Initial geometry fluctuations
and
Triangular flow

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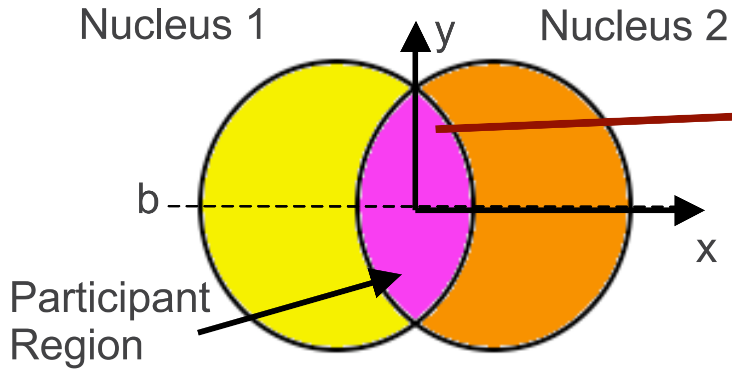
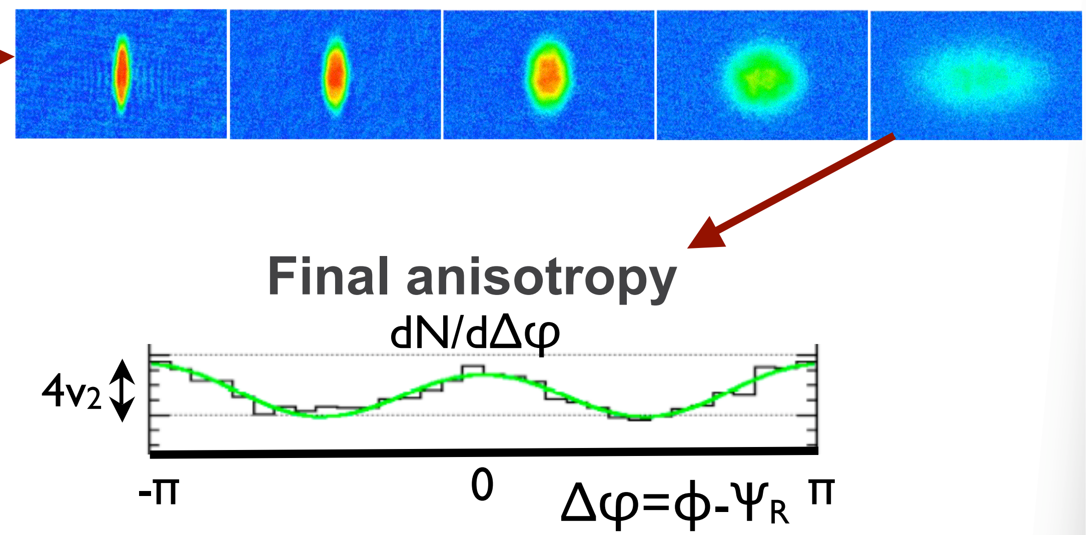
arXiv: 1003.0194

Traditional picture

Initial anisotropy



Pressure driven expansion

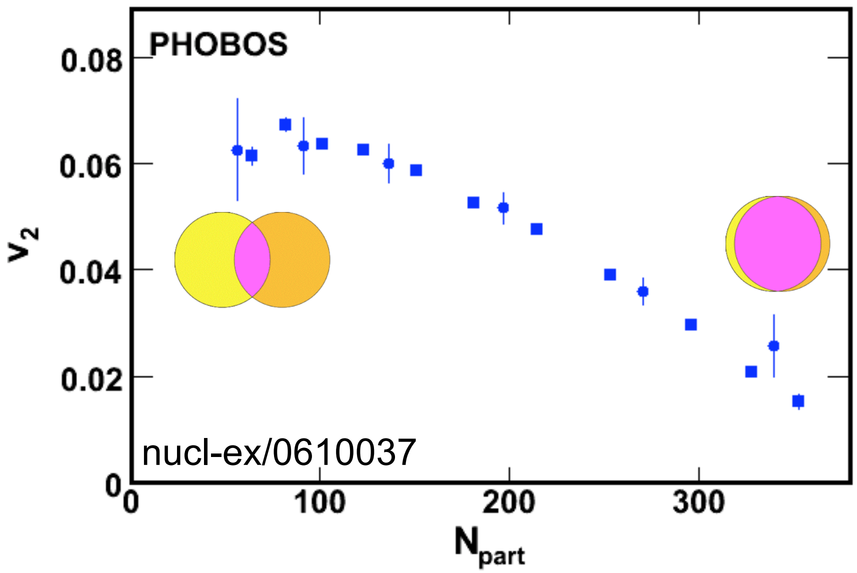


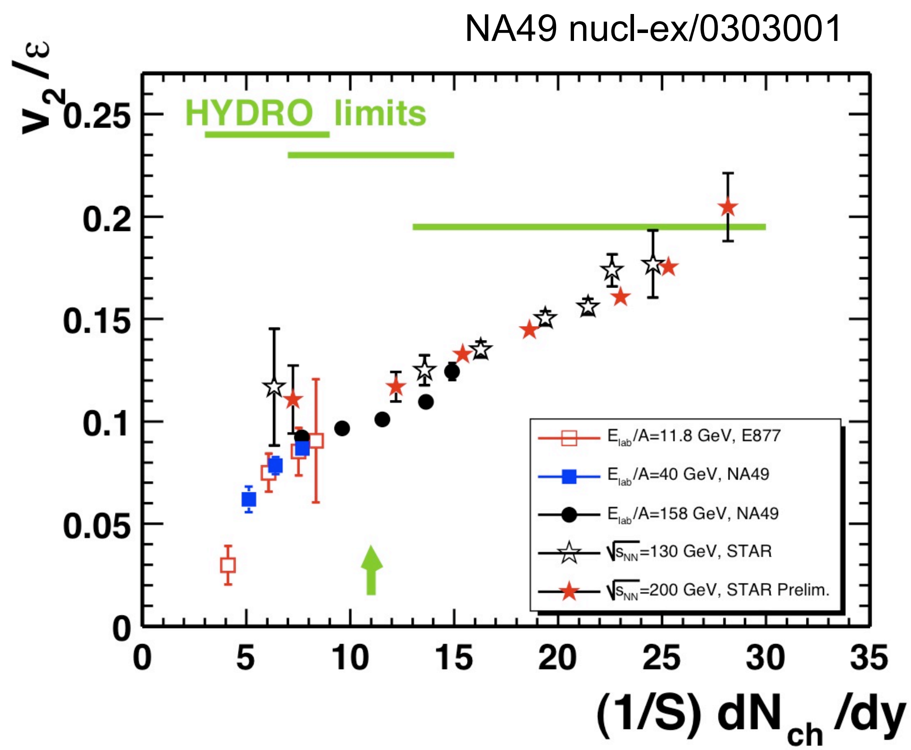
$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_R)\right)\right)$$

$$v_2 = \left\langle \cos\left(2(\phi - \underline{\psi_R})\right)\right\rangle \propto \varepsilon$$

Elliptic flow is quantified by the second Fourier coefficient (v_2) of the observed particle distribution

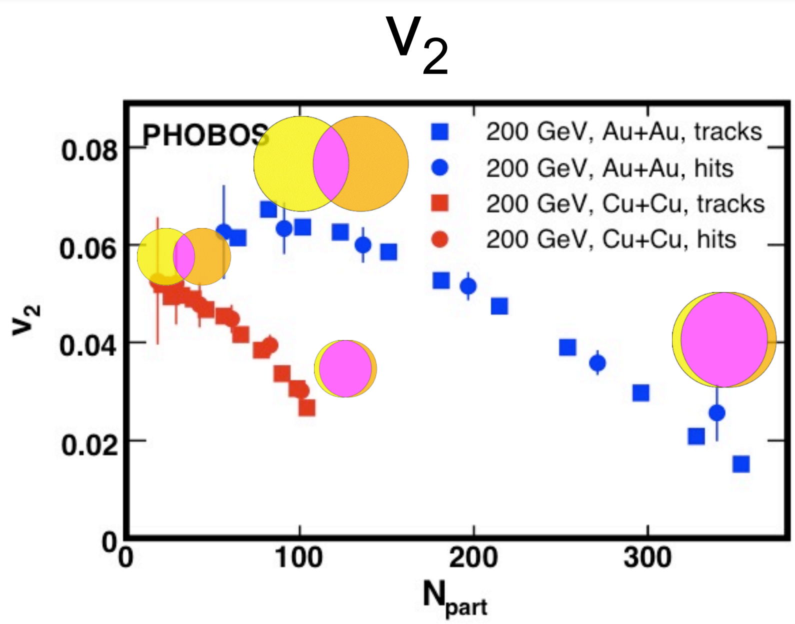
“The Perfect Liquid at RHIC”

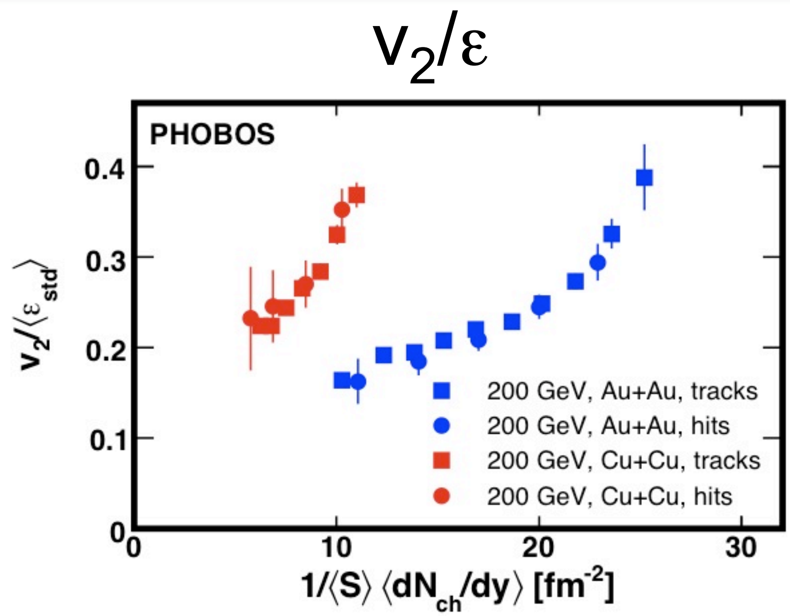




Large elliptic flow signal at RHIC suggests early thermalization and strongly interacting medium

Elliptic flow in Cu+Cu collisions





Elliptic flow signal in Cu+Cu collisions
was observed to be surprisingly large,
in particular for the most central collisions

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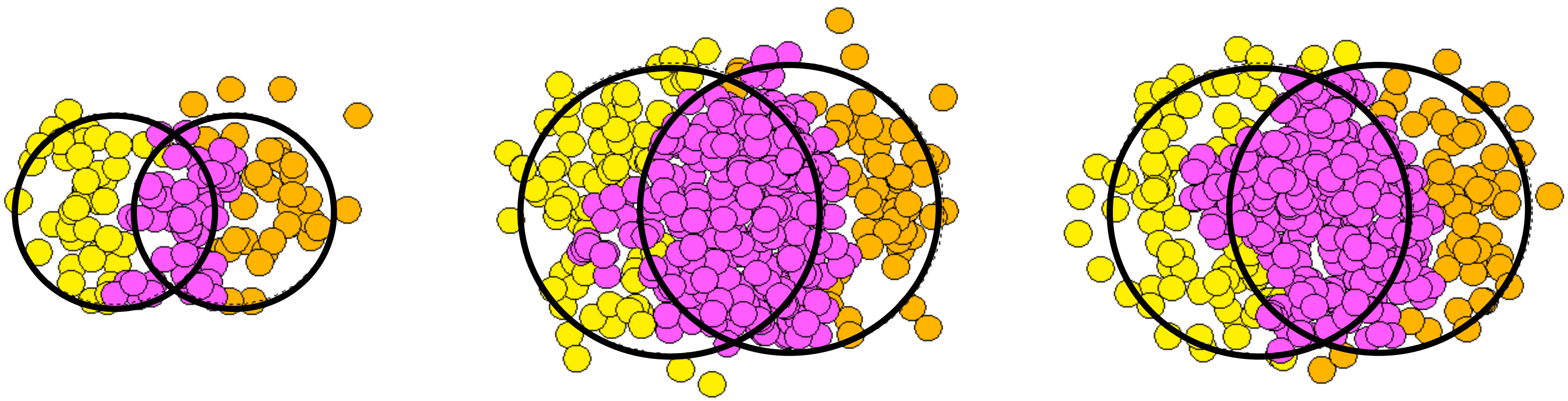
Initial geometry

Glauber Model Description of the initial geometry:

- Nuclei consist of randomly positioned nucleons
- Impact parameter is randomly selected
- Nucleons collide if closer than $D = \sqrt{\sigma_{NN} / \pi}$



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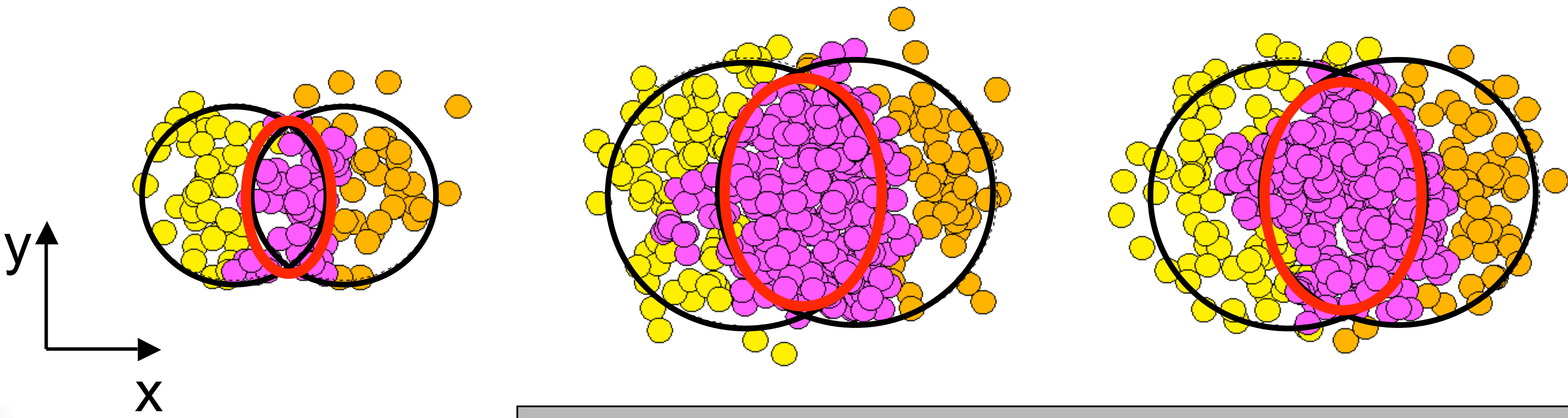
“Standard” eccentricity

Eccentricity of the collision region
can be calculated from positions of nucleons

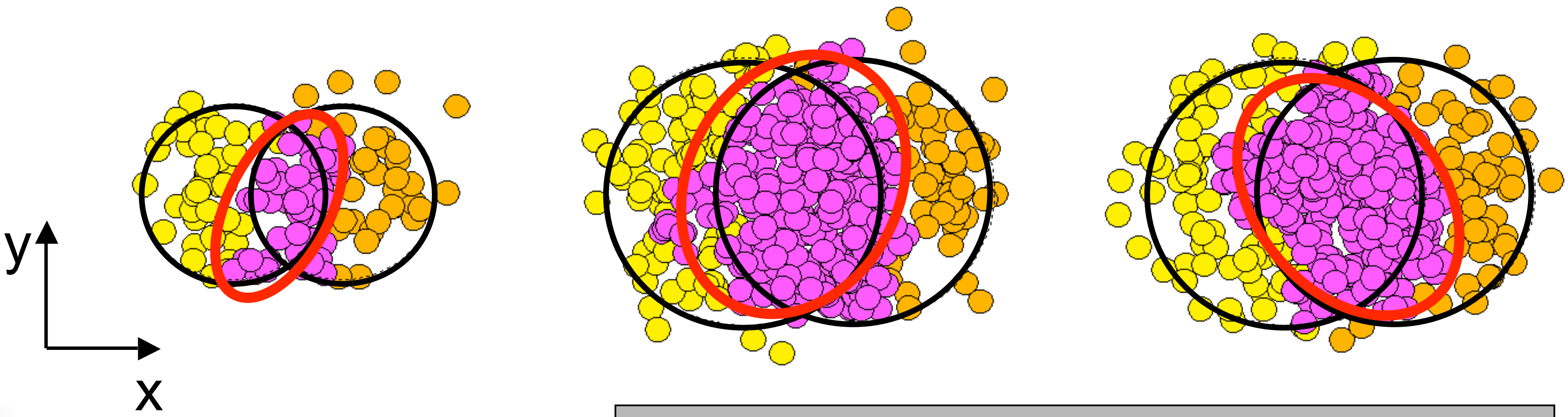


$$\varepsilon_{\mathrm{RP}} = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Underlying assumption:
Event-by-event fluctuations in
Glauber model are not physical

"Participant" eccentricity

Eccentricity of the collision region
can be calculated from positions of nucleons



$$\varepsilon_{\mathbf{part}} = \frac{\sqrt{\left(\sigma_y^2 - \sigma_x^2\right)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$

Participant eccentricity is
calculated with no reference
to the impact parameter vector

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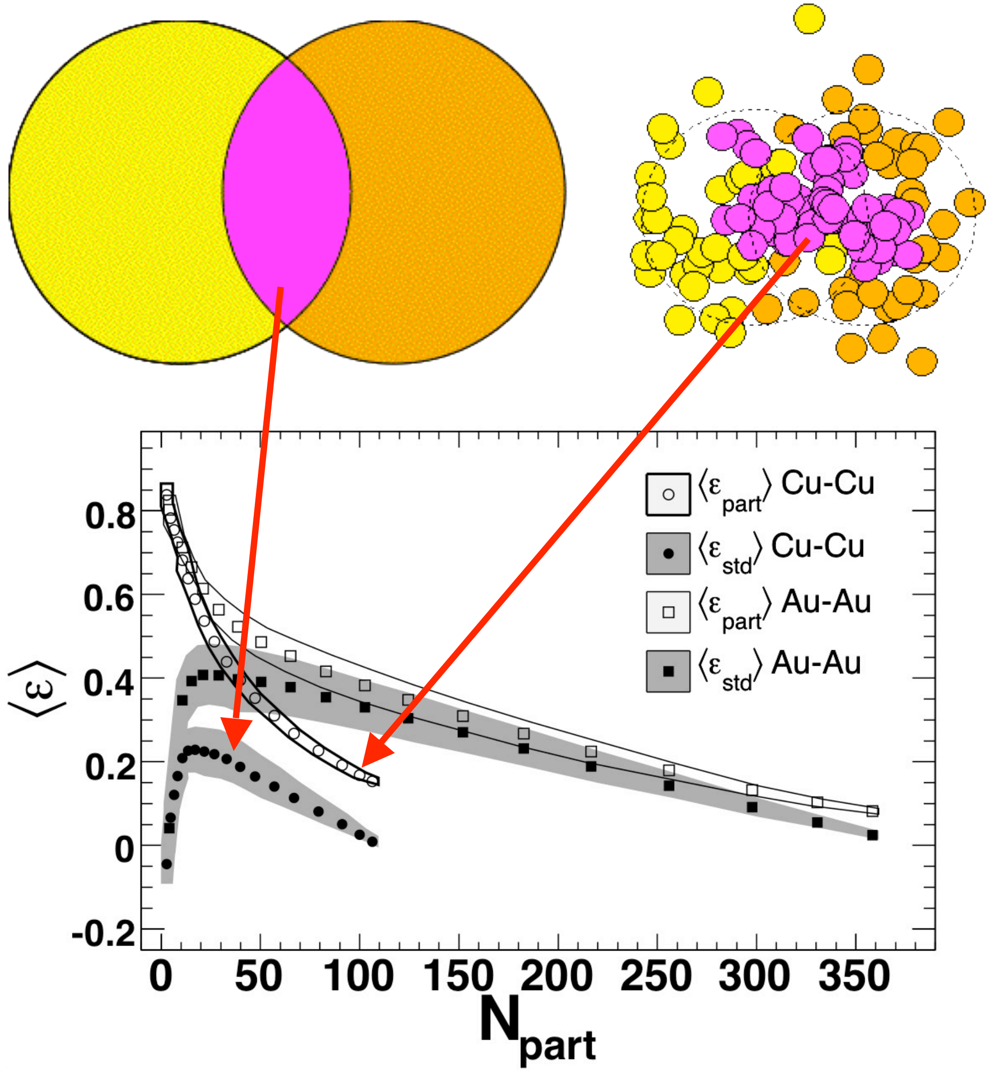
Two different pictures



Participant eccentricity is finite even for most central collisions.

A greater impact on the smaller Cu+Cu system

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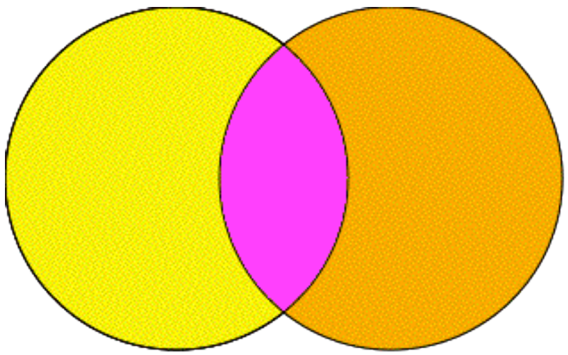
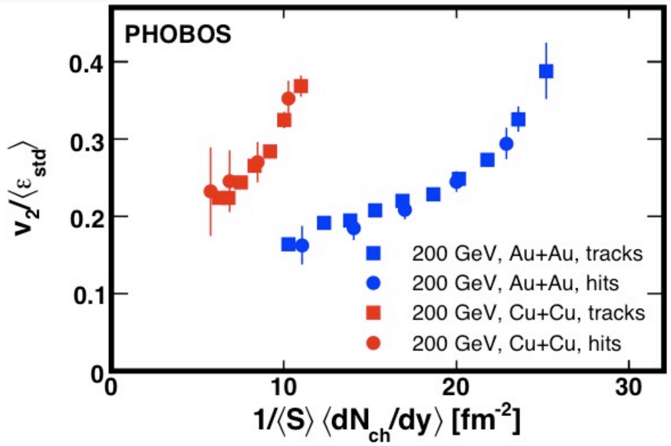
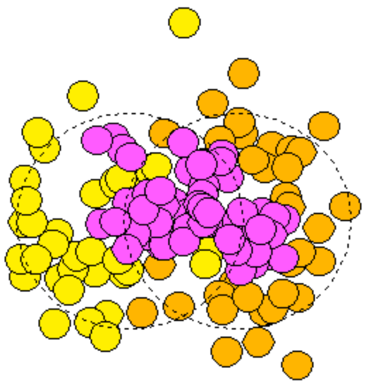
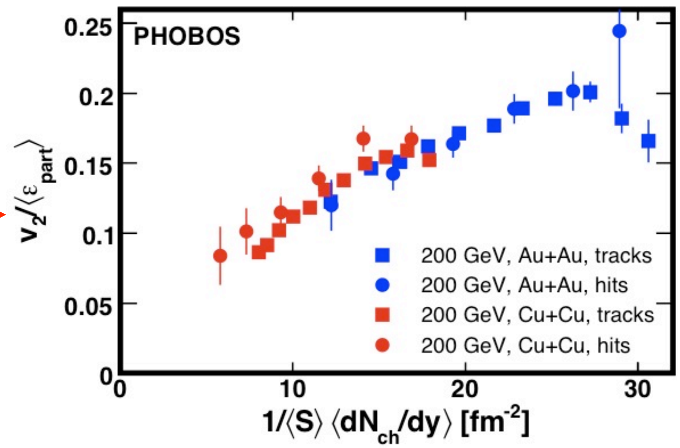
Two different pictures





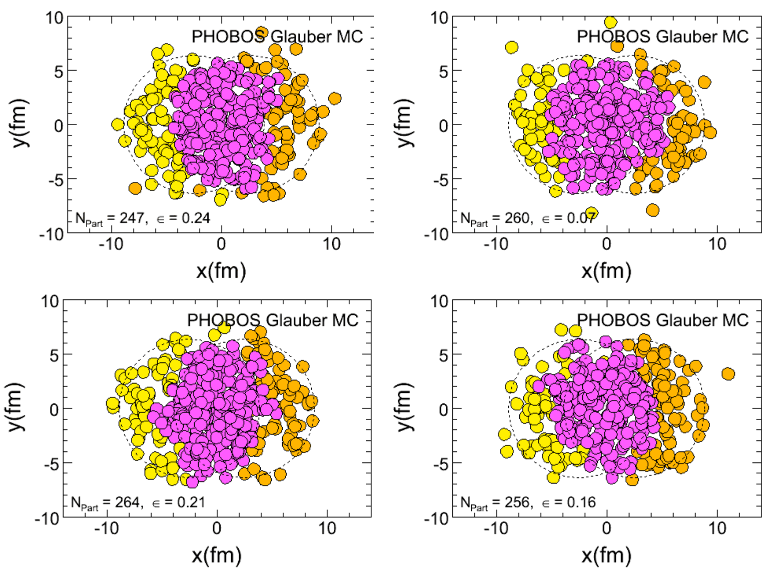


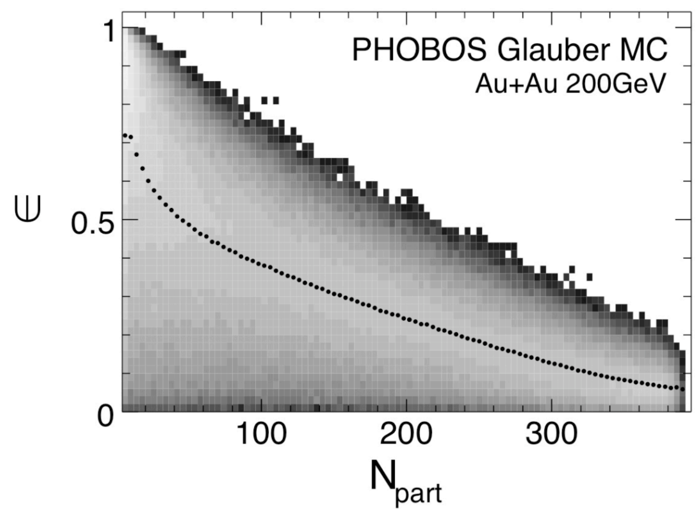


Participant eccentricity reconciles
elliptic flow for Cu+Cu and Au+Au collisions

Elliptic flow fluctuations

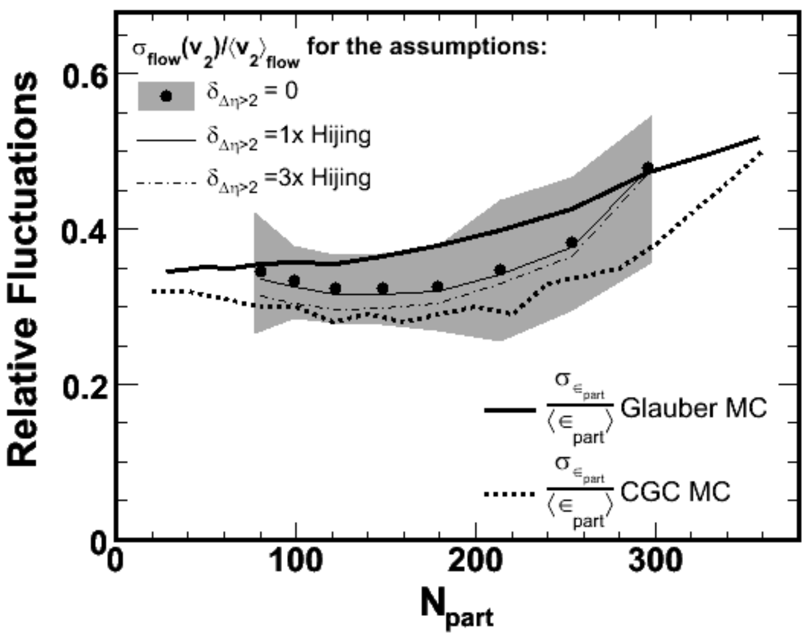
If initial geometry fluctuations are present
v_2 should fluctuate event-by-event
at fixed N_{part} or b





Elliptic flow fluctuations

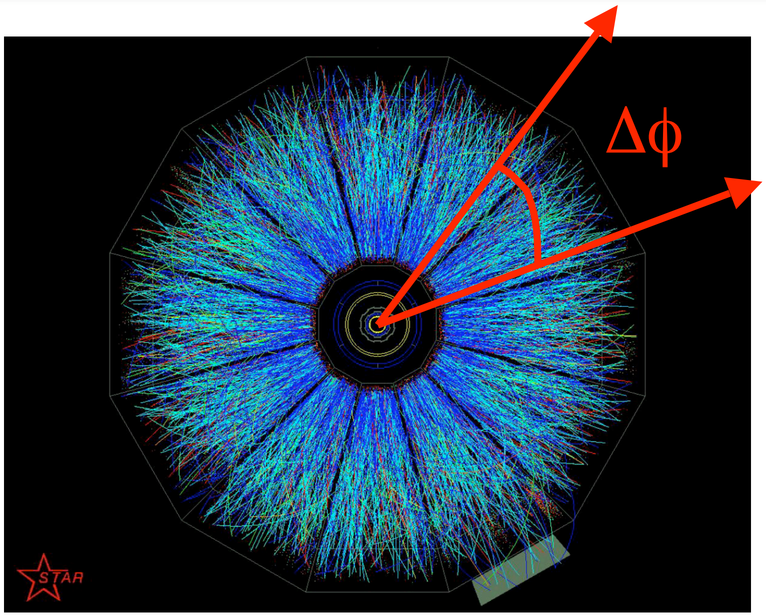
As predicted
v_2 fluctuates event-by-event
at fixed N_{part}

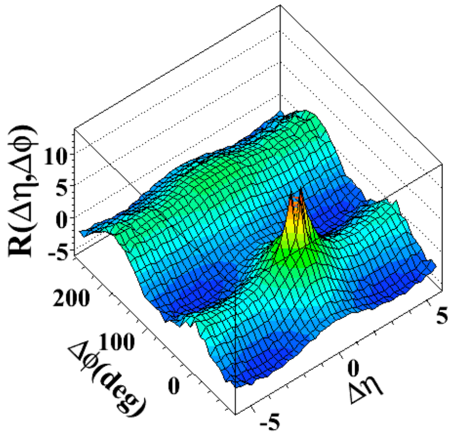


Statistical fluctuations and non-flow correlations are taken out in these results.

PHOBOS PRL arXiv:nucl-ex/0702036
PHOBOS PRC arXiv:1002.0534

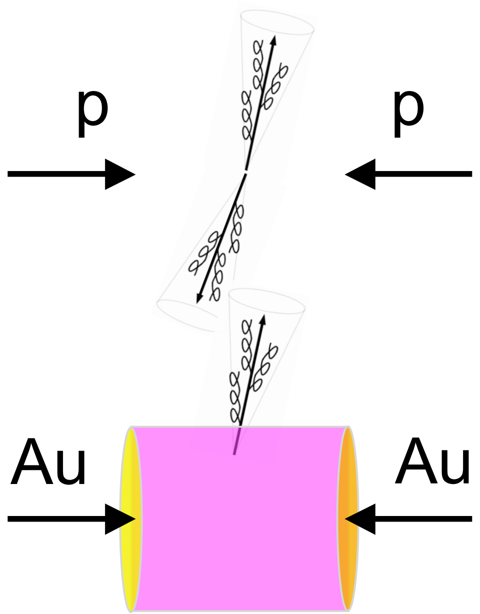
Two-particle correlations

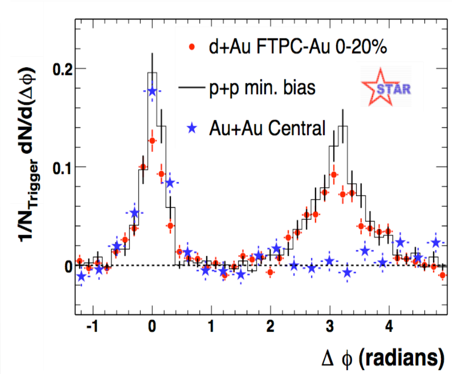


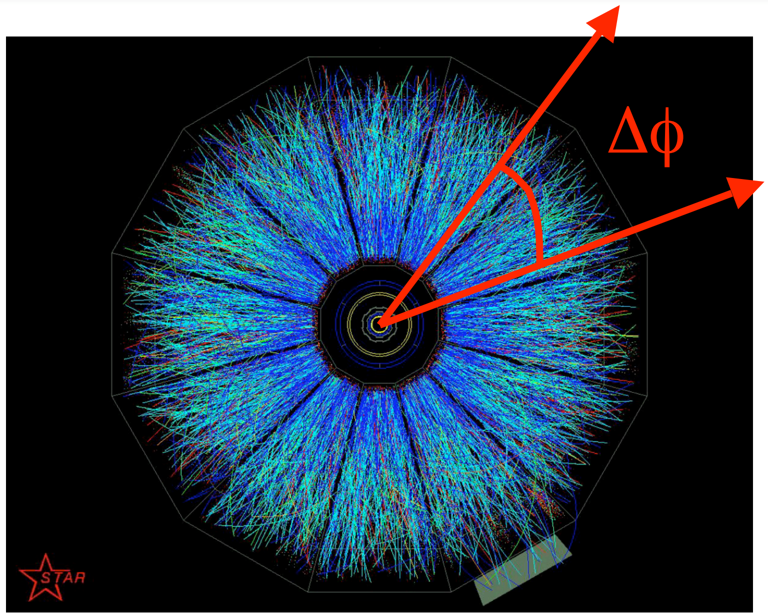


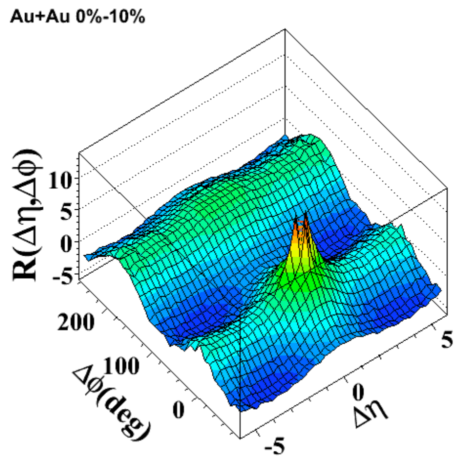
Two-particle correlations

Non-flow

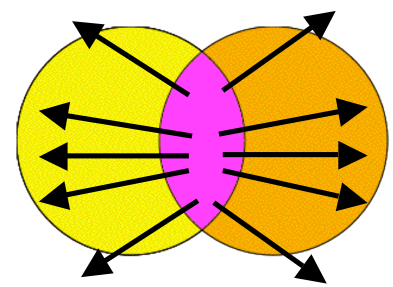


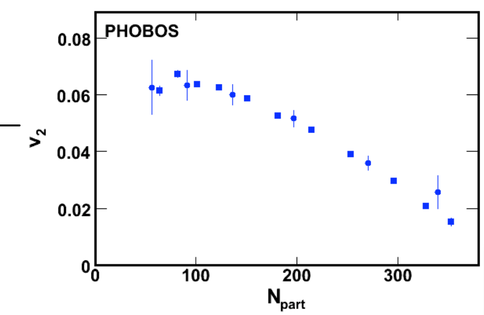




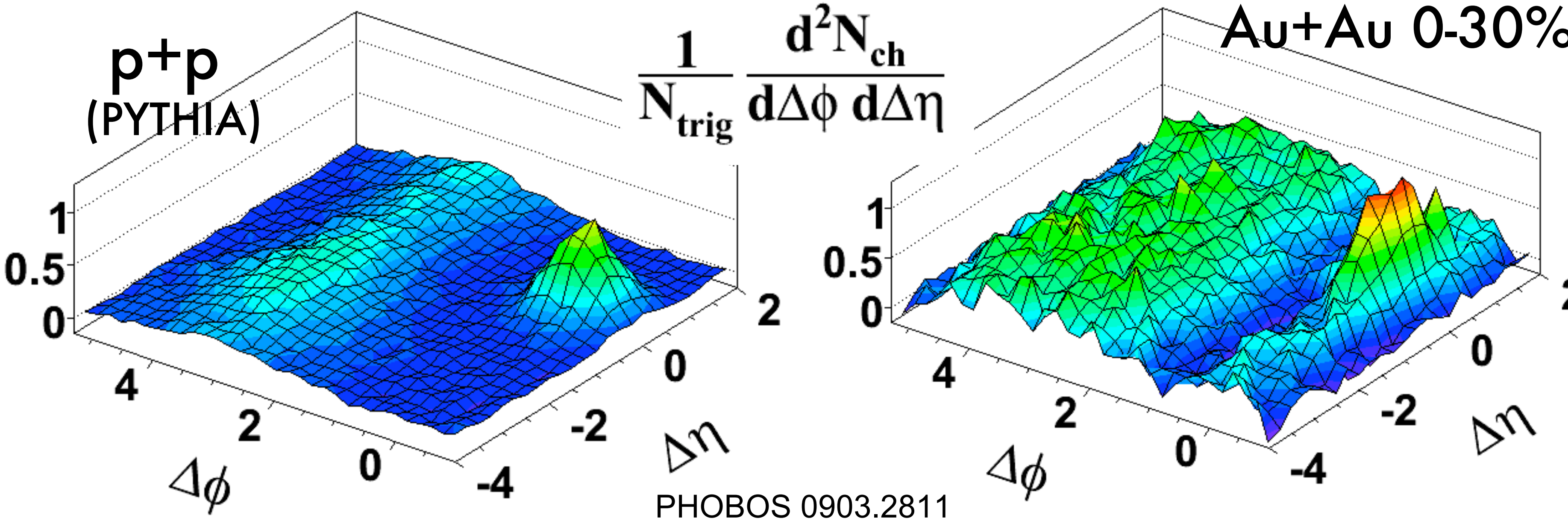


Flow



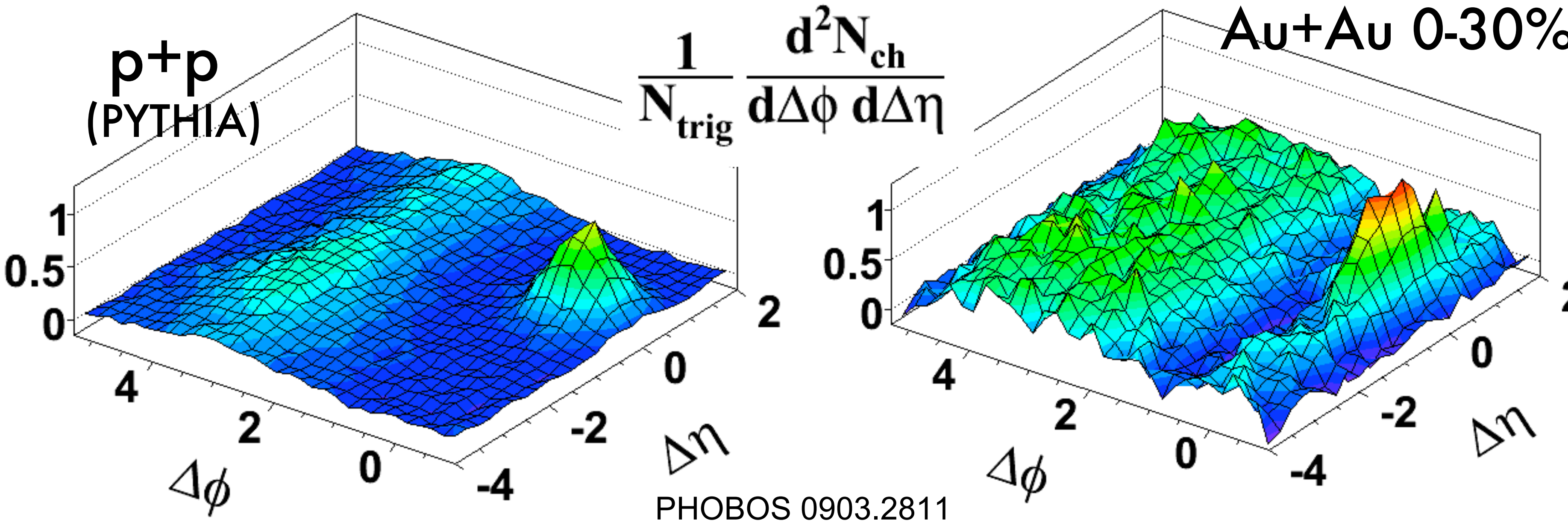


Ridge and Broad Away side



A large correlation structure at $\Delta\phi=0°$ and a broad away side at $\Delta\phi=180°$ is observed out to $\Delta\eta=4$

High p_T triggered correlations



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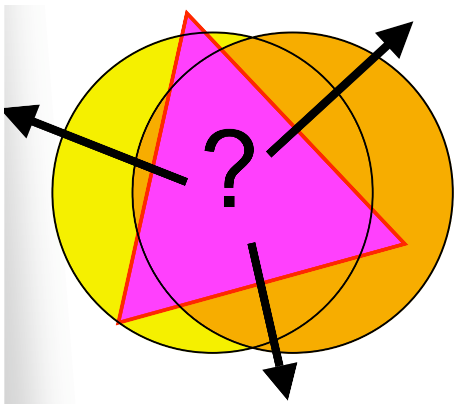


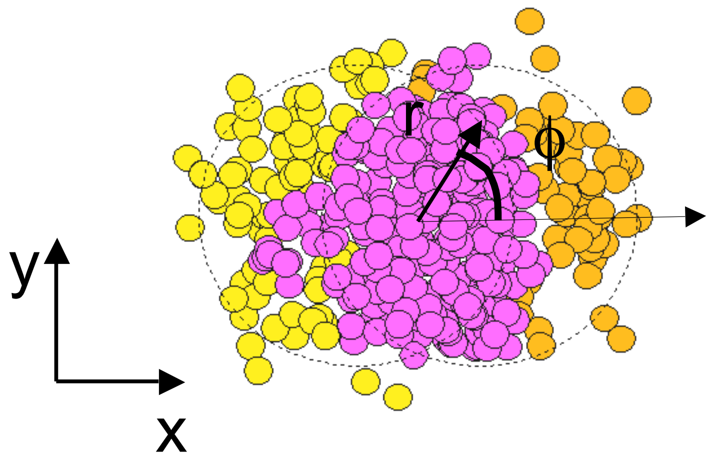
Collective Flow?

- Triangular anisotropy in initial geometry
- Description of data in terms of triangular flow
- Model description of triangular anisotropy

Participant triangularity

Triangular anisotropy in initial geometry can be quantified by "participant triangularity" analogous to participant eccentricity.

$$\varepsilon = \frac{\sqrt{\left(\sigma_y^2 - \sigma_x^2\right)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$



$$\varepsilon = \frac{\sqrt{\left\langle \left(r^2 \cos(2\phi)\right)\right\rangle^2 + \left\langle \left(r^2 \sin(2\phi)\right)\right\rangle^2}}{\left\langle r^2 \right\rangle}$$

$$\varepsilon_3 = \frac{\sqrt{\left\langle \left(r^2 \cos(3\phi)\right)\right\rangle^2 + \left\langle \left(r^2 \sin(3\phi)\right)\right\rangle^2}}{\left\langle r^2 \right\rangle}$$

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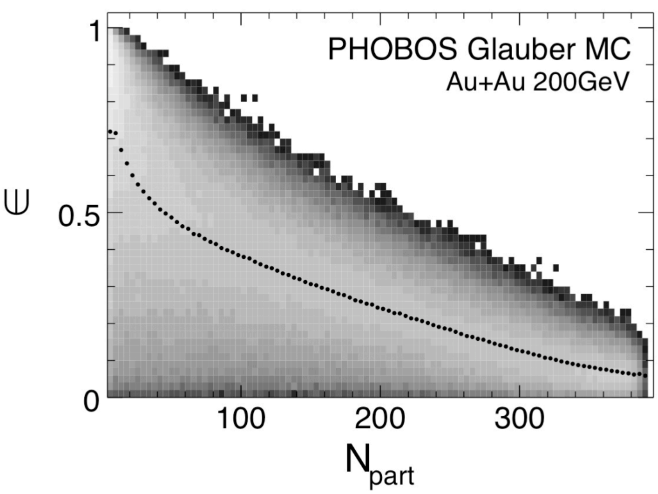
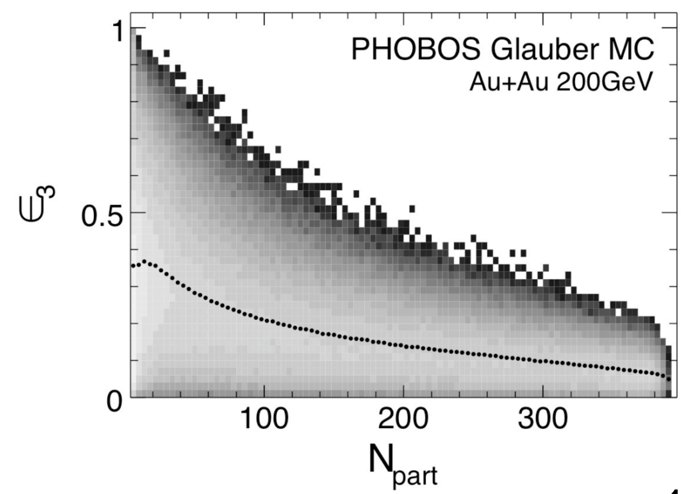
Participant triangularity

Triangular anisotropy in initial geometry can be quantified by "participant triangularity" analogous to participant eccentricity.

$$\varepsilon = \frac{\sqrt{\left\langle \left(r^2 \cos(2\phi) \right) \right\rangle^2 + \left\langle \left(r^2 \sin(2\phi) \right) \right\rangle^2}}{\left\langle r^2 \right\rangle}$$

$$\varepsilon_3 = \frac{\sqrt{\left\langle \left(r^2 \cos(3\phi) \right) \right\rangle^2 + \left\langle \left(r^2 \sin(3\phi) \right) \right\rangle^2}}{\left\langle r^2 \right\rangle}$$





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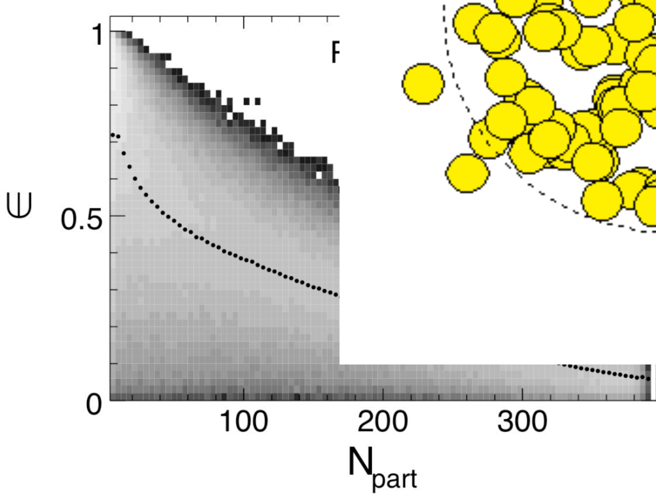
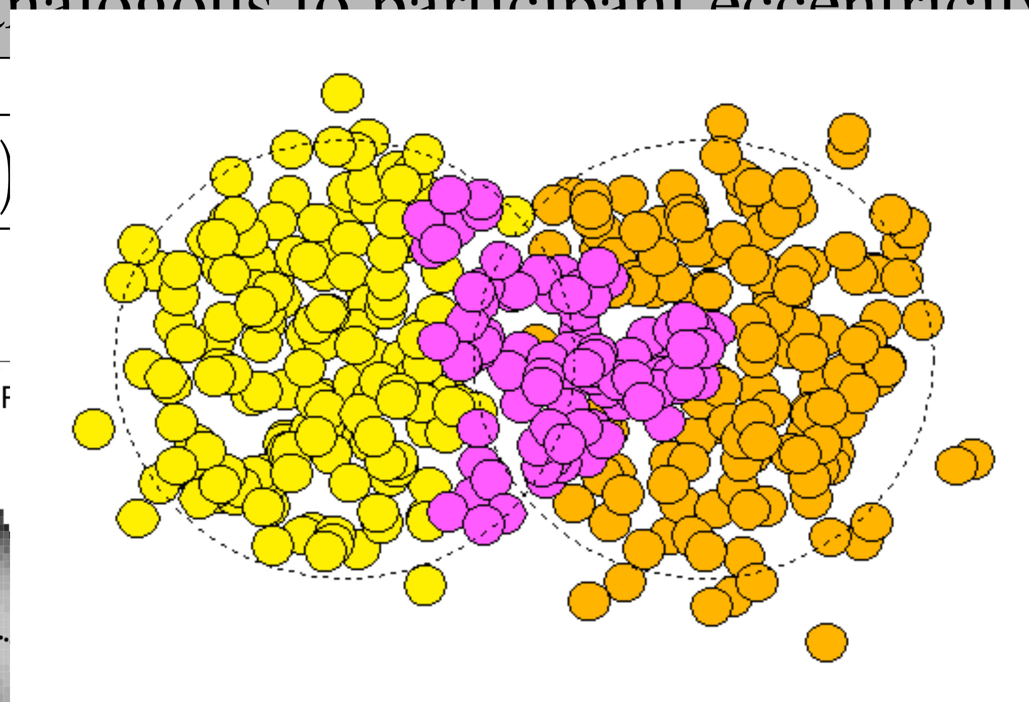
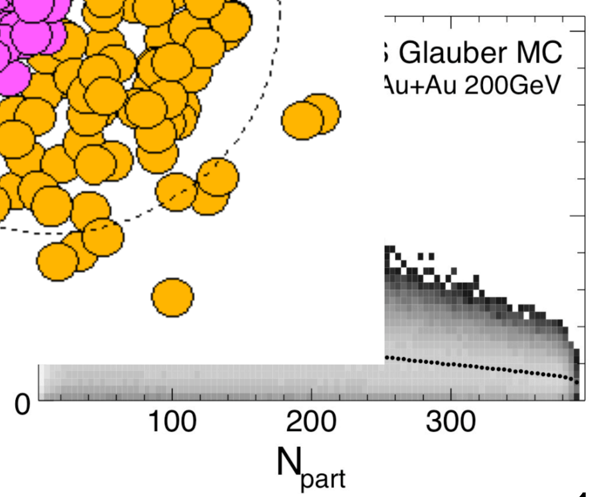
Participant triangularity

Triangular anisotropy in initial geometry
can be quantified by “participant triangularity”
analogous to participant eccentricity.

$$\varepsilon = \frac{\sqrt{\langle (r^2\cos(2\phi) \ldots}}{\ldots} \qquad \ldots \langle (r^2 \sin(3\phi)) \rangle^2$$







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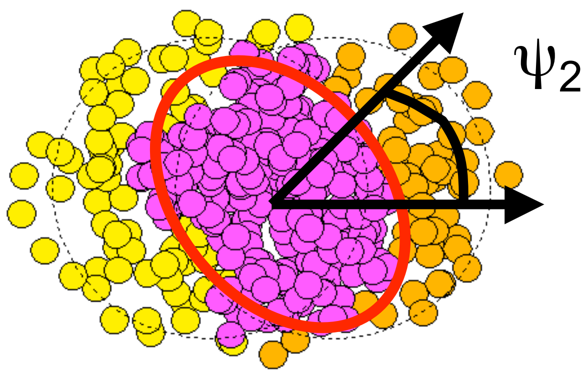
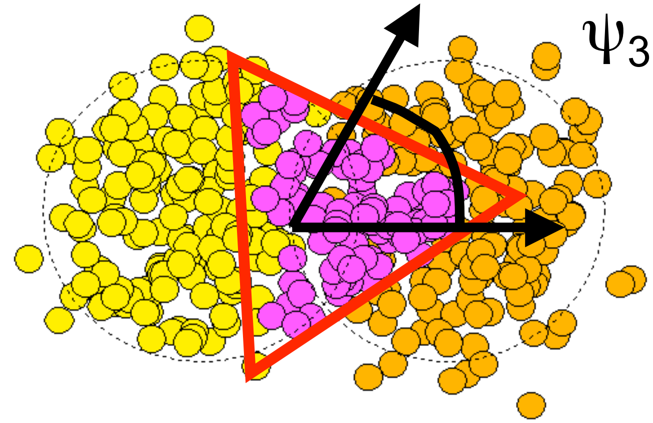
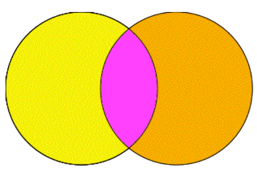
Triangular flow



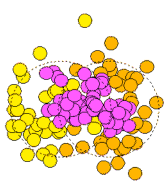




→ $$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_R)\right)\right)$$

$$v_2 = \left\langle \cos\left(2(\phi - \psi_R)\right)\right\rangle$$

$$v_3 = 0$$



→ $$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_n)\right)\right)$$

$$v_2 = \left\langle \cos\left(2(\phi - \psi_2)\right)\right\rangle$$

$$v_3 = \left\langle \cos\left(3(\phi - \psi_3)\right)\right\rangle$$

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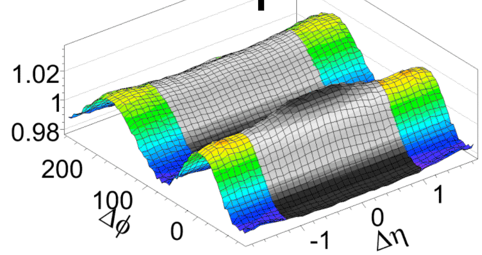
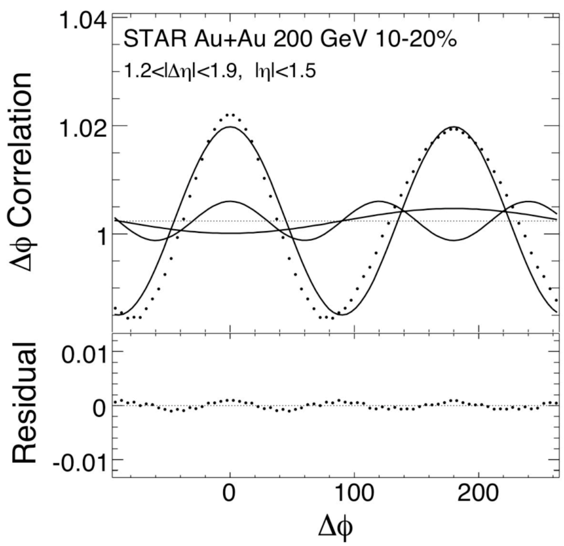
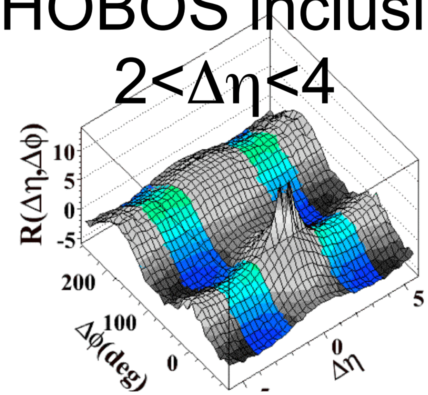
Correlations at large Δη

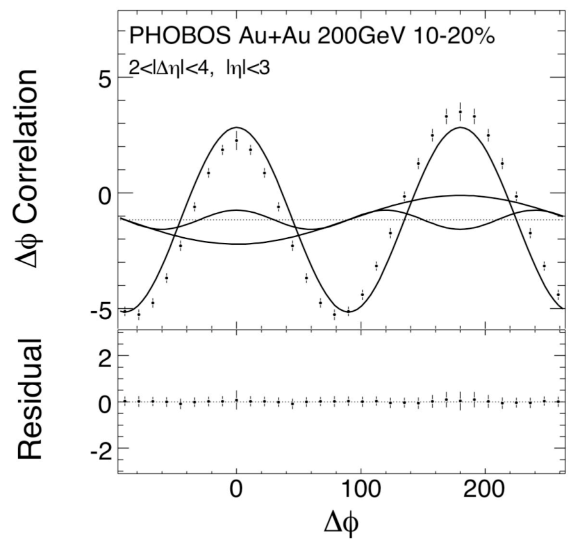
STAR inclusive
$1.2<\Delta\eta<1.9$



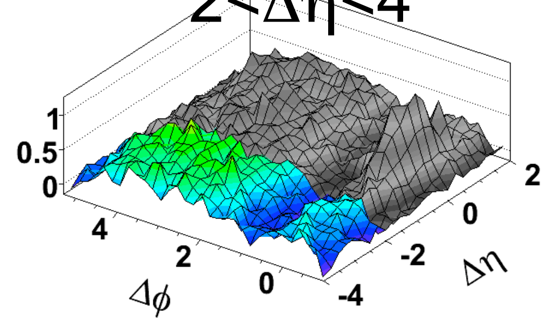


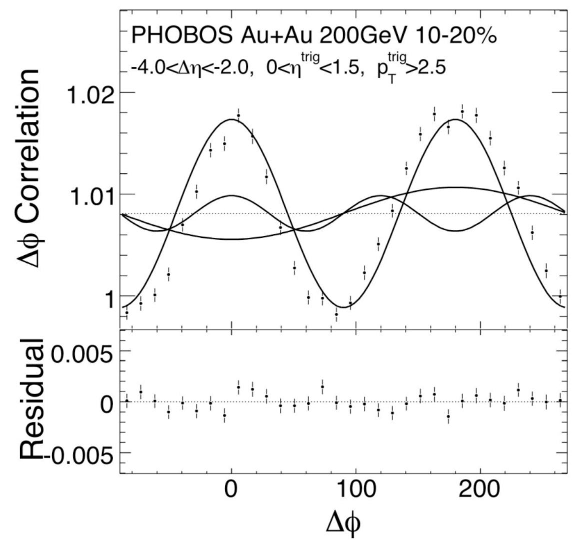
PHOBOS inclusive
$2<\Delta\eta<4$





PHOBOS $p_T^{trig}>2GeV$
$2<\Delta\eta<4$





Long range correlations are well described by 3 Fourier Components

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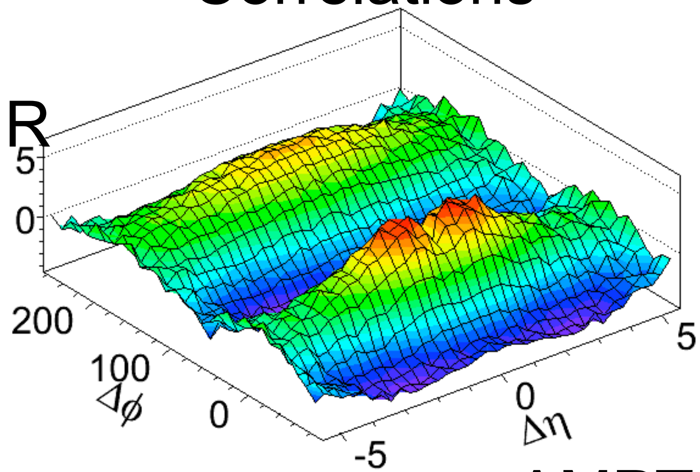
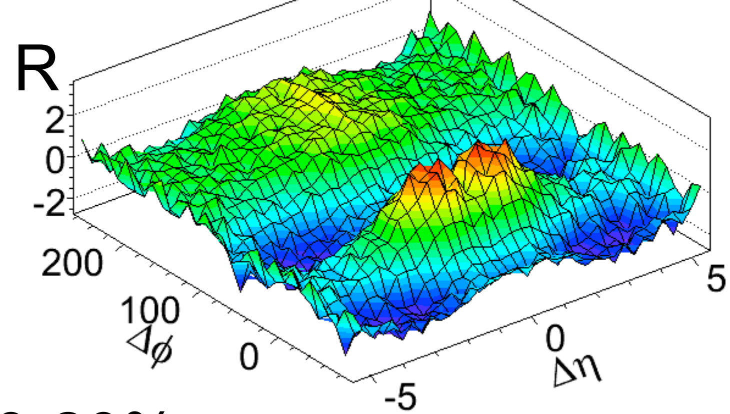
AMPT Model

AMPT model: Glauber initial conditions, collective flow

Correlations



Elliptic flow subtracted correlations

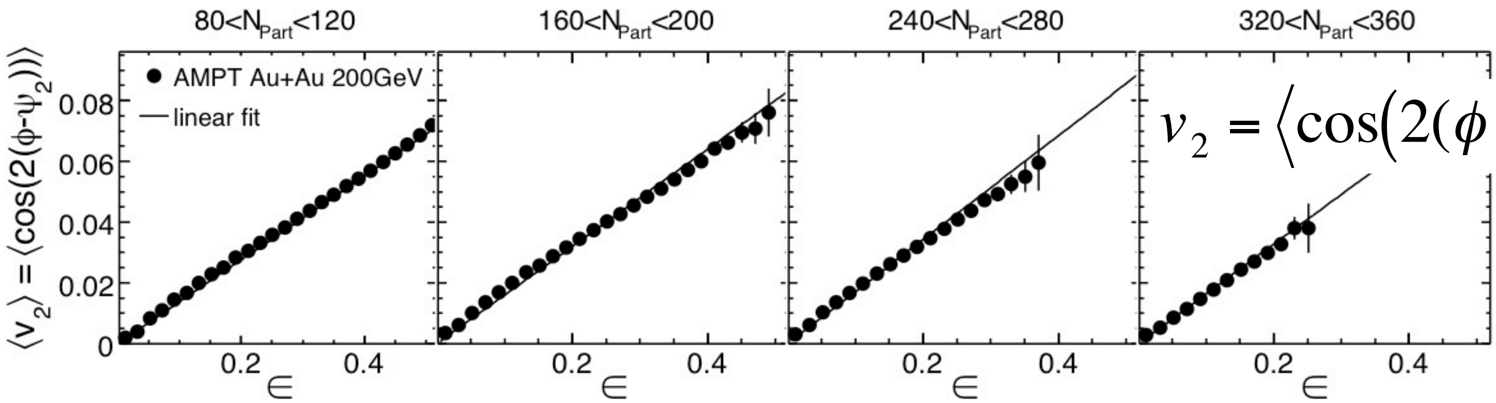


AMPT Au+Au 0-20%

AMPT model also produces similar correlation structures that extend out to long range in Δη.

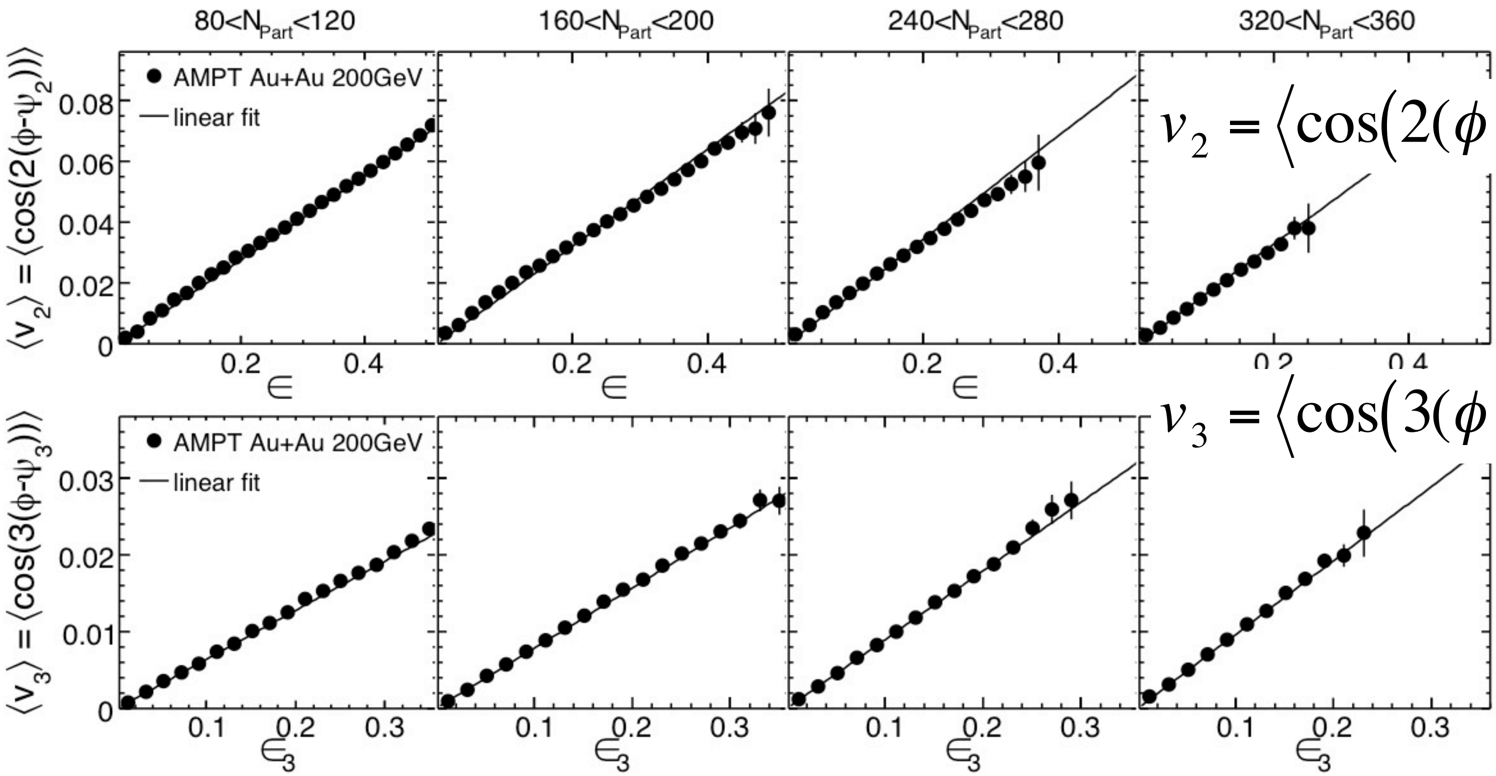
Lin et. al. nucl-th/0411110

Elliptic flow in AMPT



$$v_2 = \left\langle \cos\left(2(\phi - \psi_2)\right) \right\rangle \propto \varepsilon$$

Triangular flow in AMPT



$$v_2 = \left\langle \cos\left(2(\phi - \psi_2)\right)\right\rangle \propto \varepsilon$$

$$v_3 = \left\langle \cos\left(3(\phi - \psi_3)\right)\right\rangle \propto \varepsilon_3$$

Triangularity leads to triangular flow in AMPT

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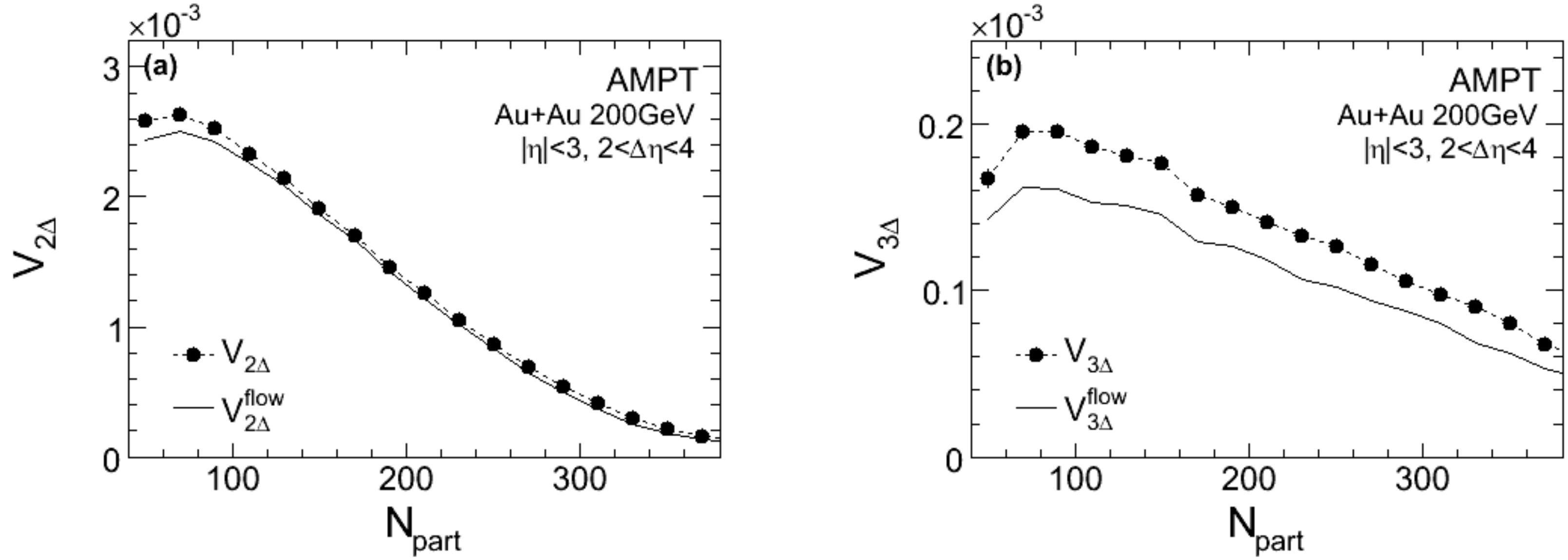
Flow and correlations in AMPT

$$\frac{dN}{d\Delta\phi} = \frac{N}{2\pi}\left(1 + \sum 2\mathbf{V}_{n\Delta}\cos\left(n\Delta\phi\right)\right) \qquad \mathbf{V}_{\mathbf{n\Delta}}^{\mathbf{flow}} \sim \int v_n(\eta) \times v_n(\eta + \Delta\eta)\,d\eta$$



$$\mathbf{V}_{\mathbf{3\Delta}} = \left\langle\cos\left(3(\phi_1 - \phi_2)\right)\right\rangle$$

$$\mathbf{V}_{\mathbf{3\Delta}}^{\mathbf{flow}} = \left\langle\cos\left(3(\phi_1 - \psi_3)\right)\right\rangle\left\langle\cos\left(3(\phi_2 - \psi_3)\right)\right\rangle$$

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Triangular flow in data

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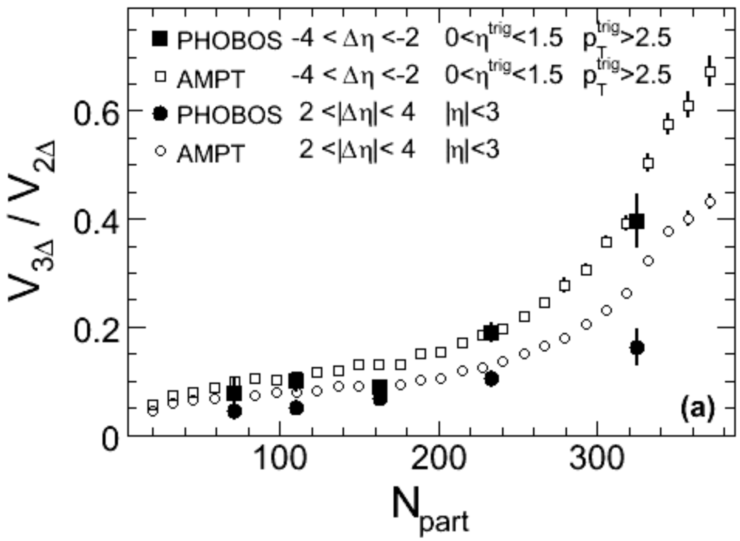

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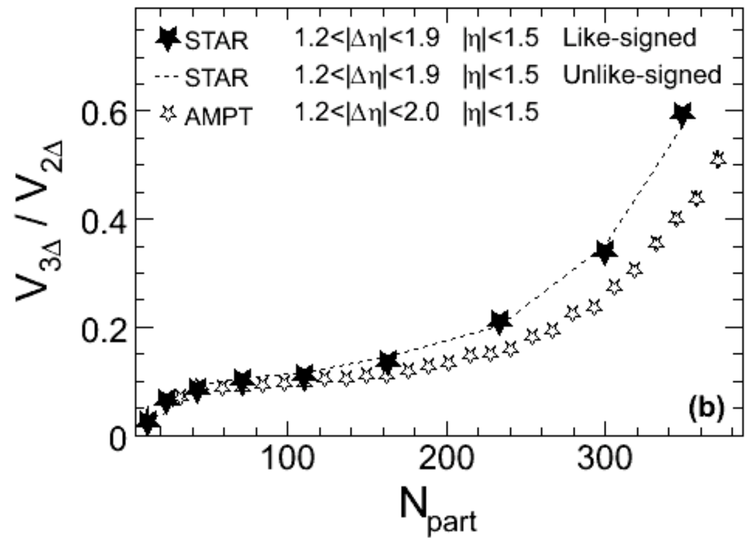

The ratio of triangular flow to elliptic flow qualitatively agree between data and AMPT

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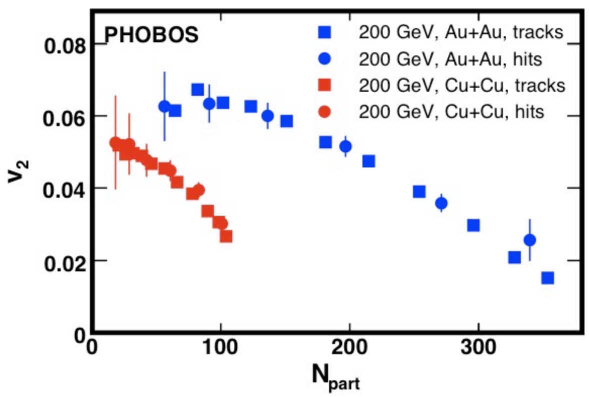
Initial geometry fluctuations

A consistent picture



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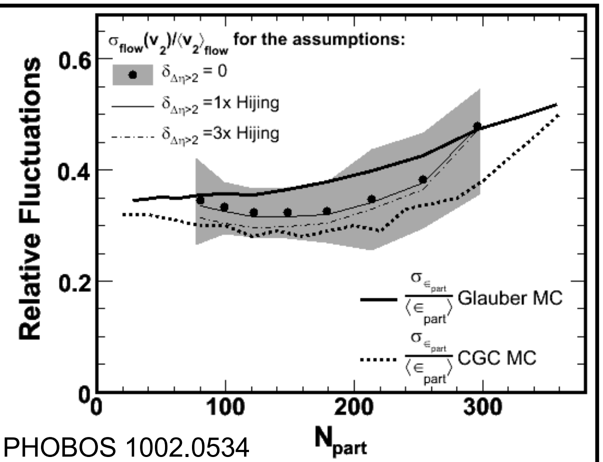

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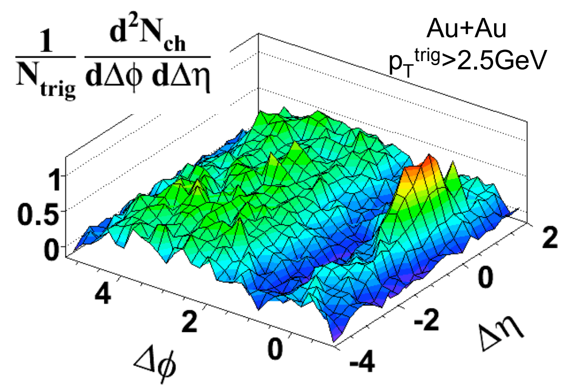

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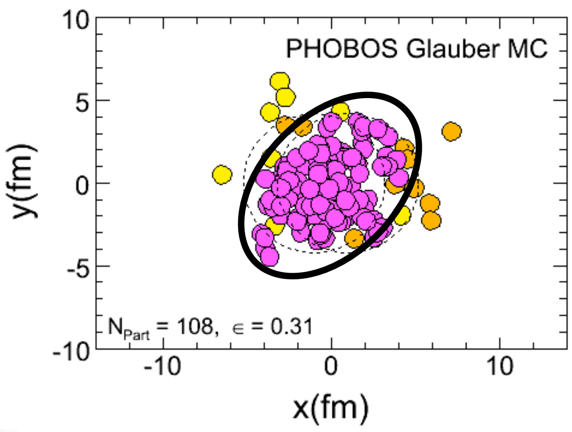

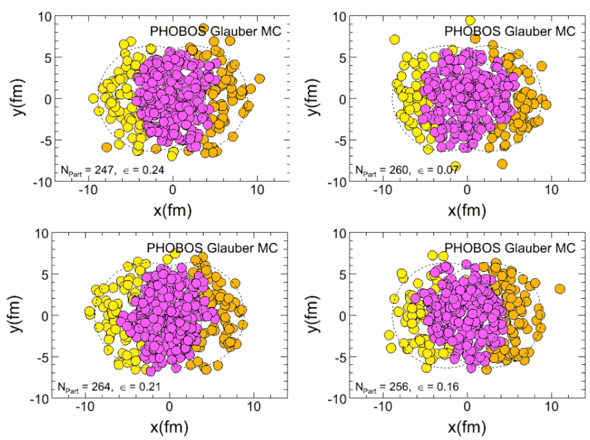

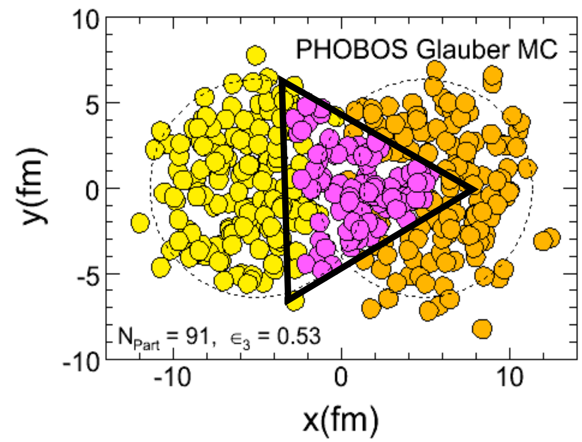

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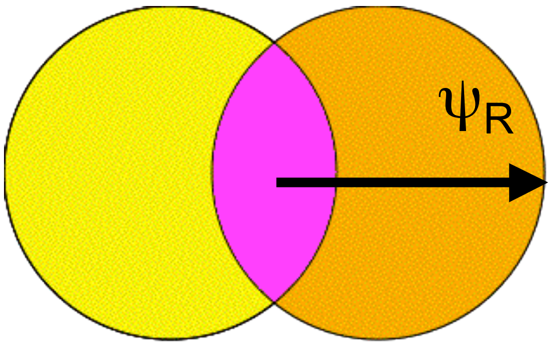
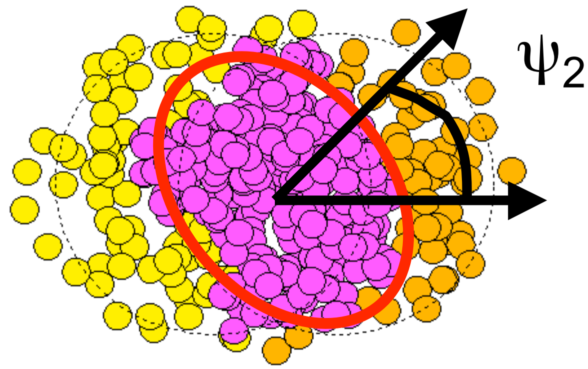
Backups

Two different pictures





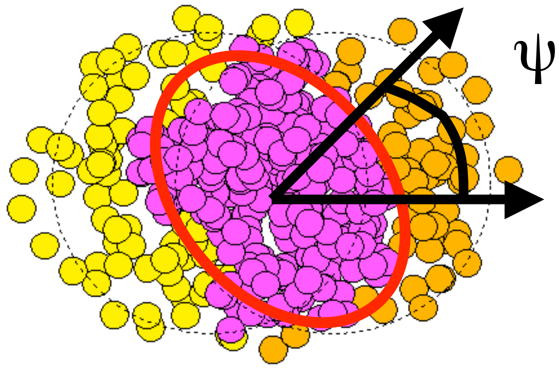
$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_R)\right)\right)$$

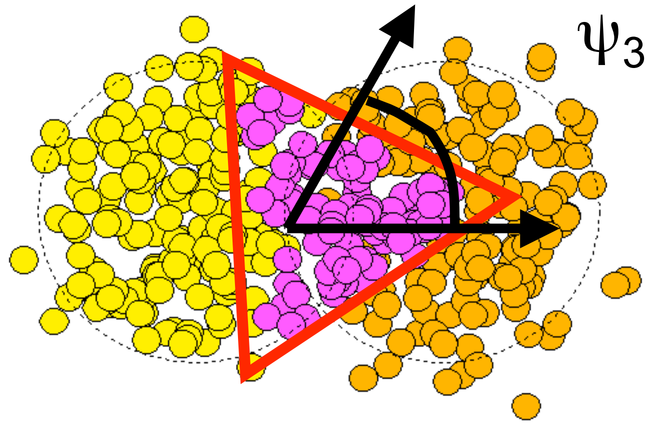
$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_n)\right)\right)$$

$$v_2 = \left\langle \cos\left(2(\phi - \psi_R)\right)\right\rangle$$

$$v_2 = \left\langle \cos\left(2(\phi - \psi_2)\right)\right\rangle$$

Triangular flow





$$\psi_2 = \frac{\mathrm{atan2}\left(\left\langle r^2 \sin\left(2\phi_{\mathrm{part}}\right)\right\rangle, \left\langle r^2 \cos\left(2\phi_{\mathrm{part}}\right)\right\rangle\right) + \pi}{2}$$

$$\psi_3 = \frac{\mathrm{atan2}\left(\left\langle r^2 \sin\left(3\phi_{\mathrm{part}}\right)\right\rangle, \left\langle r^2 \cos\left(3\phi_{\mathrm{part}}\right)\right\rangle\right) + \pi}{3}$$

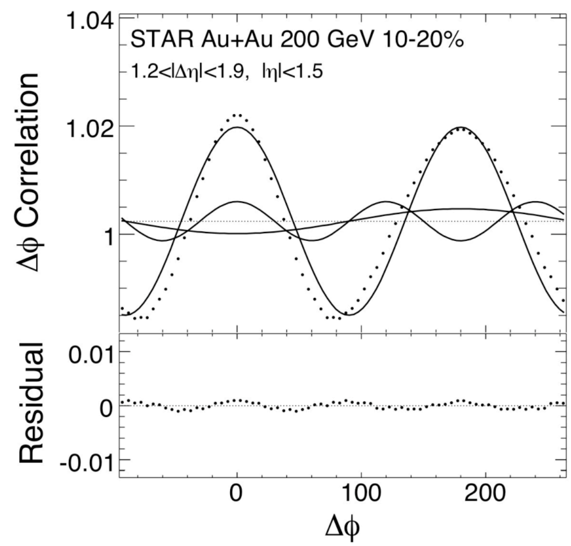
1003.0194

Phases

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_n)\right)\right)$$

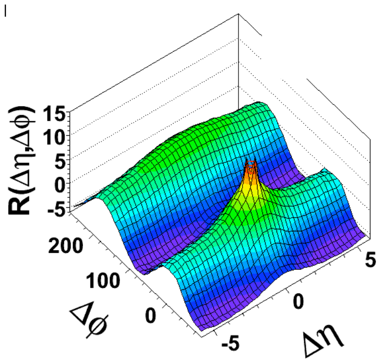
$$= \frac{N}{2\pi}\left(1 + \ldots + 2v_2 \cos\left(2(\phi - \psi_2)\right) + 2v_3 \cos\left(3(\phi - \psi_3)\right) + \ldots\right)$$

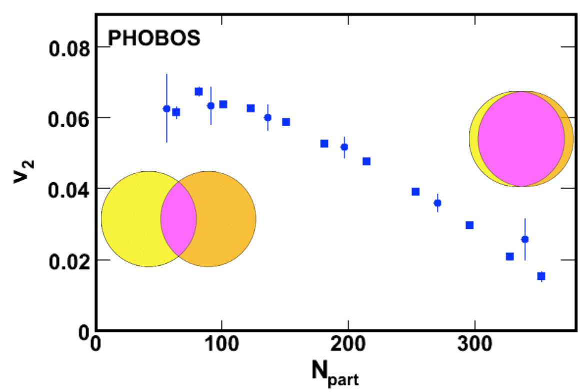
$$\frac{\mathrm{d}N^{\mathrm{pairs}}}{\mathrm{d}\Delta\phi} = \frac{N^{\mathrm{pairs}}}{2\pi}\left(1 + \ldots + 2v_2^2 \cos\left(2\Delta\phi\right) + 2v_3^2 \cos\left(3\Delta\phi\right) + \ldots\right)$$

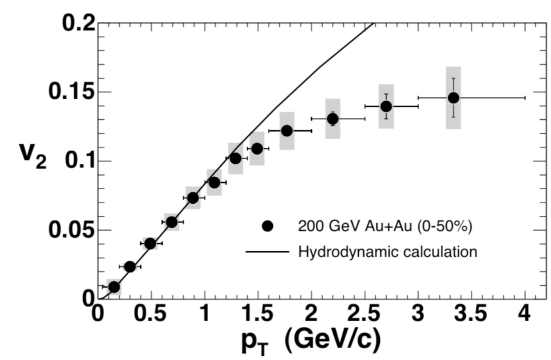


Second Fourier coefficient

- Why do we believe it is collective flow?
  - Large!
  - Present at large $\Delta\eta$: early times
  - Connection to initial geometry
    - i.e. centrality dependence
  - p_T dependence
  - Also $v_2\{4\}$, v_2 fluctuations and $v_2^2(\eta_1,\eta_2)$

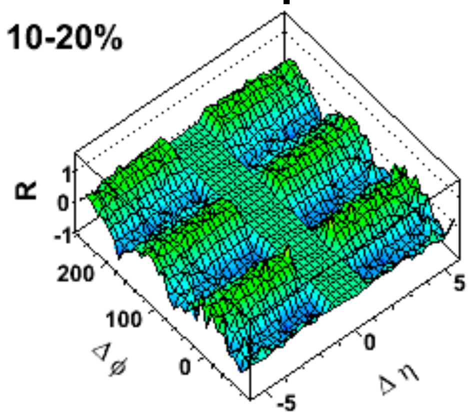


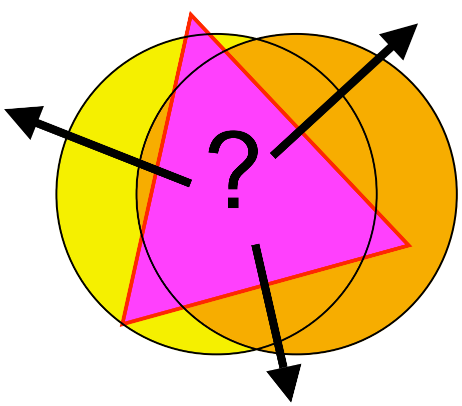




Third Fourier coefficient

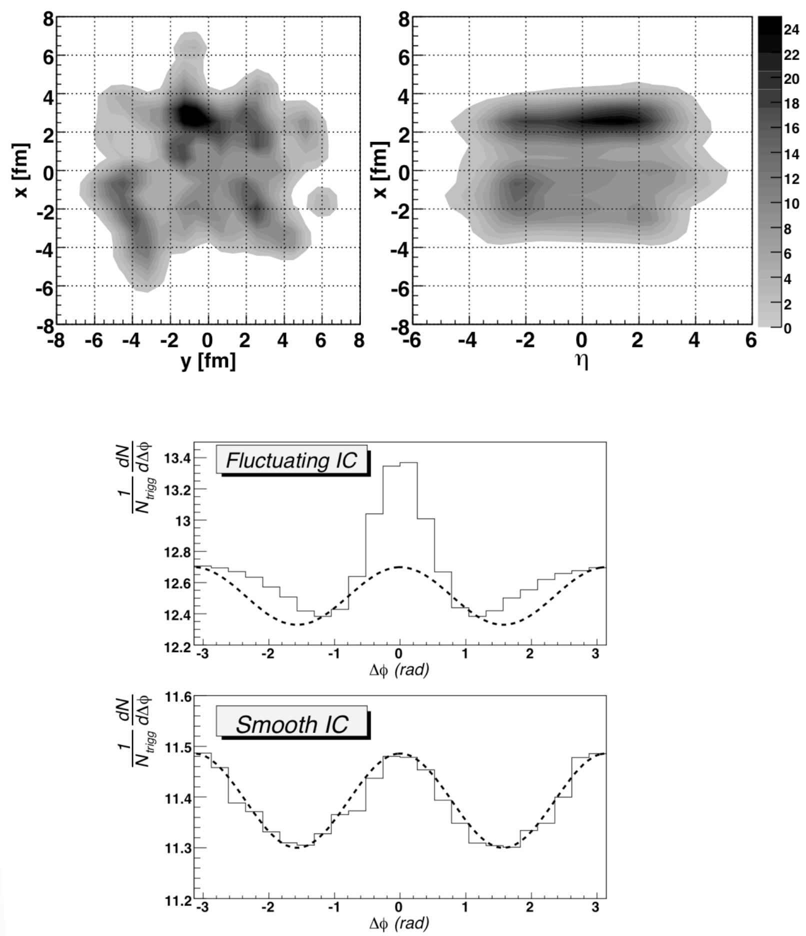
- Why should we believe it is collective flow?
  - Large!
  - Present at large $\Delta\eta$: early times
  - Connection to initial geometry
    - i.e. centrality dependence
  - p_T dependence
  - Also three particle correlations





Initial geometry fluctuations

J. Takahashi et al.



P. Sorensen