PHENIX results on the anisotropic flow of thermal photons

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What you'll hear

Quick rehash of recent published results on direct photon yields

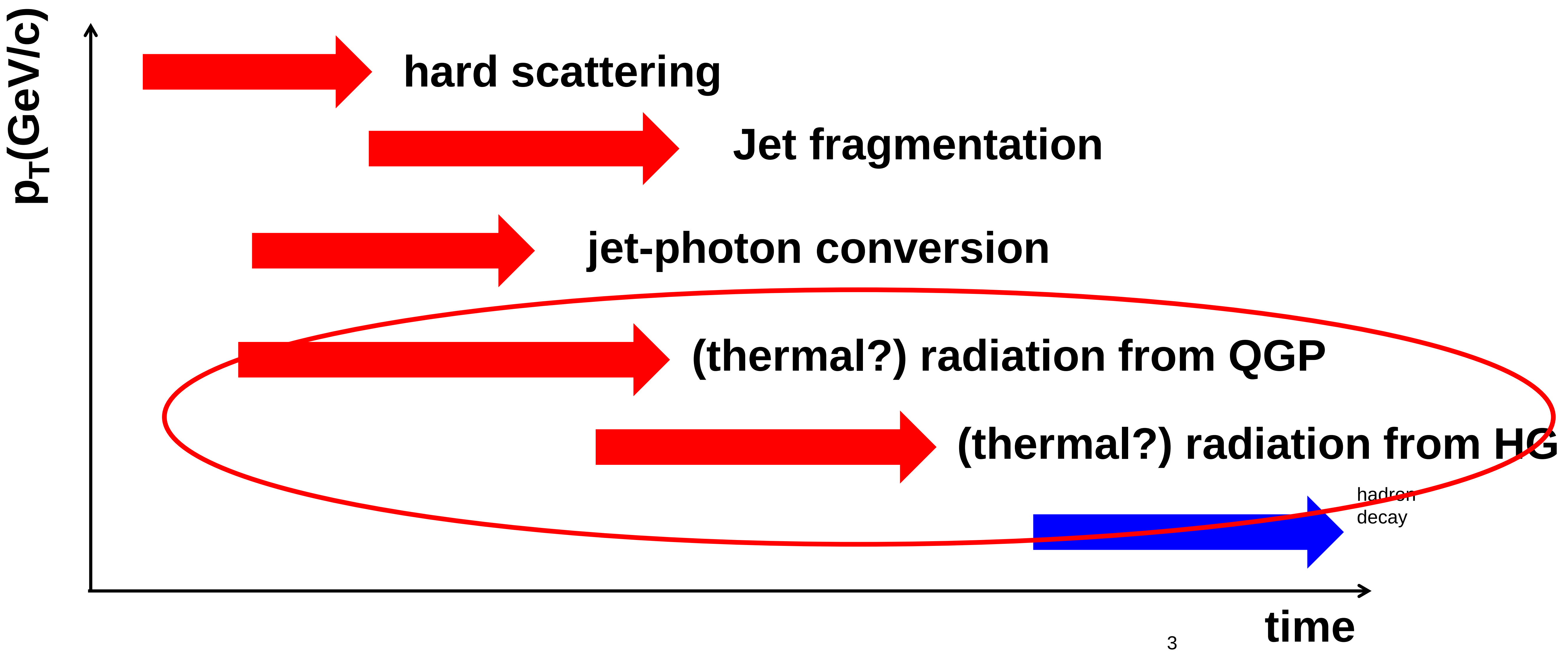
New ingenious method to extend the former low p_T limit even lower

New results on anisotropy, centrality dependence

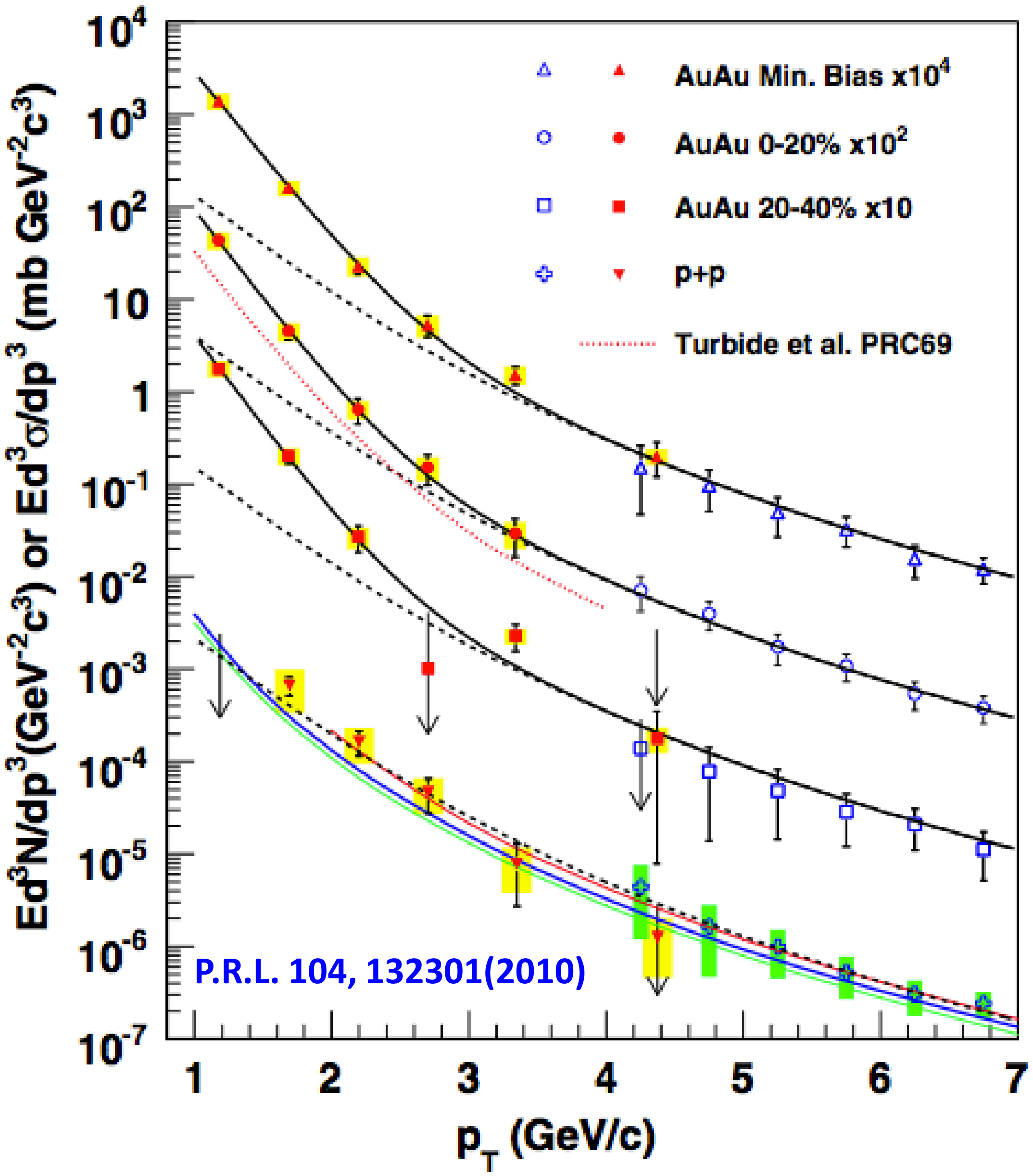
Sources of Direct Photons

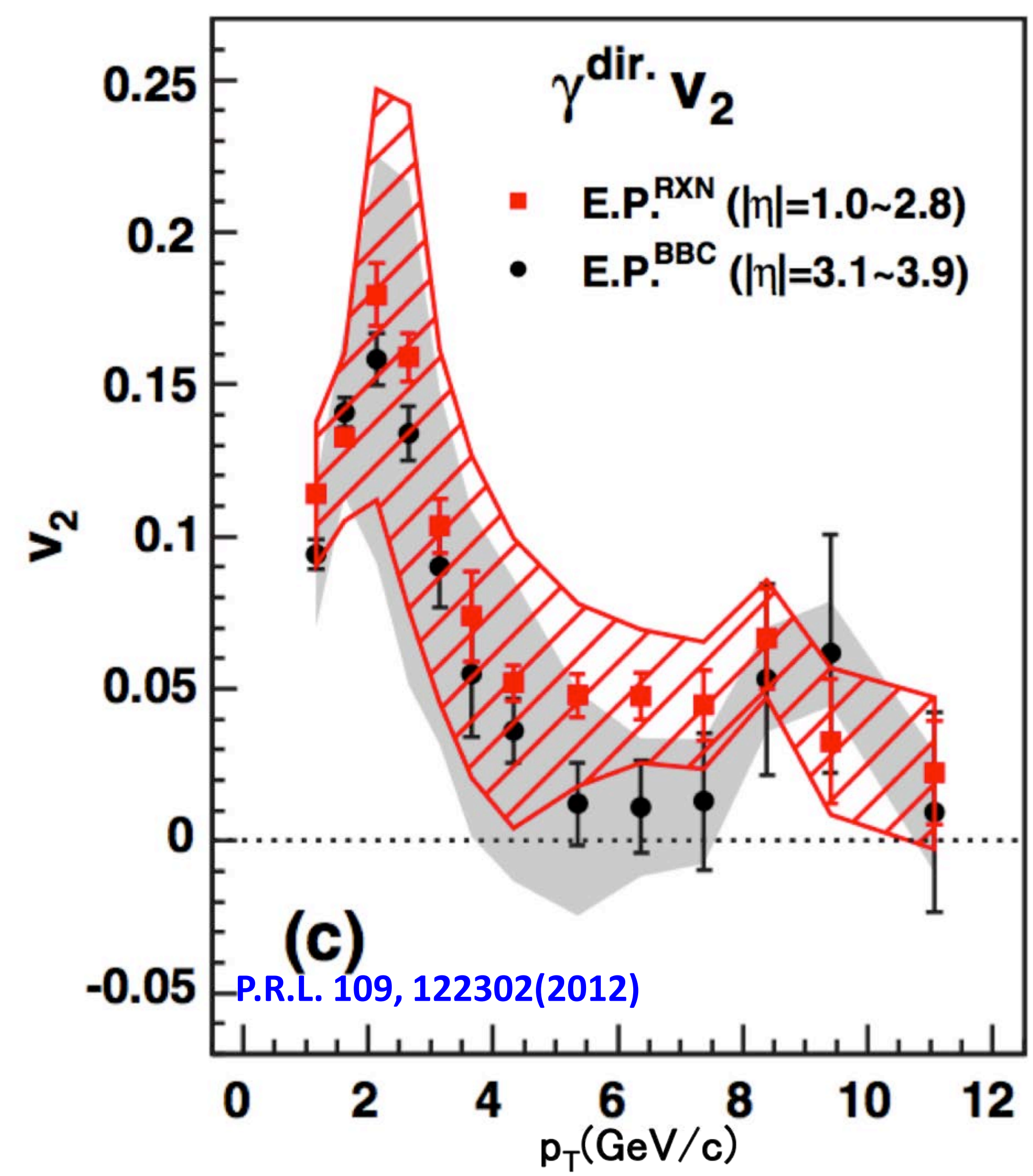
Direct photons: all photons except those coming from hadron decays.

- **Good probe since they penetrate the QGP**
- **Created during all stages of the collision**



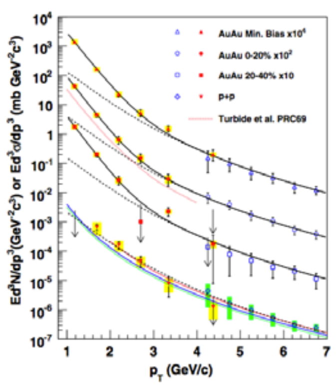
Previous Soft Photon Results

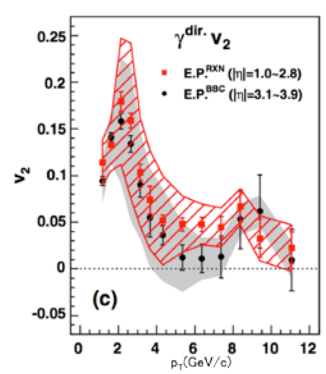


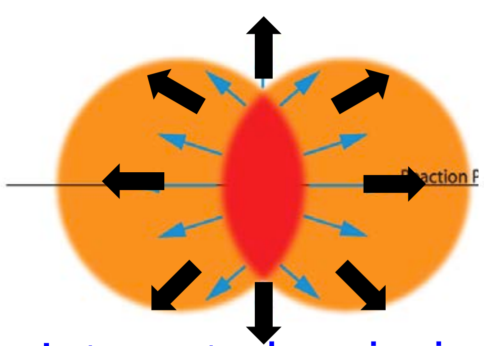


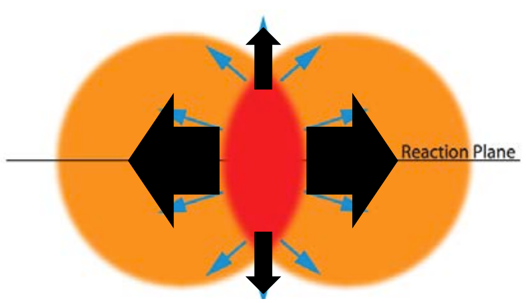
Large excess with respect to scaled p+p, and very large flow in the 1-4 GeV/c region.

The Direct Photon Puzzle









Integrated emission differential emission

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

It is a challenge for models to explain simultaneously the excess of direct photon yield and the large elliptic flow (v_2).

New Results to constrain production mechanisms

- More complete centrality dependence
- Higher-order azimuthal anisotropies
- **Extending the lower p_T range**

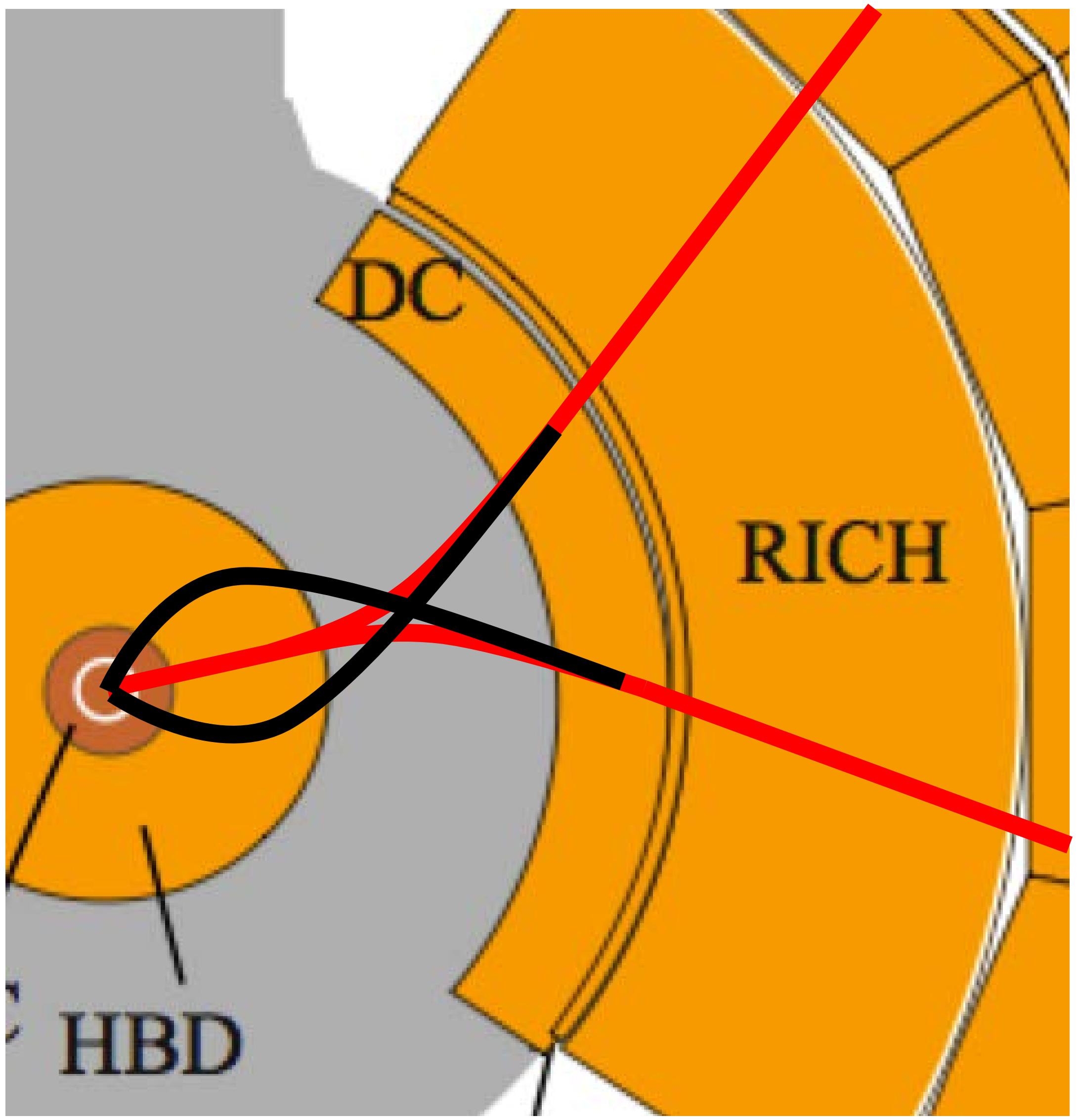
Our dedicated photon detector – the EmCal – cannot reach much below 1GeV/c

Not enough energy to make a recognizable shower

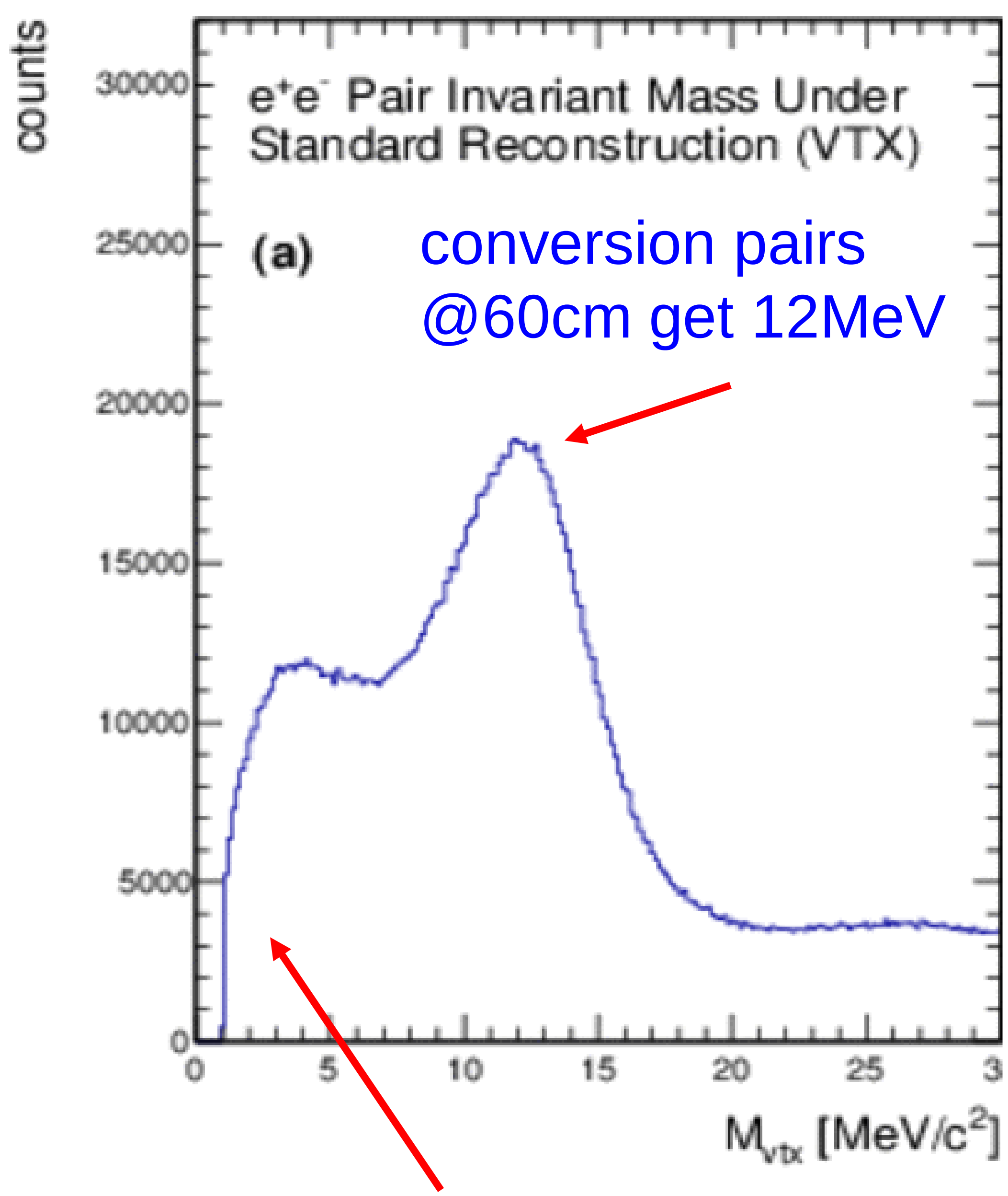
Ingenious new method to measure photons at very low p_T

Reconstruction of Photons through conversions

- The standard vertex reconstruction assumes that each track originates at the primary vertex
- The readout plane of the Hadron Blind Detector acts as an additional converter
- 2.5% of a radiation length at 60cm
- Reconstruction of the e^+-e^- inv. mass will be wrong because of the wrong origin/vertex



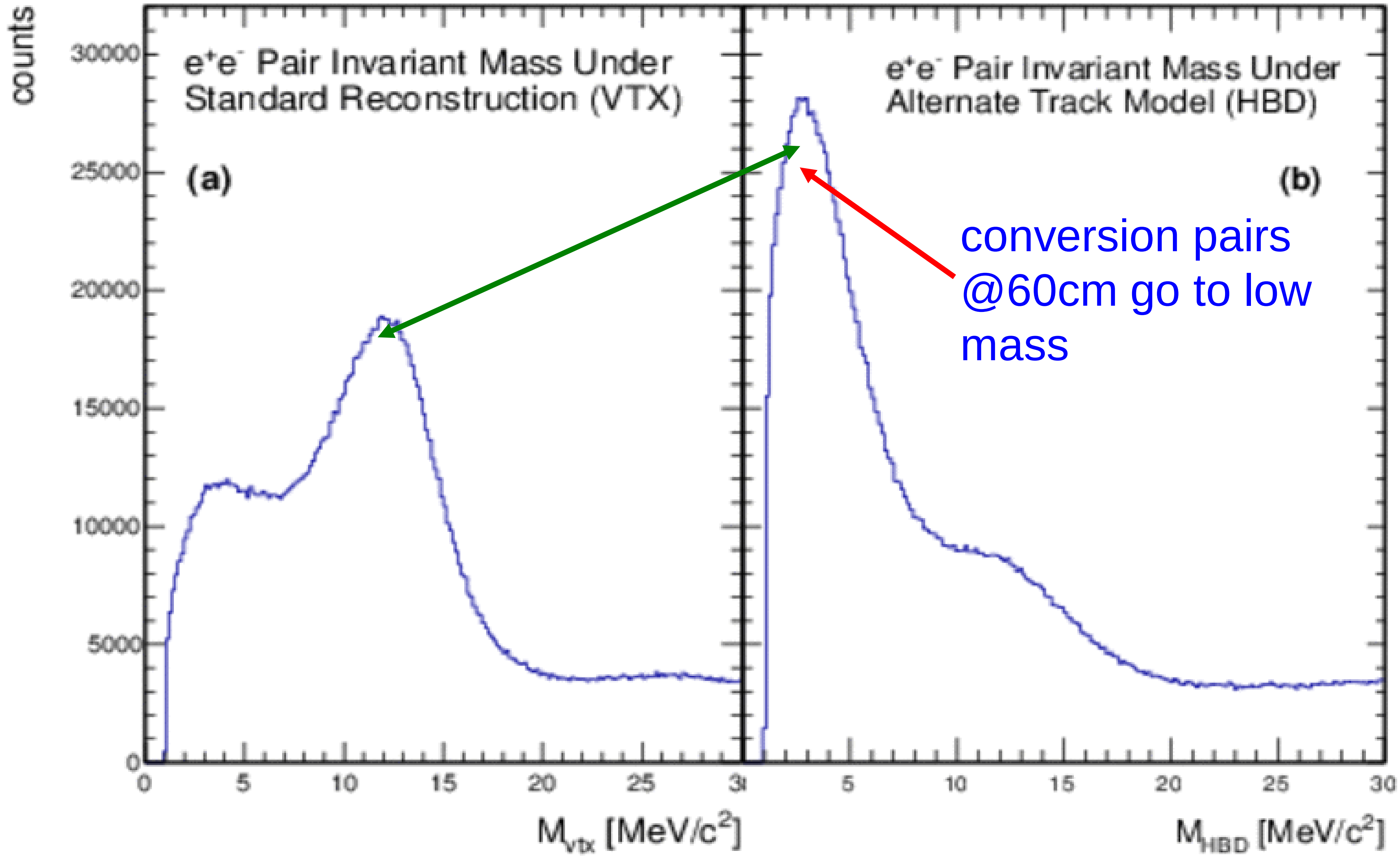
e^+ - e^- invariant mass (mis-)reconstruction



Conversions at lower radii (and π^0 Dalitz) get lower mass - "radiograph"

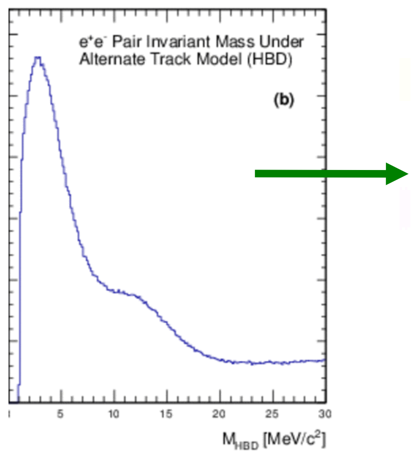
- The inv. mass calculation assumes the "standard" vertex
- Conversion electron pairs are reconstructed with about 12MeV/c^2 mass with that wrong vertex
- Lower mass values are genuine conversions at lower radii and other "genuine" sources there, such as π^0 Dalitz
- One can sort of make a "radiograph" along the radius

Assigning the right e^+ - e^- vertex

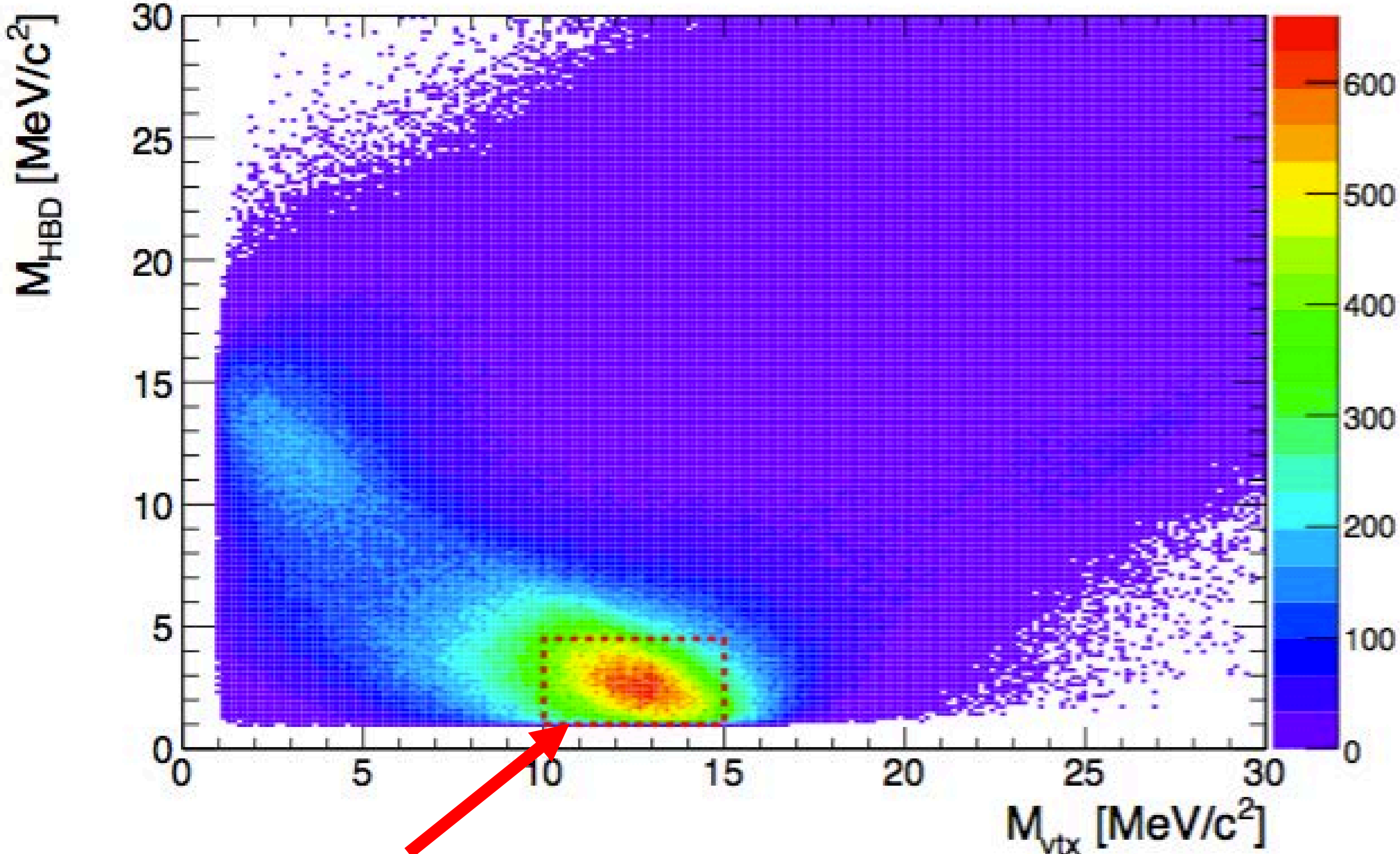


We can use this to tell “60cm” conversion pairs from others

Assigning the right e^+-e^- vertex

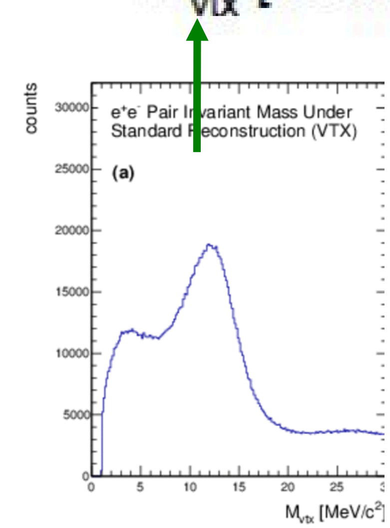


60cm
vertex



Cut to select 60cm conversion pairs

Low-p_T photon candidates



0cm
vertex

The Direct Photon Fraction R_γ

We can express the direct photon yield as the difference of the inclusive yield (all photons) and those which originate from a hadron decay:

$$\gamma^{direct} = \gamma^{inclusive} - \gamma^{hadron}$$
$$\gamma^{direct} = \gamma^{inclusive}\left(1 - \gamma^{hadron}/\gamma^{inclusive}\right)$$

Which can be written in term of the “Direct Photon Fraction” R_γ

$$\gamma^{direct} = \gamma^{inclusive}\left(1 - 1/R_\gamma\right)$$

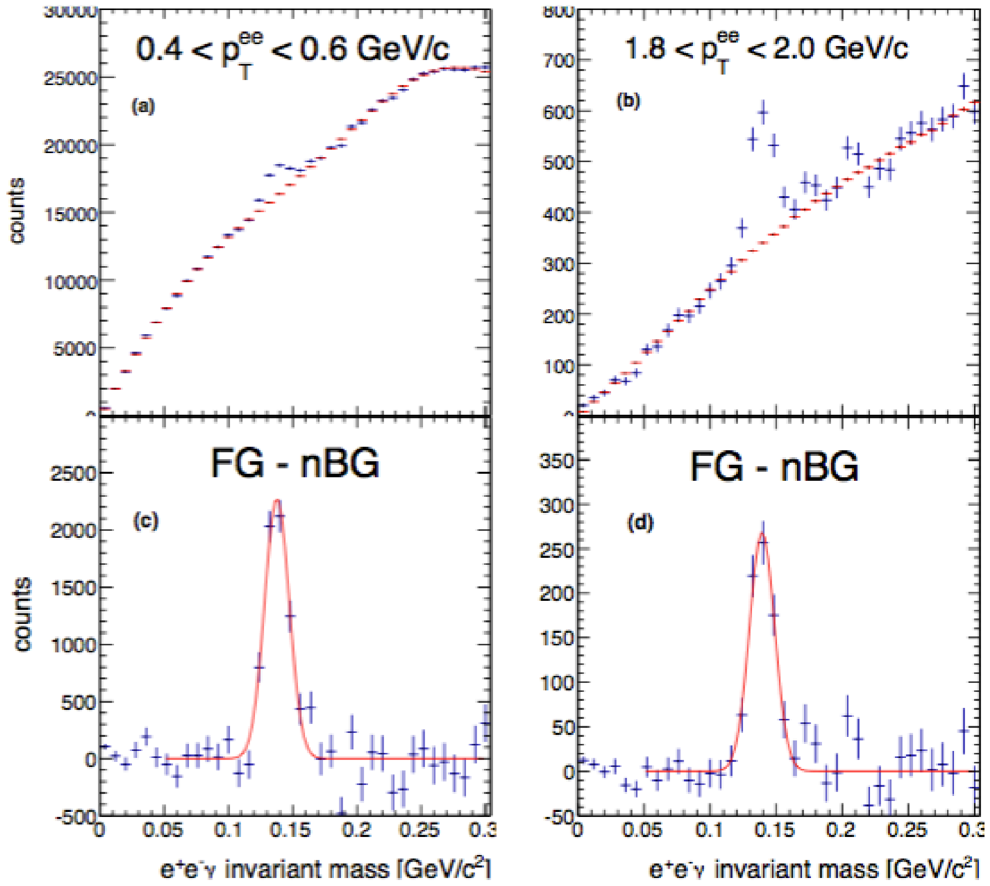
with $$R_\gamma = \frac{\gamma^{inclusive}}{\gamma^{hadron}}$$

Photon reconstruction efficiency for the pairs

The reconstructed photon candidates get paired with standard photon clusters from the EmCal to see if they reconstruct to the pion mass

A number of probabilities come into play:

- Conversion probability for a photon in the readout plane
- Probability that both e^+, e^- are in the acceptance
- Probability that 2nd photon was in the acceptance
- Probability that 2nd photon got reconstructed as such
- .. Some more higher-order corrections



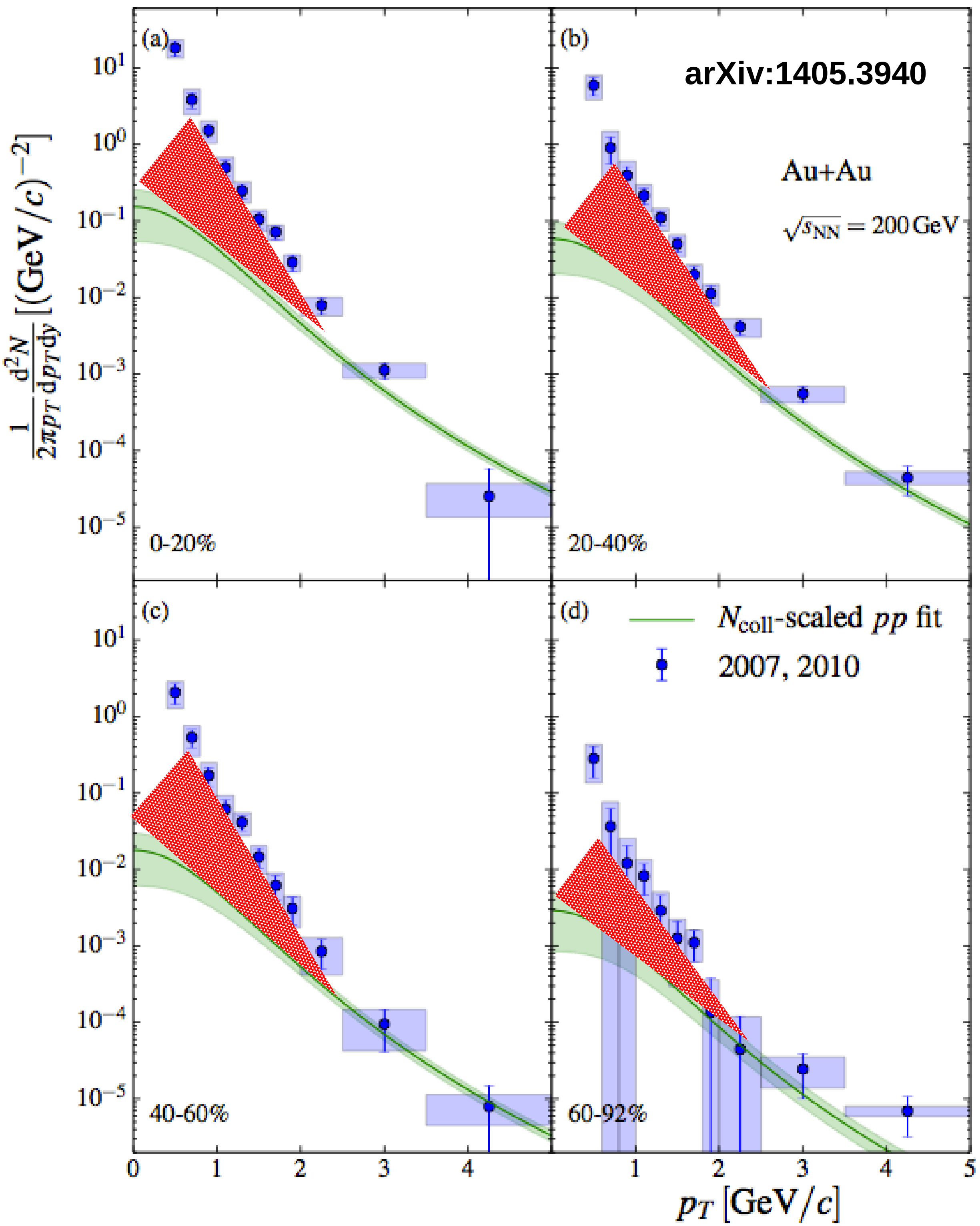
e+e- - γ invariant mass

Calculated as a yield in bins of ee p_T

You end up with the γ reconstruction efficiency for each ee p_T bin, and can calculate R_γ this way.

$$R_\gamma = \frac{\gamma^{inclusive}}{\gamma^{hadron}}$$

Enhancement of the direct photon yields



The yields from p+p data are fitted by

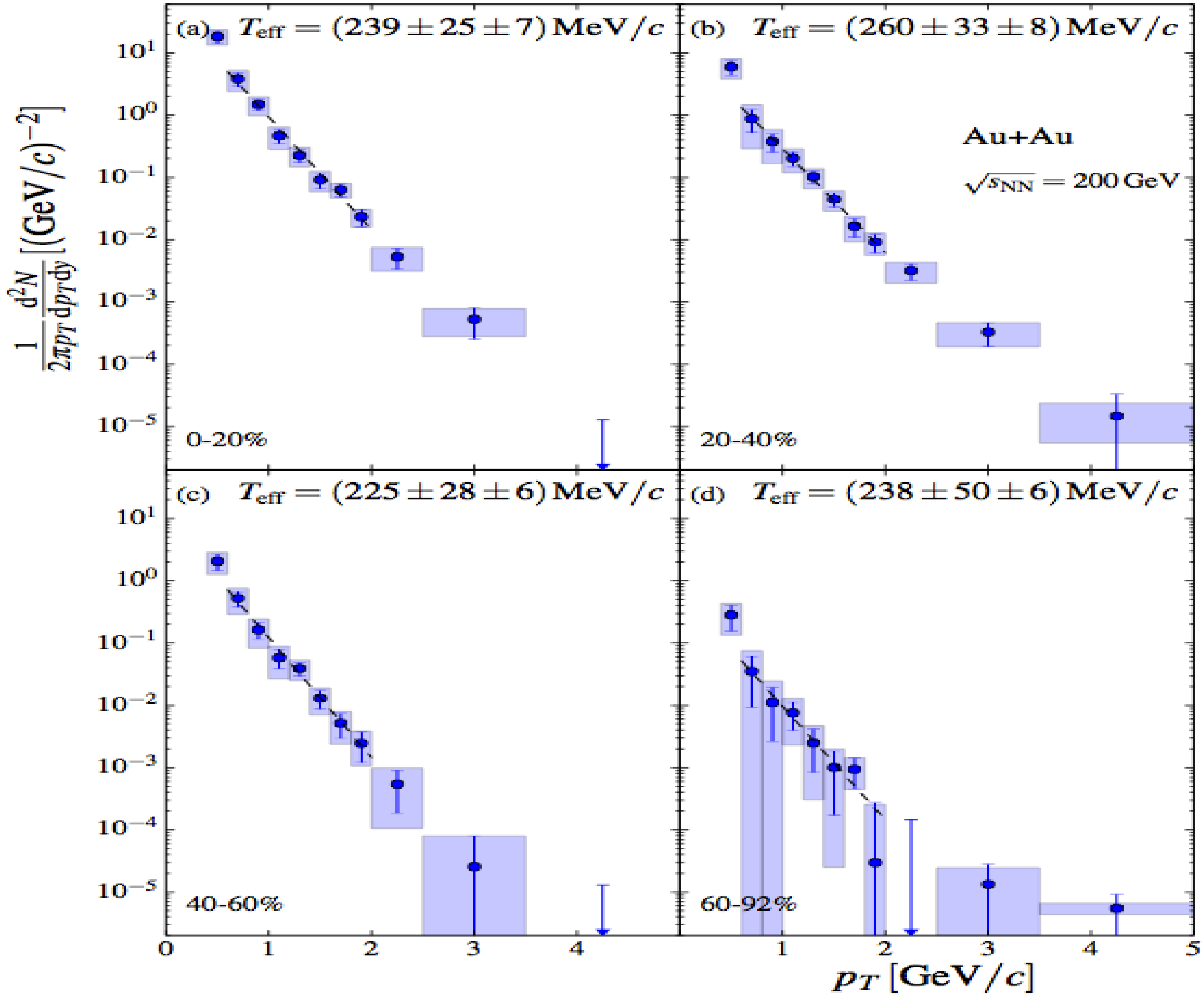
$$a(1+\frac{p_T}{b}^2)^c$$

extrapolated below 2 GeV/c.

$$T_{AA} =< N_{coll} > /\sigma_{pp}$$

Compared with a green line (extrapolation from p+p data), we get an enhancement in all centralities

Difference of photon yields (AuAu – pp)



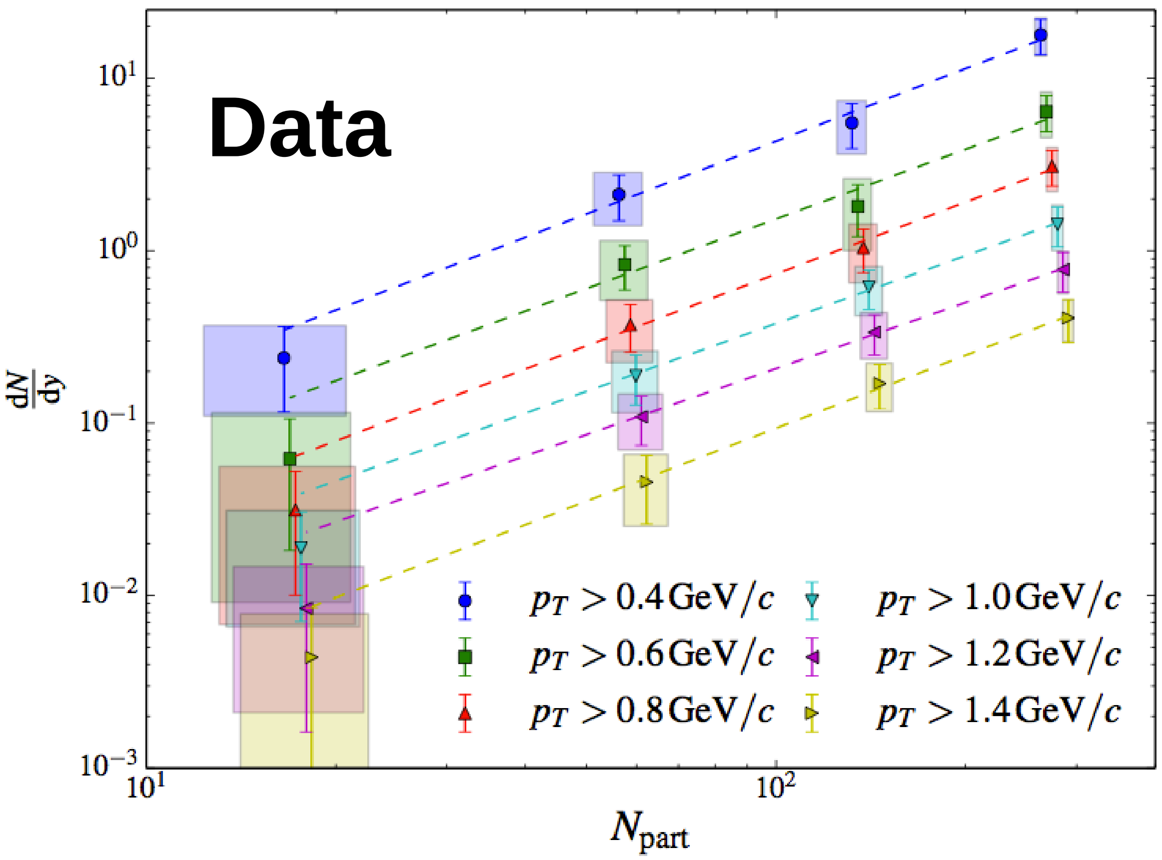
arXiv:1405.3940

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

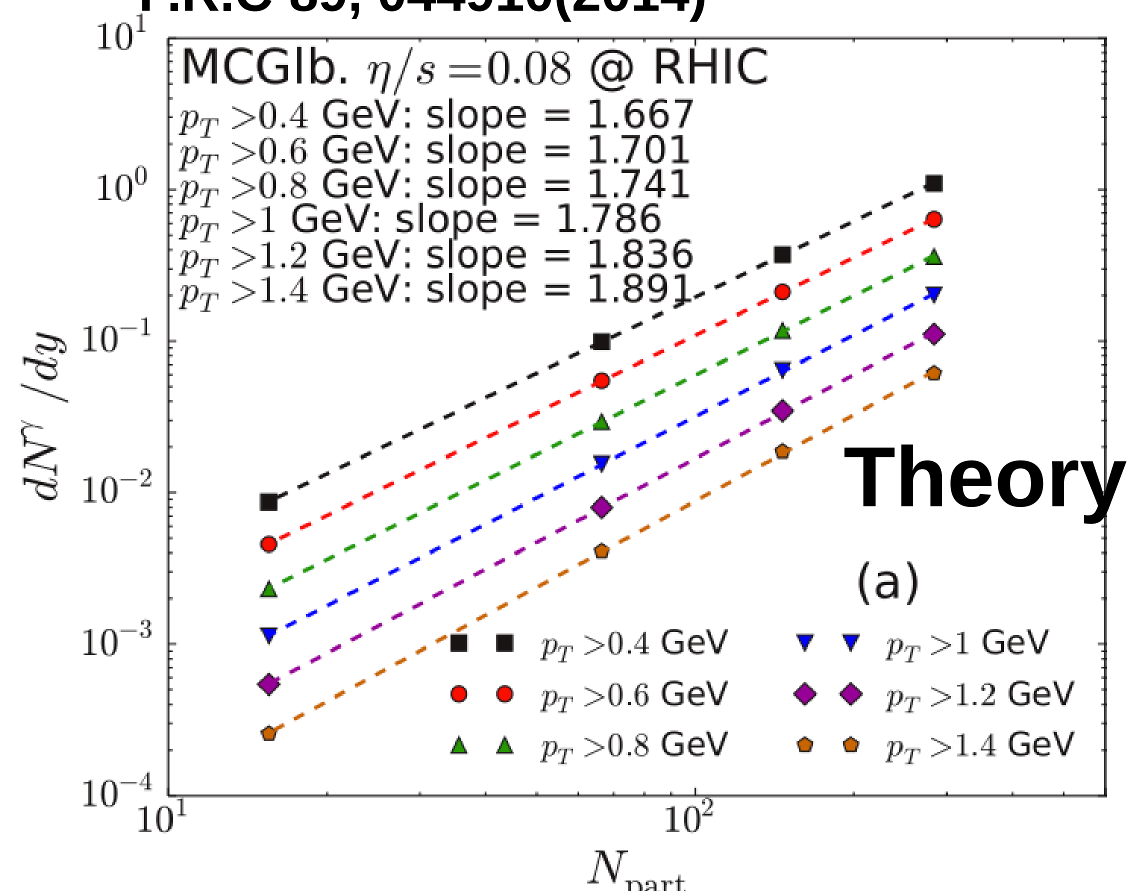
Excess yield (above expectation from scaled p+p) fitted with an exponential. The slopes are comparable within uncertainties.

Centrality (N_{part}) Dependence of the yields

arXiv:1405.3940



P.R.C 89, 044910(2014)



$$F = AN^{\alpha}_{part}$$

Excess of photon yield increases with power-law function,

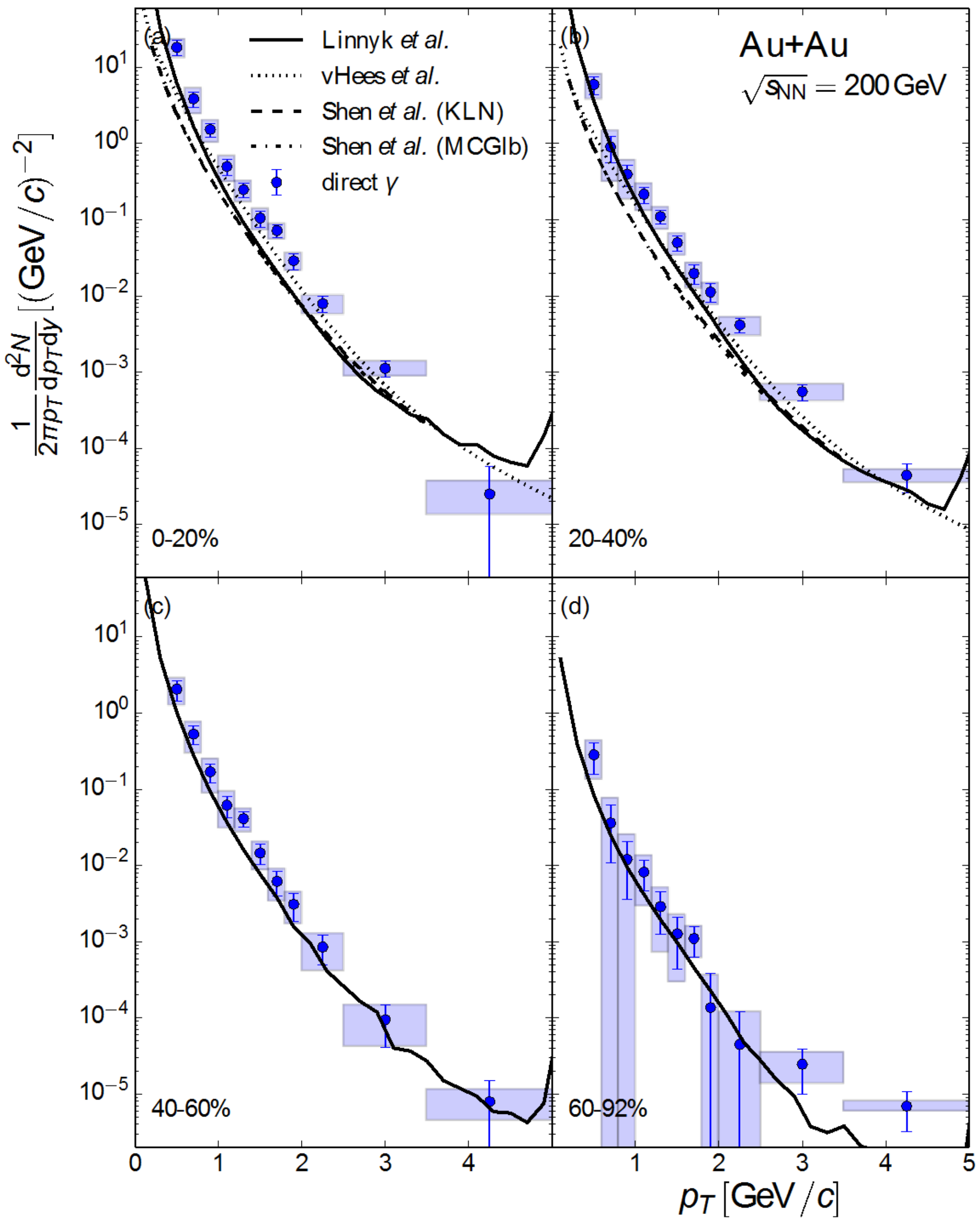
α=1.48±0.08(stat.)±0.04(sys.) ≈ 3/2

The centrality dependence is not an artifact of the very low p_T points:
same slope as we increase lower limit of integration
(upper limit is always 2GeV/c).

The shape of direct photon p_T spectra doesn't depend on centrality.

Data vs Theory - Yields

arXiv:1405.3940



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

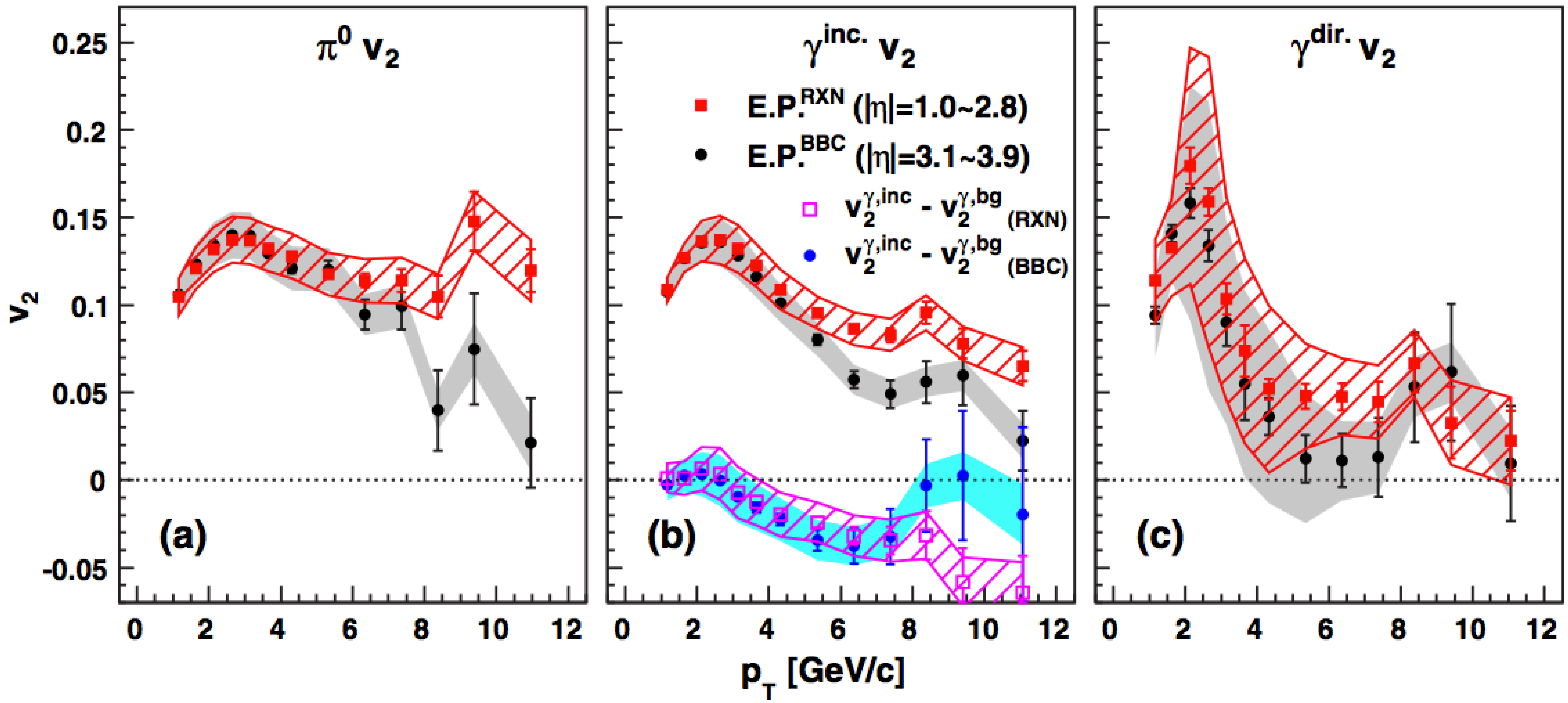
vHees et al.: Fireball model; van Hees, Gale, Rapp; P.R.C 84, 054906(2011)

Shen et al.: Ohio hydro for two different initial conditions; Shen, Heinz, Paquet, Gale; arXiv:1403.7558

The yield itself is still not perfectly described.

Flow measurement

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



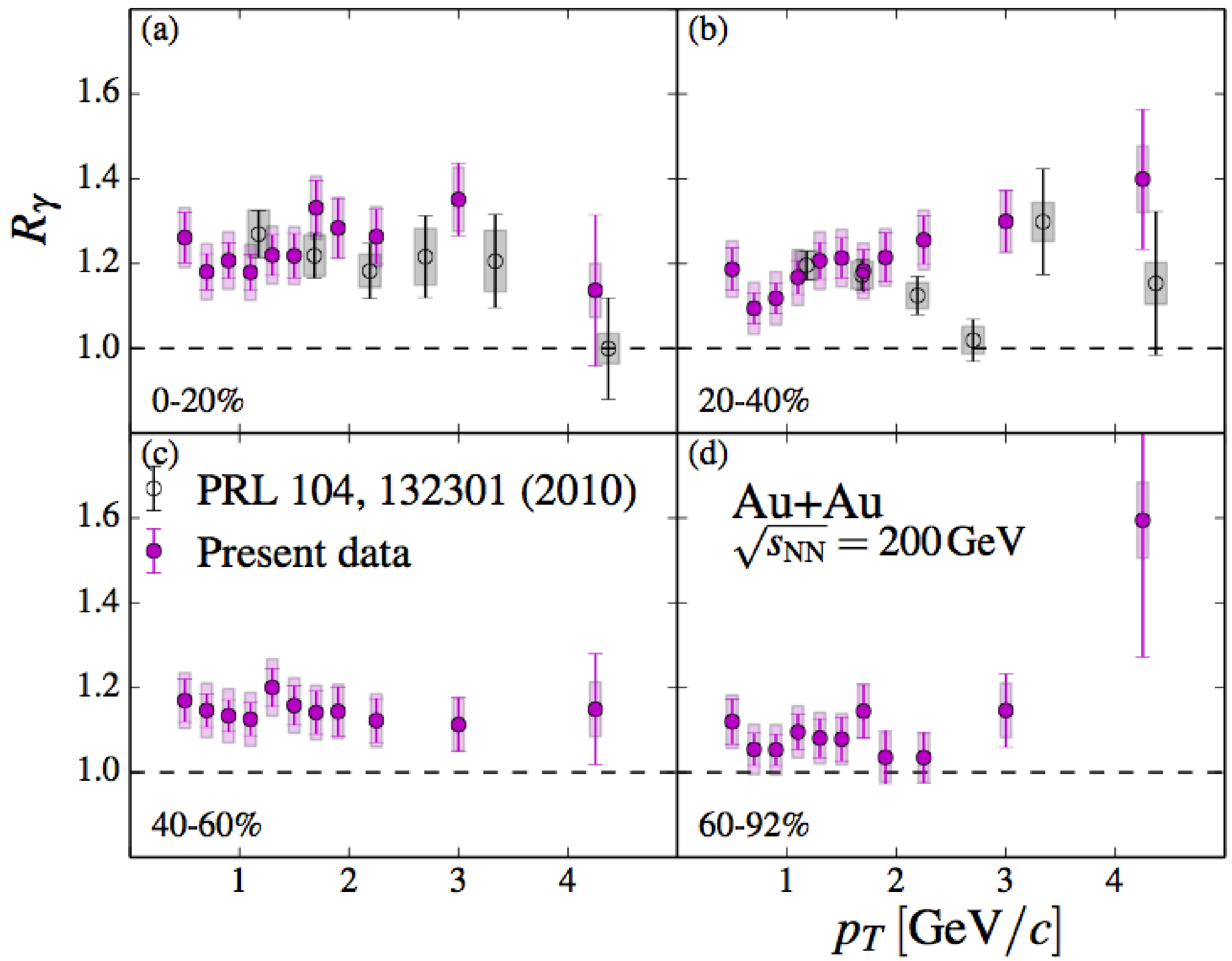
The magnitude of the direct photon v_2 is comparable to the hadron (and hadron decay photon) v_2.

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

Virtual and Real photons

We have an earlier publication of R_γ measured with virtual photons – P.R.L. 104, 132301(2010)

arXiv:1405.3940



P.R.L. 104, 132301(2010)
virtual photon analysis

Present data
external conversion analysis

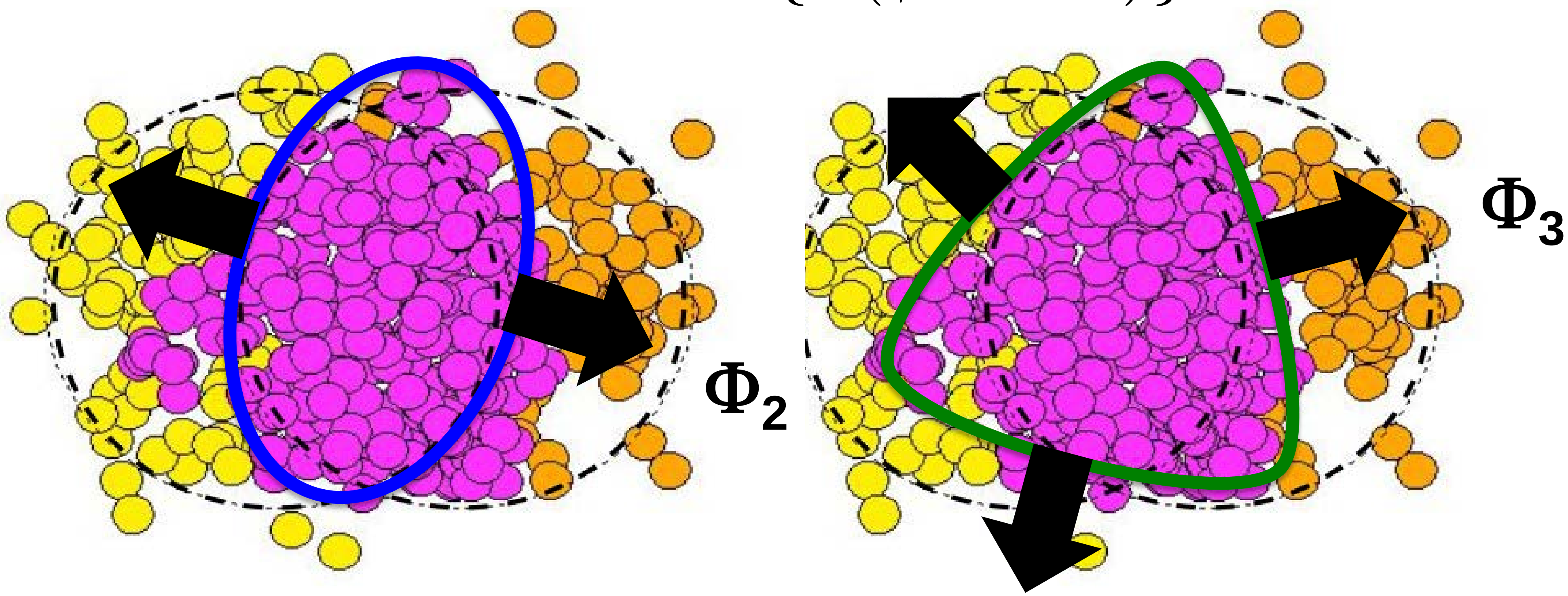
$$R_\gamma = \frac{\gamma^{inclusive}}{\gamma^{hadron}}$$

R_γ measured with real (conversion) photons is consistent with the earlier virtual photon measurement.

Higher-order azimuthal anisotropy

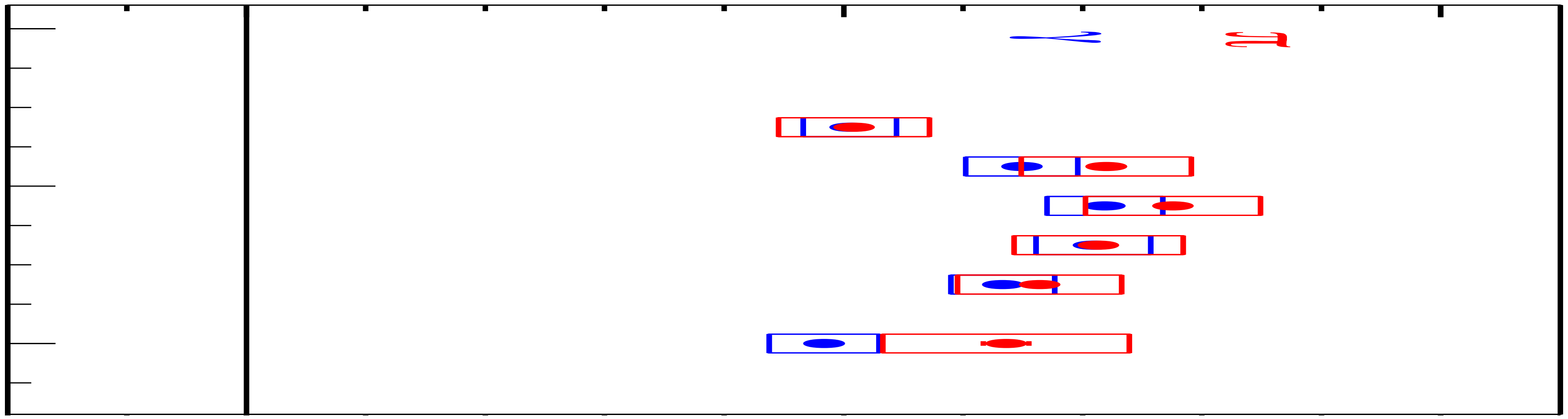
$$\frac{dN}{d(\phi - \Psi_n)} = N_0[1 + 2\sum_{n=1}^{\infty} v_n cos\{n(\phi - \Phi_n)\}]$$

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



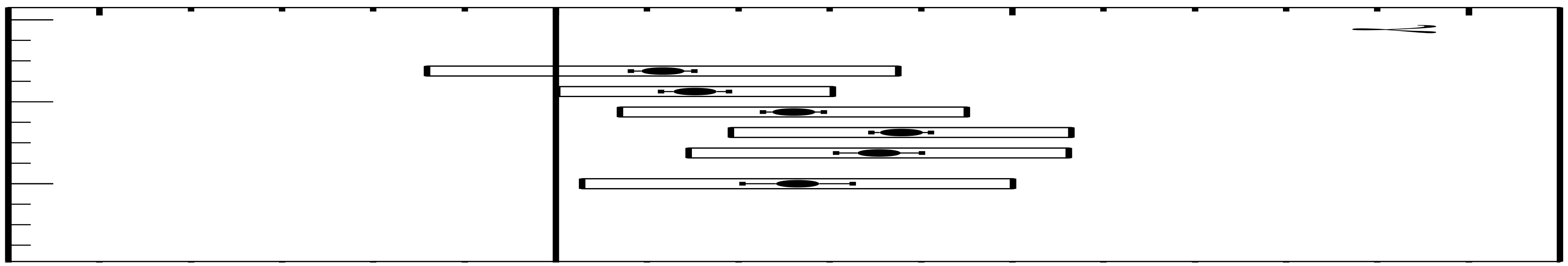
Dominant component is v_2;
v_3 comes from participant fluctuations.
Viscosity dampens higher order terms.

$\gamma^{dir.}$ v_3 measurement



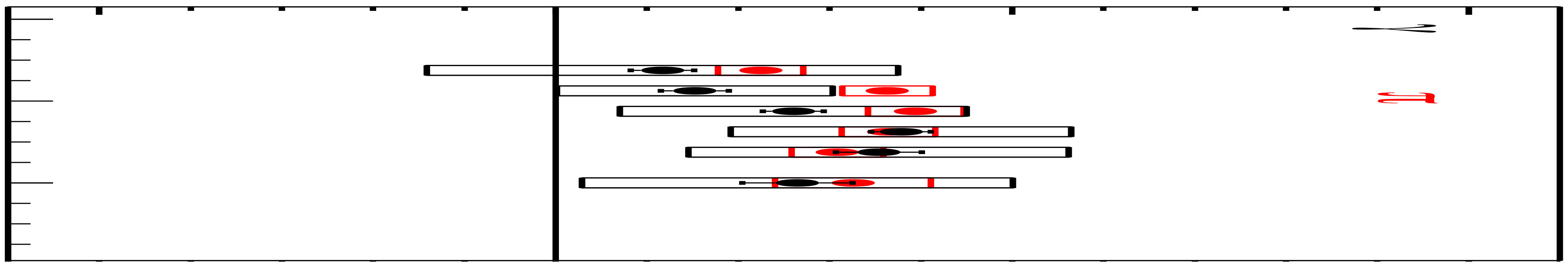
The magnitude of $\gamma^{dir.}$ v_3 is similar to π^0, a similar trend as a seen in case of v_2.

$\gamma^{dir.}$ v_3 Centrality Dependence



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.

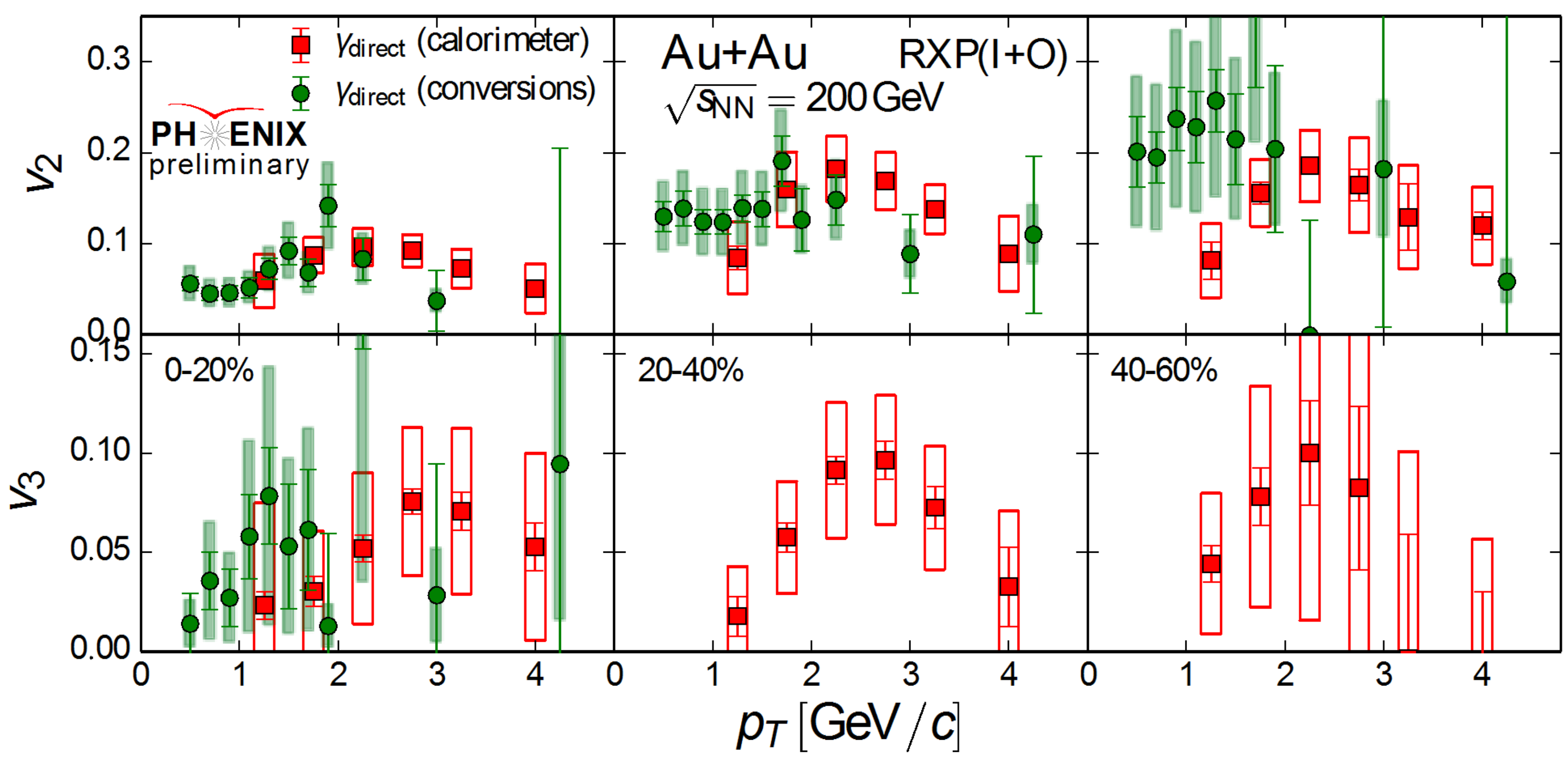
$\gamma^{dir.}$ and π^0 v_3



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

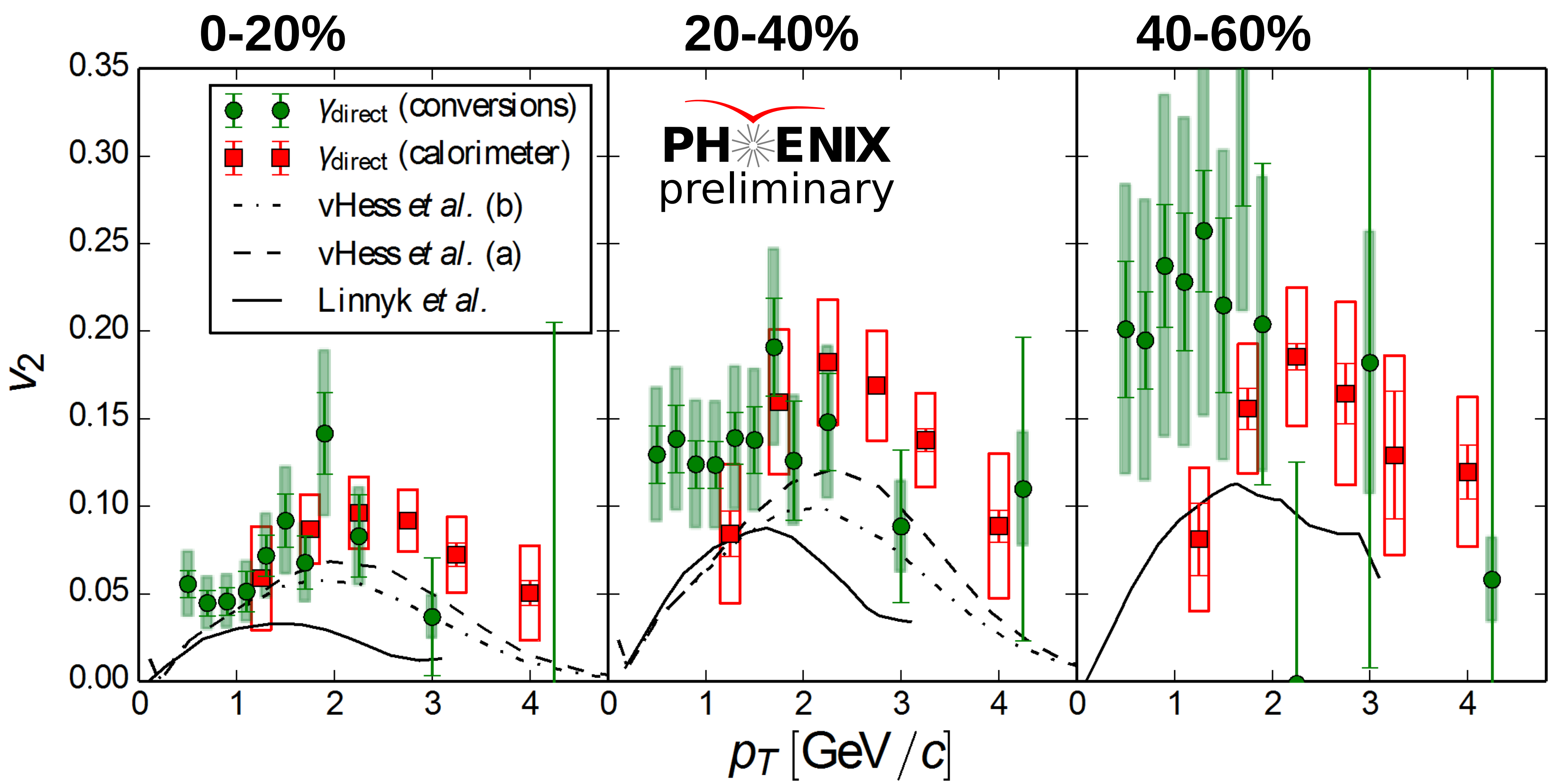
Comparison of $\gamma^{dir.}$ v_n with the two methods

In the overlap range, we can compare the ”classic” EmCal direct photon reconstruction with the conversion method



The calorimeter and conversion photon measurements are consistent within systematic uncertainty.
$\gamma^{dir.}$ v_n are extended to lower p_T, by the conversion photon analysis.

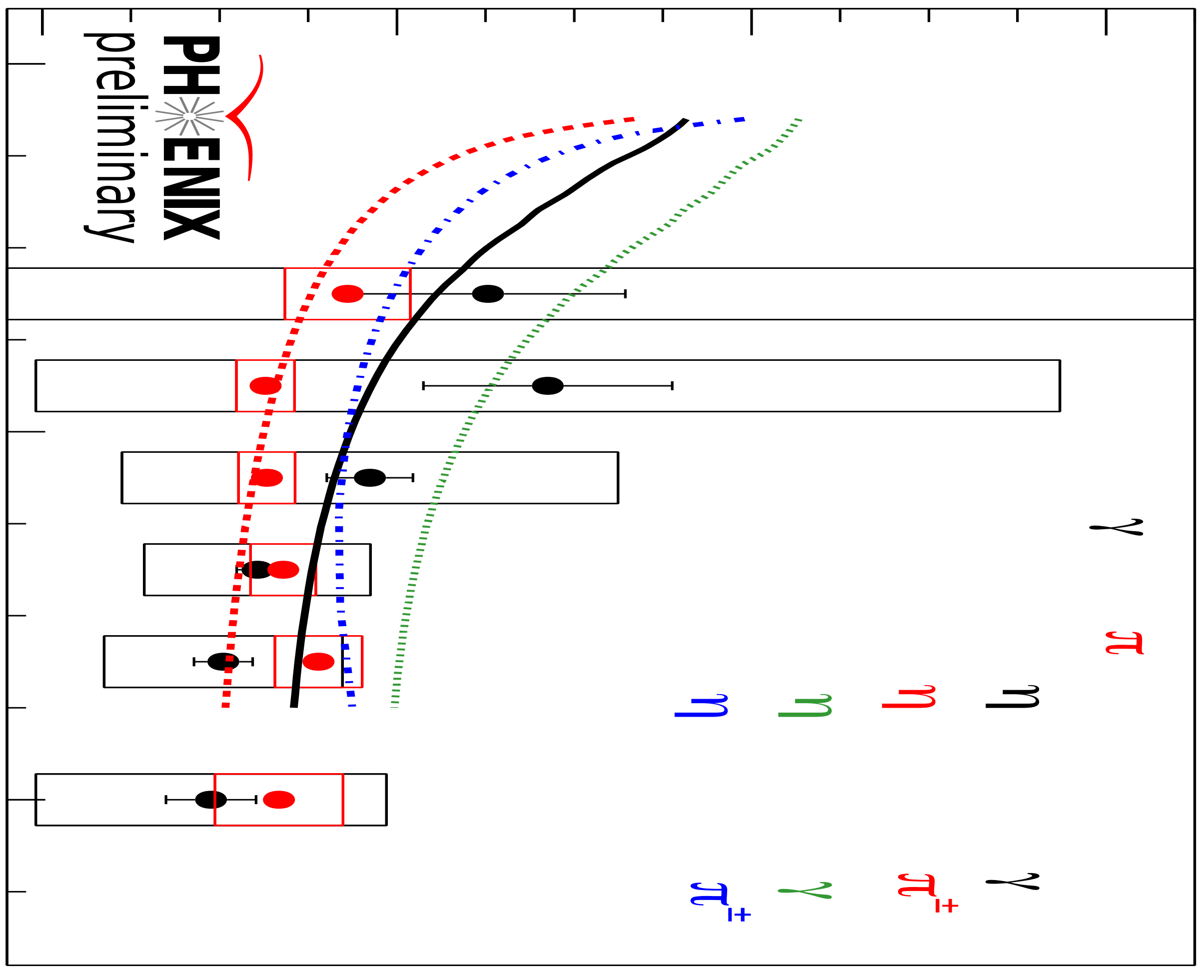
$\gamma^{dir.}$ v_2 – Comparison with theoretical calculations



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

Linnyk et al.: PHSD model, private communication

The ratio of $\gamma^{dir.}$ and π^0 v_2/v_3



Theory curves: private communication by Ch. Shen, Ch. Gale, J.-F. Paquest, U. Heinz as in 1403.7558, Calculated for RHIC.

So far all uncertainties are assumed to be uncorrelated.
The ratios – both for π^0 and γ – slightly prefer lower η/s values.

Summary

Soft photons are expected to do provide important keys to understand photon production mechanisms and medium properties, including viscosity.

Centrality dependence of direct photon yield

The shape of p_T spectra doesn't have strong centrality dependence.
The excess of yield increases with centrality like N_{part}^{α} with $\alpha \approx 1.48$.

3rd order Azimuthal anisotropy

Direct photon has as large v_3 as hadrons, which is similar to the case of v_2.
Non-zero, positive direct photon v_3 is observed in all centrality bins.
Direct photon is expected to be a viscometer of QGP.

The End

Direct photon flow – where does it come from?

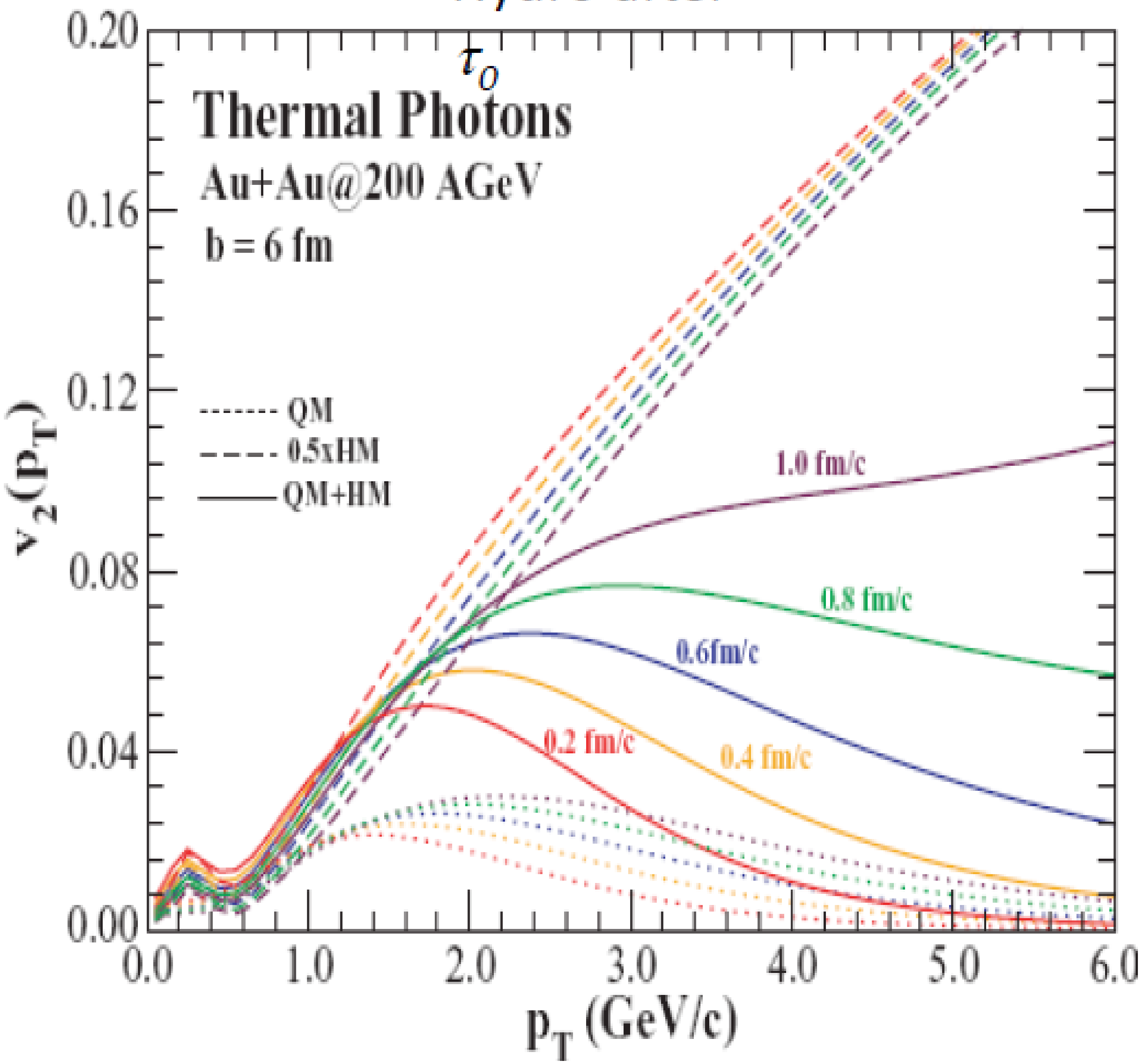
The easiest way to get high rates is high (early) temperatures → but no flow there yet, just acceleration

The easiest way to get high flow is late (long acceleration), just before kinetic freeze-out but lower (thermal) rates

Stay tuned for final publications of our new results

Hydro after τ_0

PRC 79, 021901 (2009)



PRL 110, 192301 (2013)

Bzdak, Skokov: Anisotropy of Photon Production:
Initial eccentricity or Magnetic Field?

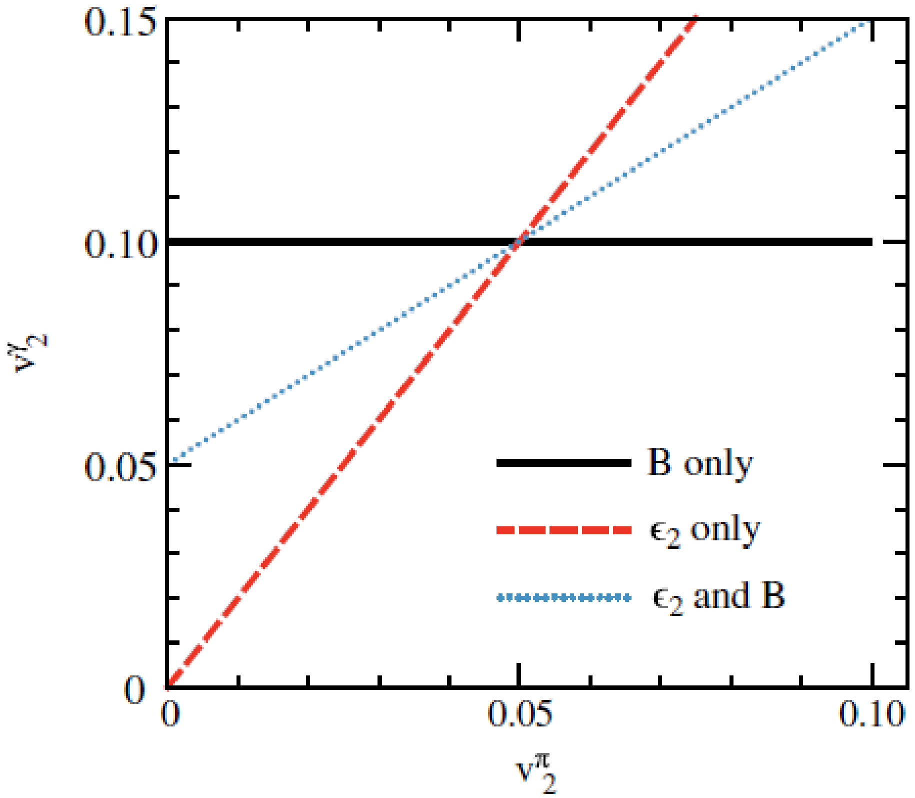


Figure 3 illustrates this idea, wherein we present three possible situations: The photon anisotropy v_2^γ is generated solely by the initial anisotropy; v_2^γ is generated by the magnetic field, and both mechanisms are present with equal strengths.

Before concluding, several comments are warranted. The measurement discussed in this Letter is best suited for midcentral and peripheral collisions, where both the elliptic flow and fluctuations of the initial eccentricity are expected to be maximal. Also, the measurement should be performed for various values of photon transverse momenta. Possibly, different mechanisms of generating v_2^γ may be applicable in different p_t regions. Finally, the analysis should be performed in a narrow centrality class, e.g., 30%–40%, so allowing us to neglect the correlation between v_2^π and the impact parameter (and consequently, the value of the magnetic field) [24].

Upshot: what we observe – Fig 2 of PPG126 – is that the direct photon flow is about the same at low pT as the pi0 flow, at all centralities.
This corresponds to the red diagonal line in Skokov's plot, i.e. the flow being an eccentricity effect, and definitely contradicts the black constant line, which would be the magnetic effect
Catch: of course you could argue that magnetic effect is only PART of the story, so there is some mixture….

The Direct Photon Fraction R_γ

$$R_\gamma = \frac{\varepsilon f \frac{N_{\gamma,\mathrm{inc}}}{N_{\gamma,\pi^0}}}{\frac{Y_{\gamma,\mathrm{hadron}}}{Y_{\gamma,\pi^0}}}$$

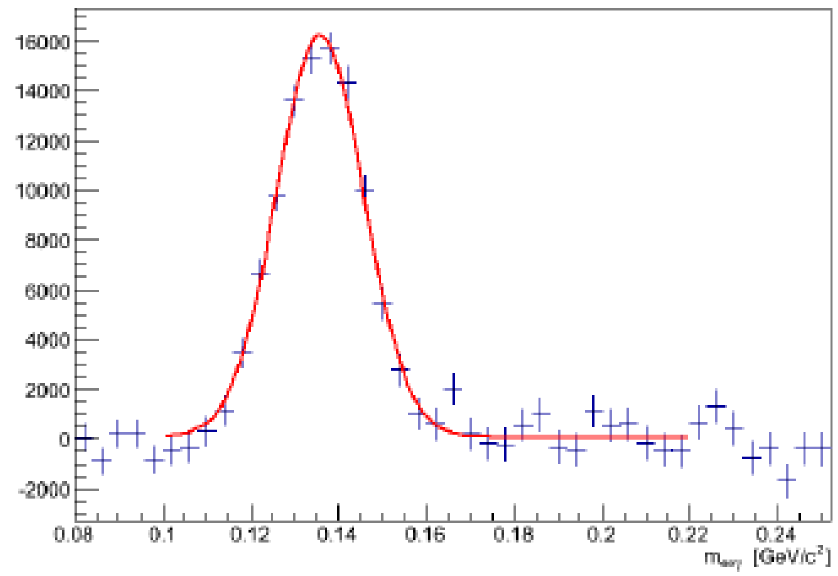
$$\varepsilon f = \frac{N_{\gamma,\pi^0}}{Y_{\gamma,\pi^0}}$$

m_T scaling

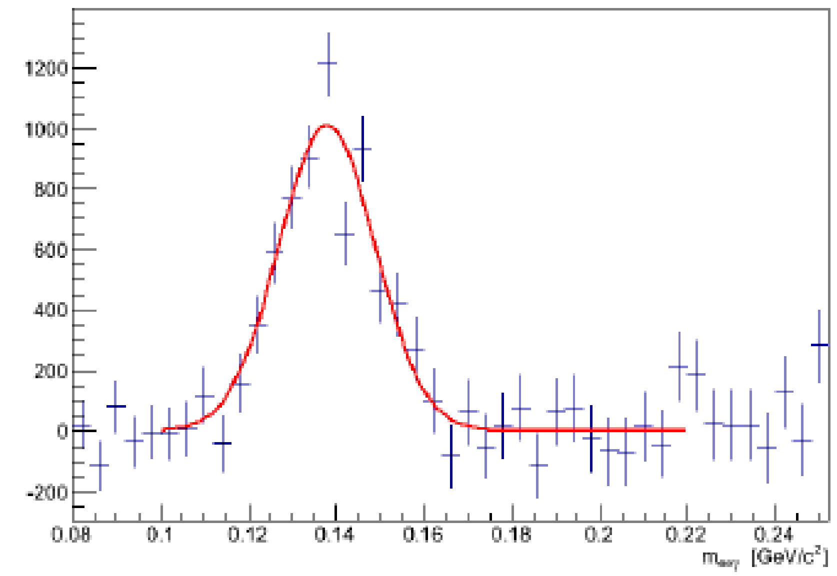
π^0-decay photon tagging

- a second photon measured with very loose cuts in the calorimeter is paired with converted photons
- the combinatorial background is modelled with a mixed-event sample of uncorrelated converted and calorimeter photons

$$N^{\gamma}_{\pi^0} = Y^{\gamma}_{\pi^0} p_{\text{conv}} a_{e^+e^-} \varepsilon_{e^+e^-} \times \langle \varepsilon f \rangle$$

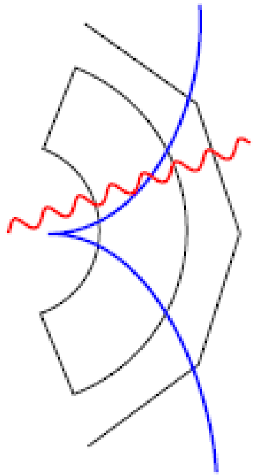


(a) $p_{T,\gamma} = 0.8 - 1.0\,\text{GeV/c}$

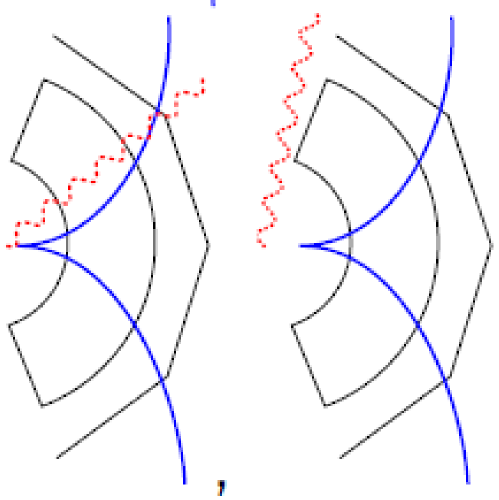


(b) $p_{T,\gamma} = 2.0 - 2.5\,\text{GeV/c}$

Tagging efficiency correction $\langle \varepsilon f \rangle$



- 2nd photon in acceptance $\rightarrow \varepsilon$



- 2nd photon lost $\rightarrow f$

The tagging efficiency $\langle \varepsilon f \rangle$ is calculated in a Monte Carlo simulation.

- f can be calculated accurately, $\varepsilon \approx 90\%$

$$\frac{N^{\gamma}_{\text{incl.}}}{N^{\gamma}_{\pi^0}} = \frac{Y^{\gamma}_{\text{incl.}} p_{\text{conv}} a_{e^+e^-} \varepsilon_{e^+e^-}}{Y^{\gamma}_{\pi^0} p_{\text{conv}} a_{e^+e^-} \varepsilon_{e^+e^-} \times \langle \varepsilon f \rangle} = \frac{Y^{\gamma}_{\text{incl.}}}{Y^{\gamma}_{\pi^0} \langle \varepsilon f \rangle}$$

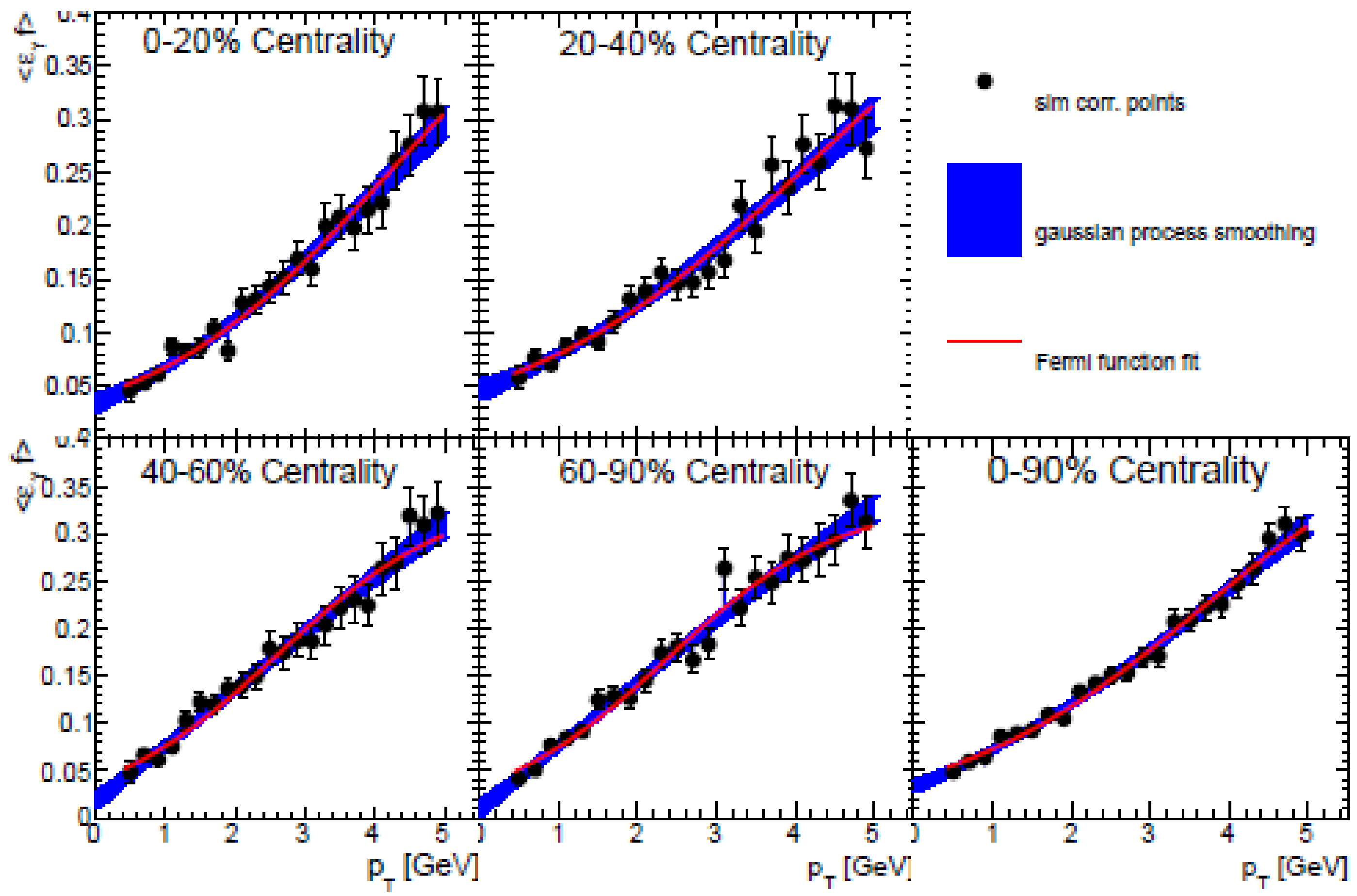


Figure 4.21: The pion tagging efficiency and acceptance correction, εf, for each centrality bin. Both the Fermi function fit and Gaussian Process (GP) regression analysis parameterizing the correction is shown. The GP procedure is ultimately chosen to smooth the correction.

$\gamma^{dir.}$ v_2 - a theory comparison

Berndt Muller et al, Phys. Rev. D 89, 026013 (2014)

Out-of-plane polarized photons have vanishing v_2 at $p_T = 0$

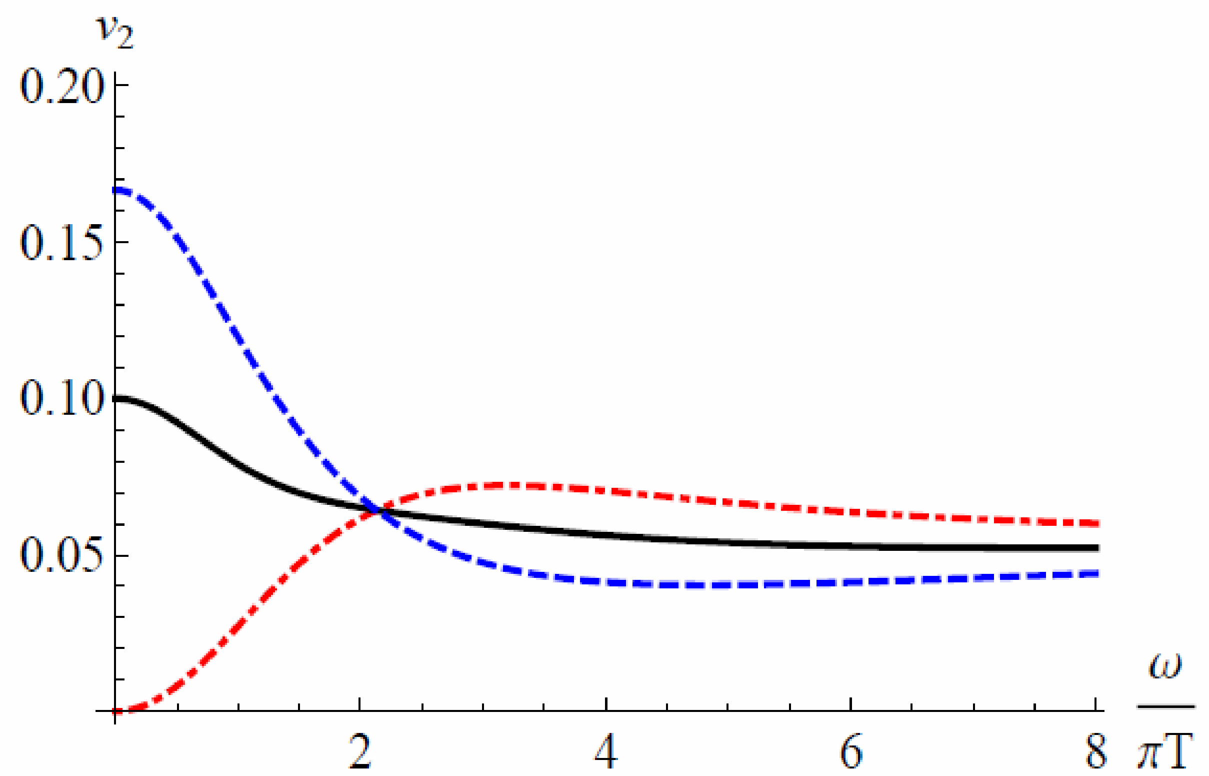


FIG. 2: The red(dot-dashed) and blue(dashed) curves correspond to the v_2 of the photons with in-plane and out-plane polarizations, respectively. The black(solid) curve correspond to the one from the averaged emission rate of two types of polarizations. Here we consider the contribution from massless quarks at $B_z = 1(\pi T)^2$.