Systematic study of the elliptic flow

~ RHIC v_2 and ALICE v_2 ~

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March 7, 2011

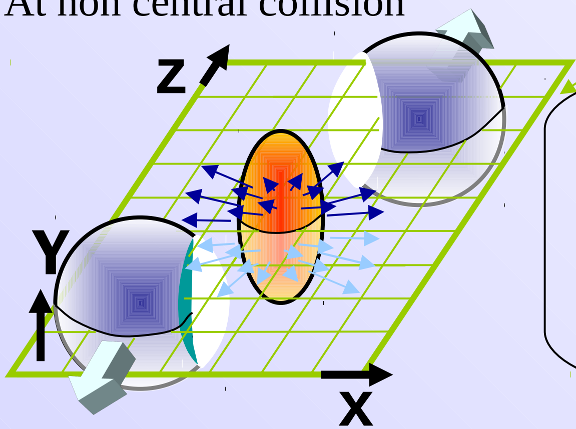
Contents

Elliptic Flow (v_2)

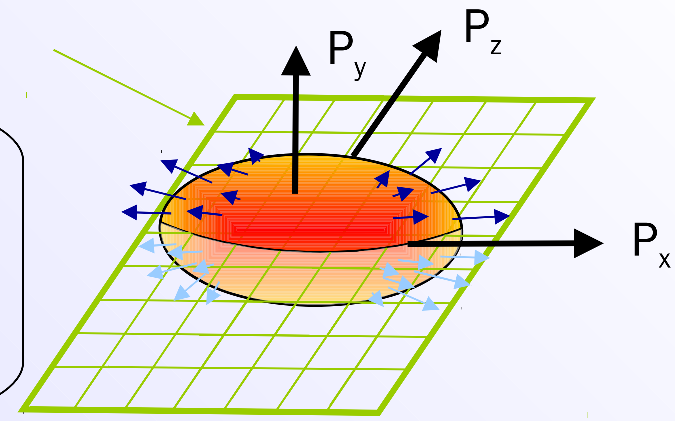
Azimuthal anisotropy of produced particles is a powerful probe for investigating the characteristic of the QGP.

At non central collision

Reaction plane (Ψ)



- *Small mean free path*
- *Thermalization*
- *Pressure gradient*



Geometrical anisotropy

Elliptic flow

Momentum anisotropy

Momentum anisotropy reflects the hot dense matter.

Fourier expansion of the distribution of produced particle angle (ϕ) to reaction plane (Ψ)

$$N(\phi) = N_0\{1 + 2v_1\cos(\phi - \Psi) + 2v_2\cos[2(\phi - \Psi)] + \ldots\}$$

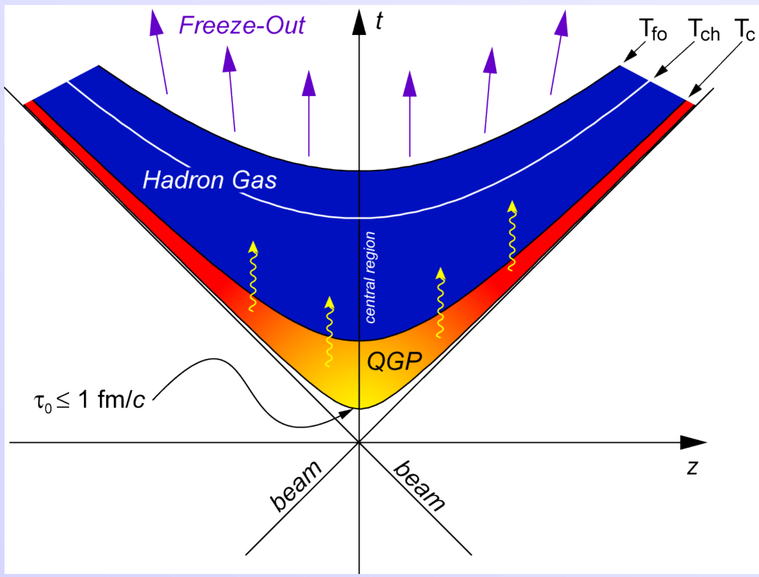
$$v_n = \langle \cos[n(\phi - \Psi)] \rangle$$

v_2 is the coefficient of the second term $\rightarrow$ indicates ellipticity

Thermalization should be occurred very early before the geometrical eccentricity is gone.

Time Evolution

The matter produced in the high energy heavy ion collision is expected to undergo several stages from the initial hard scattering to the final hadron emission.



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	Kinematical freeze-out
Hadron gas	Chemical freeze-out
Mixed phase	Hadronization Expansion & Cooling
QGP	Thermalization
pre-equilibrium	Hard scatterings
Collision	

When the matter is thermalized, we expect

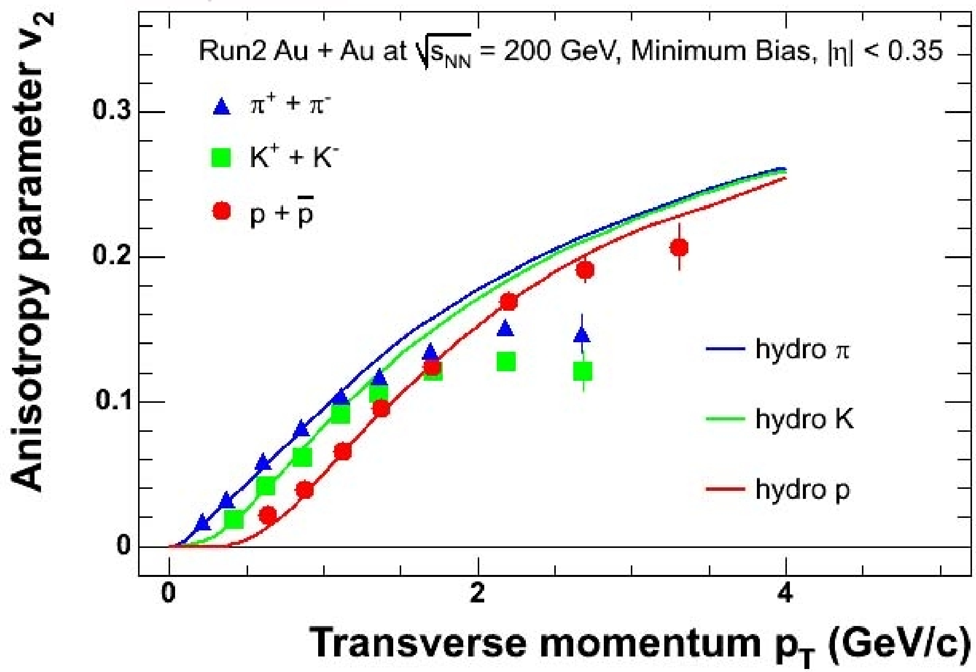
Hydro-dynamical behavior at quark level .

Need a comprehensive understanding from thermalization through hadronization to freeze-out.

***Note whenever the matter interacts each other, v_2 could change.**

v_2 at RHIC

PHENIX PRL 91, 182301



v_2 at low p_T (<~2 GeV/c) can be explained by a hydro-dynamical model assuming:

→Early thermalization(~0.6 fm/c)

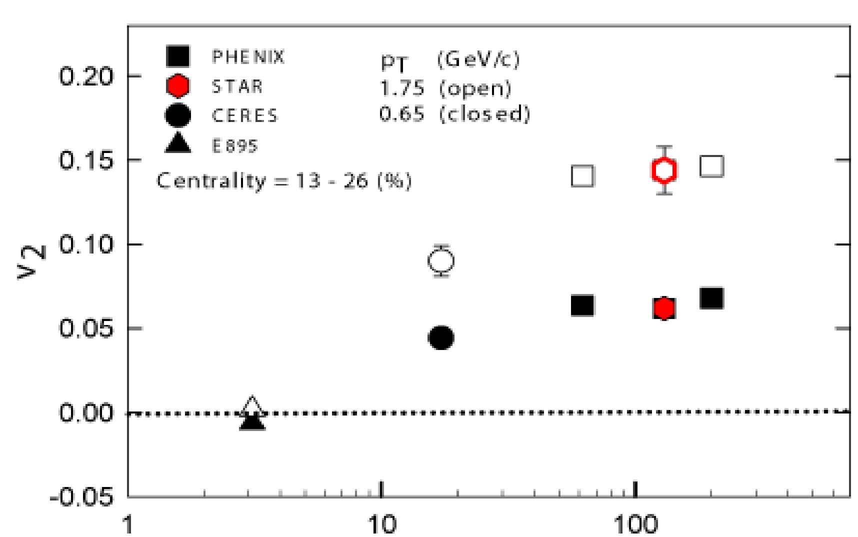
Mass Ordering: **v2(π)>v2(K)>v2(p)**

→Existence of radial flow.

~ 50% increase from SPS to RHIC.

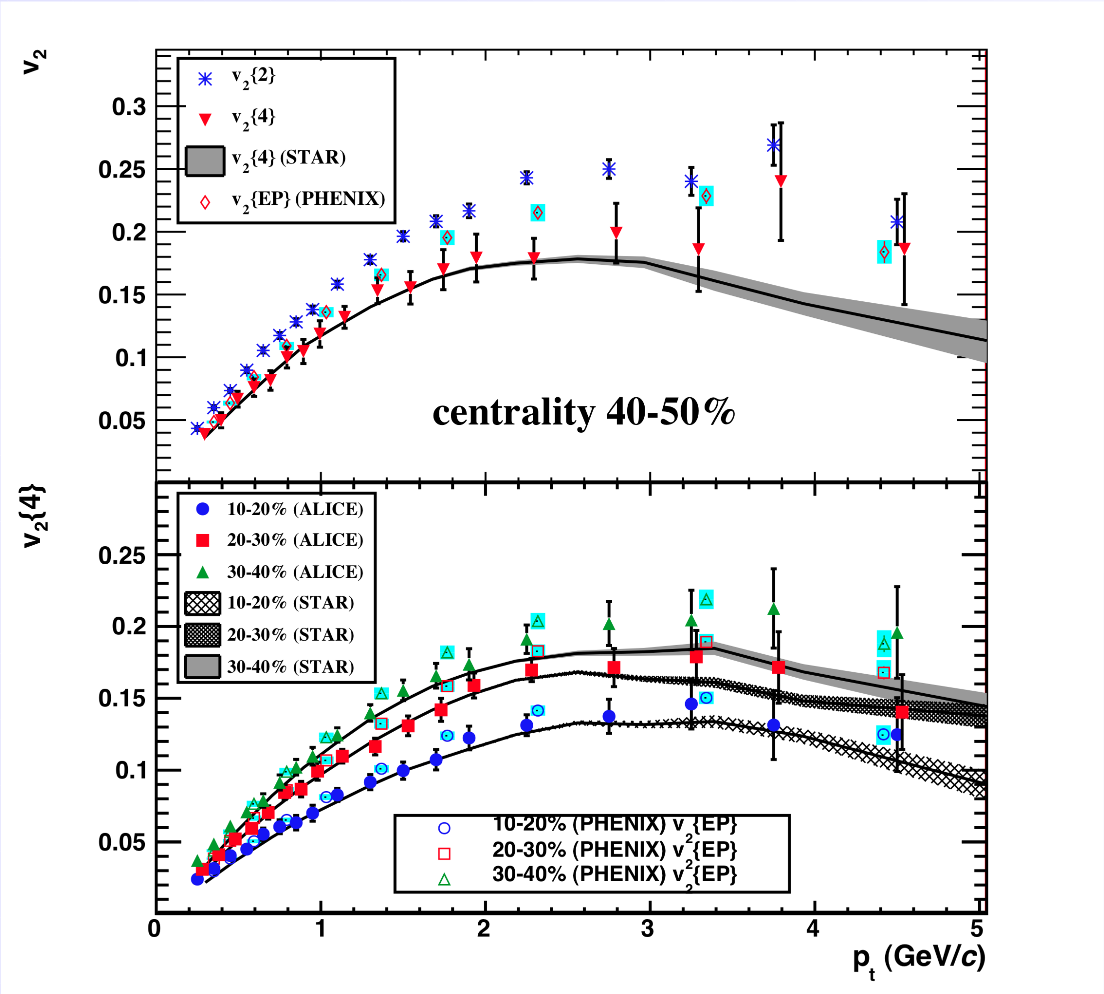
Above 62.4 GeV, v_2 seems to be saturated.

→ The matter reaches thermal equilibrium state at RHIC.



PRL 94, 232302

Comparison with ALICE



ALICE ---
Pb+Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
(nucl-ex 0147314)

PHENIX and STAR ---
Au+Au, $\sqrt{s_{NN}}$ = 200 GeV

PHENIX : Phys. Rev. C 80, 024909 (2009)
STAR : Phys. Rev. C 77, 054901 (2008)

- Mostly consistent, especially at low p_T

Scaling of v_2

- Energy dependence
- Eccentricity scaling
- N_{part} scaling
- Quark number + KE_T scaling
- Universal scaling

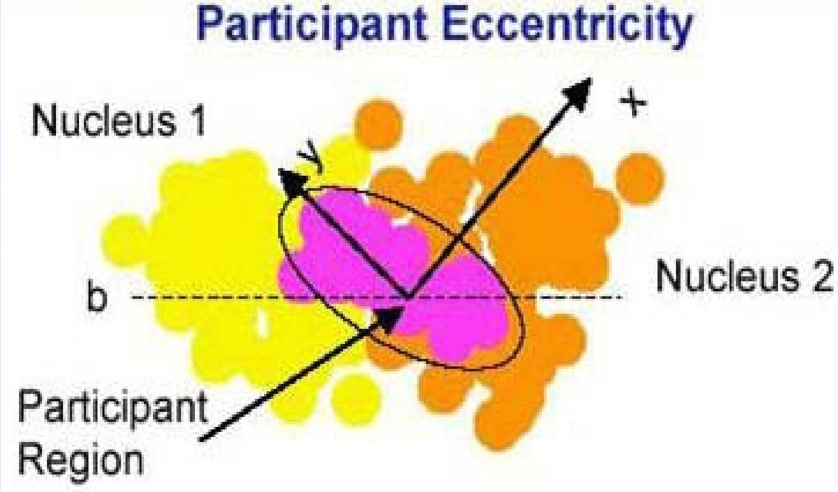
Words

N_{part} --- Number of nucleons participating the collision

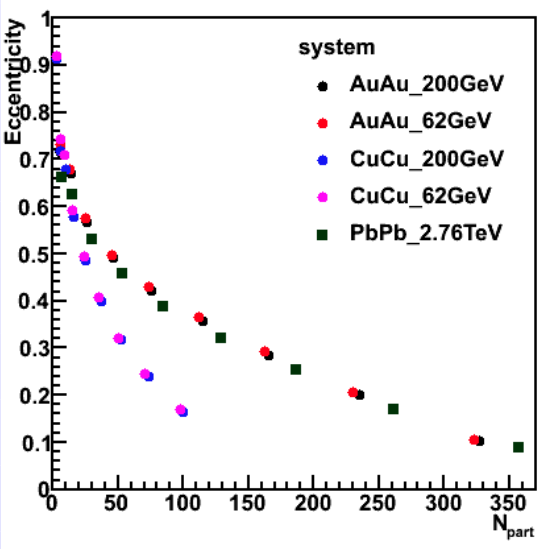
Eccentricity (ε) --- geometrical eccentricity of participant nucleons

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

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



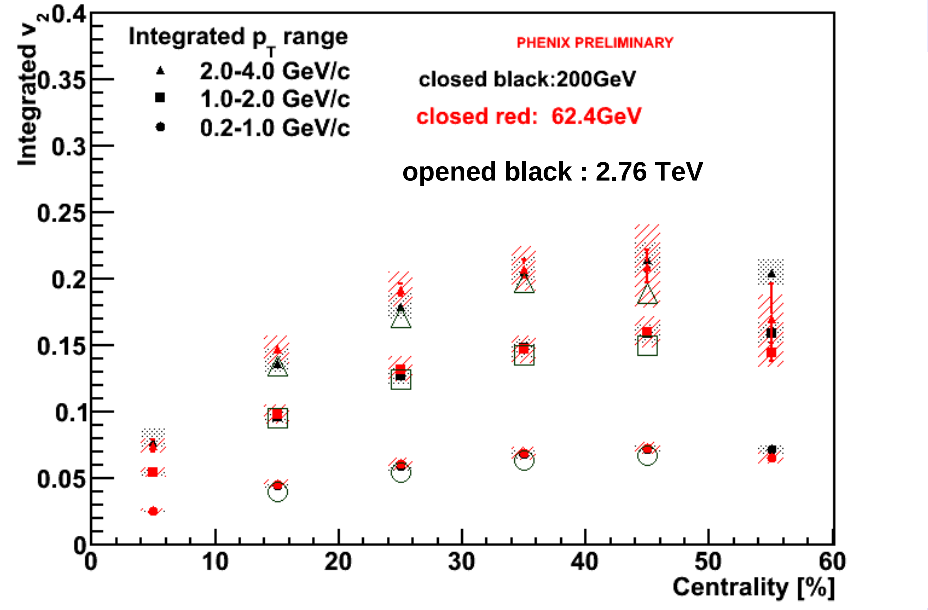
ε vs. N_{part}



Slightly different at small Npart between Au+Au and Pb+Pb.

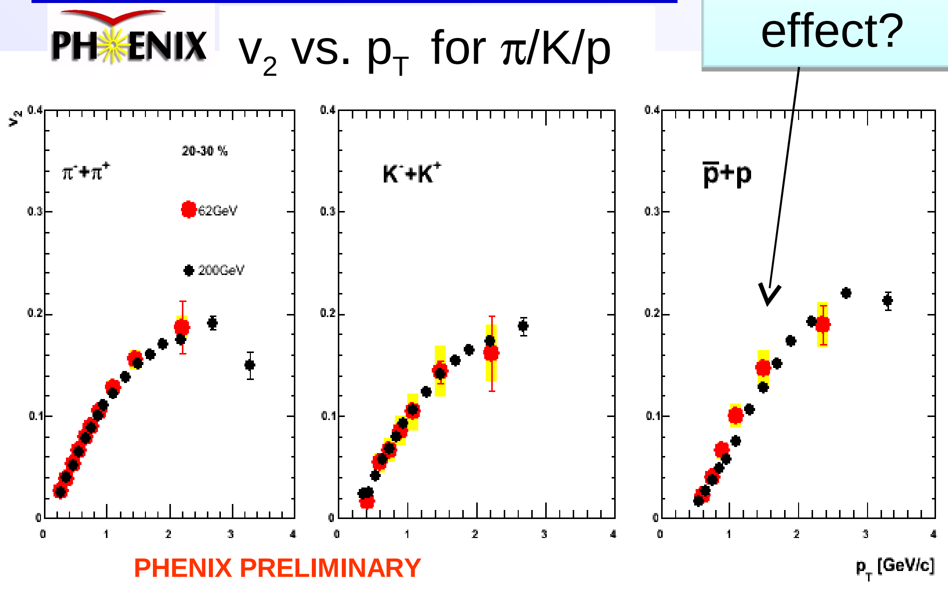
Energy dependence
2.76 TeV, 200 GeV, 62.4 GeV

Centrality dependence



Identified particles

radial flow effect?



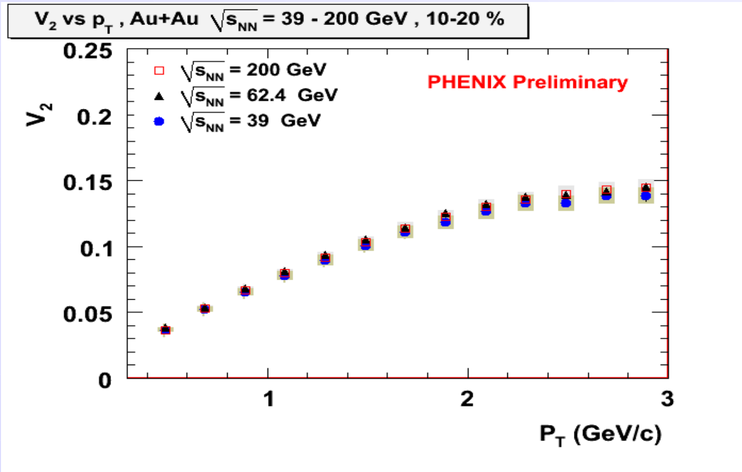
No significant difference above 62.4 GeV at RHIC.

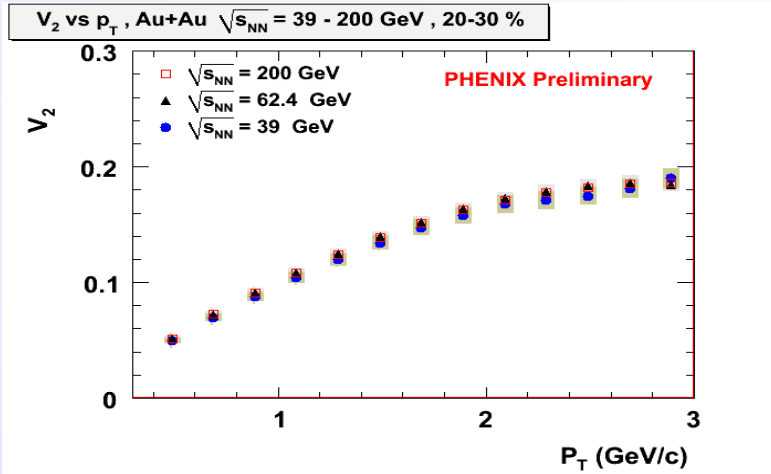
RHIC and LHC are same especially at low p_T.

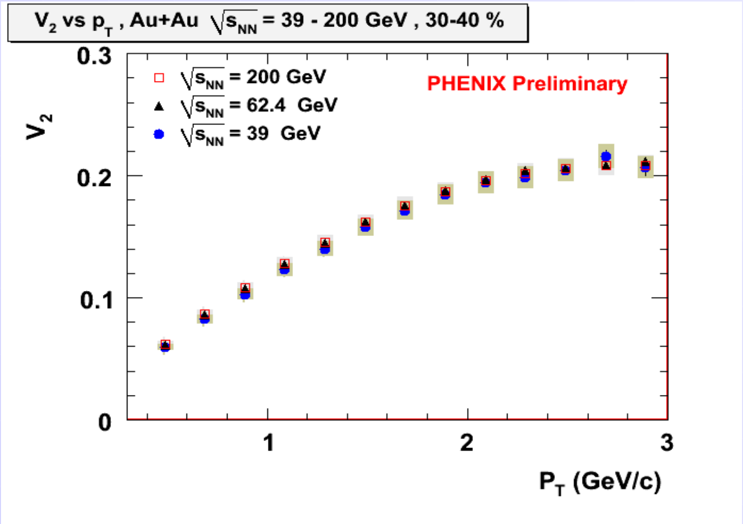
Need to measure PID v_2 at 2.76 TeV to see the radial flow effect.

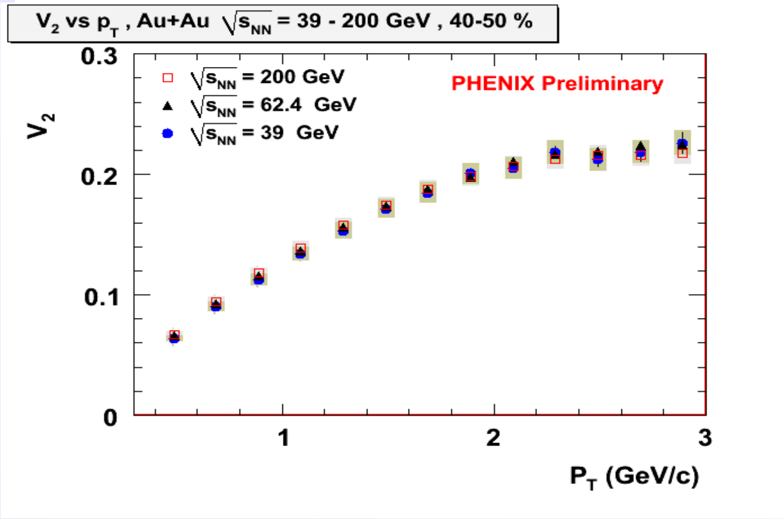
Energy dependence
200, 62.4, 39, 7.7 GeV

S. Huang, A. Taranenko, R. Lacey (WWND2011)





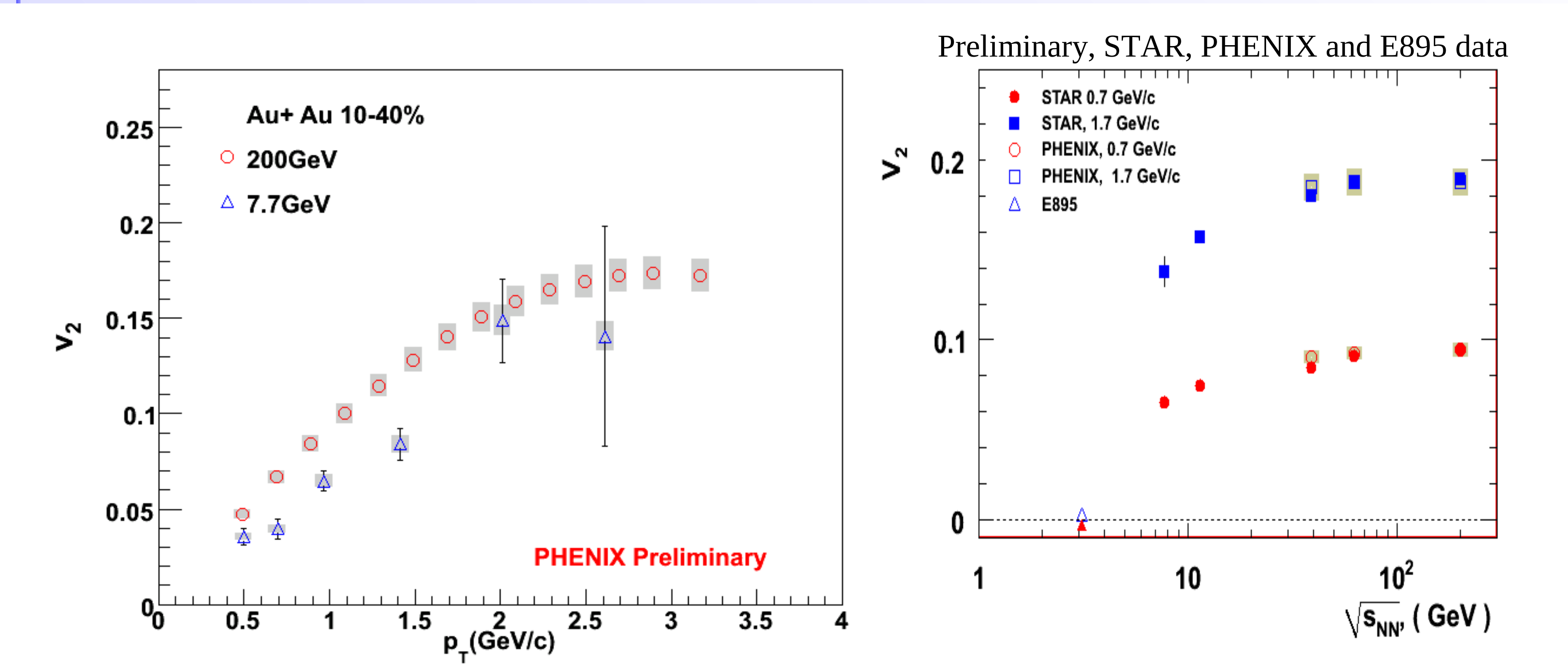




No energy dependence from 39 GeV to 200 GeV for different collision centralities.

Energy dependence 200, 62.4, 39, 7.7 GeV

S. Huang, A. Taranenko, R. Lacey (WWND2011)



The v_2 at 7.7 GeV Au+Au is much lower than v_2 of 39 - 200 GeV.

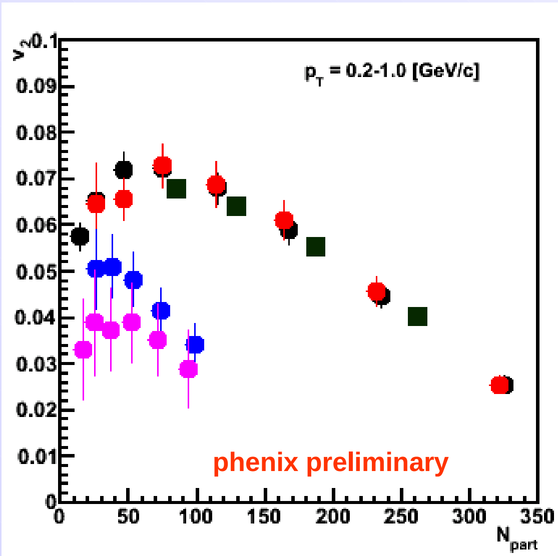
Partonic flow --> Hadronic flow : between 39 and 7.7 GeV ?

→ Need more study for this region.

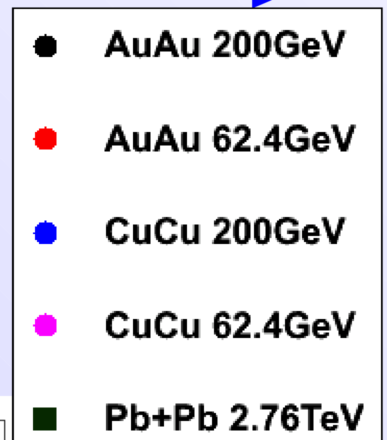
Eccentricity scaling

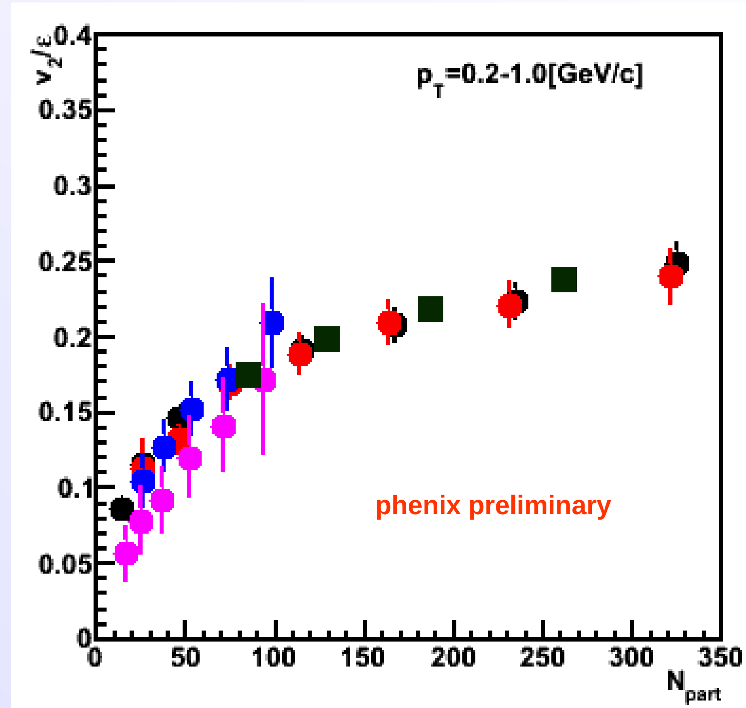
Pb+Pb, Au+Au, Cu+Cu

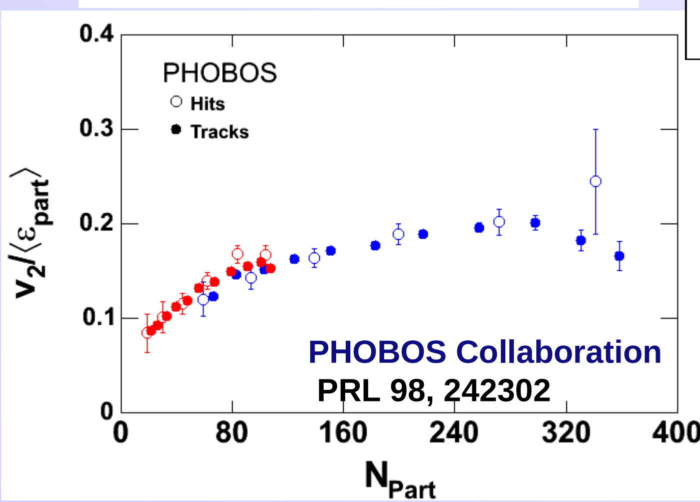
Compare v_2 normalized by eccentricity (ε) in collisions of different size.



0.2<p_T<1.0 [GeV/c]



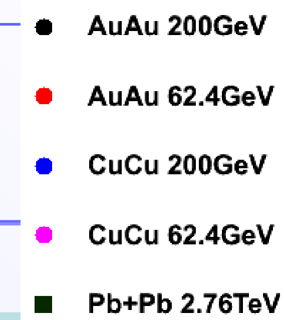




Eccentricity scaling suggests early thermalization.

There is a strong N_{part} dependence.

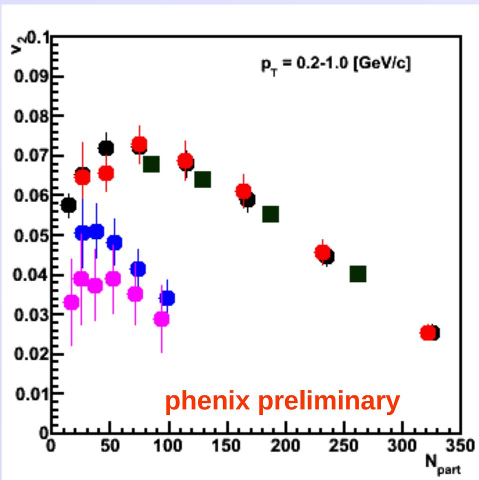
N_{part} Scaling



The dependence can be normalized by $N_{part}^{1/3}$.

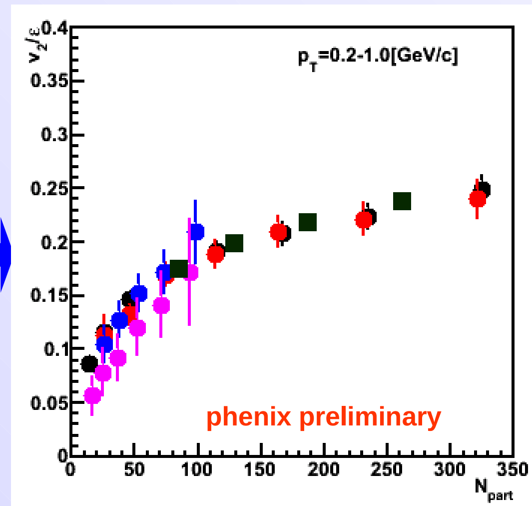
Dividing by $N_{part}^{1/3}$

v_2 vs. N_{part}

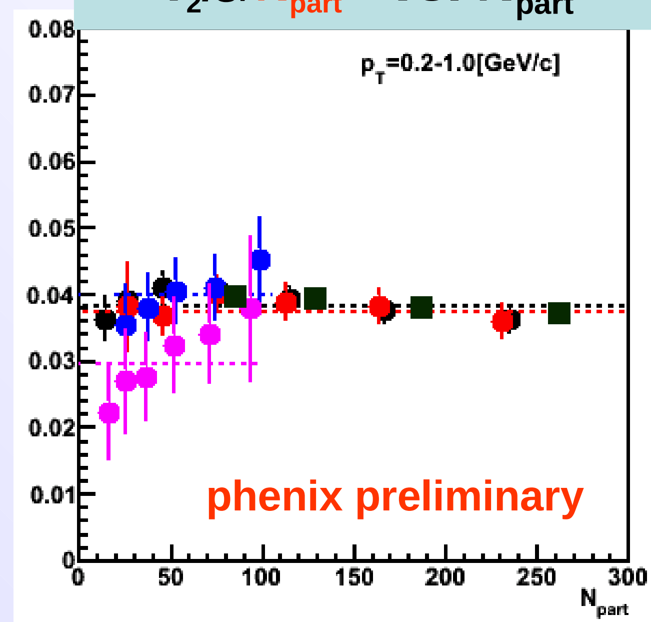


0.2<p_T<1.0 [GeV/c]

v_2/ε vs. N_{part}



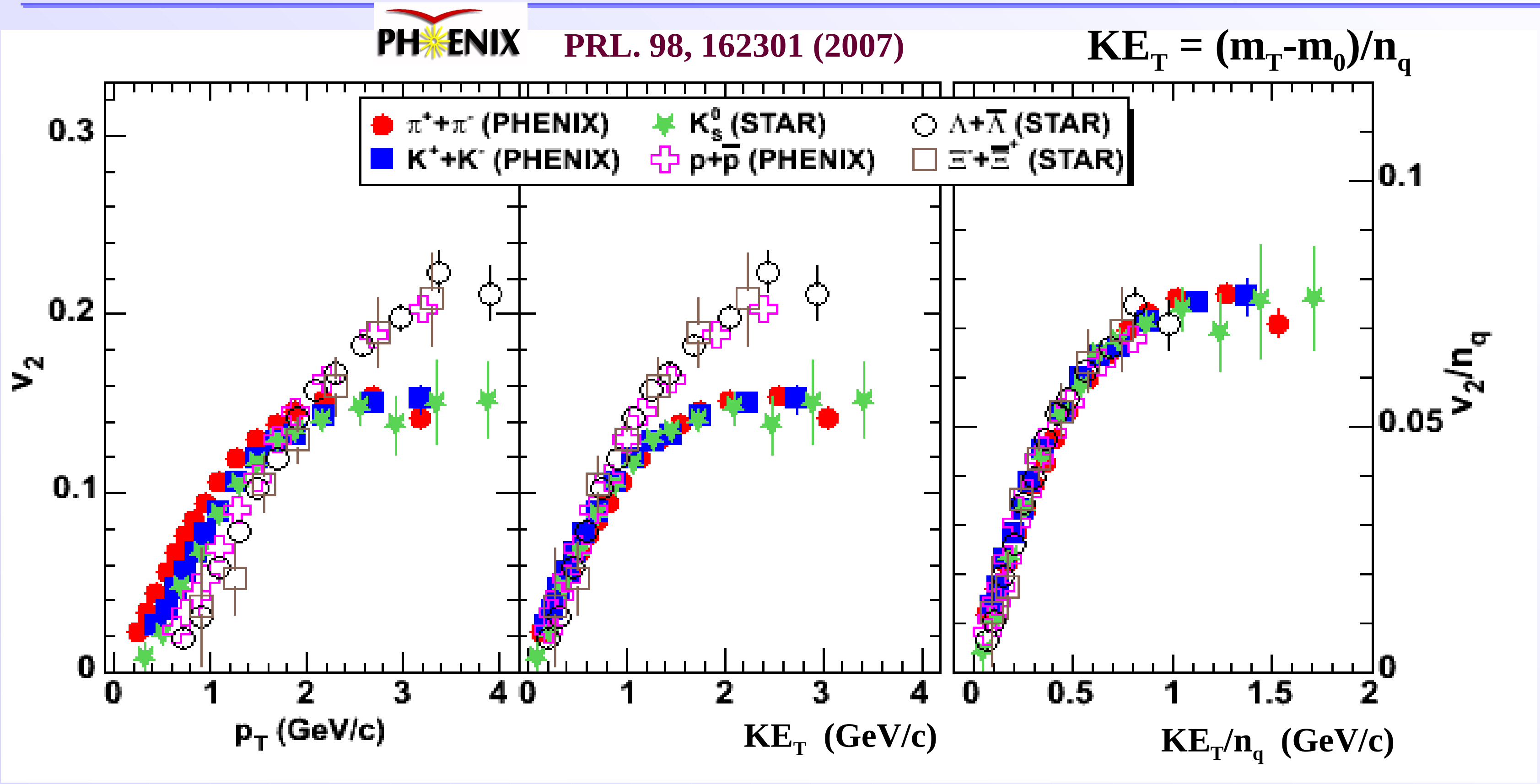
$v_2/\varepsilon/N_{part}^{1/3}$ vs. N_{part}



v_2/eccentricity/$N_{part}^{1/3}$ scaling works for all collision systems except small N_{part} at 62 GeV.

- This exception may indicate non-sufficient thermalization region.

Quark number + KE_T scaling (AuAu 200 GeV)

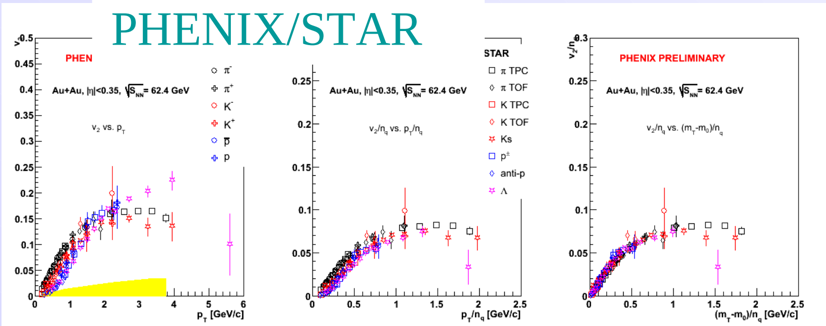


$v_2(p_T)/n_{quark}$ vs. KE_T/n_{quark} becomes one curve independent of particle species.

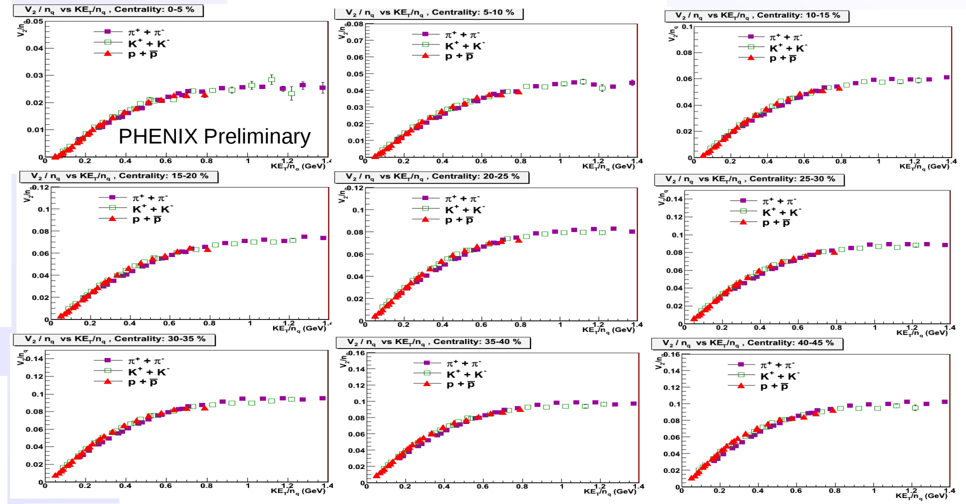
Quark number scaling is consistent to the recombination model which assumes the quark level flow at QGP phase.

Quark number scaling everywhere

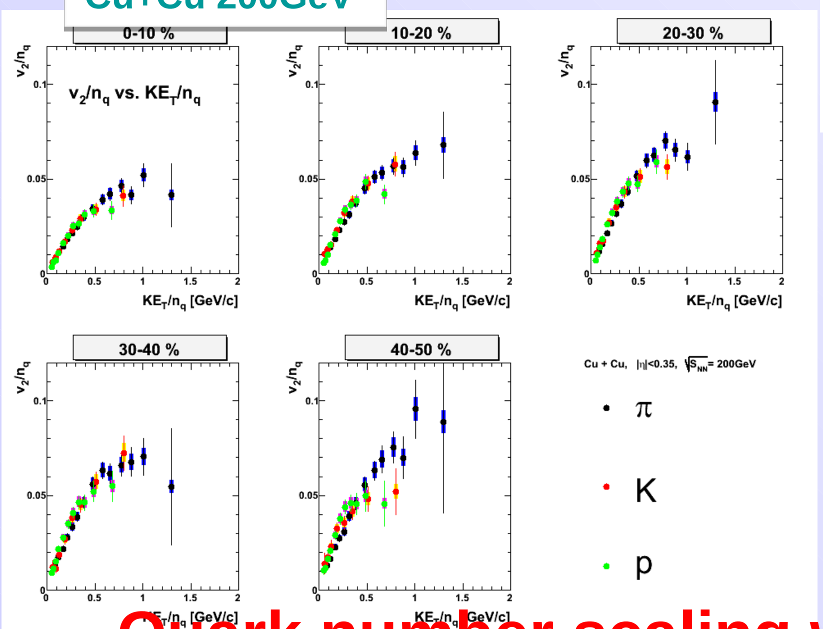
AuAu 62.4GeV PHENIX/STAR



Au+Au 200 GeV (Run7)

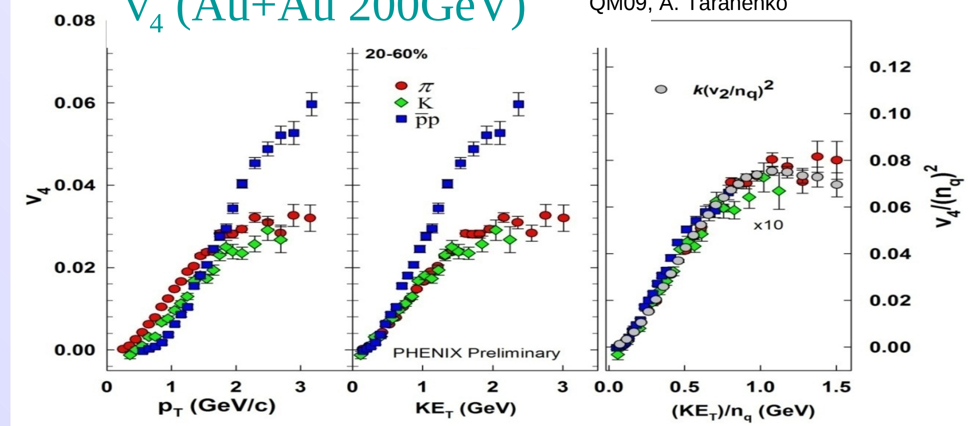


Cu+Cu 200GeV



v_4 (Au+Au 200GeV)

QM09, A. Taranenko

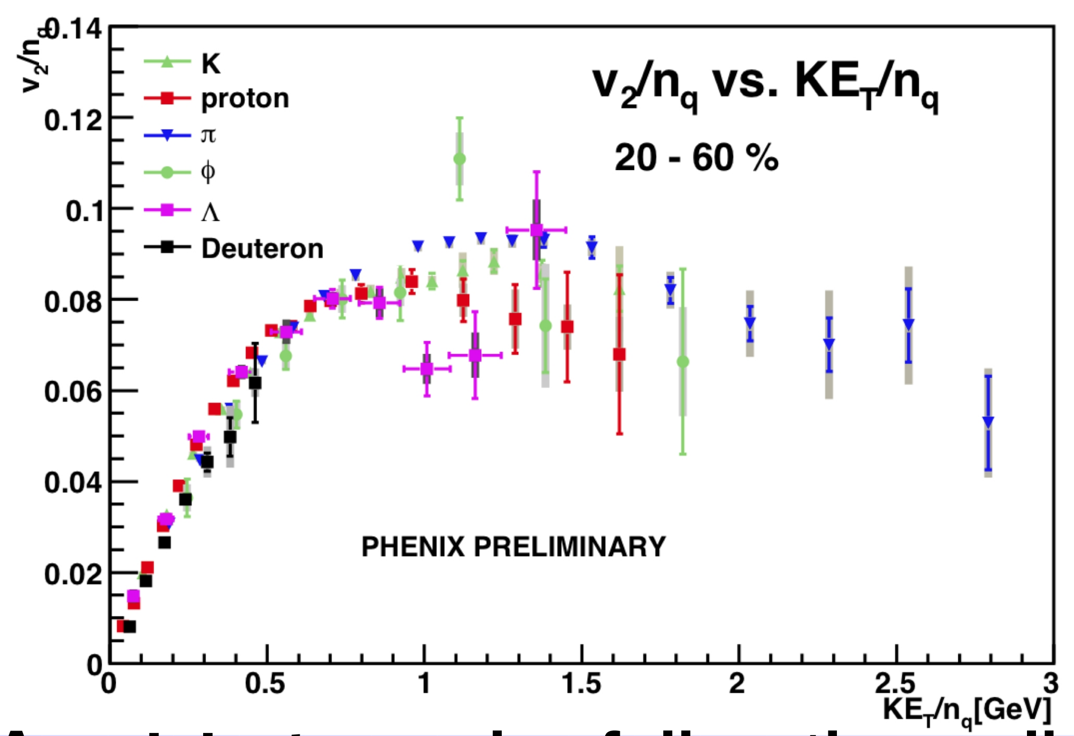


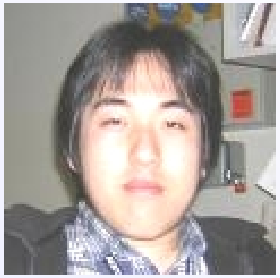
Quark number scaling work out up to K_{ET} ~1GeV.

Quark number scaling everywhere

Au+Au 200GeV (Run7)

Yoshimasa IKEDA (spring JPS 2010)





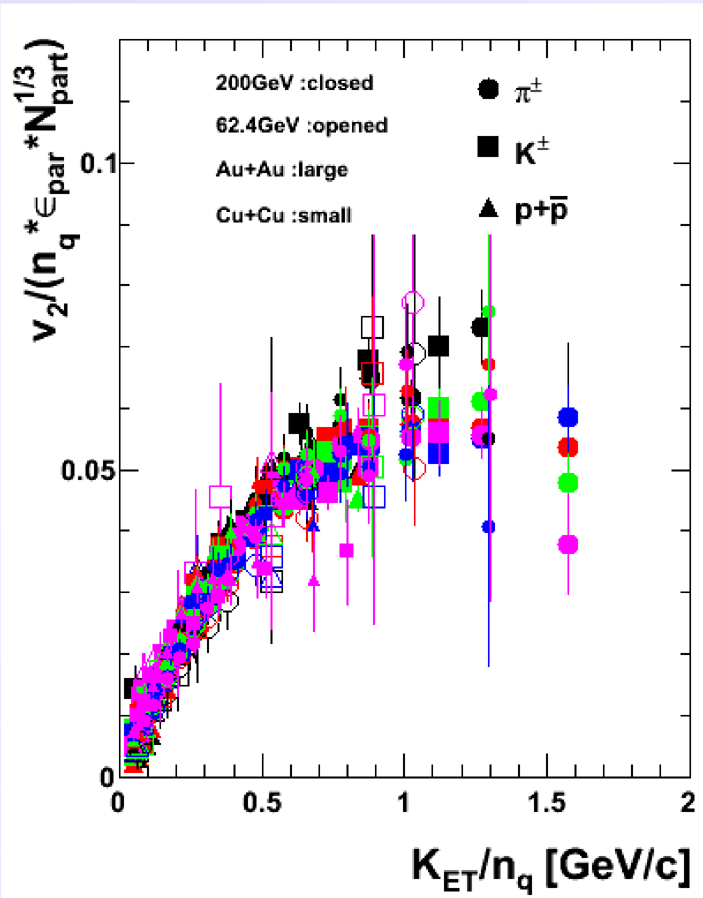
ϕ, Λ and deuteron also follow the scaling.

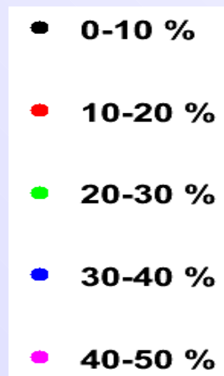
Significant part of elliptic flow at RHIC develops at quark level.→ QGP phase

New detector and high statistics enable us to see the breaking point at K_{ET} ~1GeV.

Universal v_2 for identified charged hadrons

Taking all scaling together,





- Different Energy and System (AuAu200, CuCu200, AuAu62)
- Different Centrality (0-50%)
- Different particles (π/ K /p)

45 curves

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

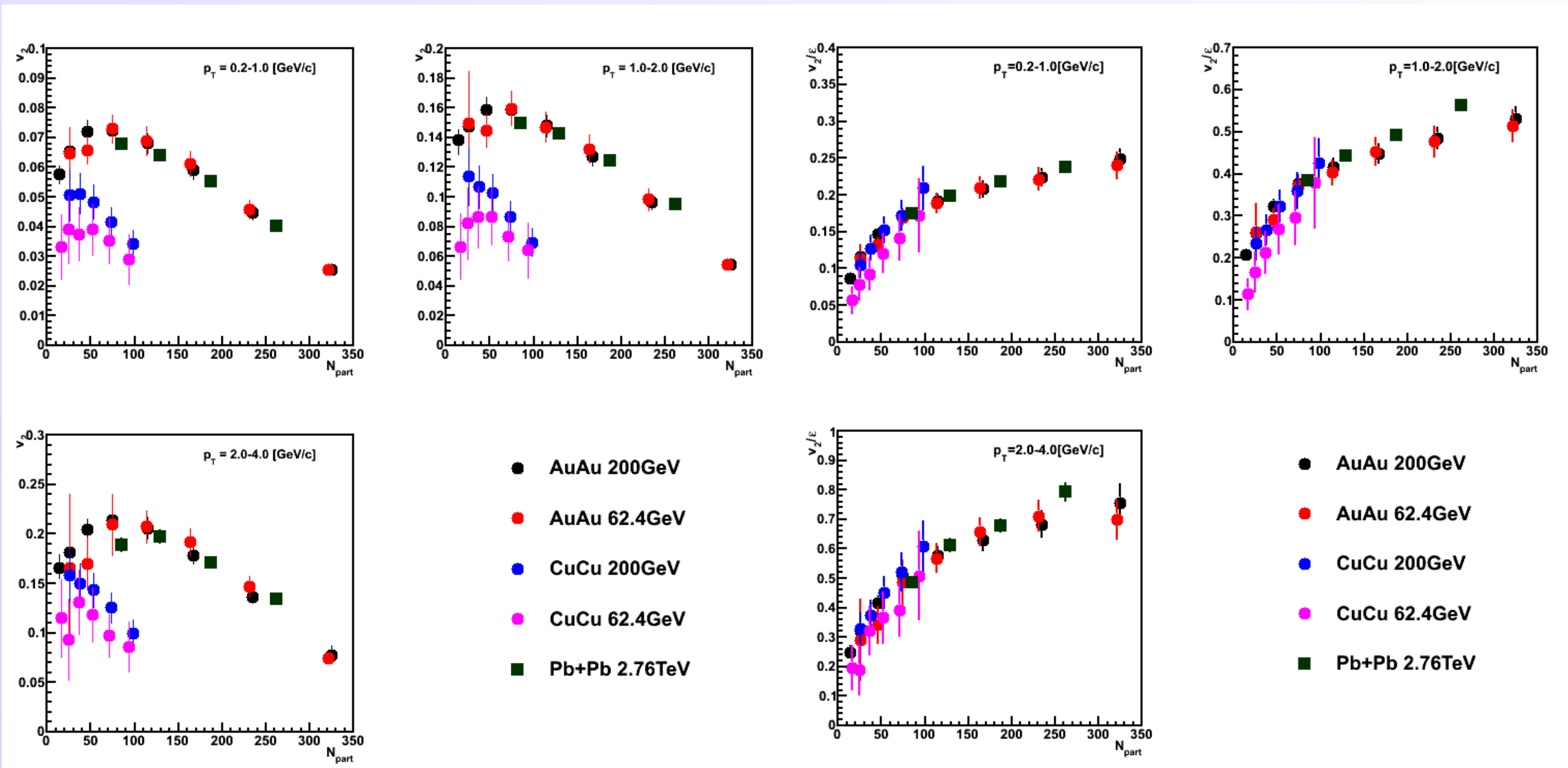
Scale to one curve.

χ2/ndf = 2.1 (with systematic errors)

Summary

- Systematic study of v_2 have been done in Au+Au/Cu+Cu at $\sqrt{s_{NN}}$ = 62.4/200 GeV and compared with Pb+Pb at $\sqrt{s_{NN}}$ = 2.76 TeV.
- v_2 values are saturated above 62.4 GeV in Au+Au and Pb+Pb.
  - Local thermalization
- $v_2(p_T)$ follows quark number + KE_T scaling in Au+Au (200,62GeV) and Cu+Cu (200GeV) .
  - Flow at quark level → QGP phase
- $v_2(N_{part})$ / ε are same between Au+Au, Pb+Pb, Cu+Cu at 200 GeV ~2.76 TeV.
  - Eccentricity scaling → Early thermalization
- $v_2(p_T)$ $/\varepsilon/N_{part}^{1/3}$ scaling works except for small N_{part} at 62 GeV.
  - Existence of a universal v_2 scaling at RHIC and Continue to LHC.
  - Exception may indicate non-sufficient thermalization region from 7.7GeV to 39 GeV.

Scaling on other p_T regions



Scaling on other p_T regions