Study of the quark-gluon matter by the PHOBOS experiment

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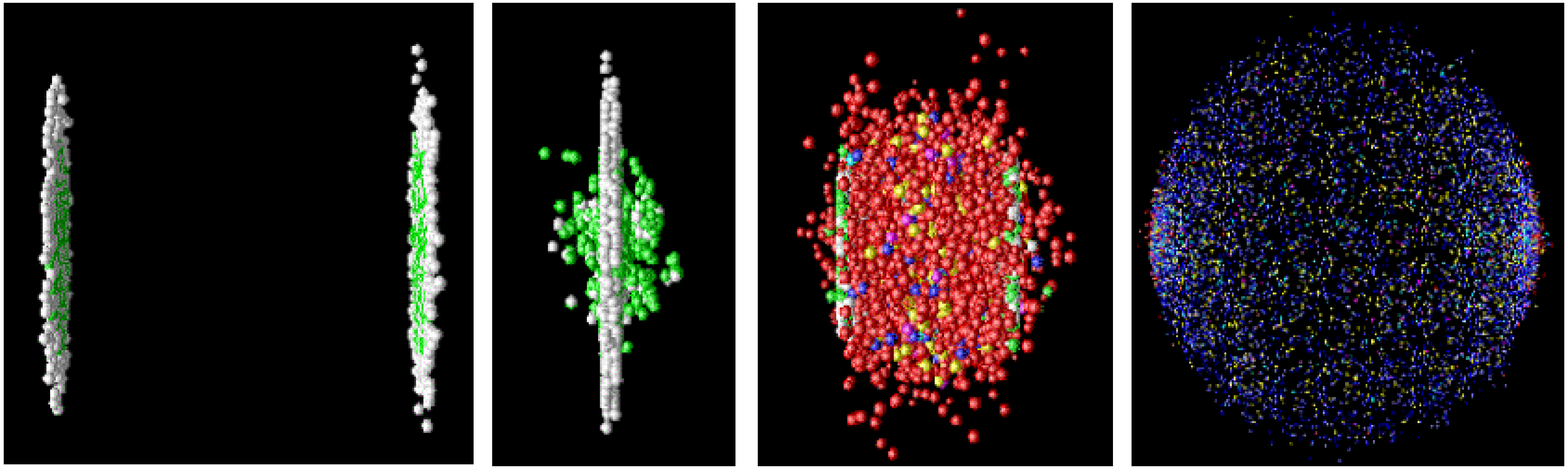
talk at HSQCD 2008, Gatchina, Russia

Heavy ion collision at RHIC in BNL

New state of matter – sQGP - strongly interacting Quark-Gluon Plasma

- Properties of the medium created in the collision of nuclei
- Evolution of the system
- Process of hadronization



PHOBOS Collaboration

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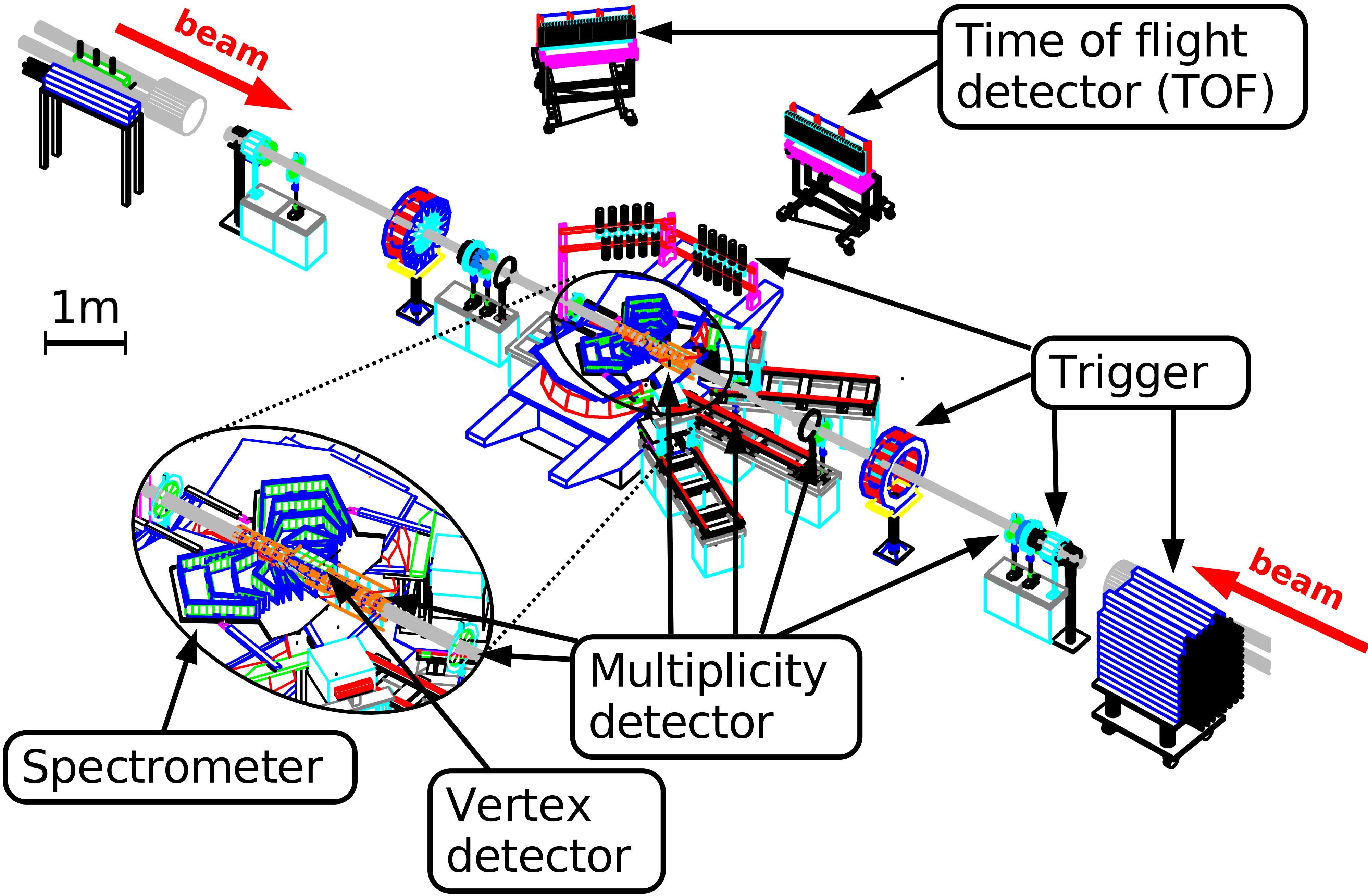
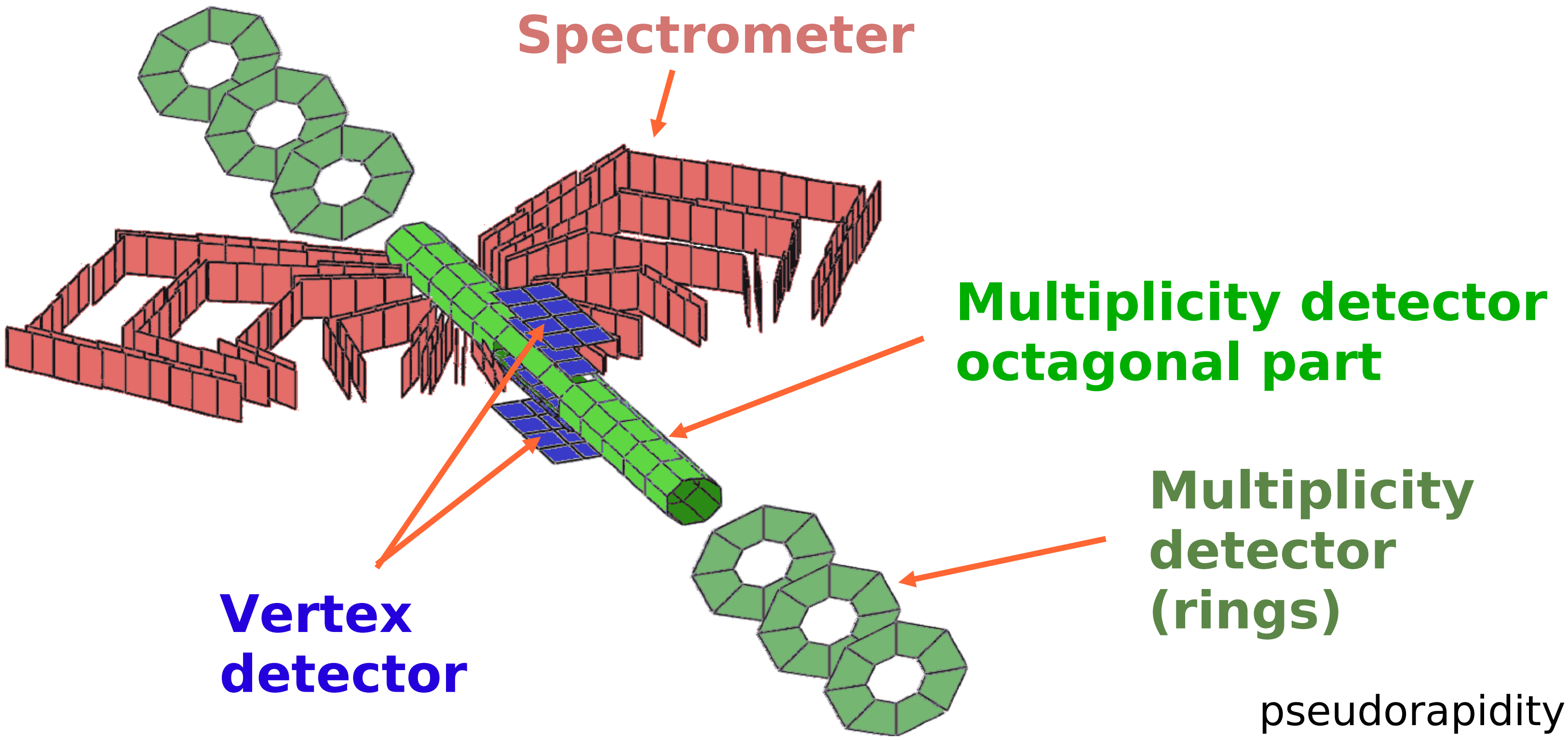
PHOBOS detector



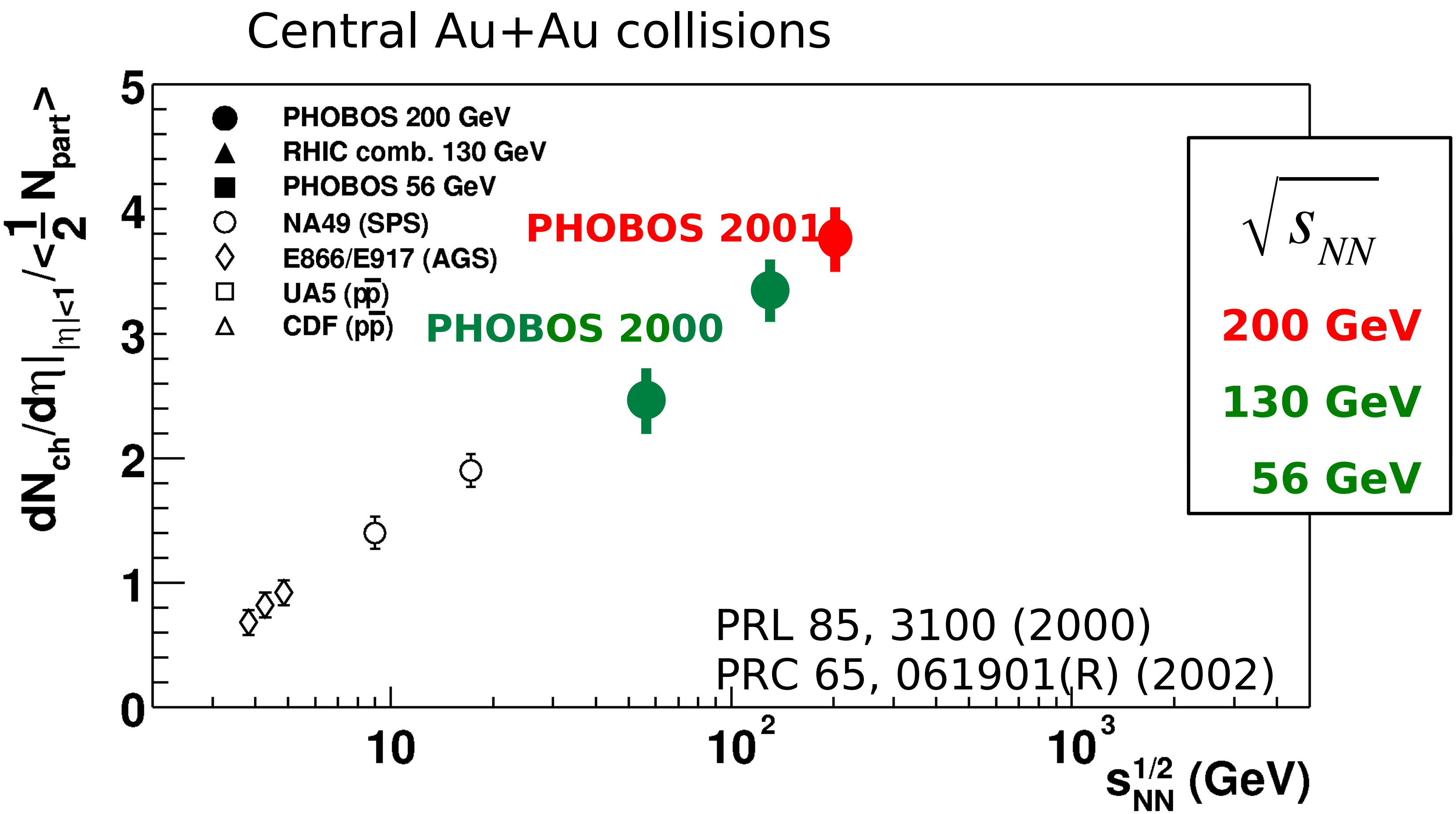
PHOBOS detector – silicon sensors



pseudorapidity:
$\eta = -\ln \tan \theta/2$

- **Multiplicity detector: $|\eta| < 5.4$**
- **Spectrometer: $0 < \eta < 2$, p_T from 30 MeV/c**
- **Vertex detector $|\eta| < 2$**

Initial energy density of the system



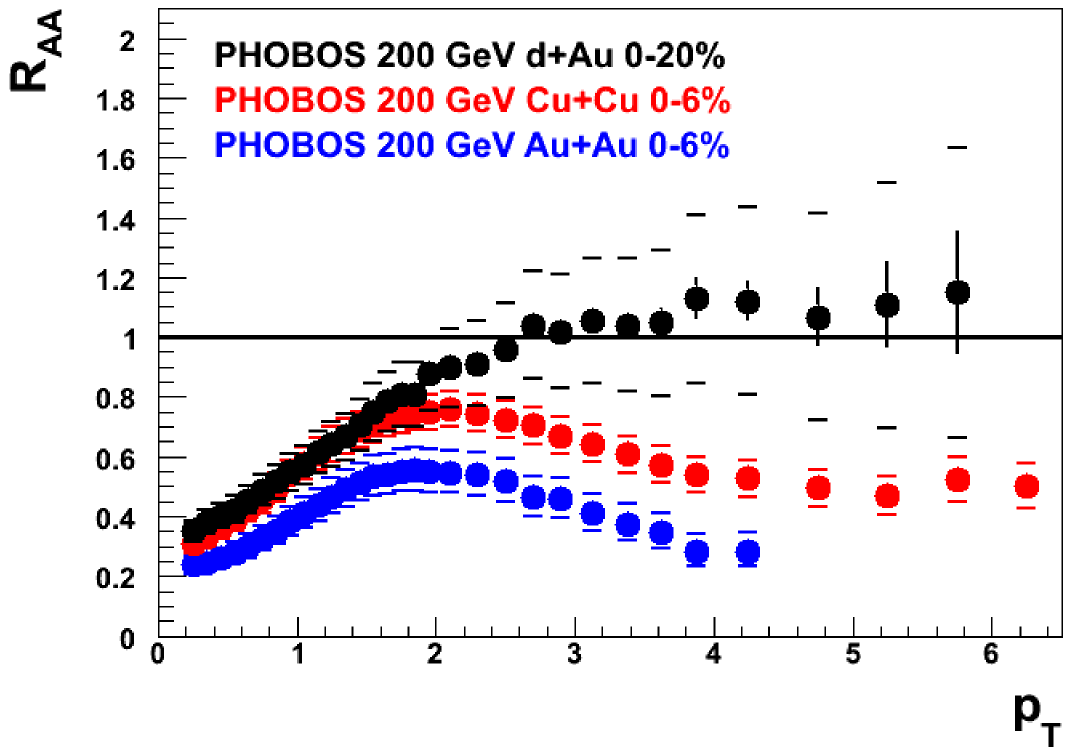
The first measurement of the particle density at midrapidity in the collisions of Au nuclei at the highest energy available in laboratory.

This measurement, with some additional assumptions, enables to estimate the energy density in the collisions of nuclei, conservative calculations give the value ~5 GeV/fm^3

Nucl. Phys. A 757, 28 (2005)

Suppression of high p_T particle production in A+A collisions

$$R_{AA} = \frac{\sigma^{inel}_{p\bar{p}}}{N_{coll}} \frac{d^2 N_{AA}/dp_T\, d\eta}{d^2 \sigma_{p\bar{p}}/dp_T\, d\eta}$$



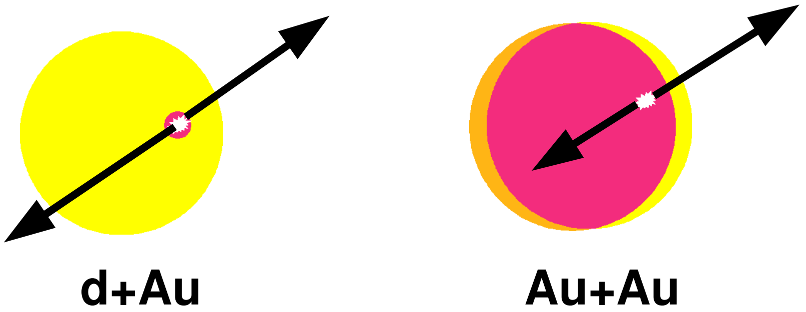
PHYS. REV. LETT. **91**, 072302 (2003)
PHYS. REV. LETT. **94**, 082304 (2005)
PHYS. REV. LETT. **96**, 212301 (2006)

R_{AA} = 1

no nuclear effects

Production of particles with high transverse momentum is strongly suppressed in central Au+Au collisions. The suppresion factor is continously changing with system size and collision energy.

This effect is caused by strong interactions of partons traversing the dense matter created in the A+A collisions.



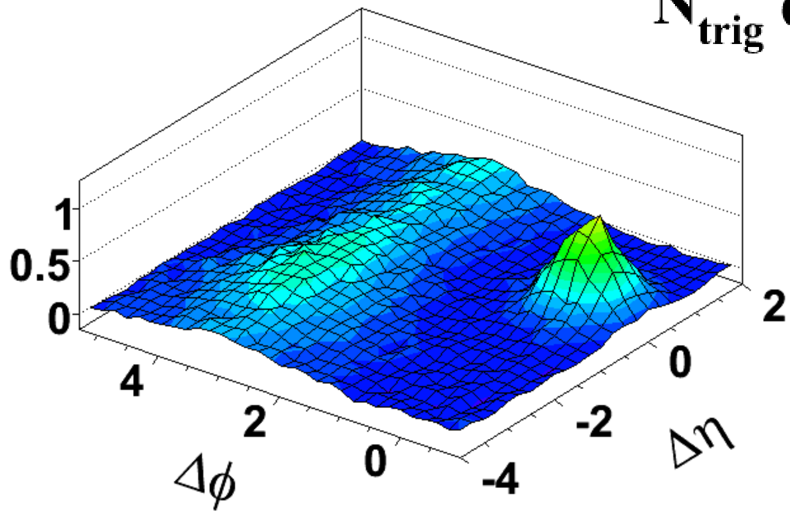
Density of associated particles
(mostly low and medium p_T)
corrected for elliptic flow

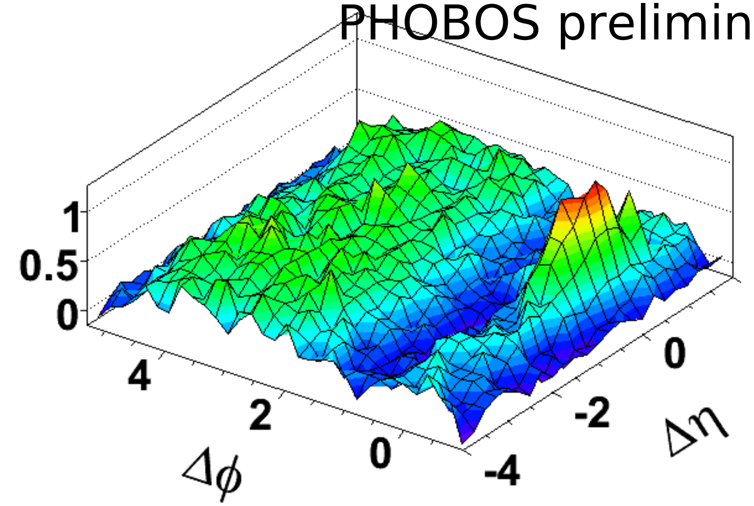
p_T^{trig} > 2.5 GeV/c
$p_T^{assoc} \geq$ 20 MeV/c

p+p PYTHIA v6.325

Au+Au 0-30% central

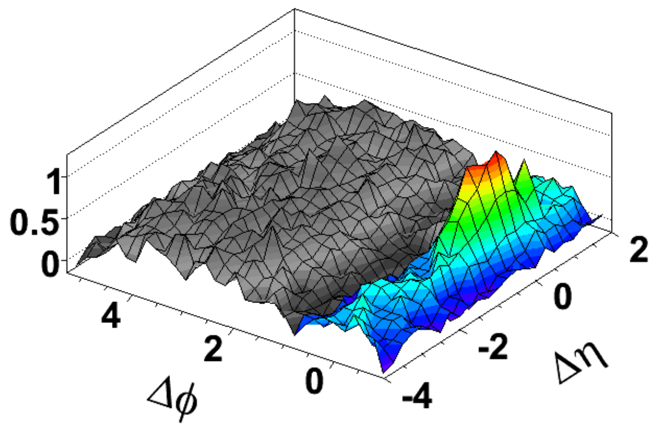
$$\frac{1}{N_{trig}} \frac{d^2N_{ch}}{d\Delta\phi\, d\Delta\eta}$$



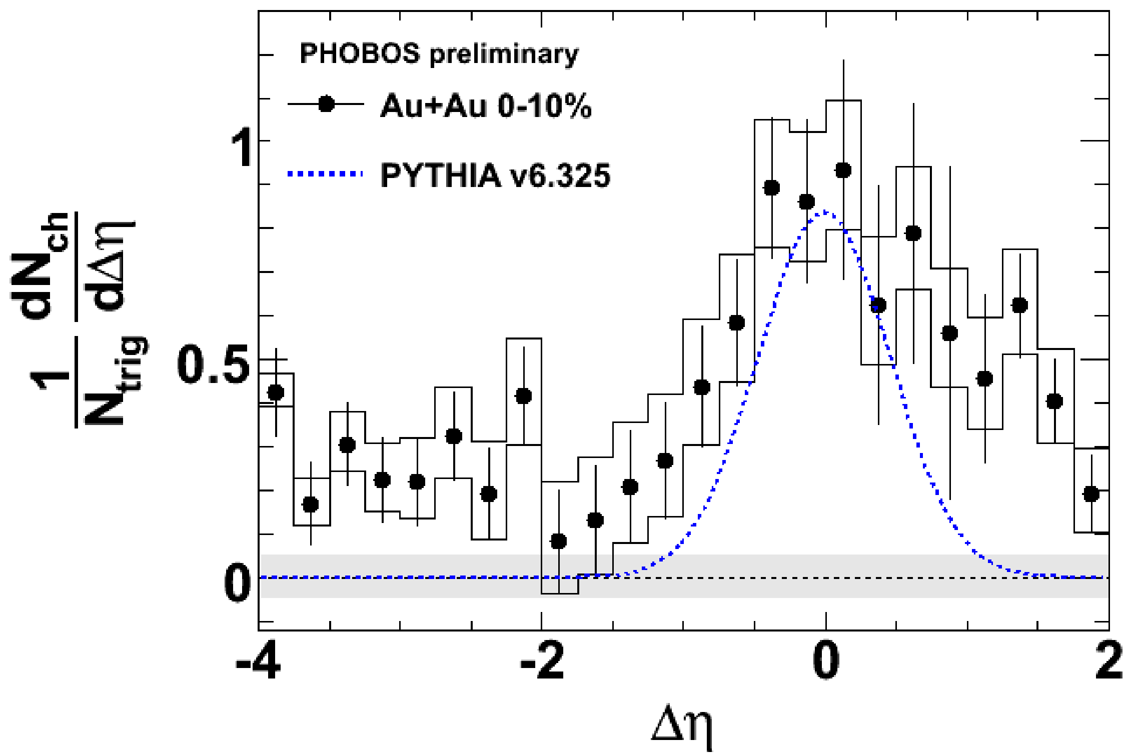


Correlations with trigger particle, p_T > 2.5 GeV/c

Correlations at “near side” ($|\Delta\phi| < 1$):



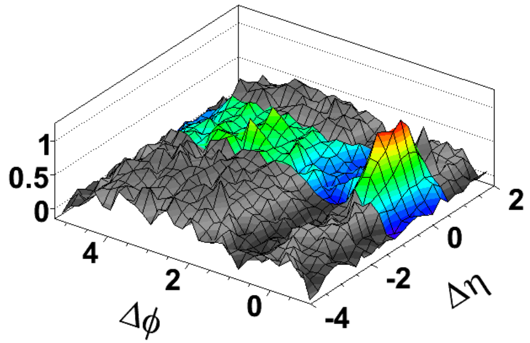
Au+Au

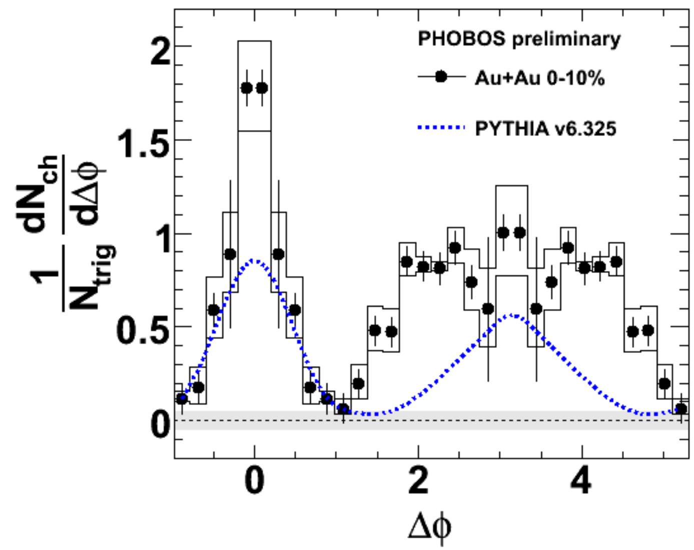


“Ridge” extending to large $|\Delta\eta|$

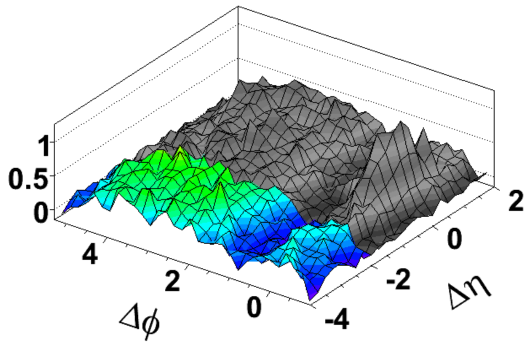
Correlations with trigger particle, p_T > 2.5 GeV/c

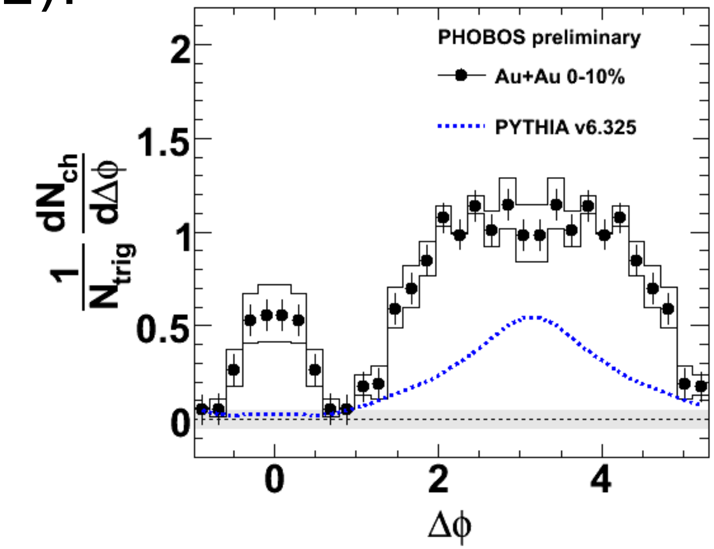
Short range correlations ($|\Delta\eta|$ < 1):





Long range correlations (-4 < $\Delta\eta$ < -2):





Broadening of "away side"
"Ridge" present at large $|\Delta\eta|$ - a possible sign of longitudinal expansion of the system

Particles with very low p_T

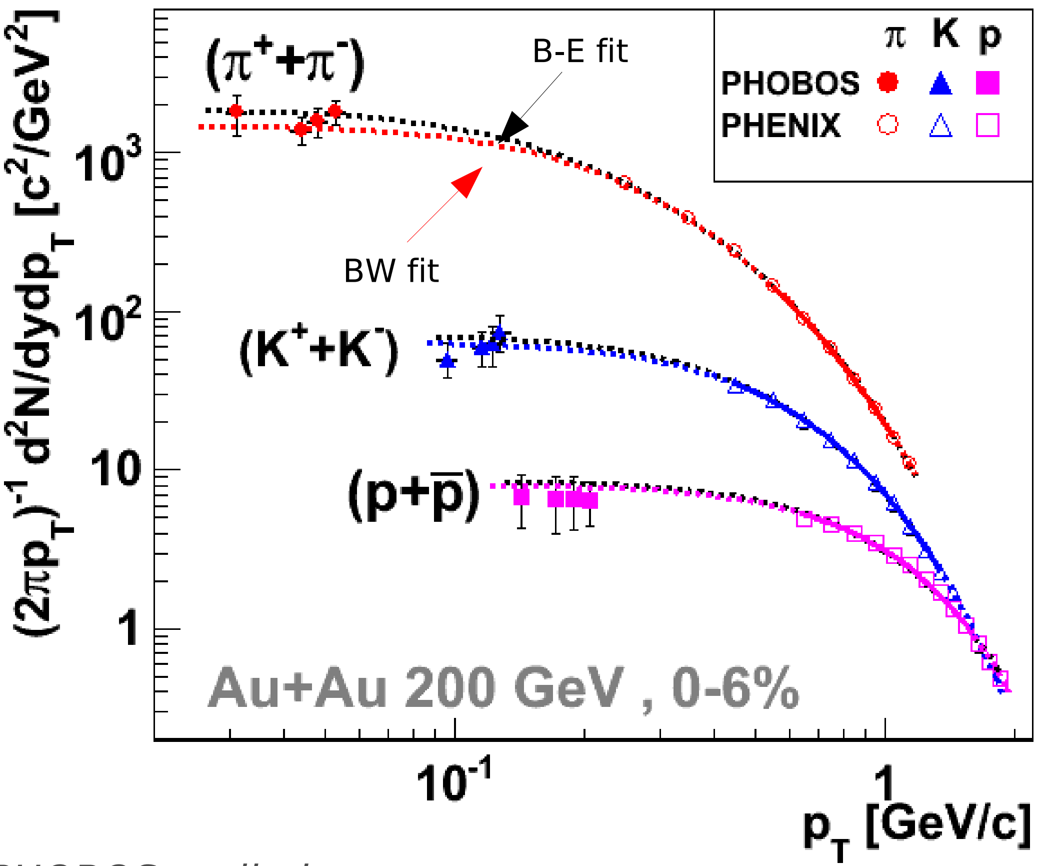
Expectations:

+ enhanced production of low pT particles from quark-gluon gas

- lower yields due to increase of the momentum of produced particles in the case of collective expansion of the system

Parametrisation (fitted to higher p_T and extrapolated to low p_T):

- **Bose-Einstein (B-E)**
- **Blast Wave (BW) ($\beta \approx 0.8$)**

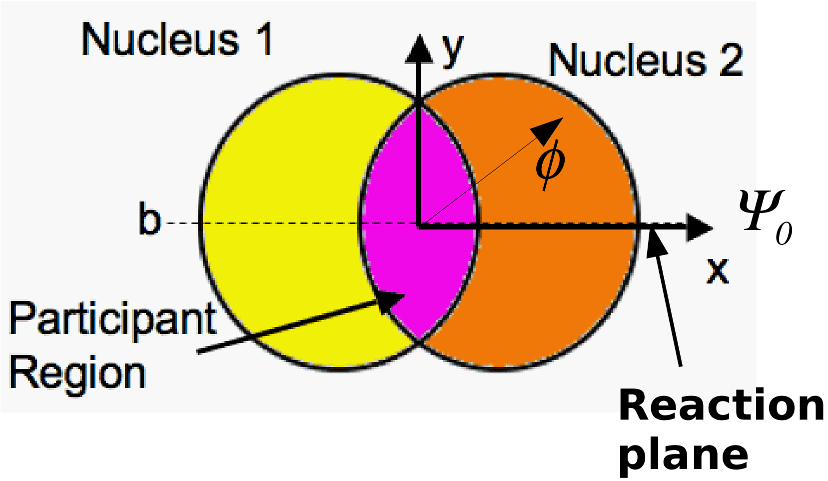


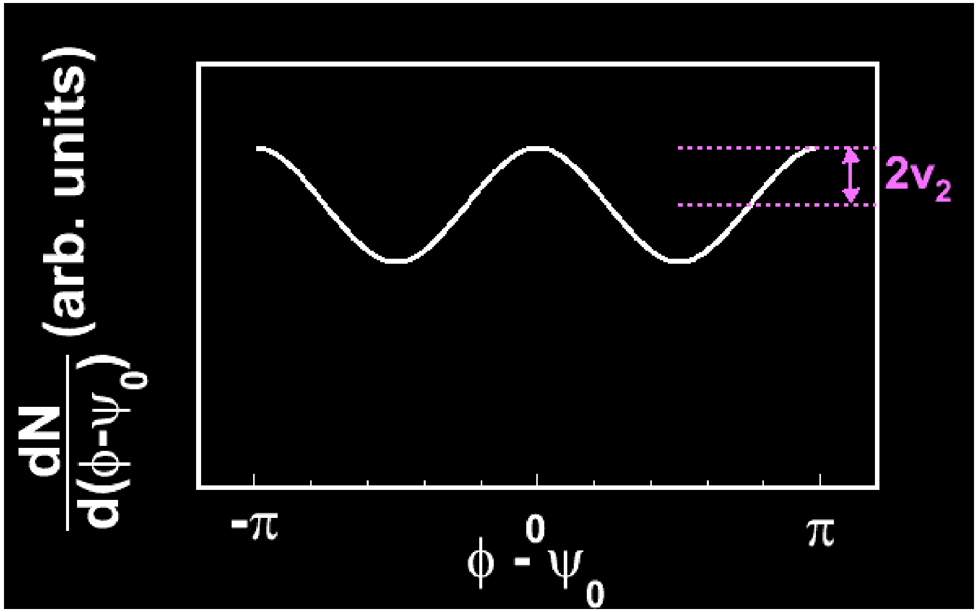
PHOBOS preliminary
arXiv:0804.4270v1 [nucl-ex]

No enhancement of very low p_T particles production.

Measured yields of these particles are consistent with expansion of the system.

Elliptic flow



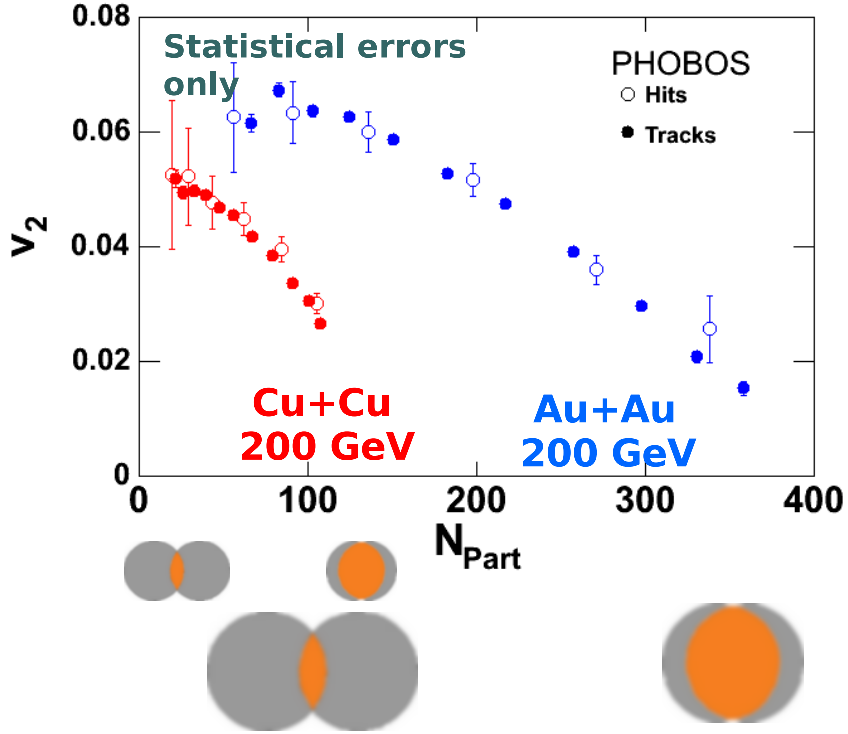


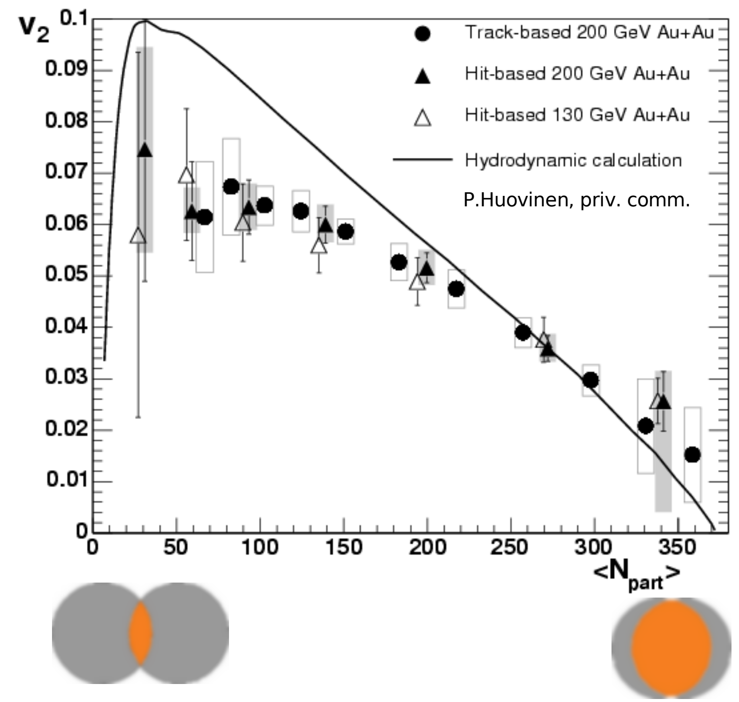
Elongated shape of the interaction area causes differences in the pressure gradients. The expansion of the system is thus anisotropic and this is reflected in the the azimuthal angles of the observed particles.

The value of the elliptic flow, v_2, is obtained from Fourier expansion of the distribution of the number of particles in the azimuthal angle:

$$dN/d(\phi-\Psi_0) = N_0\,(1 + 2v_1\cos(\phi-\Psi_0) + 2\mathbf{v_2}\cos(2(\phi-\Psi_0)) + \ldots)$$

Elliptic flow

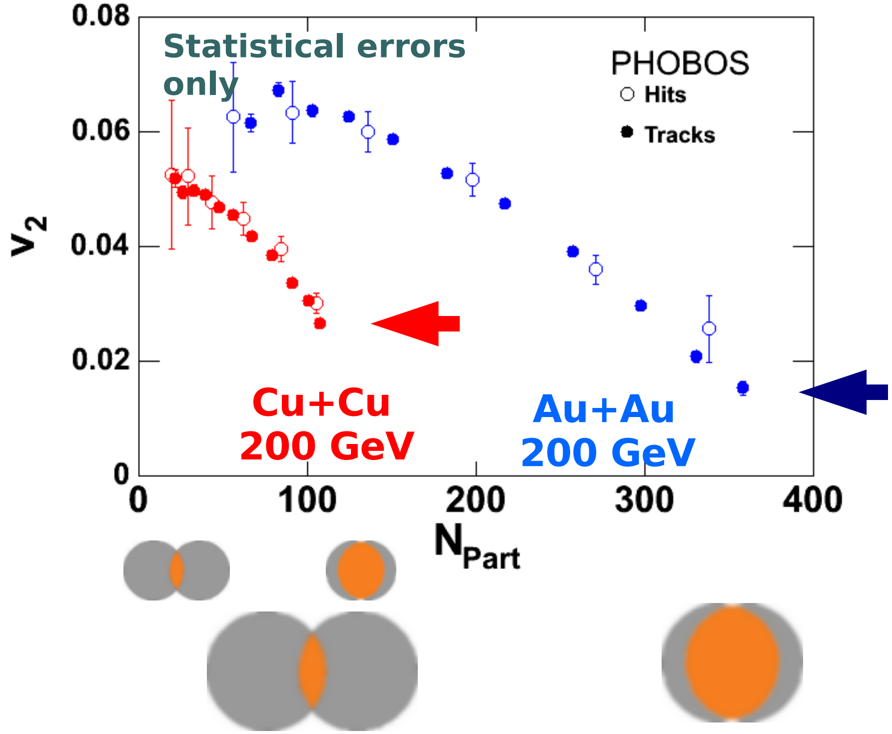




Elliptic flow v_2 decreases with N_{part}, as expected.

The value of the elliptic flow is consistent with predictions from hydrodynamic models for perfect liquid.

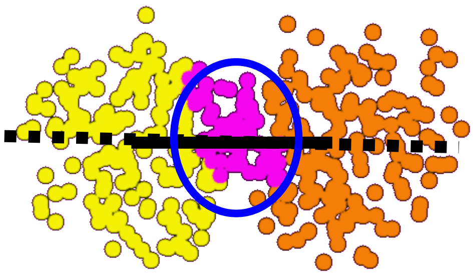
Elliptic flow



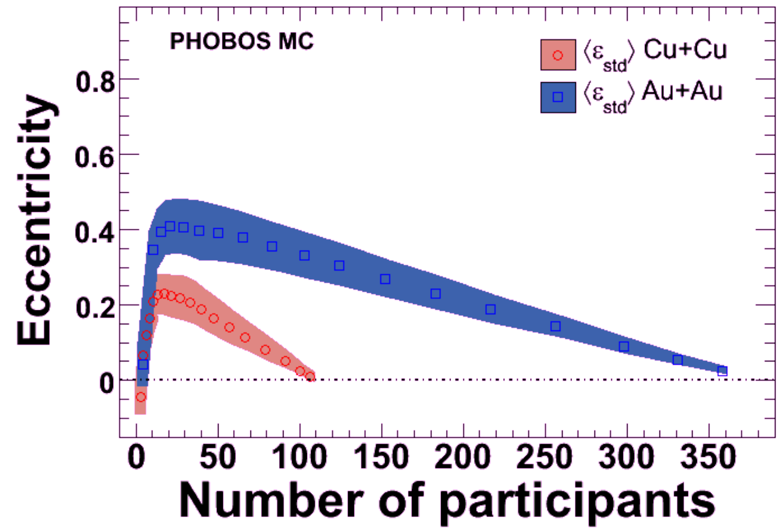
Elliptic flow is larger for the most central Cu+Cu collisions than for the most central Au+Au collisions

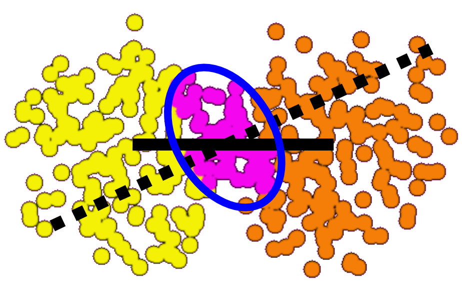
Elliptic flow

Eccentricity describes how far the interaction area deviates from azimuthal symmetry



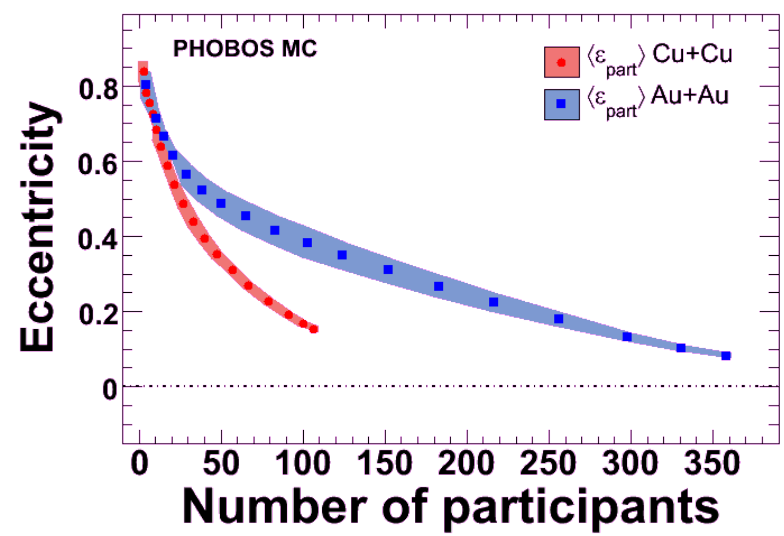
$$\varepsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$





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

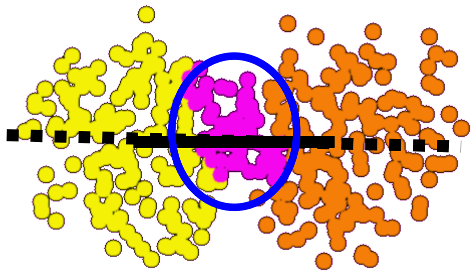
ε_{part} accounts for axis rotation and maximizes eccentricity

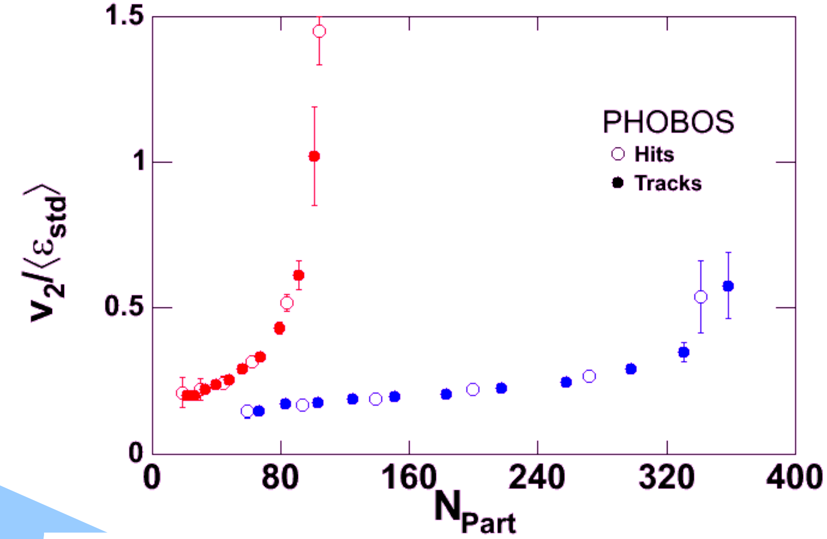


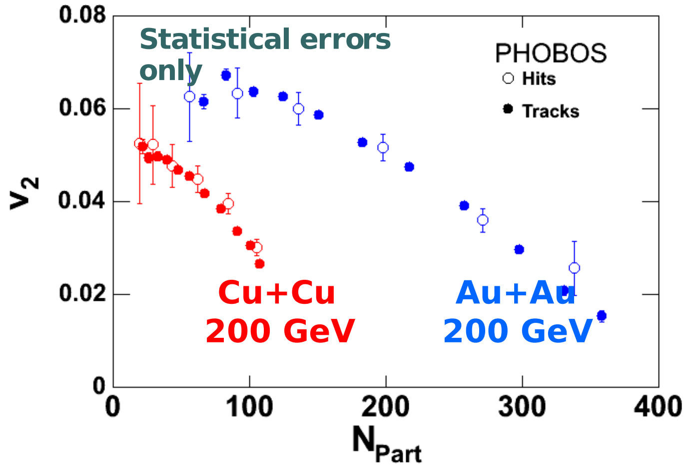
If elliptic flow reflects the shape of the interaction area, it should be proportional to the eccentricity.

Elliptic flow – divided by eccentricity

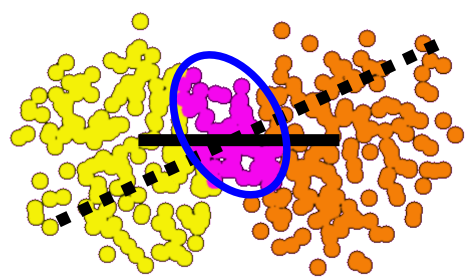
$$\varepsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

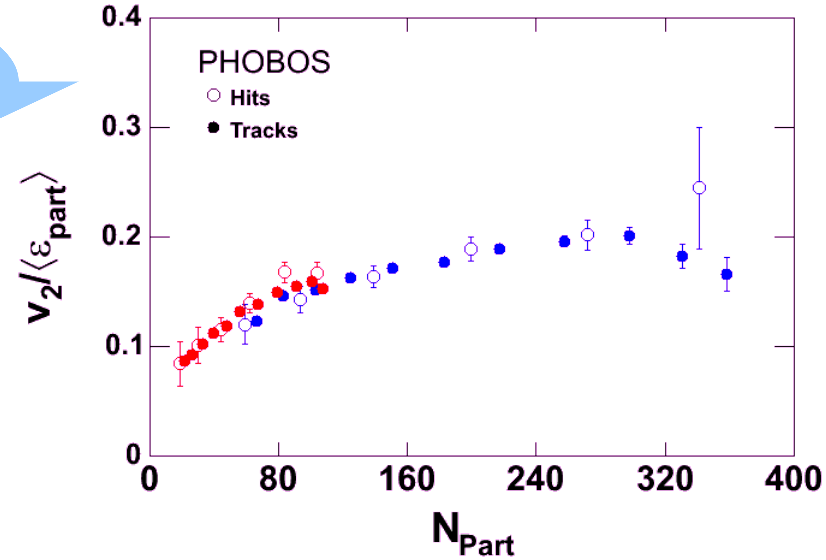






$$\varepsilon_{part} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$



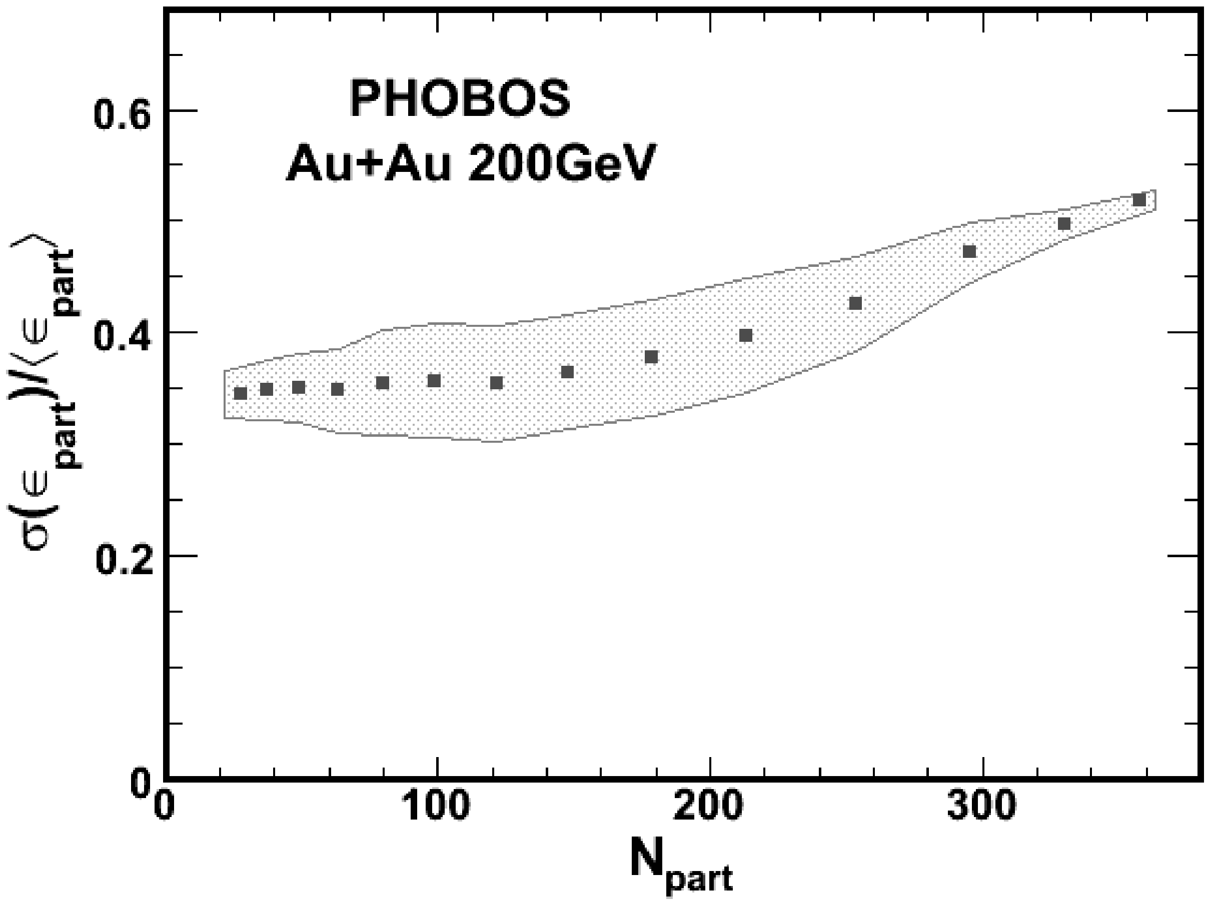


Magnitude of elliptic flow, v_2, depends on participant eccentricity ε_{part}

Phys. Rev. C 77, 014906 (2008)

Elliptic flow fluctuations

Eccentricity fluctuations (event by event) for events with very similar impact parameters can be calculated using Glauber Monte Carlo. Systematic uncertainties were obtained by varying the parameters of the model.



$$\sqrt{\left(\frac{4}{\pi}-1\right)} \simeq 0.52$$

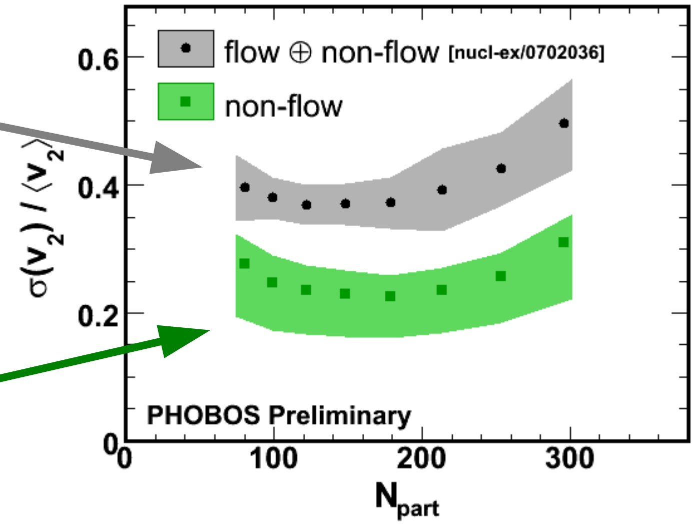
Analytic calculations

W.Broniowski PoS(CPOD07)014

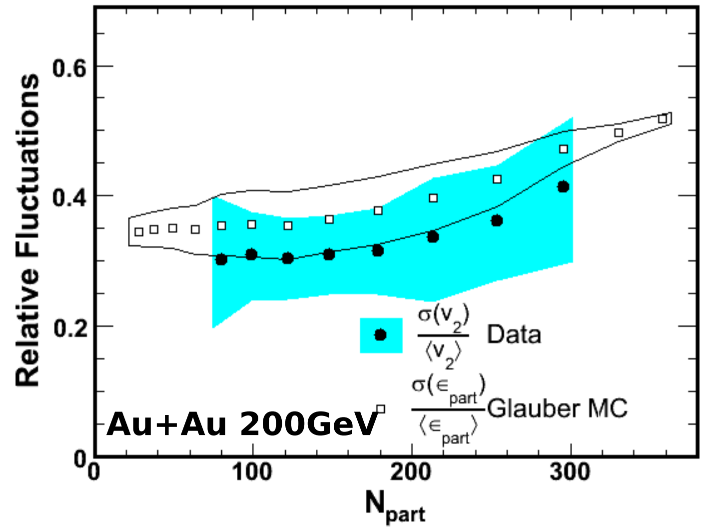
Elliptic flow fluctuations

Measured elliptic flow fluctuations contain also a contribution from non-flow effects.

This additional contribution originates mainly from **short range correlations**



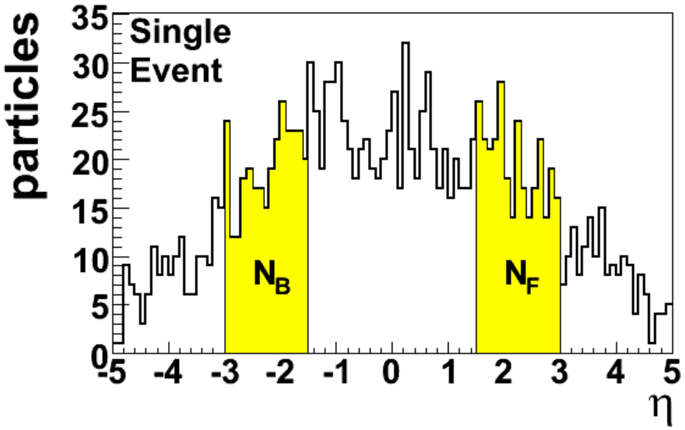
Reconstructed elliptic flow fluctuations are consistent within systematic errors with the fluctuations of eccentricity of the shape of interaction area.



In the evolution of the system created in the nucleus-nucleus collisions the fluctuations present at the very beginning are not enhanced **arXiv:0804.4297v1 [nucl-ex]**

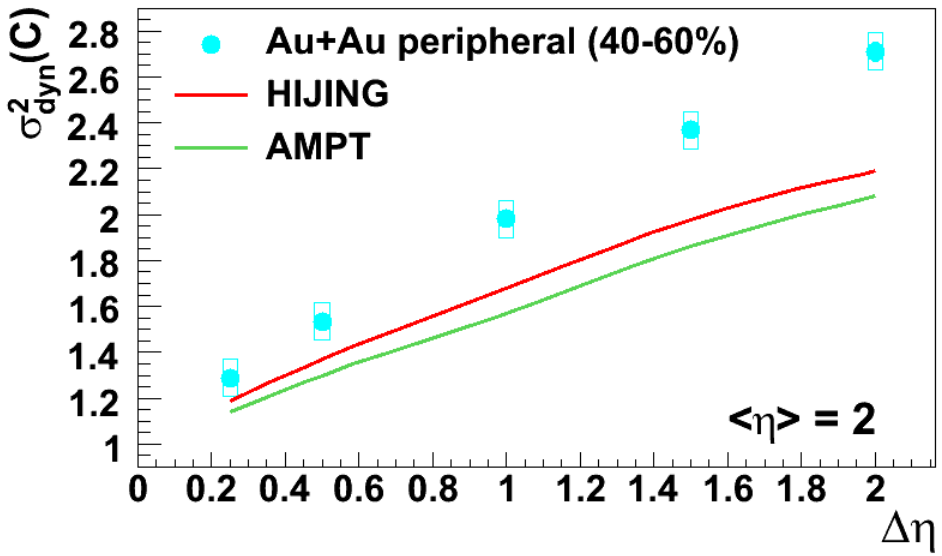
Fluctuations of the forward-backward multiplicities

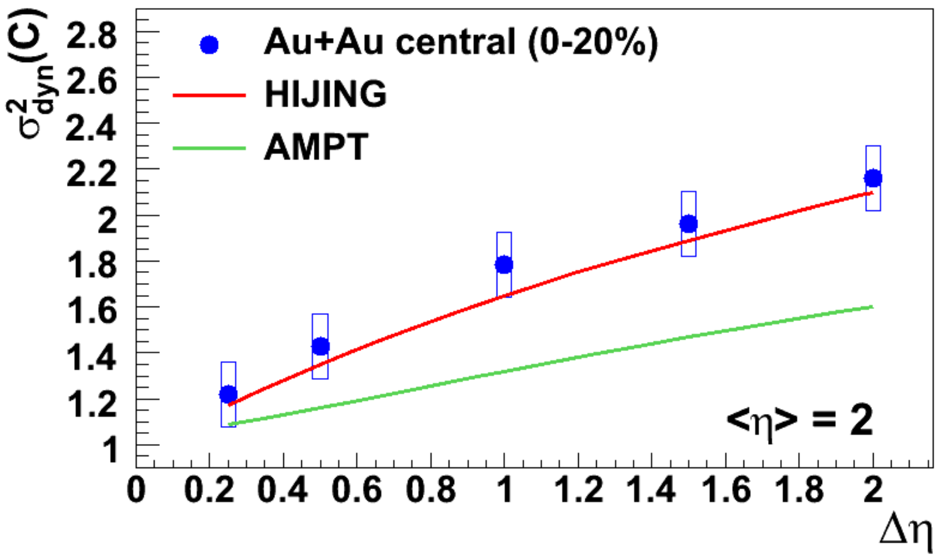
$$C = \frac{N_F - N_B}{\sqrt{N_F + N_B}}$$



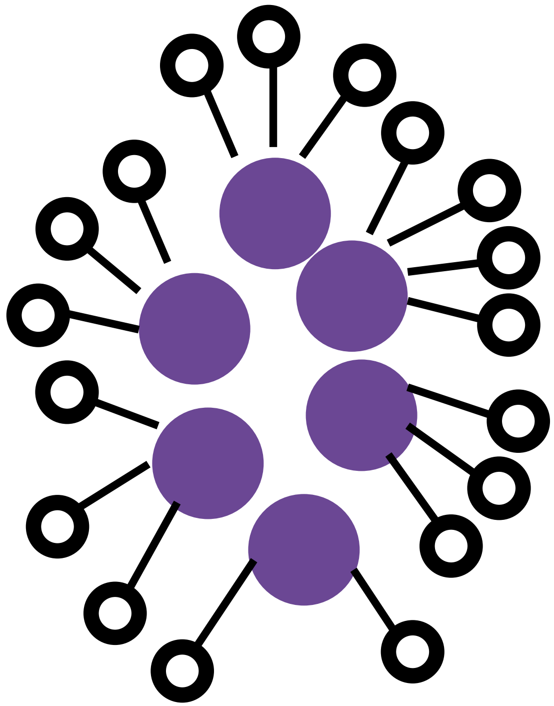
For statistical fluctuations: $\sigma^2(C) = 1$

Larger values of $\sigma^2(C)$ found in the data can be explained by short range correlations. These correlations are stronger than in the HIJING and AMPT models *Phys. Rev. C74, 011901(R) (2006)*





Simple cluster model

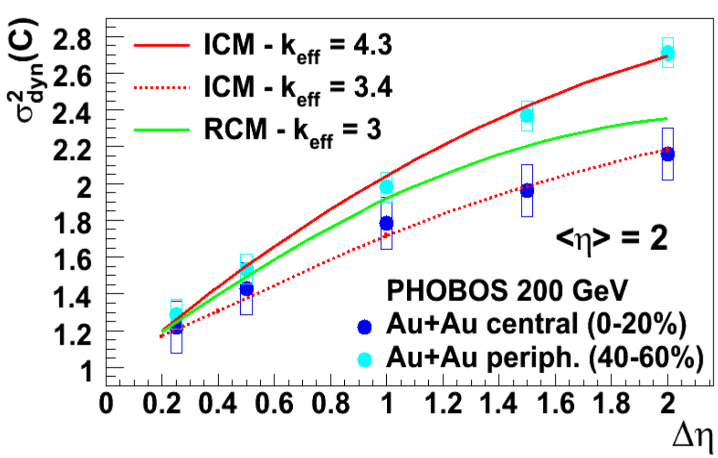


Short range correlations may be caused by production of particles in two steps:

- first some heavy, unstable objects, **clusters**, are created
- these clusters decay into particles measured in the detector

Variance of the C parameter is enhanced according to the number of particles originating from the cluster, k:

$$\sigma^2(C_{particle}) \leftrightarrow k\,\sigma^2(C_{clusters})$$

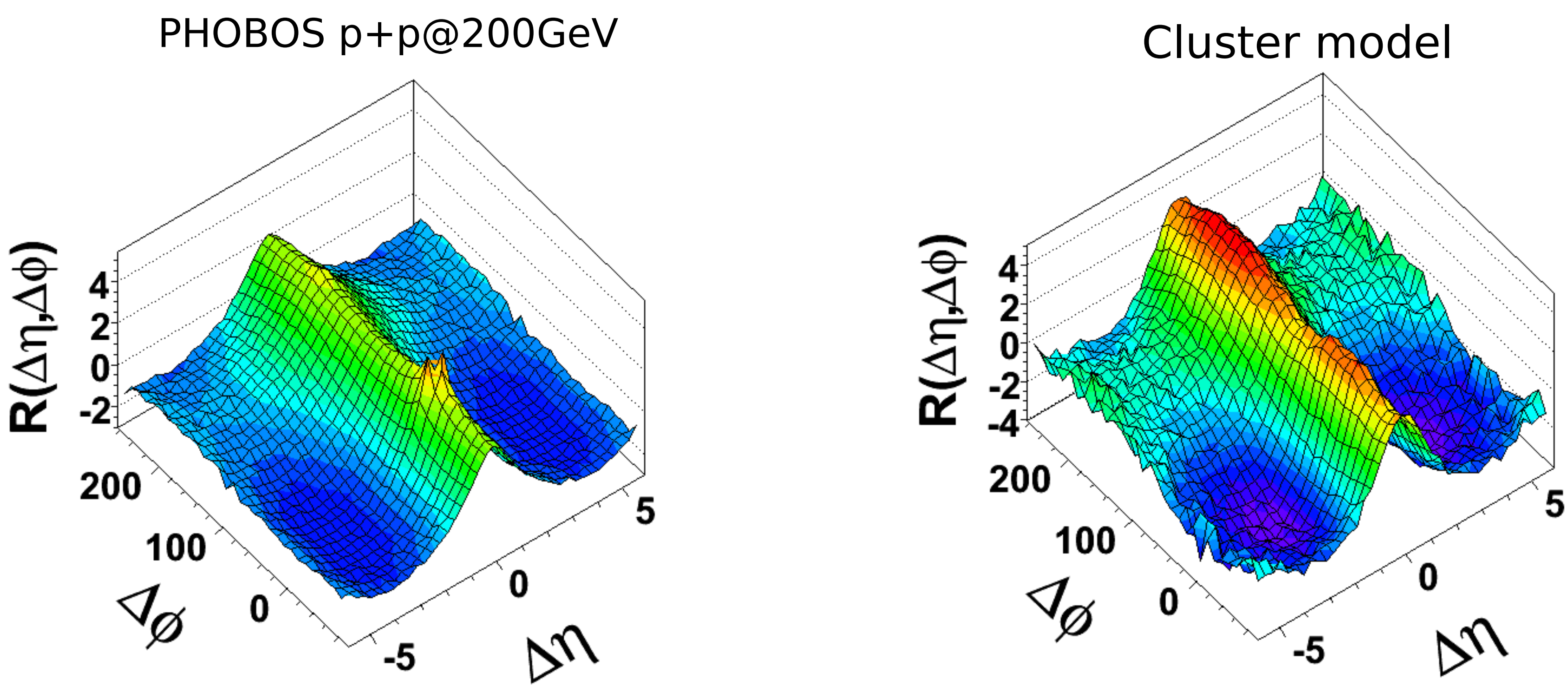


Simple cluster models can reproduce the data, but parameters of the clusters can not be reconstructed unambigiouosly

arXiv:nucl-ex/0702058v1

2-particle correlations

Measurement for elementary p+p collisions



$\Delta\eta=\eta_1-\eta_2$

$\Delta\phi=\phi_1-\phi_2$

Phys. Rev. C75(2007)054913

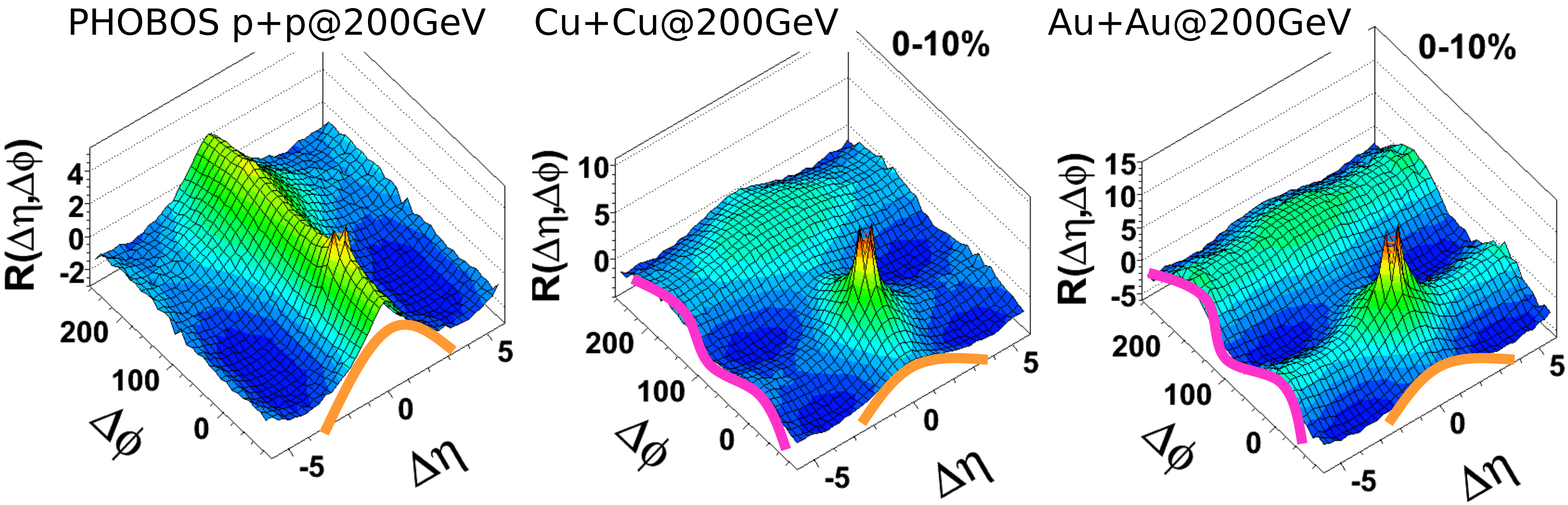
$$R(\Delta\eta,\Delta\phi)=\left\langle (n-1)\frac{F_n(\Delta\eta,\Delta\phi)}{B_n(\Delta\eta,\Delta\phi)}-1\right\rangle$$

measured particle density

background

n - event multiplicity normalization term

2-particle correlations



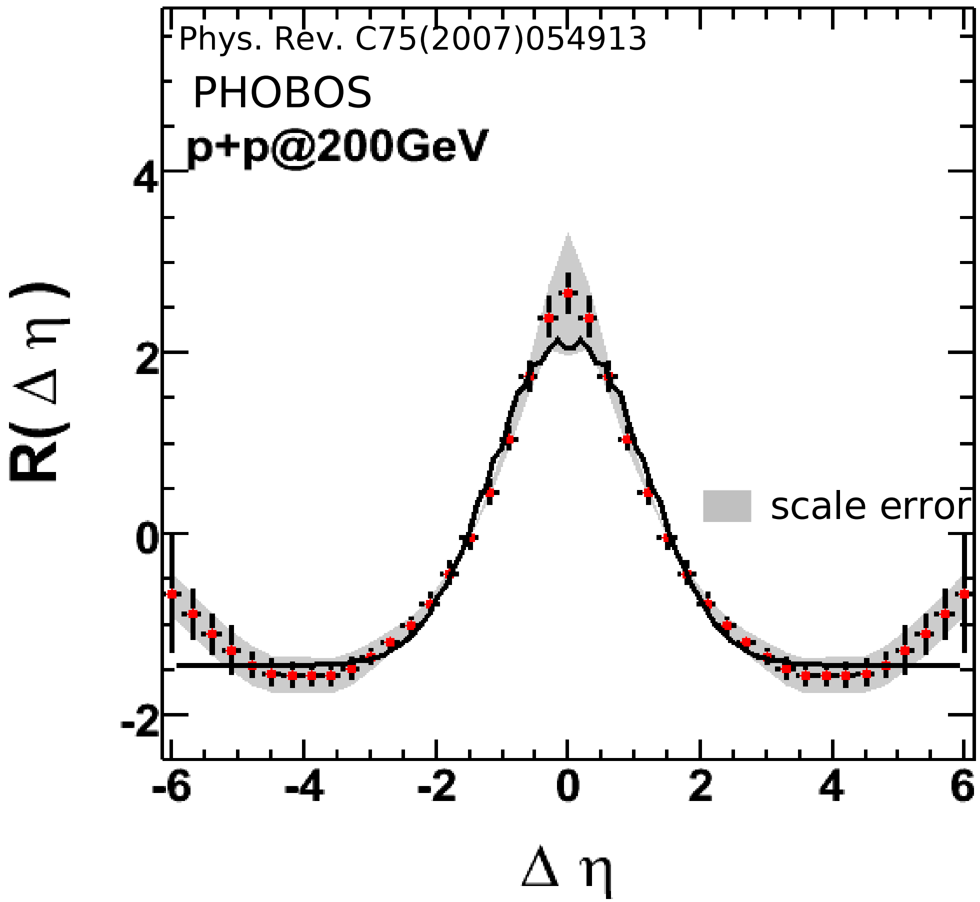
Phys. Rev. C75(2007)054913

PHOBOS preliminary

Similar structure in p+p, Cu+Cu and Au+Au collisions, but in the A+A collisions a trace of elliptic flow is visible.

2-particle correlations

Analysis of correlation in pseudorapidity ***η*** enables to extract effective parameters of the clusters: number of particles forming the cluster, k_{eff}, and the width, δ, in pseudorapidity.



Fitted function:

$$R(\Delta\eta)=(k_{eff}-1)\left(\frac{G(\Delta\eta)}{B(\Delta\eta)}-1\right)$$

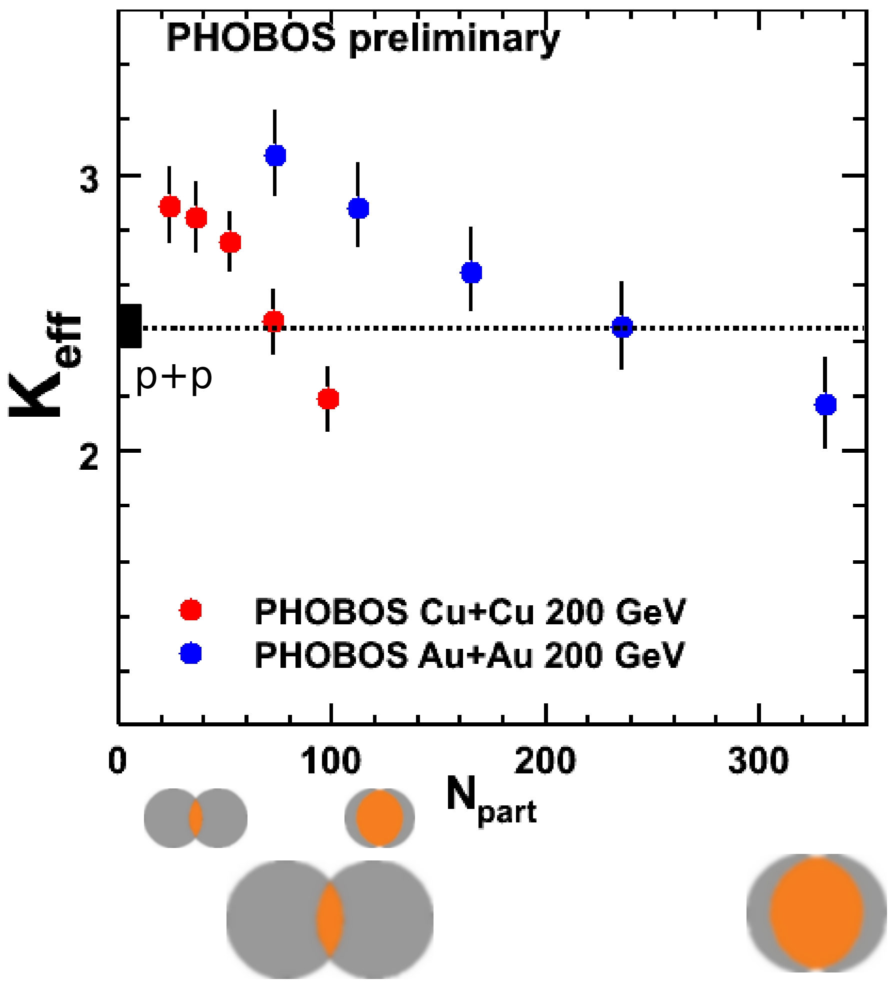
where:

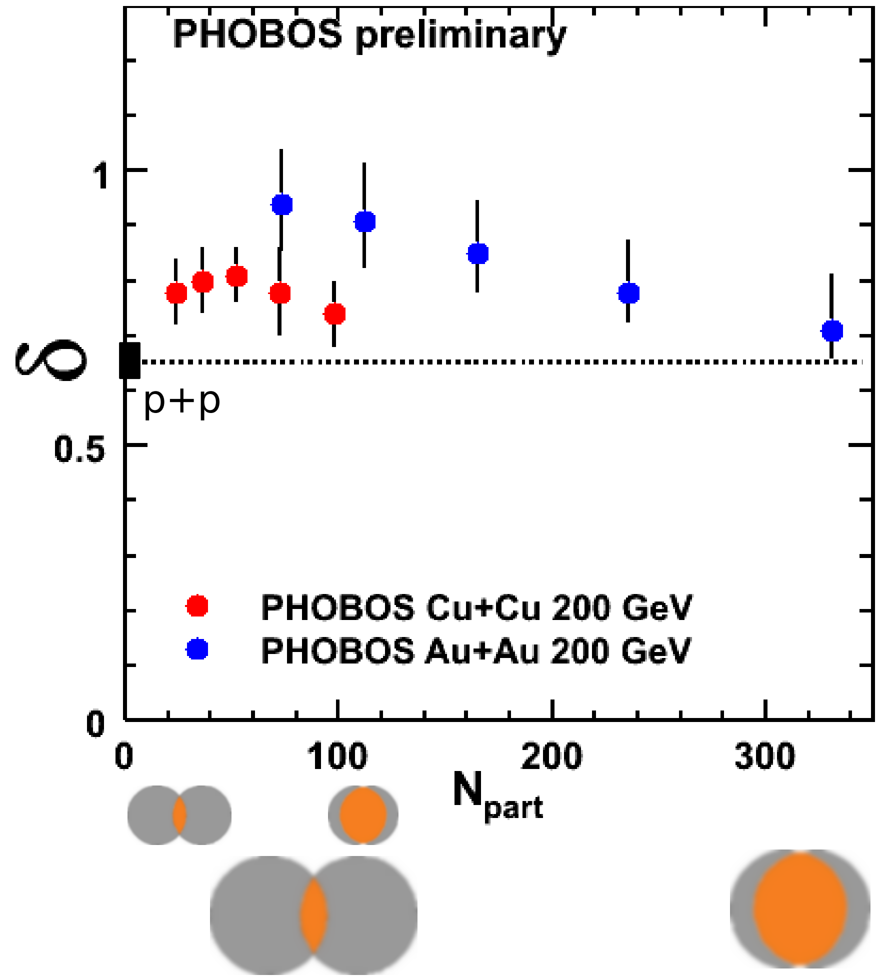
$$G(\Delta\eta)\simeq\exp\left(\frac{-(\Delta\eta)^2}{4\delta^2}\right)$$

$$B(\Delta\eta)-background$$

2-particle correlations

Corrections for acceptance (limited to $|\eta|<3$) were not done.

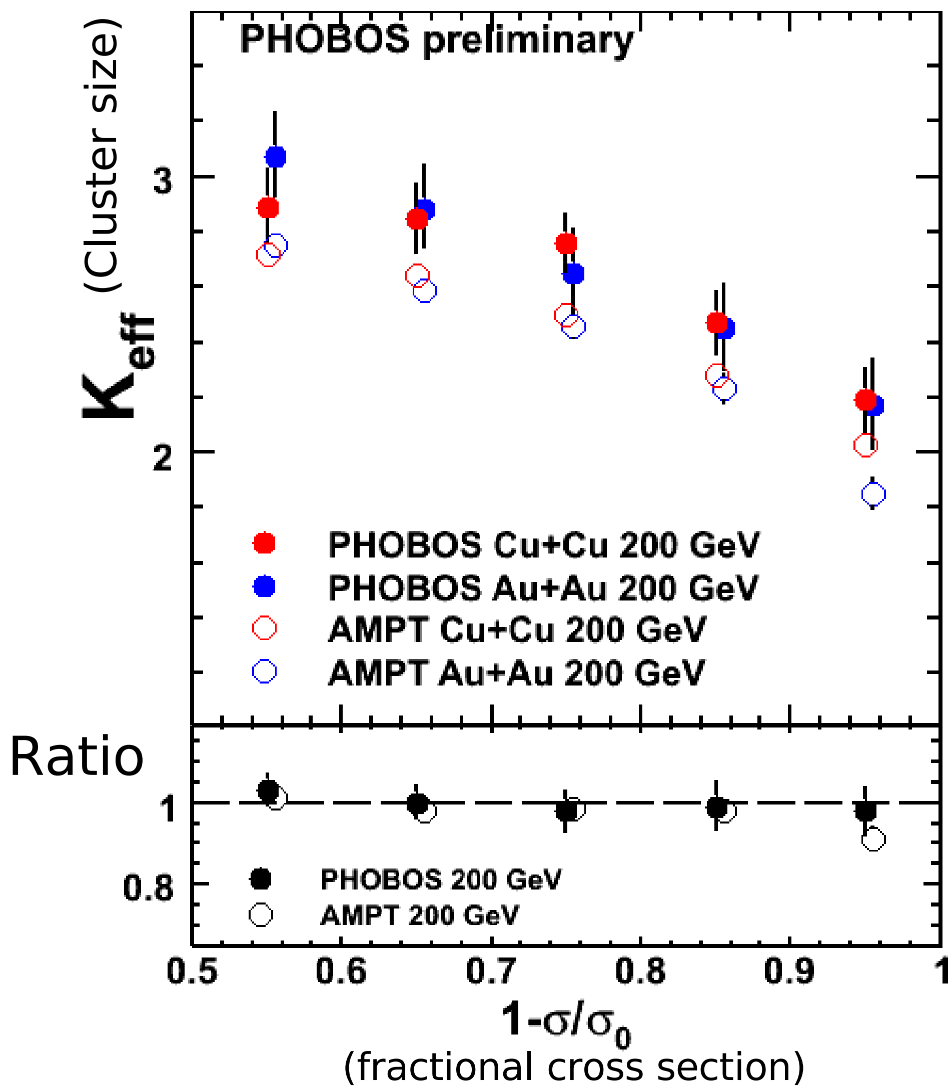




Multiplicity of the particles in the clusters decreases with centrality, width of the clusters in η is larger in A+A collisions than in p+p collisions.

Correlations involving so many particles can not be explained by low mass resonances (3 GeV or less) only.

2-particle correlations



Multiplicity of the particles in the clusters is very similar in Au+Au and Cu+Cu collisions at the same centrality, defined as the same fraction of cross section.

Does it mean that the shape of the interaction area determines even the properties of hadronization?

Summary

Latest results from PHOBOS experiment:

- correlations of associated particles with a high p_T trigger particle extend at least 4 units in pseudorapidity; this may be a sign of longitudinal expansion of the system; also the yields of low p_T particles are consistent with an radial expansion.
- shape of the interaction area, characterized by eccentricity ε_{part}, determines the value of elliptic flow, v2; fluctuations of elliptic flow are of the same size as the fluctuations of eccentricity at the very beginning of the collision
- strong short range correlations are observed in the A+A collisions, large size of clusters can not be explained by low mass resonances

Conclusions

- In the collisions of heavy nuclei at very high energies extremely high energy density is reached and a new phase of matter, sQGP, is created, which resembles a perfect liquid
- Strong interactions in the quark-gluon matter are visible as suppression of high p_T particles, no enhancement of low p_T particles production and presence of collective effects leading to elliptic flow.
- The yields of low p_T particles and the elliptic flow are consistent with the assumption of expansion of the system as predicted by hydrodynamic model for an almost perfect fluid.
- Global observables in the collisions of nuclei reveal unexpected simple relations: scaling of multiplicity with N_{part} and extended longitudinal scaling of $dN/d\eta$ and v_2.

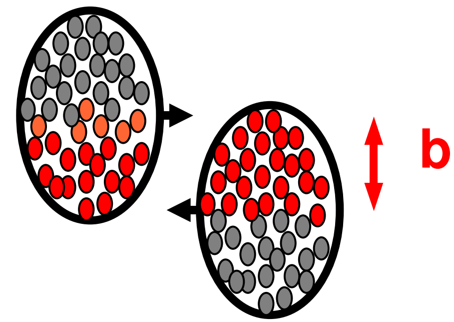
Backup

N_{part} and N_{coll}

Number of nucleons participation in the collision:

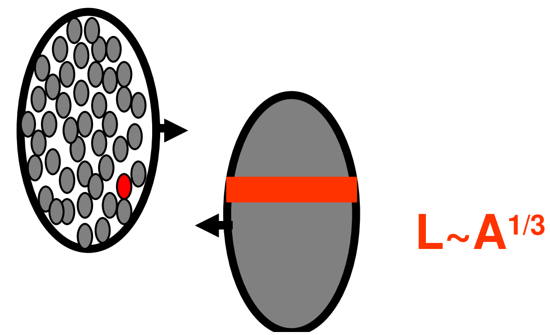
$N_{part} \sim A$

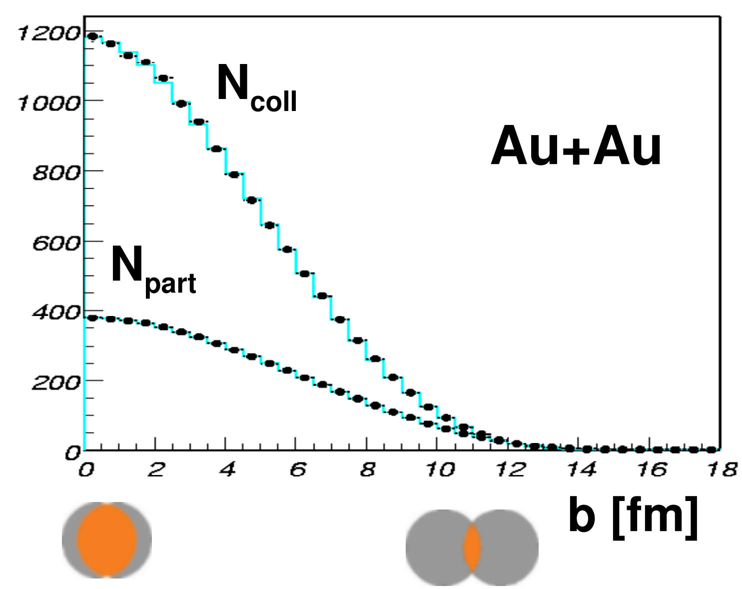
er



Number of nucleon-nucleon collisions:

$N_{coll} \sim A^{4/3}$





Global measurements

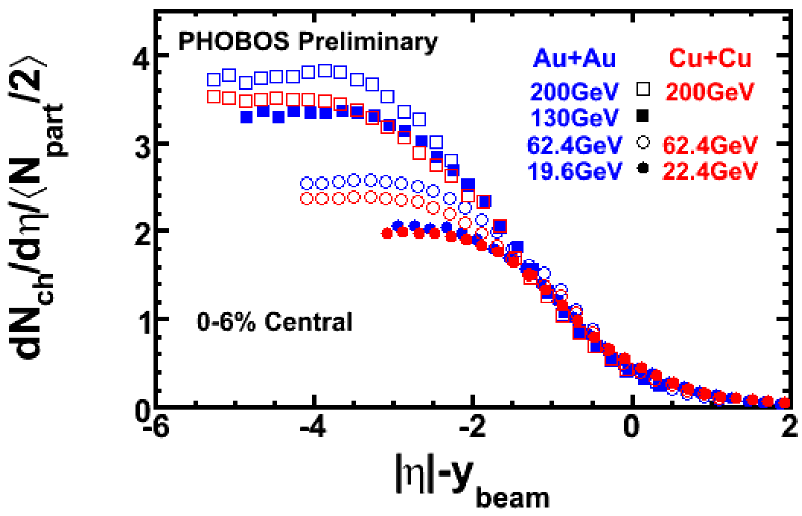
Relativistic Heavy Ion Collider in Brookhaven National Laboratory (USA):

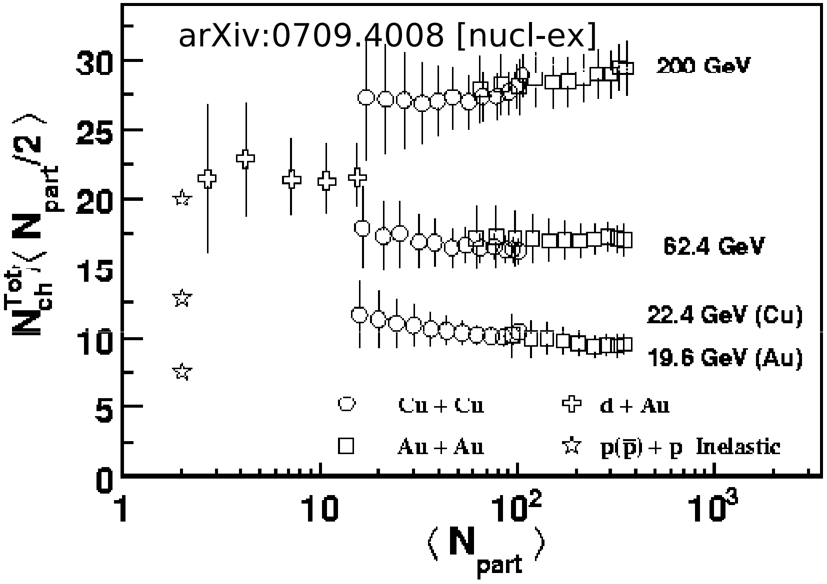
- Collisions of Au+Au, Cu+Cu, d+Au and p+p
- Energy per nucleon in CM frame $\sqrt{s_{NN}}$ from 19 to 200 GeV

General properties of A+A collisions:

- scaling of total multiplicity with N_{part}
- extended longitudinal scaling

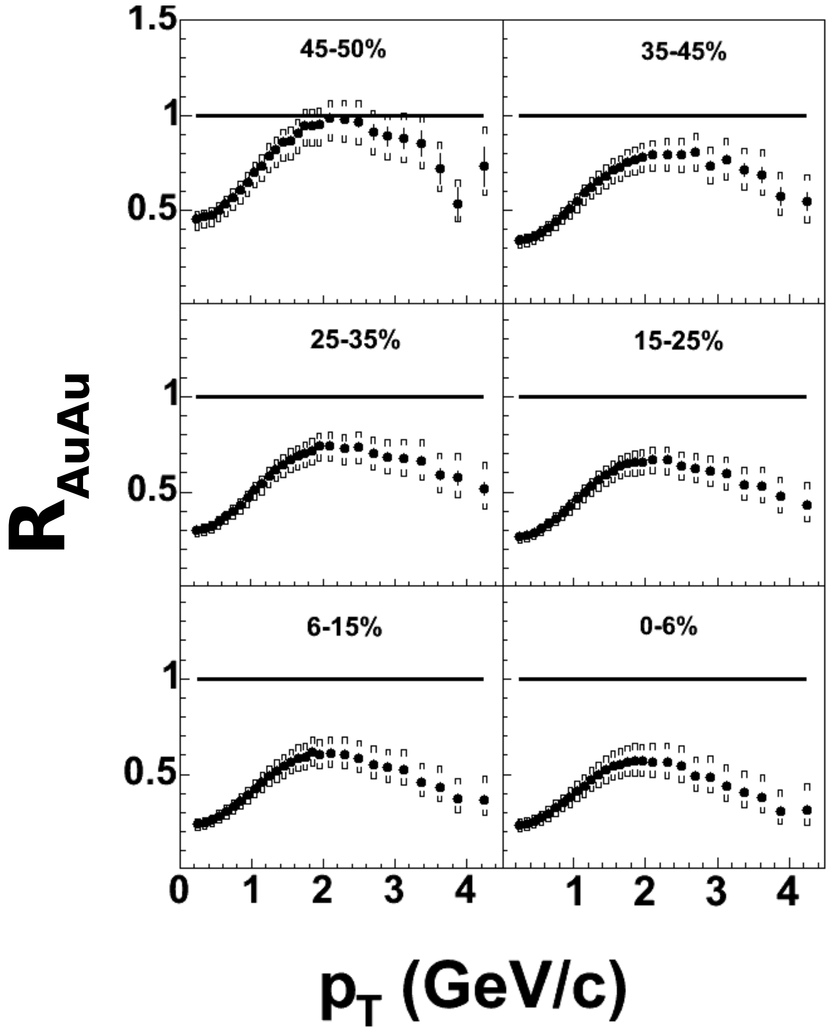
arXiv:0709.4008 [nucl-ex]

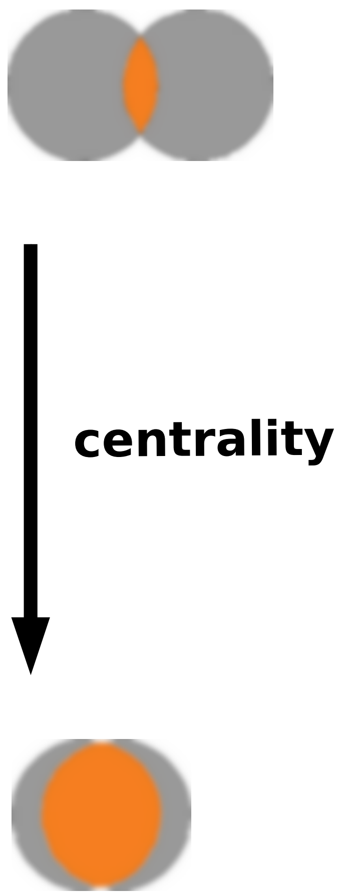




N_{part} – number of nucleons participating in A+A collision

Dependence on event centrality

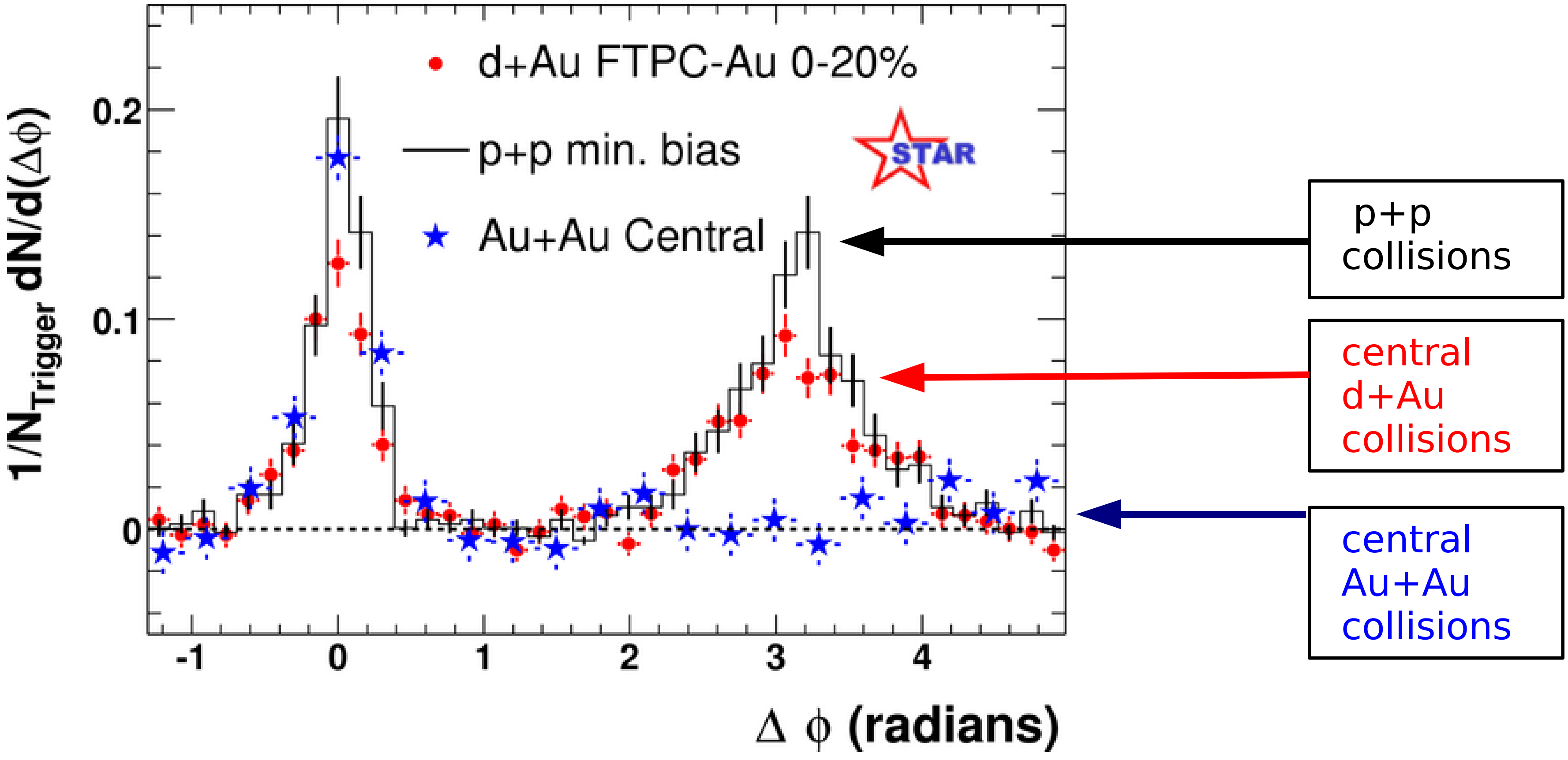




$$R_{AuAu}=\frac{\sigma^{inel}_{p\bar{p}}}{N_{coll}}\frac{d^2N_{AuAu}/dp_T\,d\eta}{d^2\sigma_{p\bar{p}}/dp_T\,d\eta}$$

High p_T suppression

STAR results:



Correlations with trigger particle, p_T > 2.5 GeV/c

Flow removal - subtraction of flow modulated background:

$$\frac{1}{N_{trig}} \frac{d^2 N_{ch}}{d\Delta\phi \, d\Delta\eta} = S(\Delta\phi, \Delta\eta) \; - \; B(\Delta\phi, \Delta\eta) \; \mathbf{a} \left[1 - 2V(\Delta\eta)\cos(2\Delta\phi) \right]$$

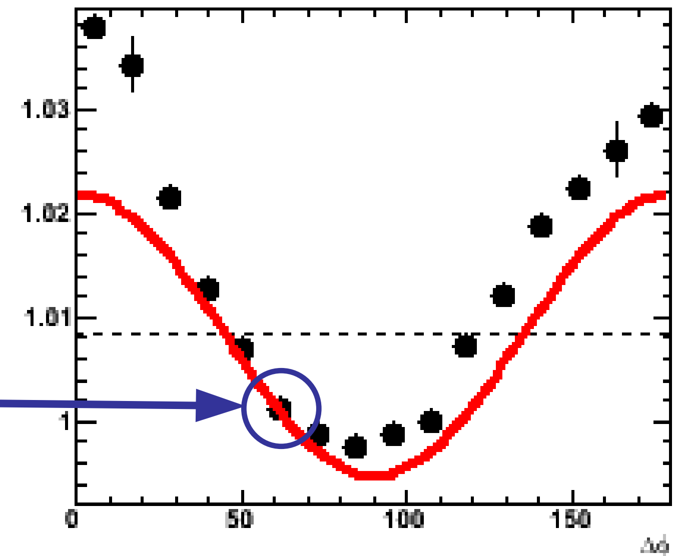
$\mathbf{V = \langle v_2^{trig} \rangle \langle v_2^{assoc} \rangle}$

Acceptance corrected mixed-event pairs (per trigger)

Modulation from elliptic flow

Signal/Background
Detector acceptance cancels in the ratio

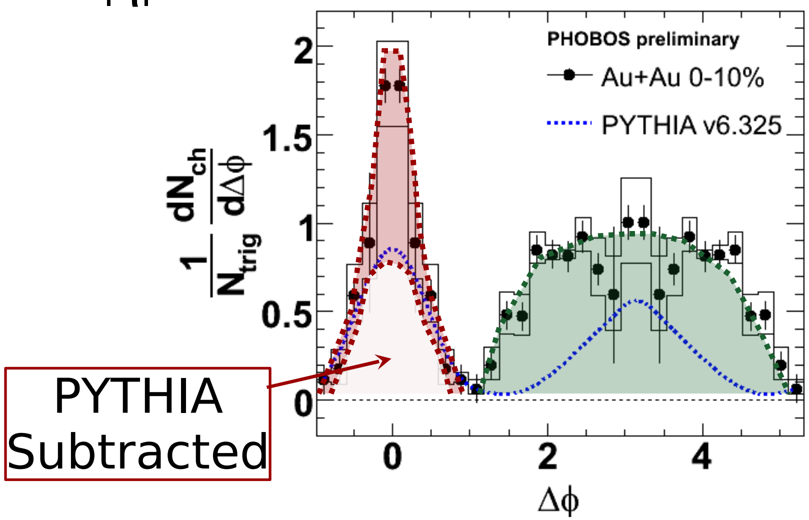
Scale factor, a,
calculated such that the yield after subtraction is zero at its minimum (ZYAM)



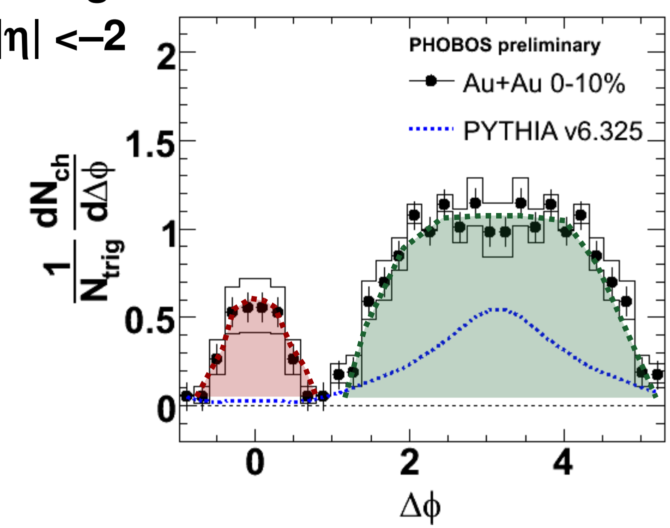
Correlations with trigger particle, p_T > 2.5 GeV/c

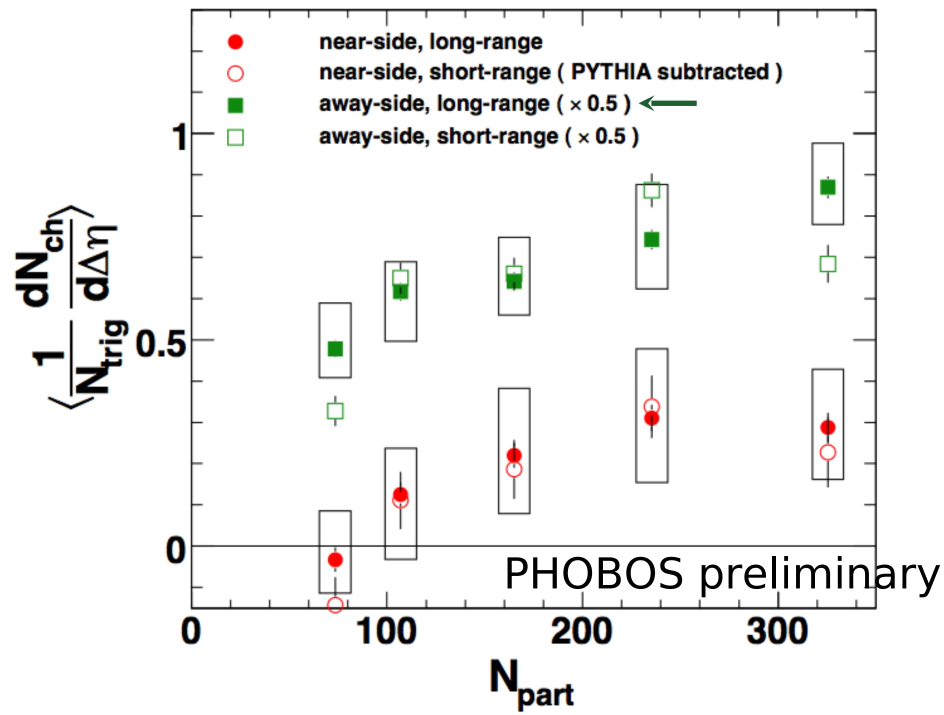
Integration od the ridge

Short-range
|η| <1



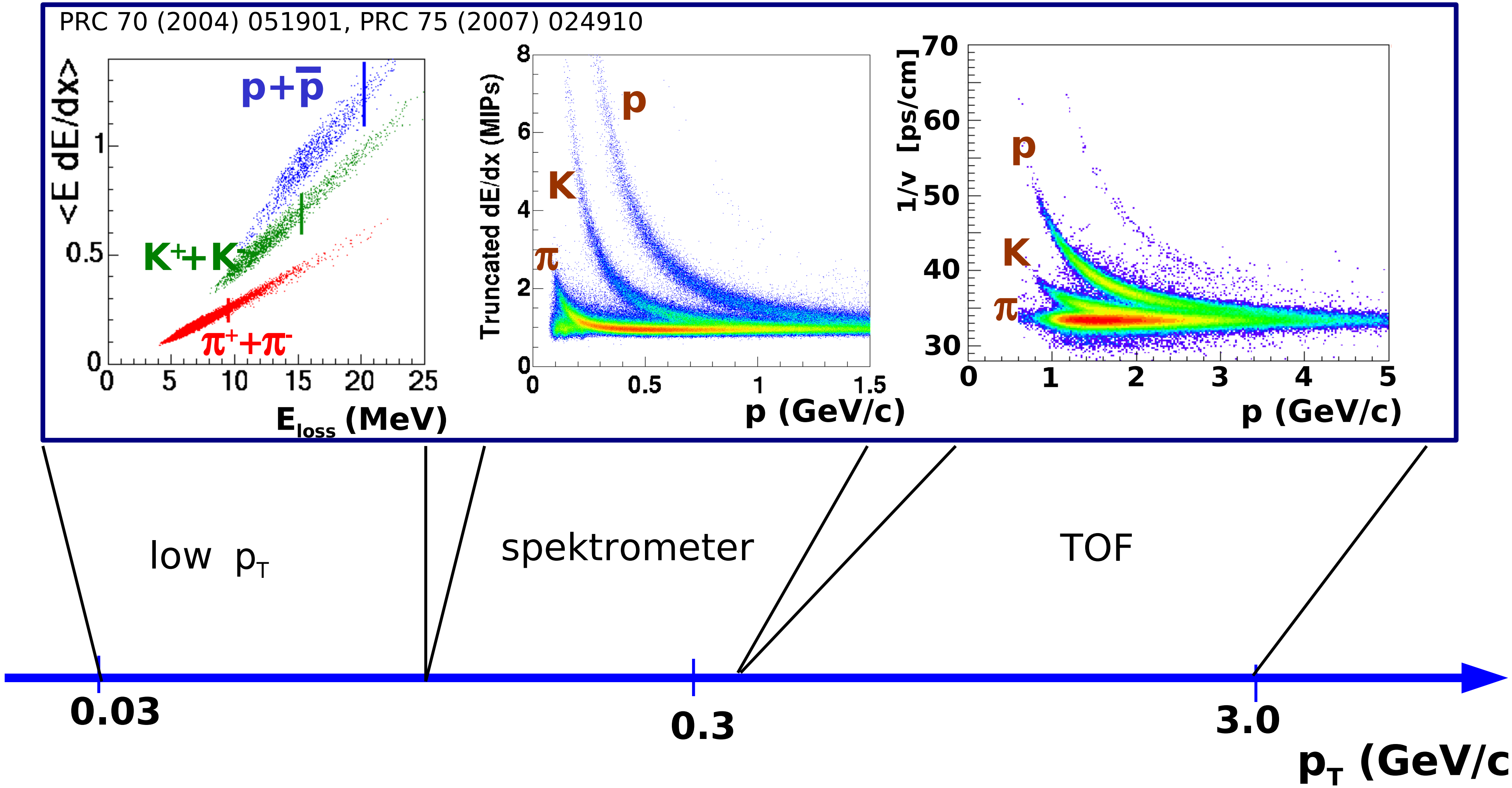
Long-range
–4< |η| <–2





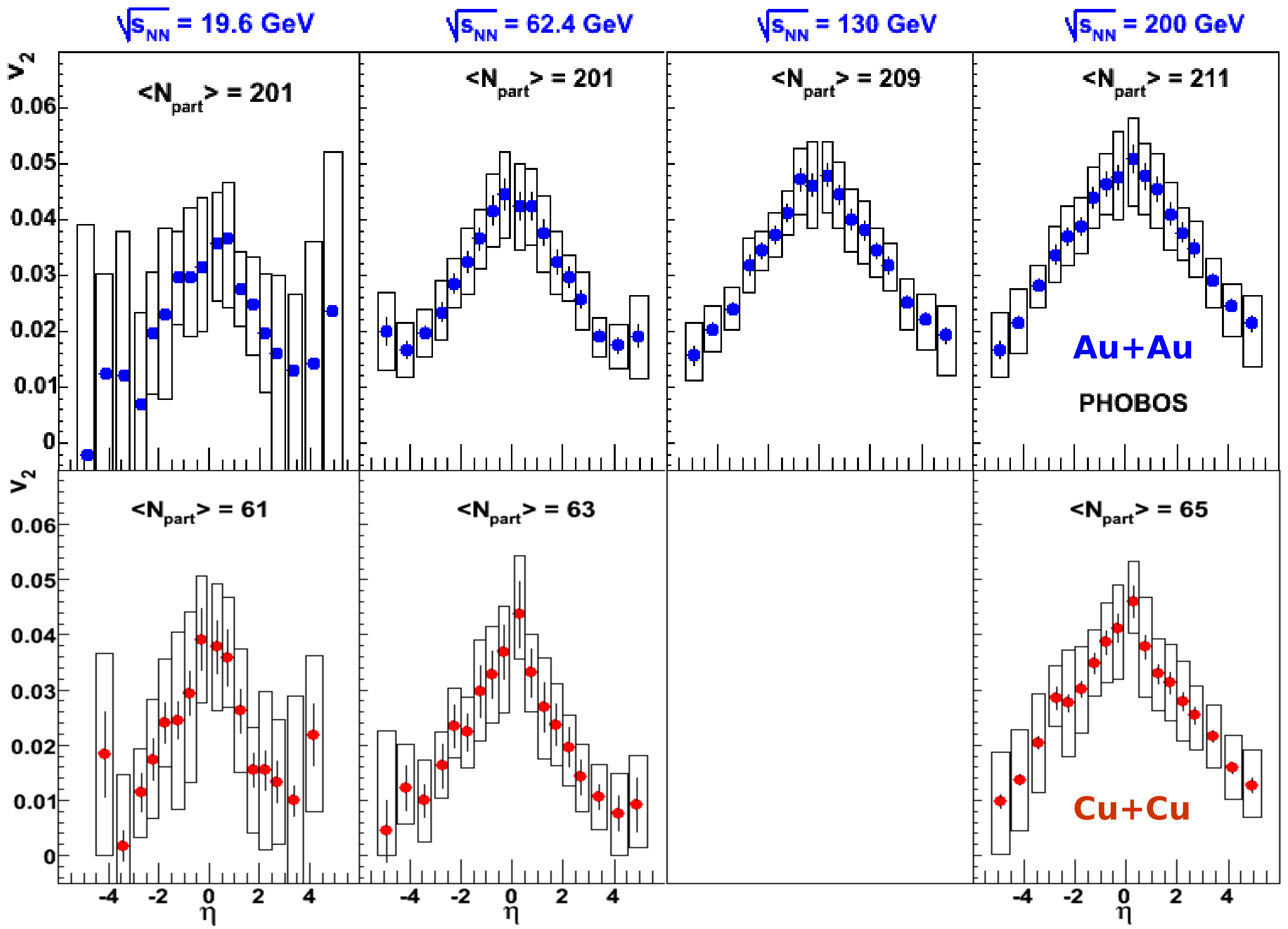
Broadening of “away side” and “Ridge” larger for more central events

Mesurements in the spectometer



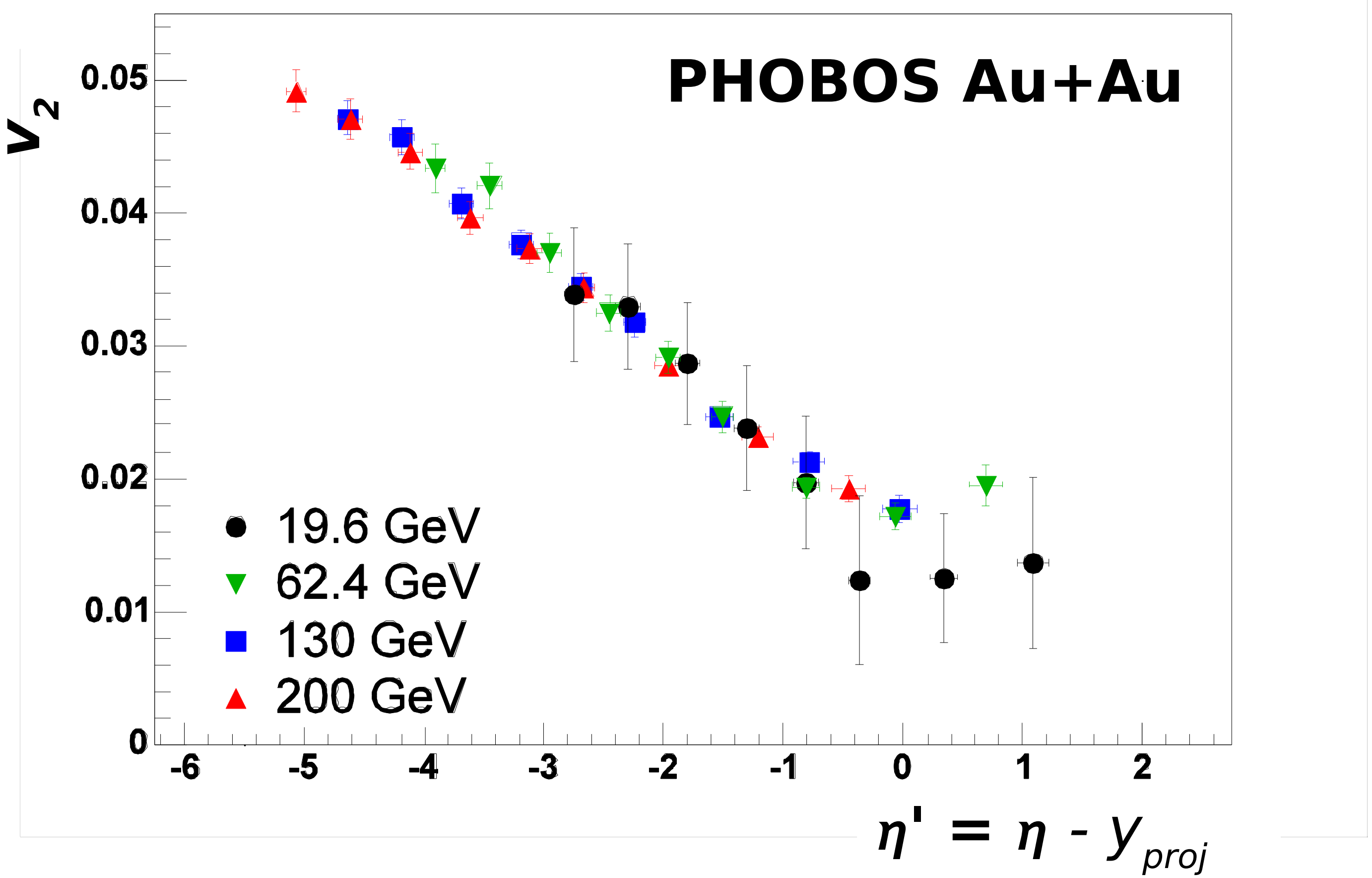
mass only | **mass and charge** | **charge only**

Elliptic flow



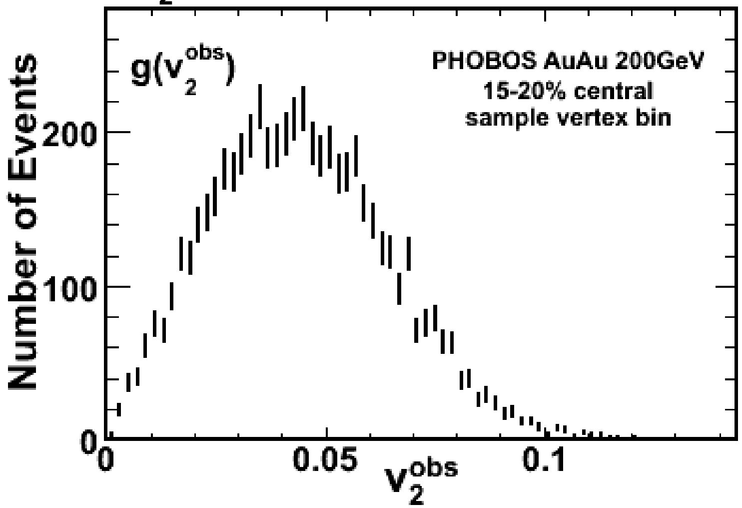
PRL 98 (2007) 242302,
PRC 72 (2005) 051901,
PRL 94 (2005) 122303

Elliptic flow – extended longitudinal scaling

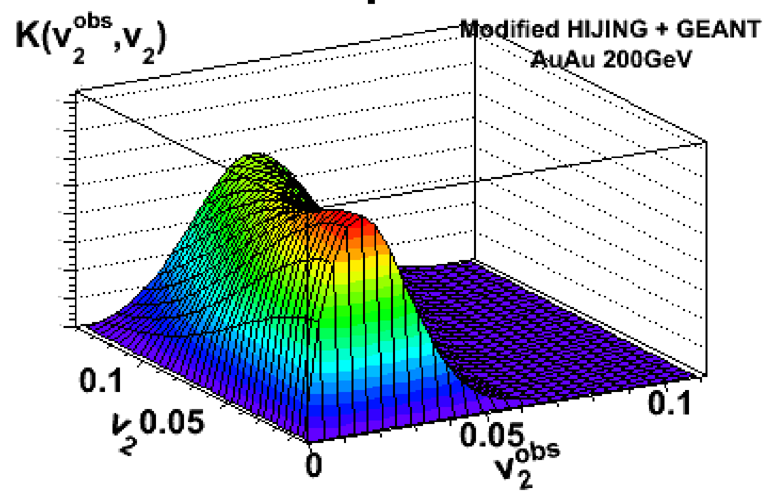


Elliptic flow fluctuations - measurement

v_2^{obs} distribution in "data"



Kernel – Response Function

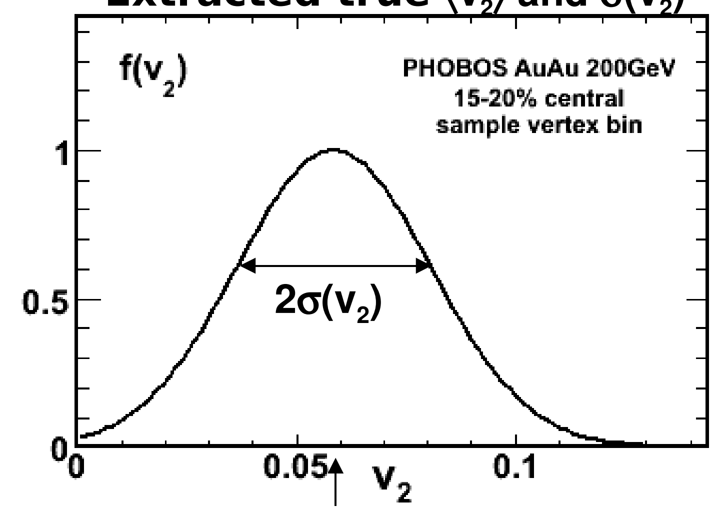


- Event-by-event measurement
- Determination of response in MC
- Extraction of true $\langle v_2 \rangle$ and $\sigma(v_2)$

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

arXiv:nucl-ex/0702036

Extracted true $\langle v_2 \rangle$ and $\sigma(v_2)$



Elliptic flow fluctuations

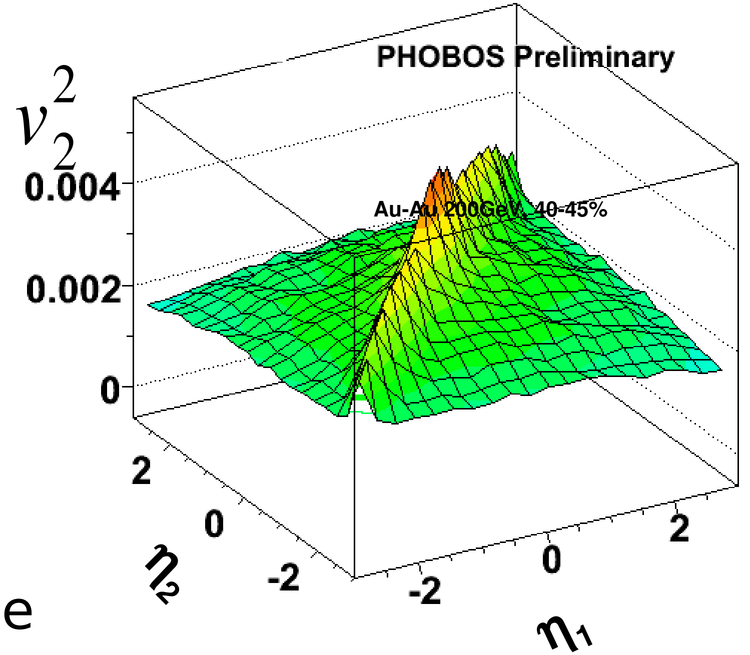
Measured fluctuations contain contribution from non-flow effects – mainly from short range correlations

Non-flow term: $\delta = \langle\cos(2\Delta\phi)\rangle_{non\text{-}flow}$, $\Delta\phi=\phi_1-\phi_2$

For each η_1 and η_2 measure the two-particle correlations in $\Delta\phi$:

$$R_n(\eta_1, \eta_2, \Delta\varphi) \propto 2v_2^2(\eta_1, \eta_2)\cos(2\Delta\varphi)$$

$$v_2^2(\eta_1, \eta_2) = \underbrace{v_2(\eta_1)\cdot v_2(\eta_2)}_{\text{flow component}} + \underbrace{\delta(\eta_1, \eta_2)}_{\text{non-flow term}}$$

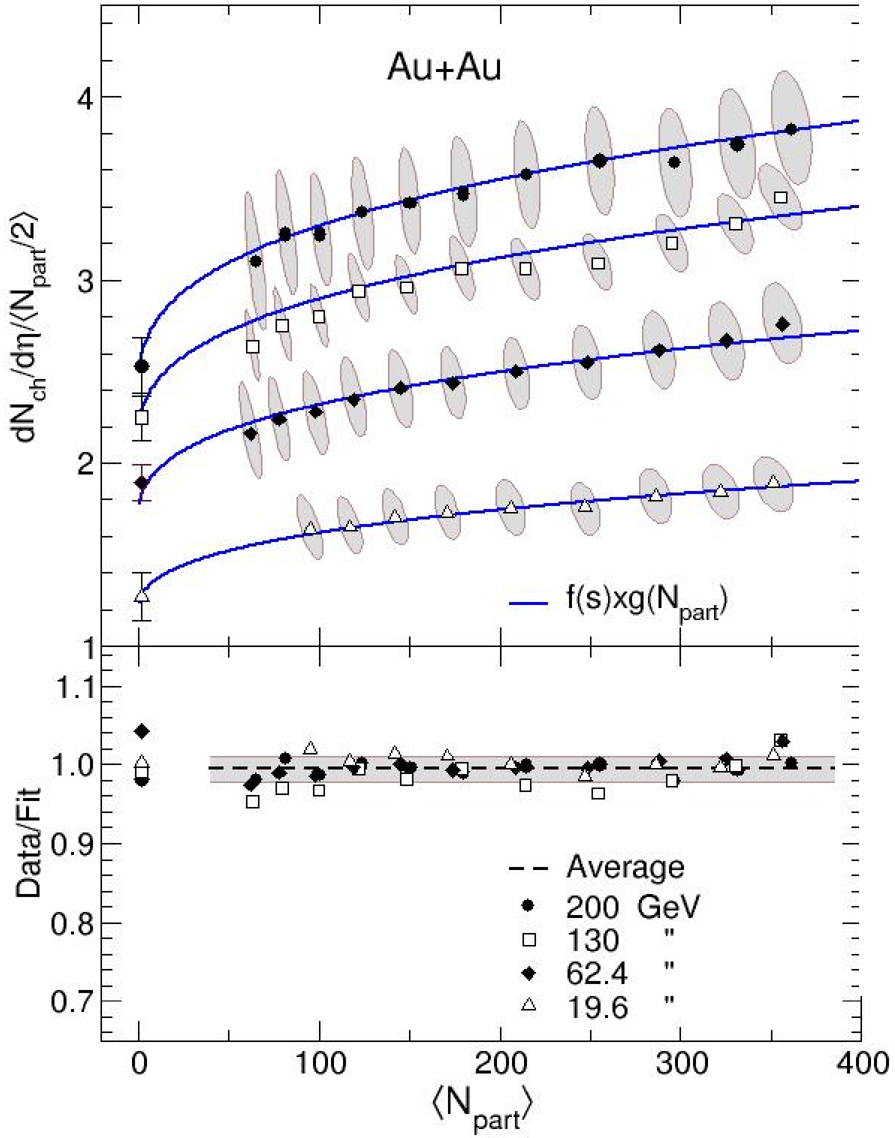


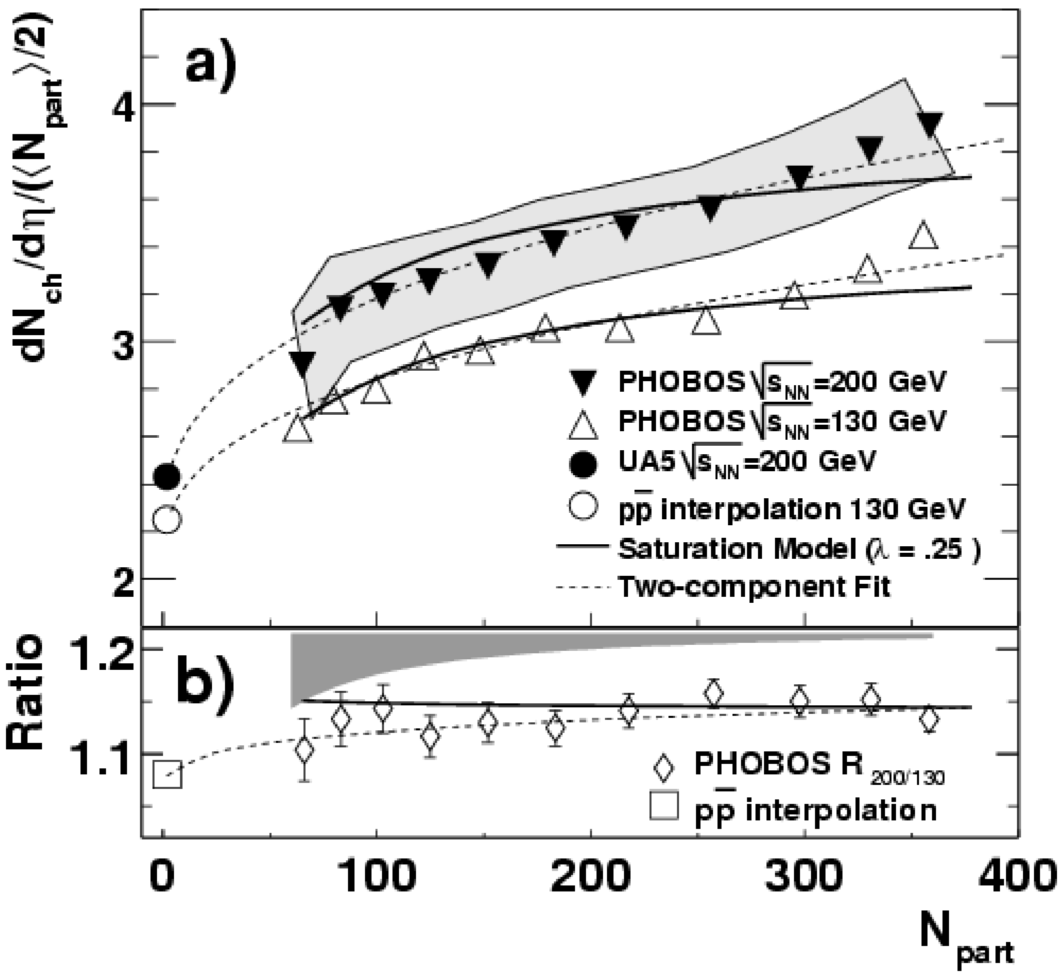
flow ⊕ non-flow

Flow component extracted at large η can be extrapolated and subtracted in order to obtain **δ :**

$$\delta(\eta_1, \eta_2) = v_2^2(\eta_1, \eta_2) - v_2(\eta_1)\cdot v_2(\eta_2)$$

Particle density at midrapidity





Particle ratios