Systematic dependence of the elliptic flow

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The 7th workshop on Particle Correlations and Femtoscopy

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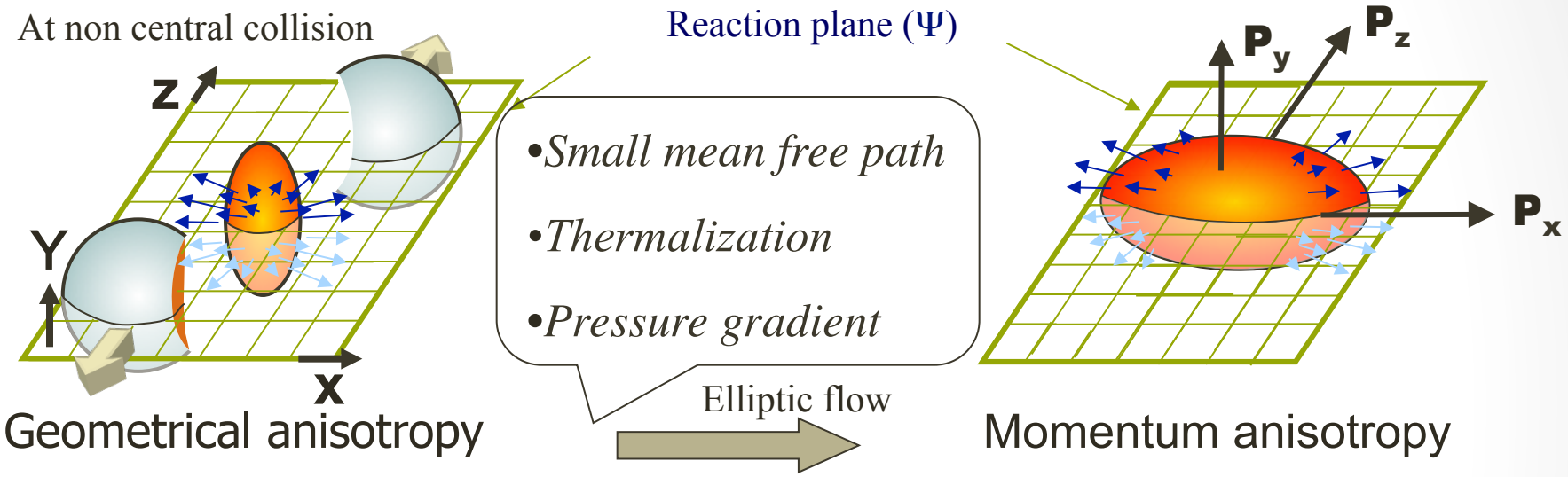
Elliptic Flow (v_2)

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



Measured v_2 reflects the hot dense matter.

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

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

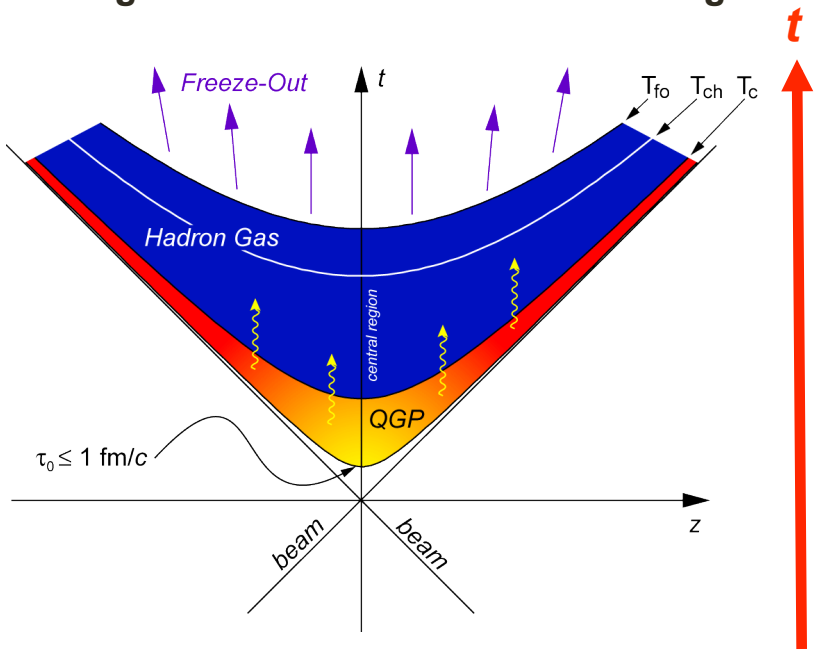
$$v_n = \langle\cos[n(\phi - \Psi)]\rangle$$

v_2 is the coefficient of the second term → 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.



Hadron gas

Mixed phase

QGP

pre-equilibrium

Collision

Kinematical freeze-out

Chemical freeze-out

Hadronization
Expansion & Cooling

Thermalization

Hard scatterings

When the matter is thermalized, we expect

Hydro-dynamical behavior at quark level .

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

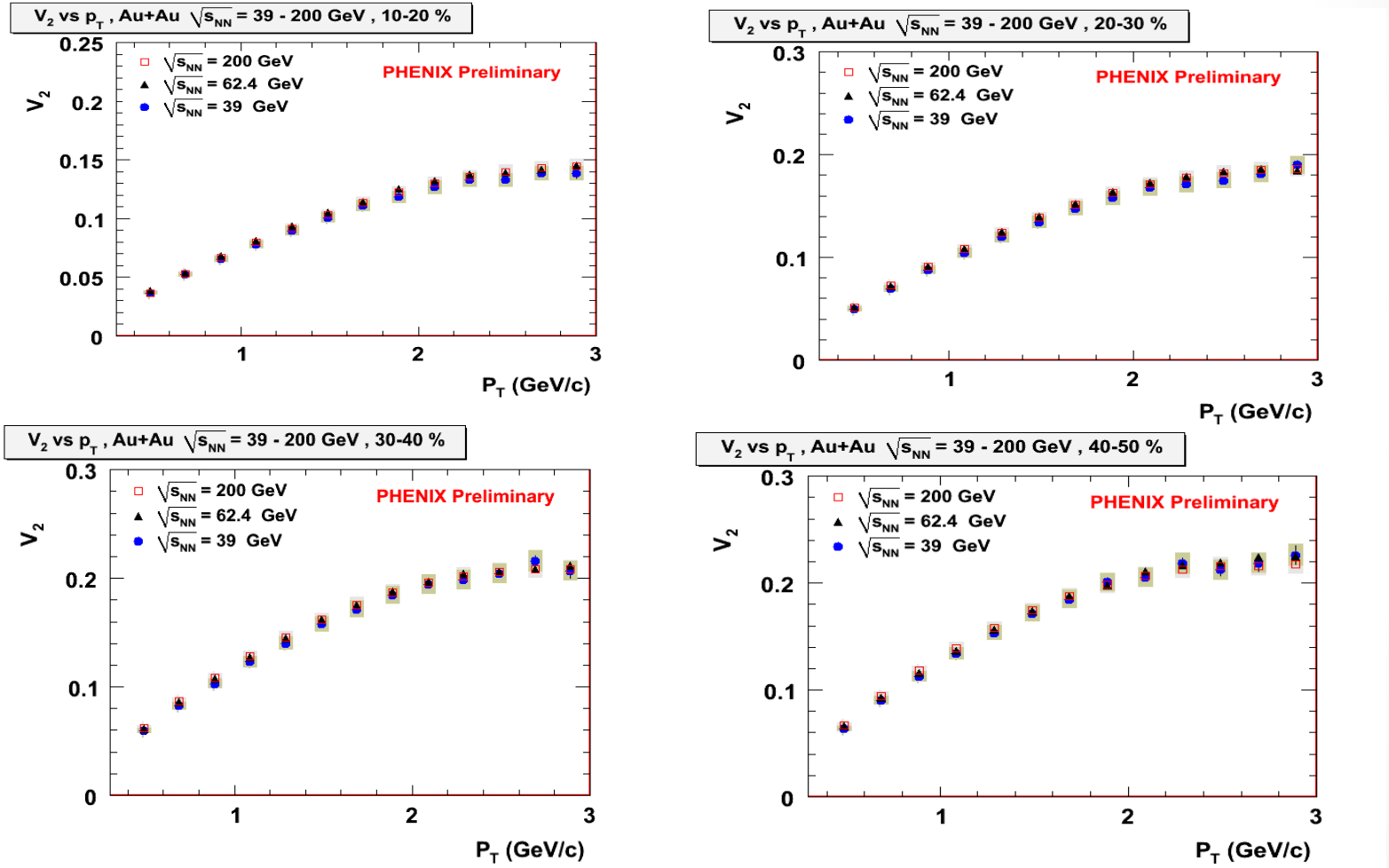
***Note whenever the matter interacts each other, v_2 could change.**

Scaling of v_2

- Energy dependence
- Eccentricity scaling
- N_{part} scaling
- Quark number + KE_T scaling and the deviation

Energy dependence 200, 62.4, 39 GeV

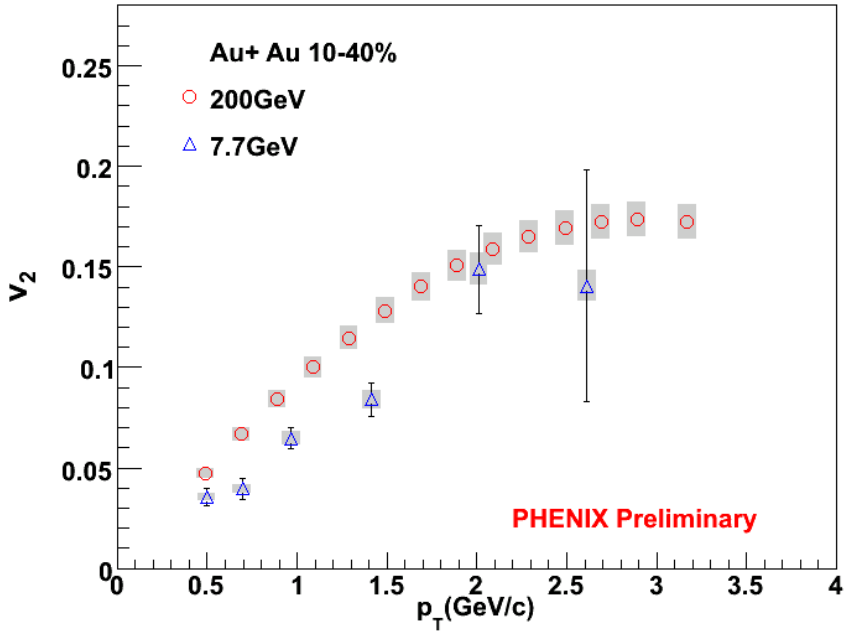
S. Huang, A. Taranenko, R. Lacey (WWND2011)

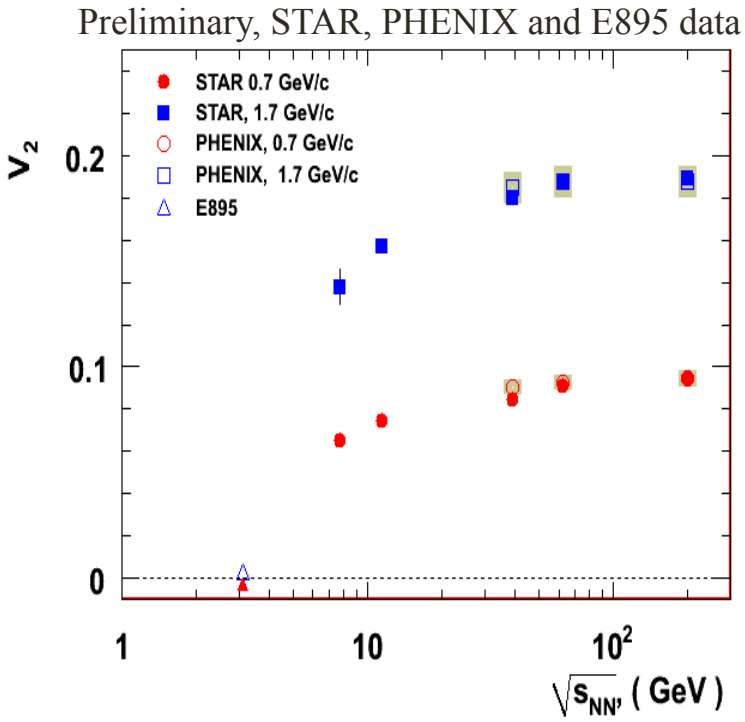


No energy dependence from 39 GeV to 200 GeV for these centralities.

Energy dependence 200, 7.7 GeV

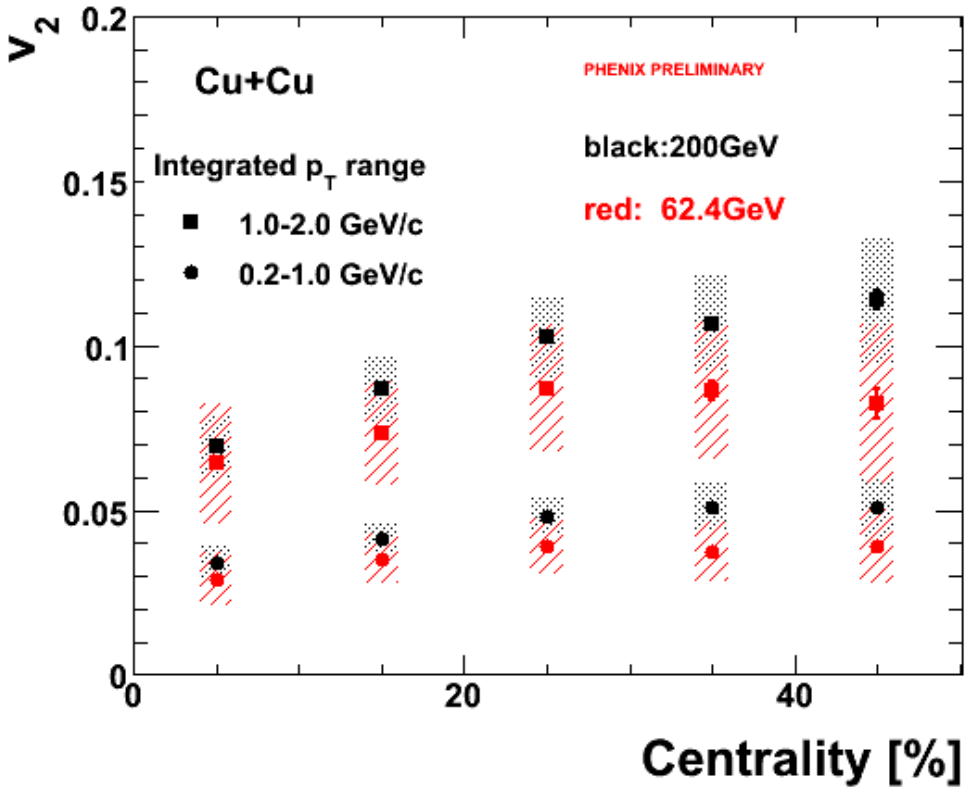
S. Huang, A. Taranenko, R. Lacey (WWND2011)





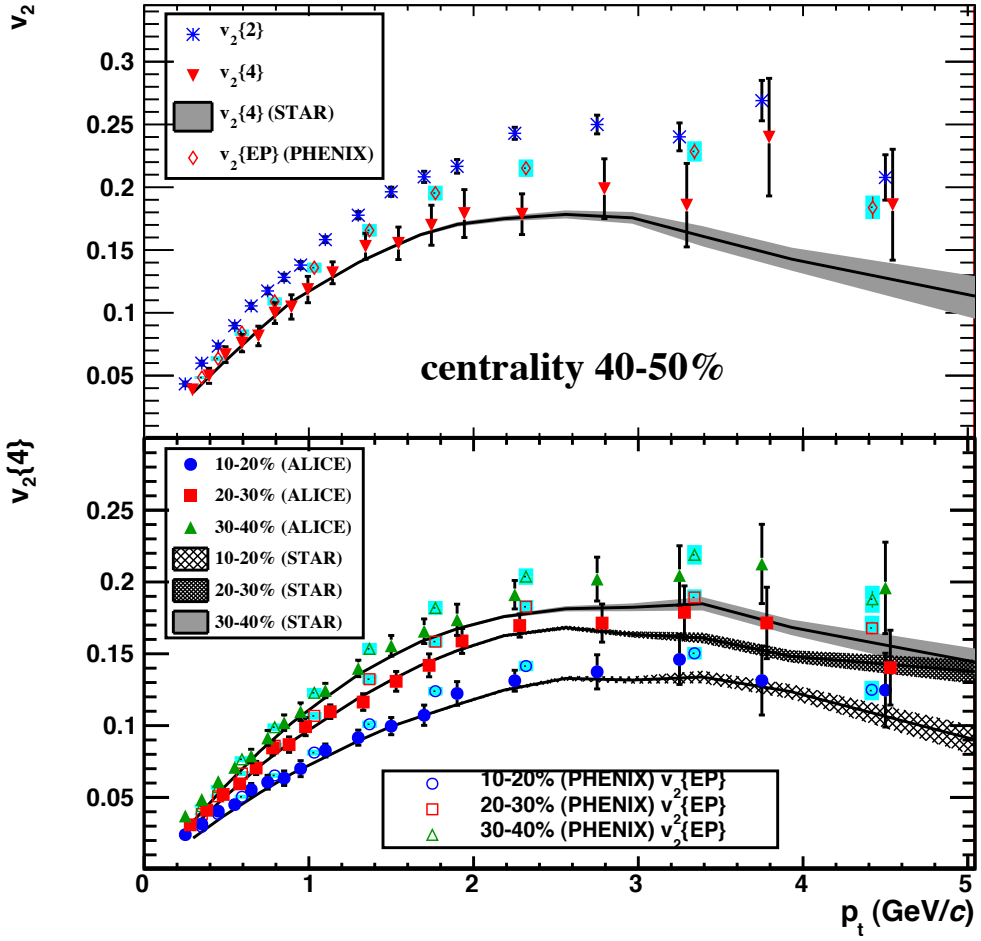
The v_2 at 7.7 GeV Au+Au is much lower than v_2 of 39 - 200 GeV.
Partonic flow --> Hadronic flow : between 39 and 7.7 GeV ?

Energy dependence of smaller system (Cu+Cu)



- 62.4 GeV and 200 GeV don't agree as Au+Au does.

Energy dependence 2.76 TeV, 200 GeV



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

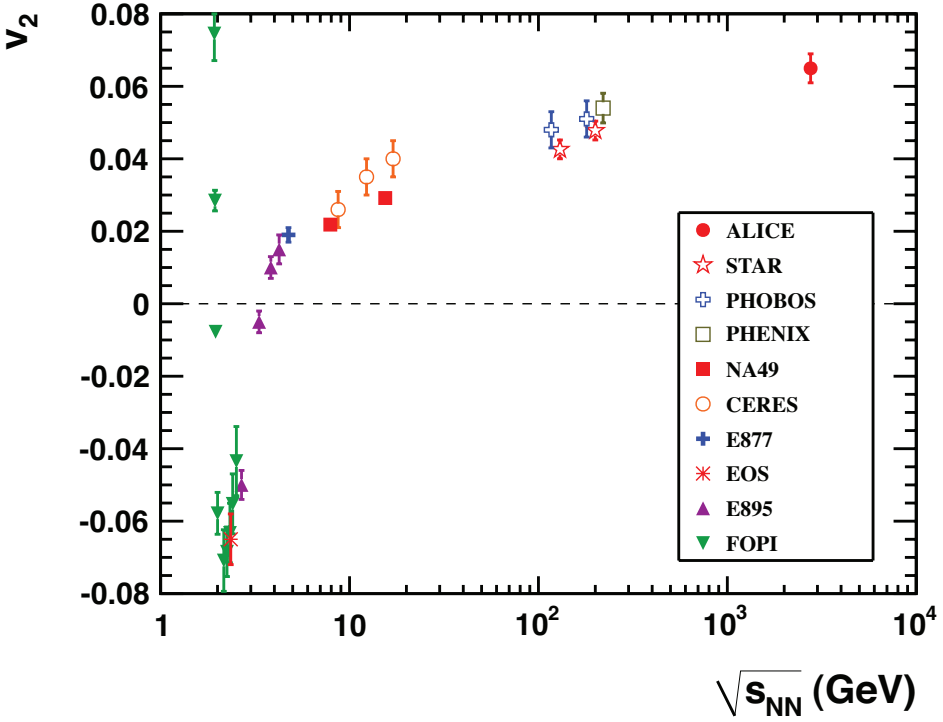
PHENIX and STAR ---
Au+Au, $\sqrt{s_{NN}} = 200$ GeV

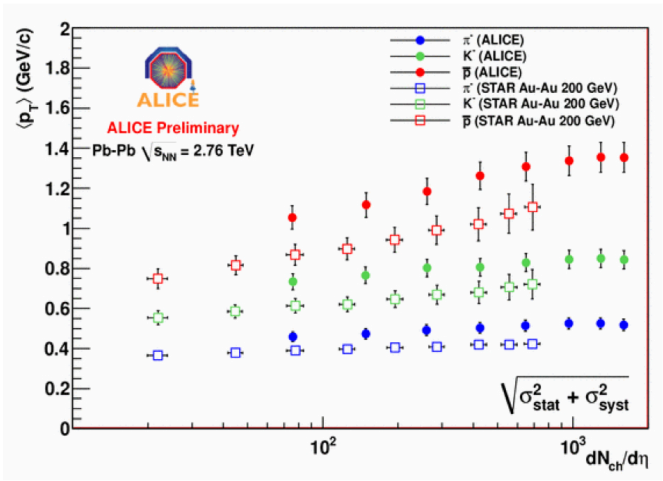
PHENIX : Phys. Rev. C 80, 024909 (2009)
STAR : Phys. Rev. C 77, 054901 (2008)

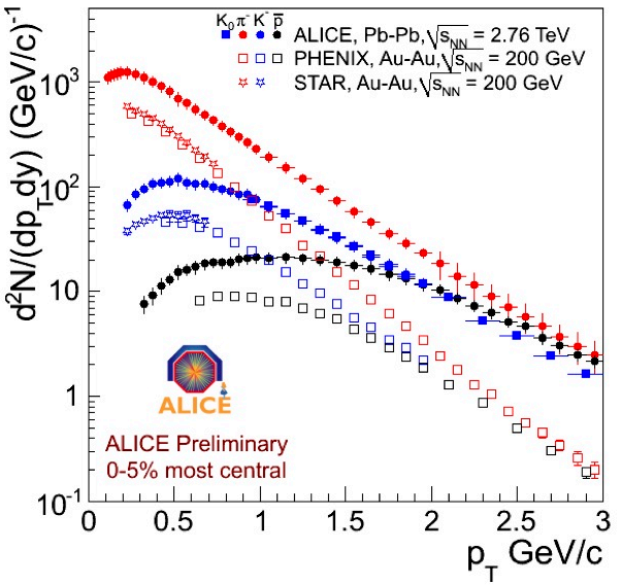
- Mostly consistent, especially at low p_T

Energy dependence - Integrated v_2

- ALICE QM2011 Alberica's talk







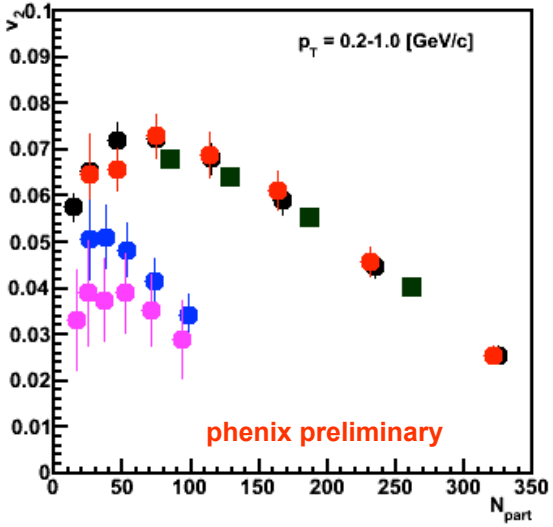
STAR, PRC 79 , 034909 (2009)
PHENIX, PRC69, 03409 (2004)

Integrated v_2 at LHC is larger than v_2 at RHIC.
Is this because of radial flow ?
Probably no.

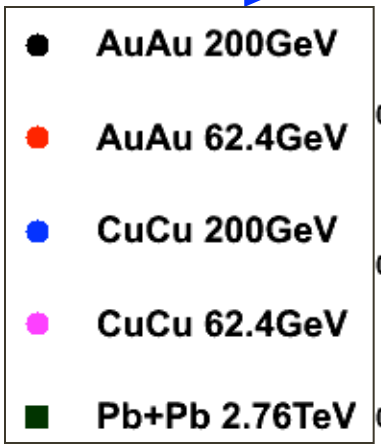
Eccentricity scaling

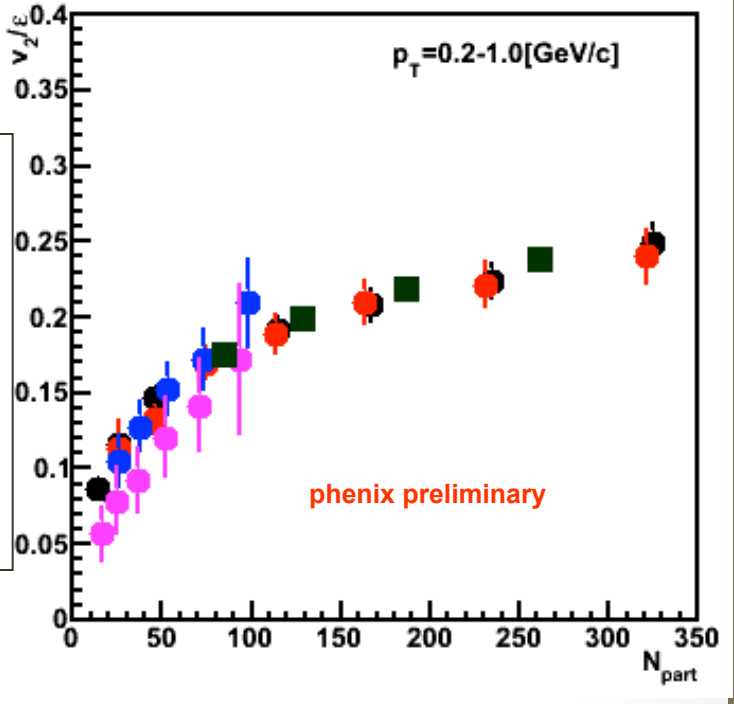
Pb+Pb, Au+Au, Cu+Cu

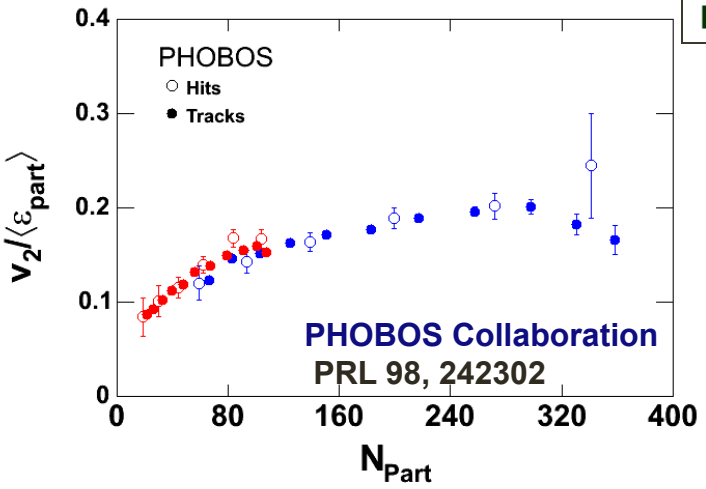
Compare v_2 normalized by eccentricity (ε) in collisions of different size.



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







Eccentricity scaling suggests early thermalization.

There is a strong N_{part} dependence.

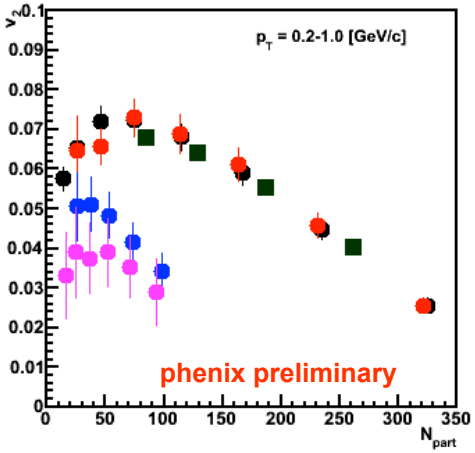
N_{part} Scaling

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

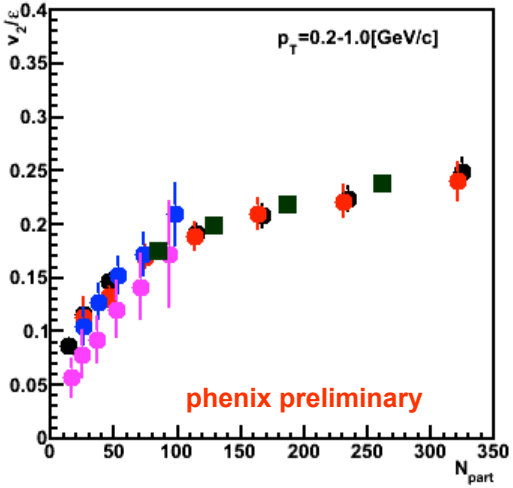
Dividing by $N_{part}^{1/3}$

AuAu 200GeV
AuAu 62.4GeV
CuCu 200GeV
CuCu 62.4GeV
Pb+Pb 2.76TeV

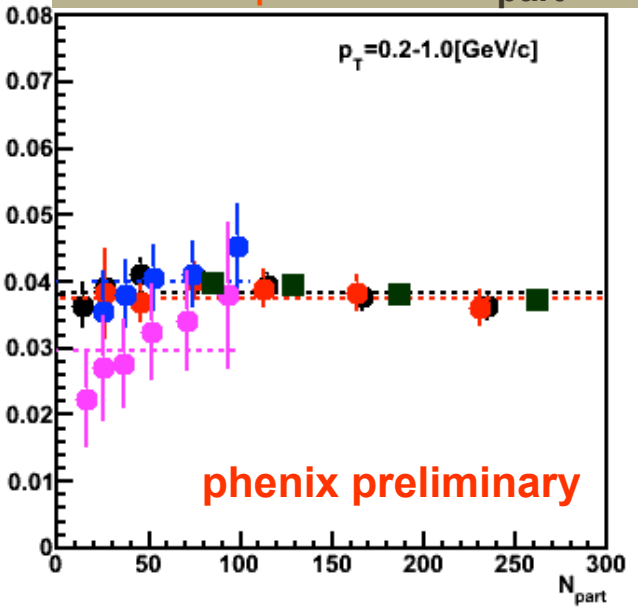
v_2 vs. N_{part}



v_2/ε vs. N_{part}



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

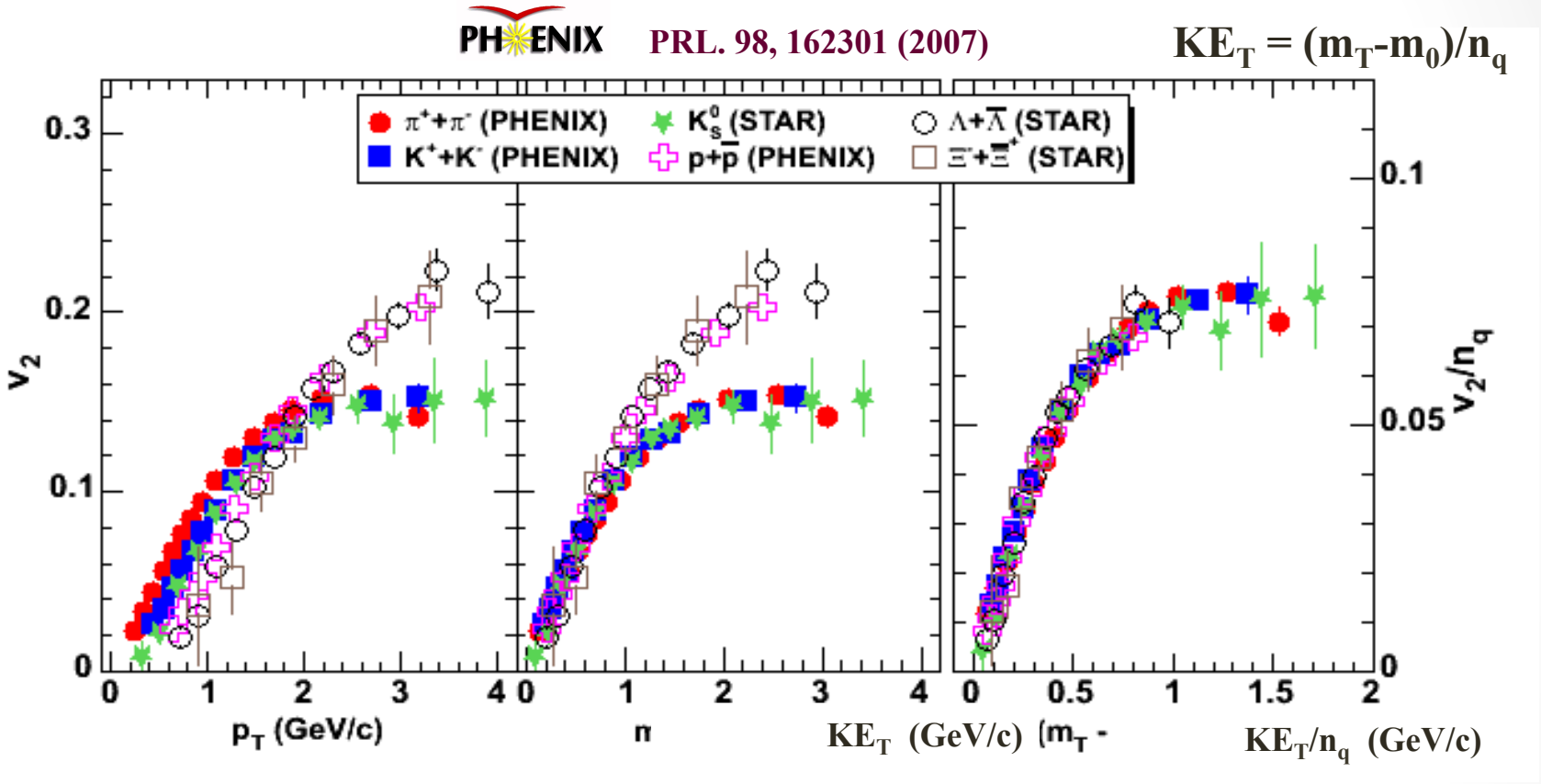


$0.2<p_T<1.0$ [GeV/c]

v_2/eccentricity/$N_{part}^{1/3}$ scaling is a universal scaling! which works for all collision systems including Pb+Pb 2.76TeV except small N_{part} at 62 GeV.

- This exception may indicate non-sufficient thermalization region.

Quark number + KE_T scaling (AuAu 200 GeV)

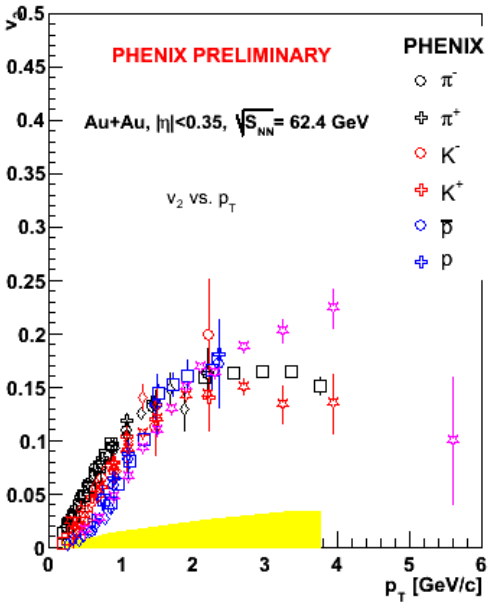


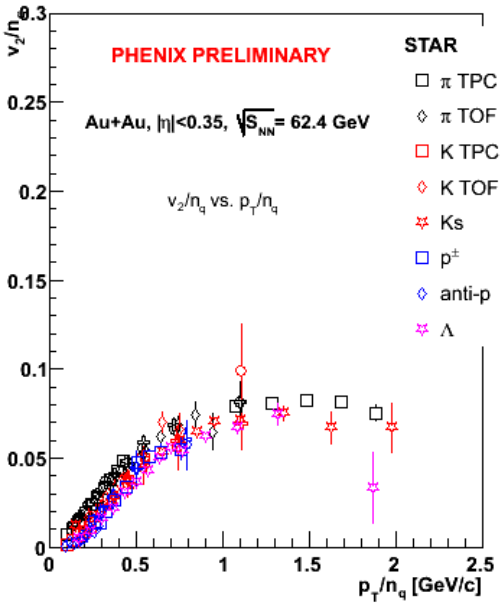
$v_2(p_T)$ /n_{quark} vs. KE_T/n_{quark} becomes one curve independent of particle species.

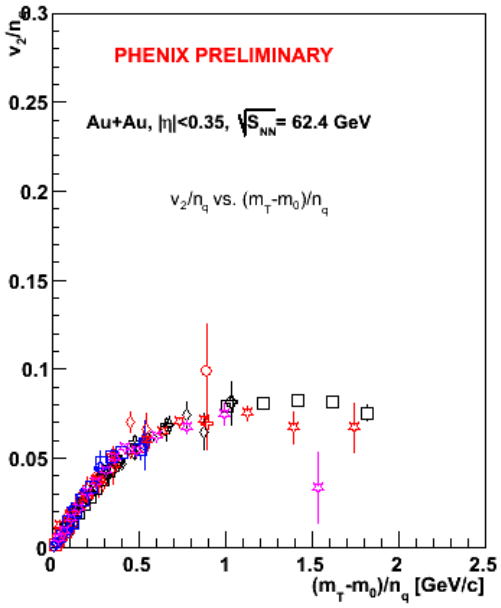
Quark number scaling is consistent to the recombination model which assumes the quark level flow at QGP phase.

Quark number scaling everywhere

AuAu 62.4GeV PHENIX/STAR



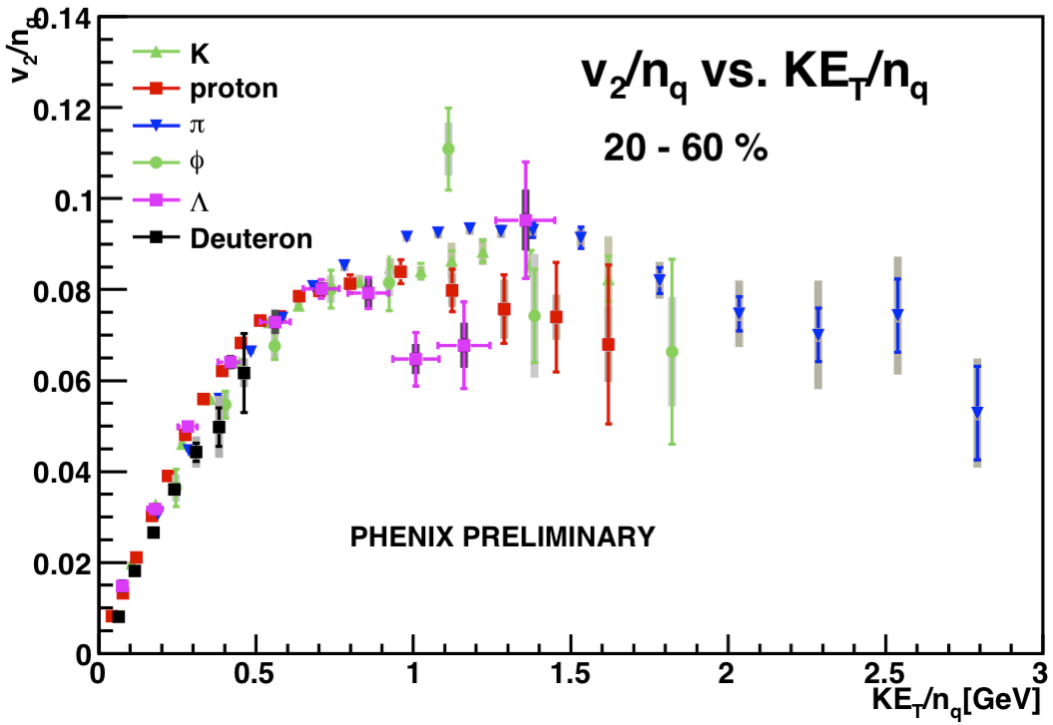




Quark number scaling work out at 62.4GeV.

Quark number scaling everywhere

Au+Au 200GeV (Run7)



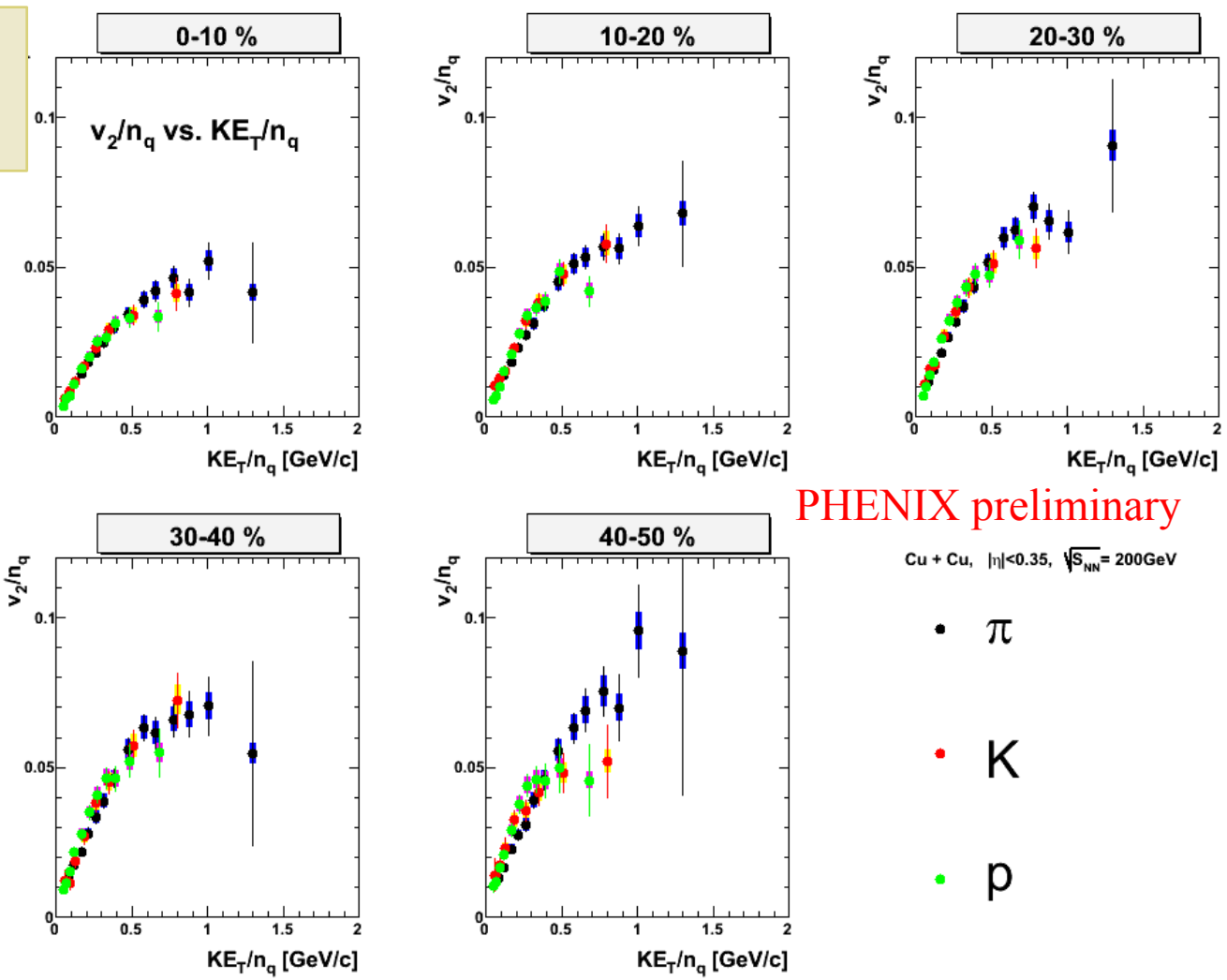
φ, Λ and deuteron also follow the scaling.

Significant part of elliptic flow develops at quark level.

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

Quark number scaling everywhere

Cu+Cu 200GeV

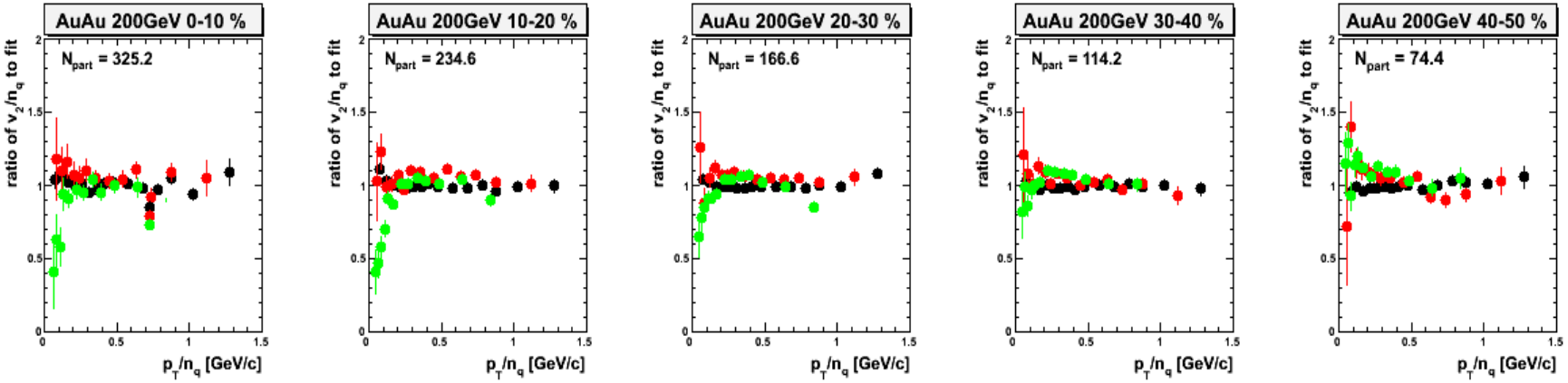


KE_T scaling mostly works out for central but not peripheral in Cu+Cu at 200GeV.

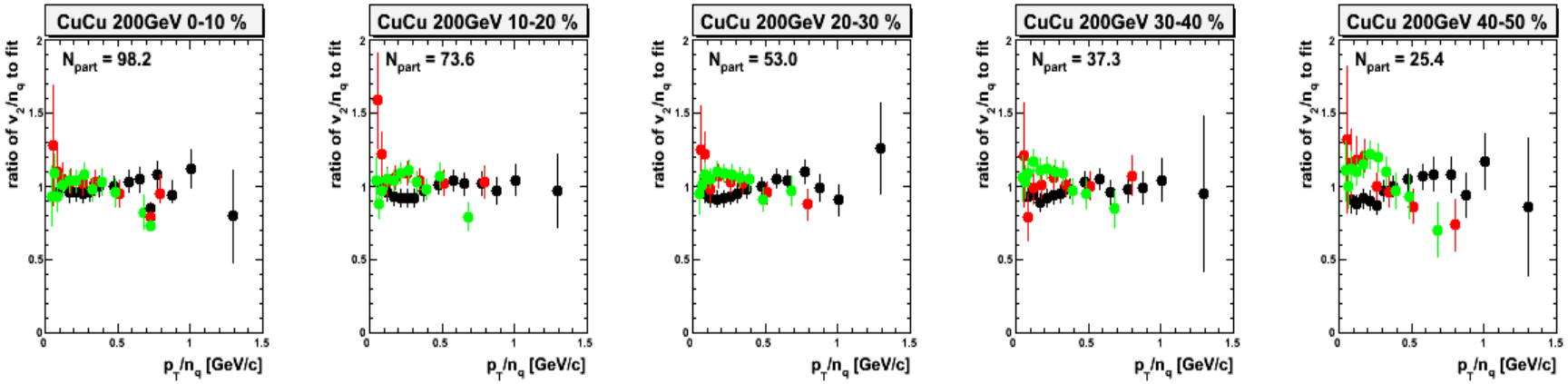
The discrepancy from KE_T scaling

π
K
p

Au+Au

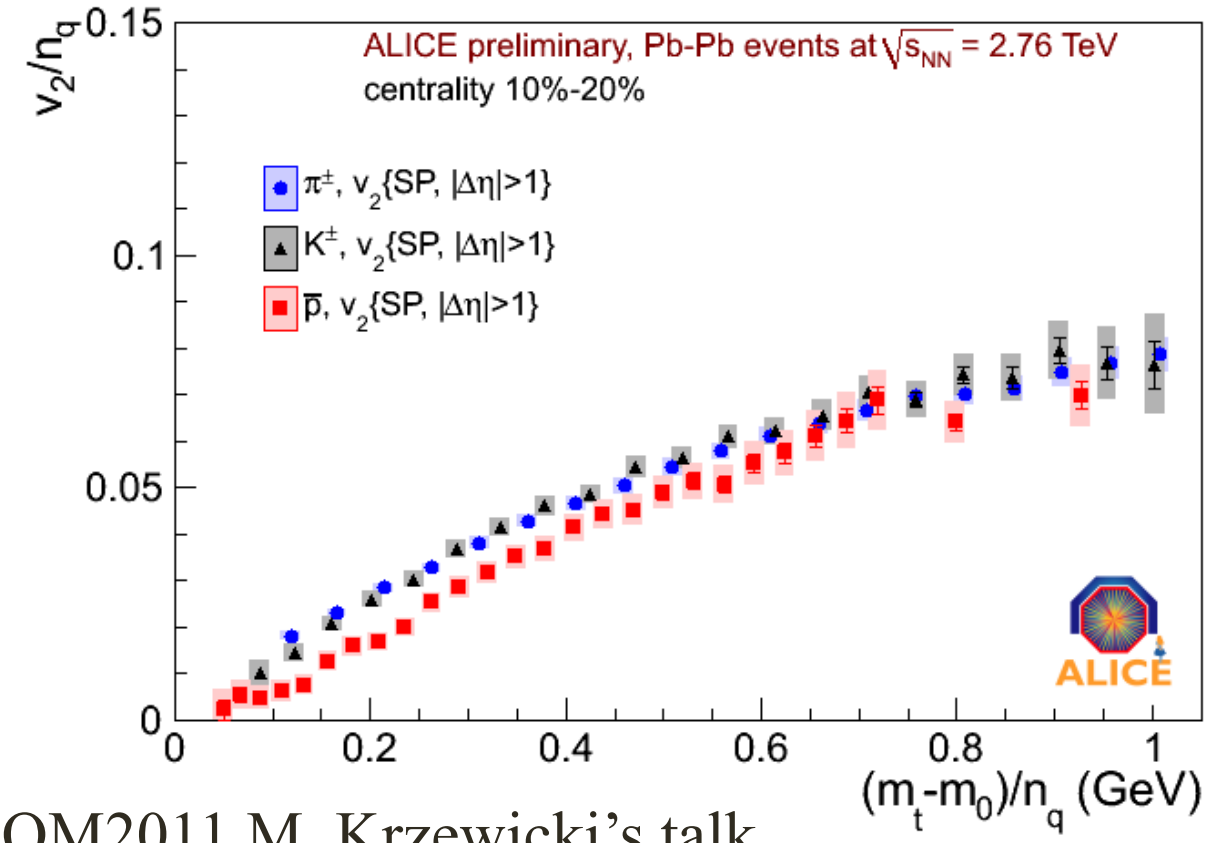


Cu+Cu



The discrepancy from the KE_T scaling depends on N_{part}.
Large N_{part} produces more shift of proton to higher p_T based on π.

Quark number scaling at LHC



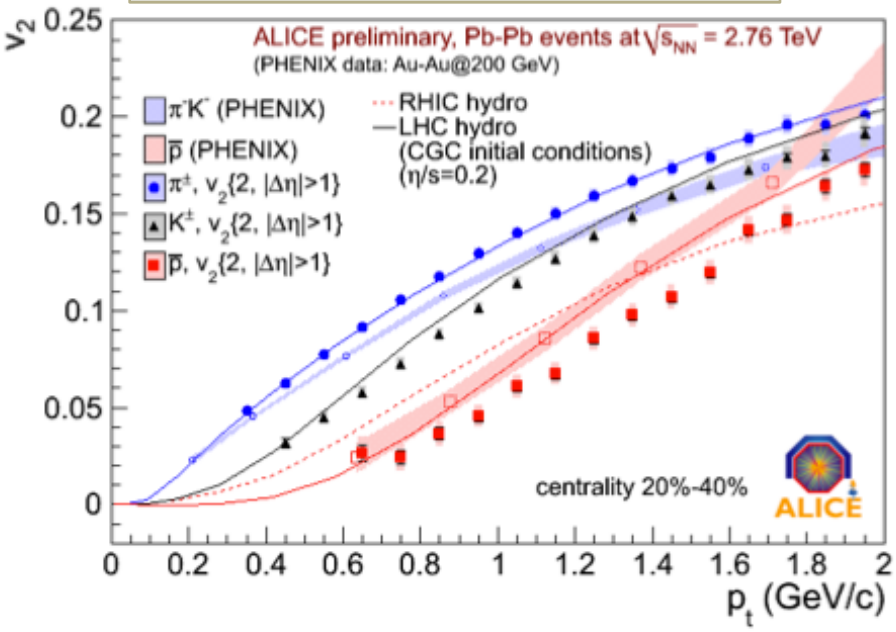
QM2011 M. Krzewicki's talk

- KET scaling doesn't work out at LHC.
- Proton is shifted to higher p_T more than RHIC results.

Radial flow effect is different at different collision energies.

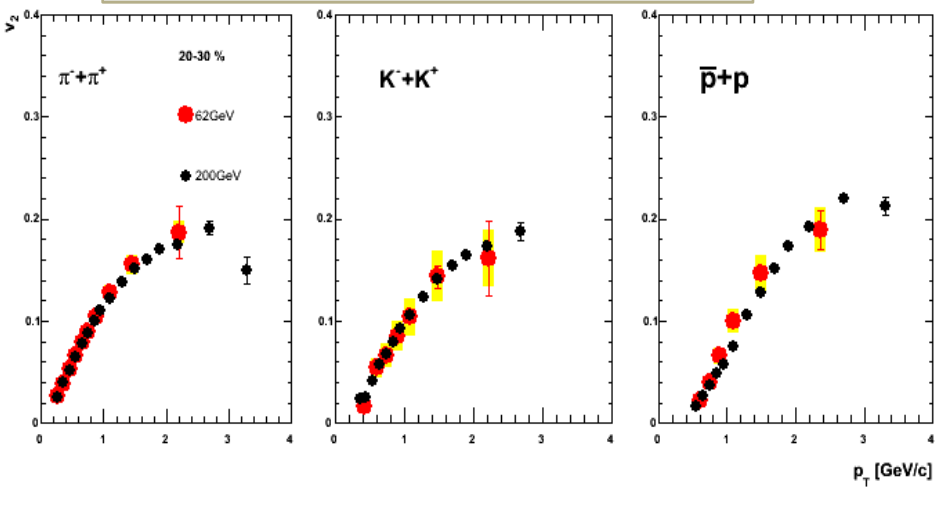
Identified particles

2.76TeV and 200 GeV



PHENIX data: Phys. Rev. Lett. 91, 182301 (2003)

200 GeV and 62.4 GeV



Higher collision energy density seems to produce larger radial flow.

Summary

- Systematic study of v_2 have been done in Au+Au/Cu+Cu at $\sqrt{s_{NN}}$ = 7.7/39/62.4/200 GeV and compared with Pb+Pb at $\sqrt{s_{NN}}$ = 2.76 TeV.
- $v_2(p_T)$ are saturated above 39 GeV in Au+Au.
  - Local thermalization
- Integrated v2 increases at higher collision energy.
  - because $<p_T>$ increases.
- $v_2(p_T)$ follows quark number + KE_T scaling in Au+Au (200,62GeV) and Cu+Cu (200GeV) .
  - Flow at quark level → QGP phase
- There are small discrepancies from KE_T scaling
  - Larger radial flow at higher collision energy density.
- $v_2(N_{part})$ / ε are same between Au+Au, Pb+Pb, Cu+Cu at 200 GeV ~2.76 TeV.
  - Eccentricity scaling → Early thermalization
- $v_2(p_T)$ /ε/$N_{part}^{1/3}$ 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.

The end.

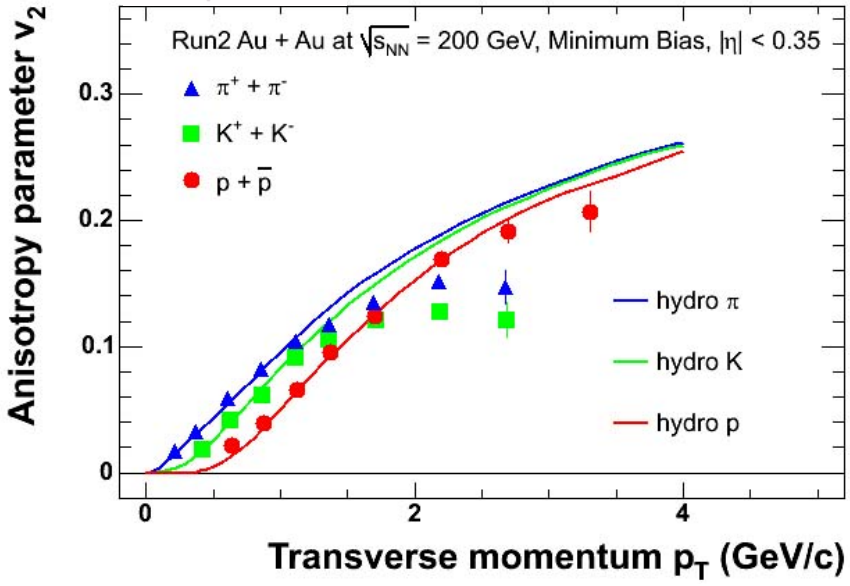
Thank you.

Back Up

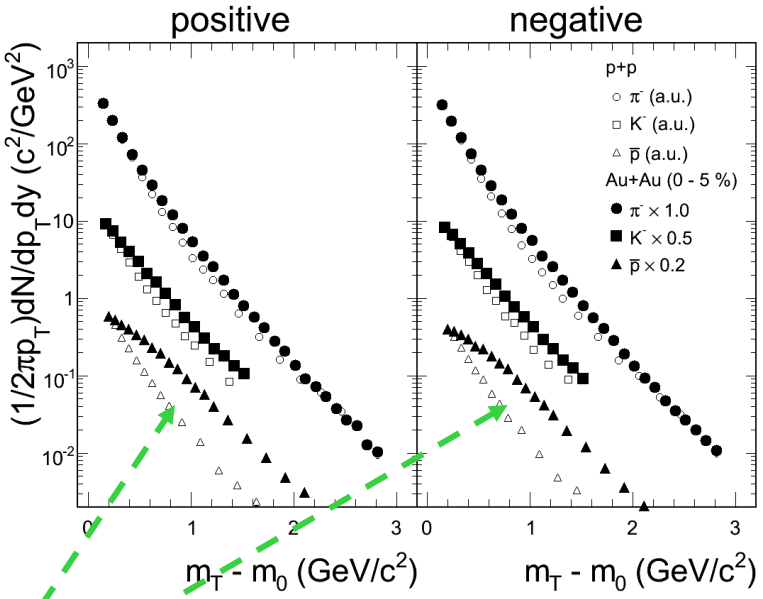
v_2 explained by hydro model

PHENIX

PRL 91, 182301



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



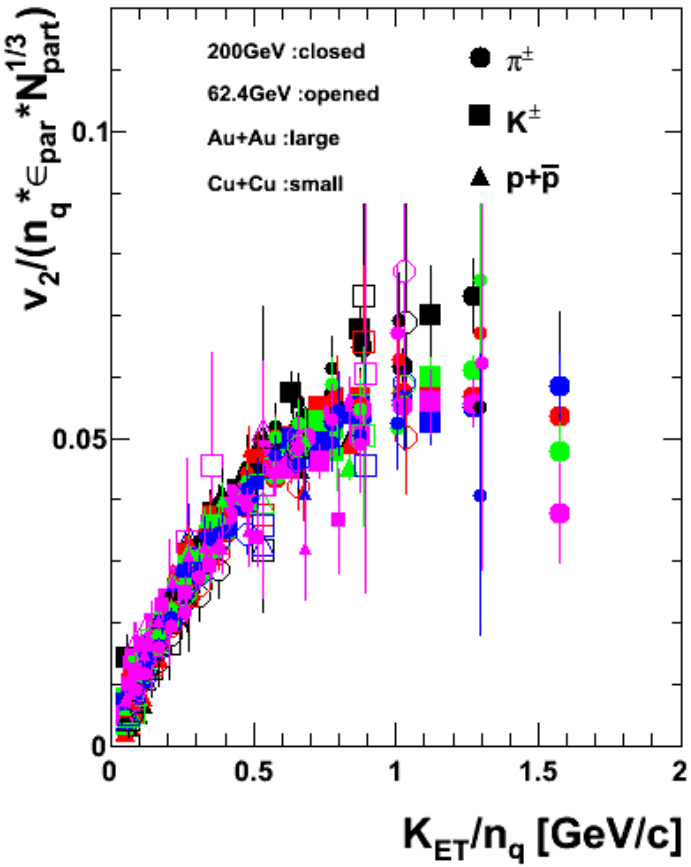
Mass Ordering: **v2(π)>v2(K)>v2(p)**
→Existence of radial flow.
Single particle spectra also indicates radial flow.

convex shape due to radial flow.

PHENIX: Au+Au: PRC **63**, 034909 (2004);
p+p: PRC**74**, 024904 (2006)

Universal v_2 for identified charged hadrons at RHIC energy.

Taking all scaling together,



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

0-10 %
10-20 %
20-30 %
30-40 %
40-50 %

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)