Glauber Monte-Carlo predictions for LHC *

Maciej Rybczyński

Institite of Physics, Świętokrzyska Academy,
Kielce, Poland

based on W. Broniowski, P. Bożek and M. Rybczyński, PRC 76 054905 (2007)

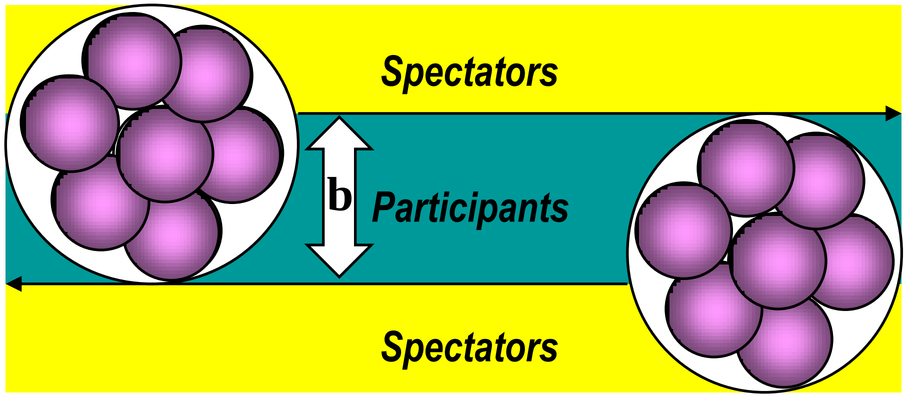
OUTLINE

1. What is Glauber Monte-Carlo?

2. Perfect tool: GLISSANDO –
   GLauber Initial State Simulation AND mOre

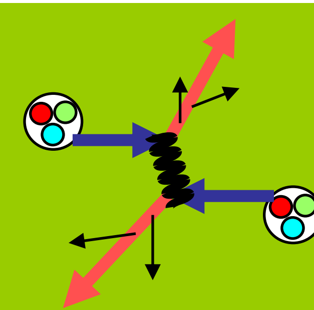
3. Physical phenomena and quantities used for simulation:
   a) Flow, eccentricity, event-by-event
      fluctuations of flow,
   b) Multiplicity fluctuations.

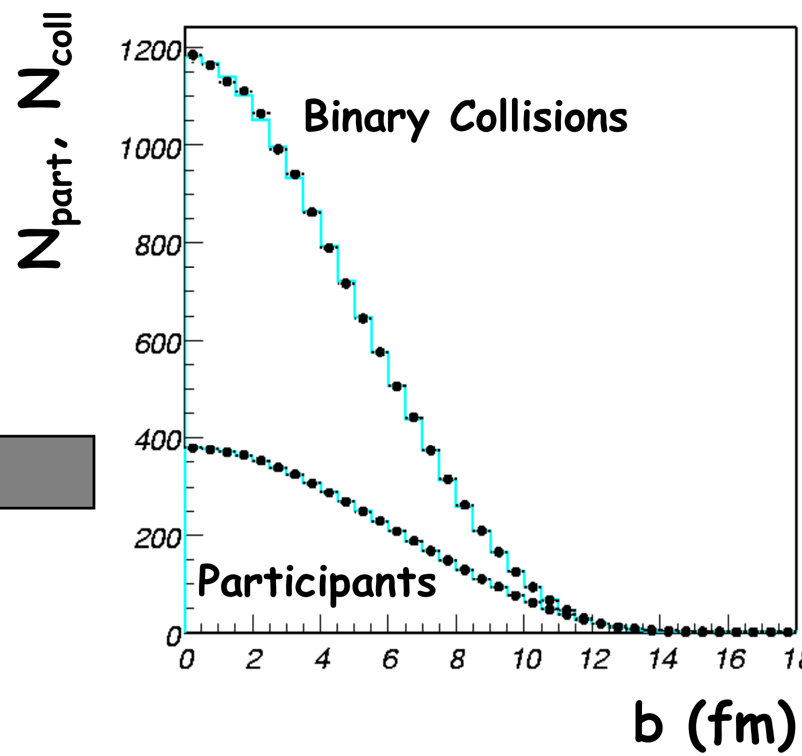
WHY GEOMETRY MATTERS?



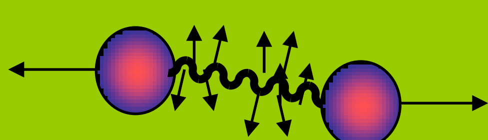
"Glauber" model of AA

Binary Collisions:
1. Jet Production
2. Heavy Flavor





Color Exchange:
1. Soft Hadron Production
2. Transverse Energy



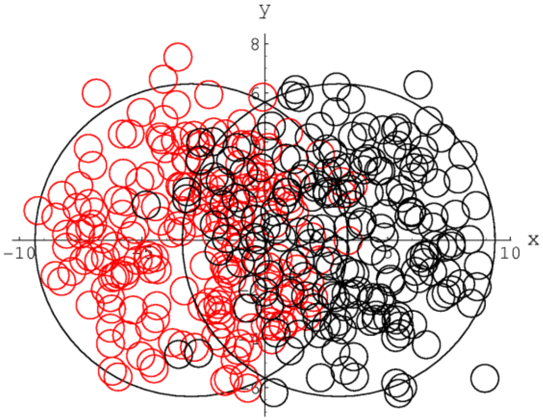
"wounded nucleon model"

GLAUBER CALCULATIONS

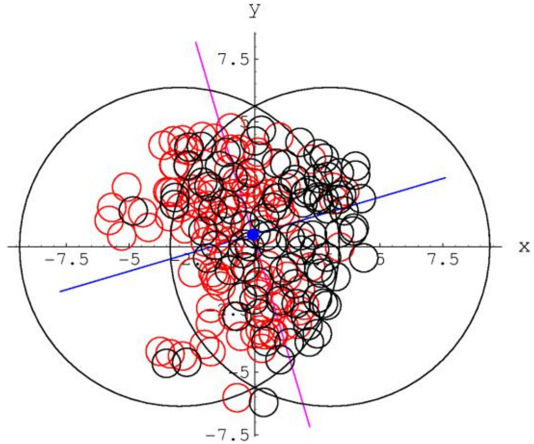
- Nucleons are distributed according to a density function (e.g. Woods-Saxon)
- Nucleons travel in straight lines and are not deflected as they pass through the other nucleus
- Nucleons interact according to the **inelastic cross section** σ_{NN} measured in pp collisions, even after interacting
  - Participants – counts nucleons which interact
  - Binary collisions – counts collisions

Roy Glauber

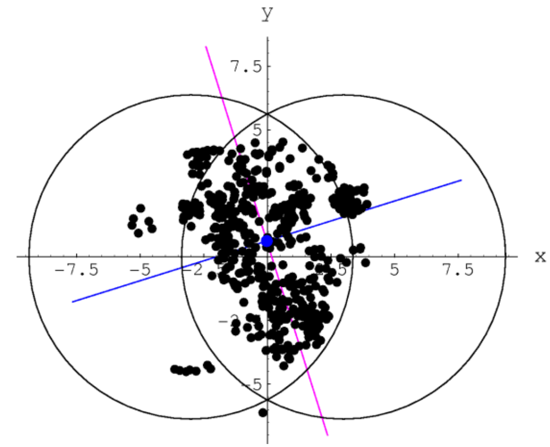
MONTE-CARLO SIMULATONS IN GLAUBER MODELS: A TYPICAL GOLD-GOLD EVENT



all nucleons



wounded nucleons



binary collisions

Sizeable fluctuations of the center of mass and the quadrupole axes

Aguiar+Kodama+Osada+Hama 2001, Miller+Snellings 2003,
Bhalerao+Blaizot+Borghini+Ollitrault 2005,
Andrade+Grassi+Hama+Kodama+Socolowski 2006, Voloshin 2006, ...

MONTE-CARLO SIMULATONS IN GLAUBER MODELS: GLAUBER-LIKE MODELS TESTED

- ✓ wounded nucleons, e.g.: $\sigma_w = 65\ \mathrm{mb}, d = 0.4\ \mathrm{fm}$
- ✓ mixed model, e.g.: 85.5% wounded + 14.5% binary, $\sigma_w = \sigma_{bin} = 65\ \mathrm{mb}$
- ✓ hot spots, e.g.: $\sigma_w = 65\ \mathrm{mb}, \sigma_{bin} = 0.5\ \mathrm{mb}$.
- ✓ hot spots + Γ.

One goal:

compare various Glauber-like models

PERFECT TOOL:

GLISSANDO

GLauber Initial State Simulation AND mOre

GENERAL FEATURES

GLISSANDO is a Glauber Monte-Carlo generator for early-stages of relativistic heavy-ion collisions, written in c++ and interfaced to Root.

The program can be used for simulation of large variety of colliding systems: p+A, d+A and A+A at wide spectrum of energies.

Several models are implemented: the wounded-nucleon model, the binary collisions model, the mixed model, and the model with hot-spots.

GENERAL FEATURES

The program generates inter alia the fixed axes (standard) and variable-axes (participant) two-dimensional profiles of the density of sources in the transverse plane and their Fourier components.

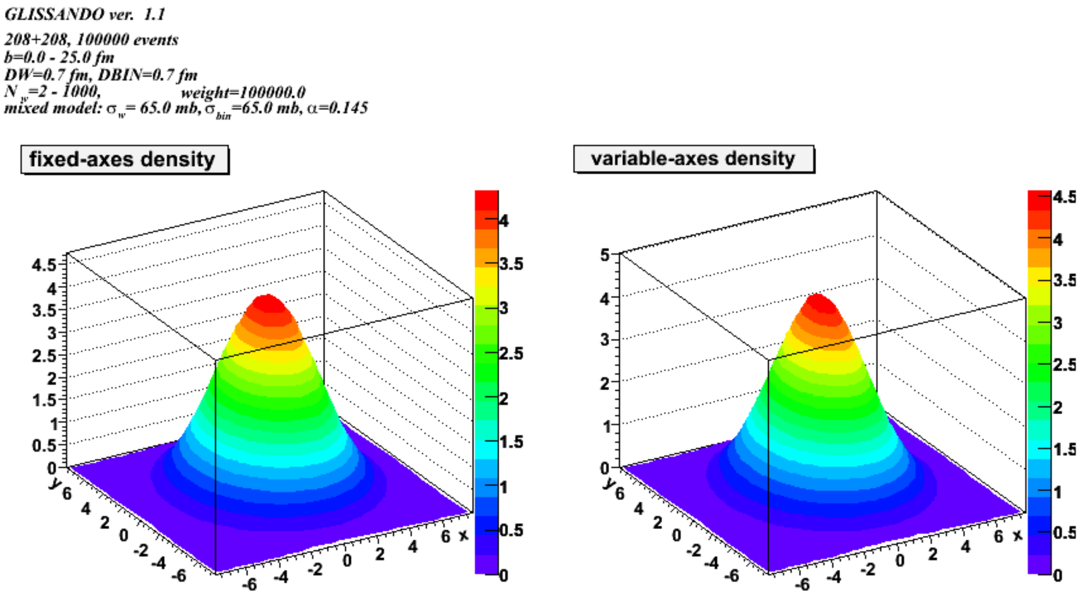
These profiles can be used in further analyses of physical phenomena, such as the jet quenching, event-by-event hydrodynamics, or analysis of the elliptic flow and its fluctuations.

GENERAL FEATURES

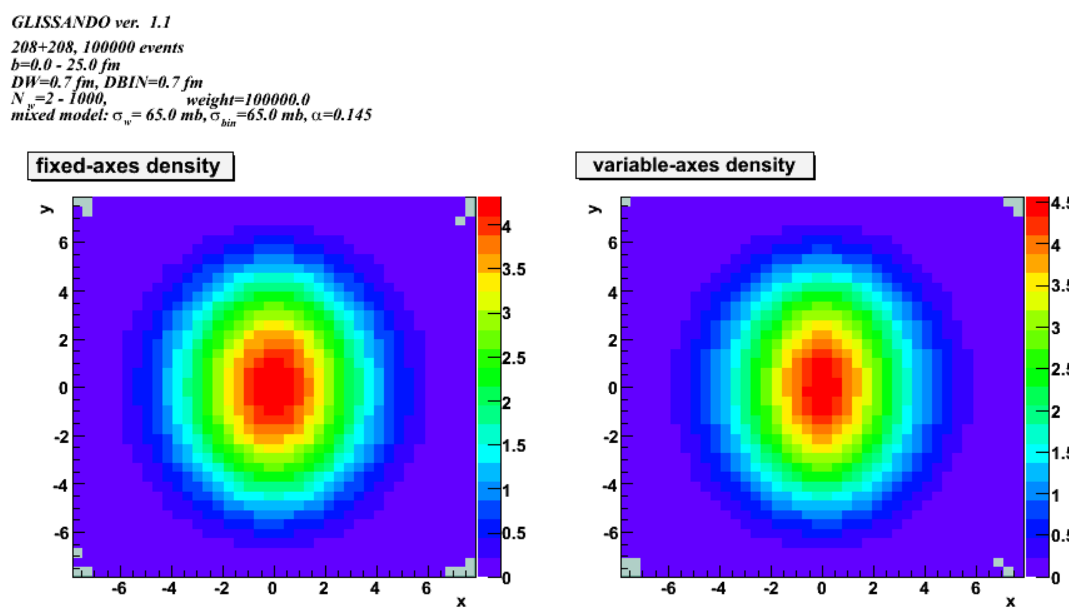
Characteristics of the event (multiplicities, eccentricities, Fourier coefficients, etc.) are evaluated and stored in a file for further off-line studies.

A number of scripts is provided for that purpose.

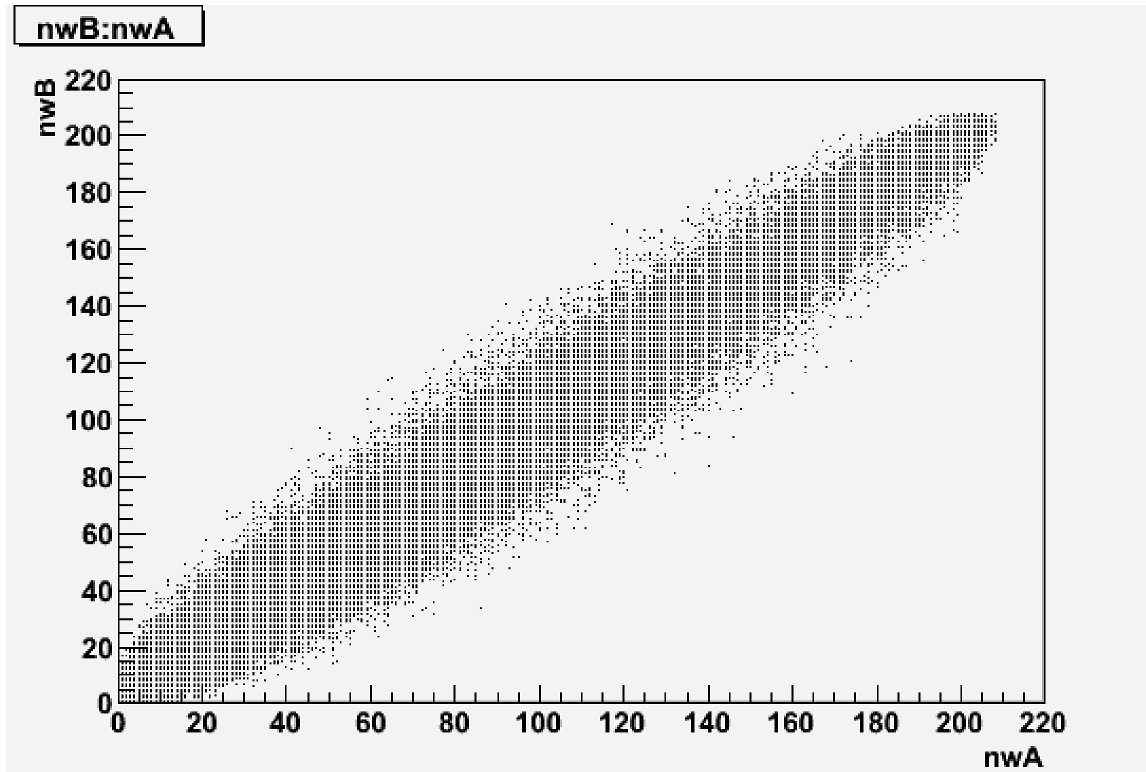
EXAMPLE ANALYSIS: Pb+Pb@5.5 TeV/n minbias



Three-dimensional density profiles

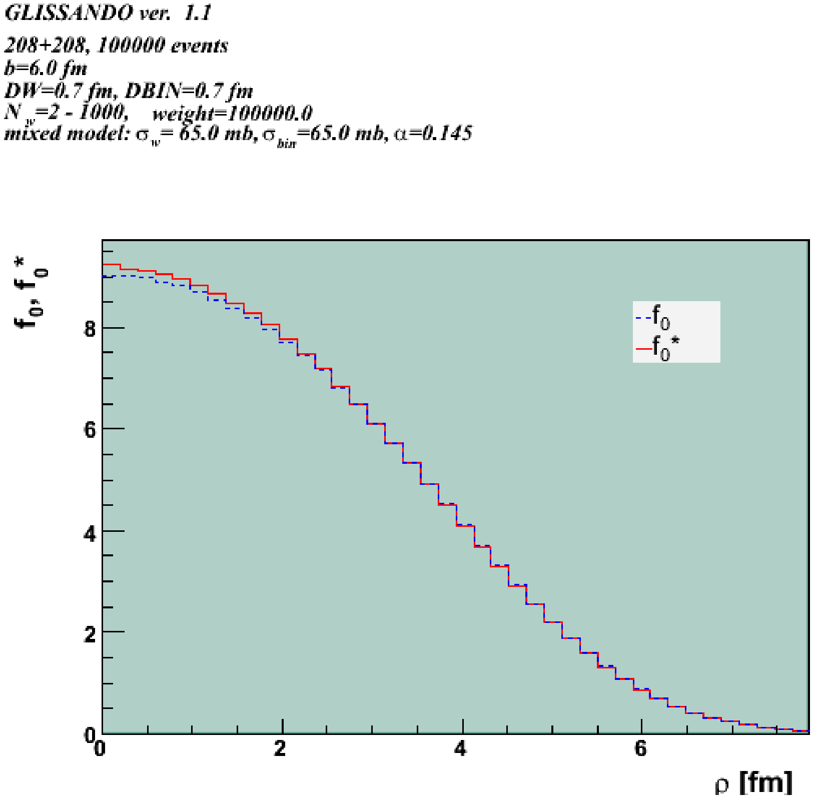


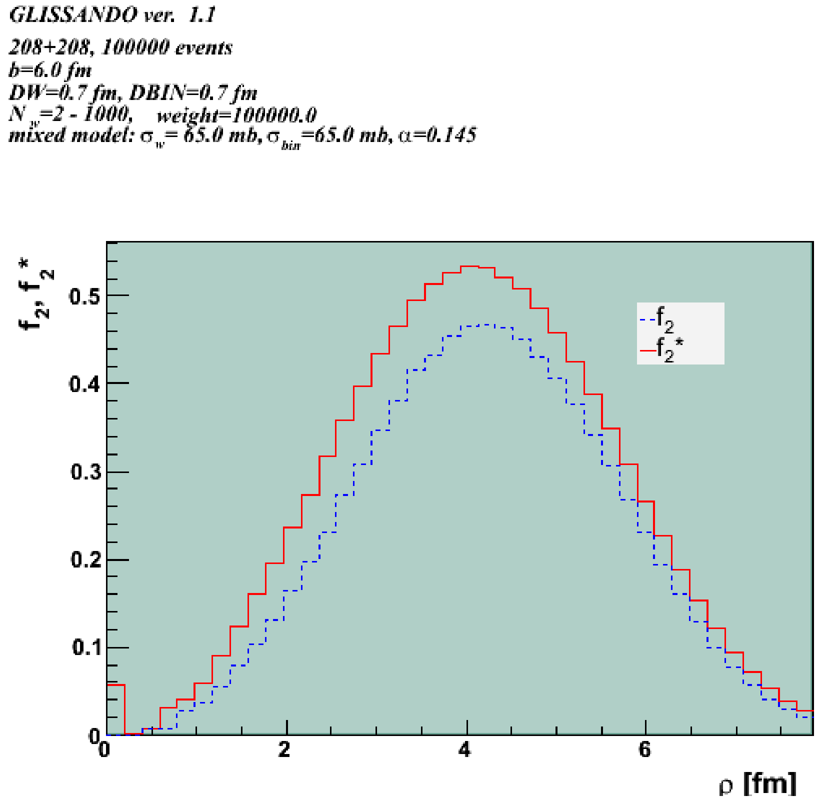
EXAMPLE ANALYSIS: Pb+Pb@5.5 TeV/n minbias



A simple correlation plot…

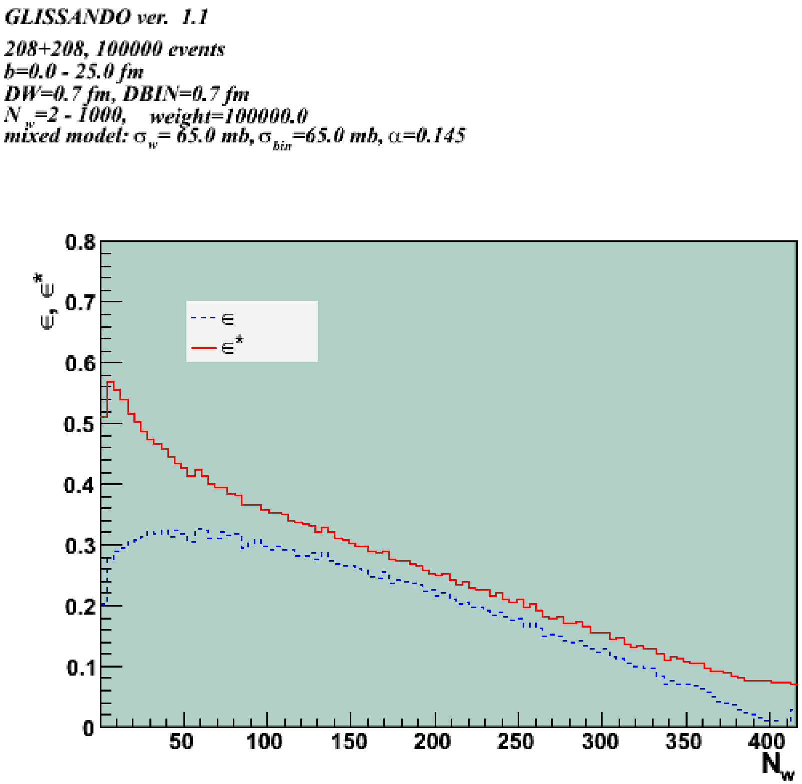
EXAMPLE ANALYSIS: Pb+Pb@5.5 TeV/n semi-central

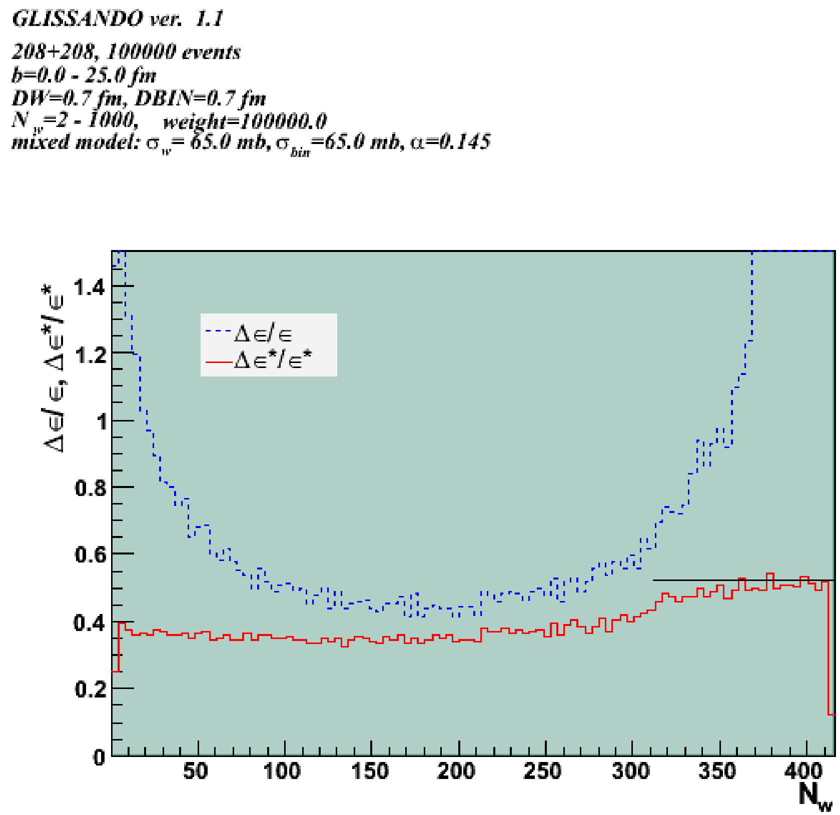




Fixed- and variable-axes Fourier profiles

EXAMPLE ANALYSIS: Pb+Pb@5.5 TeV/n minbias





Fixed- and variable-axes eccentricities and their scaled standard deviations as functions of number of wounded nucleons

FLOW

Flow has been observed in heavy ion experiments in a wide energy range.

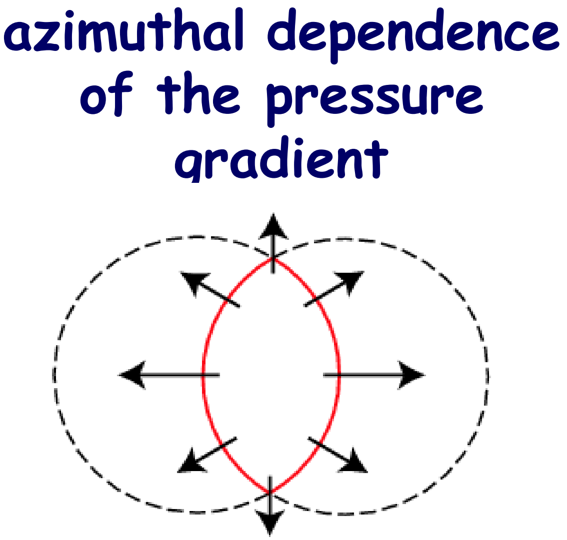
Elliptic flow v_2 provides information on the early stage of the collision, where QGP is expected.

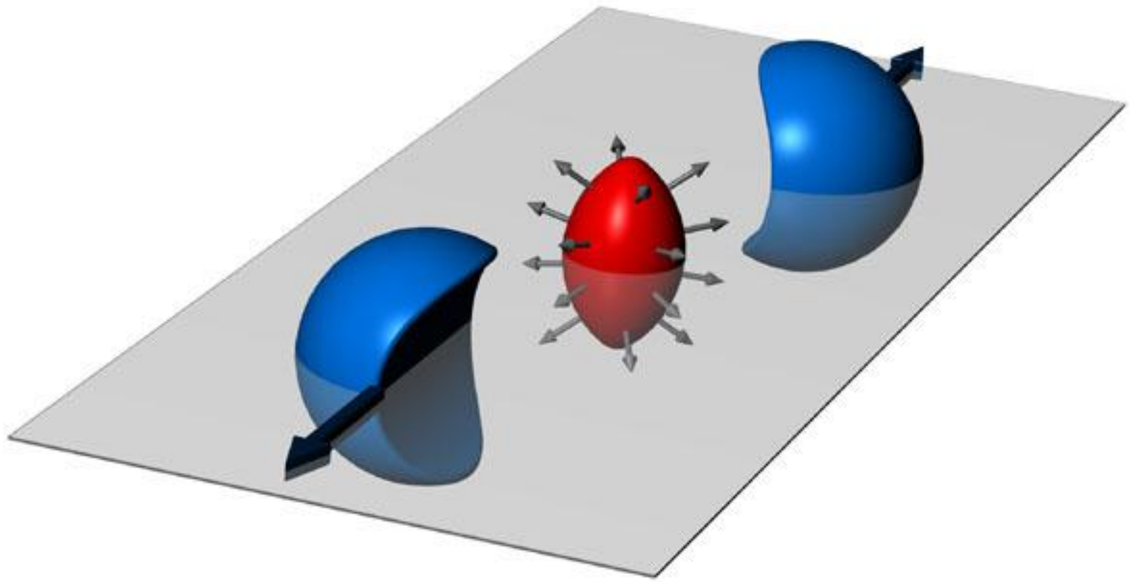
Hydrodynamic calculations are capable to describe existing data.

The same models can be used to make extrapolations to LHC .

FLOW

Flow is an ever present phenomenon in nucleus-nucleus collision, which correlates the momentum distribution of particles with the <u>spatial eccentricity</u> of the overlap.





Elliptic flow is the second coefficient of the Fourier expansion of the azimuthal particle distribution:

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left(1 + \sum_n 2v_n \cos(n[\phi - \Psi_R])\right) \qquad v_n = \langle \cos(n[\phi - \Psi_R]) \rangle$$

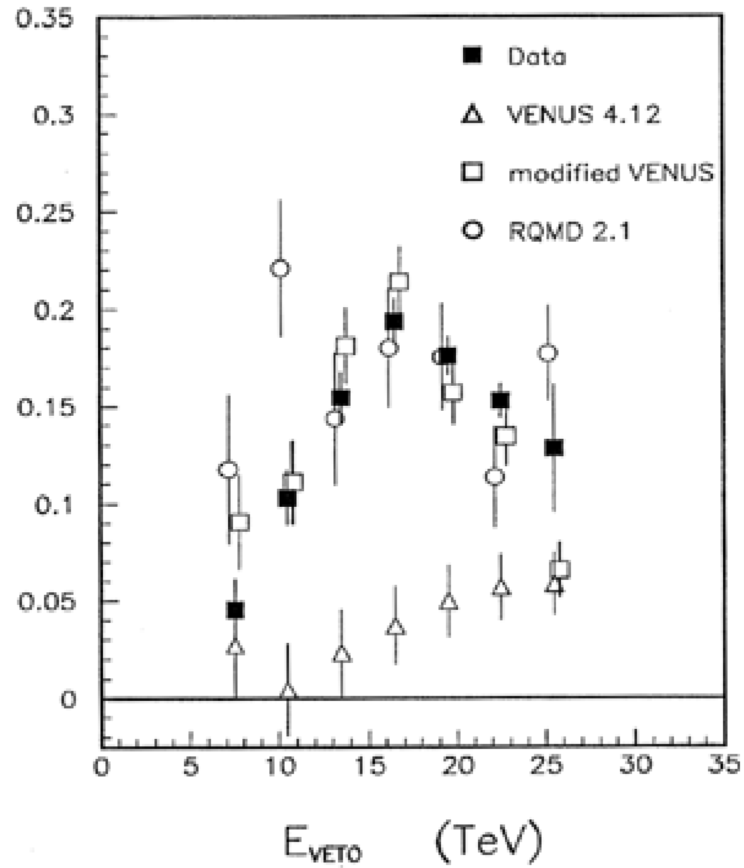
ORIGIN OF FLOW

Elliptic Flow originates from the amount of rescattering between particles and the spatial eccentricity:

- amount of rescattering increases with centrality
- spatial eccentricity decrease with centrality

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$



NA49, T. Wienold et al., Nucl. Phys. **A610**, 76c (1996)

← (centrality)

EVENT-BY-EVENT FLUCTUACTIONS OF v_2

At low azimuthal asymmetry one expects on hydrodynamical grounds:

$$\frac{\Delta v_2^*}{v_2^*} = \frac{\Delta \varepsilon^*}{\varepsilon^*}$$

$$\frac{\Delta v_2^*}{v_2^*}(b=0) = \frac{\Delta \varepsilon^*}{\varepsilon^*}(b=0) = \sqrt{\frac{4}{\pi} - 1} \simeq 0.52$$

For peripheral collisions (collection of a few p – p collisions) also:

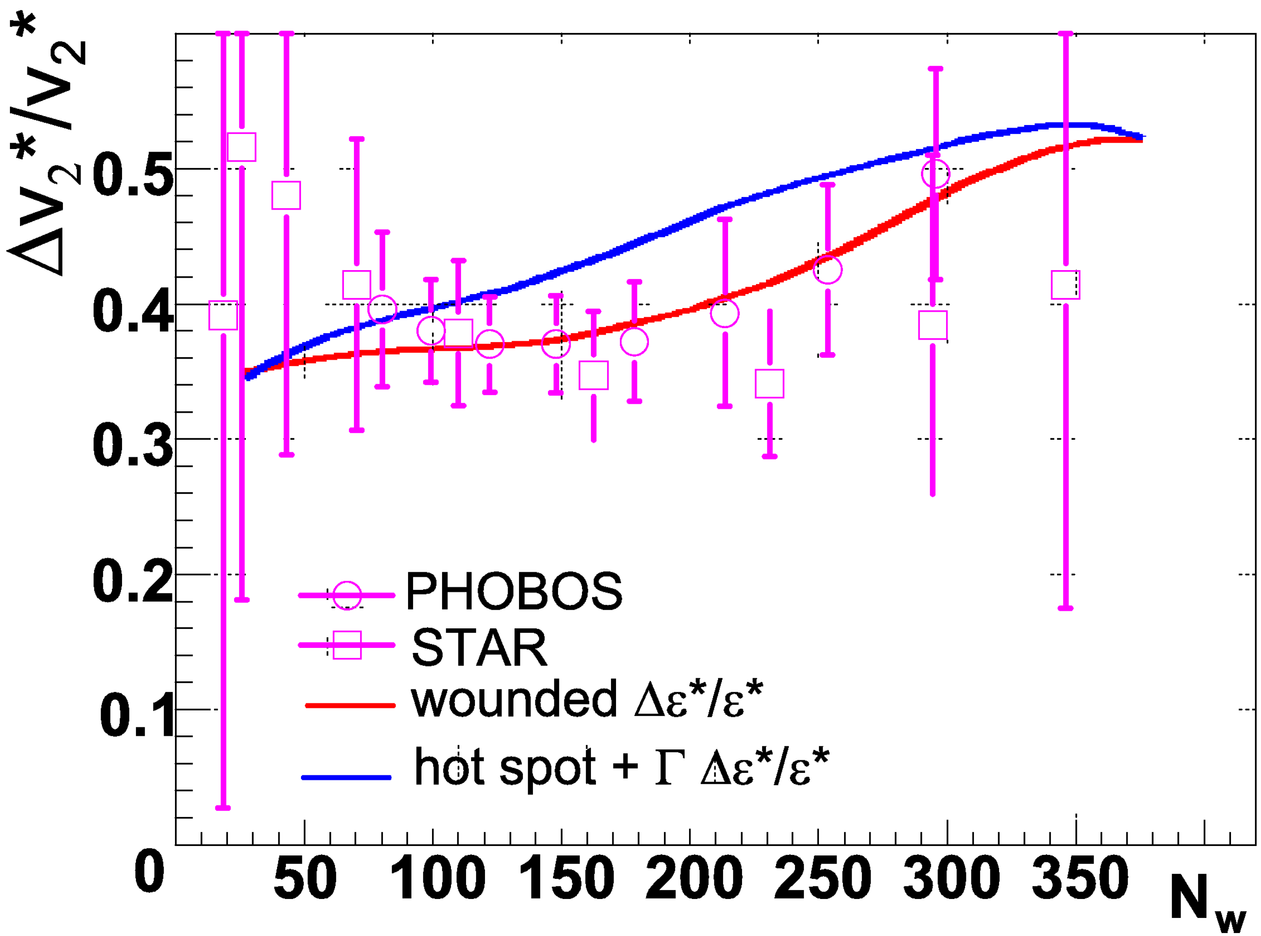
$$\frac{\Delta v_2^*}{v_2^*}(b \sim 2R) = \sqrt{\frac{4}{\pi} - 1} \simeq 0.52$$

(replace coordinates by momenta and repeat the above analysis)

At intermediate *b* lower values

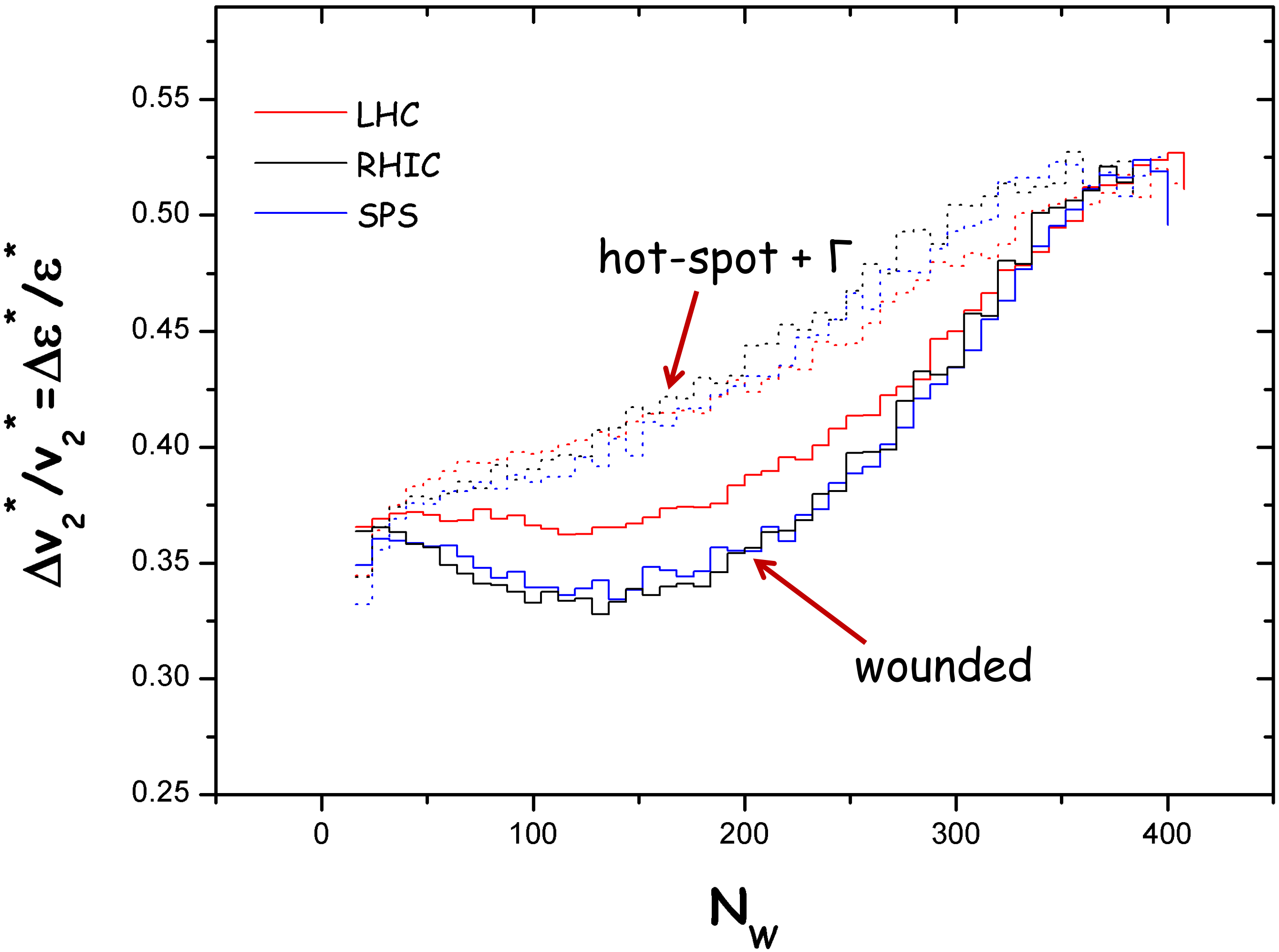
Details in: *PRC 76 054905 (2007)*

EVENT-BY-EVENT FLUCTUACTIONS OF v_2



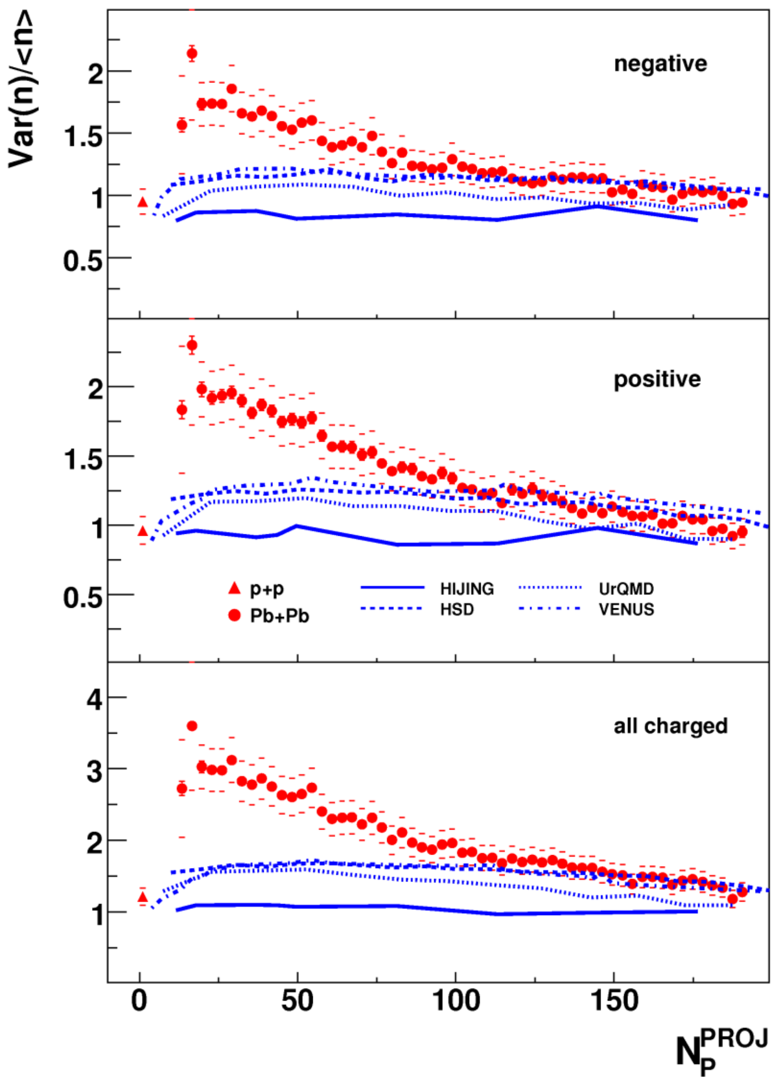
RHIC measures the v_2^*, as it cannot determine accurately the reaction plane!

EVENT-BY-EVENT FLUCTUACTIONS OF v_2

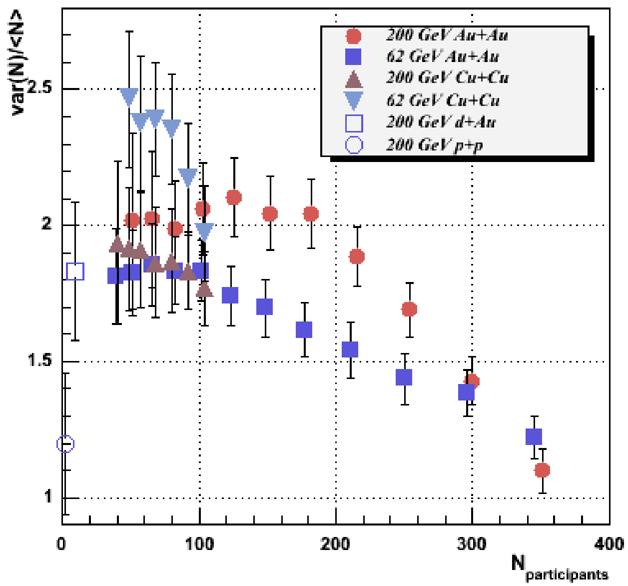


Glauber Monte-Carlo prediction for LHC energy

EXPERIMENTAL RESULTS ON MULTIPLICITY FLUCTUATIONS



NA49 data @17.3 GeV

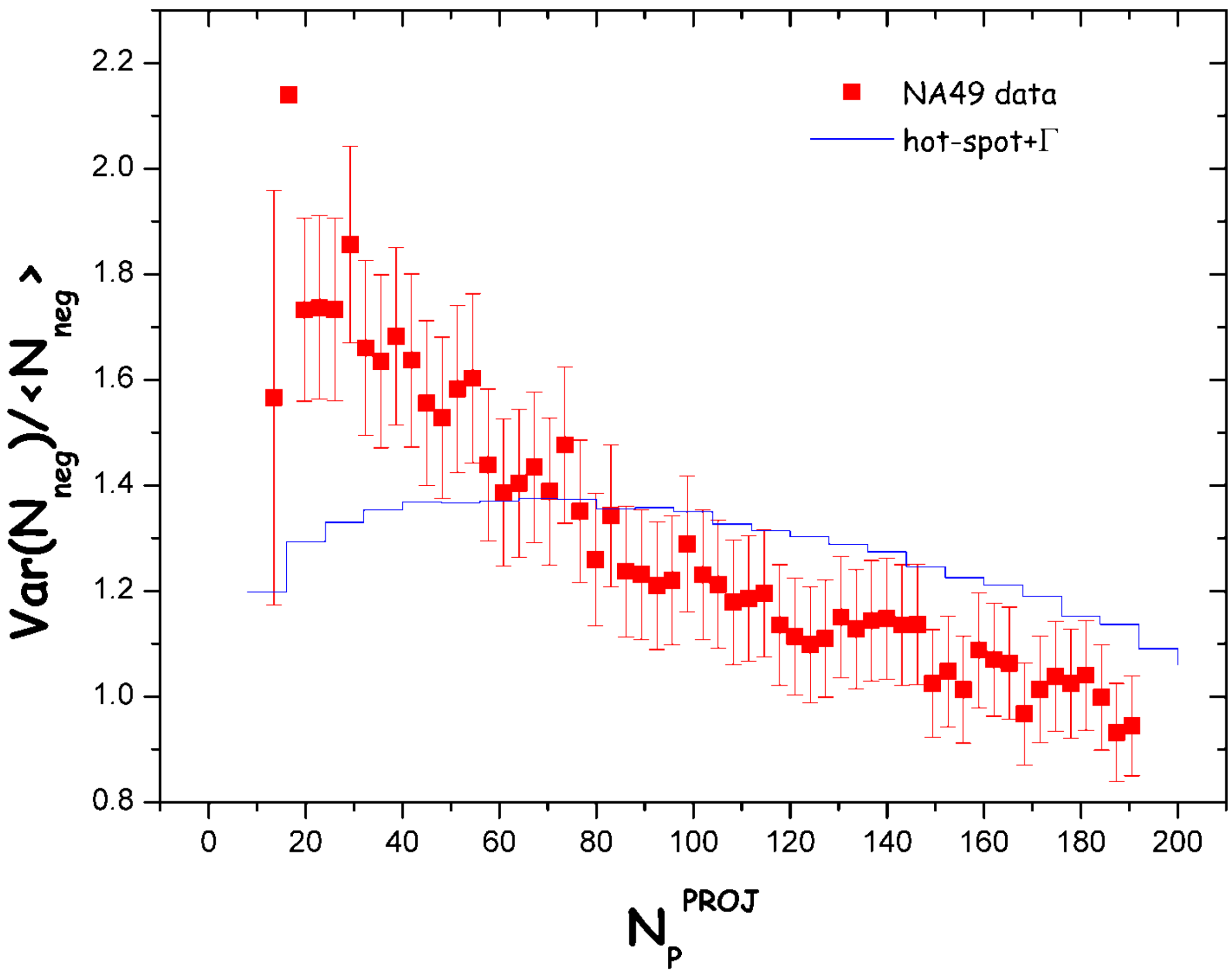


PHENIX data

LARGE

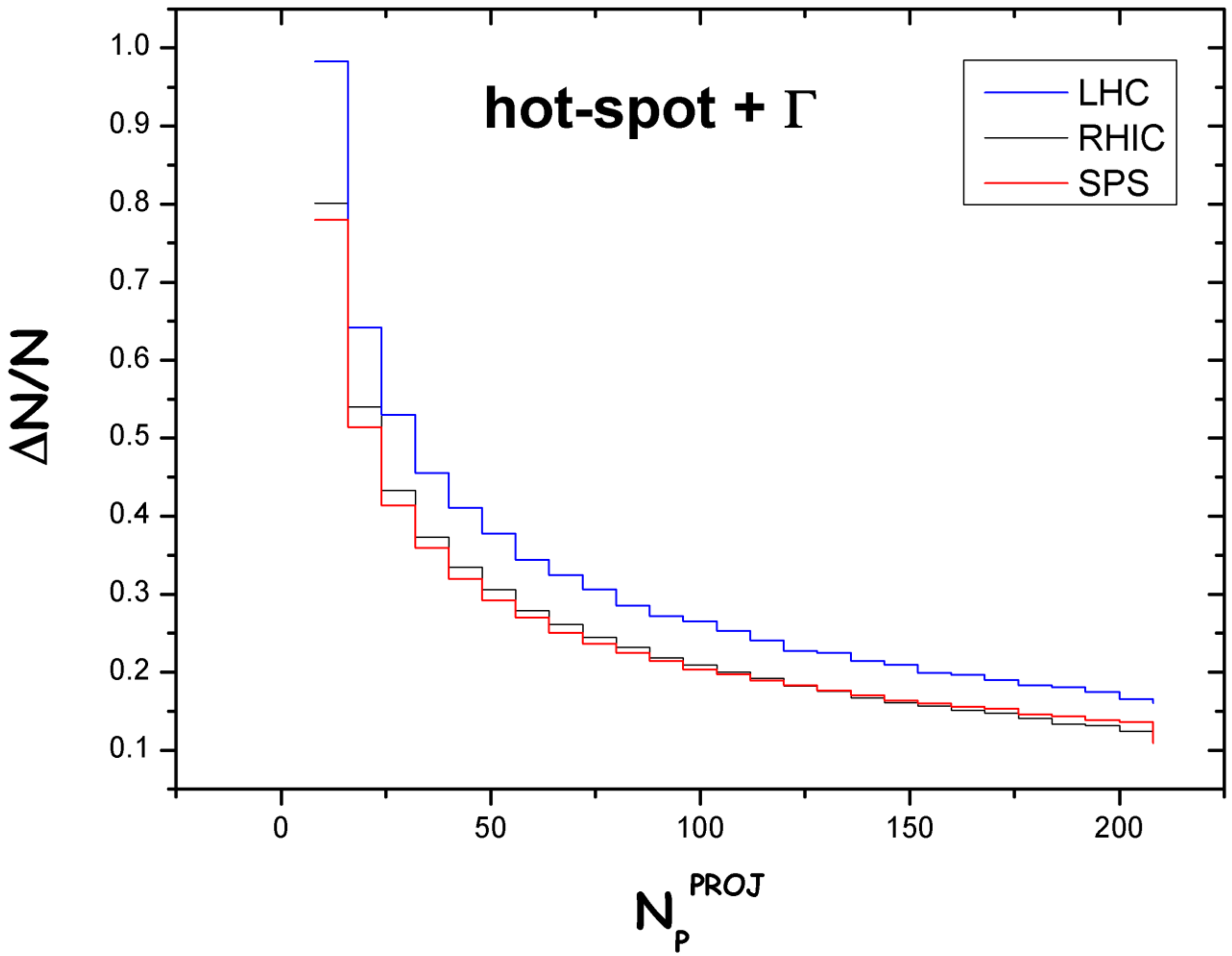
fluctuations for semi-peripheral collisions

MULTIPLICITY FLUCTUATIONS @ SPS



Glauber Monte-Carlo in NA49 acceptance

MULTIPLICITY FLUCTUACTIONS @ LHC



Glauber Monte-Carlo prediction for LHC energy

SUMMARY (I)

- ✓ Predictions of Glauber Monte-Carlo calculations for fluctuations of elliptic flow at LHC energy were done.

- ✓ Glauber Monte-Carlo calculations cannot fully explain the non-monotonic behaviour of multiplicity fluctuations at SPS and RHIC energies.

SUMMARY (II)

- We hope that with its flexibility and simplicity GLISSANDO will become a useful tool for the heavy-ion community.

- The open-source nature of the code allows for check-ups additions and improvements.

- We have provided examples of numerous applications: determination of A+B cross-section and centrality classes, analysis of eccentricities both in the fixed- and variable-axes frame, event-by-event fluctuations, correlation of various quantities.

- Program is obtainable from: http://www.pu.kielce.pl/homepages/mryb/GLISSANDO/

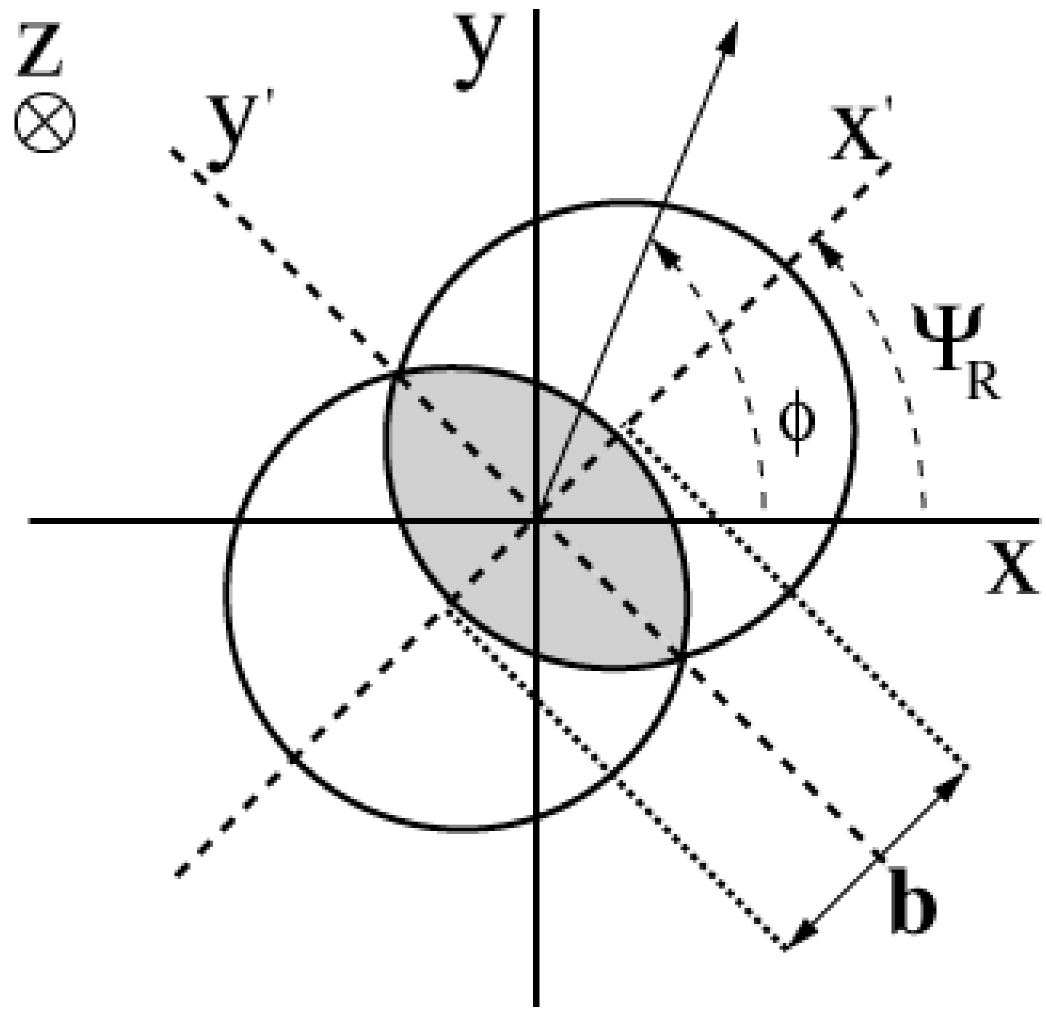
Back-up

NON-CENTRAL HEAVY-ION COLLISIONS: COORDINATE SYSTEM

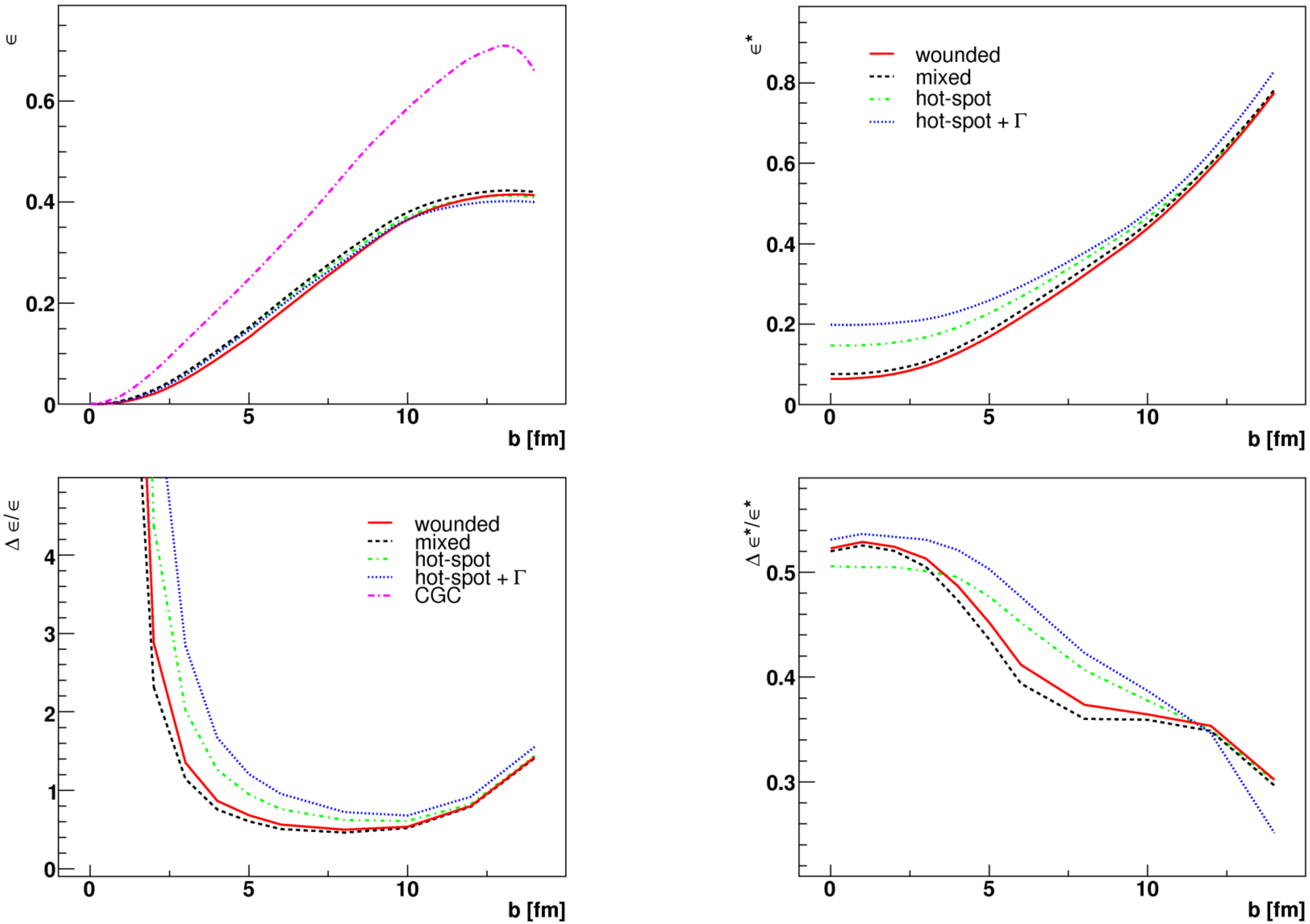
$$v_2 = \langle \cos(2[\phi - \Psi_R]) \rangle$$

$$\phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

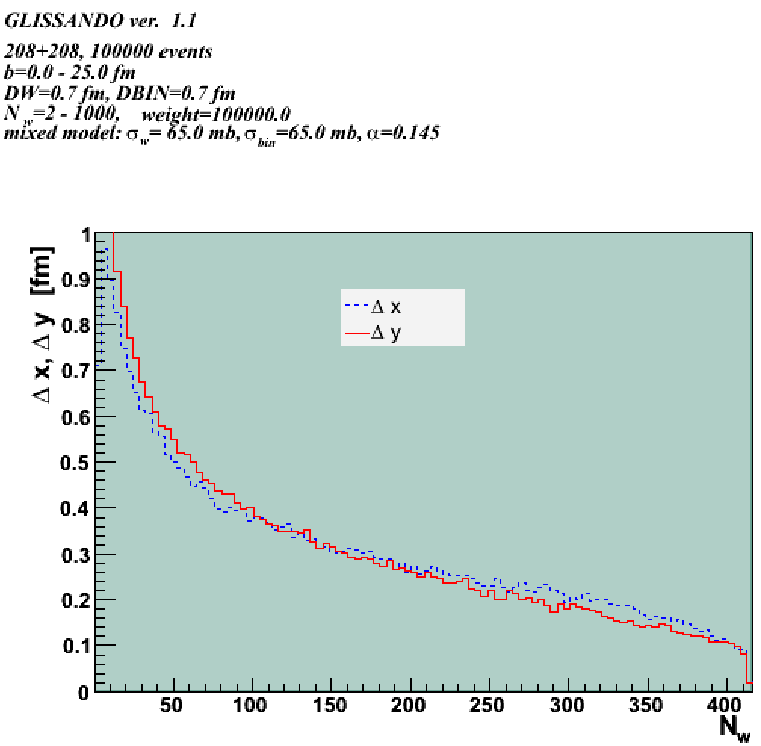
$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$



MONTE-CARLO SIMULATONS IN GLAUBER MODELS: ECCENTRICITY VS CENTRALITY AT RHIC

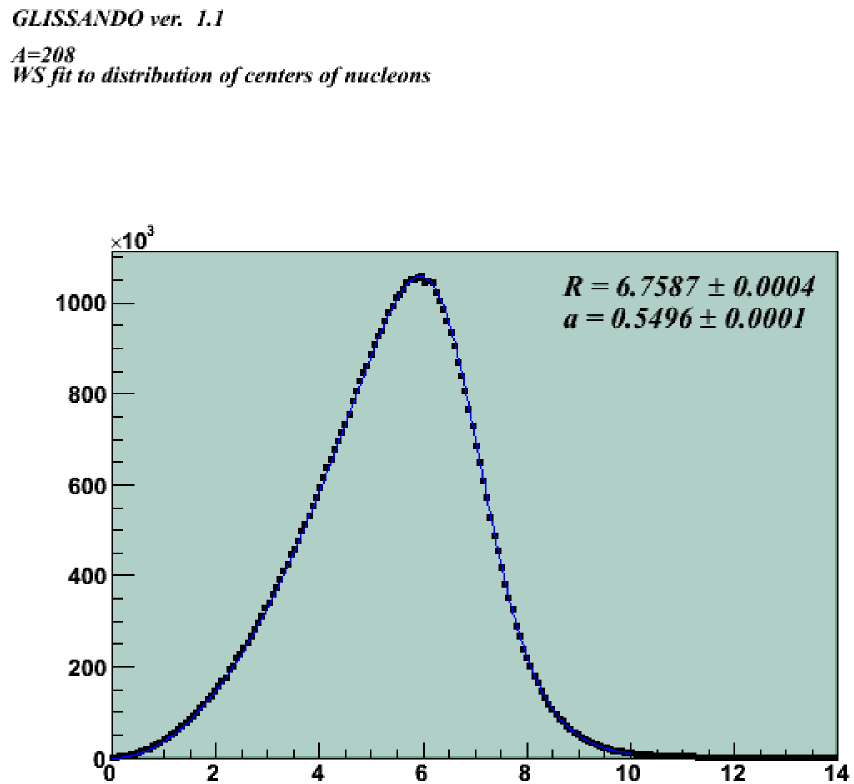


EXAMPLE ANALYSIS: Pb+Pb@5.5 TeV/n minbias



Disperssions of the x and y locations of sources as a function of number of wounded nucleons

The histogram of the radial density for the distribution of centers of nucleons



ECCENTRICITY FLUCTUATIONS: TOY MODEL

fixed axes (standard): $\varepsilon = \langle \frac{1}{n} \sum_{k=1}^{n} \cos(2\phi_k) \rangle = 0$

variable axes (participant): $\varepsilon^* = \langle \frac{1}{n} \sum_{k=1}^{n} \cos[2(\phi_k - \phi^*)] \rangle$

ϕ^* : quantity $\frac{1}{n} \sum_{k=1}^{n} \cos[2(\phi_k - \phi^*)]$ maximized in each event.

$$X = \frac{1}{n} \sum_{k=1}^{n} \sin(2\phi_k) \qquad Y = \frac{1}{n} \sum_{k=1}^{n} \cos(2\phi_k)$$

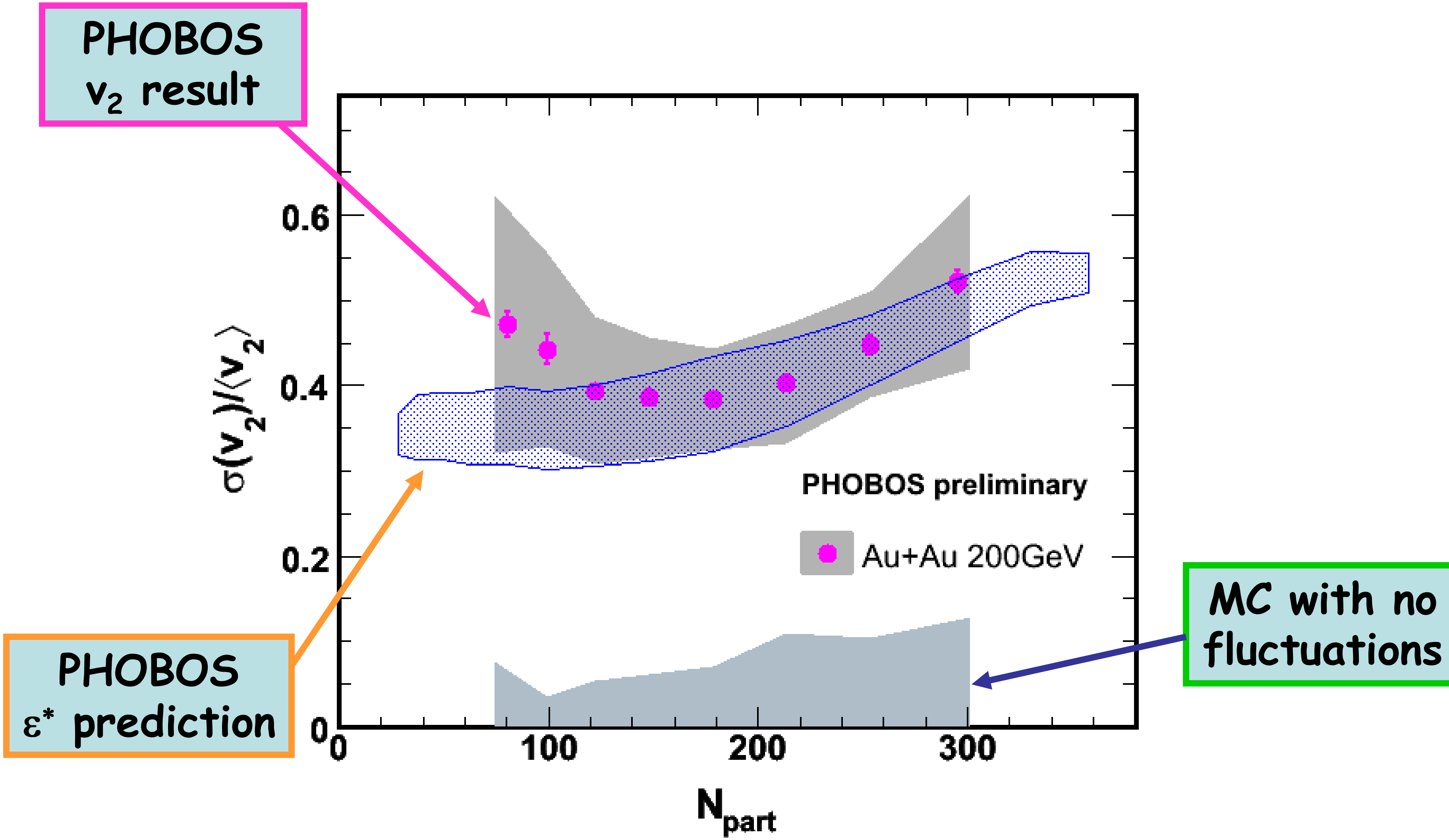
For large n the distribution of X and Y is Gaussian, thus from Central Limit Theorem we have:

$$\langle \varepsilon^* \rangle = \int dX dY \sqrt{X^2 + Y^2} \exp\left(-n(X^2 + Y^2)\right)$$

$$\langle \varepsilon^{*2} \rangle = \int dX dY (X^2 + Y^2) \exp\left(-n(X^2 + Y^2)\right)$$

$$\frac{\Delta \varepsilon^*}{\varepsilon^*} = \frac{\sqrt{\langle \varepsilon^{*2} \rangle - \langle \varepsilon^* \rangle^2}}{\varepsilon^*} = \sqrt{\frac{4}{\pi} - 1} \simeq 0.523$$

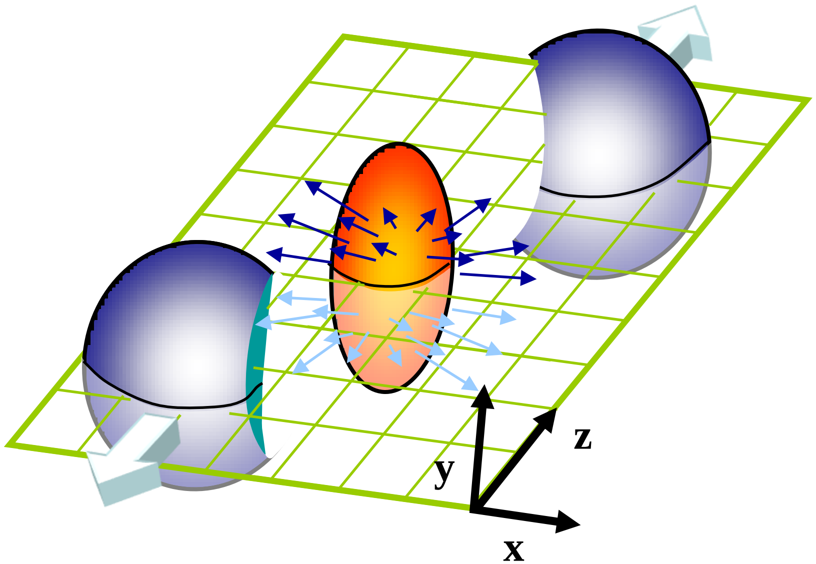
v_2 AND ε^* FLUCTUATIONS: RHIC DATA

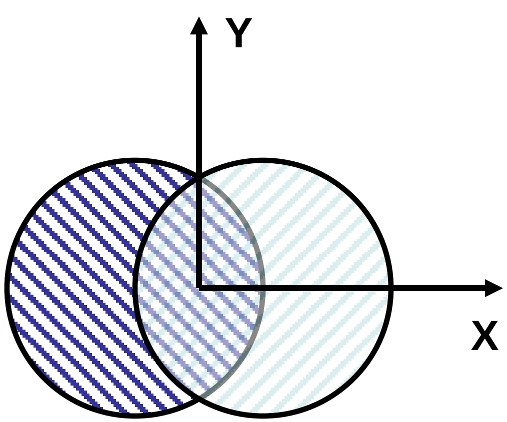


Magnitude of v_2 fluctuations is in agreement with ε^* fluctuations

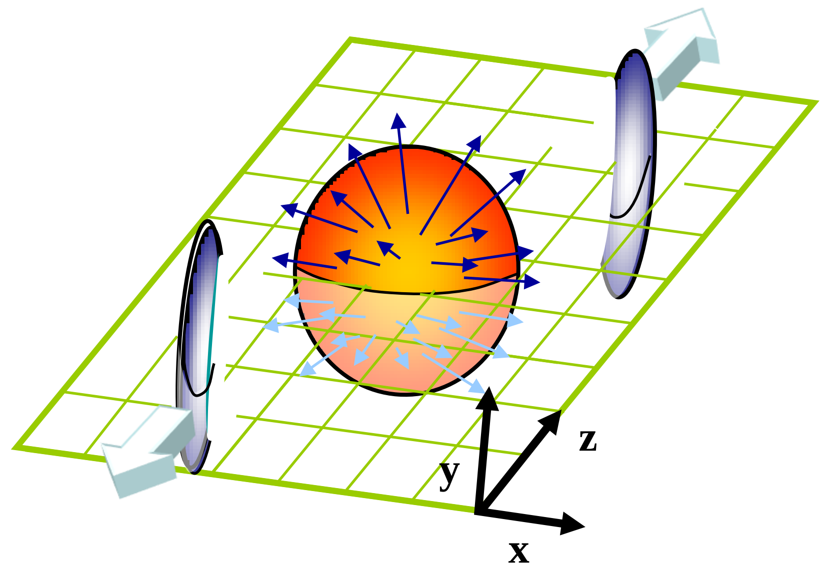
FLOW & CENTRALITY OF COLLISION

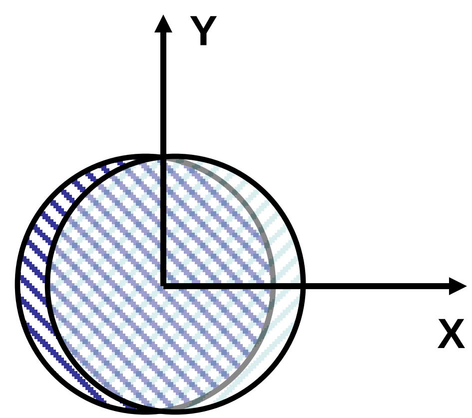
Peripheral Collision





(near) Central Collision



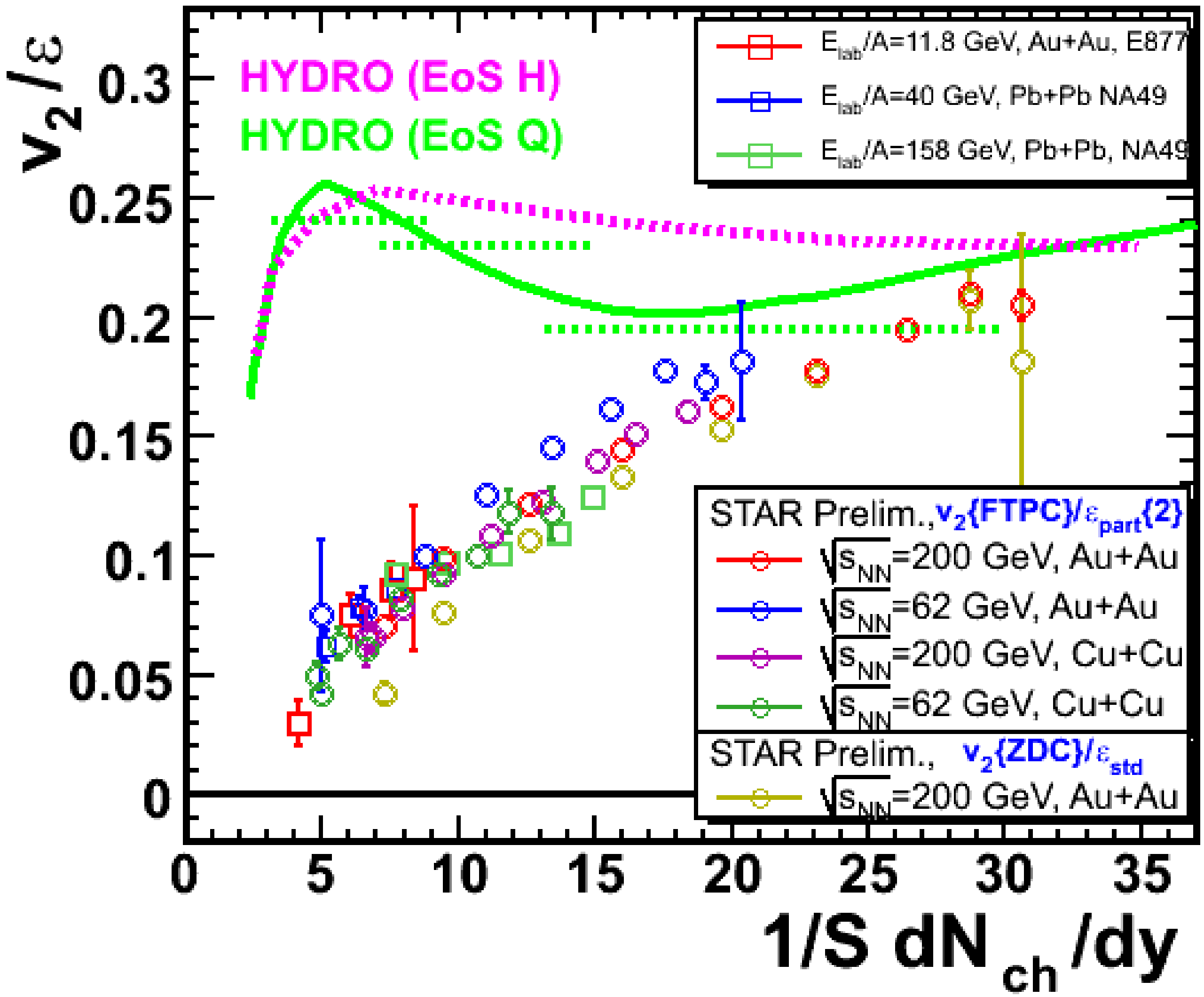


HYDRO PREDICTIONS ON v_2

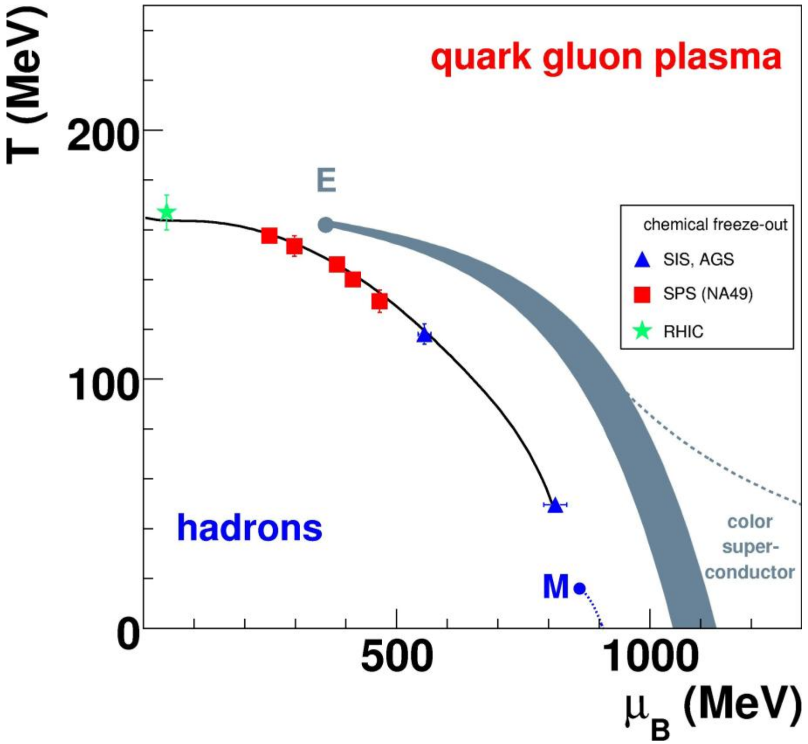
$$v_2 \propto \varepsilon \frac{1}{S}\frac{dN}{dy}$$

$$S = \pi\sqrt{\langle x^2\rangle\langle y^2\rangle}$$

$$\varepsilon = \frac{\langle y^2\rangle - \langle x^2\rangle}{\langle y^2\rangle + \langle x^2\rangle}$$



SEARCHING FOR QGP STATE



The transition to the QGP state is expected when the matter is:

10x denser than atomic nuclei

10^5x hotter than interior of the Sun

$$T \sim 150\ \mathrm{MeV}\ \ (1\ \mathrm{eV} \sim 10^4\ \mathrm{K})$$

$$\varepsilon \sim 1\ \mathrm{GeV/fm^3}$$

Non-monotonic dependence of p_T and N fluctuations on control parameters (energy, centrality, ion size) can help to locate the second-order critical end-point, if it coincides with the freezeout point.

M. Stephanov, K. Rajagopal, E. V. Shuryak, Phys. Rev. D60, 114028, 1999

FLUCTUATIONS AT PHASE BOUNDARIES!

MONTE-CARLO SIMULATONS IN GLAUBER MODELS: GLAUBER-LIKE MODELS TESTED

✓ wounded nucleons, $\sigma_w = 42\ \mathrm{mb}, d = 0.4\ \mathrm{fm}$

✓ mixed model: 85.5% wounded + 14.5% binary, $\sigma_w = \sigma_{bin} = 42\ \mathrm{mb}$

✓ hot spots: $\sigma_w = 42\ \mathrm{mb}, \sigma_{bin} = 0.5\ \mathrm{mb}.$ When a rare binary collision occurs it produces on the average a large amount of the transverse energy $= 14.5\% \times \sigma_w/\sigma_{bin}$

✓ hot spots + Γ : Sources may deposit the transverse energy with a certain probability distribution. We superimpose the Γ distribution with $\kappa = 0.5$ over the distribution of sources,

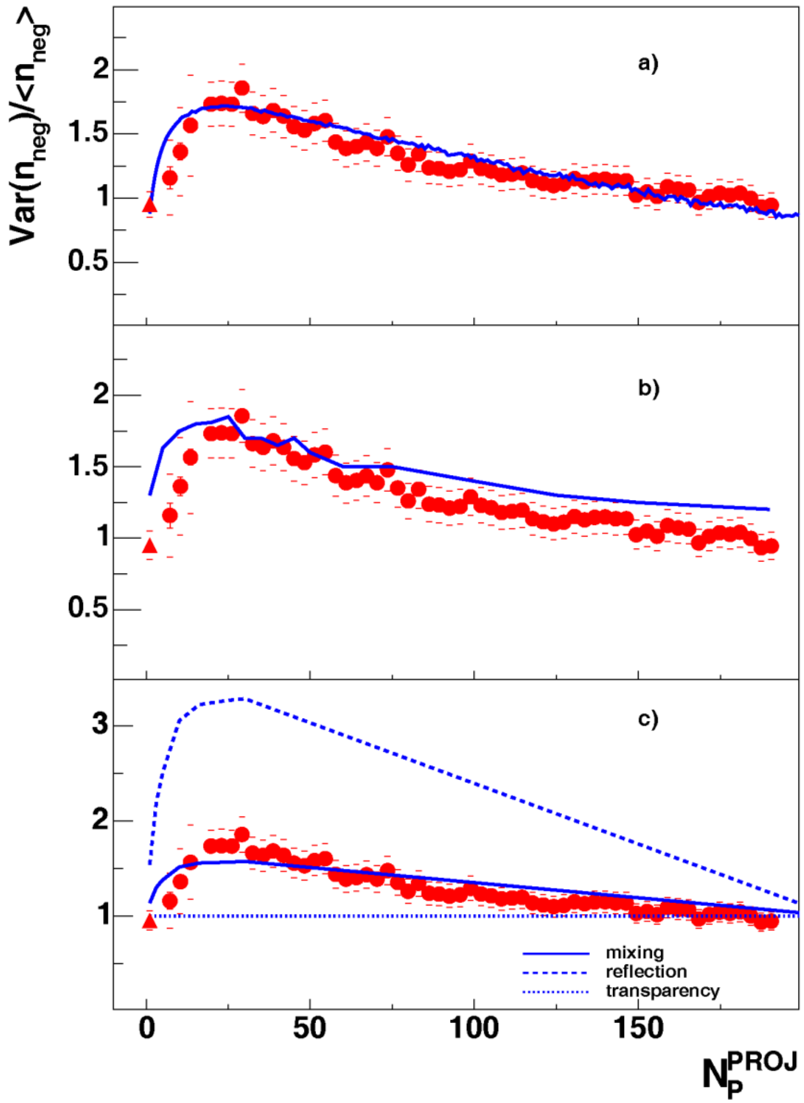
$$g(w,\kappa) = w^{\kappa-1}\kappa^{\kappa}\exp(-\kappa w)/\Gamma(\kappa),$$

where $\bar{w} = 1$ and $\mathrm{var}(w) = 1/\kappa$

One goal:

compare various Glauber-like models

COMPARISON WITH MODELS



TWO-PARTICLE CORRELATIONS

J. Phys.:Conf. Series 5 (2005) 238

PERCOLATIONS

Phys. Rev. C 72 (2005) 044903

MIXING

Phys. Lett. B 640 (2006) 155