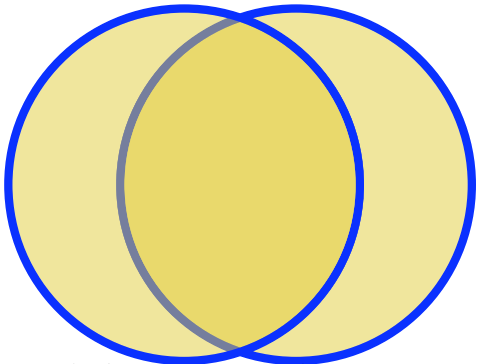
Good agreement using various η slices is a valuable cross-check

New Tests for Hydrodynamics

While Au+Au continues to hold many challenges for hydrodynamics, Cu+Cu provides a number of new and unique experimental constraints.

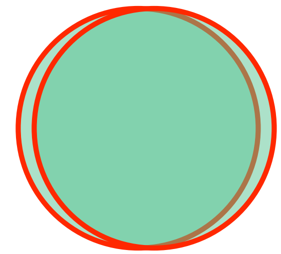


Why study flow in Cu+Cu?



Mid-central AuAu collision

roughly same number of participants



Central CuCu collision

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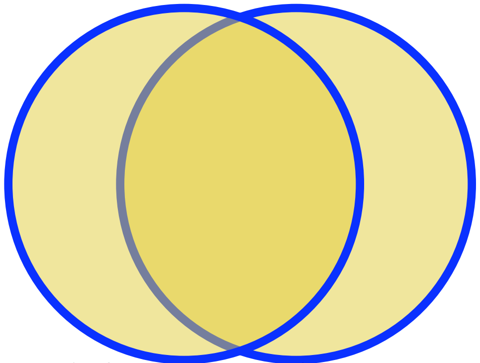
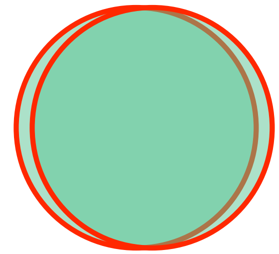


Mid-central AuAu collision

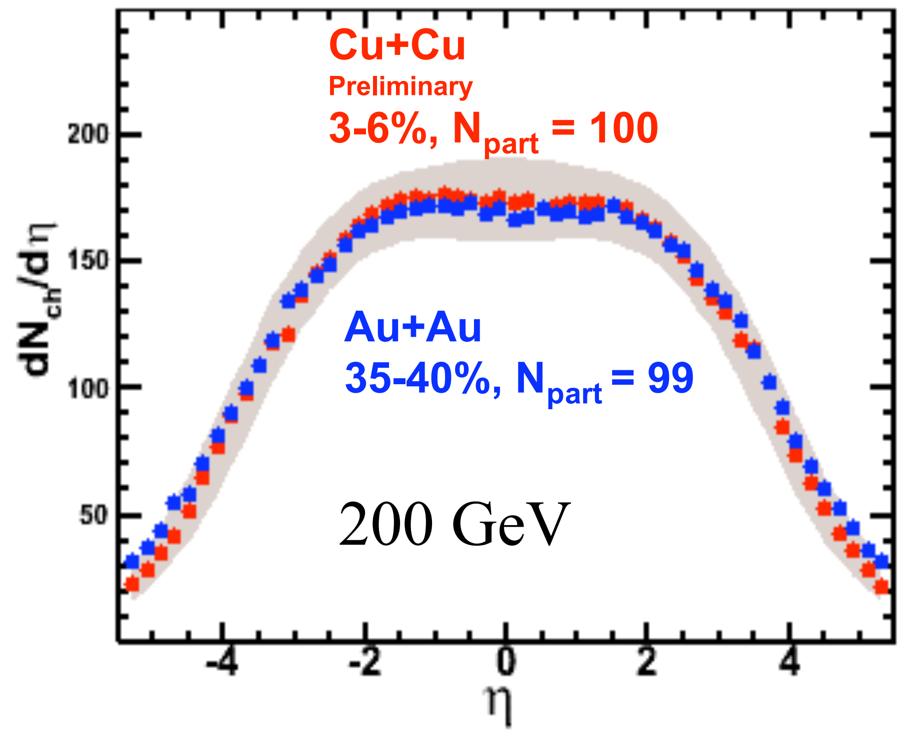
roughly same number of participants



Central CuCu collision

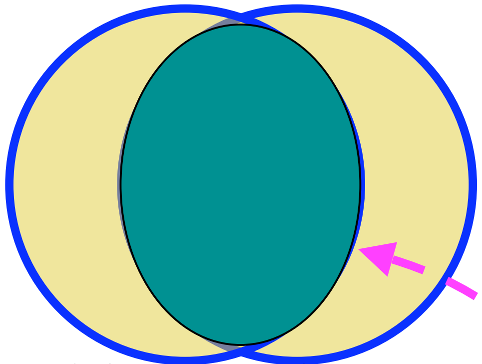
Some observables scale with number of participants

Similar dN/dη



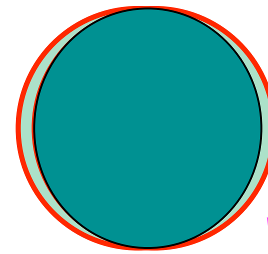
B.B. Back *et al.*, (the PHOBOS Collaboration) PRL 91,052303 (2003)
G. Roland *et al.*, (PHOBOS Collaboration) Proc. QM2005, nucl-ex/0510042

Why study flow in Cu+Cu?



Mid-central AuAu collision

roughly same number of participants



Central CuCu collision

Some observables scale with number of participants

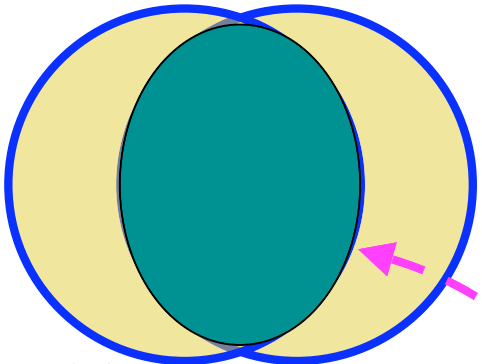
Similar dN/dη

However…

Flow is expected to depend on

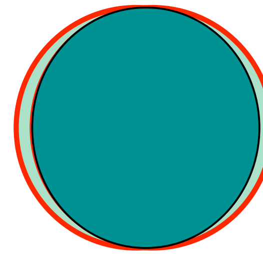
Geometry!

Why study flow in Cu+Cu?



Mid-central AuAu collision

roughly same number of participants



Central CuCu collision

Some observables scale with number of participants

Similar dN/dη

However…

Flow is expected to depend on

Geometry!

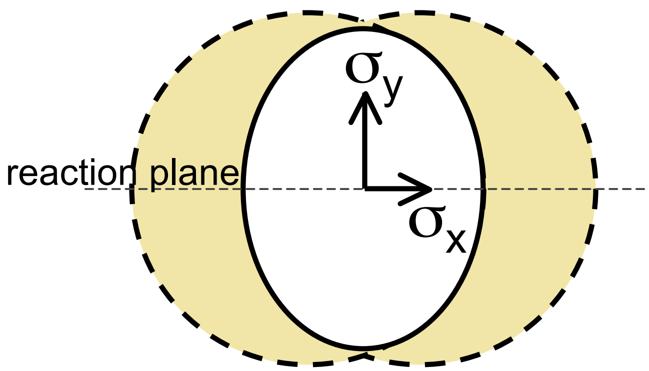
Using two species lets us change the geometry while holding the number of participants constant

What can we say about the geometry?

The shape of the participant region is generally expressed by the eccentricity

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

Cartoon of a collision.



x-axis along the reaction plane
y-axis is the major axis of the ellipse

I'll denote eccentricity ***in this orientation*** as

$\varepsilon_{\text{standard}}$

(of course, experimentally, the position of each nucleon is not observable and therefore neither is σ_x^2 or σ_y^2)

Bridging experiment and geometry

Since experiments cannot measure the underlying geometry directly, models remain a necessary evil.

Experiment

multiplicity, etc.

Models

Geometry

- centrality
- impact parameter
- number of participants
- eccentricity

Models are also needed to connect fundamental geometric parameters with each other

Modeling the Geometry

Nearly the most straightforward approach to describing collision geometry has been to invoke Glauber's formalism for the scattering of a particle off of a nuclear potential.

Glauber Assumptions

- Nucleons are distributed according to a density function (e.g. Woods-Saxon)
- Nucleons proceed in a straight line, undeflected by collisions
- Irrespective of previous interactions, nucleons interact according to the inelastic cross section (measured in pp collisions).

Modeling Geometry

One application of the Glauber formalism is a *Monte Carlo* technique

In a Glauber Monte Carlo, nuclei are randomly generated given certain physical constraints (Woods-Saxon probability distribution, etc.)

Numerous simulated nuclei are “thrown” at each other and the average of various geometric properties are taken from these events.

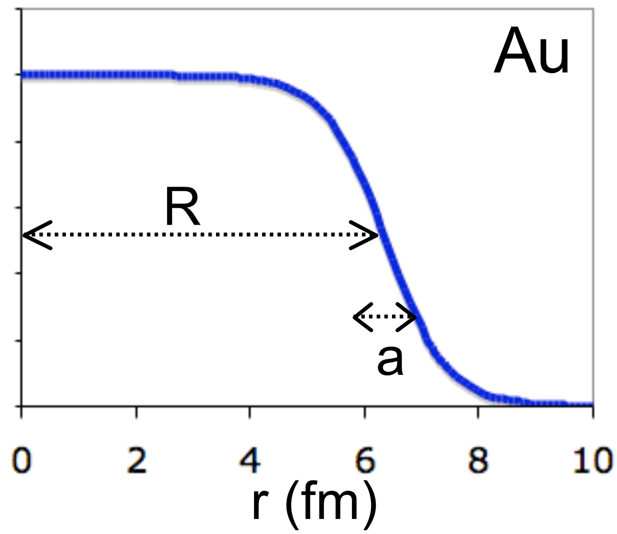
This has been a very successful tool at RHIC in relating fundamental geometric variables

(cross section, impact parameter, number of participating nucleons, etc.)

GlauBall Algorithm

"GlauBall" is the PHOBOS implementation of a Glauber MC

Nucleons are distributed randomly based on an appropriately chosen Woods-Saxon radial density, and polar coordinates are assigned arbitrarily.



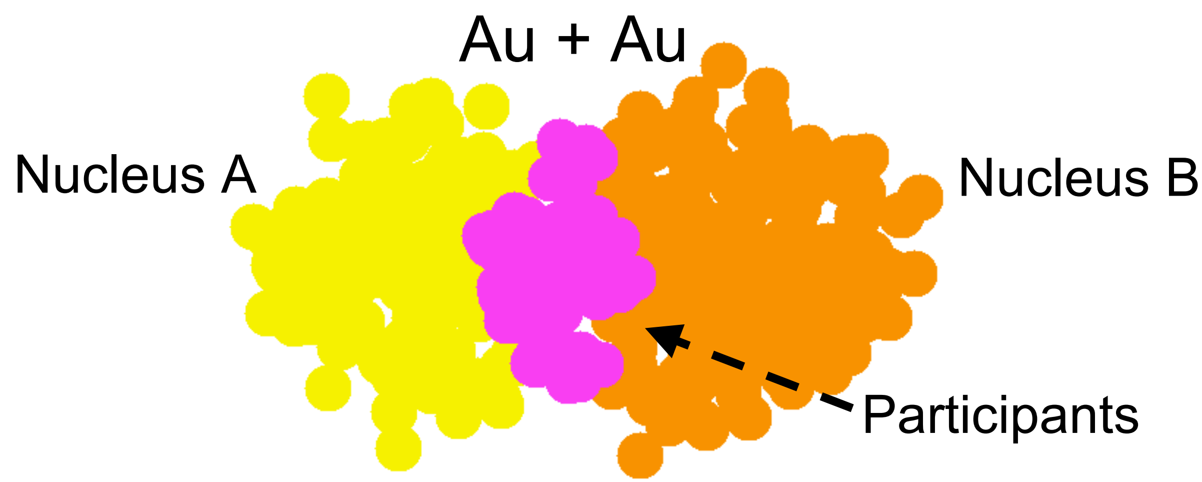
Note: An internucleon separation can be introduced at this step

Subsequently, only the x and y nucleon positions are relevant, so the nuclei can be thought of as 2 dimensional projections

GlauBall Algorithm

The nuclei are offset by an impact parameter generated randomly from a linear distribution

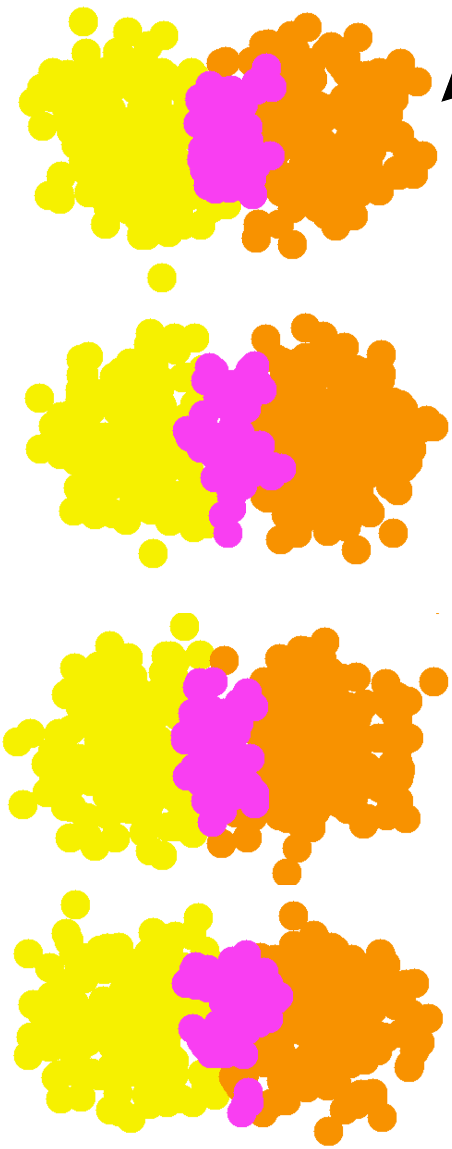
Nucleons are treated as hard spheres. Their 2D projections are given an area of σ_{NN} (taken from pp inelastic collisions)



The nuclei are "thrown" (their x-y projections are overlapped), and opposing nucleons that touch are marked as participants.

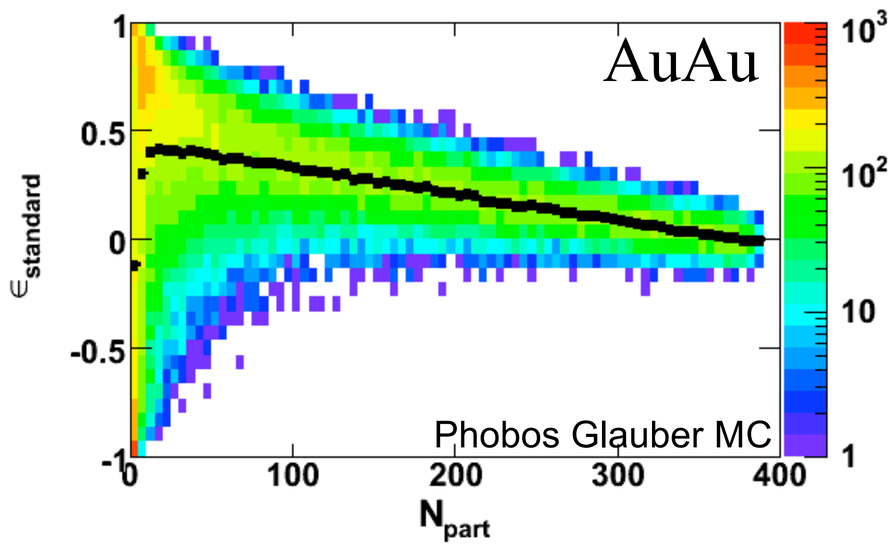
Can we use the model to relate eccentricity to a well understood variable such as the number of participants?

Eccentricity versus N_{part}



AuAu collisions with same N_{part}

- Glauber collisions are modeled over a range of impact parameters and are sorted by the number of participants.
- An eccentricity distribution is built up for each N_{part}



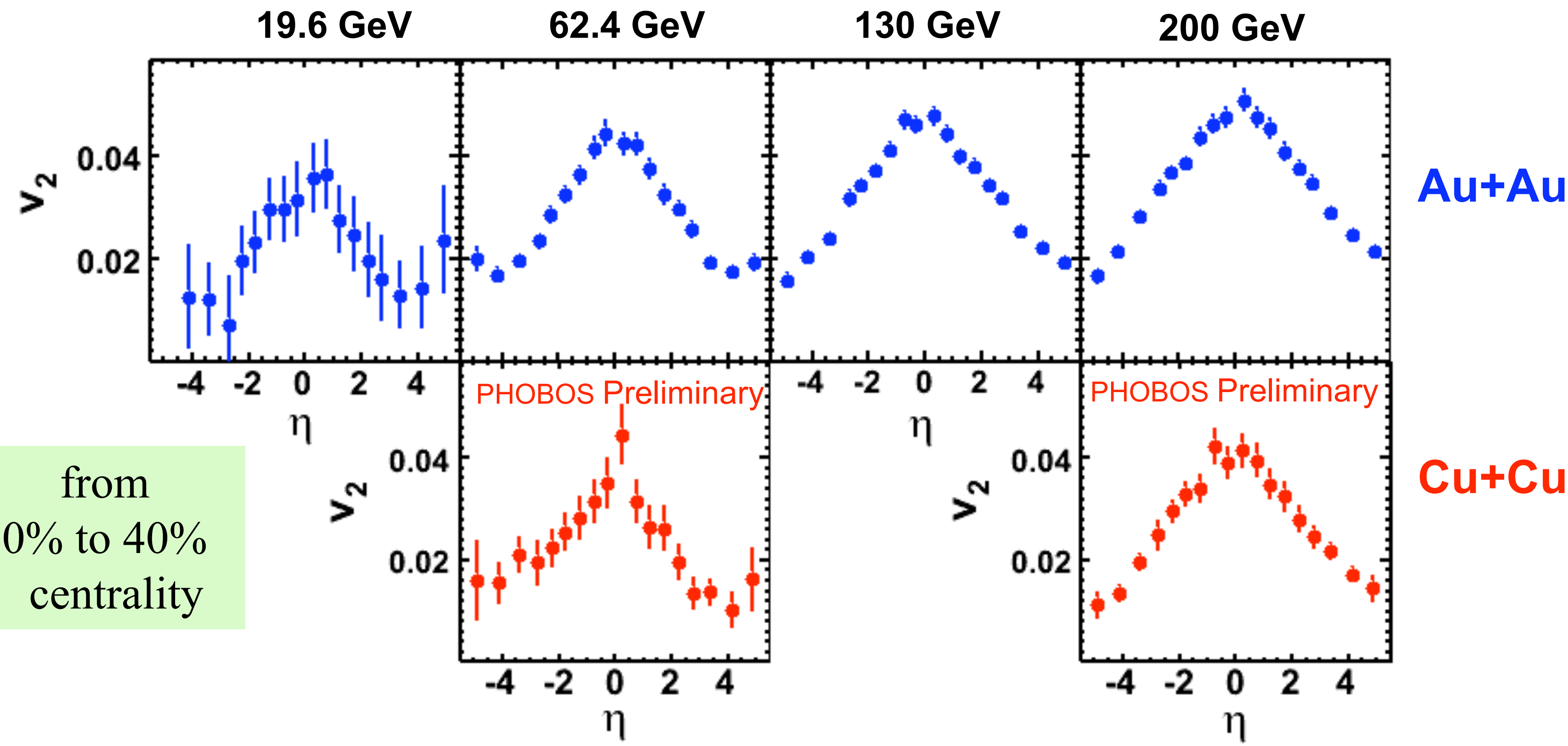
- The black line shows the average eccentricity (which will be used later on)

The Data

PHOBOS has produced an extensive series of flow measurements probing multiple controlling parameters:

- Centrality
- Transverse Momentum
- Pseudorapidity
- Energy
- Species / System Size

v_2 vs η

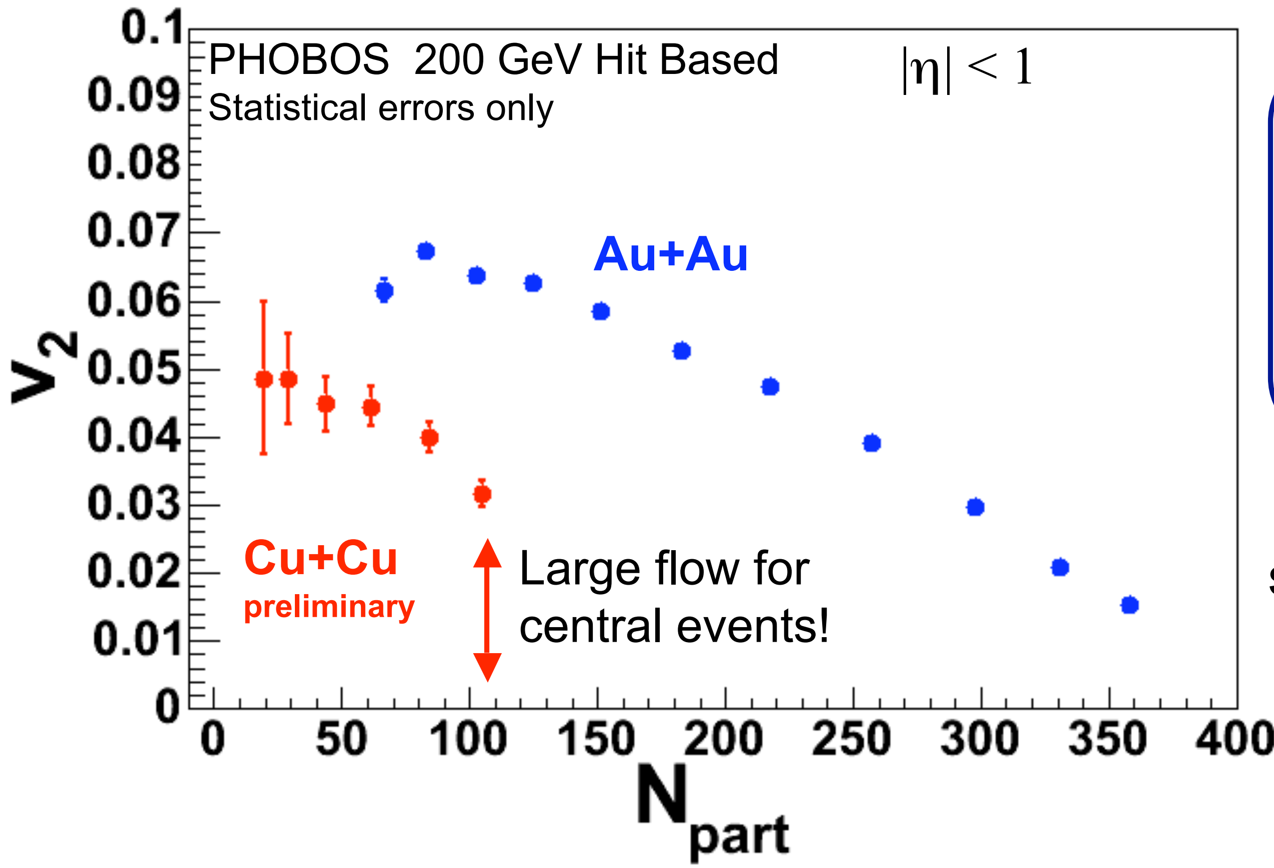


from
0% to 40%
centrality

Cu-Cu: S. Manly *et al.*, (PHOBOS Collaboration) Proc. QM05, nucl-ex/0510031
Au+Au: B.B. Back *et al.*, (PHOBOS Collaboration) PRL 94 122303 (2005)

Cu+Cu about 20% lower than Au+Au

v_2 vs N_{part} for Au and Cu

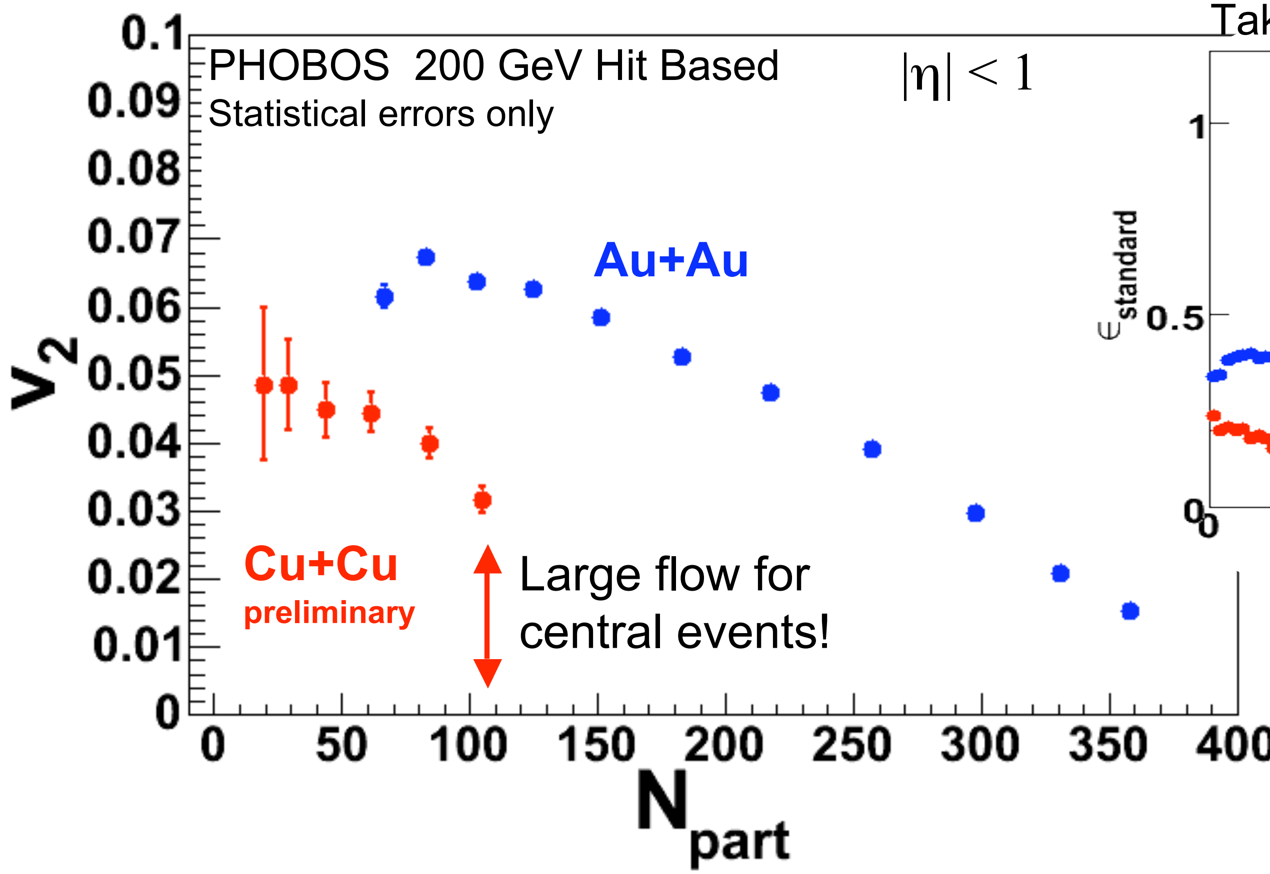


Can this be explained by the geometry?

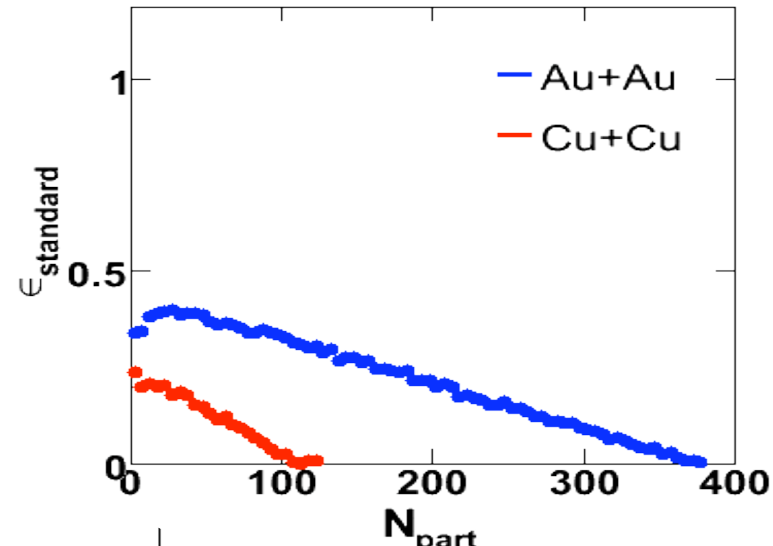
Very different flow at the same N_{Part}, but the overlap geometry is different

Au-Au: B.B. Back *et al.*, (PHOBOS Collaboration), Phys.Rev. C72 (2005) 051901
Cu-Cu: S. Manly *et al.*, (PHOBOS Collaboration), Proc. QM05, nucl-ex/0510031

v_2 vs N_{part} for Au and Cu



Taken from Phobos Glauber MC

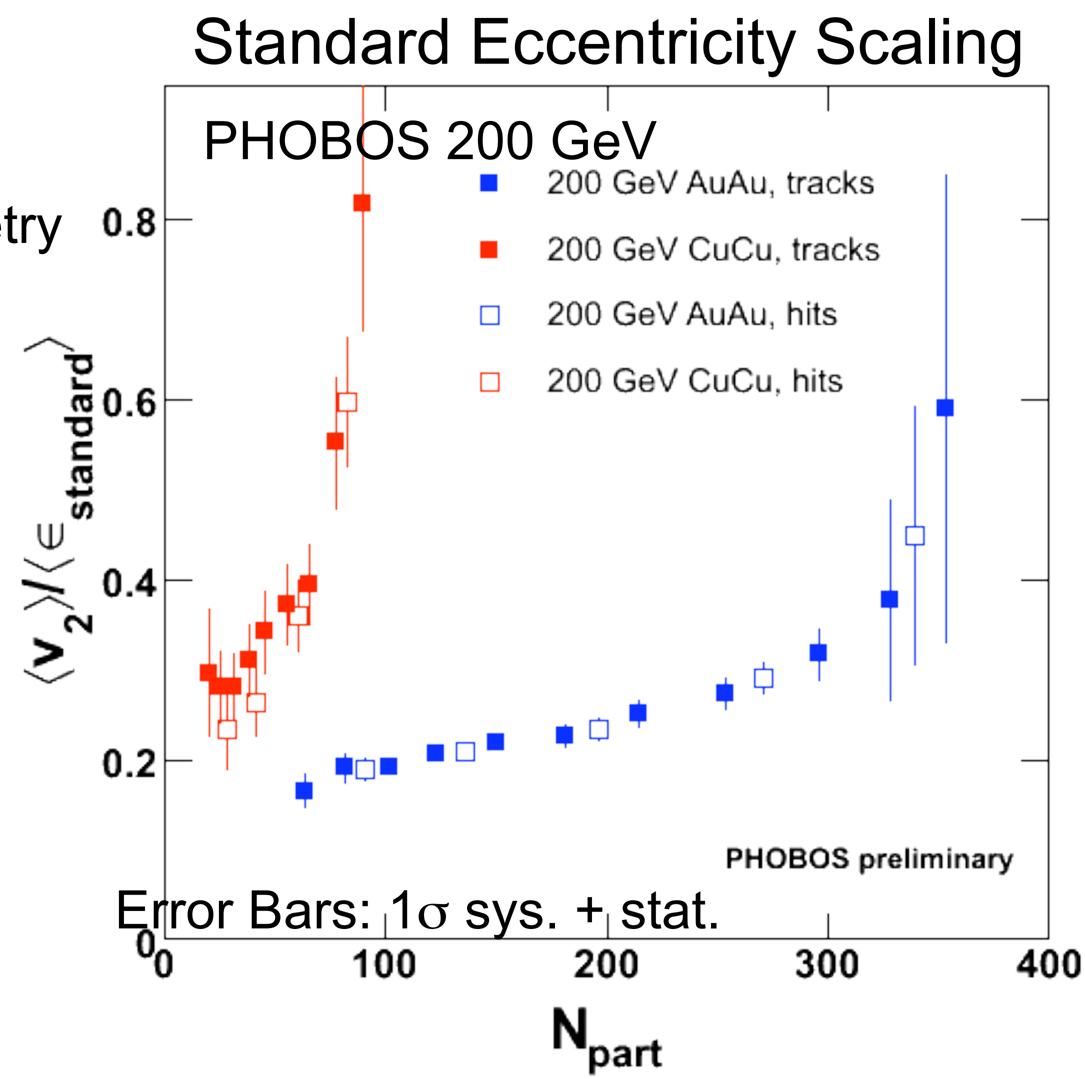


$\varepsilon_{standard}$ drops to zero for central events!

Au-Au: B.B. Back *et al.*, (PHOBOS Collaboration), Phys.Rev. C72 (2005) 051901
Cu-Cu: S. Manly *et al.*, (PHOBOS Collaboration), Proc. QM05, nucl-ex/0510031

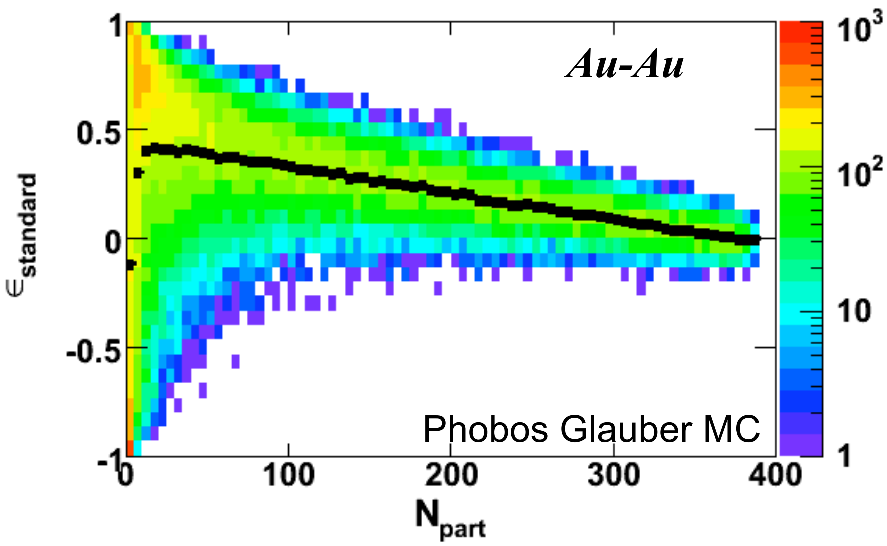
Normalized by the eccentricity

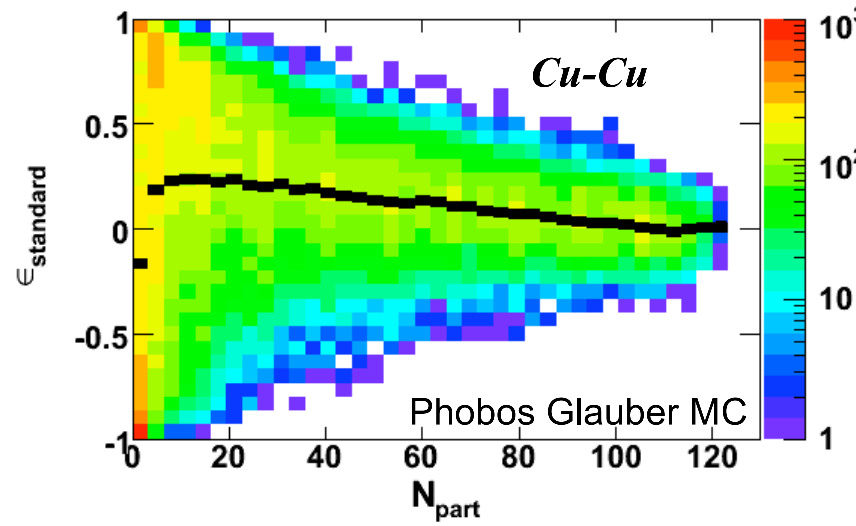
if we scale out the geometry hydrodynamic considerations would lead us to believe that the elliptic flow should be continuous between the two species



No agreement between Cu and Au scaled by the standard eccentricity

Reexamining Eccentricity





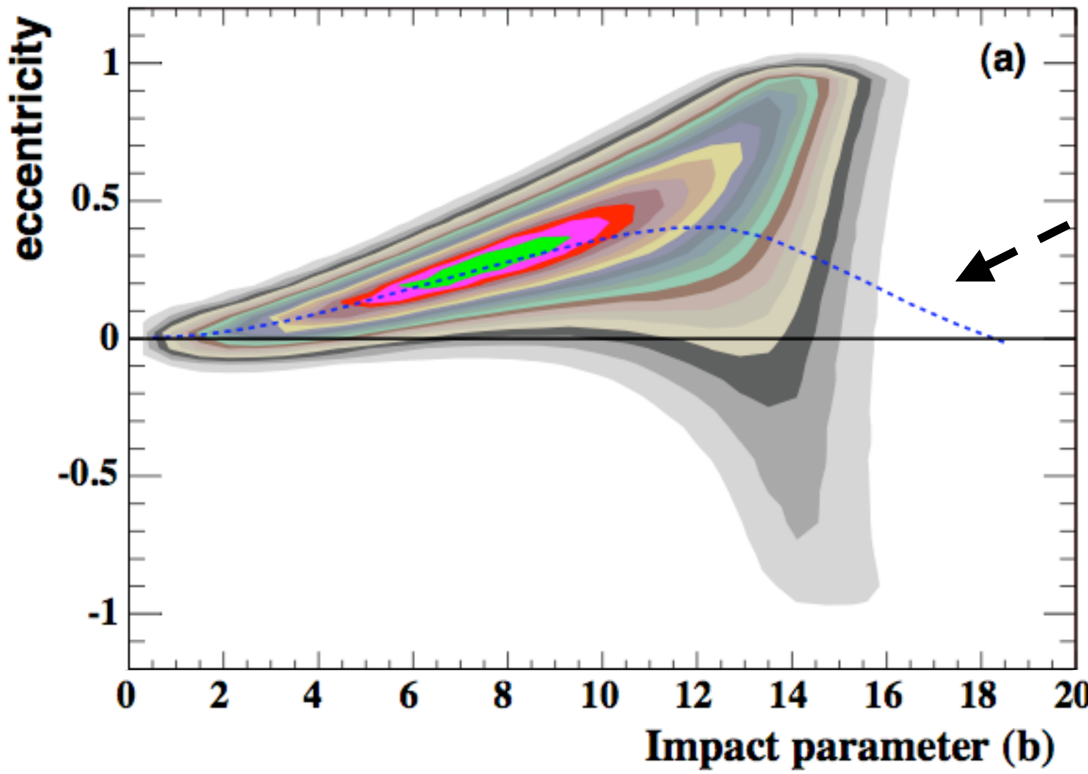
- When we examine the eccentricity distribution for CuCu, it looks much broader than AuAu
- Also, notice that there are many more events with *negative* eccentricity.

Previous studies of eccentricity fluctuations

Fluctuations in eccentricity have been studied before using Glauber MC.

Miller and Snellings suggested that eccentricity fluctuations might generate differences between the two particle correlation methods and higher order cumulant analyses.

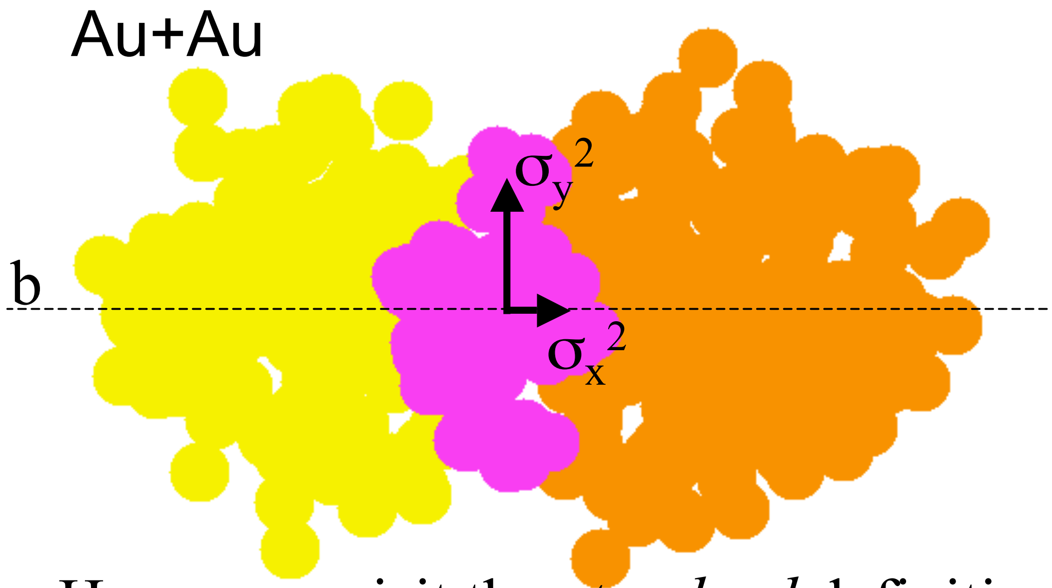
M. Miller and R. Snellings, nucl-ex/0312008



Blue line is the average eccentricity

In particular, negative eccentricity fluctuations contribute strongly to this difference

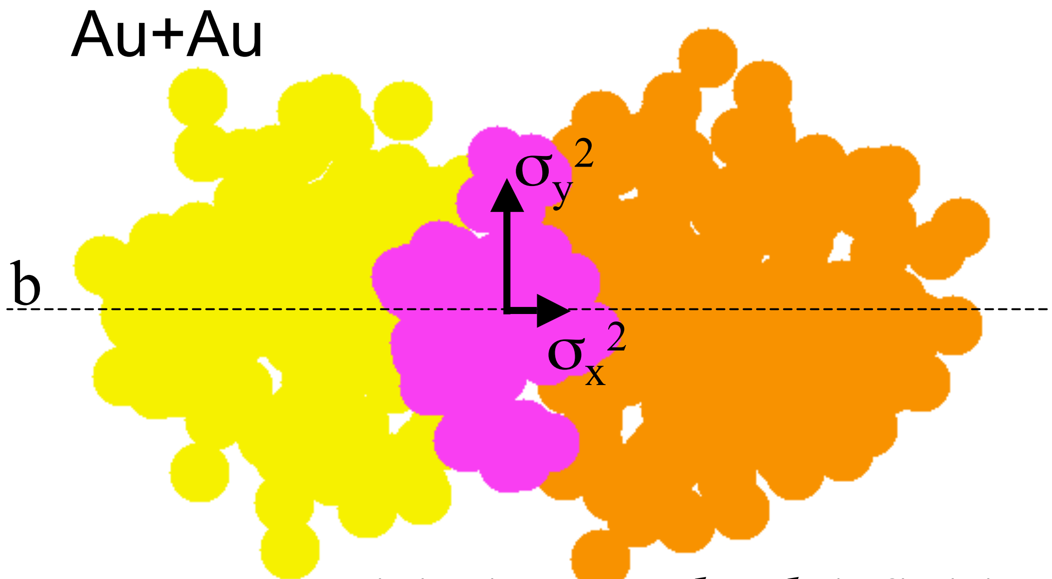
Meaning of Negative Eccentricity



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

Here we revisit the *standard* definition of eccentricity applied to a Gluaber model.

Meaning of Negative Eccentricity



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

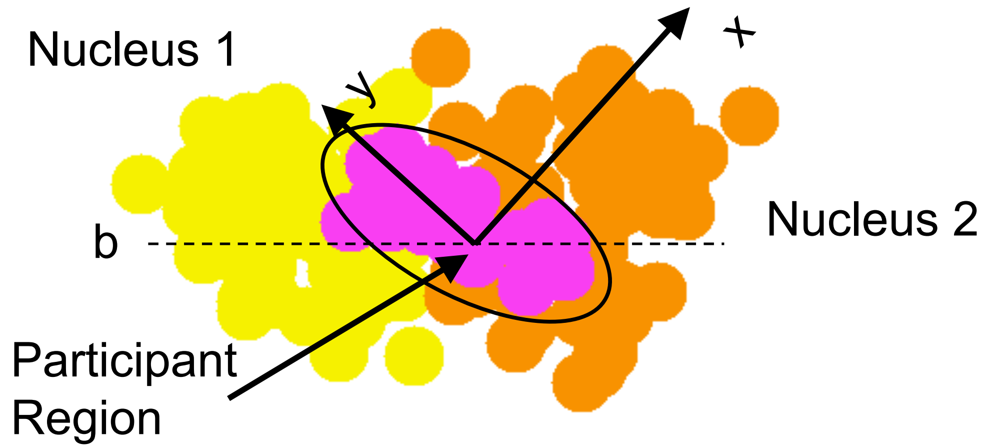
Here we revisit the *standard* definition of eccentricity applied to a Gluaber model.

Negative eccentricity results when $\sigma_x^2 > \sigma_y^2$, apparently due to fluctuations in the positions of the nucleons.

Because of its smaller size, CuCu is more susceptible to fluctuations

Redefining Eccentricity

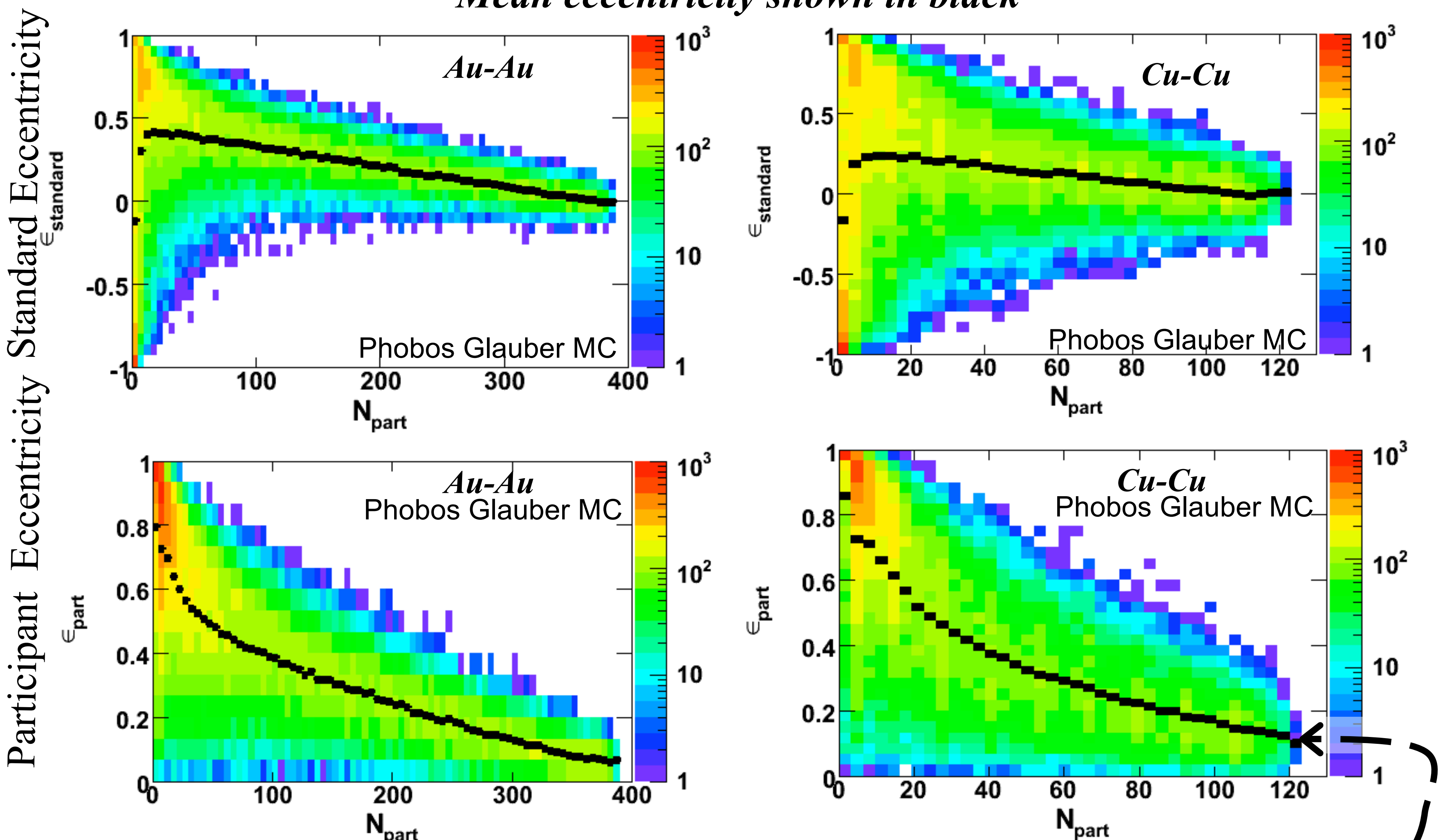
One reasonable method is to realign the coordinate system to maximize the ellipsoidal shape (a principal axis transformation)



The eccentricity *found in the rotated, participant coordinate system* is denoted $\varepsilon_{\text{participant}}$

Standard and Participant Eccentricity

Mean eccentricity shown in black



Greater fluctuations in Cu+Cu. Positive fluctuations lead to non zero mean.

Robustness of Geometry Variables

- Distance of closest approach between nucleons

  little change from 0 fm, to 0.4 fm, all the way up to 0.8 fm

- Skin depth

  modified within reason, and all the way down to zero for fun

- Nucleon-nucleon cross section at $\sqrt{s}$=200 GeV

  from 35 mb to 45 mb

- Nuclear radius

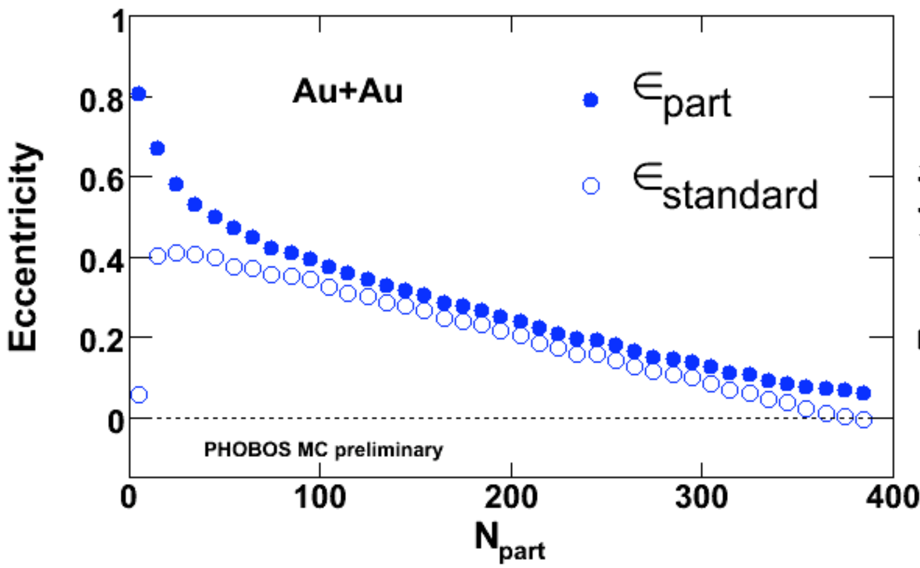
  deviated ±10% from the nominal values

$\varepsilon_{\text{participant}}$ even slightly more robust than $\varepsilon_{\text{standard}}$

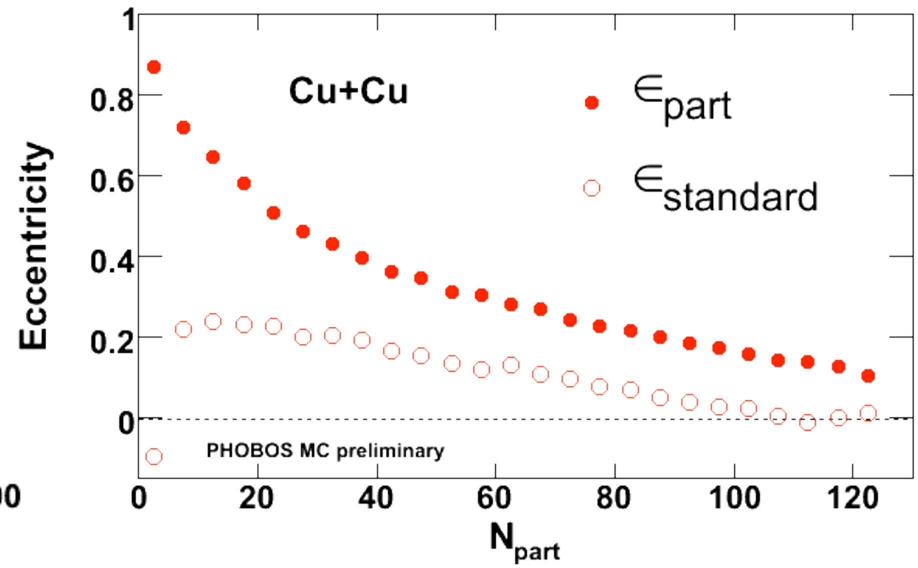
Impact of Eccentricity Fluctuations

Fluctuations in eccentricity are important for the Cu-Cu system.

small difference, not quite inconsequential



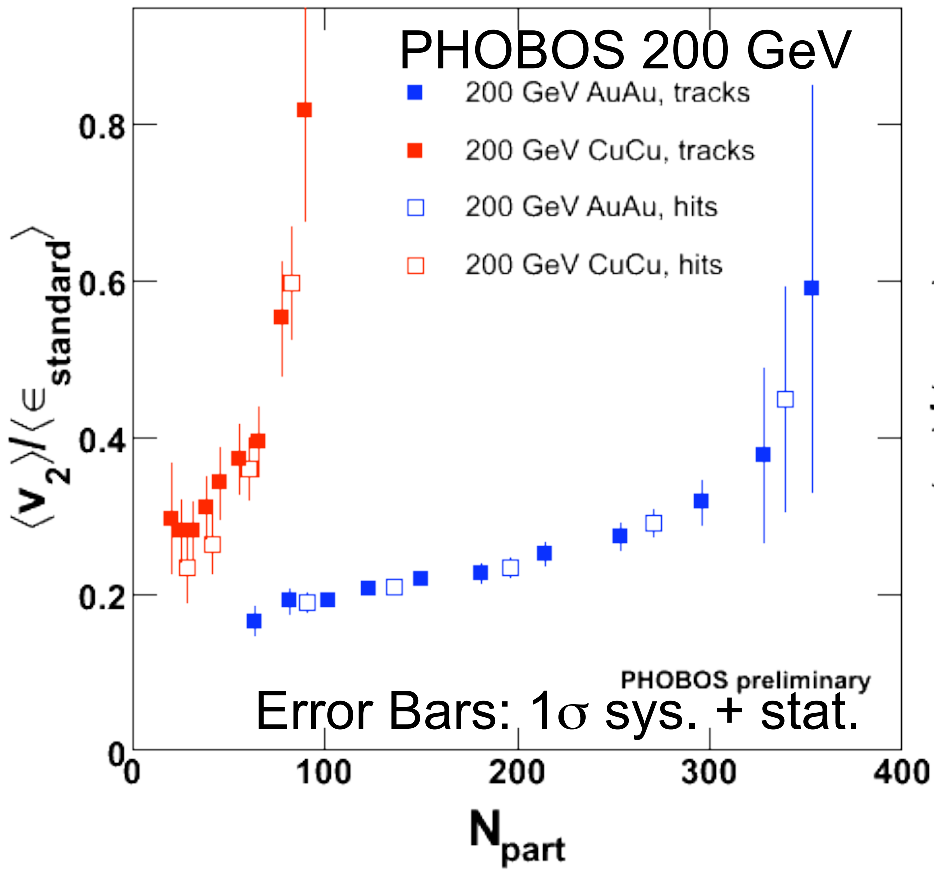
much more pronounced difference



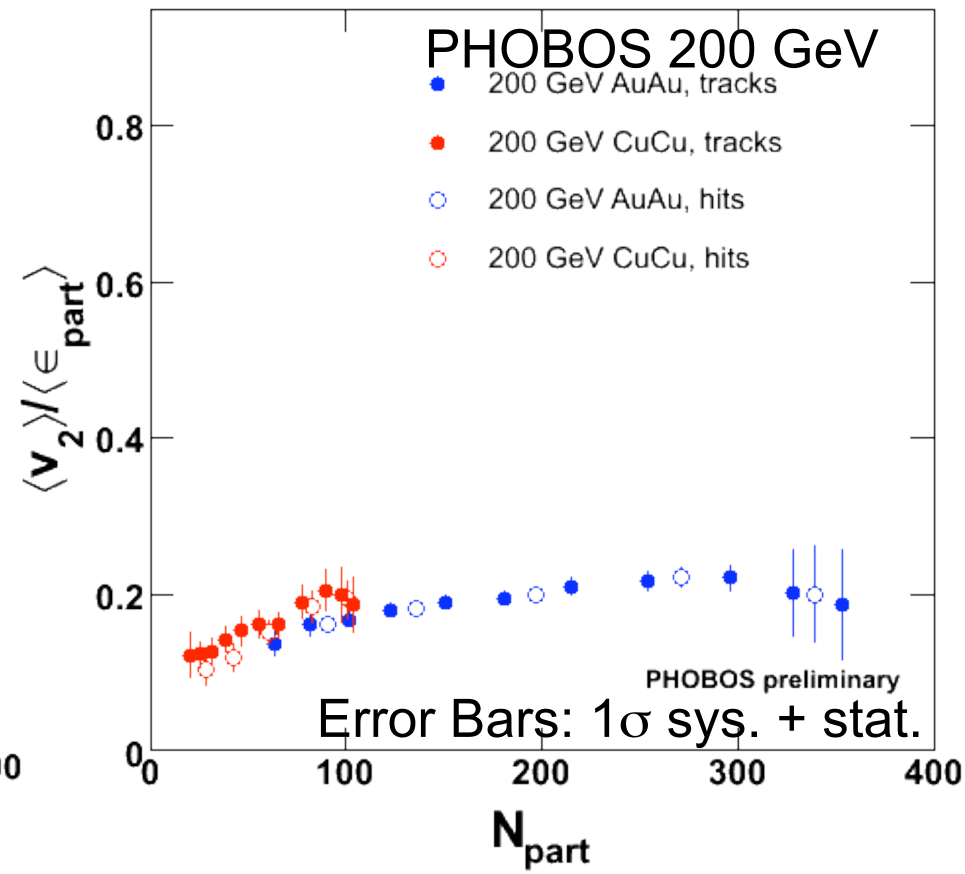
Must use care in doing Au-Au to Cu-Cu flow comparisons.
Eccentricity scaling depends on definition of eccentricity.

Elliptic Flow Puzzle Solved?

Standard Eccentricity Scaling

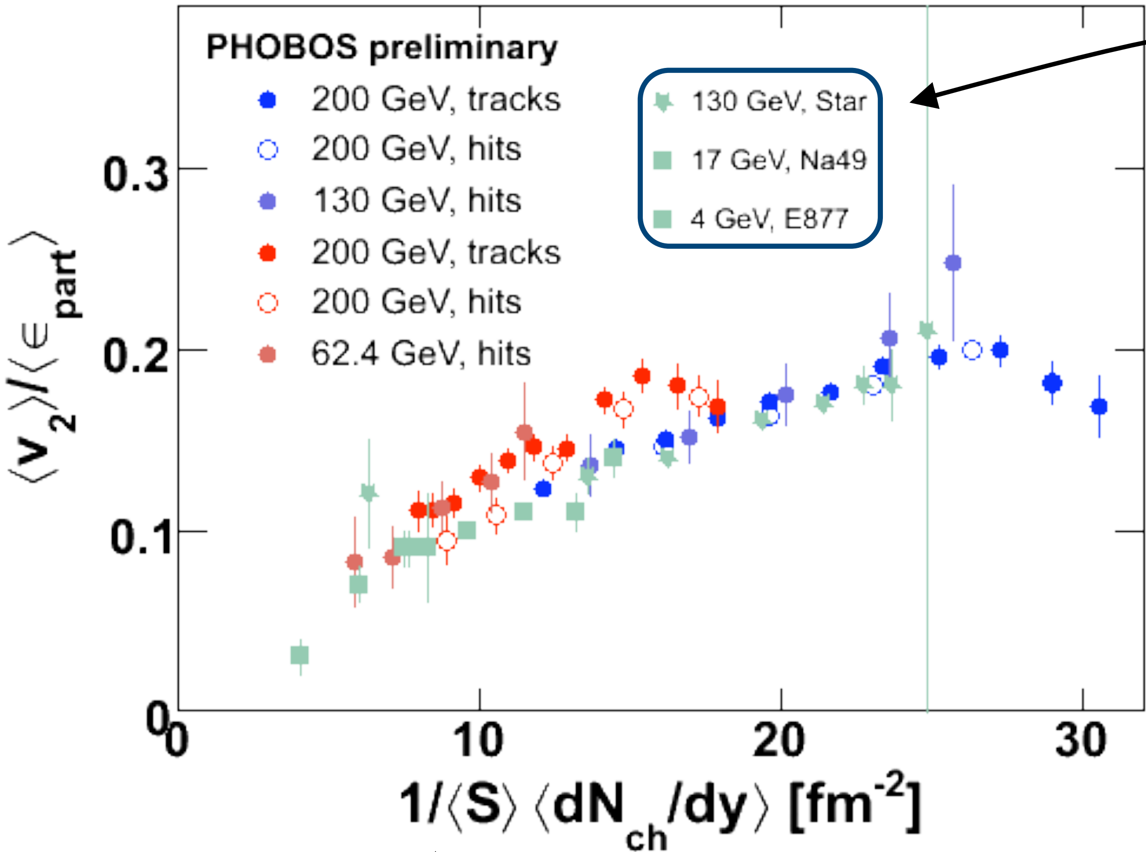


Participant Eccentricity Scaling



<dN/dy> / <S> scaling

G. Roland *et al.*, Proc. QM2005, nucl-ex/0510042



Overlap Area

Caveat: $dN_{ch}/d\eta$ corrected to dN_{ch}/dy

STAR and AGS Au+Au and CERN Pb+Pb results have not been modified to scale by ε_{part}

(1/<S>)dN/dy scaling:

C. Adler *et al.* (STAR), PRC **66** 034904 (2002)

A.M. Poskanzer and S.A. Voloshin, Nucl. Phys. **A661**, 341c (1999)

J. Barrette *et al.* (E877), PRC **51**, 3309 (1995); **55**, 1420 (1997)

Au-Au:

B.B. Back *et al.*, (PHOBOS Collaboration), Phys.Rev. C72 (2005) 051901

Cu-Cu:

S. Manly *et al.*, (PHOBOS Collaboration), Proc. QM05, nucl-ex/0510031

Conclusions

• Flow in Cu+Cu is found to be larger than initially anticipated, and it is not vanishingly small for the most central events.

• We encourage careful consideration of the definition of eccentricity. Particularly in the case of Glauber Monte Carlo calculations, we suggest that the participant eccentricity may be the relevant variable.

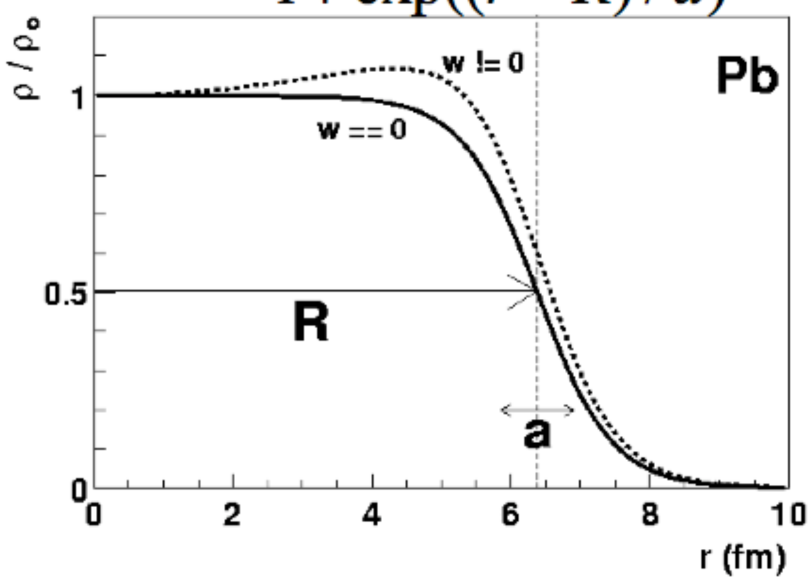
• When expressed in terms of participant eccentricity, v_2/ε is consistent for Cu+Cu and Au+Au, and scales with other elliptic flow measurements at AGS, SPS, and RHIC energies.

Backup Slides

Glauber Parameters Changed

Systematic Source	Standard	How Much We Vary
Nucleon-nucleon cross-section	42 mb (for 200GeV)	30 mb (<20GeV) 45 mb (>200GeV)
Nuclear skin depth	0.535fm (Au) 0.596fm (Cu)	±10%
Nuclear radius	6.38fm (Au) 4.2fm (Cu)	±10%
Minimum nucleon separation (center-to-center)	0.4fm (like HIJING)	0fm 0.8fm

$$\rho(r) = \frac{\rho_0 \left(1 + wr^2 / R^2\right)}{1 + \exp((r - R)/a)}$$



Nucleus	A	R	a	w
C	12	2.47	0	0
O	16	2.608	0.513	-0.051
Al	27	3.07	0.519	0
S	32	3.458	0.61	0
Ca	40	3.76	0.586	-0.161
Ni	58	4.309	0.516	-0.1308
Cu	63	4.2	0.596	0
W	186	6.51	0.535	0
Au	**197**	**6.38**	**0.535**	**0**
Pb	208	6.68	0.546	0
U	238	6.68	0.6	0

H. DeVries, C.W. De Jager, C. DeVries, 1987