Direct Photon Flow in Au+Au Collisions at PHENIX

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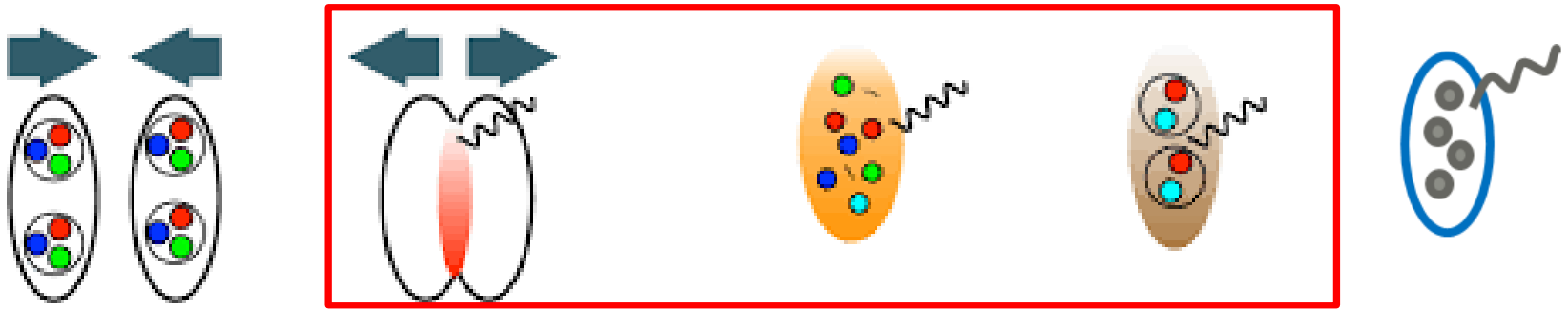
On behalf of the PHENIX Collaboration

Introduction: Direct Photons



- Photons leave the medium with little interaction and are emitted at all stages of the heavy ion collision
- Direct photons are photons which do not come from hadron decays
  - *Measurements of yield and flow constrain initial conditions, sources, emission rates, and spacetime evolution*

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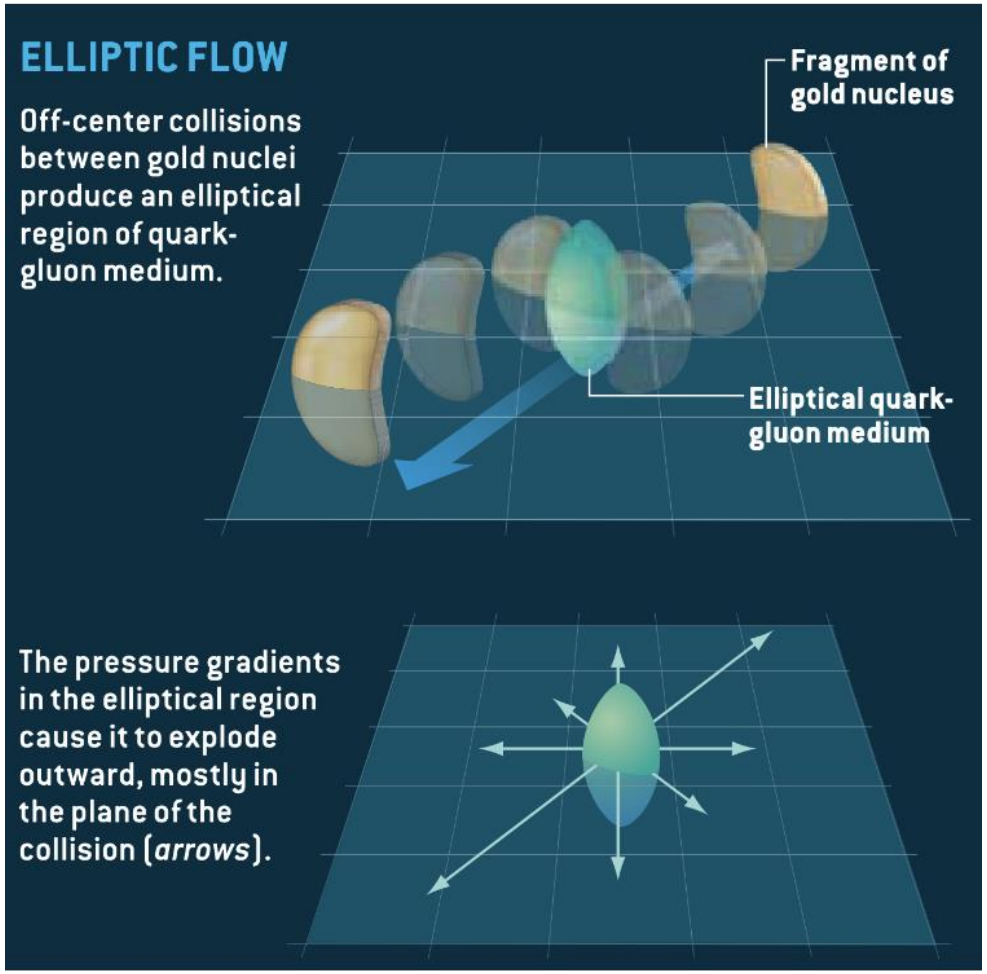
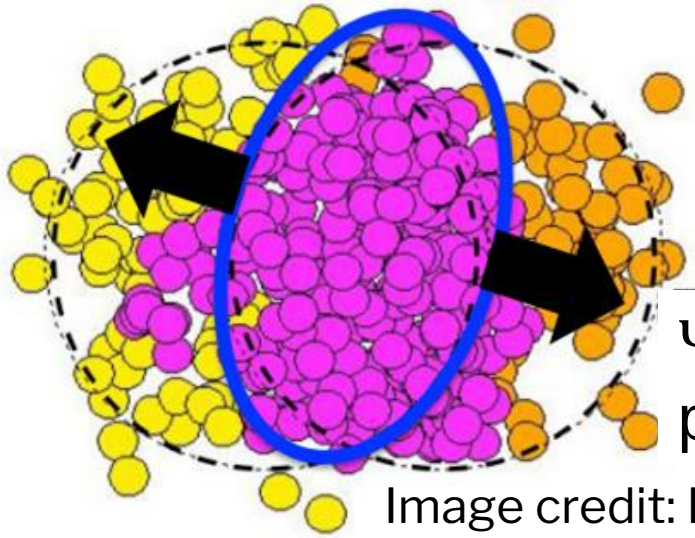
Elliptic Flow

$$\frac{dN}{d(\varphi - \Psi_2)} \propto 1 + 2v_2\cos(2(\varphi - \Psi_2))$$



M. Riordan, W. Zajc, Sci. Am., May 2006, 34-41.



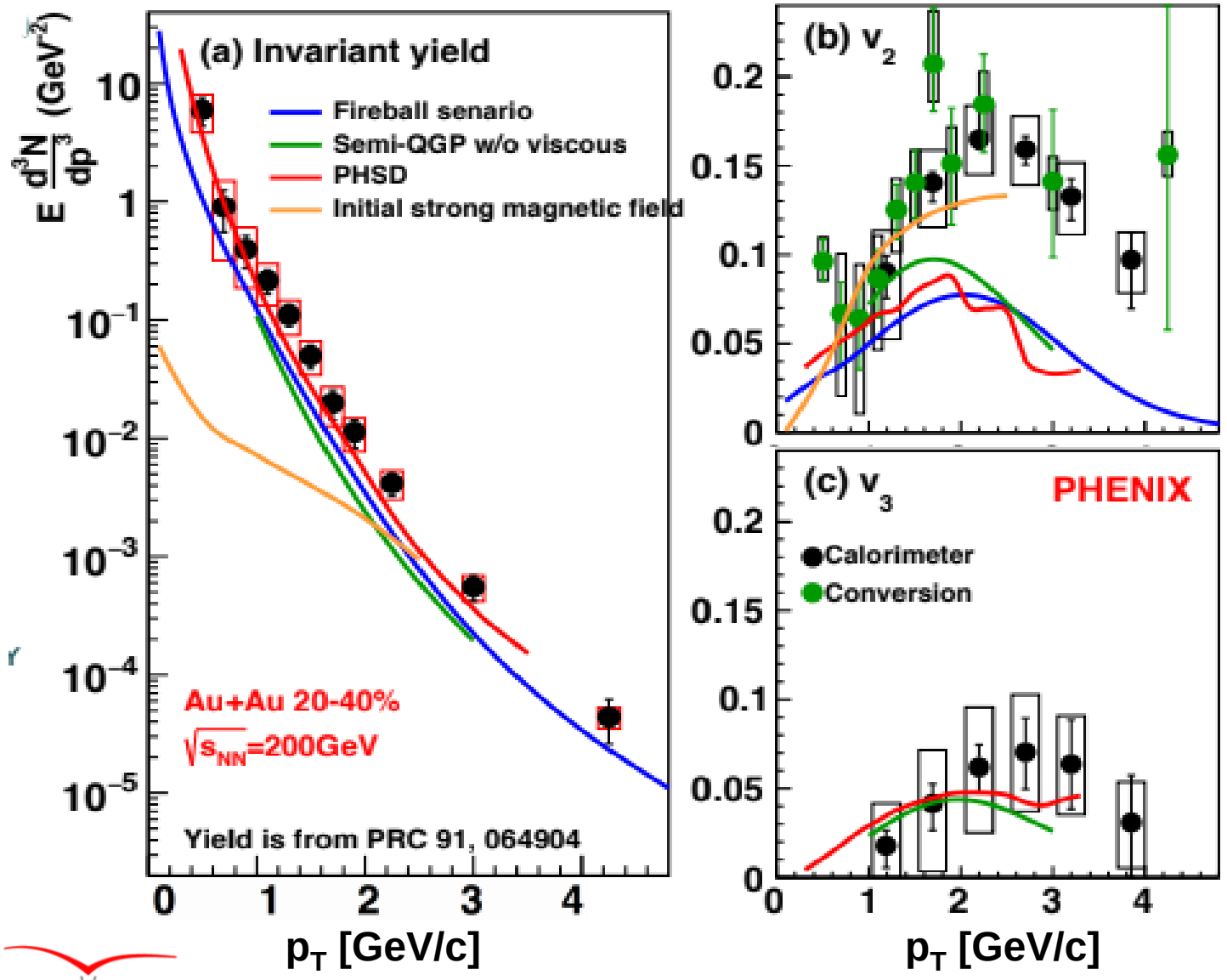
Ψ_2 event plane

Image credit: Ron Belmont

- Low momentum direct photon flow corresponds to the medium's anisotropic pressure gradient
- High momentum corresponds to prompt photons from initial hard scattering

Direct Photon Puzzle

PRC 94, 064901 (2016)



- Theoretical models do not predict both a large photon yield and a large elliptic flow
- Low momentum photons emitted later in collision, high momentum photons emitted early in collision

Qualitative agreement with thermal source

Quantitative tension with model predictions

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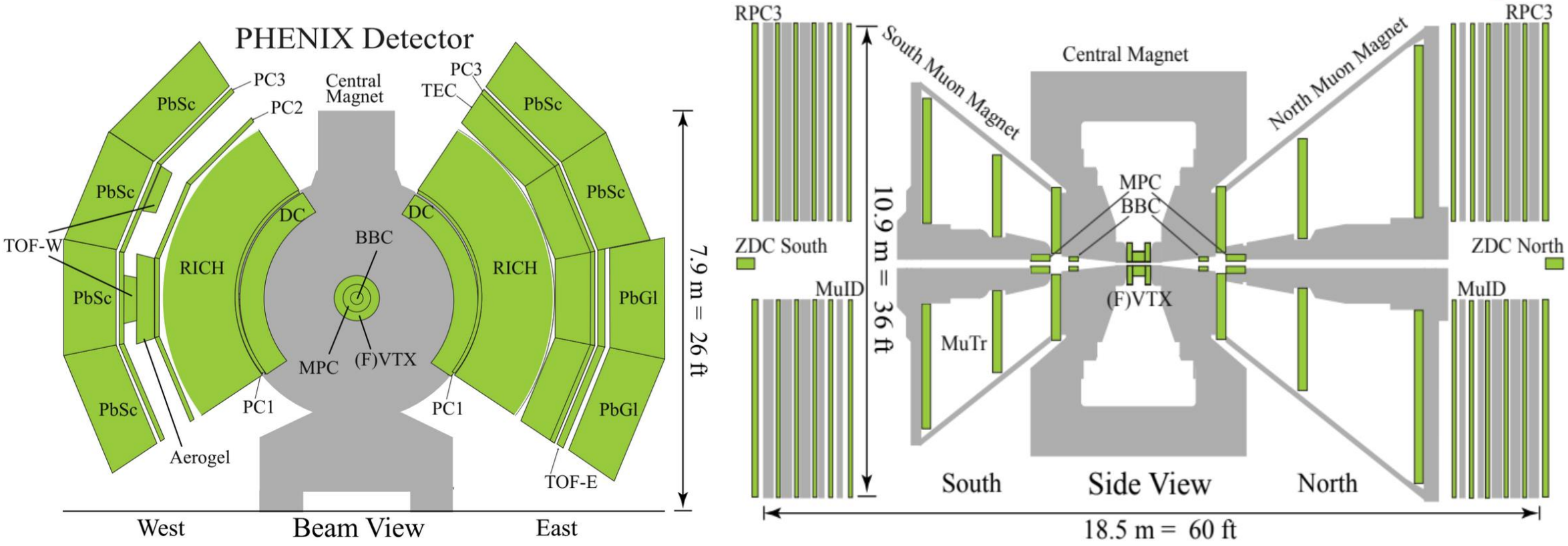
PHENIX Detector System



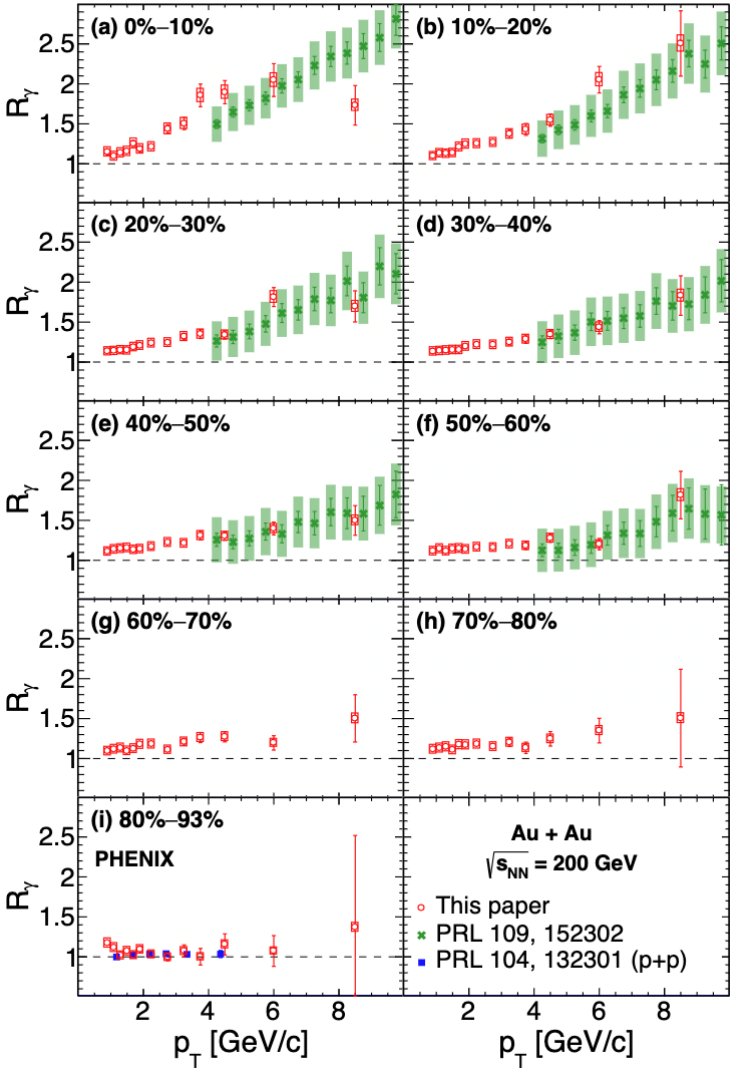
- EMCal used to detect photons from energy deposited
- FVTX is used to measure the event plane

Direct Photon Yield Results

$$R_\gamma = \frac{\gamma^{incl}}{\gamma^{decay}}$$

- High-statistics data set for Au+Au taken in 2014
- In low p_T region R_γ on order of 20% excess of inclusive photons over decay photons

arXiv:2203.17187



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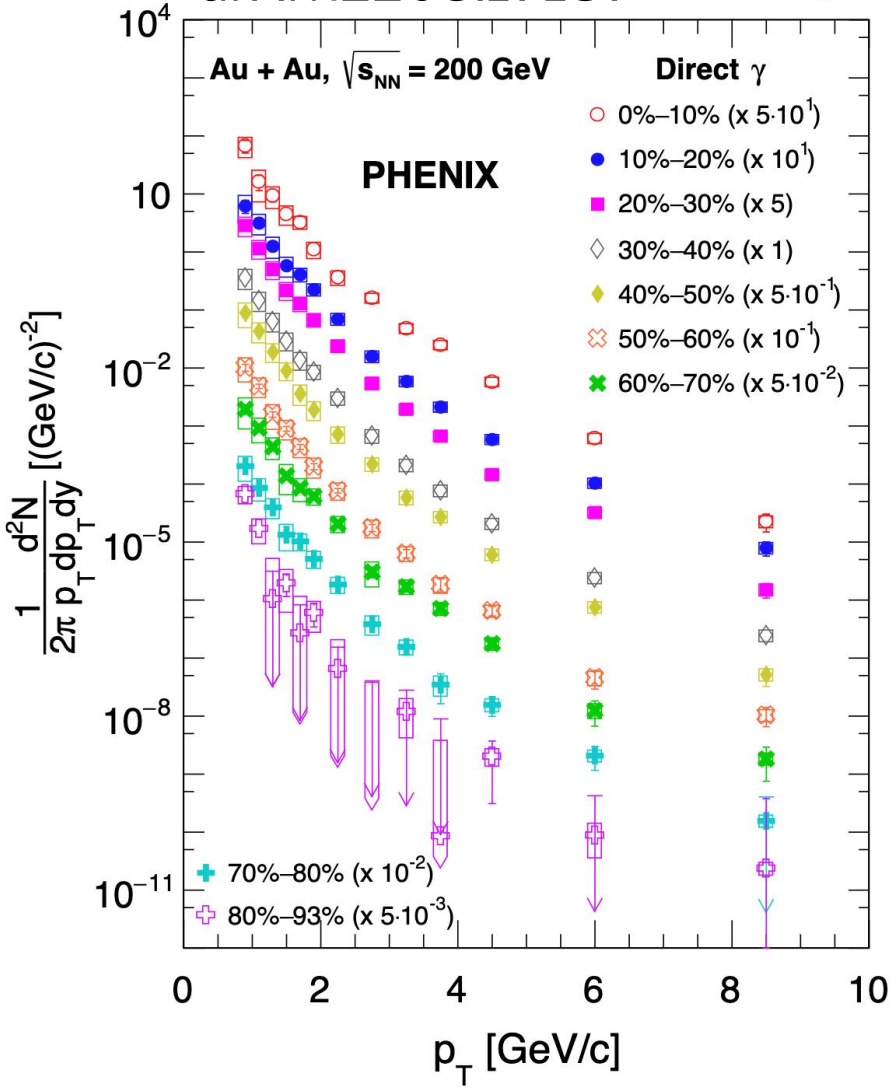
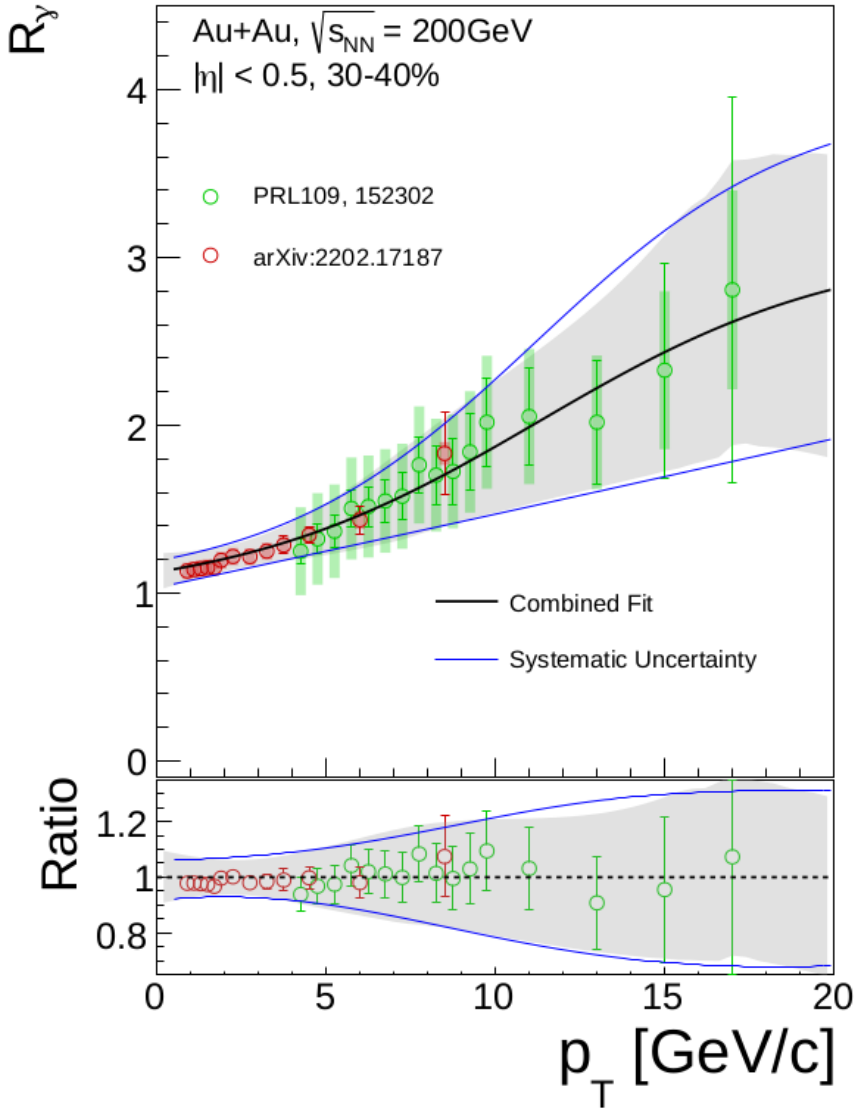


R_γ Determination

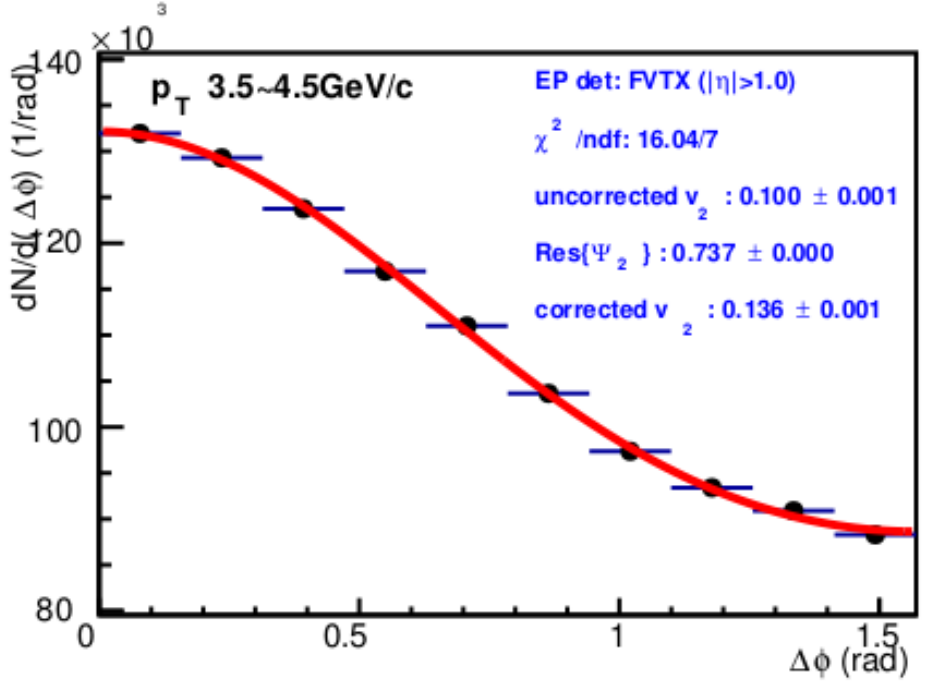
$$v_2^{dir} = \frac{R_\gamma v_2^{incl} - v_2^{dec}}{R_\gamma - 1}$$

- Combined fit of multiple measurements from both the 2014 data set and previous measurements
- Systematic uncertainty calculated using an MC sampling method

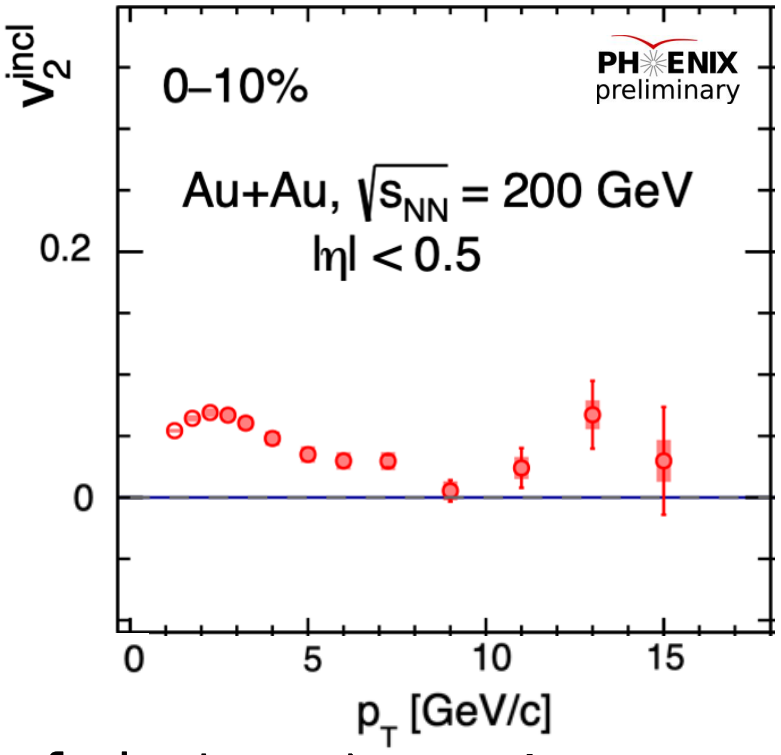


v_2 Extraction

$$v_2^{dir} = \frac{R_\gamma v_2^{incl} - v_2^{dec}}{R_\gamma - 1}$$

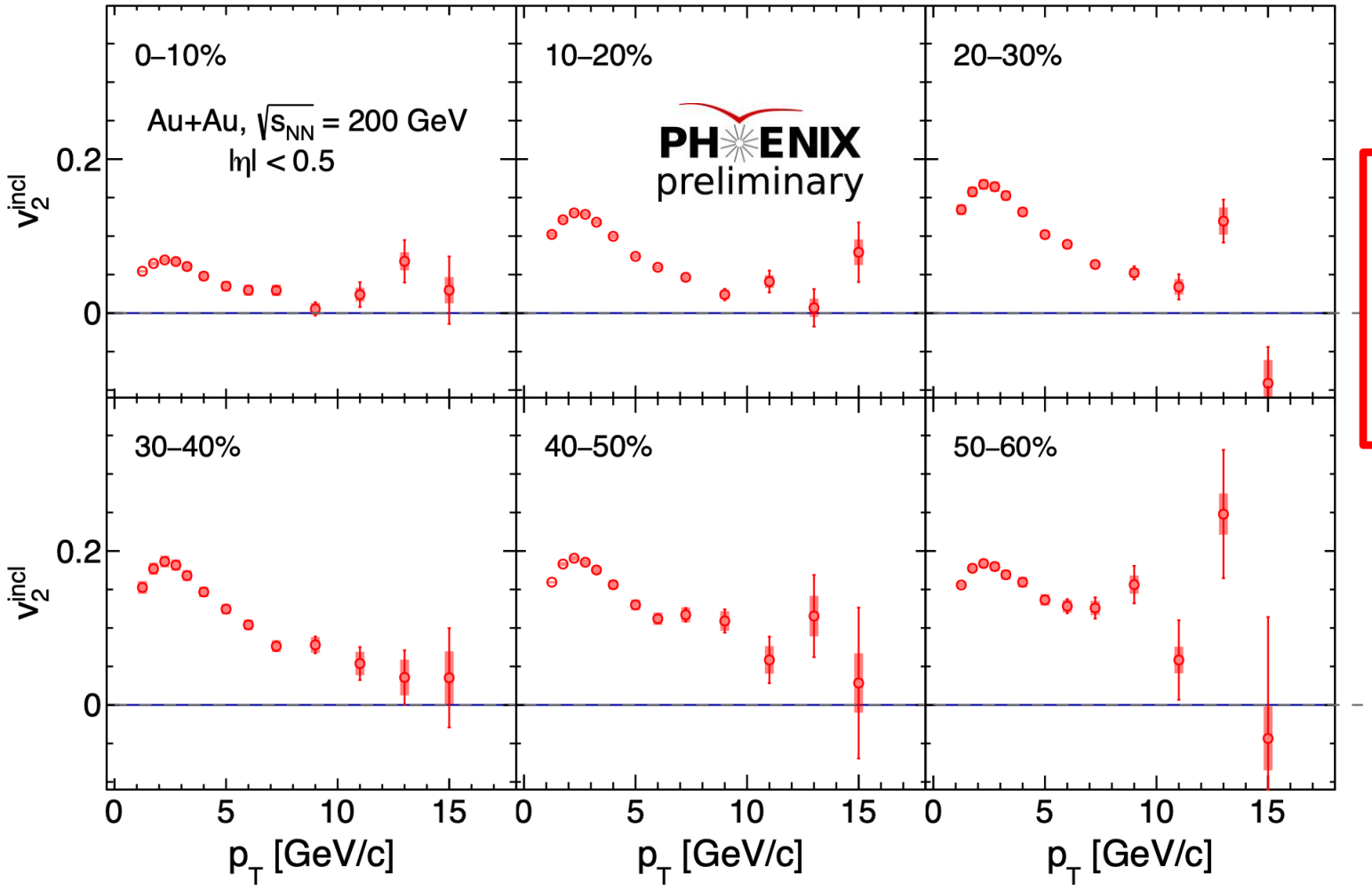


Repeat fit over all p_T



- Flow calculated by fitting azimuthal distribution of photons to cosine curve
- Inclusive flow uses all reconstructed photons, decay photon flow includes only photons from hadron decays

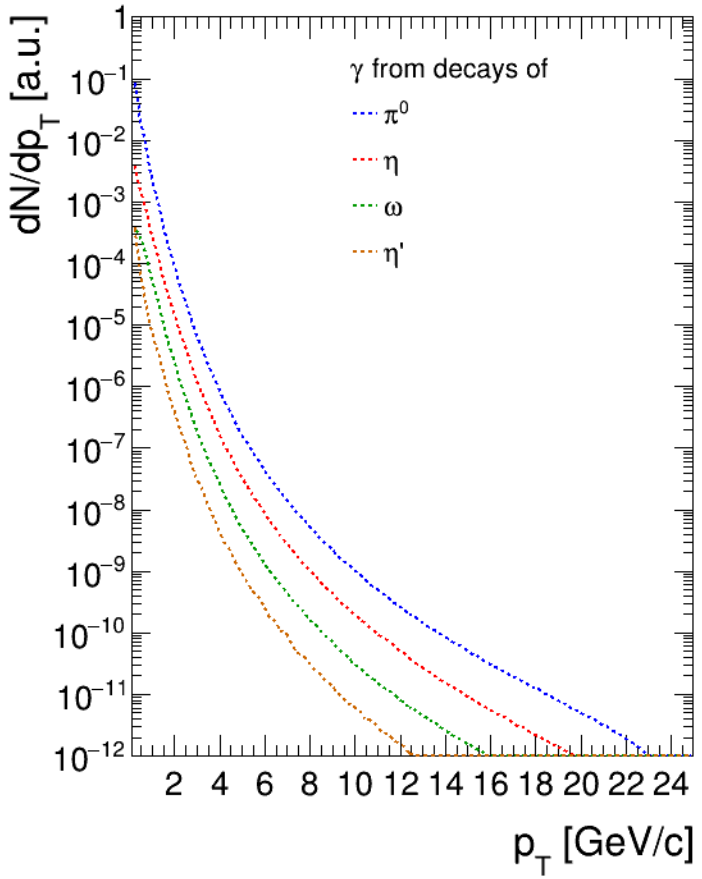
Result: Inclusive Photon Flow

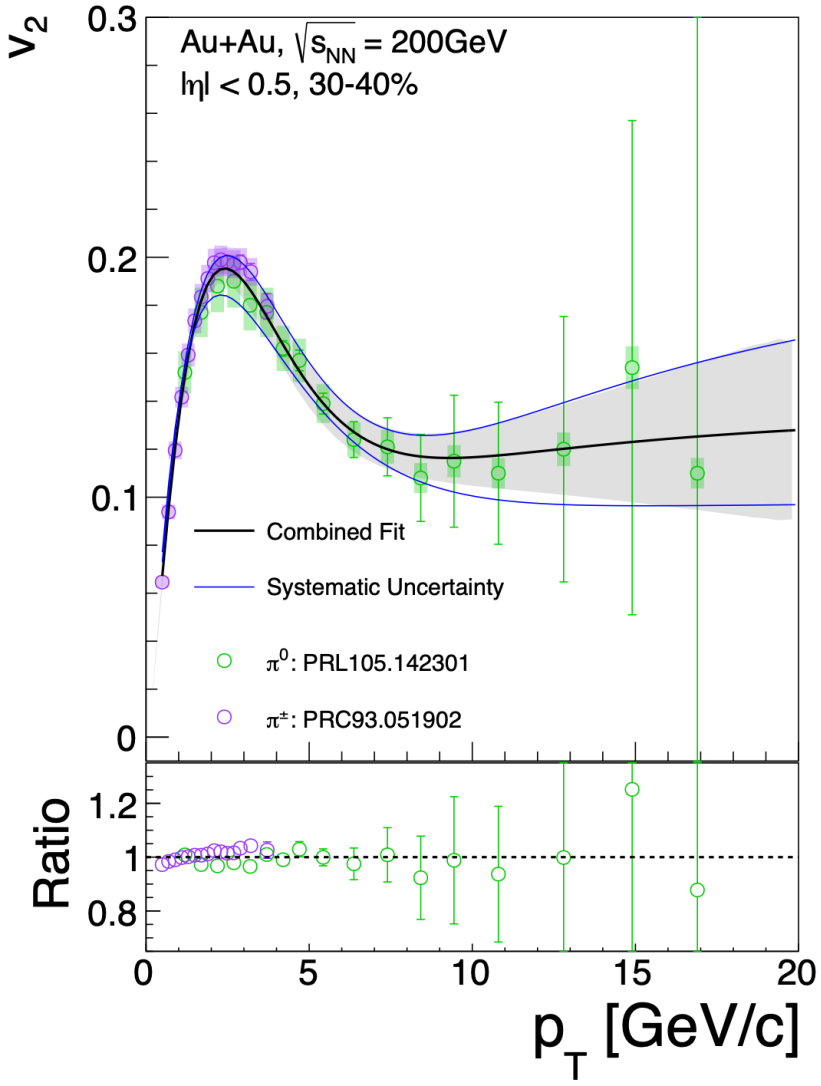


Inclusive photon flow for high p_T is consistently nonzero, with a centrality dependence

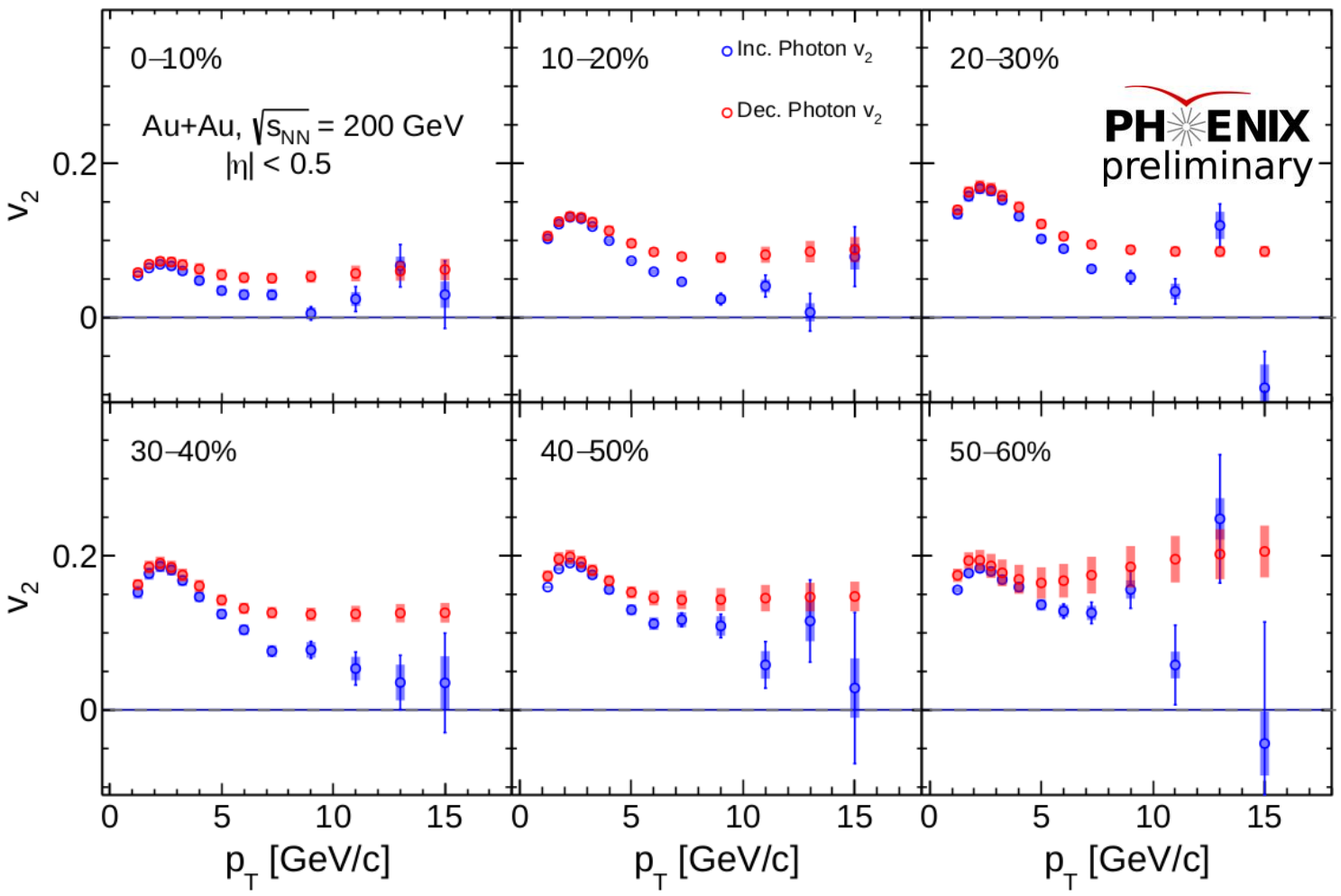
Hadron Decay v_2 Determination

- Combined fit of multiple measurements
- Fit is input into decay photon v_2 simulation
  - Contributions of other mesons assumed to take the same functional form, scaled by KE_T





Result: Decay Photon Flow



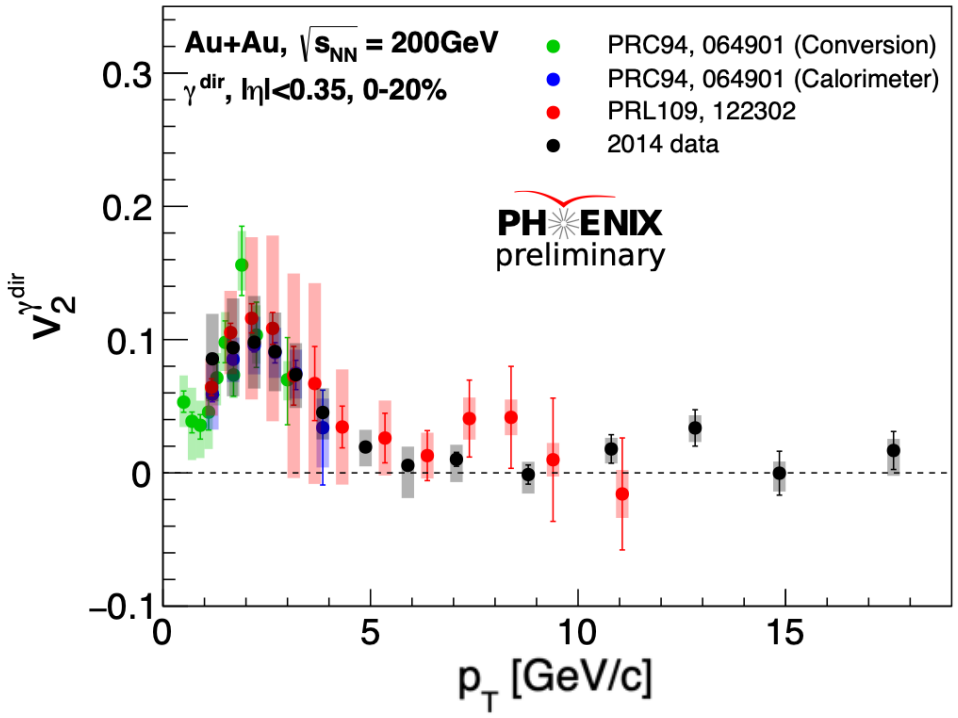
Decay photon flow for high p_T is consistently nonzero with a dependence on centrality

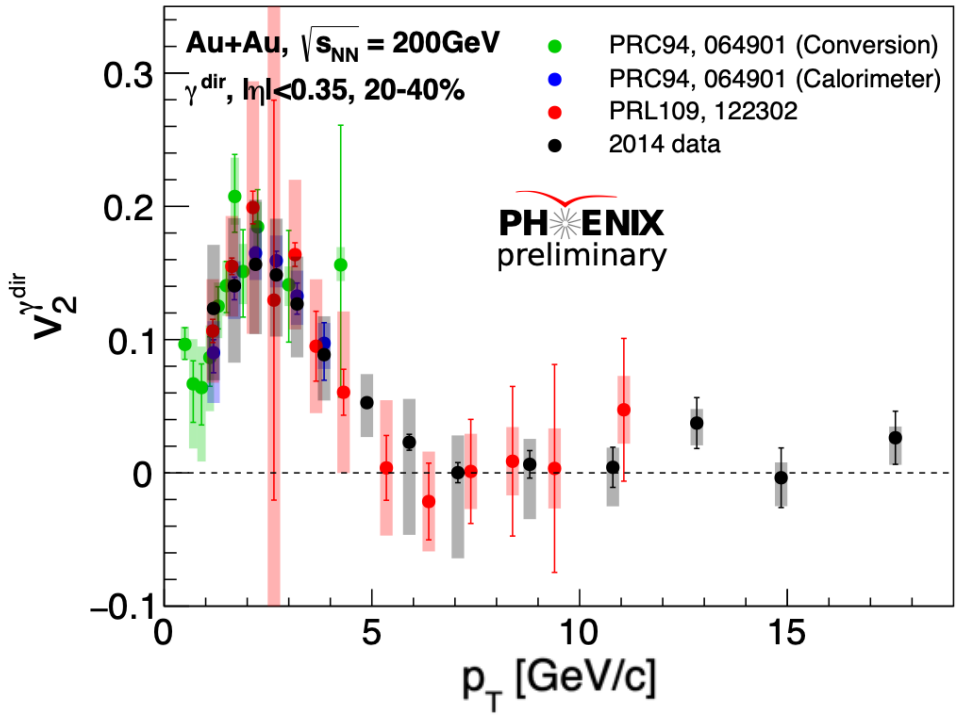
In low p_T region, decay and inclusive photon flow are comparable

Over all p_T, inclusive photon flow is consistently lower than decay photon flow

Result: Direct Photon Flow

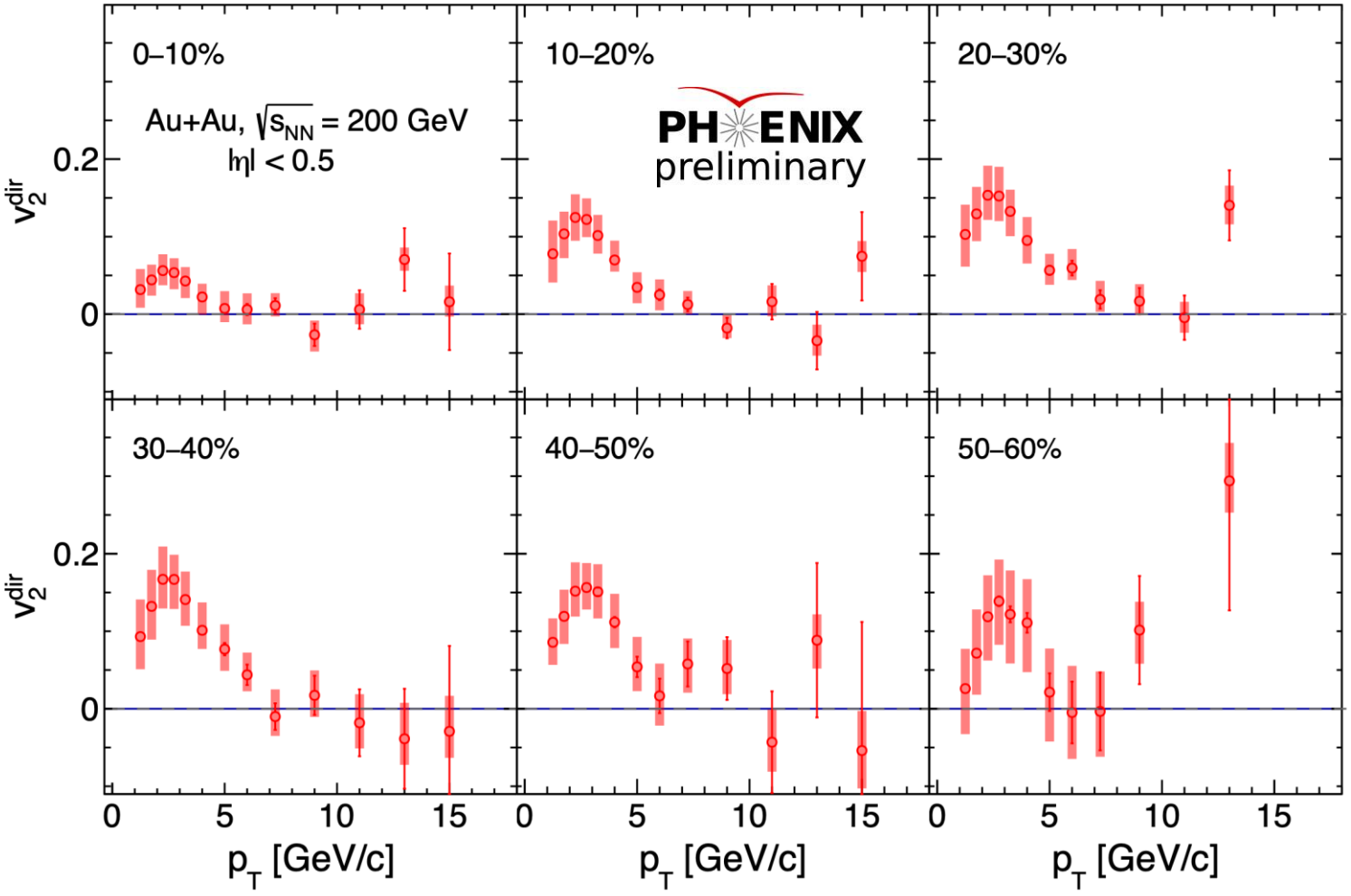
$$v_2^{dir} = \frac{R_\gamma v_2^{incl} - v_2^{dec}}{R_\gamma - 1}$$





- Newest data is consistent with previous measurements within uncertainty
- New measurements extend to higher p_T than previous results

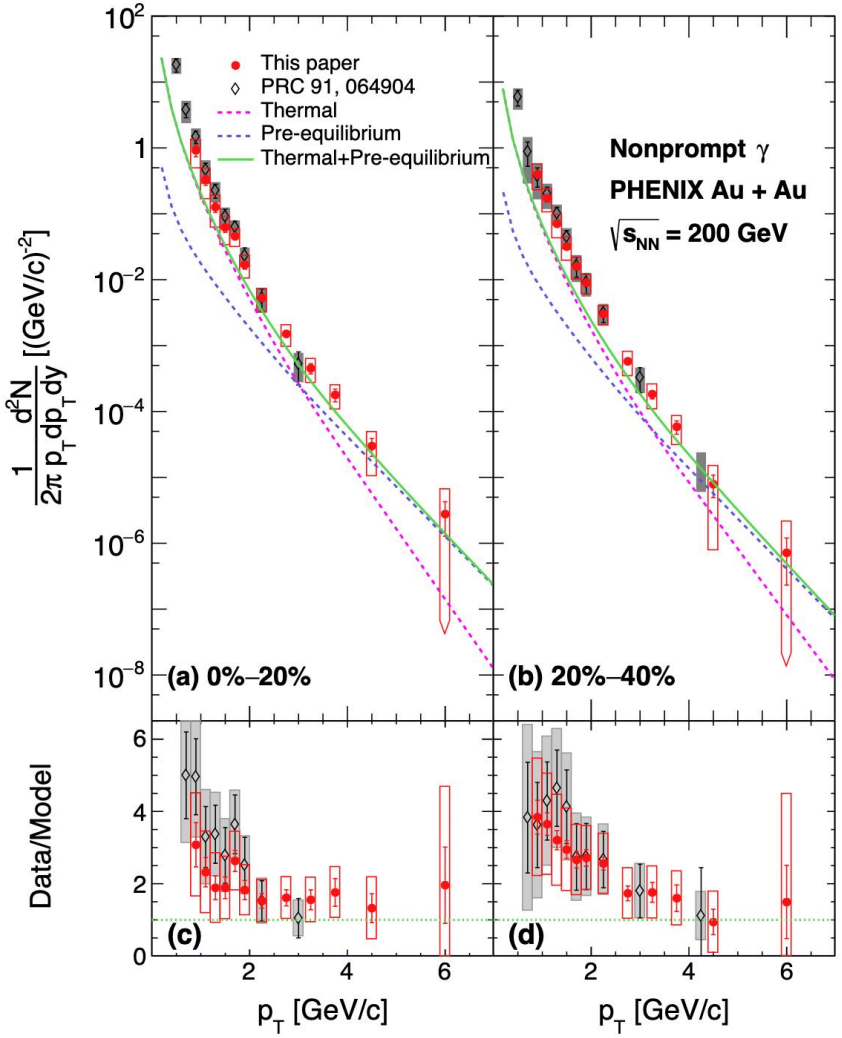
Result: Direct Photon Flow



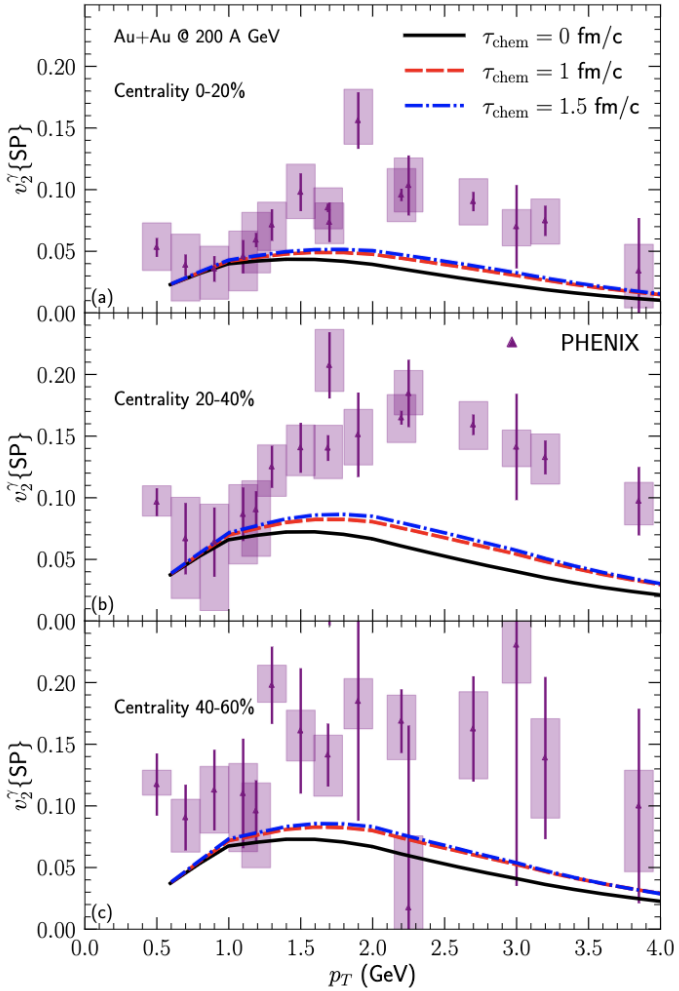
Direct photon flow for high p_T is consistent with zero within uncertainty

Model Comparison

arXiv:2203.17187



Phys. Rev. C 105 014909 (2022) C. Gale et. al.



Multi-messenger heavy ion physics

- Hybrid model accounts for all stages of a collision

Qualitative agreement with data but model falls short quantitatively

Summary

- Measurement of direct photon v_2 is presented using the high statistics data for Au+Au taken in 2014
- Statistical uncertainties are constrained compared to previous measurements
- New results are now in finer centralities and extend to higher p_T
- For direct photon flow, the high p_T region is consistent with zero within uncertainty

Thank you!

Sources of Systematic Uncertainty

Table 7: Systematic Uncertainties for Direct Photon v_2

Input	Source	Centrality 0-20%	Centrality 20-40%	Centrality 40-60%	Type
R_γ ($\leq$5GeV)		5.5%	5.5%	5.5%	B
R_γ (>5GeV)		16%	20%	22%	B
v_2^{inc}	photon ID	2%	2%	2%	B
	EW difference ($\leq$4.5GeV)	2%	1%	2%	B
	EW difference (>4.5GeV)	7%	3.5%	4.5%	B
	event plane	2.5%	1%	5%	C
v_2^{dec}	pion v_2	6-26%	2.5-9%	3.5-15%	B
	η/π^0 ratio	<0.05%	<0.05%	<0.05%	B
	KE_T scaling	2%	2%	2%	B
	event plane	3%	3%	3%	C

Propagation of Uncertainty

$$v_2^{dir} = \frac{R_\gamma v_2^{inc} - v_2^{dec}}{R_\gamma - 1}$$

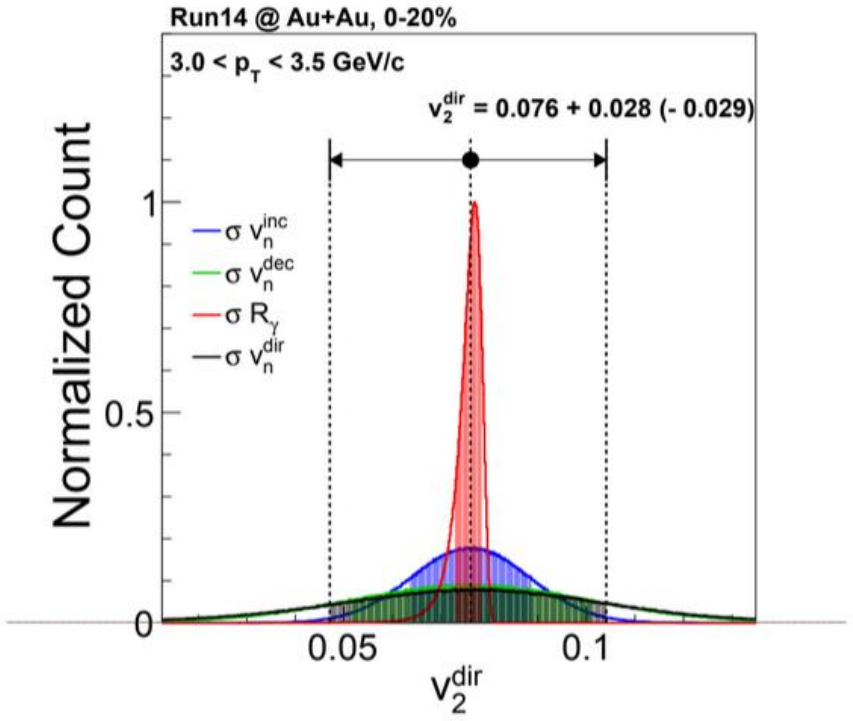


Figure 101: v_2^{dir} distribution using MC sampling in 3.0-3.5 GeV/c p_T bin and 0-20% centrality bin. Blue curve corresponds to if including only the contribution of v_2^{inc} systematic uncertainty. Green curve corresponds to if including only the contribution of v_2^{dec} systematic uncertainty. Red curve corresponds to if including only the contribution of R_γ systematic uncertainty. Black curve corresponds to if including the contributions of all systematic uncertainty sources.

Image credit: Benjamin Bannier, Wenqing Fan

- Correlations between terms in the formula, and R_γ in both numerator and denominator
  - *Asymmetric uncertainties not described by normal Gaussian error propagation*
  - *Use a MC sampling method, moving each term according to their uncertainties to get distribution of direct photon flow*
  - *Distribution is integrated from infinity until 68% of the total is in the integral to determine upper and lower uncertainty bounds*

Sources of Direct Photons

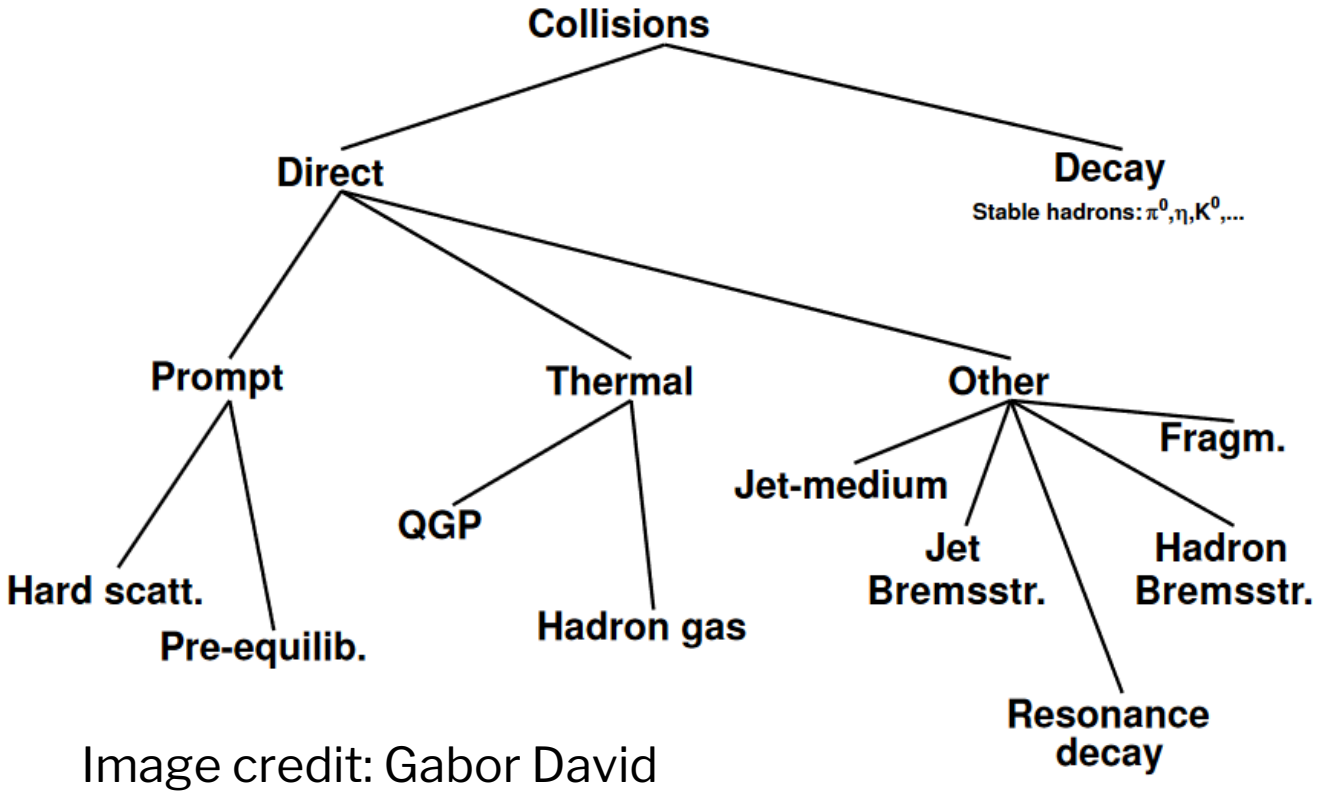


Image credit: Gabor David

- Prompt Photons
  - *From before QGP phase*
  - *Initial hard scattering*
  - *Pre-equilibrium*
    - *Conjectured early sources (strong initial B-field, Glasma, etc.)*
- Thermal photons
  - *From collective media (QGP and Hadron Gas)*
  - *Local thermalization at best*
- Other
  - *Mainly from jets, jet-medium interactions*
  - *Resonance decay*

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Comparison of Pion Fit and Direct Photon Flow