Direct Photon Flow Measurements in PHENIX

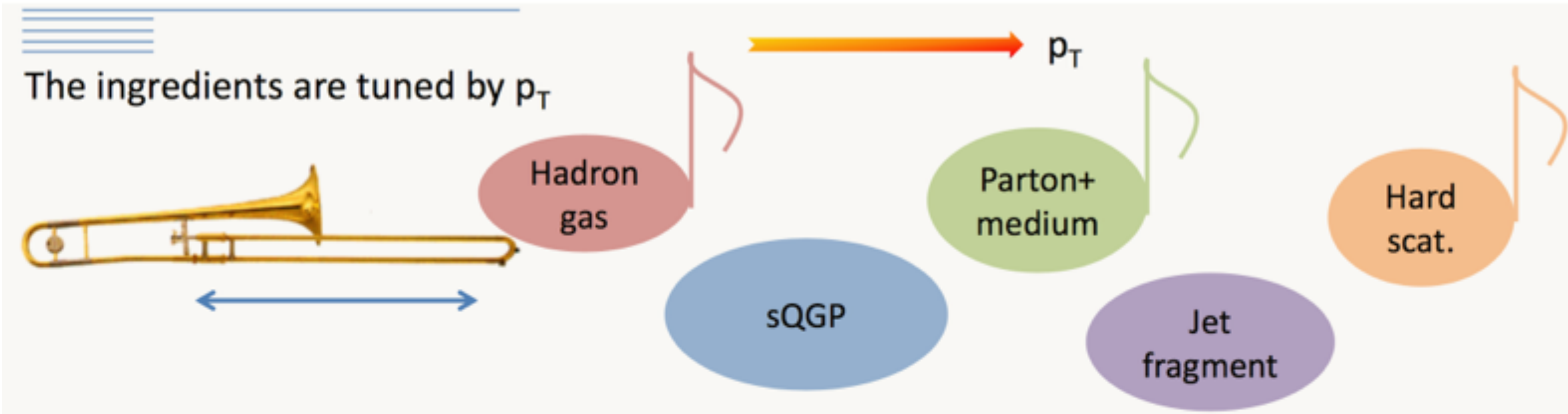
Wenqing Fan for PHENIX Collaboration

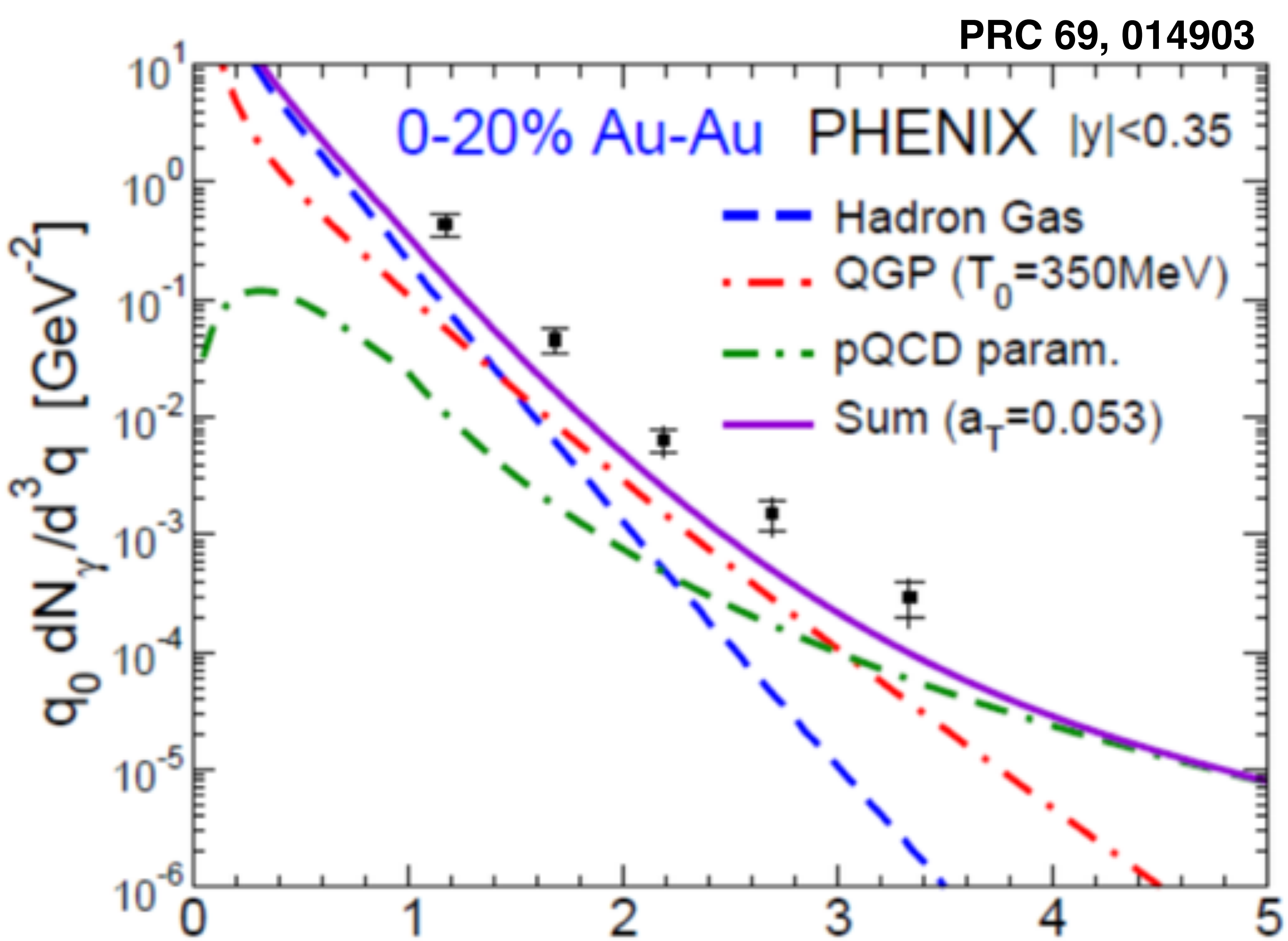
ECT* 2018

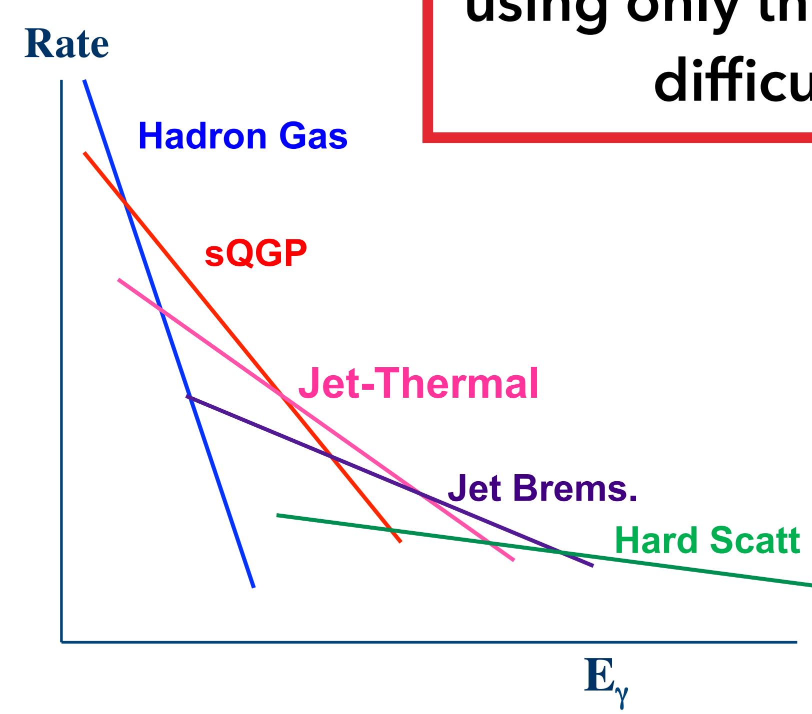
PHENIX

Stony Brook University

Different photon sources



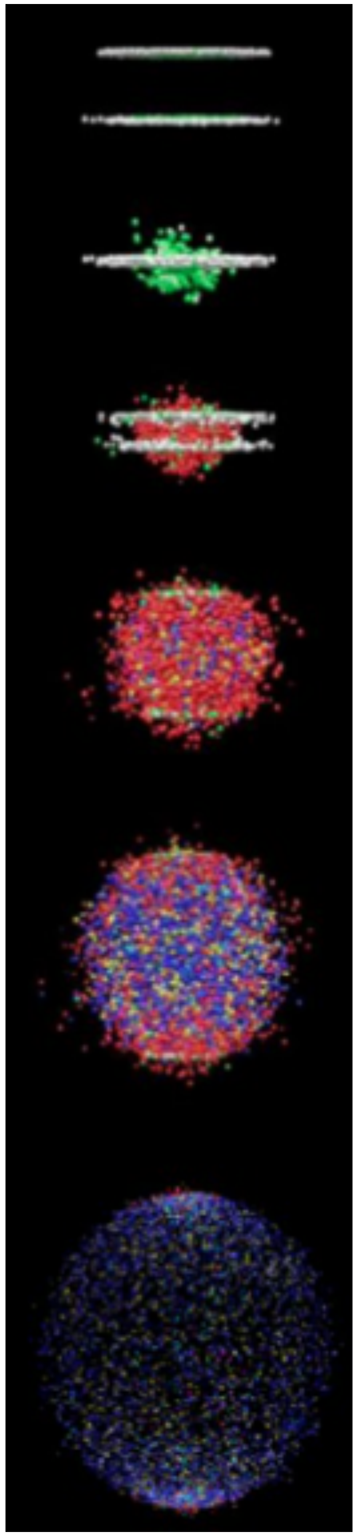




To disentangle different contributions using only the yield is difficult

Different photon sources

- Corresponding timeline & processes in heavy ion collisions



❖ Hard scattering

- $v_2 \sim 0$, high p_T

❖ Jet-medium interaction

- $v_2 < 0$, mid p_T

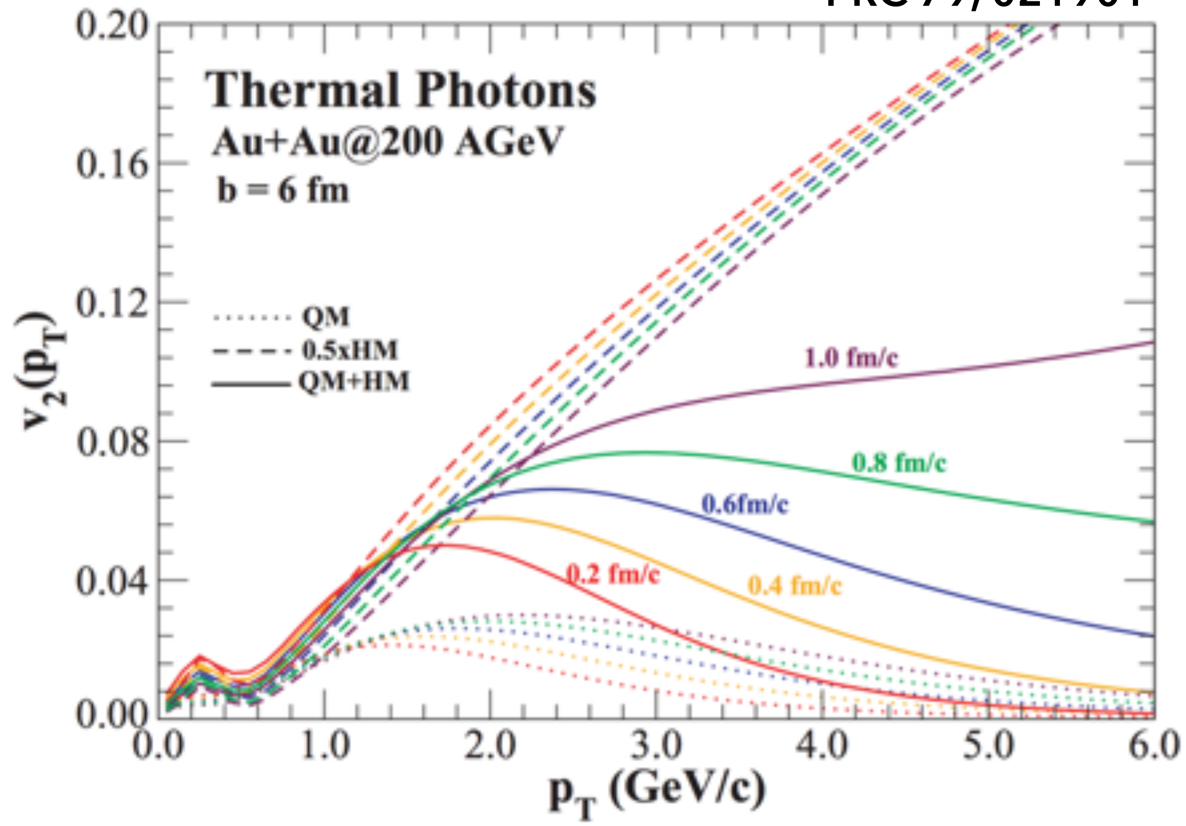
❖ Thermal photons (QGP)

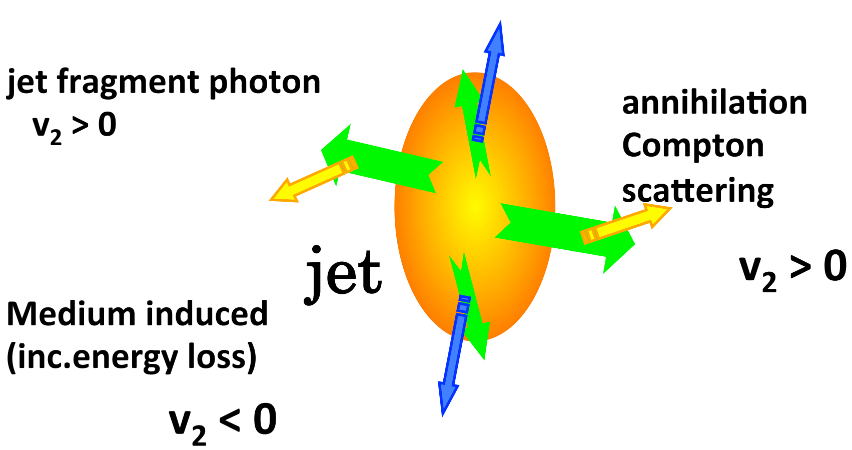
- $v_2 > 0$ but small, mid p_T

❖ Thermal photons (Hadron Gas)

- $v_2 > 0$ and sizable, low p_T

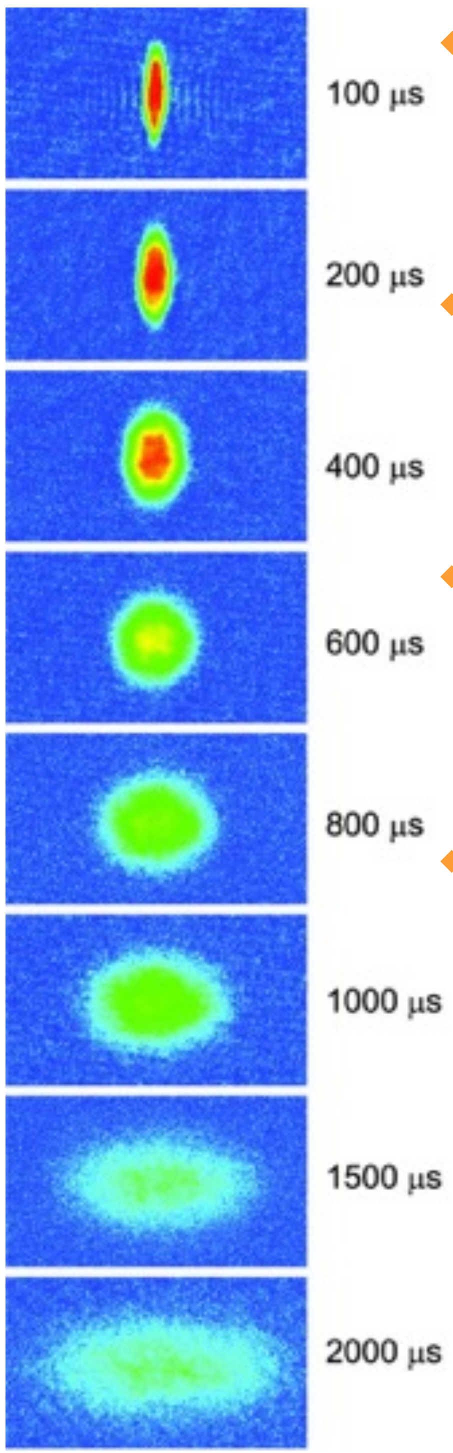
PRC 79, 021901





- Corresponding timeline & processes in heavy ion collisions

cold atoms



SCIENCE Vol: 298 2179 (2002)

- Hard scattering
  - v_2~0, high p_T
- Jet-medium interaction
  - v_2<0, mid p_T
- Thermal photons (QGP)
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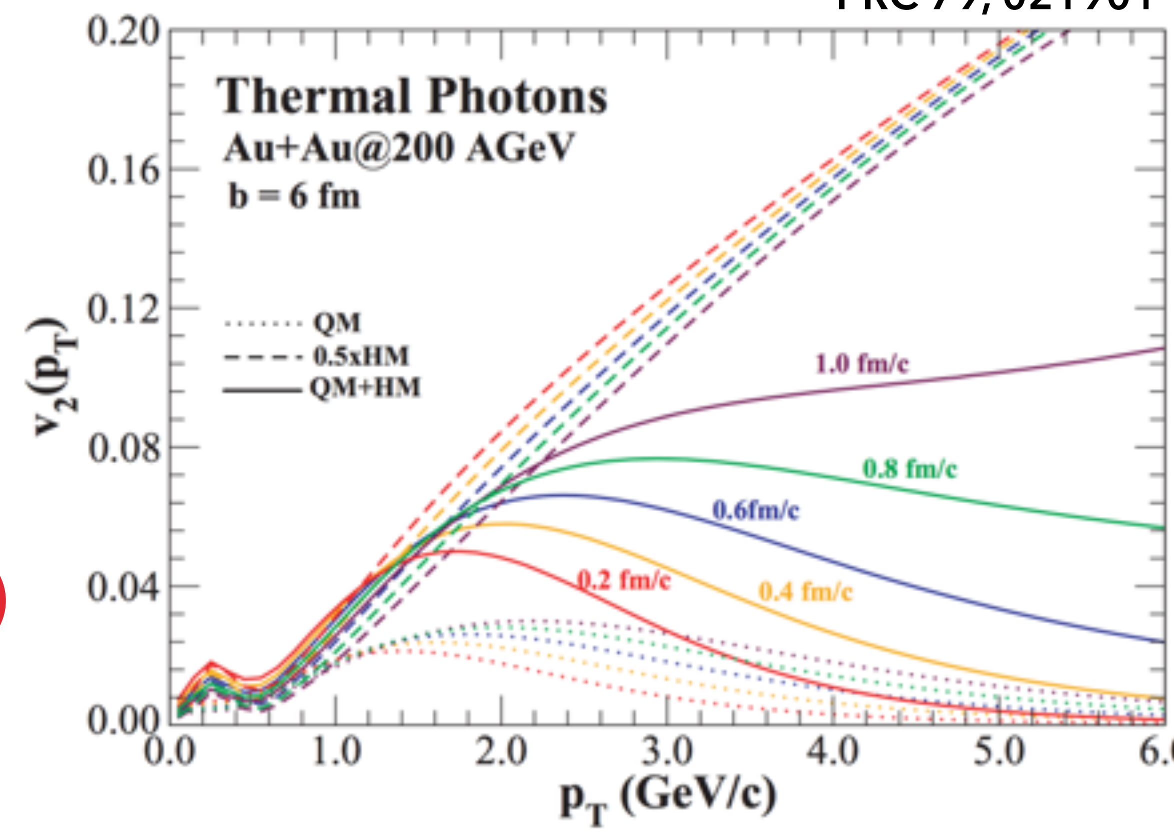
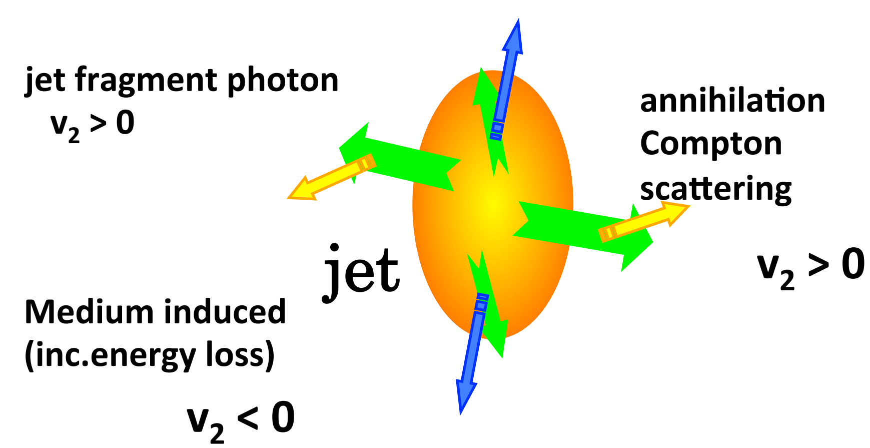
  - v_2>0 and sizable, low p_T

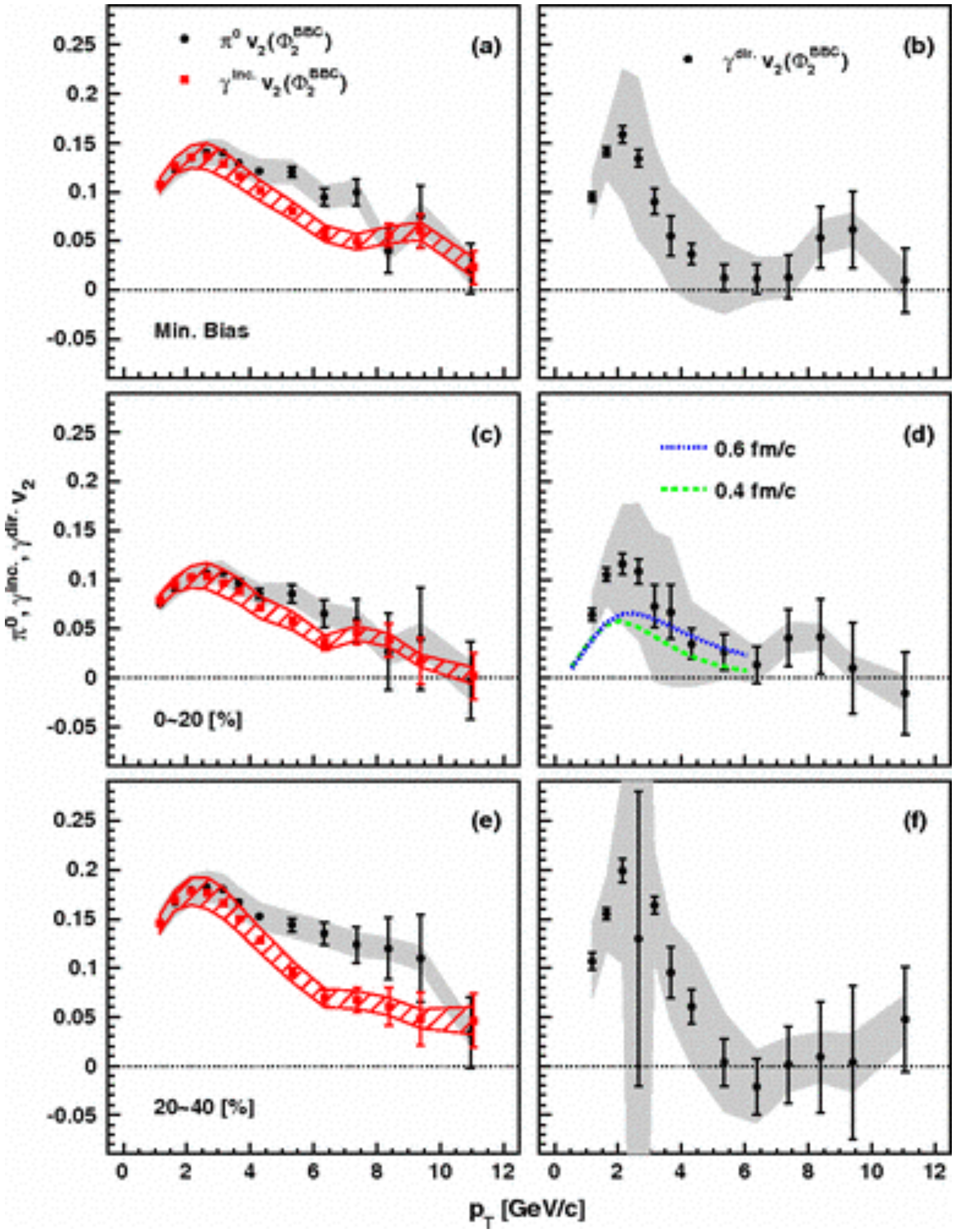
PRC 79, 021901





First direct photon flow measurement at PHENIX

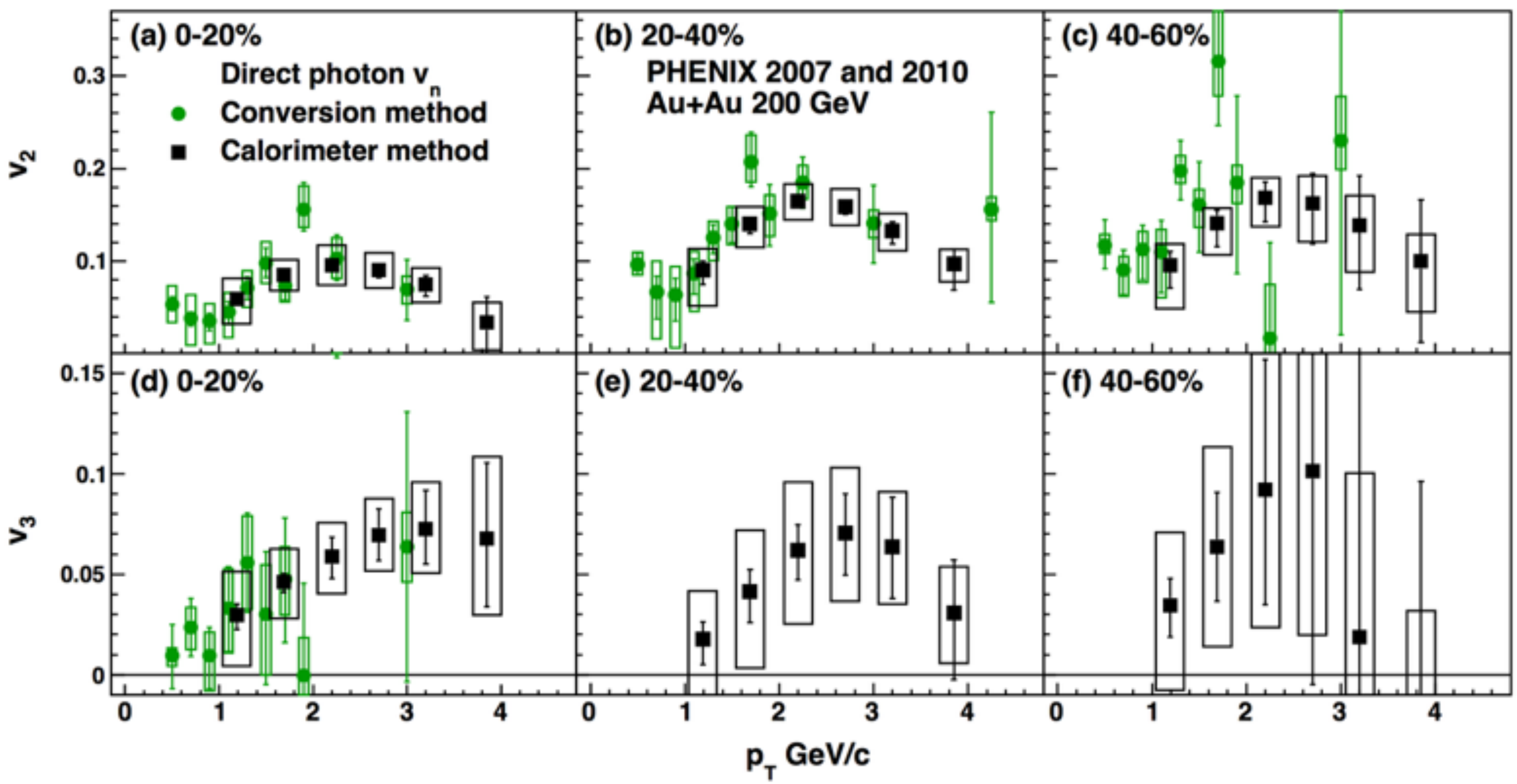
PRL 109, 122302 (Calculation from PRC 79, 021901)



- At high p_T, v_2~0, consistent with the hard scattering source
- At low p_T, a large v_2 signal is observed
- Theoretical predictions qualitatively agree with data, but seem to be systematically smaller in the low p_T range

More precise measurement down to lower p_T

PRC 94, 064901



- Large v_2 and v_3 (~ $v_2/2$) observed
- Strong centrality dependence for v_2, not so clear in v_3

Model comparisons

- Thermal photons (HG+QGP), pQCD with fireball scenario

- H.van Hees, C. Gale, R. Rapp PRC 84 054906 (2011)
- Include finite initial flow at thermalization
- Include resonance decays and hadron-hadron scattering
- Blue shift of HG spectrum included

- Microscopic transport (PHSD)

- O. Linnyk, W. Cassing, E.L. Bratkovskaya, PRC 89, 034908 (2014)
- Parton-Hadron-String dynamics
- Include large contribution from hadron-hadron interaction in HG using Boltzmann transport
- Include thermal photons from QGP

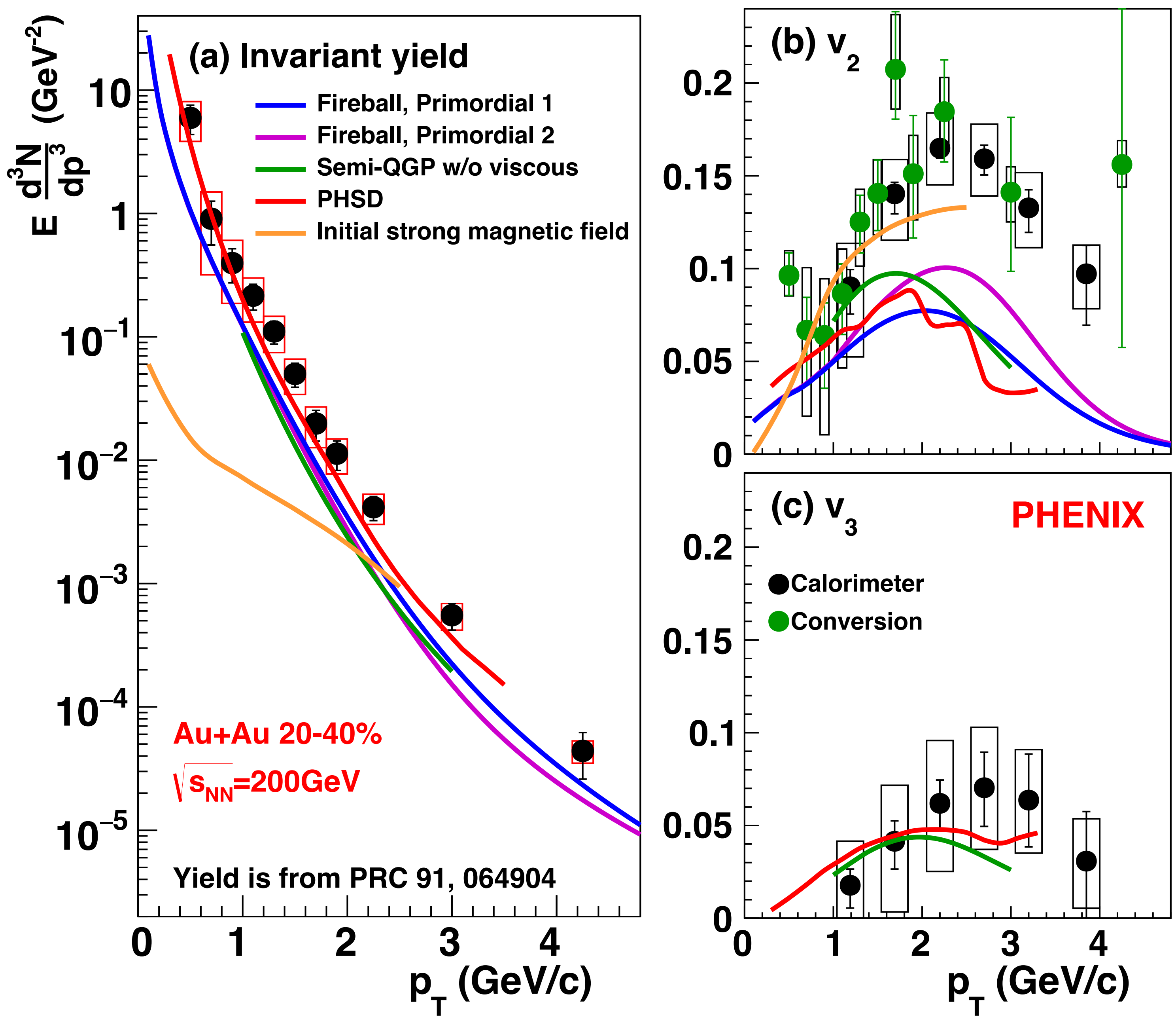
- Enhanced emission from non-equilibrium effects (glasma, etc.)

- C. Gale et al., PRL114, 072301 + priv.comm. with Y Hidaka and J-F. Paquet
- Semi-QGP is the QGP near T_c
- Annihilation and Compton processes around hadronization time are naturally included

- Enhanced early emission from magnetic field

- G. Basar, D. E. Kharzeev, V. Skokov, PRL 109 202303 (2012)
- Initial strong magnetic field produces anisotropy of photon emission
- magnetic field + thermal photons (lattice QCD)

PRC 94, 064901

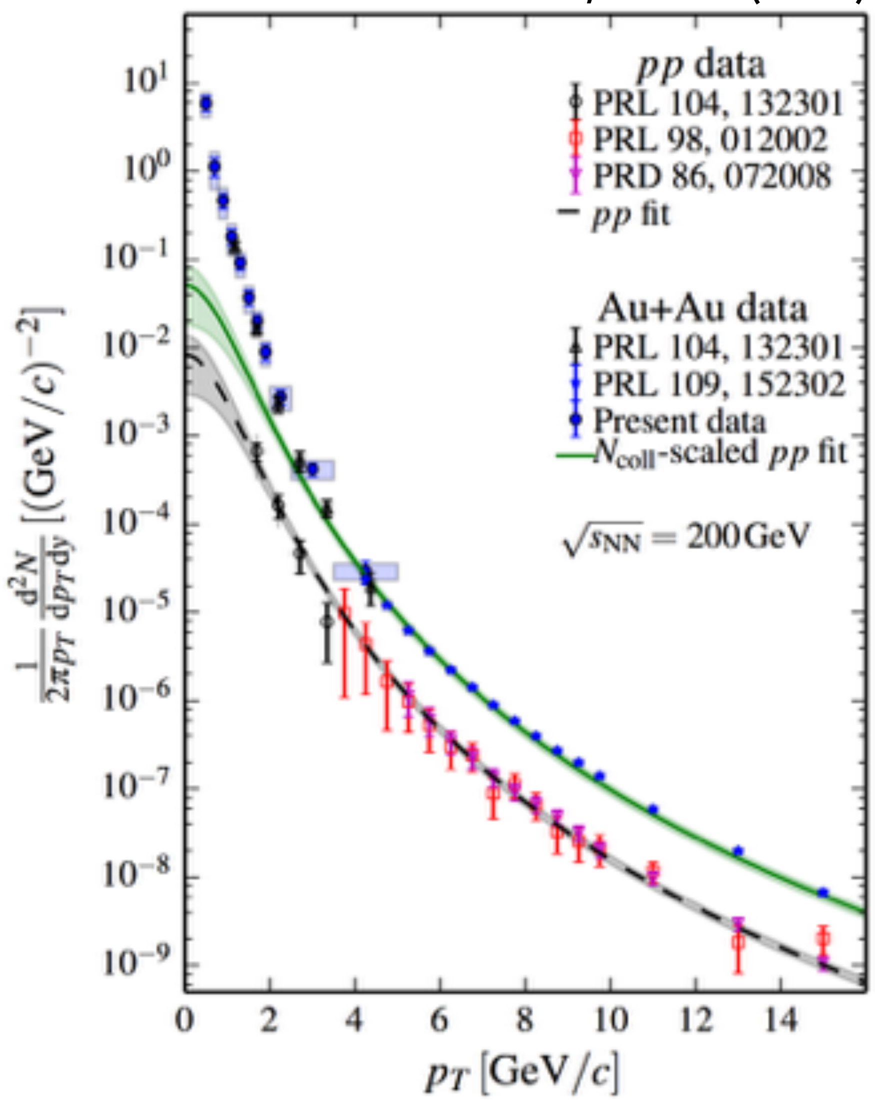


Large yield & large v_2

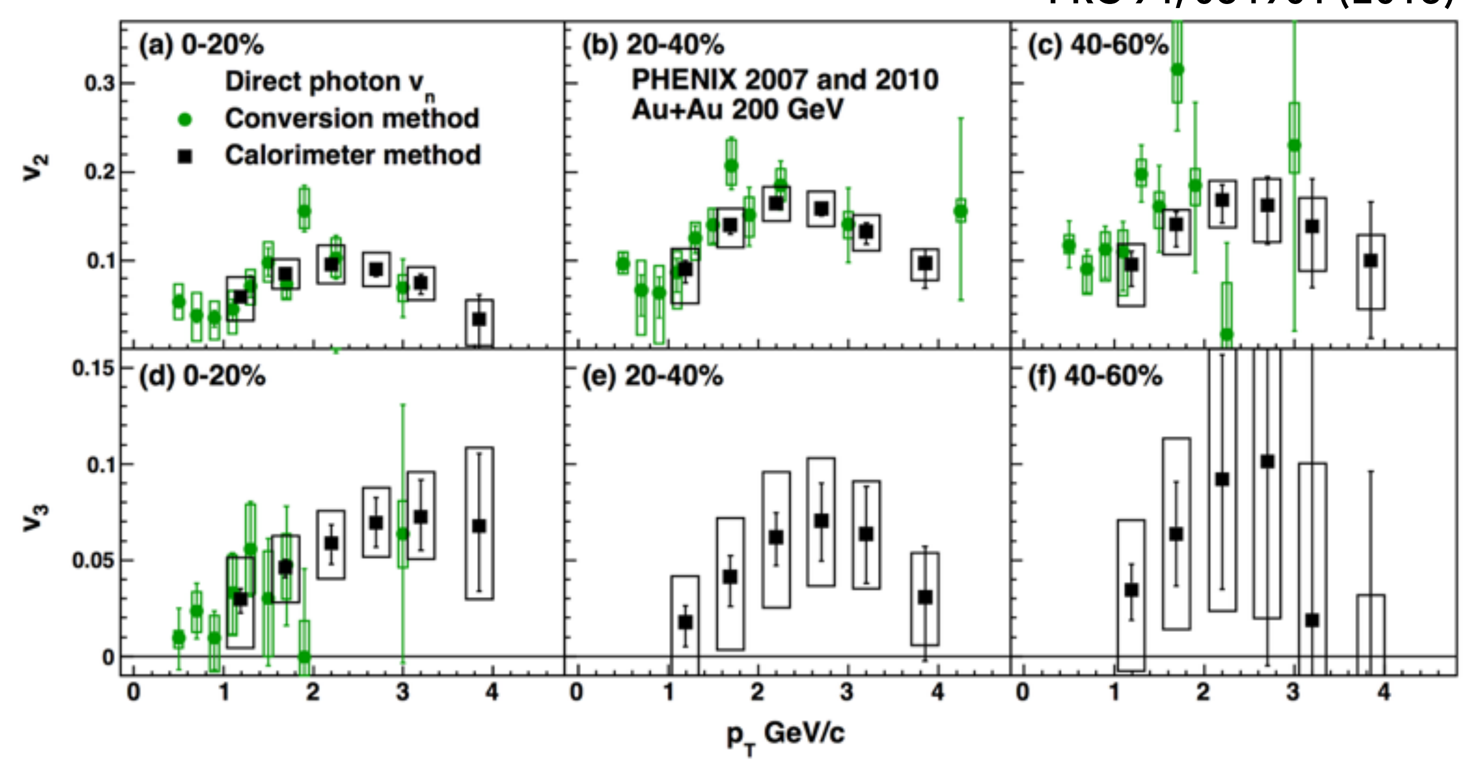
- Large yield: emissions from the early stage when temperature is high
- Large v_2: emissions from the late stage when the collective flow is sufficiently built up

Challenging for current theoretical models to describe large yield and v_2 simultaneously!

PRC 91, 064904 (2015)



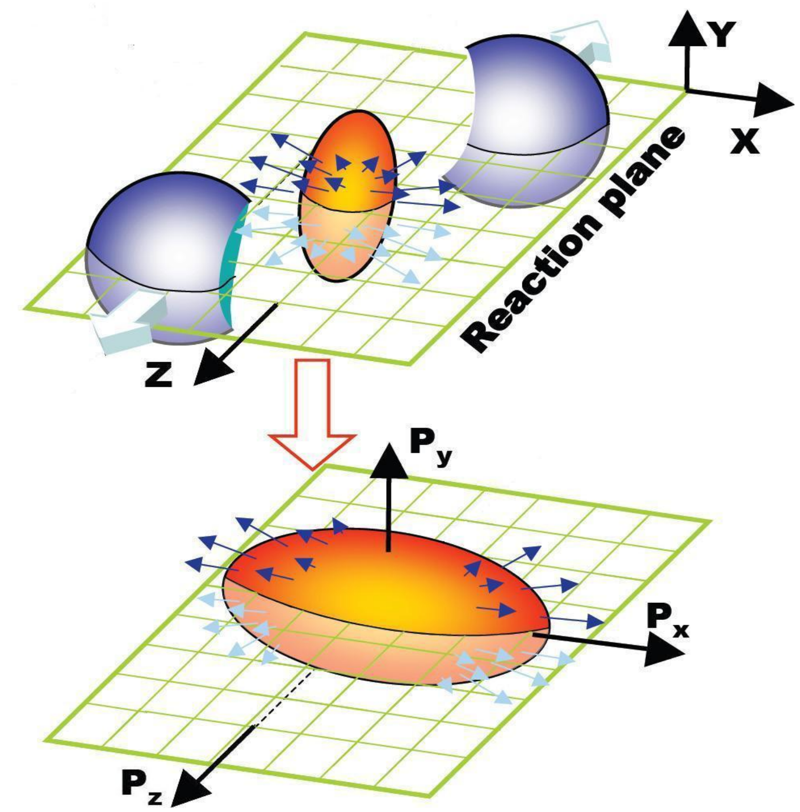
PRC 94, 064901 (2016)



Event Plane Method

- Flow and reaction plane

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n\cos(n(\phi-\Psi_{RP}))\right)$$



ψ_{RP} cannot be directly measured, but can be estimated from the particle azimuthal distribution event-by-event → ψ_{EP}

$$Q_{n,x} = \sum_i w_i\cos(n\phi_i) = \mathbf{Q}_n\cos(n\Psi_n),$$
$$Q_{n,y} = \sum_i w_i\sin(n\phi_i) = \mathbf{Q}_n\sin(n\Psi_n),$$

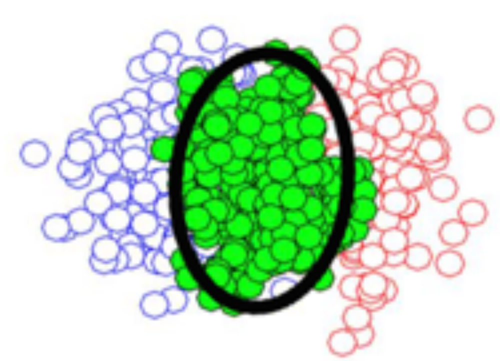
$$\Psi_n = \arctan2(Q_{n,y}, Q_{n,x})/n,$$ ← Event Plane

- Event plane method

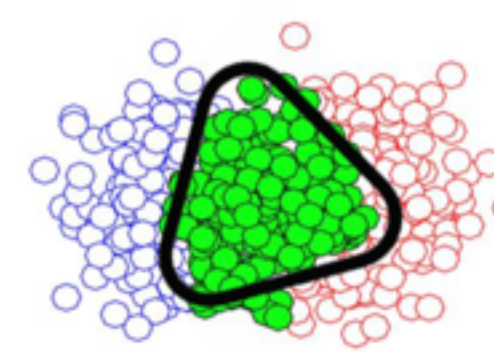
Measure azimuthal distributions of particles pf interest (photons) with respect to event plane

$$\frac{dN}{d(\phi-\Psi_k)} \propto 1 + \sum_n [v_{kn}\cos\{n(\phi-\Psi_k)\}]$$

elliptic flow



trianglar flow



Other Flow Analysis Methods

- Pair-wise correlation (scalar product)
  - an estimator of $<v_n^2>^{1/2}$, can be subjected to non-flow effect and fluctuations like EP method

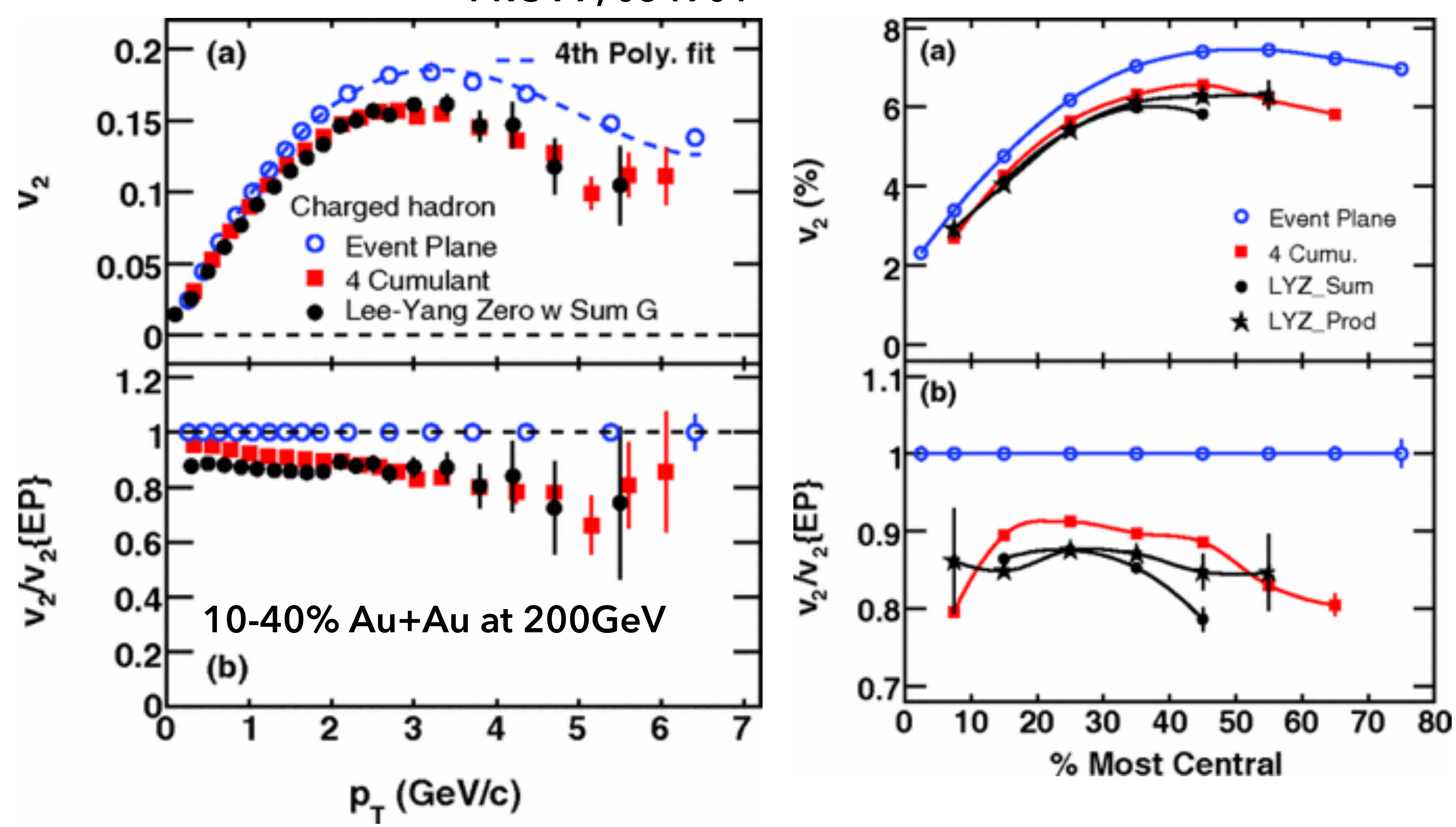
$$v_n(p_T, y) = \frac{\left\langle \mathbf{Q}_n u_{n,i}^*(p_T, y) \right\rangle}{2\sqrt{\langle Q_n^a Q_n^{b*} \rangle}}$$

- Higher Order Cumulants

$$\langle\langle u_{n,1} u_{n,2} u_{n,3}^* u_{n,4}^* \rangle\rangle \equiv \langle u_{n,1} u_{n,2} u_{n,3}^* u_{n,4}^* \rangle - 2\langle u_{n,1} u_{n,2}^* \rangle^2 = -v_n^4\{4\}$$

  - Larger statistical uncertainty
  - Non-flow are highly suppressed

PRC 77, 054901



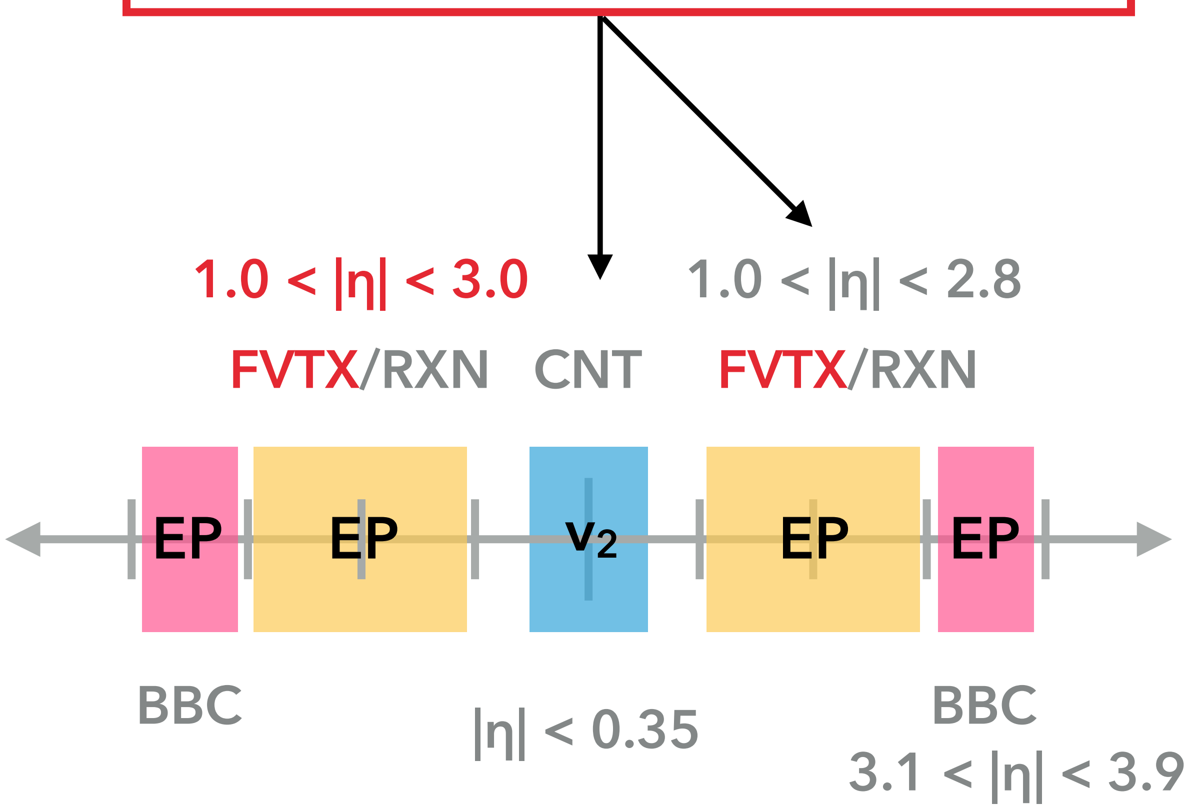
Event Plane Detector

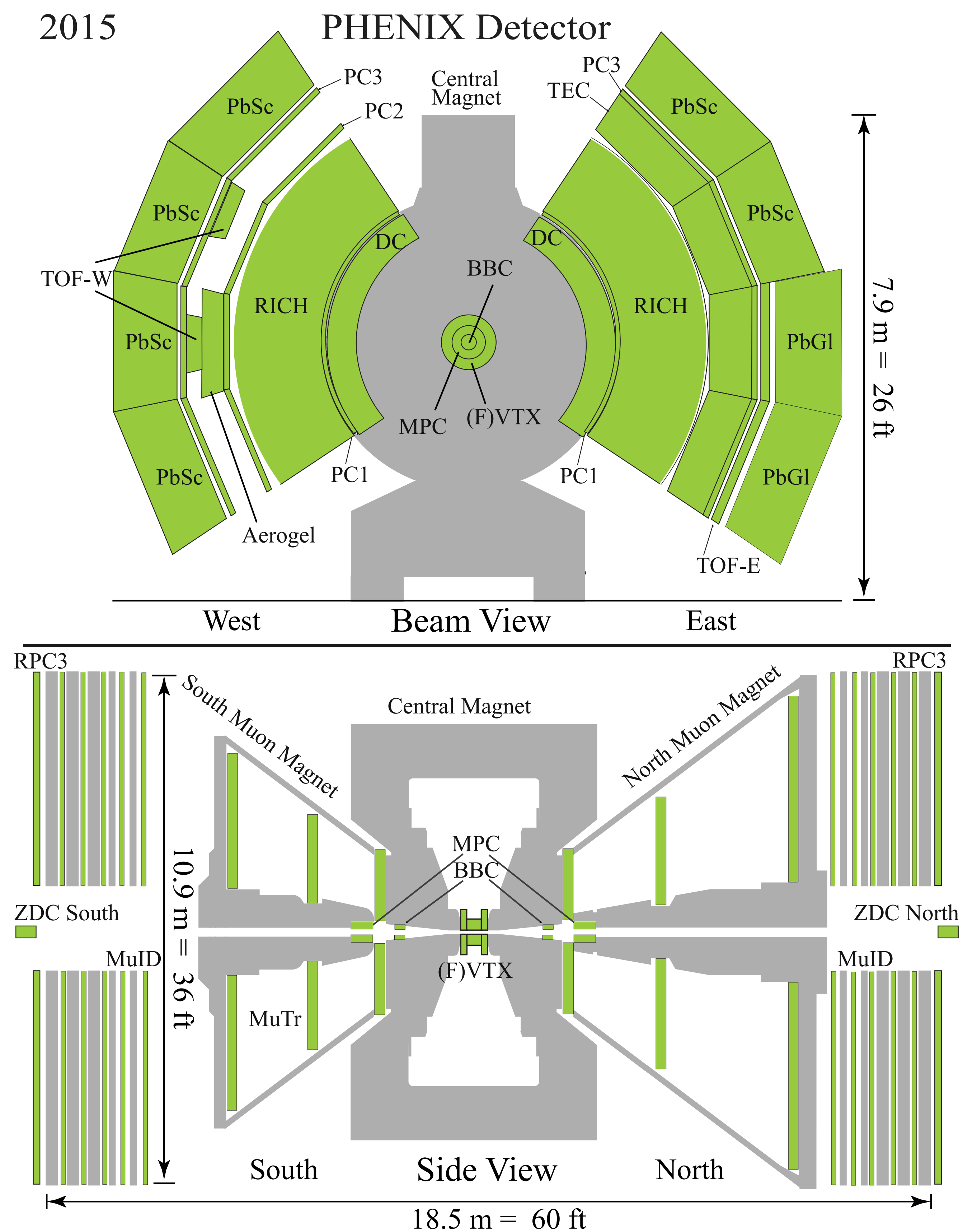
CNT – **Photon reconstruction**

FVTX – **Unidentified particle tracking, Event Plane**

BBC – **Event Plane reconstruction, Centrality determination**

large η gap to suppress non-flow





Event Plane Resolution

- **Finite multiplicity limits the estimation of the angle of reaction plane**

$$v_n^{\text{obs}}(p_T, y) = \langle \cos[n(\phi_i - \Psi_n)] \rangle$$

$$v_n = \frac{v_n^{\text{obs}}}{\mathcal{R}_n}$$

$$\mathcal{R}_n = \langle \cos[n(\Psi_n - \Psi_{\text{RP}})] \rangle$$

Depends on resolution parameter → $\chi = v_n \sqrt{M}$

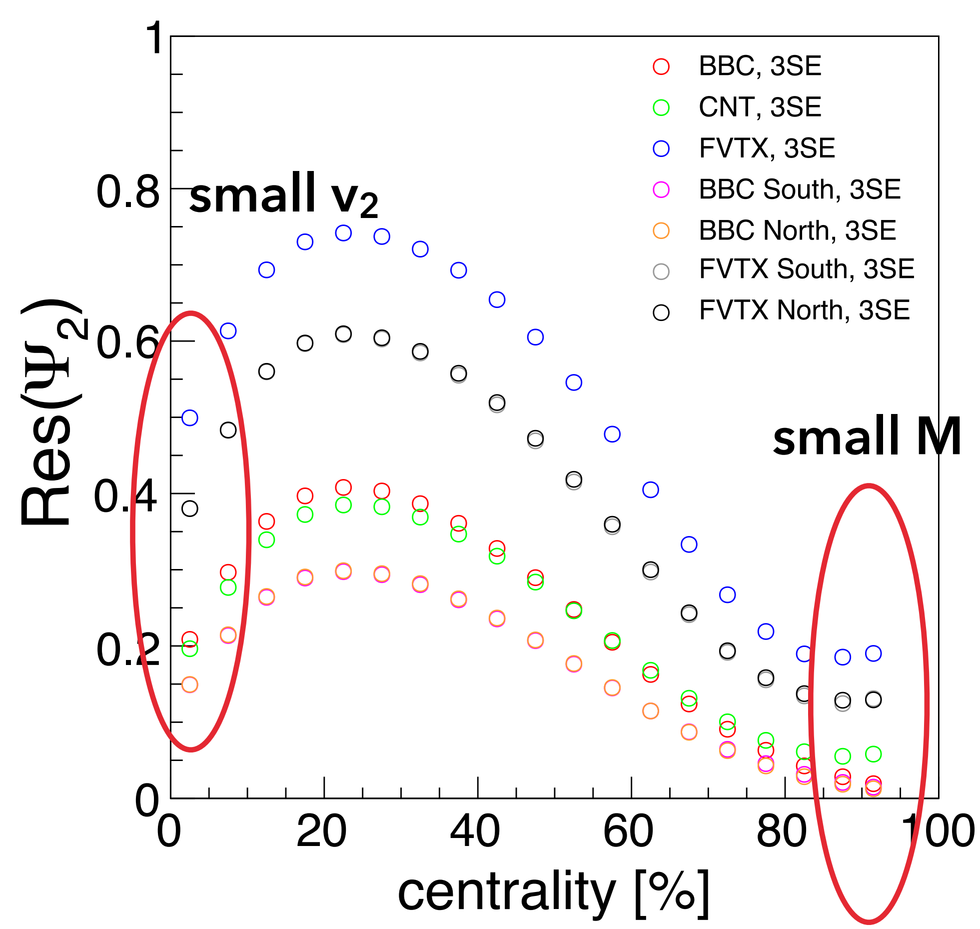
- **2-subevent method**

$$R(\psi_n^A) = R(\psi_n^B) = \sqrt{\langle \cos(n(\psi_n^A - \psi_n^B)) \rangle}$$

EP detector A & B need to have the same resolution (multiplicity)

- **3-subevent method**

$$R(\psi_n^A) = \sqrt{\frac{\langle \cos(n(\psi_n^A - \psi_n^B)) \rangle \langle \cos(n(\psi_n^A - \psi_n^C)) \rangle}{\langle \cos(n(\psi_n^B - \psi_n^C)) \rangle}}$$



How to measure photons in central arms?

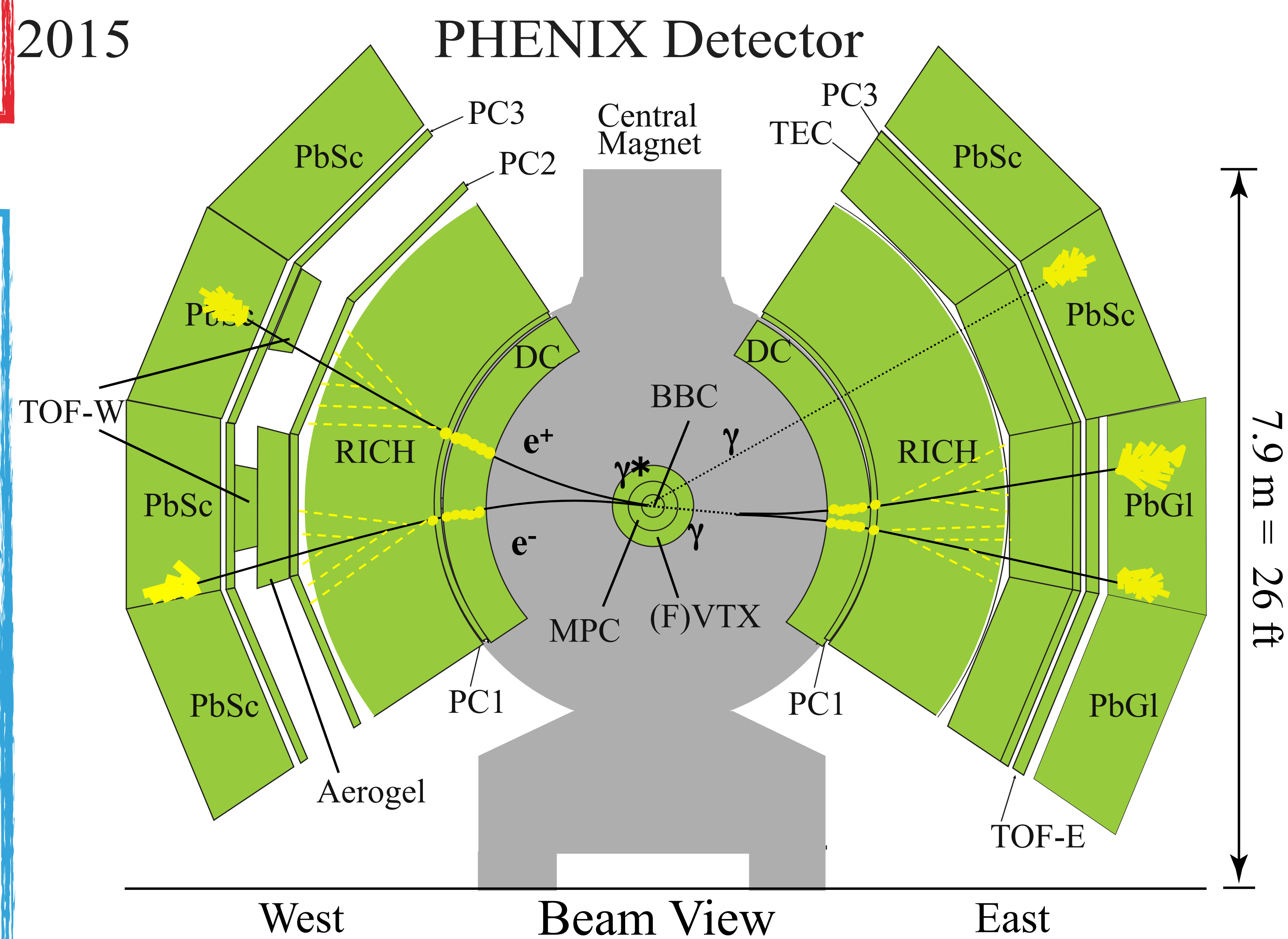
Acceptance: |η|<0.35, Δϕ 2x90°

- **Electromagnetic Calorimeter:**
  - 2 PbGl: 0.8 % + 5.9 %/√E
  - 6 PbSc: 2.1 % + 8.1 %/√E

- **Tracking:**
  - Drift Chambers (DC)
    $\delta p/p = 0.7\ \% + 1.1\% p$
  - Pad Chambers (PC)
    $\sigma = \pm 1.7$ mm

- **Particle Identification:**
  - RICH – $e^{\pm}$
  - TOF East and TOF West:
    - $\sigma_T \cong 100$ps
    - π/K $p_T < 2.5$ GeV/c
    - K/p $p_T < 4.0$ GeV/c
  - EMCal timing:
    - $\sigma_T \cong 600$ps

Measure photon from its energy deposit at calorimeter

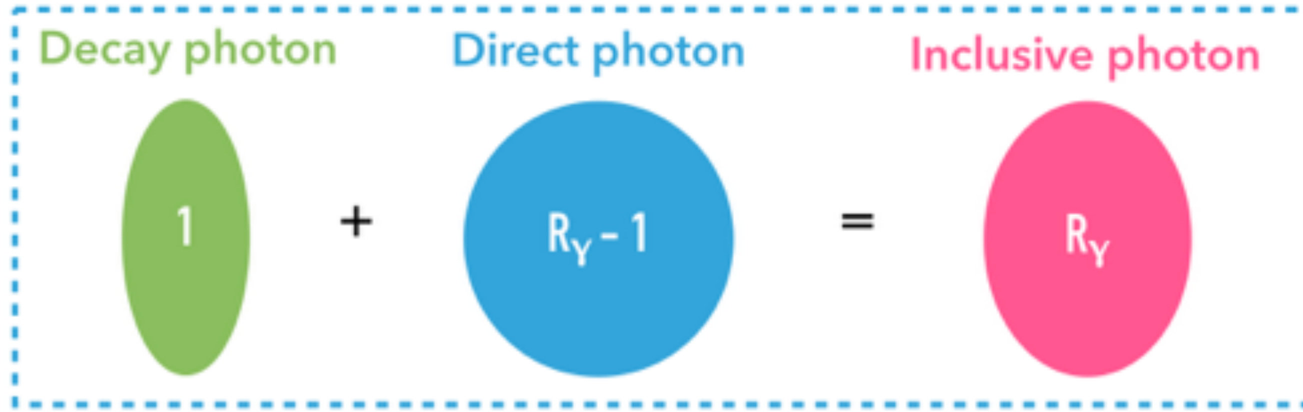


Measure photon from external conversions $\gamma \rightarrow e^{+} + e^{-}$

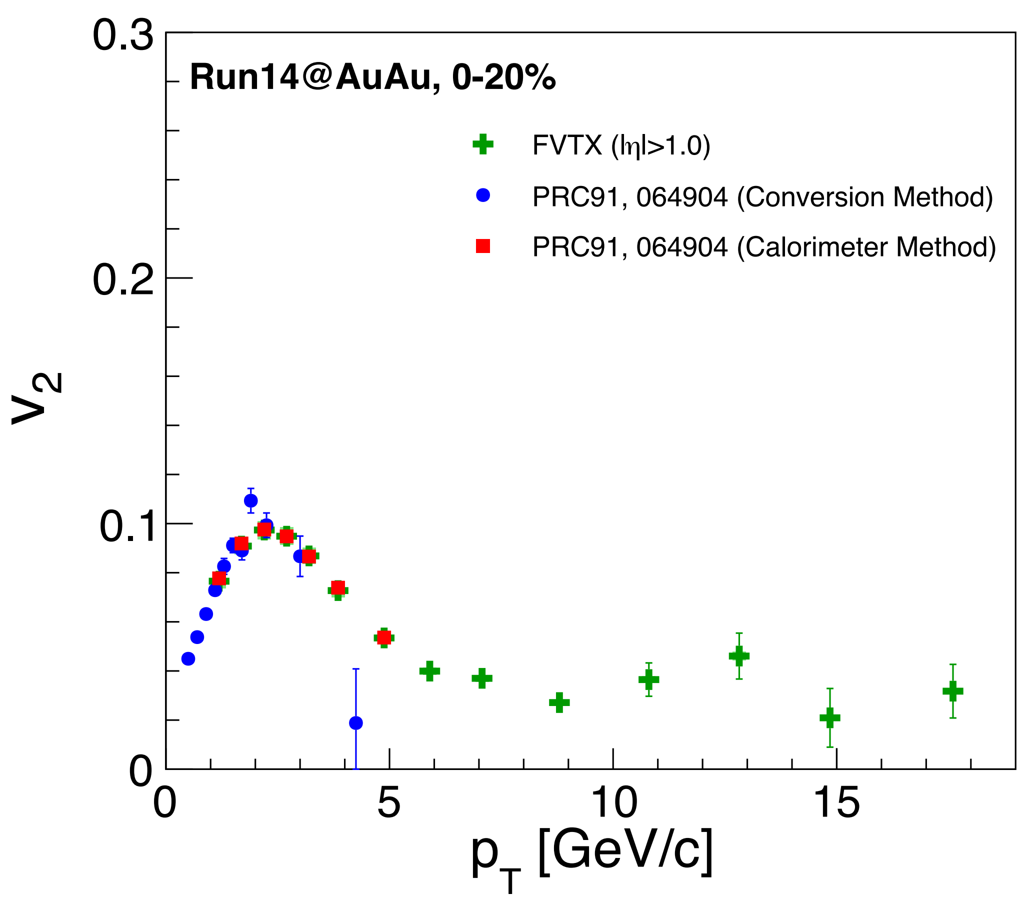
Direct Photon v_n Extraction

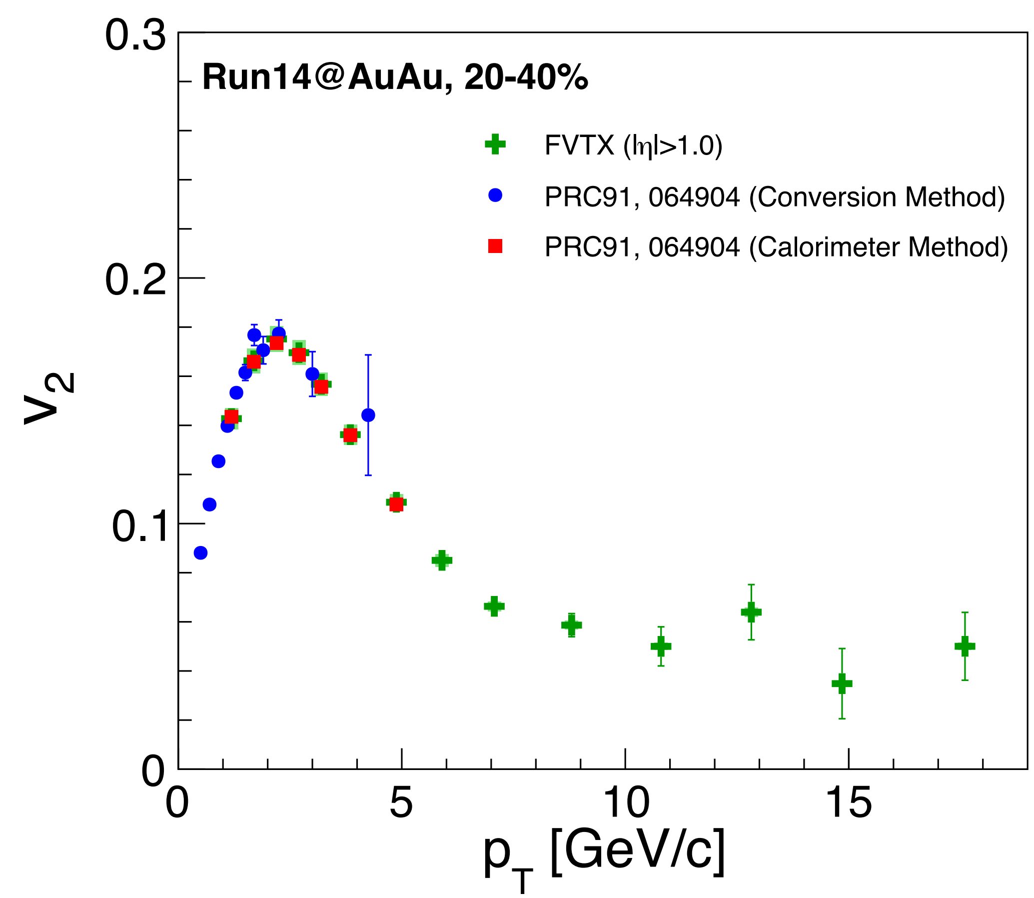
- To determine direct photon v_n

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



- Inclusive photon v_2 with calorimeter method (using EMCal clusters as inclusive photons)

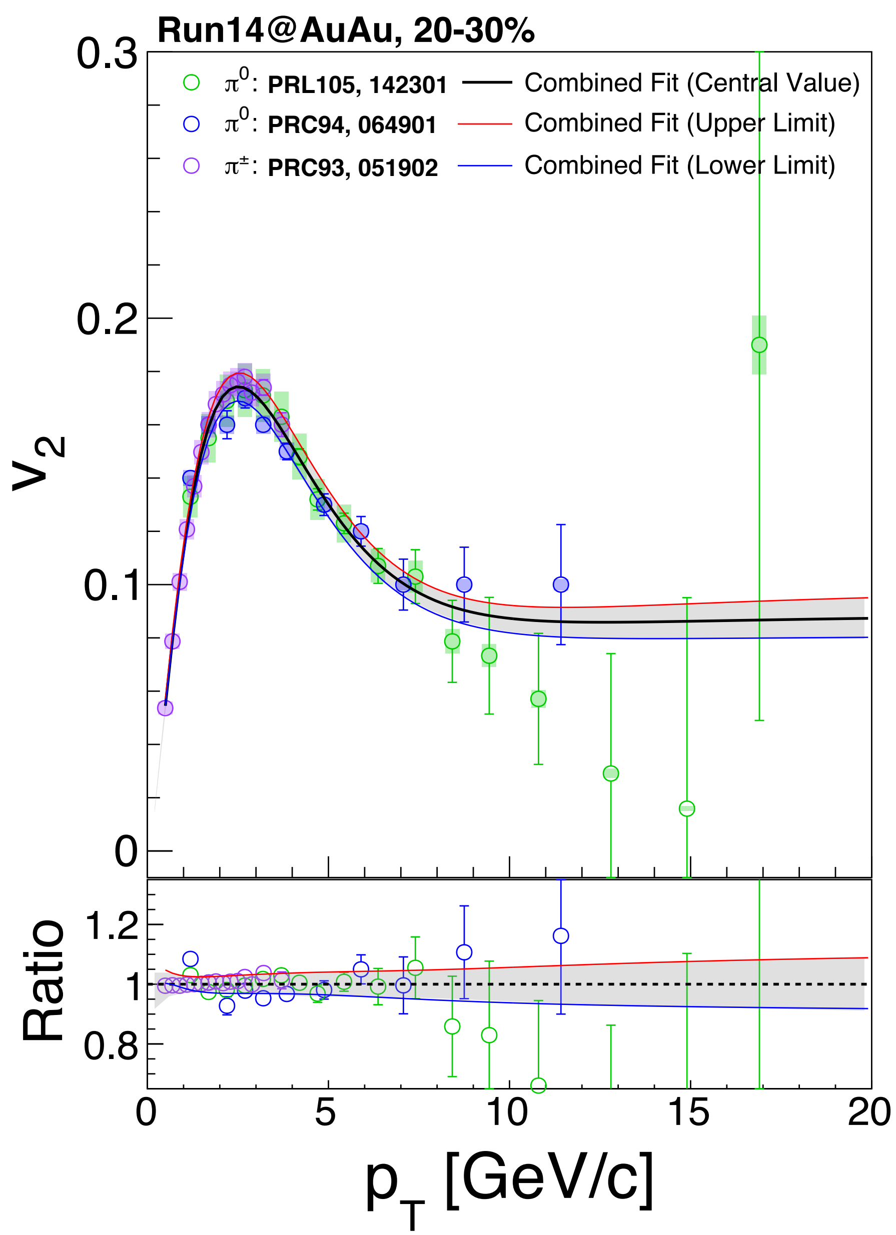




Decay Photon v_n

- Estimate decay photon v_n
  - Use measured yield and anisotropy of charged and neutral pions
  - v_n for heavier mesons estimated by KE_T

$$v_n^{meson}(KE_T) = v_n^{\pi}(KE_T) \quad \text{with} \quad KE_T = m_T - m = \sqrt{p_T^2 + m^2} - m$$



Extract anisotropy of pions

$$\frac{v_n}{n_q^{n/2}} = N_1 \arctan(ax) + N_2(x^2 + bx)e^{-\lambda x}$$

- $v_n = 0$ for $p_T = 0$,
- $v_n = \text{const.}$ for $p_T \to \infty$, and
- a single peak in the low p_T range.

Decay Photon v_n

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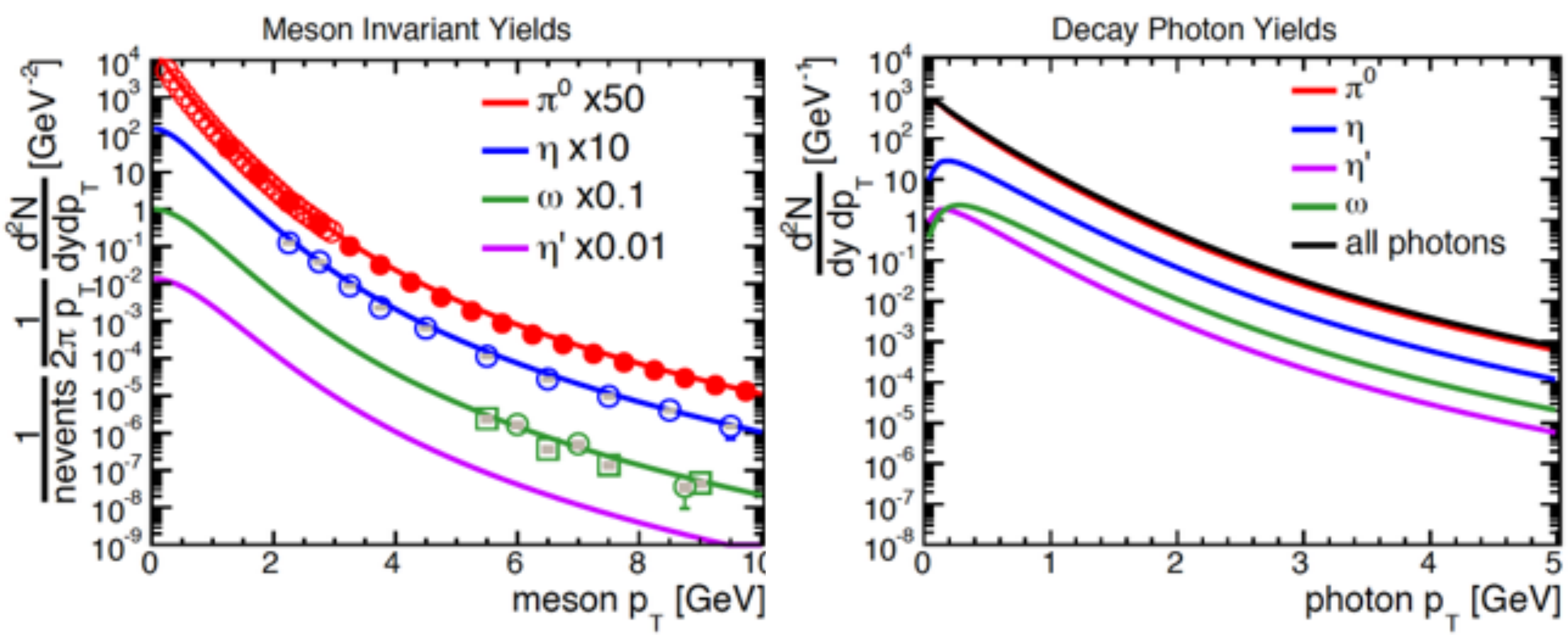
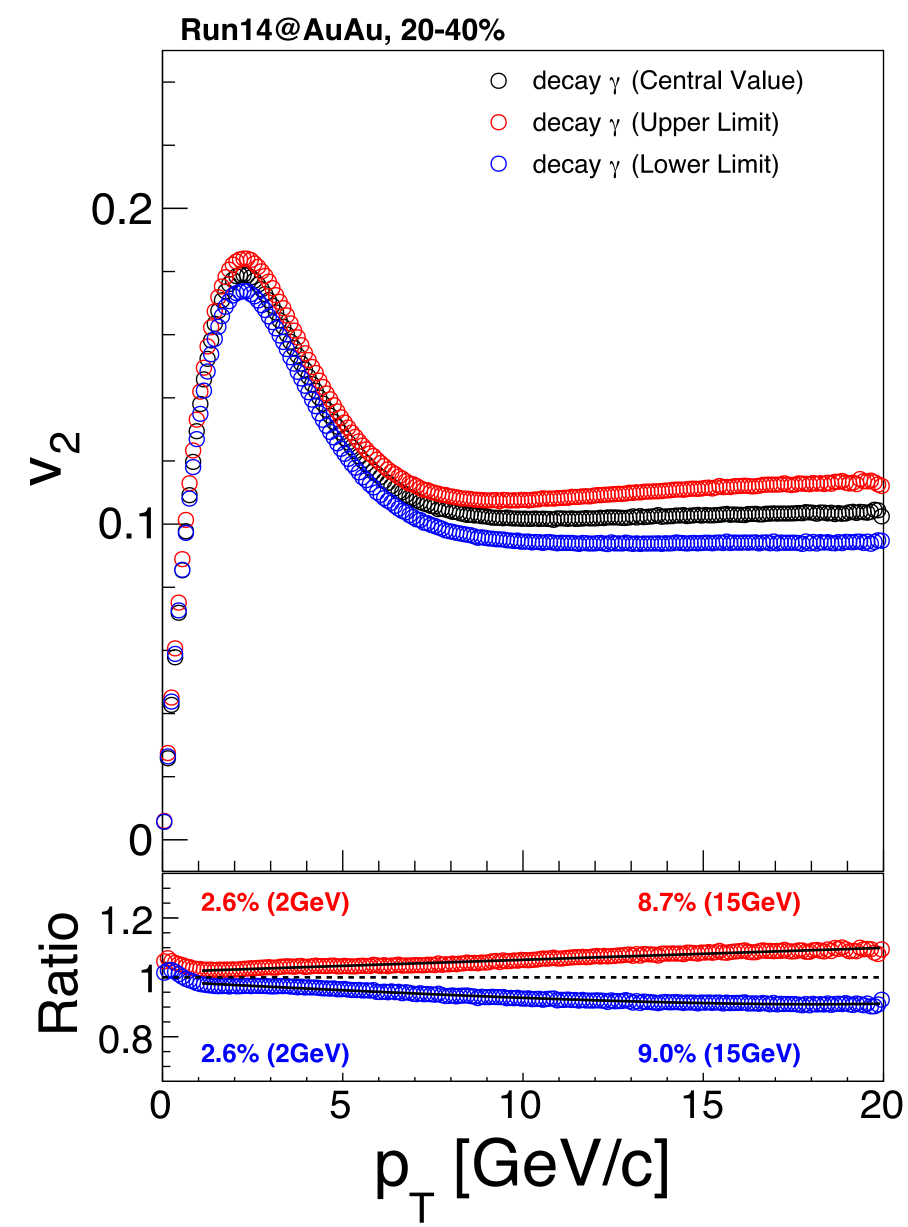
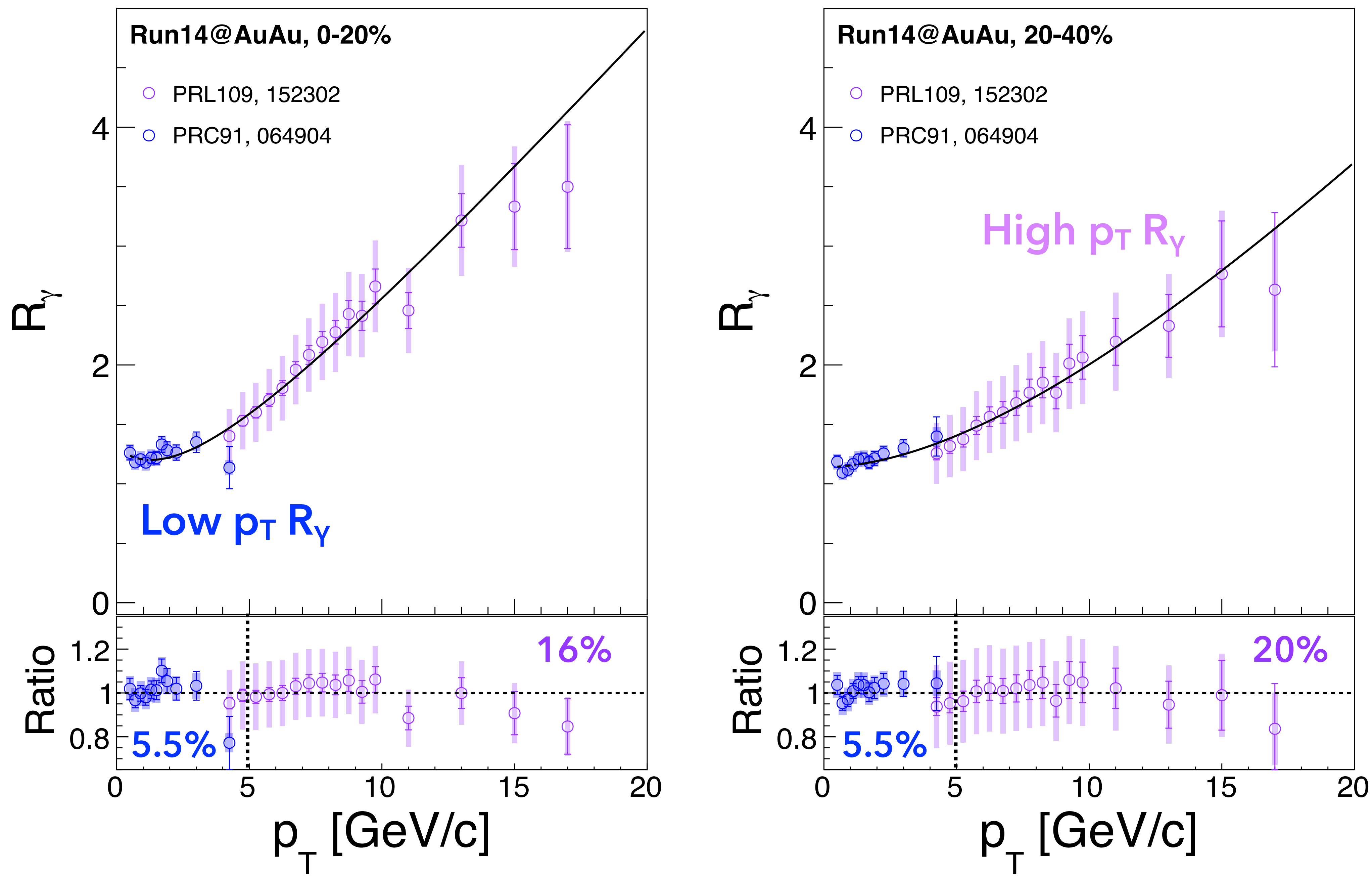




  - Use the meson yields and v_n in MC, process them through all decay chains including photons ⟶ calculate the decay photon v_n

- Extrapolate R_γ to higher p_T from a combined fit to previous R_γ measurements

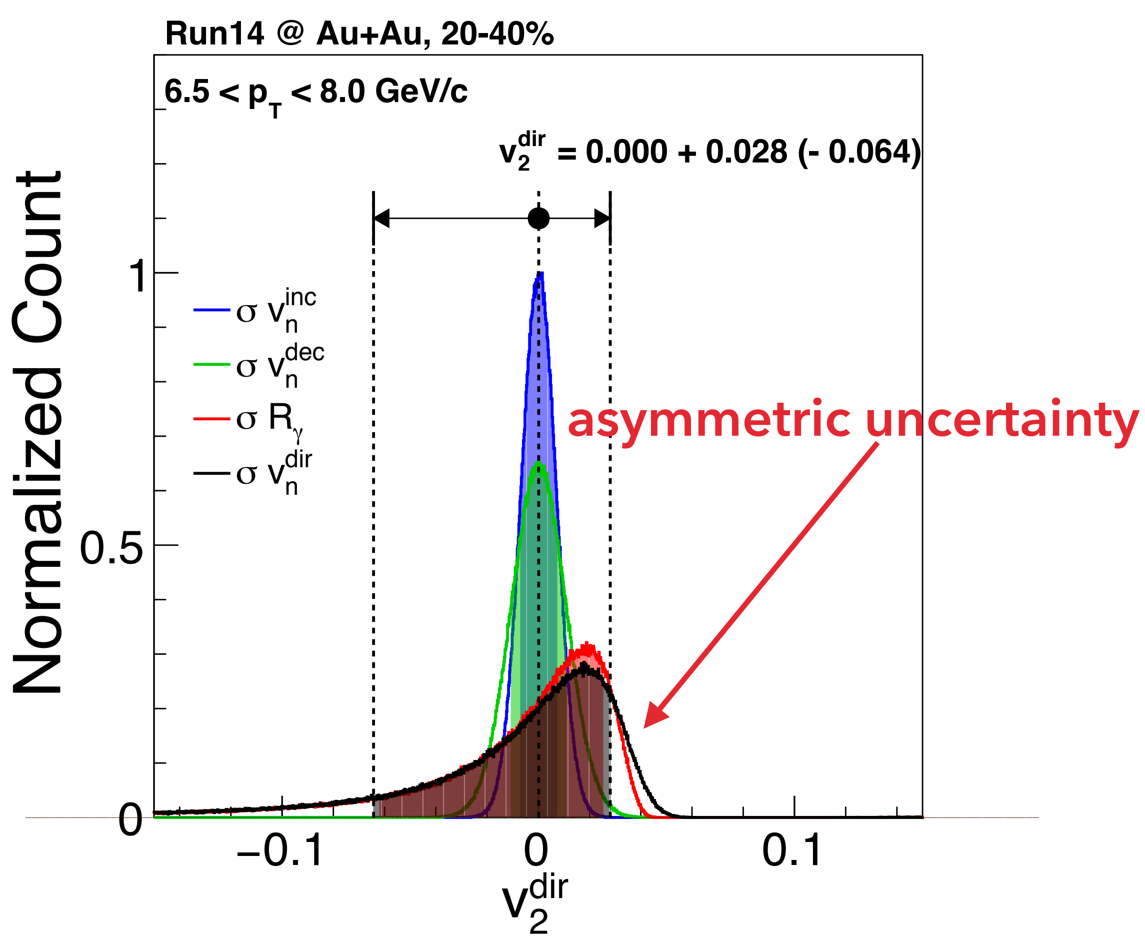


- Using Gaussian error propagation

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

$$\sigma^2_{v_n^{dir}} = \left(\frac{R_\gamma}{R_\gamma - 1}\right)^2 \times \sigma^2_{v_n^{inc}} + \left(\frac{1}{R_\gamma - 1}\right)^2 \times \sigma^2_{v_n^{dec}} + \left(\frac{v_n^{dec} - v_n^{inc}}{R_\gamma - 1}\right)^2 \times \sigma^2_{R_\gamma} + \sigma^2_{EP}$$

- Non-linear dependence of uncertainty on R_γ
  - Modeling the probability distribution of possible values of v^{dir}
  - Assuming the individual statistical and systematic uncertainties follow Gaussian probability distributions

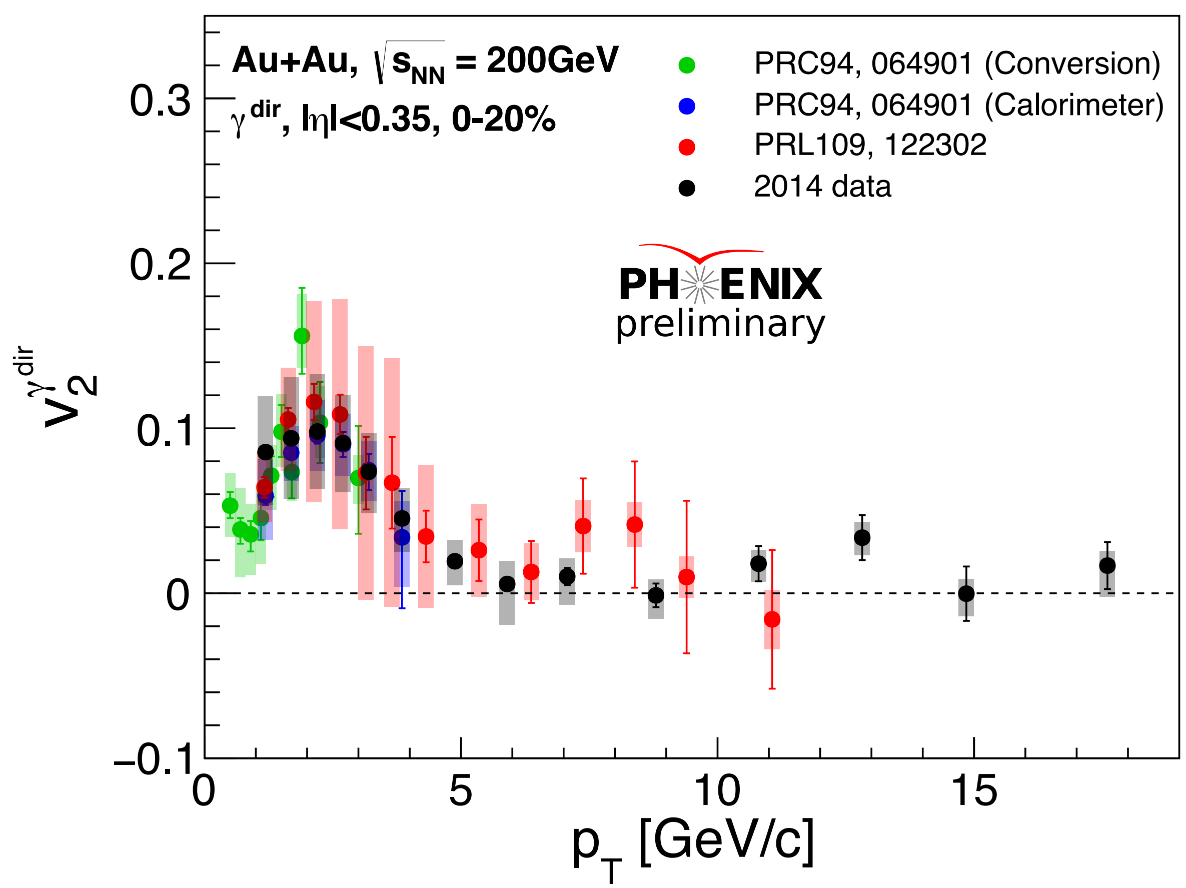


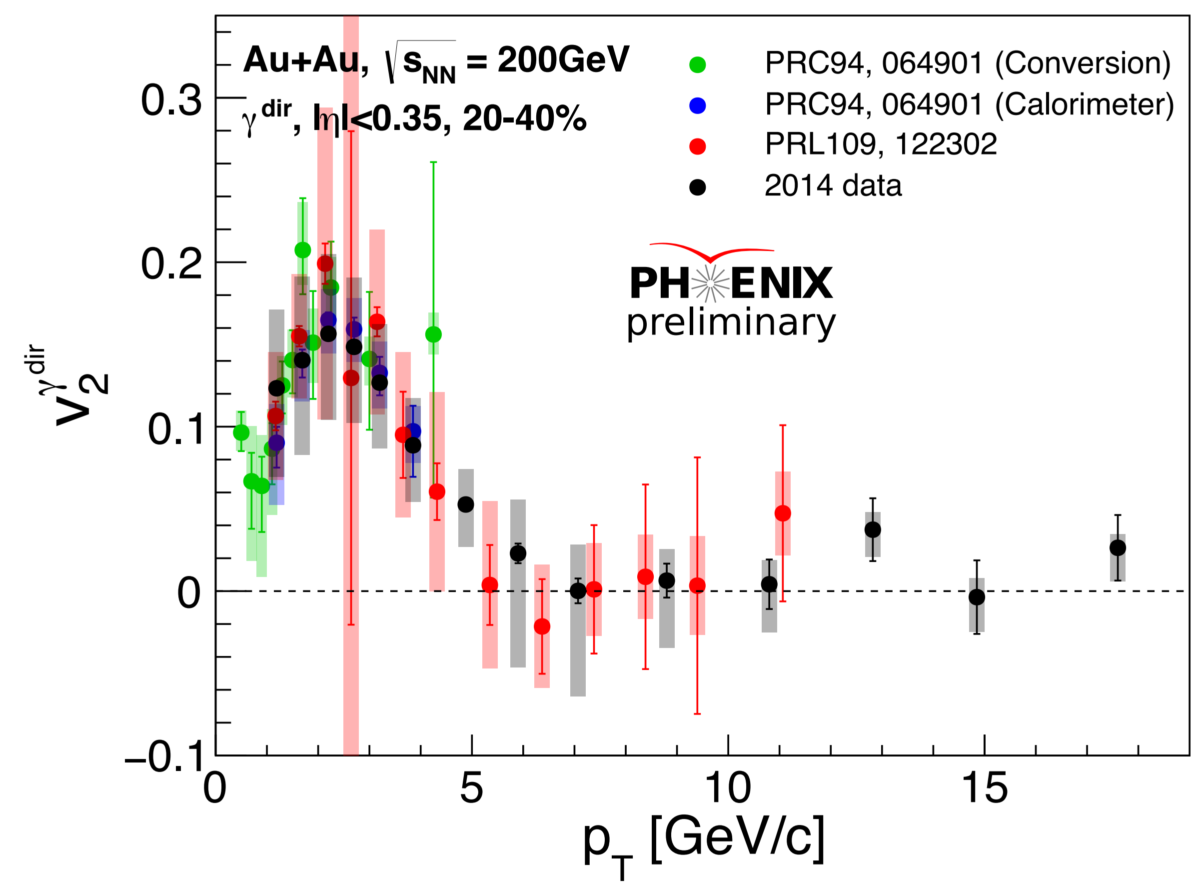
Systematic Uncertainties for v_2 in 20-40%

Sources	<5GeV	>5GeV
R_γ	5.5%	20%
v_2^{inc}	2.5%	4%
v_2^{dec}	5%	5%

Direct Photon v_2 Result in Au+Au @ 200GeV

- New direct photon v_2 consistent with published result with a higher p_T reach up to 18GeV





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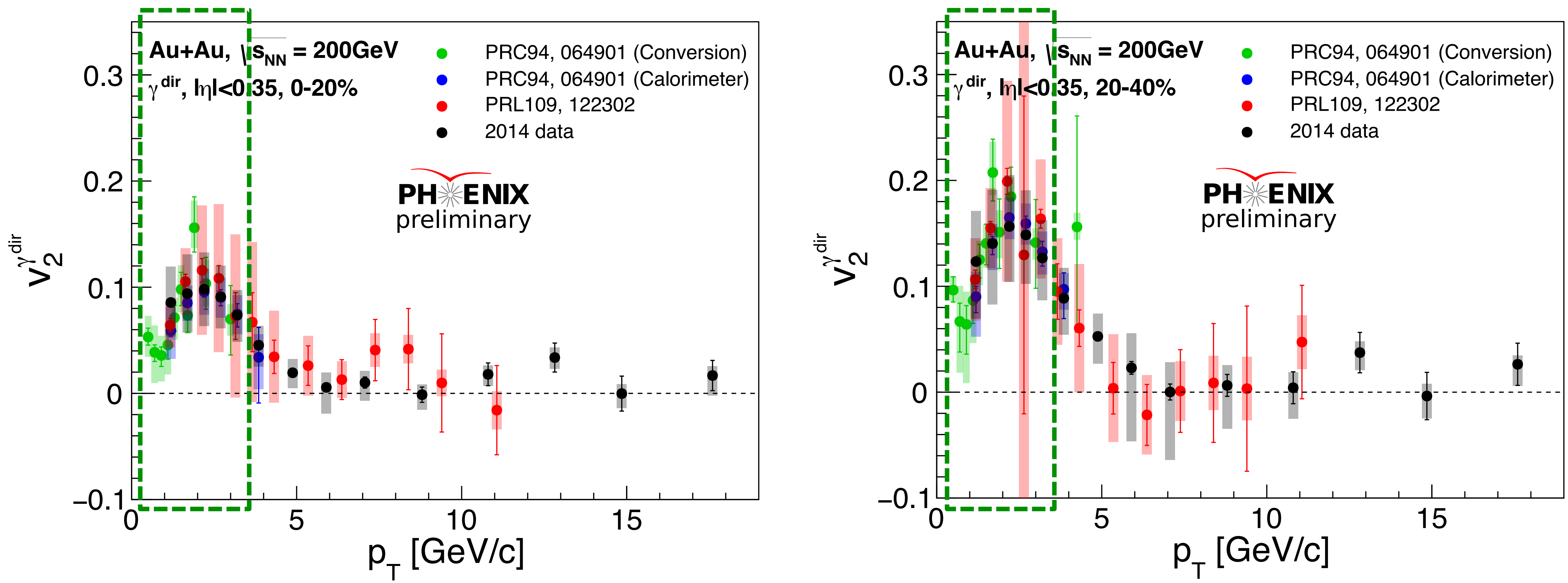

Low p_T: Large azimuthal anisotropy for direct photons (mixture of direct photons from initial scattering and thermal radiation (QGP and HG))

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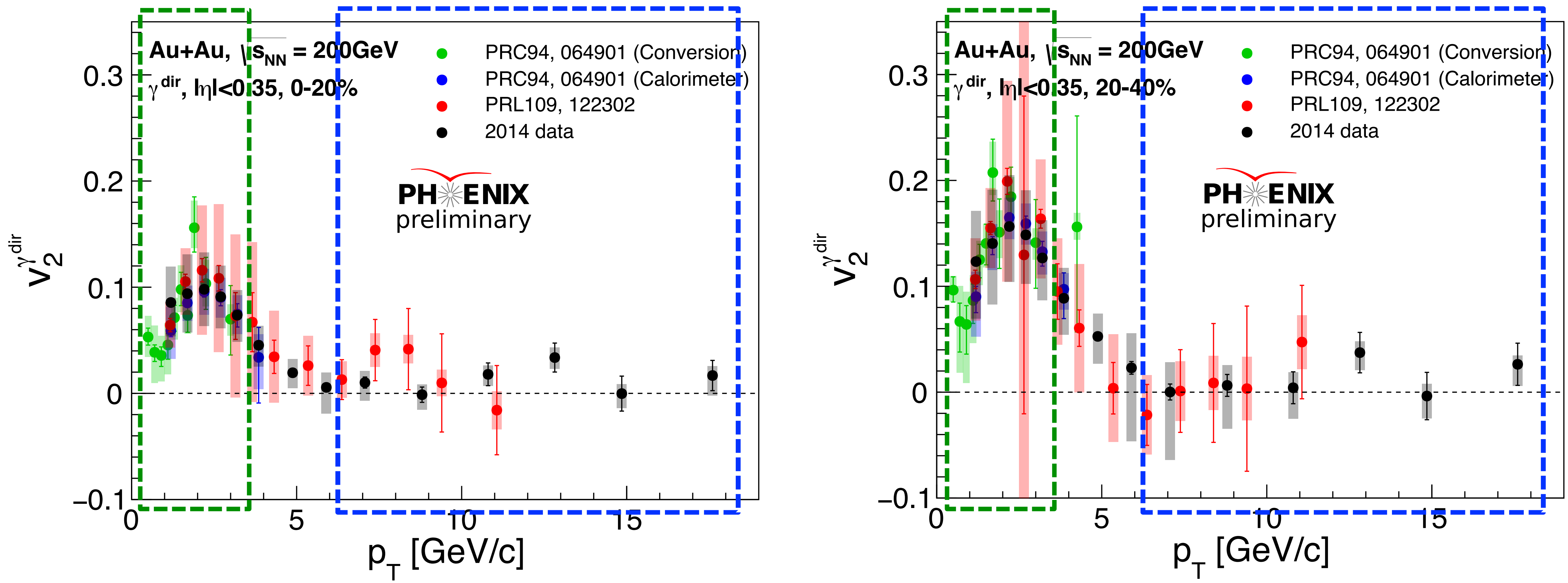


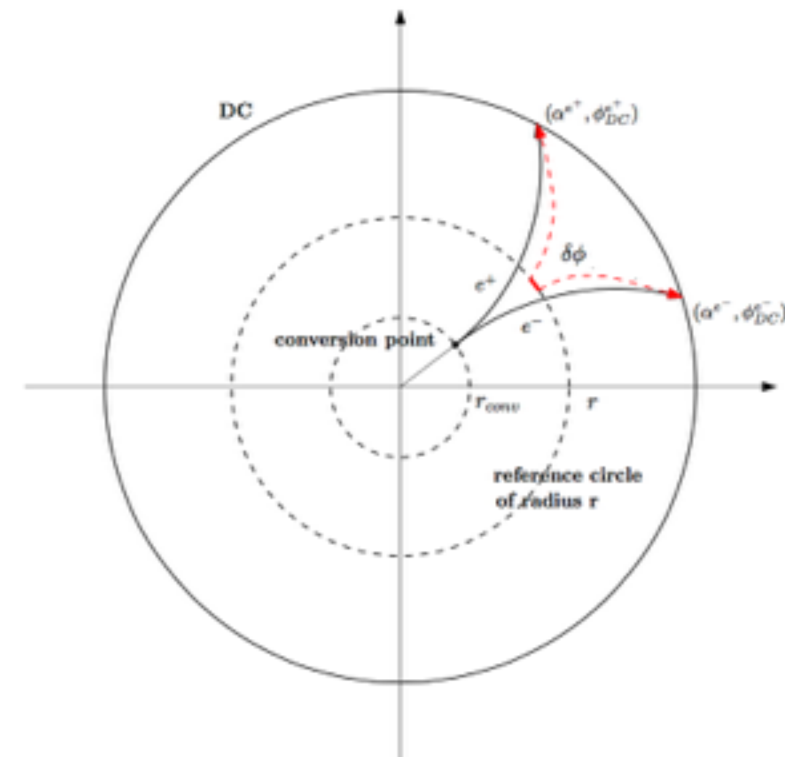
Low p_T: Large azimuthal anisotropy for direct photons (mixture of direct photons from initial scattering and thermal radiation (QGP and HG))

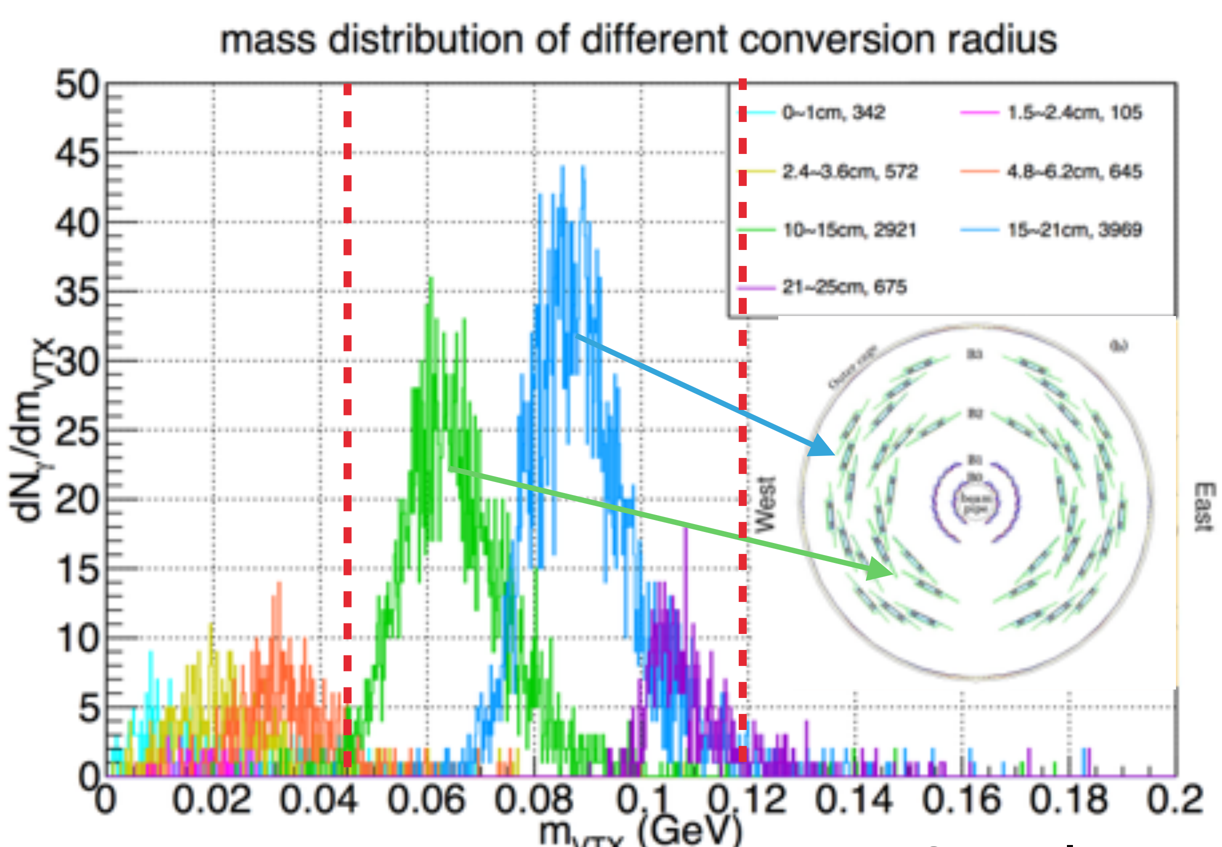
High p_T: ~0 azimuthal anisotropy for the direct photons (dominant source of direct photons is from initial scattering)

New Conversion Photon Reconstruction Technique

Identify and reconstruct photons via external conversion to e^+e^- pairs

- Previous method used single e^+/e^- tracks (2010)
  - Conversions at fixed radius (Hadron Blind Detector readout plane at 60cm, ~3%)
- New method used e^+e^- pairs (>2011)
  - Conversions at any material (VTX 3rd and 4th layer, ~10%)
  - Other systems: AuAu, CuAu, He3Au, pp, pA, dAu





MC simulation

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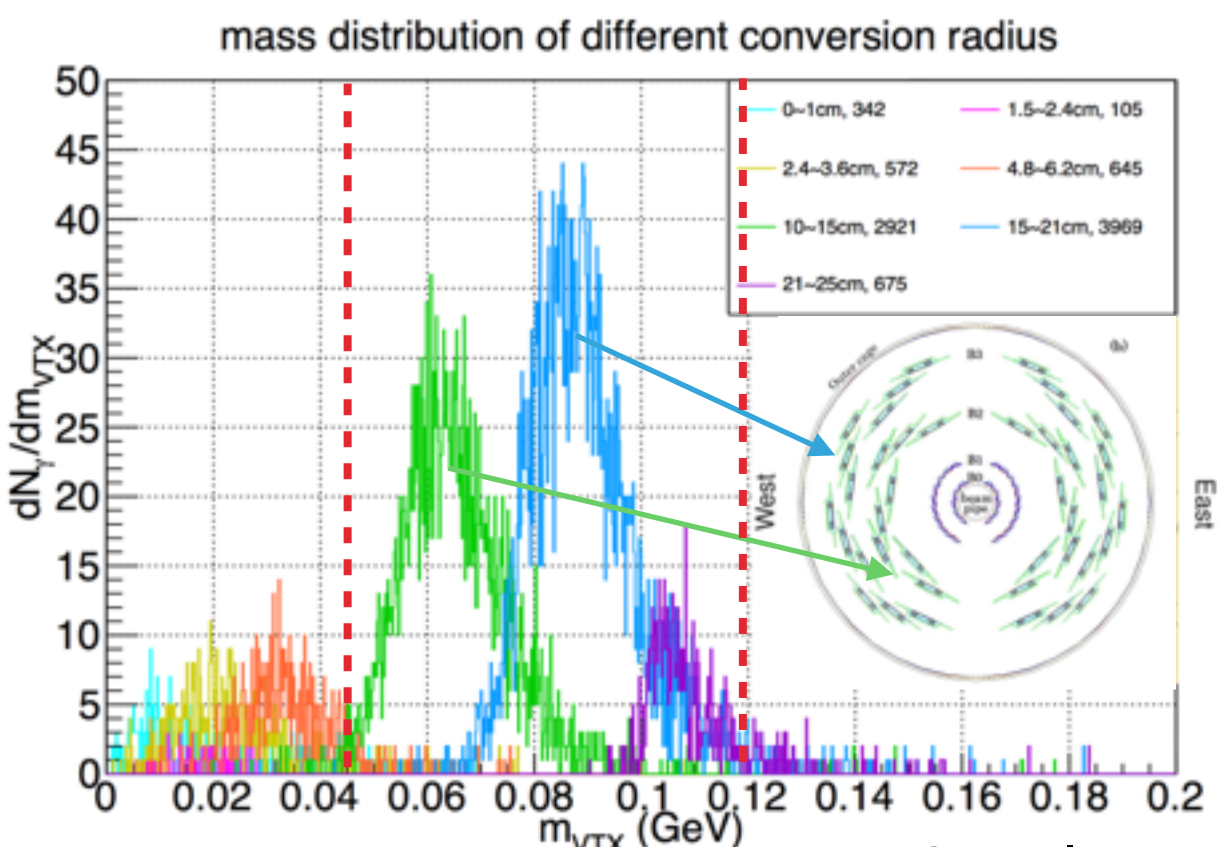
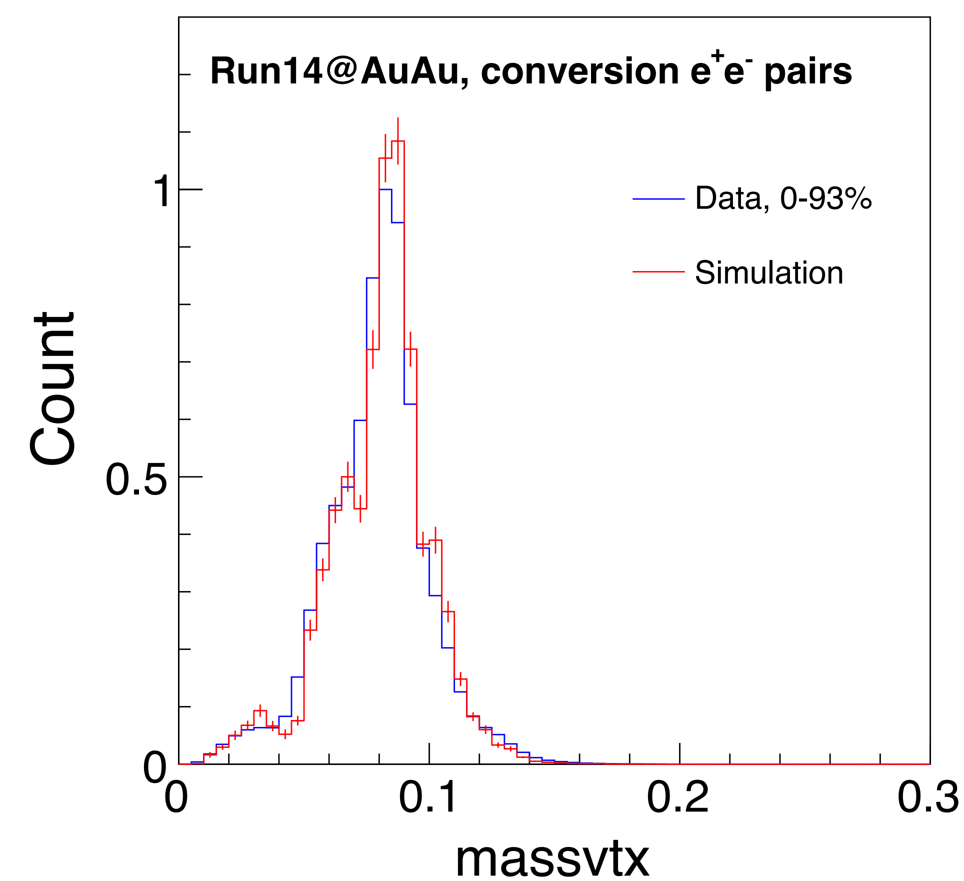
default cut for photon selection

- two tracks from the same arm
- $\pi - \phi_V < 0.1 rad$
- $|dz_{DC}| < 4cm$
- $9cm < r_{conv} < 23cm$
- $|d\theta_{conv}| < 0.1rad$



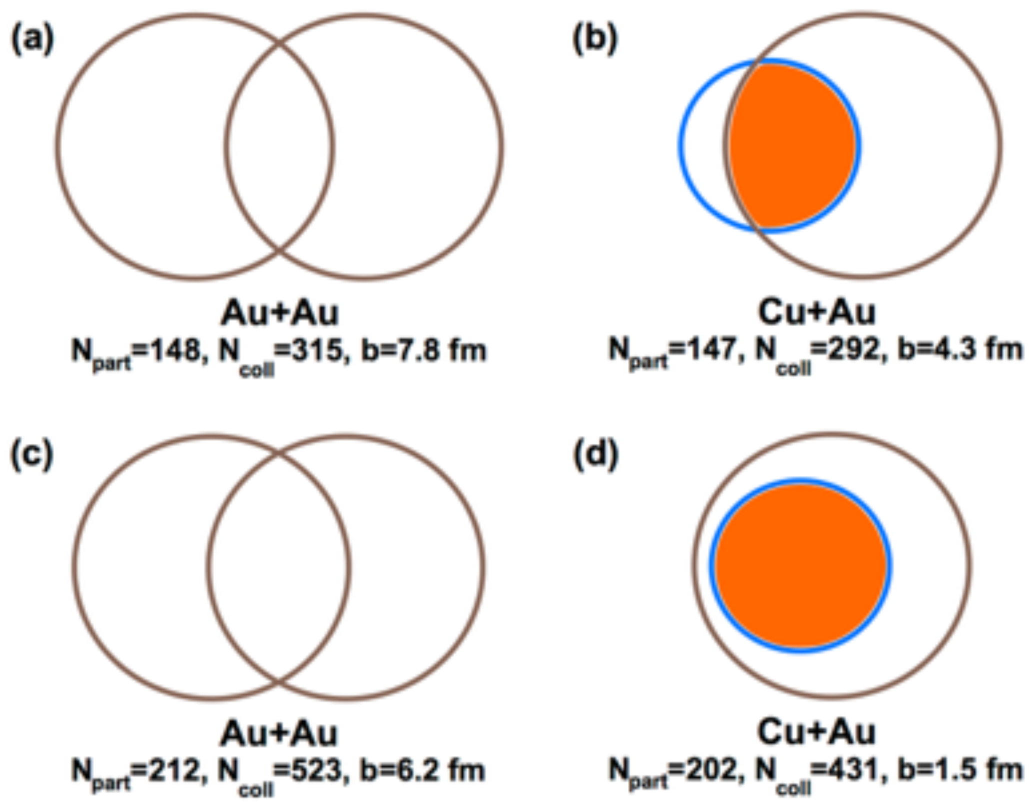
MC simulation

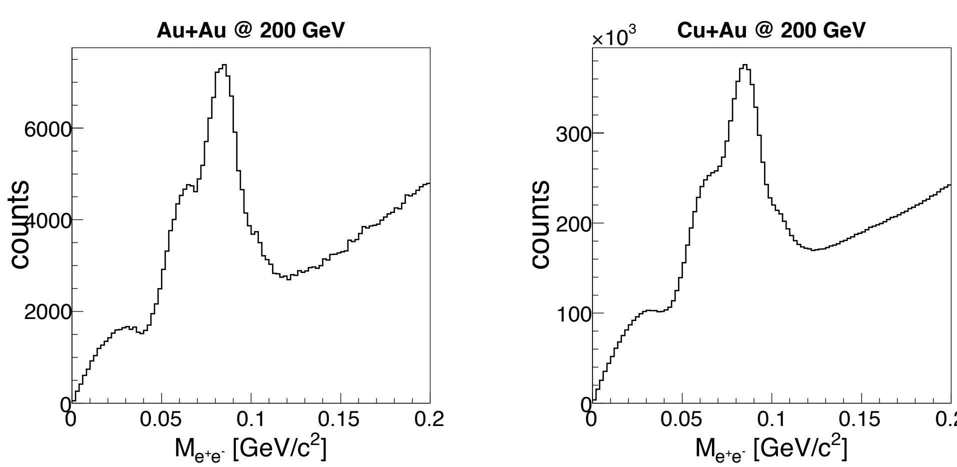


Future Measurements: Different Systems

high statistics

different collision geometry

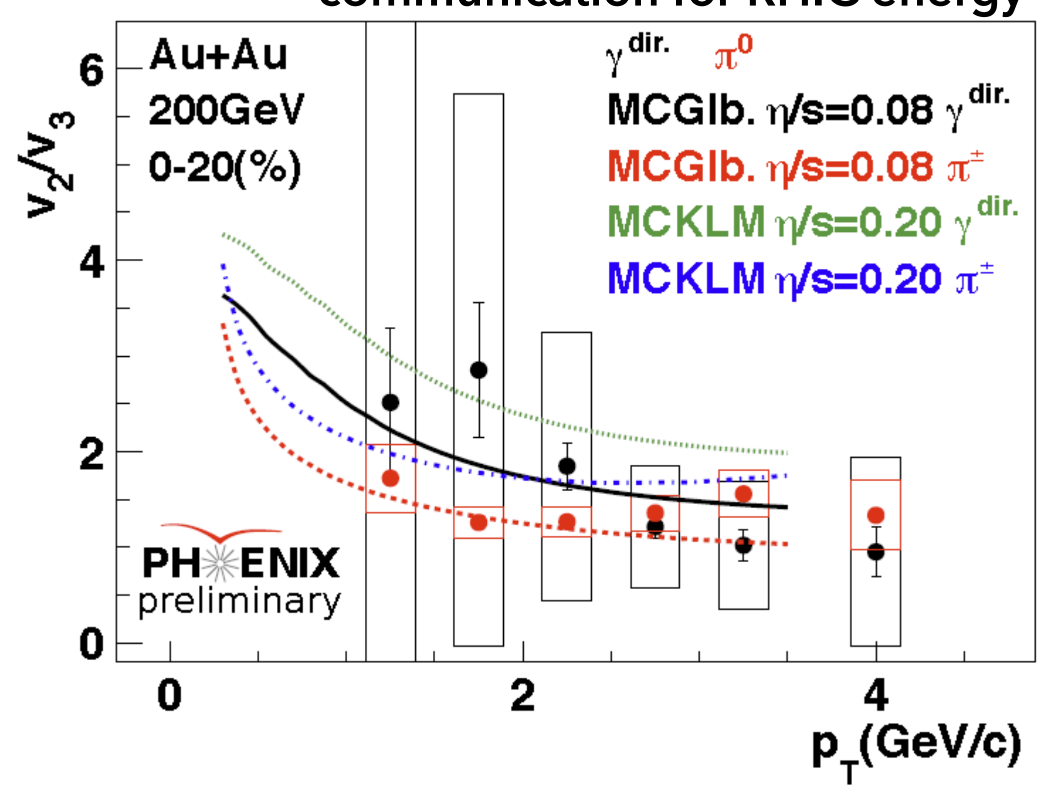




clear conversion photon signal

- High statistics Au+Au data will provide a more precise measurement of higher order harmonics at low p_T
- More precise v_2/v_3 ratio measurement
- Flow measurement in Cu+Au might provide useful input in understanding of chiral magnetic field effect, if any

Based on arXiv 1403. 7558, private communication for RHIC energy



Summary & Outlook

- New direct photon v_2 results in Au+Au 0-20% and 20-40% centralities
  - Good agreement with published results, large v_2 signal at low p_T
  - More precise direct photon v_2 at high p_T (consistent with 0), but including the non-flow and fluctuations

- Outlook
  - More precise measurement of higher order harmonics (v_3) with the high statistic AuAu dataset
  - Measurement of direct photon flow with different collision geometry using CuAu dataset

THANKS

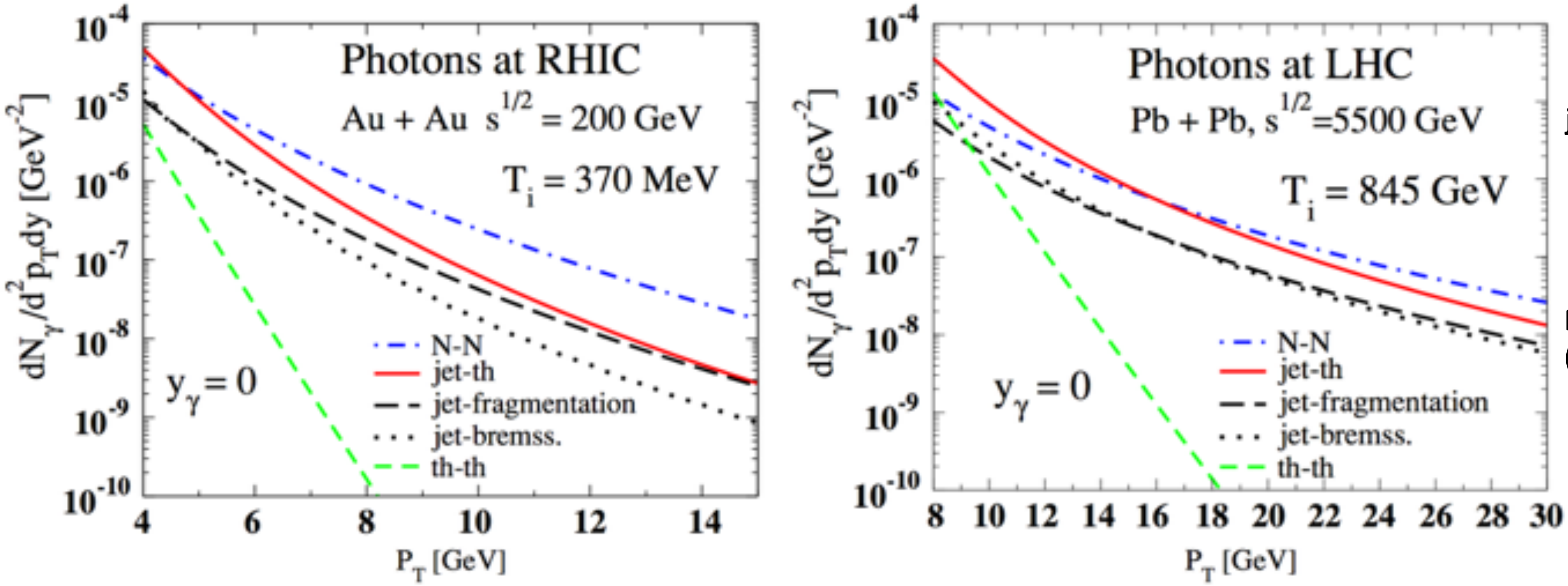
Systematic uncertainty

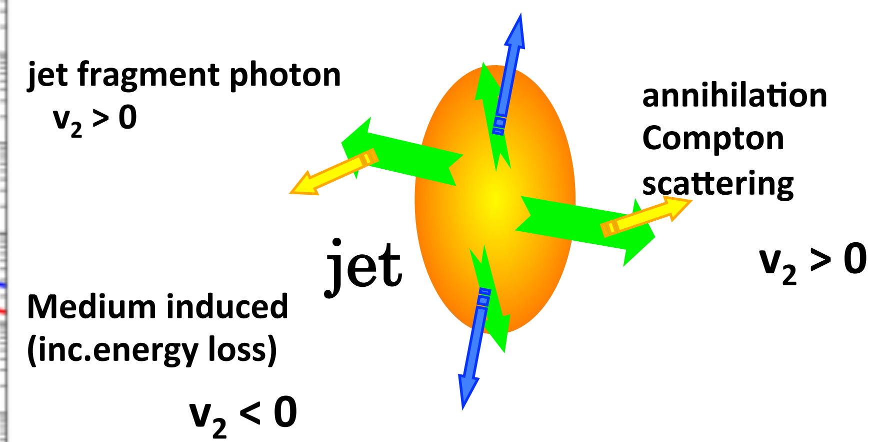
Input	Source	0-20%	20-40%	40-60%	Type
Inclusive photon v_2 (calorimeter method)	photon ID (sys)	2%	2%	2%	B
	EW difference (<4.5GeV)	2%	2%	2%	B
	EW difference (>4.5GeV)	7%	3.5%	4.5%	B
	Event Plane	2.5%	1%	5%	C
	Total (<4.5GeV)	**3.5%**	**3%**	**6%**	
	Total (>4.5GeV)	**7.5%**	**4%**	**7%**	

Input	Source	0-20%	20-40%	40-60%	Type
Decay photon v_2	pion v_2 (sys)		p_T dependent function		B
	η/π^0 ratio (sys)	<0.05%	<0.05%	<0.05%	B
	η v_2 (KE_T scaling)	2%	2%	2%	B
	Event Plane	3%	3%	3%	C

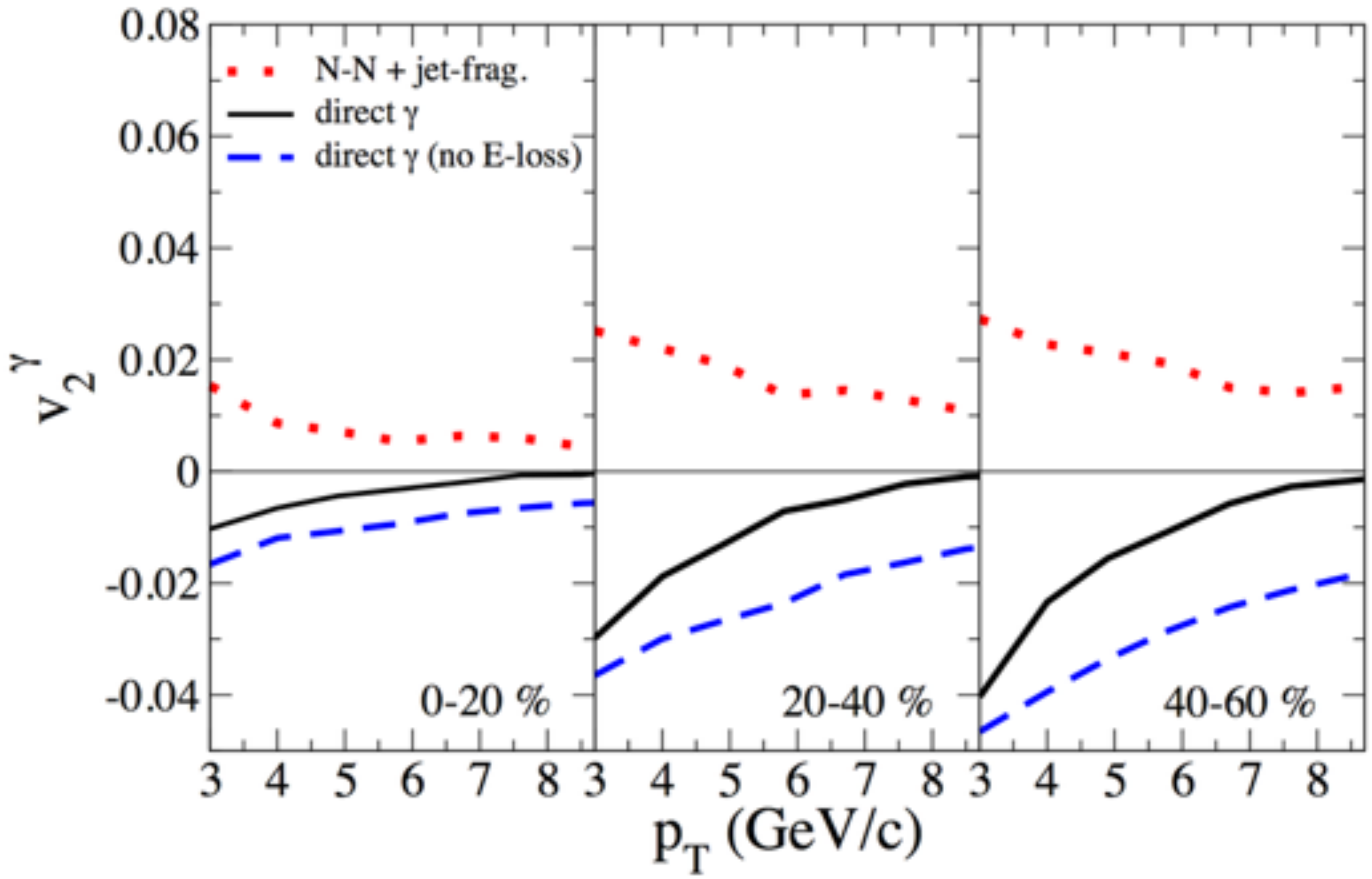
Jet-medium interaction

PRC 72. 014906





arXiv 0904, 2184



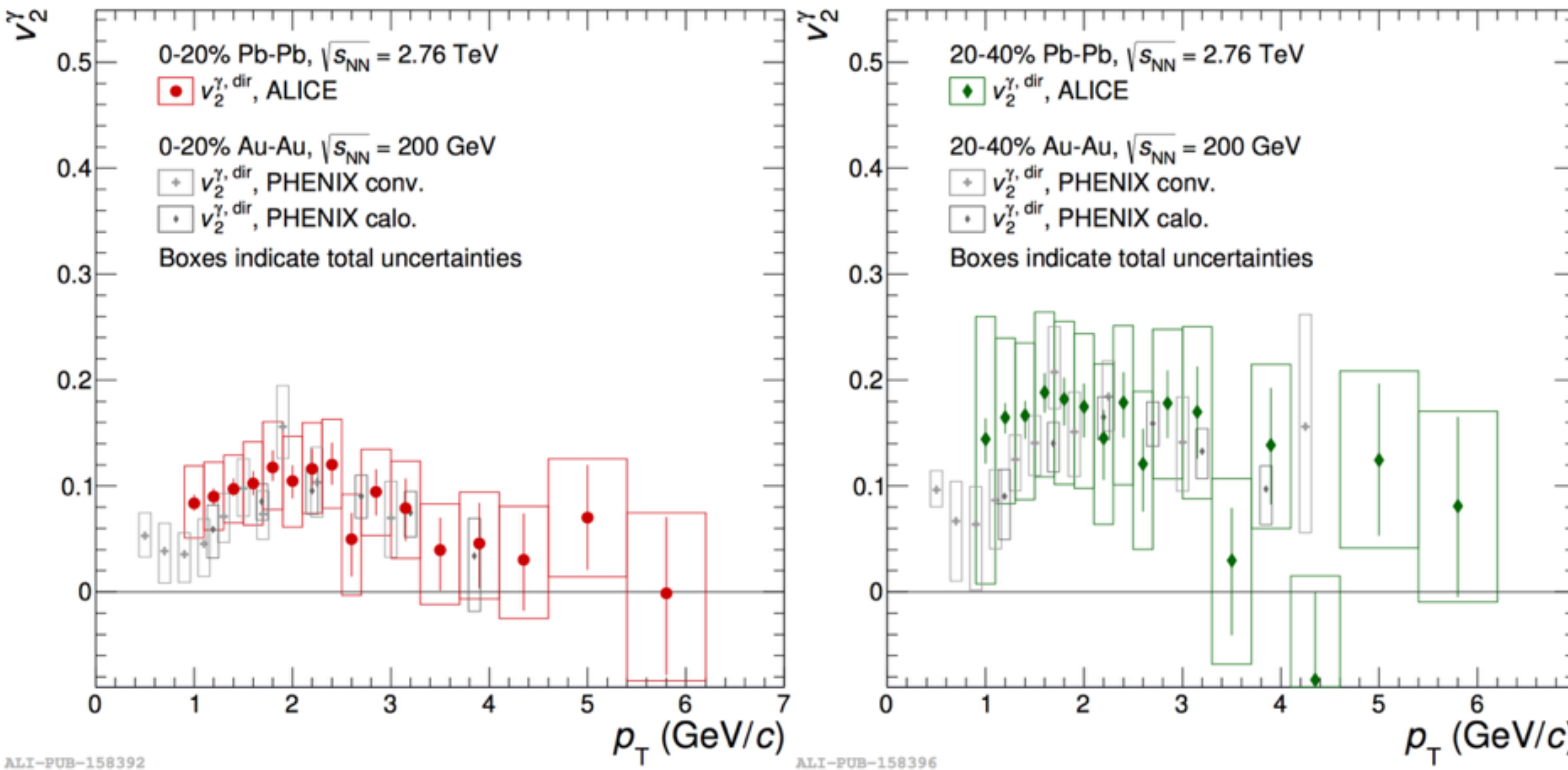
Significant contribution in the intermediate pT range

Expect negative v2 from jet-medium interaction

Need a better way to tag photons coming from jet-medium interaction

Comparison of PHENIX & ALICE results

Combined direct photon flow:



Taken from QM18 flash talk by Mike Sas

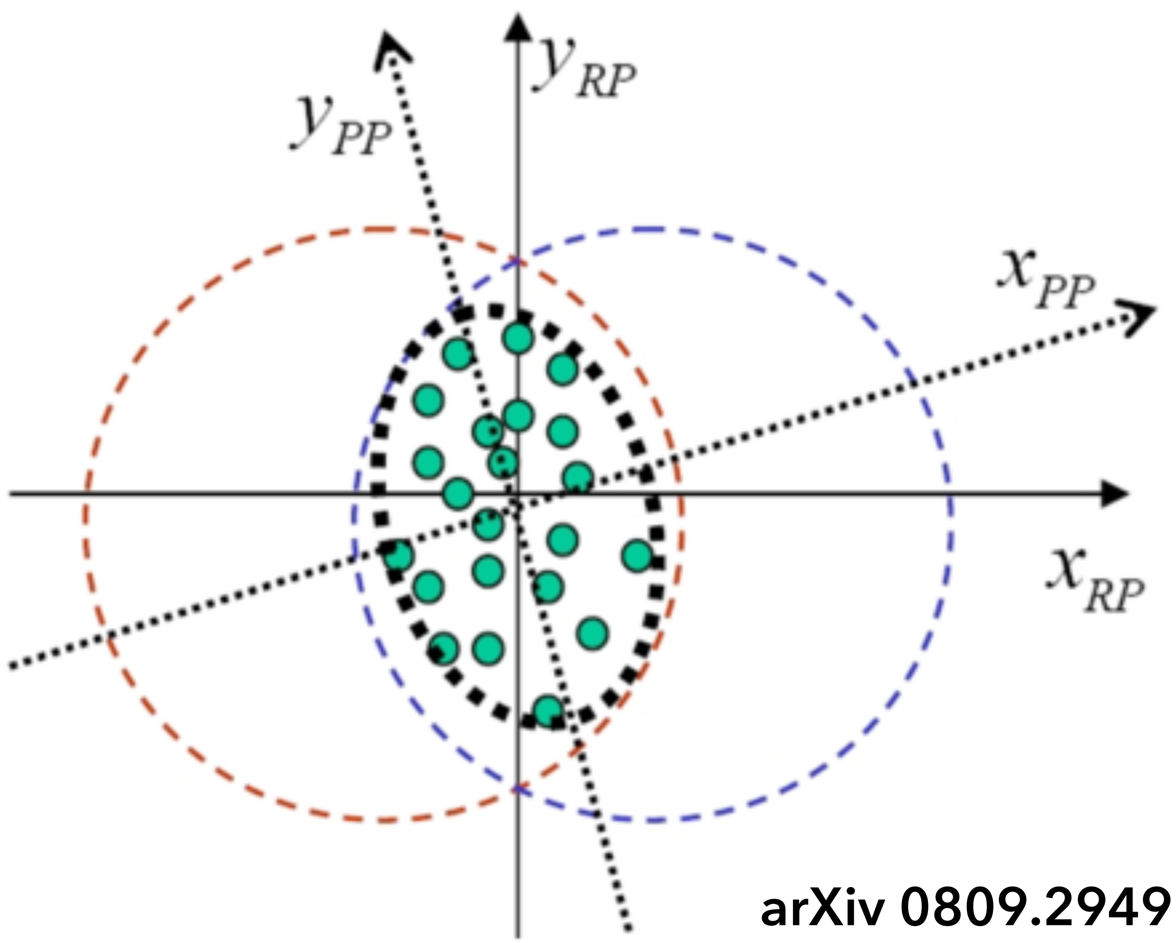
- Direct photons = prompt photons + thermal photons

$$E\frac{dN}{d^3p} = ABT_{AB} \times E\frac{d\sigma^{pp}}{d^3p} + \int E\frac{dR_{\text{thermal}}}{d^3p}(u^\mu, T)dx^4 + E\frac{dN_{\text{addtional}}}{d^3p}?$$

- Modifications in thermal photon emission?
  - Emission rate
    - Liu & Liu, PRC 89, 034906 (2014)
    - Monnai, PRC 90, 021901 (2014)
    - Hees, He & Rapp, NPA 933, 256 (2015)
    - Gale et al., PRL 114, 072301 (2015)
    - Monnai, 1504.00406
    - McLerran & Schenke, 1504.07223
  - Bulk evolution
    - Hees, Gale & Rapp, PRC 84, 054906 (2011)
    - Dion et al, PRC 84, 064901 (2011)
    - Linnyk et al., PRC 88, 034904 (2013)
    - Linnyk et al., PRC 89, 034908 (2014)
    - Heinz, Liu & Shen, 1403.8101
    - Shen et al, PRC 91, 024908 (2014)
- Modifications in prompt photon emission? — Monnai, 1408.1410
- Other sources of photons (e.g. glasma)? — McLerran & Schenke, NPA 933, 256 (2014)
- Other effects (e.g. magnetic field)?
  - Basar, Kharzeev & Skokov, PRL 109, 202303 (2012)
  - Bzdak & Skokov, PRL 110, 192301 (2013)
  - Goloviznin et al., JTEPL 98, 61 (2013)
  - Basar, Kharzeev & Shuryak, PRC 90, 014905 (2014)
- Experimental data needs more statistics?

It could be a combination of those or something entirely different

Reaction Plane



arXiv 0809.2949

- Reaction plane: defined by the overlap region of the colliding nuclei
- Participant plane: defined by the geometry of the colliding nucleons (participants)
- Event plane: what can be measured experimentally from the particle azimuthal distribution event-by-event

Cumulant Method in PHENIX

arXiv 1804.10024

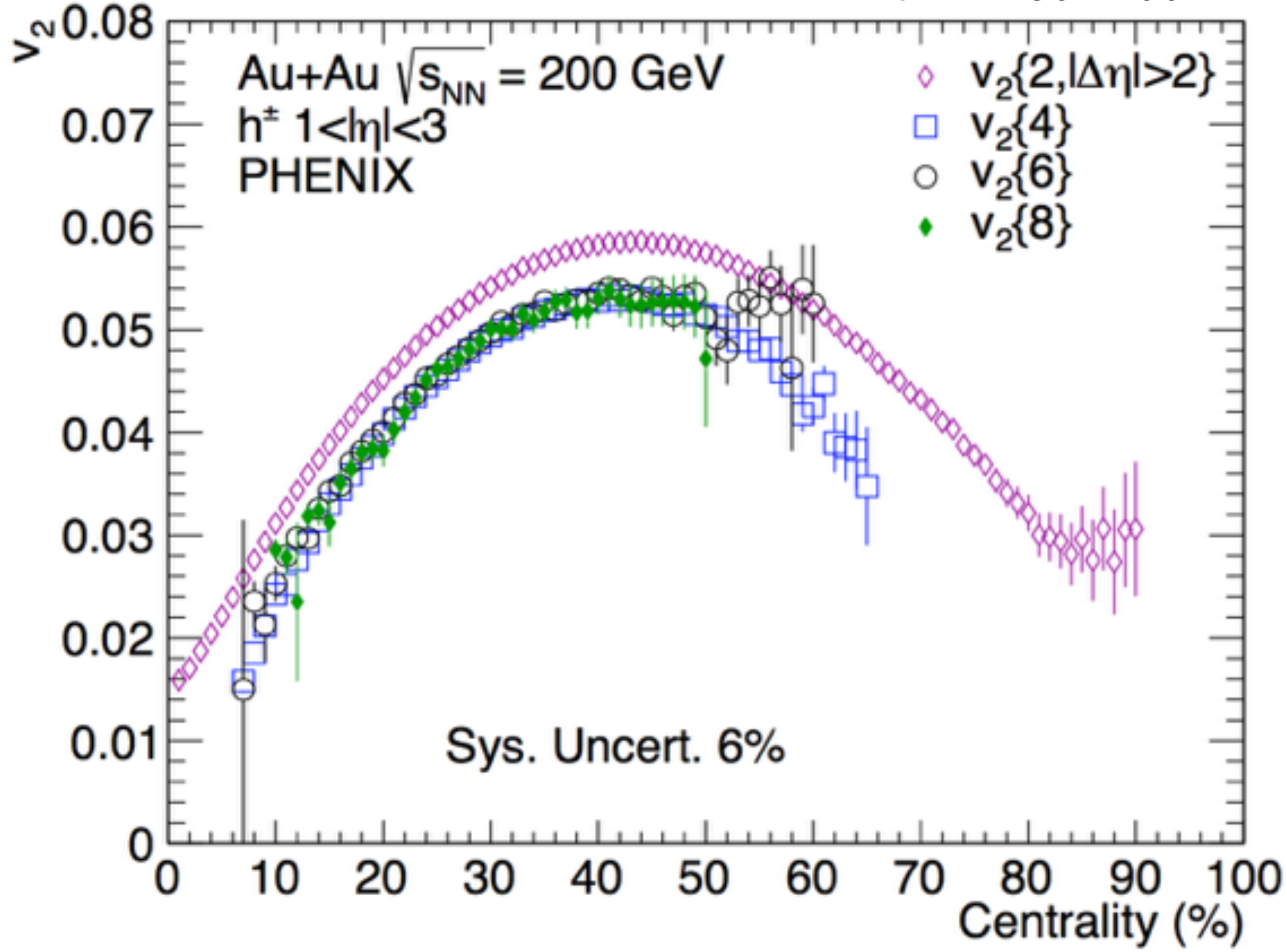
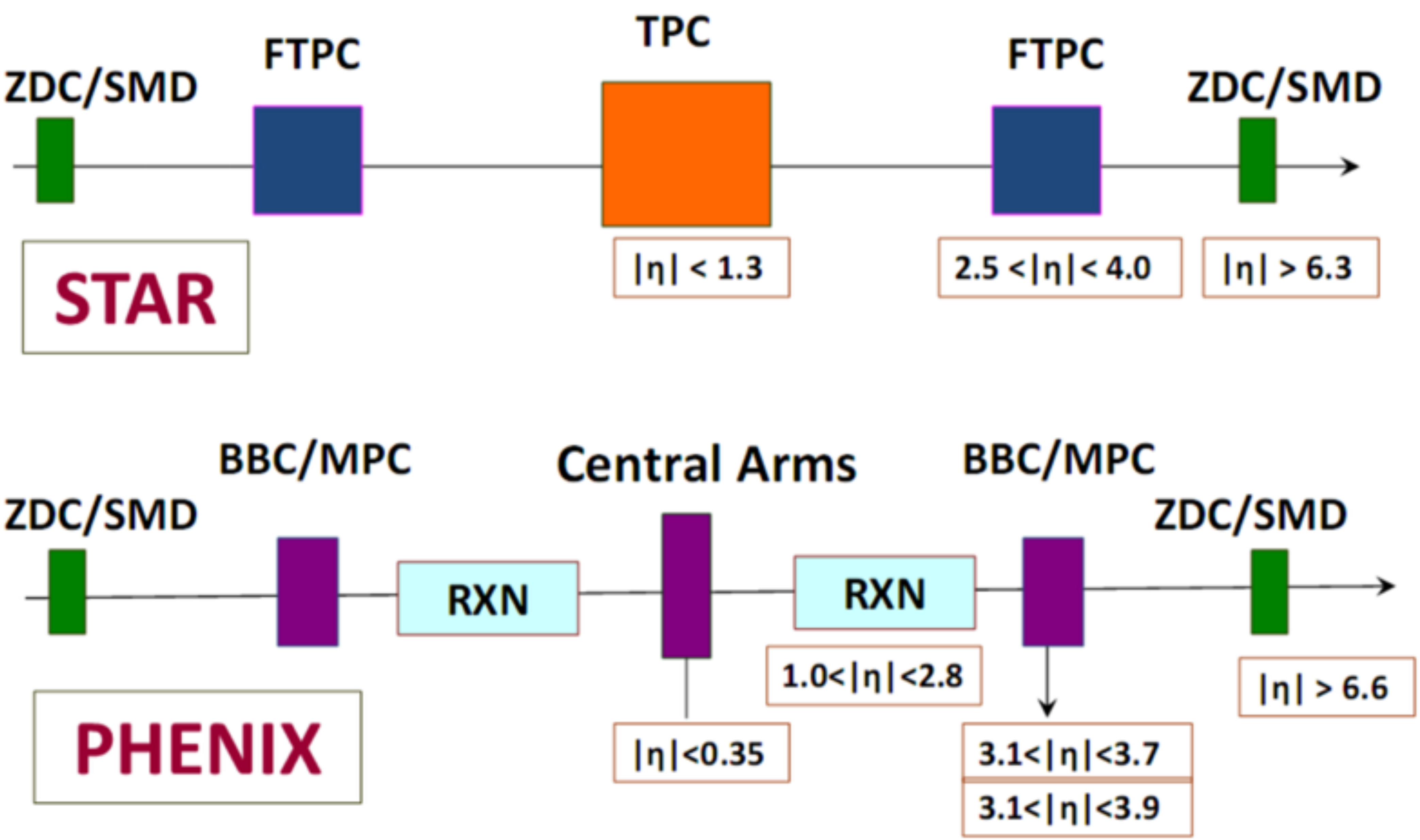


FIG. 7. Multi-particle v_2 as a function of centrality in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The magenta open diamonds indicate the $v_2\{SP\}$, the blue open squares indicate $v_2\{4\}$, the black open circles indicate $v_2\{6\}$, and the green filled diamonds indicate $v_2\{8\}$.

PHENIX and STAR



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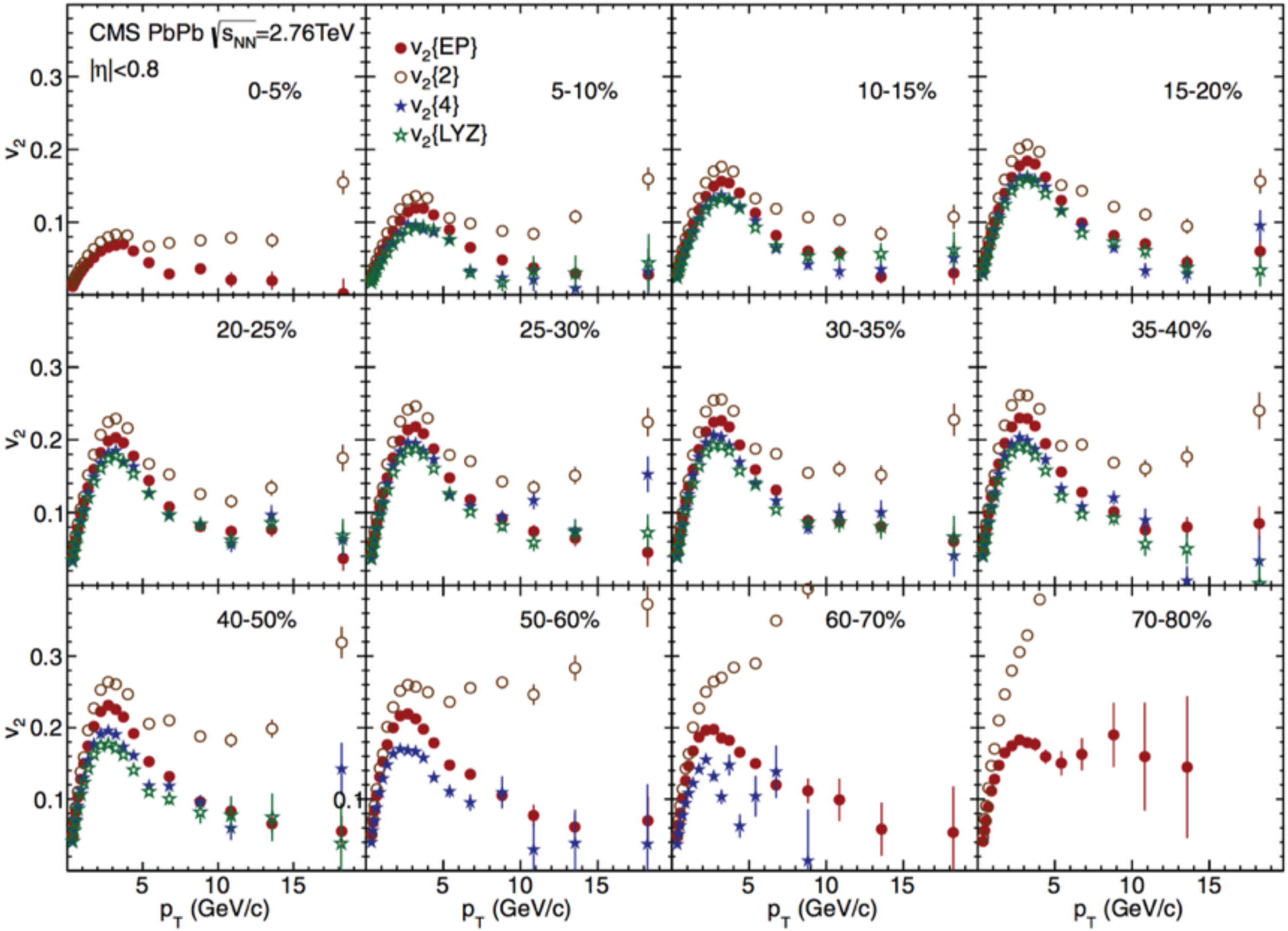
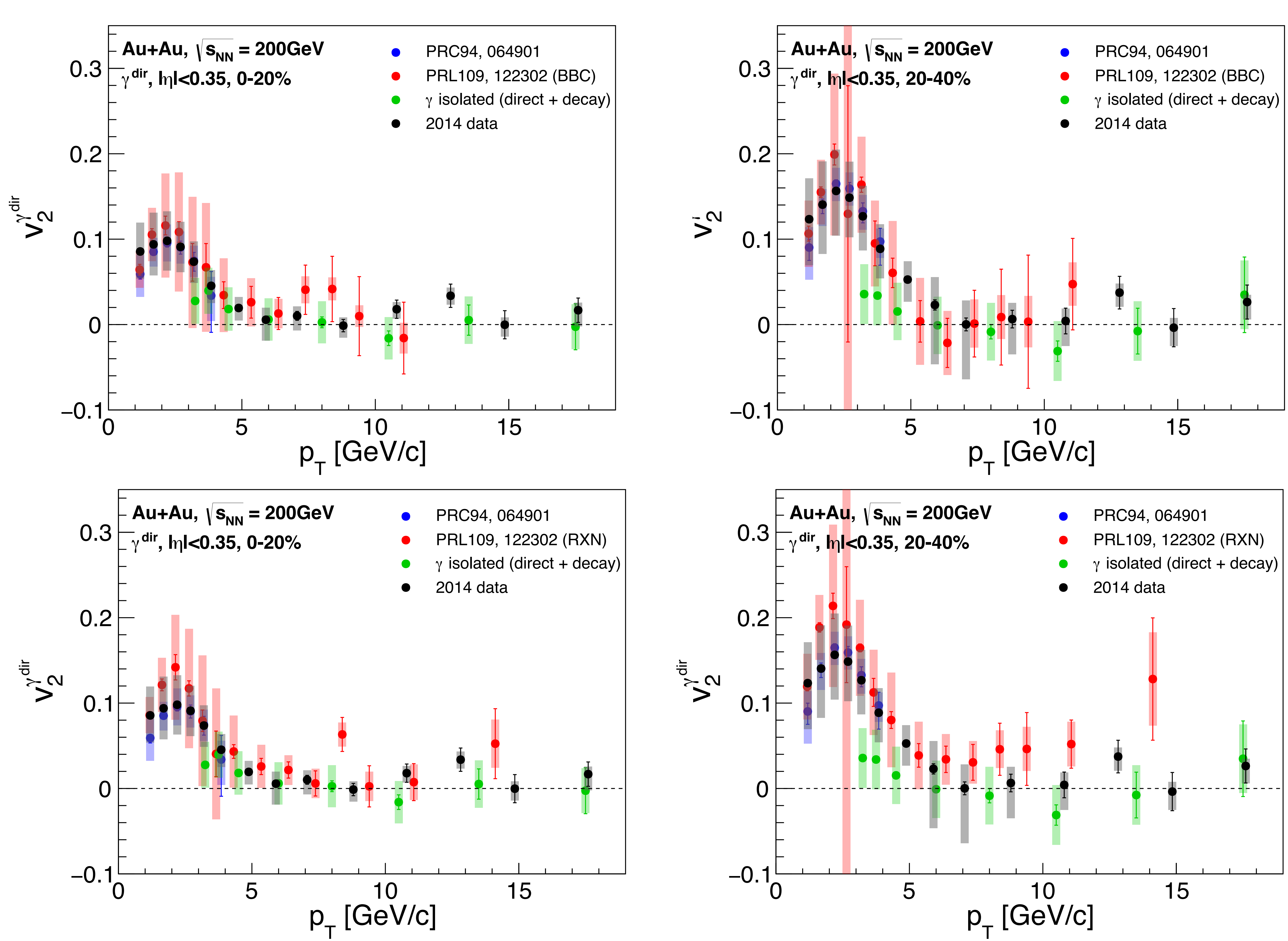
Non-flow

PRC 87, 014902



Non-flow


Au+Au, √sNN = 200GeV
γdir, |η|<0.35, 0-20%
PRC94, 064901
PRL109, 122302 (BBC)
γ isolated (direct + decay)
2014 data
Au+Au, √sNN = 200GeV
γdir, |η|<0.35, 20-40%
PRC94, 064901
PRL109, 122302 (BBC)
γ isolated (direct + decay)
2014 data
Au+Au, √sNN = 200GeV
γdir, |η|<0.35, 0-20%
PRC94, 064901
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γ isolated (direct + decay)
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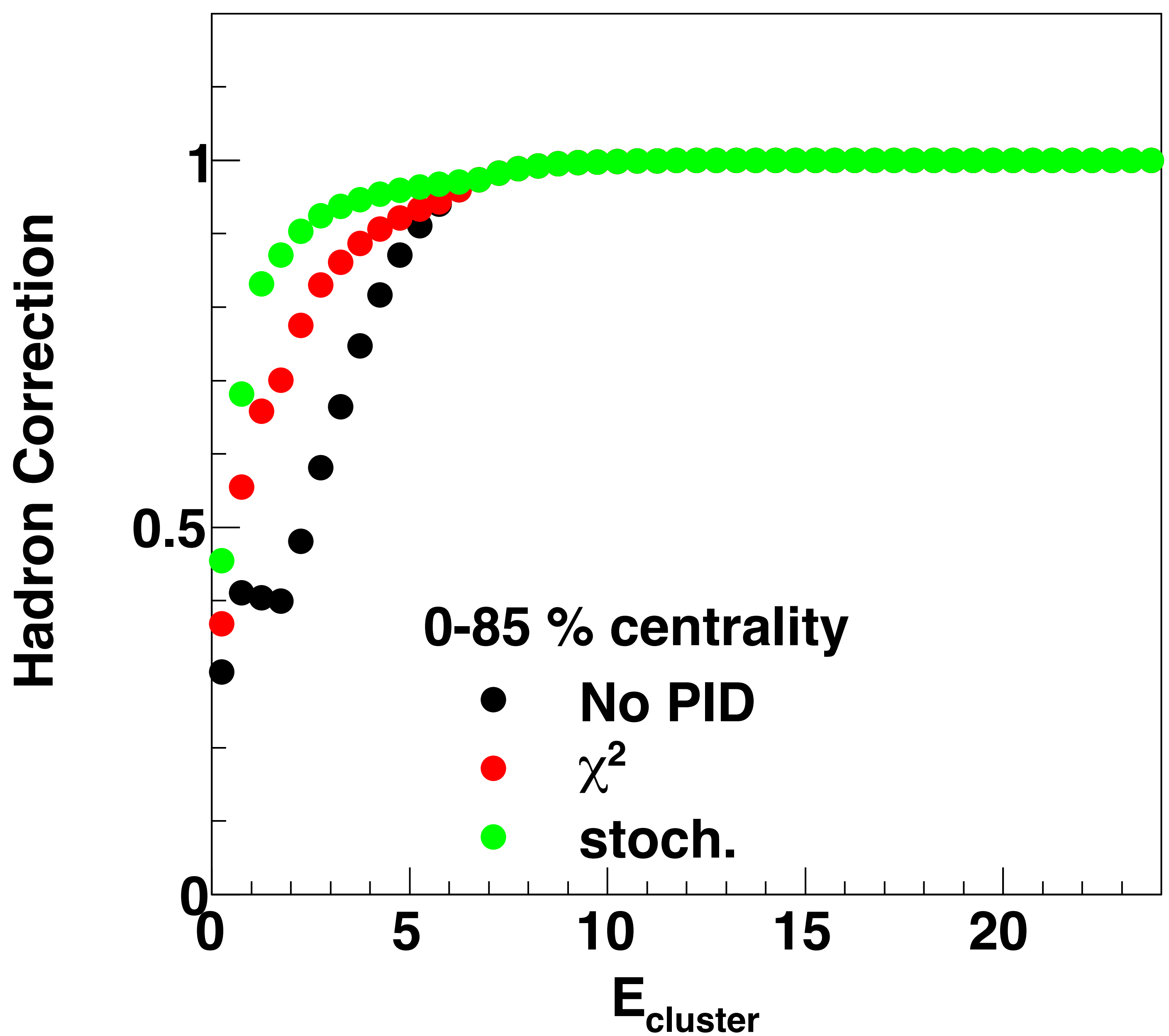
Au+Au, √sNN = 200GeV
γdir, |η|<0.35, 20-40%
PRC94, 064901
PRL109, 122302 (RXN)
γ isolated (direct + decay)
2014 data
pT [GeV/c]
v2γdir

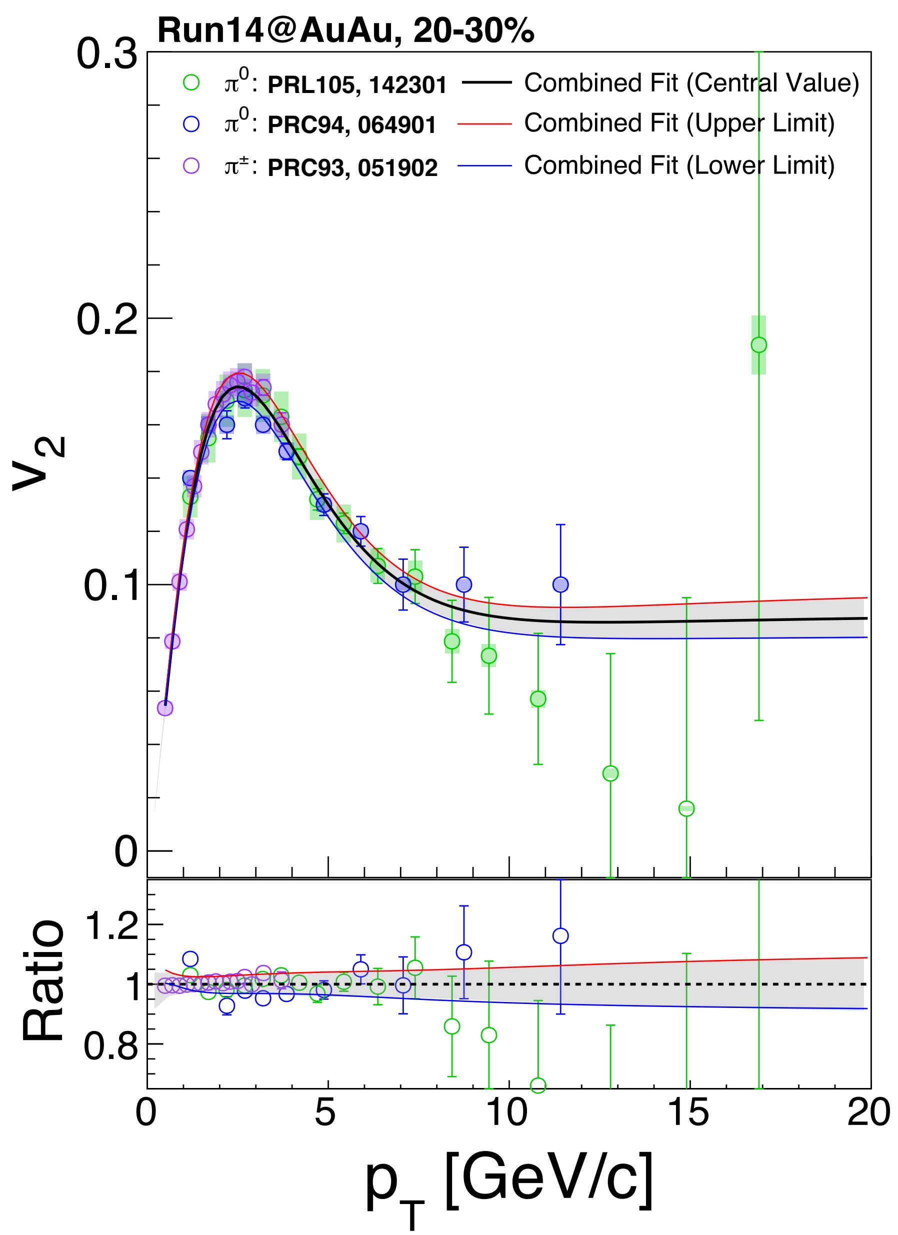
EMCal photon ID



Decay Photon v_n

- Estimate decay photon v_n
  - Use measured yield and anisotropy of charged and neutral pions
  - v_n for heavier mesons estimated by KE_T scaling

$$v_n^{meson}(KE_T) = v_n^{\pi}(KE_T) \quad \text{with} \quad KE_T = m_T - m = \sqrt{p_T^2 + m^2} - m$$



Extract anisotropy of pions

$$\frac{v_n}{n_q^{n/2}} = N_1 \arctan(ax) + N_2(x^2 + bx)e^{-\lambda x}$$