Latest results of charged hadron flow measurements in CuAu collisions at RHIC-PHENIX

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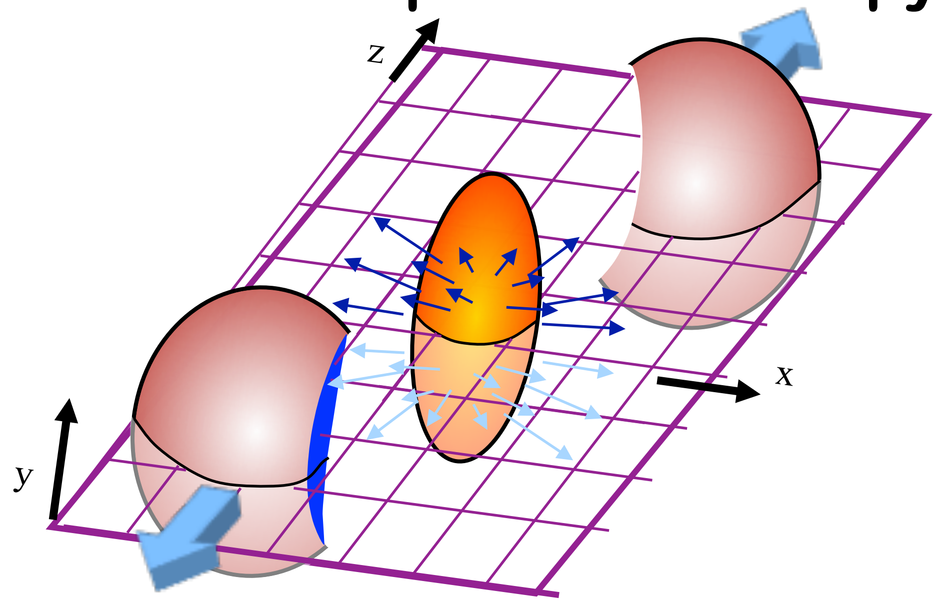
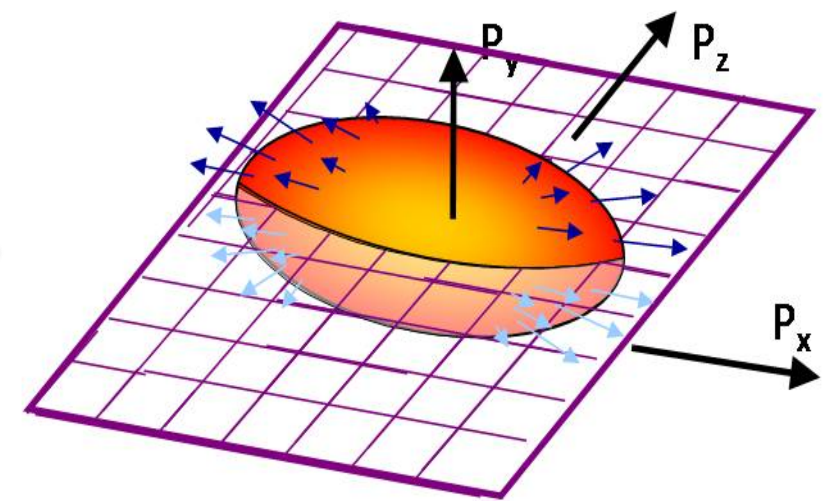
Azimuthal anisotropic flow

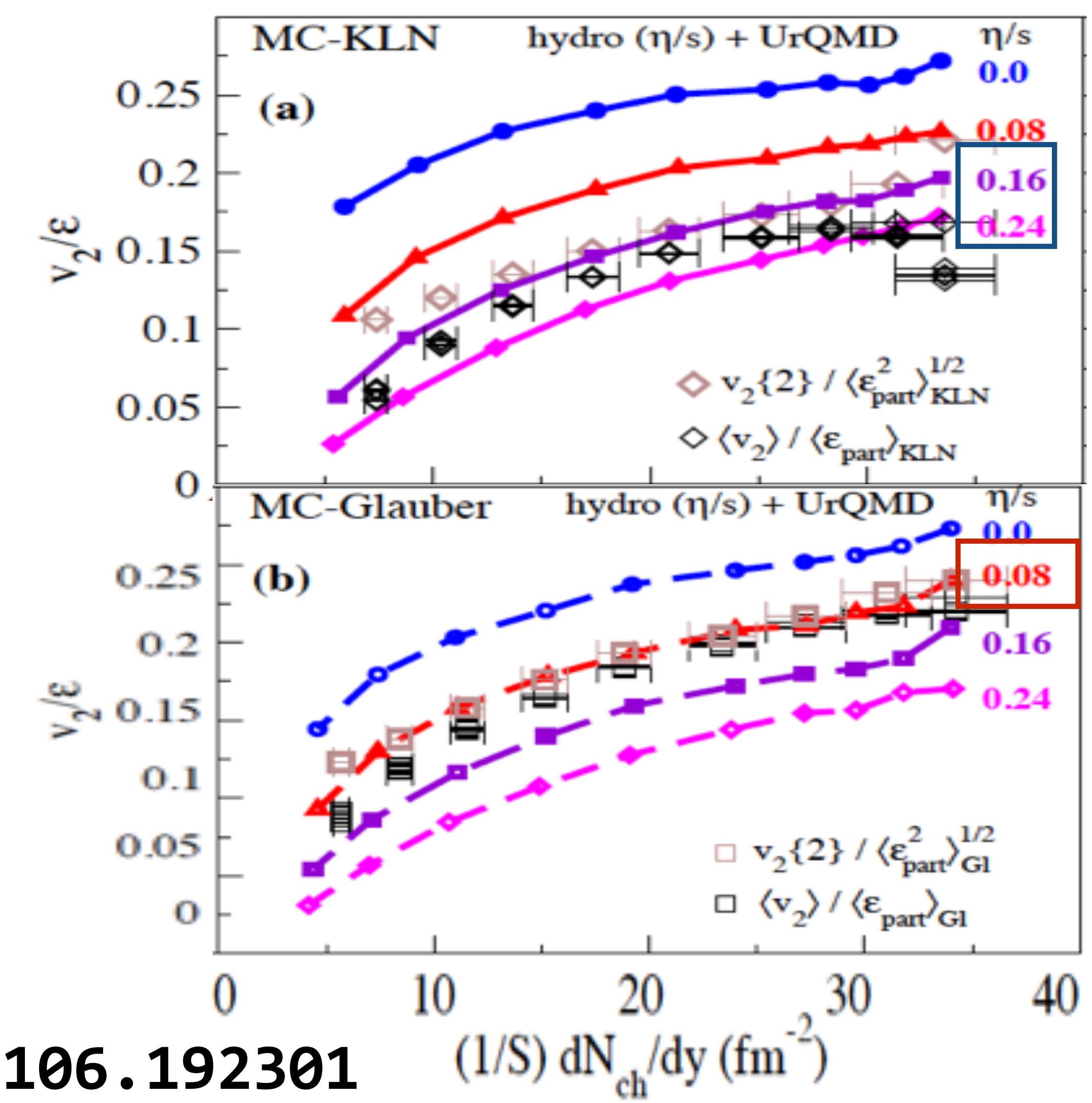
Initial spatial anisotropy: ε_2



momentum anisotropy: v_2



Anisotropic particle production v_n
- Initial spatial condition is converted to momentum anisotropy

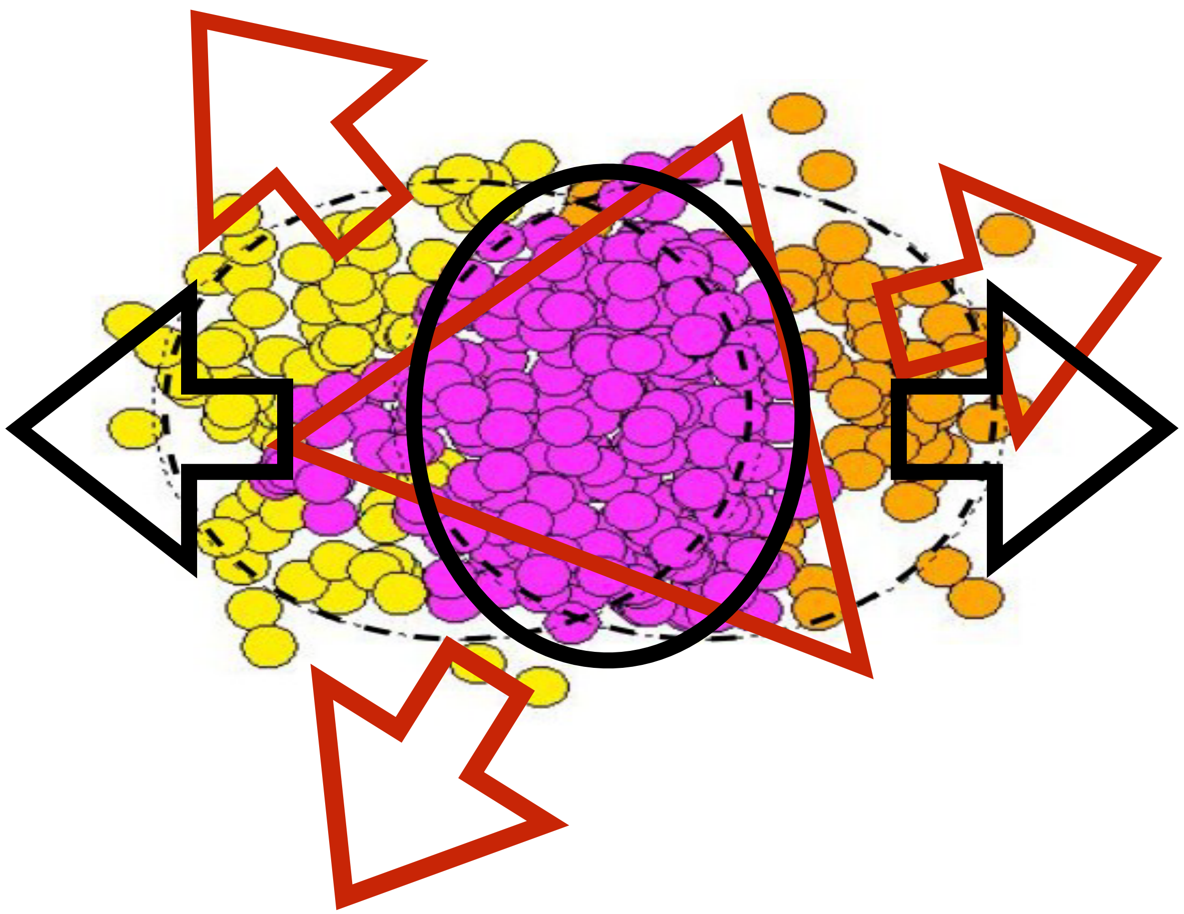


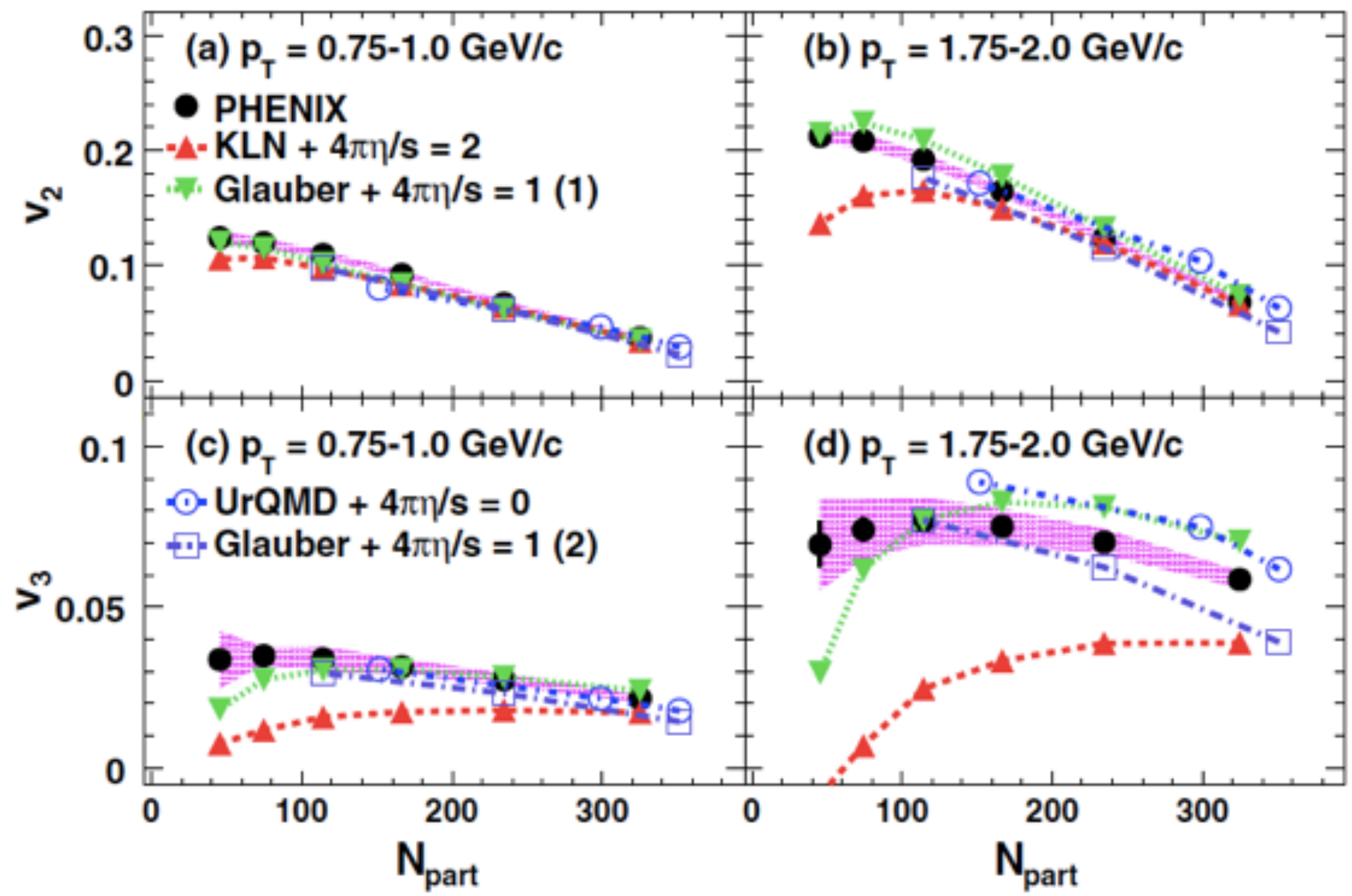
Sensitive to
- initial condition
- viscosity

PRL 106.192301

Higher order flow harmonics

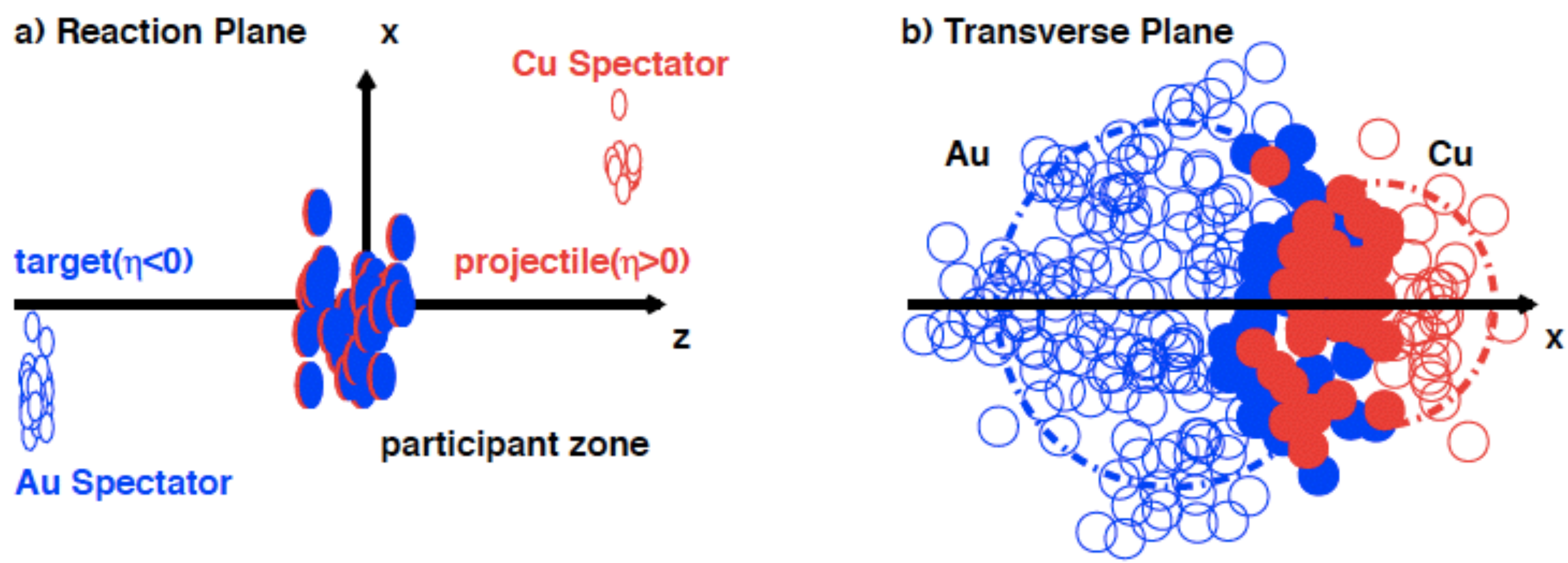
PRL 107. 252301





Event-by-event initial participant fluctuation can lead to triangular particle production anisotropy v_3.
v_3 is expected to further constrains initial condition and viscosity

Cu+Au collisions

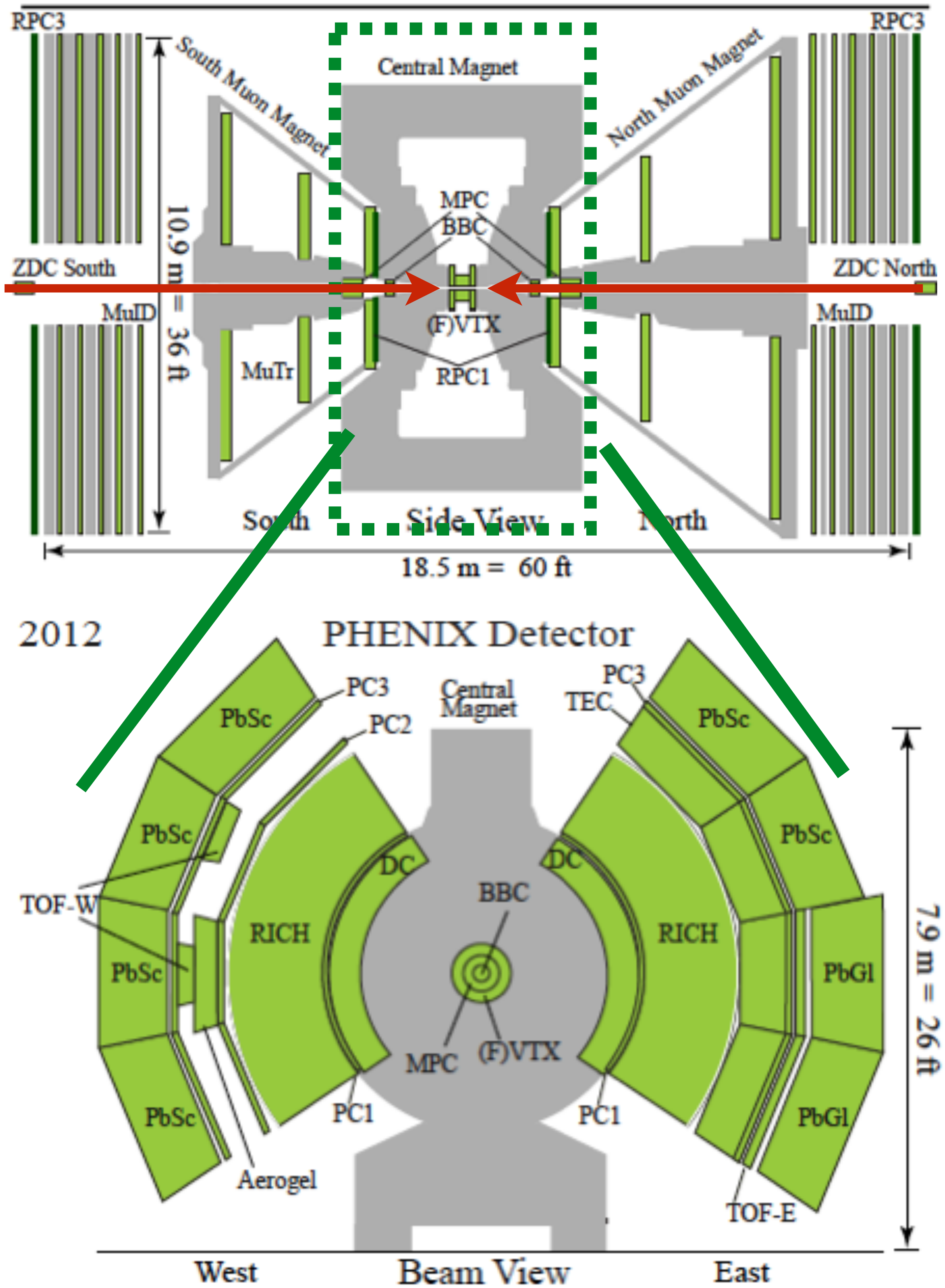


Asymmetric initial condition provides

- Different left/right pressure gradient, particle production....
- Longitudinally, above characteristics could be different in Au-going/Cu-going

v_n measurements in CuAu collisions provide additional insight into the mechanism

PHENIX detectors



2nd 3rd Participant Event Plane
-Beam Beam counter(BBC)
Spectator Plane
-Shower Max Detector(SMD)

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) ($|\eta|<0.35$)

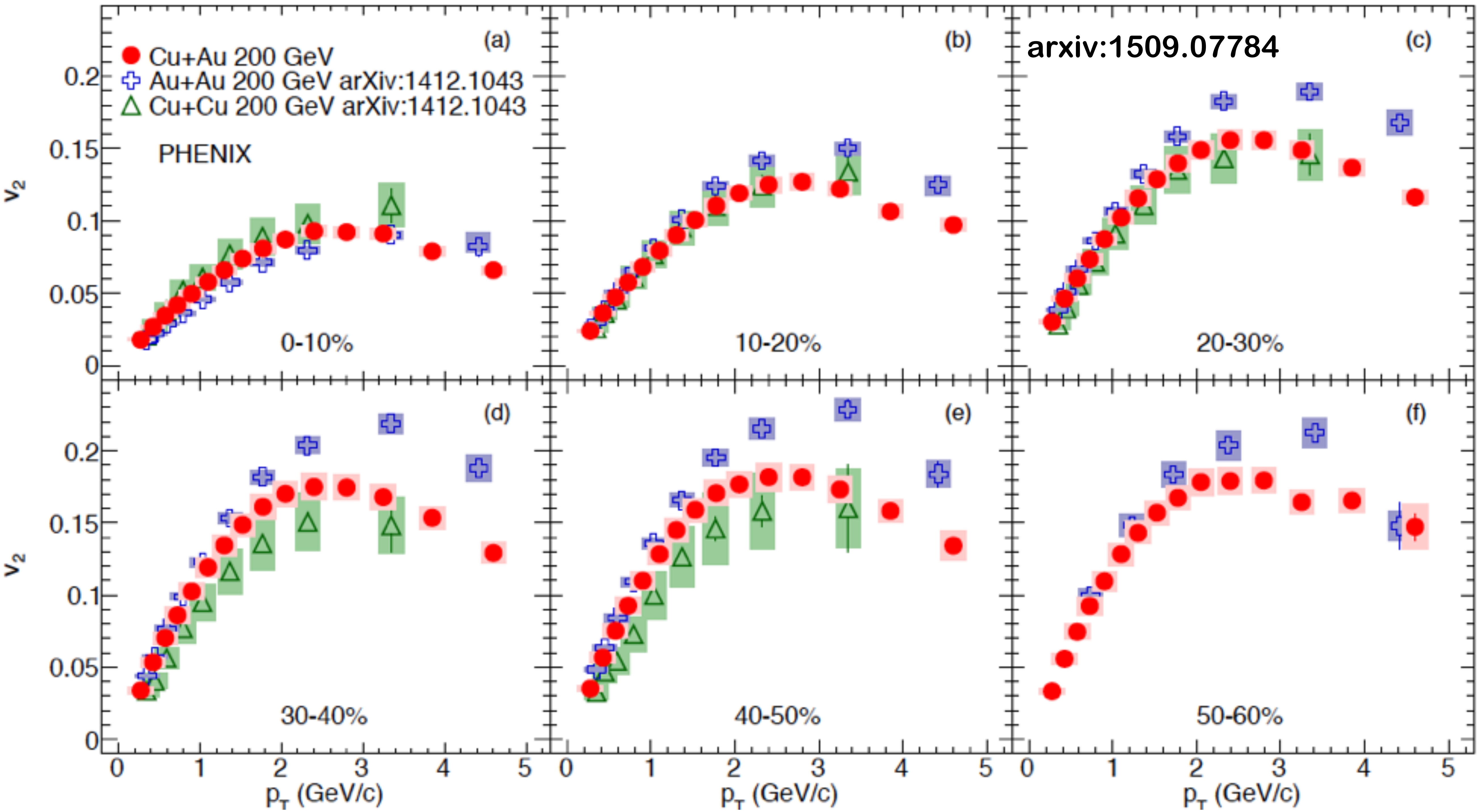
Charged hadron v_n in CuAu

-p_T dependence of v_2, v_3

System size dependence

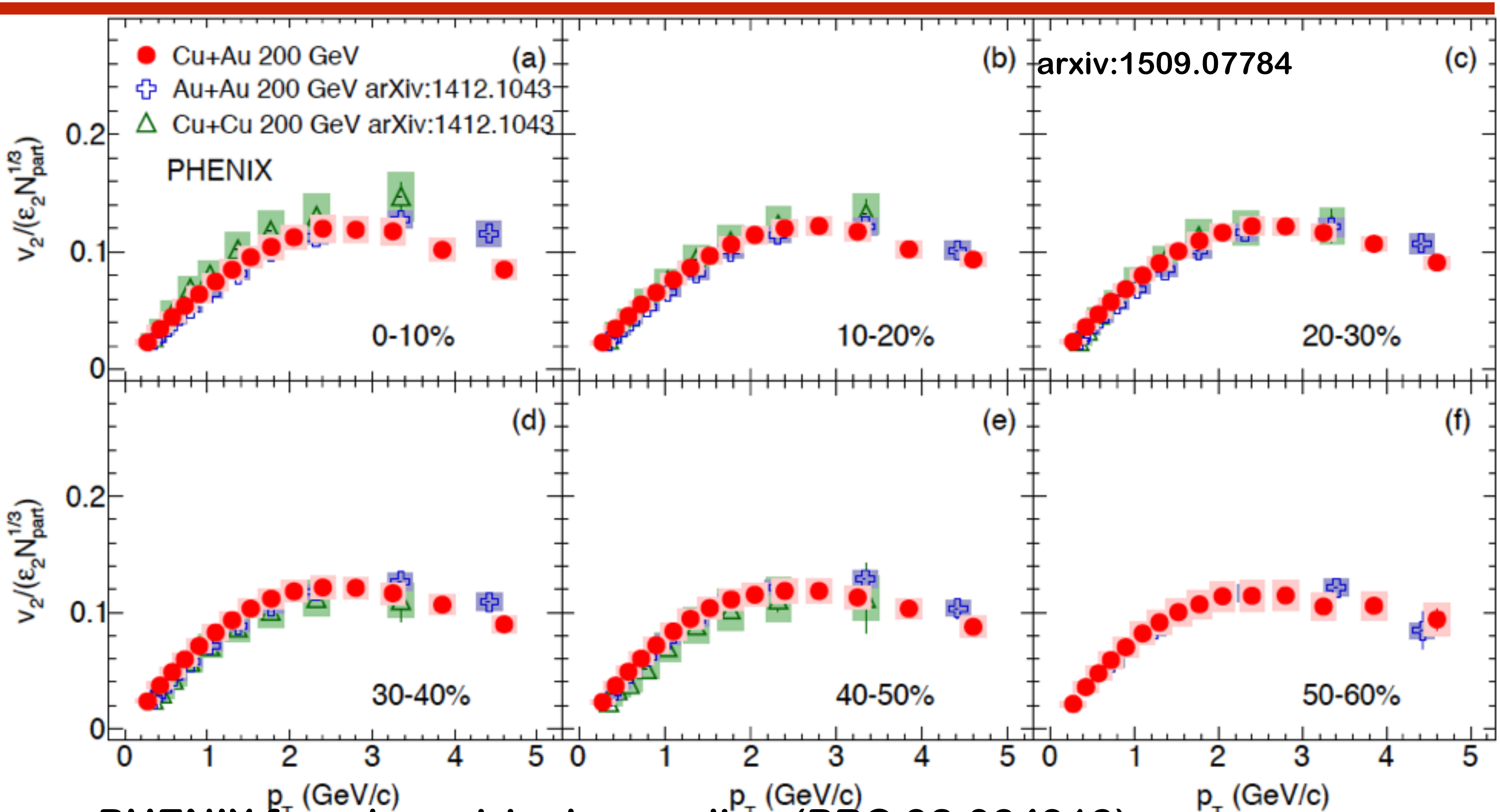
-p_T and eta dependence of v_1

System size dependence of v_2



v_2 for different systems has similar centrality and pT dependence
v_2 in CuAu is always between those in AuAu and CuCu

Scale v2 with $\varepsilon_2 * N_{part}^{(1/3)}$



PHENIX found empirical v_2 scaling (PRC.92.034913)

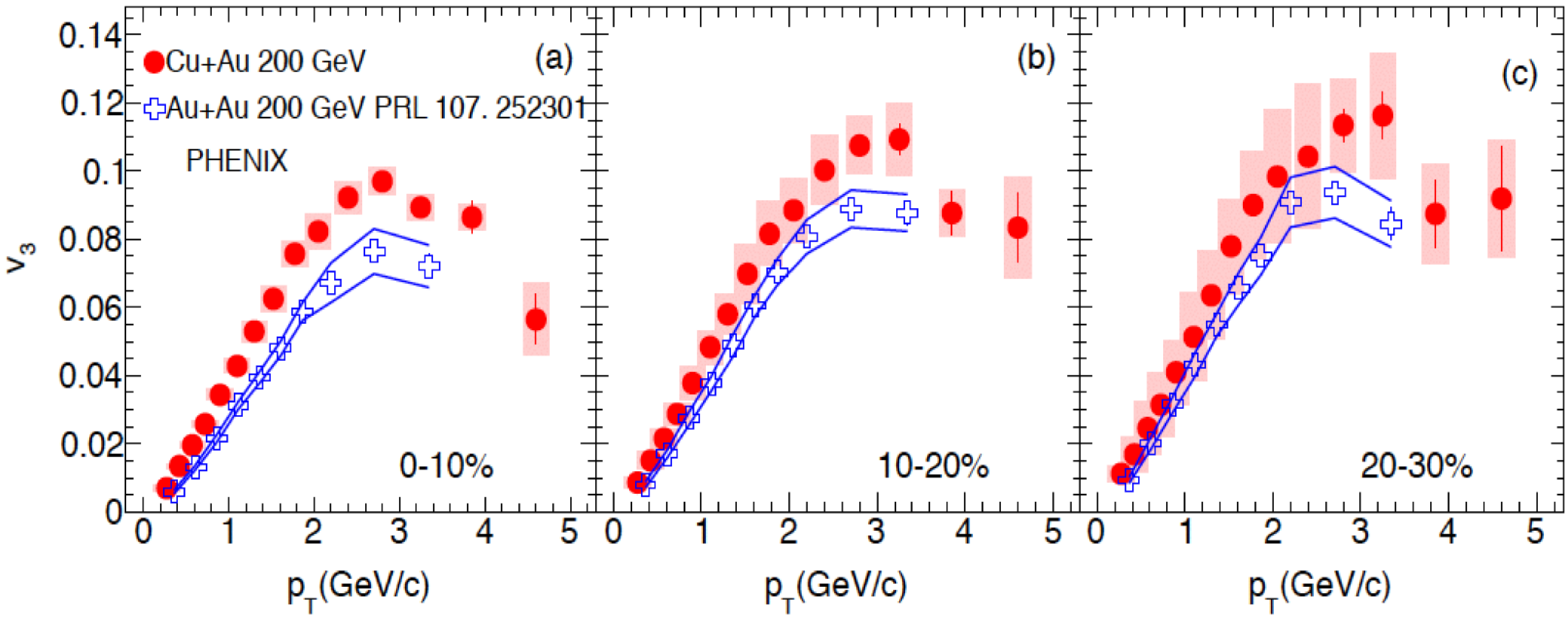
-v_2 is scaled with $\varepsilon_2 N_{part}^{(1/3)}$

-$N_{part}^{(1/3)}$ is proportional to length scale

$\varepsilon_2 N_{part}^{(1/3)}$ scaling works well in CuAu!

System size dependence of v_3

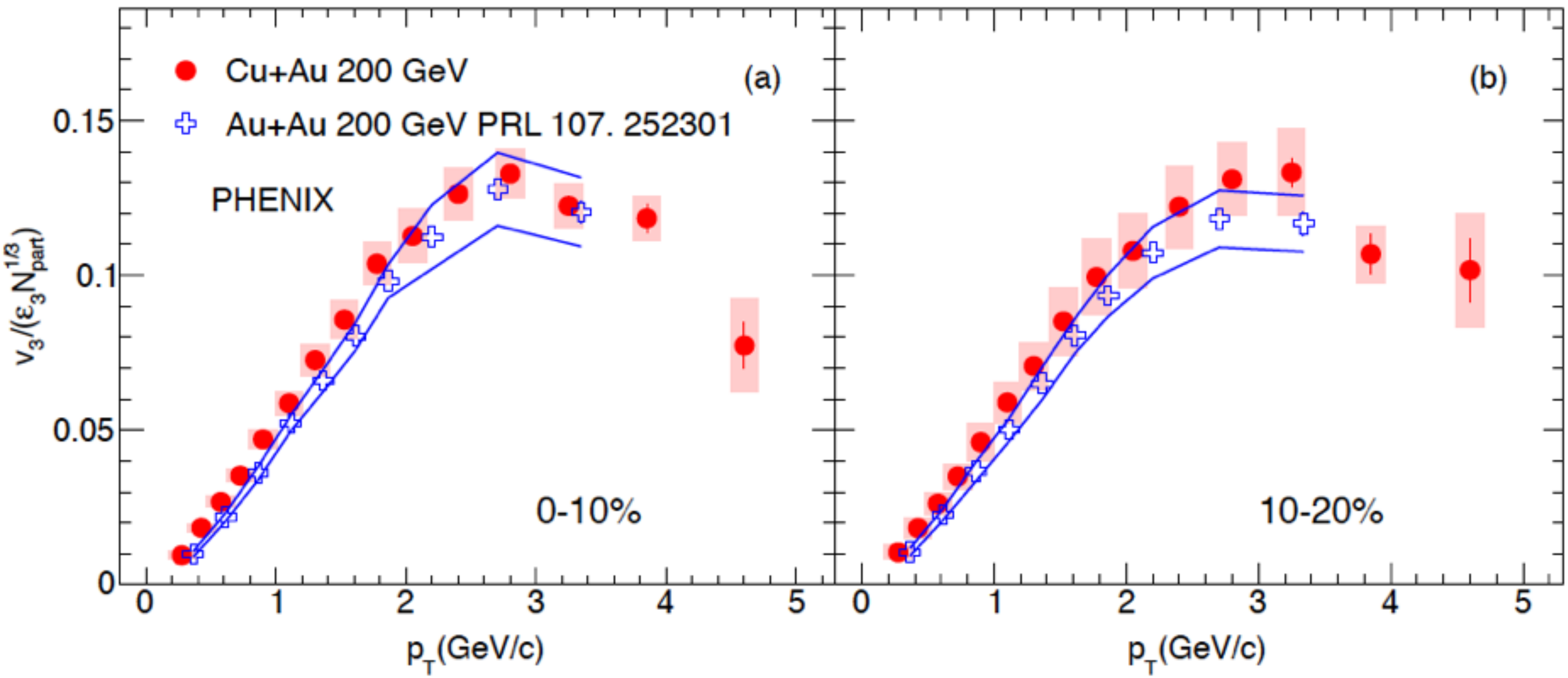
arxiv:1509.07784



v_3 for different systems has weak centrality dependence
v_3 in CuAu is always bigger than those in AuAu

Scale v_3 with $\varepsilon_3 * N_{part}^{(1/3)}$

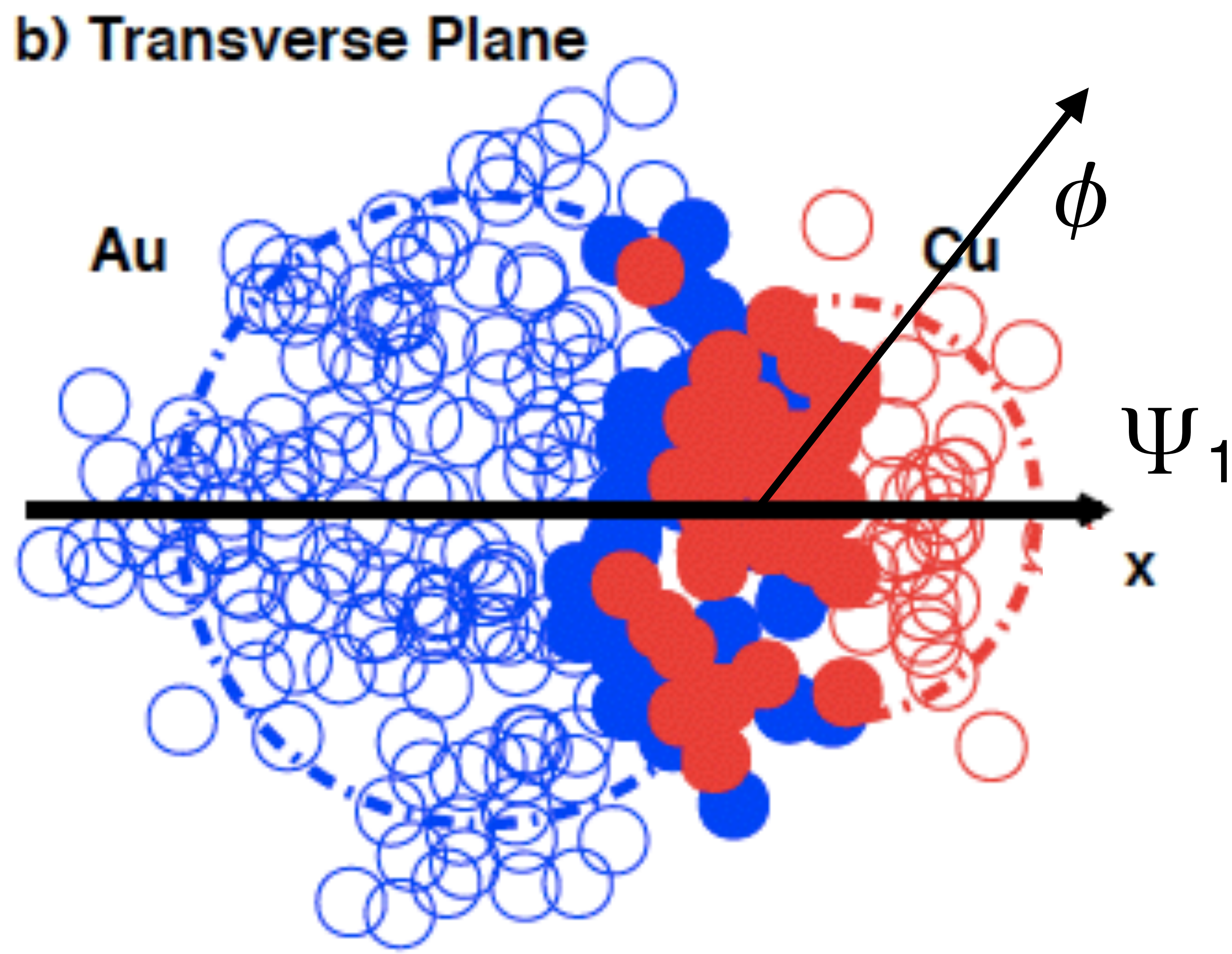
arxiv:1509.07784



Empirical $\varepsilon_3 N_{part}^{(1/3)}$ scaling is performed
-v_3 is scaled with $\varepsilon_3 N_{part}^{(1/3)}$
-$N_{part}^{(1/3)}$ is proportional to length scale
$\varepsilon_3 N_{part}^{(1/3)}$ scaling works well in v_3!

v_1 measurement

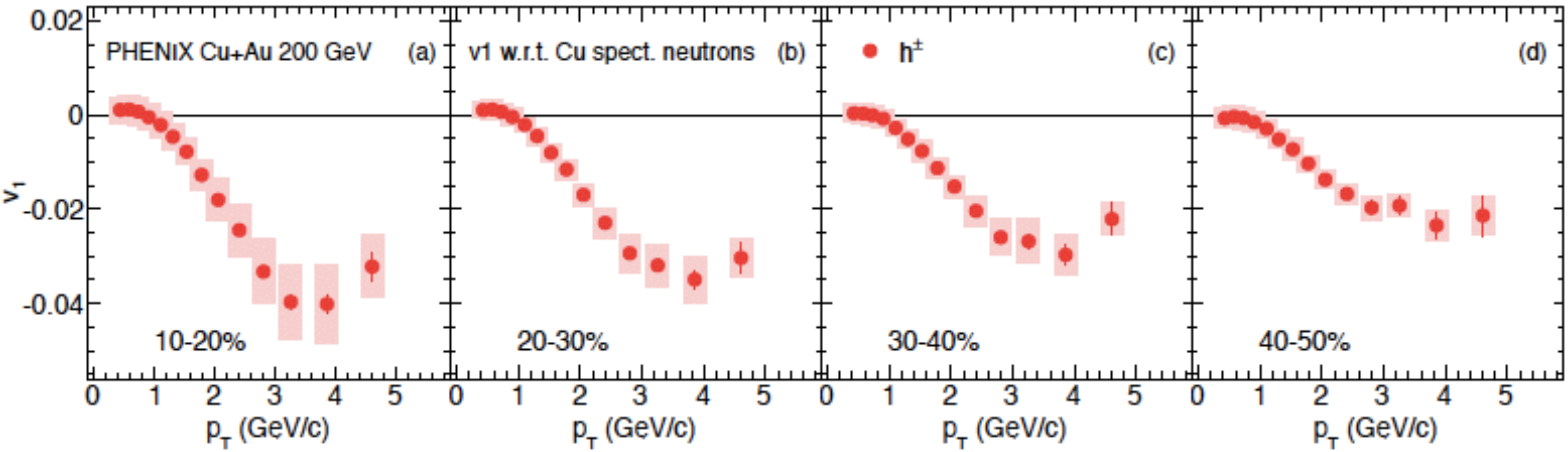
$v_1 = \langle\cos(\varphi-\Psi_1)\rangle$



The direction of Ψ_1 is defined in Cu side spectator
->v_1>0 : more particle are emitted to Cu
->v_1<0 : more particle are emitted to Au
-Measurement of v_1 w.r.t Ψ_1 using Au spectator and flipping its sign

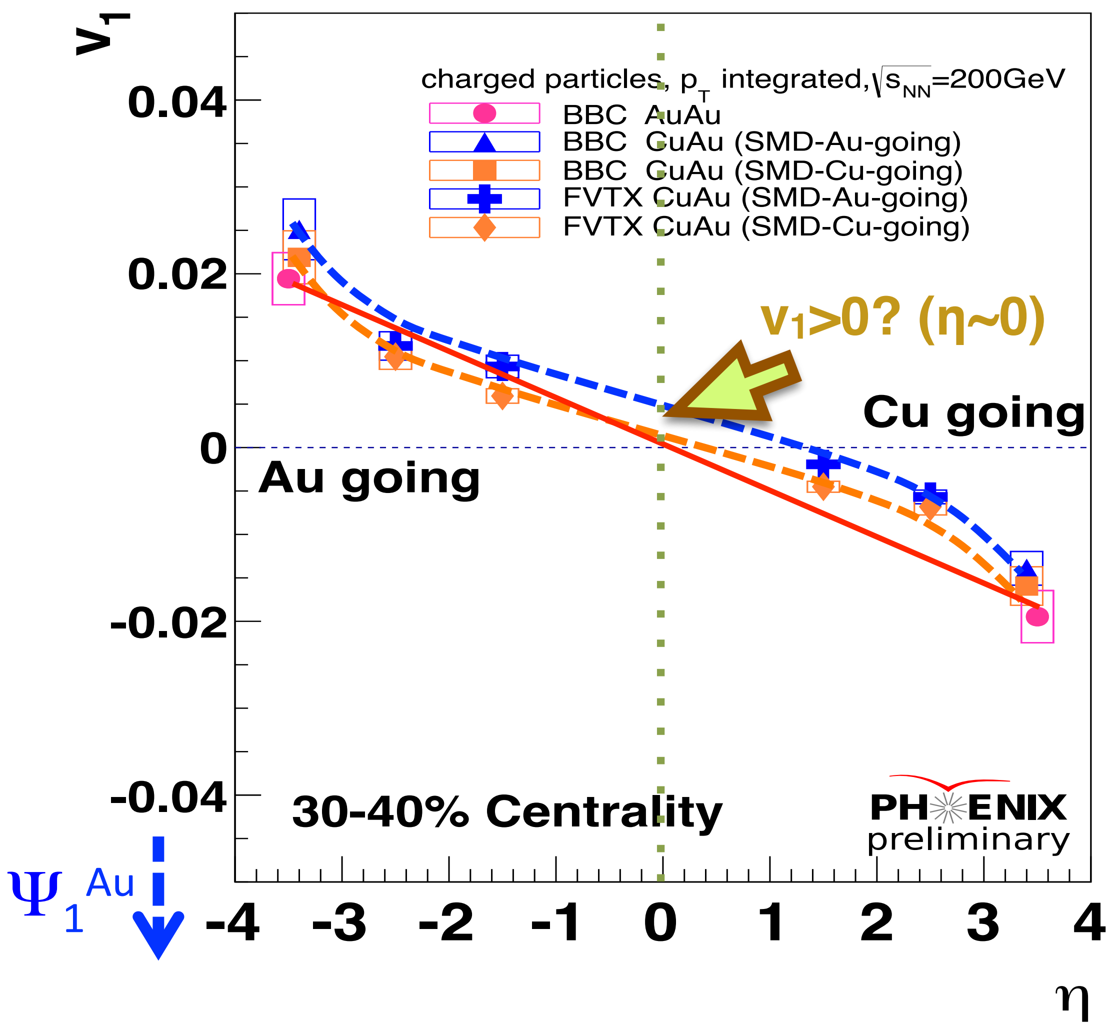
Charged hadron v1

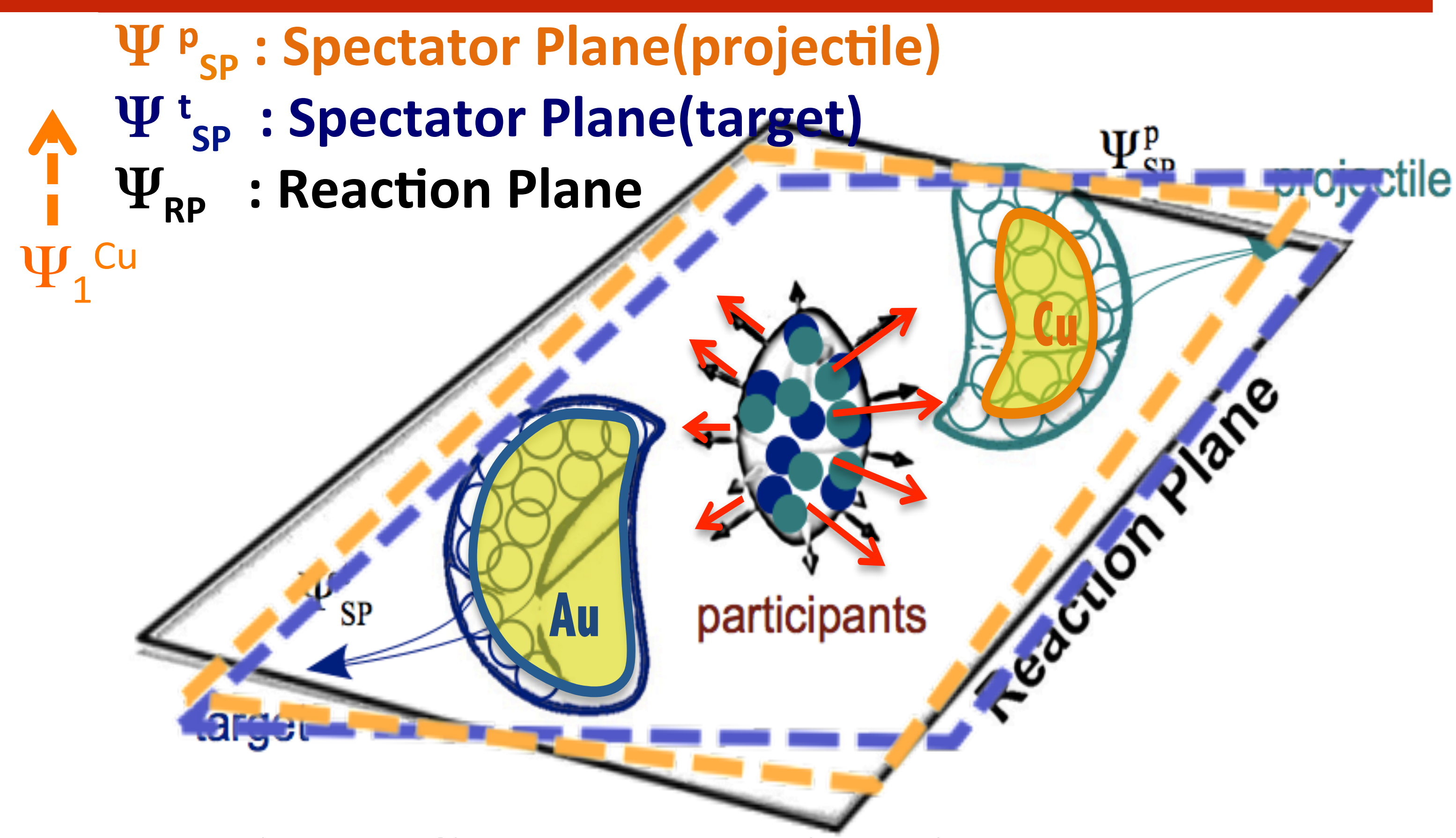
arxiv:1509.07784



Sizable v1 at mid-rapidity is observed for 10-50%
High pt particle are emitted to Au side
-Magnitude decreases from central to more peripheral events
-In peripheral events, Left/Right path length becomes similar

Rapidity dependence of v_1





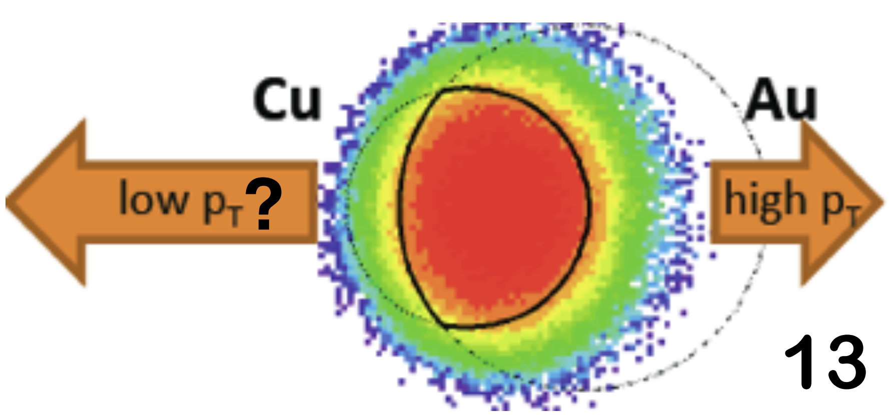
E-by-E fluctuation lead to
"ΨS.P ≠ ΨS.P" -> "v_1(ΨS.P) ≠ v_1(ΨS.P)"
-> v_1 = v_1(Traditional=η symmetric)
+ v_1(fluctuation)

The difference of v_1 is seen between two spectator planes.

- Same difference as seen in ALICE
- Fluctuation ?

Traditional v_1 in CuAu is positive at mid-rapidty ?

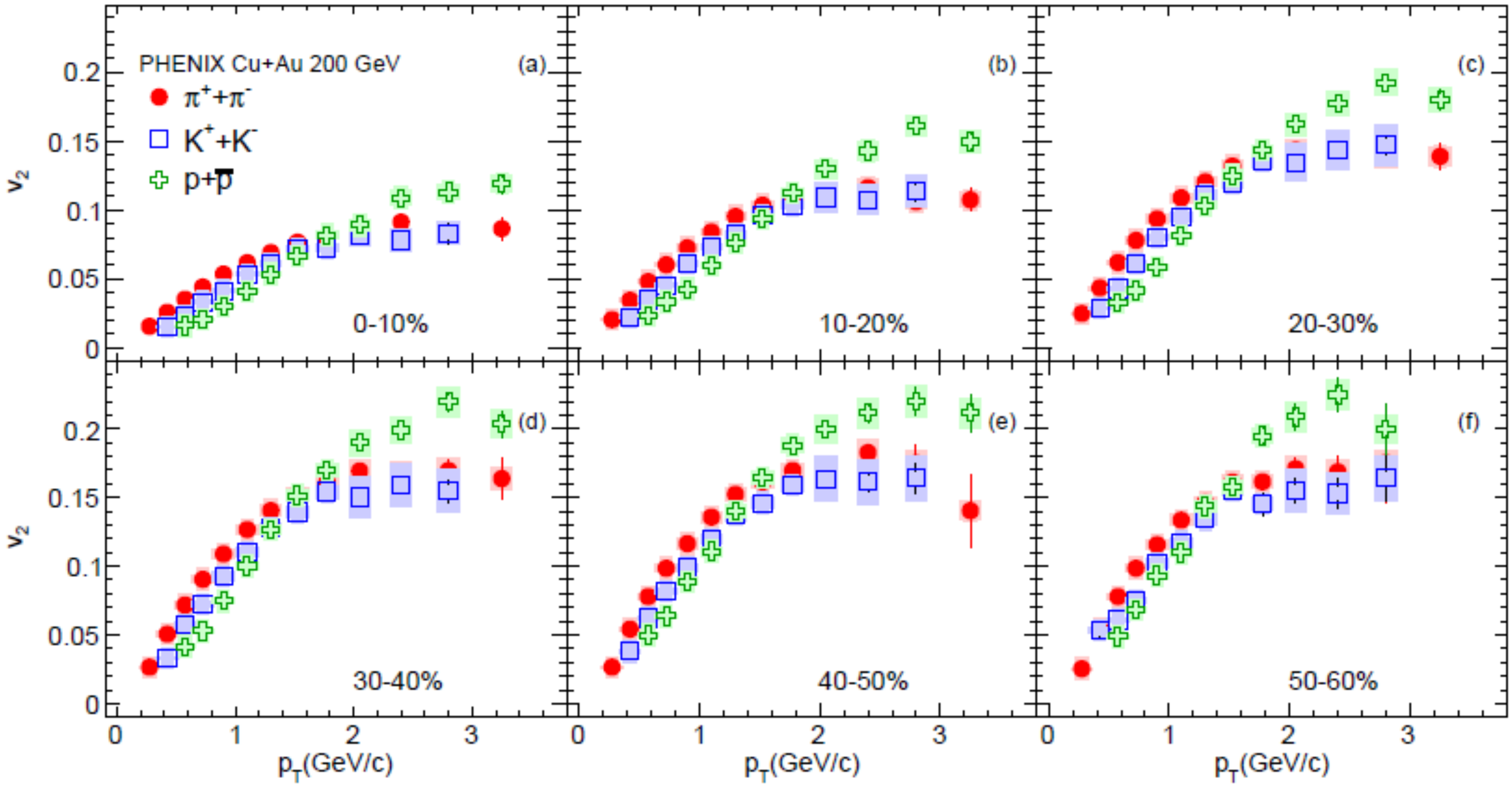
- more low p_T particle emitted to Cu side ?



Identified hadron vn

Identified particle v_2 in CuAu

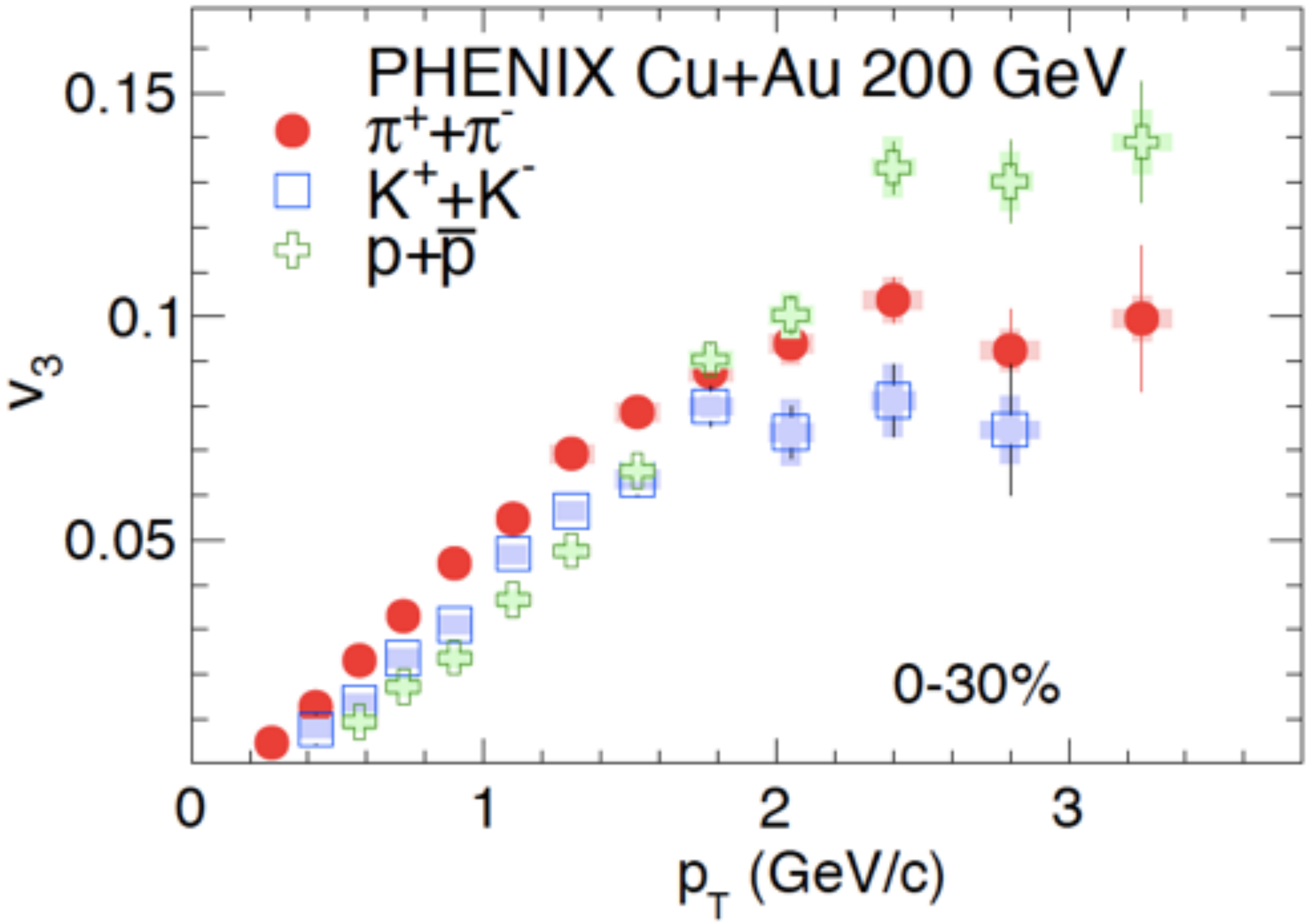
arxiv:1509.07784

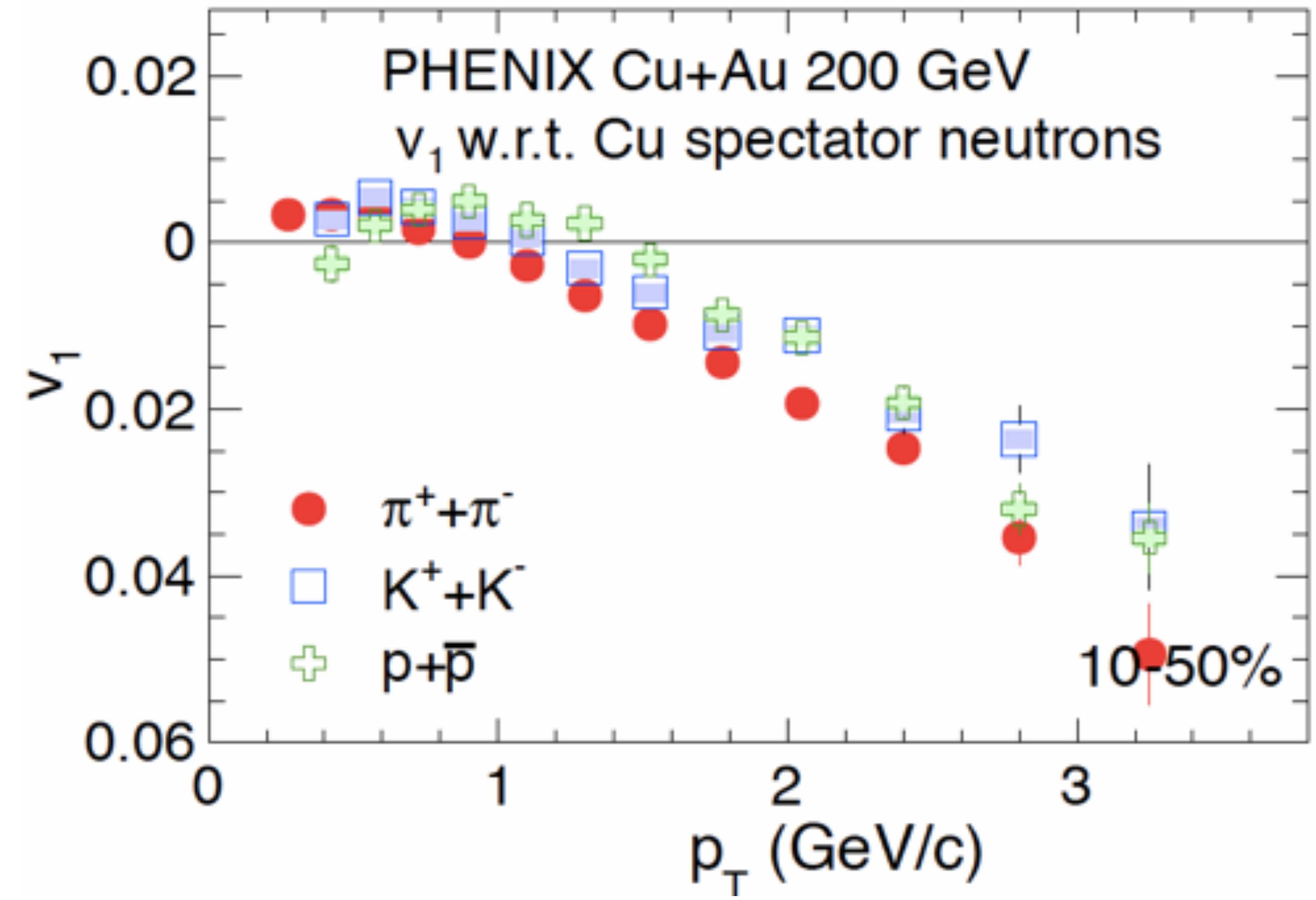


Mass ordering at low p_T for v_2 for all centralities
Baryon and meson splitting at mid-p_T is seen

Identified particle v_3, v_1 in CuAu

arxiv:1509.07784





PID v_3

-Same particle dependence of v_3 is seen as seen in v_2

PID v_1

-At low pt , mass ordering is not observed.

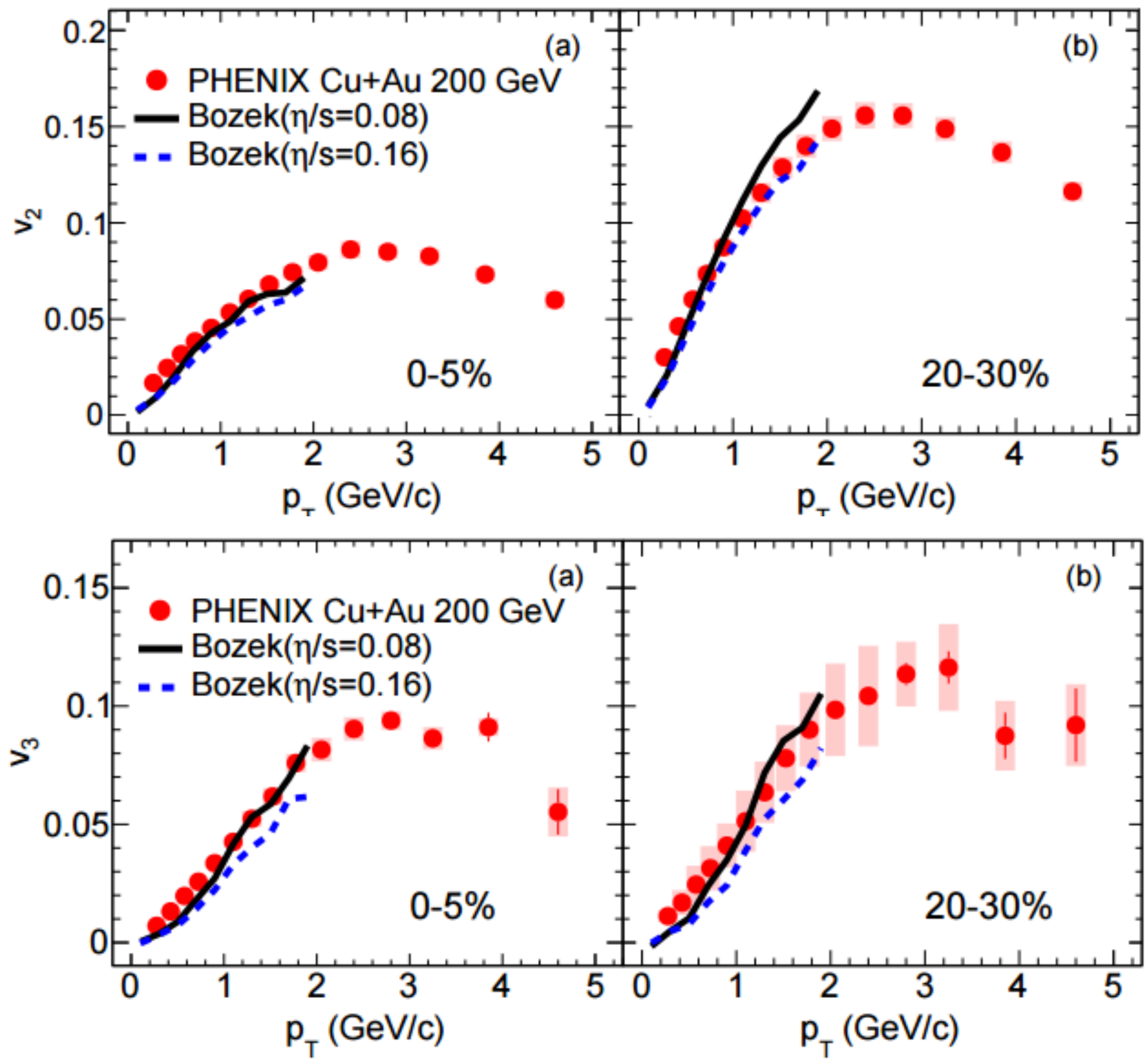
-Mass ordering is seen for v_1 at $1 < pT < 2.5$GeV

-At high pt, baryon and meson splitting is not observed

Comparison to theory

-Event-by-Event Hydro

MC-Glauber E-by-E hydro v_2, v_3

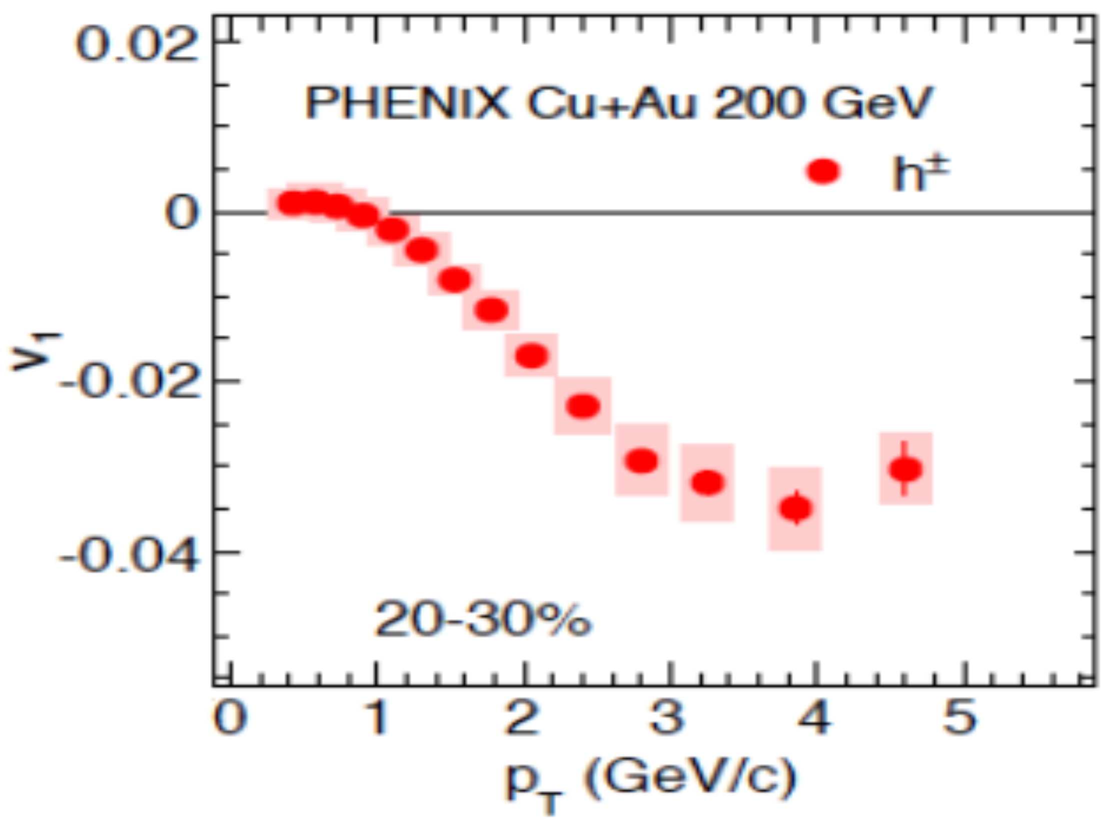


arxiv:1509.07784

For both centrality, both values of η/s agree with data

MC-Glauber E-by-E hydro v1(pt)

arxiv:1509.07784



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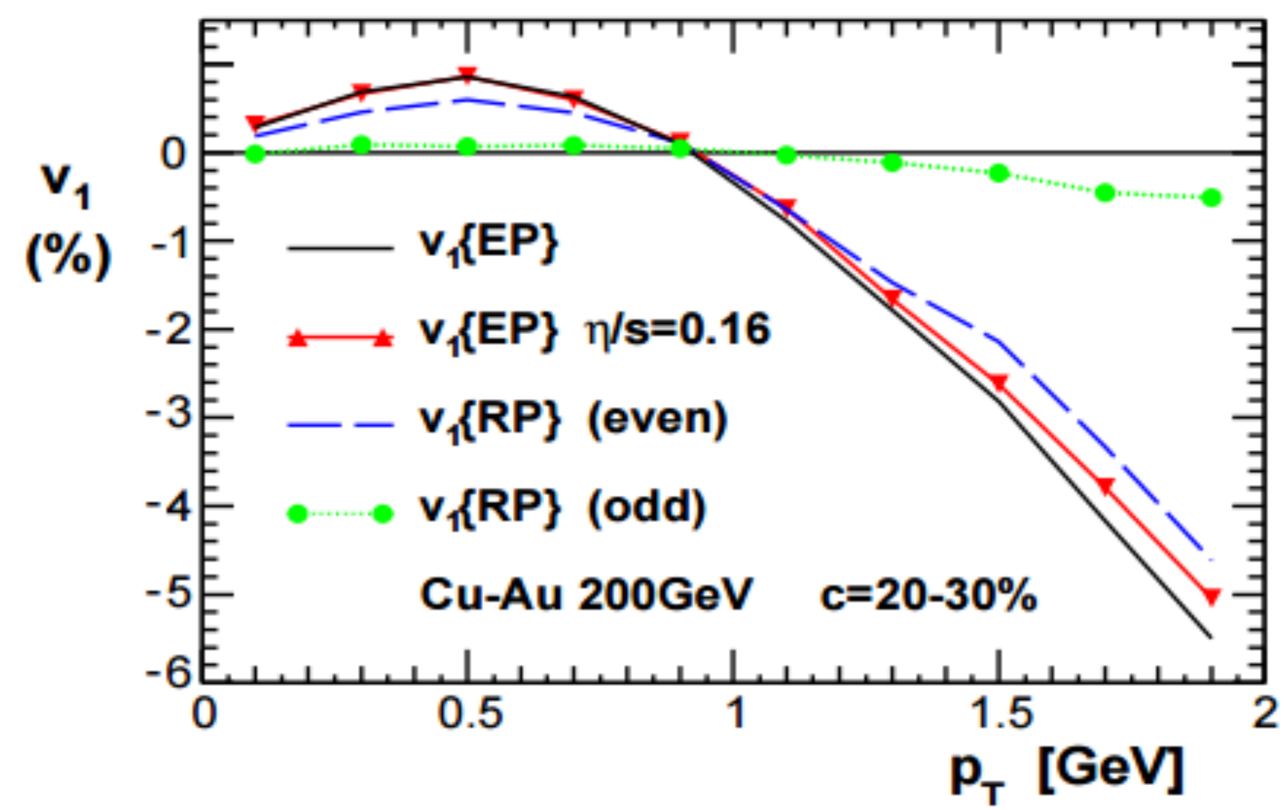


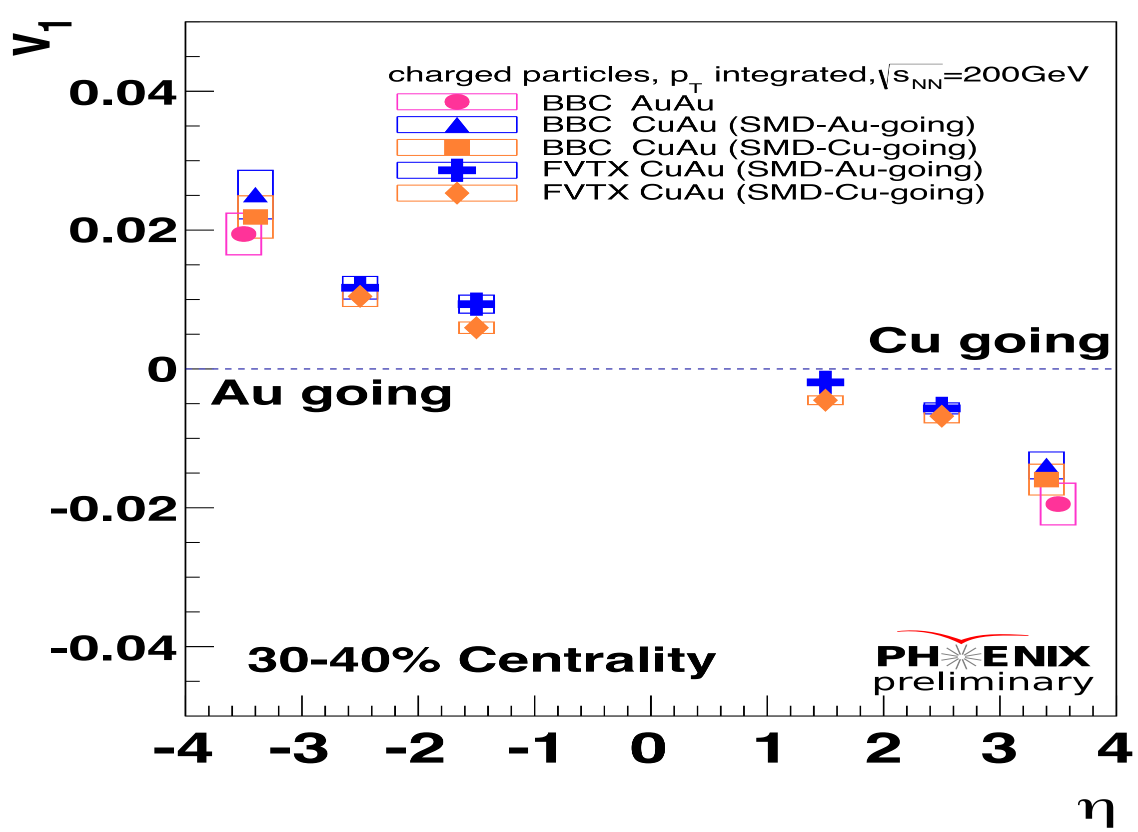
In hydro calculation,

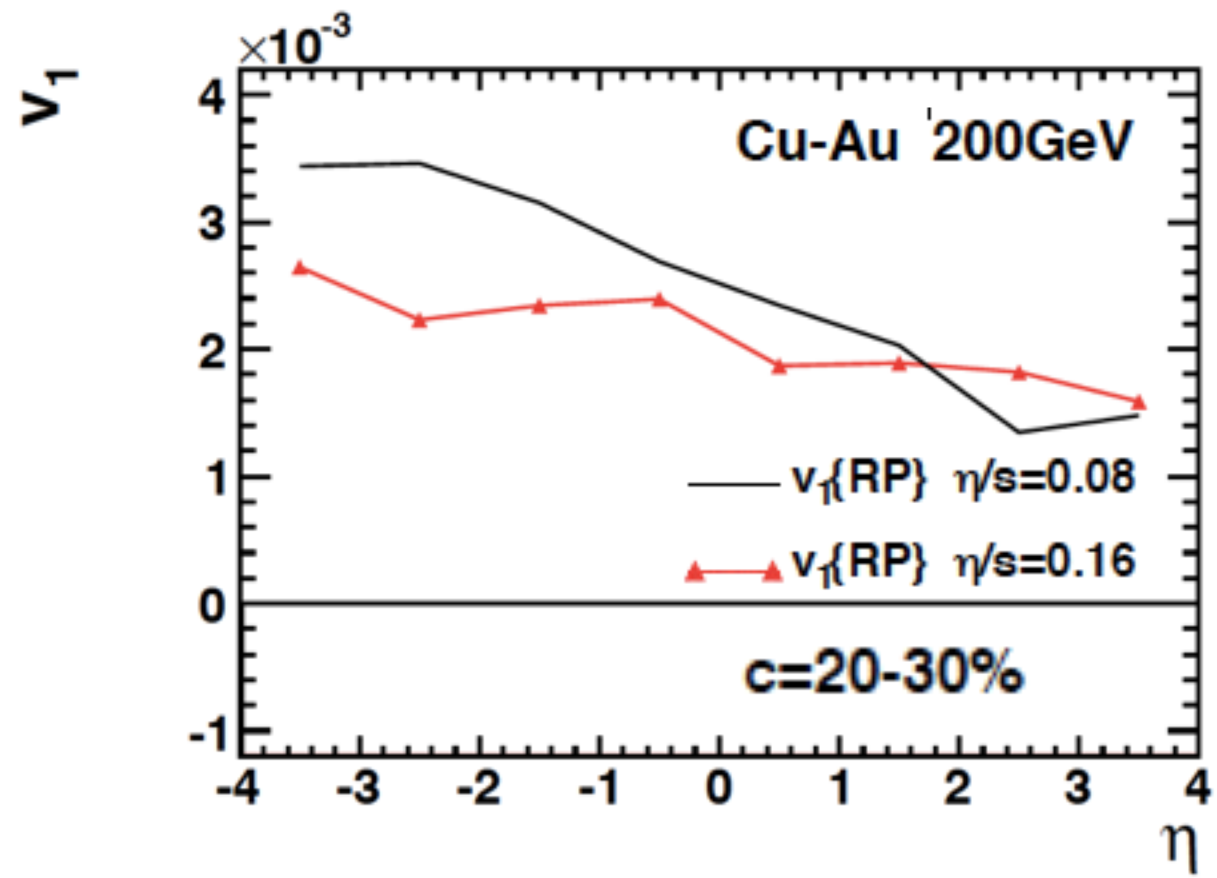
-More low pT , particles are emitted to Cu side

-More high pT, particles are emitted to Au side

Theory calculation shows qualitative agreement.

MC-Glauber E-by-E hydro v1(eta)





Comparison to theory for different centrality class

Hydro calculation doesn't show a sign change of v1

-In |eta|<4, sign of v1 is not changed

Magnitude of theory calculation is much smaller than those of experimental data

Summary

Charged Hadron v_n
- v_2, v_3 show same p_T and centrality dependence as seen symmetric collisions
- Sizable v_1 is measured at mid-rapidity
- Fluctuation v_1 is observed at RHIC

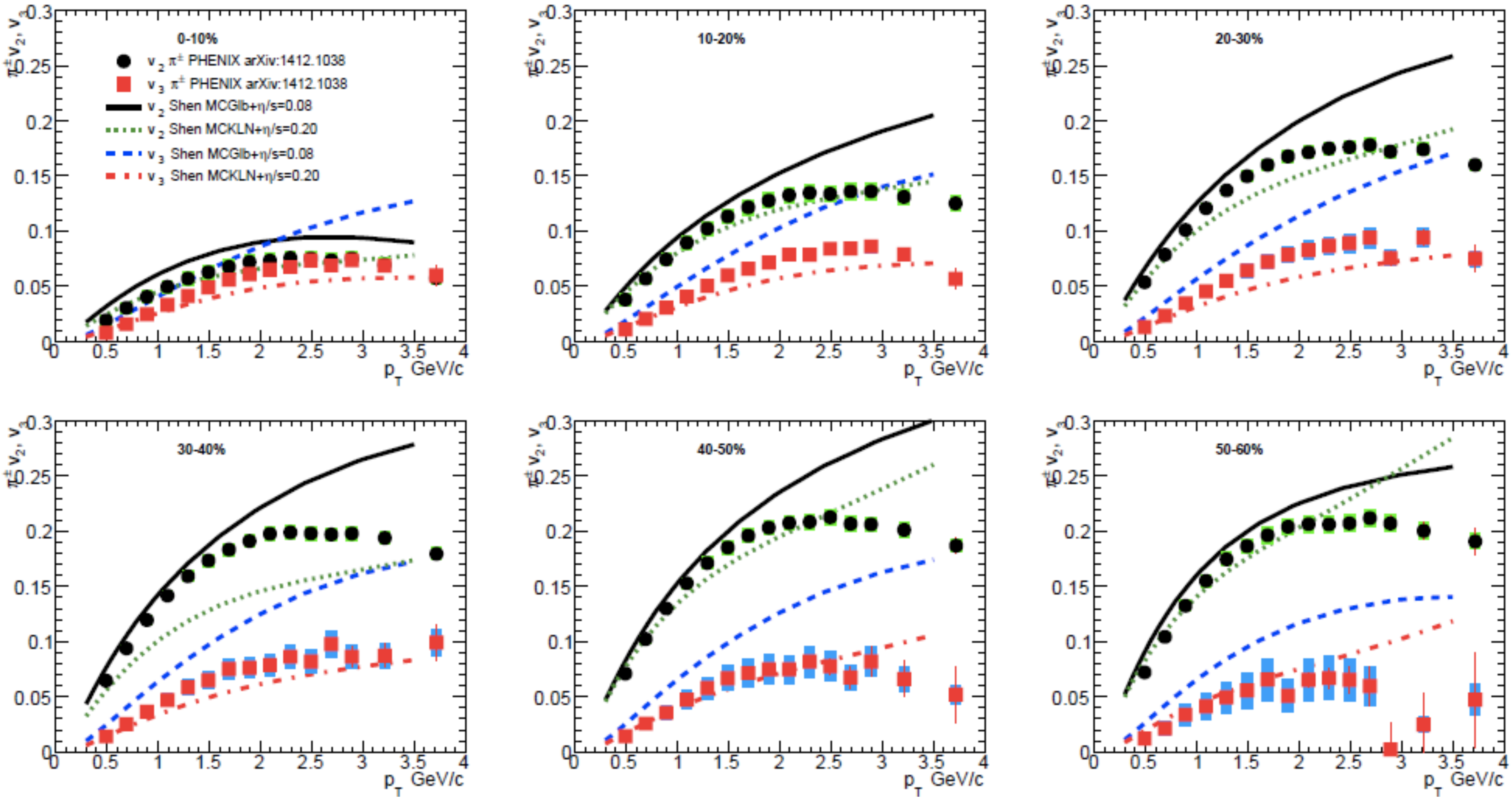
System size dependence of v_2, v_3
- CuAu v_2, v_3 are scaled with $\varepsilon_n N_{part}^{(1/3)}$

Identified Hadron v_n
- Mass ordering and Baryon and Meson splitting are seen in v_2, v_3
- In mid-p_T, Mass ordering is seen in v_1, Not observe Baryon and Meson splitting in v_1

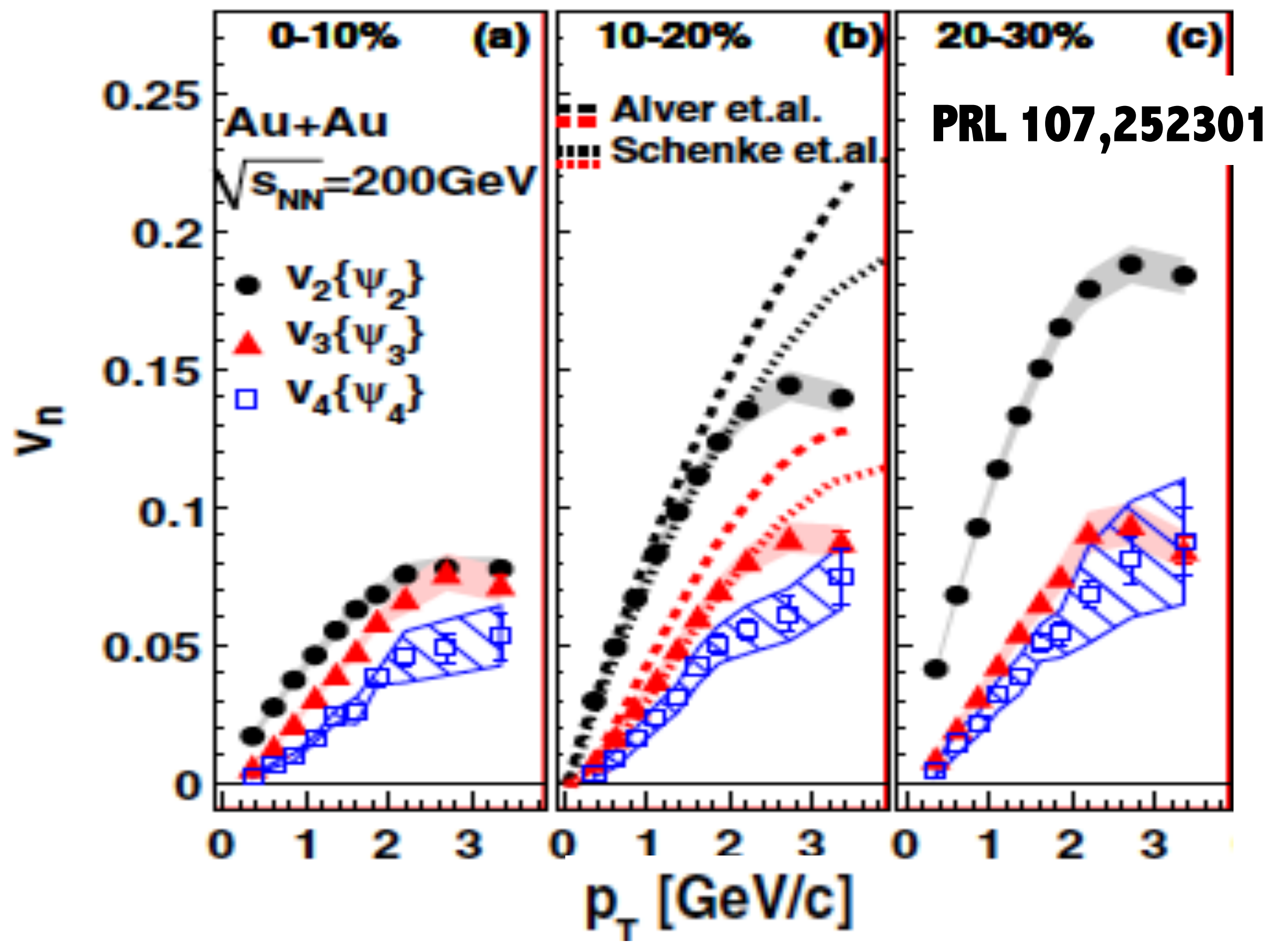
E-by-E hydro comparison
- reproduces pt dependence of v_2, v_3
- qualitatively reproduces pt dependence of v_1, but fails to explain η dependence of v_1

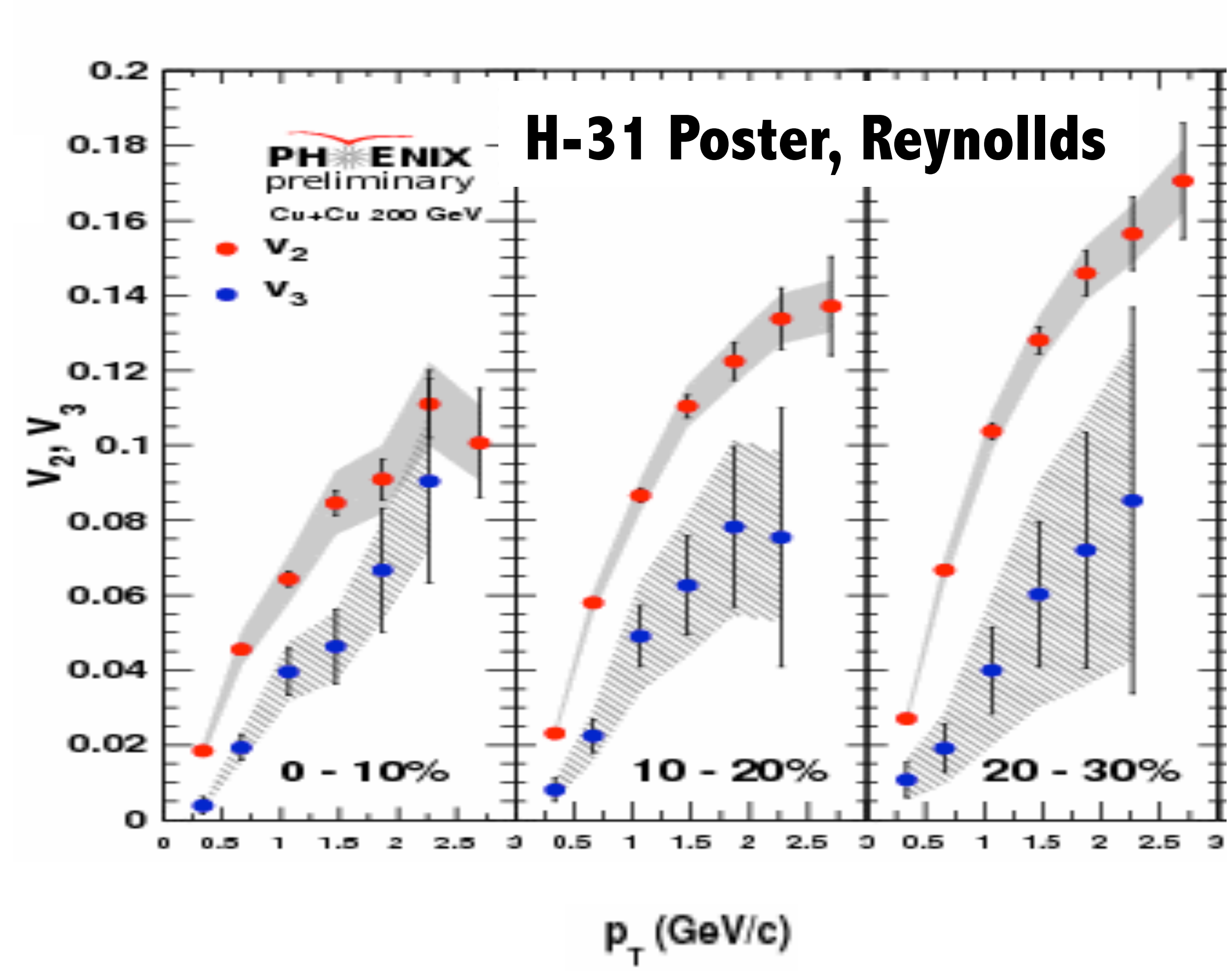
Back Up

Charged pion v2, v3 in AuAu

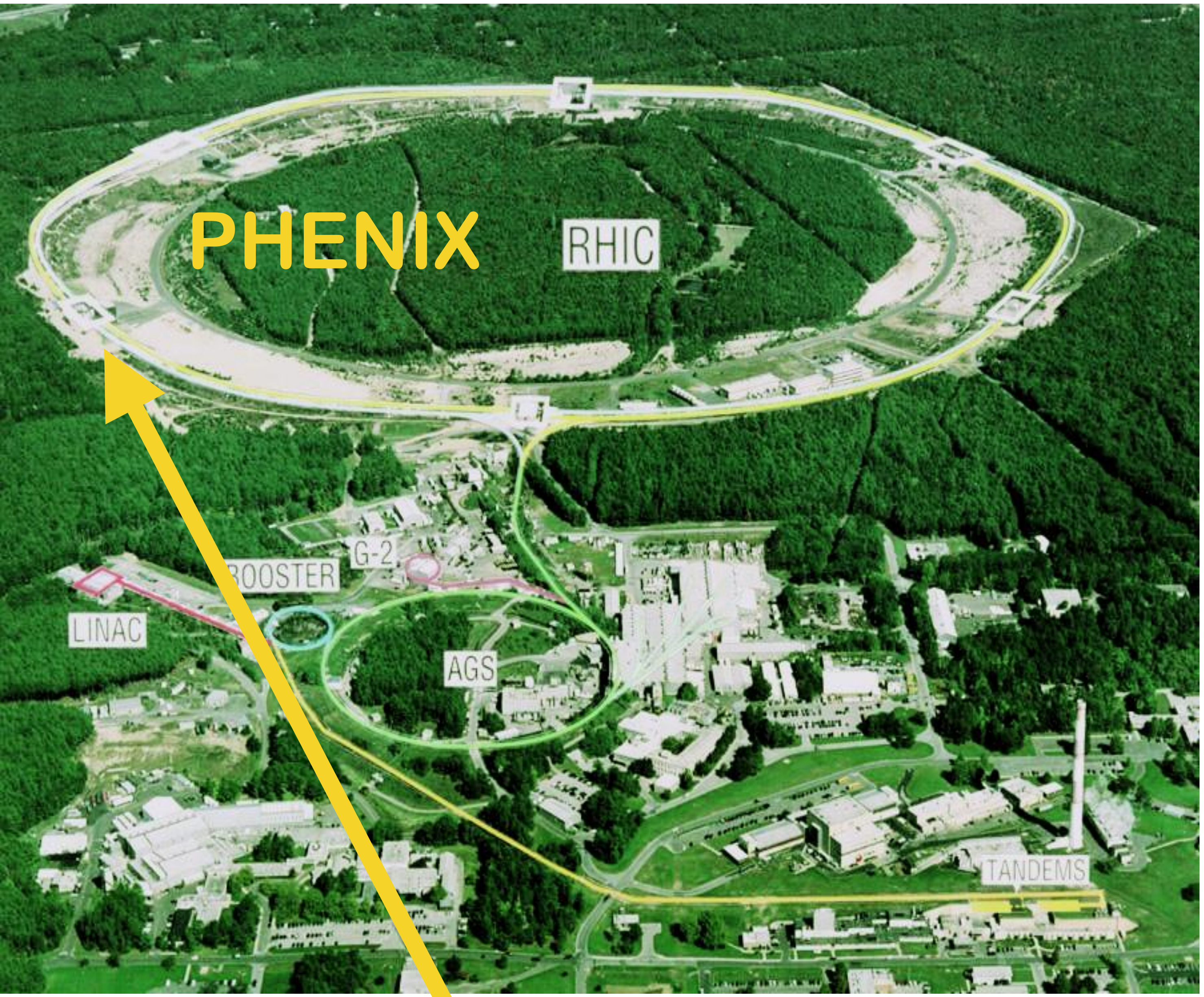


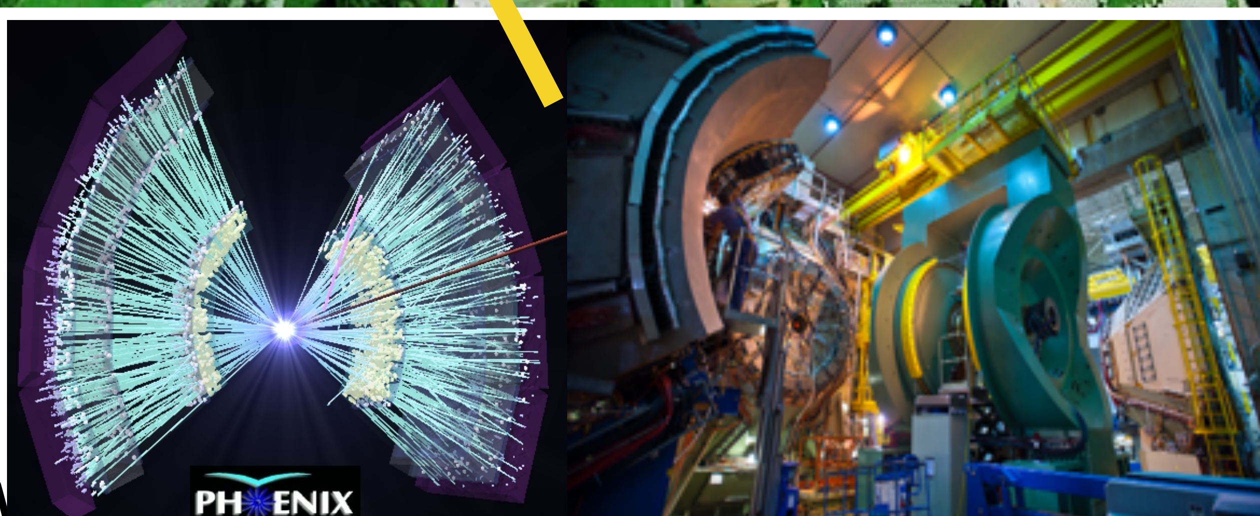
Flow in symmetric collisions system





Relative Heavy Ion Collider(RHIC)

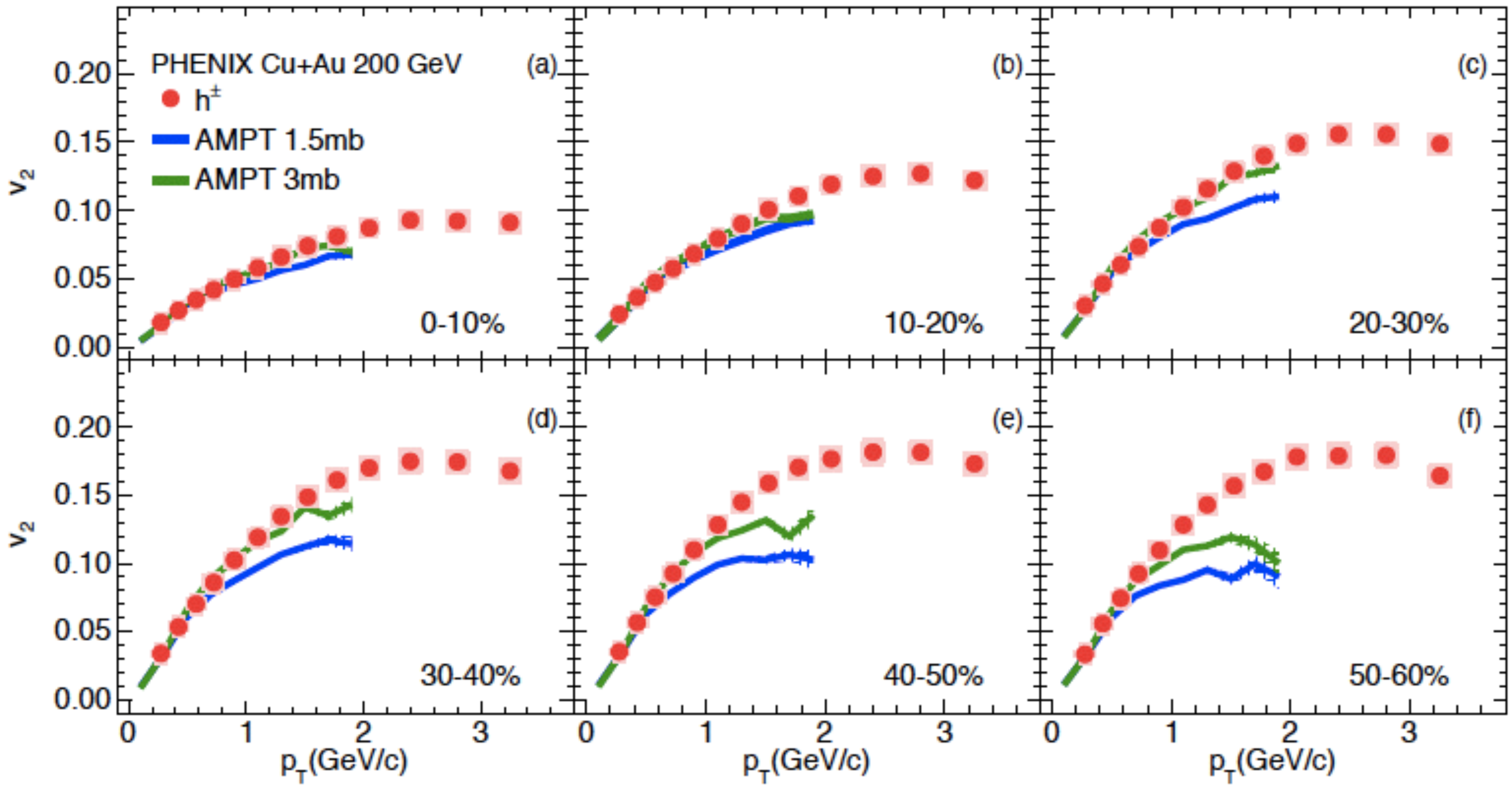




Species	Energies
Au+Au	200, 130, 62.4GeV 39, 27, 22.4GeV 19.6 14.6, 7.7GeV
Cu+Cu	200, 62.4, 22.4GeV
U+U	193GeV
Cu+Au	200GeV
3He+Au	200GeV
d+Au	200GeV
p+Au	200GeV
p+Al	200GeV
p+p	510, 500, 200GeV 62.4GeV

Comparison to AMPT v2

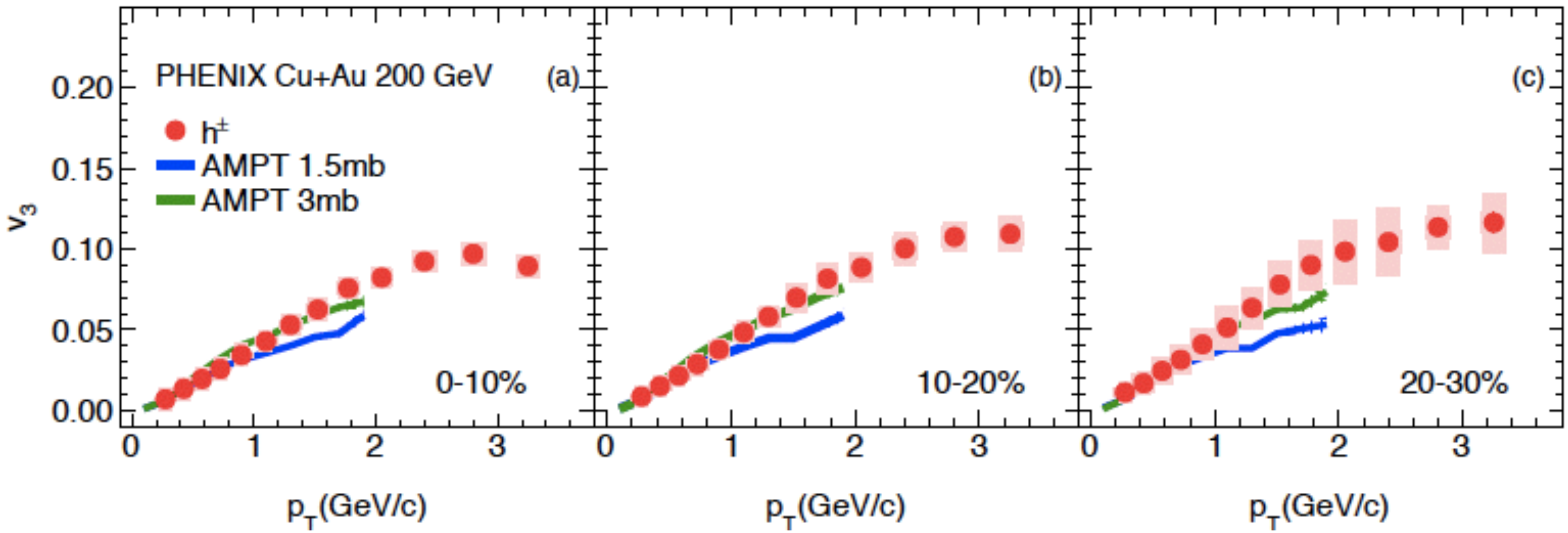
arxiv:1509.07784



AMPT with 3mb reproduce v2
-In 0-30%, up to 2GeV
-In 30-60%, up to 1GeV

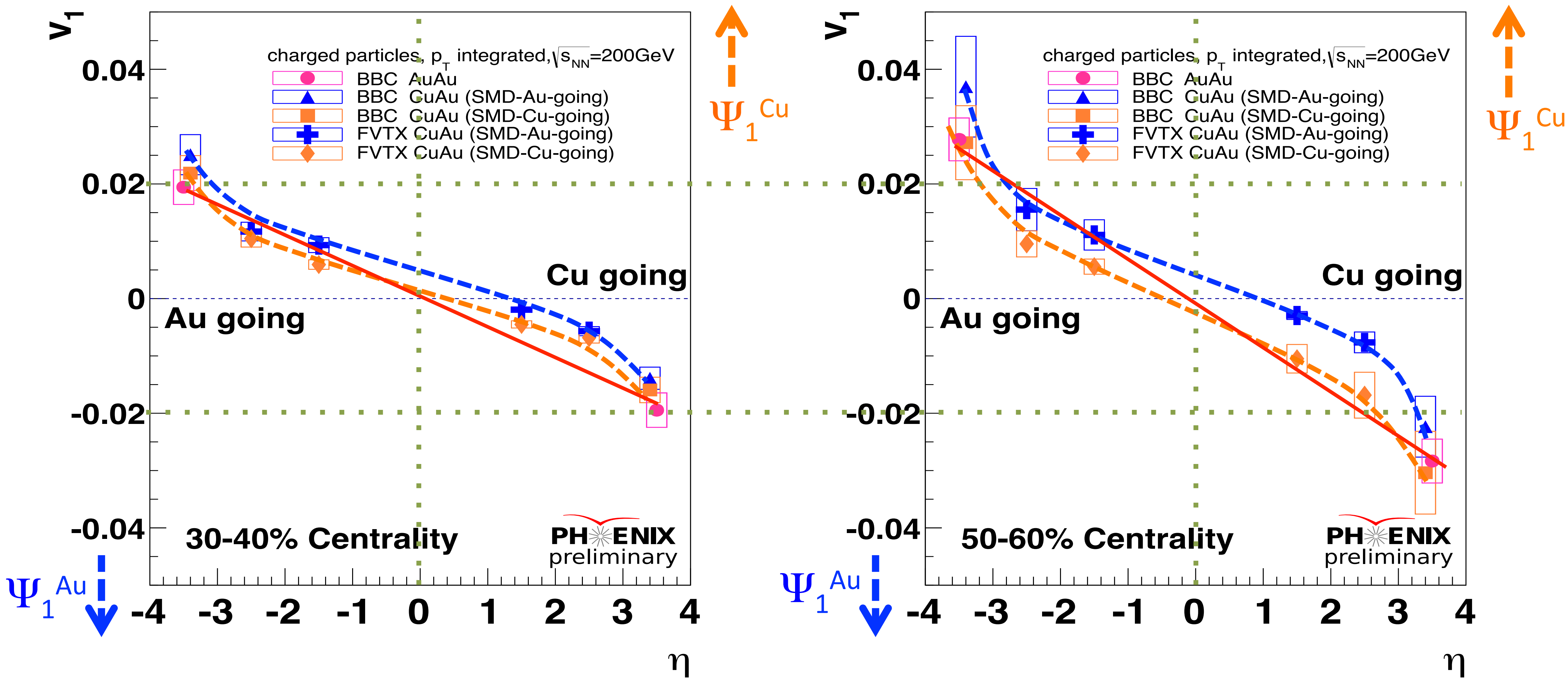
Comparison to AMPT v3

arxiv:1509.07784

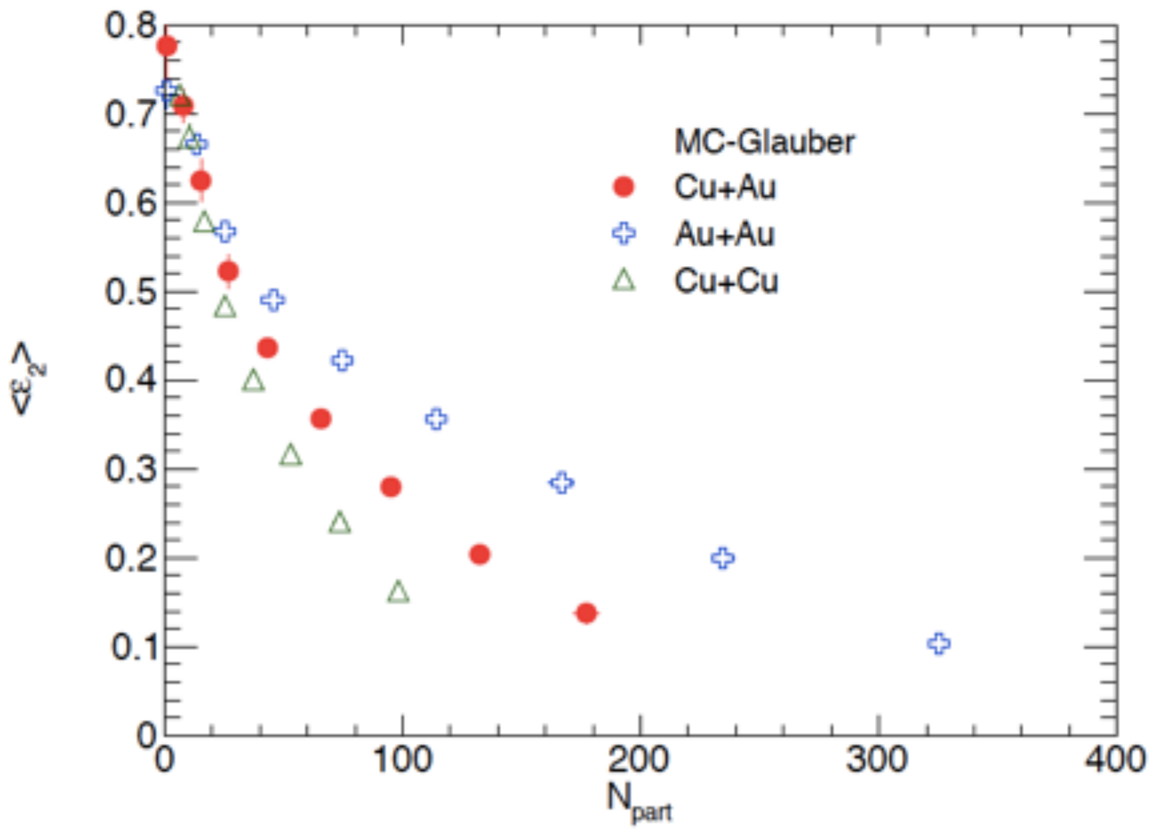


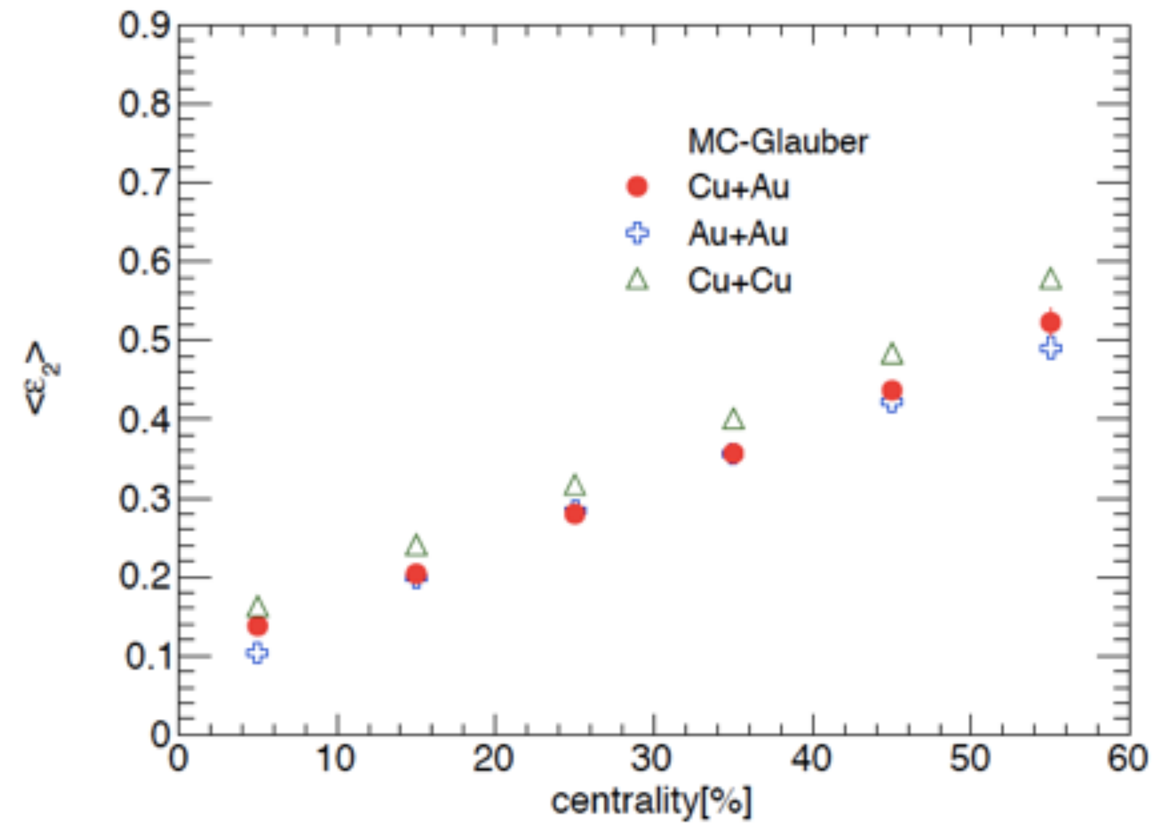
AMPT with 3mb reproduce v3
-In 0-30%, up to 2GeV

Rapidity dependence of v_1

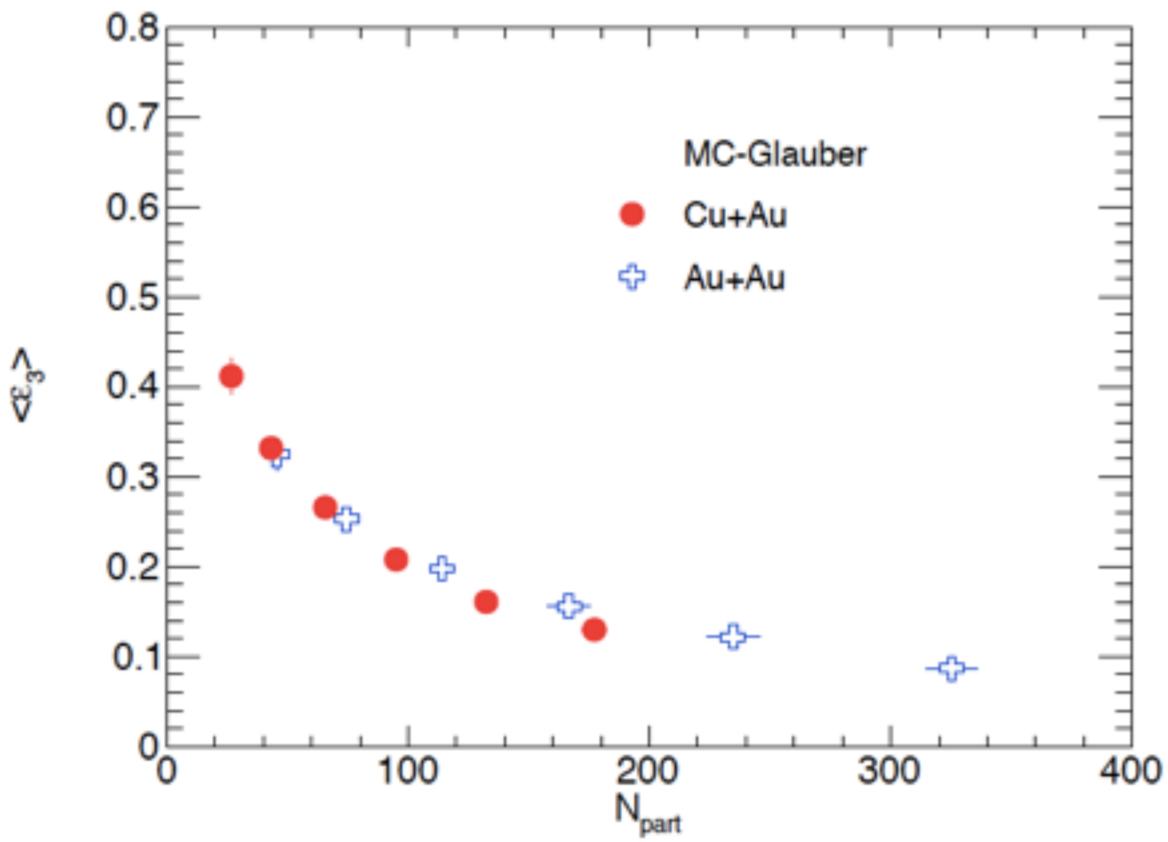


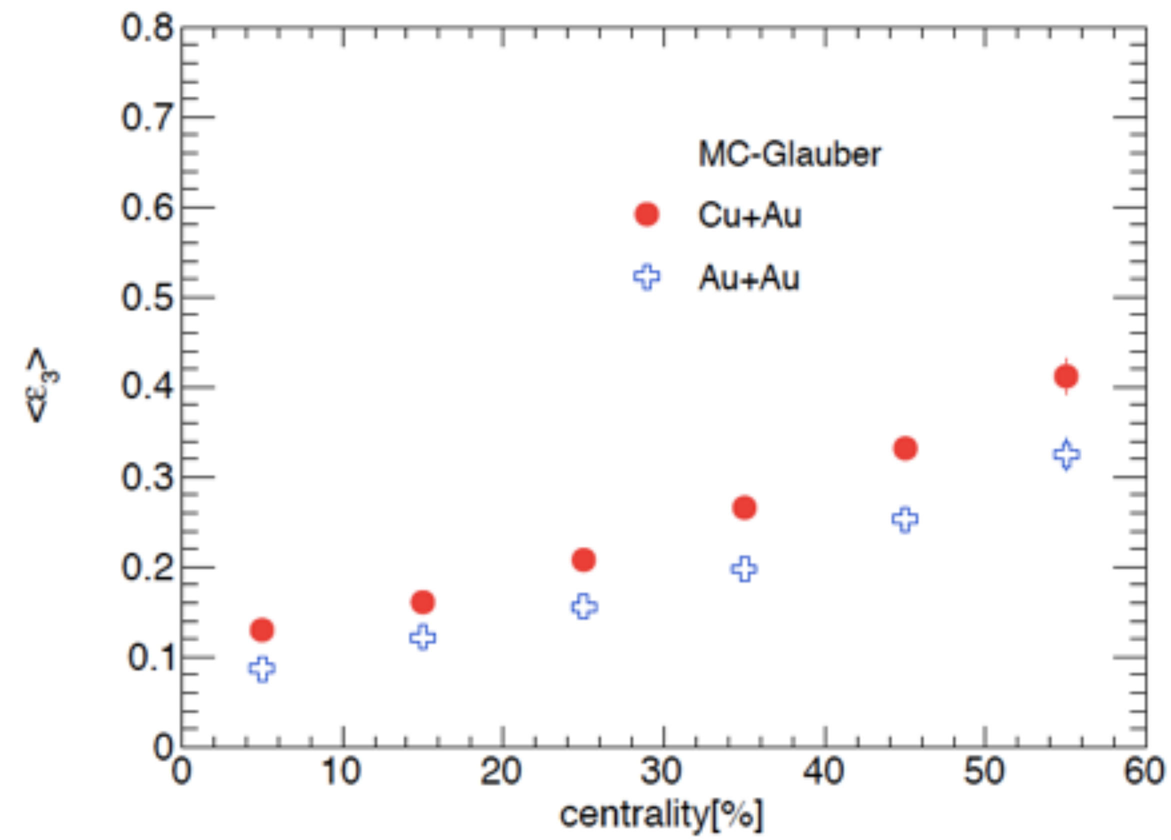
$<\varepsilon_2>$



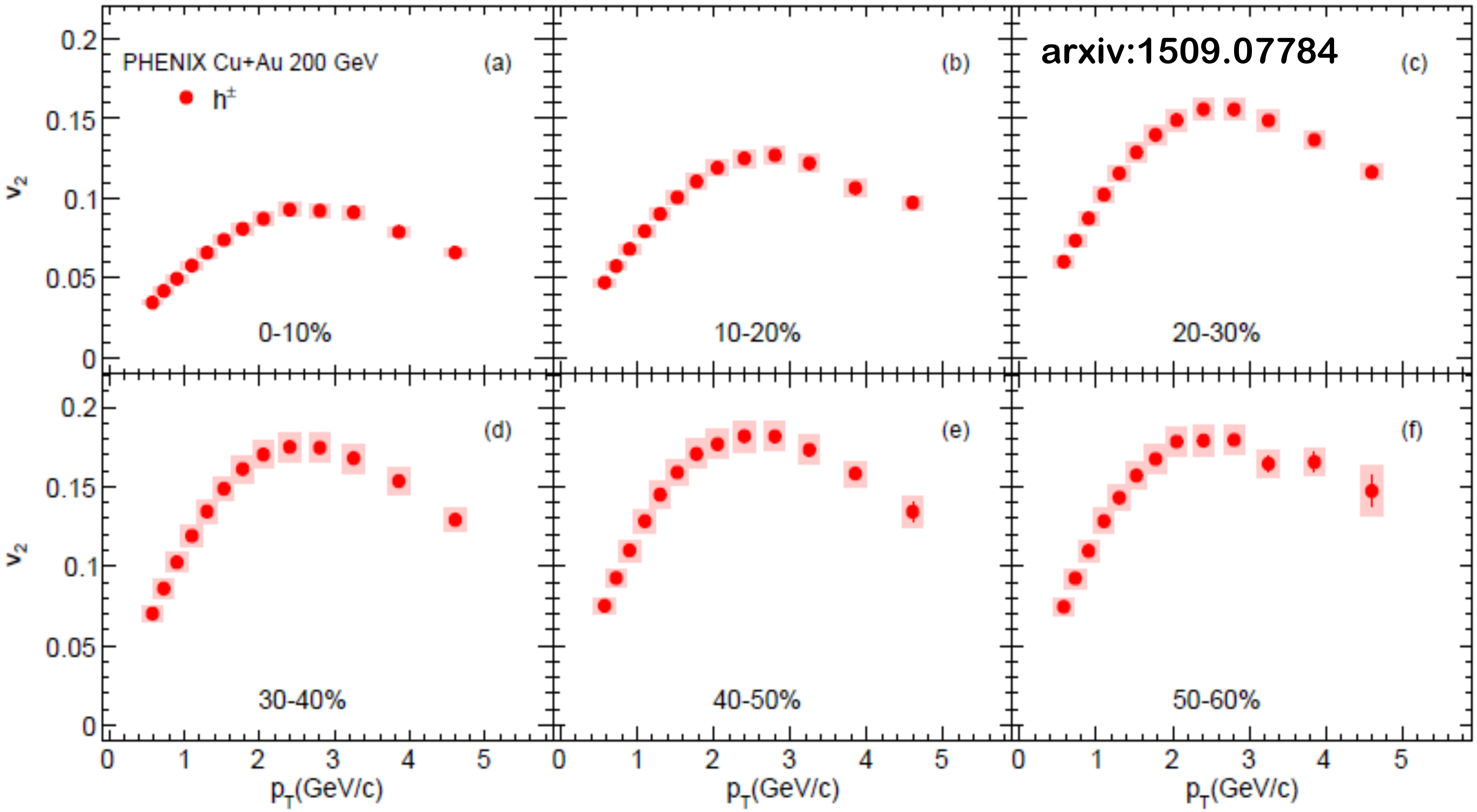


$\langle \varepsilon_3 \rangle$





Charged hadron v_2

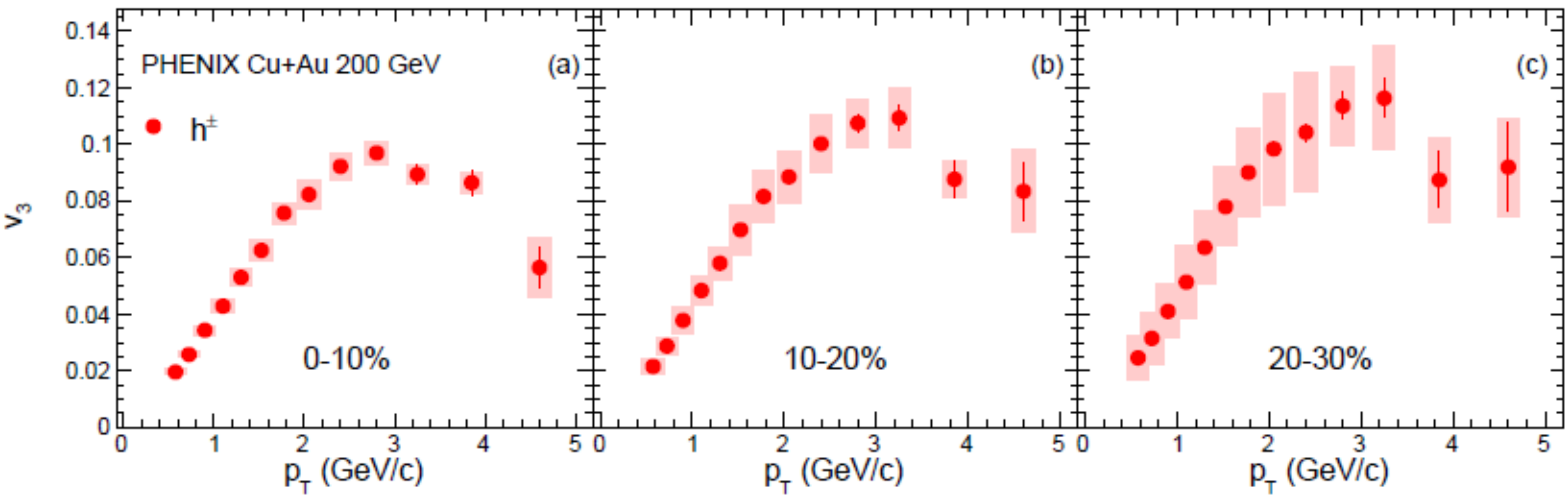


Similar p_T and centrality dependence of v_2 as seen in symmetric collisions

- **Strong centrality dependence, magnitude increase from central to peripheral**

Charged hadron v3

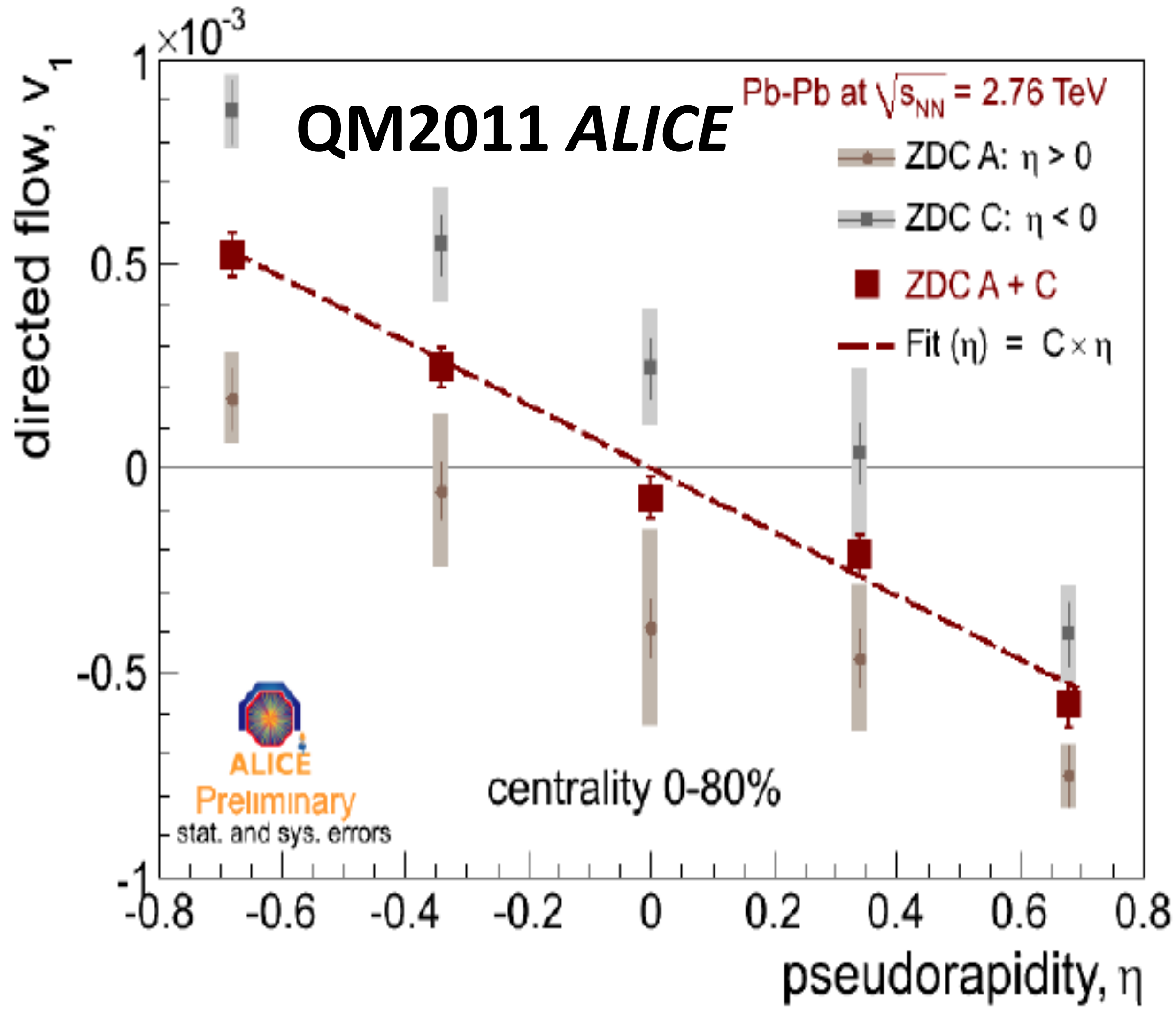
arxiv:1509.07784



Similar pT and centrality dependence of v3 as seen in symmetric collisions

- Weak centrality dependence, magnitude slightly increase from central to peripheral

v_1 Even, Odd Components in PbPb



✓ v_1(even + odd) = v_1(even) + v_1(odd) is observed in PbPb 2.75[TeV]

- v(even): v1(η) = v1(-η)
- v1(odd) : v1(η) = -v1(-η)
- The source of even component is expected from spectator fluctuation

$$v_1^{\rm odd}\{\Psi_{\rm SP}\} = \left[v_1\{\Psi_{\rm SP}^{\rm p}\} + v_1\{\Psi_{\rm SP}^{\rm t}\}\right]/2$$

$$v_1^{\rm even}\{\Psi_{\rm SP}\} = \left[v_1\{\Psi_{\rm SP}^{\rm p}\} - v_1\{\Psi_{\rm SP}^{\rm t}\}\right]/2.$$

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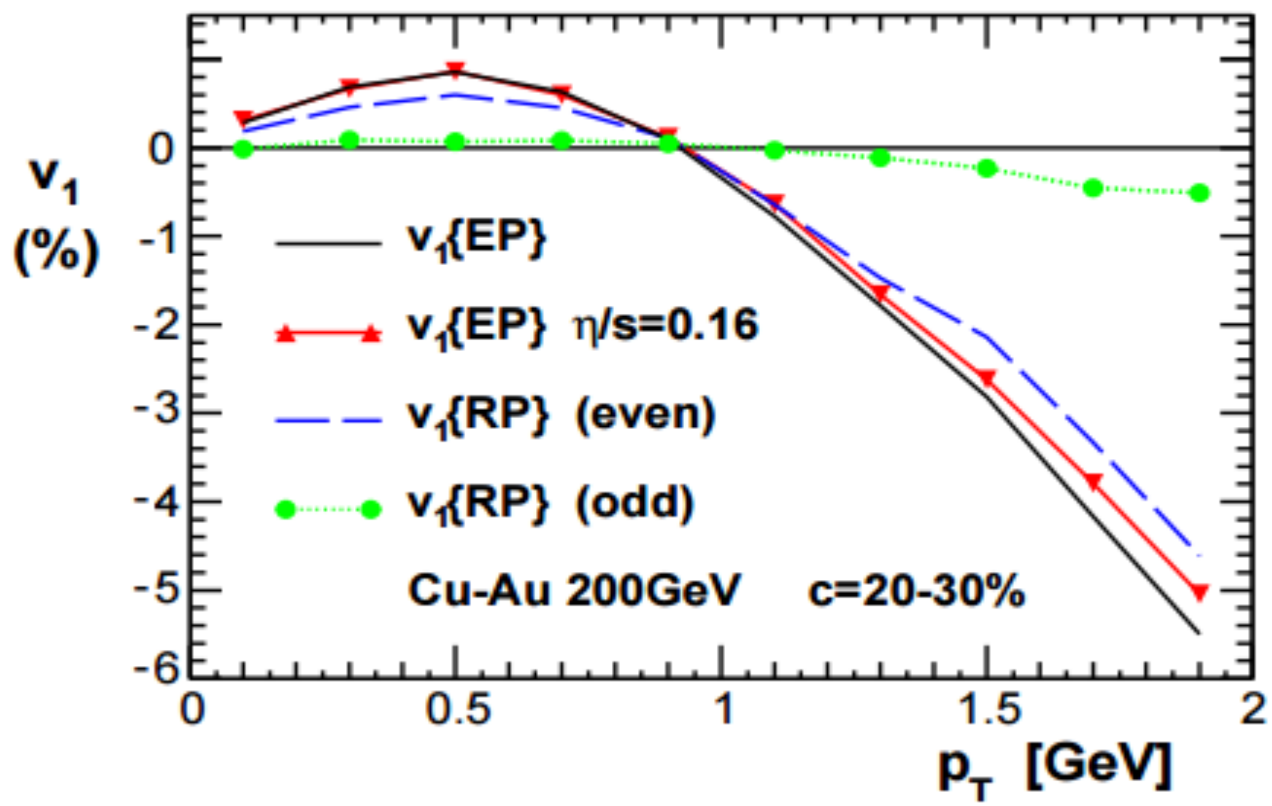
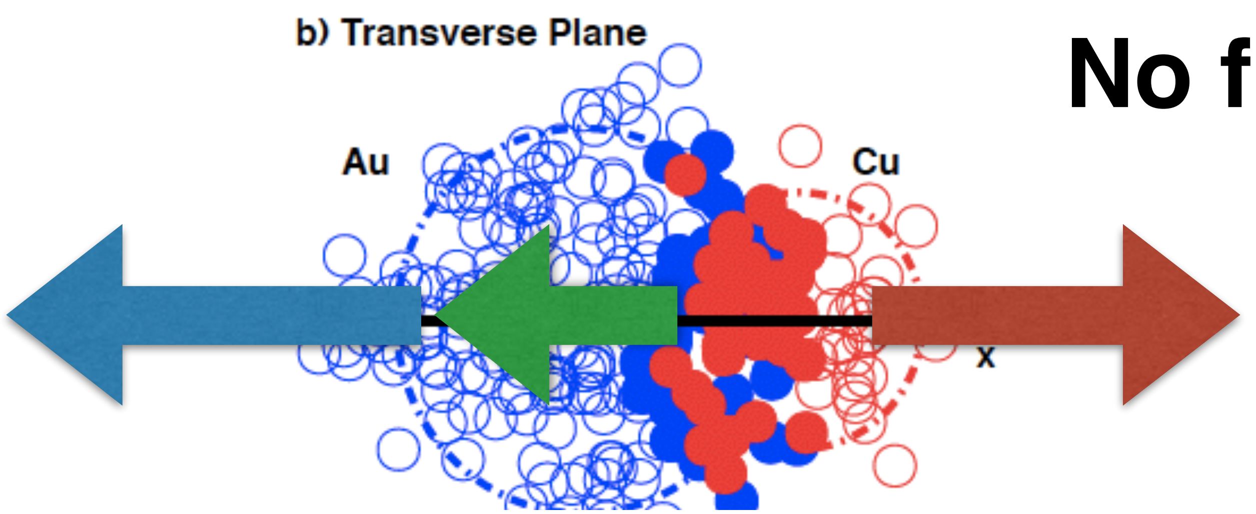


v1 even

$$v_1(p_\perp)\{RP\} = \langle \cos(\phi_i - \Psi_{RP}) \rangle$$

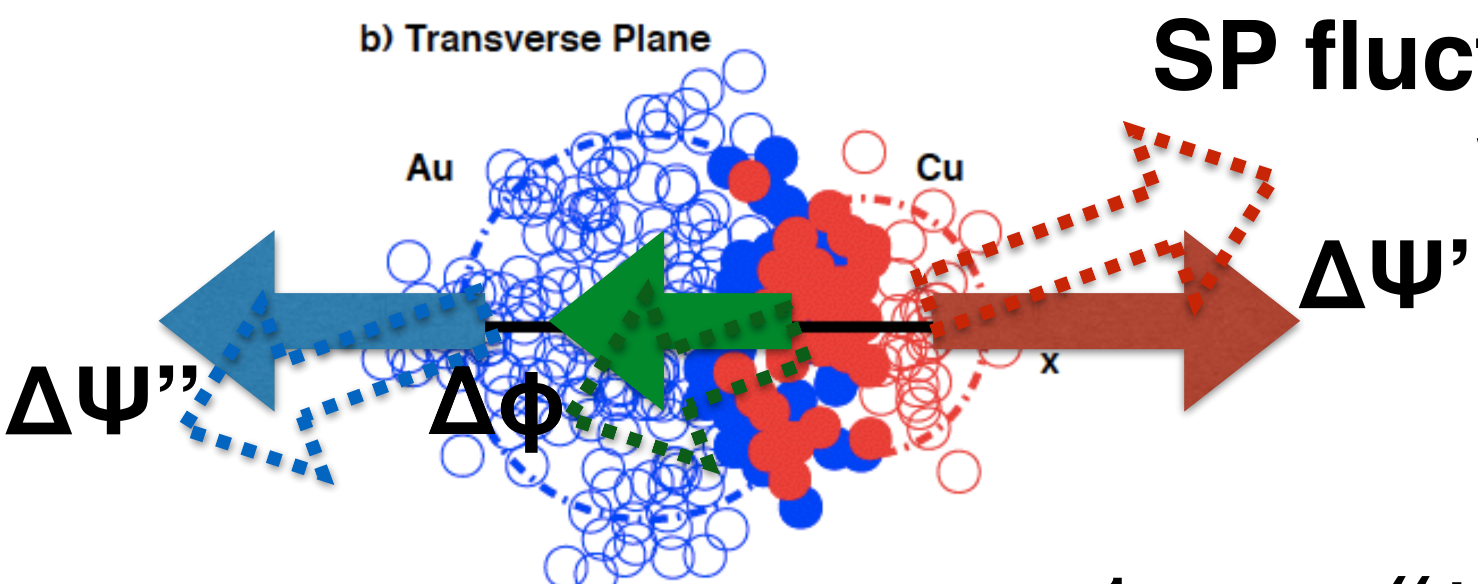
v1 odd

$$v_1(p_\perp)\{RP\}(odd) = \langle \mathrm{sgn}(\eta_{PS}) \cos(\phi_i - \Psi_{RP}) \rangle$$



No fluctuation

$$v1 = \langle \cos(\phi-\Psi) \rangle$$



SP fluctuation

Weakly spectator fluctuation and participant fluctuation are correlated

$$\begin{aligned} v1 &= \langle \cos((\phi+\Delta\phi)-(\Psi+\Delta\Psi)) \rangle \\ &= \langle \cos(\phi-\Psi) \rangle + \langle \cos(\Delta\phi-\Delta\Psi) \rangle \\ &= v1(\text{traditional}) + v1(\text{SP fluctuation}) \end{aligned}$$

$\Delta\phi \sim \Delta\Psi' \sim \Delta\Psi'$: v1(SP fluctuation) >0 or <0

$\Delta\phi \neq \Delta\Psi \neq \Delta\Psi'$: no correlation v1(SP fluctuation)=0