Azimuthal Anisotropy of Soft Photon Production in PHENIX

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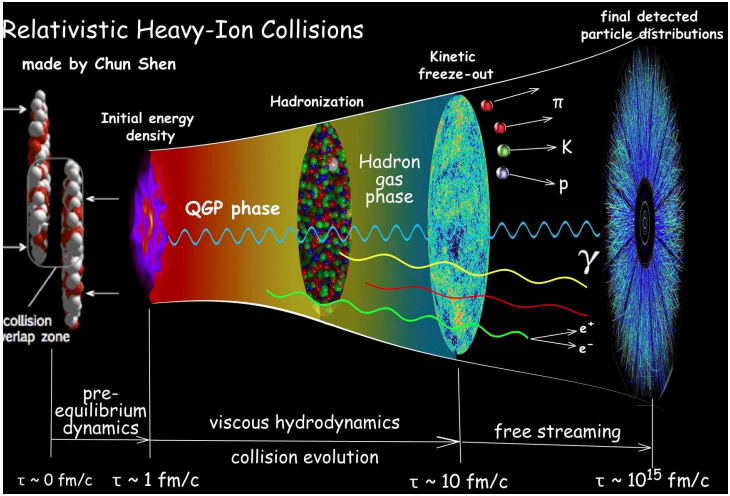
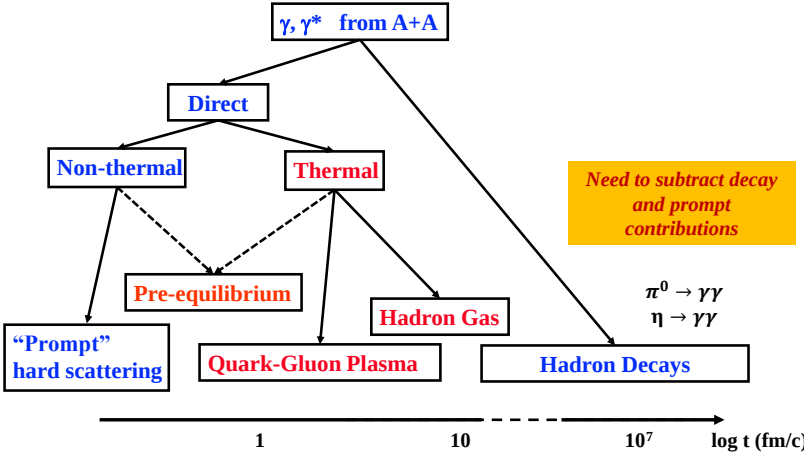
Photon production in heavy ion collisions

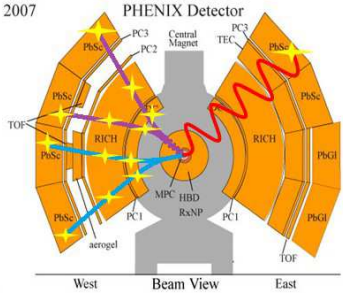


photons probe the full time-evolution of the medium
Can we isolate various photon sources?

Isolating Interesting Sources



Other than hadron decays, we cannot directly separate out the remaining sources. Theoretical guidance is needed.



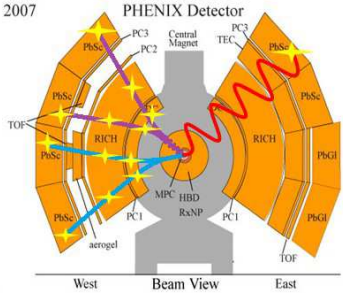
Electromagnetic Calorimeter

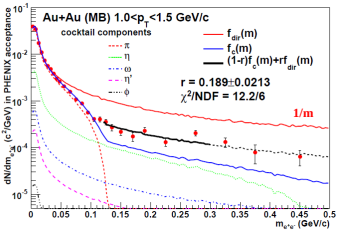
Great at high momentum

- good energy resolution
- little background

Poor at low momentum

- bad energy resolution
- background from MIPs
- background from noise





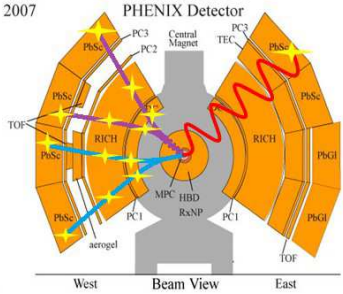
Virtual Photons

Measure $e^{\pm}$ pairs at non-zero mass and extrapolate to zero mass

Little background from π^0 Dalitz decays

Independent systematics from calorimeter measurement

Limited in p_T by the requirement that $m << p_T$ for extrapolation



Photon Conversions

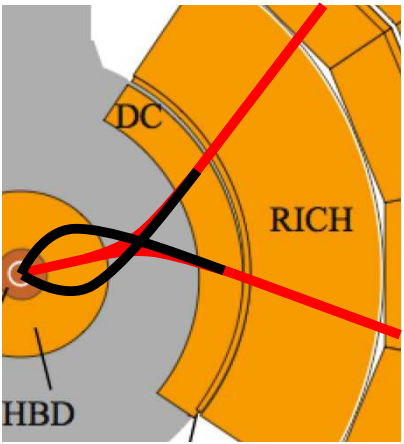
Measure photons which convert in material to $e^{\pm}$ pairs

Uses charged particle tracking instead of calorimetry to measure kinematics

Good at low momentum

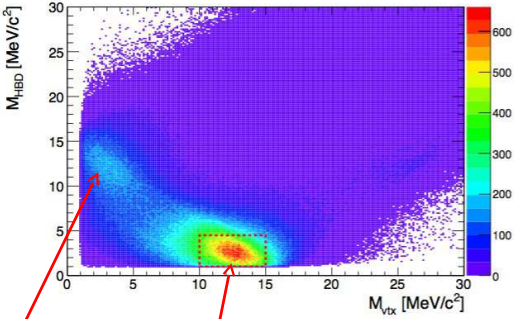
- good momentum resolution
- makes use of electron ID detectors
  - little hadron contamination

The External Conversion Method



- For run 10 and earlier, PHENIX does tracking beyond the magnetic field, assuming track originate from the vertex
- conversion pairs originate from the vertex displaced by 60 cm in radius (HBD back plane)
- this results in mis-reconstruction of momenta and invariant masses of conversion pairs
- alternative tracking model is proposed to focus on conversion in HBD; model assumes that charged tracks originate at HBD back plane

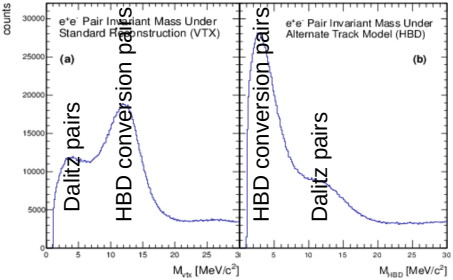
The External Conversion Method



projection to 1D

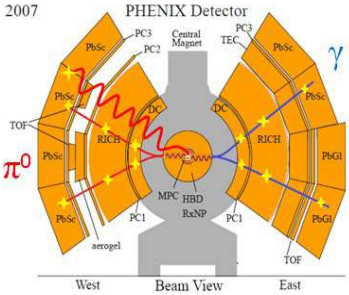
Dalitz pairs

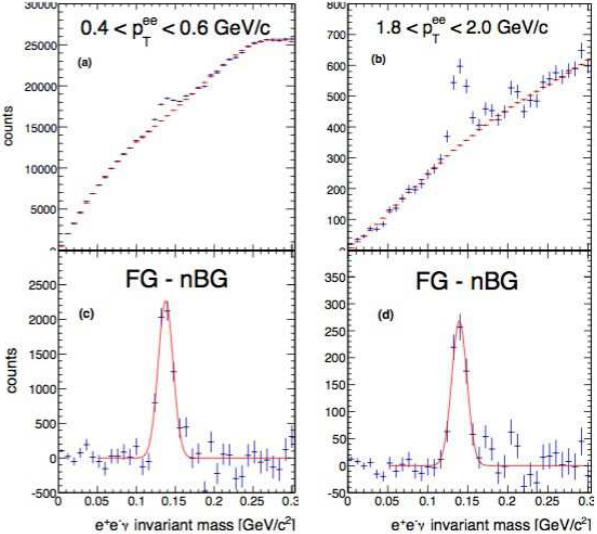
HBD conversion pairs



Tagging conversion from π^0 decays

- tag inclusive photon as coming from pions by reconstructing pions





Putting it all together

Explicit cancellation of systematic uncertainties

conditional tagging efficiency

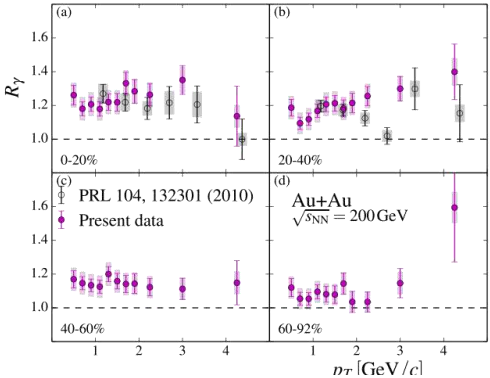
measured raw yields

$$R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{hadr}} = \frac{\langle \varepsilon f \rangle \times \left(\frac{Y_\gamma^{incl}}{Y_\gamma^{\pi^0 tag}} \right)^{Data}}{\left(\frac{N_\gamma^{hadr}}{N_\gamma^{\pi^0}} \right)^{MC}}$$

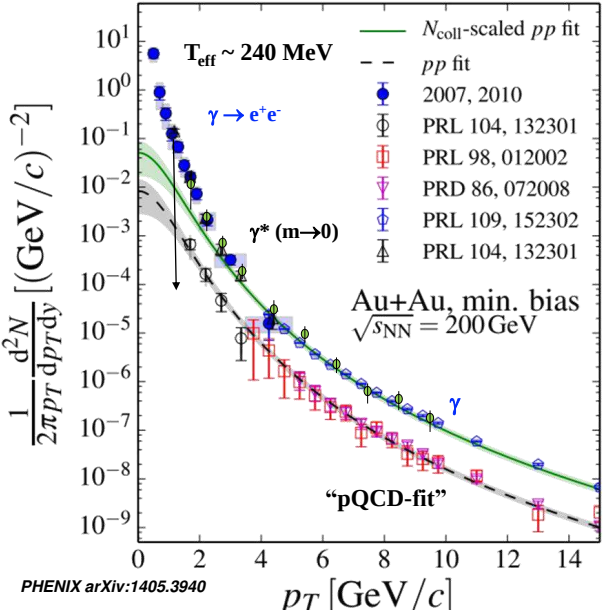
simulated based On hadron data

$$\frac{Y_\gamma^{incl}}{Y_\gamma^{hadr}} = \frac{N_\gamma^{incl}}{N_\gamma^{\pi^0 tag}} \frac{p_{conv} a_{ee} \varepsilon_{ee}}{p_{conv} a_{ee} \varepsilon_{ee} \langle \varepsilon f \rangle} = \frac{N_\gamma^{incl}}{N_\gamma^{\pi^0 tag} \langle \varepsilon f \rangle}$$

PHENIX arXiv:1405.3940



Direct Photon Yields at RHIC



PHENIX arXiv:1405.3940

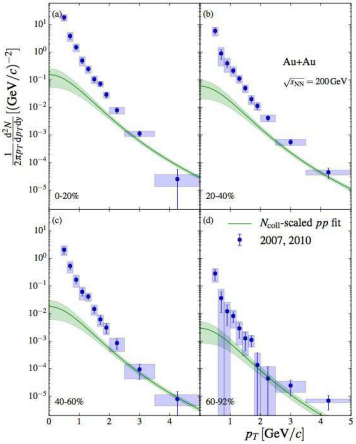
PHENIX arXiv:1405.3940

STAR preliminary γ^* (m → 0)
arXiv:1408.2371

- Direct Photon Yield is well-established
  - p+p consistent with pQCD
  - Au+Au follows N_{coll} scaling at high p_T
  - Excess has exponential shape

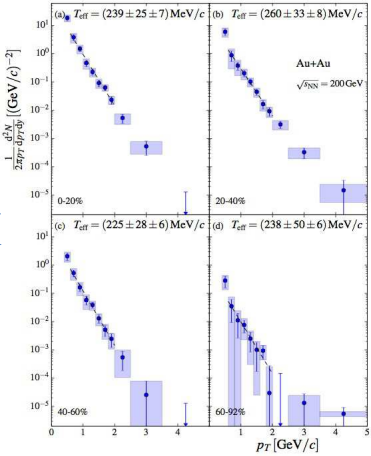
Centrality Dependence of the Yield

- $\gamma_{\text{direct}} = (R_\gamma - 1)\gamma_{\text{hadron}}$
- fit p+p yield to $a\left(1 + b p_T^2\right)^c$ to estimate hard component and scale by N_{coll}
- Fit excess to $A e^{-p_T/T_{\text{eff}}}$. T_{eff} independent of centrality within uncertainties



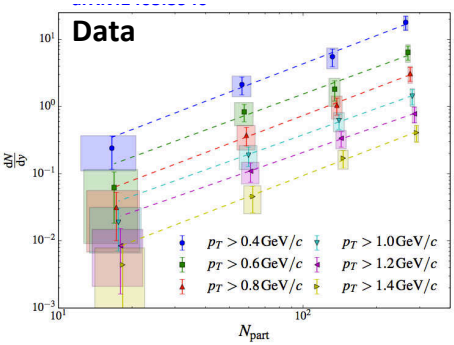
subtract scaled p+p

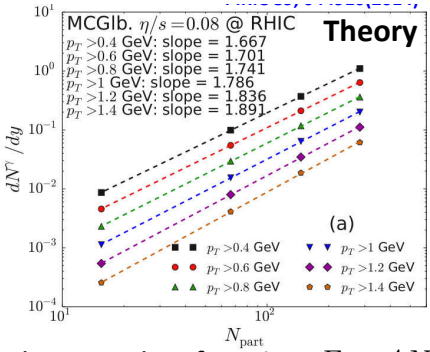
to isolate excess



arXiv:1405.3940

Centrality Dependence of the Yield





Excess of photon yield increases with power-law function, $F = AN_{part}^{\alpha}$

α=1.48±0.08(stat.)±0.04(sys.) ≈ 3/2

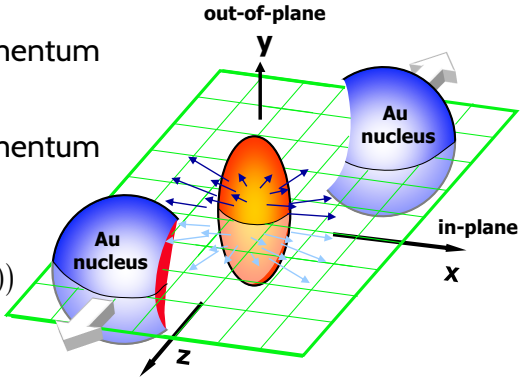
The centrality dependence is not an artifact of the very low p_T points:
same slope as we increase lower limit of integration
(upper limit is always 2GeV/c).

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

Elliptic Flow

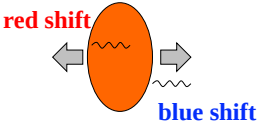
- spatial asymmetry → momentum asymmetry
- thermal matter has momentum asymmetry

$$E\frac{d^3N}{d^3p} = \frac{d^3N}{p_T d\varphi dp_T dy}\sum_{n=0}^{\infty} 2v_n \cos\left(n\left(\varphi - \Psi_R\right)\right)$$



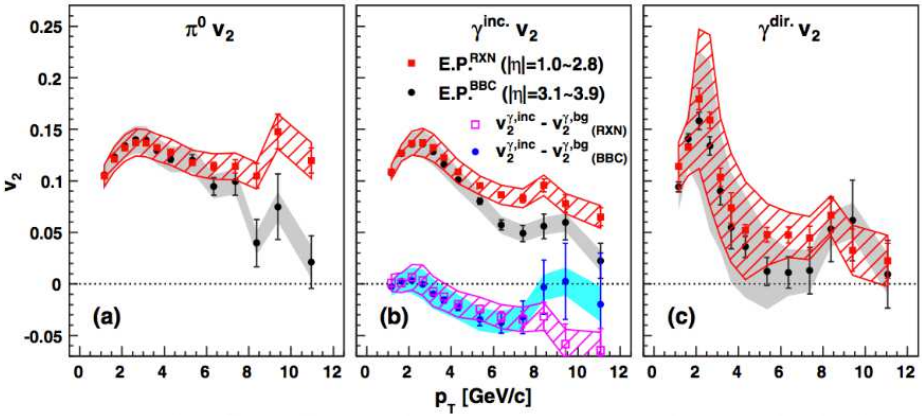
Non-central Collisions

- thermal radiation is thus Doppler-shifted



v_2 of inclusive photons is large

PHENIX Phys.Rev.Lett 109 (2012) 122302

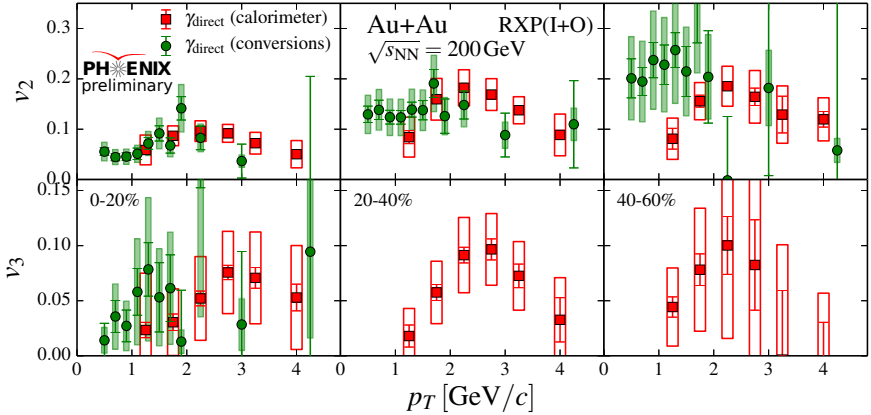


$$\nu_n^{dir.} = \frac{R_\gamma \nu_n^{inc.} - \nu_n^{dec.}}{R_\gamma - 1}$$

- **R_γ (p_T) ~ constant > 1**
- **At 2 GeV $v_2^{inc} \sim v_2^{dec}$**

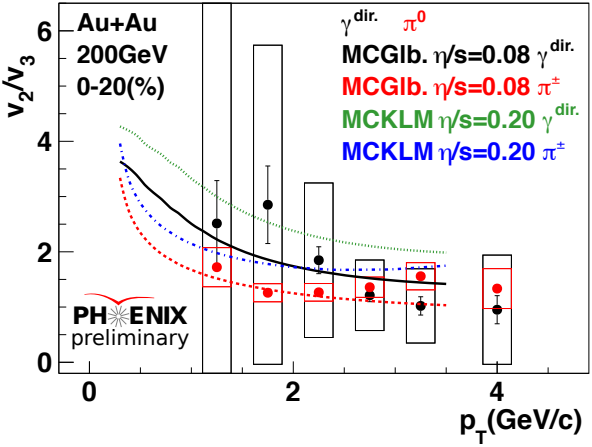
} **$v_2^{dir} \sim v_2^{inc}$**

v_2 and v_3 from different methods



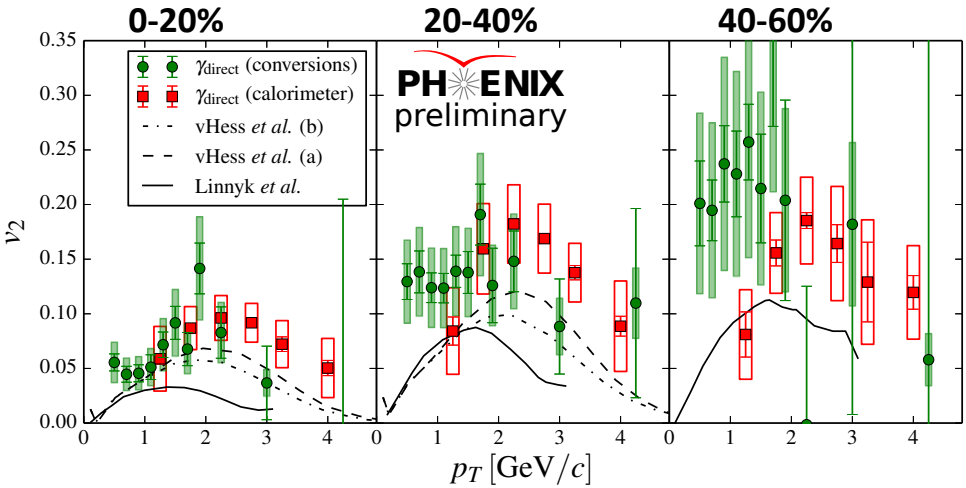
- The two methods are consistent within uncertainties
- v_2 is sizeable at low p_T

v_2/v_3 looks like hydro...



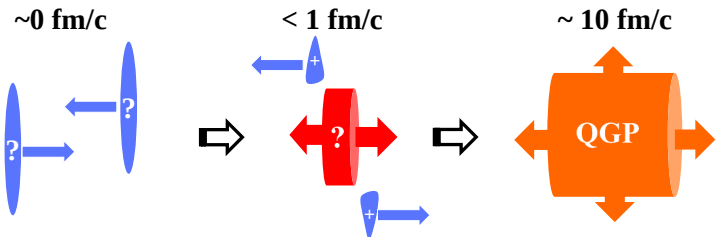
Theory curves: private communication by Ch. Shen, Ch. Gale, J.-F. Paquest, U. Heinz as in 1403.7558, Calculated for RHIC.

... and yet v_2 does not?



van Hees et al: P.R.C 84, 054906 (2011)
Linnyk et al.: PHSD model, private communication

Thermal Photon Puzzle



- Data show
  - Large yield → early emission
  - Large v_2 → late emission
- Theory based on
  - standard photon rates
  - hydro-like evolution

Fail to describe the data

What are we missing?

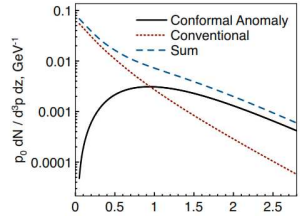
- are the rates right?
- Pre-equlibrium dynamics?
- Large magnetic fields?

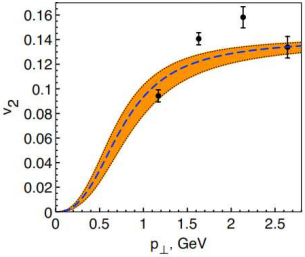
Large Magnetic Fields

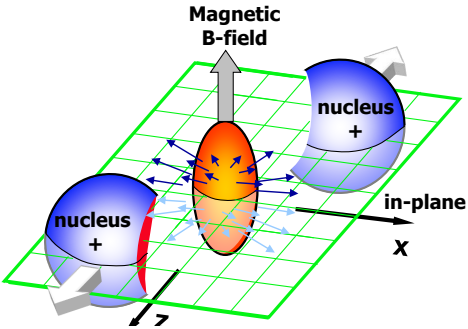
Basar, Kharzeev, Skokov PRL 109 (2012) 202303

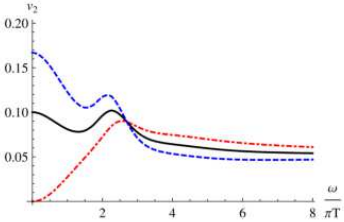
Large magnetic field

- enhanced thermal emission
- anisotropy with respect to reaction plane





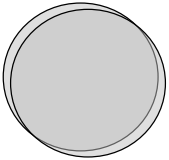




B.Müller, S.Y.Wu, D.LYang PRD 89 (2014) 026013

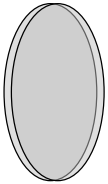
Outlook : Experimentally Controlling the B-Field

Au+Au
central



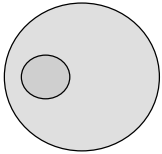
$\mathbf{B = 0}$
$\mathbf{v_2 = 0}$

U+U
central



$\mathbf{B = 0}$
$\mathbf{v_2 \neq 0}$

Cu+Au
semi-central



$\mathbf{B \neq 0}$
$\mathbf{v_2 = 0}$

U+U and Cu+Au analysis is in the pipeline, using the silicon vertex detector as an active photon converter

Summary

- PHENIX has measured low-momentum direct photons
  - Large yield above pQCD contribution
  - Large azimuthat anisotropy
- Thermal photon puzzle
  - Models fail to simultaneously describe yield, temperature, and v_2
  - are there additional sources from early-times?
- More measurements are coming from PHENIX
  - Varying collision geometry
  - Varying collision energy