New results on direct photon yield and flow in 200GeV Au+Au collisions

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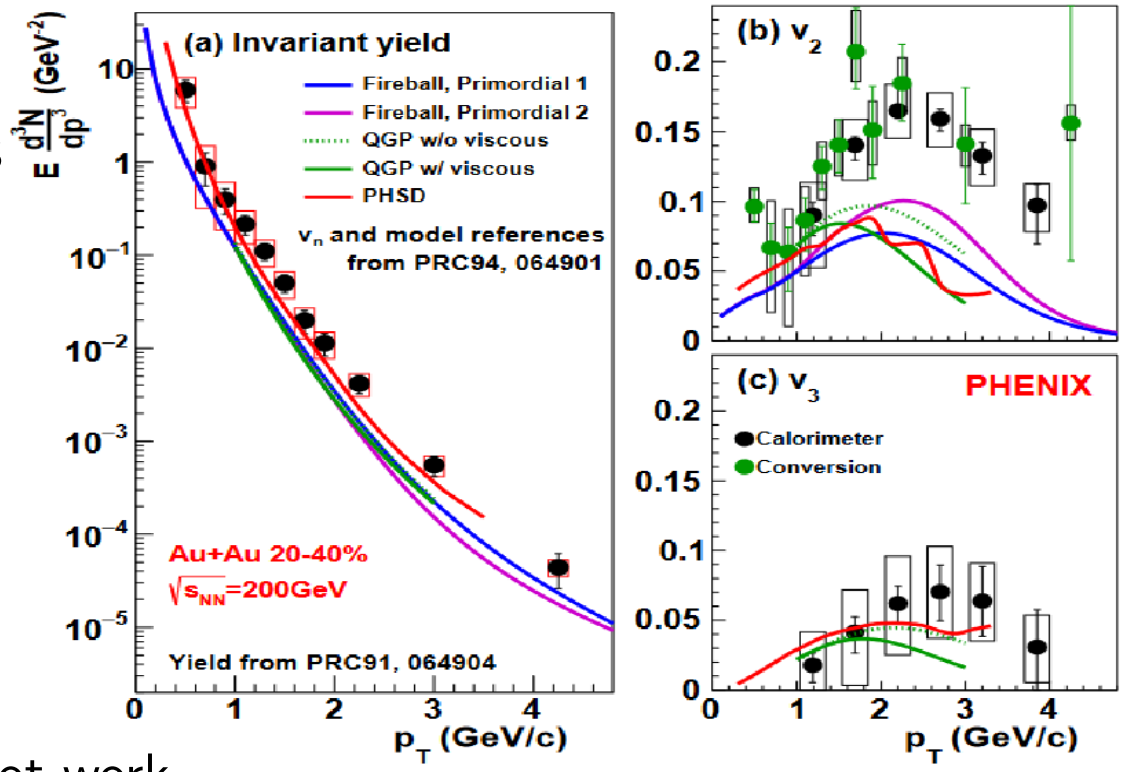
PHENIX

Introduction

- Direct photons are defined as photons not originating from hadron decays (e.g., $\pi^0 \to \gamma\gamma$)
- Due to their electromagnetic nature, direct photons:
  - Escape the medium without strong interactions and final-state effect
  - Carry information from all stages of the heavy-ion collision
- Different p_T regions are sensitive to different sources. While the high-p_T ($\gtrsim$ 5–6 GeV/c) dominated by prompt photons from initial hard scatterings, the low-p_T ($\lesssim$ 4 GeV/c): sensitive to thermal and pre-equilibrium emission $\to$ **nonprompt**
- Two key observables give complementary insights. **Yield**: sensitive to temperature, system size, emission time $\Leftrightarrow$ **Azimuthal anisotropy (v_2)**: probes flow buildup and emission chronology
- Recent PHENIX results provide precision measurements of both:
  - Nonprompt photon yields using external conversion method
  - Direct photon v_2 in finer centrality bins and wider p_T range

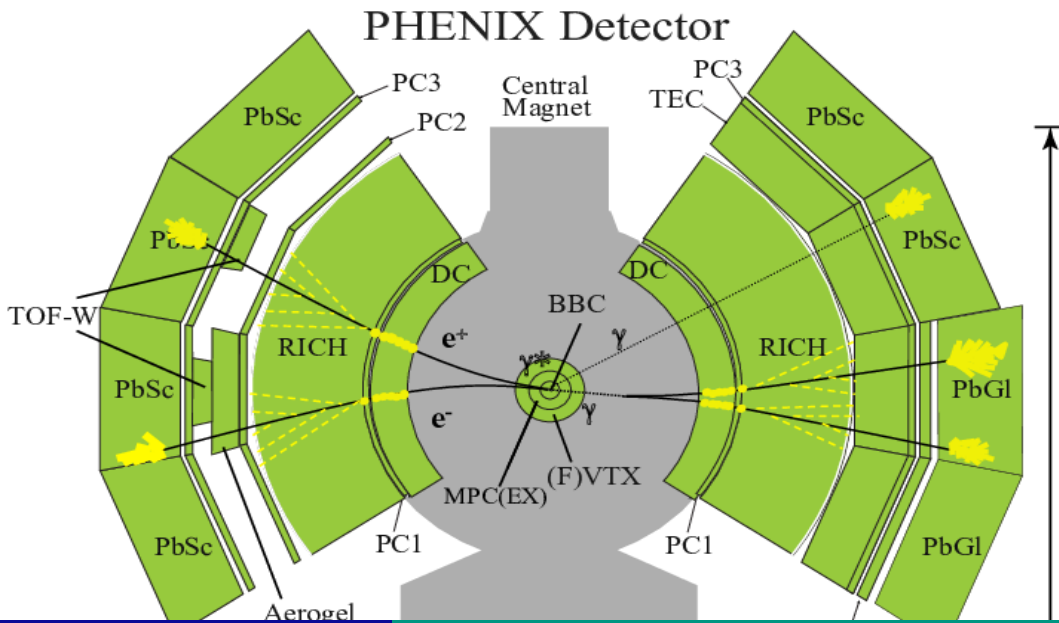
Direct photon puzzle

- Several theoretical models have been developed
- Most of the models qualitatively ✓
- For quantitatively ø
- What was seen earlier?
  - high yield and high v_2 at the same time
  - $\leftrightarrow$ old paradigm will not work
  - high yields means high T (early emission) $\leftrightarrow$ high v_2 means late emission, where T is low
- Theoretical curves are below the yield and flow
- Plot from PRC 94, 064901



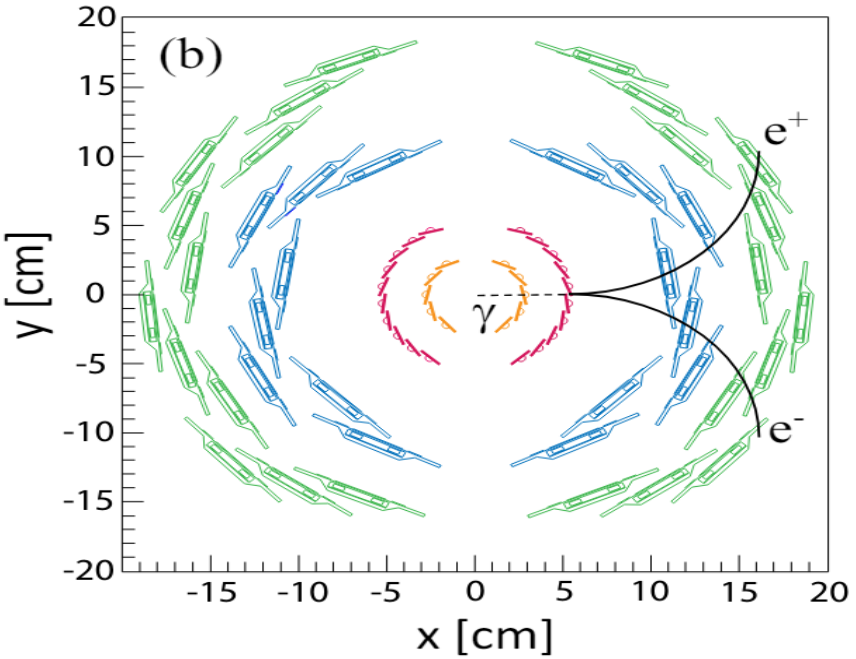
Experimental Setup

- For further insights → PHENIX results from the 2014 Au+Au data at $\sqrt{S_{NN}} = 200 GeV$, with a 10× more statistics
- A new analysis method using the silicon-vertex detector (VTX) as photon converter
- The forward silicon-vertex detector (FVTX) was used, to measure the event plane Ψ_2
- The direct-photon measurement is based on the tracking and identification of e^- and e^+ from photon conversions in the detector material
- Internal conversion
- External conversion close and far from vertex
- Real photons in calorimeter



Experimental Setup

- The VTX here acts as the photon converter, which is critical for this analysis
- Charged tracks are identified as electrons or positrons with a ring-imaging Ĉerenkov detector
- For the calorimetric identification of the $e^- e^+$ pair, E/p cut was used
- For the calorimetric identification of photons, two types of calorimeters are used: PbSc and PbGl



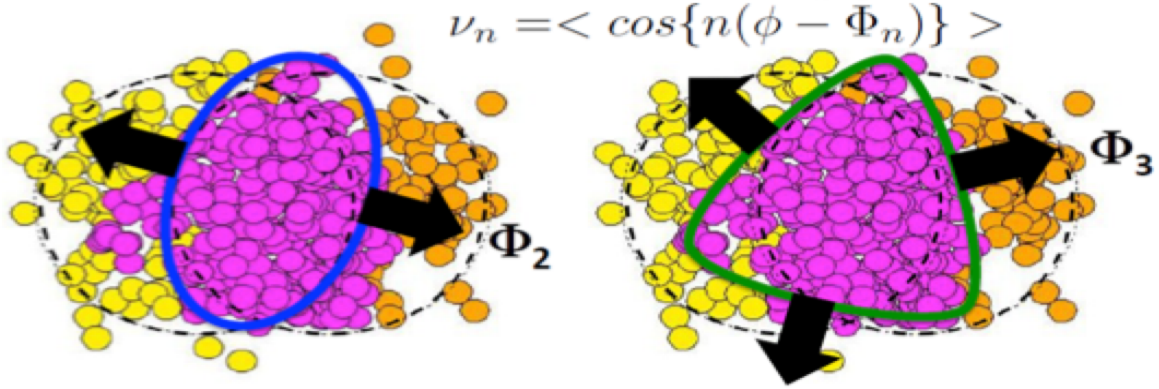
- A new track-reconstruction algorithm is developed $\rightarrow$ the e^+ and e^- from a conversion have the same origin and that their momenta were initially parallel in radial direction

Experimental Setup - Event plane

- The reaction plane of a collision is the plane defined by the beam direction and the impact parameter vector
- Instead: estimated using the event plane Ψ_2 measured from the distribution of particles detected in the FVTX
- The orientation of the event plane Ψ_2 in global coordinates is calculated using the azimuthal distribution of the charged particle tracks reconstructed in the FVTX for a given event
- The event-plane resolution depends on the number of charged particles produced in a collision and the size of the anisotropy of the charged-particle production for a given centrality class

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

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

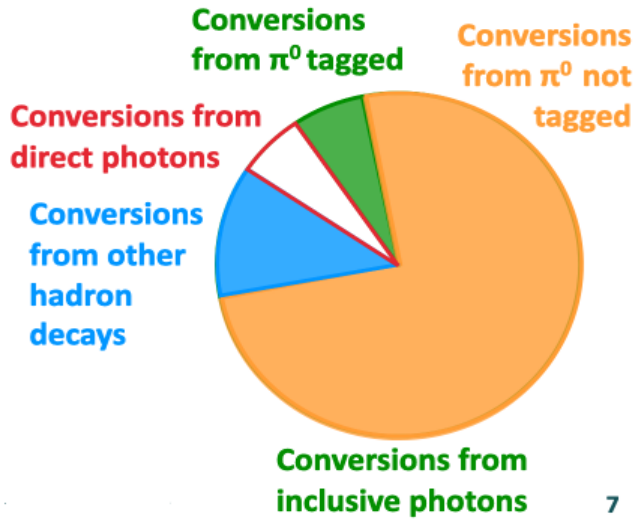


Double-ratio tagging method

- The number of direct photons is small $\leftrightarrow$ the number of photons from hadron decays is large $\rightarrow$ for a precise measurement we need a **tagging method**

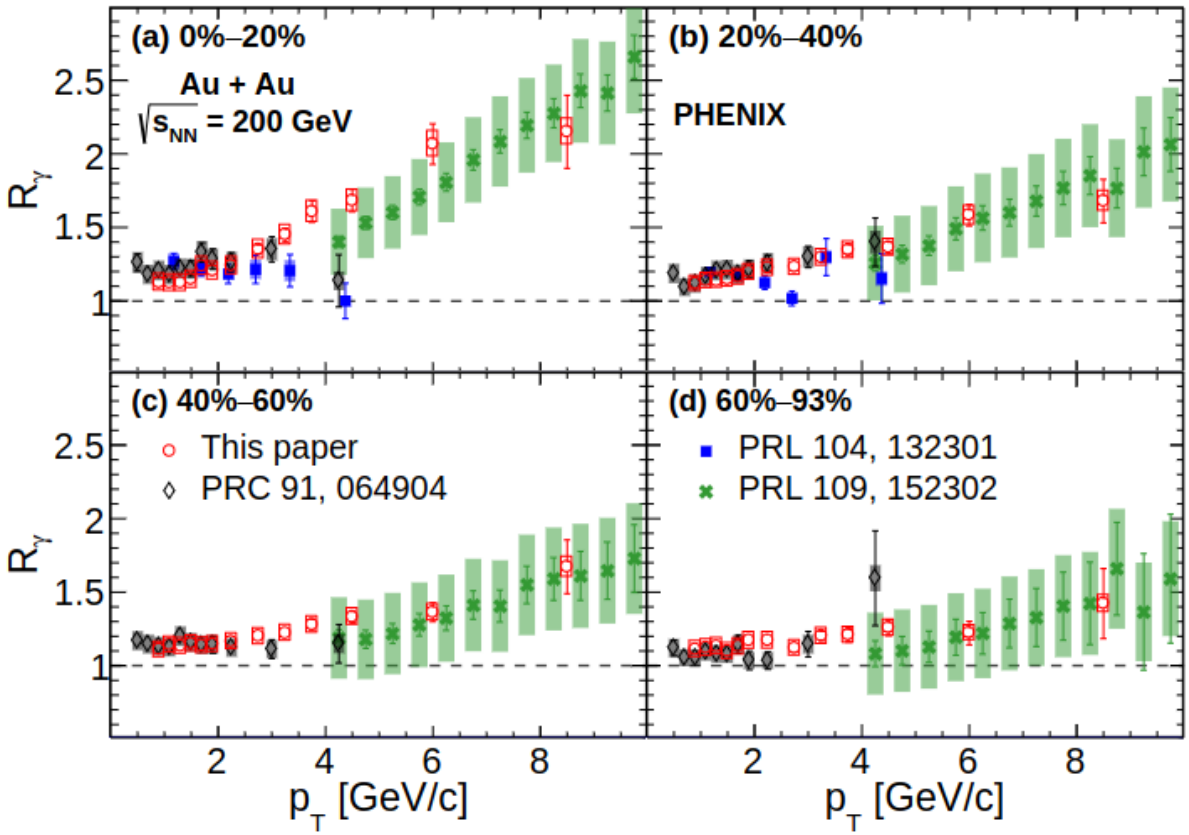
$$R_\gamma = \frac{\gamma^{incl}}{\gamma^{hadr}} = \frac{\frac{\gamma^{incl}}{\gamma^{\pi^0}}}{\frac{\gamma^{hadr}}{\gamma^{\pi^0}}} = \frac{< \epsilon_\gamma f > (\frac{N_\gamma^{incl}}{N_\gamma^{\pi^0,tag}})_{Data}}{(\frac{\gamma^{hadr}}{\gamma^{\pi^0}})_{Sim}} \quad (1)$$

- $N_\gamma^{incl}/N_\gamma^{\pi^0,tag}$ the ratio of measured photon yields
- $< \epsilon_\gamma f >$ is the conditional acceptance and efficiency
- $\gamma^{hadr}/\gamma^{\pi^0}$ is the cocktail ratio



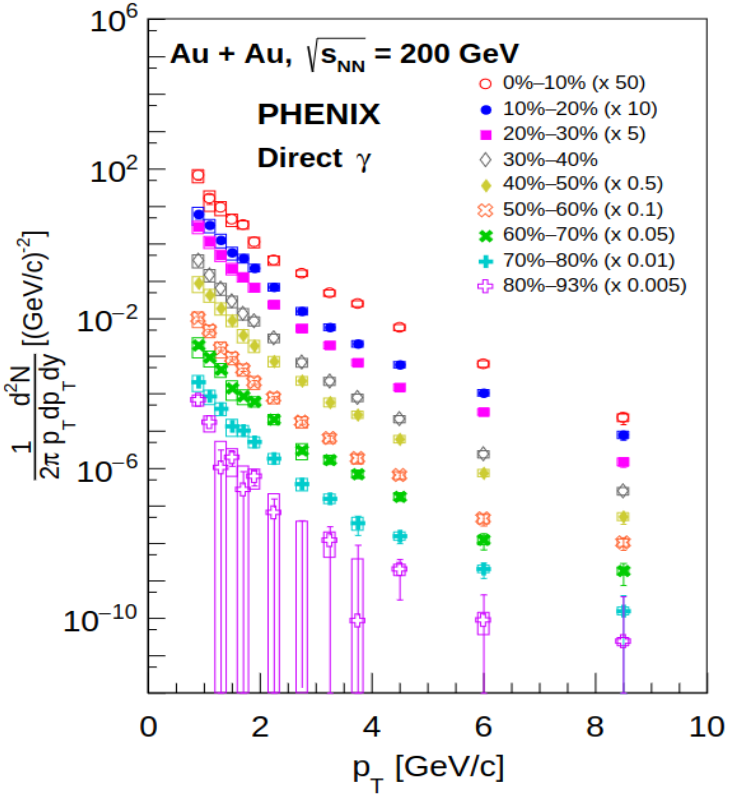
Result - 4 different R_γ PHENIX measurements

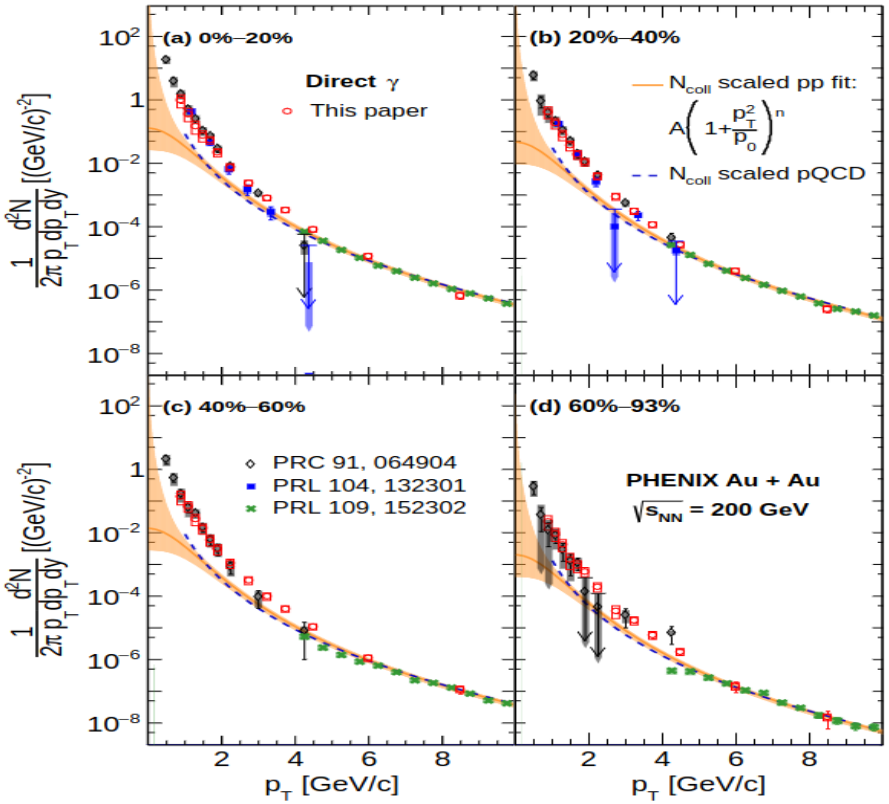
- The new results are compared with all other published PHENIX results $\rightarrow$ different methods + independent systematic uncertainties.
- $R_\gamma = \frac{\gamma^{incl}}{\gamma^{hadr}}$
- Internal conversion (PRL 104, 132301)
- External conversion far from vertex (PRL 91, 064904)
- Real photons in calorimeter (PRL 109, 152302)
- External conversion close to the vertex (PRC 109, 044912)



Result - Direct photon yield comparison

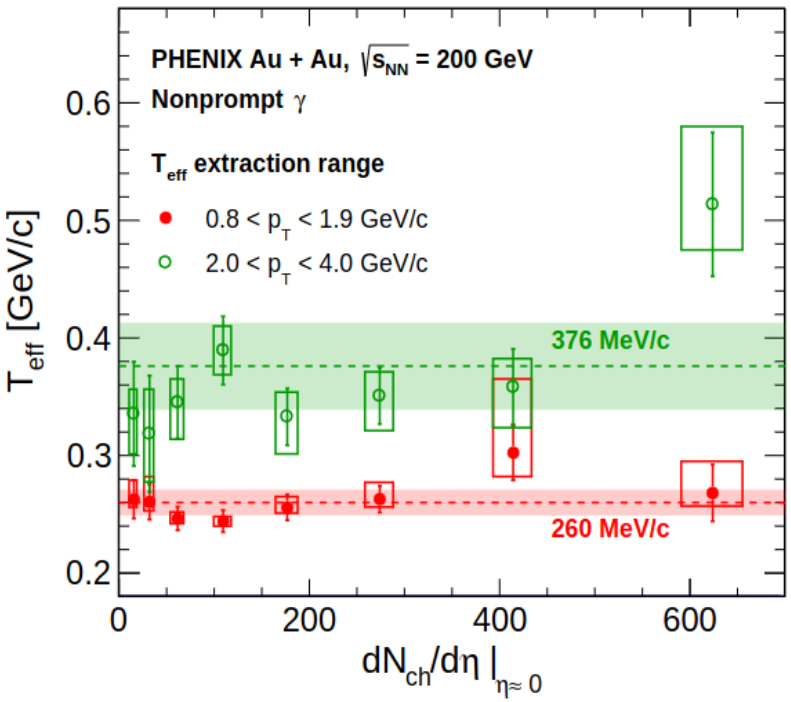
- The direct photon yield: $\gamma^{dir} = (R_\gamma - 1)\gamma^{hadr}$ $\rightarrow$ left picture for all centralities
- $p_T > 5 GeV/c$ is well described by the N_{coll}-scaled p+p result and pQCD calculations $\rightarrow$ high-pT direct photons are from hard-scattering processes
- Non-prompt photon yield = measured direct γ yield - N_{coll} scaled $\times$ (pp fit or pQCD), from PRC 109, 044912

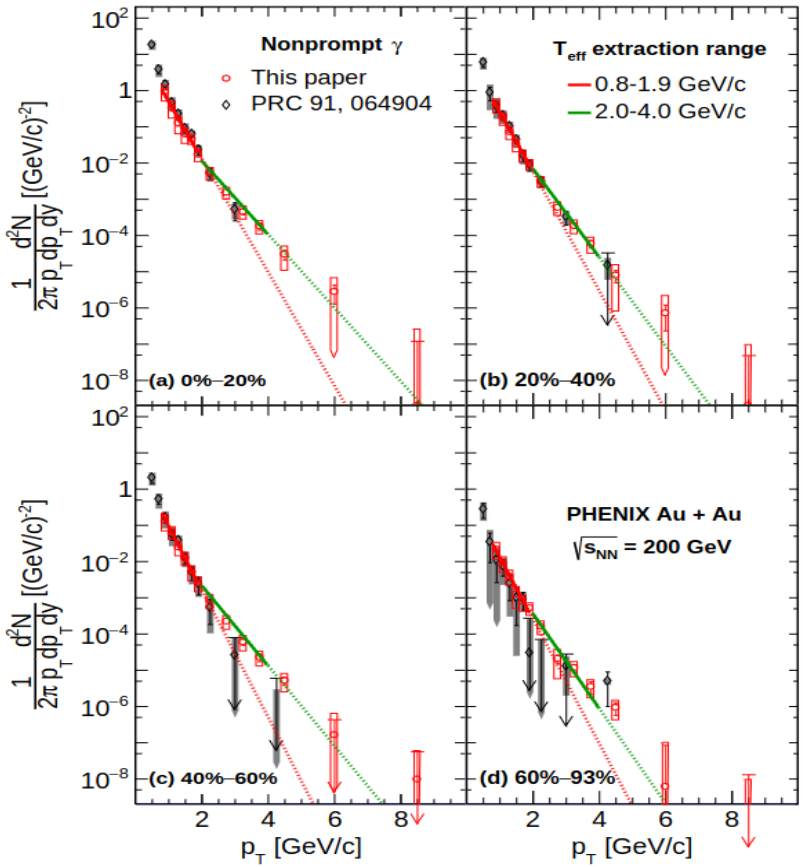




Result - Non-prompt photons

- The invariant yields are very consistent in the region of overlap
- The p_T-dependent inverse slopes (T_{eff}) for different fitting ranges are shown as a function of $dN_{ch}/d\eta$, a measure of centrality
- T_{eff} depends on the fitted p_T range, but almost no dependence on centrality
- From PRC 109, 044912



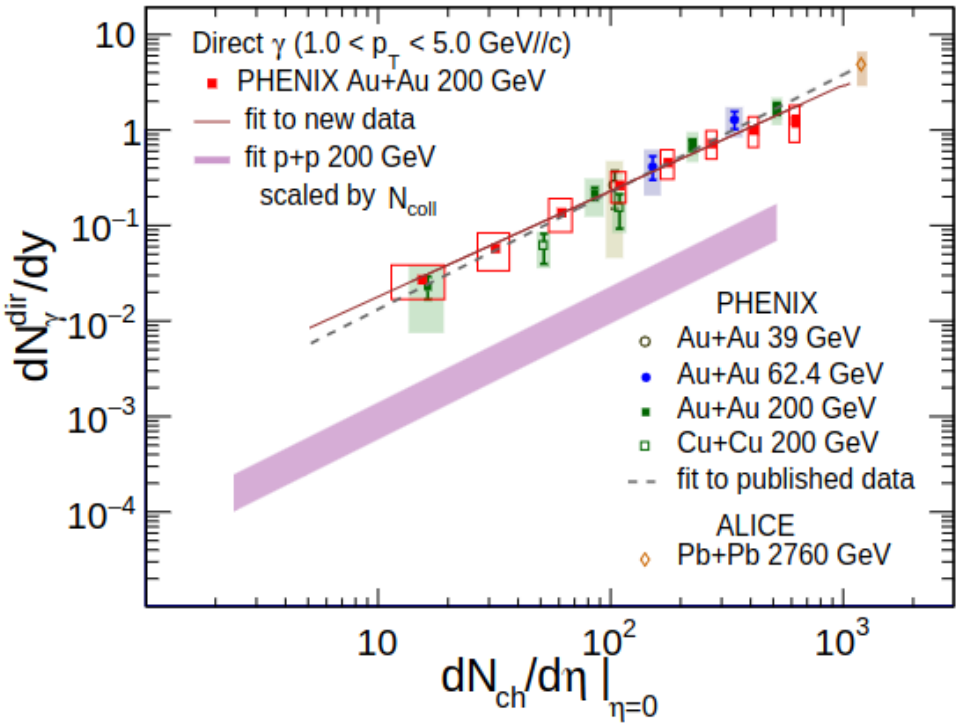


Scaling with multiplicity - integrated yields

- The integrated direct photon yield scaling function:

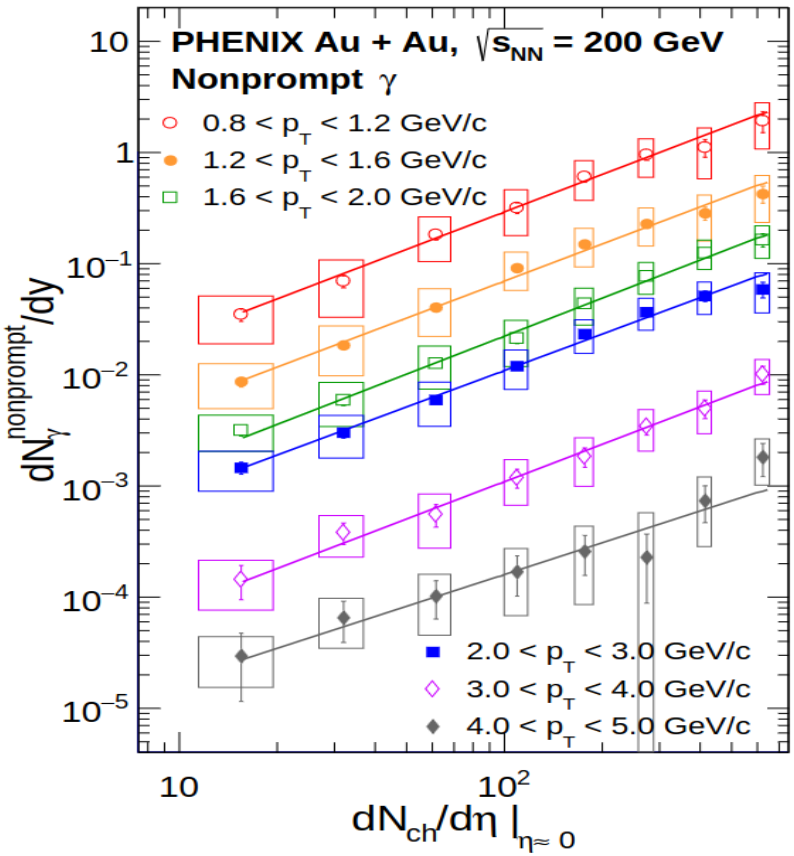
$$\frac{dN_\gamma}{dy} = \int_{p_T,min}^{p_T,max} \frac{dN_\gamma^{dir}}{dp_T dy} dp_T = A \times \left(\frac{dN_{ch}}{d\eta}\right)^\alpha \quad (2)$$

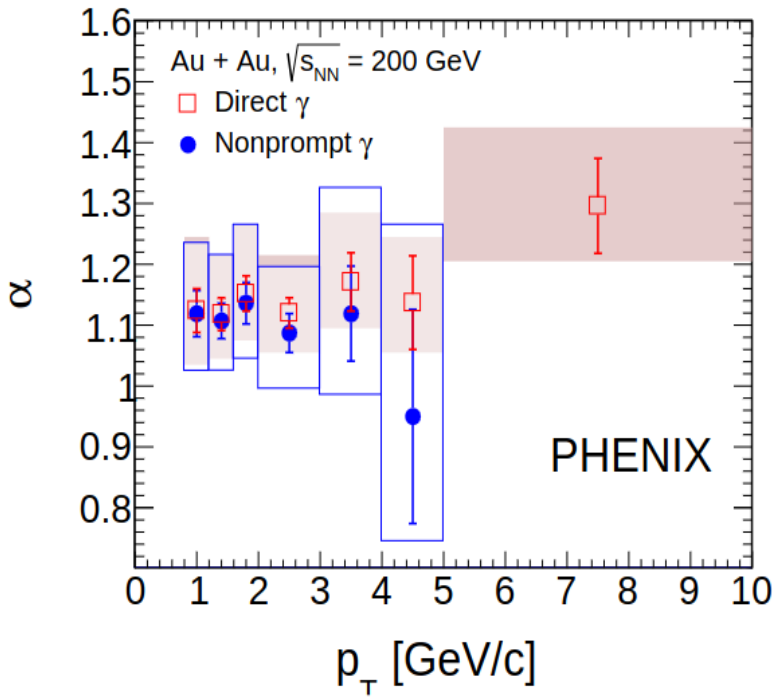
- Agreement with other direct-photon results
- Fit for previously published data: $\alpha = 1.23 \pm 0.06 \pm 0.18$
- Fit from the current data: $\alpha = 1.11 \pm 0.02 \pm 0.09$
- α smaller than predicted $\rightarrow$ HG $= 1.25$ and QGP $= 1.8$
- The same scaling holds over vastly different collision energies (39-2760GeV) and systems (CuCu - PbPb)
- From PRC 109, 044912



Scaling with charged multiplicity - p_T ranges

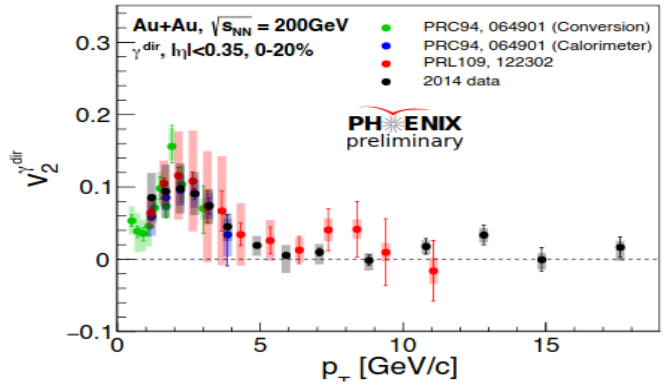
- At higher p_T the α values are slightly lower for non-prompt γ, than for direct γ BUT! they are consistent with each other
- The values of α for the non-prompt component are constant with no evidence p_T dependence, from PRC 109. 044912

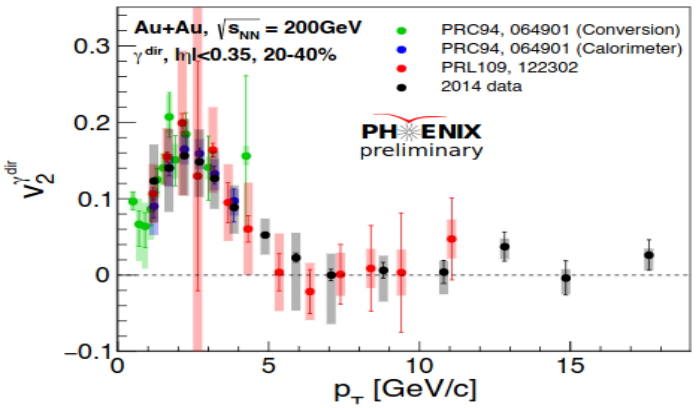


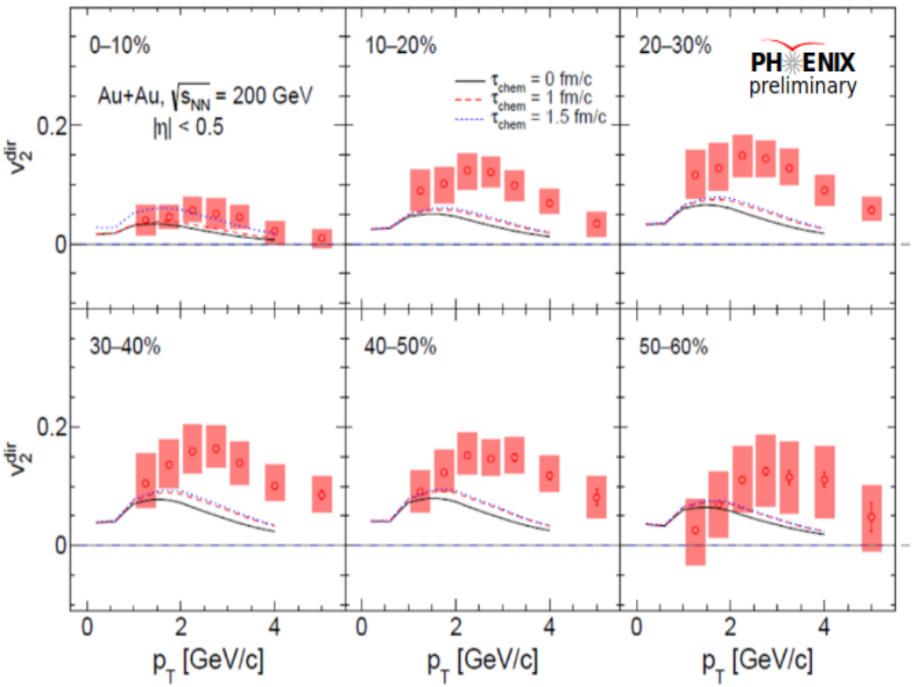


Results on azimuthal asymmetries - v_2

- Preliminary results from a recent analysis of direct photon elliptic flow
- Finer centrality bins than previously published
- The new results are consistent with earlier measurements $\rightarrow$ the elliptic flow of direct photons in the low p_T region is large, and consistent with that of final state hadrons

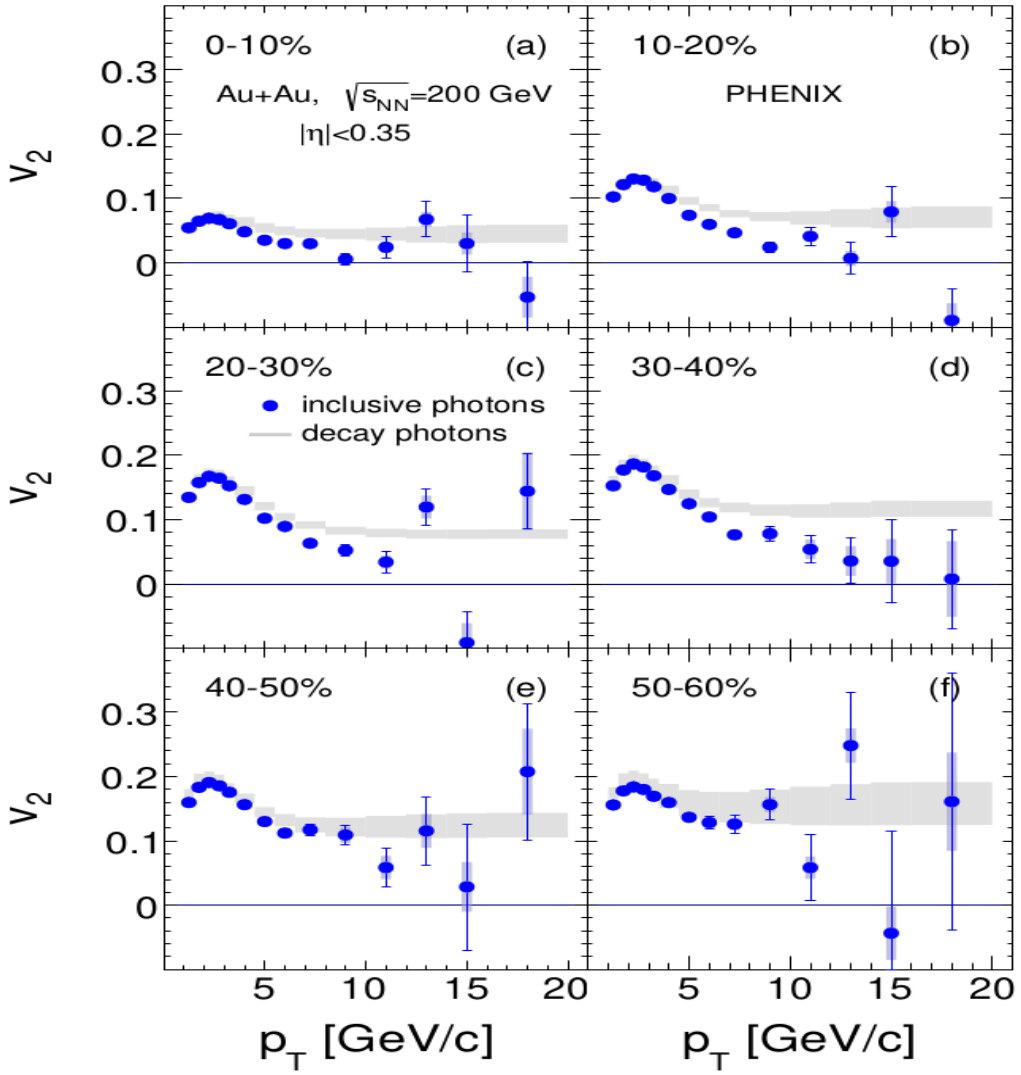






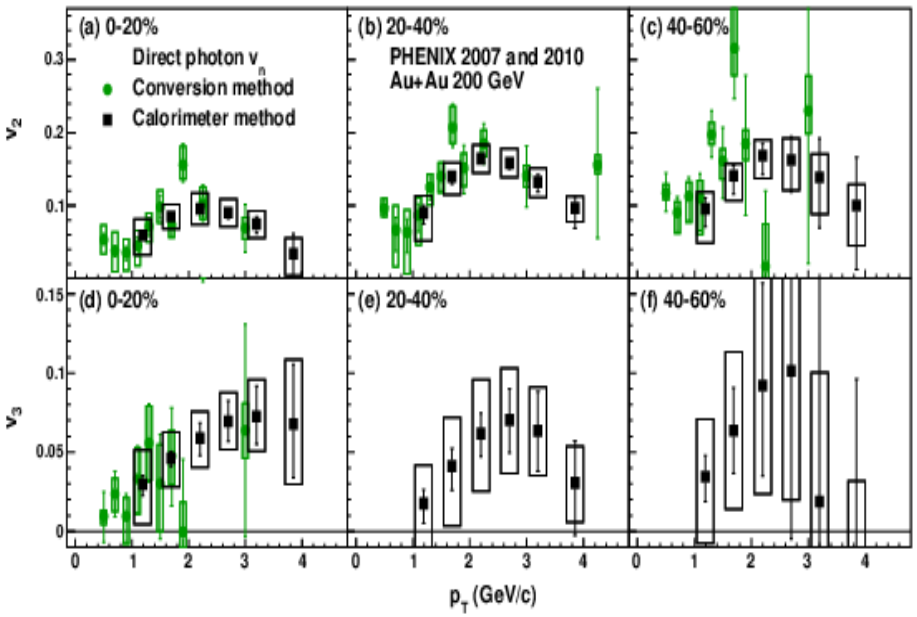
Inclusive and decay photon v_2

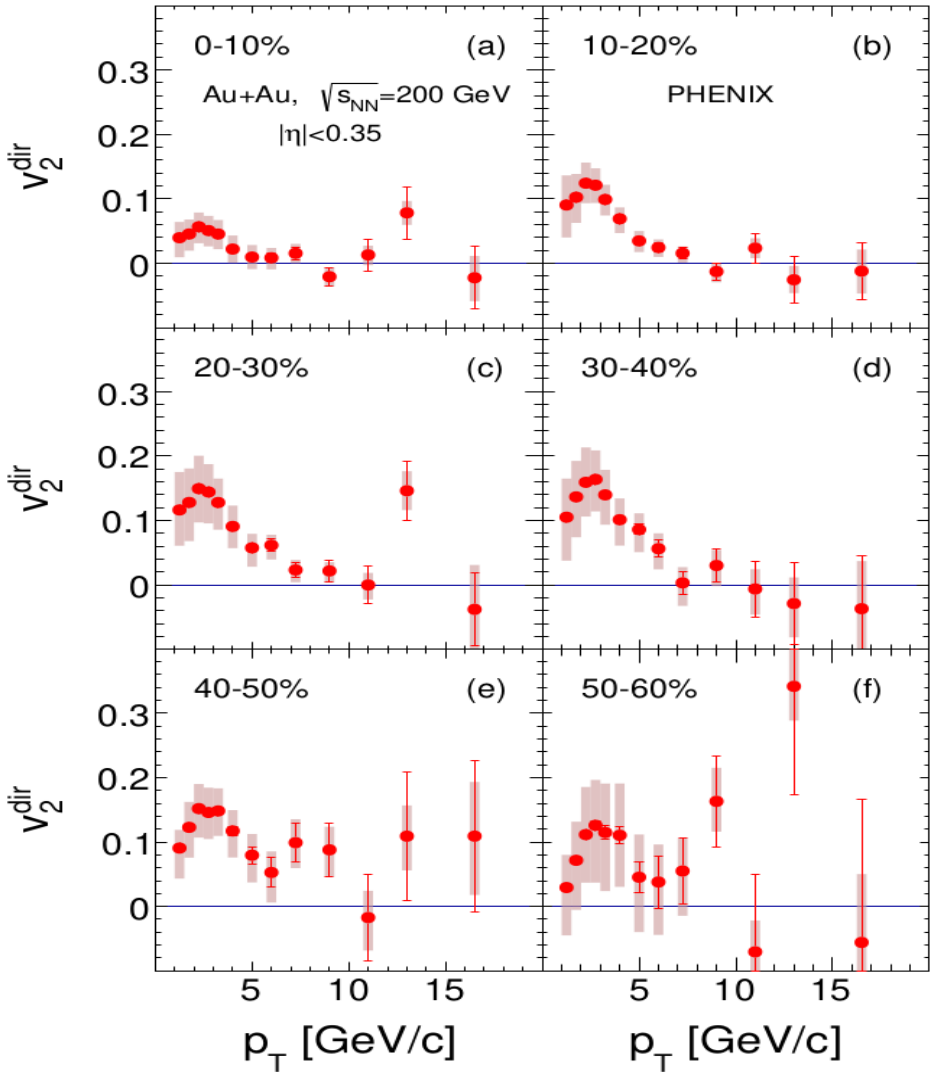
- From: arXiv:2504.02955
- Low p_T: both inclusive and decay v_2 the same
- High p_T: they are strongly separeted
- $v_2^{\text{dir}} = \frac{R_\gamma v_2^{\text{incl}} - v_2^{\text{decay}}}{R_\gamma - 1}$
- Systematic uncertainties dominated by R_γ and v_2^{decay}



Direct photon v_2

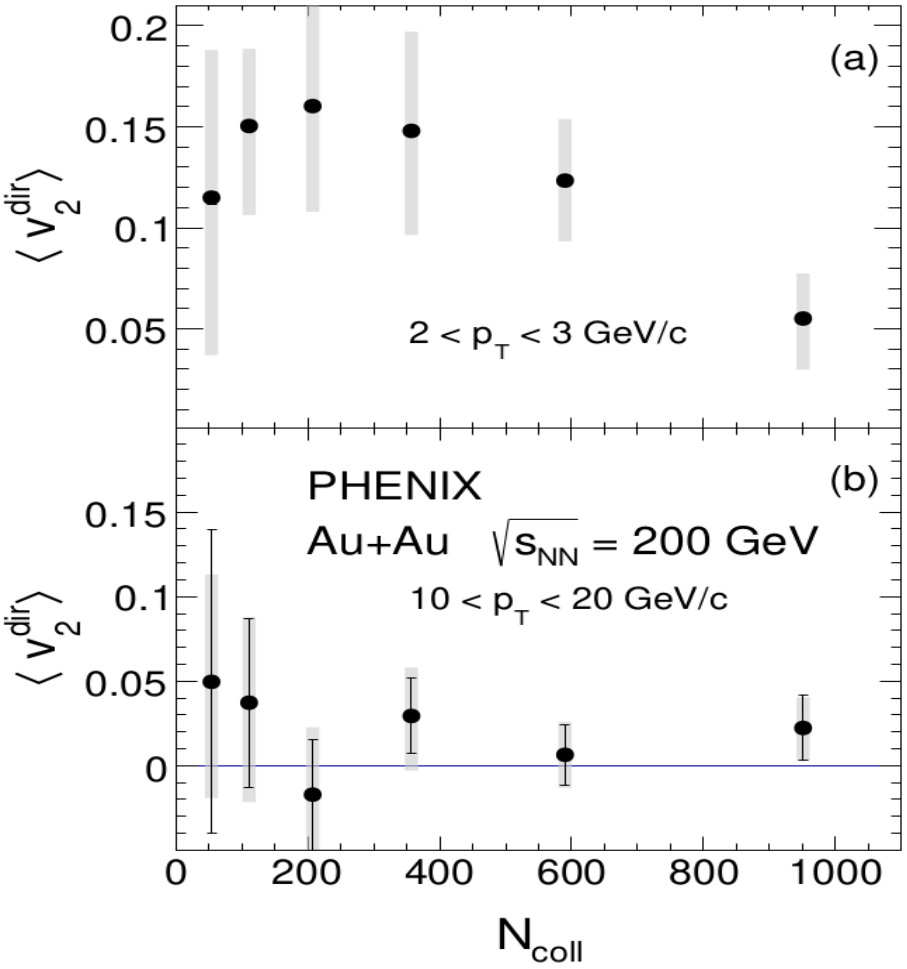
- Previous: PRC 94, 064901 (2016) $\Leftrightarrow$ recent: arXiv:2504.02955
- The v_2^{dir} large at low p_T and peaks around 2–3 GeV/c
- v_2^{dir} decreases with increasing p_T





Centrality Dependence

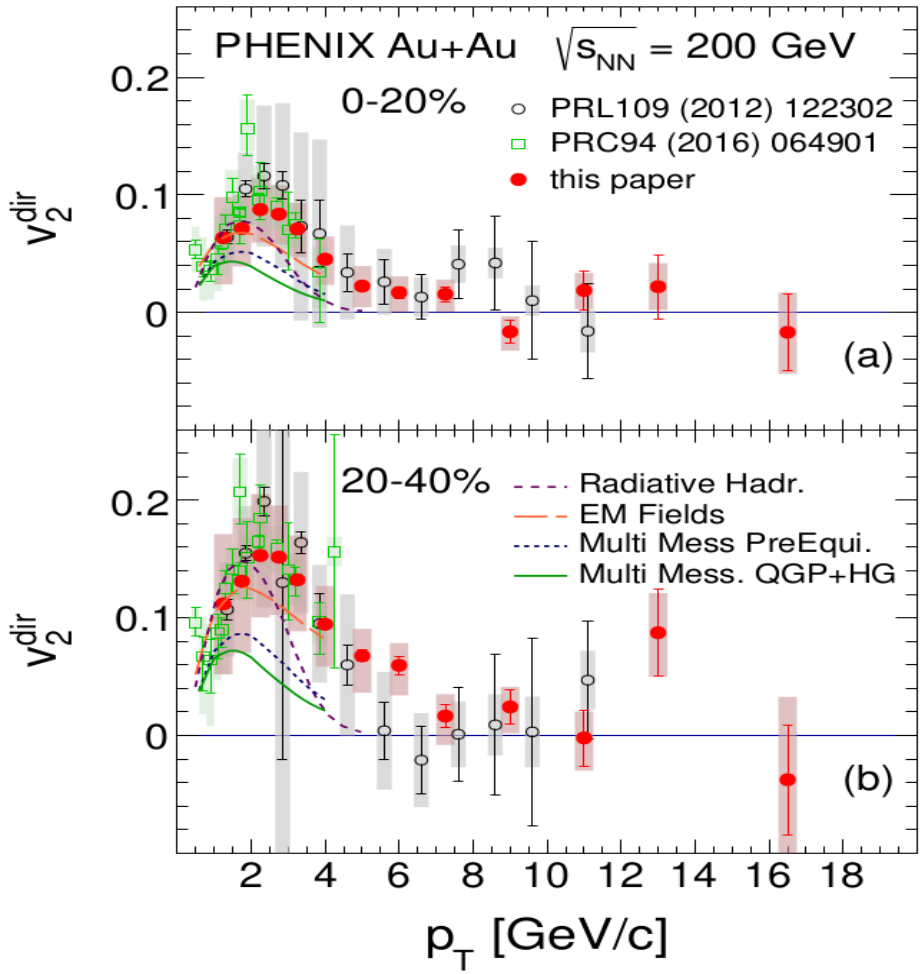
- From: arXiv:2504.02955
- The peak value of v_2^{dir} (0.16) occurs in midcentral collisions (30–40% centrality, $N_{coll} \approx 200$) and decreases at both higher and lower collision centralities
- At high $p_T > 10 GeV$, v_2^{dir} is consistent with zero across all centrality classes, supporting the picture of dominant prompt photon production at high transverse momentum



v_2 vs p_T

- v_2 peaking at 2–3GeV/c, decreasing at high p_T, compared to previous models
- Promising agreement over the previously measured p_T range up to 4GeV/c

source	multim.	rad. hadr.	magnetic
prompt	X	X	X
magnetic			X
pre-eq	X		X
QGP th	X	X	X
HG th	X	X	X
rad. hadr.		X	



Summary

- New PHENIX data: $10\times$ more statistic $\rightarrow$ + confirm earlier results + new kind of analysis $\rightarrow$ "direct photon puzzle" is still alive
- The experimentally observed inverse slopes of the p_T spectra are qualitatively consistent with predictions for thermal and pre-equilibrium radiation
- Large anisotropy is observed for photons at $p_T \approx 2$–$3 GeV/c$, the yield is larger than expected
- The centrality dependence of the nonprompt direct-photon yield, expressed in terms of the scaling power $\alpha(p_T)$, shows no indication of changing with p_T range
- Large v_2^{dir} at low p_T, peaking at 2–3 GeV/c with values up to 0.16 in midcentral collisions. At high $p_T > 8 - 10 GeV$ v_2^{dir} is consistent with zero $\rightarrow$ expected for prompt photon

Thank you for your attention!

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