Measurement of azimuthal anisotropy at RHIC-PHENIX

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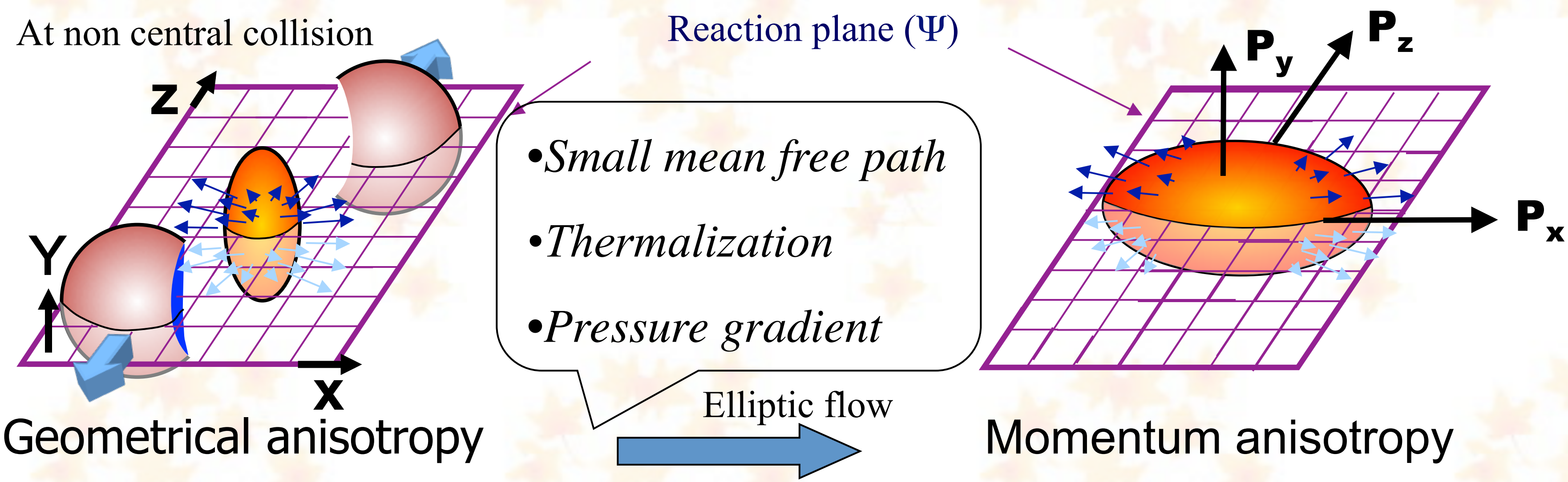
Nara Women's University

Elliptic Flow (v_2)

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



Momentum anisotropy reflects the hot dense matter.

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

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

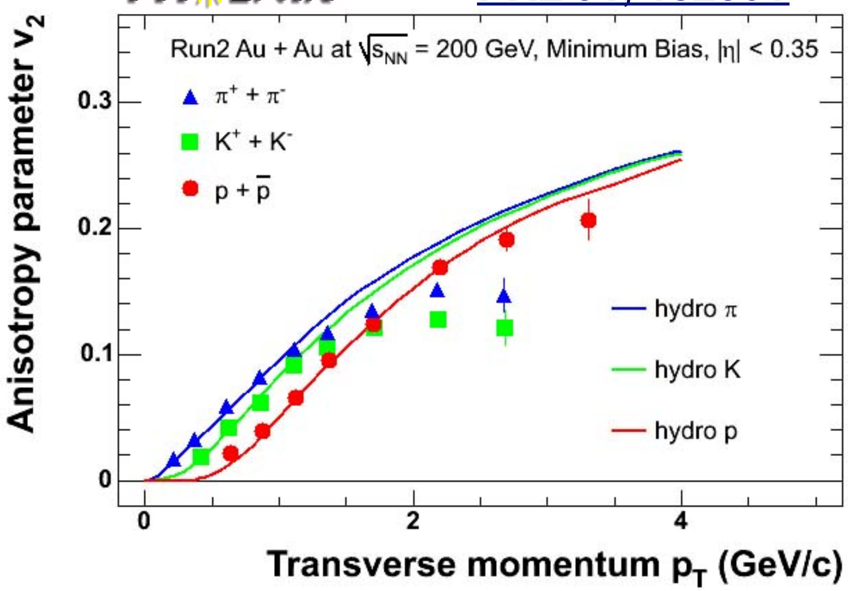
$$v_n = \langle \cos[n(\phi - \Psi)] \rangle$$

v_2 is the coefficient of the second term → indicates ellipticity

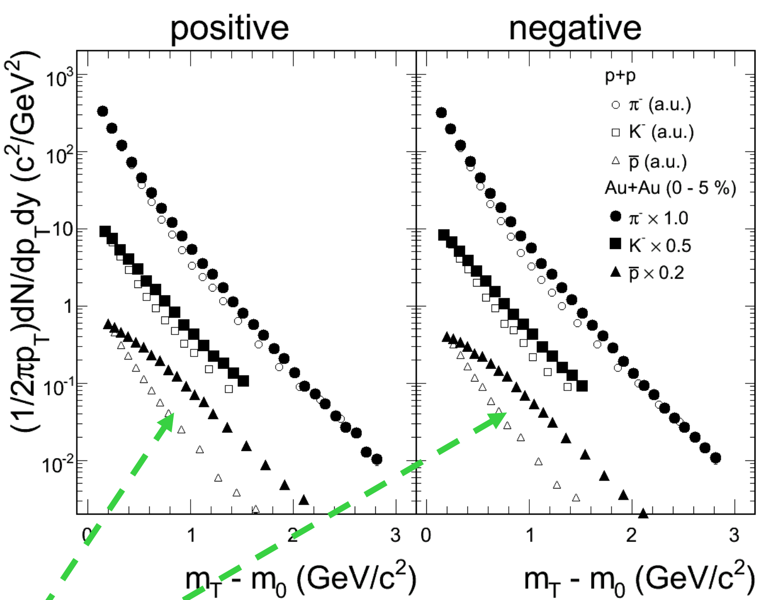
Thermalization should be occurred very early before the geometrical eccentricity is gone.

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

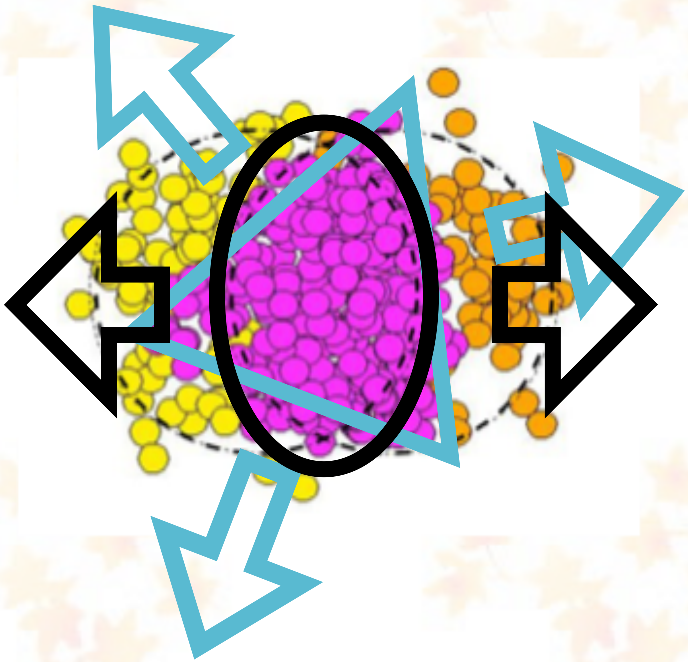


PHENIX: Au+Au: PRC **63**, 034909 (2004);
p+p: PRC**74**, 024904 (2006)

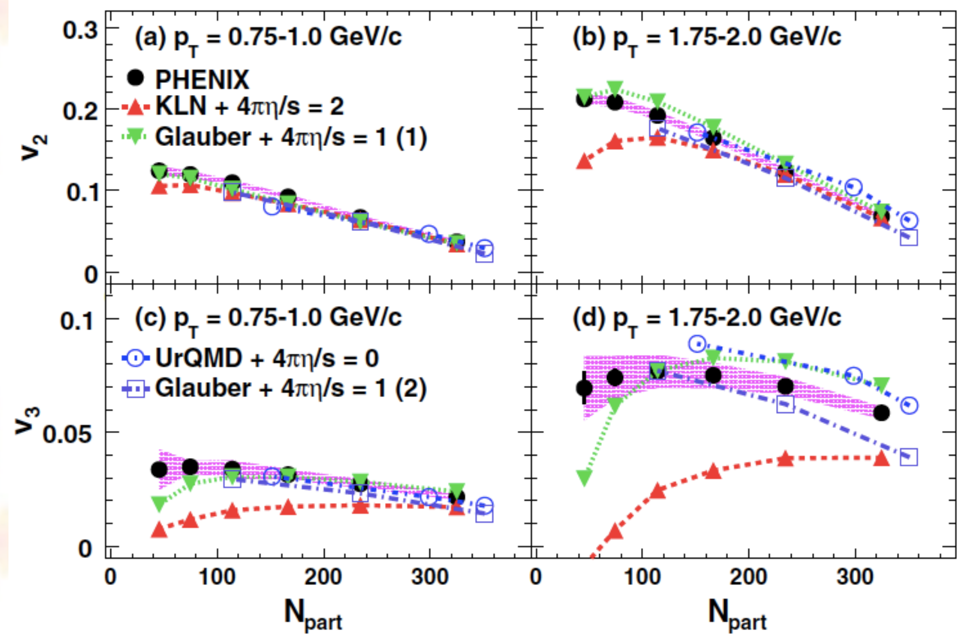
Mass Ordering: **v2(π)>v2(K)>v2(p)**
→Existence of radial flow.
Single particle spectra also indicates radial flow.

convex shape due to radial flow.

Higher order flow harmonics (v_3)

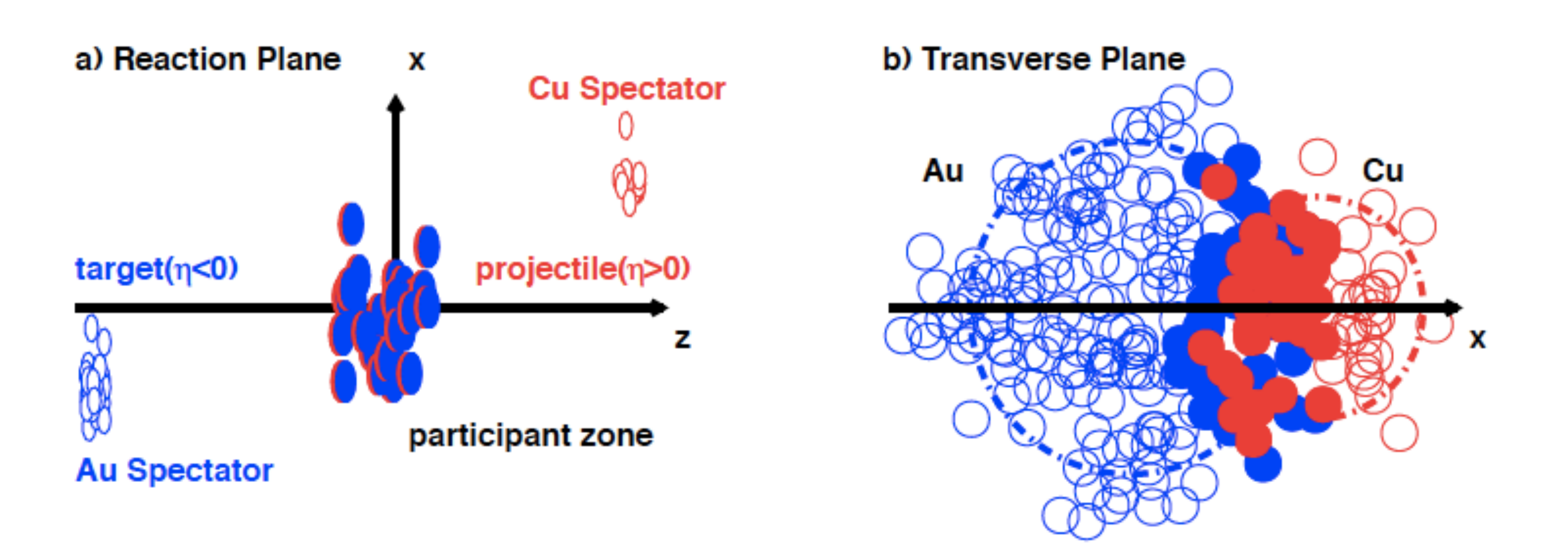


Au+Au 200GeV PRL 107. 252301



Initial participant fluctuation at event-by-event can lead to <u>triangular particle production</u> (v_3).
v_3 is expected to further constrains initial condition and viscosity

Cu+Au collisions



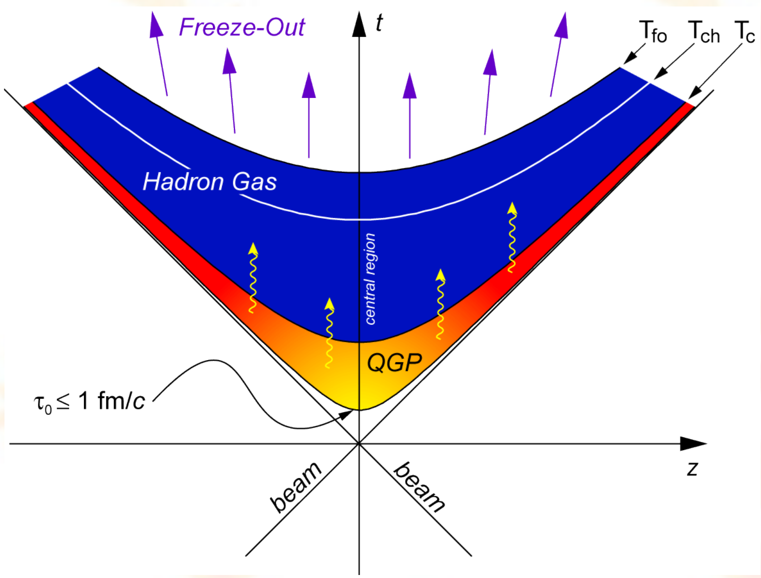
Asymmetric initial condition provides

- Different left/right pressure gradient, particle production.
- Initially triangle anisotropy without the participant fluctuation.

v_n measurements in CuAu collisions provide additional insight.

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

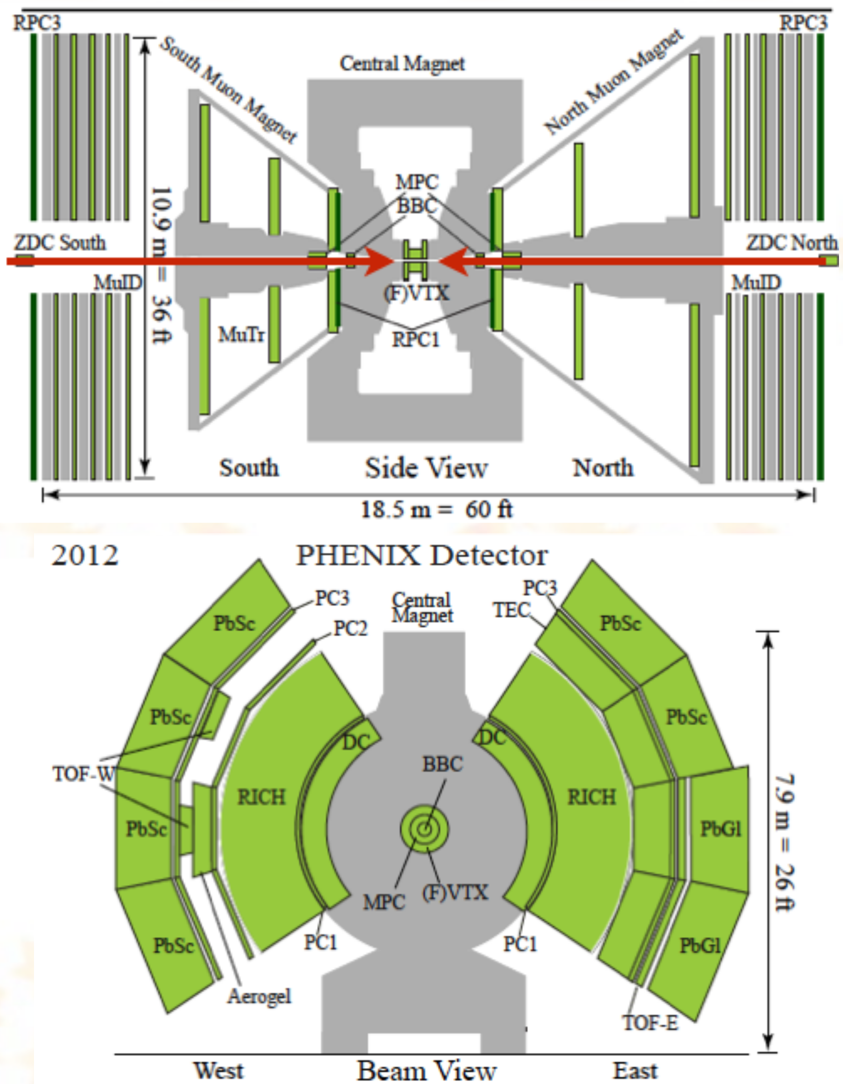
When the matter is thermalized, we expect

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.**

PHENIX detectors



2nd & 3rd Participant Event Plane

-Beam Beam counter(BBC)

Charged particle Tracking

-Drift Chamber(DC) ($|\eta|<0.35$)

-Pad Chamber(PC) ($|\eta|<0.35$)

-Electro magnetic calorimeter(EMC) ($|\eta|<0.35$)

-Forward Vertex Detector(FVTX) ($1<|\eta|<3$)

Hadron identification

-Time of flight(TOF) ($|\eta|<0.35$)

- Electro magnetic calorimeter(EMC) ($|\eta|<0.35$)

Charged hadron v_n

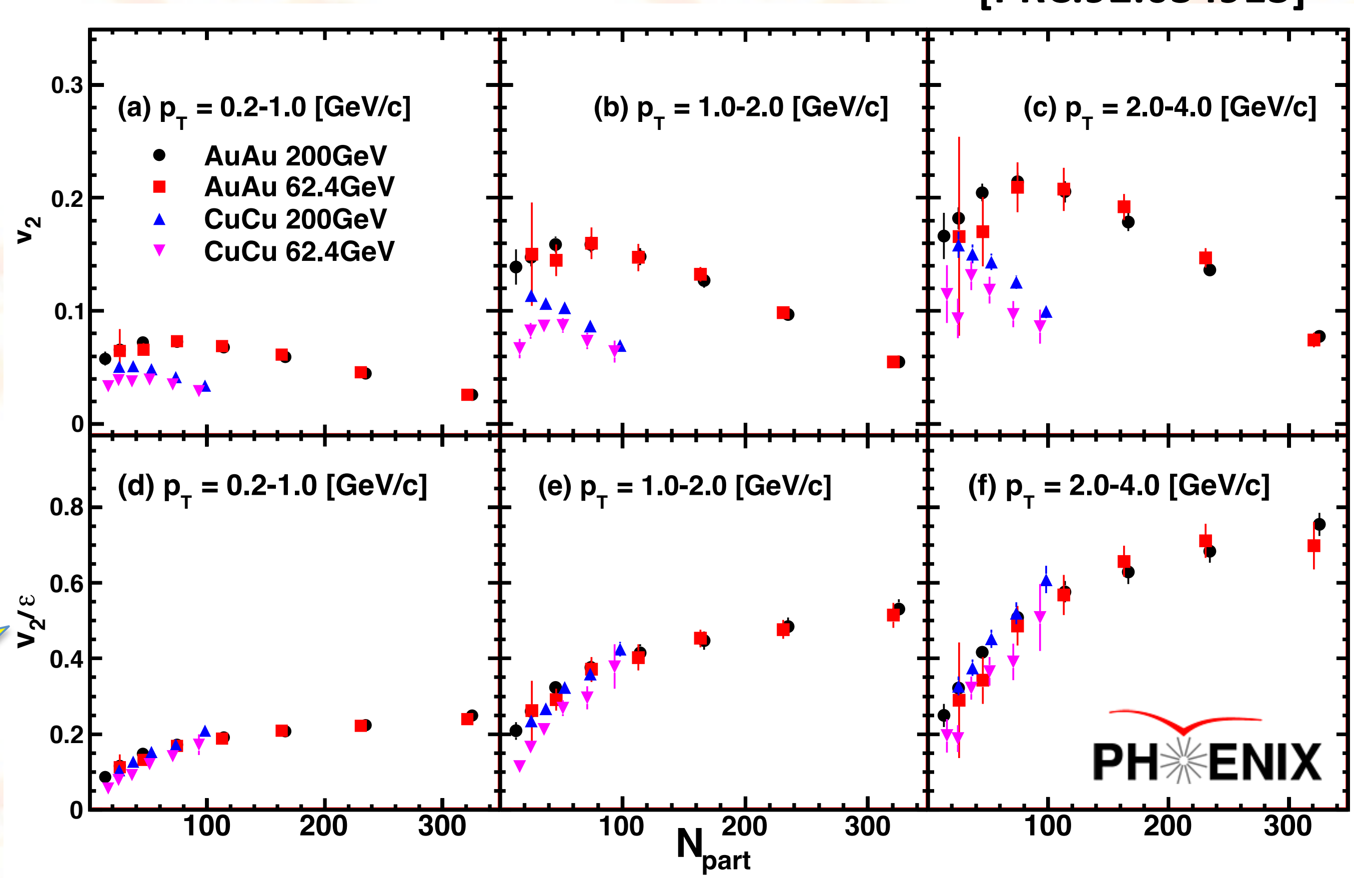
[**PRC.92.034913**]
[arxiv:1509.07784]

Energy dependence and Eccentricity scaling

[PRC.92.034913]

v_2 vs. N_{part}

v_2/ε_2 vs. N_{part}



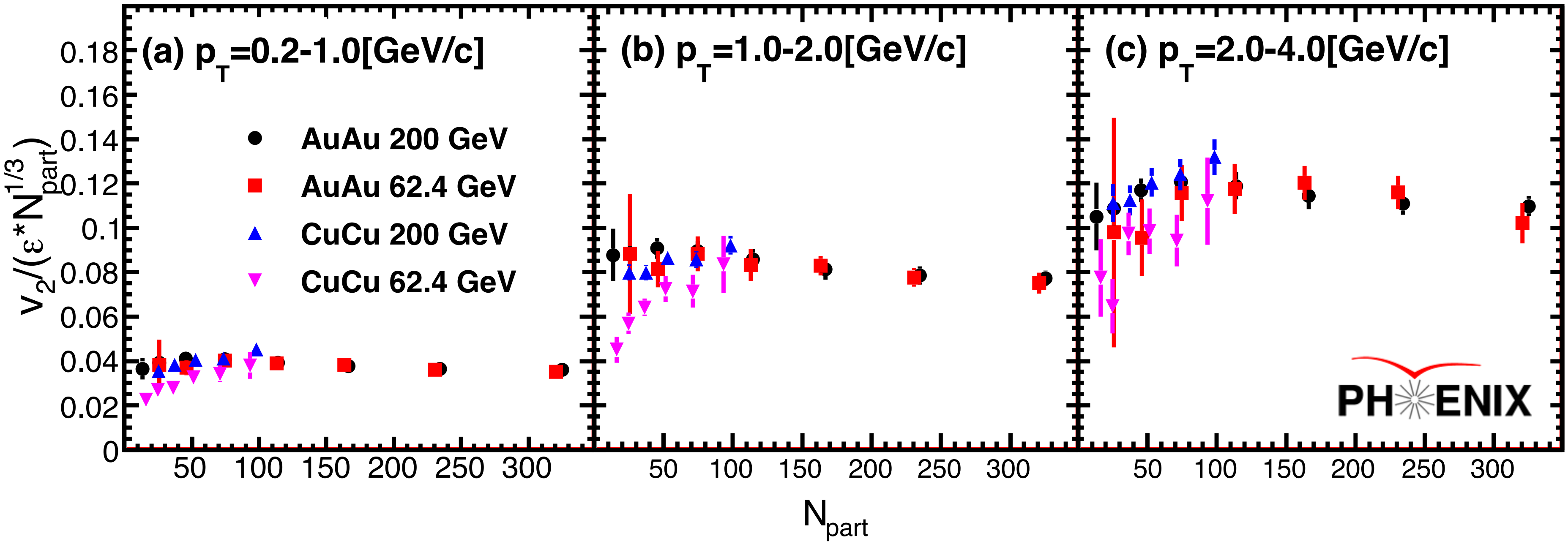
v_2/ε_2 at Cu+Cu and Au+Au agree at same N_{part}.

After ε Scaling, still strong N_{part} dependence

$N_{part}^{1/3}$ Scaling

$v_2/(\varepsilon_2 N_{part}^{1/3})$ vs. N_{part}

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

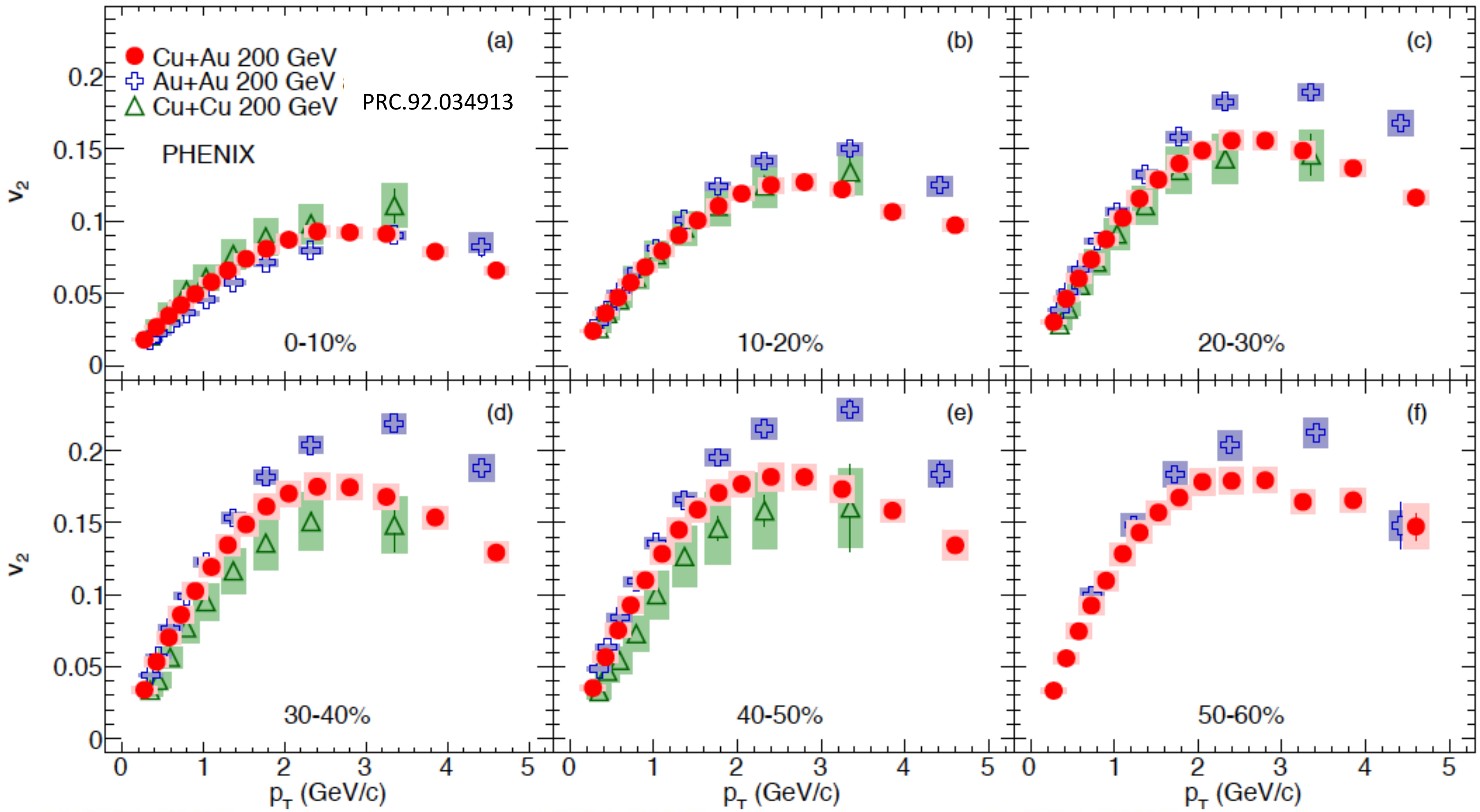


Empirical v_2 scaling [PRC.92.034913]

- v_2/(eccentricity*$N_{part}^{1/3}$) scaling works for all collision systems except small N_{part} at 62 GeV.
- $N_{part}^{(1/3)}$ is proportional to length scale

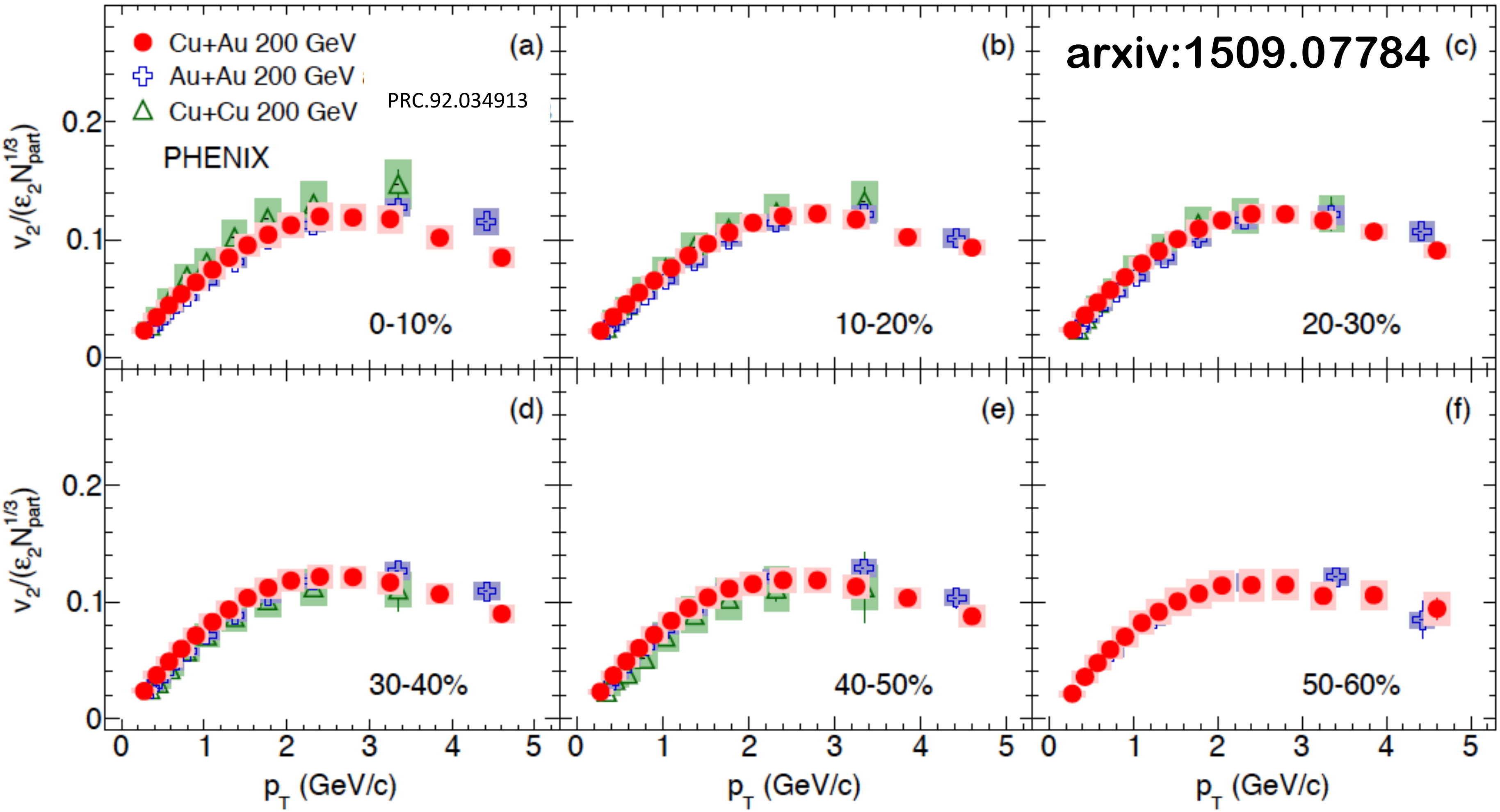
v_2 vs. p_T for AuAu/CuCu/CuAu

Au+Au and Cu+Cu [PRC.92.034913] Cu+Au [arxiv:1509.07784]



CuAu is always between AuAu and CuCu.
Similar dependences of centrality and p_T

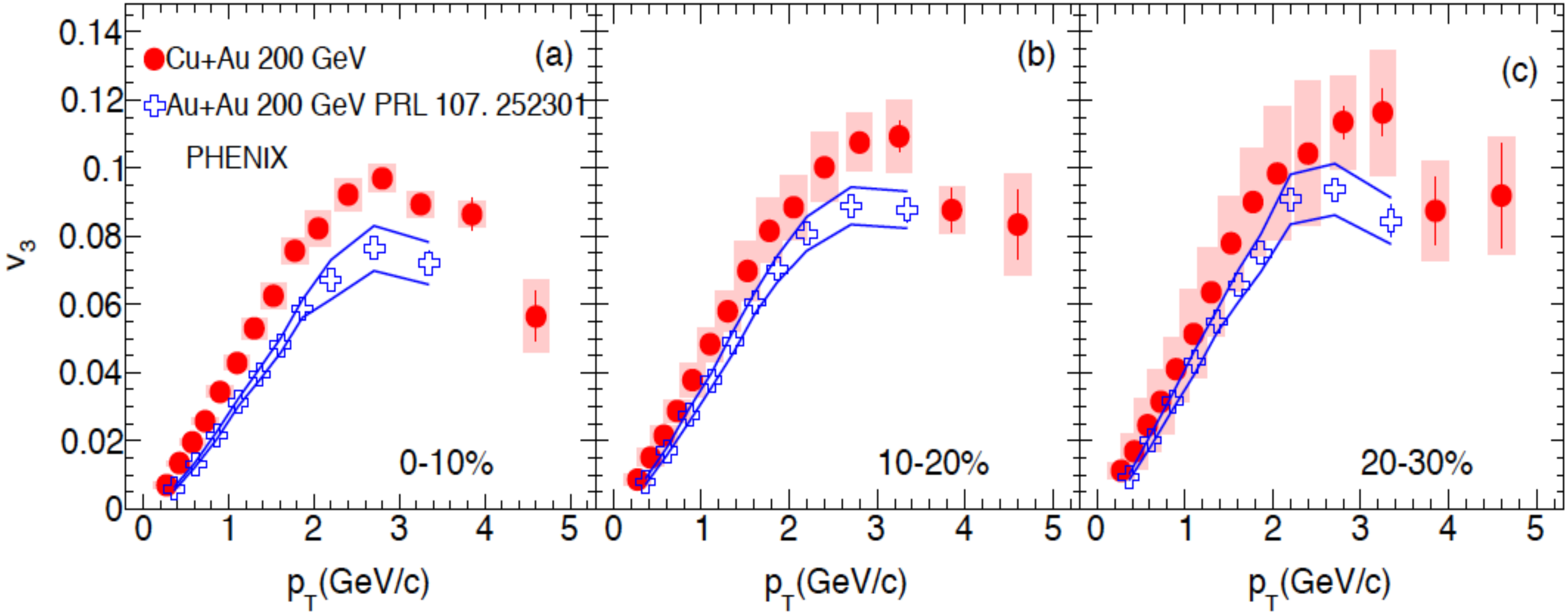
$v_2 / \varepsilon_2 * N_{part}^{(1/3)}$ vs. p_T



- v_2 is scaled with $\varepsilon_2 N_{part}^{(1/3)}$
- $\varepsilon_2 N_{part}^{(1/3)}$ scaling works well in CuAu too.

v_3 vs. p_T for AuAu/CuAu

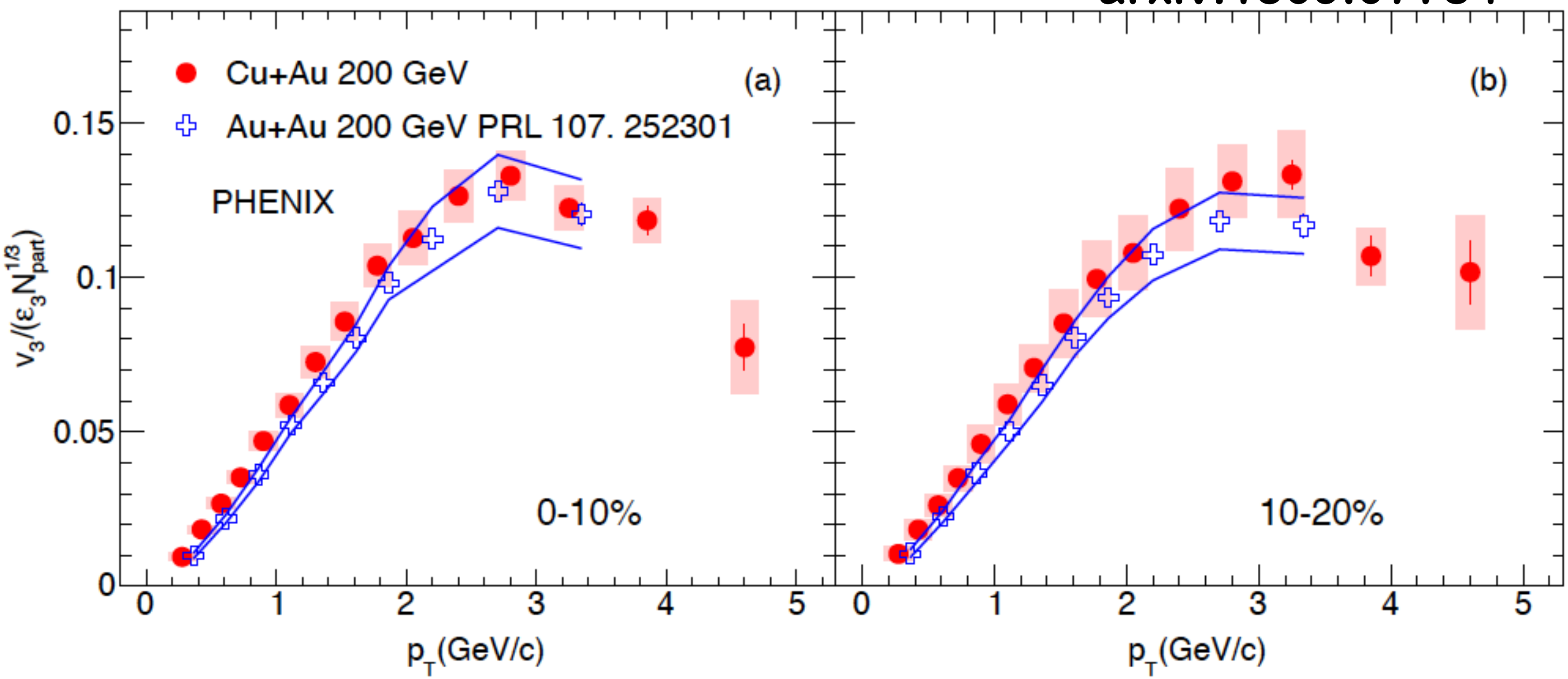
arxiv:1509.07784



- Weak centrality dependence in AuCu
- CuAu is always bigger than AuAu.

$\varepsilon_3 * N_{part}^{(1/3)}$ scaling for v_3

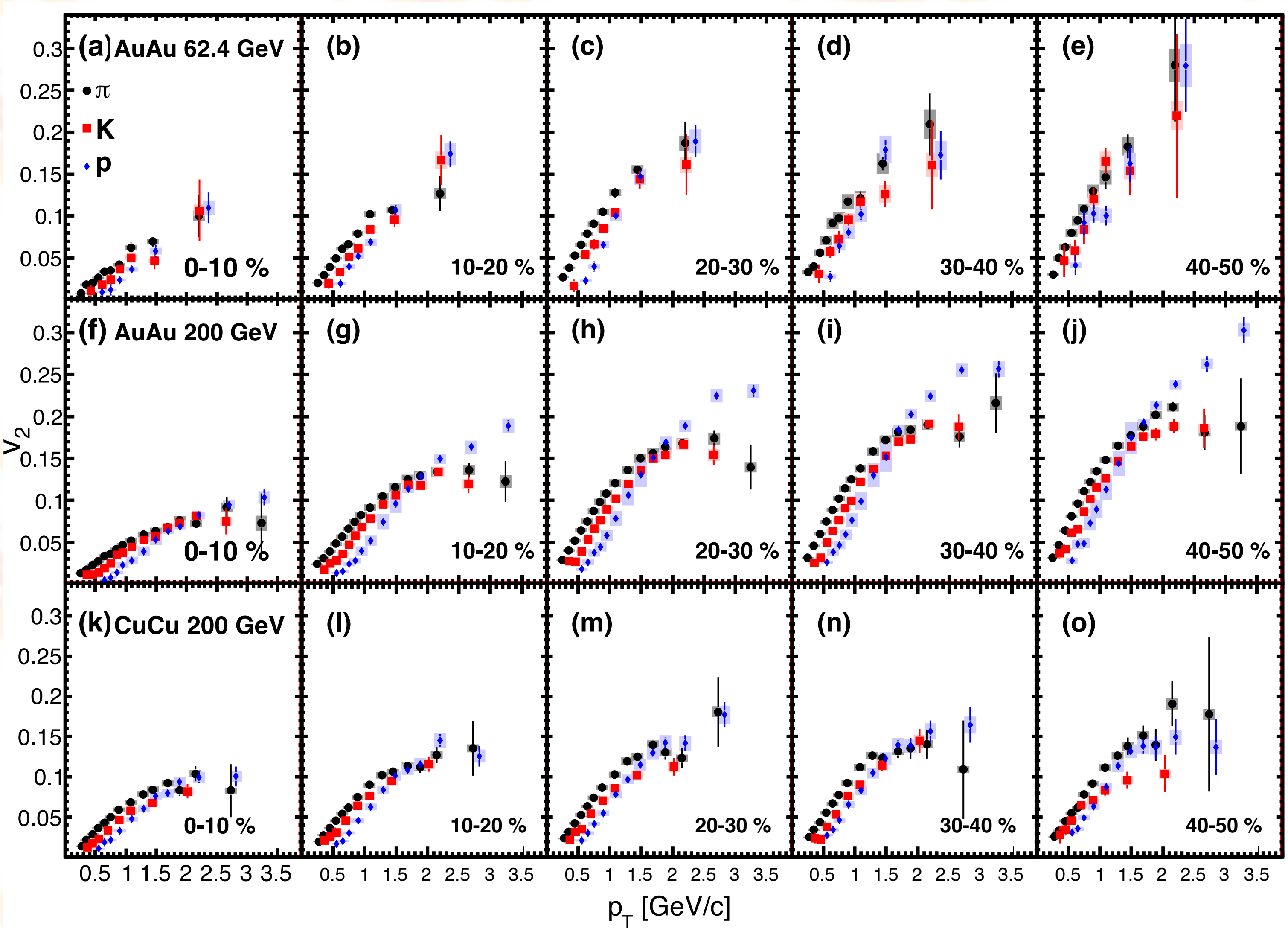
arxiv:1509.07784



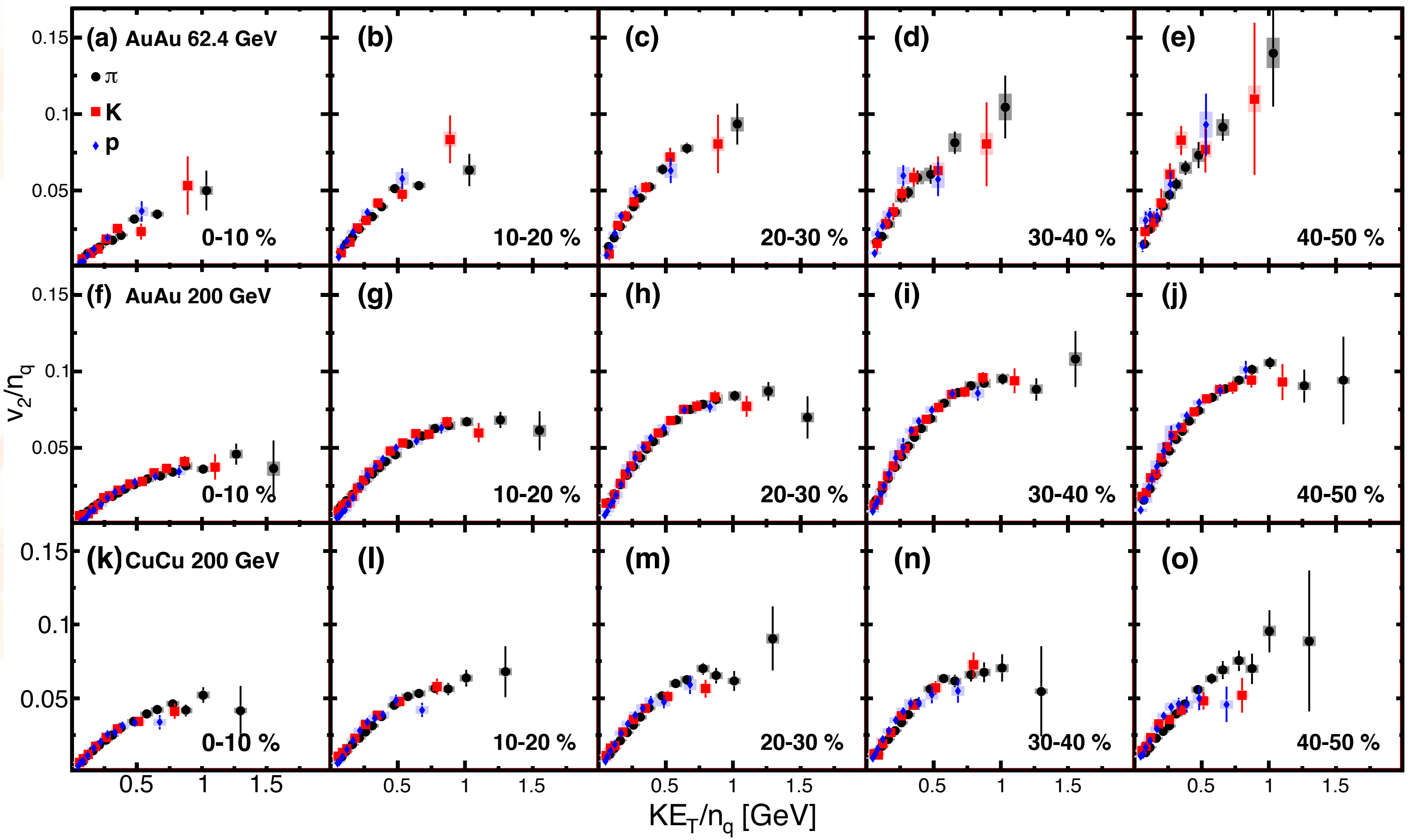
$\varepsilon_3 N_{part}^{(1/3)}$ scaling works well in v_3.

Identified hadron vn

PID v_2 vs p_T in AuAu/CuCu



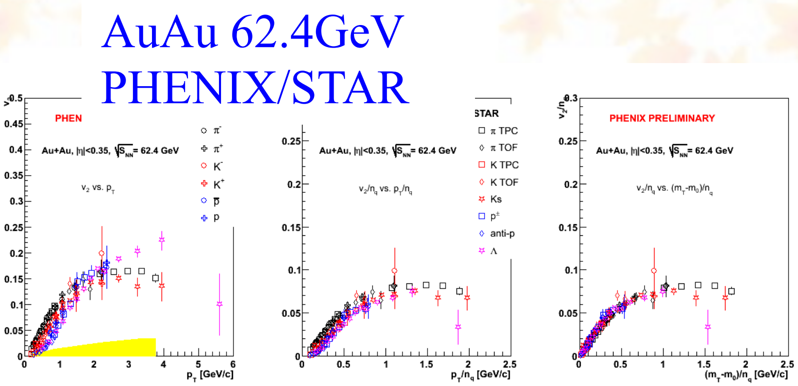
PID v_2 vs p_T in AuAu/CuCu

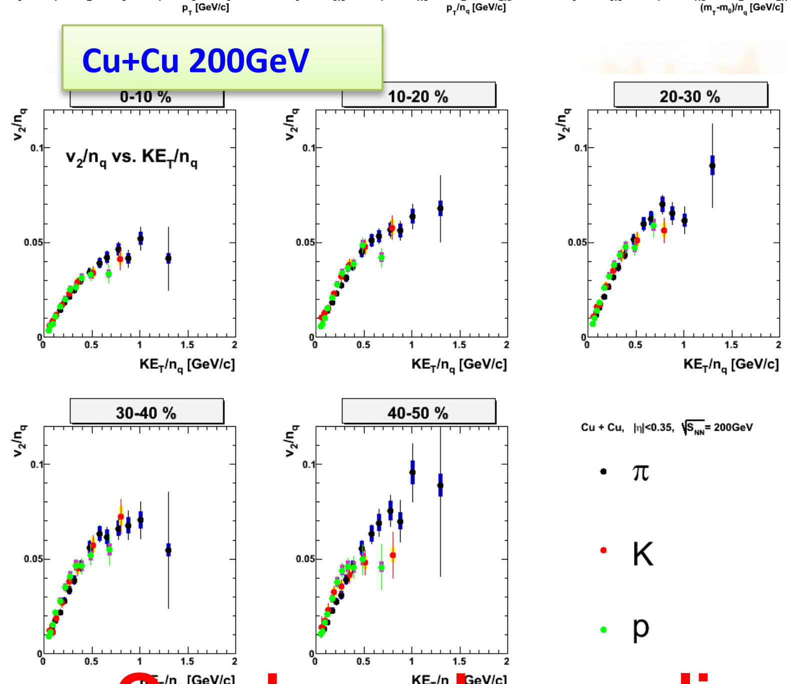


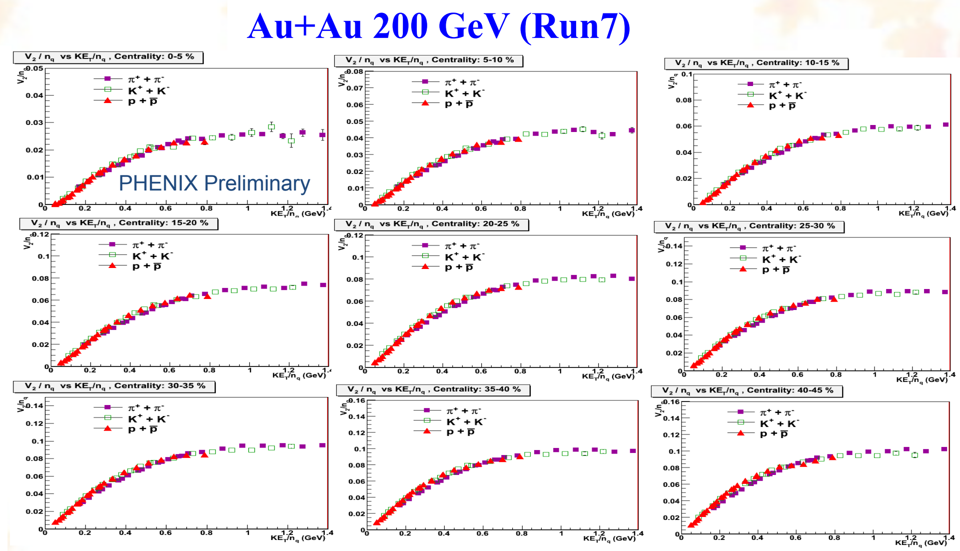
$v_2(p_T)$ /n_{quark} vs. KE_T/n_{quark} becomes one curve independent of particle species.

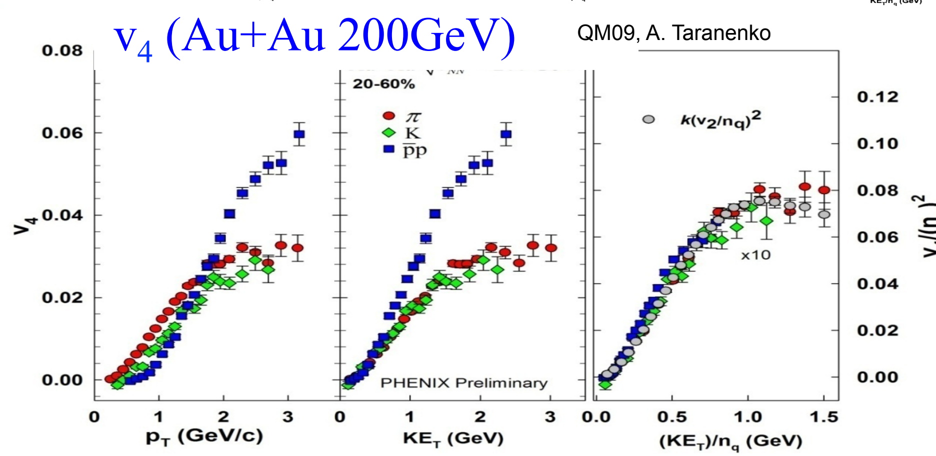
Quark number scaling is consistent to the recombination model which assumes the quark level flow at QGP phase.

Quark number scaling everywhere







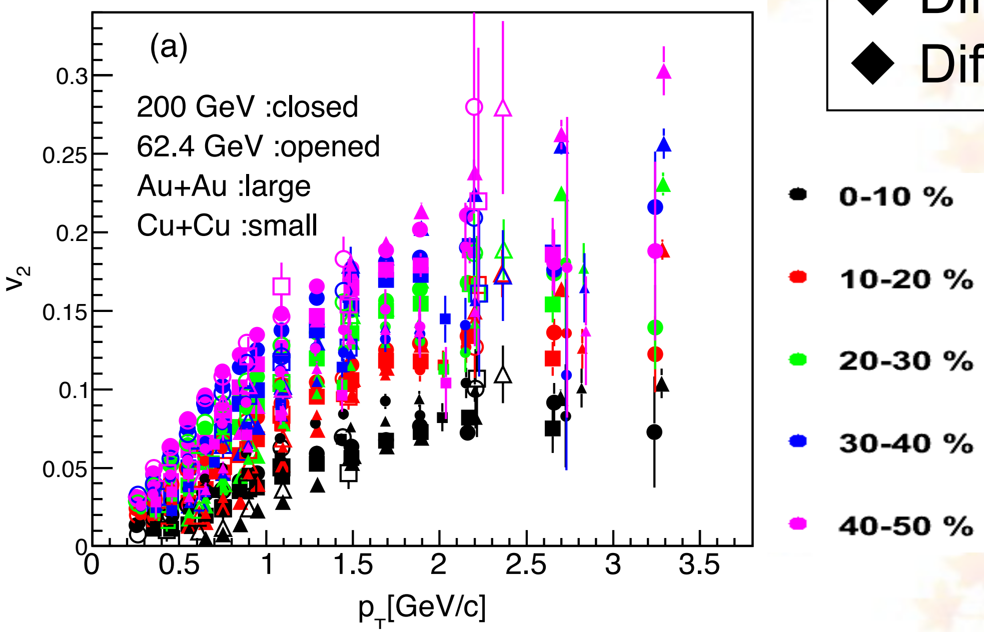


Quark number scaling work out up to K_{ET} ~1GeV.

v_2 scaling

Taking all scaling together,

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



●π
■K
▲p

200 GeV :closed
62.4 GeV :opened
Au+Au :large
Cu+Cu :small

45 curves

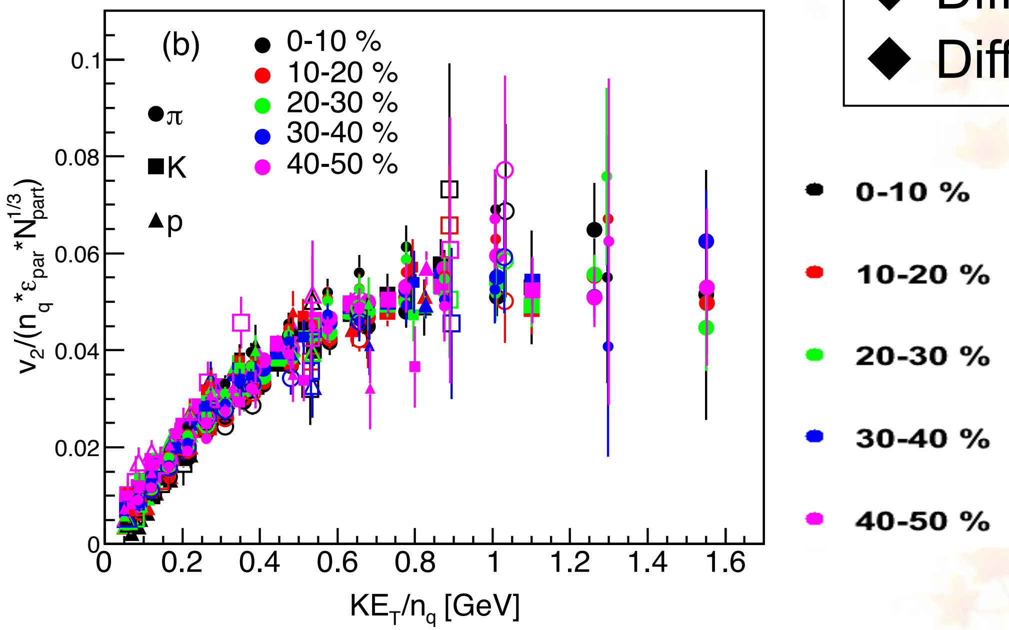
$$\frac{v_2(K_{ET}/n_q)}{n_q \times \varepsilon \times N_{part}^{1/3}}$$

Scale to one curve.

χ2/ndf = 2.1 (with systematic errors)

v_2 scaling

Taking all scaling together,



●π	200 GeV :closed
■K	62.4 GeV :opened
	Au+Au :large
▲p	Cu+Cu :small

- ◆ Different Energy and System (AuAu200, CuCu200, AuAu62)
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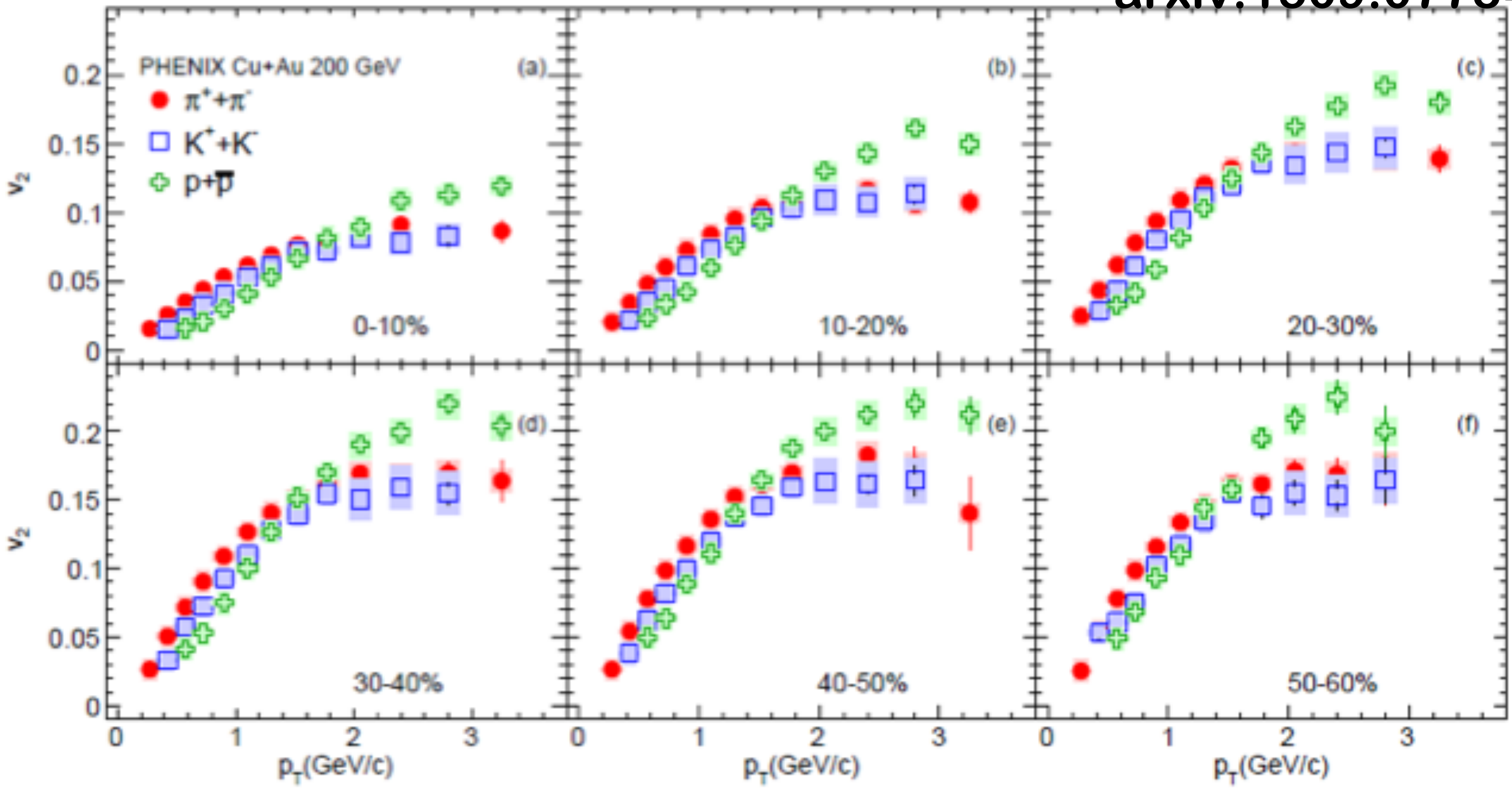
$$\frac{v_2(K_{ET}/n_q)}{n_q \times \varepsilon \times N_{part}^{1/3}}$$

Scale to one curve.

χ2/ndf = 2.1 (with systematic errors)

PID v_2 vs p_T in CuAu

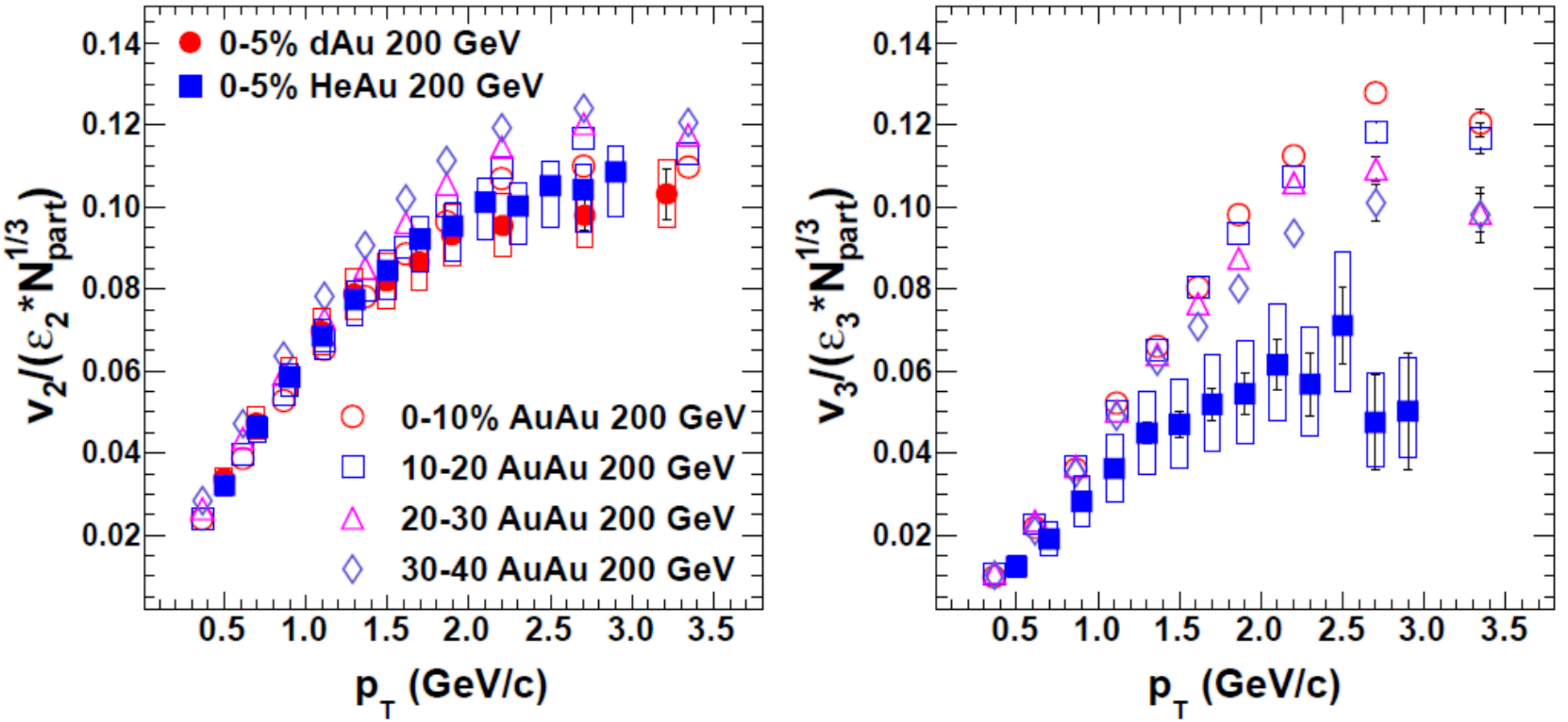
arxiv:1509.07784



Mass ordering can be seen at low p_T

Baryon and meson splitting at mid-p_T

$\varepsilon_n * N_{part}^{(1/3)}$ scaling at small system



Does not work as well in small collision systems, especially v_3

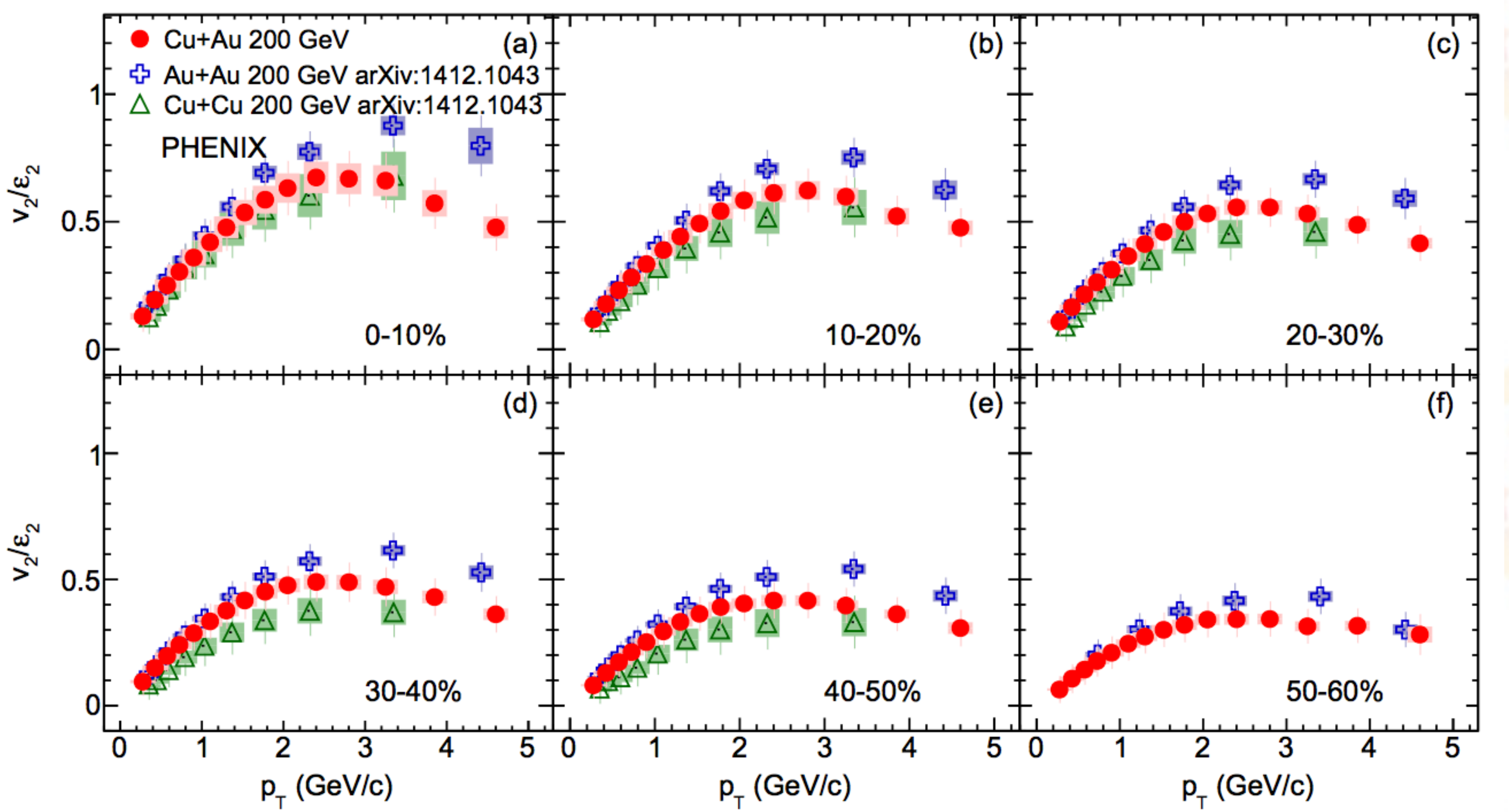
By Sarah compbell at ICHEP2016

Summary

- Systematic study of v_2 have been done in Au+Au, Cu+Cu at $\sqrt{s_{NN}}$ = 62.4/200 GeV and recently Cu+Au at 200 GeV.
- $v_2(p_T)$ follows quark number + KE_T scaling in Au+Au (200,62GeV) and Cu+Cu (200GeV).
- $v_2(N_{part})$ / ε_2 are same between Au+Au, Cu +Cu
- v_n (p_T) $/(\varepsilon_n * N_{part}^{1/3})$ scaling works in Au+Au (200,62GeV), Cu+Cu(200GeV) and Cu+Au (200GeV) for n =2 and in Au+Au(200GeV) and Cu+Au(200GeV) for n =3, but not for the small system.

Back Up

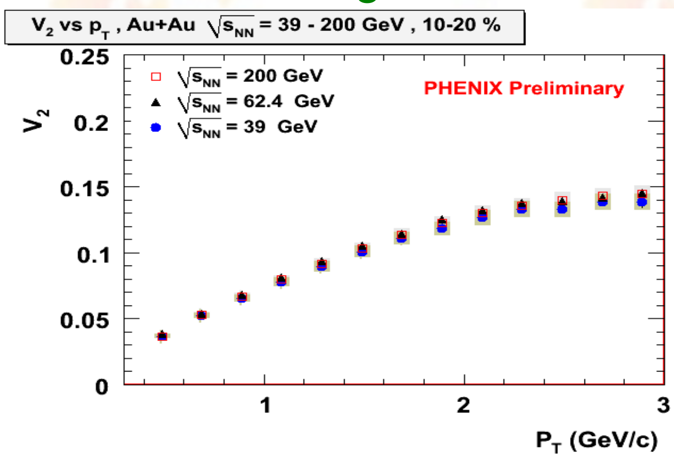
v_2/ε_n

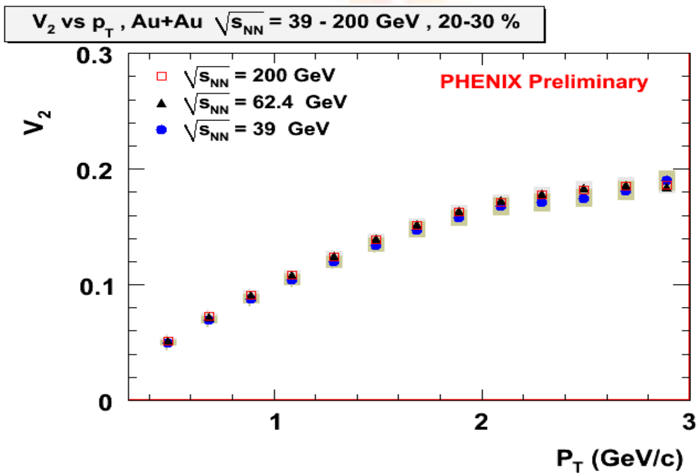


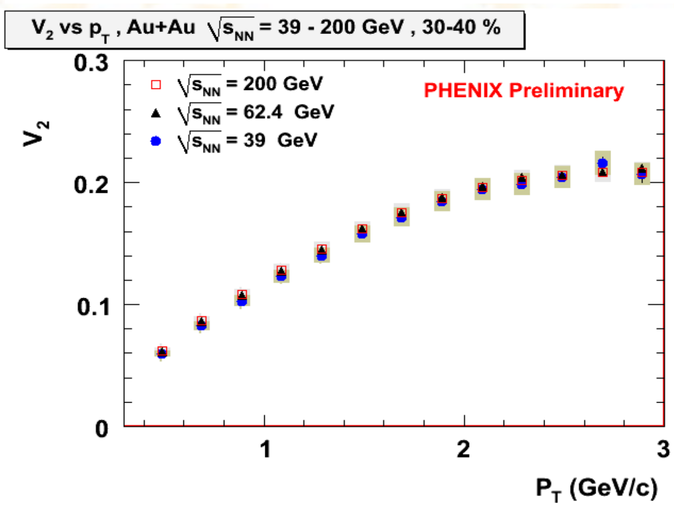
- This is natural since N_{part} is different.

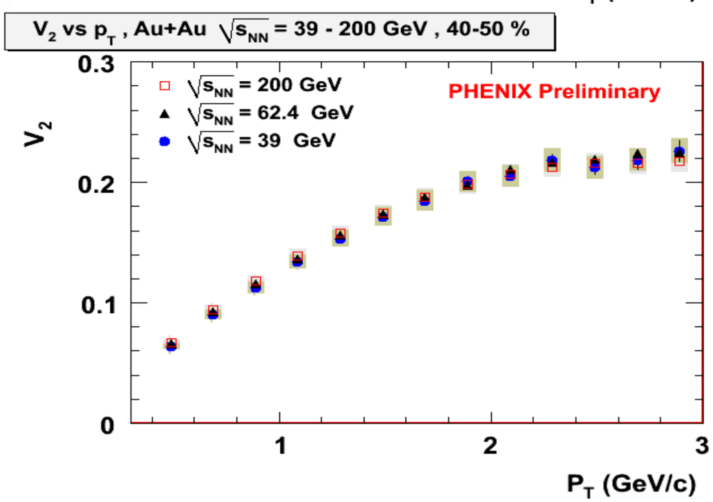
Energy dependence
200, 62.4, 39 GeV

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





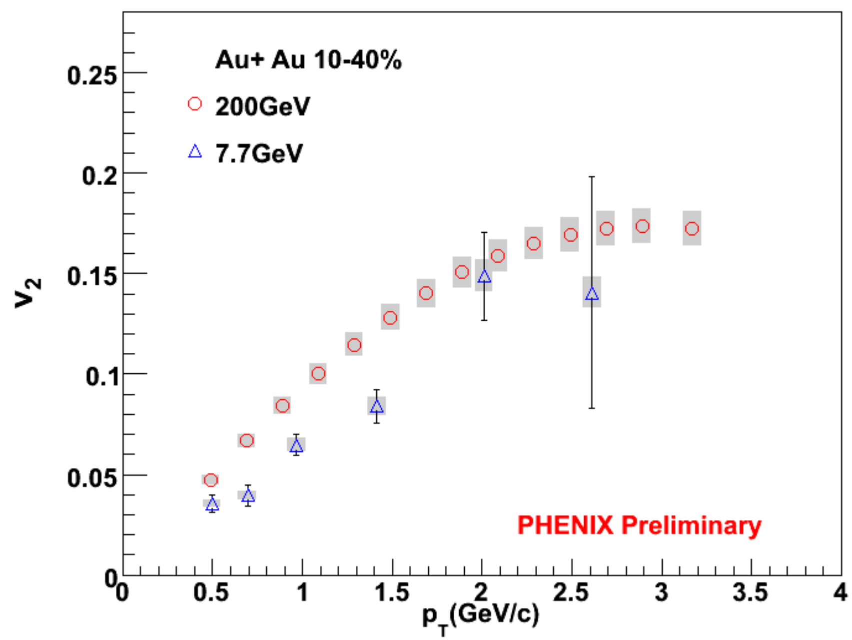


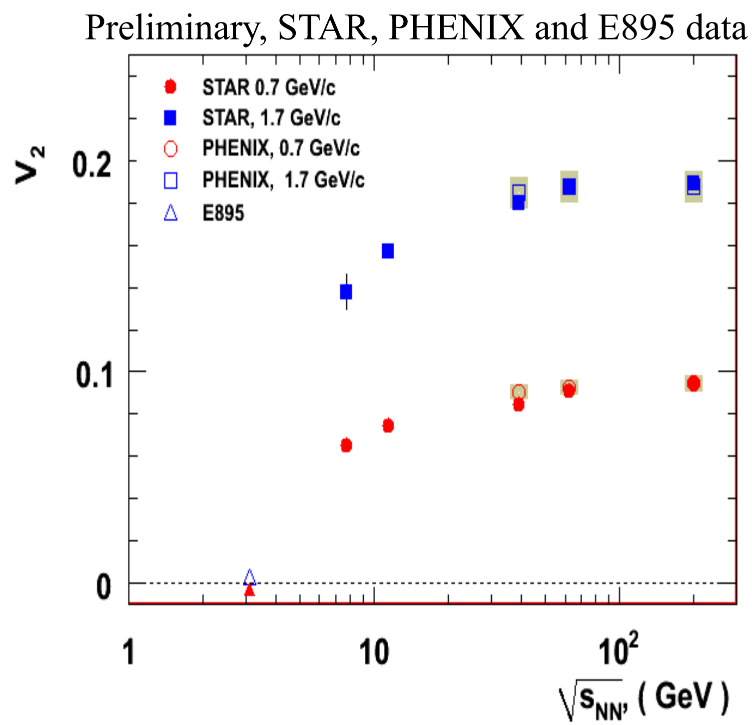


No energy dependence from 39 GeV to 200 GeV for different collision centralities.

Energy dependence
200, 7.7 GeV

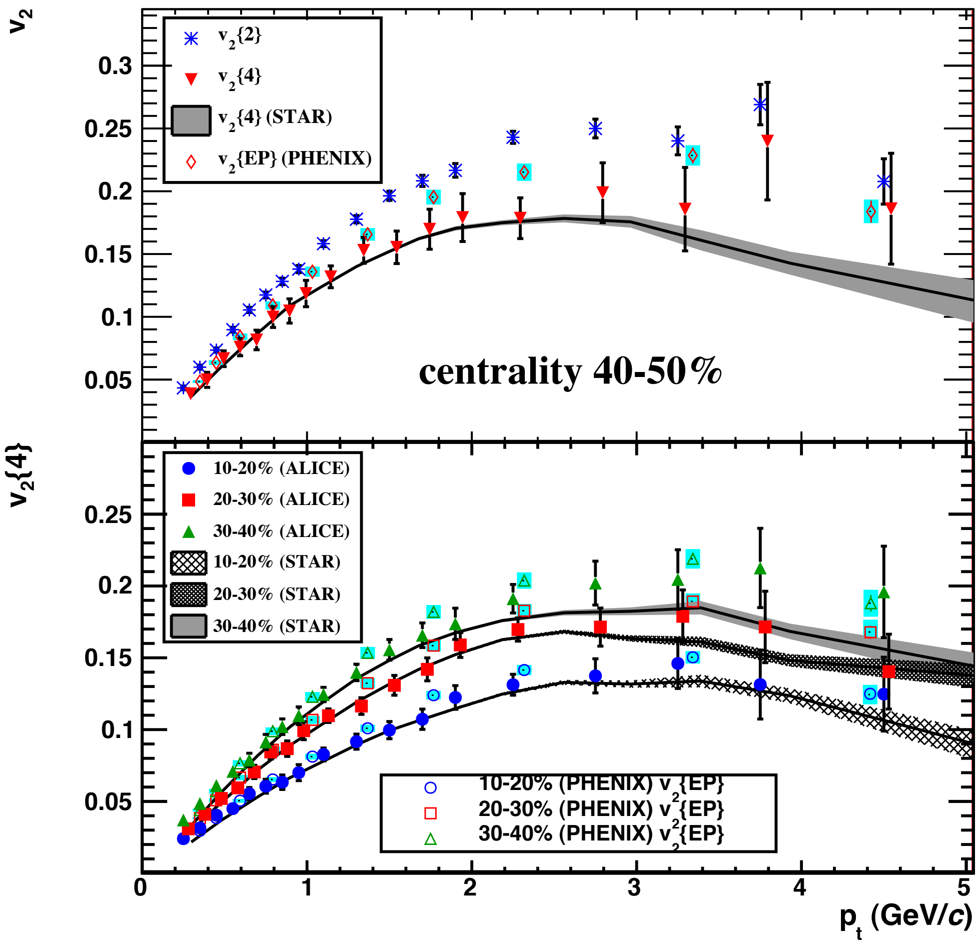
S. Huang, A. Taranenko, R. Lacey (WWND2011)





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 ?
→ Need more study for this region.

Energy dependence 2.76 TeV, 200 GeV



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

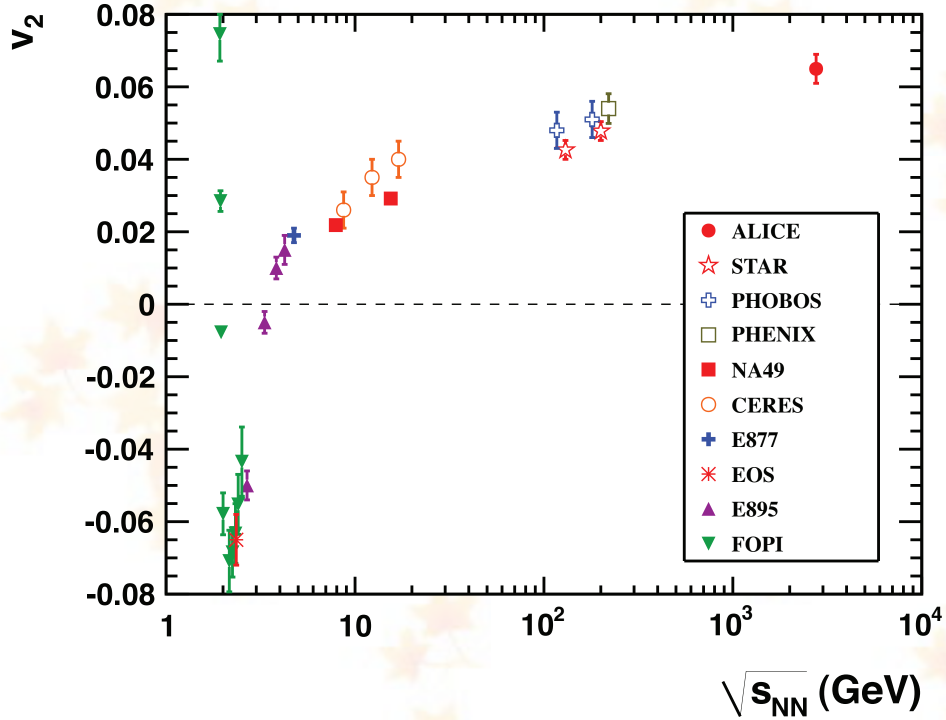
PHENIX and STAR ---
Au+Au, $\sqrt{s_{NN}} = 200$ GeV

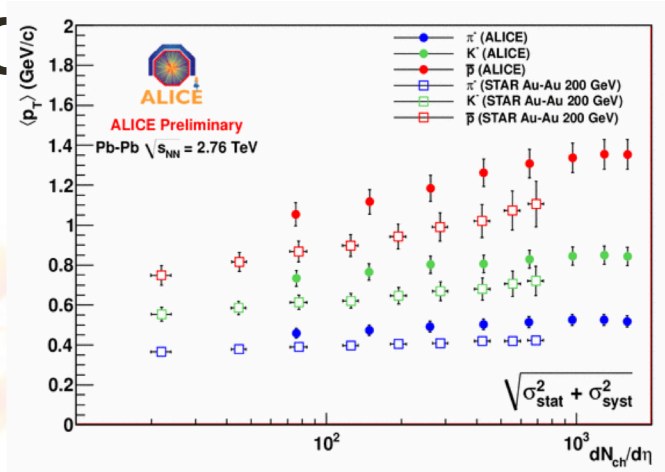
PHENIX : Phys. Rev. C 80, 024909 (2009)
STAR : Phys. Rev. C 77, 054901 (2008)

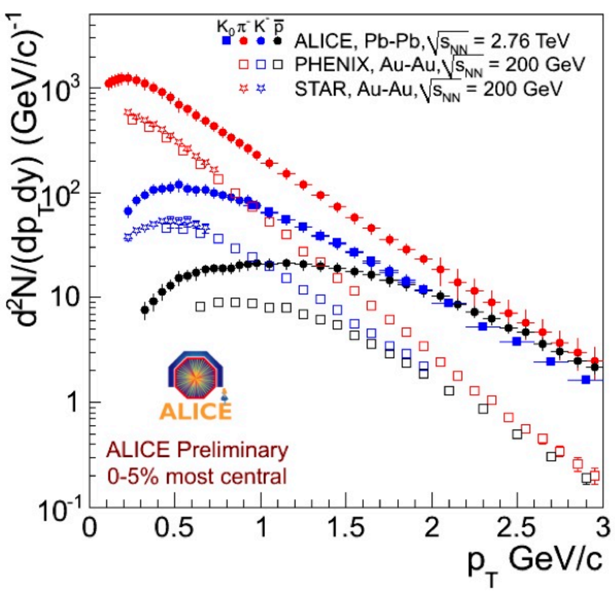
- Mostly consistent, especially at low p_T

Energy dependence - Integrated

- ALICE QM2011 Alberica's talk







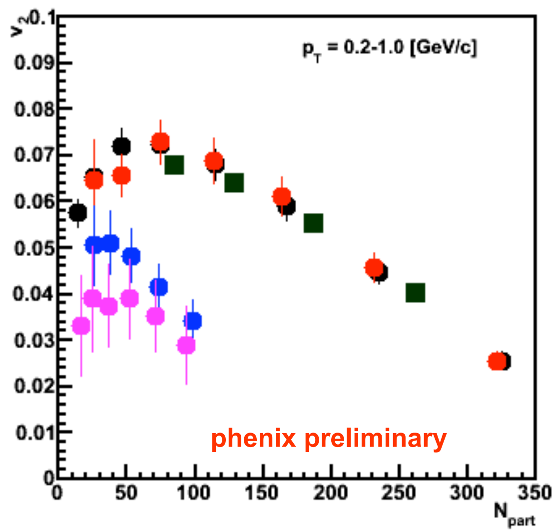
STAR, PRC 79 , 034909 (2009)
PHENIX, PRC69, 03409 (2004)

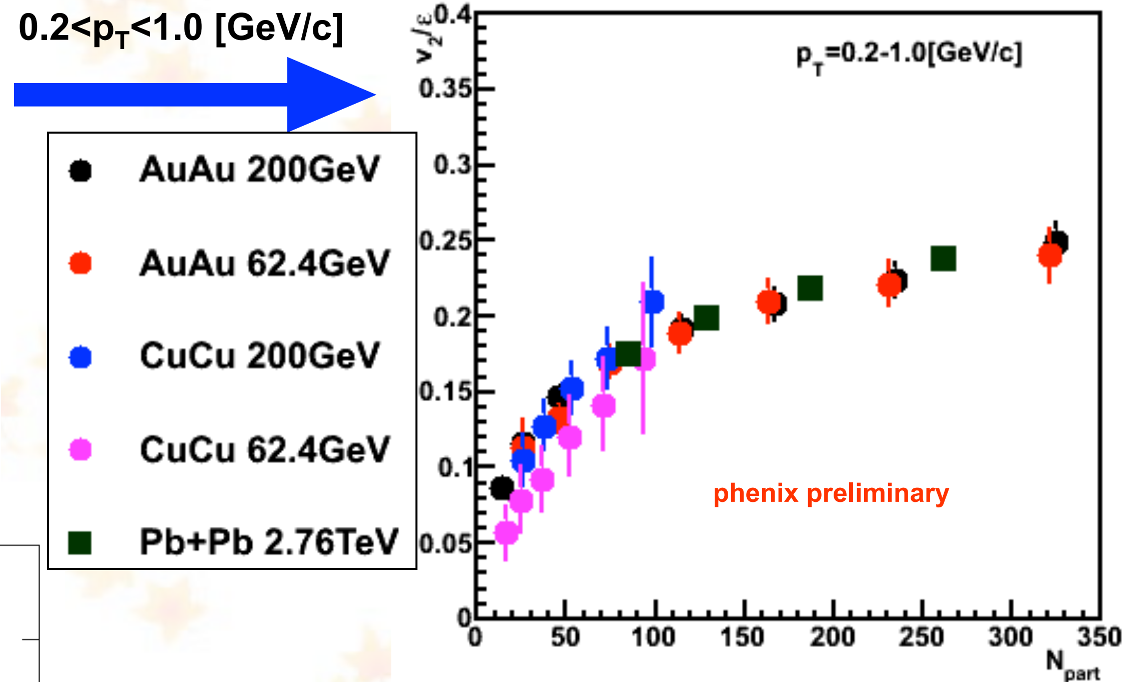
Integrated v_2 at LHC is larger than v_2 at RHIC.
Is this because of radial flow ?
Probably no.

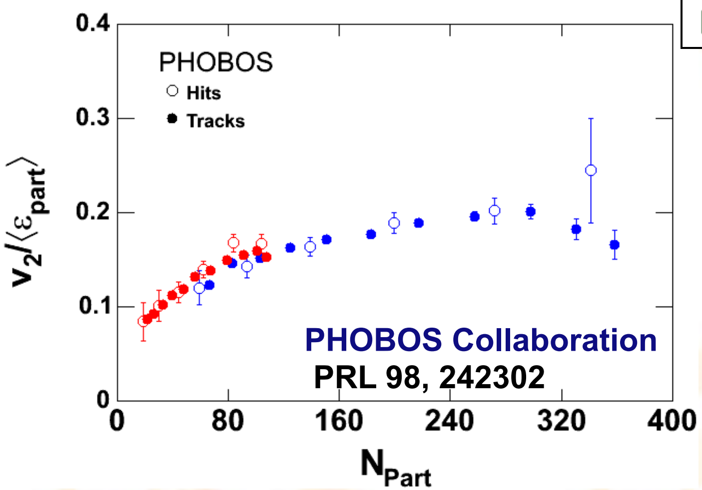
Eccentricity scaling

Pb+Pb, Au+Au, Cu+Cu

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







Eccentricity scaling suggests early thermalization.

There is a strong N_{part} dependence.

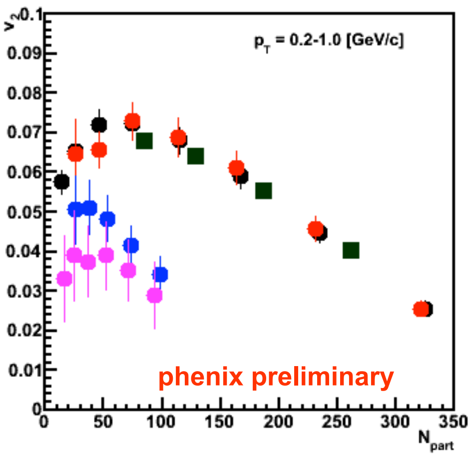
N_{part} Scaling

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

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

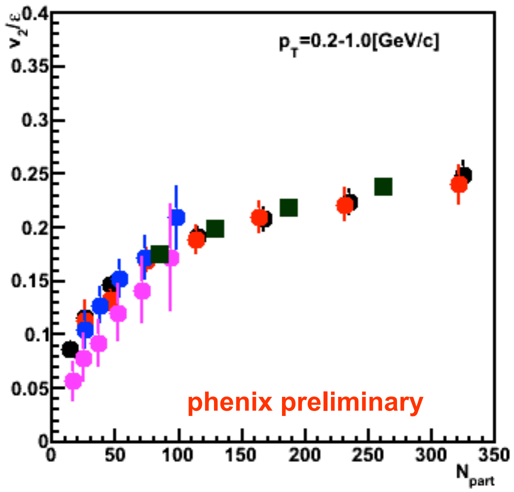
- ● AuAu 200GeV
- ● AuAu 62.4GeV
- ● CuCu 200GeV
- ● CuCu 62.4GeV
- ■ Pb+Pb 2.76TeV

v_2 vs. N_{part}

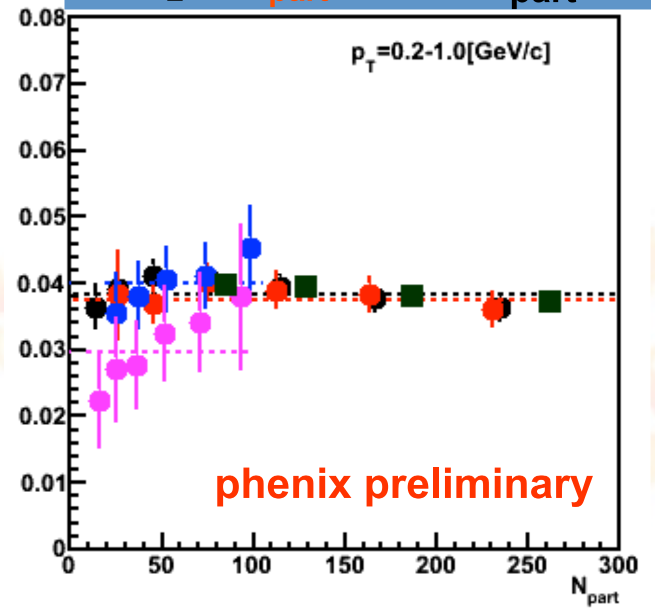


0.2<p_T<1.0 [GeV/c]

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 including Pb+Pb 2.76TeV

except small N_{part} at 62 GeV.

- This exception may indicate non-sufficient thermalization region.

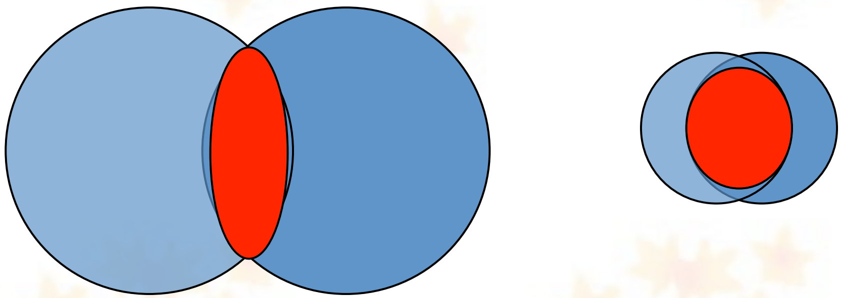
Back Up

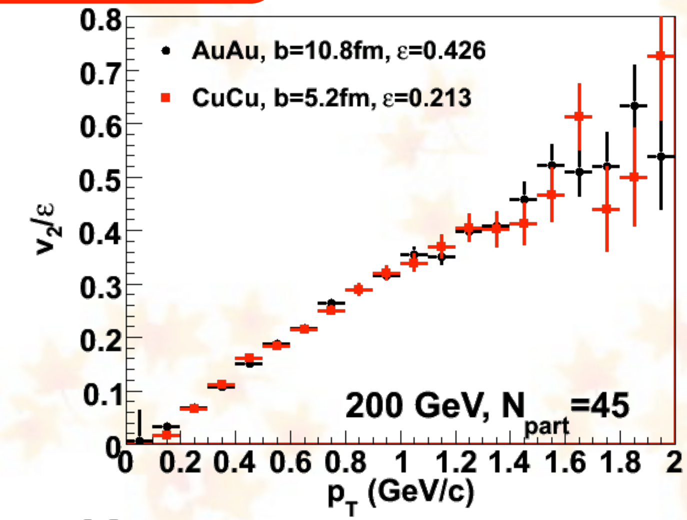
For Hydro simulation

Differential v_2 in Au+Au and Cu+Cu Collisions

QGP fluid+hadron gas with Glauber I.C.

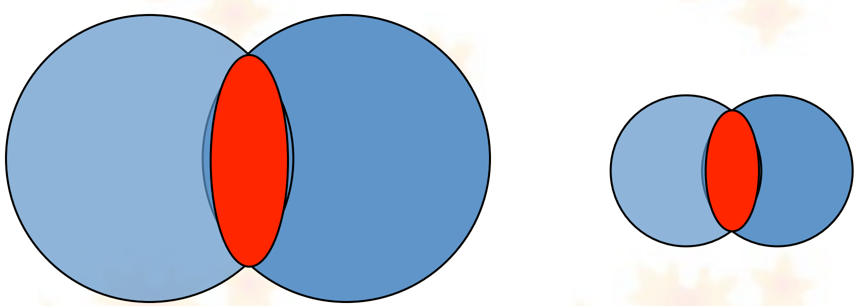
Au+Au **Cu+Cu**

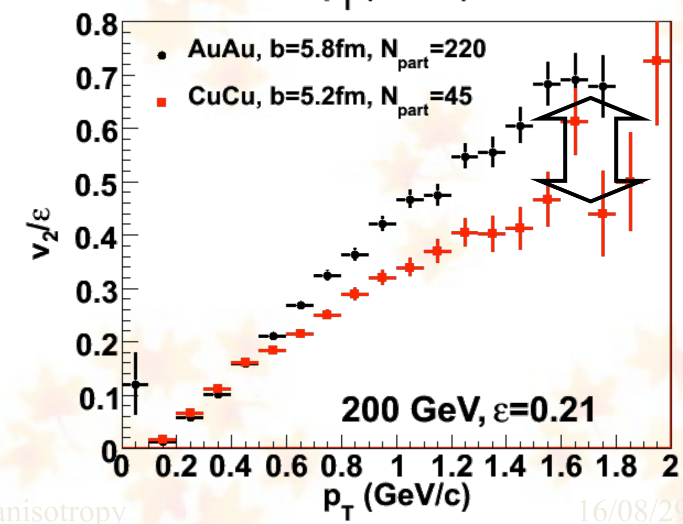




Same N_{part}, different eccentricity

Au+Au **Cu+Cu**





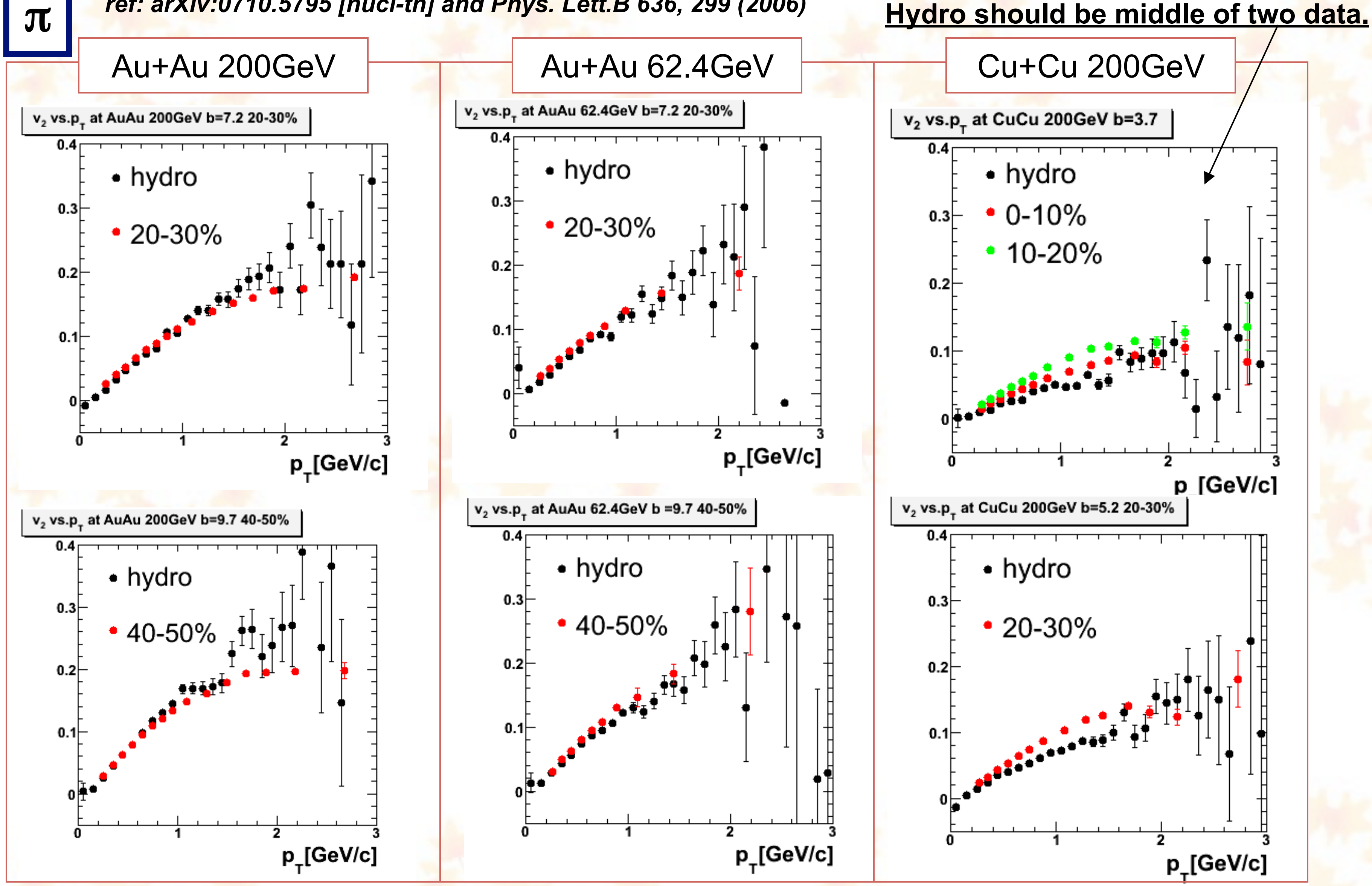
Same eccentricity, different N_{part}

Comparison with hydro-simulation

Hydro calculations done by Prof. Hirano.

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

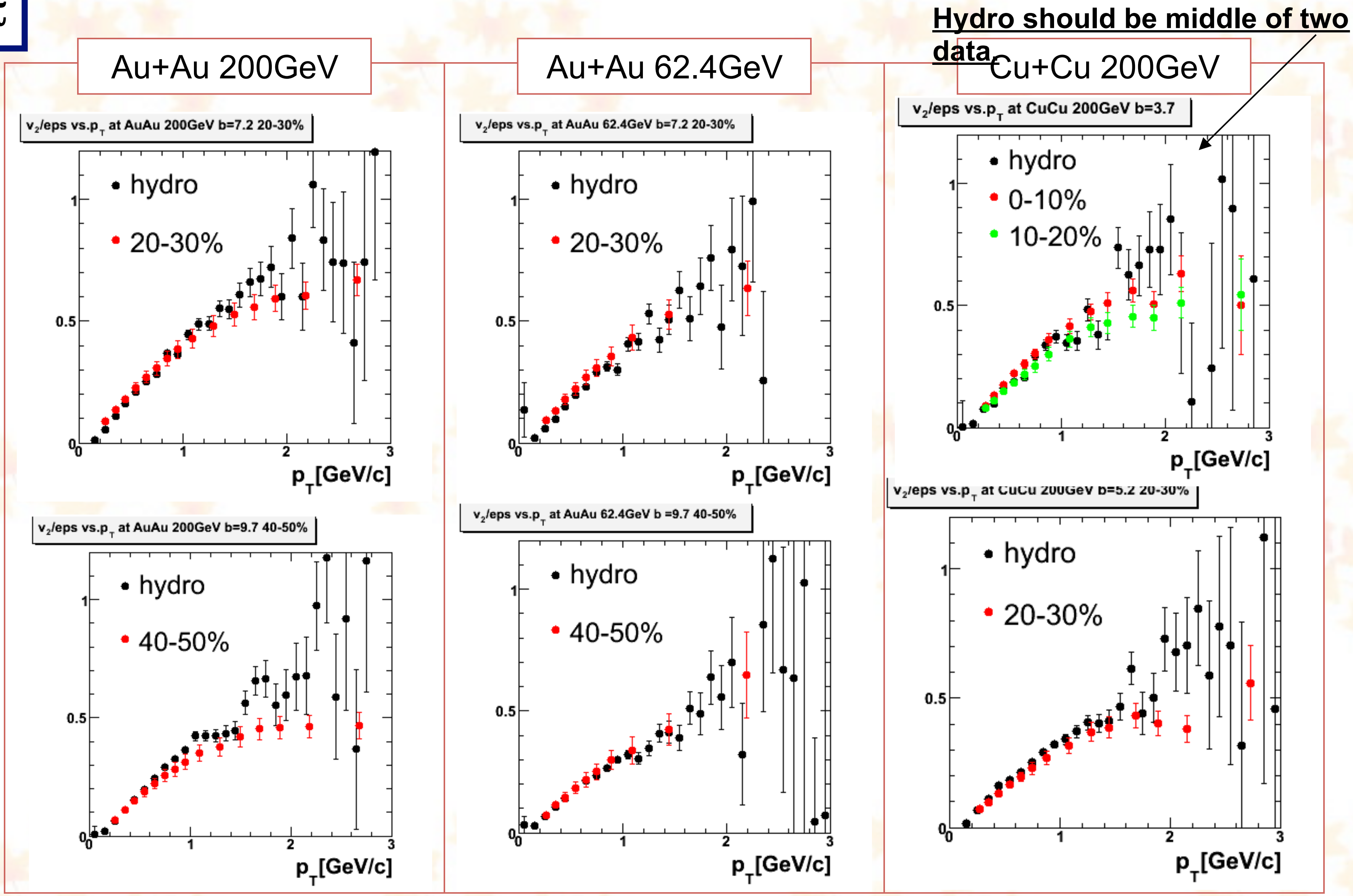
π



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

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

π



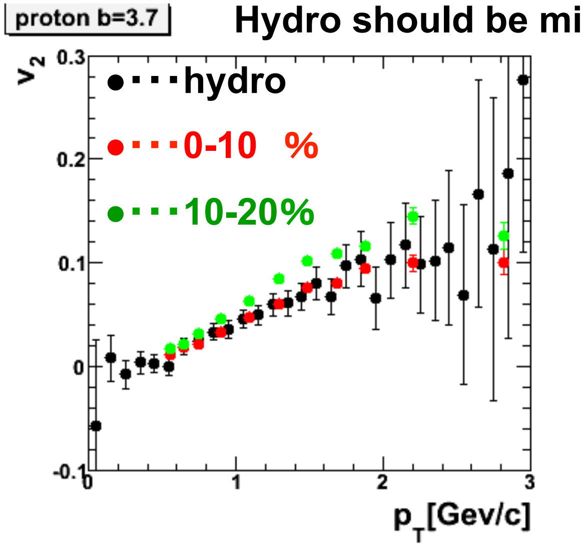
The Au+Au and Cu+Cu results agree well with hydro.

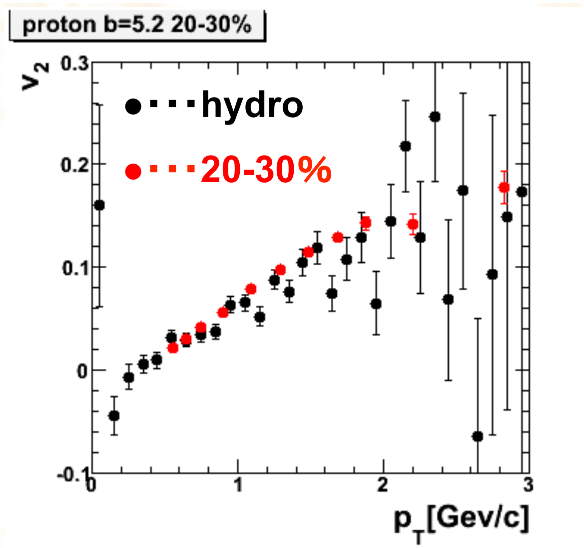
Comparison with hydro-simulation

Cu+Cu 200GeV

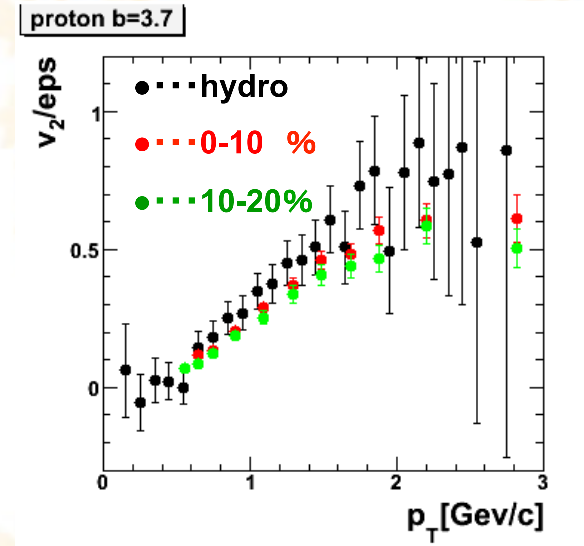
p

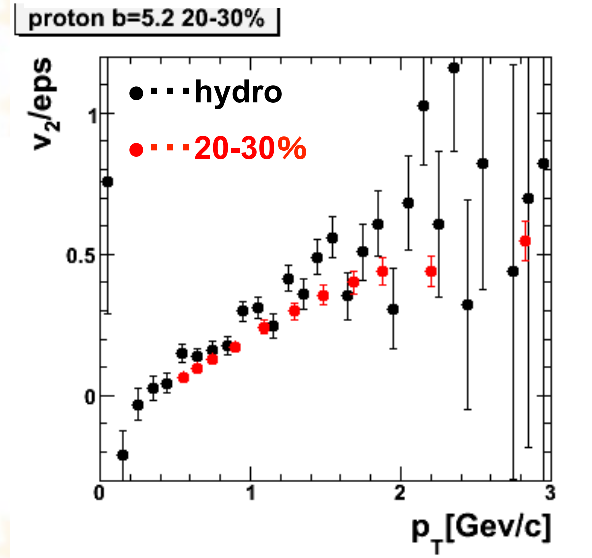
Hydro should be middle of two data.





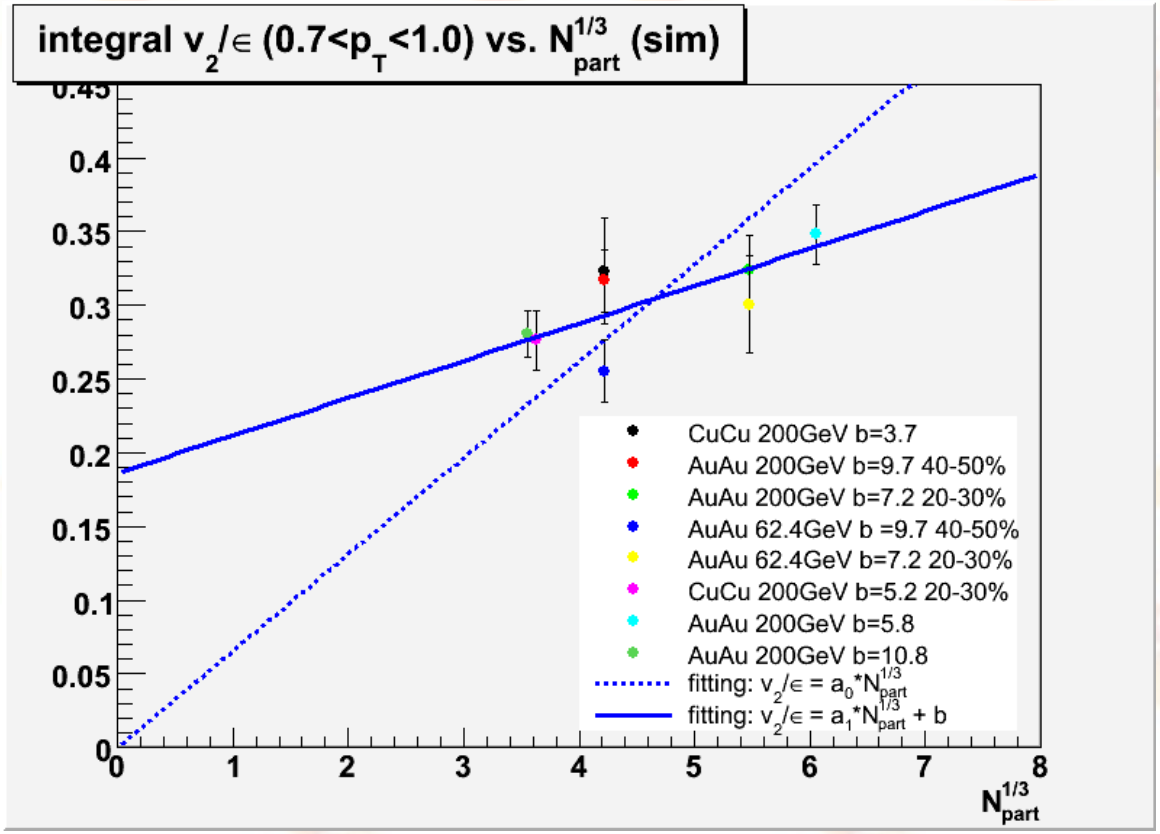
Normalized by eccentricities





v_2(data)/$\varepsilon_{participant}$ for proton doesn't agree with v_2(hydro)/$\varepsilon_{standard}$

Hydro v_2/ε vs. $N_{part}^{1/3}$



Fitting lines: dash line $v_2/\varepsilon = a*N_{part}^{1/3}$

solid line $v_2/\varepsilon = a*N_{part}^{1/3} + b$