Measurement of soft photon collective flow in $\sqrt{s_{NN}}$=200GeV Au+Au collisions at RHIC-PHENIX experiment

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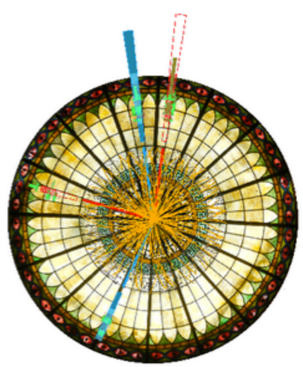
DIS 2015
XXIII International Workshop on Deep-Inelastic Scattering and Related Subjects

Dallas, Texas
April 27 – May 1, 2015



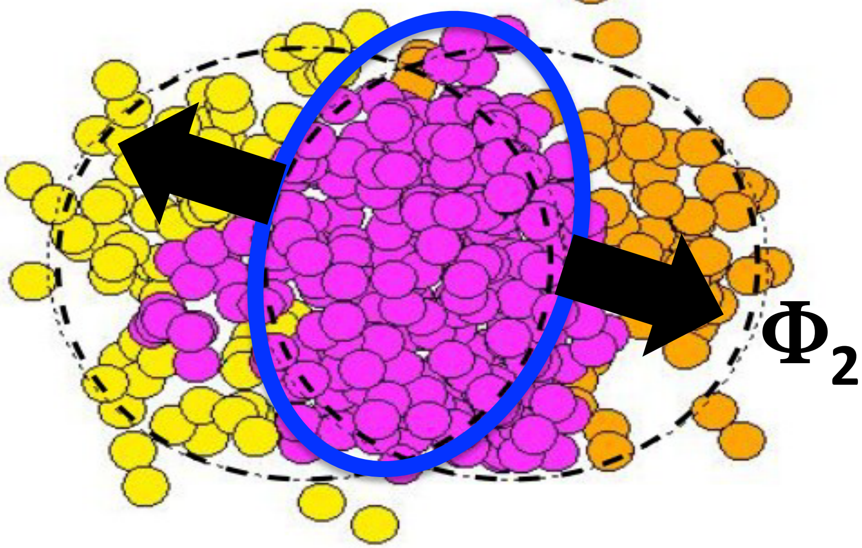
PHENIX

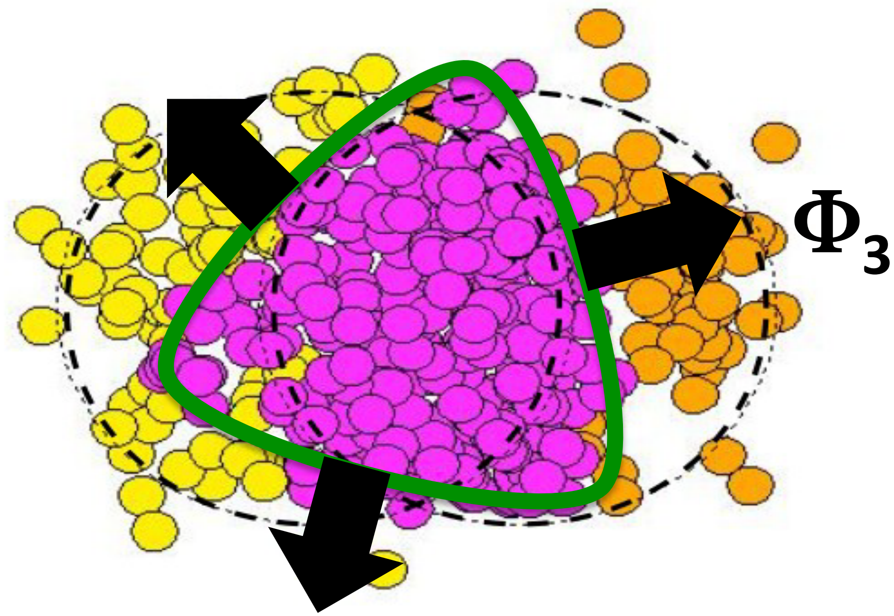
(Higher order) Azimuthal anisotropy

$$\frac{dN}{d(\phi - \Phi_n)} = N_0 \left[1 + 2\sum v_n \cos\{n(\phi - \Phi_n)\}\right]$$

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

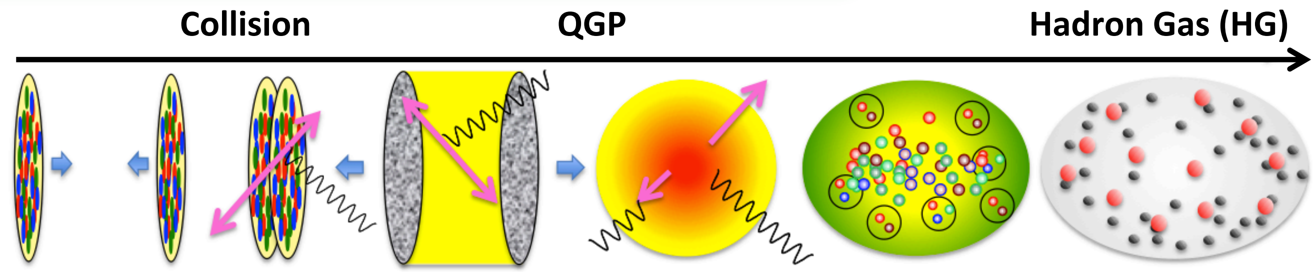
Φ_n : Participant Plane





We can study collective motion of quarks and gluons in QGP.
Higher order fluctuations come from participant position fluctuations.
Initial geometrical anisotropy + hydrodynamic expansion (η/s)

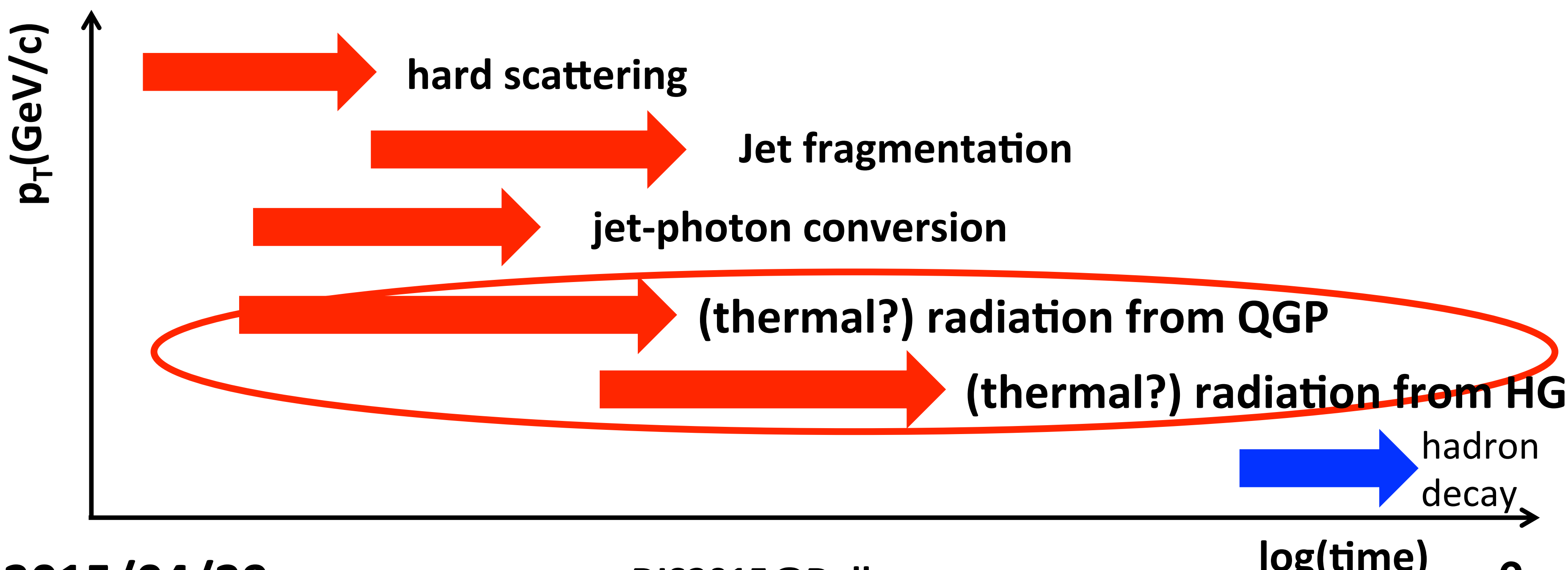
What are direct photons ?



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

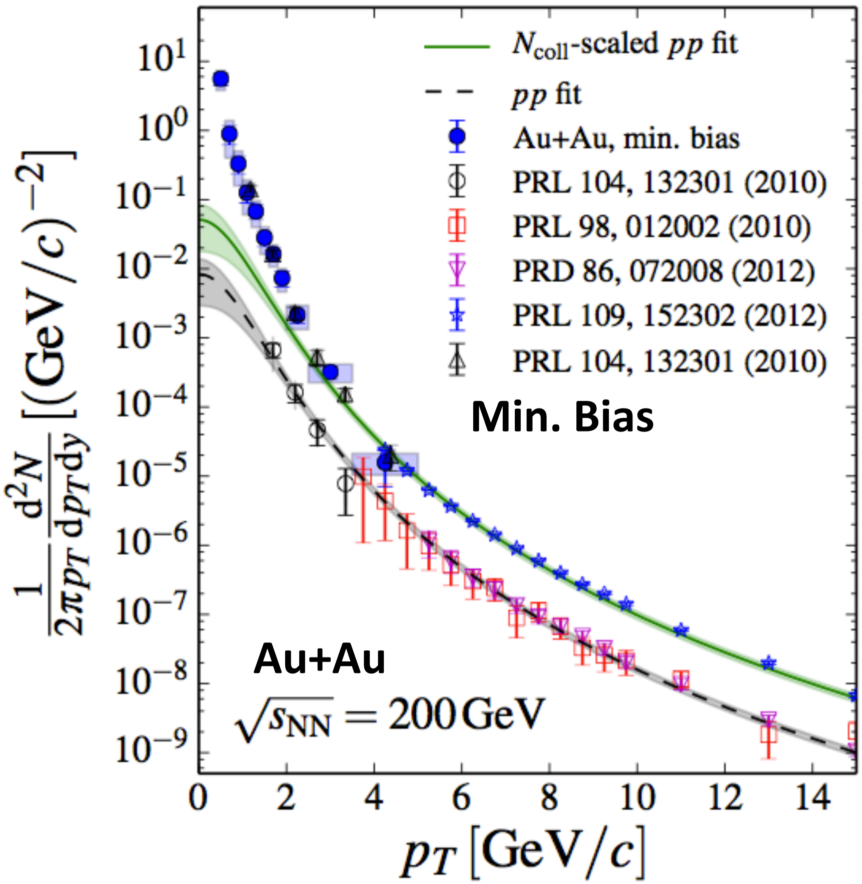
- **Penetrating the medium since they are color-less**
- **Created during all stages of the collision**

We can investigate the evolution of QGP.



Large Excess of Direct Photon p_T spectra

arXiv:1405.3940



- **p_T > 4 GeV/c**
  spectra (Au+Au) ≈ spectra (p+p) x N_{coll}
- **p_T < 4 GeV/c**
  spectra (Au+Au) > spectra (p+p) x N_{coll}

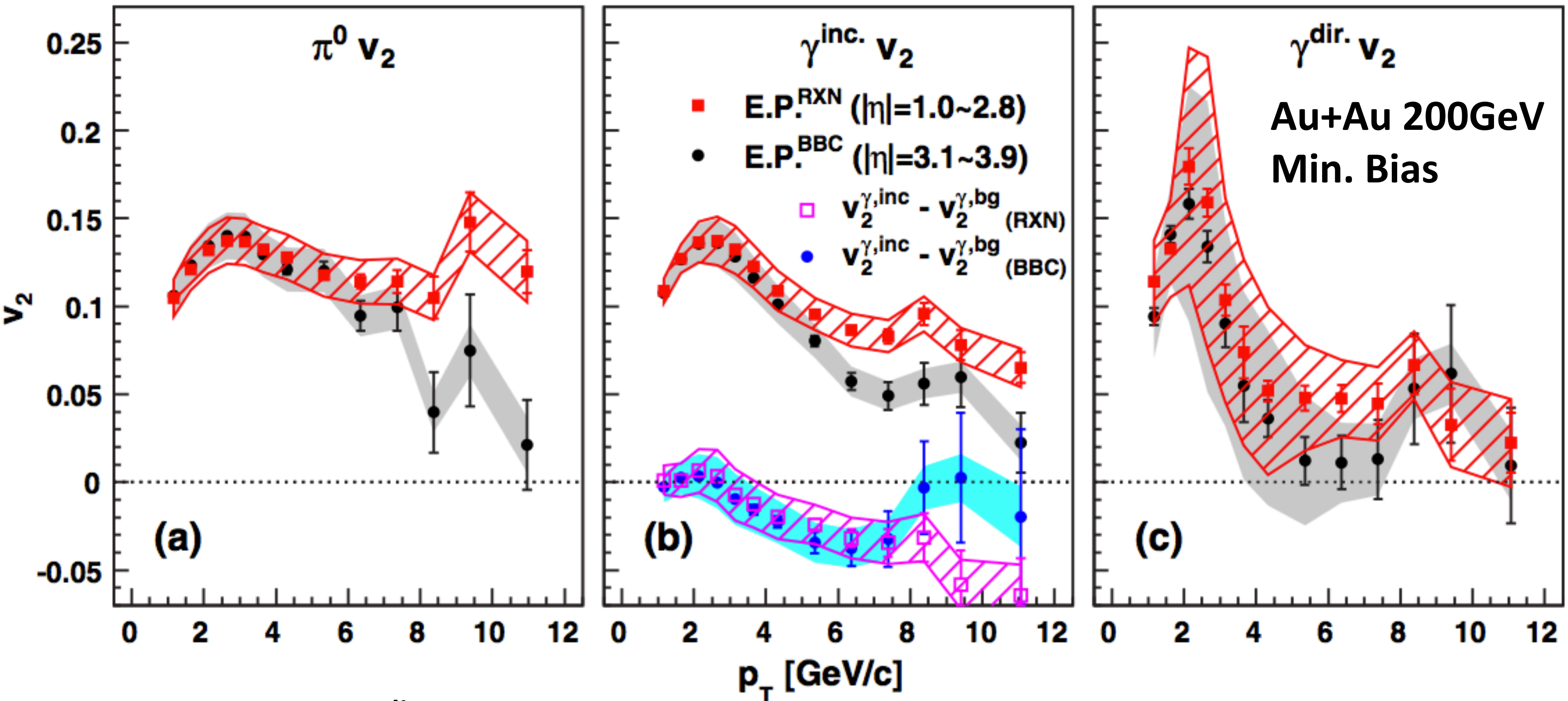
Photons in excess of pQCD expectations are emitted in Au+Au collisions. Suggested thermal photons from the flowing medium.

The excess of p_T spectra are fitted and effective temperature is extracted. It is approximately 240 MeV, but the connection to true temperature is complicated (and model-dependent).

Conventional wisdom : p_T < 4 GeV/c
Photons are emitted from very hot medium at early time of collisions.

Large Direct Photon Elliptic Flow (v_2)

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



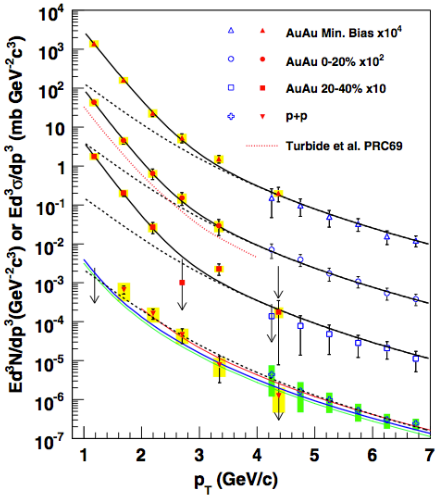
p_T > 4 GeV/c : $\gamma^{dir.}$ $v_2 \approx 0$

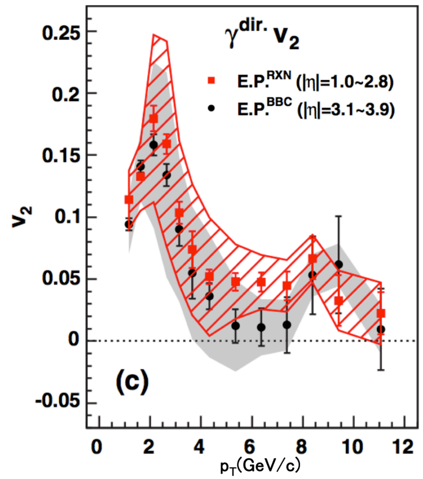
p_T < 4 GeV/c ($p_T \approx$ 2 GeV/c) : hadron $v_2 \approx \gamma^{dir.}$ $v_2 > 0$

Conventional wisdom : p_T < 4 GeV/c

Photons are emitted at late stage of collisions, temperature is low.

Direct Photon Puzzle



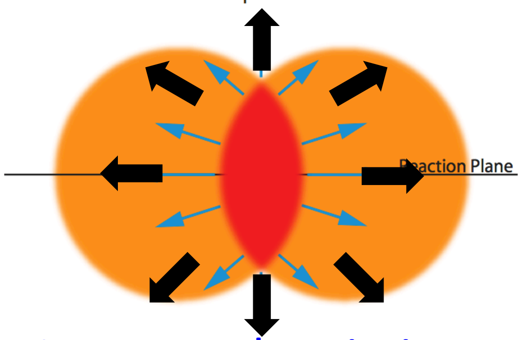


Yield enhancement

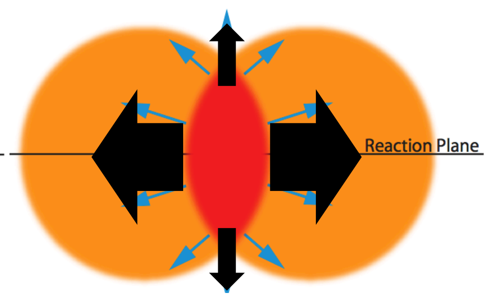
Suggests early emission when temperature is high at or above 300MeV (true T), but flow is still small.

Large elliptic flow (v_2)

Suggests late emission when collective motion is large but temperature is low.



Integrated emission



differential emission

There is no models to explain simultaneously the large excess of photon **yield** and the large **elliptic flow** (v_2).

It is "**direct photon puzzle**".

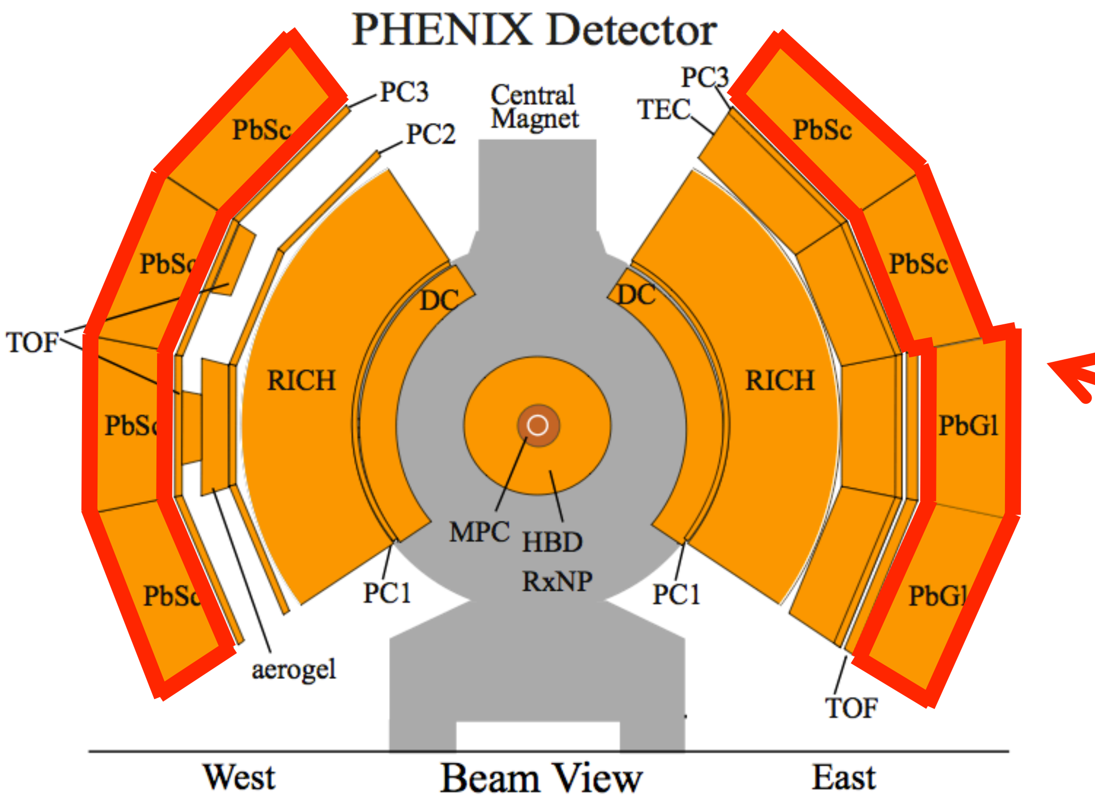
Motivation

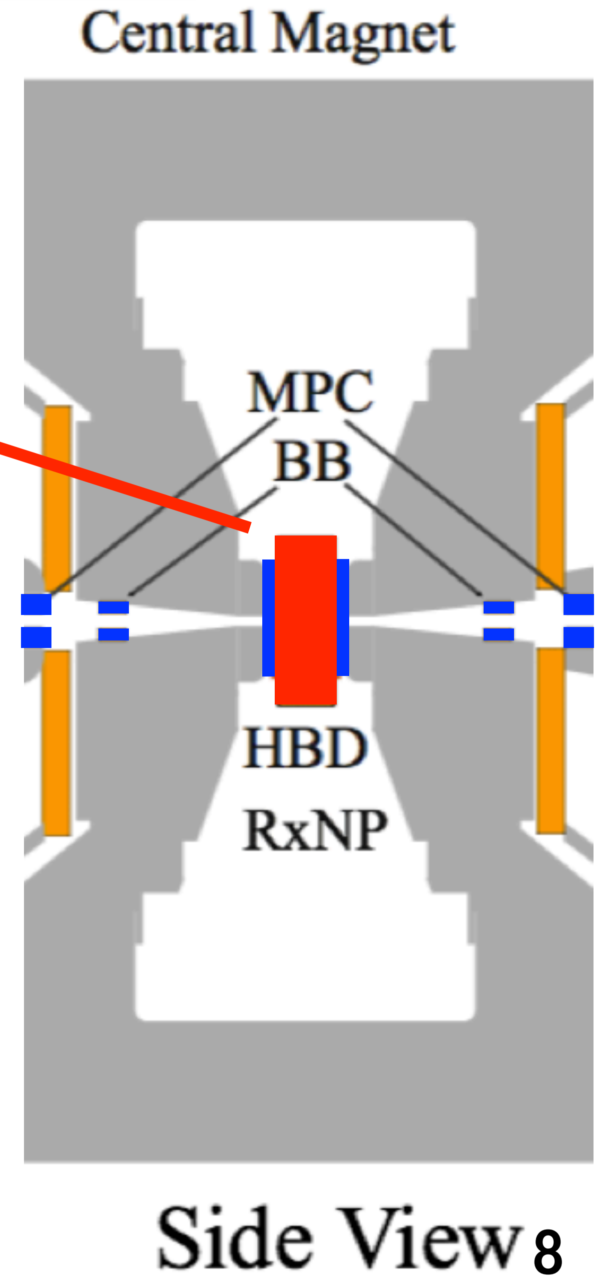
To resolve the puzzle and constrain photon production mechanisms, more differential measurements are needed.

- **Centrality dependence of higher order azimuthal anisotropy (v_3)**

Photon sources	v_2	v_3
Hadron-gas	Positive and sizable	Positive and sizable
QGP	Positive and small	Positive and small
Jet-medium interaction	positive or negative	positive or negative
Jets	very small	very small
Magnetic field effect	**Positive**	**Zero**

Data set and PHENIX detector





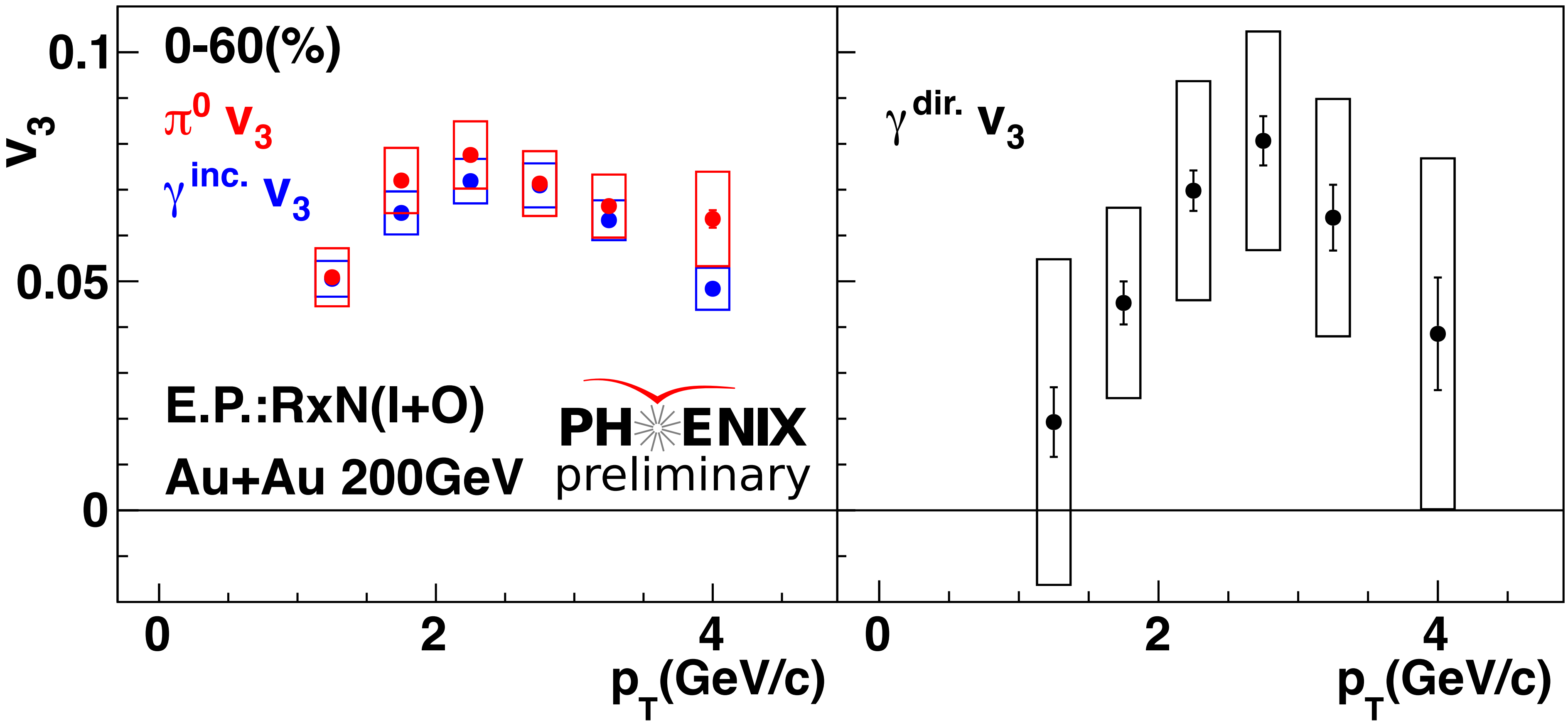
Data set : Au+Au 200 GeV

Event plane : Reaction plane detector

Photon : Electromagnetic calorimeter

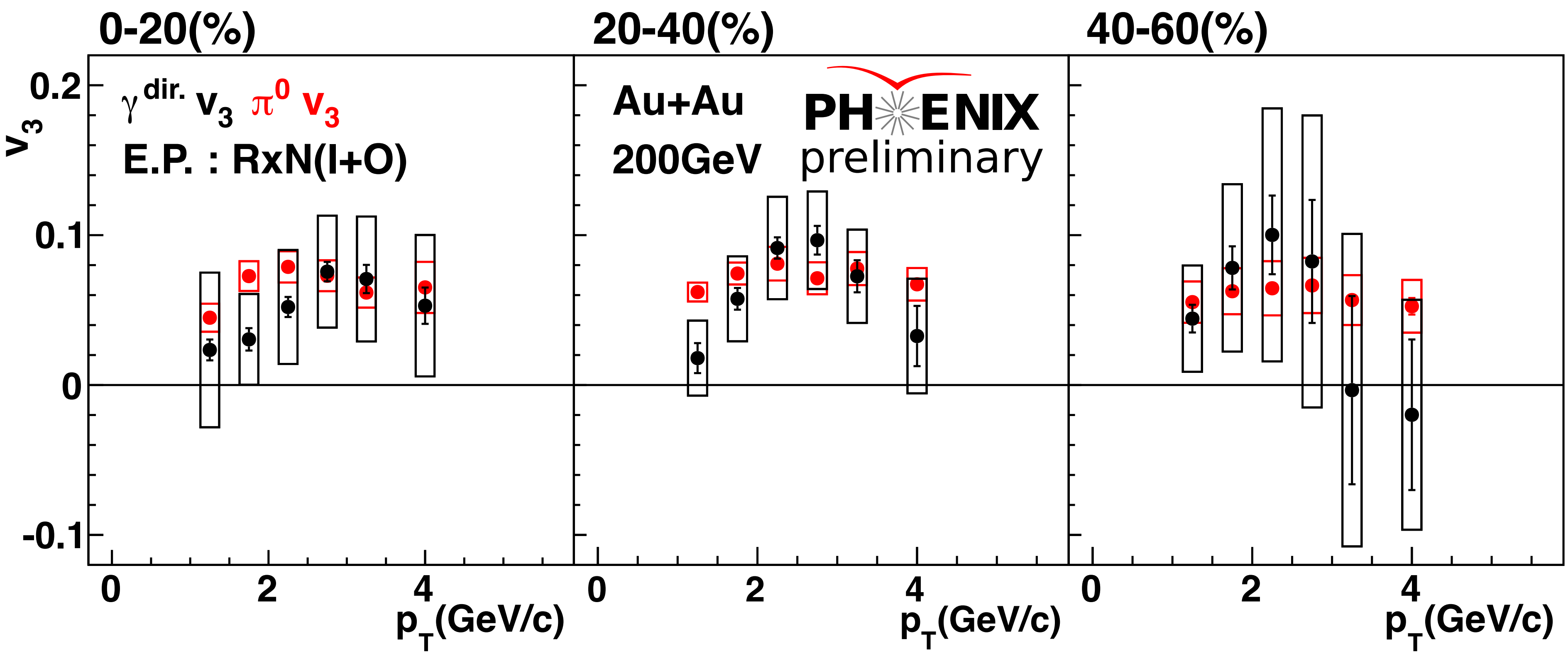
$$v_n = \langle \cos\{n(\phi - \Psi_n)\}\rangle$$

Non-zero and positive direct photon v_3



The magnitude of direct photon v_3 is comparable to neutral pion v_3 in $2 < p_T < 3$ GeV/c.
It is a similar trend as a seen in case of v_2.

$\gamma^{dir.}$ and π^0 v_3 indicate similar centrality dependence

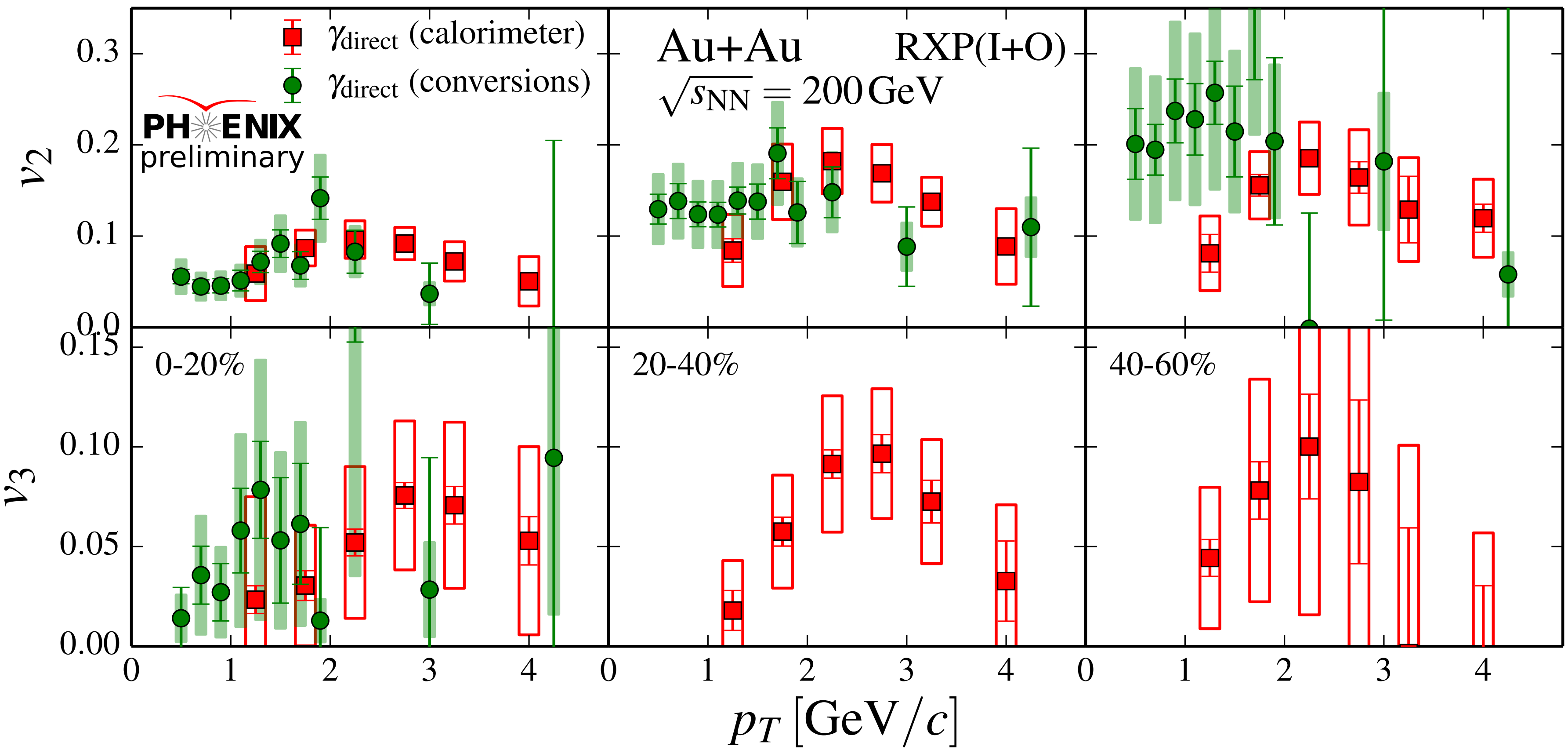


The magnitude of photon v_3 in $2 < p_T < 3$ GeV/c is comparable to hadron v_3 in all centralities.

Large photon v_n could originate from

Initial geometrical anisotropy + hydrodynamic expansion of medium

$\gamma^{dir.}$ v_2 and v_3 with the two methods



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

Conversion method allows to extend the measurement to lower p_T.

Theoretical models

- **Parton-Hadron-String-Dynamics (PHSD) (O.Linnyk et al) (P.R.C 89, 034908)**

Microscopic transport model
pQCD + QGP (e.g. $q+\bar{q}\to g+\gamma$) + HG (e.g. $m+m\to m+m+\gamma$, $m+B\to m+B+\gamma$)

- **Hydrodynamic calculation (Chun Shen et al.) (arXiv:1403.7558)**

Initial geometry (MCGlb or MCKLN) + η/s correction to photon emission rate
Start at τ_0=0.6 fm/c and finish at T=120 MeV

- **Hydrodynamic calculation (Gojko Vujanovic et al.) (arXiv:1404.3714)**

3+1D viscous hydrodynamics with Glauber initial conditions + varying shear relaxation time (model parameter)

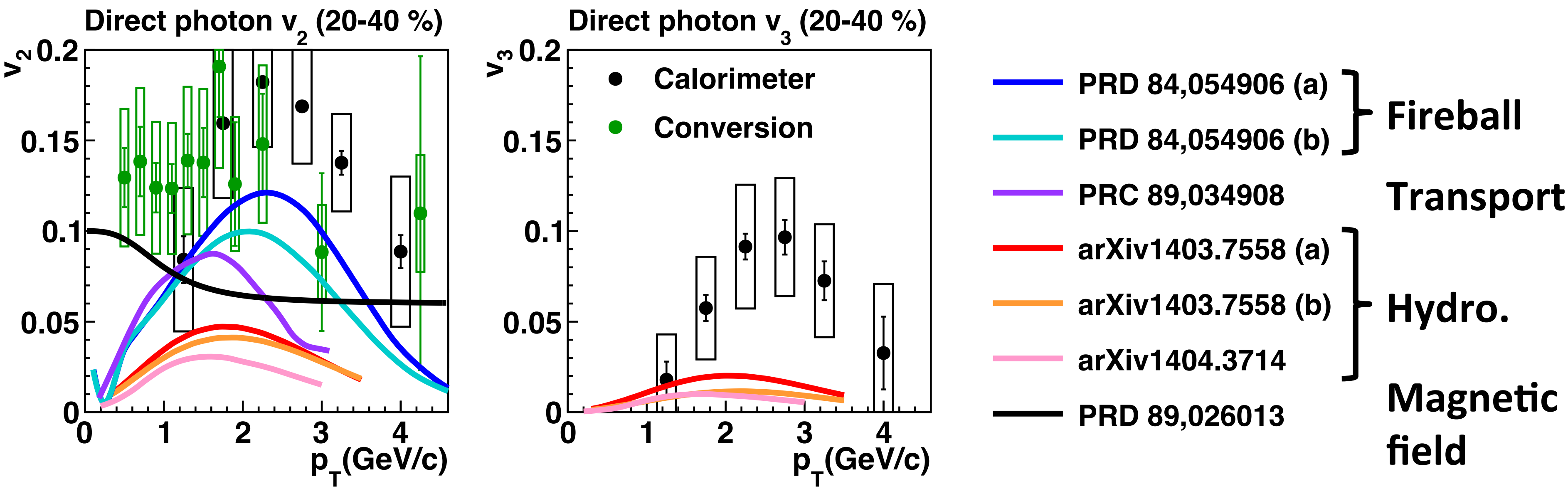
- **Phenomenological calculation (Fireball) (H. van Hees et al.) (P.R.C 84,054906)**

Parameterized time evolution of fireball radius and profile -> LO AMY rates
-> QGP/HG switch at 170 MeV

- **Magnetic field (Berndt Müller et al.) (P.R.D 89,026013)**

Magnetic field could affect photon emitting angle.

Comparison of $\gamma^{dir.}$ v_n with model calculations



Every calculations indicate non-zero and positive v_n while they are lower than experimental measurements.

Hydrodynamic calculations underestimate in $1 < p_T < 4$ GeV/c. Photons generated in hadron gas phase seem important.

Assuming that ALL photons are produced at hadronization time and by only $q+\bar{q}$ annihilation, similar to $q+\bar{q}$ coalescence, then the photon v_2 could be described (arXiv:1504.01654).

Summary

Centrality dependence of direct photon v_3 in Au+Au 200 GeV collisions at RHIC-PHENIX is measured.

- ✓ $\gamma^{dir.}$ v_3 is non-zero and positive in $2 < p_T < 4$ GeV/c.
- ✓ The magnitude of $\gamma^{dir.}$ v_3 in $2 < p_T < 3$ GeV/c is comparable to hadron v_3.

  Large photon v_n could be created by

  initial geometry + hydrodynamic expansion of medium

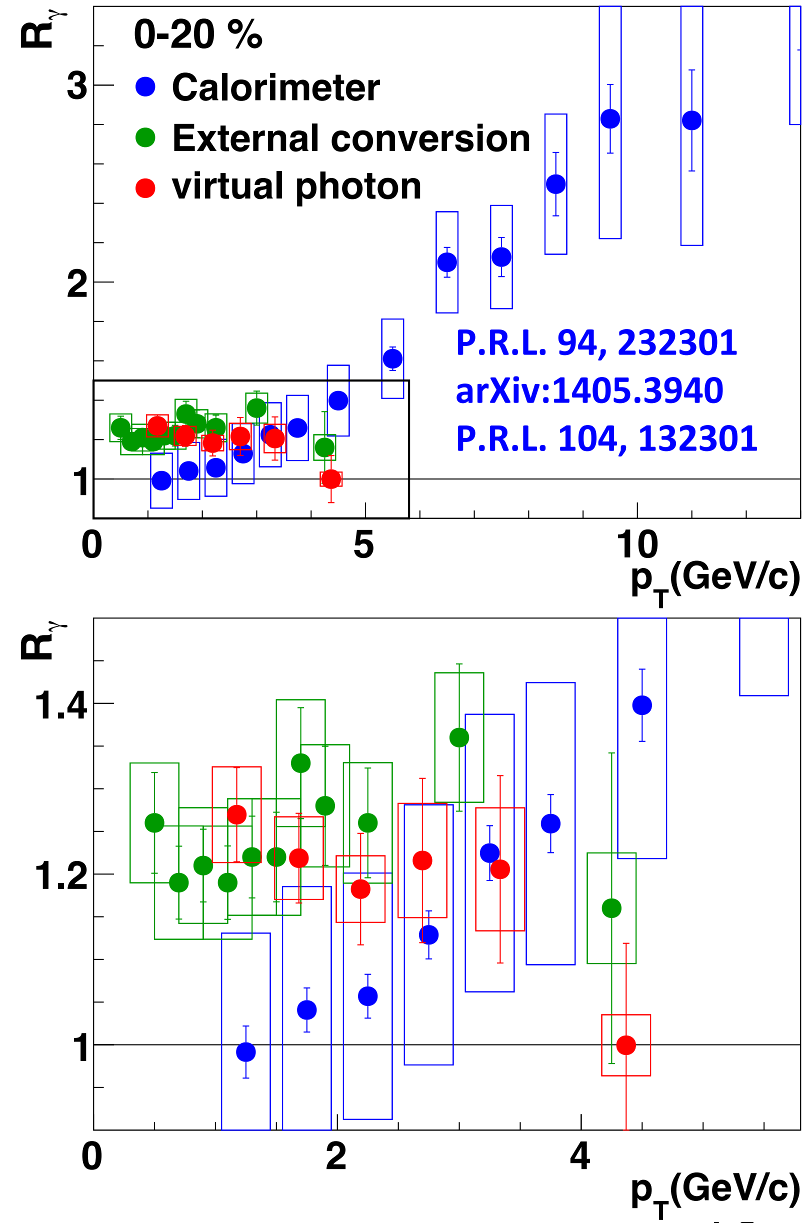
Photon v_n is compared with several theoretical calculations.

Photons generated during hadron gas phase (late stage of the collisions) could be important.

The v_3 results will help to constrain photon production mechanisms.

The excess of direct photon

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

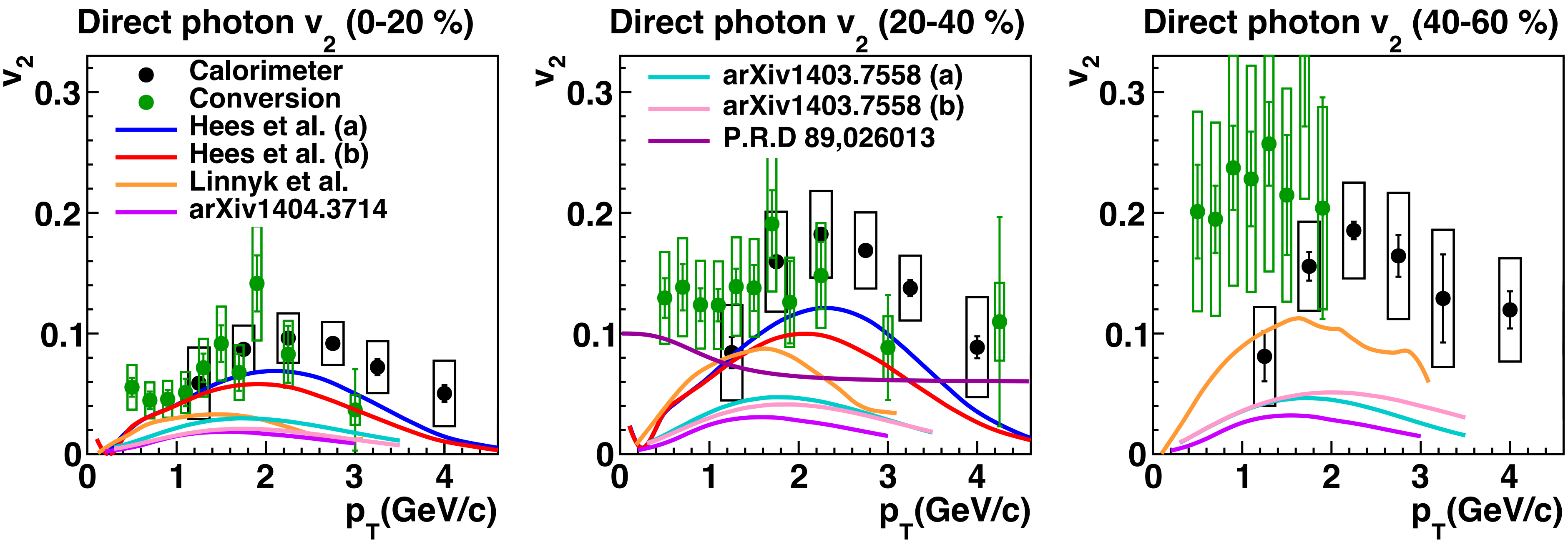


The excess of direct photons has been measured in a wide p_T range, but at low p_T the calorimeter measurement suffers from low energy resolution and very high backgrounds.

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

At low pT direct photons constitute 20% of inclusive photons.

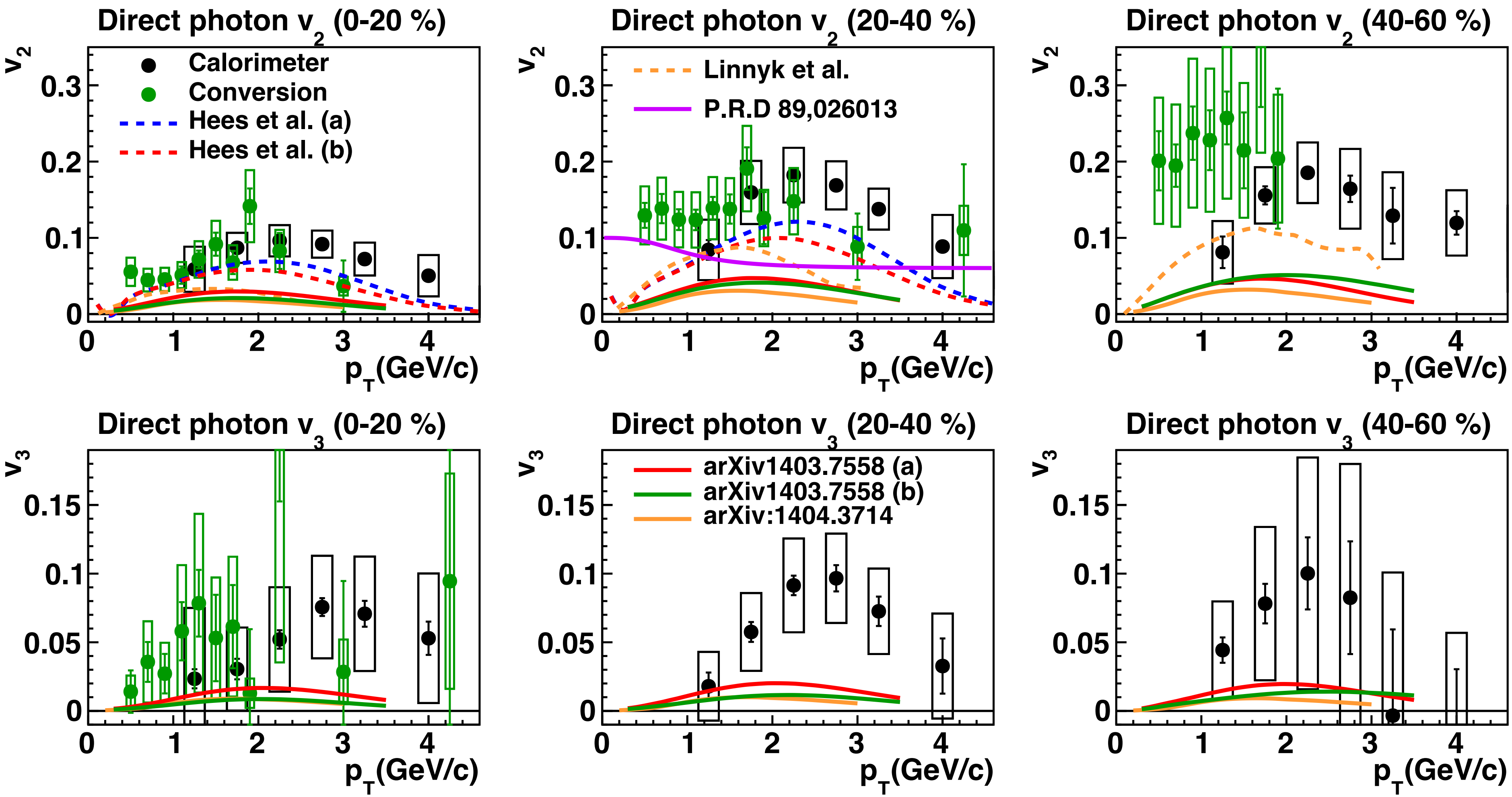
Comparison of $\gamma^{dir.}$ v_n with model calculations



Direct photon v_n are compared with
Transport, PHSD, Hydrodynamics, magnetic field model calculations.

Transport : Linnyk et al.
Fireball : Hees et al.
Hydro : 1404.3714, 1403.7558
Magnetic field : PRD 89,026013 (maximum value assuming all photons coming from magnetic field effect)

Comparison of $\gamma^{dir.}$ v_n with model calculations



Every calculations indicate non-zero and positive v_n while they are lower than experimental measurements.

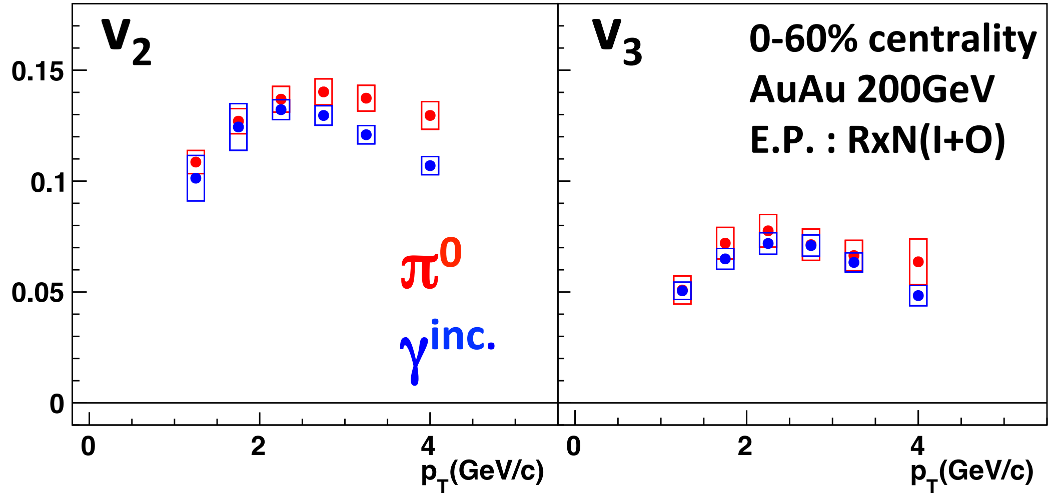
Expectations vs experimental results

Photon sources	v_2	v_3
Hadron-gas	Positive and sizable	Positive and sizable
QGP	Positive and small	Positive and small
Jets	very small	very small
Jet-medium interaction	positive or negative	positive or negative
~~Magnetic field effect~~	~~Positive~~	~~Zero~~

The magnitude and centrality dependence of photon v_n in $p_T \approx 2$ GeV/c are similar to those of hadron v_n.

- Photon azimuthal anisotropy could be described by hydrodynamics.
- The time dependence of the evolution could be improved.

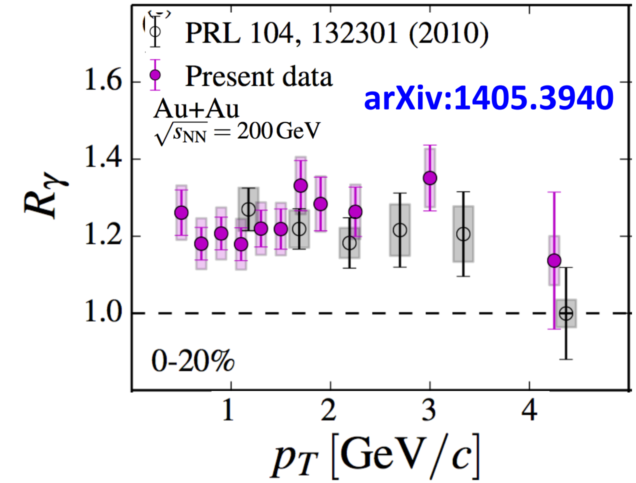
Analysis Flow



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

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

Mesons spectra are assumed by m_T scaling.
Mesons v_n are assumed by NCQ scaling.



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

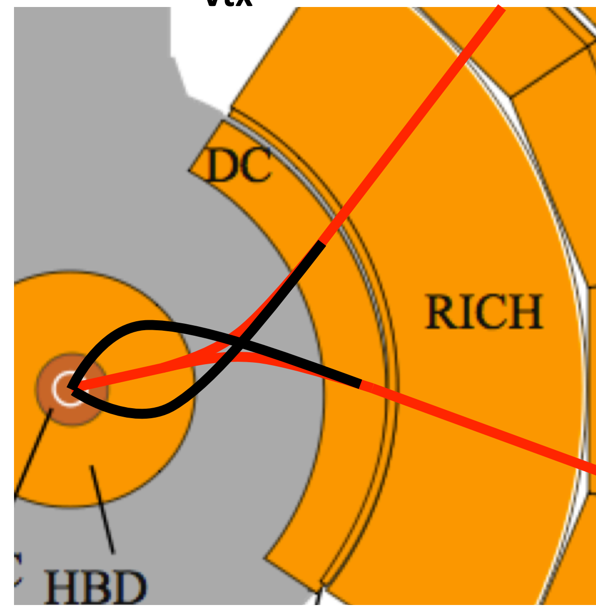
R_γ measured by external photon conversion method is used.

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

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

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.

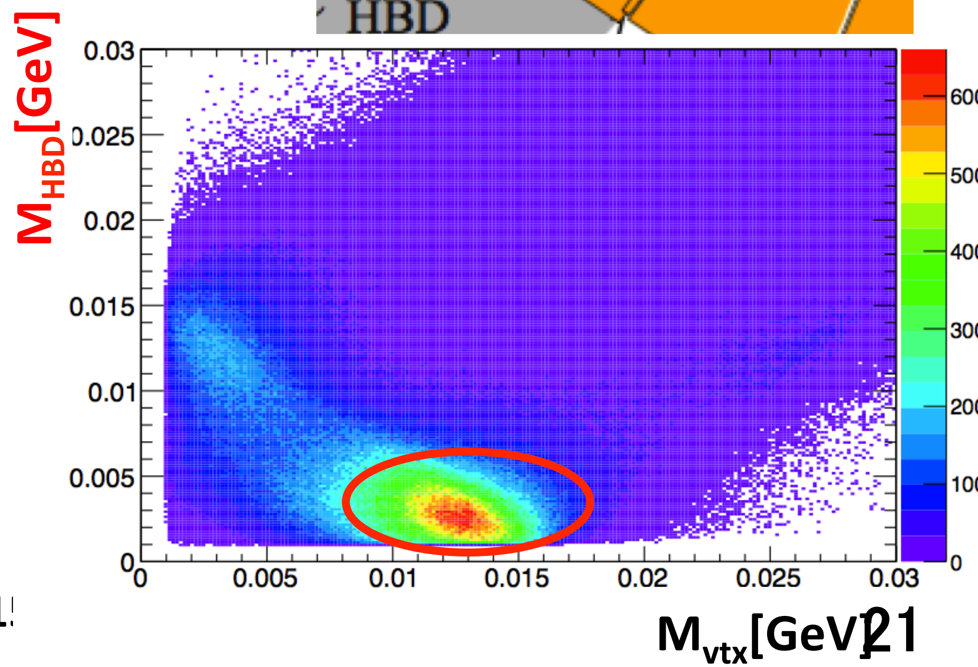
✓ less hadron contamination

✓ good momentum resolution

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

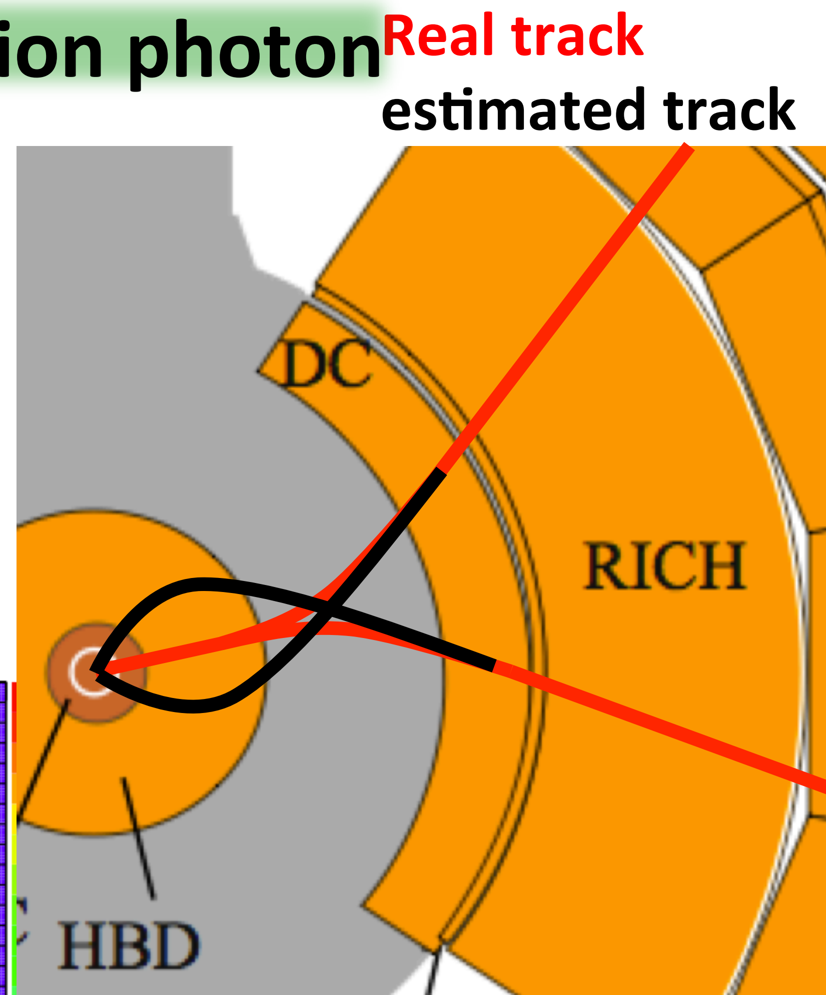
Extended to lower p_T

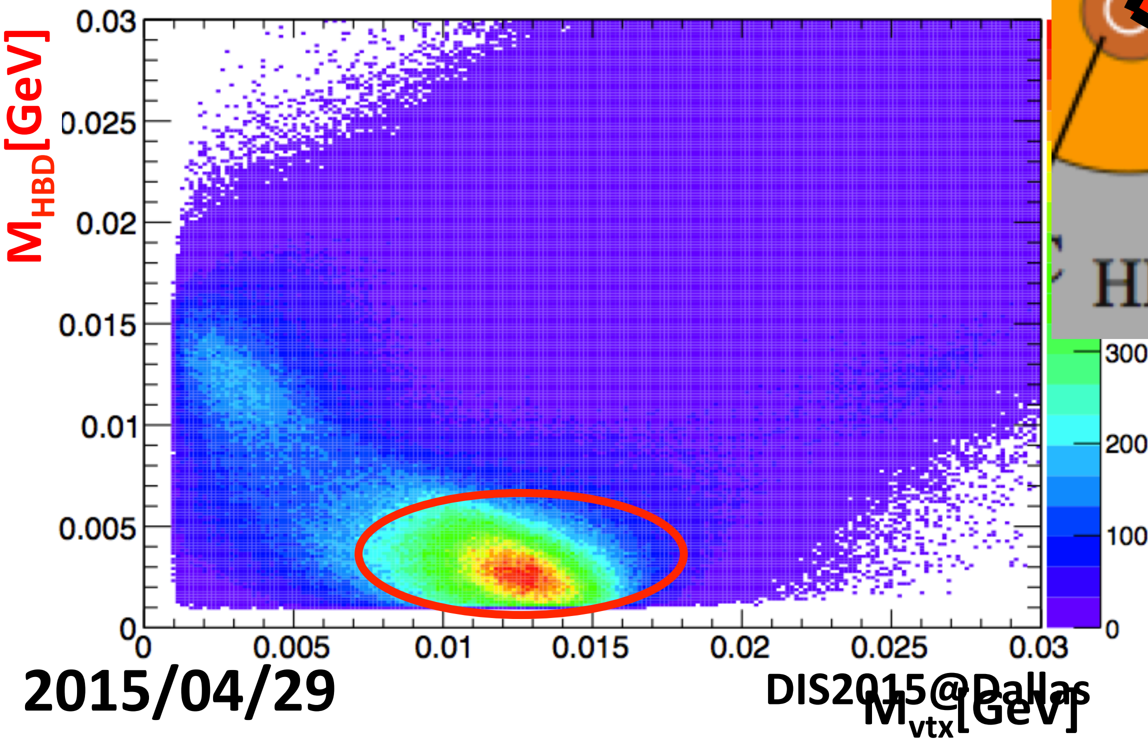
low statistics



External conversion photon

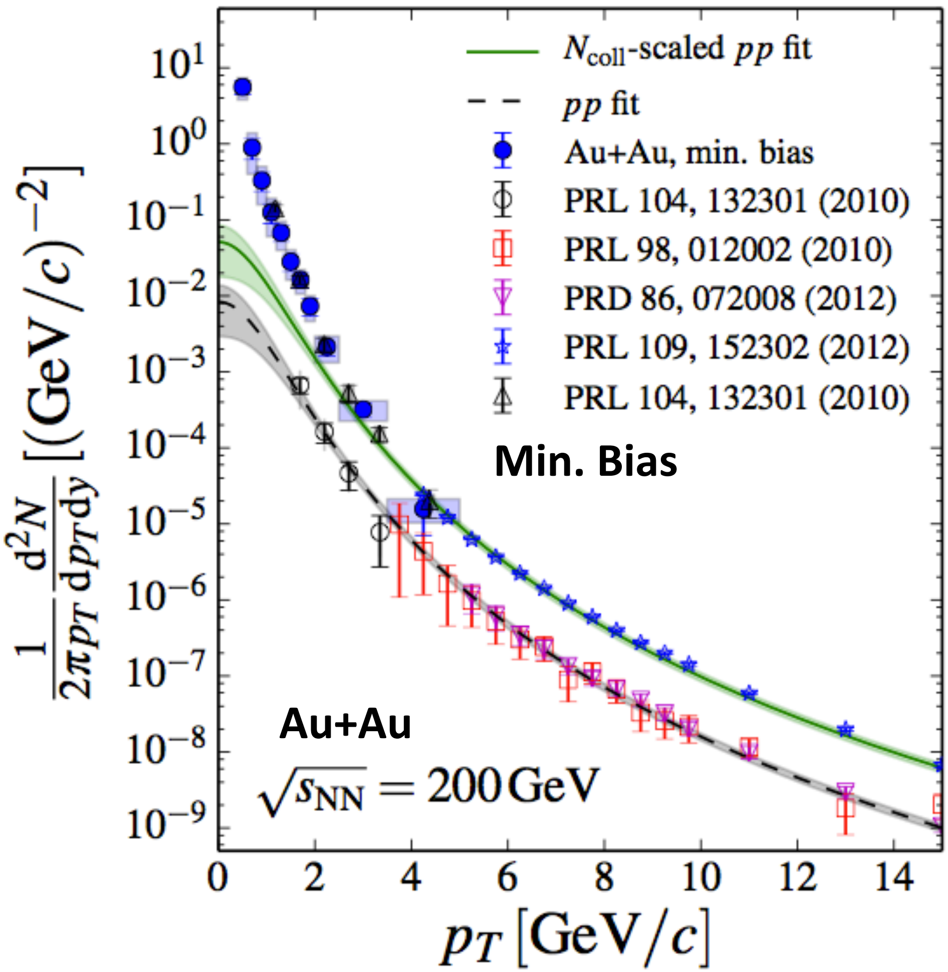
1) real photon converts to e^+e^- in HBD backplane
2) default assumption: track come from the vertex
3) momentum of the conversion tracks will be mis-measured (see black tracks)
4) apparent pair-mass (about 12MeV) will be measured for phtons
5) assume the same tracks originate in the HBD backplane
6)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





Comparable measurement is achieved

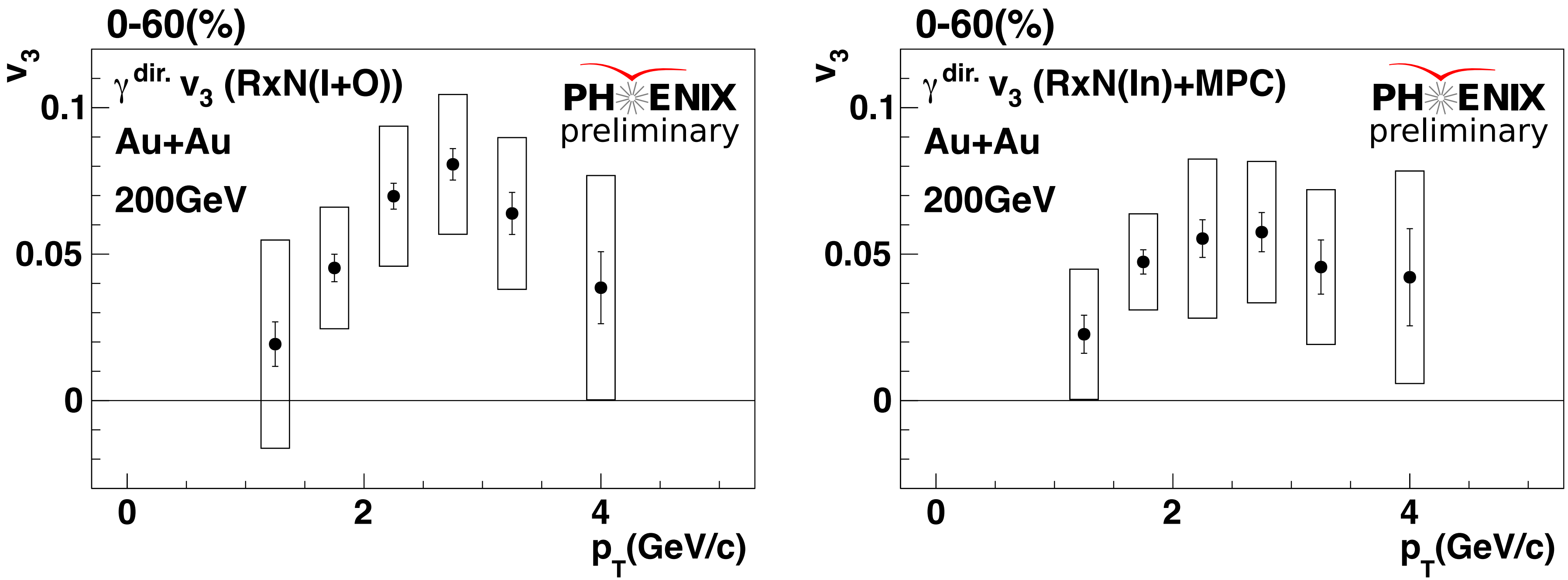
arXiv:1405.3940



Ncoll-scaled pp fit
external conversion
pp virtual photon
pp in EMCal(Run2003 data)
pp in EMCal(Run2006 data)
AuAu in EMCal(Run2004 data)
AuAu from virtual photon(Run4 data)

Using external photon conversion method achieved good agreement with previous results.

Comparison $\gamma^{dir.}$ v_3



RxN(I+O) : $1.0 < |\eta| < 2.8$

RxN(In)+MPC : $1.5 < |\eta| < 3.8$

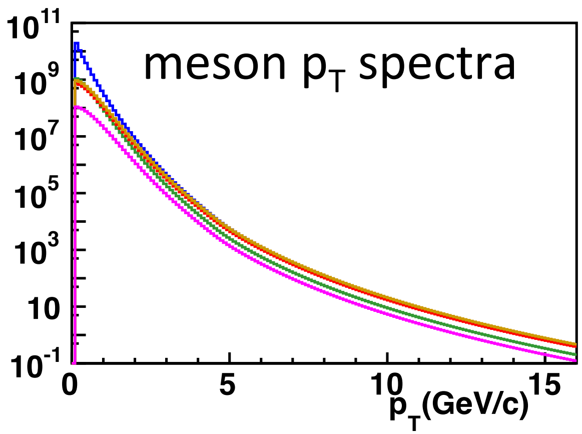
The magnitude of v_3 is comparable.

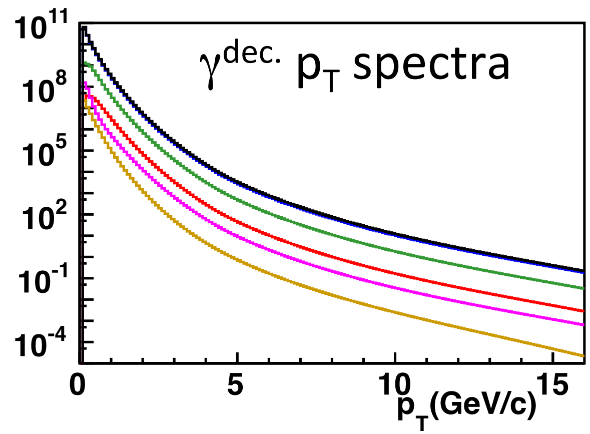
Hadoronic Decay Photon

π ρ
η η'
ω all $\gamma^{dec.}$

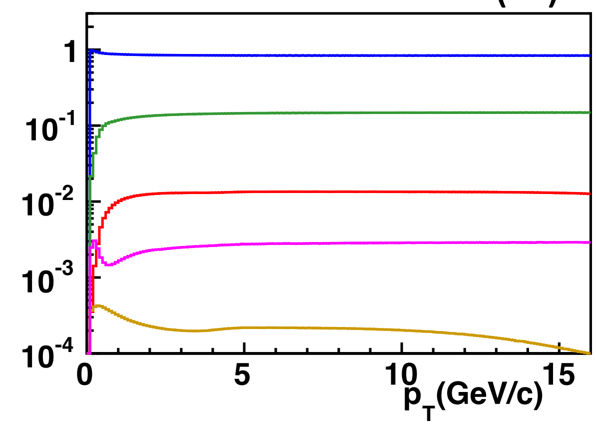
The p_T spectra and v_n are estimated from π.

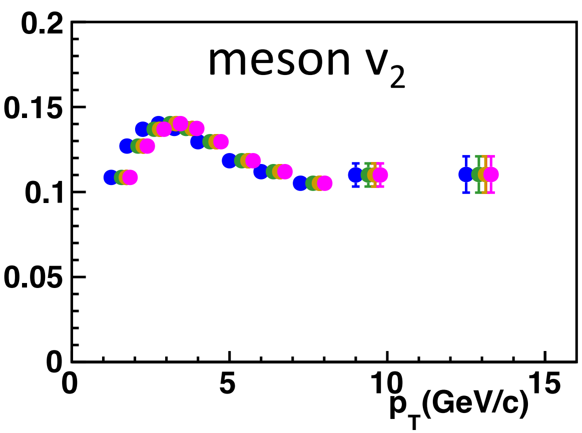
- p_T spectra : m_T scaling
- v_n : quark number scaling

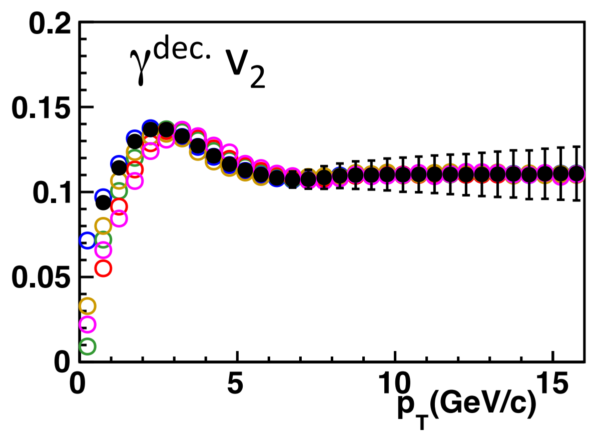




contribution ratio (R^i)







m_T scaling

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

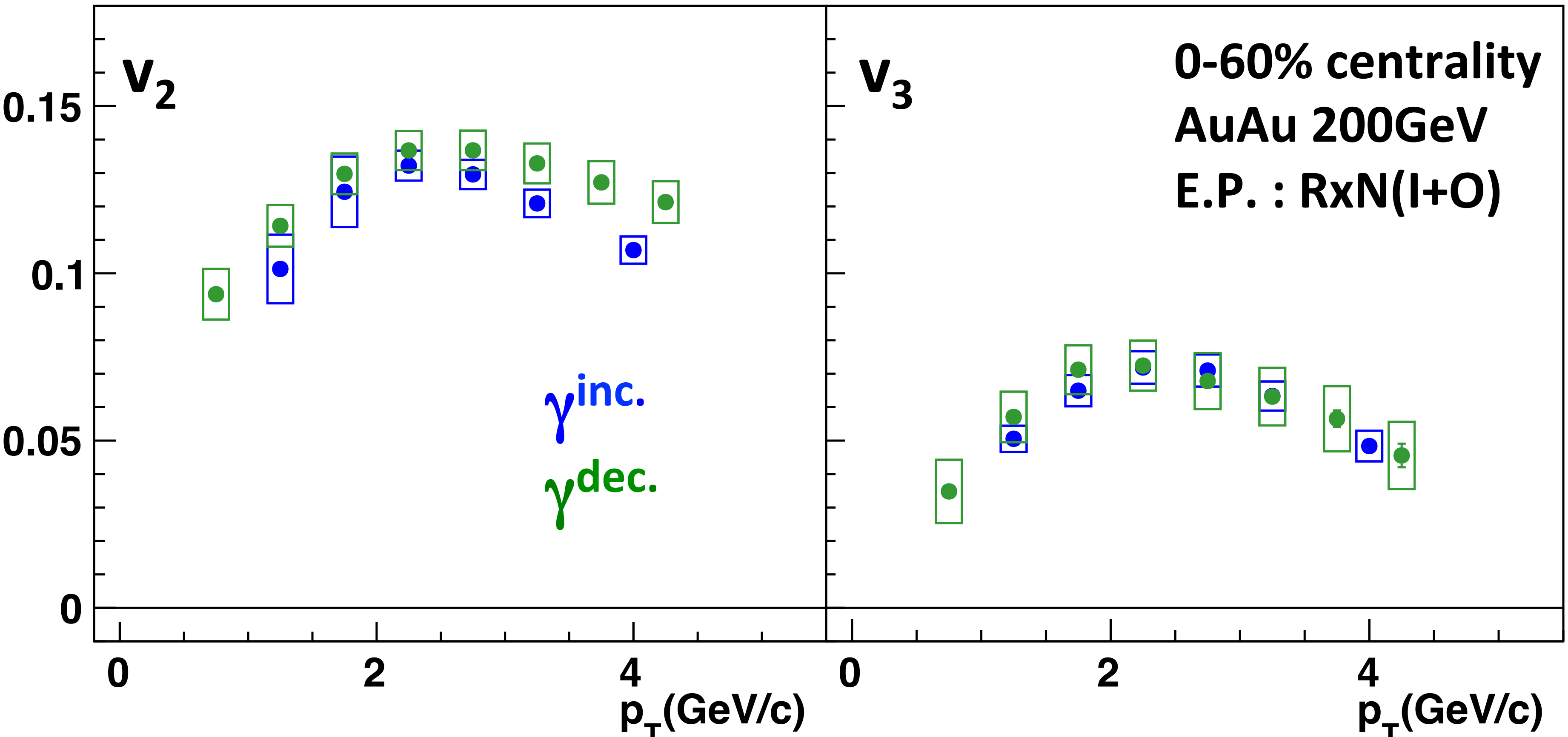
decay photon v_n

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

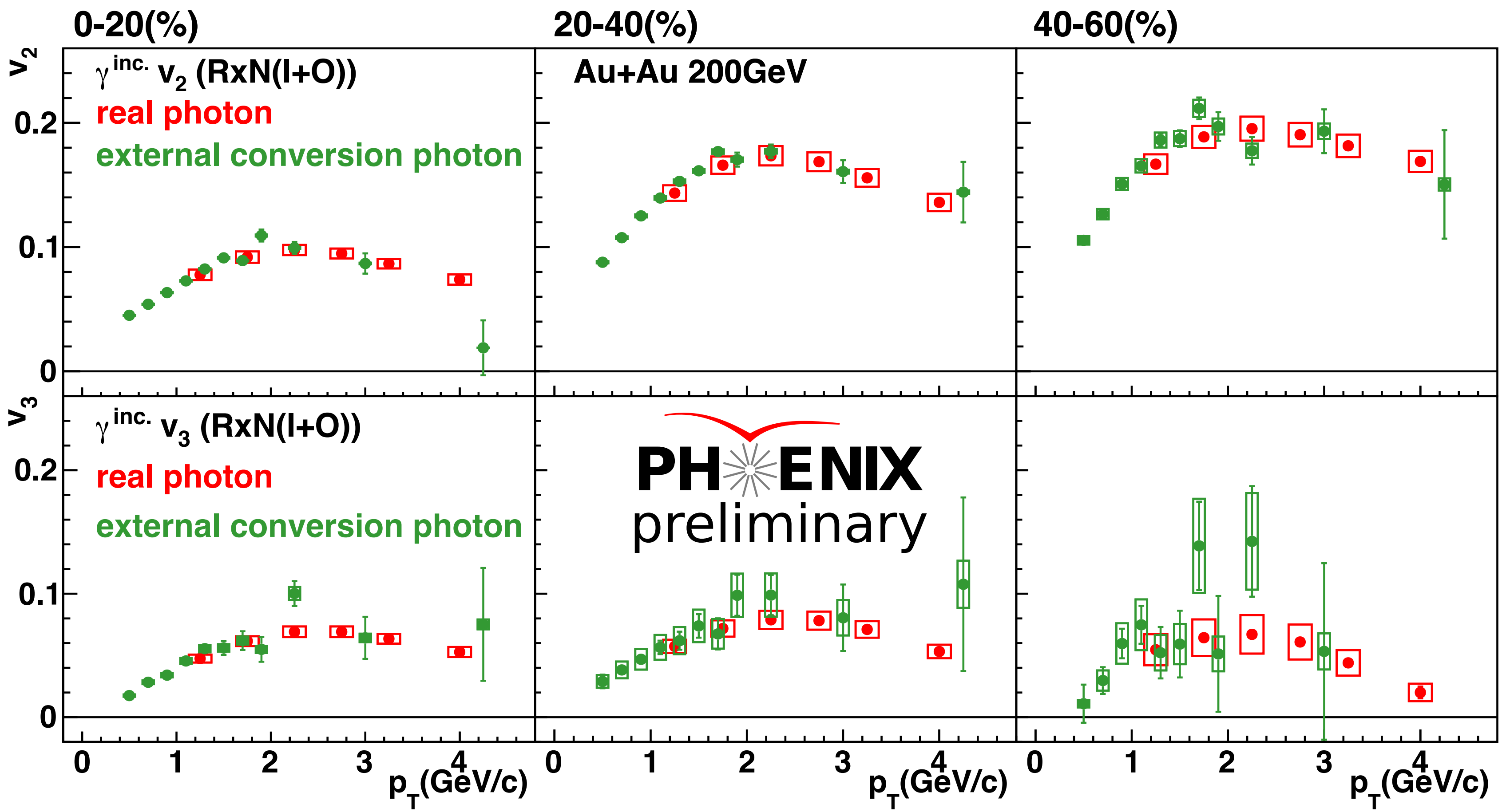
Inclusive and decay photon v_n comparison

Direct photon v_n are extracted from these deviation via below function.

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

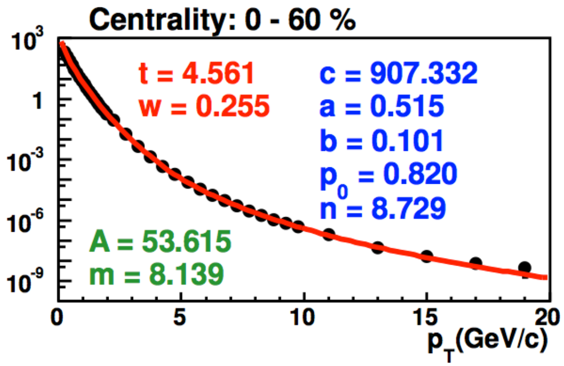


Comparison inclusive photon v_n



Inclusive photon v_n is measured via conversion photon, and p_T range is extended to low p_T region.

Input decay photon : p_T spectra

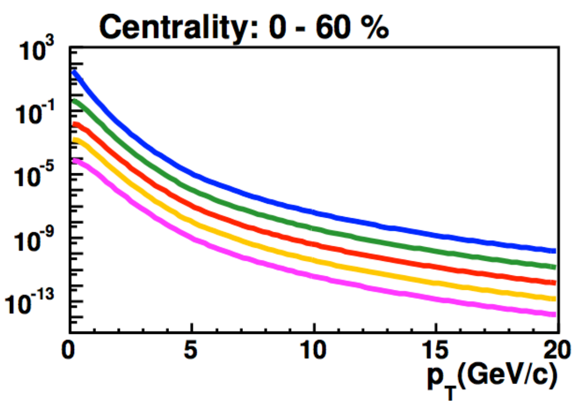


$$T(p_T)=\frac{1}{1+\exp((p_T-t)/w)}$$

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

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

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



- $\pi^0 \times 1.0$
- $\eta \times 0.1$
- $\omega \times 0.01$
- $\rho \times 0.001$
- $\eta' \times 0.0001$

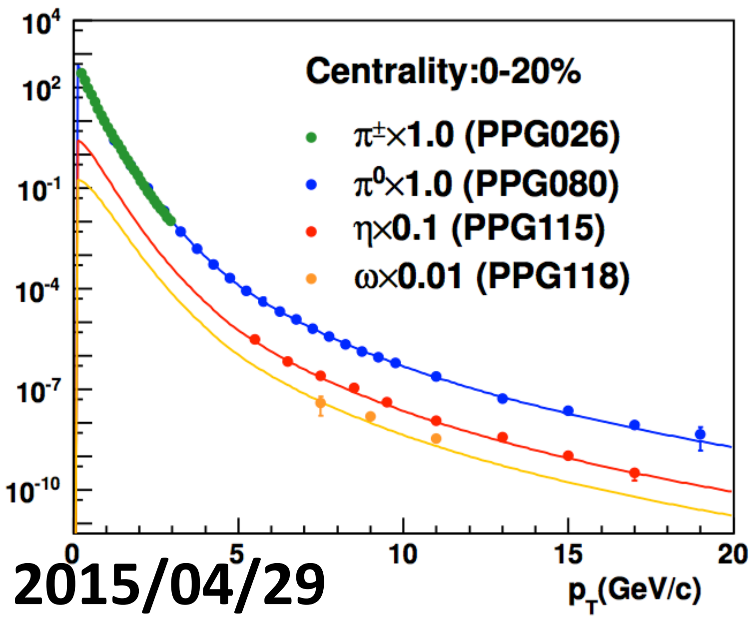
$$p_T' = \sqrt{p_{T,\pi^0}^2 + M_{meson}^2 - M_{\pi^0}^2}$$

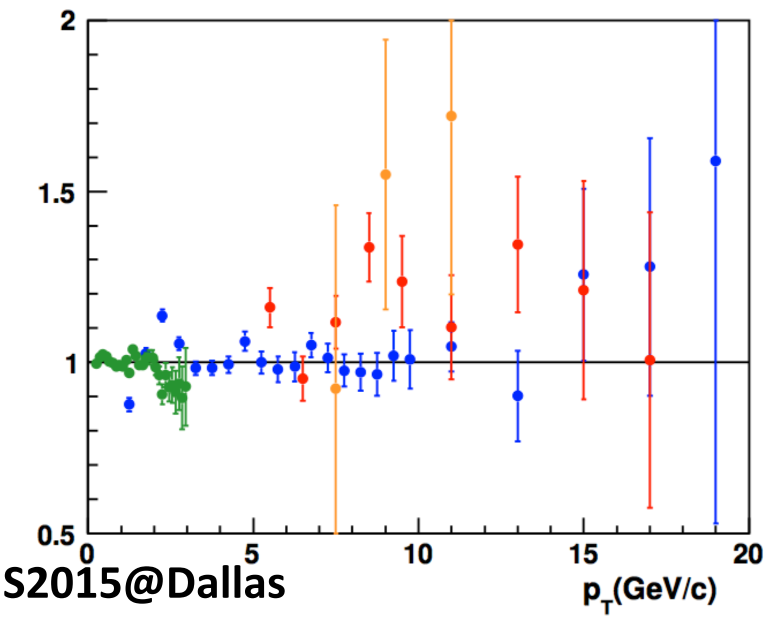
$\pi^\pm$ and π^0 p_T spectra are fitted and its function is used for estimating the other meson p_T spectra by m_T scaling.
They are used as a input.

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.

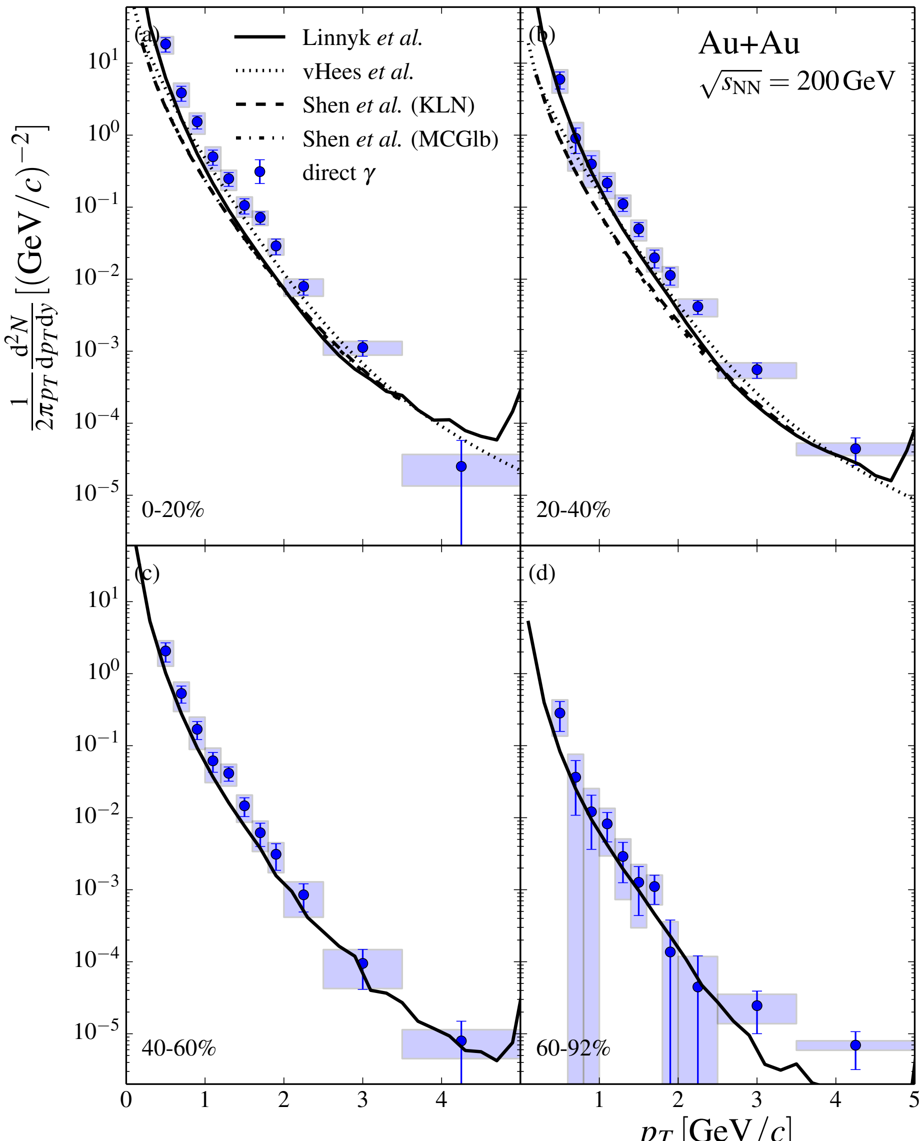
The table of each meson spectra ratio to π^0	
η/π^0	0.45±0.060
ω/π^0	0.83±0.120
ρ/π^0	1.00±0.300
η'/π^0	0.25±0.075





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)

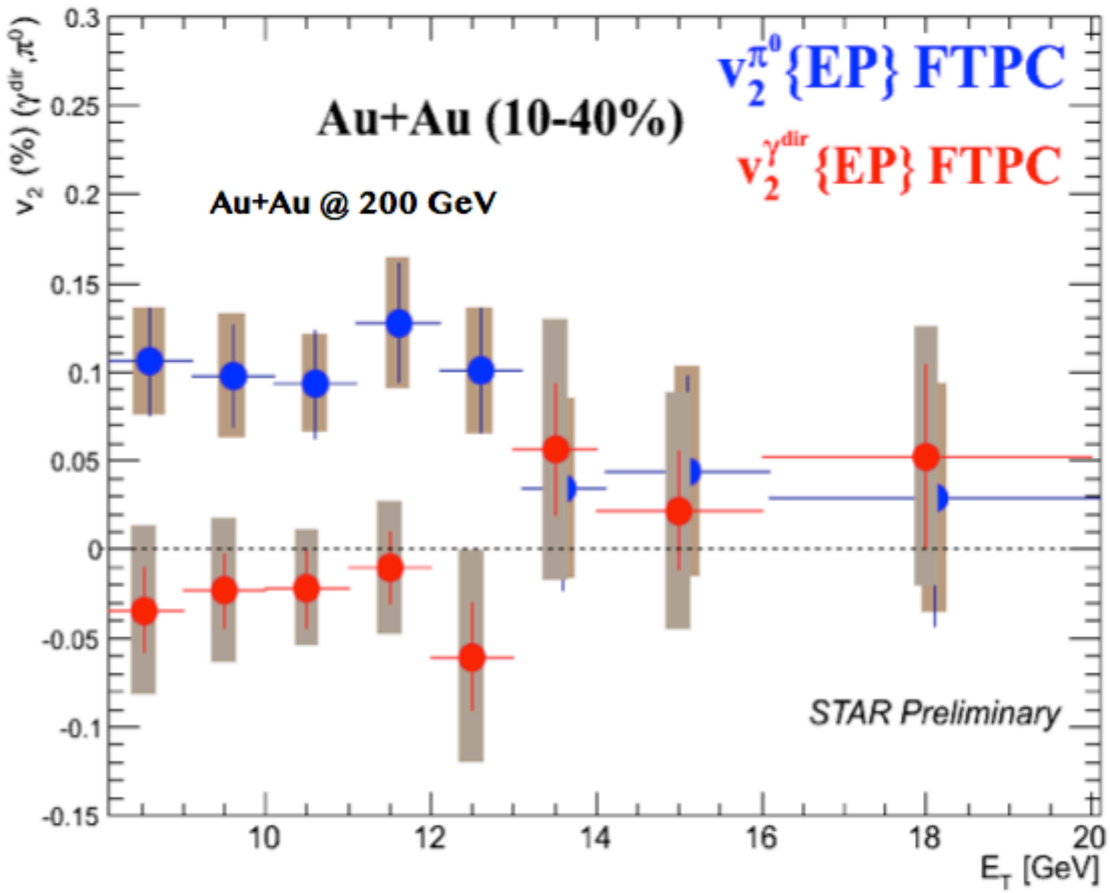
Shen et al.: Ohio hydro for two different initial conditions; Shen, Heinz, Paquet, Gale; P.R.C 84, 064903(2014)

The yield itself is still not perfectly described.

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

Ahmed M. Hamed shown at QM

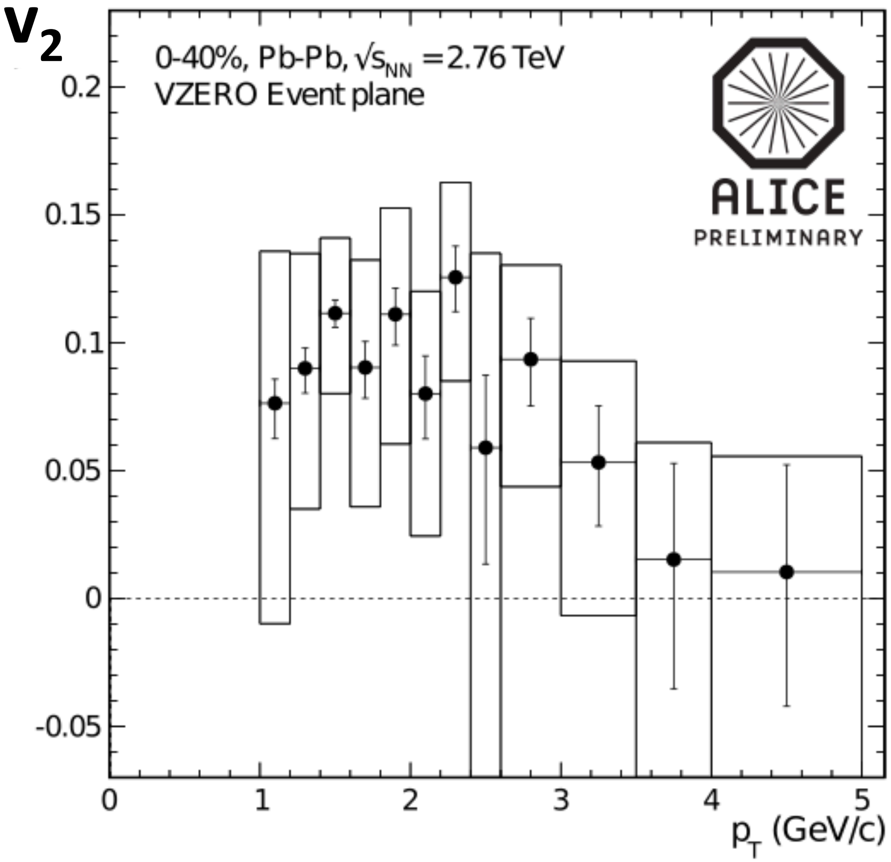
✓ BEMC: |η| < 1.0, FTPC: 2.5 < |η| < 4.0



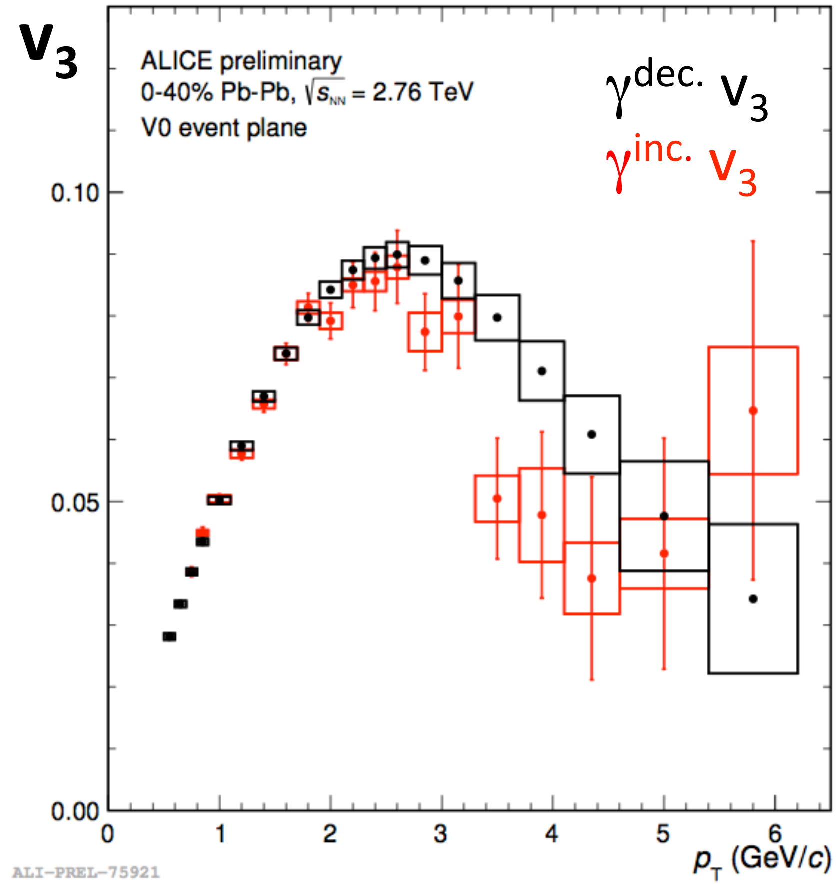
$\gamma^{dir.}$ v_2 in high E_T region are consistent with 0 within systematic uncertainty, while π^0 has positive v_2.

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.