Study Of Identified Particle Higher Order Azimuthal Anisotropy At RHIC-PHENIX Experiment

RHIC-PHENIX実験における 高次方位角異方性の粒子依存性測定

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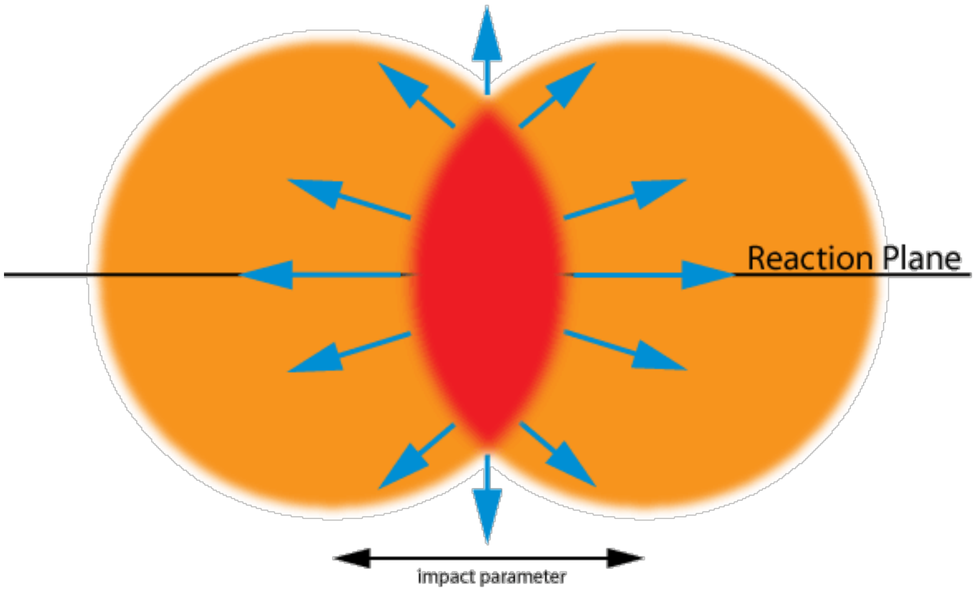
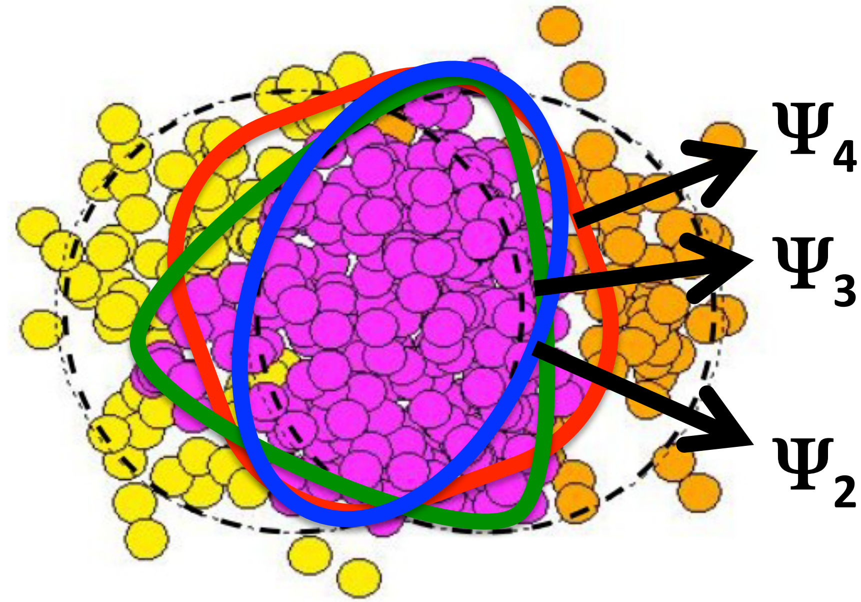
29a-HA-12

Azimuthal anisotropy





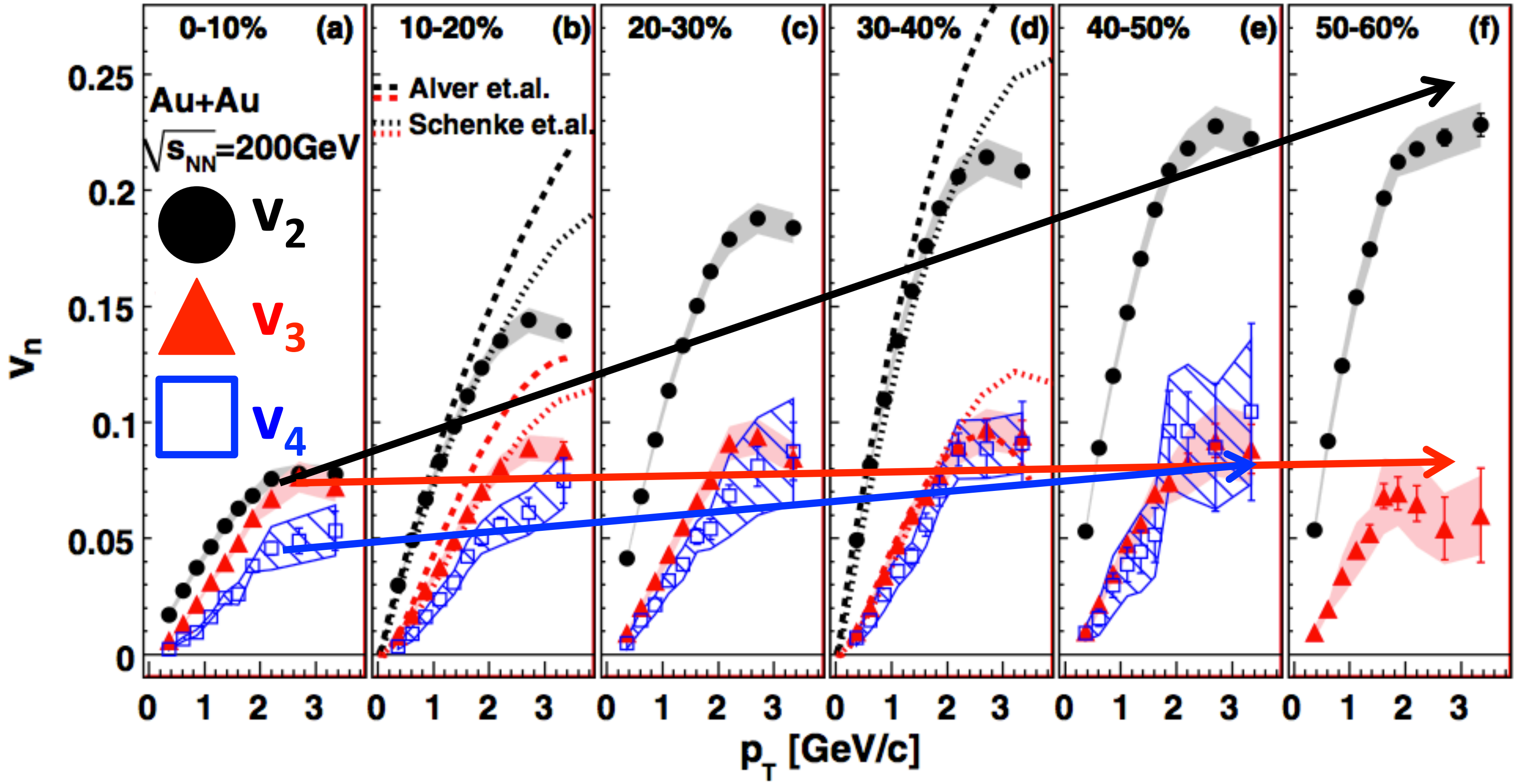
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + 2\sum_{n=1}^{\infty} \nu_n \cos\{n(\phi - \Psi_n)\}\right]$$

$$\nu_n = <\cos\{n(\phi - \Psi_n)\}>$$

Because higher harmonics flows are more sensitive to initial geometry and η/s of QGP, they are studied actively in order to determine the calculating model of initial geometry and constrain η/s.

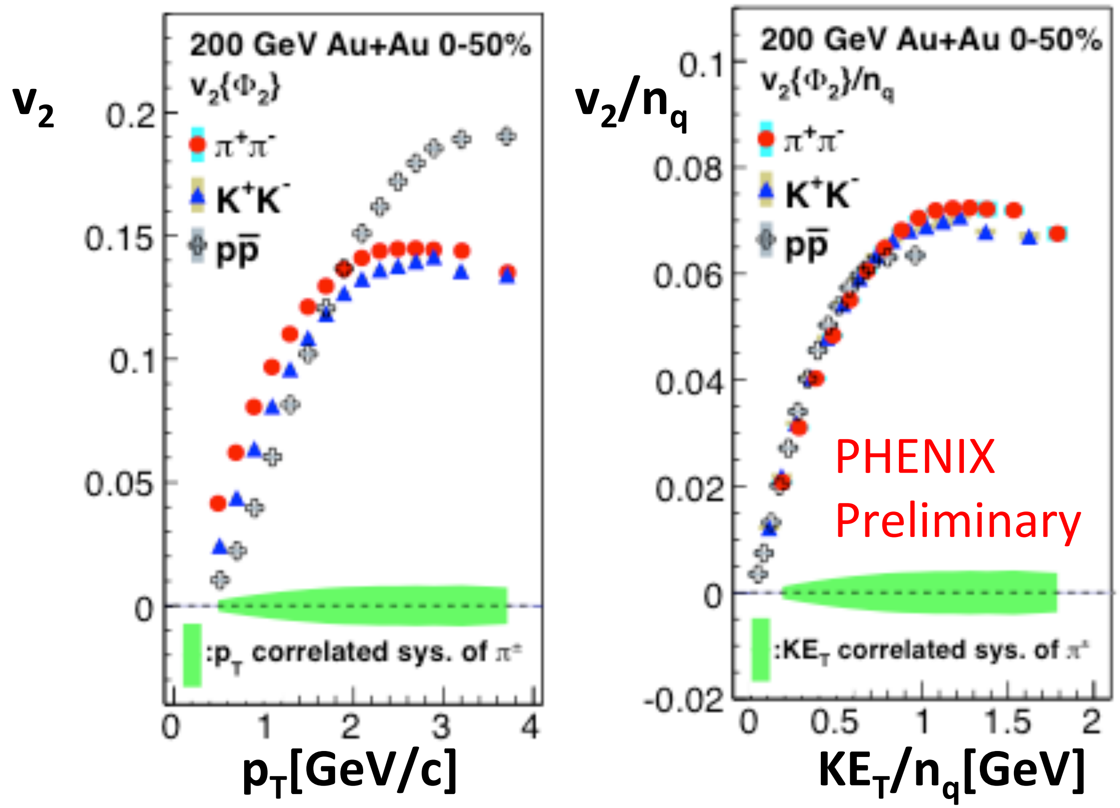
Charged particle azimuthal anisotropy

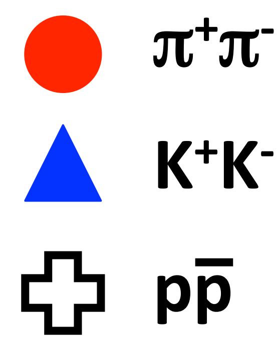
P.R.L. 107, 252301(2011)



v_3 and v_4 have weak centrality dependence while v_2 has strong dependence.
It indicates v_3,v_4 are created by the initial geometry deformation.

The number of constituent quark scaling of v_2

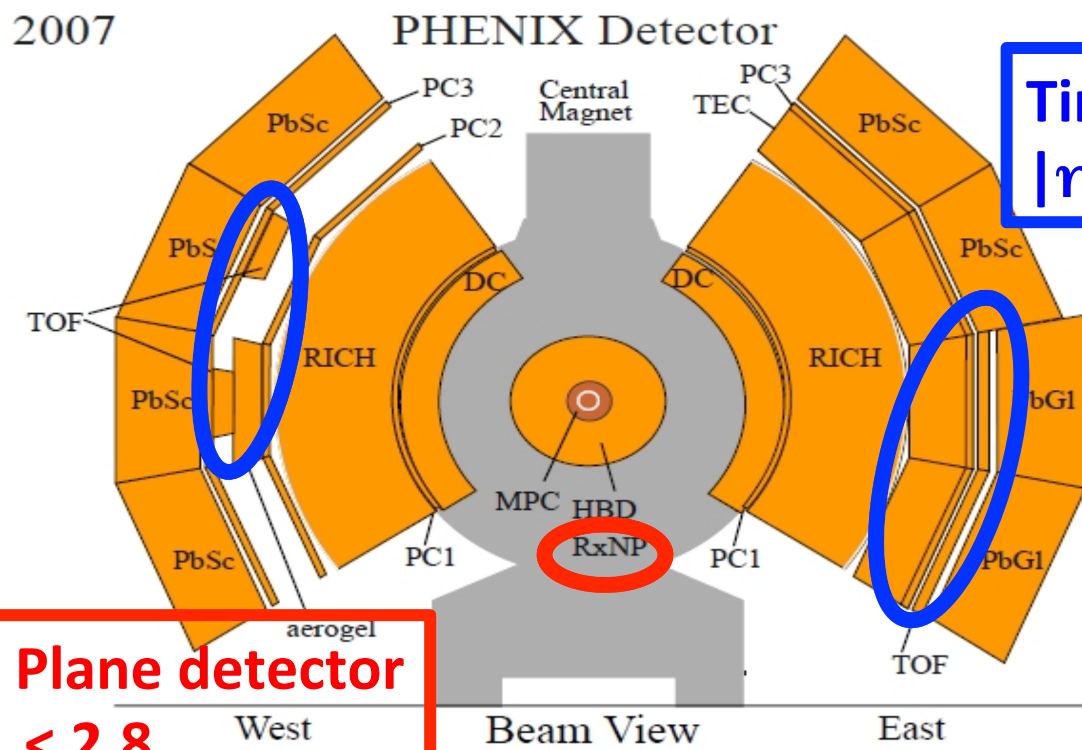




$$KE_T = \sqrt{m_0^2 + p_T^2} - m_0$$

v_2 has mass ordering in low p_T and meson/baryon dependence higher p_T region.
$v_2(KE_T)$ is well scaled by the number of constituent quarks, less than 1.0[GeV].
It is known that hydrodynamic model can describe v_2 in low p_T region.

Data set and PHENIX detector



Time of Flight
$|\eta| < 0.35$

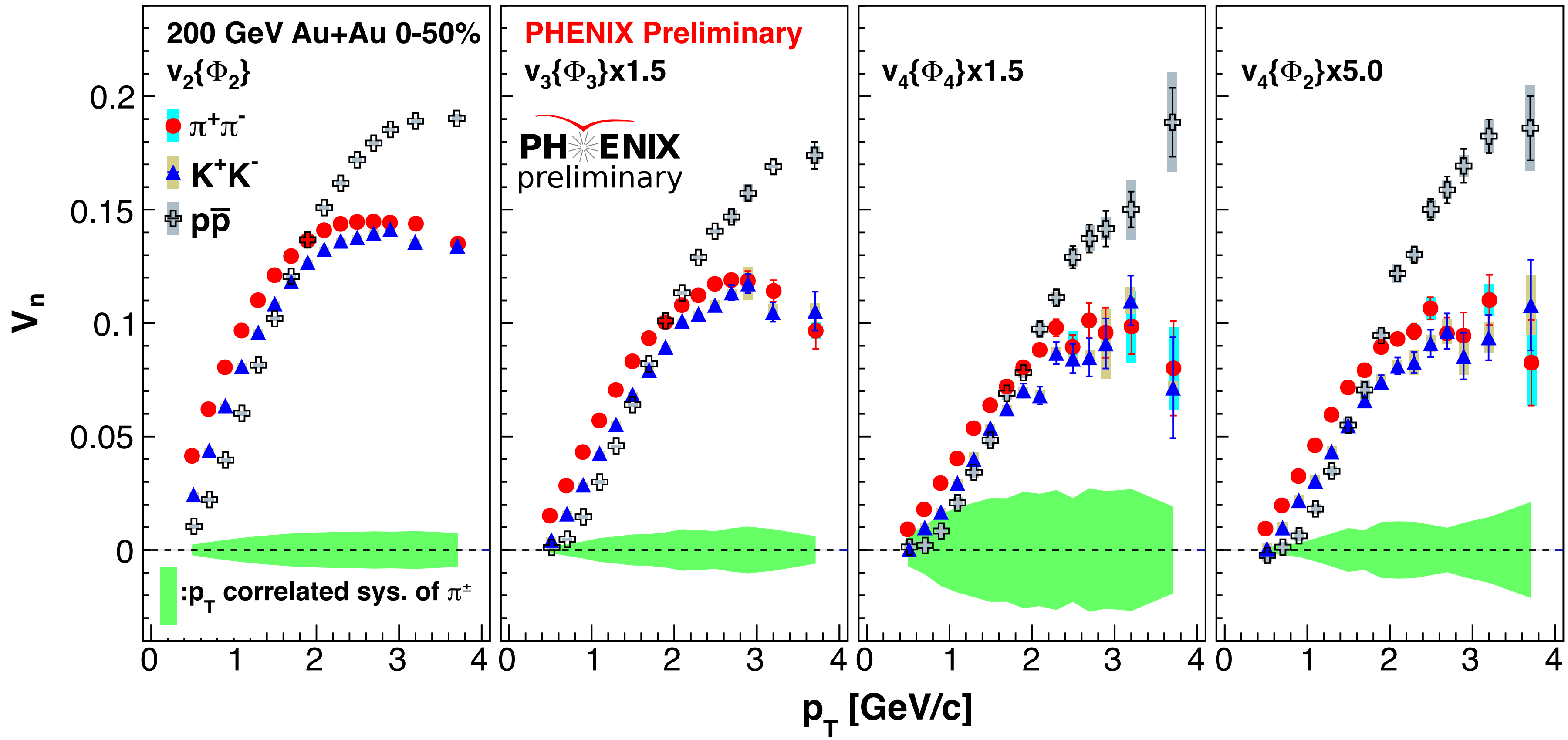
Reaction Plane detector
$1.0 < |\eta| < 2.8$

$$v_n = < \cos\{n(\phi - \Psi_n)\} >$$

Data set is Au+Au 200 GeV taken in 2007 period.

In order to reduce the effect of non-flow, the detectors which measure Event Plane and emitted particle angles should have some distances.

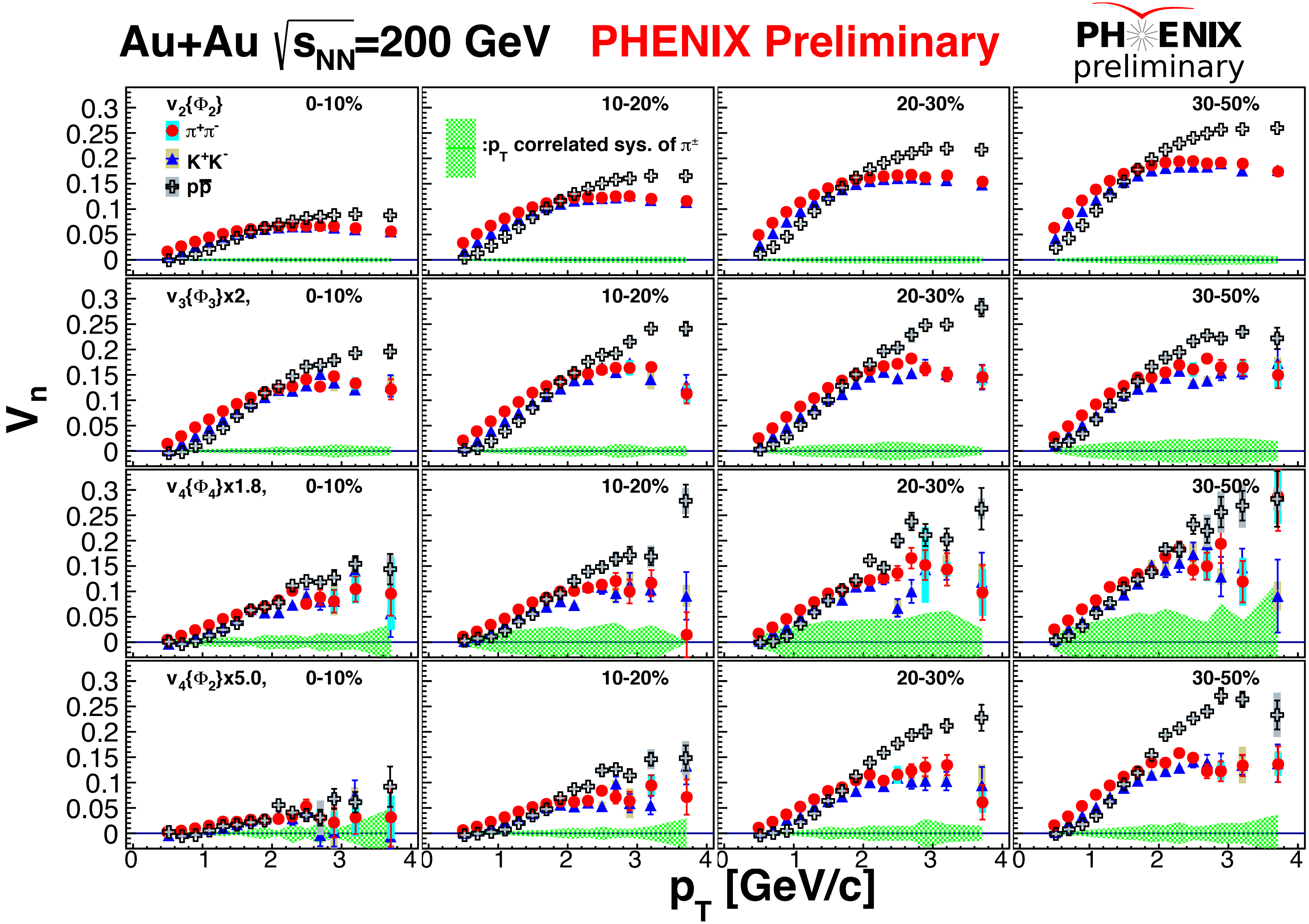
v_n of charged π,K,p result



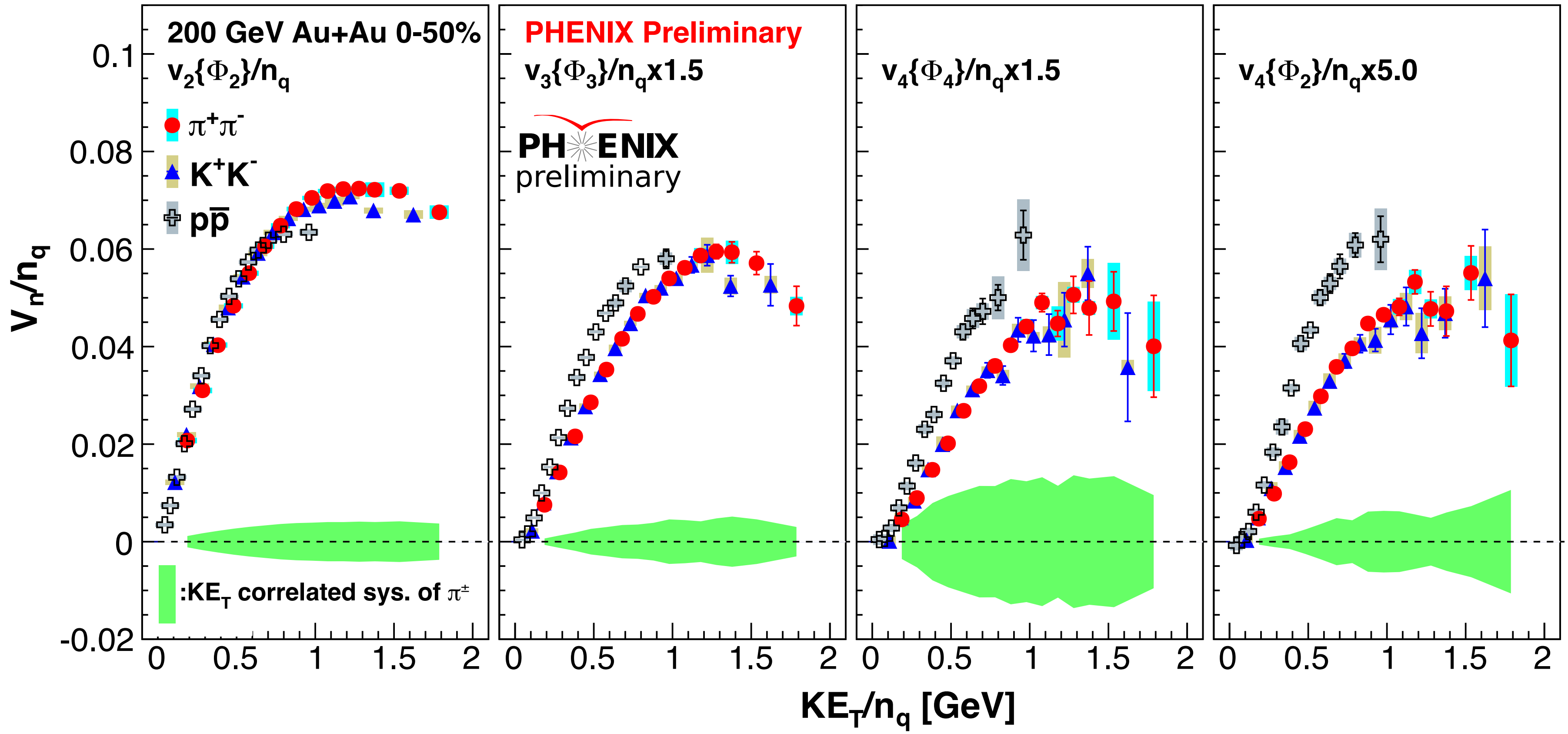
Azimuthal anisotropy has particle species dependence, which are mass dependence and meson/baryon dependence.

Higher harmonics are created from initial geometry deformation, they are affected by the effect of QGP expansion.

PIDed v_n with fine centrality bin



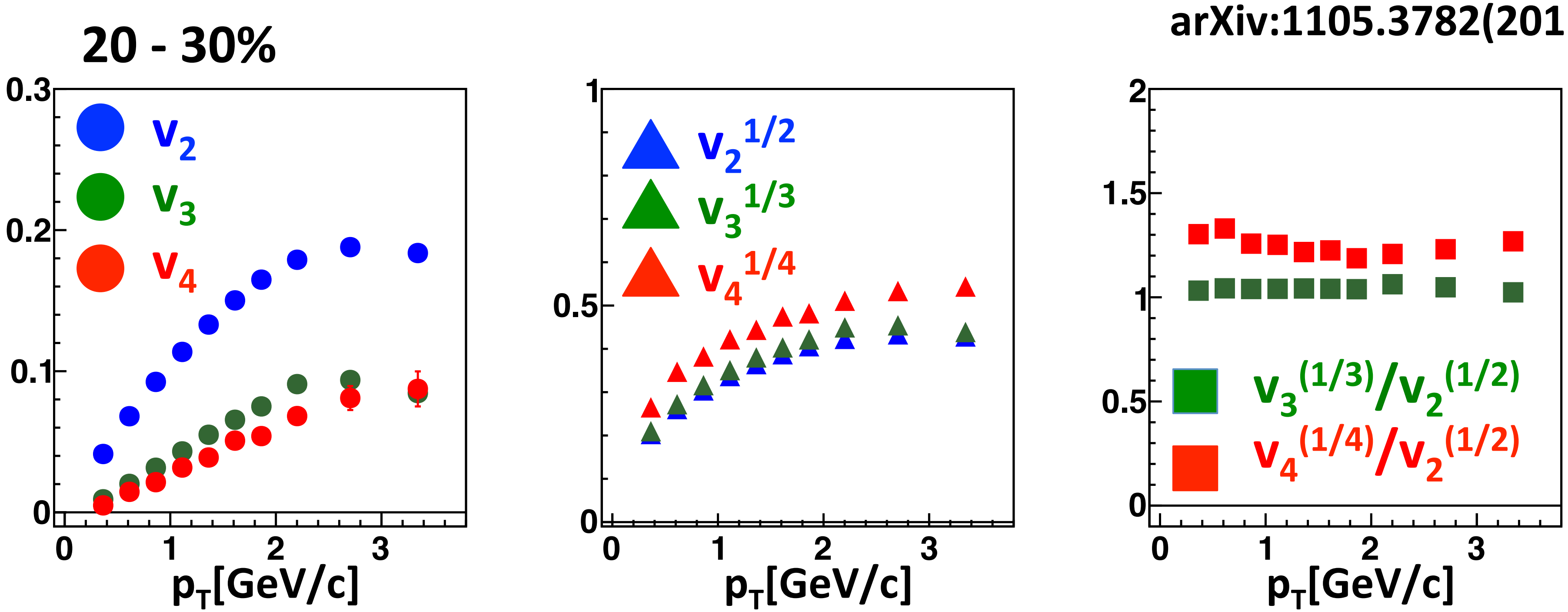
Break the number of constituent quark scaling



While v_2 is well scaled, higher harmonics have deviation.
The scaling for all harmonics and particle species are searched.

$v_n^{1/n}$ scaling among harmonics

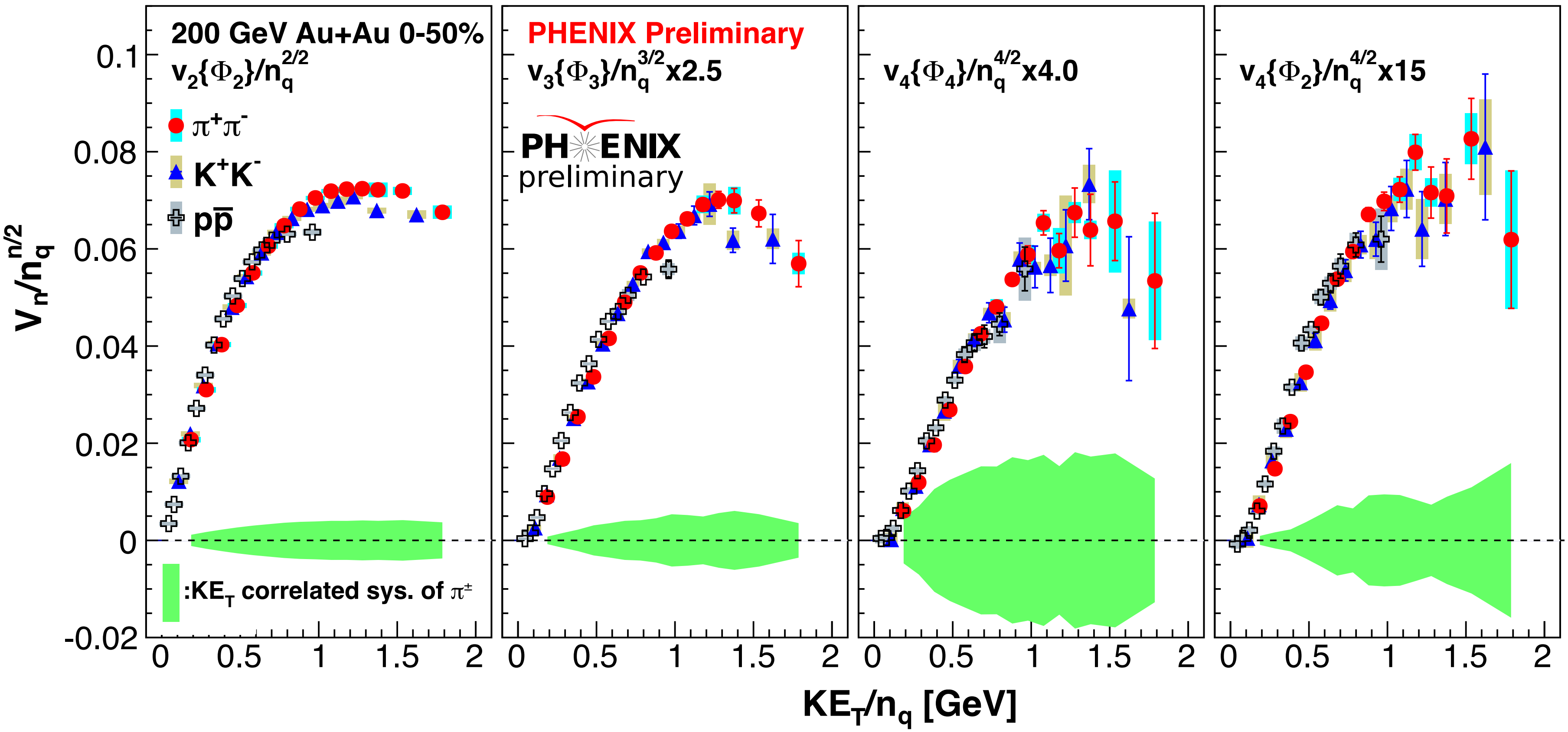
arXiv:1105.3782(2011)



Charged particle $v_n^{(1/n)}$ is scaled beyond harmonics.
$v_n^{1/n}/v_2^{1/2}$ ratio shows flat dependence on p_T.

$$v_2(KE_T/n_q)/n_q \rightarrow (v_2(KE_T/n_q)/n_q)^{n/2} \rightarrow v_n(KE_T/n_q)/n_q^{n/2}$$

Modified the quark number scaling



Modified scaling works well for all harmonics.

$v_2(KE_T/n_q)/n_q$ -> $(v_2(KE_T/n_q)/n_q)^{n/2}$ -> $v_n(KE_T/n_q)/n_q^{n/2}$

(a) : $v_2(KE_T)/n_q$
(b) : $v_n^{1/n}$ scaling
(a)+(b) : $v_n(KE_T)/n_q^{n/2}$

Summary

$v_2, v_3, v_4, v_4(\Psi_2)$ of charged π,K,p are measured.

It is found that there are mass ordering in low p_T and meson/baryon dependence larger than 2 [GeV/c] as v_2.

The number of constituent quarks scaling are tested.

The scaling which works well for $v_2(KE_T)$, doesn't work for $v_n(KE_T)_{n>2}$.

Modified scaling $v_n(KE_T/n_q)/n_q^{n/2}$ is checked to work well for all harmonics.

Next step

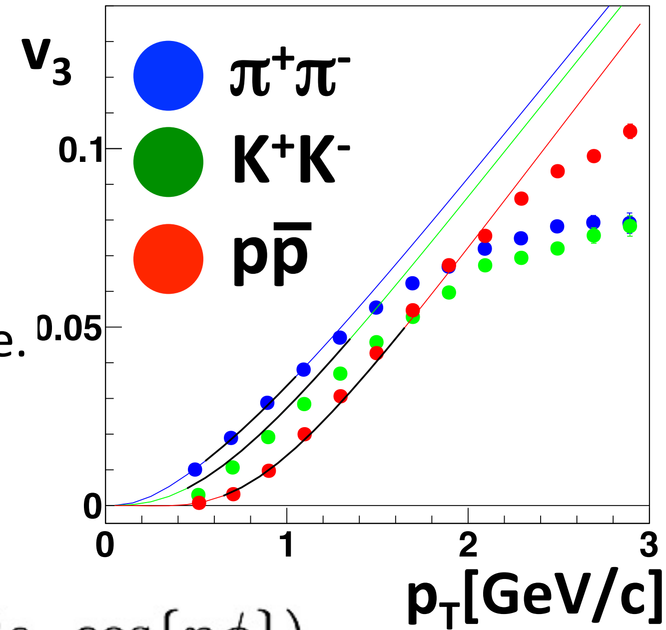
v_n of ϕ will be measured, because it is meson and heaver than proton.
And scaling test will be operated.

v_n of photon will be measured.

BACK UP

Blast Wave Model

QGP valuables are extracted by comparison with Blast Wave model, which can describe final state from information at freeze-out such as temperature.



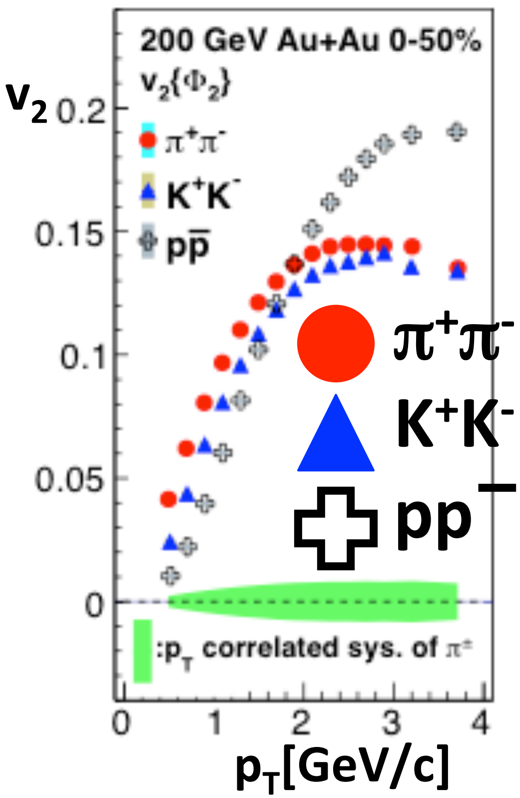
$$\frac{dN}{p_T dp_T} \propto \int\int r dr d\phi m_T I_0(\alpha_T) K_1(\beta_T)$$

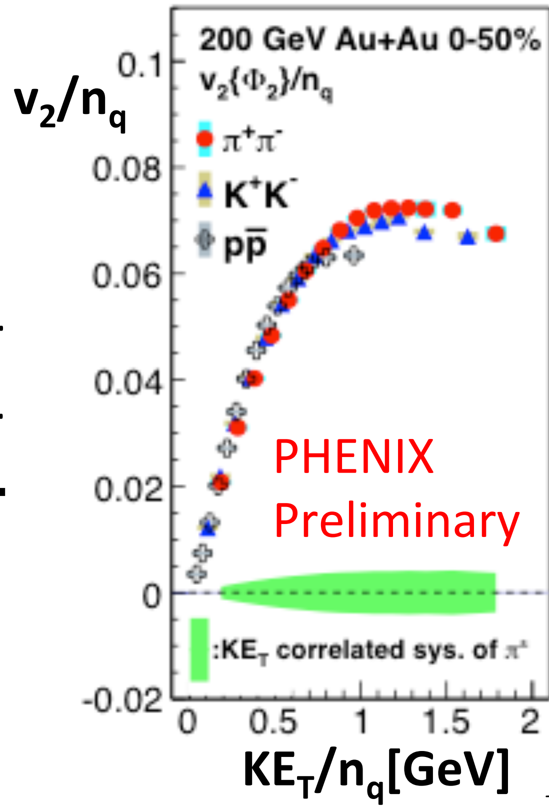
$$v_n = \frac{\int\int r dr d\phi \cos\{n\phi\} I_n(\alpha_T) K_1(\beta_T)(1 + 2s_n \cos\{n\phi\})}{\int\int r dr d\phi I_0(\alpha_T) K_1(\beta_T)(1 + 2s_n \cos\{n\phi\})}$$

T_f : temperature
ρ_0 : average velocity
ρ_n : velocity anisotropy
(anisotropy in velocity)
s_n : geometrical anisotropy
(like eccentricity at freeze-out)

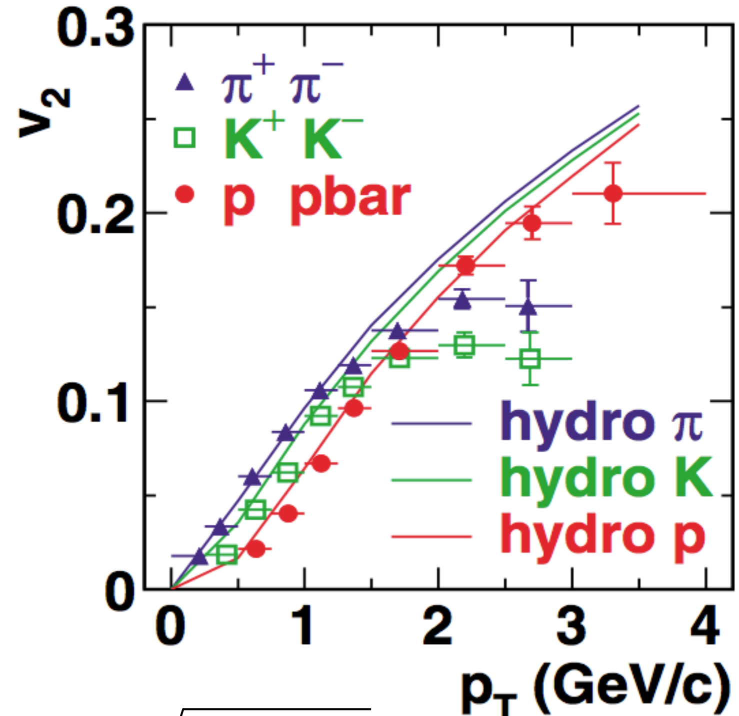
$\rho(\phi, r) = \rho_0(1+2\rho_n\cos(n\phi))*r$
$\alpha_T(\phi, r) = (p_T/T_f)\sinh(\rho(\phi, r))$
$\beta_T(\phi, r) = (m_T/T_f)\cosh(\rho(\phi, r))$

The number of constituent quark scaling of v_2





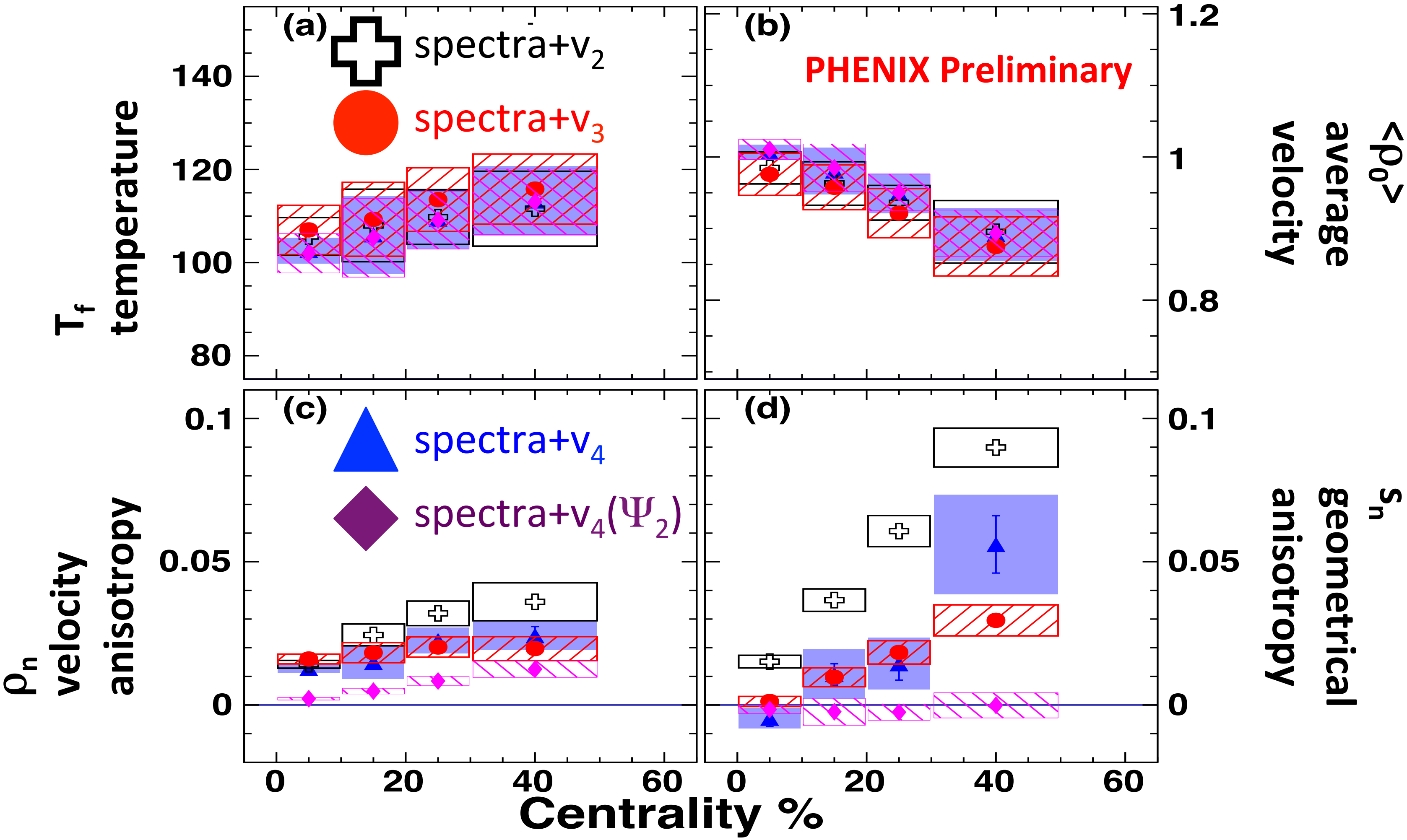
P.R.L.91, 182301



$$KE_T = \sqrt{m_0^2 + p_T^2} - m_0$$

v_2 has mass ordering in low p_T and meson/baryon dependence higher p_T region.
$v_2(KE_T)$ is well scaled by the number of constituent quarks, less than 1.0[GeV].
It is known that hydrodynamic model can describe v_2 in low p_T region.

Freeze-out parameters extracted by comparison with BW



ρ_n behavior is similar to centrality dependence of charged particle v_n.

s_3 and s_4 are smaller than s_2 but not zero in non-central.

Summary

v_2,v_3,v_4,$v_4(\Psi_2)$ of charged π,K,p are measured.

It is found that there are mass ordering in low p_T and meson/baryon dependence larger than 2 [GeV/c] as v_2.

The number of constituent quarks scaling doesn't work for $v_n(KE_T)_{n>2}$.

Modified scaling $v_n(KE_T/n_q)/n_q^{n/2}$ is checked to work well for all harmonics.

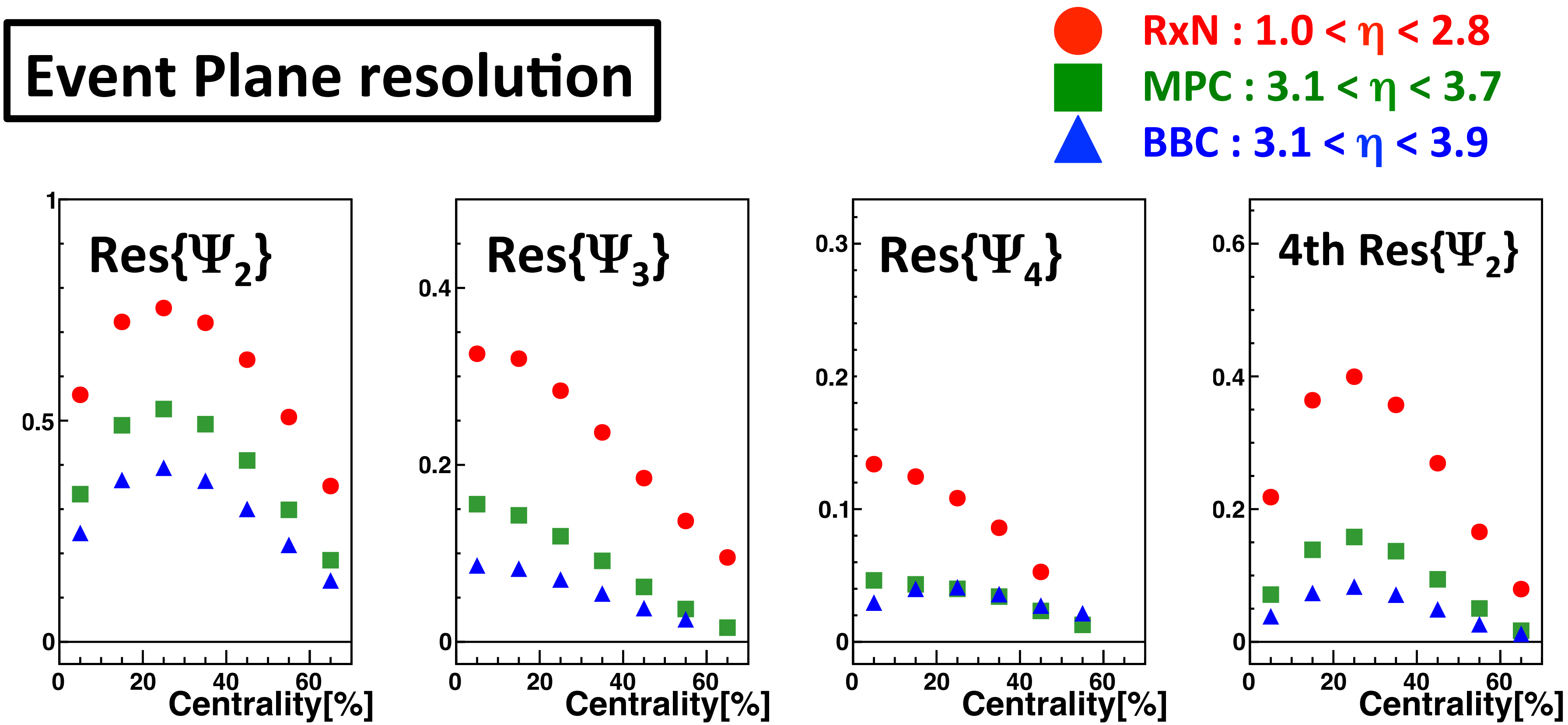
QGP at freeze-out is parameterized by comparison with Blast Wave model.

It is found that ρ_n(velocity anisotropy) behavior looks like charged particle v_n behavior.

s_2(Geometry anisotropy) is larger than s_3 and s_4.

There are geometrical anisotropy at freeze-out.

Event Plane resolution



$$\nu_{n,true} = \nu_{n,obs}/\mathrm{Res}\{\Psi_n\}$$

$$\mathrm{Res}\{\Psi_n\} = < \cos\{n(\Psi_{n,\mathrm{real}} - \Psi_{n,\mathrm{obs}})\} >$$

$\mathrm{Res}\{\Psi_n\}$ is estimated from correlation observed Ψ_n.
Because RxN has best resolution, Ψ_n measured by RxN is used in this analysis.

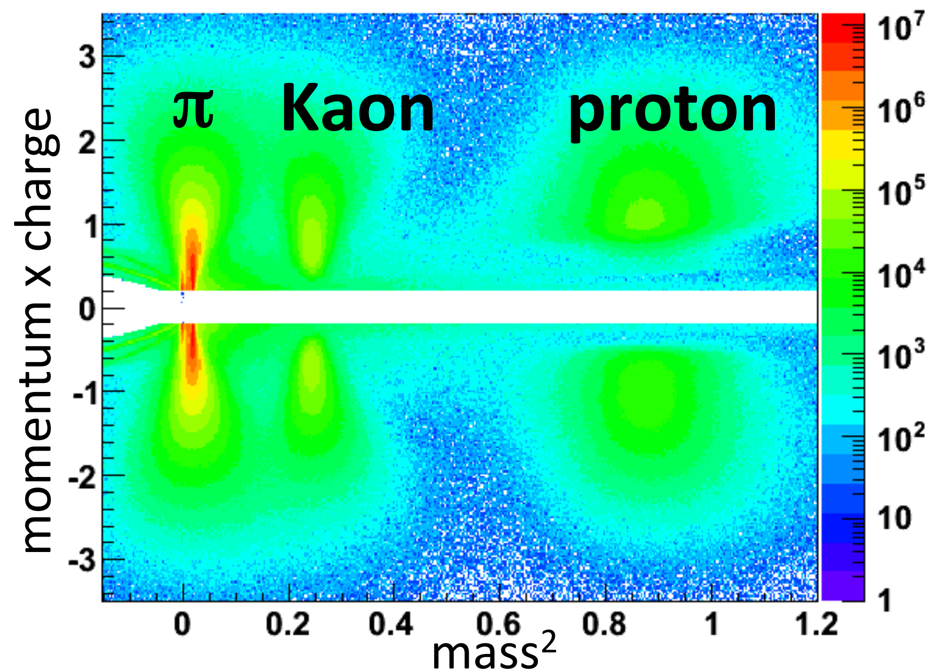
Time-Of-Flight detector

Particle species are identified by TOF method.
AGEL and RICH are used to separate them finer.

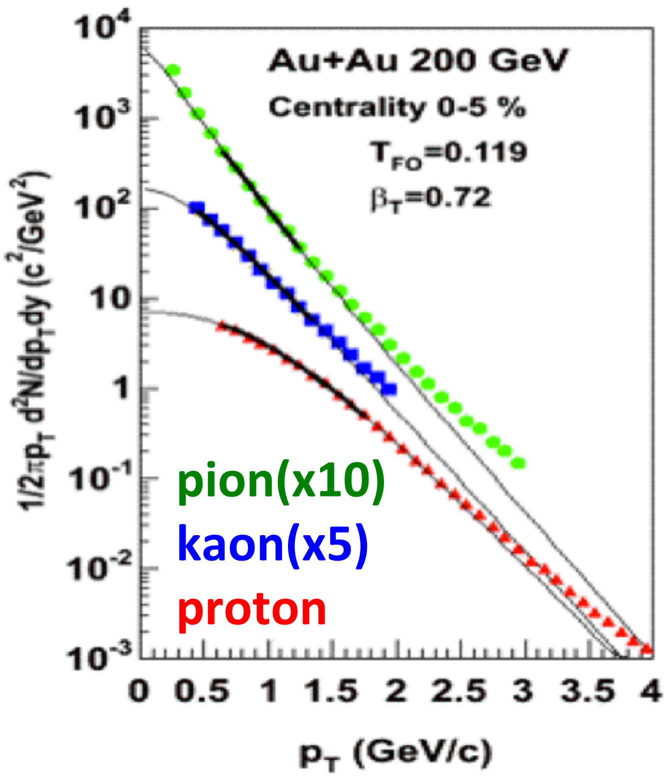
TOF.E detector

$$m^2 = p^2\left(\frac{c^2t^2}{L^2} - 1\right)$$

mass^2 distribution via TOF.E



Hydrodynamic model describe identified particle valuable



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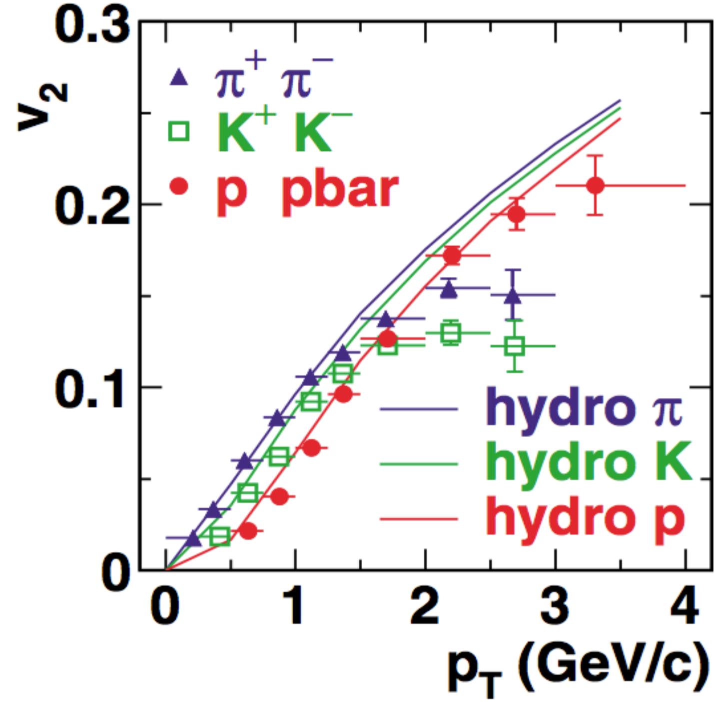
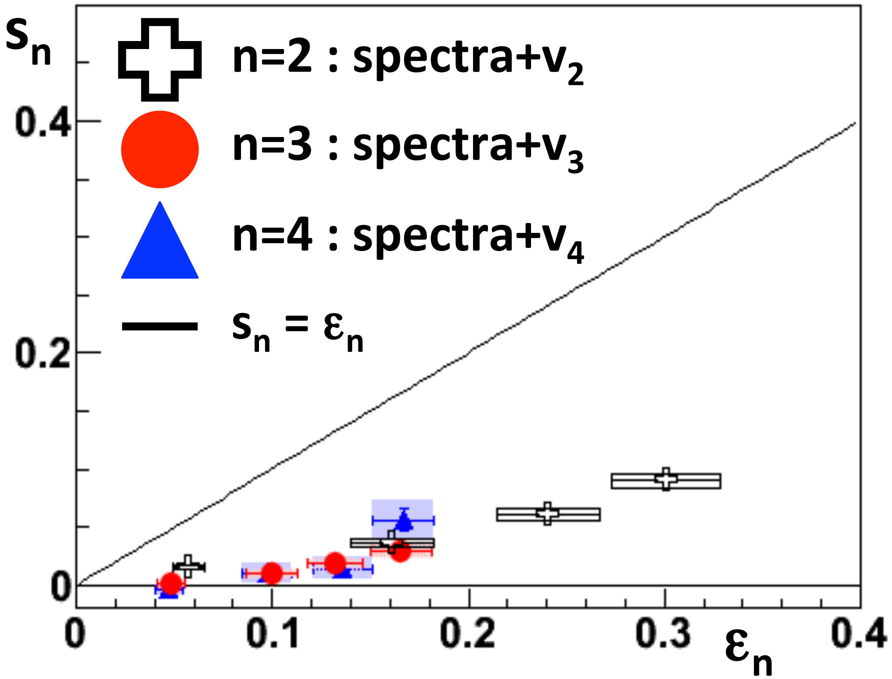


Spectra and PID v2 have mass ordering in low pT region, and they are known that they can be described.
QGP parameters are extracted by comparison with model calculating.

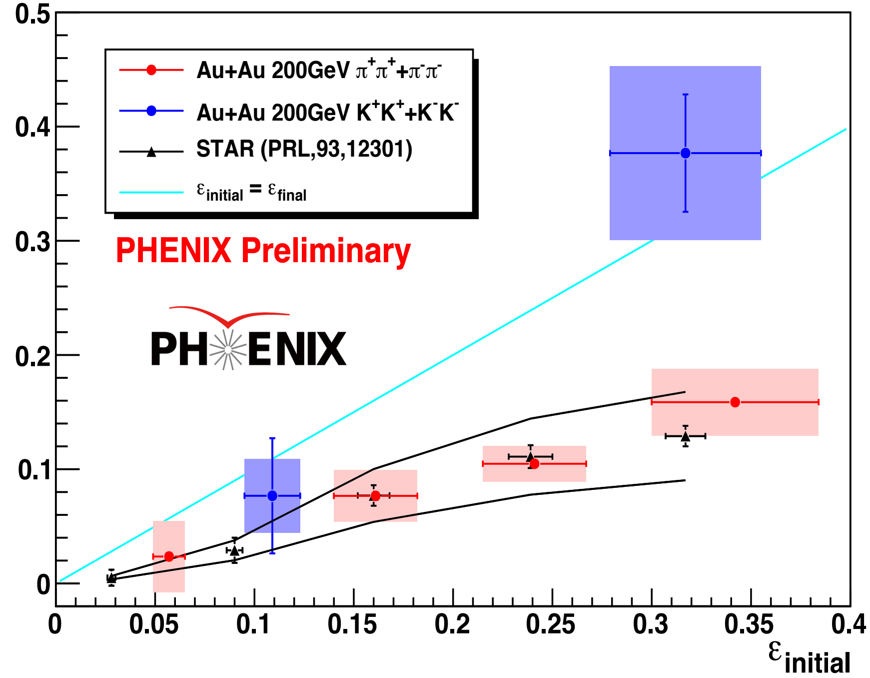
s_2 behavior is similar with HBT analysis

Takafumi (QM2012)

BW



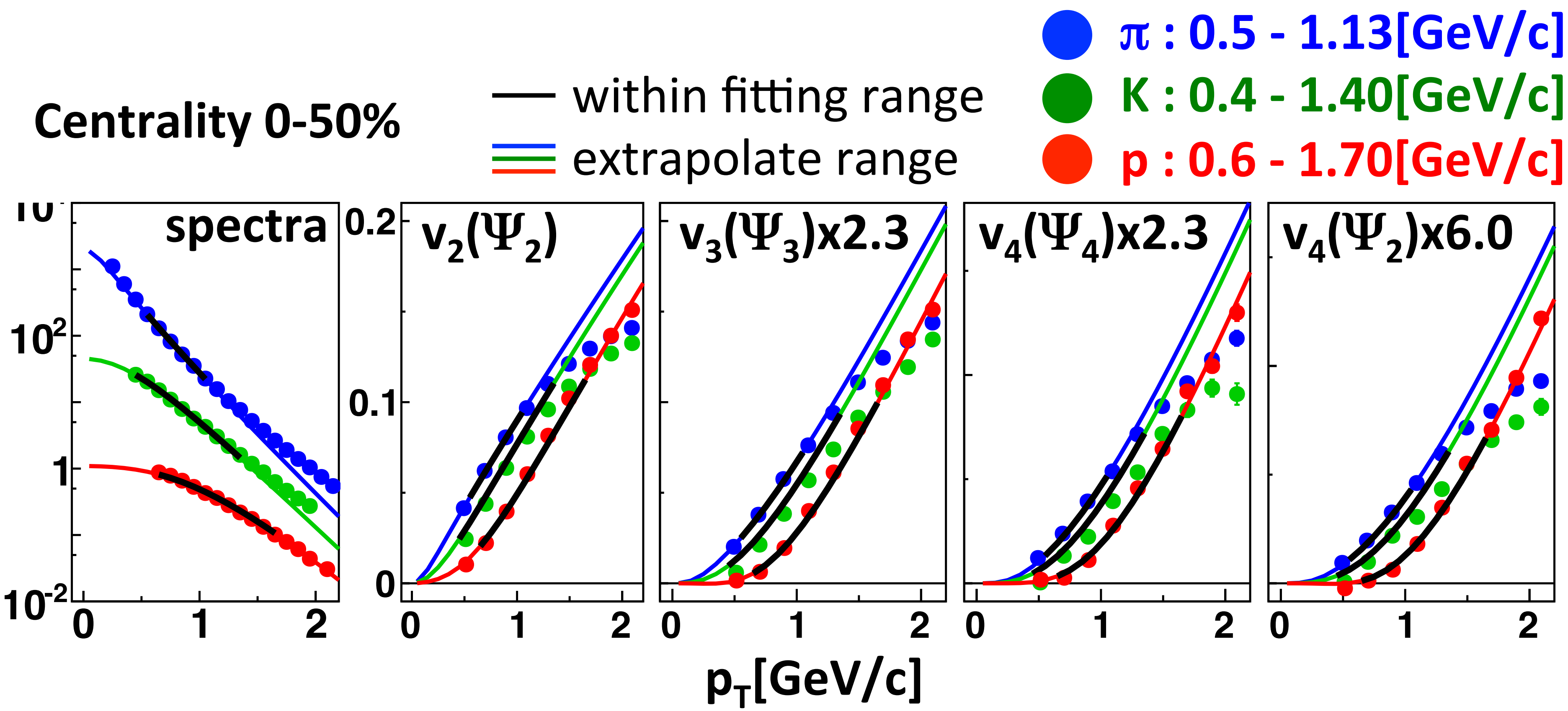
HBT (2nd order geometrical anisotropy)



s2 behavior is similar to HBT result.

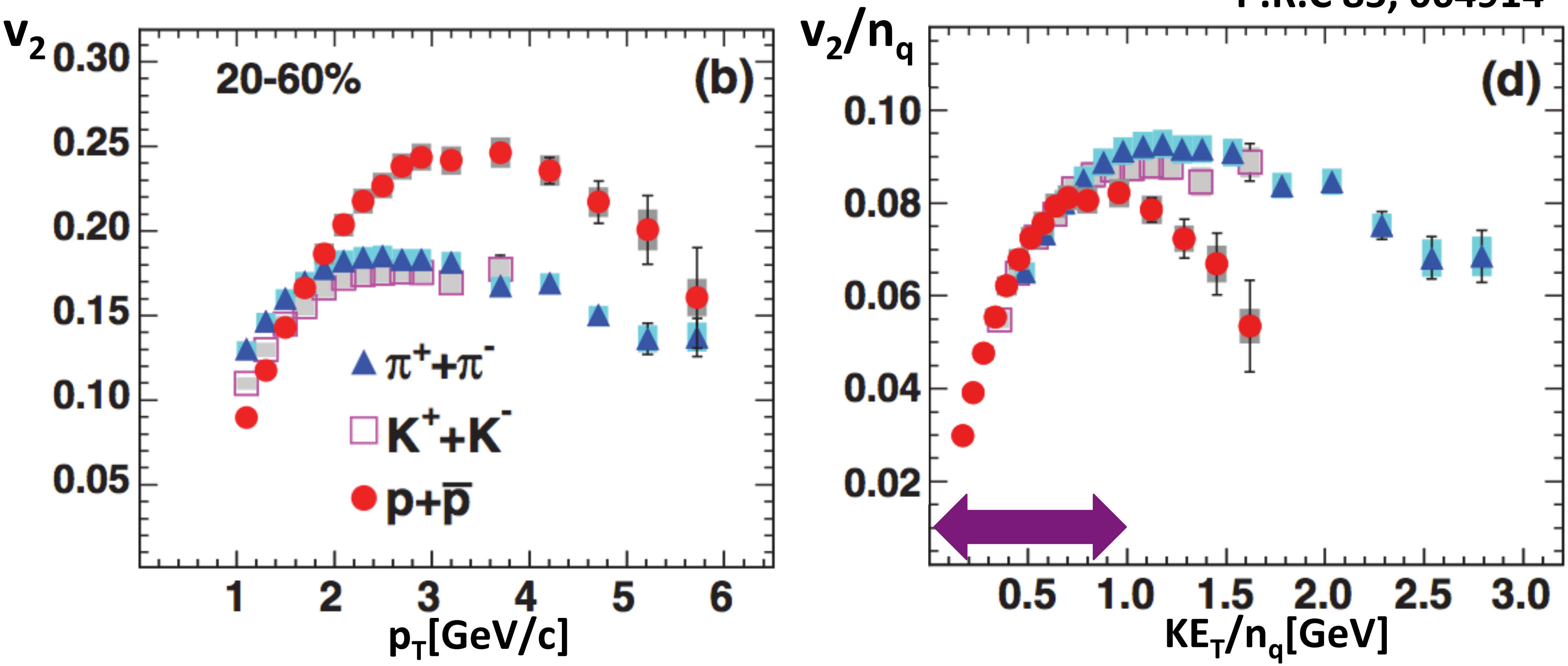
Comparison model

Centrality 0-50%



The number of constituent quark scaling of v_2

P.R.C 85, 064914

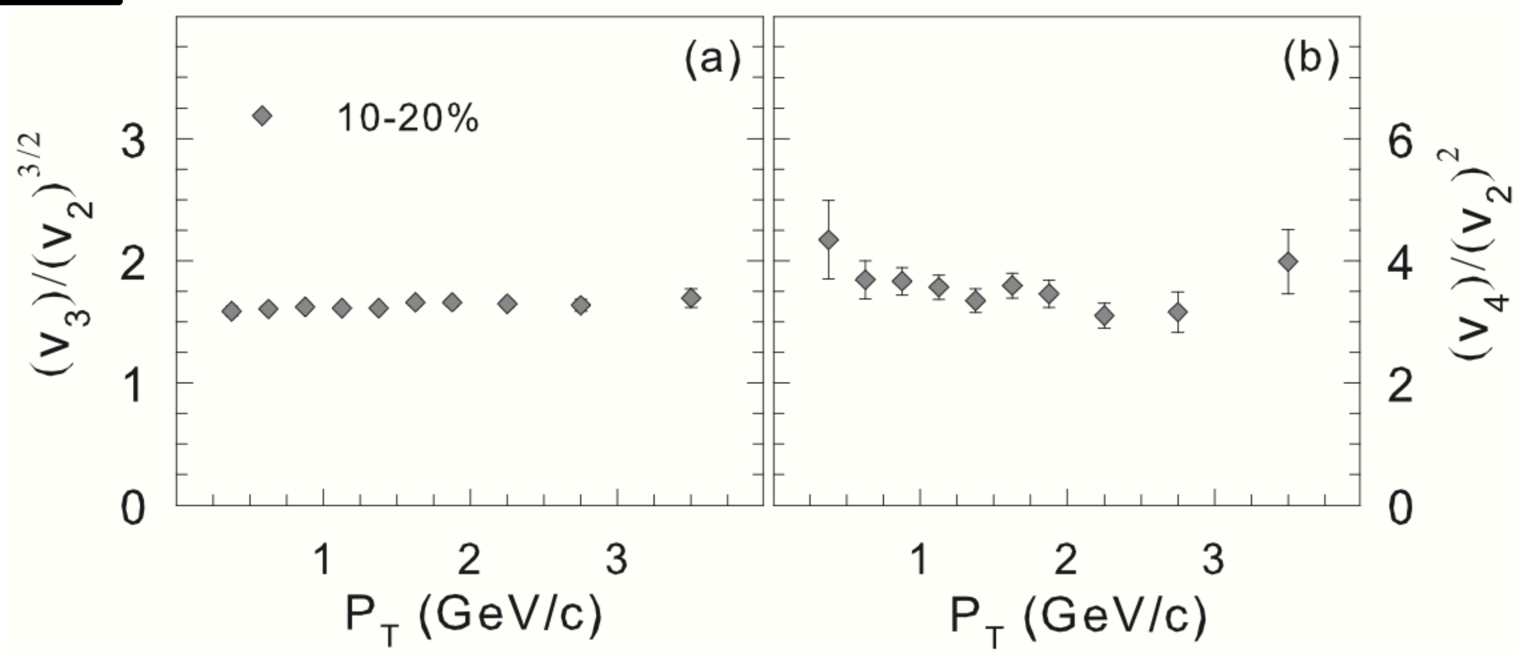


v_2 has mass ordering in low p_T and meson/baryon dependence higher p_T region.
$v_2(KE_T)$ is well scaled by the number of constituent quarks, less than 1.0[GeV].

$$KE_T = \sqrt{m_0^2 + p_T^2} - m_0$$

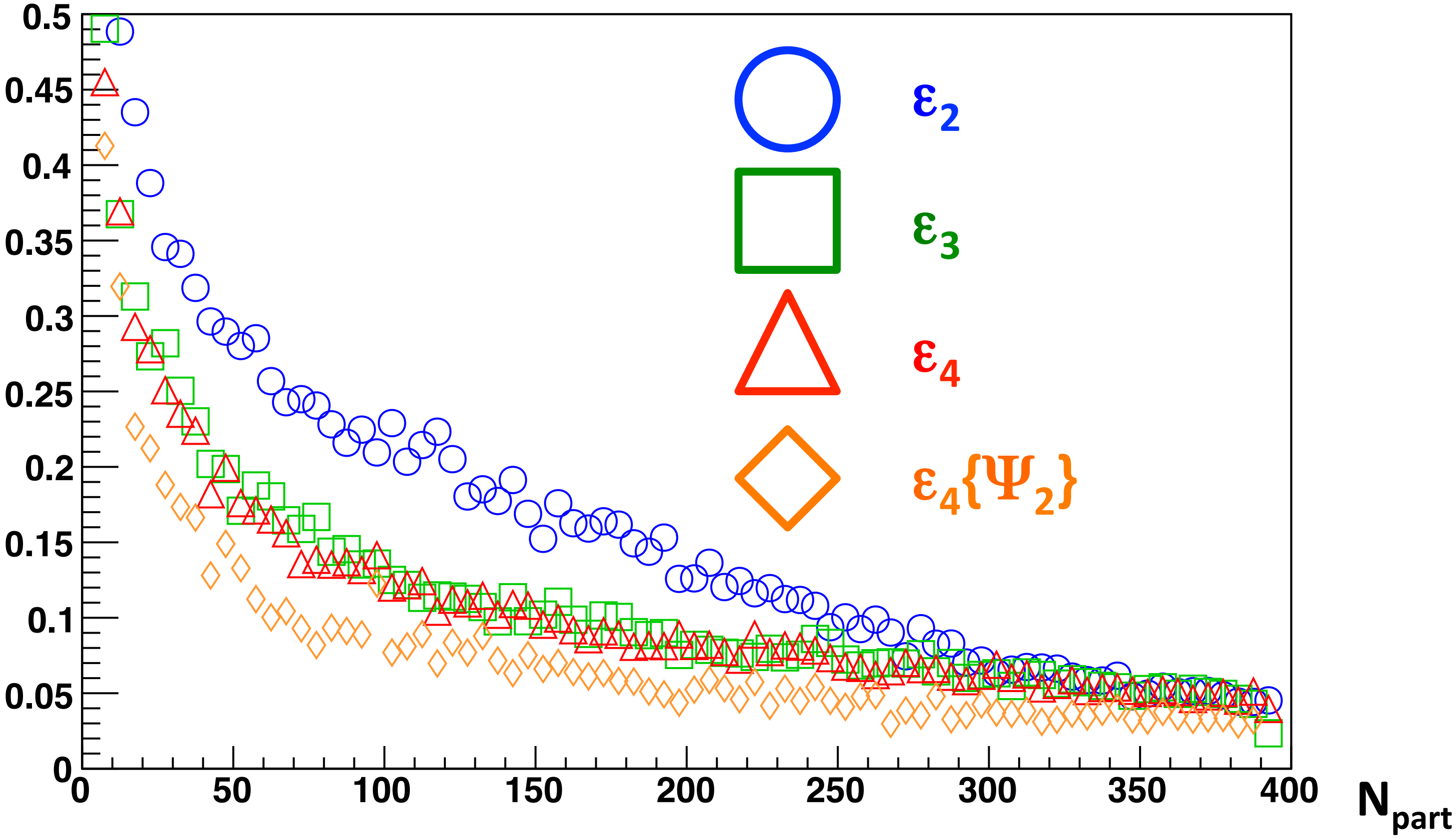
arXiv:1105.3782
P.R.B 642 227-231

Scaling



$v_n/v_2^{n/2}$ is scaled.

Comparison initial geometry anisotropy

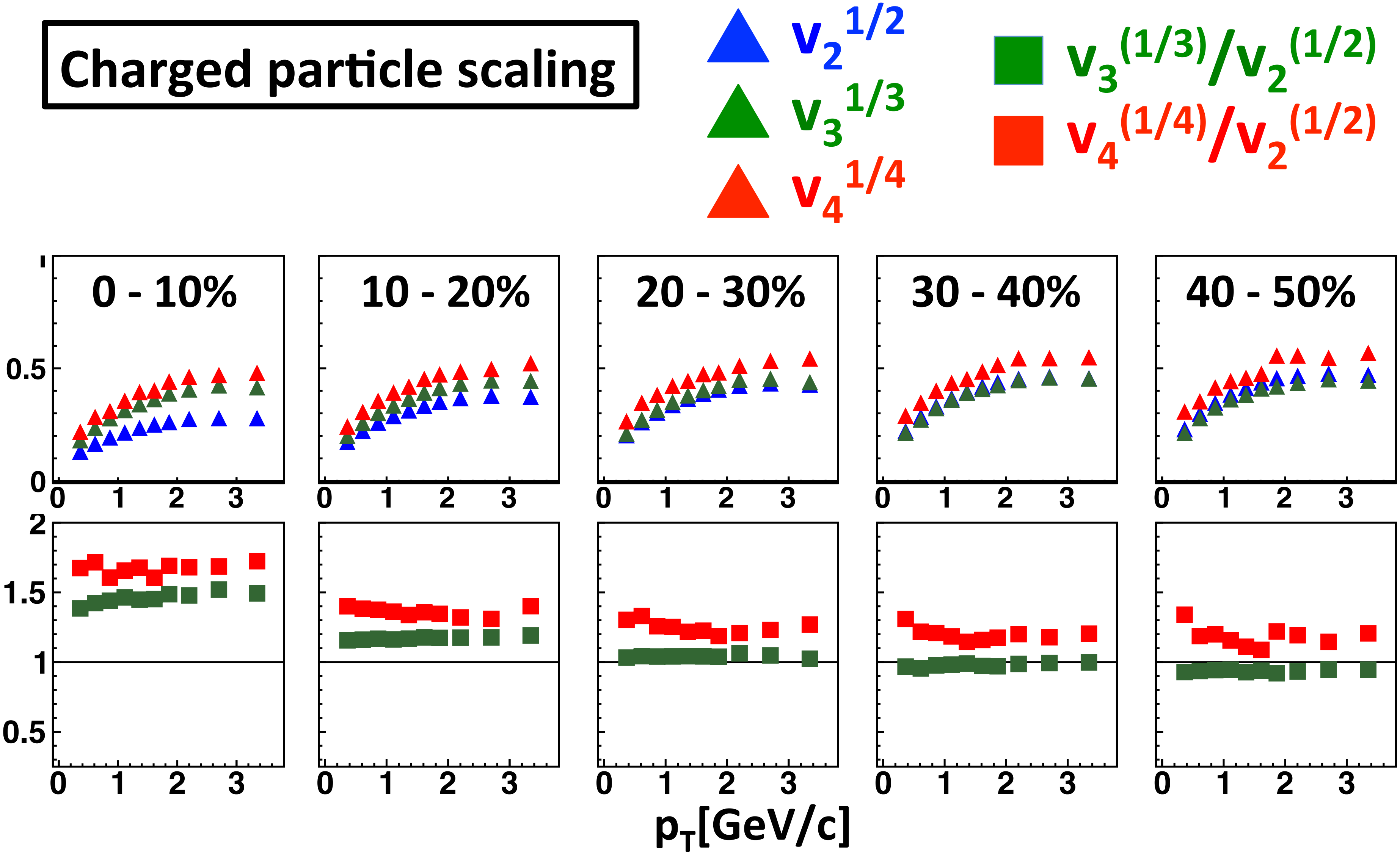


Eccentricity is calculated by Glauber model.

ε_2 N_{part} dependence is larger than higher order.

This dependence resembles v_n centrality dependence.

Charged particle scaling



Charged particle are scaled by $v_n^{1/n}$ beyond harmonics.

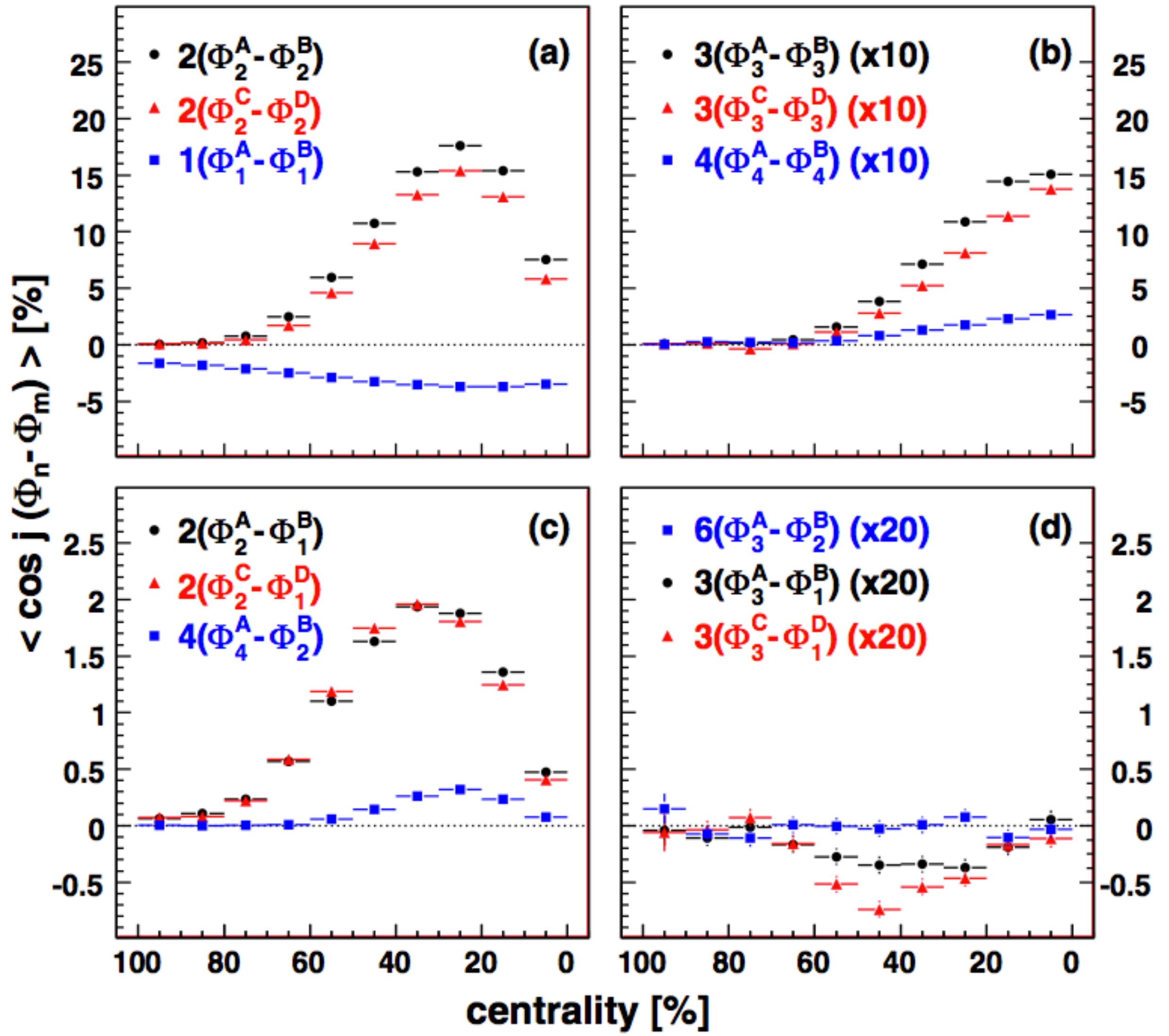
$v_2(KE_T)/n_q$ is scaled

$v_n^{1/n}$ is able to be scaled to $v_2^{1/2}$

So, $v_n(KE_T)$ is scaled by $v_2(KE_T)^{n/2}$

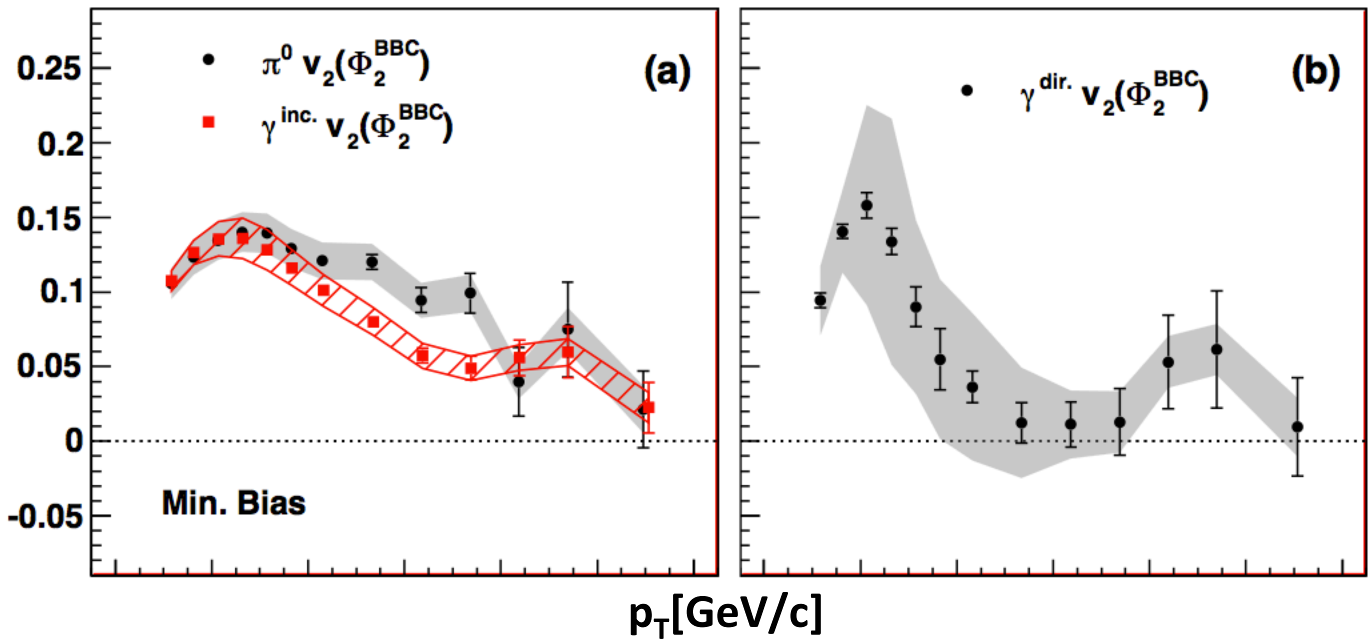
$v_2(KE_T/n_q)/n_q$ -> $v_2^{n/2}(KE_T/n_q)/n_q^{n/2}$ -> $v_n(KE_T/n_q)/n_q^{n/2}$

Event Plane


(a)
2(Φ$_2^A$-Φ$_2^B$)
2(Φ$_2^C$-Φ$_2^D$)
1(Φ$_1^A$-Φ$_1^B$)
(b)
3(Φ$_3^A$-Φ$_3^B$) (x10)
3(Φ$_3^C$-Φ$_3^D$) (x10)
4(Φ$_4^A$-Φ$_4^B$) (x10)
(c)
2(Φ$_2^A$-Φ$_1^B$)
2(Φ$_2^C$-Φ$_1^D$)
4(Φ$_4^A$-Φ$_2^B$)
(d)
6(Φ$_3^A$-Φ$_2^B$) (x20)
3(Φ$_3^A$-Φ$_1^B$) (x20)
3(Φ$_3^C$-Φ$_1^D$) (x20)
< cos j (Φ$_n$-Φ$_m$) > [%]
centrality [%]

v_2 of photon result

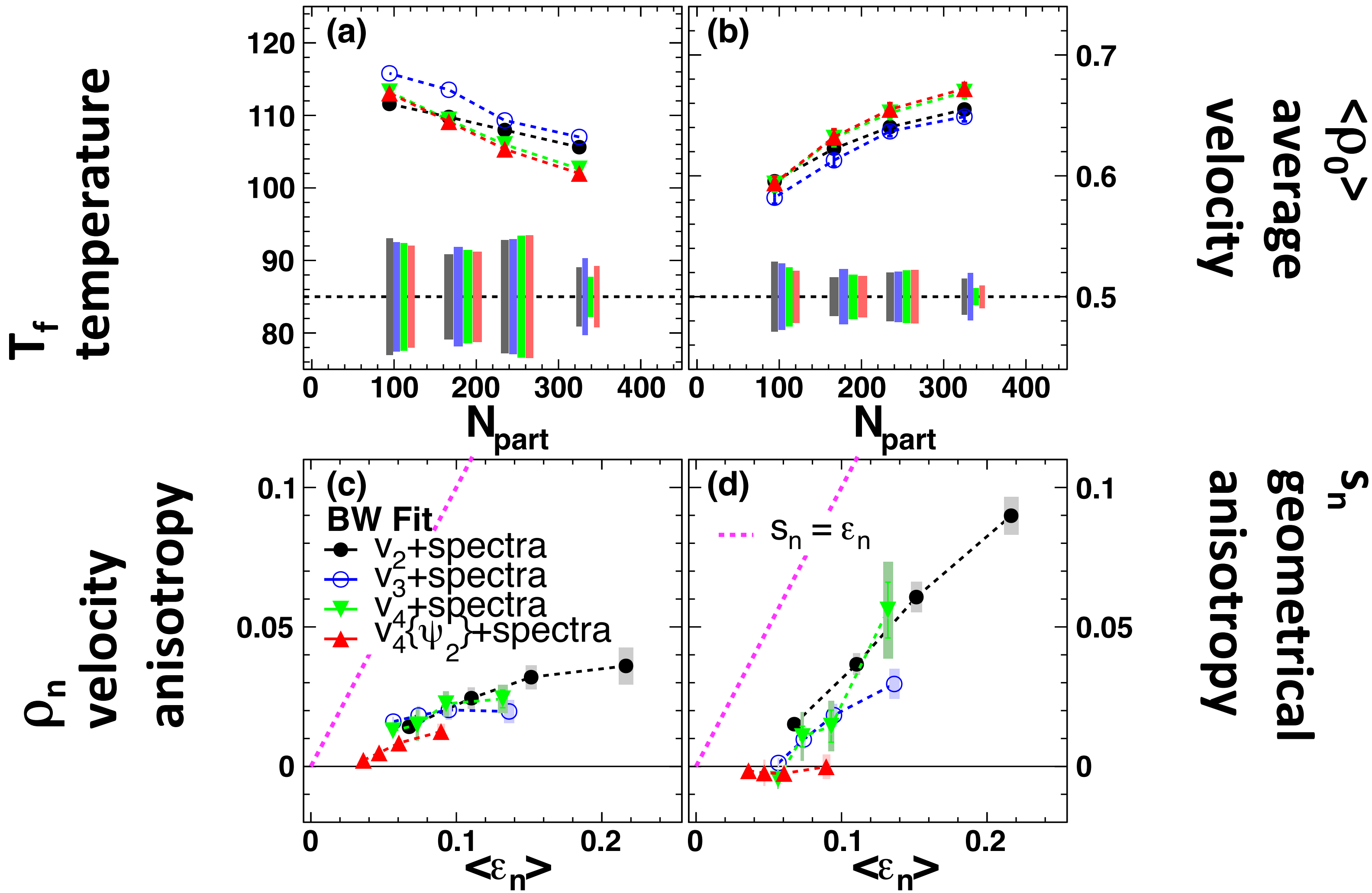
P.R.L. 109, 122302(2012)



Because photon doesn't correlate with QGP, it can provide initial information.
v_2 of direct photon is as large as ones of hadron in low p_T.
What causes?

If it is affected by Magnetic field created by collision, v_3 may have 0.

Model comparison

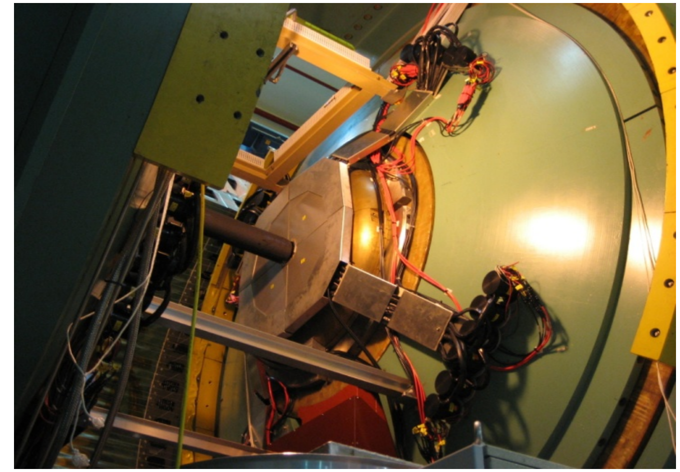


Event Plane calculation

Event Plane is calculated by three steps.

1. gain correction
2. re-centering
3. flattening

$$\nu_{n,real} = \nu_{n,obs} / \mathrm{Res}\{\Psi_\mathrm{n}\}$$

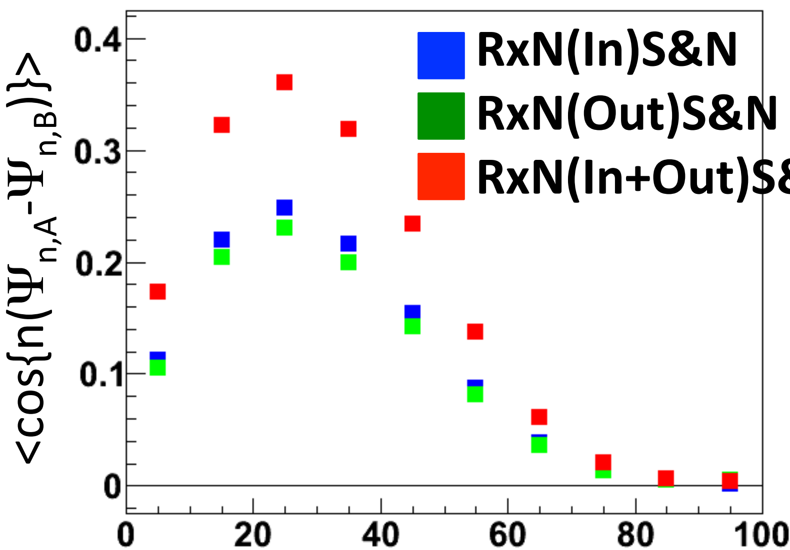


Reaction Plane detector(RxN)

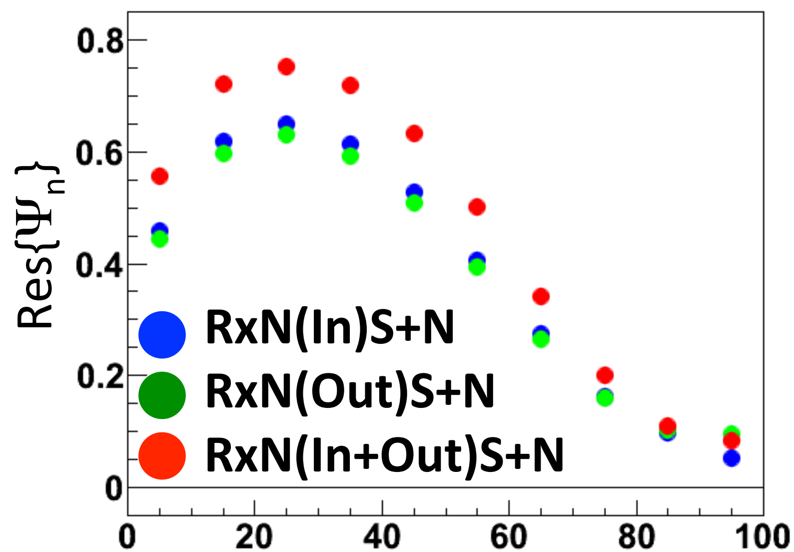
Inner : 1.5 < |η| < 2.8

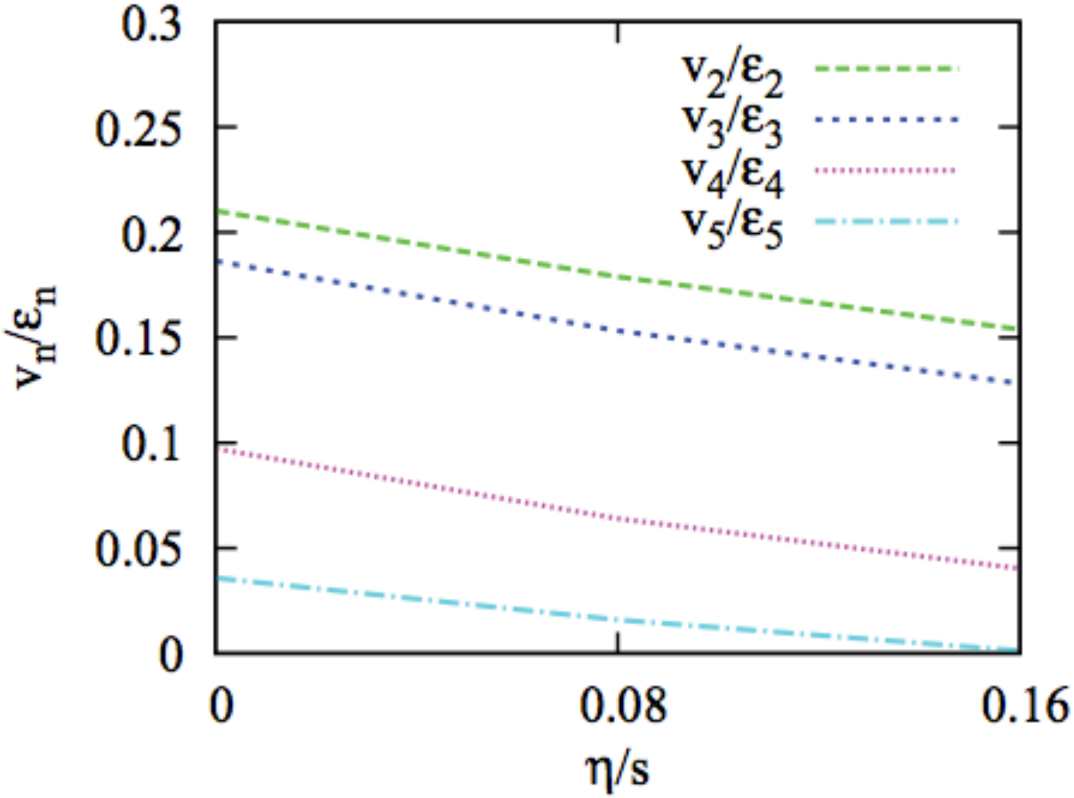
Outer : 1.0 < |η| < 1.5

2nd Event Plane correlation



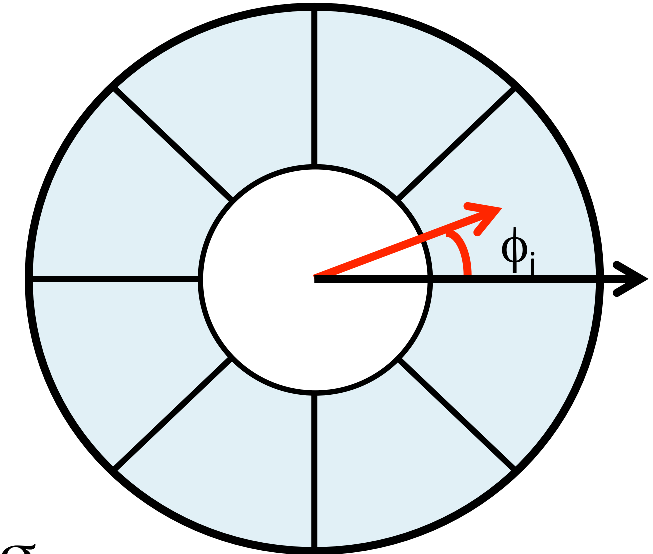
2nd Event Plane resolution





0.3
0.25
0.2
0.15
0.1
0.05
0
v_n/ε_n
v_2/ε_2
v_3/ε_3
v_4/ε_4
v_5/ε_5
0
0.08
0.16
η/s

Event Plane Calculation



1. Gain correction

   $w_i = adc_i / \langle adc \rangle$

   $Q_{x,n} = \Sigma w_i \cos(n\phi_i)$, $Q_{y,n} = \Sigma w_i \sin(n\phi_i)$

   $\Phi_n = \mathrm{atan2}(Q_{x,n}, Q_{y,n}) / n$

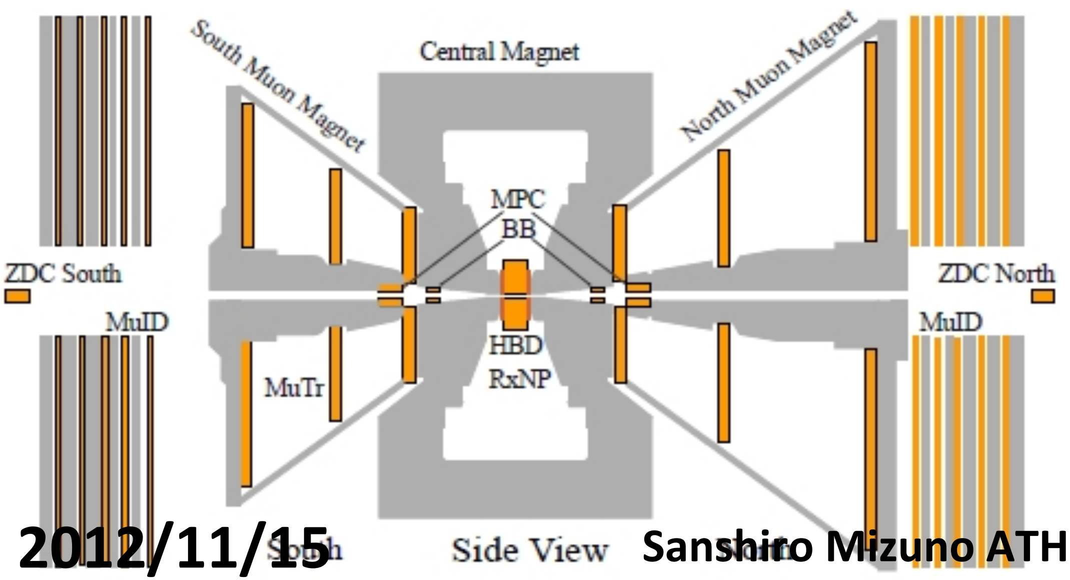
2. Re-centering

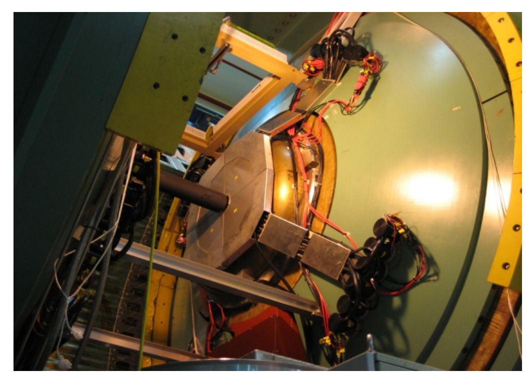
   $Q'_{x,n} = (Q_{x,n} - \langle Q_{x,n} \rangle)/\sigma_{Qx,n}$, $Q'_{y,n} = (Q_{y,n} - \langle Q_{y,n} \rangle)/\sigma_{Qy,n}$

   $\Phi'_n = \mathrm{atan2}(Q'_{x,n}, Q'_{y,n}) / n$

3. Flattening

   $n\Phi''_n = n\Phi'_n + \Sigma 2/i\{-\langle \sin(in\Phi'_n) \rangle \cos(in\Phi'_n) + \langle \cos(in\Phi'_n) \rangle \sin(in\Phi'_n)\}$

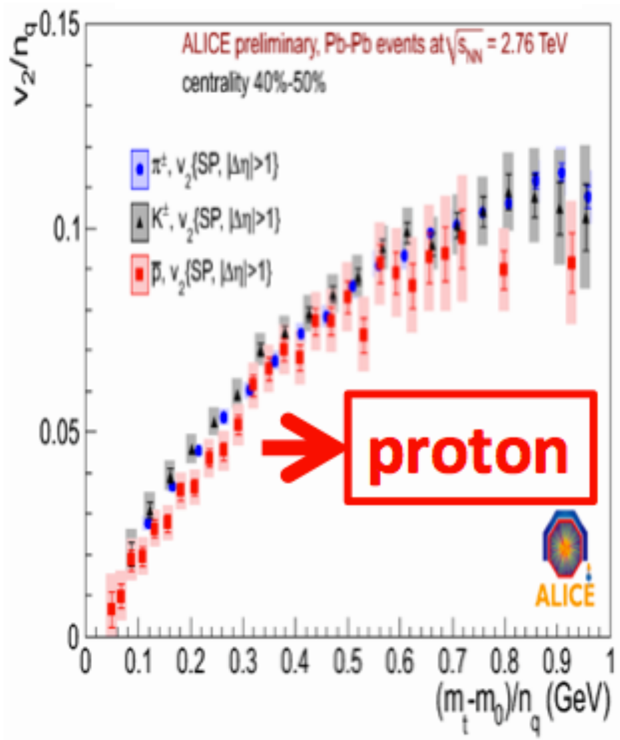




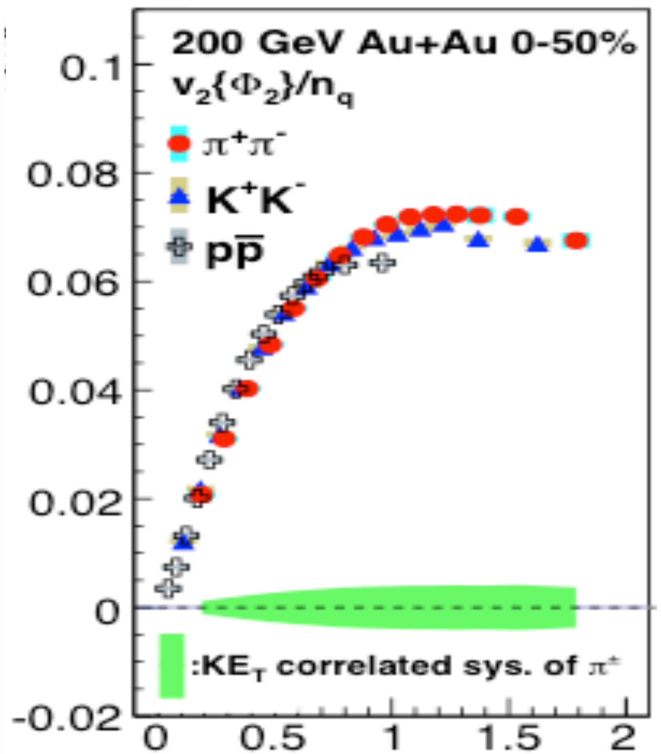
reaction plane detector(RxN)
inner $1.5 < |\eta| < 2.8$
outer $1.0 < |\eta| < 1.5$

Comparison scaling among different energy

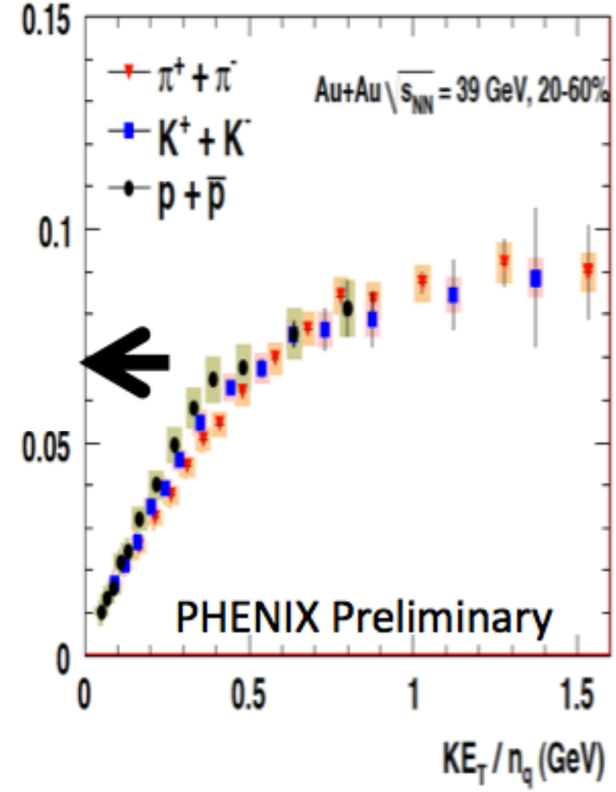
Pb+Pb 2760GeV



Au+Au 200GeV



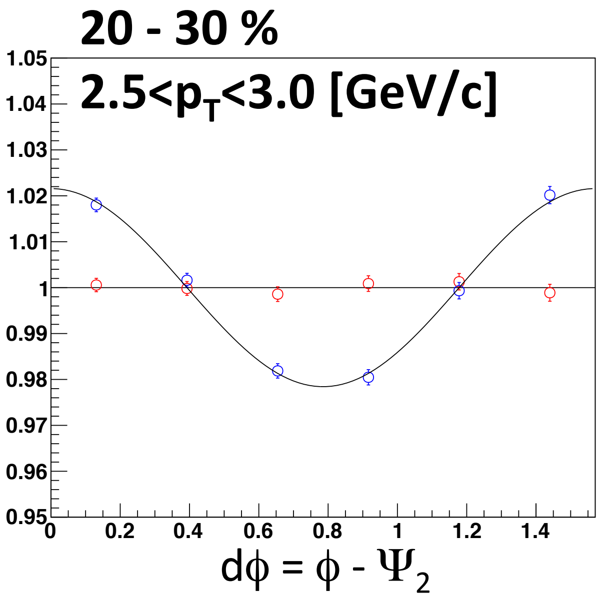
Au+Au 39GeV



- **Proton is shifted**

  Is the strength of radius expansion related?

Fit function dependence w.r.t. v_2

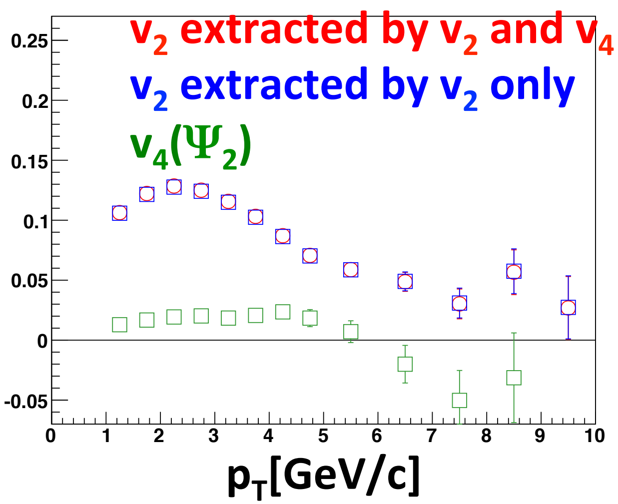


$data / N_0[1+2v_2\cos\{2d\phi\}+2v_4\cos\{4d\phi\}]$

$data / N_0[1+2v_2\cos\{2d\phi\}]$

Black line is $1+2v_4\cos\{4d\phi\}$

These v_2 are consistent within 3%.



v_2(fitted by v_2 only)/v_2(fitted by v_2+v_4)