Measurement Of Direct Photon Collective flow In $\sqrt{s_{NN}}$=200GeV AuAu Collisions at RHIC-PHENIX experiment

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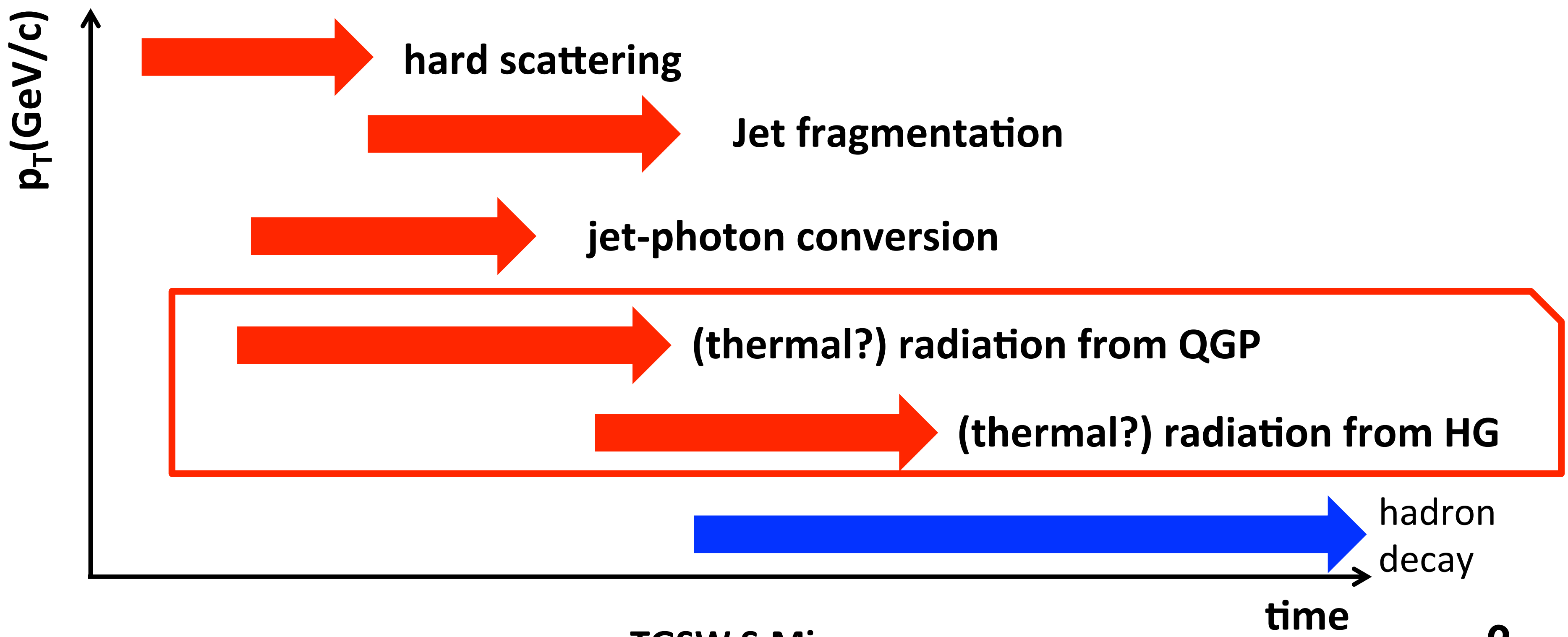
What are direct photons ?

Direct photons: all photons except those originating from hadron decays.

- **Good probe since they penetrate the QGP**
- **Access to the initial stage of the collisions**

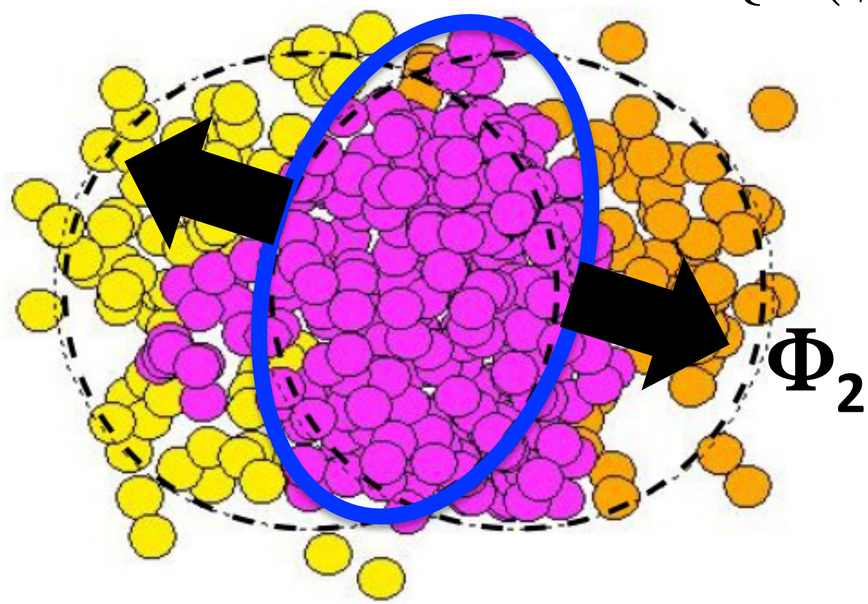


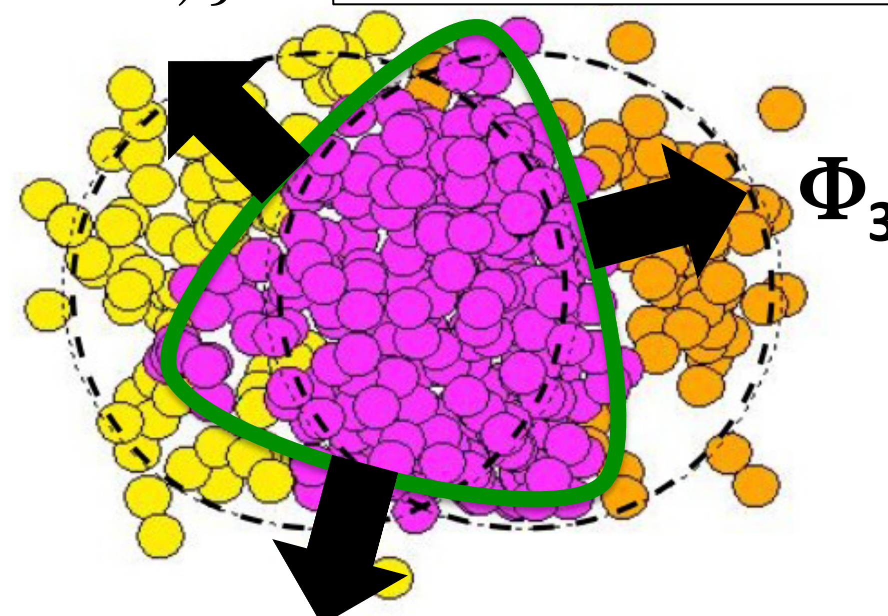
Higher Order Azimuthal Anisotropy

$$\frac{dN}{d(\phi - \Psi_n)} = N_0[1 + 2\sum_{n=1}^{\infty} v_n cos\{n(\phi - \Phi_n)\}]$$

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

Φ_n : Participant Plane



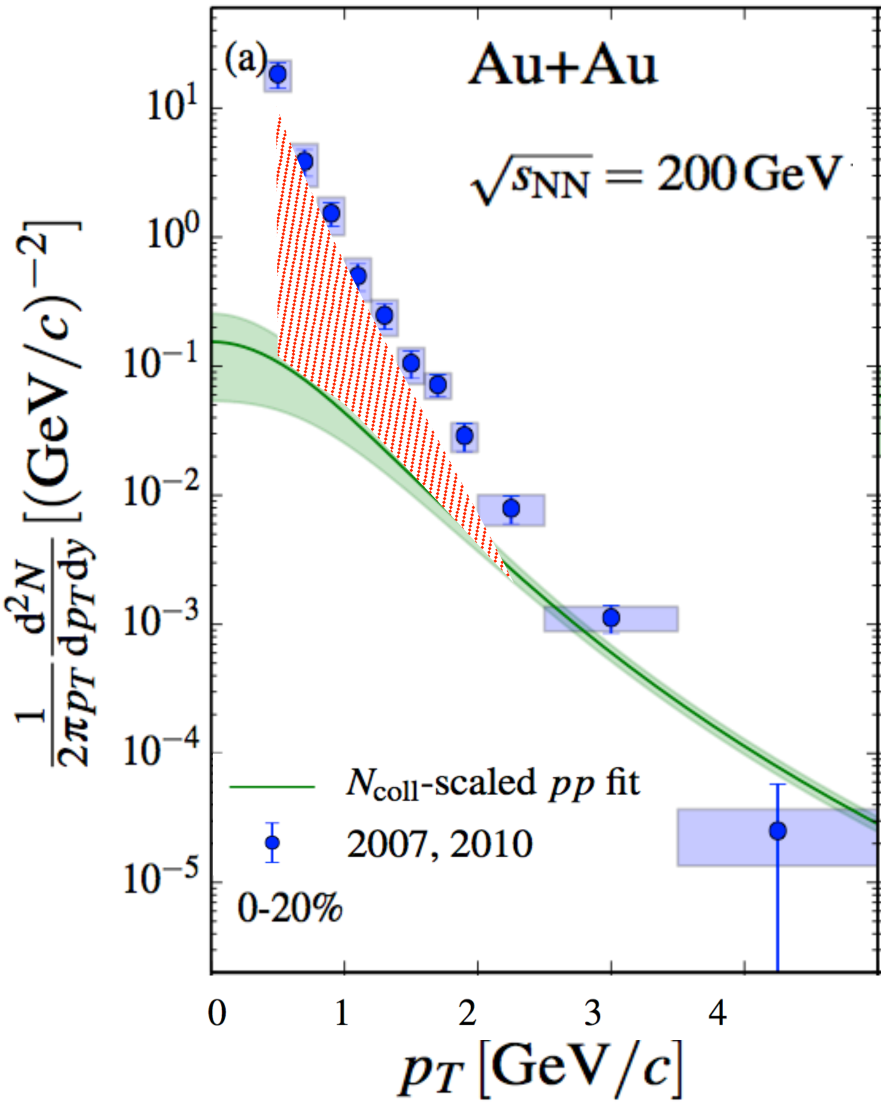


v_3 comes from participant position fluctuations, viscosity dampens higher order terms.

- **Define initial geometry calculating model**
- **Constrain viscosity(η/s) of QGP**

Radiated from very hot medium (p_T spectra)

arXiv:1405.3940v1



$$a(1+p_T^2/b)^c$$

The p_T spectra from p+p data is fitted and extrapolated below 2 GeV/c.

$$Ae^{-p_T/T_{eff}}$$

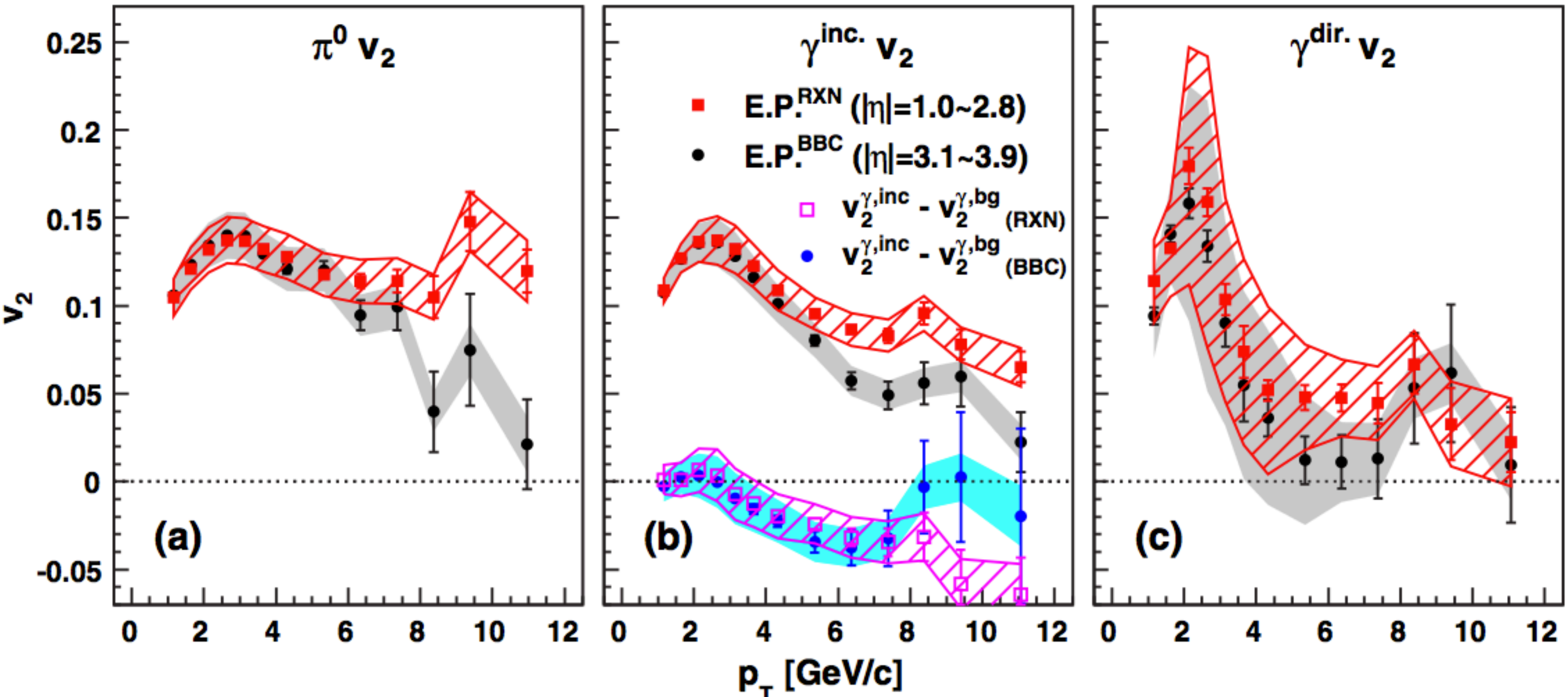
The excess of p_T spectra are fitted and effective temperature is extracted.

It is about 240 MeV. (T_{FO}≈100MeV)

Photons are emitted from very hot medium at early time of collisions.

Very large direct photon v_2

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

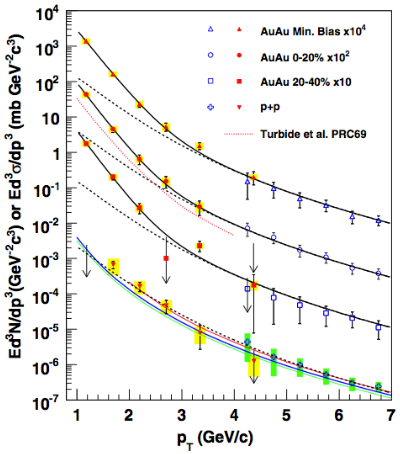


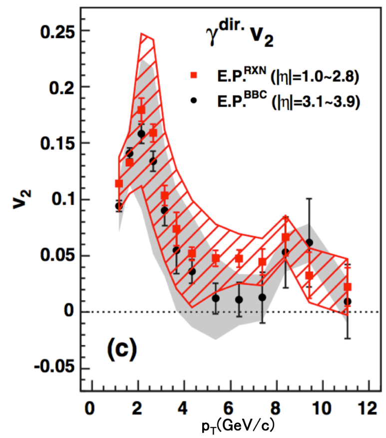
It is consistent with hard photons produced in the initial hard collision at high p_T.

The strength of photon v_2 at low p_T is comparable to that of hadron v_2.

Photons are mainly emitted from late stage of the collisions.

Direct Photon Puzzle



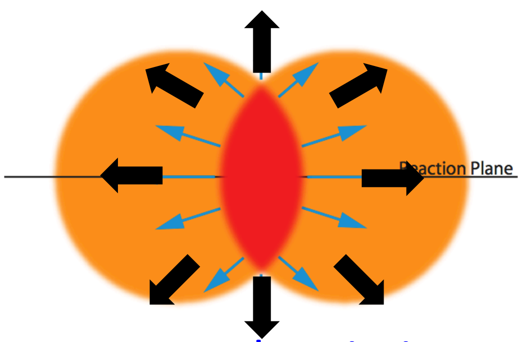


Yield enhancement

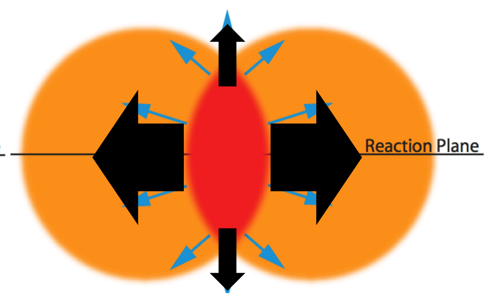
Suggests early emission when temperature is high at or above 300MeV

Large elliptic flow (v_2)

Suggests late emission, when temperature is low, collective motion is large



Integrated emission



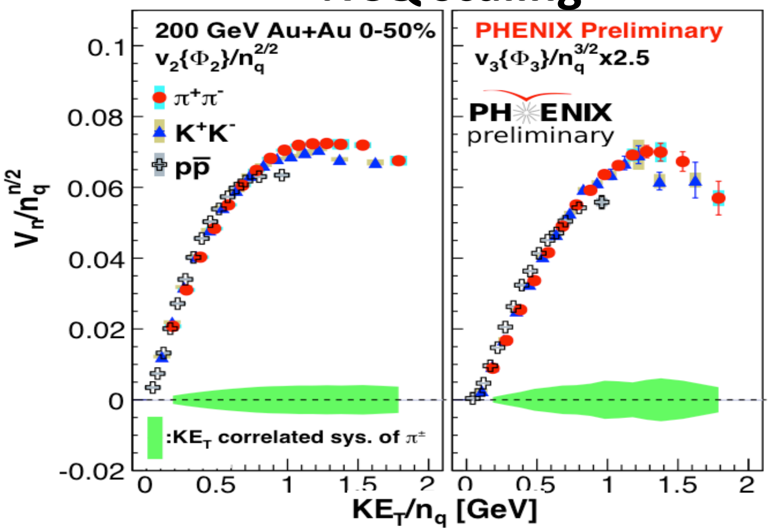
differential emission

It is a challenge for models to explain simultaneously the excess of direct photon yield and the large elliptic flow (v_2).
Direct photon v_3 is studied for additional constraining photon production mechanism.

Analysis flow

1. π^0, $\gamma^{inc.}$ v_n measurement

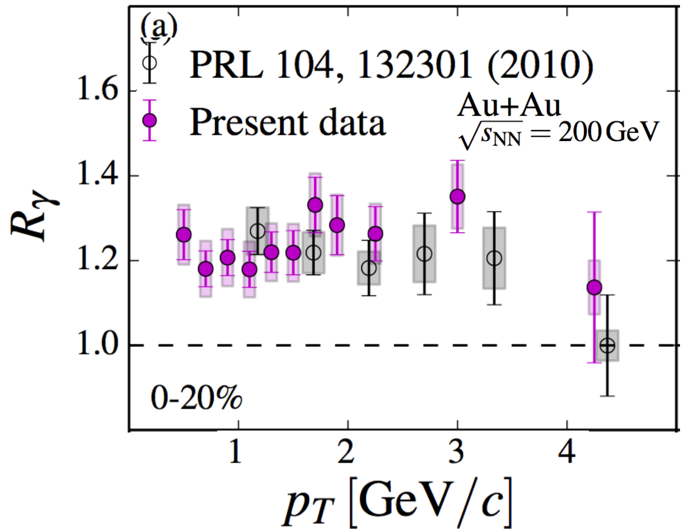
NCQ scaling



arXiv:1405.3940

2. $\gamma^{dec.}$ v_n estimation from π^0 v_n

Meson spectra are assumed by m_T scaling.
Meson v_n are assumed by the number of constituent quark (NCQ) scaling.



3. $\gamma^{dir.}$ v_n calculation

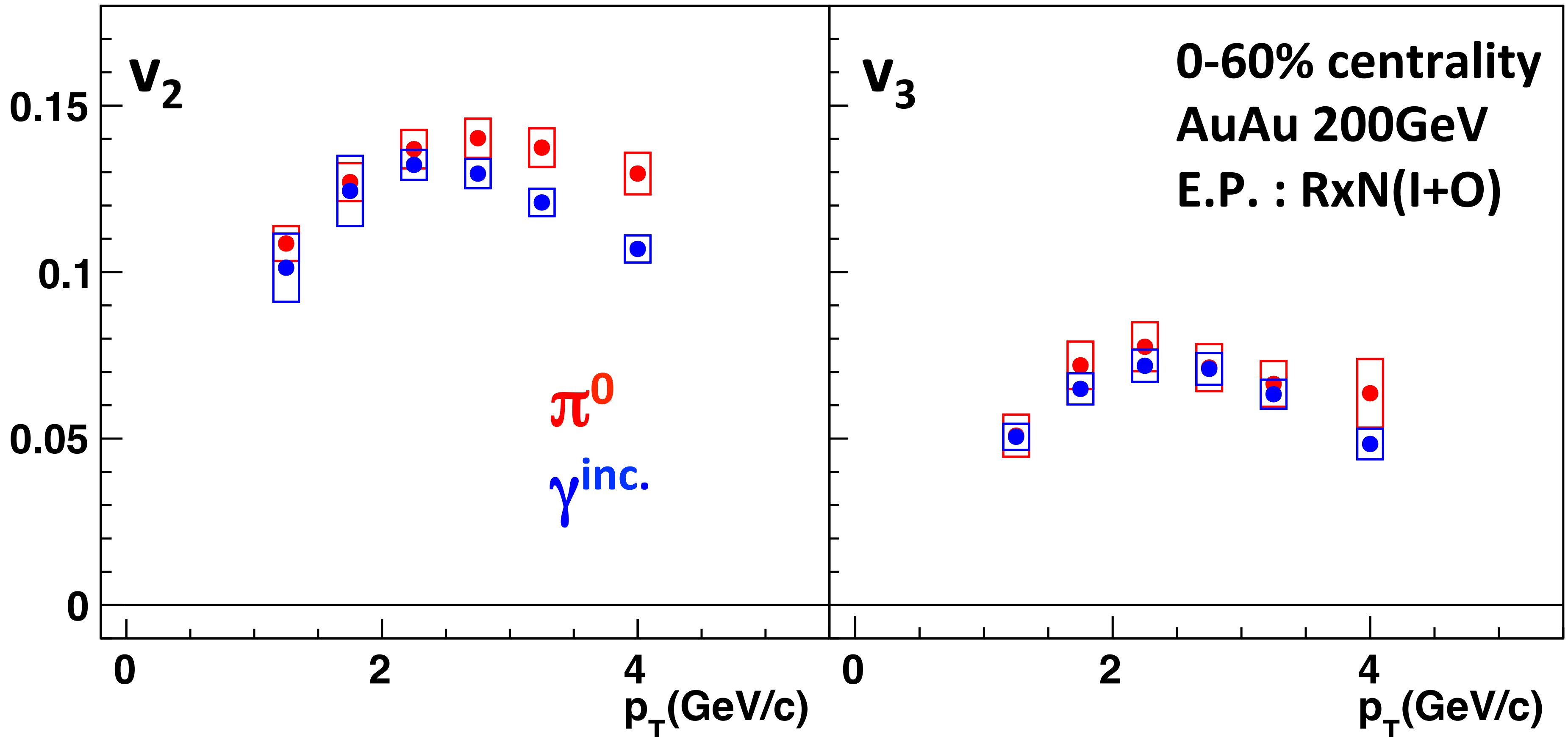
R_γ is measured by external photon conversion method.

$$\nu_n^{dir.} = \frac{R_\gamma \nu_n^{inc.} - \nu_n^{dec.}}{R_\gamma - 1}$$

$$R_\gamma = N_{inc.}/N_{dec.}$$

π^0 and inclusive photon v_n resuluts

π^0 and inclusive photon v_2 and v_3 are measured.
Mesons v_n are estimated by the NCQ scaling from π^0 v_n results.

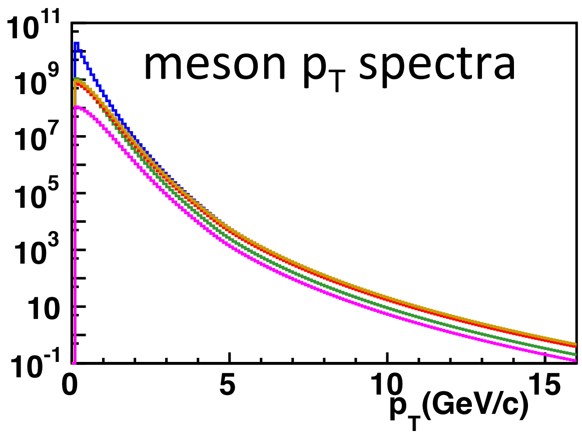


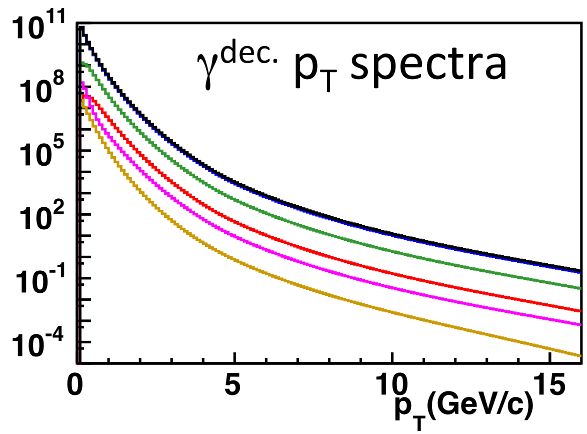
Hadronic decay photon

π ρ
η η'
ω **all $\gamma^{dec.}$**

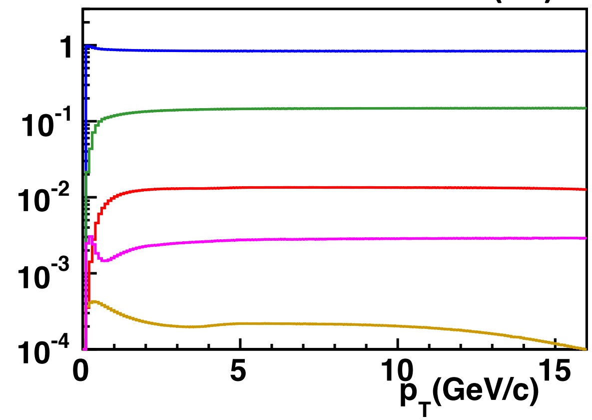
The p_T spectra and v_n are estimated from π.

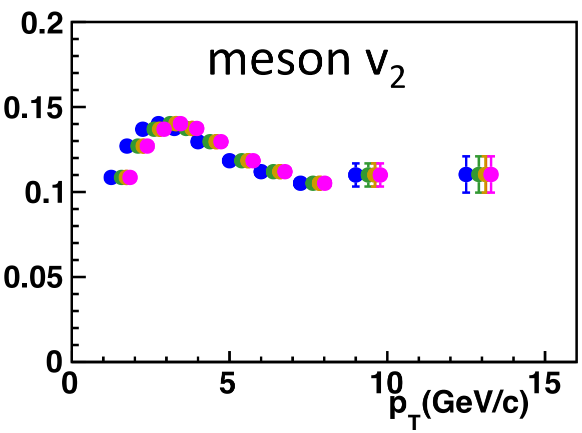
- p_T spectra : m_T scaling
- v_n : quark number scaling

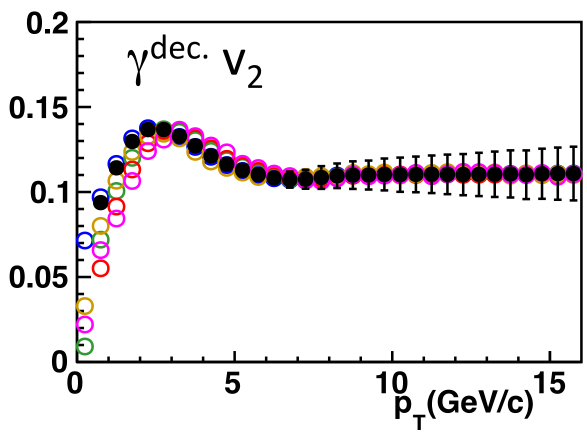




contribution ratio (R^i)







m_T scaling

$$p_T^{'} = \sqrt{p_{T,\pi^0}^2 + M_{meson}^2 - M_{\pi^0}^2}$$

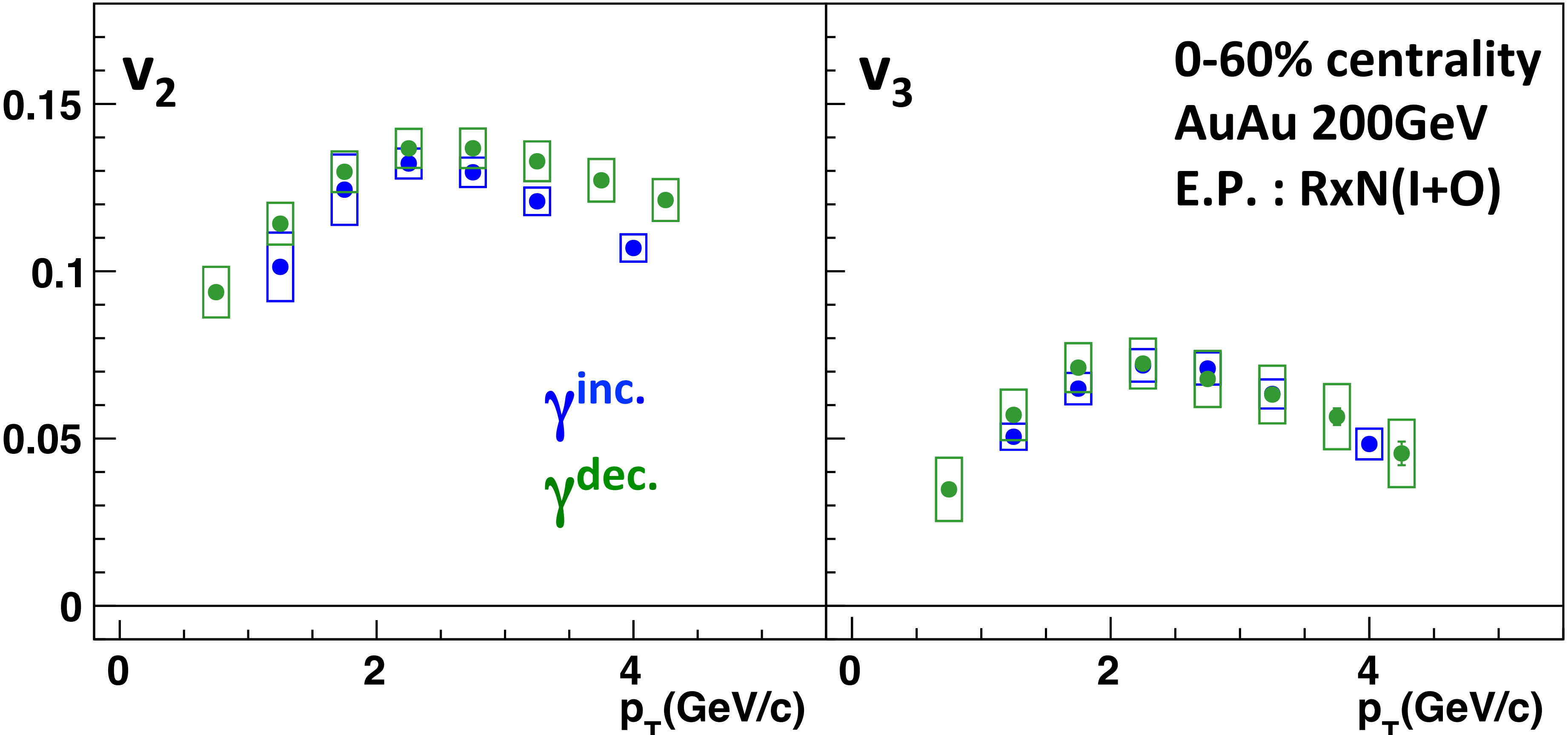
decay photon v_n

$$v_n^{dec.} = \sum_i R^i v_n^{dec.i}$$

Inclusive and decay photon v_n comparison

Direct photon v_n are extracted from the deviation between inclusive and decay photon via below function.

$$\nu_n^{dir.} = \frac{R_\gamma \nu_n^{inc.} - \nu_n^{dec.}}{R_\gamma - 1}$$



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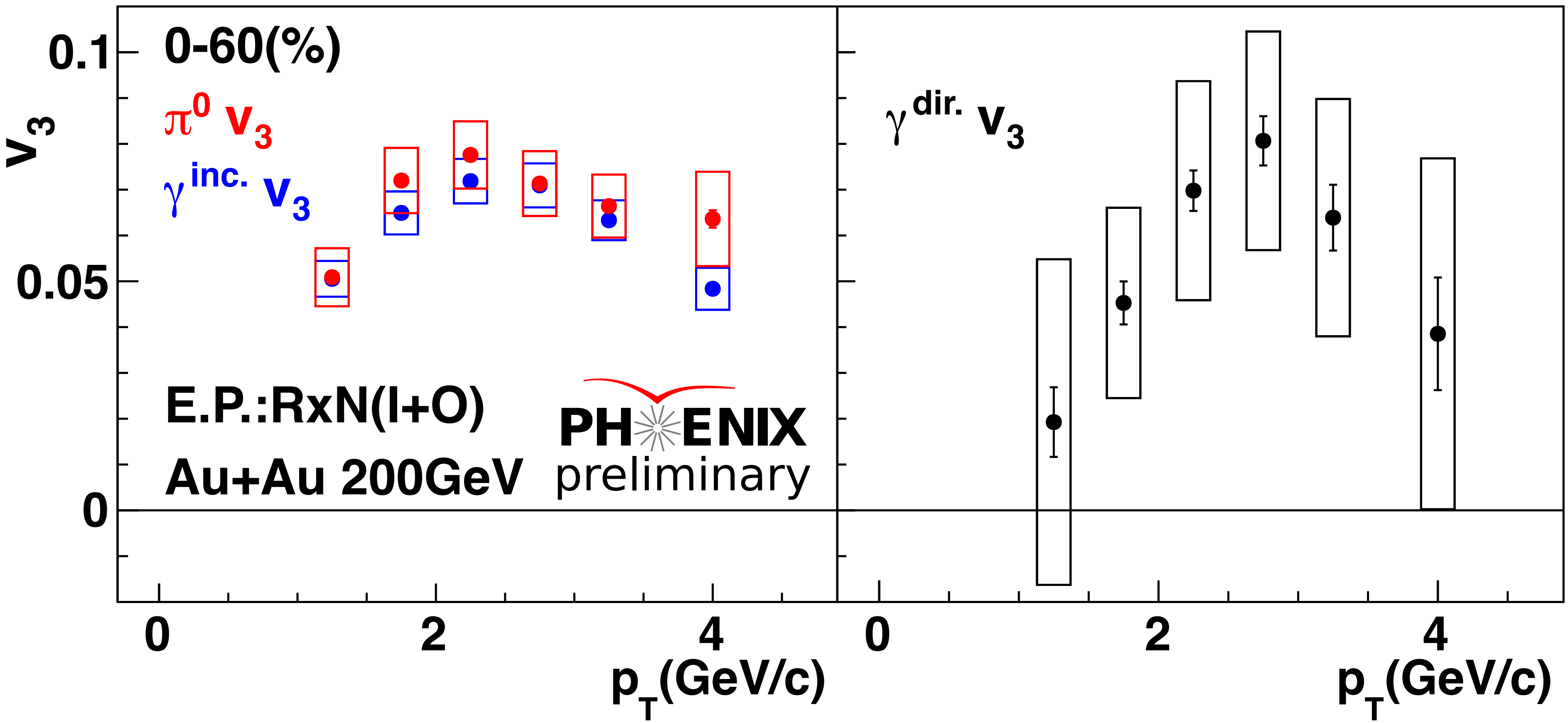
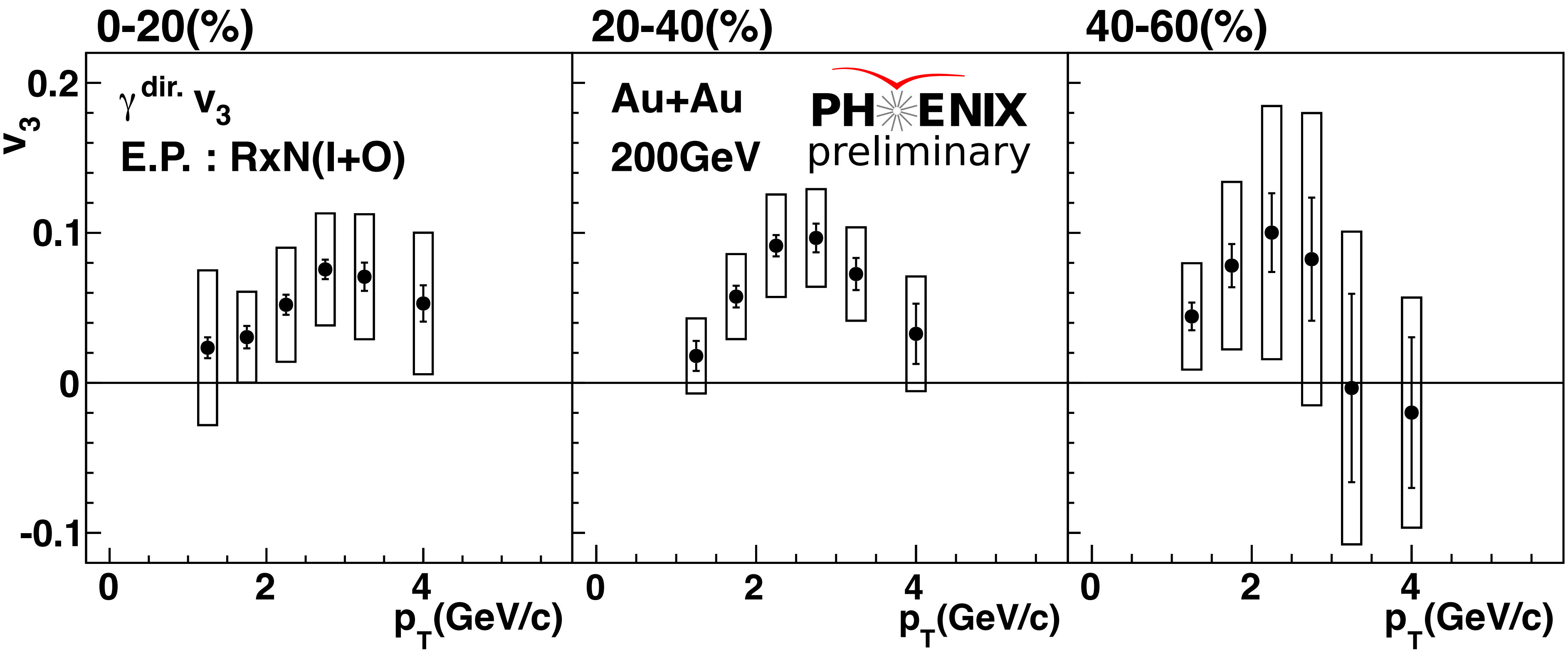
The result of direct photon v_3



The magnitude of $\gamma^{dir.}$ v_3 is similar to π^0, a similar trend as a seen in case of v_2.

Photon azimuthal anisotropies may be affected by expansion of QGP.

Centrality dependence of direct photon v_3

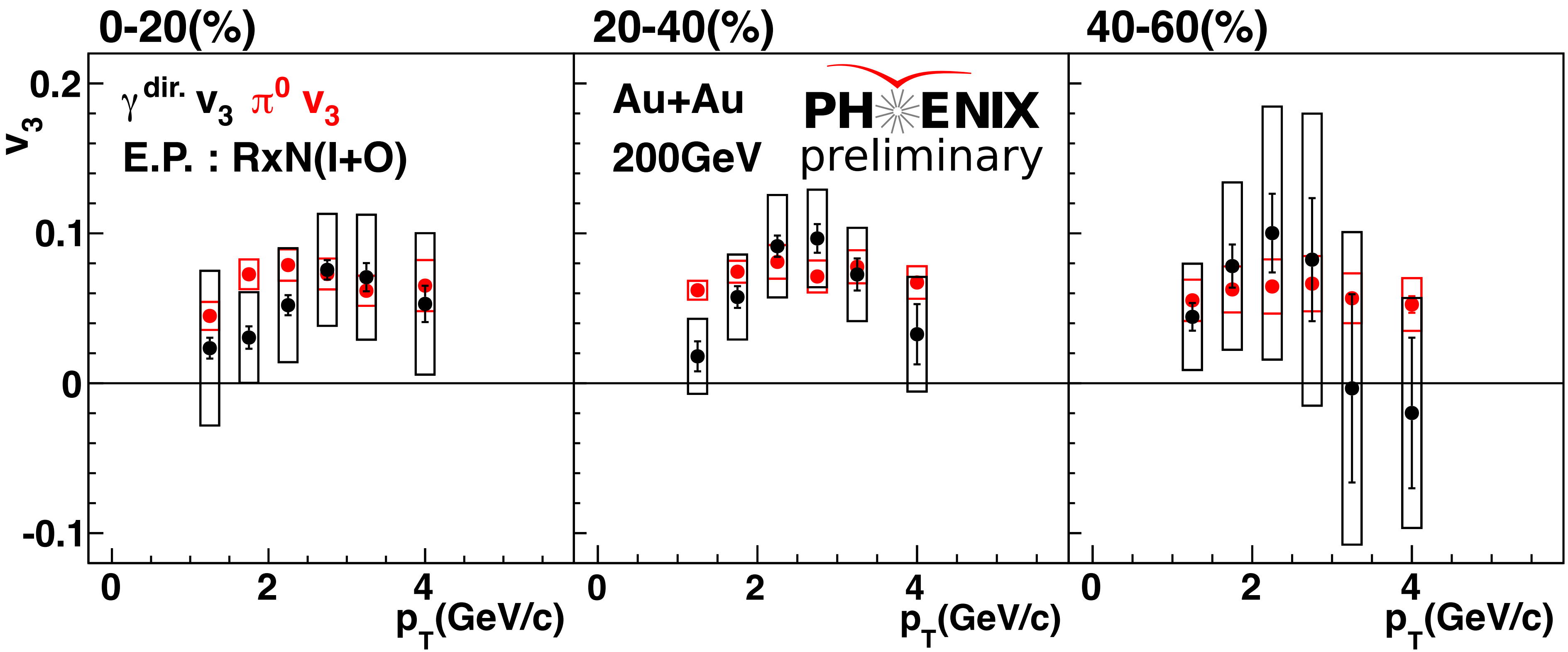


η range of RxN(I+O) is from 1.0 to 2.8.

Non-zero, positive v_3 is observed in all centrality bins.

No strong centrality dependence: similar tendency as for charged hadrons (P.R.L. 107, 252301 (2011)) and π^0.

$\gamma^{dir.}$ and π^0 v_3 show similar trend



The centrality (in)dependence of $\gamma^{dir.}$ v_3 is also observed for π^0 v_3.

Summary

Soft photons have provided many interesting physics.
There is the direct photon puzzle, and it has not yet been understood.

Direct photon v_3 is measured in several centrality bins.
It is observed that

- $\gamma^{dir.}$ v_3 is non-zero and positive
- the strength of $\gamma^{dir.}$ v_3 is comparable to hadron v_3

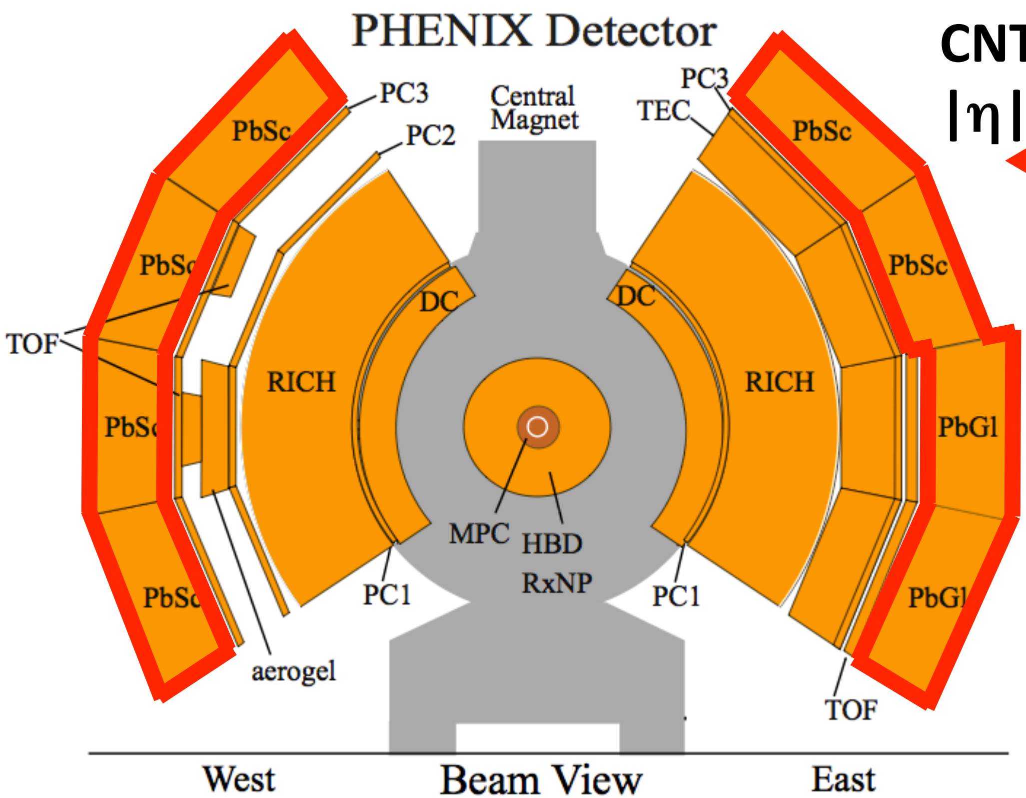
They are similar trend to $\gamma^{dir.}$ v_2.

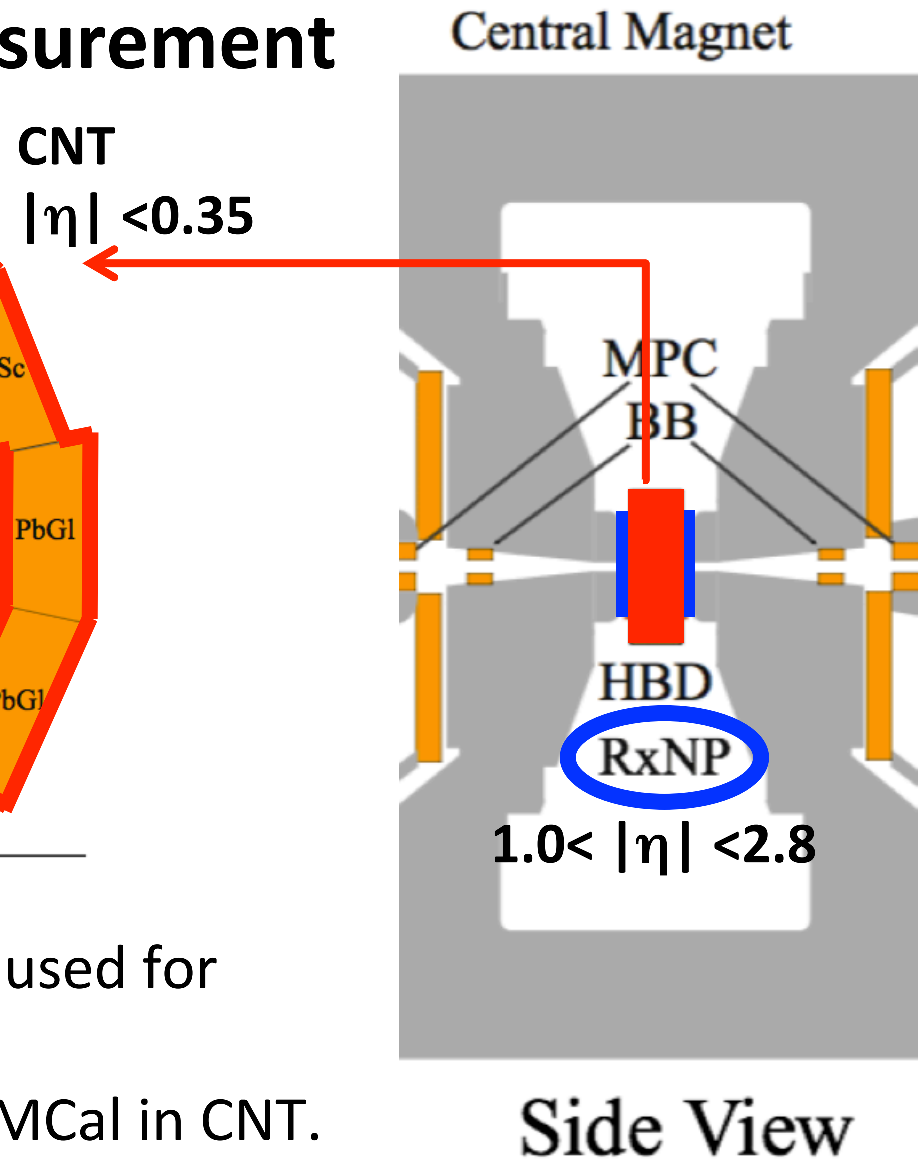
- don't have strong centrality dependence

It is similar tendency to hadron v_3.

The results of direct photon v_3 could provide important keys for understanding photon production mechanism.

Azimuthal anisotropy measurement



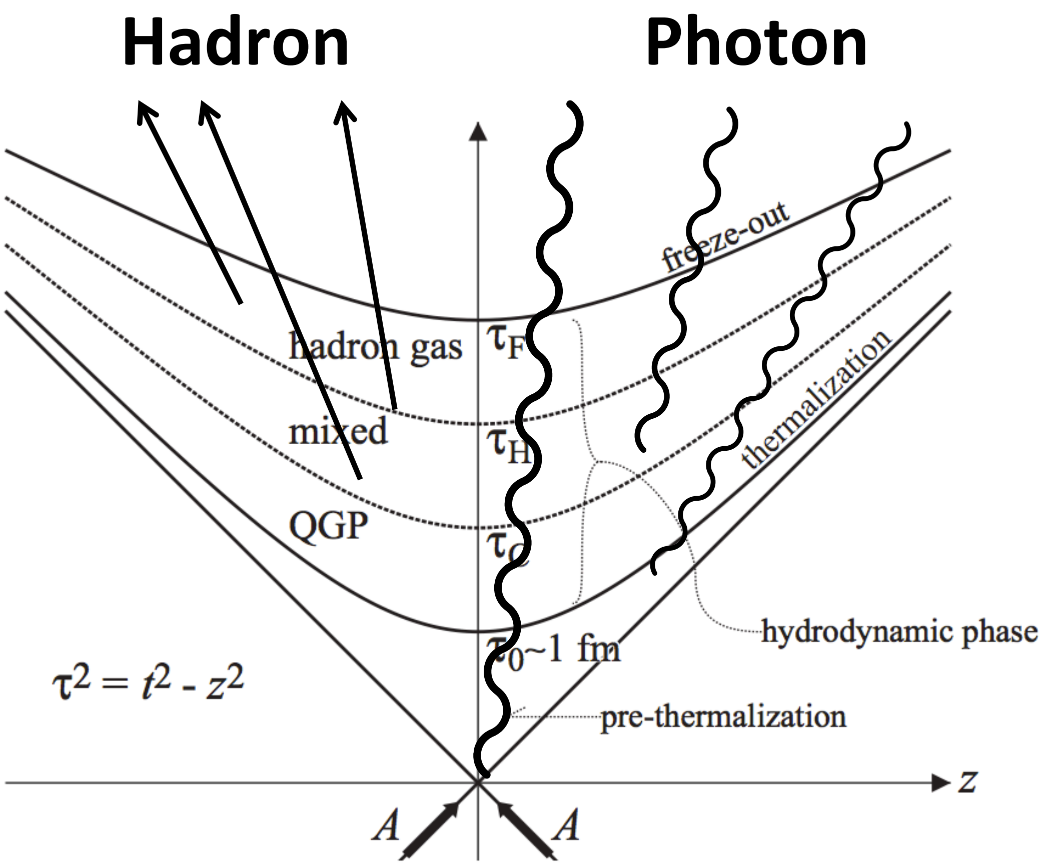


Reaction Plane detector (RxNP) is used for measuring Event Plane.

Photons and π^0 are detected by EMCal in CNT.

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

Photon analysis in Heavy Ion Collision



Hadron : after freeze-out
Photon : any stages

Production mechanism

Initial hard scattering
parton - medium interaction
Jet fragmentation
Radiation from QGP and Hadron Gas
hadron decay

Photon analysis

✓ **Advantage :**

Penetrating the medium
Color-less and charge-less
Access to the initial stages of collision

✓ **Disadvantage :**

Photons from different stages superimposed

Direct photon puzzle

Elliptic flow:

It is needed enough time to get large collective flow.
Hadrons are emitted from QGP at freeze-out, when it is late state.
Photons from QGP and HG are dominant at low p_T and they have large v_2.

-> Photons are emitted at late state??

p_T spectra:

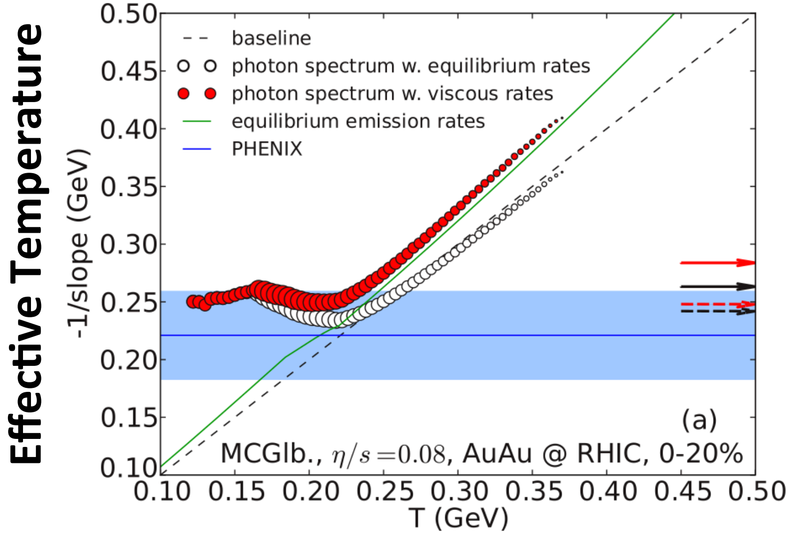
radiation from QGP and HG are dominant at low p_T
emitted from very hot medium ($T_{eff} \approx 240$MeV) at early time

There is discrepancy.
There is no model to explain simultaneously the both observable.

Why v_3 is measuremed?

Strong photon v_2 has not yet been understood.

P.R.C 89, 044910 (2014)



Radial flow effect :

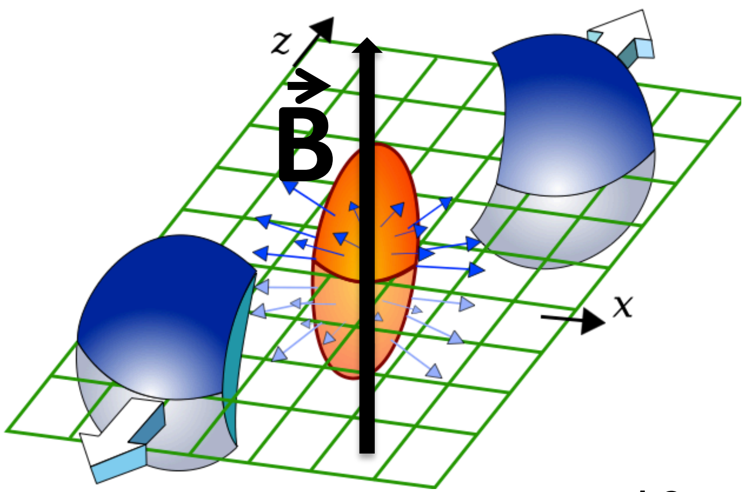
Effective temperature is affected by radial flow.

$v_2>0$: $v_3>0$

Strong magnetic field :

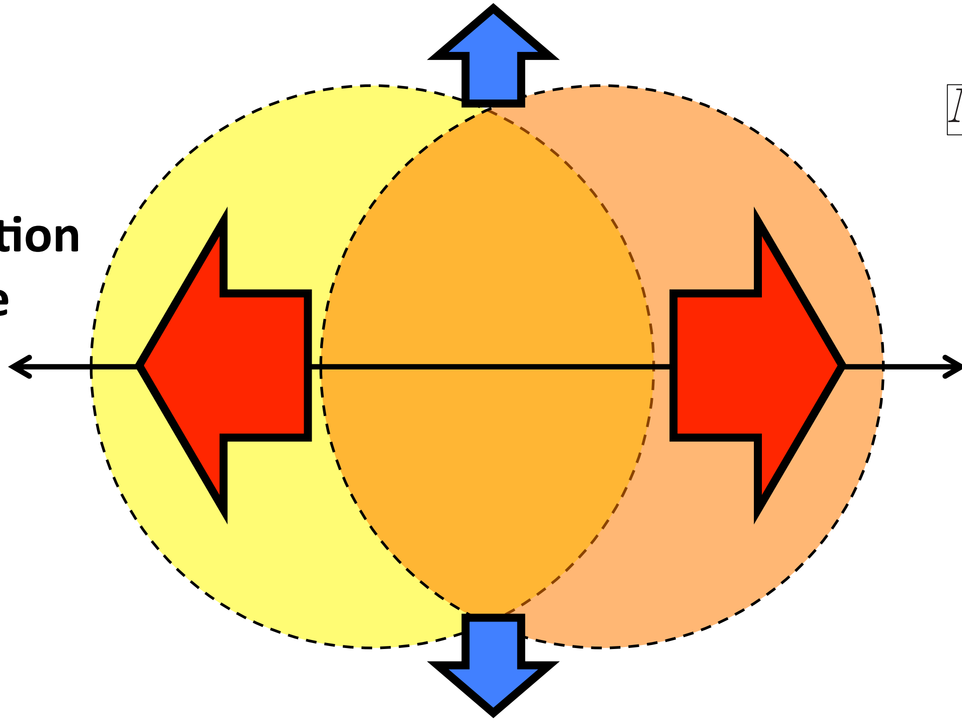
Direction of magnetic field and Ψ_2(R.P.) are related.

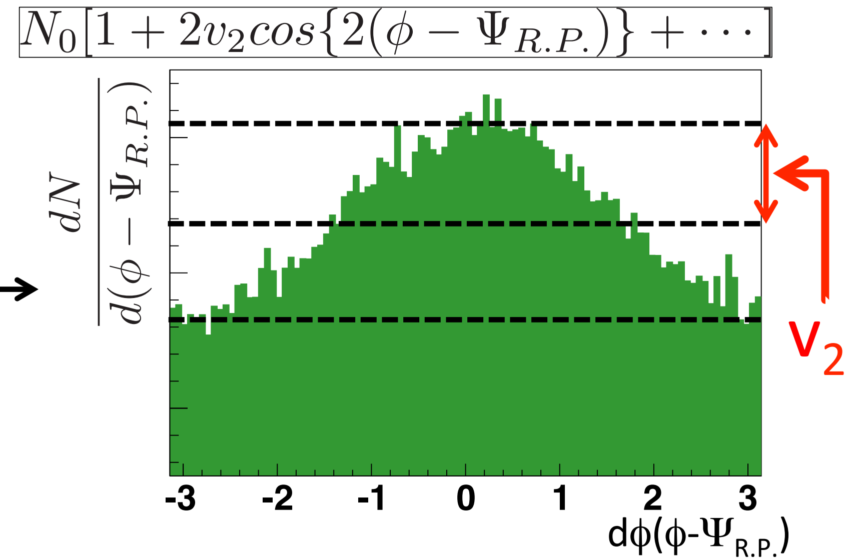
$v_2>0$: $v_3\approx0$



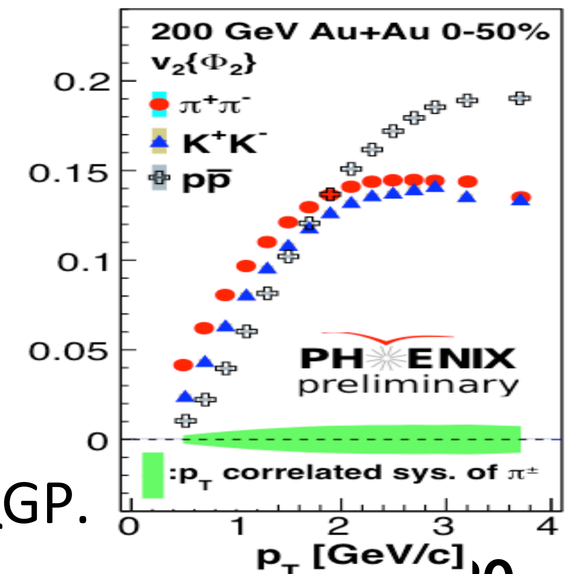
v_3 measurement could provide additional constrain photon production mechanism.

Azimuthal anisotropy (Elliptic flow)



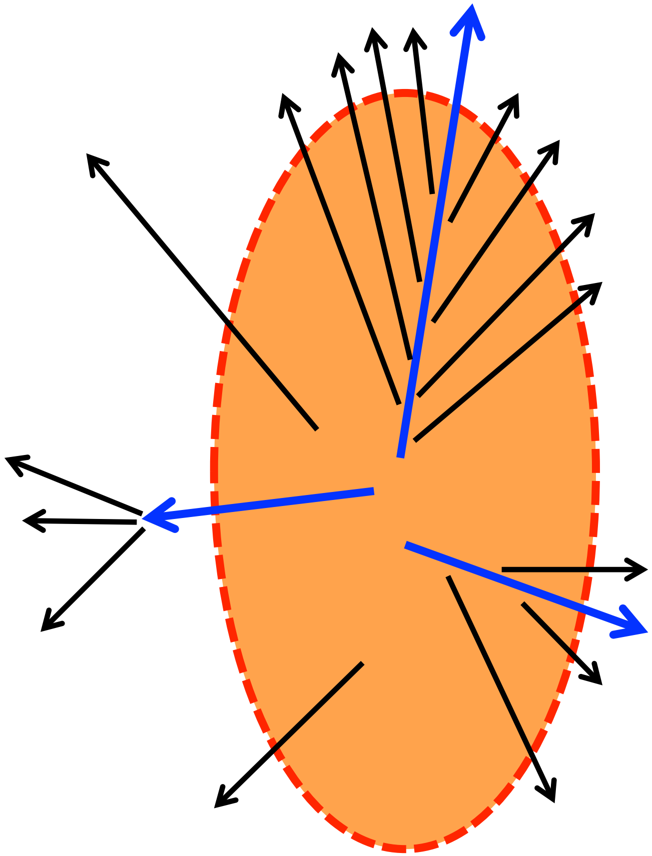


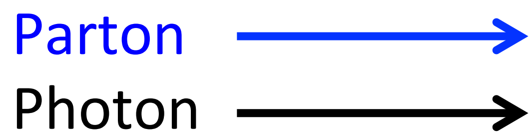
- anisotropic pressure gradient in participant (Initial geometry)
- QGP expansion (viscosity (η/s))
- particles emission (coalescence)



It relates **<u>participant initial geometry</u>** and η/s of QGP.

Photon emitting angle dependence w.r.t. R.P.





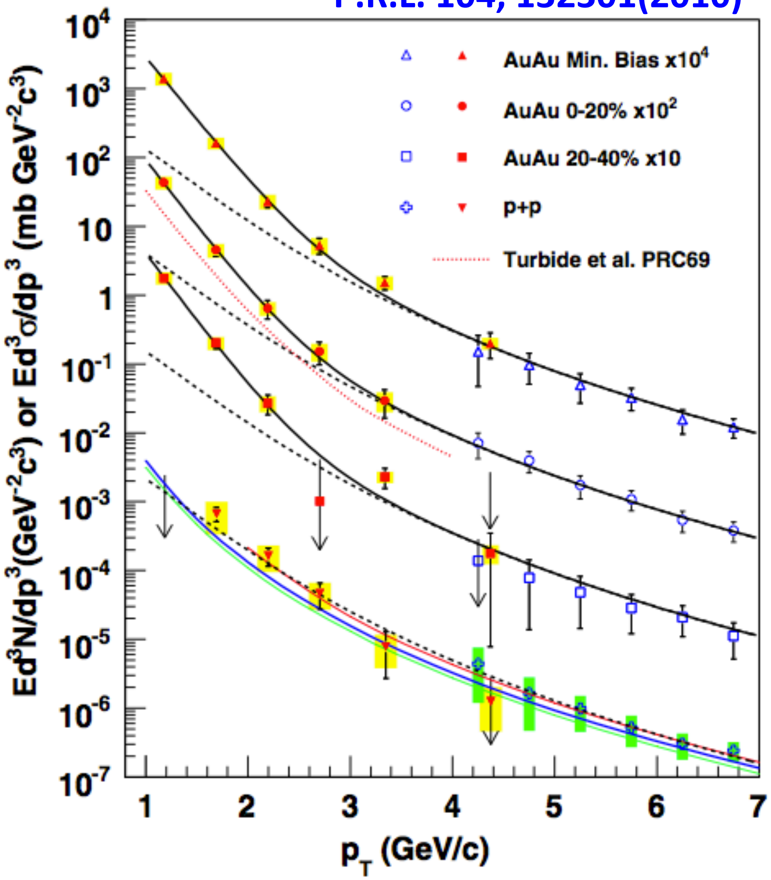
Angular dependence of emission

Initial hard scattering : $\mathbf{v_2 \approx 0}$
Medium induced : $\mathbf{v_2 \leq 0}$
Jet fragmentation : $\mathbf{v_2 \geq 0}$
Radiation from medium : $\mathbf{v_2 > 0}$

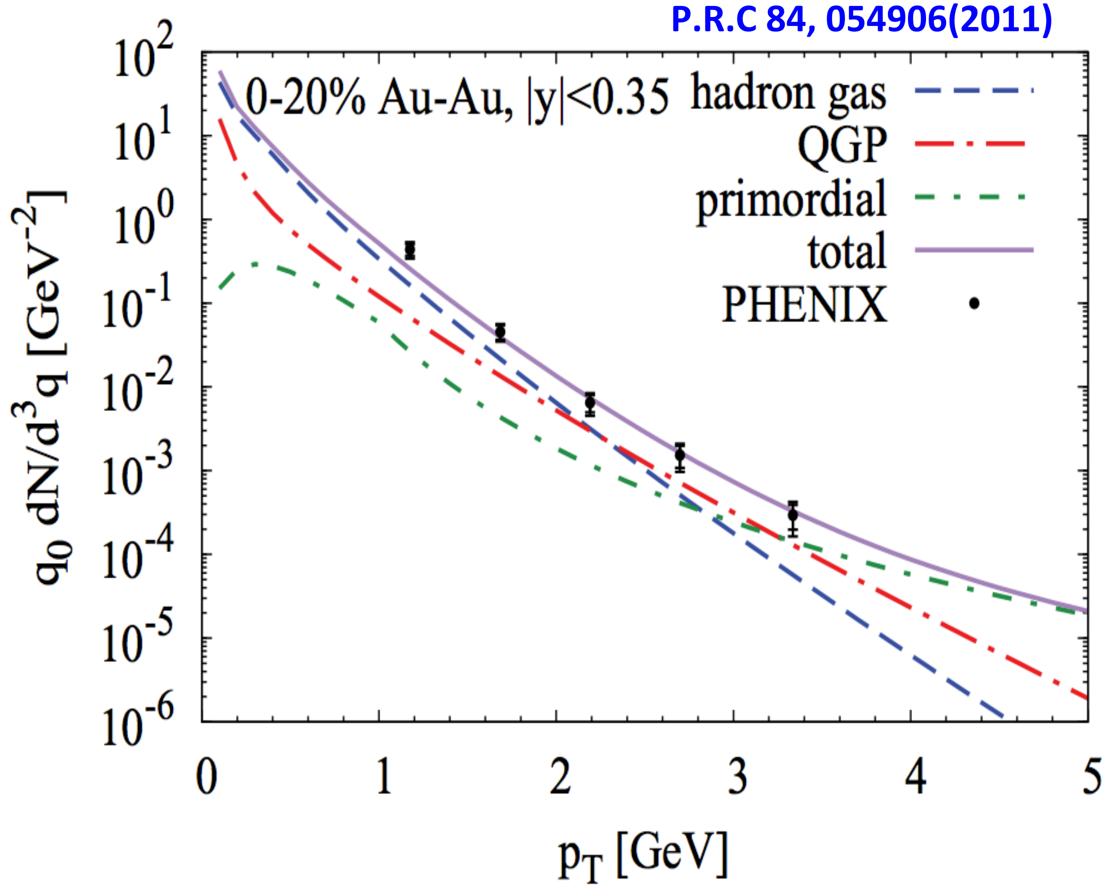
Photon v_2 measurement is a powerful probe to constrain the photon source.

Direct photon p_T spectra

P.R.L. 104, 132301(2010)



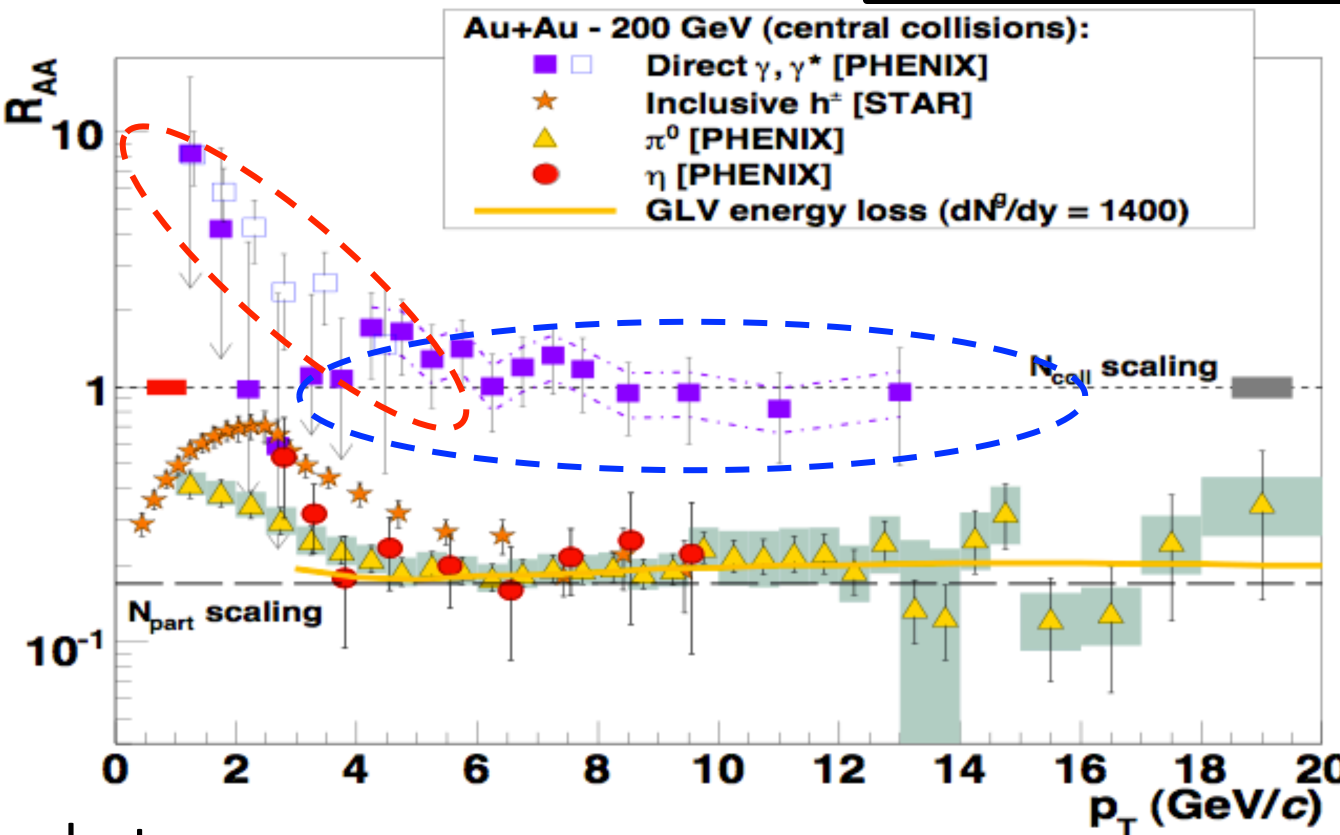
P.R.C 84, 054906(2011)



Photons from each source have different p_T distribution pattern. Photons radiated from QGP and HG are dominant in low p_T and fraction of photons from other sources increases with increasing p_T.

Medium effect (R_{AA})

$$R_{AA} = \frac{(1/N_{AA}^{evt})d^2N_{AA}/dp_T dy}{< N_{coll} > /\sigma_{pp}^{inel} \times d^2\sigma_{pp}/dp_T dy}$$



R_{AA}=1
not modified
R_{AA}≠1
medium effect

Hadron
less than unity
-> medium effect

photon

R_{AA}=1 : not modified

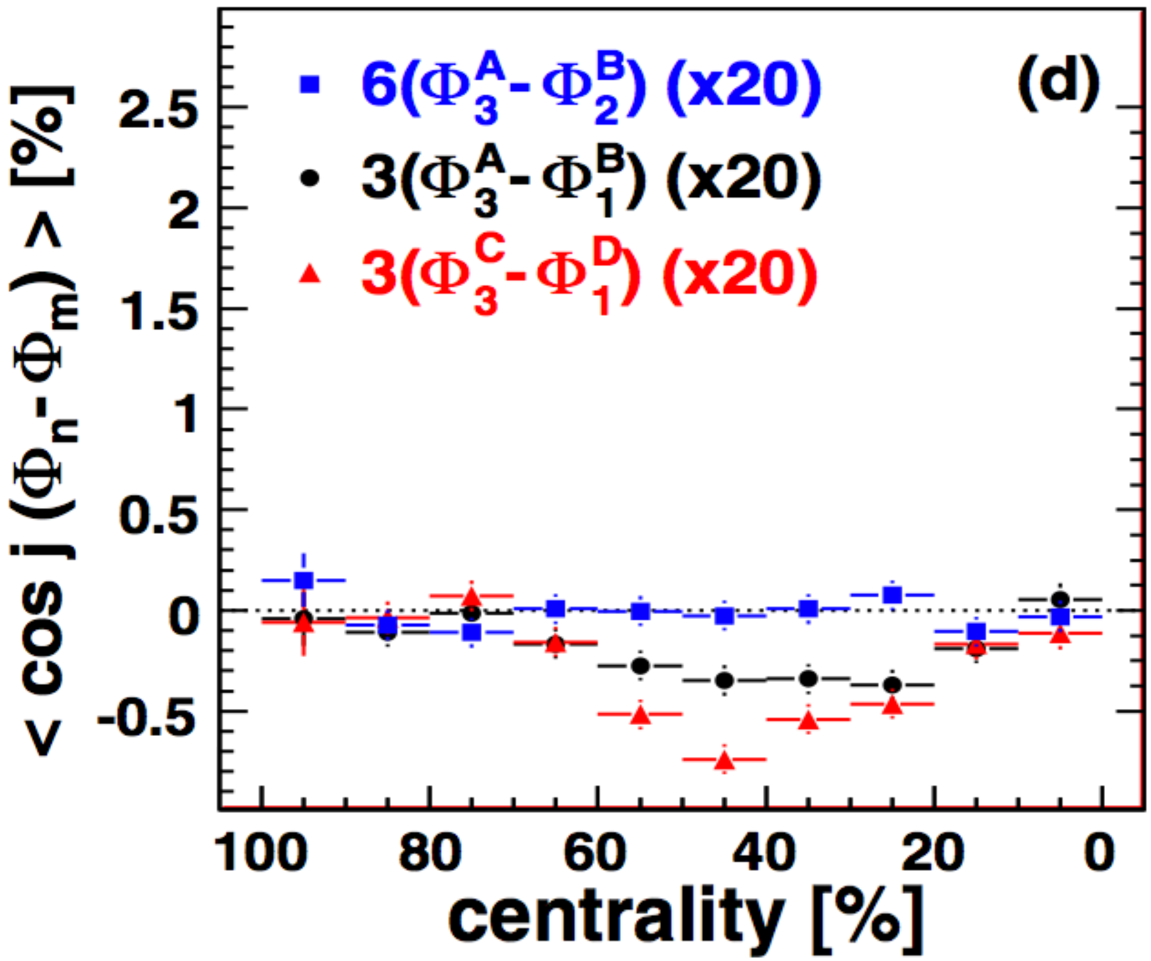
-> Emitted from initial hard scattering is dominant.

R_{AA}<<1 : There are other photon sources which is not in p+p collisions

-> radiated from hot medium??

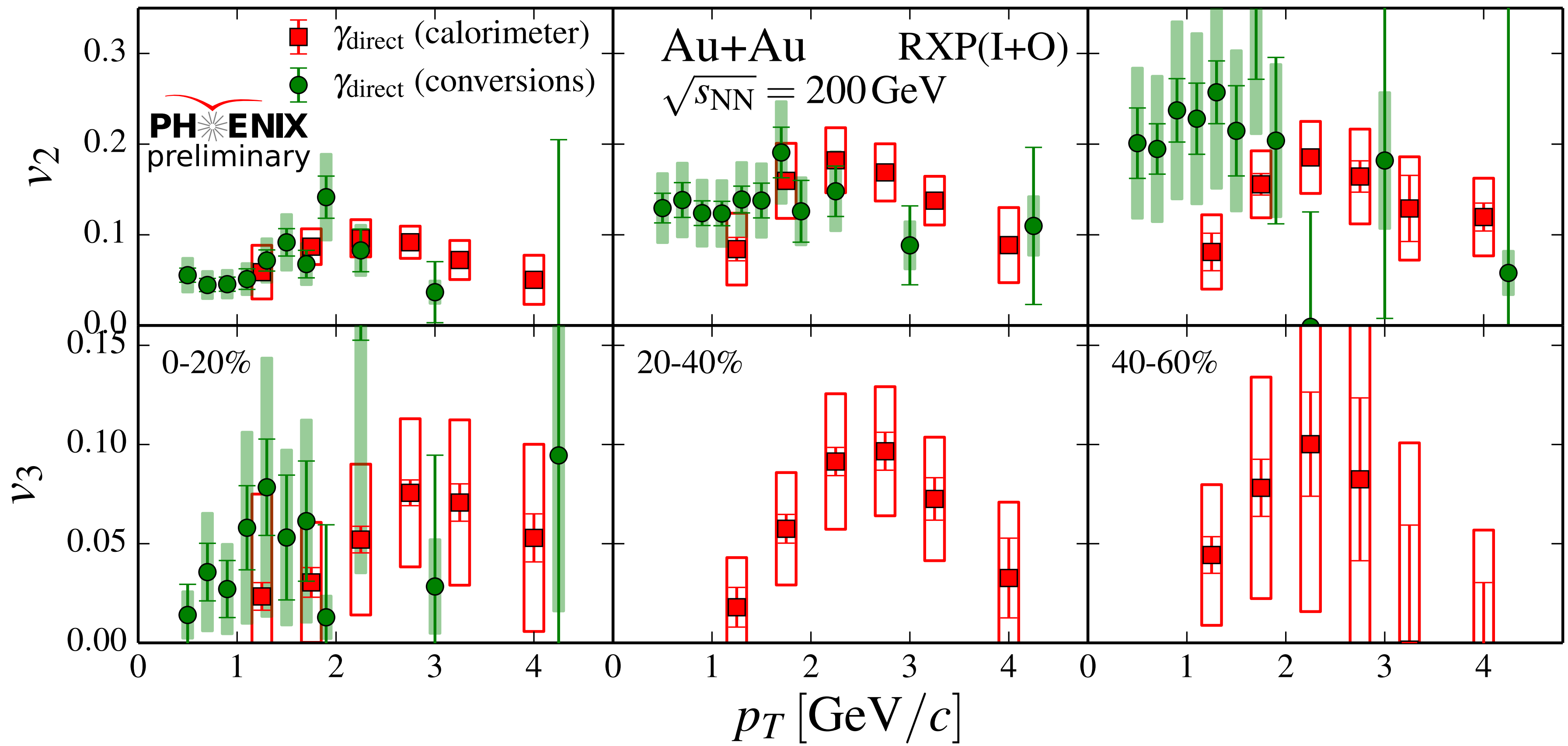
Event Plane correlation

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



Ψ_2 and Ψ_3 are uncorrelated.

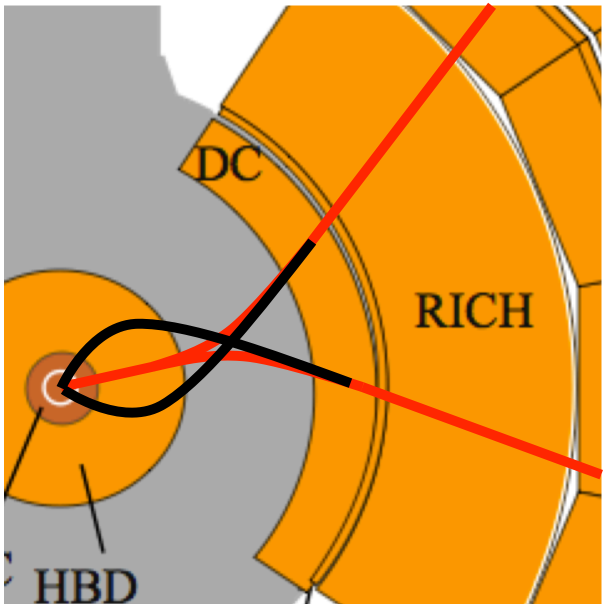
Comparison of $\gamma^{dir.}$ v_n with the two methods



The calorimeter and conversion photon measurements are consistent within systematic uncertainty.

Photons by external conversion

M_{HBD}: Real track
M_{vtx} : Measured track



Published

Real photons in EMCal : 1 - 20 GeV/c

large errors at low p_T (resolution, contamination)

Virtual photons from e^+e^- : 1 - 4 GeV/c

New method

Real photons are measured by e^+e^- pair from **external photon conversion** at the HBD readout plane.

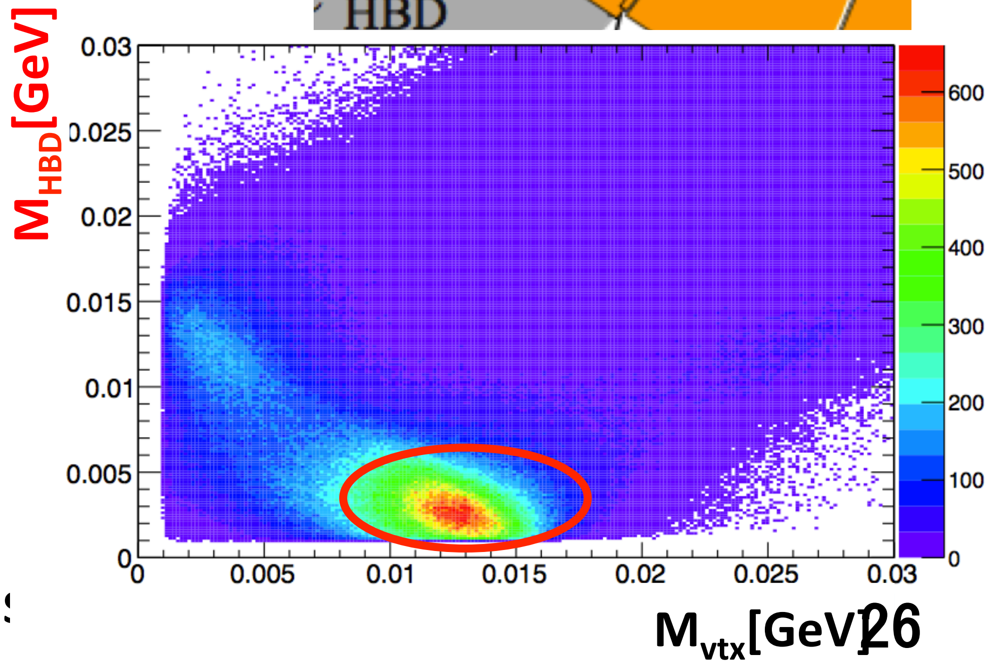
✓ less hadron contamination

✓ good momentum resolution

p_T range : **0.4 ~ 5GeV/c**

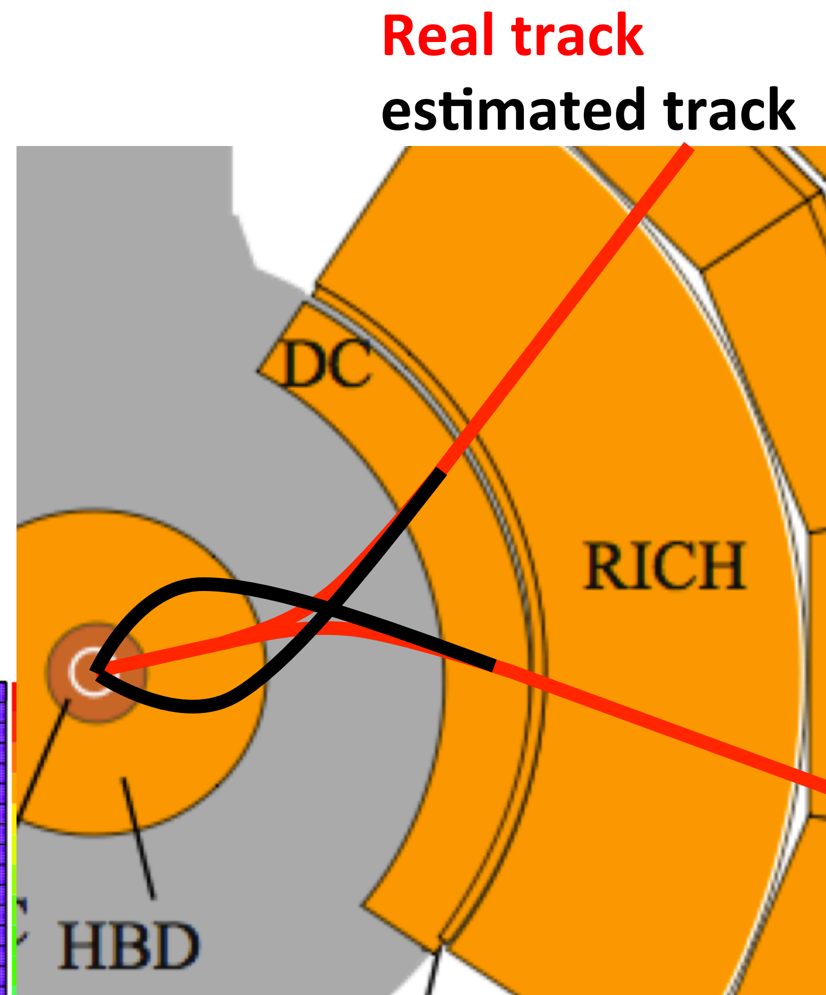
Extended to lower p_T

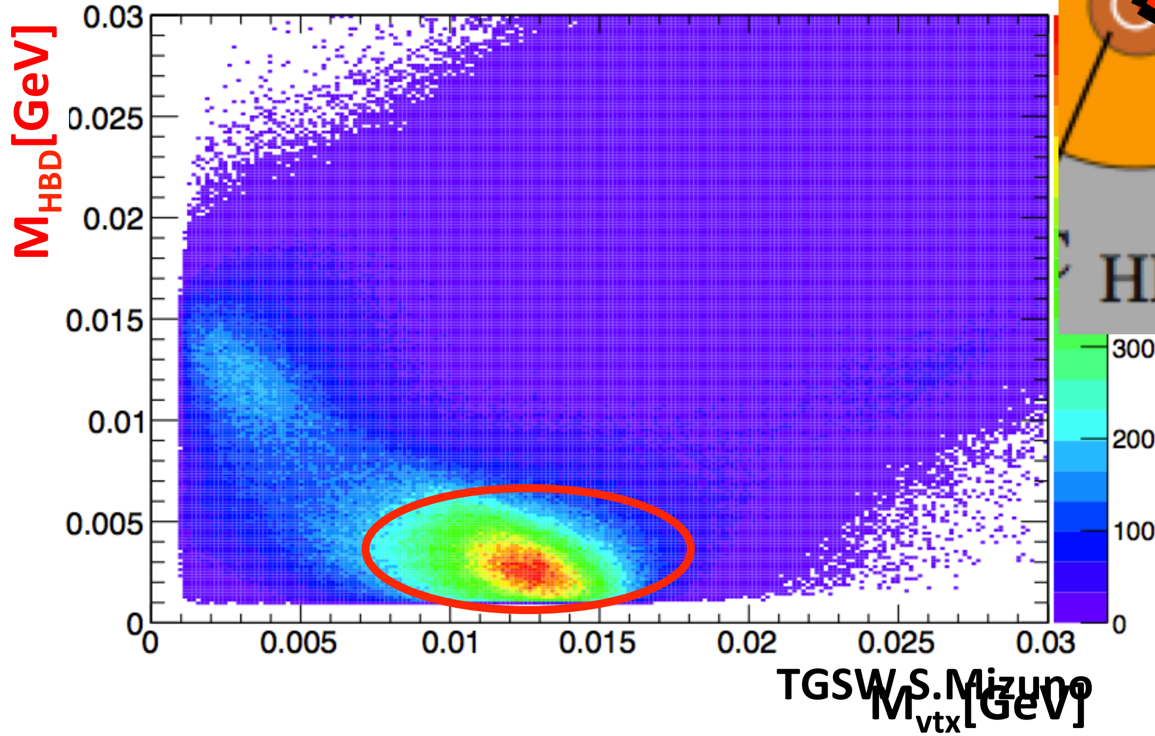
low statistics



External conversion photon

1) real photon converts to e^+e^- in HBD backplane
2) default assumption: track come from the vertex
3) momentum of the conversion tracks will be mis-measured (see black tracks)
4) apparent pair-mass (about 12MeV) will be measured for phtons
5) assume the same tracks originate in the HBD backplane
6) re-calculate momentum and pair mass with this “alternate tracking model”
7) for true converted photons M_{atm} will be around zero





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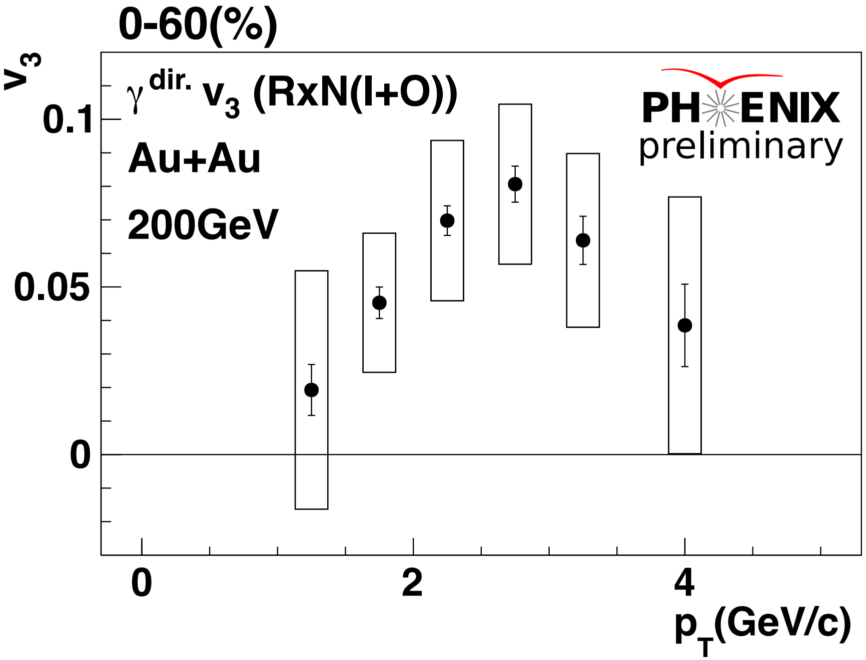
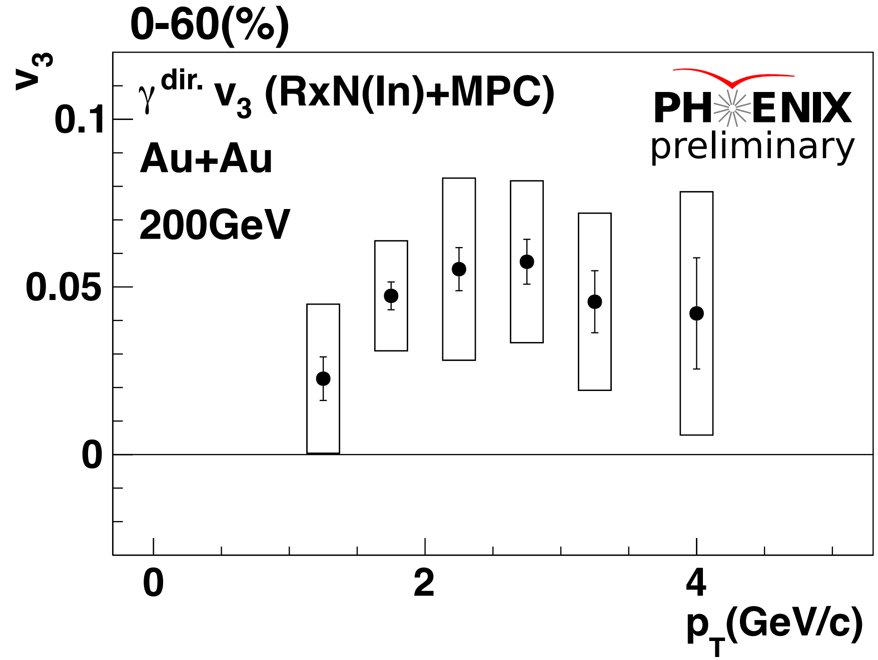
Comparison $\gamma^{dir.}$ v_3

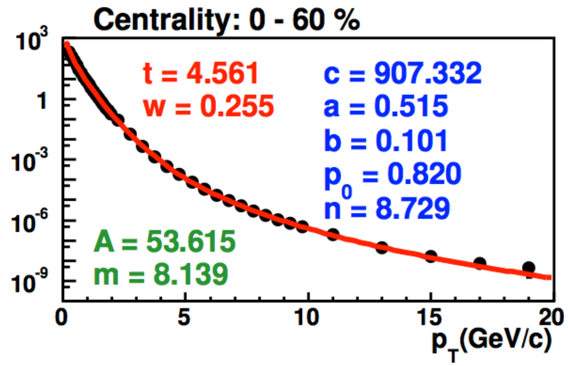




RxN(I+O) : $1.0 < |\eta| < 2.8$
RxN(In)+MPC : $1.5 < |\eta| < 3.8$

The magnitude of v_3 is comparable.

Input decay photon : p_T spectra

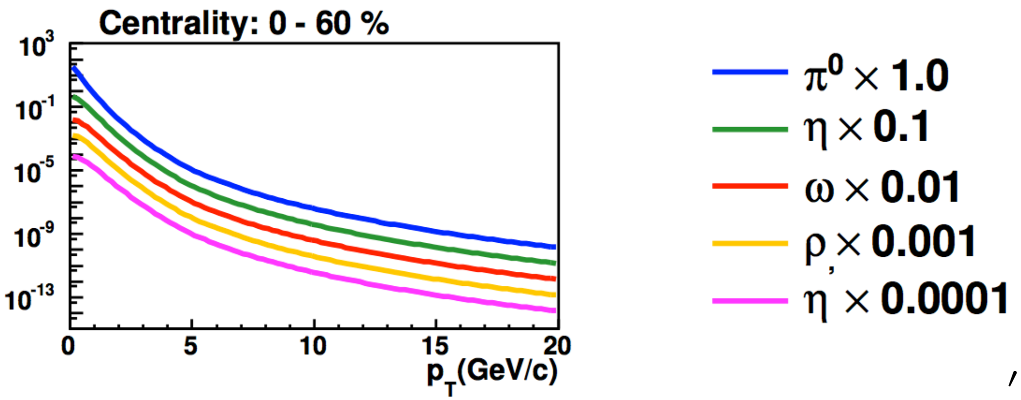


$$T(p_T)=\frac{1}{1+\exp((p_T-t)/w)}$$

$$F_0=\frac{c}{(\exp(-a*p_T-b*p_T^2)+p_T/p_0)^n} \text{ : 0-10GeV/c}$$

$$F_1=\frac{A}{p_T^m} \text{ : 6-20GeV/c}$$

$$\frac{d\sigma}{p_T dp_T}=T(p_T)F_0+(1-T(p_T))F_1$$



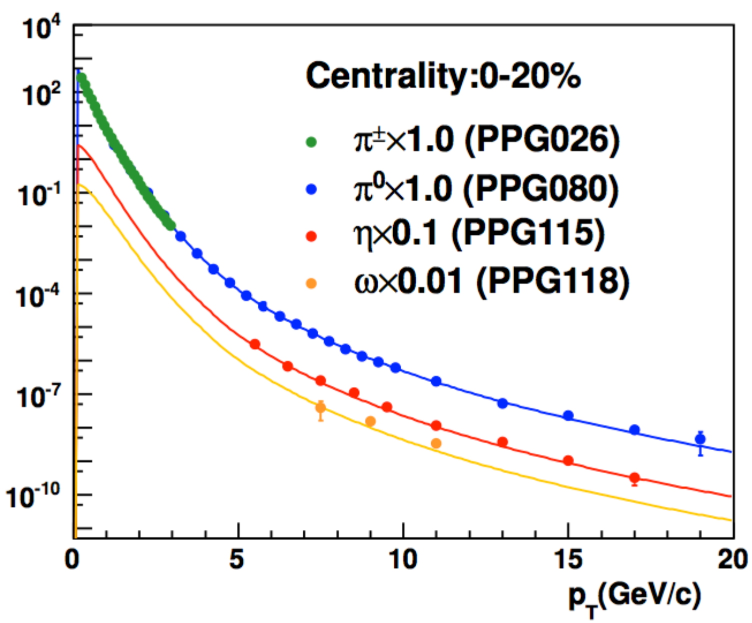
$$p_T^{'} = \sqrt{p_{T,\pi^0}^2 + M_{meson}^2 - M_{\pi^0}^2}$$

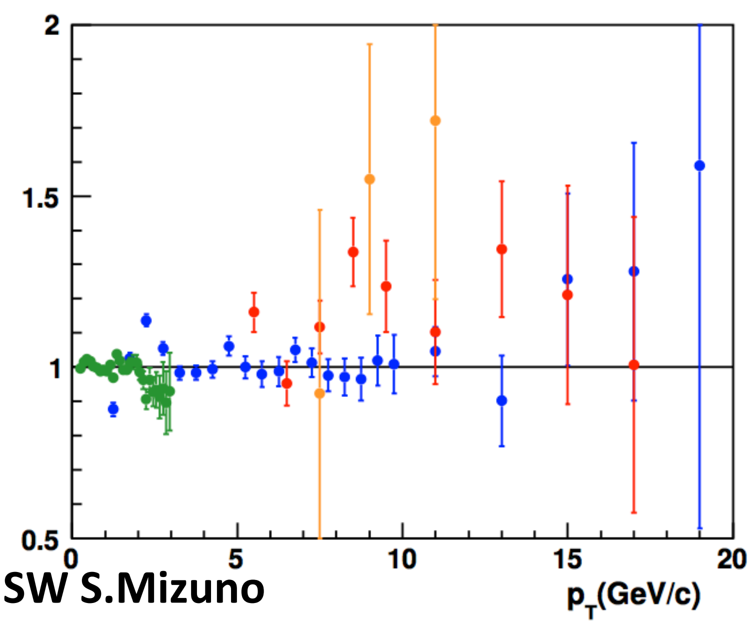
$\pi^{\pm}$ and π^0 p_T spectra are fitted and its function is used for estimating the other meson p_T spectra by m_T scaling.
They are used as a input.

Input decay photon : p_T spectra

The ratio of Each meson p_T spectra to π^0 p_T spectra is known to be constant at high p_T.

The table of each meson spectra ratio to π^0	
η/π^0	0.45±0.060
ω/π^0	0.83±0.120
ρ/π^0	1.00±0.300
η'/π^0	0.25±0.075





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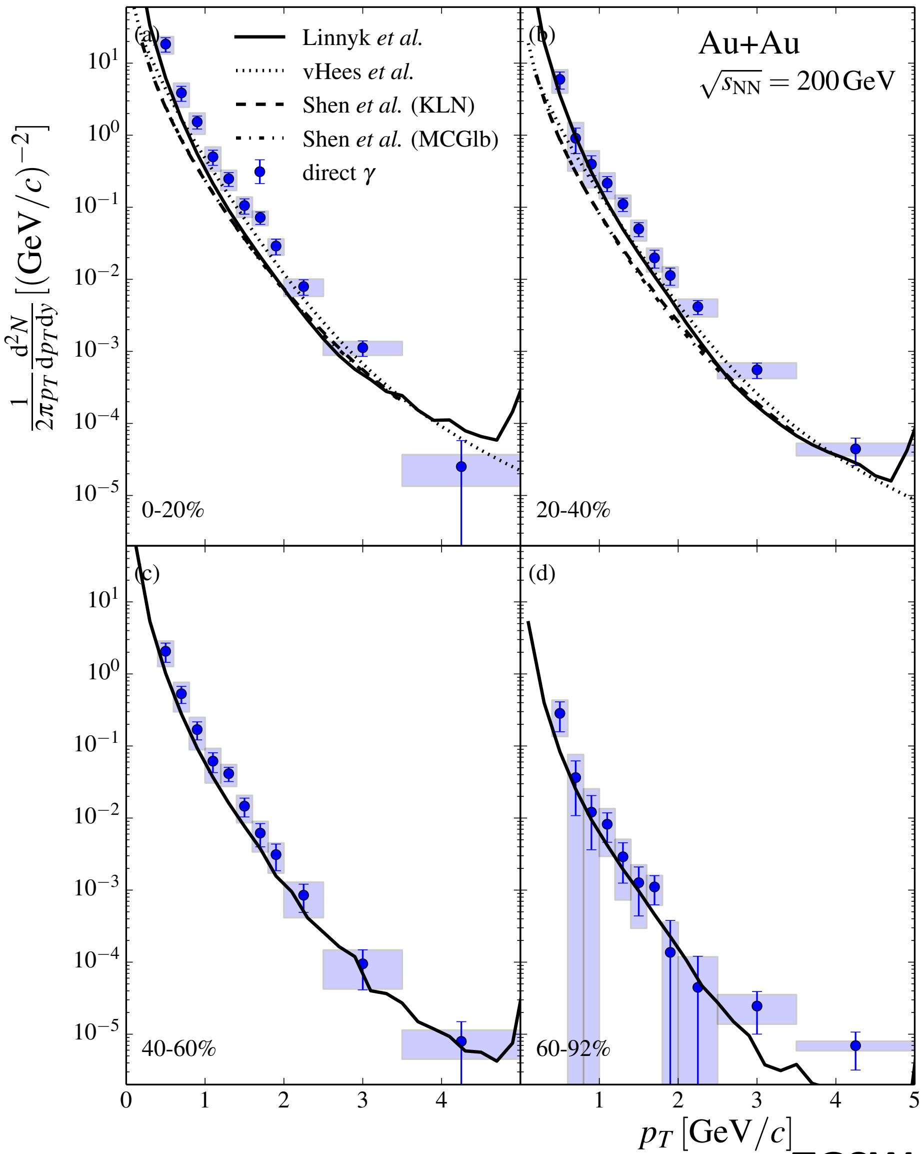
Yield : data vs theories

arXiv:1405.3940



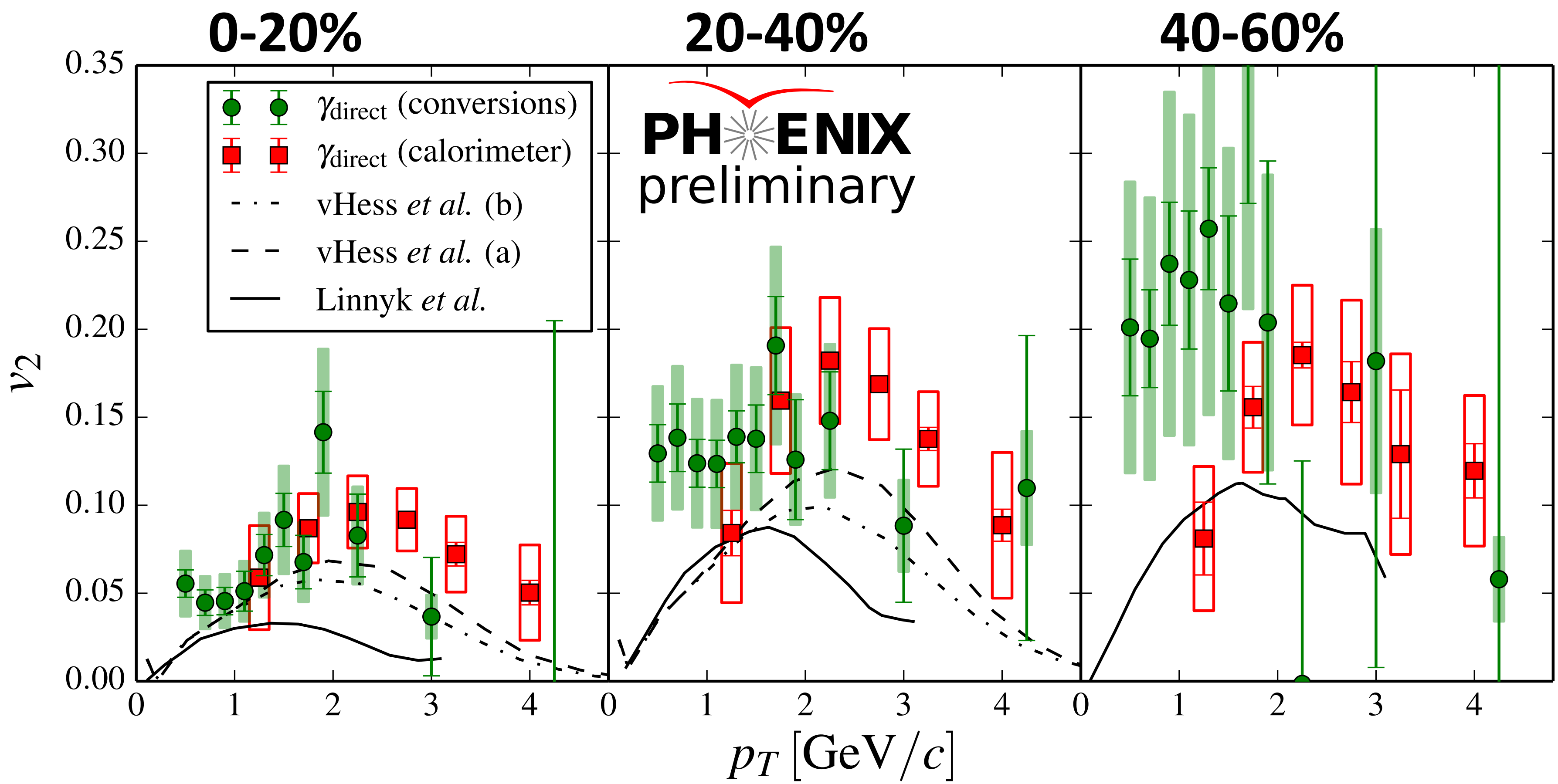
Linnyk et al.: PHSD transport model; Linnyk, Cassing, Bratkovskaya, P.R.C 89, 034908(2014)

vHees et al.: Fireball model; van Hees, Gale, Rapp; P.R.C 84, 054906(2011)

Shen et al.: Ohio hydro for two different initial conditions; Shen, Heinz, Paquet, Gale; P.R.C 84, 064903(2014)

The yield itself is still not perfectly described.

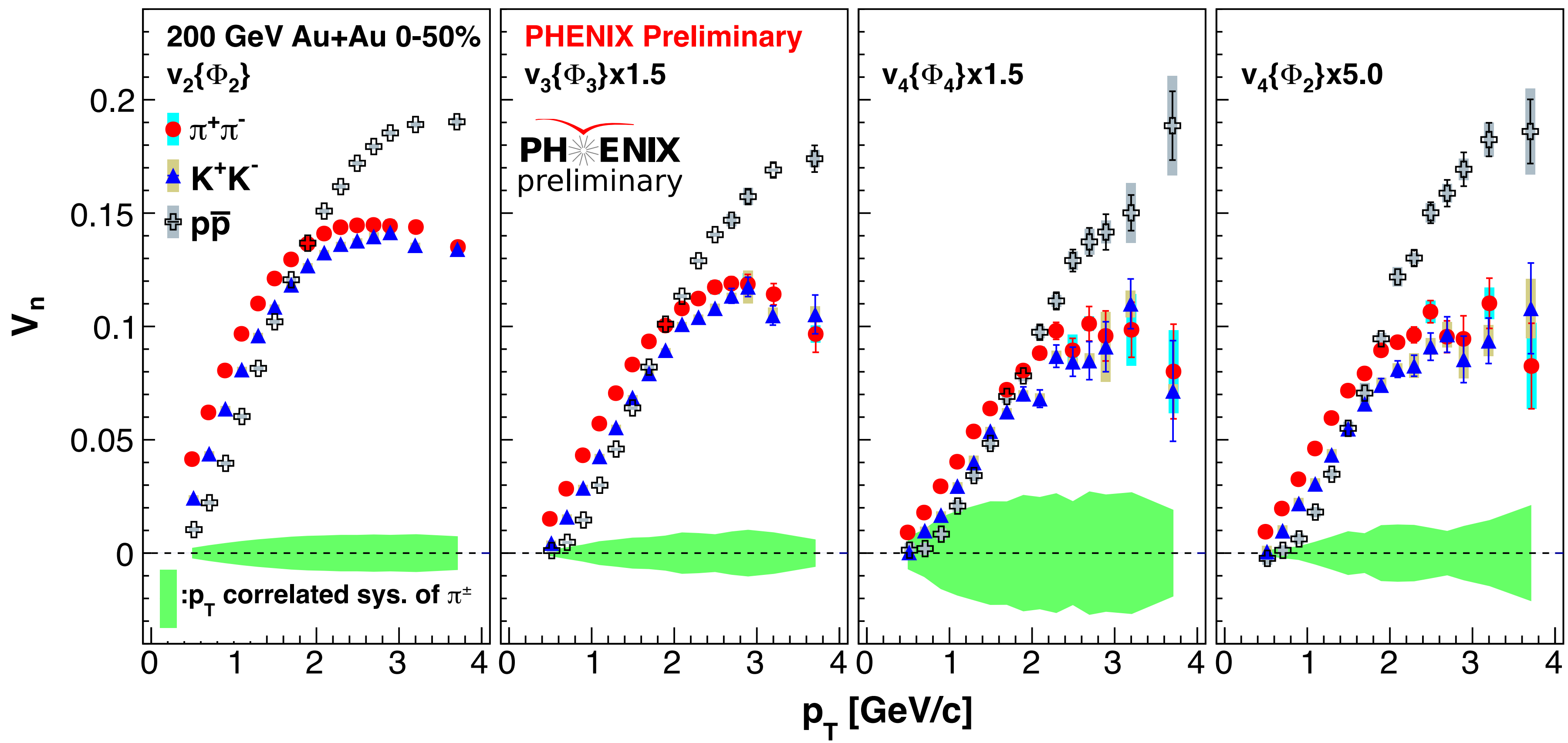
Comparison $\gamma^{dir.}$ v_2 with theoretical calculations



van Hees et al: P.R.C 84, 054906 (2011)

Linnyk et al.: PHSD model, private communication

Identified charged particle v_n

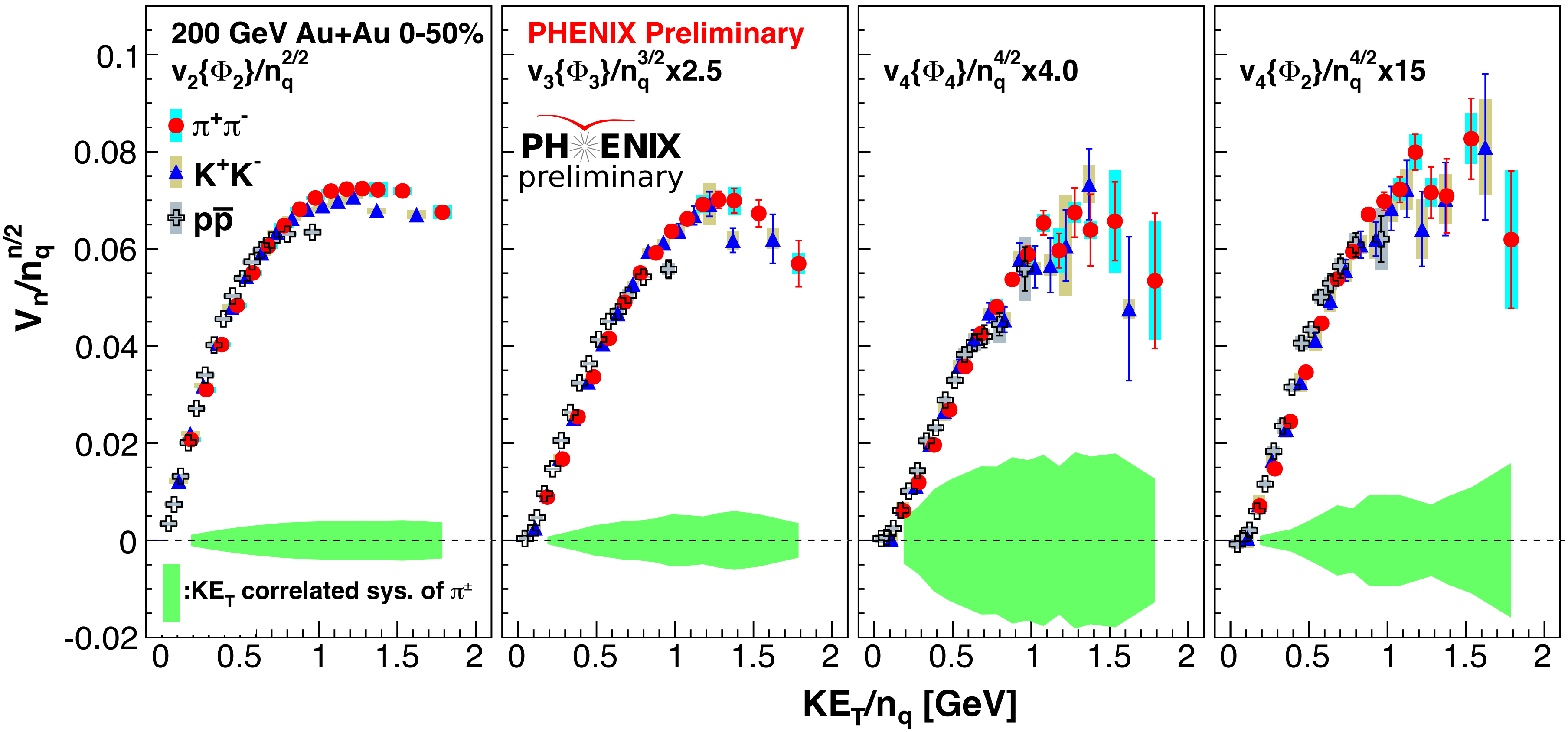


It is observed that

all harmonics have mass ordering

there are meson and baryon splitting

The number of constituent quark scaling (NCQ scale)



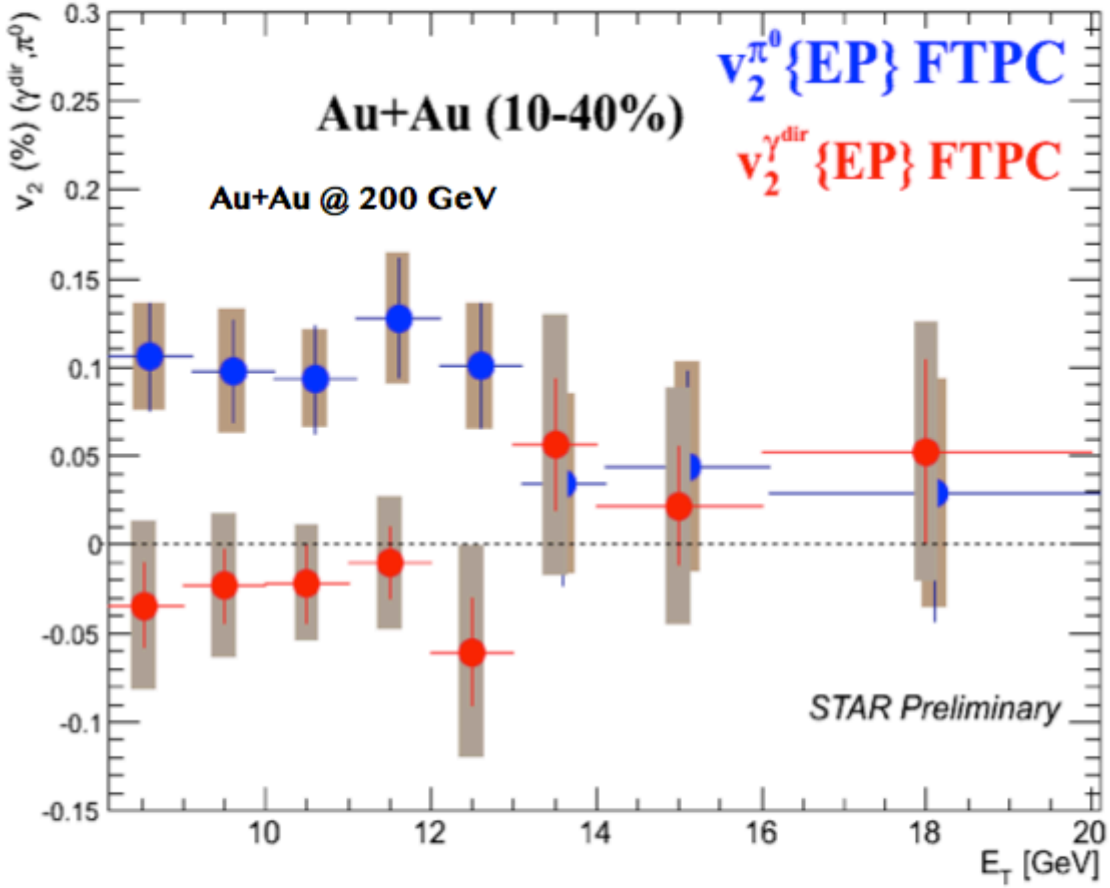
All particles are scaled by modified NCQ scaling.

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

π^0 and $\gamma^{dir.}$ v_2 measurement by STAR

Ahmed M. Hamed
shown at QM

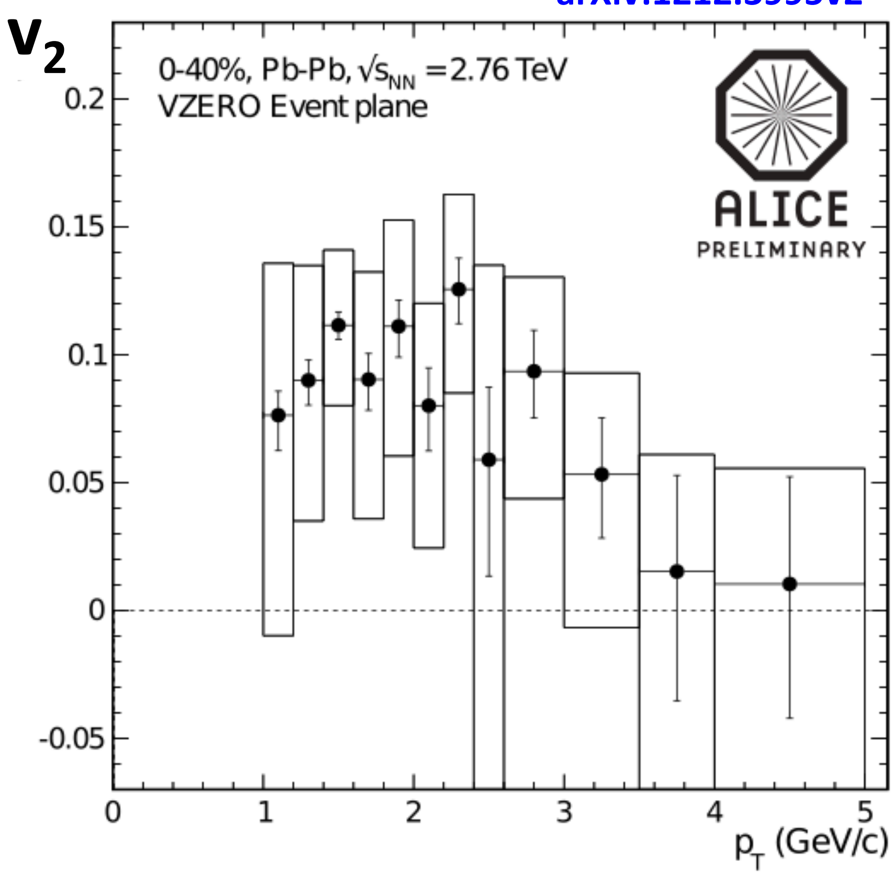
✓ BEMC: |η| < 1.0, FTPC: 2.5 < |η| < 4.0



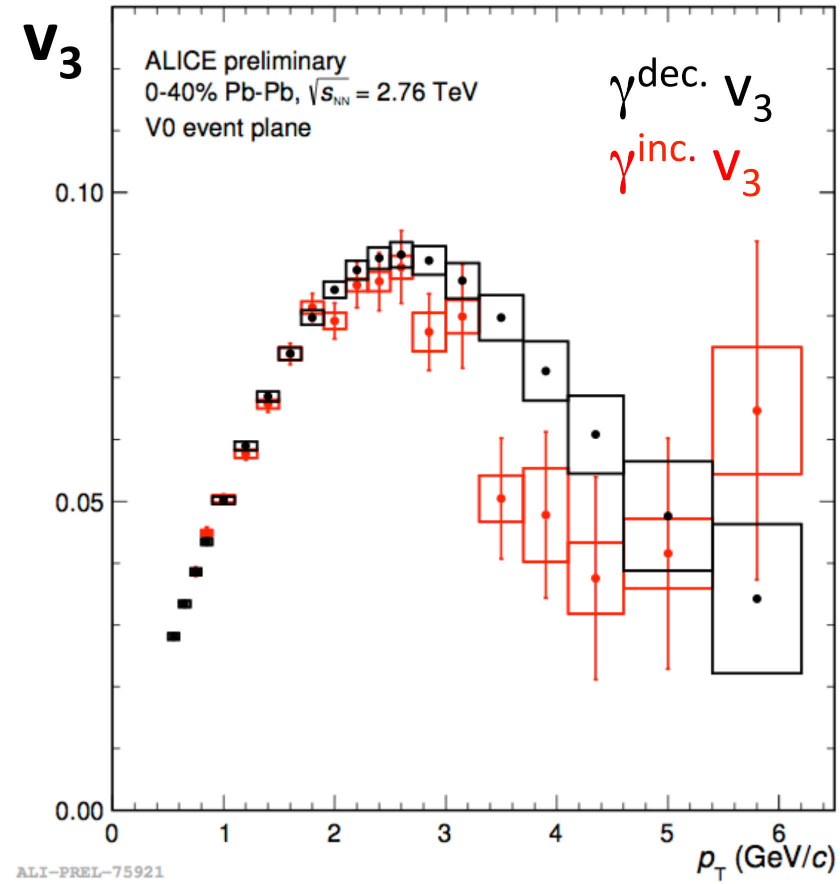
$\gamma^{dir.}$ v_2 in high E_T region are consistent with 0 within systematic uncertainty, while π^0 has positive v_2.

photon v_n measurement by ALICE

arXiv:1212.3995v2



Friederike shown at QM



It is also observed that $\gamma^{dir.}$ v_2 is positive in low p_T at LHC-ALICE.
v_3 measurement is ongoing.