The Measuring of Direct Photon Azimuthal Anisotropy In Au+Au 200GeV Collisions at RHIC-PHENIX

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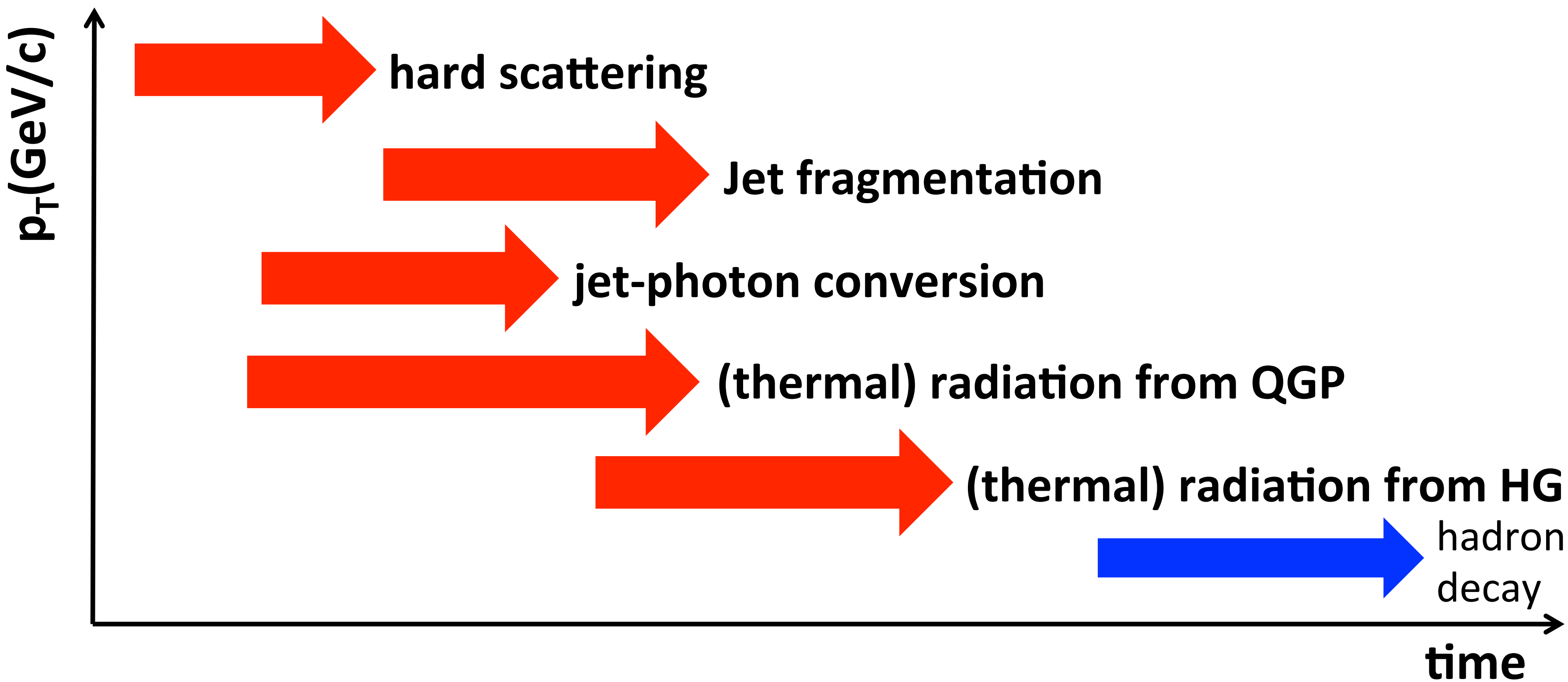
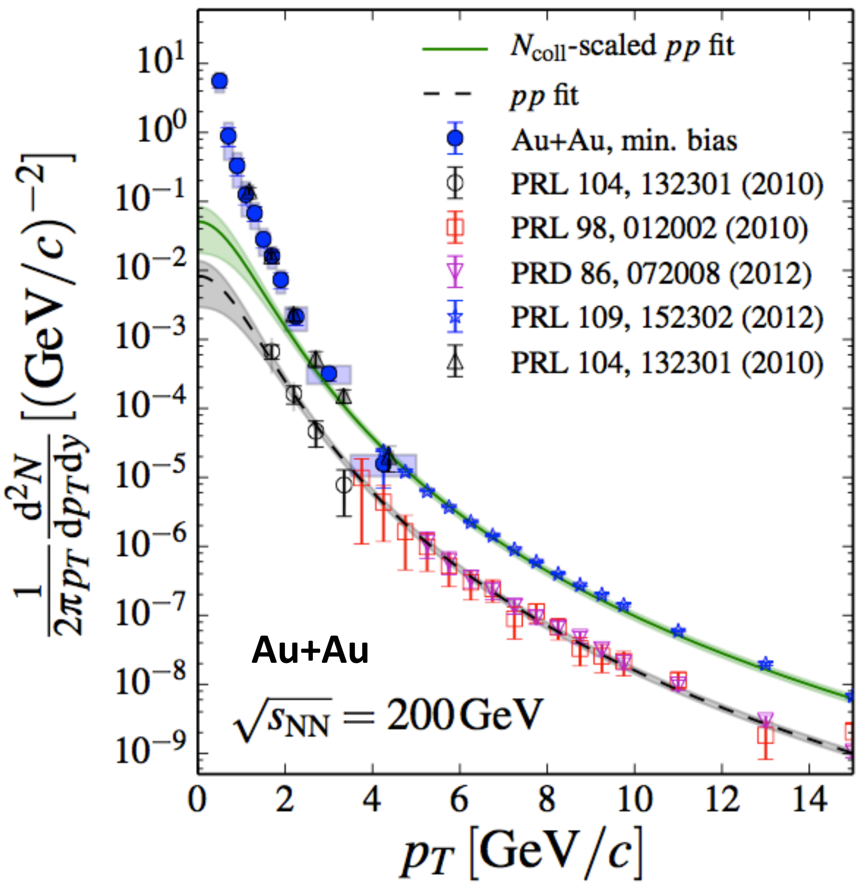
What is direct photon?

Direct photons are all photons except those originating from hadron decay.
They penetrate the medium without the interaction.
It is challenging to identify photon sources.
by p_T distribution? emitting angle?



Direct photon p_T spectra

arXiv:1405.3940(2014)



The p_T spectra in Au+Au collision is enhanced compared with that in p+p collision scaled by the number of binary collisions less than 4 GeV/c.

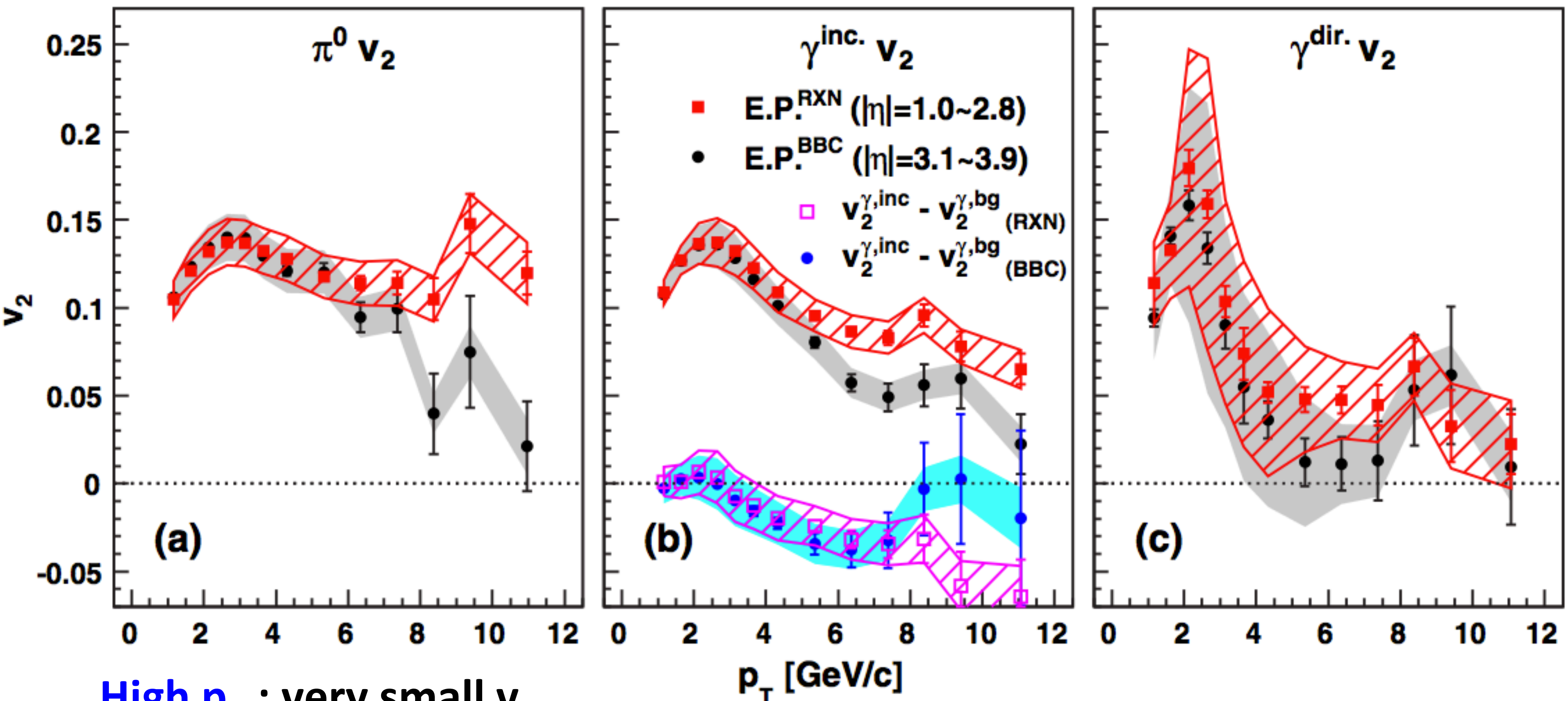
The excess of p_T spectra is fitted and effective temperature is extracted. (Freeze-out temperature of hadrons are about 100MeV)

Centrality	Effective temperature
0% - 20%	239 ± 25 ± 7 (MeV)
20% - 40%	260 ± 33 ± 8 (MeV)
40% - 60%	225 ± 28 ± 6 (MeV)

Photons in low p_T are mainly radiated from very hot medium at early time of collisions.

Elliptic flow of direct photon

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



High p_T : very small v_2

It could be because photons produced in the initial hard scattering are dominant plus no interaction of photon in QGP (R_{AA}≈1).

Low p_T : Comparable to hadron v_2 at around 2 GeV/c

It is suggested that photons are emitted from late stage.

Direct photon puzzle

Thermal radiation photons are dominant in low p_T region.

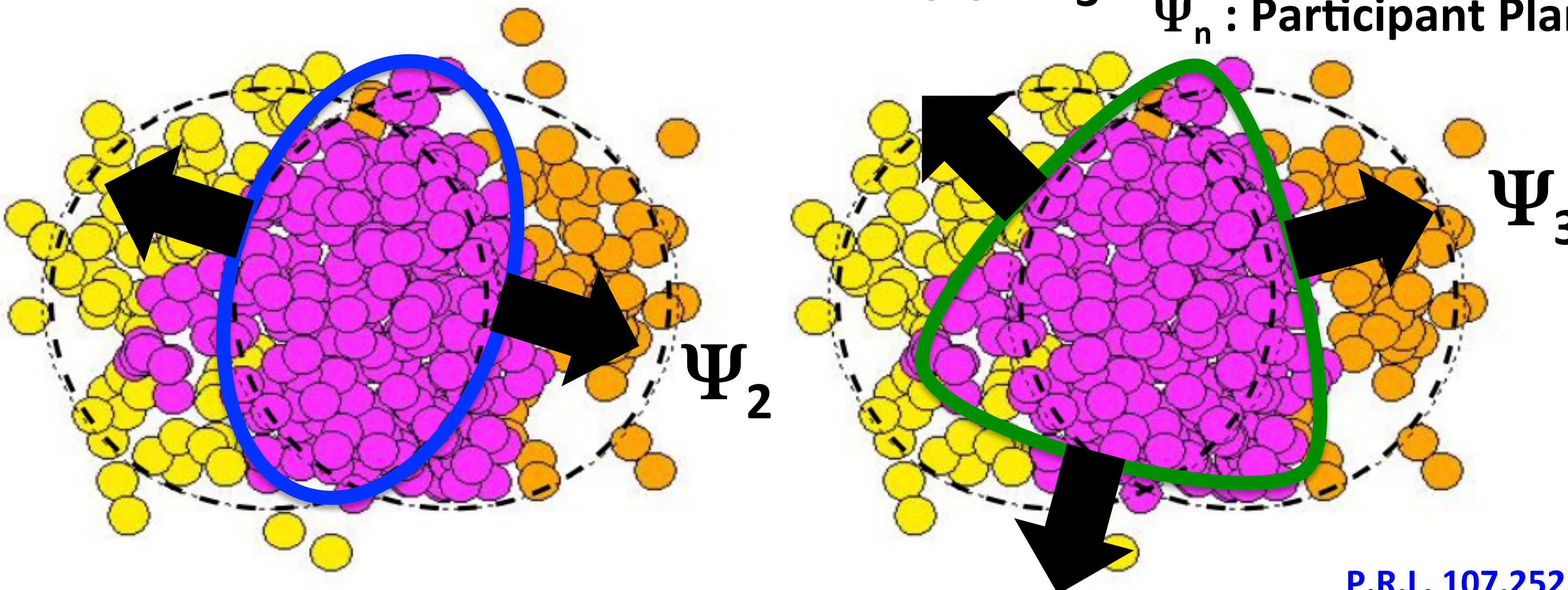
p_T spectra :
Emitted from very hot medium ($T_{eff} \approx 240$MeV).
-> Photons are dominantly emitted at early stage.

Elliptic flow :
It was expected that photon has small v_2, since it includes ones from early stage having small v_2.
-> Photons are dominantly emitted at late stage.

There is a discrepancy, and it is called "direct photon puzzle".
There is no models to explain both observables simultaneously.

Third order azimuthal anisotropy (v_3)

Ψ_n : Participant Plane

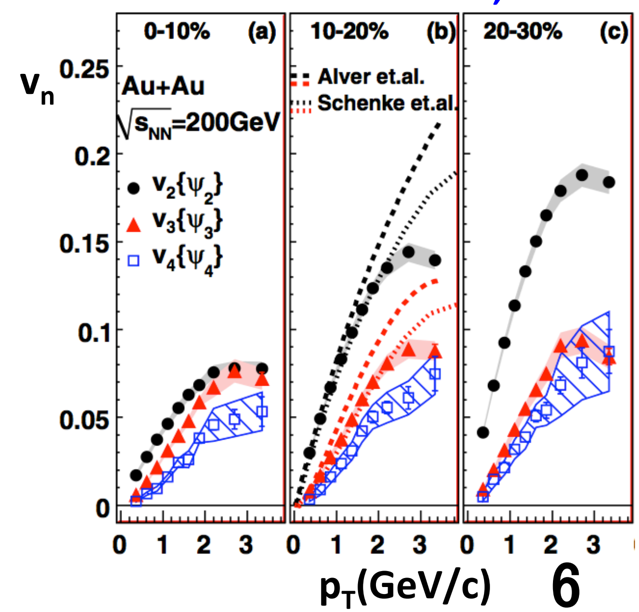


$$N(\phi - \Psi_n) \propto 1 + 2\sum v_n \cos\{n(\phi - \Psi_n)\}$$

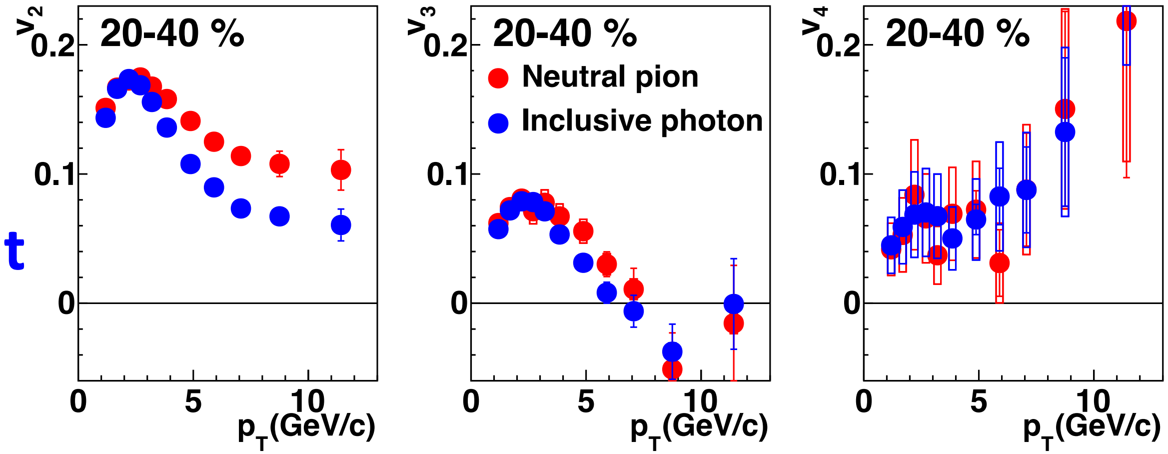
$$v_n = \langle \cos\{n(\phi - \Psi_n)\}\rangle$$

The higher order flow is originating from the fluctuation of the shape of participant zone. It is expected to constrain the initial geometry calculating model and η/s of QGP.

P.R.L. 107,252301



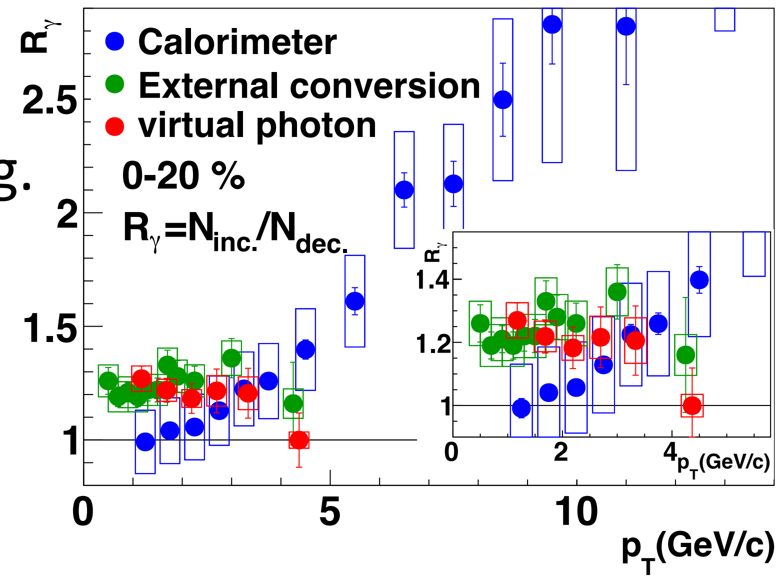
Analysis flow



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

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

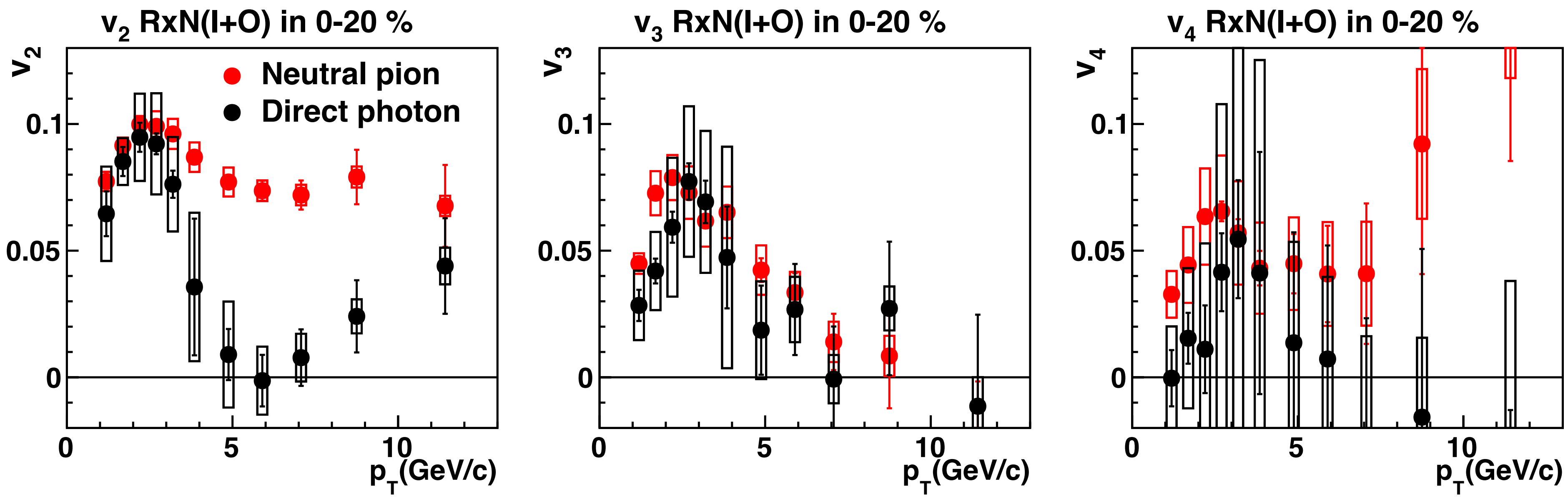
Meson spectra are assumed by m_T scaling.
Meson v_n are assumed by the number of constituent quark (NCQ) scaling.



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

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

The comparison of neutral pion and direct photon v_n



- In high p_T region

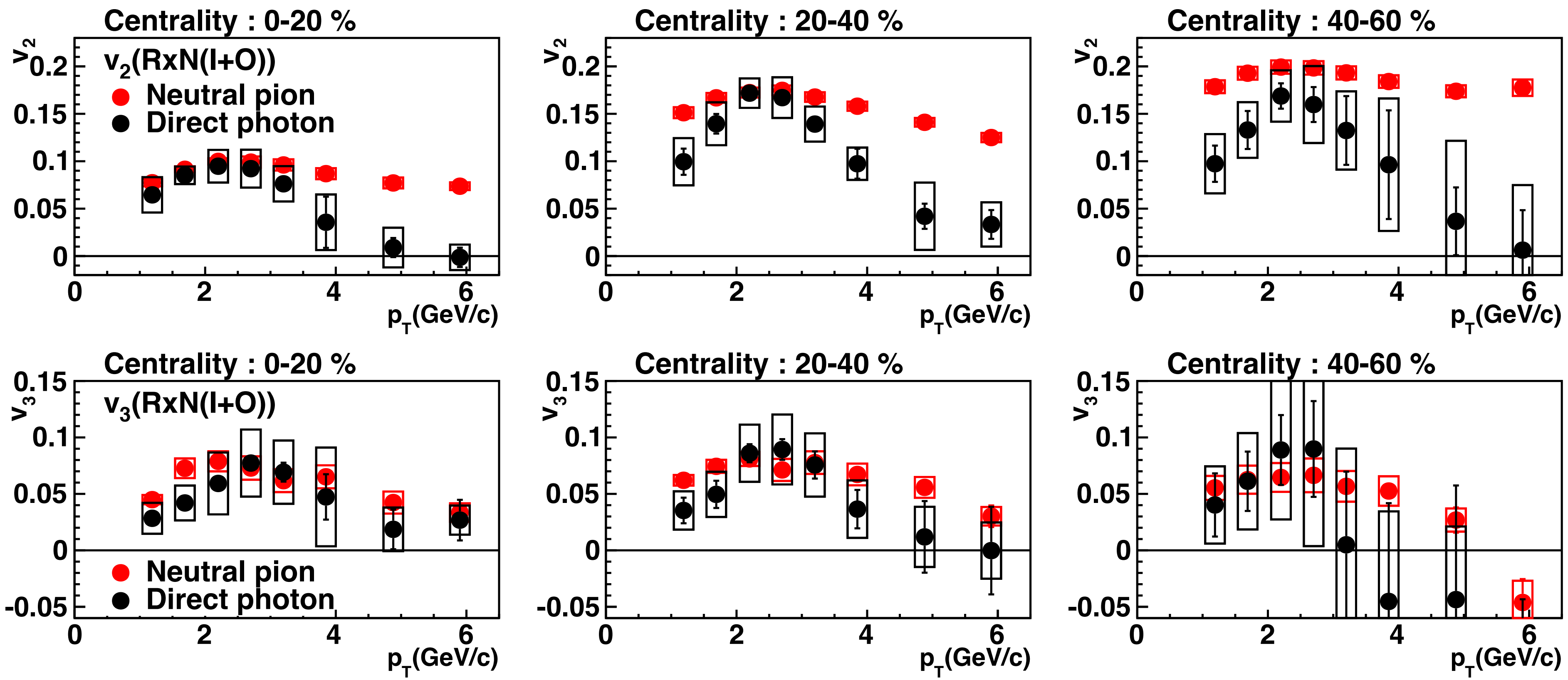
  Direct photon v_n is close to zero.

  It is consistent with the expectation that prompt photons having $v_n \approx 0$ are dominant. ($R_{AA} \approx 0$)

- In low p_T region

  Direct photon has non-zero and positive v_2 and v_3.

Centrality dependence of $\gamma^{dir.}$ and π^0 v_n in low p_T

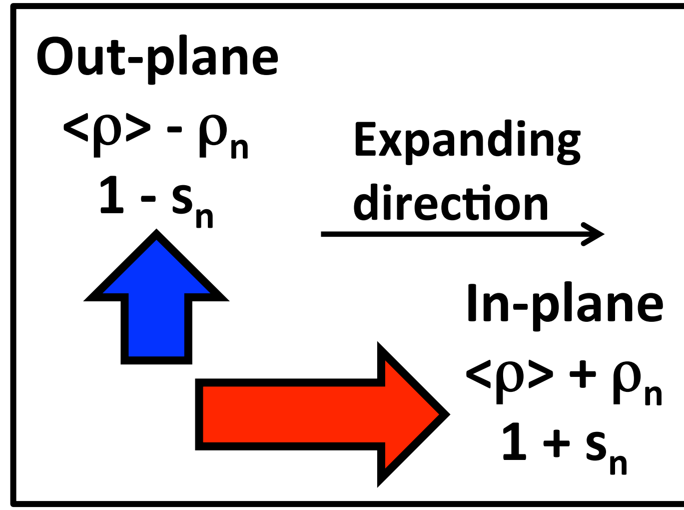


Strong dependence for v_2 : weak dependence for v_3

It could be suggested that photon v_n is created by the expansion of the medium from the initial geometry.

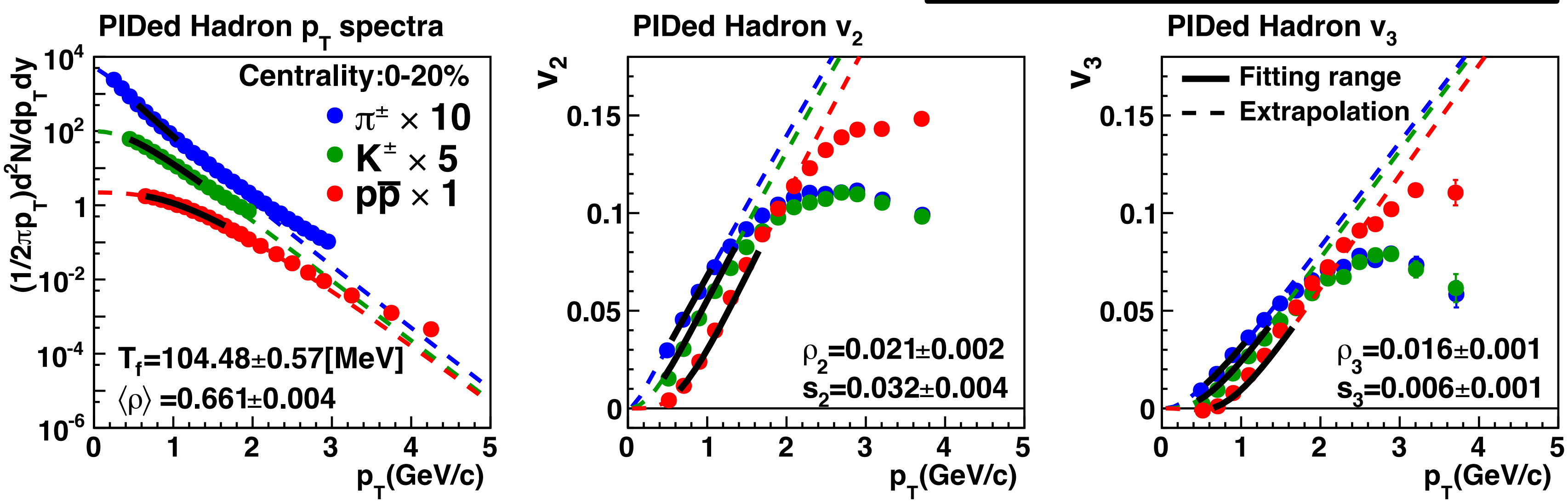
Blast wave model prediction for photon observables

Based on hydrodynamic model.
Hadron observables in low p_T region are well described by the parameters when kinetic freeze-out.

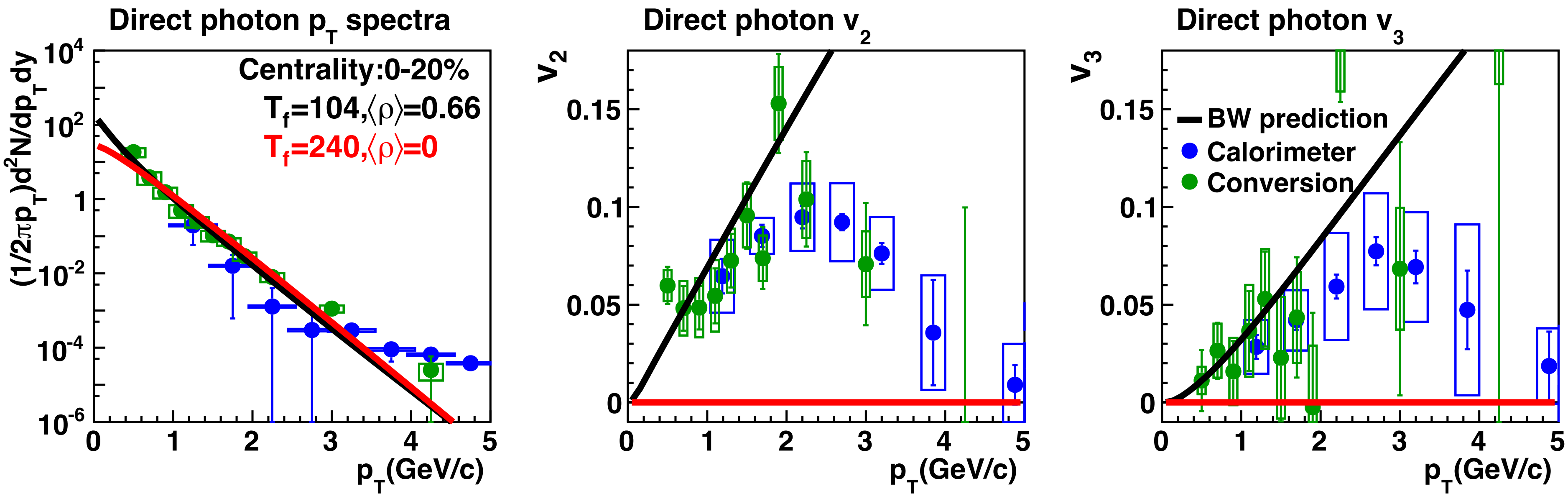


6 parameters

- Kinetic freeze-out temperature : T_f
- Average transverse rapidity : $\langle\rho\rangle$
- Rapidity anisotropy : ρ_2, ρ_3
- Spatial density anisotropy : s_2, s_3



Photon observables predicted by blast wave model



The photon p_T spectra and v_n are predicted as a massless particle.

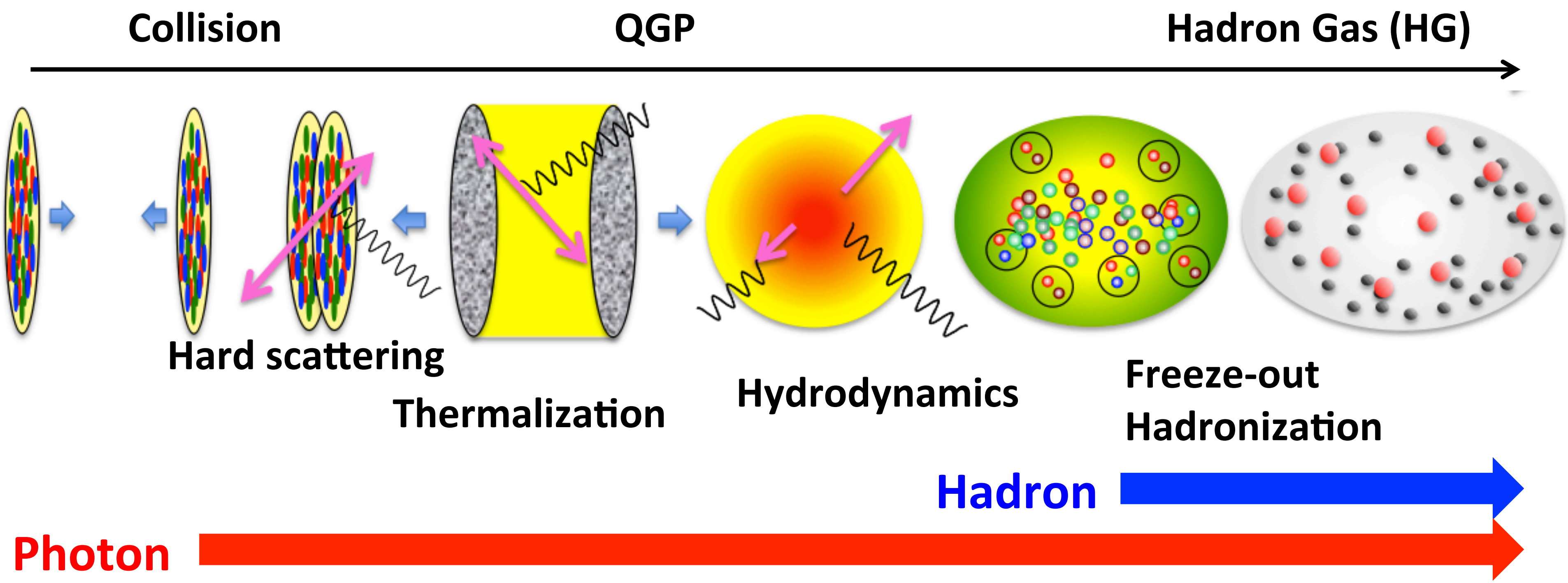
The p_T spectra predicted with T_f=104 MeV & <ρ>=0.66 and T_f=240 MeV & <ρ>=0 are similar.
It could be due to blue shift correction.
The v_n with <ρ>=0 is zero.

Summary

Direct photon azimuthal anisotropy is measured in Au+Au 200 GeV collisions at RHIC-PHENIX experiment.

- **In high p_T region**
  - **Photon v_n is close to zero while hadron shows non-zero v_n.**
    - ✓ **Prompt photons which are $v_n \approx 0$ are dominant.**
- **In low p_T region**
  - **It is found non-zero and positive v_3 in low p_T.**
    - ✓ **Photon v_n is created by the expansion of medium from the initial geometry.**
  - **Blast wave model describes photon observables well.**
    - ✓ **It is suggested that the evolution of the medium is needed to be taken into account.**

Photon analysis in heavy ion collision



The properties of photon in high energy heavy ion collision

- **emitted during all stages of the collisions**
- **don’t interact with the medium**

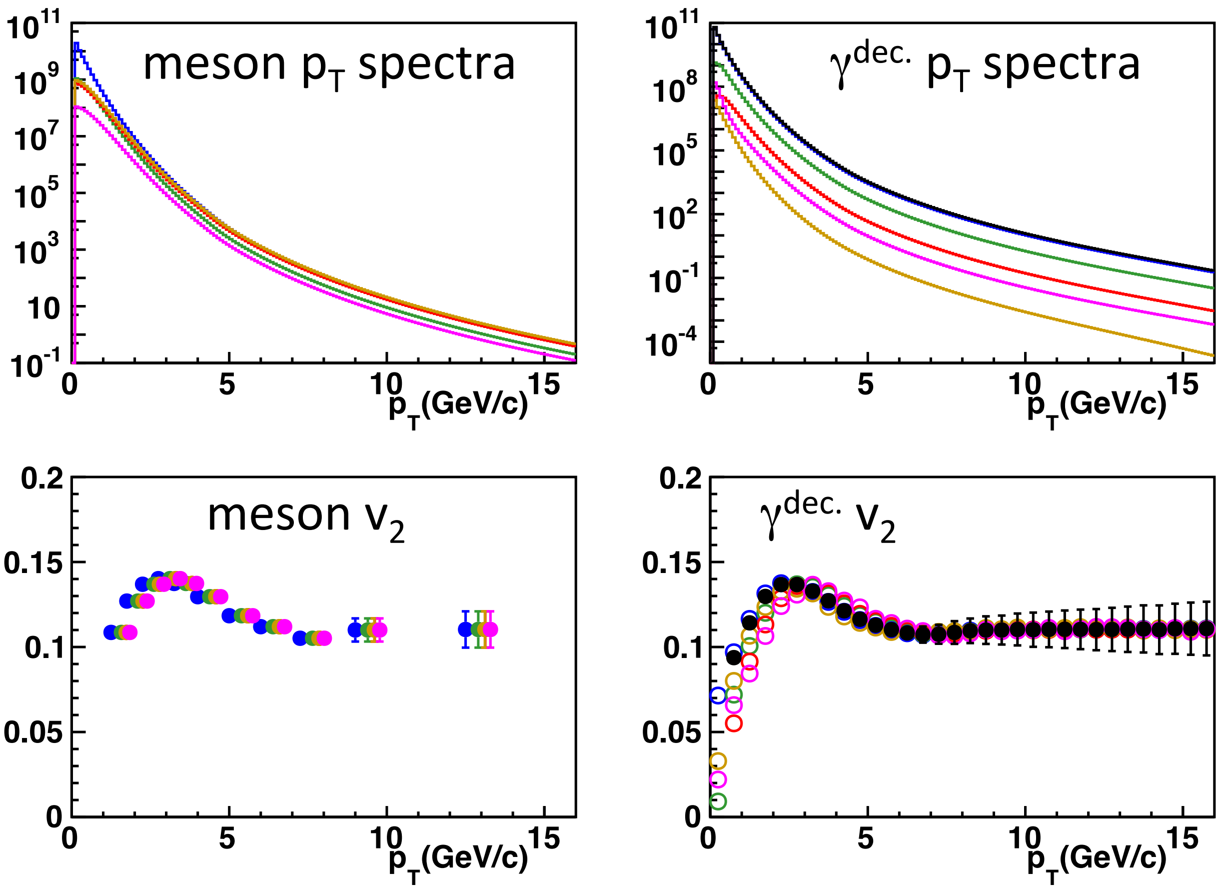
We can access the evolution of the collision.

Hadronic decay photon

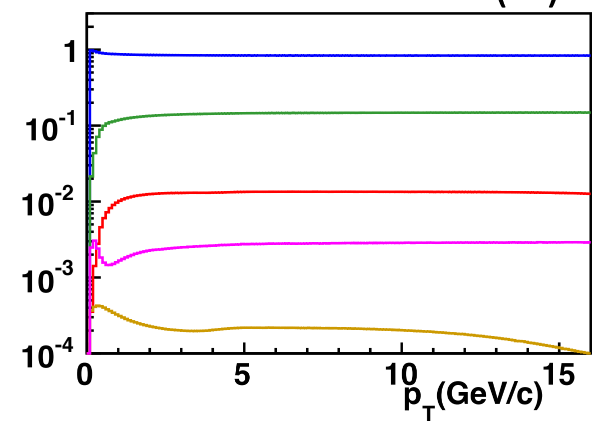
π ρ
η η'
ω **all $\gamma^{dec.}$**

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)



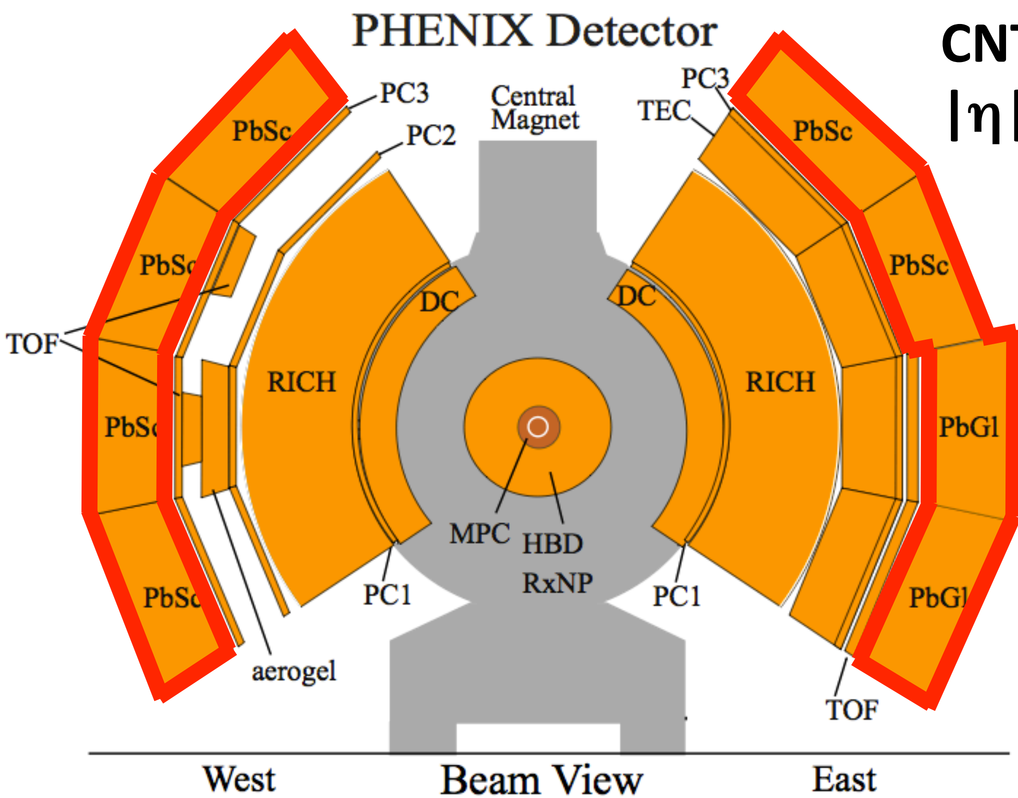
m_T scaling

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

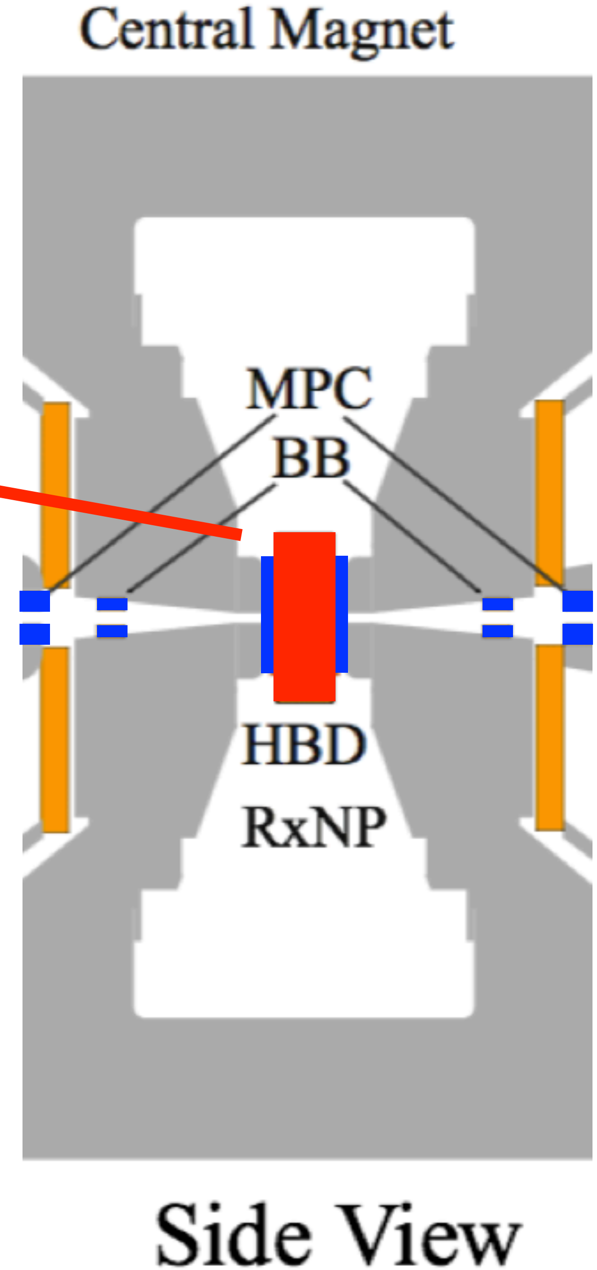
decay photon v_n

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

PHENIX detector



CNT
$|\eta| < 0.35$



Data set : Au+Au $\sqrt{s_{NN}}$=200GeV collisions
4.4 billion events are analyzed.

$$v_n = \langle \cos\{n(\phi - \Psi_n)\}\rangle$$

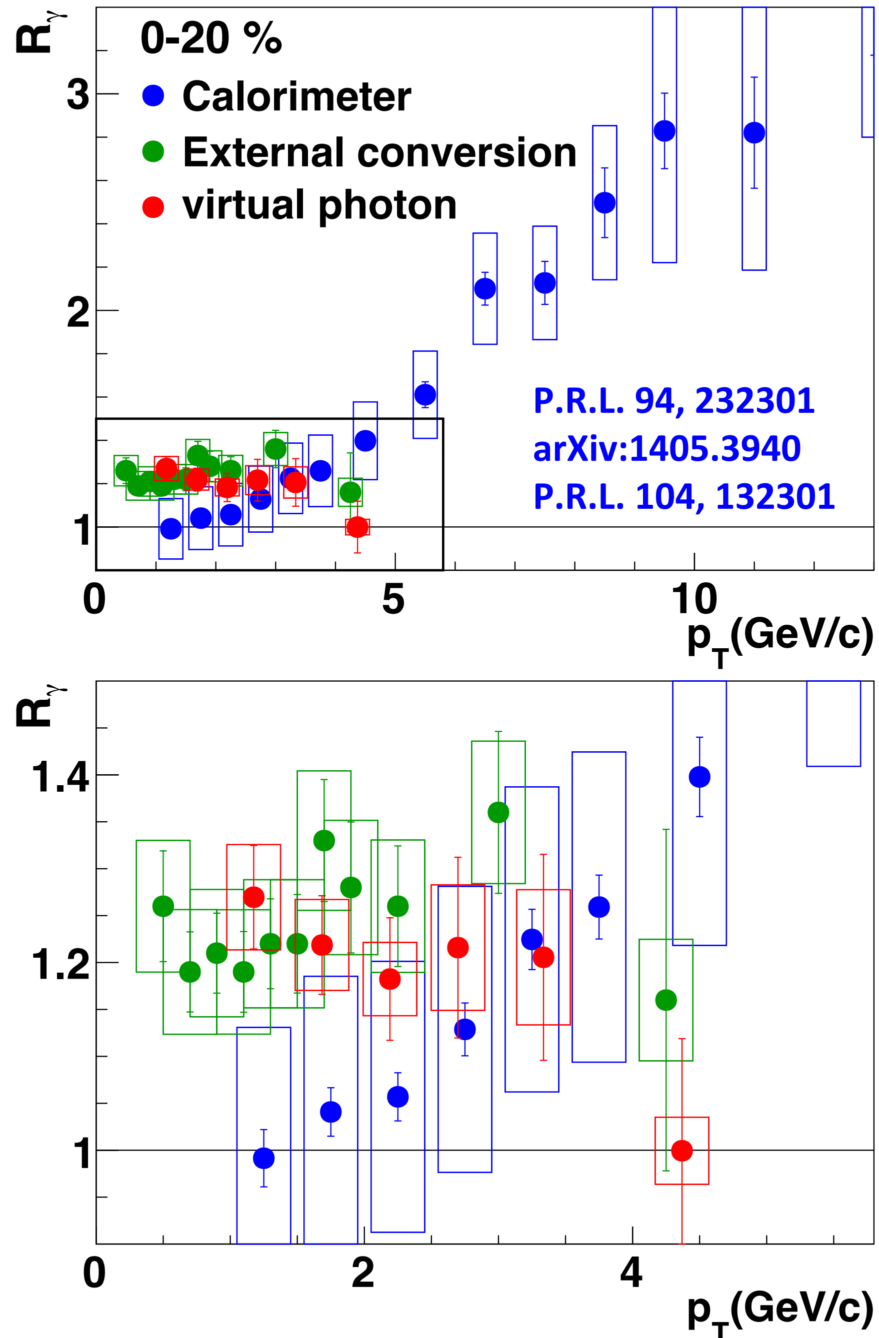
The excess of direct photon

The excess of direct photon has been measured in the wide p_T range.

The methods of virtual photon and external conversion photon are sensitive to low p_T region.

Less than 4 GeV/c, direct photons are included by 20 % in inclusive photon.

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

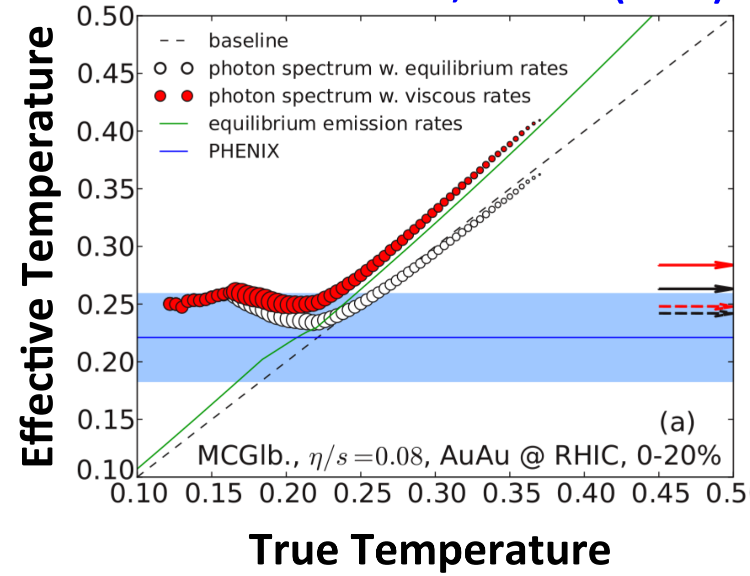


Why direct photon v_3 is measured?

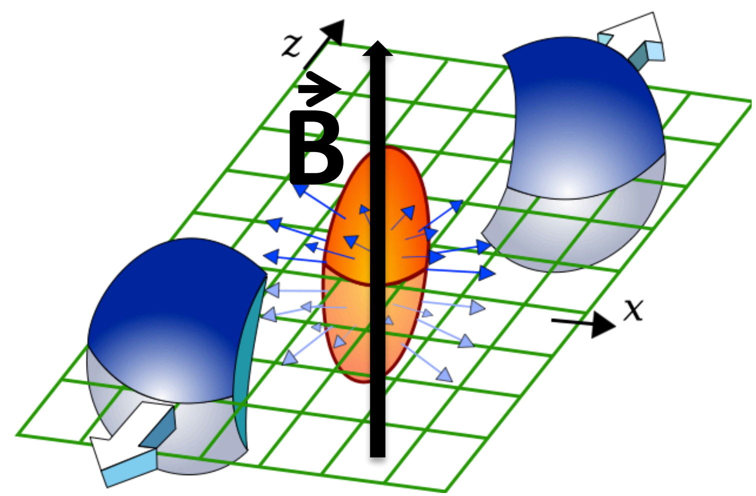
$$T' = T\sqrt{\frac{1+\beta}{1-\beta}}$$

Radial flow effect (blue shift effect) :
It makes apparent temperature higher than true temperature.
Photons from late state are dominant.
$v_2>0$: $v_3>0$

P.R.C 89, 044910 (2014)



Large magnetic field :
Direction of magnetic field is strongly related with Ψ_2(R.P.) but not with Ψ_3.
$v_2>0$: $v_3\approx0$

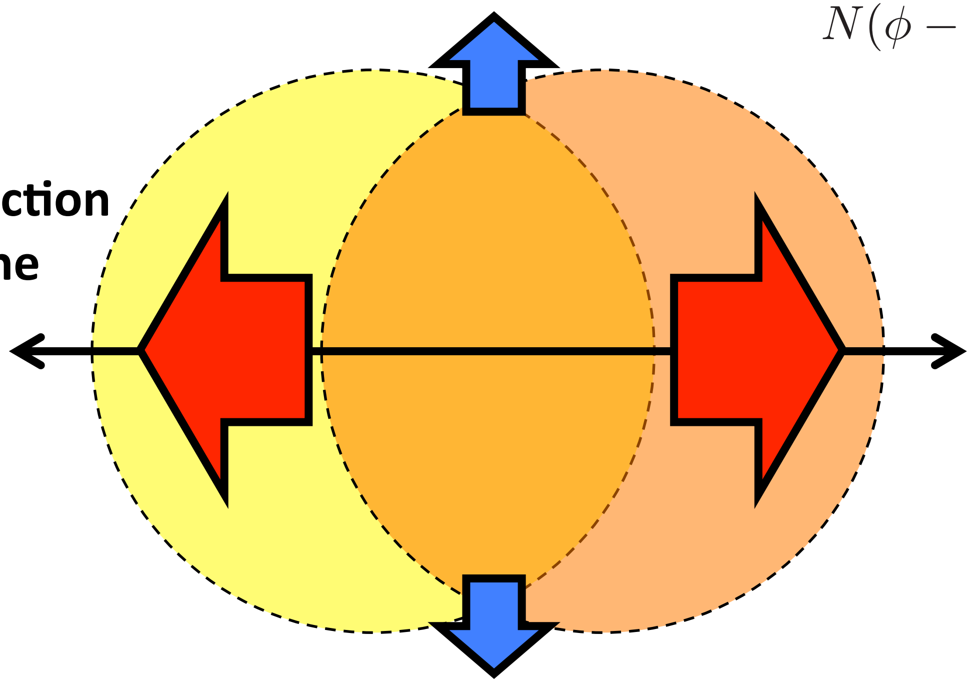


v_3 measurement could provide additional constraint on photon production mechanism.

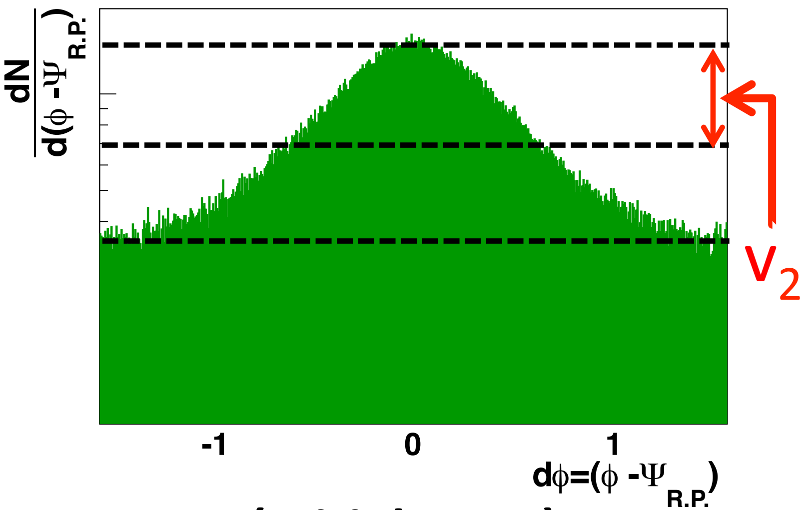
Azimuthal anisotropy (Elliptic flow)

$$N(\phi - \Psi_{R.P.}) \propto 1 + 2\sum v_n \cos\{n(\phi - \Psi_{R.P.})\}$$

$$v_2 = \langle \cos\{2(\phi - \Psi_{R.P.})\}\rangle$$



charged particle dϕ distribution

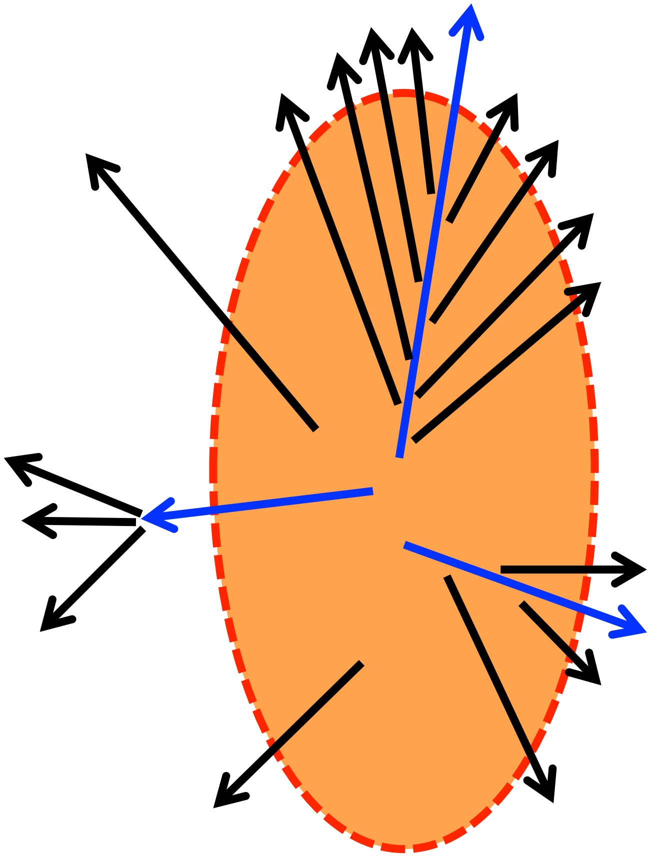


- **anisotropic pressure gradient in participant zone (Initial state)**
- **QGP expansion (hydrodynamic motion, η/s)**
  (η is shear viscosity and s is entropy density)
- **hadron production mechanism (coalescence)**

(1) : Initial geometry is converted into final azimuthal anisotropy

(2) : (expected to be) sensitive to η/s

Photon emitting angle dependence



Parton
Photon
Participant zone

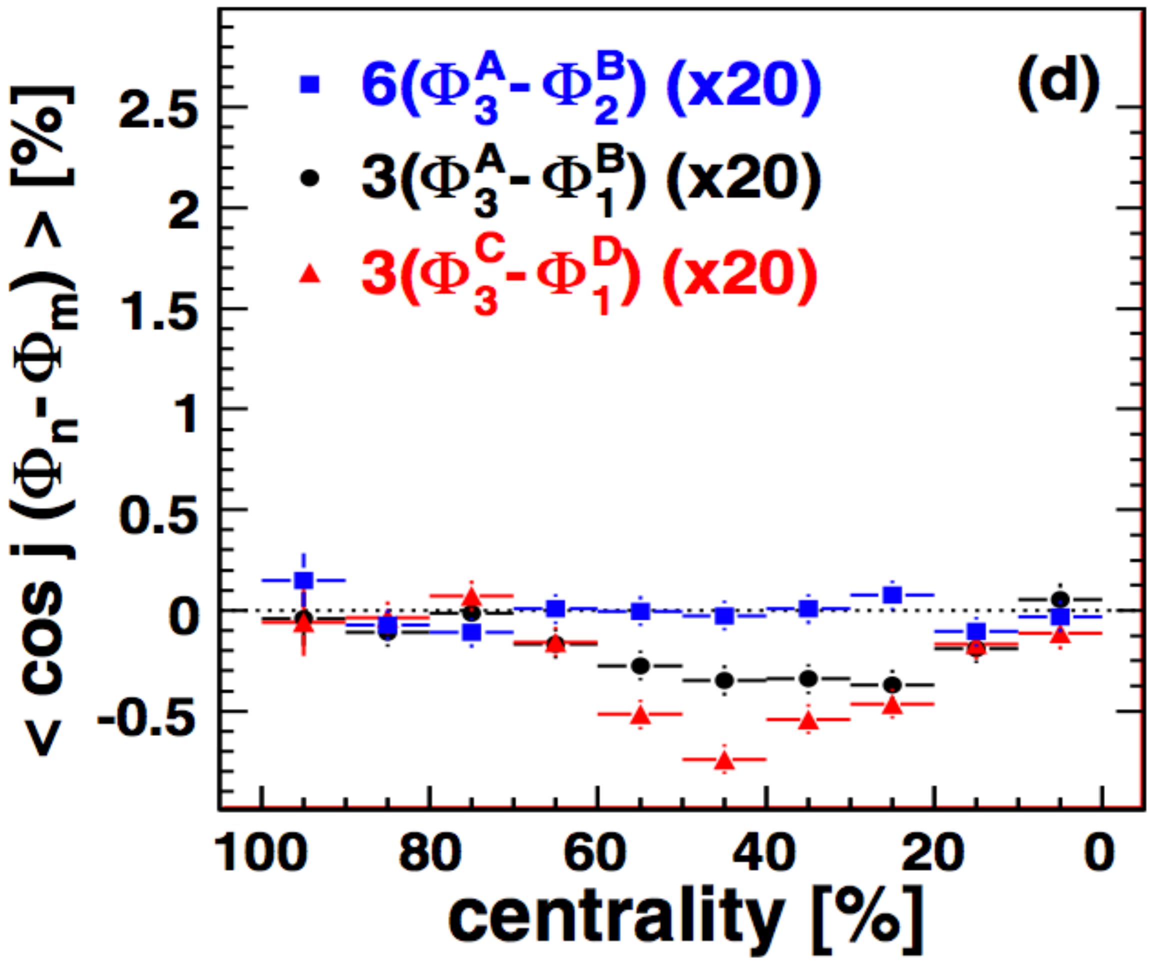
It is expected that the emitted angle of photons depends on their sources.

- Initial hard scattering : $v_2 \approx 0$
- Medium induced : $v_2 \leq 0$
- Jet fragmentation : $v_2 \geq 0$
- Radiation from expanding medium : $v_2 > 0$

The measurement of photon azimuthal anisotropy is a powerful probe to identify the photon sources.

Event Plane correlation

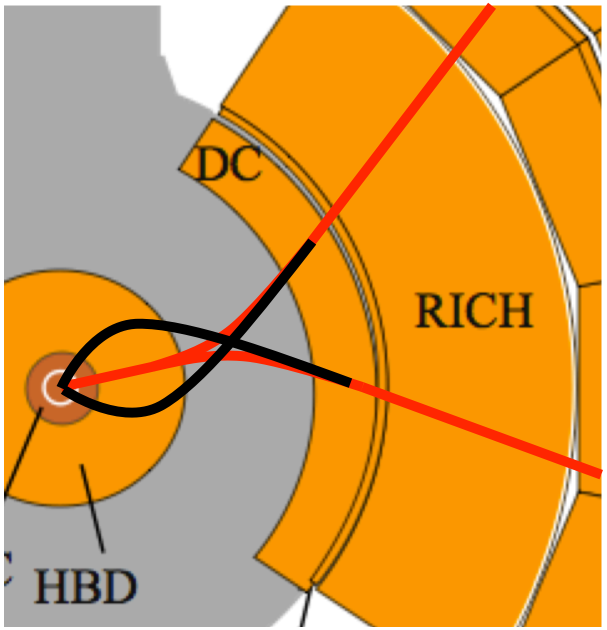
P.R.L. 107, 252301 (2011)



Ψ_2 and Ψ_3 are uncorrelated.

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.

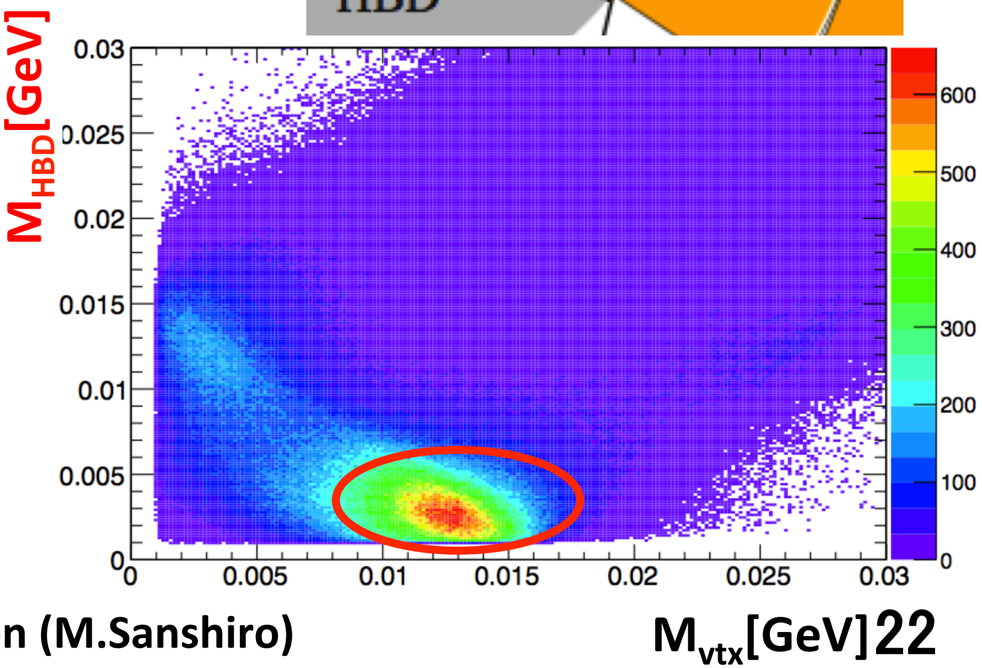
✓ less hadron contamination

✓ good momentum resolution

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

Extended to lower p_T

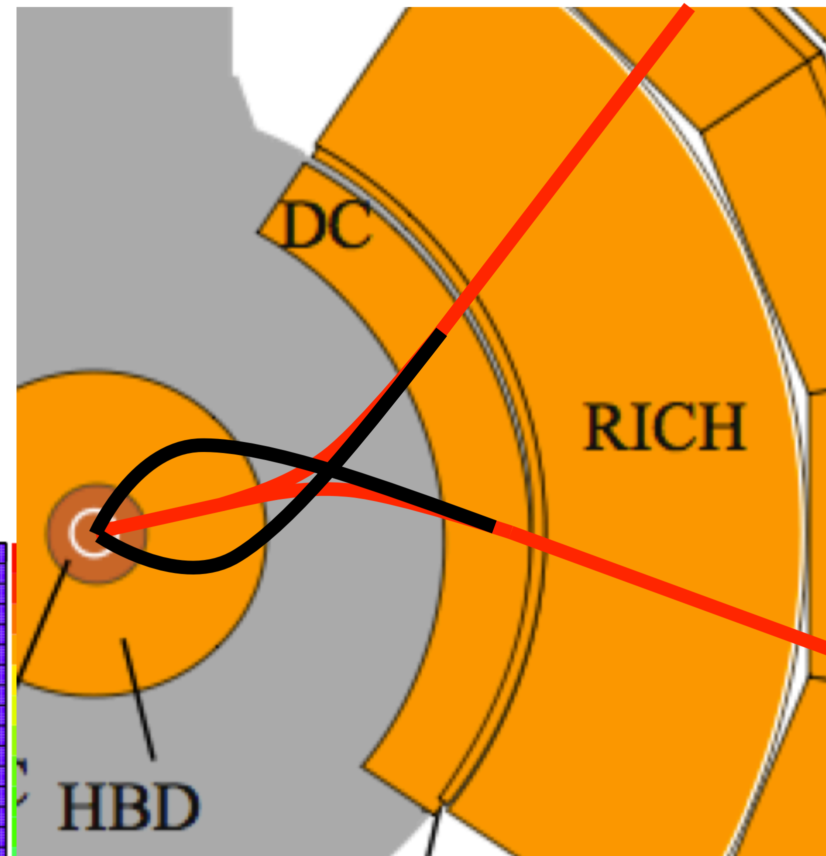
low statistics



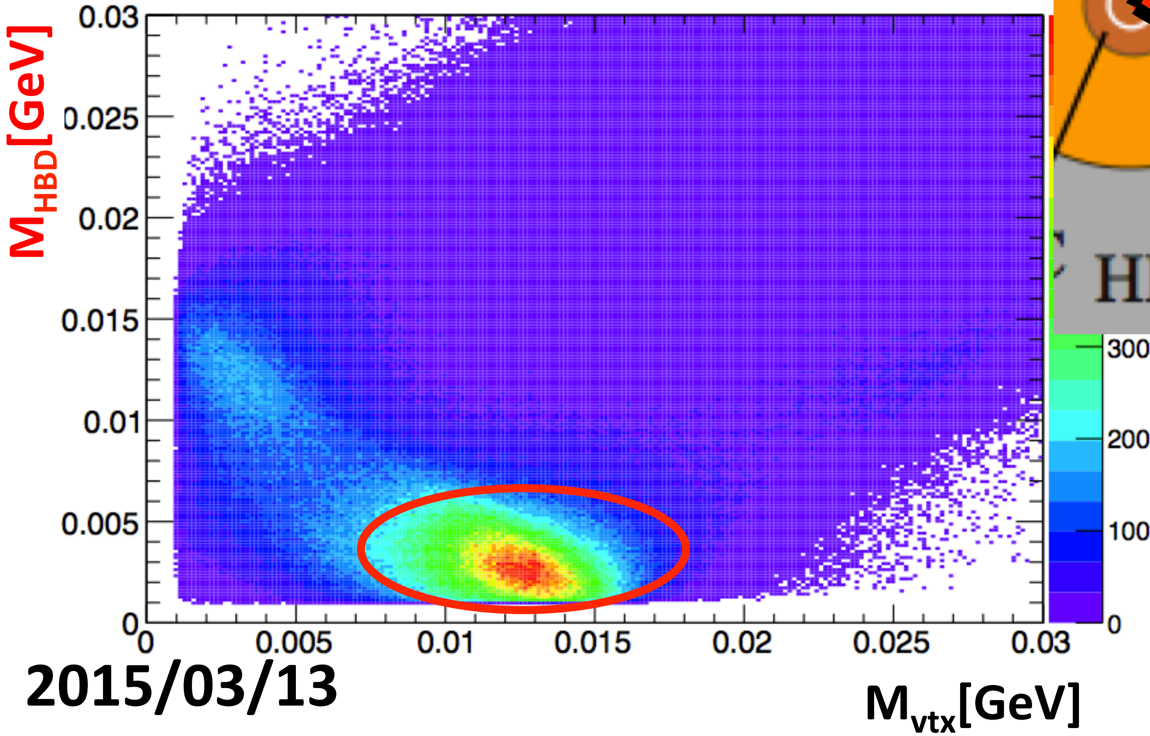
Direct photon (M.Sanshiro)

External conversion photon

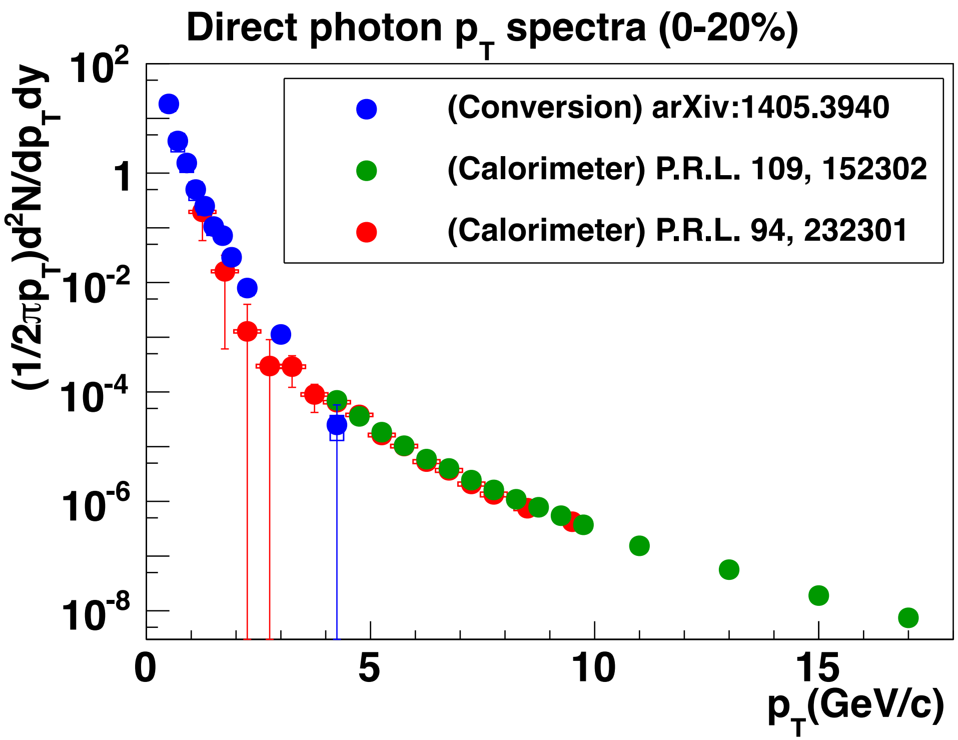
Real track
estimated track



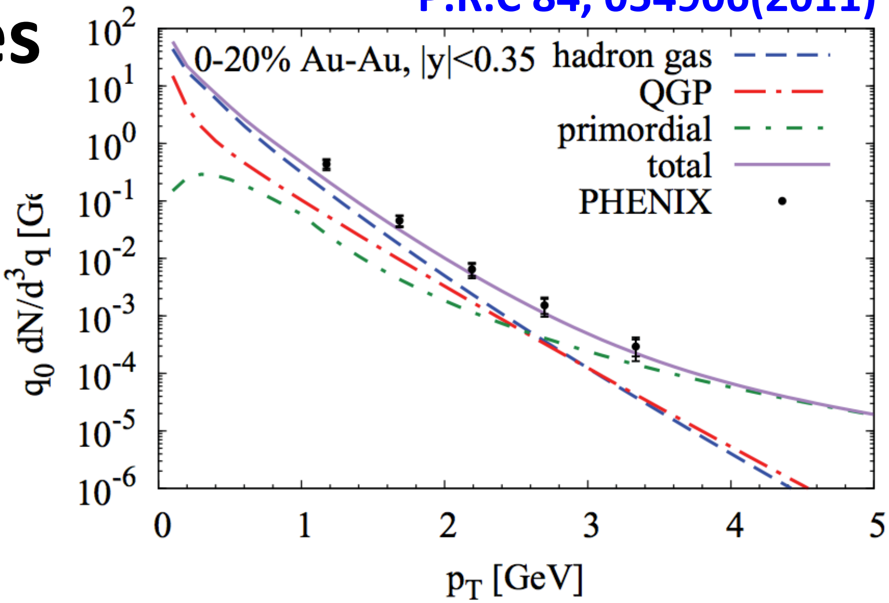
1) real photon converts to e^+e^- in HBD backplane
2) default assumption: track come from the vertex
3) momentum of the conversion tracks will be mis-measured (see black tracks)
4) apparent pair-mass (about 12MeV) will be measured for phtons
5) assume the same tracks originate in the HBD backplane
6)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



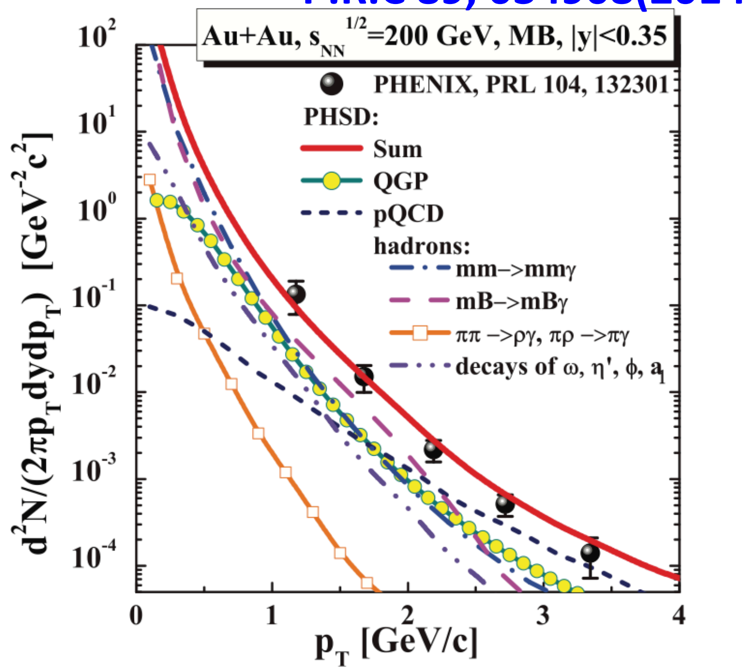
Identification photon sources from p_T spectra



P.R.C 84, 054906(2011)



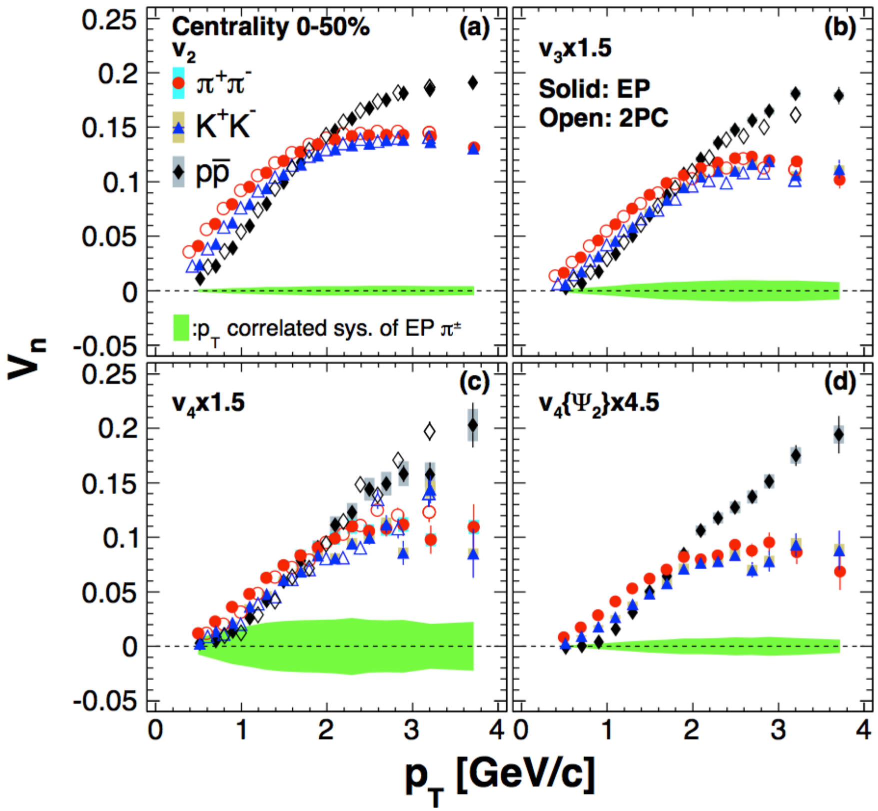
P.R.C 89, 034908(2014)

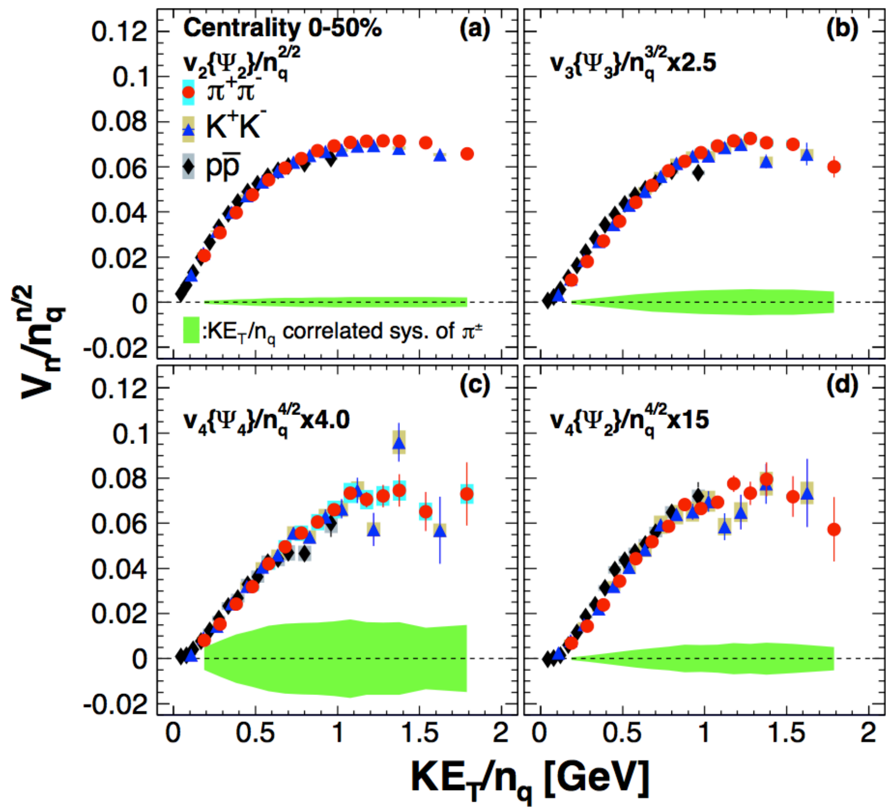


The photon sources are identified via the p_T spectra.

Identified charged particle v_n

arXiv:1412:1038





It is observed that

- all harmonics have mass ordering
- there are meson and baryon splitting

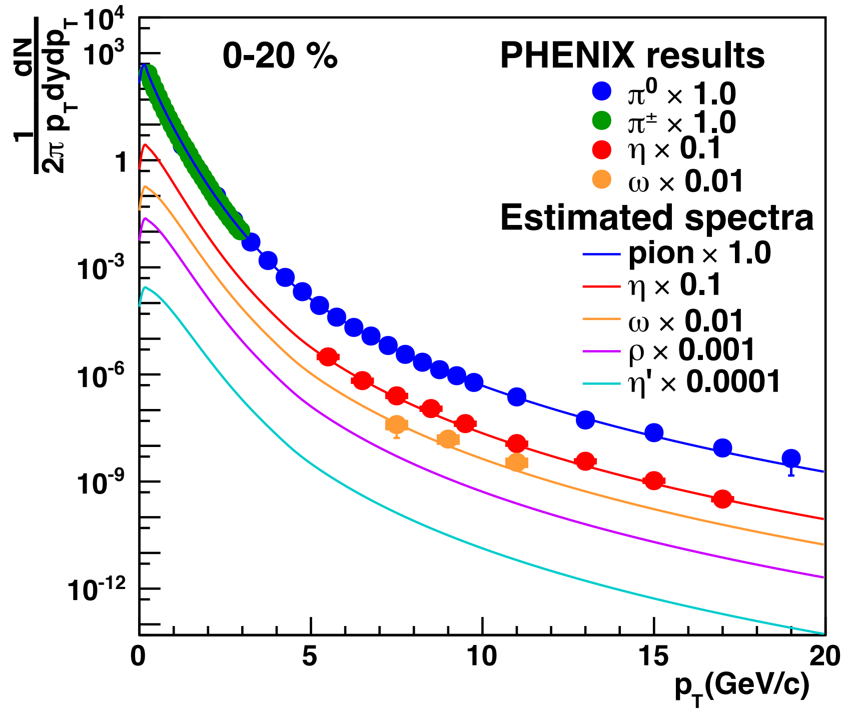
All particles are scaled by modified NCQ scaling.

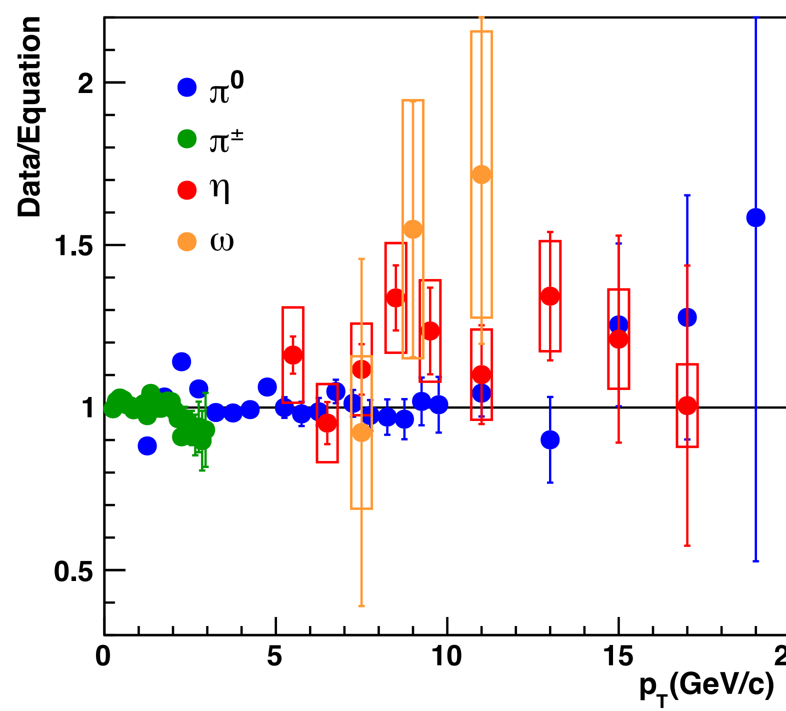
(a) : $v_2(KE_T)/n_q$
(b) : $v_n^{1/n}$ scaling
(a)+(b) : $v_n(KE_T)/n_q^{n/2}$

Meson p_T spectra estimation

$$p_{T,meson} = \sqrt{p_{T,pion}^2 + M_{meson}^2 - M_{pion}^2}$$

$$\begin{aligned}
\frac{d\sigma}{p_T dp_T} &= T(p_T)F_0 + (1 - T(p_T))F_1, \\
T(p_T) &= \frac{1}{1 + \exp\{(p_T - t)/w\}}, \\
F_0 &= \frac{c}{\{\exp(-ap_T - bp_T^2) + p_T/p_0\}^n}, \\
F_1 &= \frac{A}{p_T^m},
\end{aligned}$$





Since it is difficult to measure mesons except for pion, the other mesons p_T spectra are estimated by m_T scaling from pion experimental data.

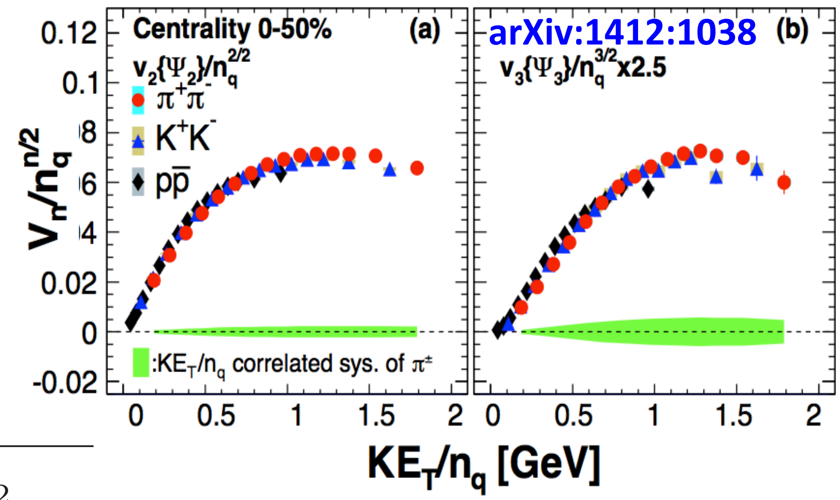
P.R.C 69,034909
P.R.L. 101,232301
P.R.C 82,011902
P.R.C 84,044902

Meson v_n estimation

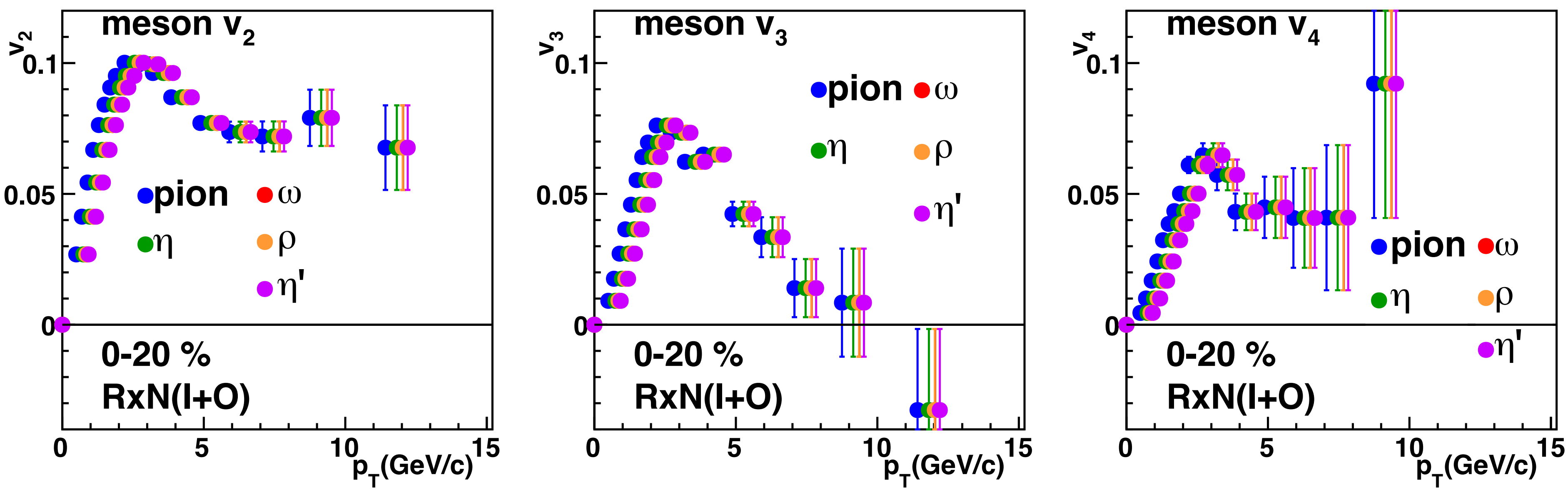
It has been known that hadron v_n as a function of KE_T are scaled by the number of constituent quark.

Meson v_n is estimated from pion v_n.

The number of constituent scaling

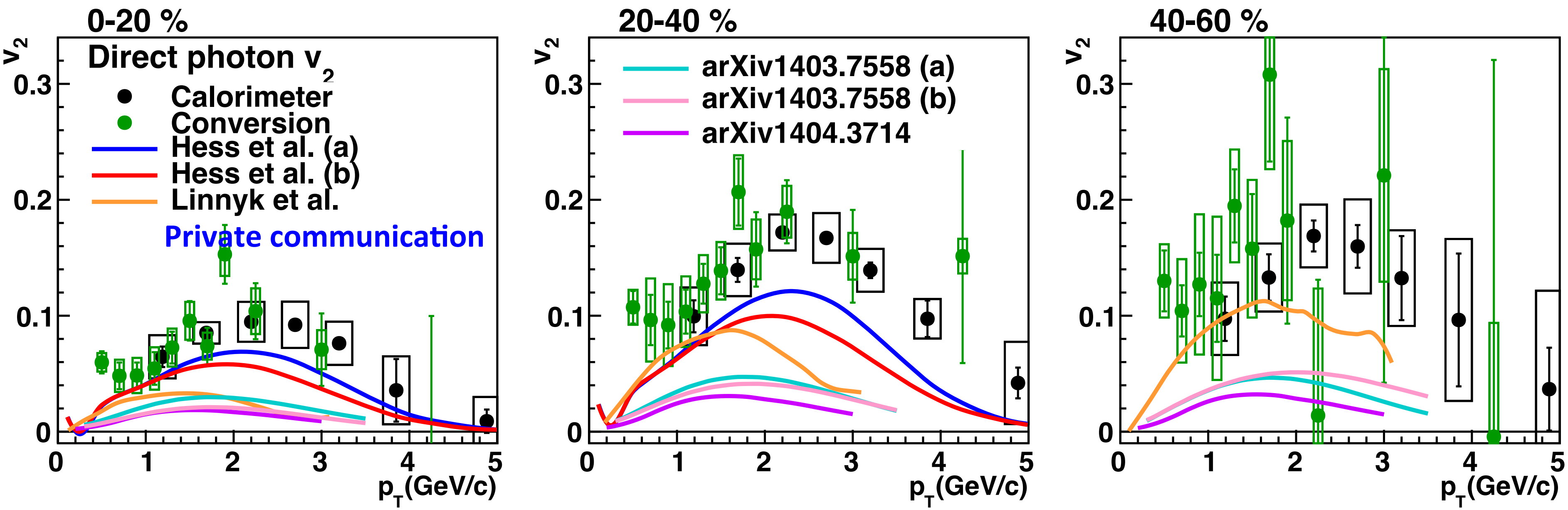


$$p_{T,meson} = \sqrt{\left(\sqrt{p_{T,\pi}^2 + M_\pi^2} - M_\pi + M_{meson}\right)^2 - M_{meson}^2}$$



Model comparison of photon v_2

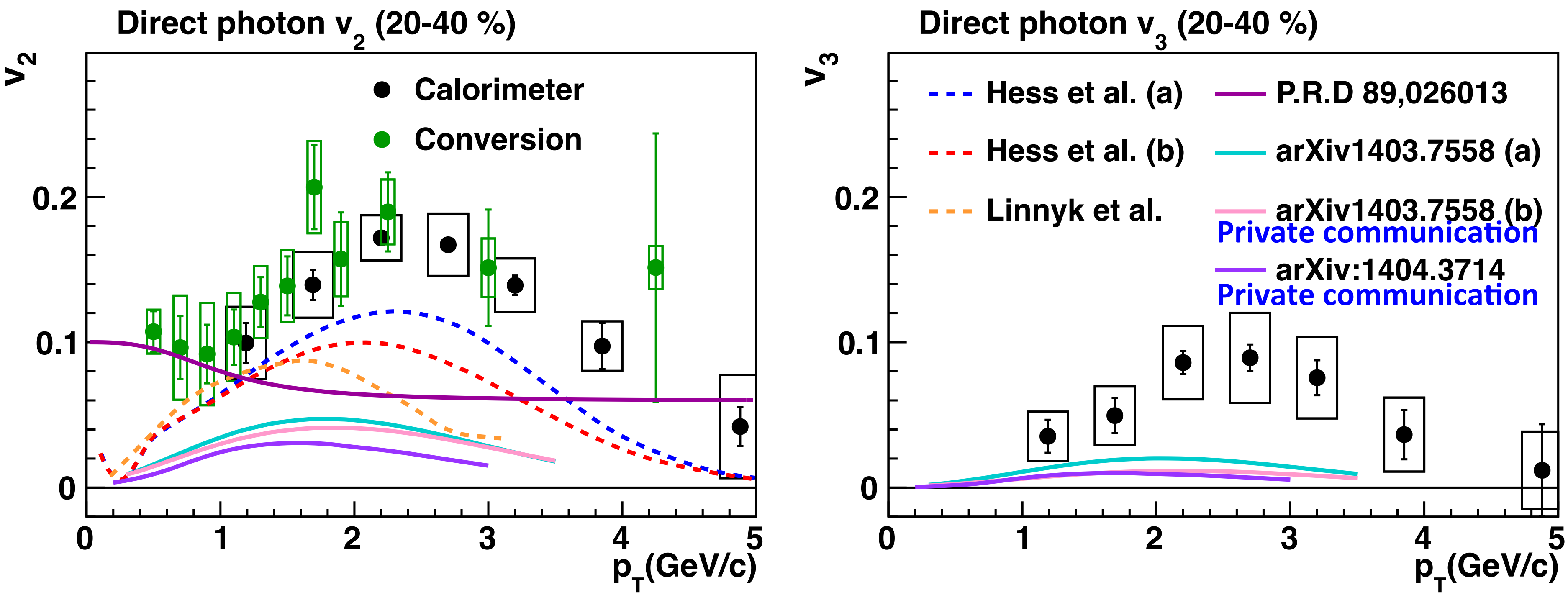
PRC 84,054906
PRC 89,034908



(Orange) Transport model considering photons from hadron phase
(Blue, red) Fireball model
Hydrodynamic calculations (cyan, pink, and violet) including photons from late state, are much underestimated.

Model comparison of v_2 and v_3

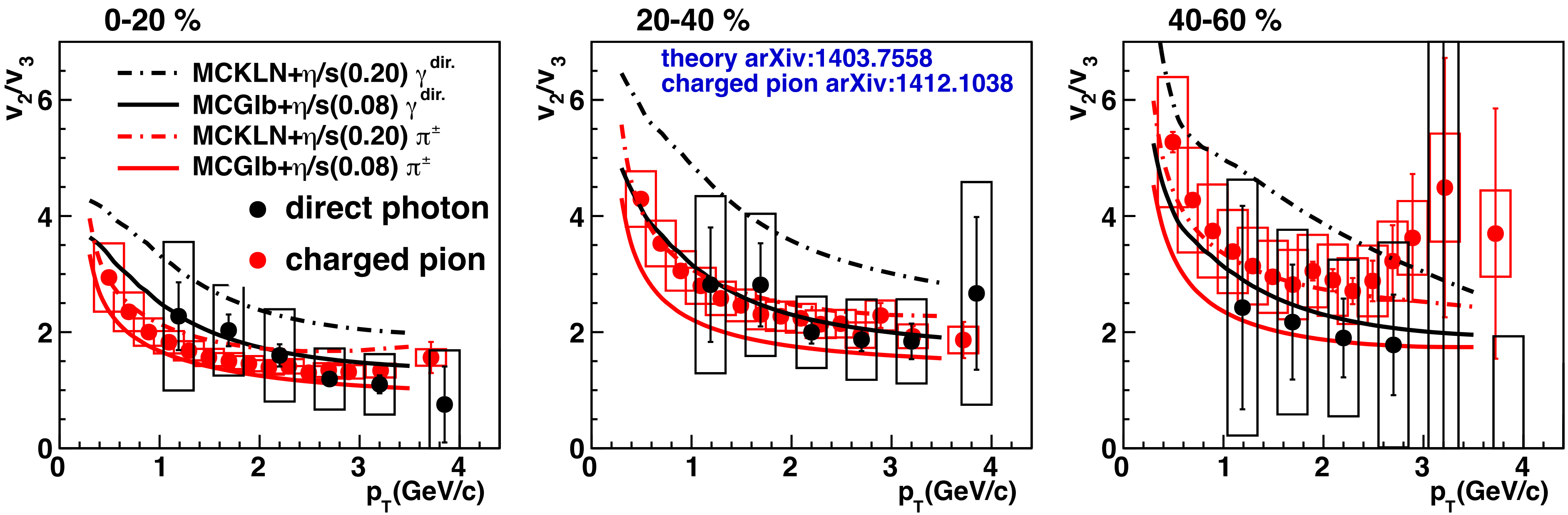
PRC 84,054906
PRC 89,034908
P.R.D 89,026013
arXiv:1404.3714



Dark violet is based on magnetic field effect, upper limit is shown.
Model calculations of photon v_3 are much smaller than experimental data.
The data of v_3 may help to constrain parameters in model calculations.

The ratio of v_2 to v_3 in p_T region

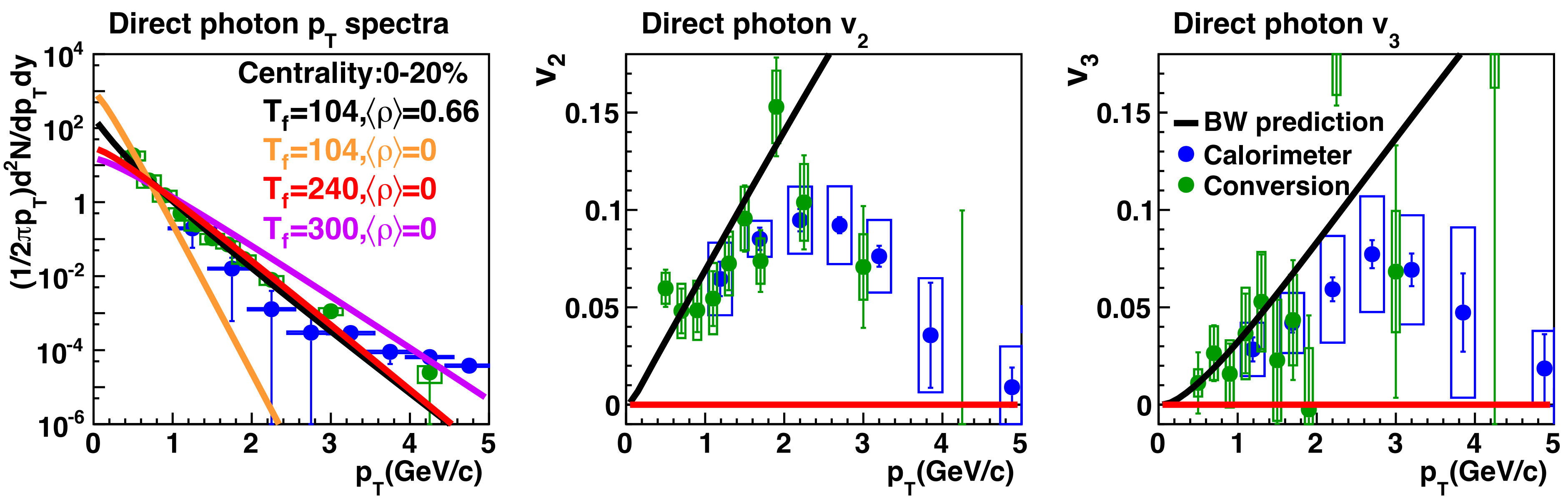
$\pi^\pm$: arXiv:1412:1038
Model : arXiv:1403.7558
Private communication



- Photons don't have strong centrality dependence at around 2-3 GeV/c
- Pions increase from central to peripheral

Photon and pion show different centrality dependence.

Photon observables predicted by blast wave model



The p_T spectra is well described by

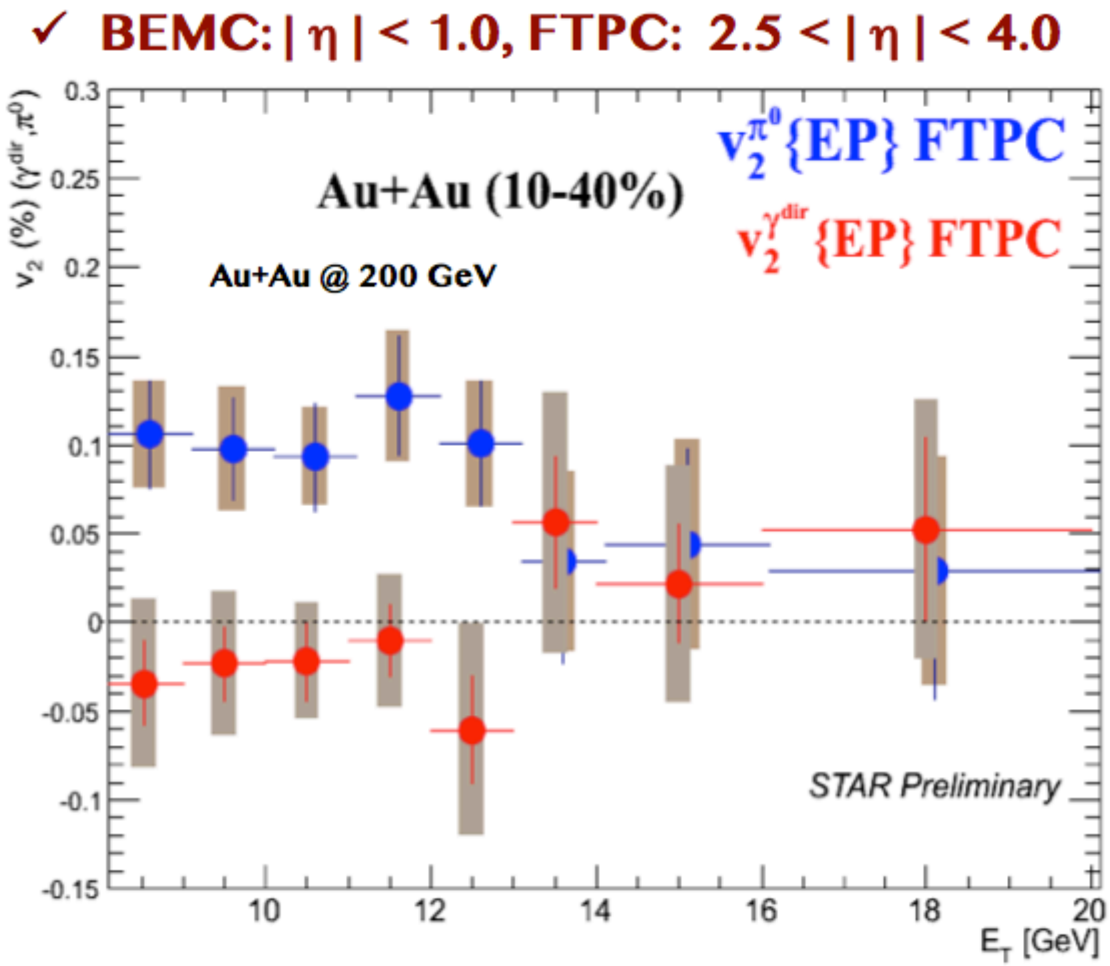
- Low temperature (T_f=104) with radial flow <ρ>=0.66
- High temperature (T_f=240) with radial flow <ρ>=0

v_n=0 with radial flow <ρ>=0

Blast wave could suggest that photon puzzle is understood by the radial flow effect.

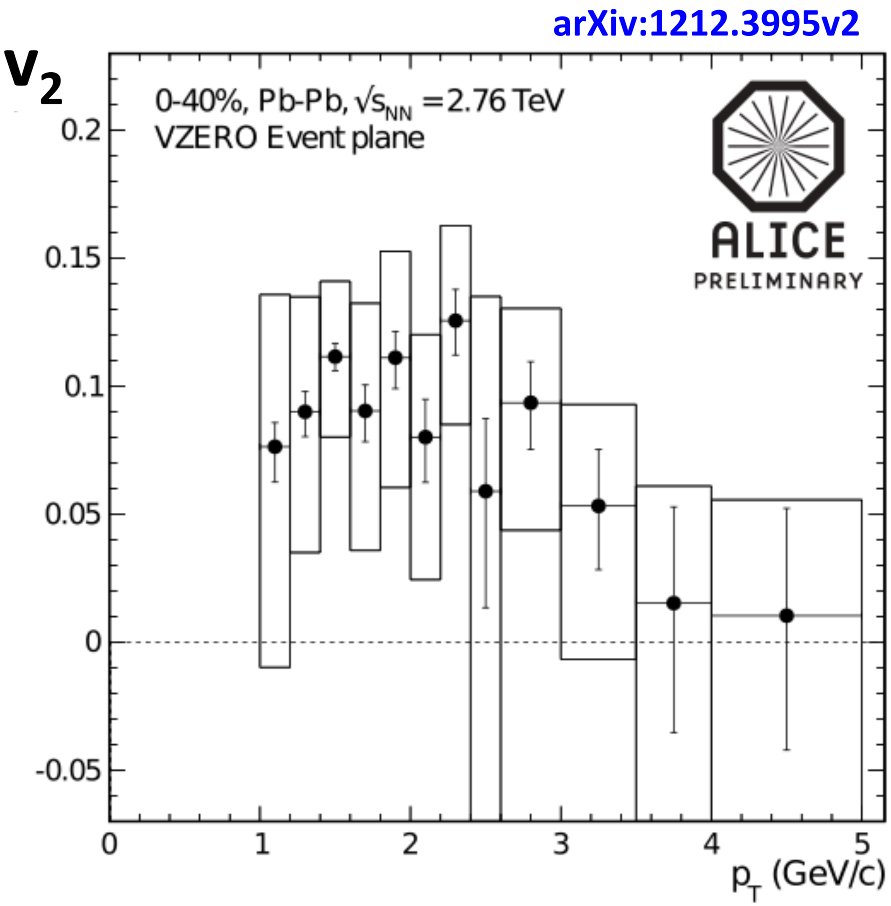
π^0 and $\gamma^{dir.}$ v_2 measurement by STAR

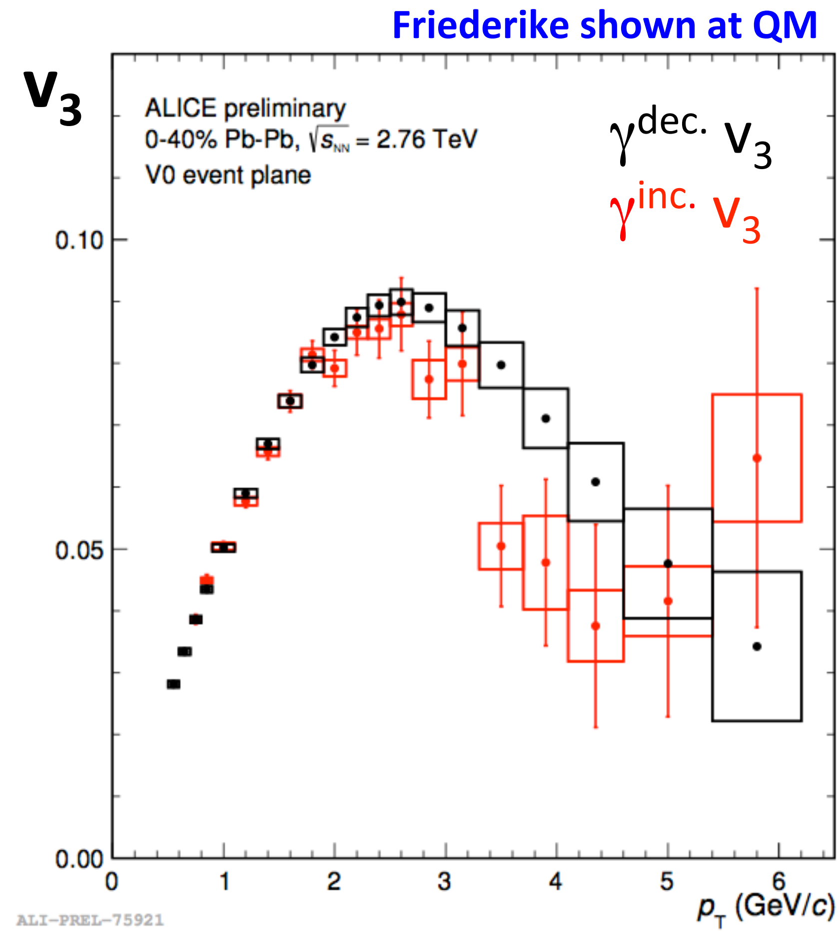
Ahmed M. Hamed
shown at QM



$\gamma^{dir.}$ 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





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