RHIC-PHENIX実験における荷電ハドロン楕円フローの系統的研究

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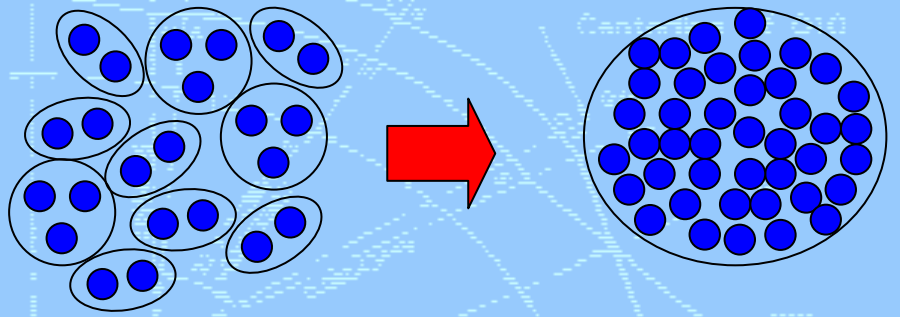
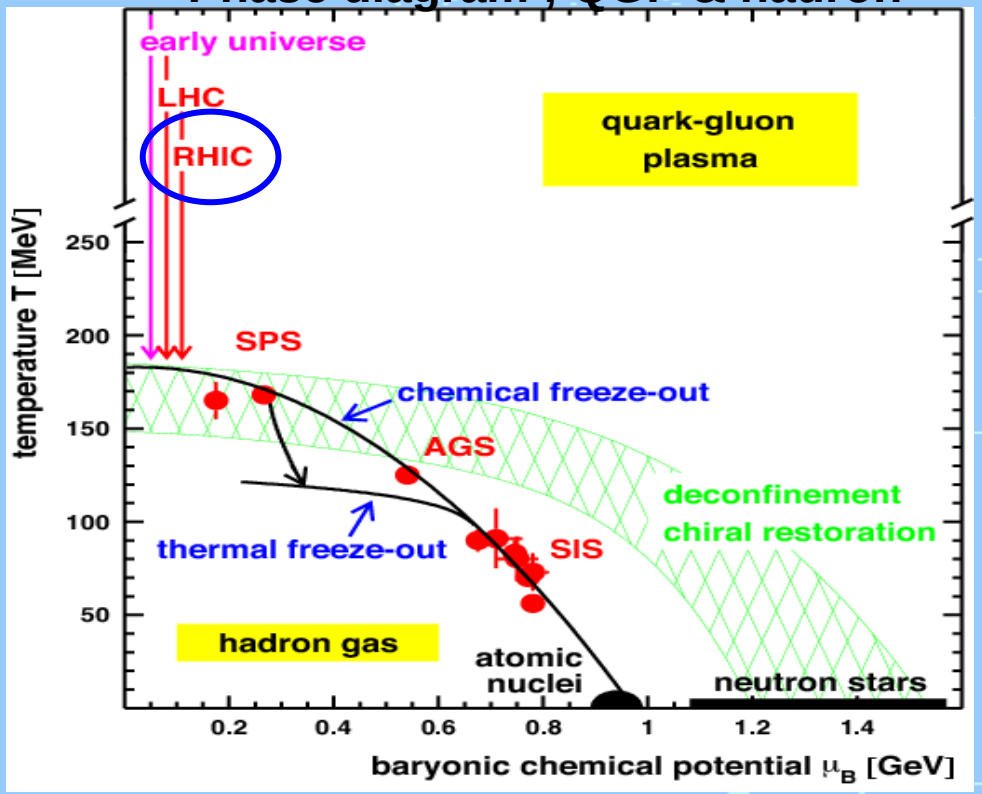
Quark Gluon Plasma (QGP)



Phase diagram ; QGP & hadron



- **Prediction from Lattice QCD**
  - **T ~ 170 MeV**
  - **ε ~ 1.0 GeV/fm³**

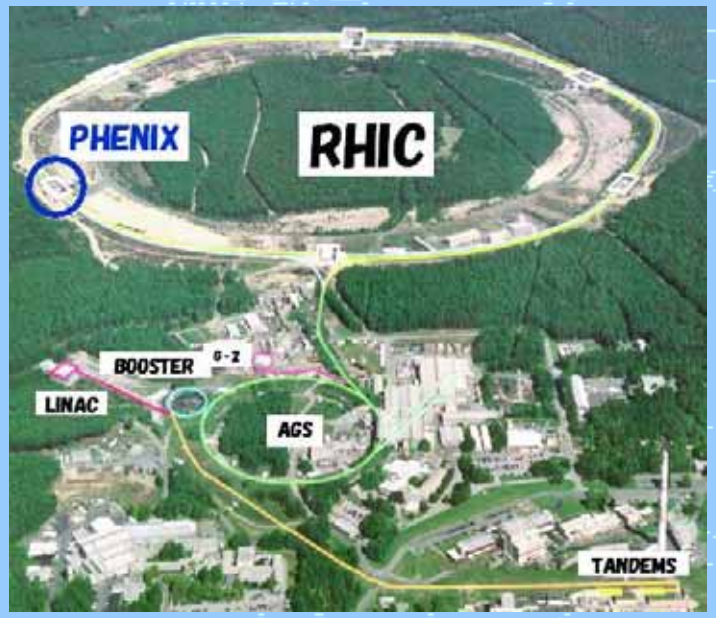
Quarks become de-comfined

Phase transition to QGP

*** Normal Nucleus: ε ~ 0.2 GeV/fm³**

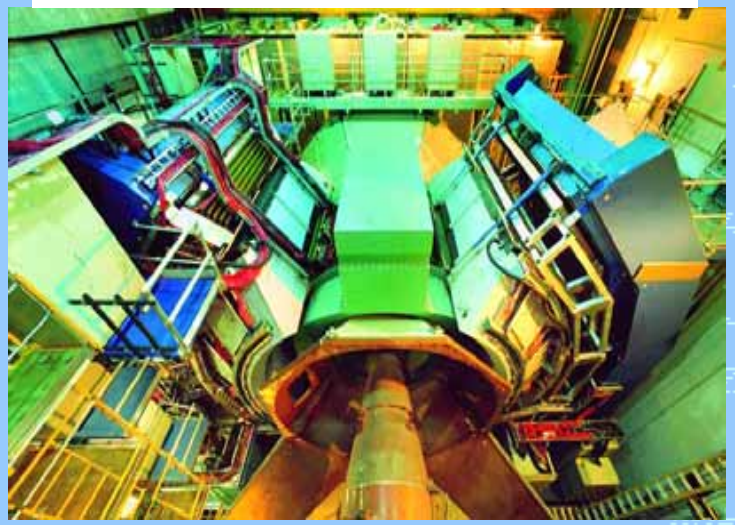
- **High energy nuclear collision**
  Au+Au $\sqrt{s}$=200GeV
  - **RHIC : 5 ~ 15 GeV/fm³**

Relativistic Heavy Ion Collider (RHIC)

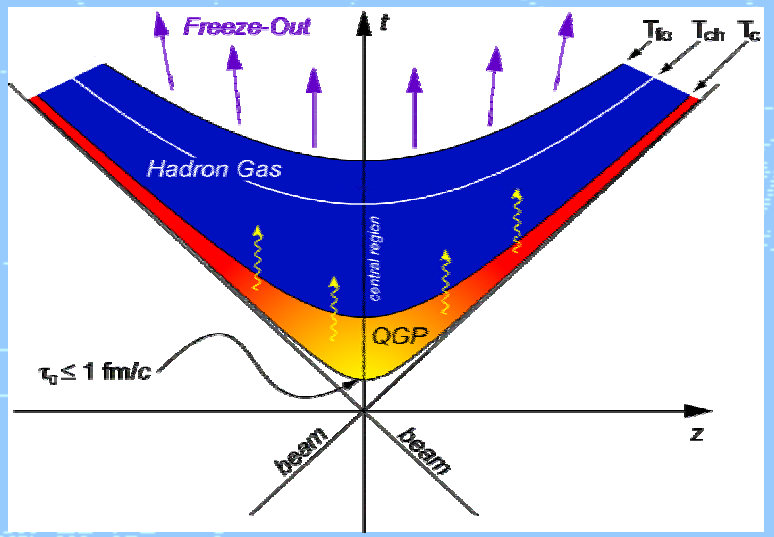


- Brookhaven National Laboratory
- First relativistic heavy ion collider in the world
- Circumference 3.83 km, 2 rings
- Collision species (Au+Au, Cu+Cu, d+Au, p+p)
- Energy (A+A); up to 100 GeV/nucleon
- PHENIX is the one of the main experiment group

PHENIX Experiment



Time-evolution after collision



Thermal freezeout

Chemical freezeout

hadronization

QGP

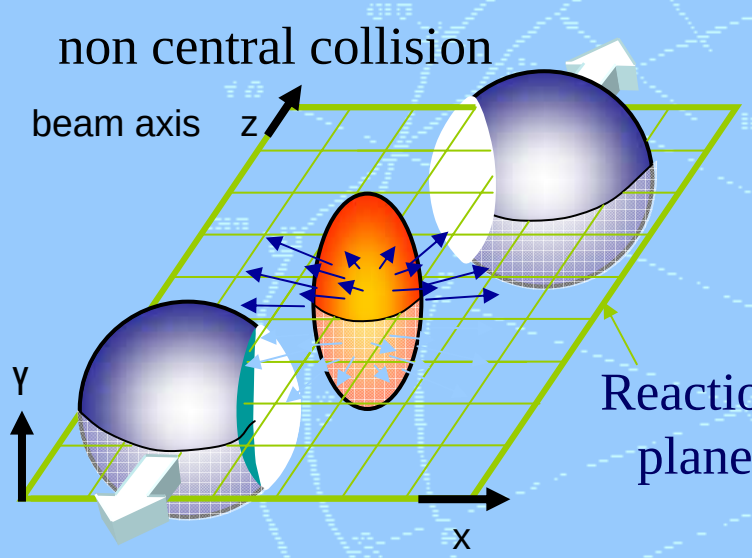
thermal equilibrium

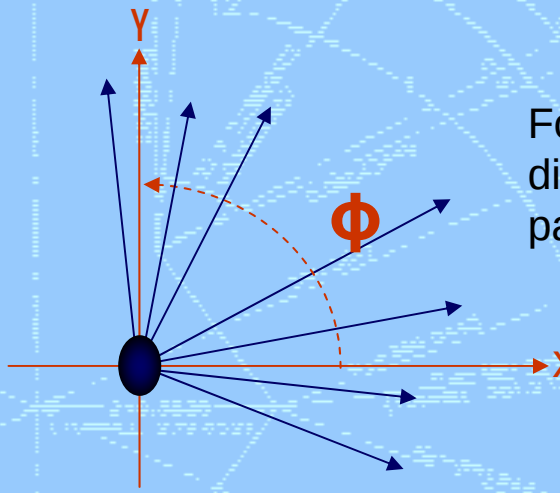
collision

Elliptic Flow (v_2)

v_2 is the strength of the elliptic anisotropy of produced particles.

A sensitive probe for studying properties of the hot dense matter made by heavy ion collisions.





Fourier expansion of the distribution of produced particle angle, **Φ**, to RP

$$\frac{dN}{d\varphi} = n\{1 + 2V_2\cos[2(\varphi - \Phi_{RP})]\}$$

v_2 is the coefficient of the second term
→ indicates ellipticity

If yield is (x direction)>(y direction), v_2 >0.

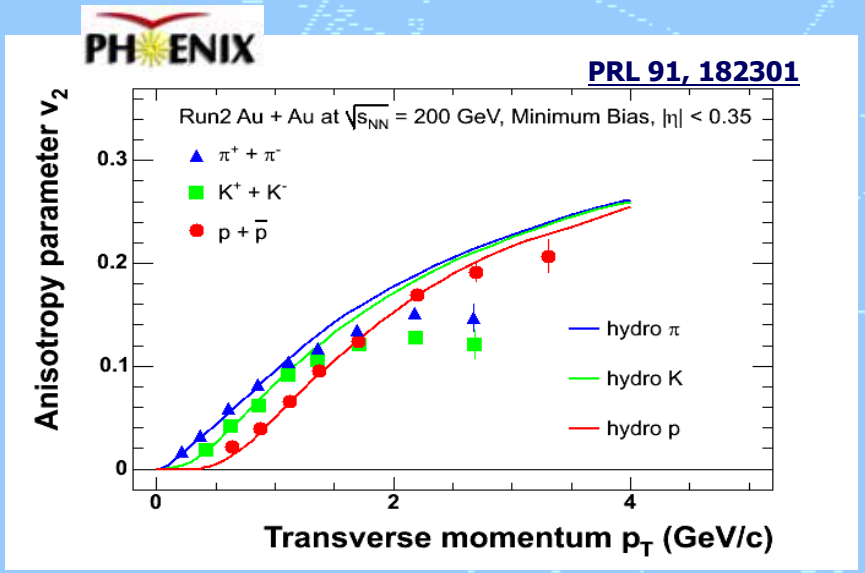
The initial geometrical anisotropy is transferred by the pressure gradients into a momentum space anisotropy → the measured v_2 reflects the dense matter produced in the collisions.

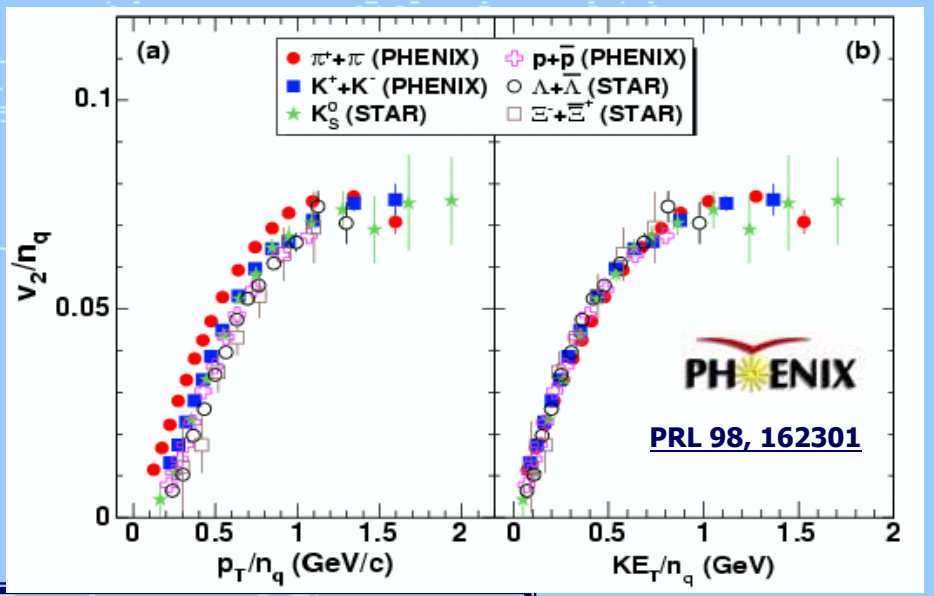
Motivation

From the results at Au+Au in 200GeV

v_2 at low p_T (< ~2 GeV/c) → can be explained by a hydro-dynamical model
v_2 at mid p_T (<4~6 GeV/c) → is consistent with recombination model

The results are consistent with Quark number +KE_T scaling.





How about other systems and energies !?

$KE_T = m_T - m_0$

Results

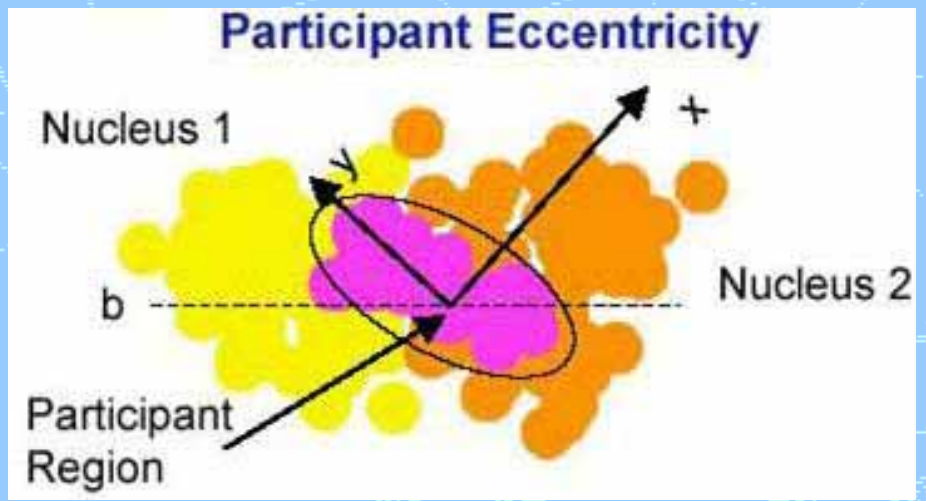
- Energy dependence
- System size dependence
  - Eccentricity scaling
- Universal v_2
  - Quark number + K_{ET} scaling
  - Universal scaling

<words>

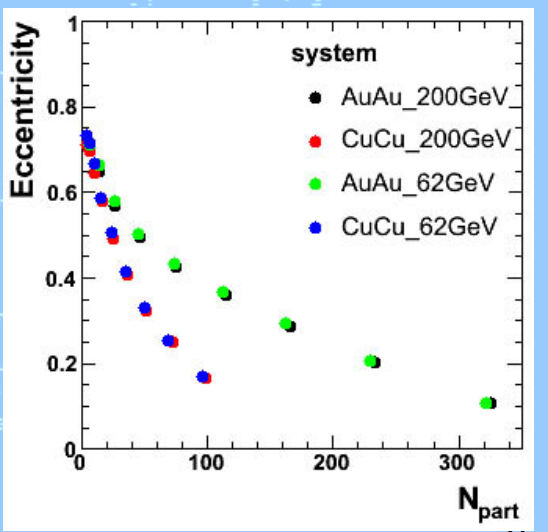
N_{part} --- Number of nucleons participating the collision
N_{coll} --- Number of binary collisions
eccentricity(ε) --- geometirical eccentricity of participant nucleons

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

-Nucleus formed by wood-Saxon shape
-Monte-Carlo simulation with Glauber model
- Participant eccentricity which is calculated with long and short axis determined by distribution of participants at each collision.



ε vs. N_{part}



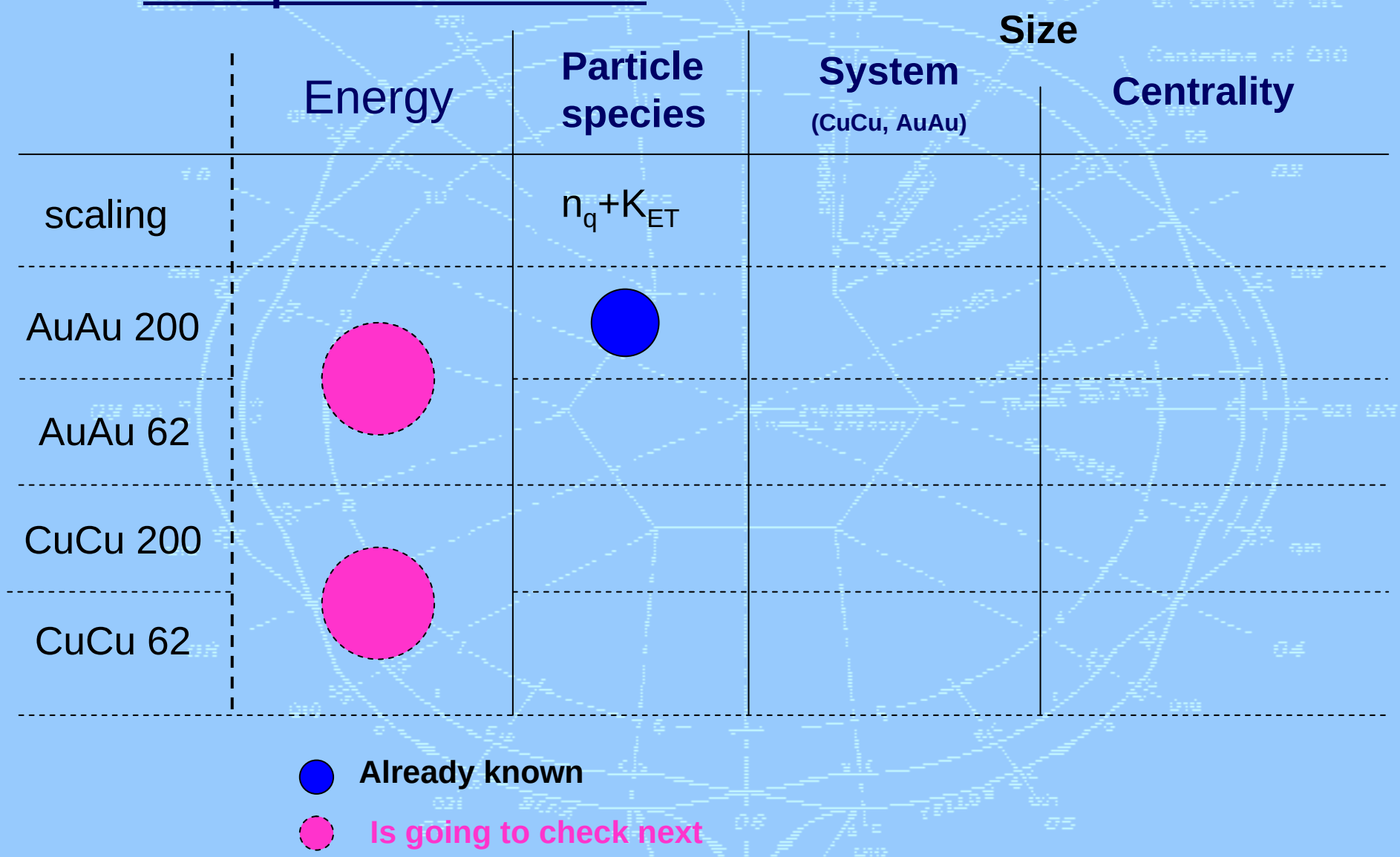
Comparison Table

	Energy	Particle species	Size: System (CuCu, AuAu)	Size: Centrality
scaling		n_q+K_{ET}		
AuAu 200		●		
AuAu 62				
CuCu 200				
CuCu 62				

● **Already known**

● **Is going to check next**

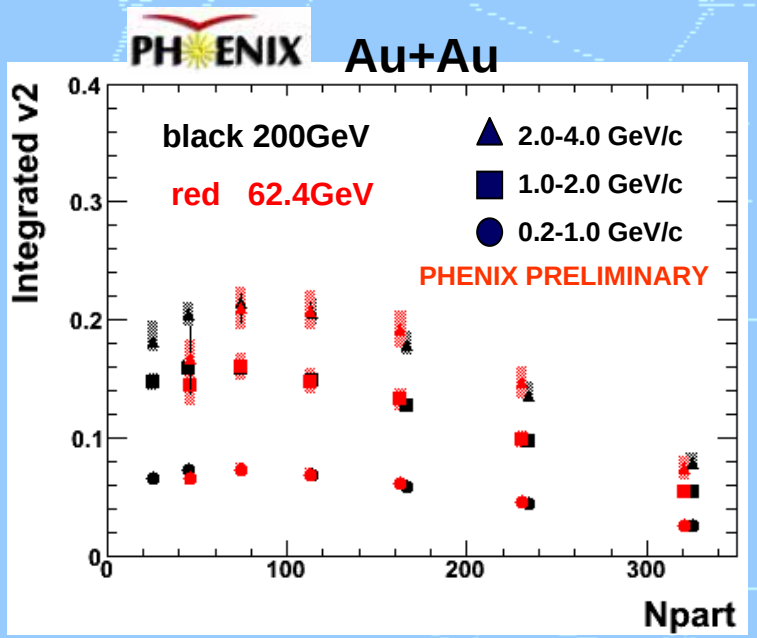
Comparison Table

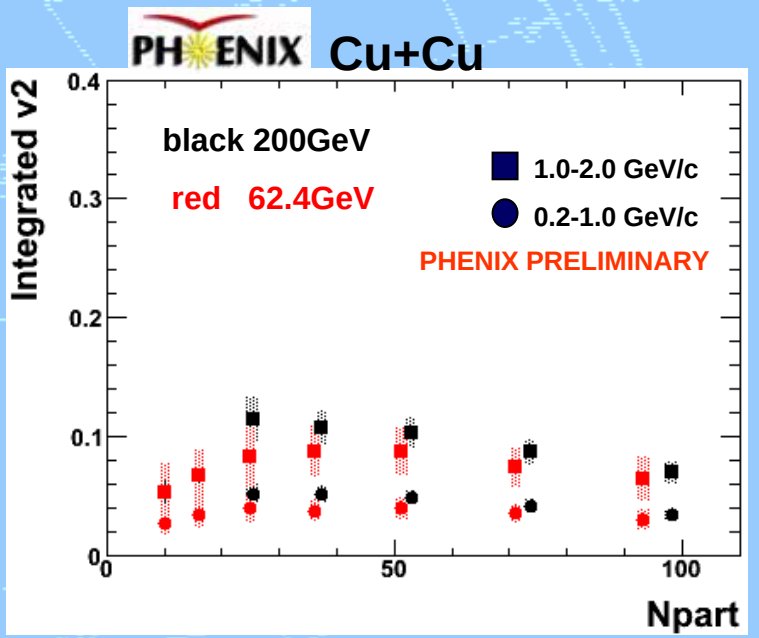


Energy dependence

Comparison of
$\sqrt{s}$ = 62.4 and 200 GeV

- dependence of centrality (Npart)
- compare the results in Cu + Cu which is smaller collision size than Au+Au
- comparison of PID hadrons. pi/K/p →next page



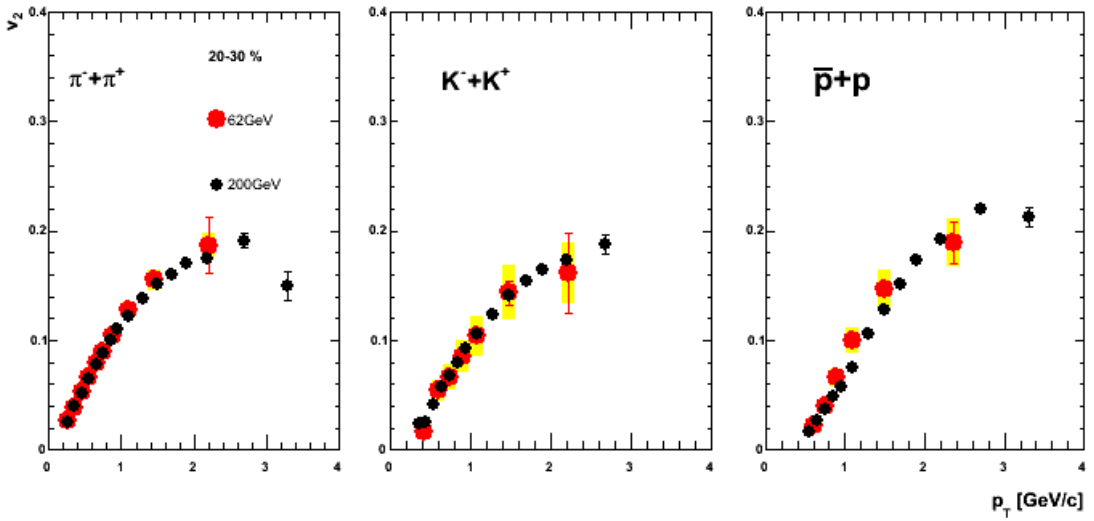


v_2 of 200GeV and 62GeV are consistent

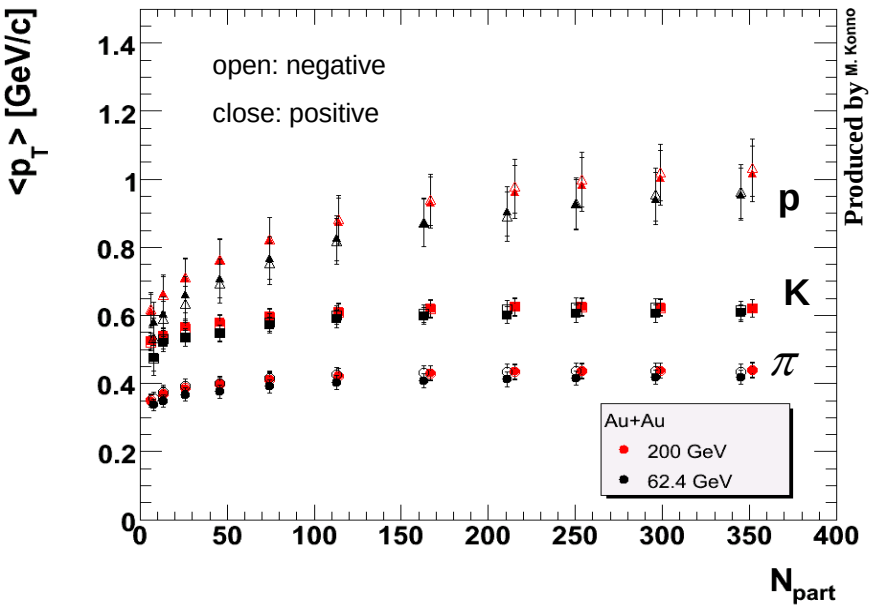
Energy dependence

- **identified hadrons (π/K/p)**
- **p_T dependence**

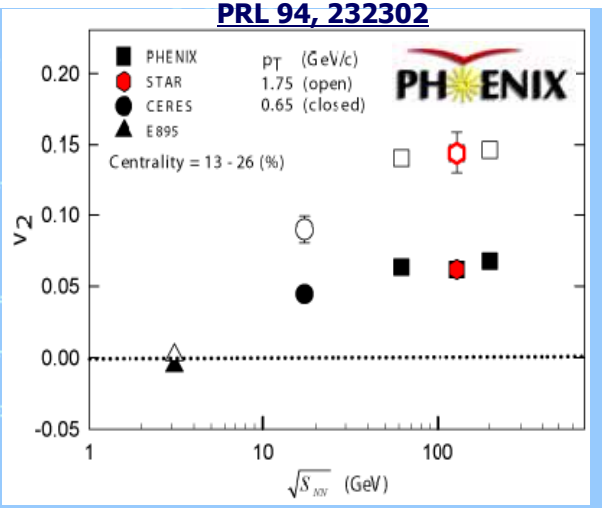
Au+Au v_2 vs. p_T



Mean p_T



<p_T> of 62.4 GeV and 200 GeV are consistent within errors on pi/K/p. Therefore v_2 agree at any p_T region in figures.



v_2 of √s = 17GeV (SPS) decreases to about 50% of RHIC energies. Higher collision energy has larger v2 up to RHIC energy. Above 62.4 GeV, v_2 is saturated.

→ indicate the matter reached thermal equilibrium state at RHIC

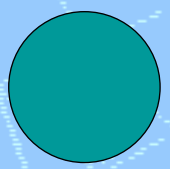
System Size Dependence

- Eccentricity Scaling

What can change the size of collision system.

- Species of collision nucleus (Au+Au ,Cu+Cu)
- Centrality

Comparison Table

	Energy	Particle species	Size: System (CuCu, AuAu)	Size: Centrality
scaling	no change	n_q+K_{ET}		
AuAu 200				
AuAu 62				
CuCu 200				
CuCu 62				

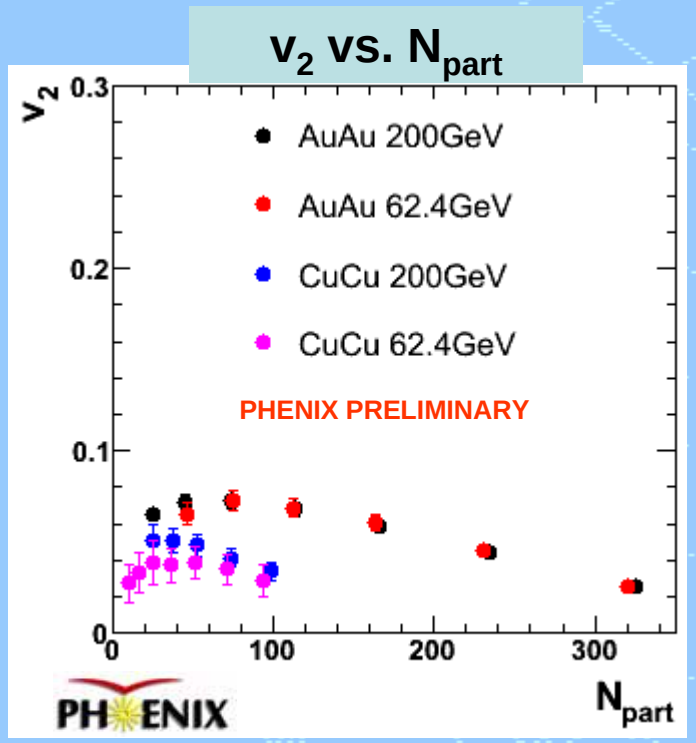
 **Already known**

 **Is going to check next**

 **checked**

System size dependence

Compare v_2 normalized by eccentricity (ε) in the collisions of different size.

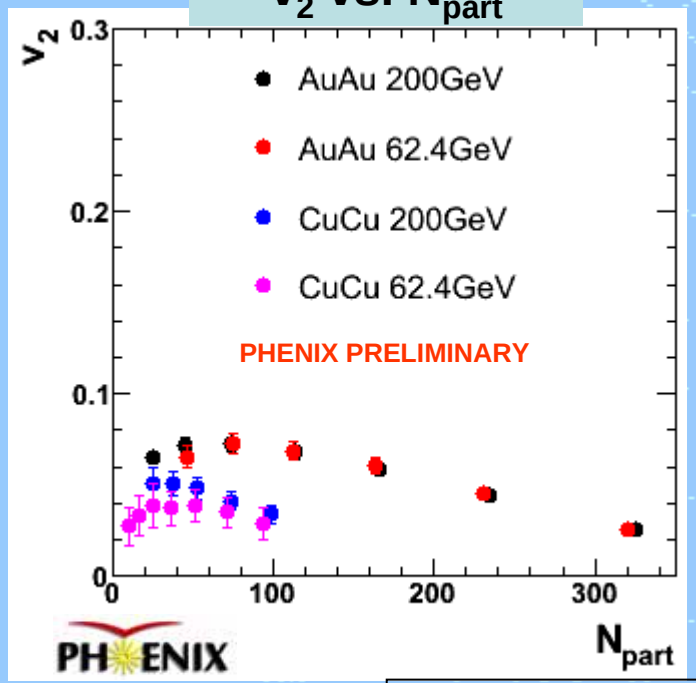


$0.2<p_T<1.0$ [GeV/c]

System size dependence

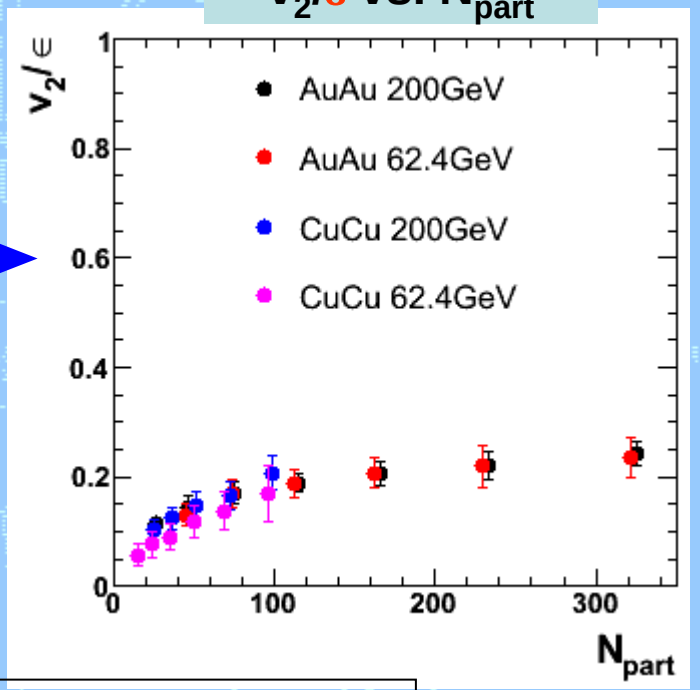
Compare v_2 normalized by eccentricity (ε) in the collisions of different size.

v_2 vs. N_{part}



$0.2<p_T<1.0$ [GeV/c]

v_2/ε vs. N_{part}



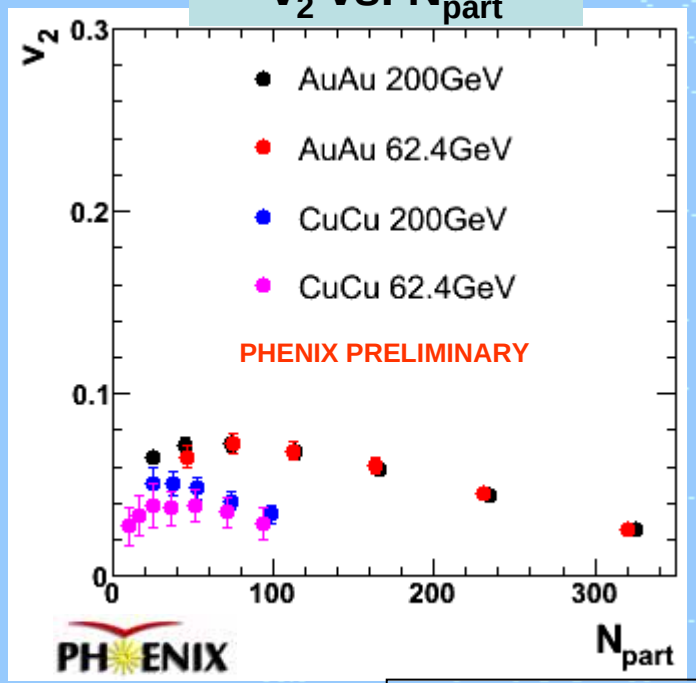
v_2/ε (Au+Au) = v_2/ε (Cu+Cu) !

Systematic errors from eccentricity is not included here.

System size dependence

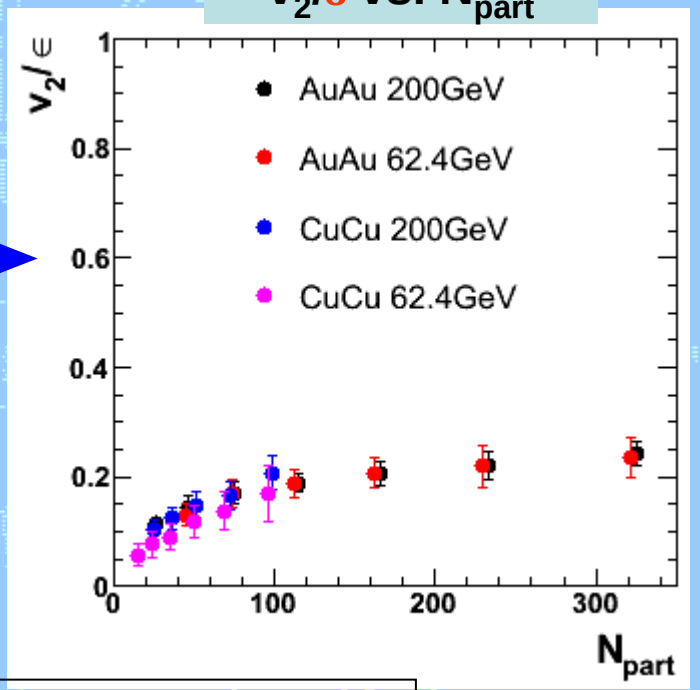
Compare v_2 normalized by eccentricity (ε) in the collisions of different size.

v_2 vs. N_{part}



$0.2<p_T<1.0$ [GeV/c]

v_2/ε vs. N_{part}



v_2/ε (Au+Au) = v_2/ε (Cu+Cu) !

but v_2/ε is not constant and it shades depending on N_{part} .

Systematic errors from eccentricity is not included here.

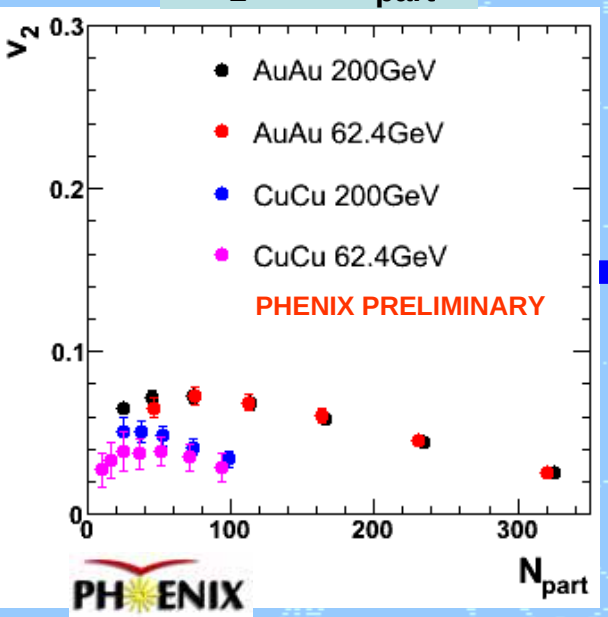
→v_2 <u>can be normalized by ε at same N_{part}</u> , but ε is not enough to determine v_2 .

System size dependence

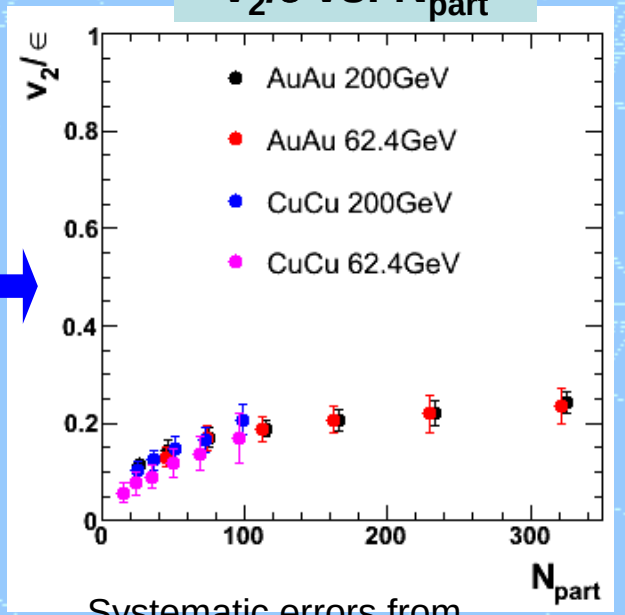
$0.2<p_T<1.0$ [GeV/c]

Dividing by $N_{part}^{1/3}$

v_2 vs. N_{part}

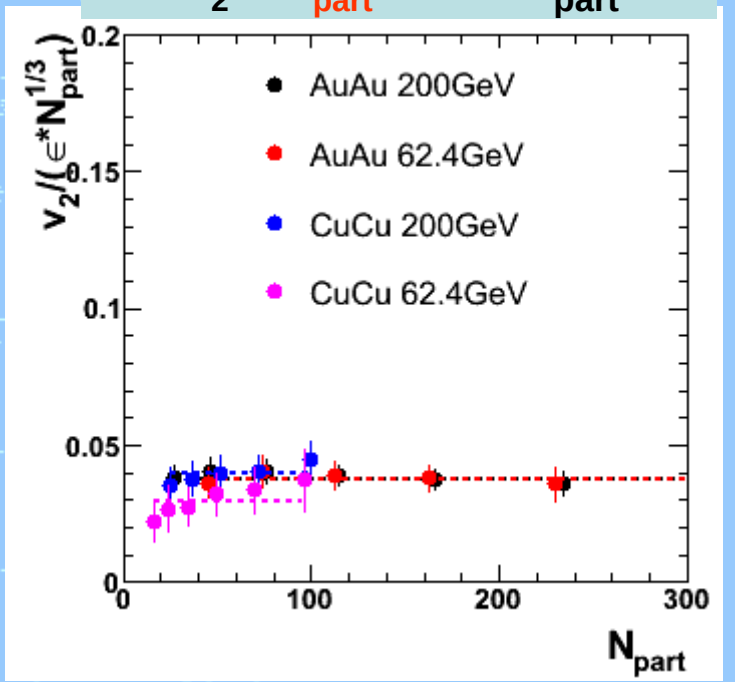


v_2/ε vs. N_{part}



Systematic errors from eccentricity is not included here.

$v_2/\varepsilon/N_{part}^{1/3}$ vs. N_{part}



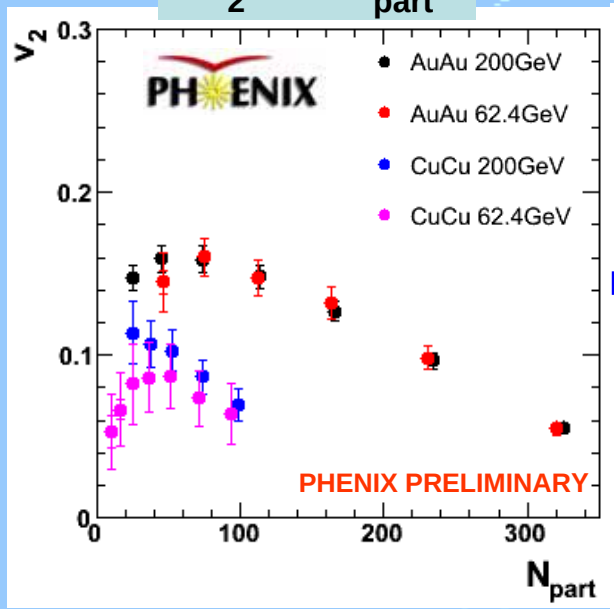
v_2/ε (Au+Au) = v_2/ε (Cu+Cu)
v_2/eccentricity is scaled by $N_{part}^{1/3}$ and not dependent on the collision system.

System size dependence

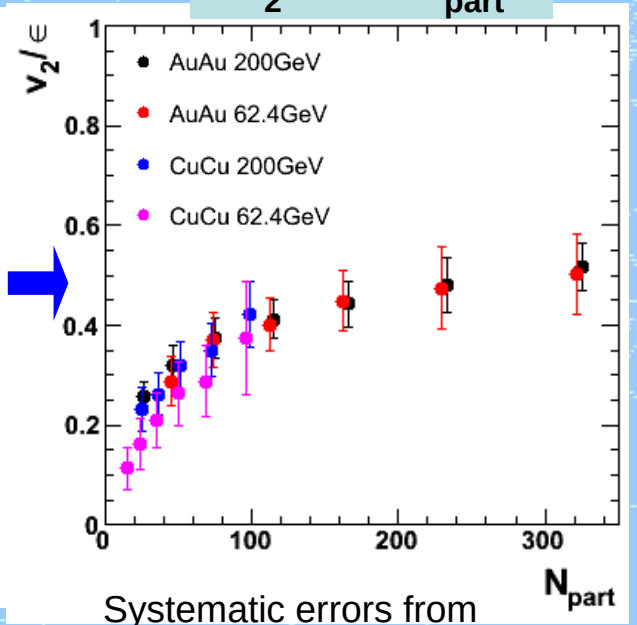
$1.0<p_T<2.0$ [GeV/c]

Dividing by $N_{part}^{1/3}$

v_2 vs. N_{part}

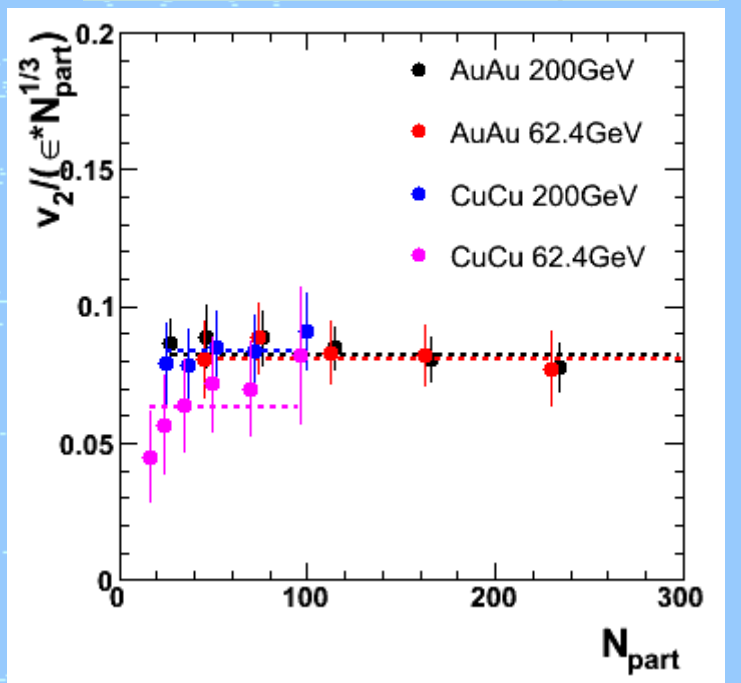


v_2/ε vs. N_{part}



Systematic errors from eccentricity is not included here.

$v_2/\varepsilon/N_{part}^{1/3}$ vs. N_{part}



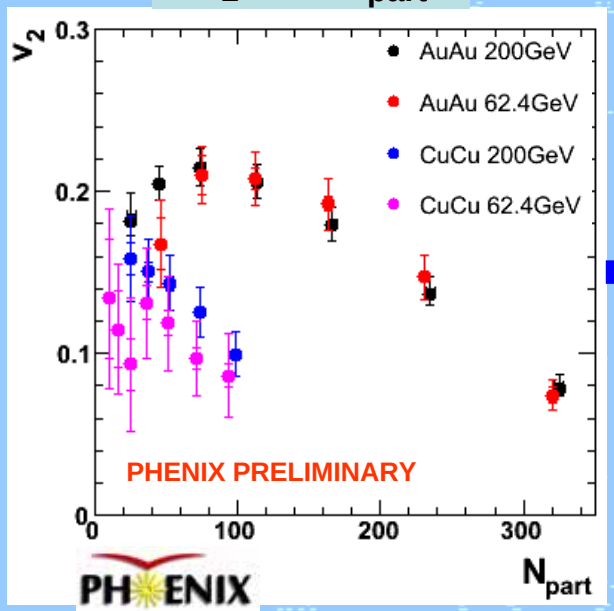
v_2/eccentricity is scaled by $N_{part}^{1/3}$ and not dependent on the collision system.

System size dependence

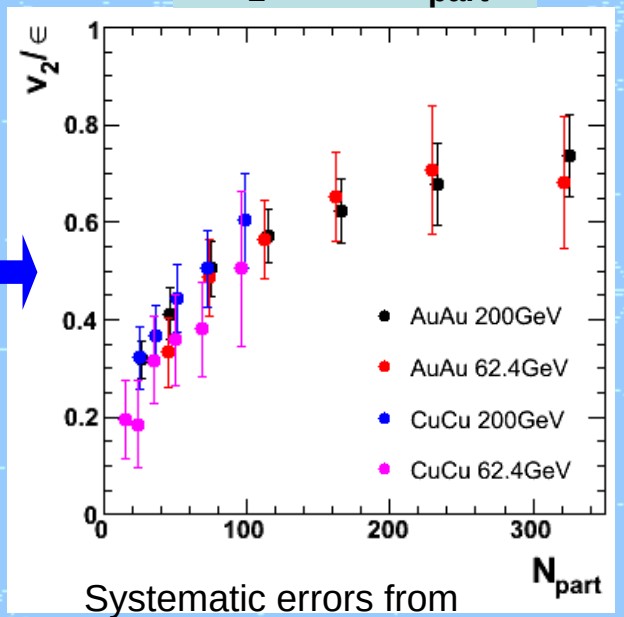
$2.0<p_T<4.0$ [GeV/c]

Dividing by $N_{part}^{1/3}$

v_2 vs. N_{part}

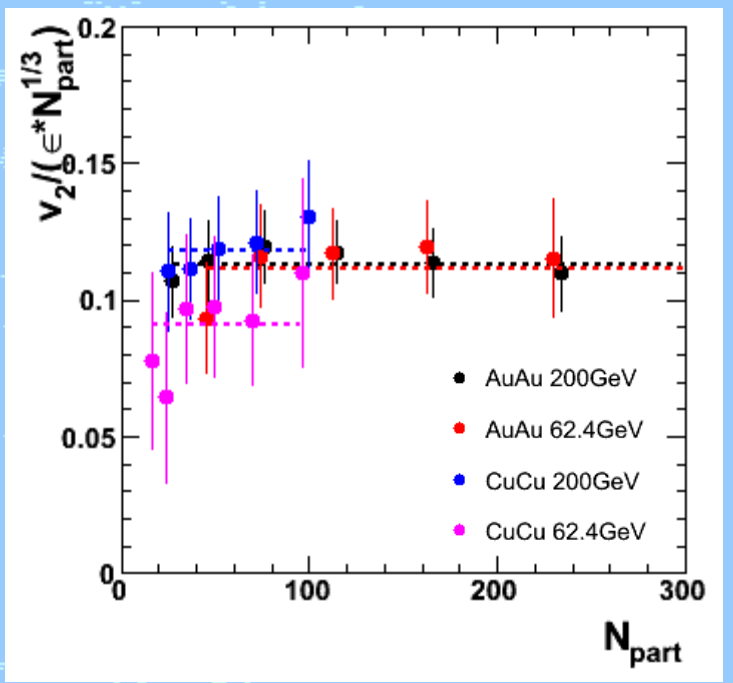


v_2/ε vs. N_{part}



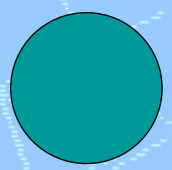
Systematic errors from eccentricity is not included here.

$V_2/\varepsilon/N_{part}^{1/3}$ vs. N_{part}



v_2/eccentricity is scaled by $N_{part}^{1/3}$ and not dependent on the collision system.

Comparison Table

	Energy	Particle species	Size: System (CuCu, AuAu)	Size: Centrality
scaling	no change	n_q+K_{ET}	eccentricity	$N_{part}^{1/3}$
AuAu 200				
AuAu 62				
CuCu 200				
CuCu 62				

 **Already known**

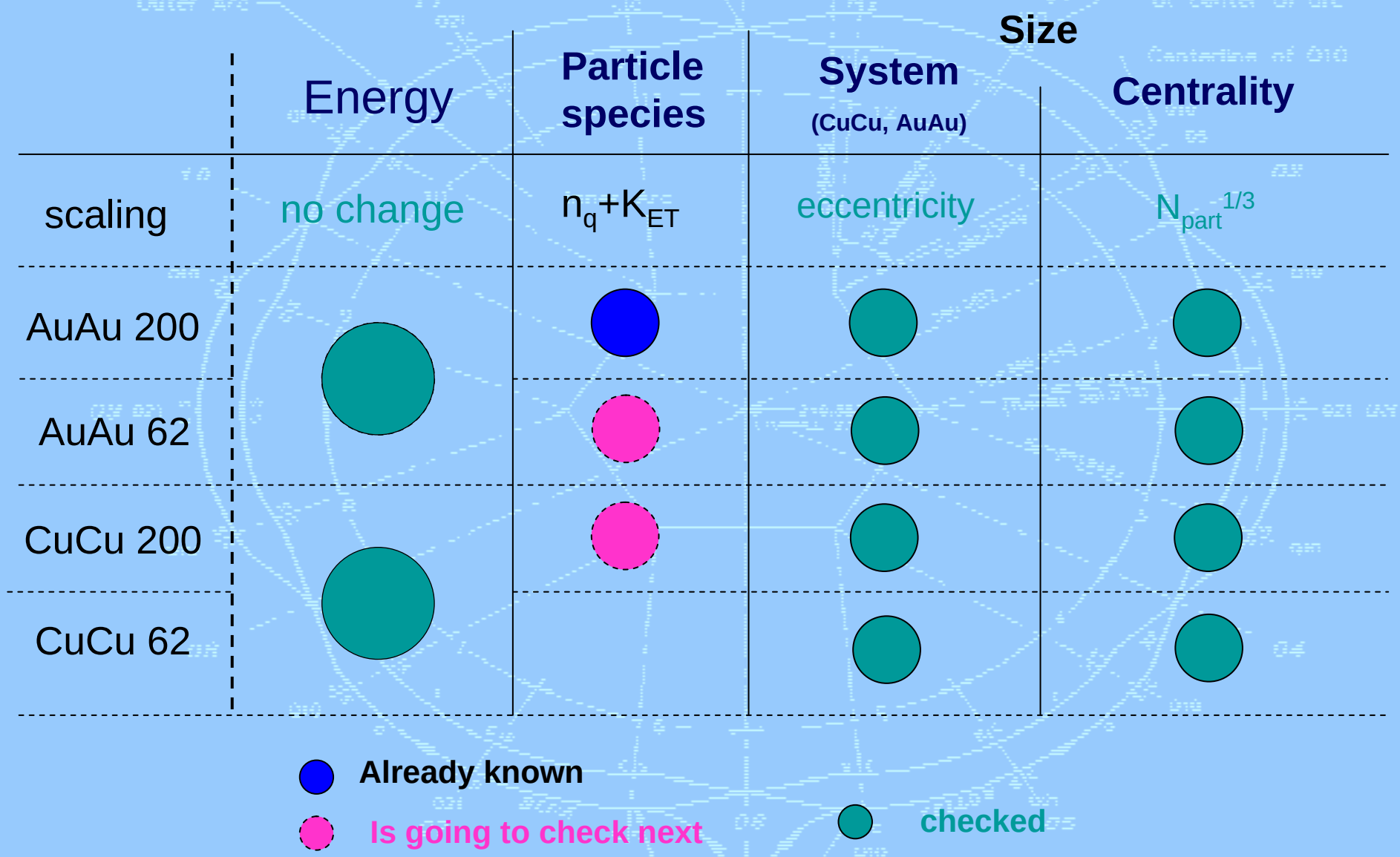
 **Is going to check next**

 **checked**

Universal v_2

- Quark number + K_{ET} scaling
- Universal Scaling

Comparison Table



Quark number + K_{ET} scaling (AuAu 62.4GeV)

Centrality 10-40 %

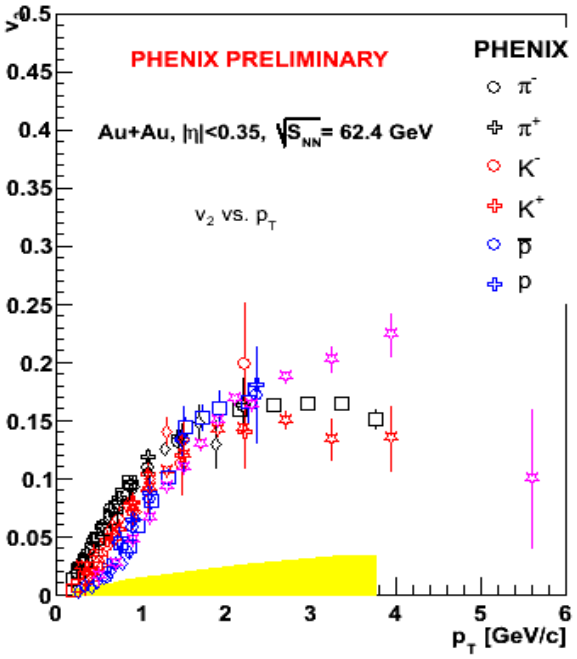
PHENIX: Error bars include both statistical and systematic errors.

STAR: Error bars include statistical errors. Yellow band indicates systematic errors.

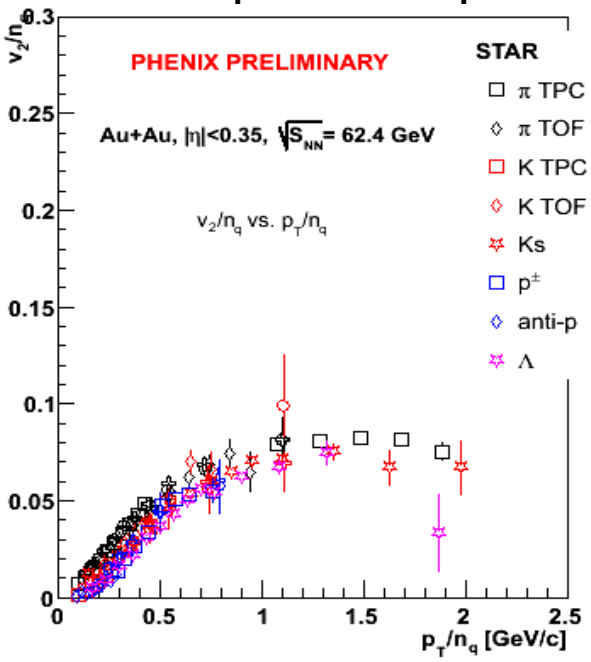
Star results : Phys. Rev. C 75

PHENIX

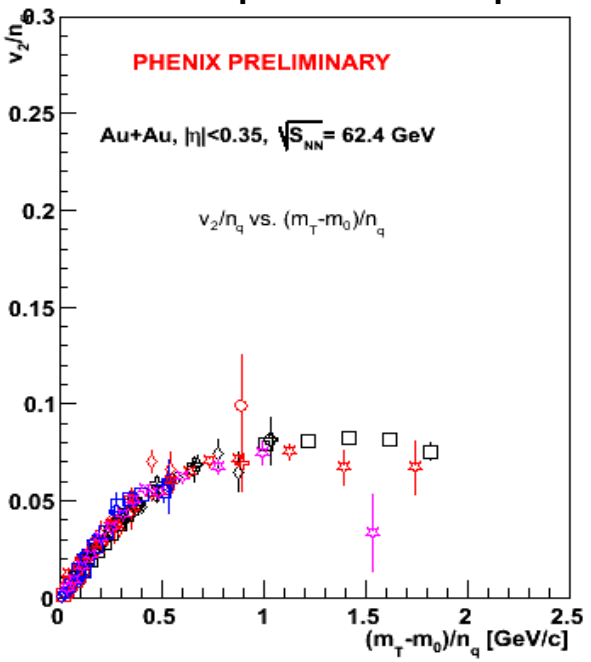
v_2 vs. p_T



v_2/n_q vs. p_T/n_q



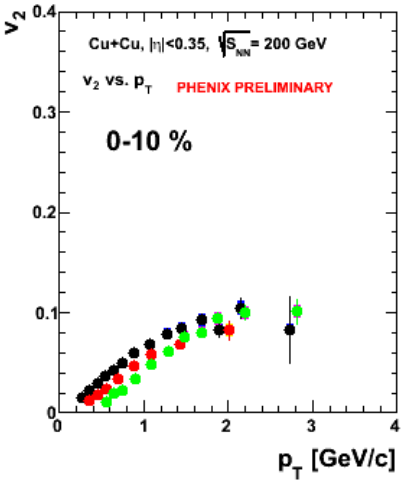
v_2/n_q vs. K_{ET}/n_q

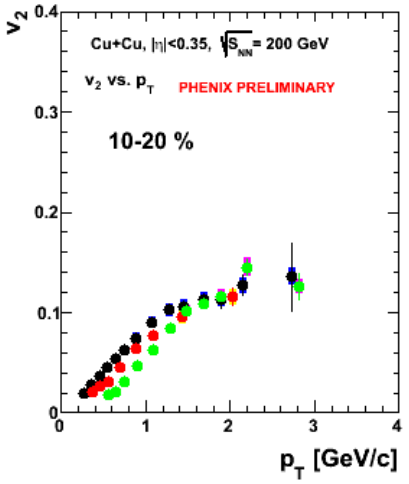


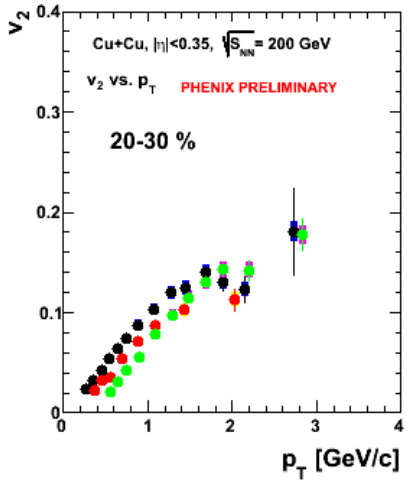
quark number + K_{ET} scaling is OK at 62.4 GeV, too!

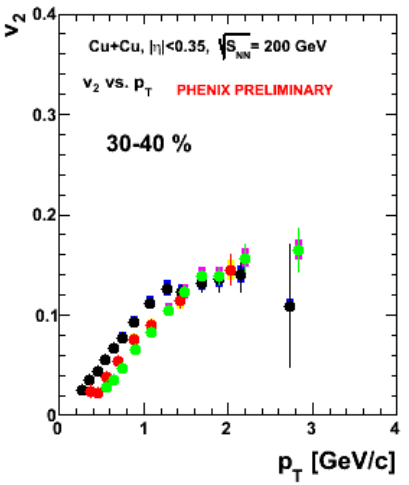
$v_2(p_T)$ /n_{quark} vs. K_{ET}/n_{quark} is the universal curve independent on particle species.

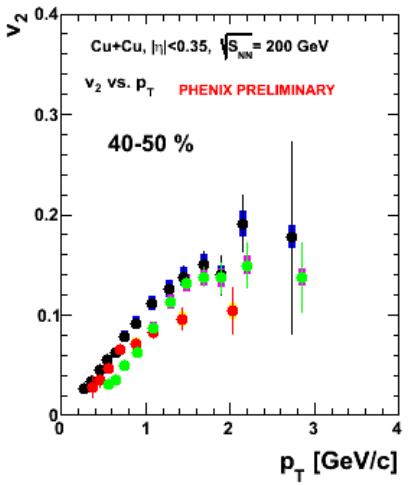
v_2 vs. p_T at Cu+Cu in 200GeV collision

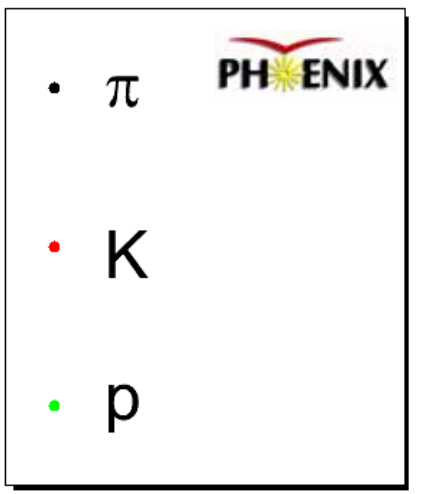








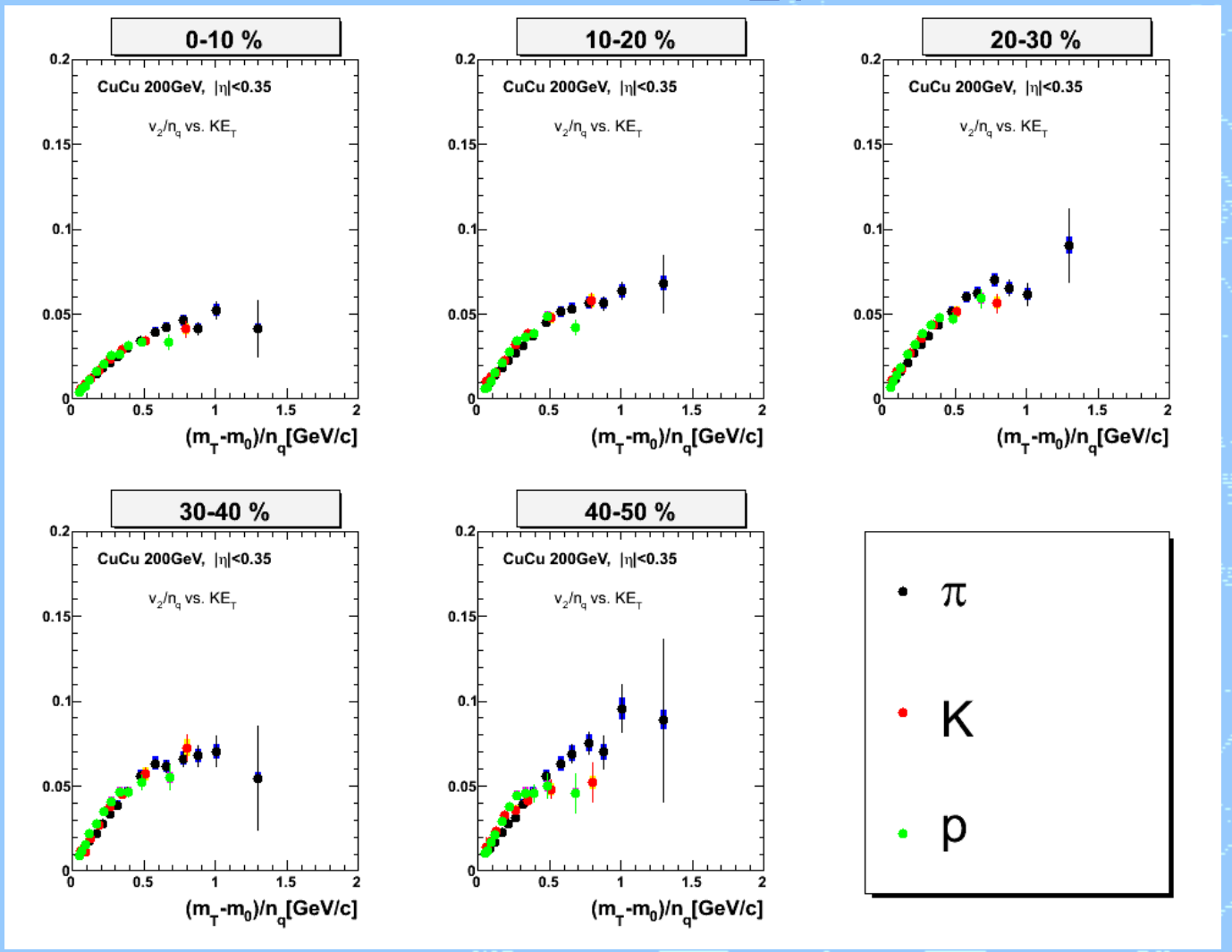




Centrality dependence of PID v_2 vs. p_T for Cu+Cu 200GeV is measured.

Quark number + K_{ET} scaling

Cu+Cu √s = 200GeV



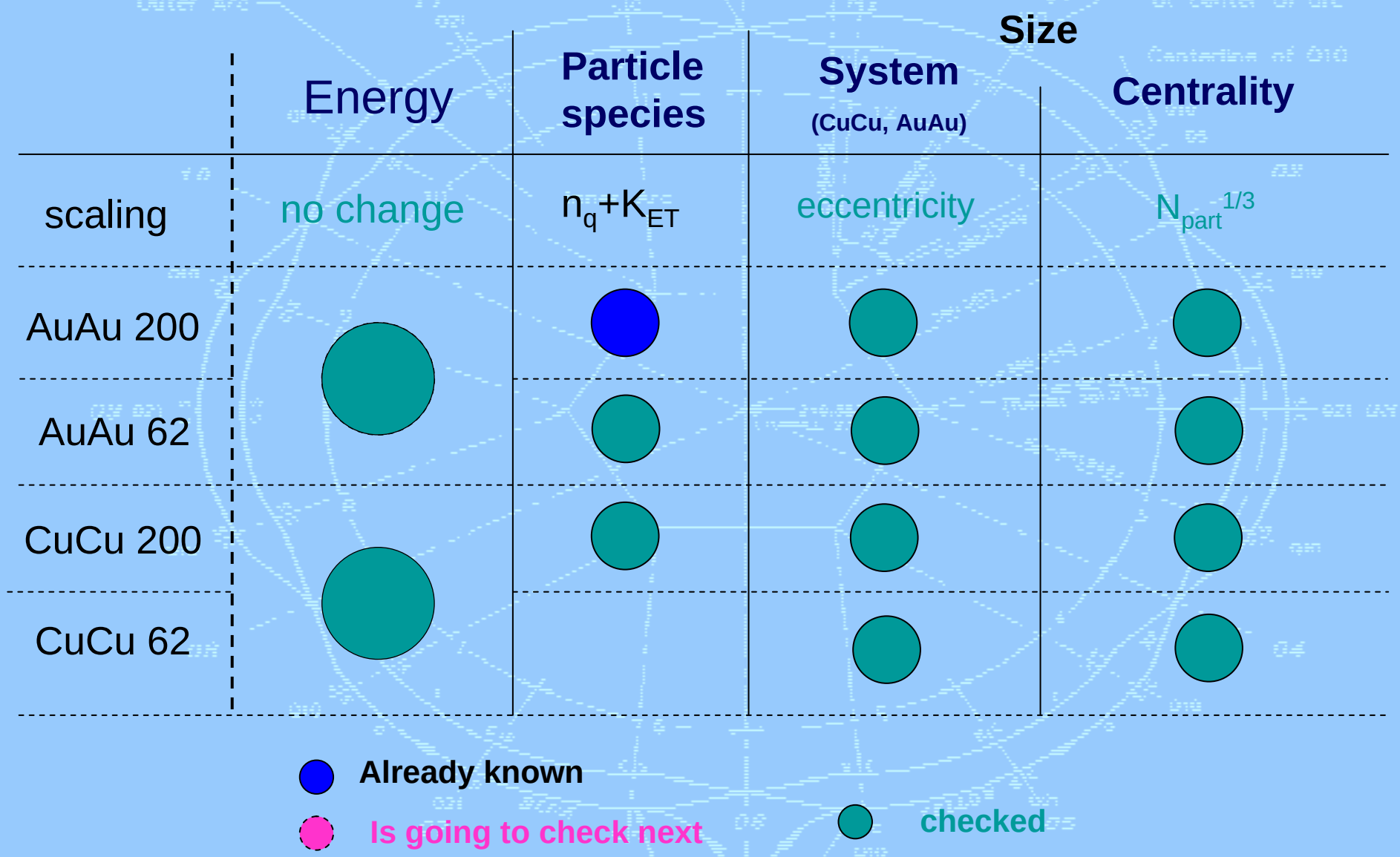
At all centrality, (between 0- 50 %) v_2 of π/K/p is consistent to quark number + K_{ET} scaling.

quark number + K_{ET} scaling seems to works out at Cu+Cu 200GeV.

Summary of Scaling

- Collision energy → no change
- Eccentricity of participants → eccentricity scaling
- Particle species → n_q +K_{ET} scaling
- Number of participants → $N_{part}^{1/3}$ scaling

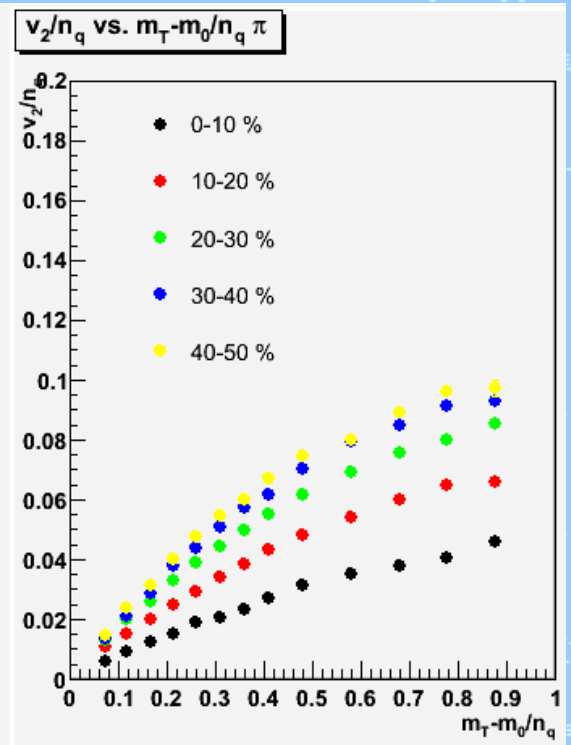
Comparison Table



Universal Scaling

ex. Au+Au 200GeV π

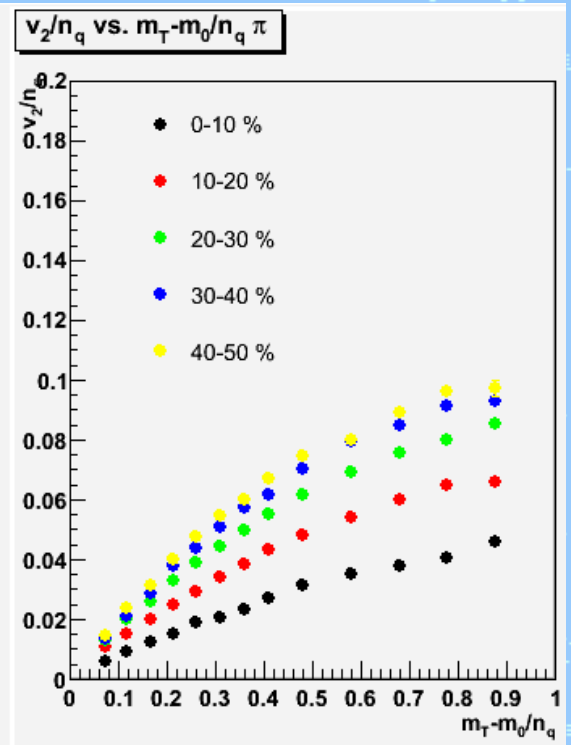
quark number + K_{ET} scaling.



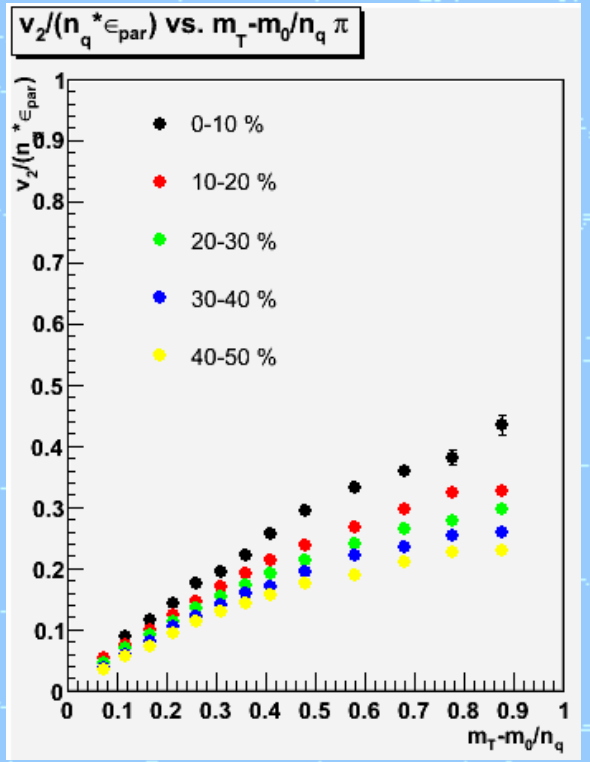
Universal Scaling

ex. Au+Au 200GeV π

quark number + K_{ET} scaling.



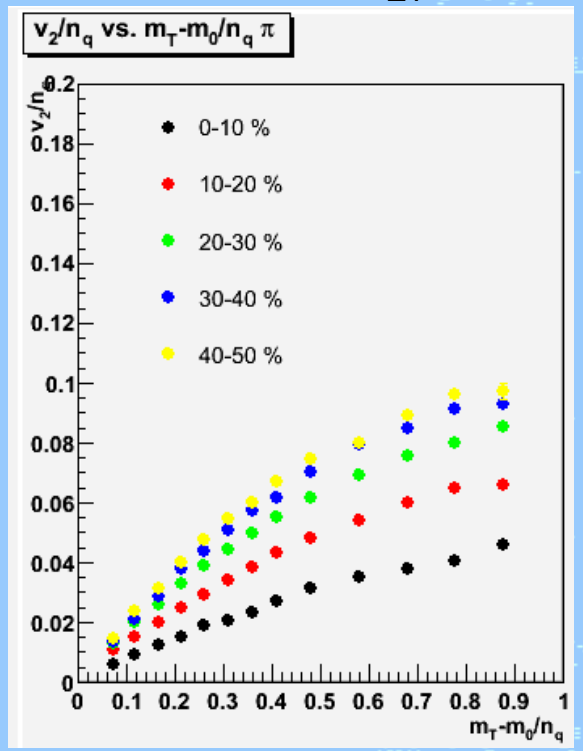
+ eccentricity scaling



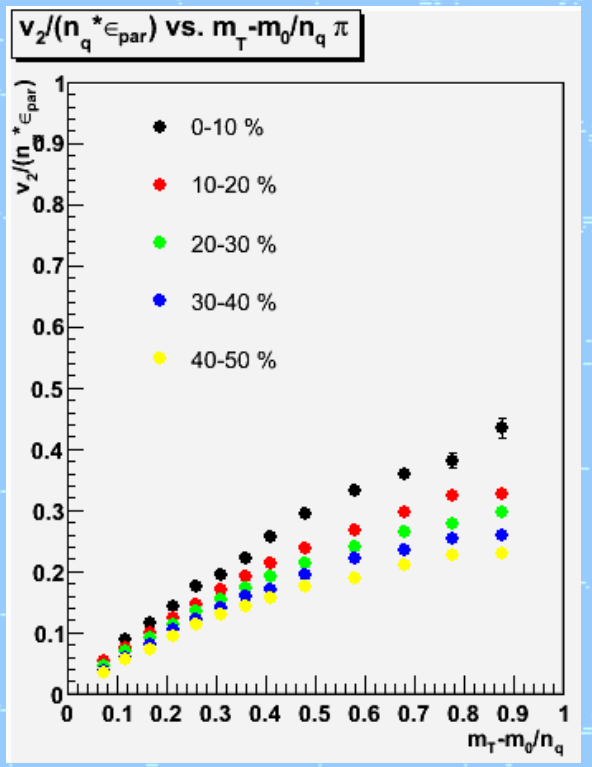
Universal Scaling

ex. Au+Au 200GeV π

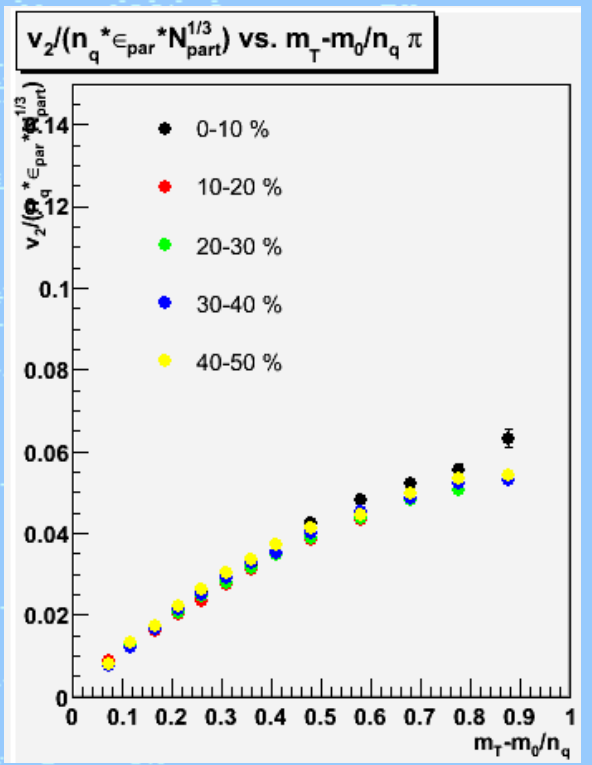
quark number + K_{ET} scaling.



+ eccentricity scaling

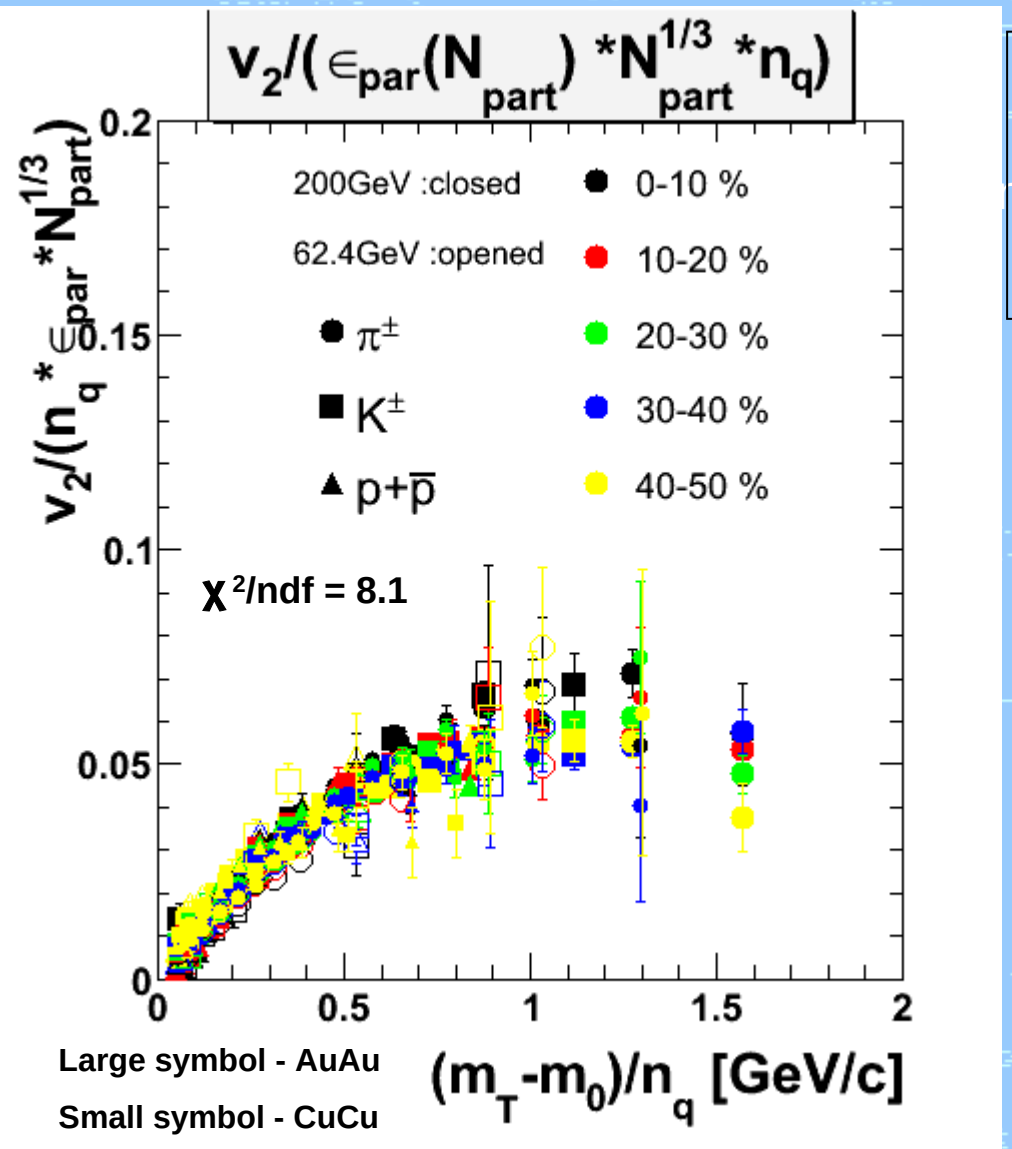


+ $Npart^{1/3}$ scaling



$v_2(K_{ET}/n_q)/n_q/\varepsilon_{par}/N_{part}^{1/3}$ is consistent at 0-50% centralities.

Universal Scaling



- Different System (Au+Au, Cu+Cu)
- Different Energy (200GeV - 62.4GeV)
- Different Centrality (0-50%)
- Different particles (π/ K /p)

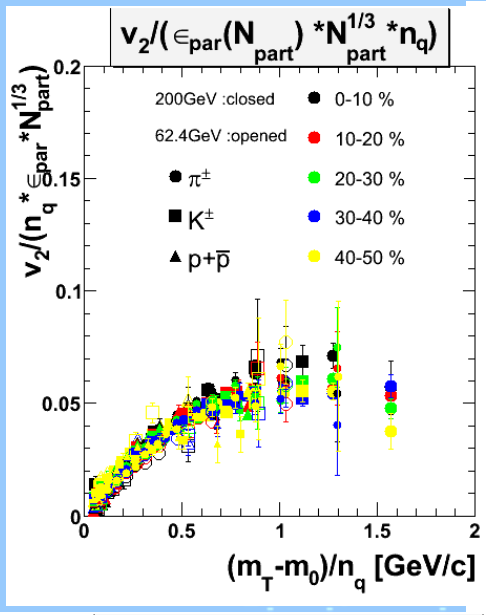
$$\frac{v_2(K_{ET}/n_q)}{n_q \times \varepsilon \times N_{part}^{1/3}}$$

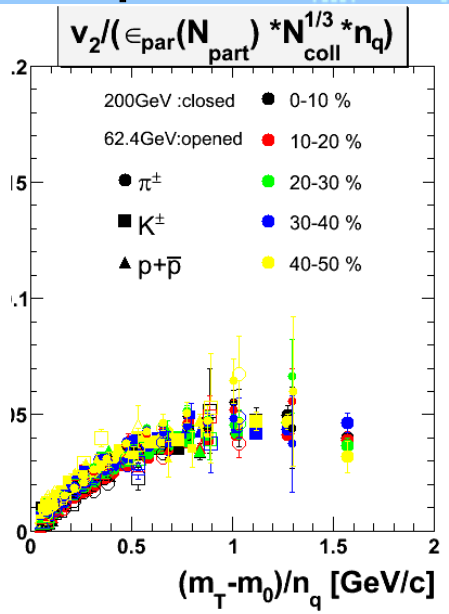
Universal Curve !!

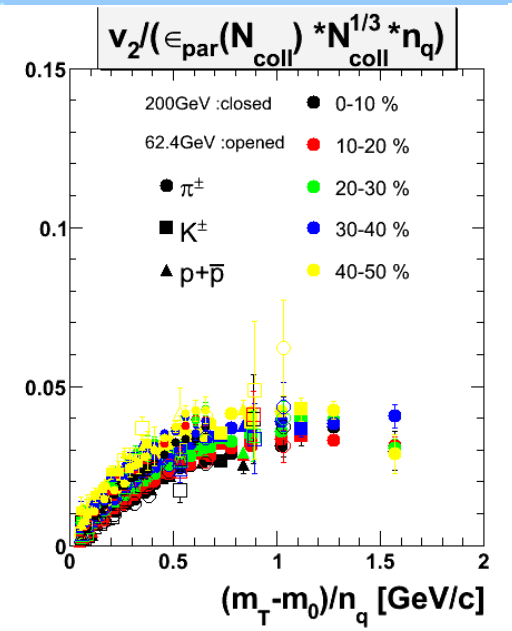
Conclusion

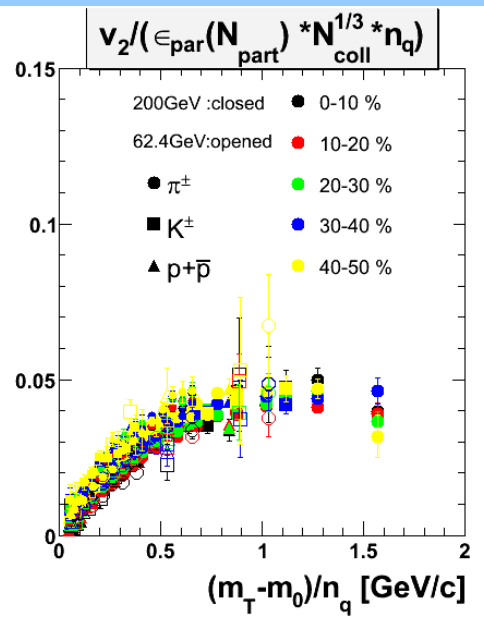
- v_2 were measured at 4 systems.
  - (Au+Au, Cu+Cu) x (62.4GeV, 200GeV)
- Same $v_2(p_T)$ are obtained in different collision energies ($\sqrt{s}$ = 62.4 - 200GeV)
- $v_2(p_T)$ of various hadron species are scaled by quark number + K_{ET} scaling at these three systems. (no results for Cu+Cu 62.4GeV)
- $v_2(N_{part})$ scaled by participant Eccentricity are consistent between Au+Au and Cu+Cu collisions
- $v_2(p_T)$ /ε_{par} are scaled by $N_{part}^{1/3}$.
- $v_2(K_{ET}/n_q)/n_q/\varepsilon_{par}/N_{part}^{1/3}$ has Universal Curve.
  - →This indicates v_2 are determined by the initial geometrical anisotropy and its time evolution effect depending on the initial volume.

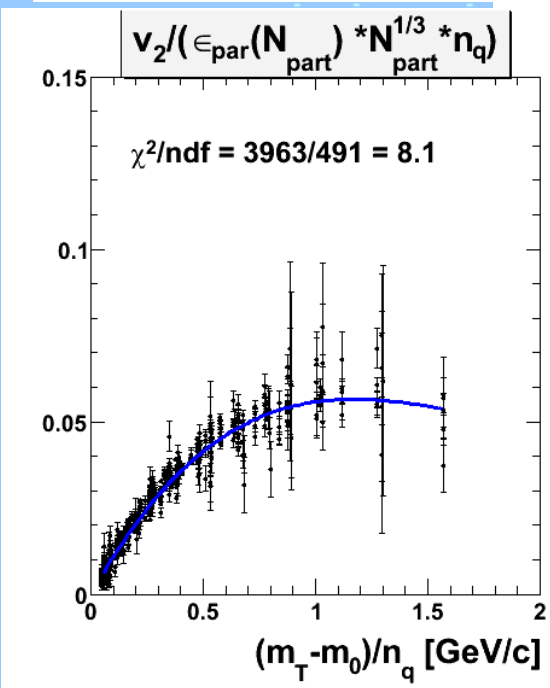
3 systems comparison

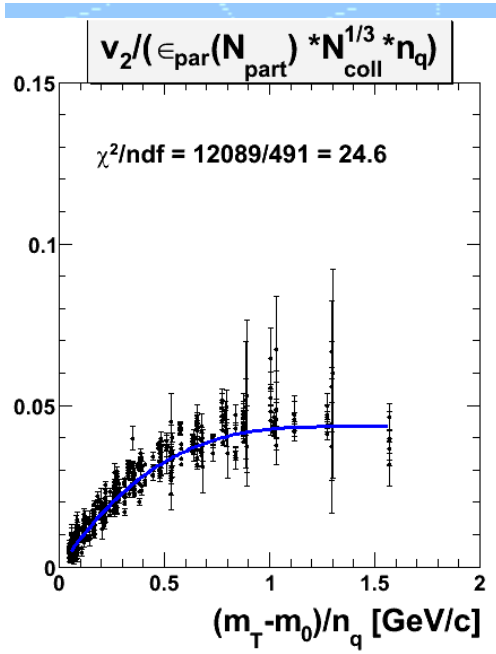








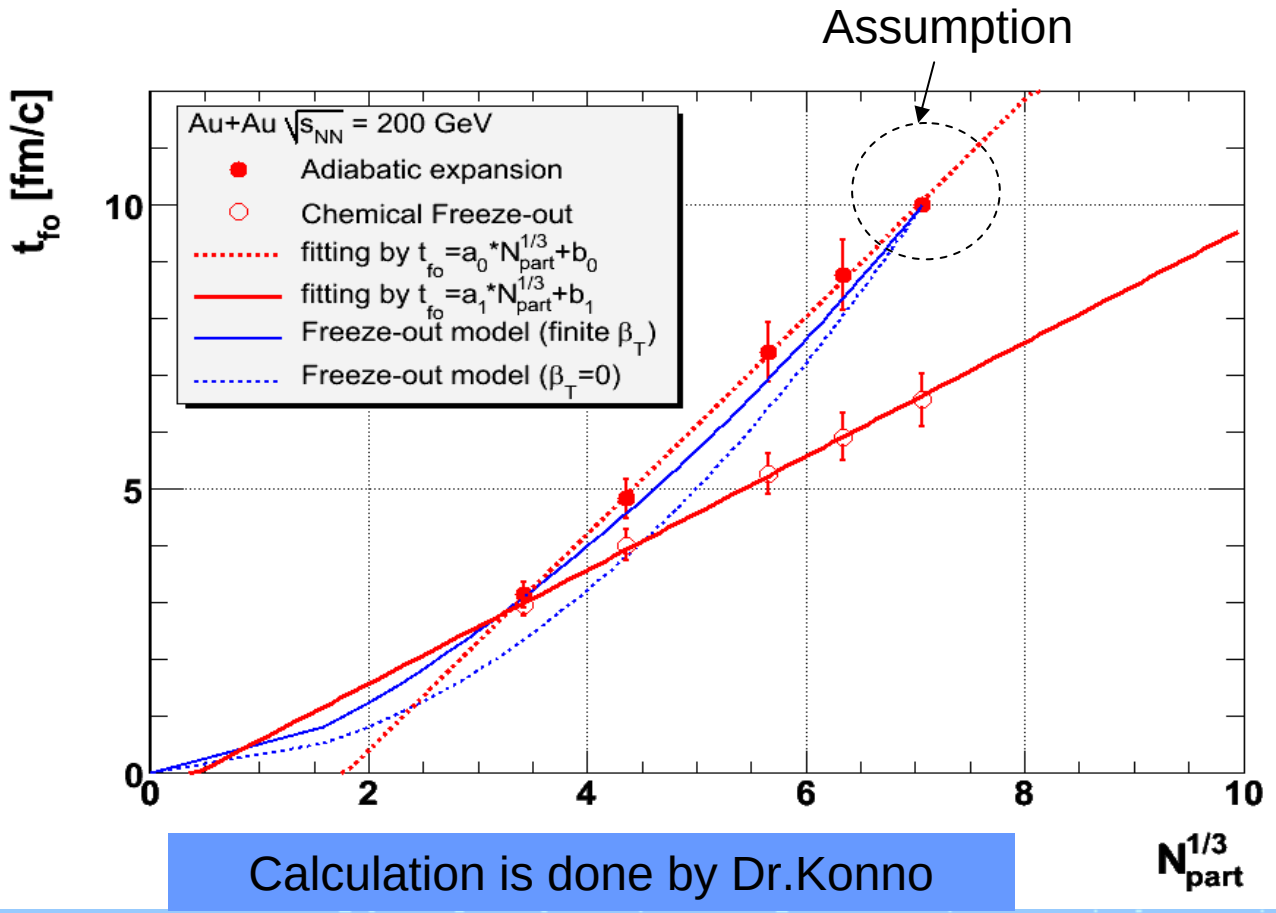




Various scalings.
Eccentricity of N_{part} and $N_{part}^{1/3}$ looks best.

Back Up

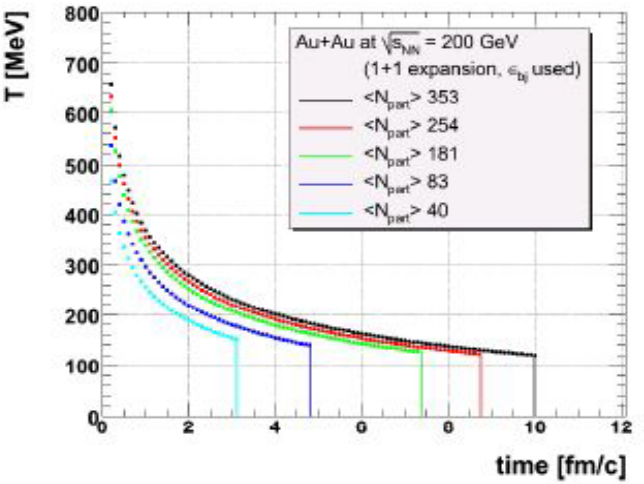
Calculation by simple expansion model



Calculation is done by Dr.Konno

$$T(t) = T_0\left(\frac{t_0(R_0+\beta_T t_0)^2}{t(R_0+\beta_T t)^2}\right)^{1/3}$$

$$t_{fo} = \left(\sqrt{R_0^2 + 4\beta_T K N_p} - R_0\right)/2\beta_T$$



Time until chemical freeze-out is proportional to $N_{part}^{1/3}$.

Summary of v_2 production and development

Low to mid p_T

Time t

collision

Determine initial geometrical eccentricity, ε, with the participant.

thermal equilibrium

Determine pressure gradient from ε.

expanding

v_2 is expanding during finite time.

Not depending on the kind of quarks.

hadronization

This finite time becomes longer with larger collision system, and the v_2 increases proportionally.

radial flow depending on each mass expands.

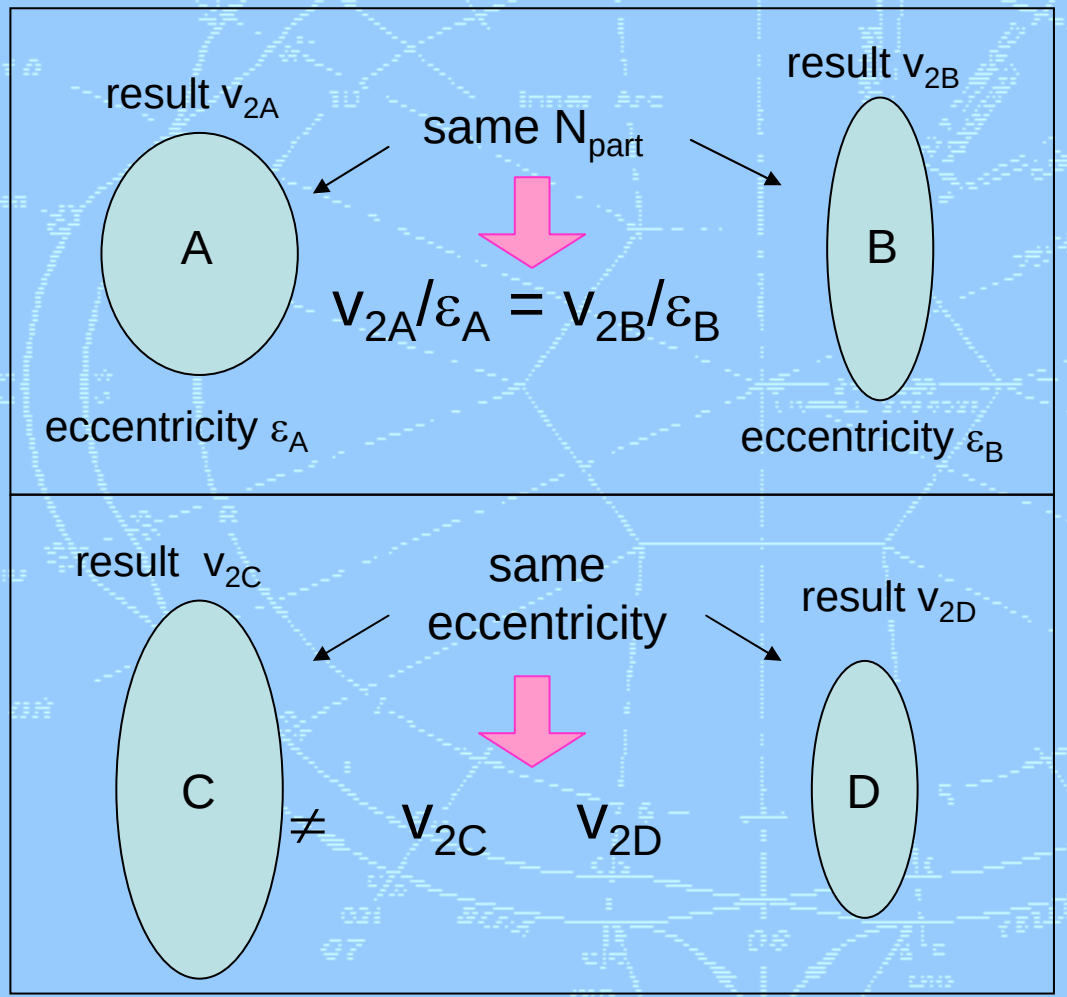
freeze out

No change

Measurement

Summary (1)

When the systems have same N_{part}, v_2 is scaled by ε of paricipant geometry.

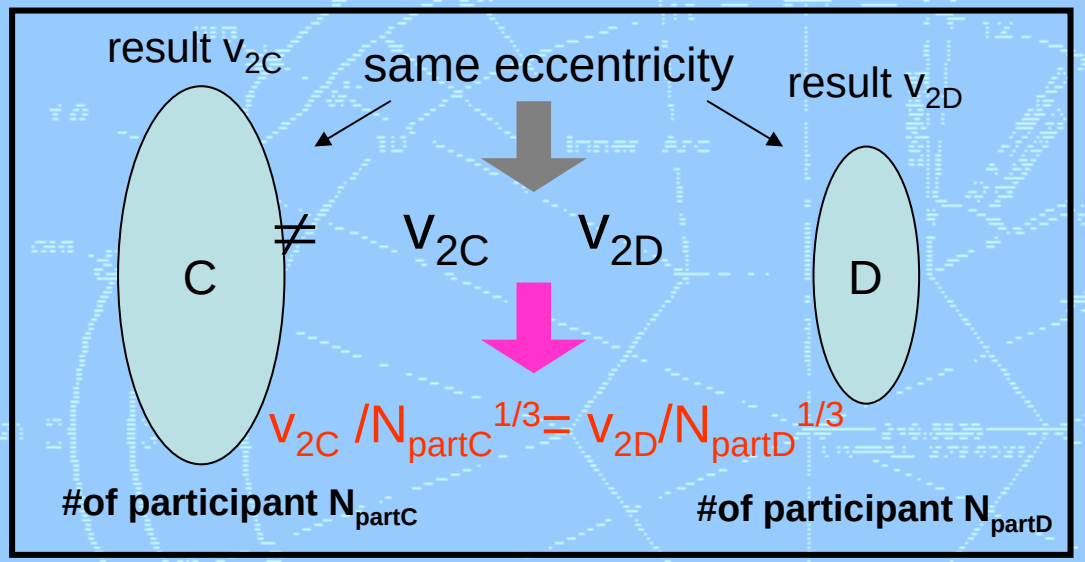


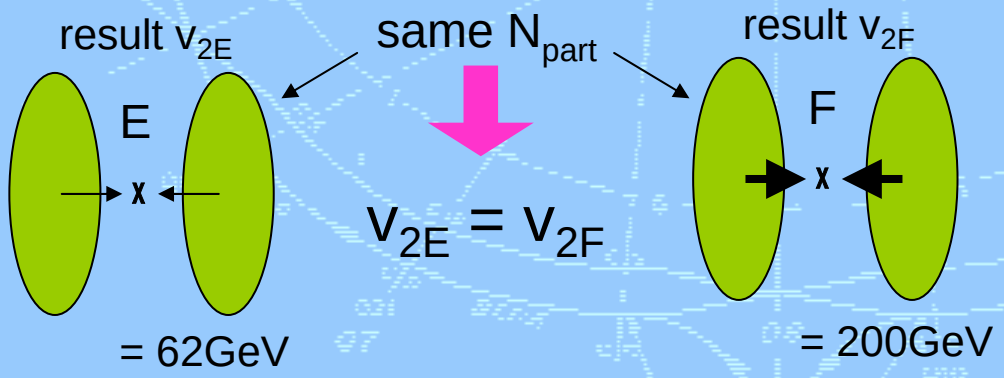
If v_2 only depends on eccentricity of initial participant geometry, v_2/ε should be constant at any N_{part}, but it is not.

Therefore, to explain v_2, in addition to the initial geometrical eccentricity, there are something related to N_{part}.

Summary (2)

With same eccentricity, v_2 is scaled by (number of participants)$^{1/3}$.





v_2 becomes consistent after scaled by not only ε but also $N_{part}^{1/3}$.

Is it because of thickness increasing along beam axis then energy per unit area increasing ?

v_2(200GeV) = v_2(62.4GeV)

This concludes that increasing dN/dy doesn't change v_2 at RHIC energy.

It might be because that number of participant to 1/3 (like length) is proportional to the time period taken to freeze out v_2 , and v_2 expands proportional to that period.

Comparison of experimental results to hydro calculation.

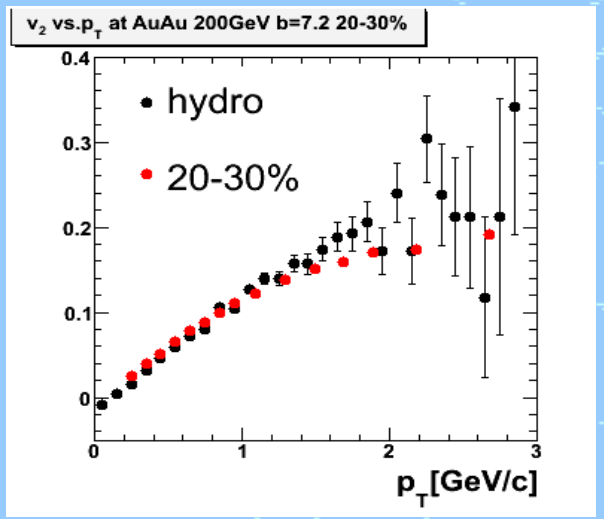
Hydro calculations are done by Dr. Hirano.

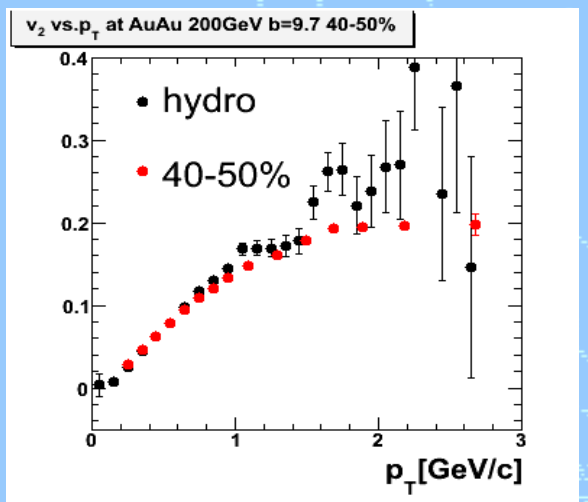
ref: ***arXiv:0710.5795 [nucl-th] and Phys. Lett.B 636, 299 (2006)***

QGP fluid+hadron gas with Glauber I.C.

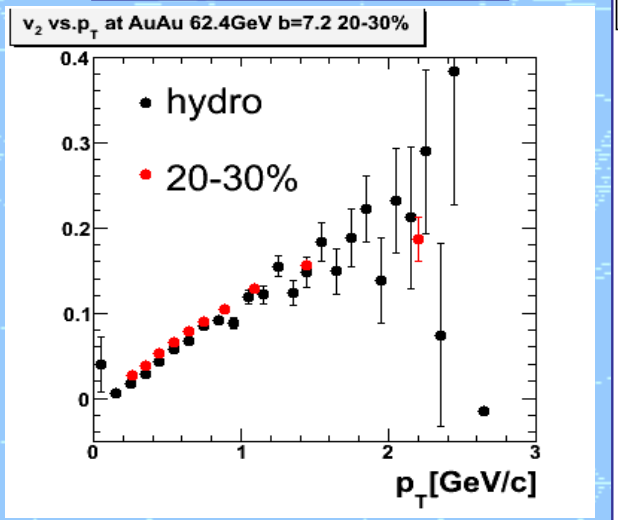
Comparison of data to hydro-simulation

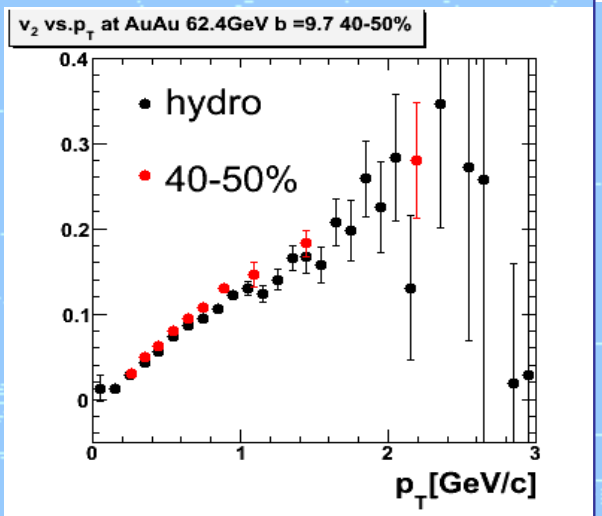
Au+Au 200GeV



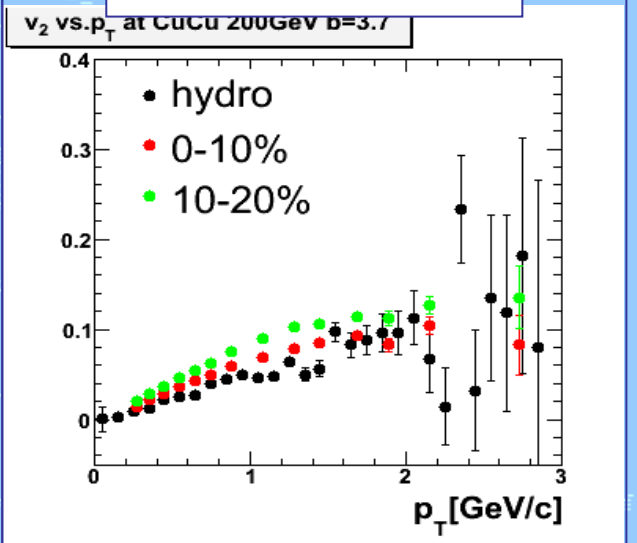


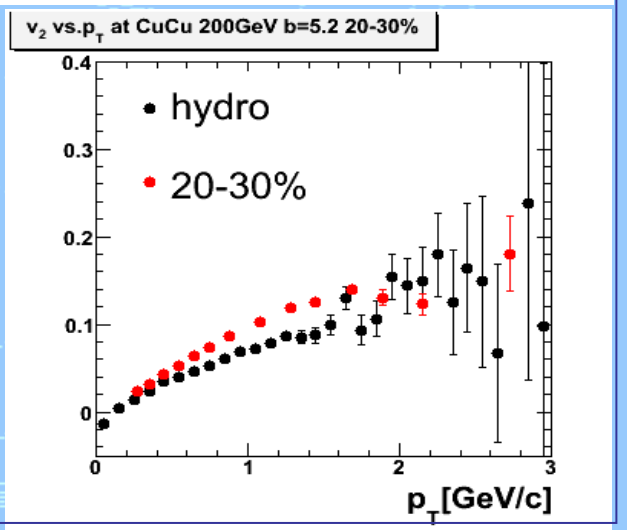
Au+Au 62.4GeV





Cu+Cu 200GeV

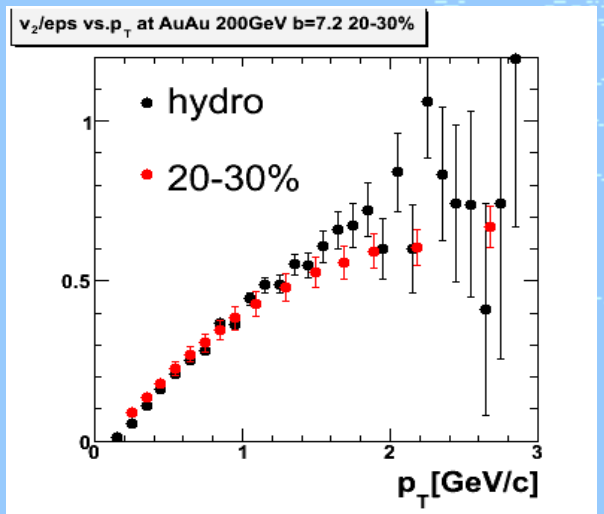


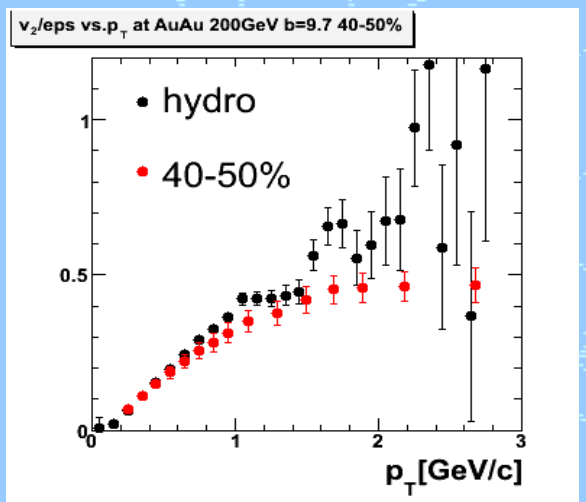


The Au+Au results agree well with hydro but Cu+Cu results don't.

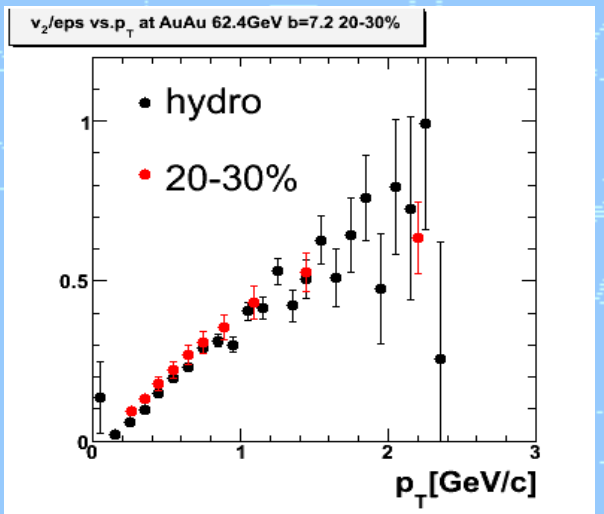
Comparison of $v_{2(data)}/\varepsilon_{participant}$ to $v_{2(hydro)}/\varepsilon_{standard}$

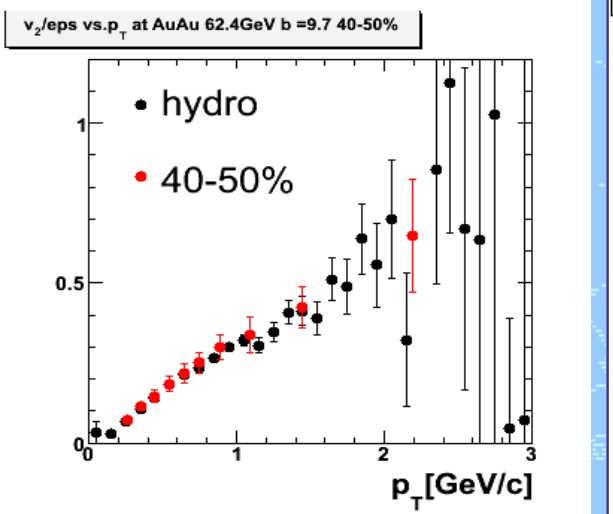
Au+Au 200GeV



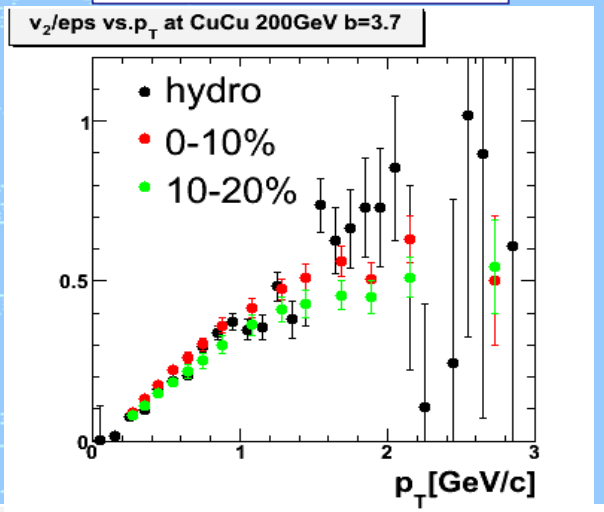


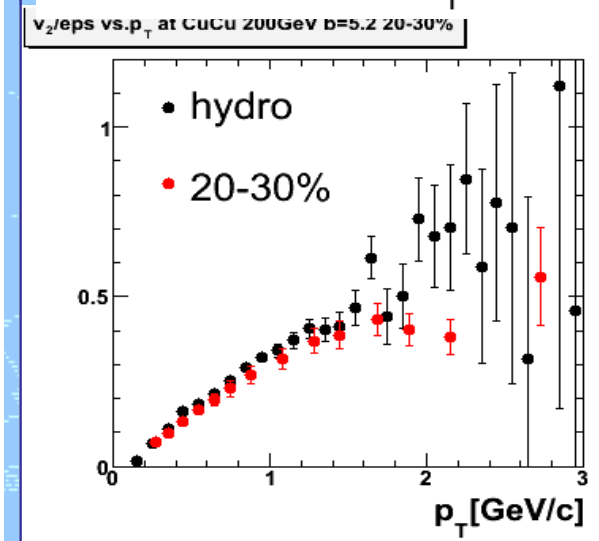
Au+Au 62.4GeV





Cu+Cu 200GeV



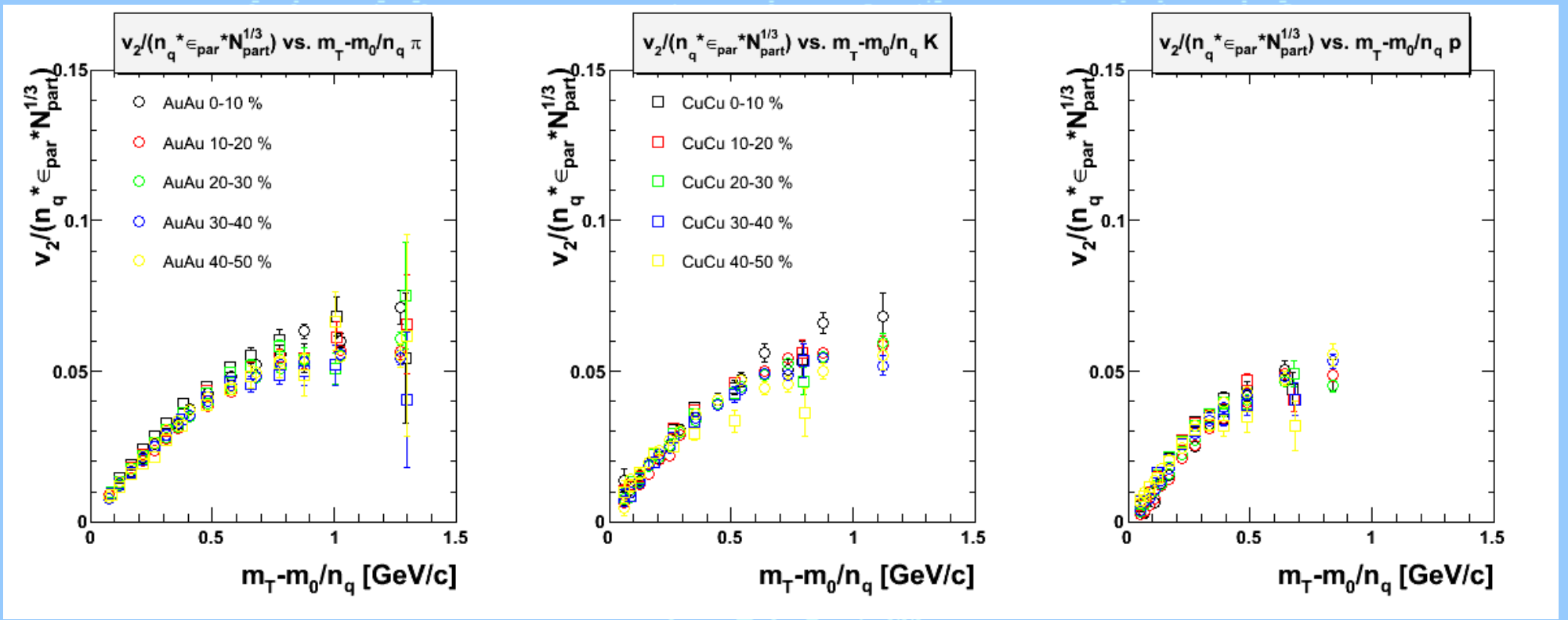


The Au+Au and Cu+Cu results agree well with hydro.

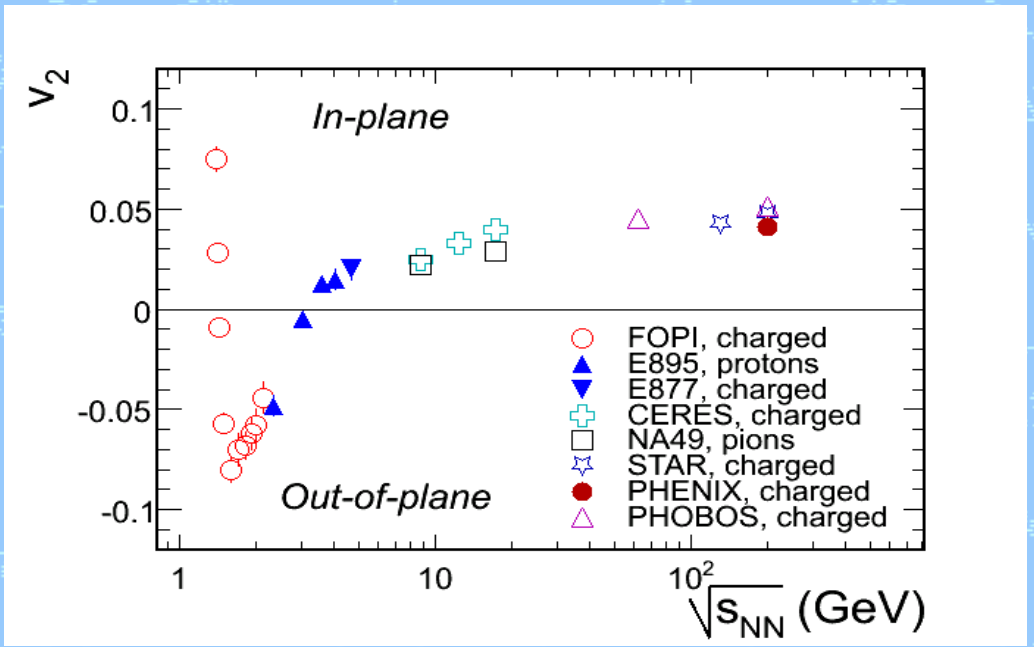
Comparison of AuAu to CuCu

Cu+Cu and Au+Au, 200GeV, PID by EMC

Apply quark number + KET scaling, eccentricity scaling and Npart$^{1/3}$ scaling.



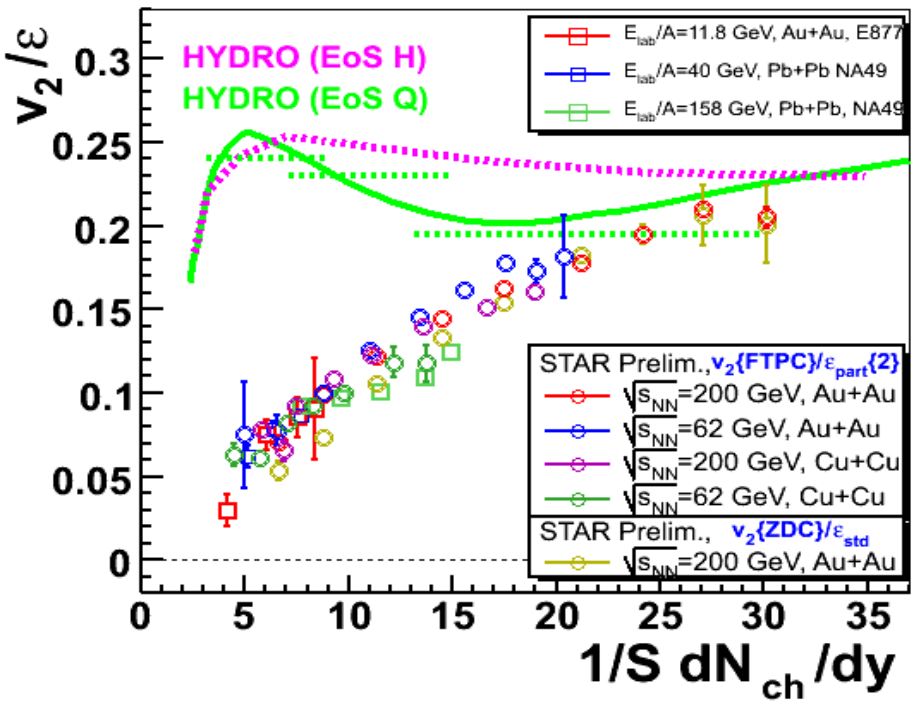
Energy dependence



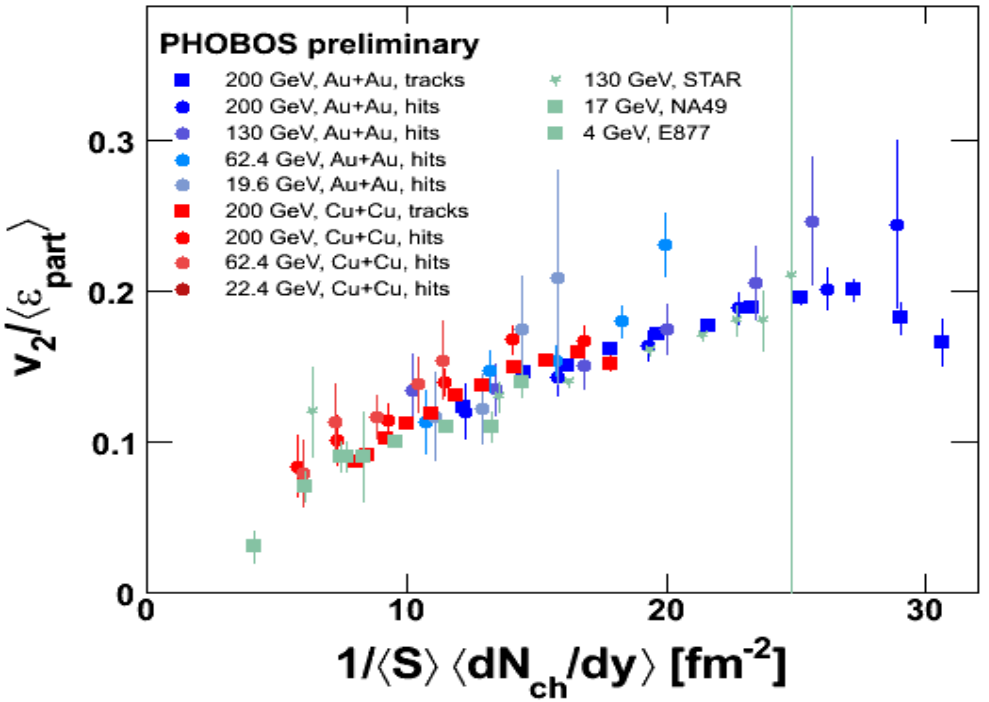
FOPI : Phys. Lett. B612, 713 (2005). E895 : Phys. Rev. Lett. 83, 1295 (1999)
CERES : Nucl. Phys. A698, 253c (2002). NA49 : Phys. Rev. C68, 034903 (2003)
STAR : Nucl. Phys. A715, 45c, (2003). PHENIX : Preliminary.
PHOBOS : nucl-ex/0610037 (2006)

Scaling (another)

QM2006, S. A. Voloshin

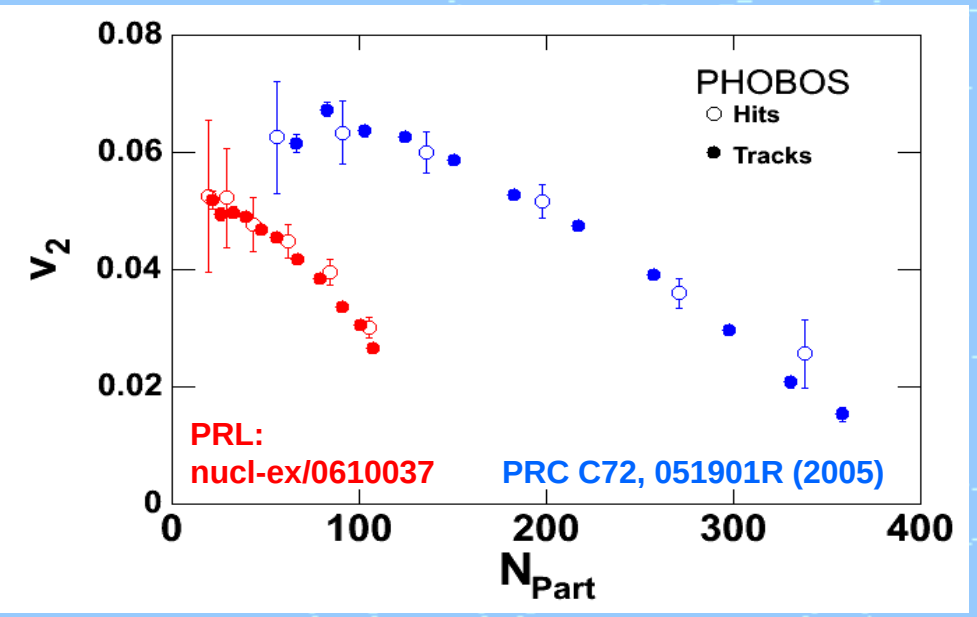


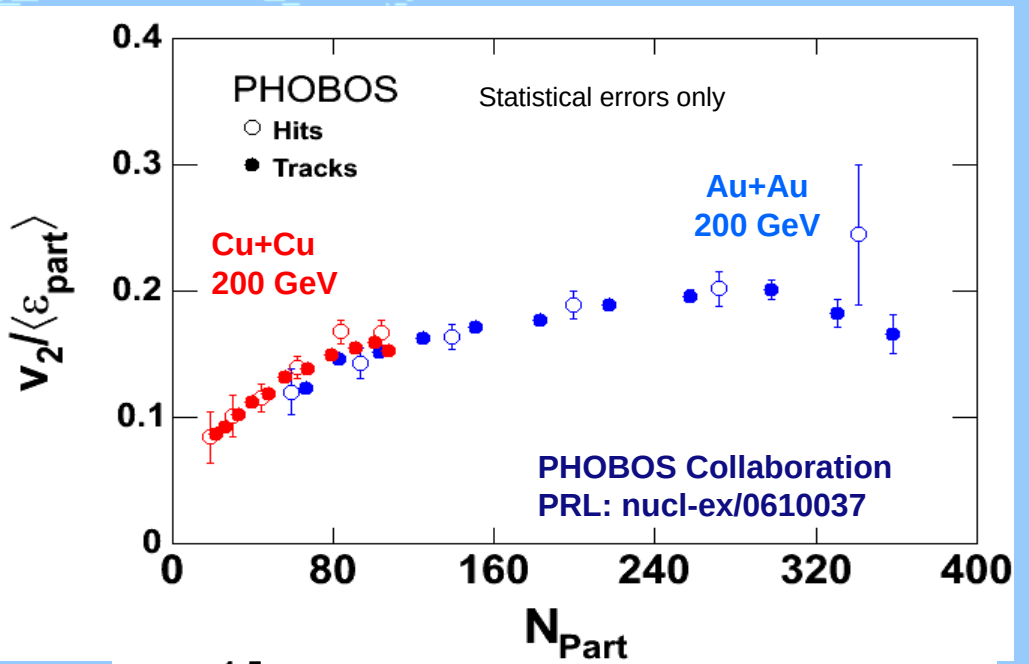
QM2006, R. Nouicer



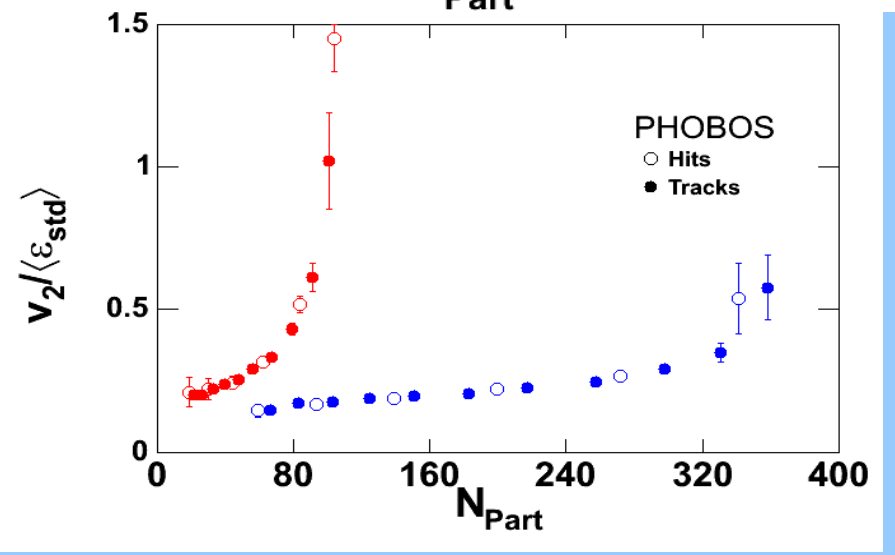
- From SPS to RHIC
- At central collision, it reach to hydro limit which suggest perfect fluid.

additional

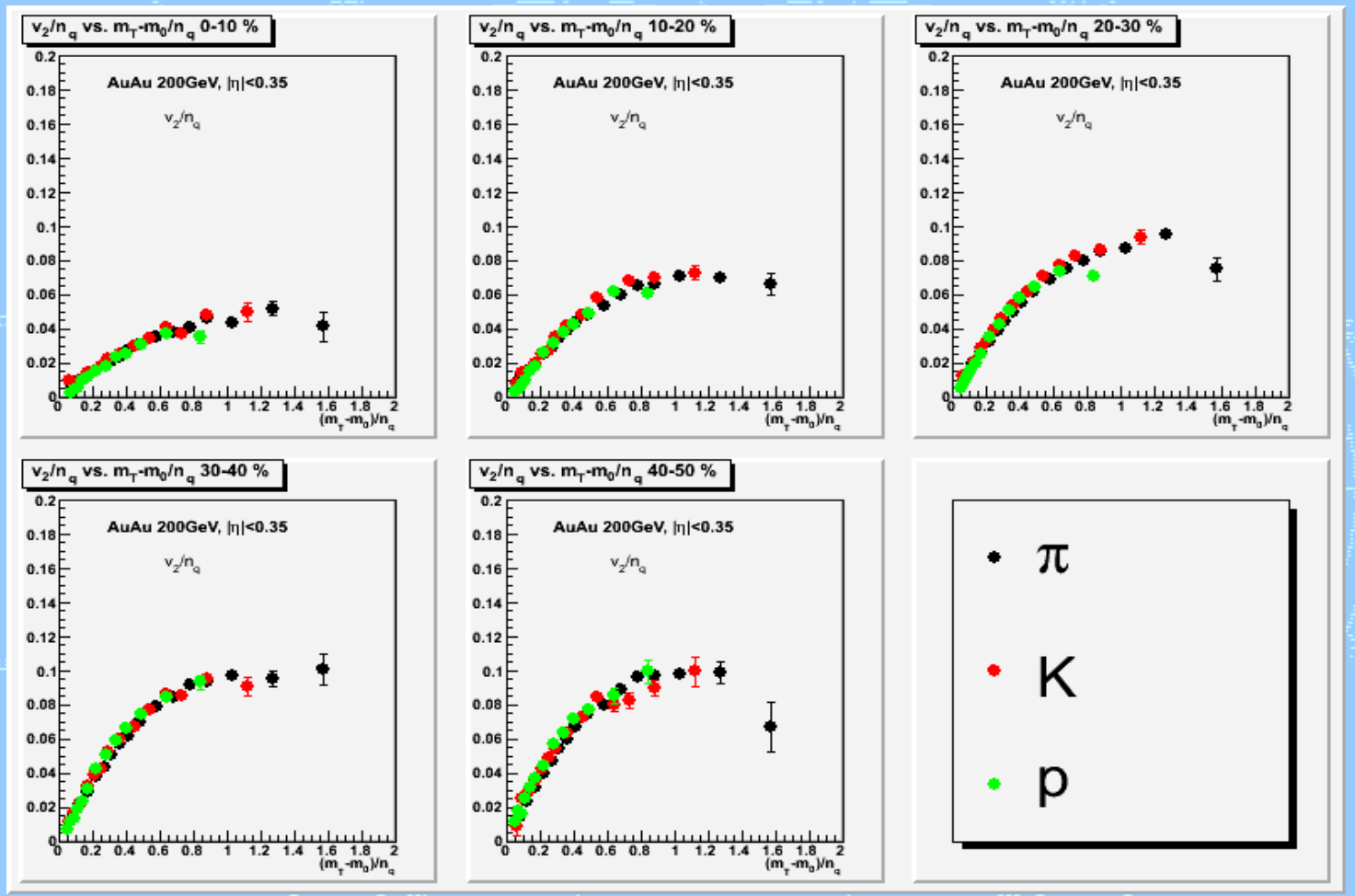




- Comparison between Standard and participant eccentricity.
- Standard eccentricity doesn't include the effect of the participant fluctuation in experiment. The effect of the fluctuation is larger at smaller system.



Quark number + K_{ET} scaling (AuAu 200GeV)

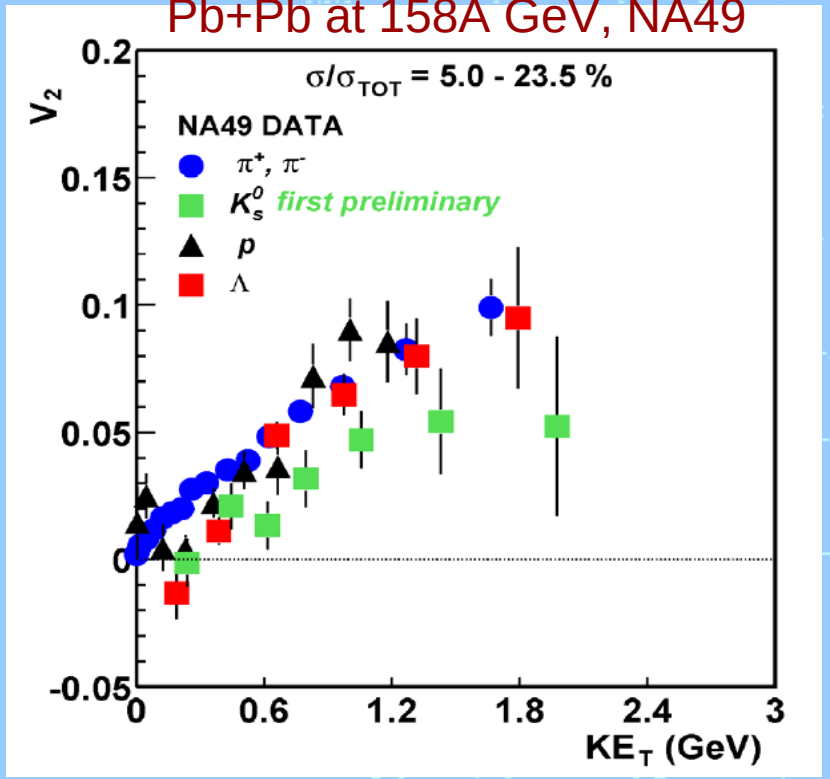


- Quark number + K_{ET} scaling exists.

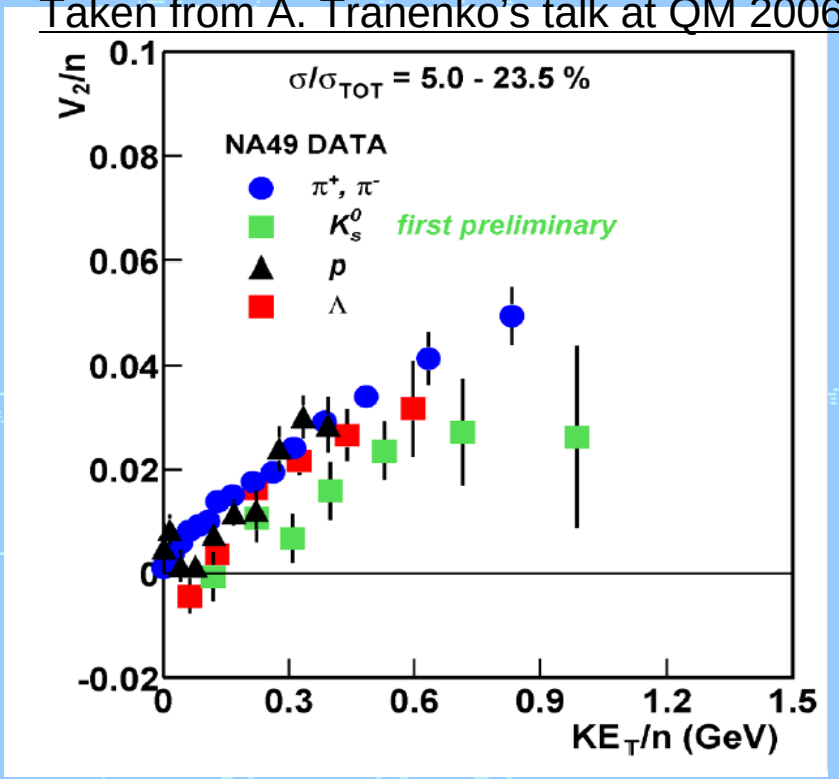
Additional quark number + K_{ET} scaling (PbPb 17.2GeV)

v_2 of p, **π**, **Λ** - C. Alt et al (NA49 collaboration) nucl-ex/0606026 submitted to PRL
v_2 of K^0 (preliminary) - G. Stefanek for NA49 collaboration (nucl-ex/0611003)

Pb+Pb at 158A GeV, NA49



Taken from A. Tranenko's talk at QM 2006

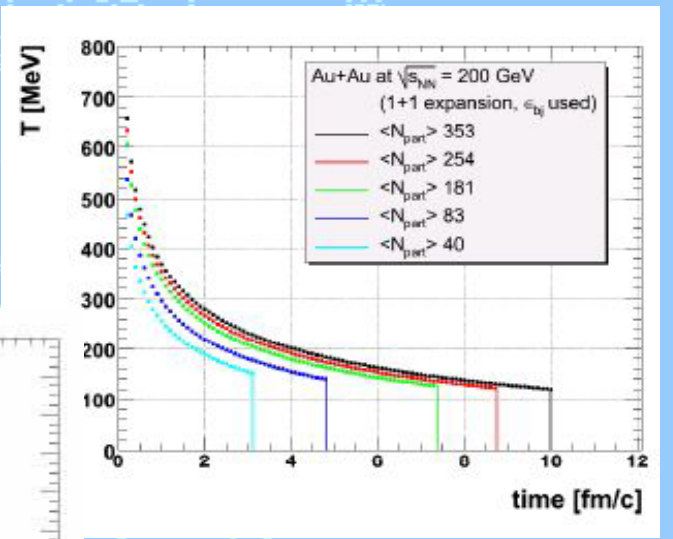


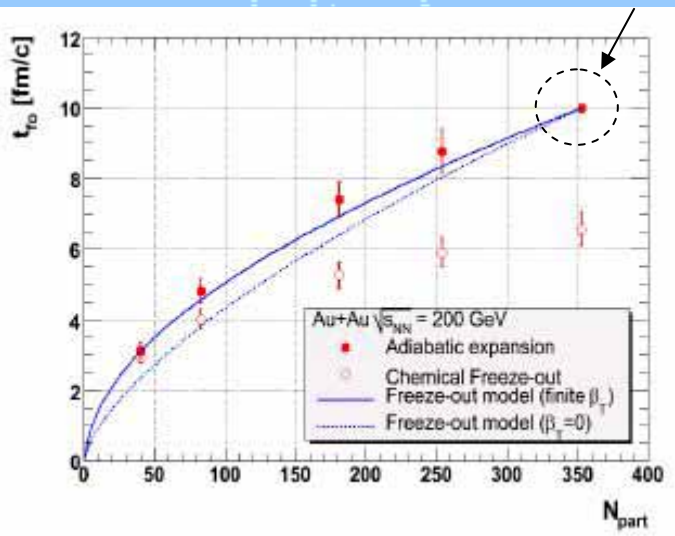
- Quark number + K_{ET} scaling doesn't seem to work out at SPS.
- No flow at partonic level due to nonexistence of QGP ?
- Errors are to big to conclude it.

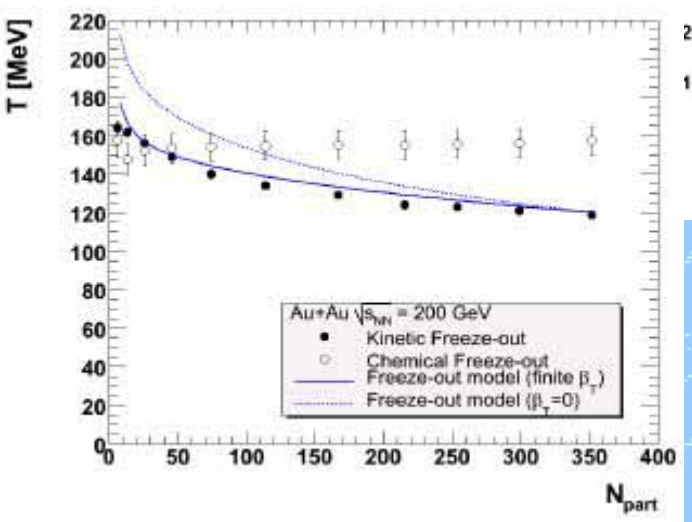
t_{f0} vs. N_{part}

$$T(t) = T_0\left(\frac{t_0(R_0+\beta_T t_0)^2}{t(R_0+\beta_T t)^2}\right)^{1/3}$$

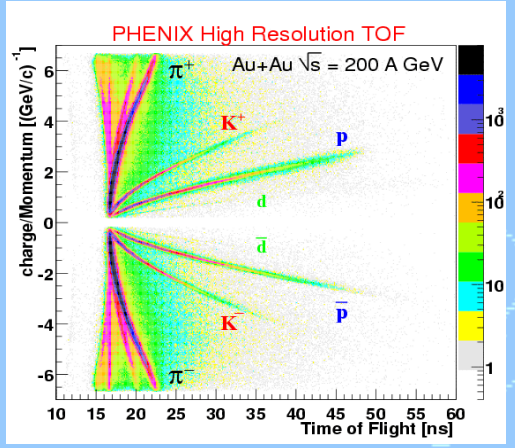
$$t_{fo} = (\sqrt{R_0^2 + 4\beta_T K N_p} - R_0)/2\beta_T$$

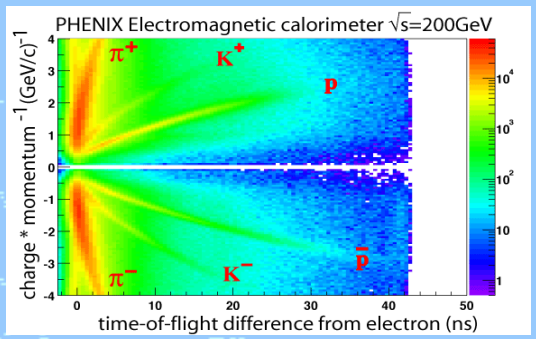






Analysis





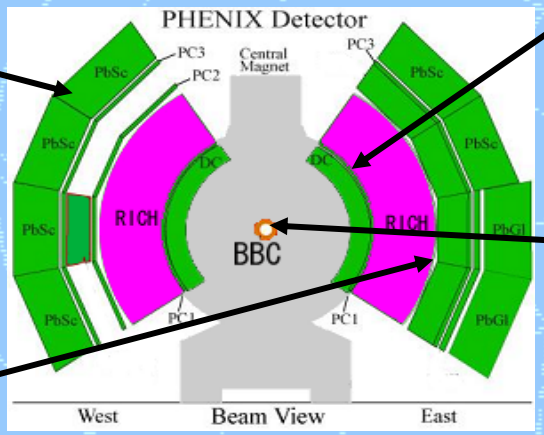
<Data set for this analysis>

- **Au+Au Cu+Cu collision**
- **taken in 2003-2005 at RHIC-PHENIX**
- **Collision energy ：200, 62.4 GeV/2 nucleons**

<PHENIX detectors>

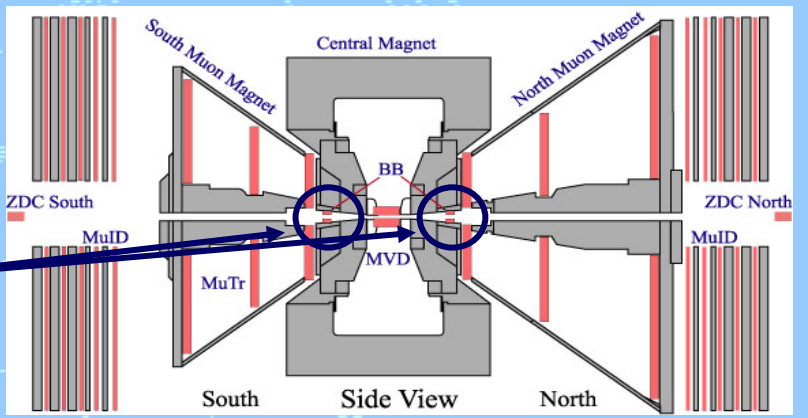
EMCAL
for Particle Identification
resolution=380ps

TOF for Particle Identification
resolution=120ps



DC + PC1
for good track selection and to determine p

BBC
to determine reaction plane and vertex



<PID by TOF measurement>

Using TOF or EMC with BBC, the flight time of the particles is obtained. Mass of the particle is calculated by the flight time and the momentum measured by DC.

<Reaction Plane determination>

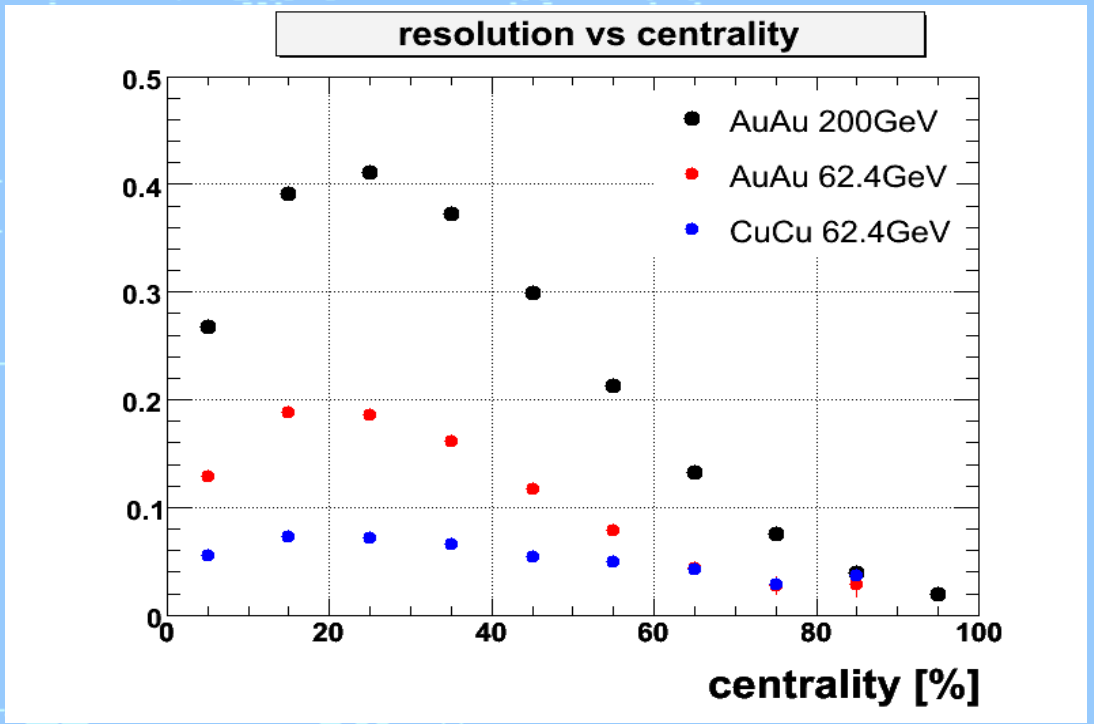
The reaction plane is obtained by measurement of the anisotropic distribution for the produced particles with north and south BBCs located at $|\eta| \sim 3 - 4$.

Resolution Calculation of Reaction Plane

$$resolution = <\cos[2(\Psi_{measured} - \Psi_{true})]> \sim \sqrt{<\cos[2(\Psi_A - \Psi_B)]>}$$

ΨA,B : reaction plane determined for each sub sample.

$$v_2^{real} = \frac{v_2^{measured}}{resolution}$$



- BBC North + South combined