PHENIX

Stony Brook University

Direct Photons Production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with PHENIX

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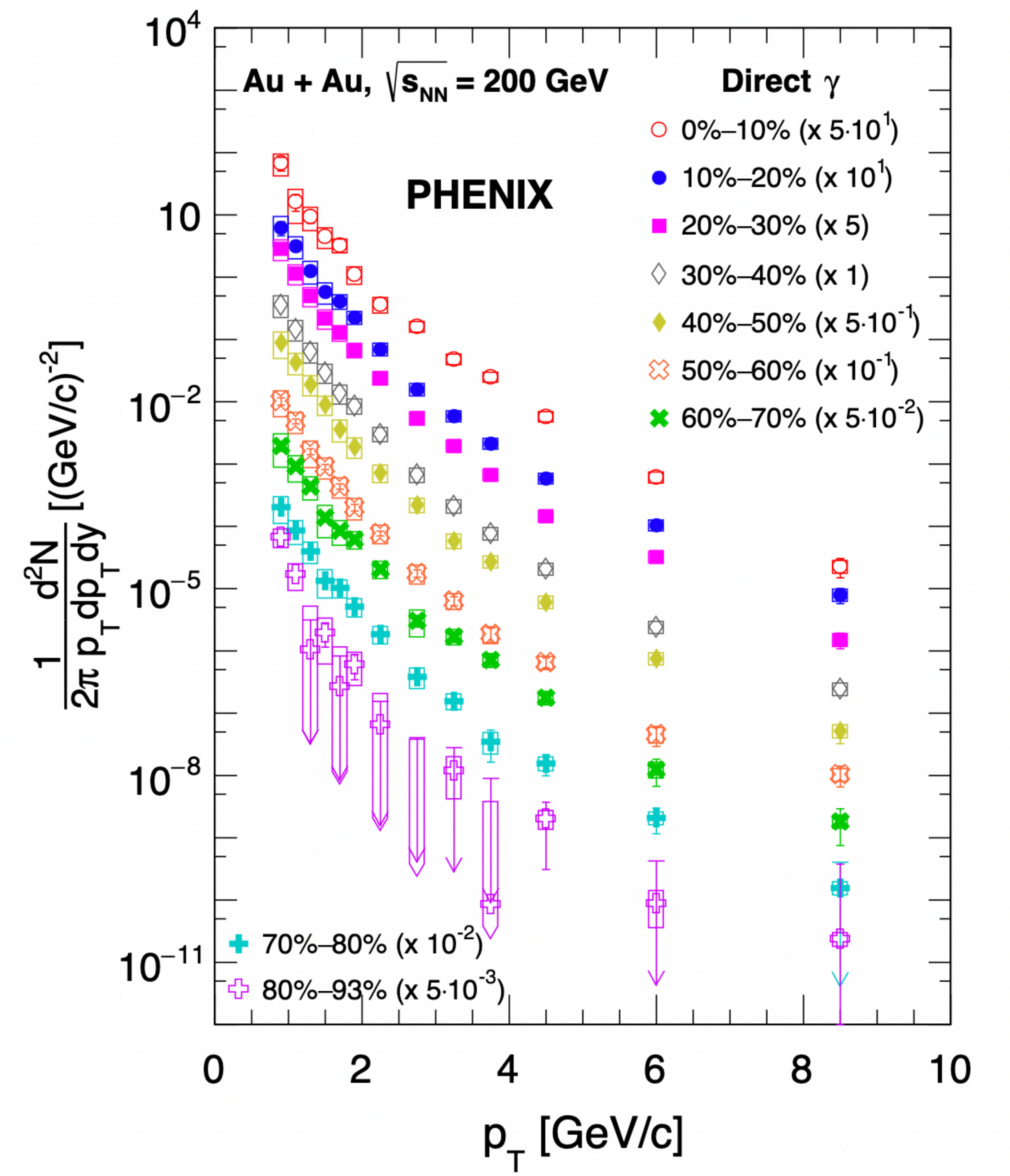
02/14/2024

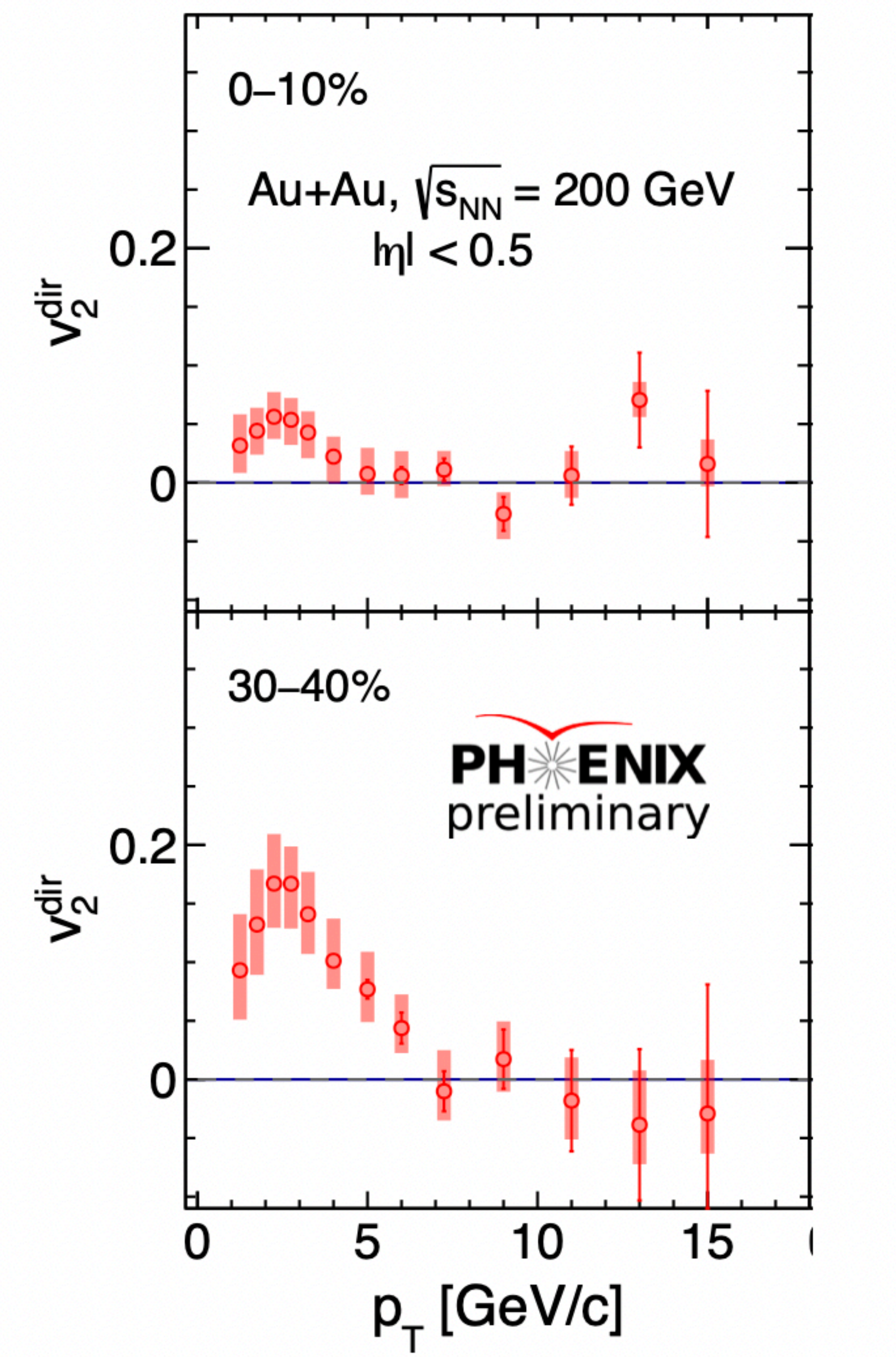
Outline

(A)
Direct Photon Spectra



Accepted by PRC(arXiv:2203.17187)

(B)
Direct Photon Flow



To be published soon!

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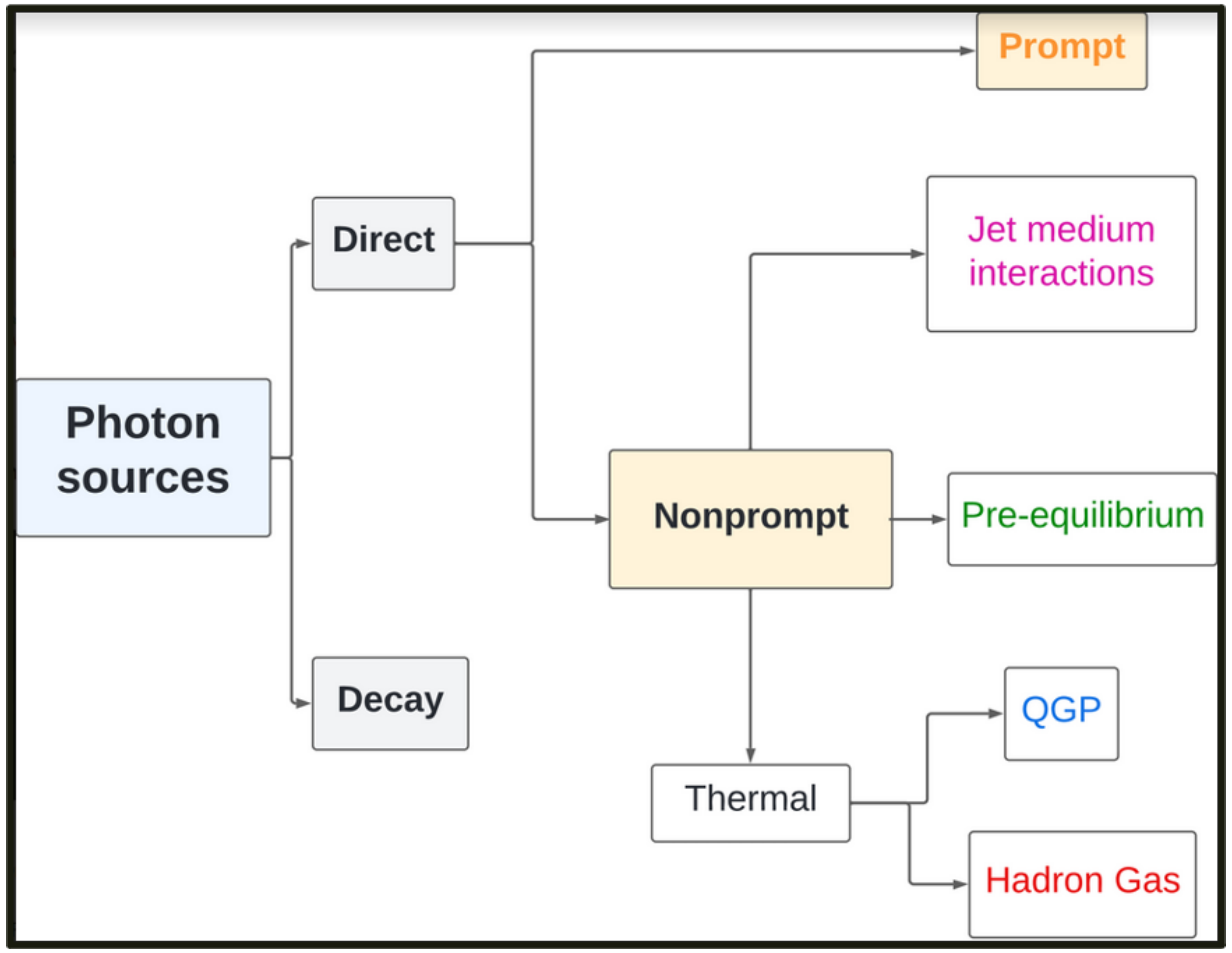
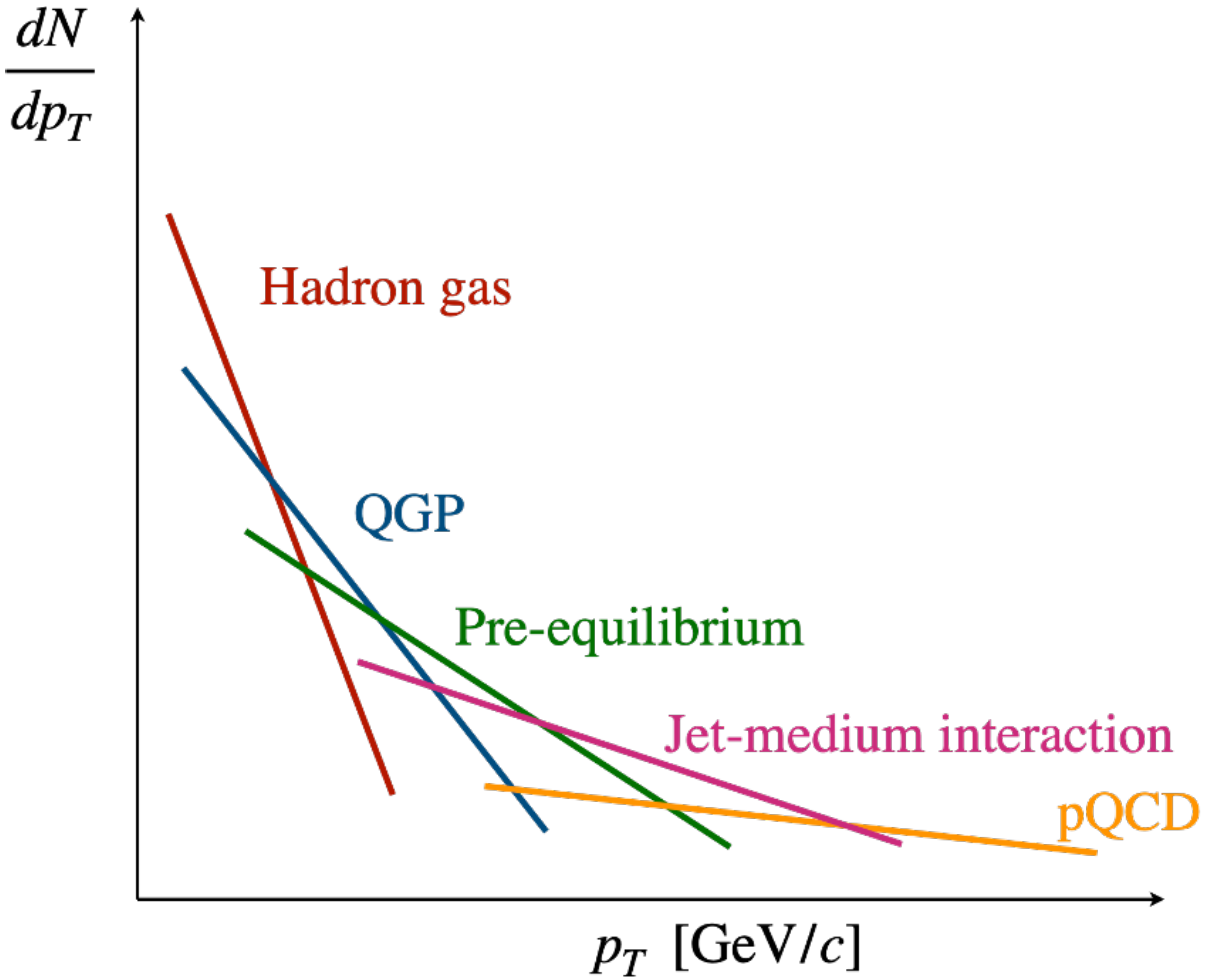
Why Photons ?

Photons are color blind probes of Quark Gluon Plasma



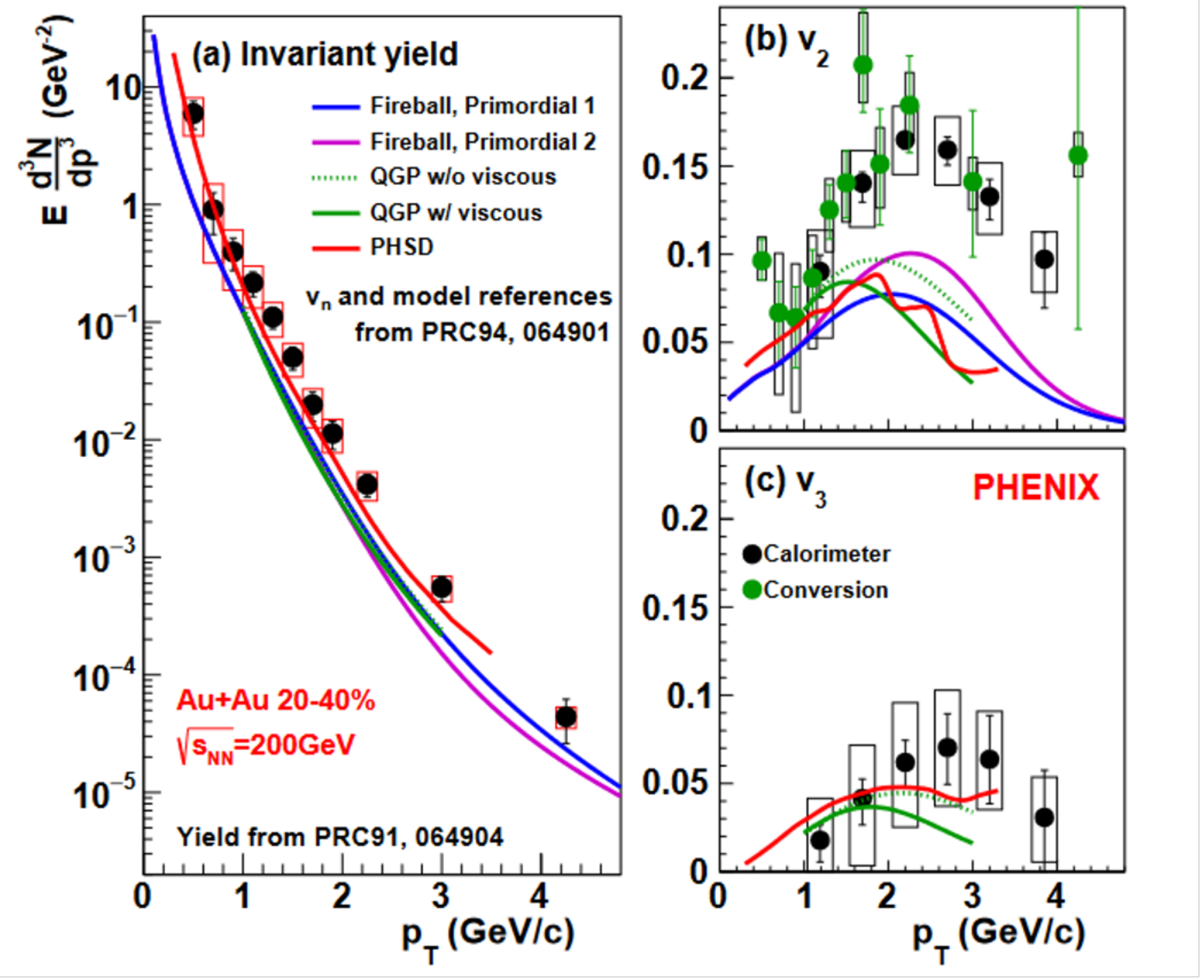


Sensitive to **space-time** evolution and **temperature** of matter produced!

Measurement of yield constrains initial conditions, sources, emission rates and space-time evolution

Direct Photon Puzzle:

Early vs Late Emission ?



- **Large yield and large v2**

· Large yield: emissions from the **early stage** when temperature is high

· Large v2: emissions from the **late stage** when the collective flow is sufficiently built up

Challenging for current theoretical models to describe large yield and elliptic flow simultaneously

Photon Measurements in PHENIX

Calorimeter Method → Photons that directly deposit energy into EMCals.

Phys. Rev. Lett. 109, 152302 (2012)

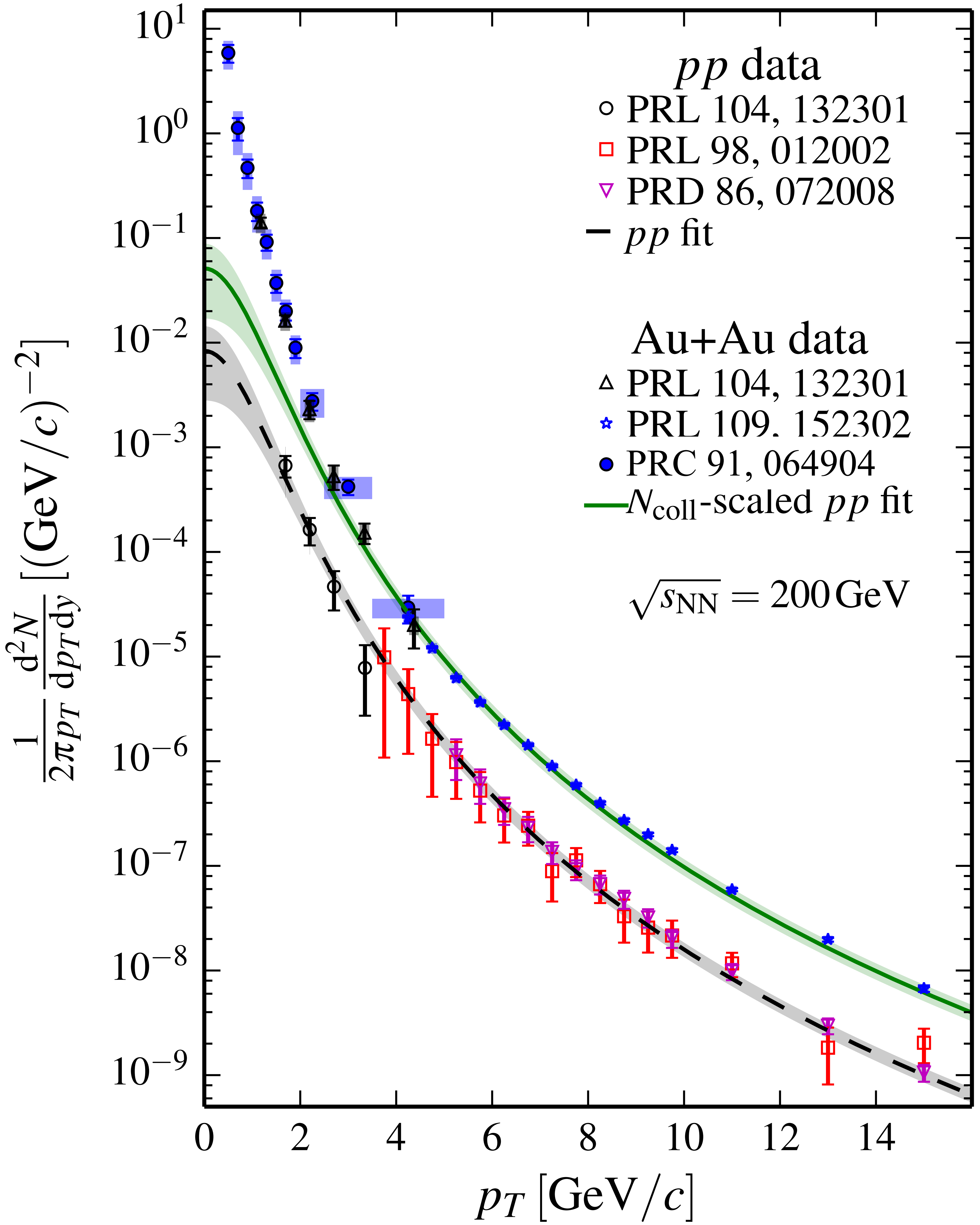
External Conversion Method → Photons that convert into e^+e^- pairs in the detector material. → Au+Au dataset at $\sqrt{s_{NN}} = 200$ GeV (2014)

arXiv:2203.17187
Phys. Rev. C 107, 024914 (2023)
Phys. Rev. C 91, 064904 (2015)

With the Silicon Vertex Detector (~ 14% X_0)

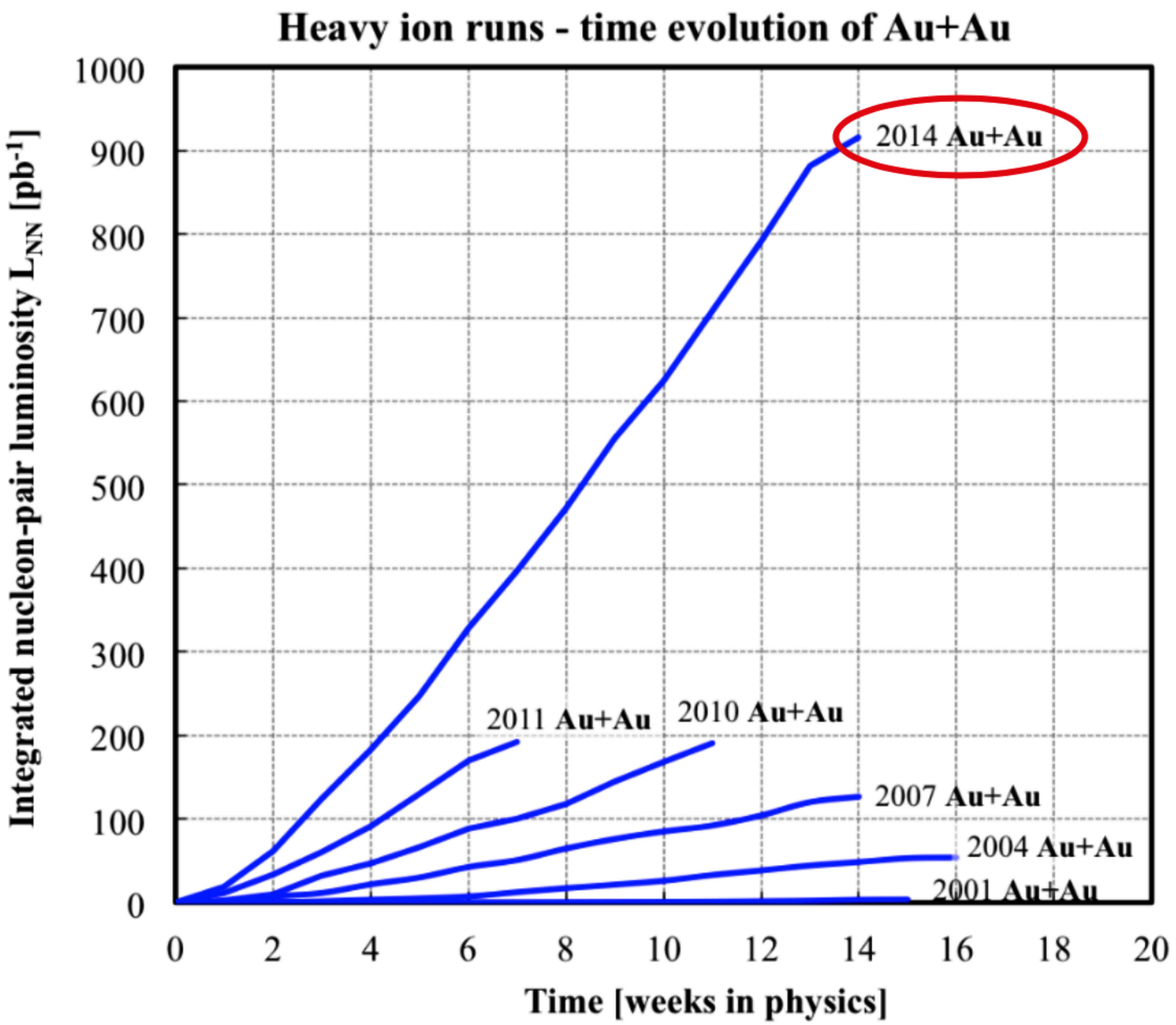
Internal Conversion Method → Virtual photons that internally convert into e^+e^- pairs.

Phys. Rev. Lett. 104, 132301 (2010)



3 independent measurements in good agreement with each other

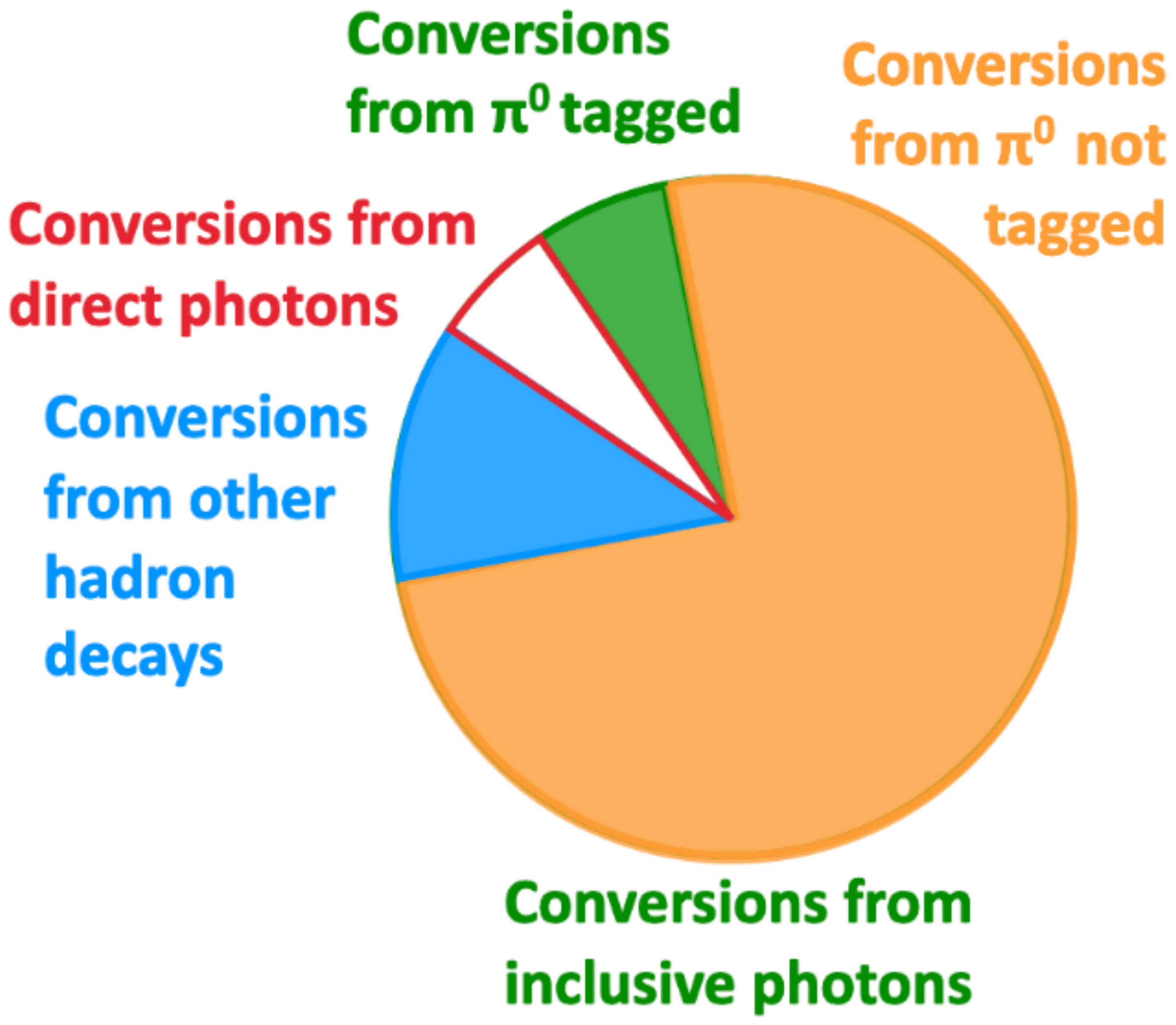
Towards Precision Measurement with "Golden Data Set"

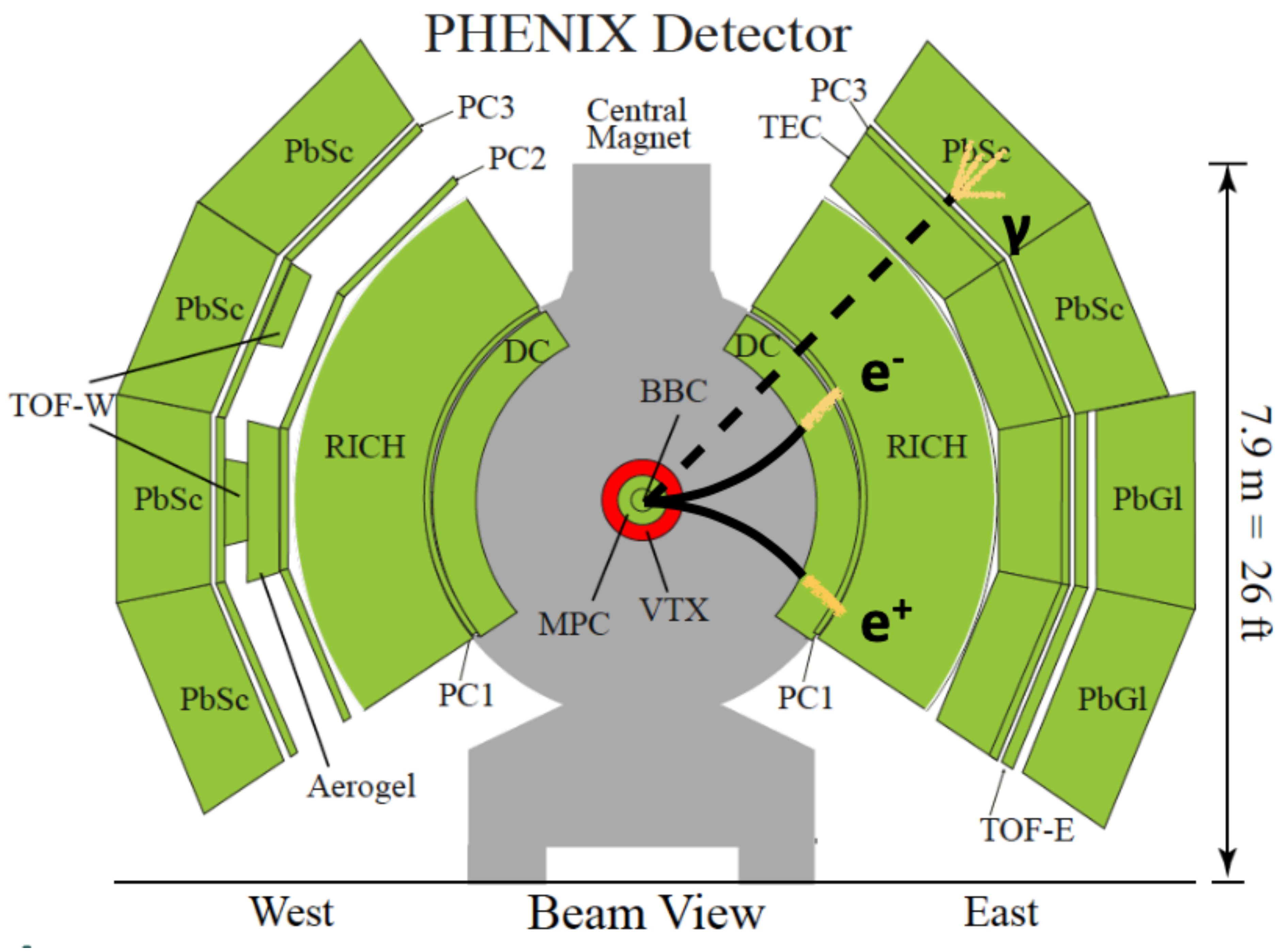


- Results from the high statistics 2014 dataset
  - more conversions at the PHENIX silicon vertex detector (VTX) (X/X_0 ~ 14%)
  - double differential analysis of shape and rapidity density of direct photon spectra as a function of p_T and charged particle multiplicity, $dN_{ch}/d\eta$
  - larger p_T coverage
  - v_2 measurements in finer centrality bins
  - smaller uncertainties

External Conversion: Double Ratio Tagging Method

$$R_\gamma = \frac{\gamma_{inclusive}}{\gamma_{hadron}} = \frac{\frac{\gamma_{inclusive}}{\gamma^{\pi^0}}}{\frac{\gamma_{hadron}}{\gamma^{\pi^0}}} = \frac{\langle \epsilon f \rangle \left(\frac{N_\gamma^{incl}}{N_\gamma^{\pi^0}} \right)_{Data}}{\left(\frac{\gamma^{hadron}}{\gamma^{\pi^0}} \right)_{Sim}}$$

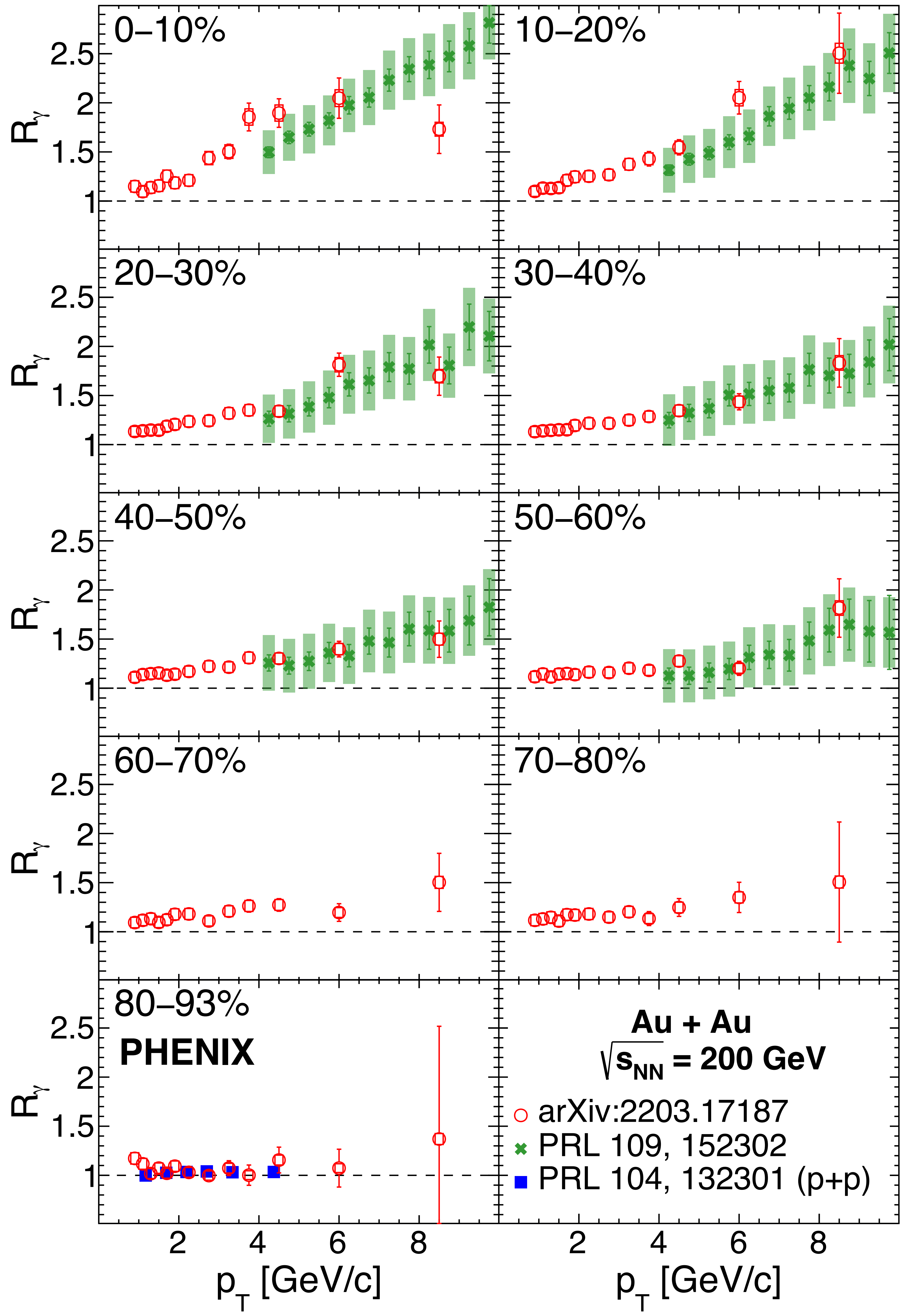




Double ratio tagging method reduces systematic uncertainties!

Direct γ for Au+Au at 200 GeV

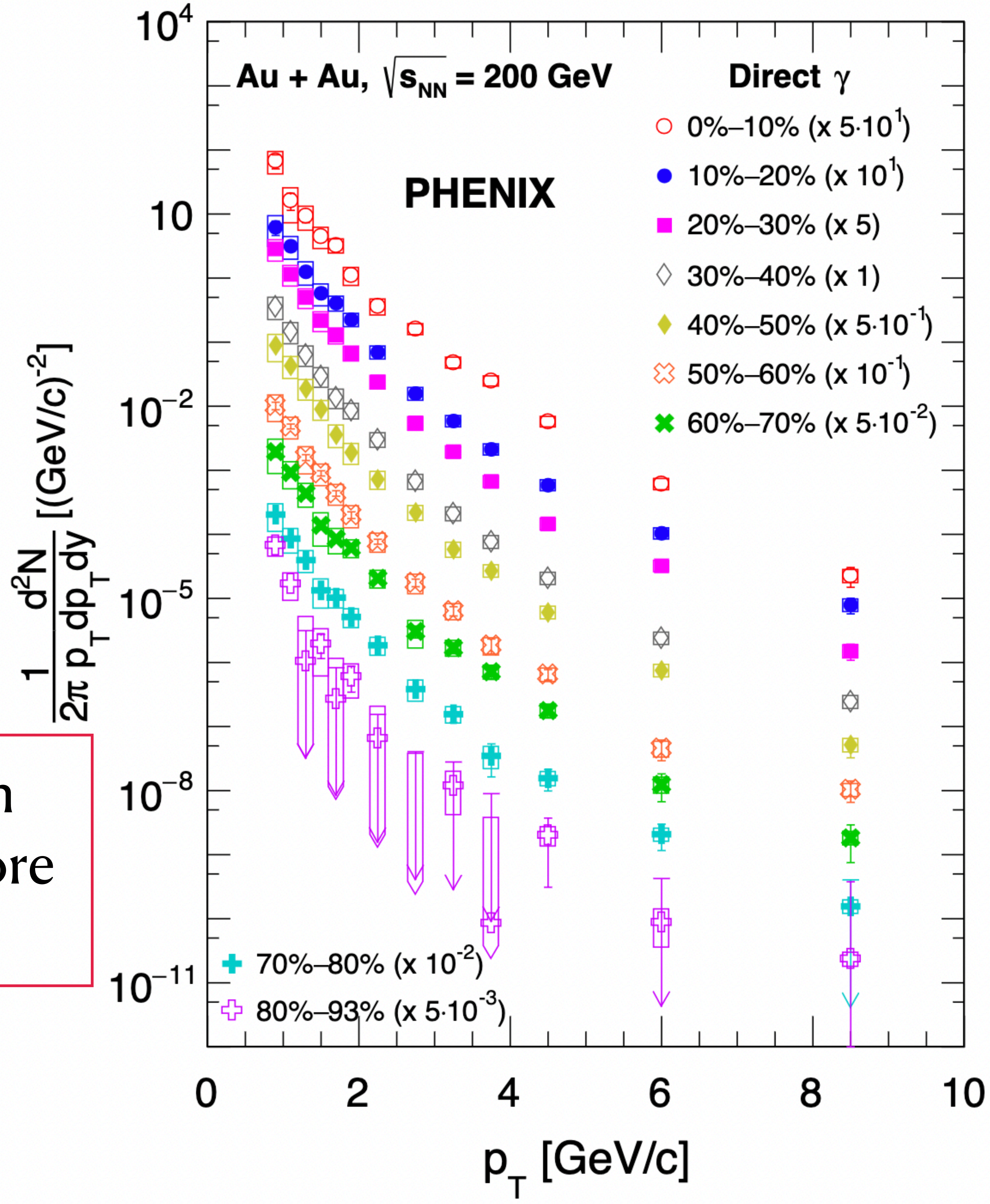
arXiv:2203.17187 (Accepted by PRC)



$$R_\gamma = \frac{\gamma_{inclusive}}{\gamma_{hadron}} = \frac{\frac{\gamma_{inclusive}}{\gamma^{\pi^0}}}{\frac{\gamma_{hadron}}{\gamma^{\pi^0}}}$$

$$\gamma^{dir} = (R_\gamma - 1)\ \gamma^{hadron}$$

About 20% direct photon component is seen in more central collisions.



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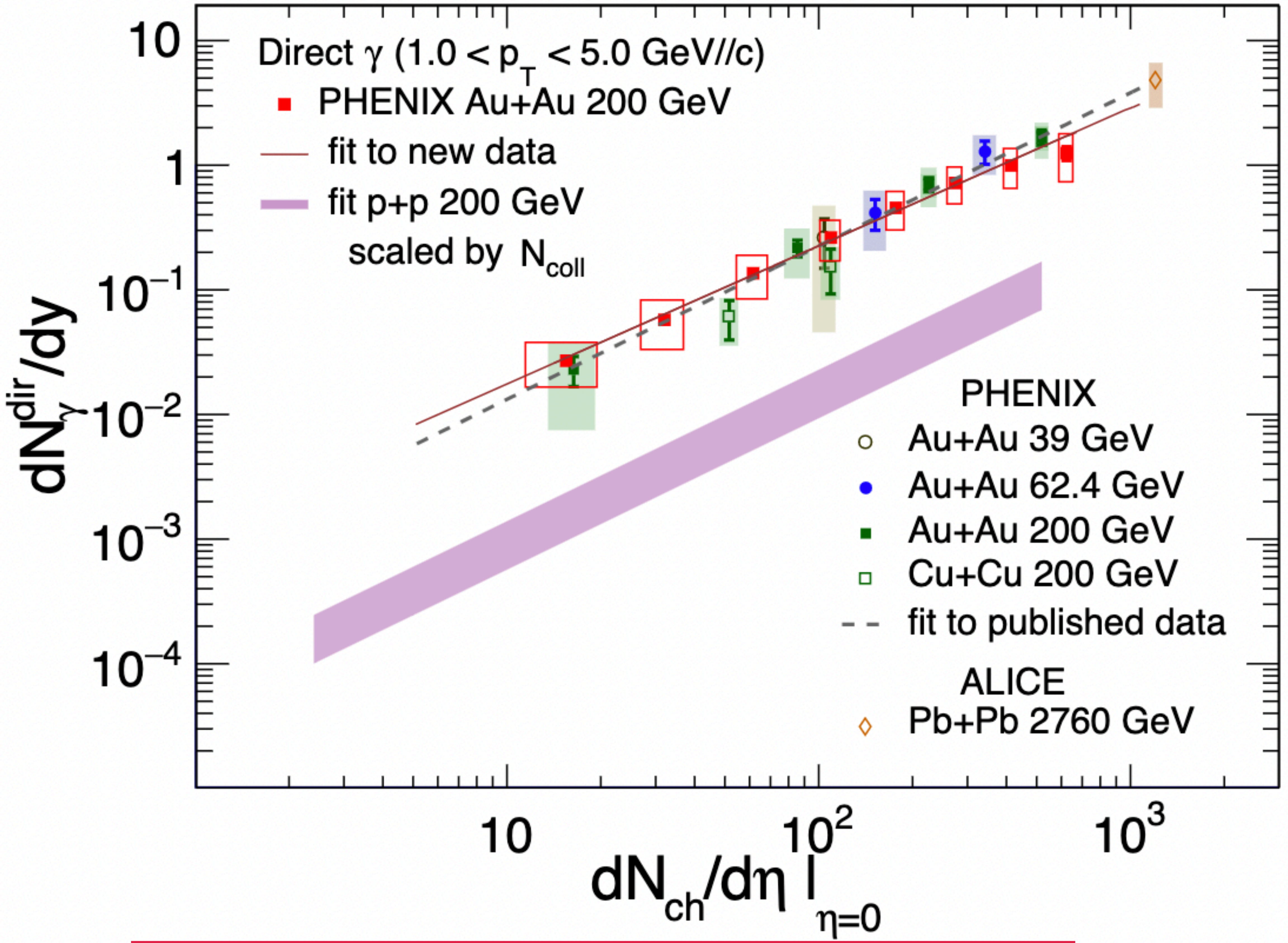
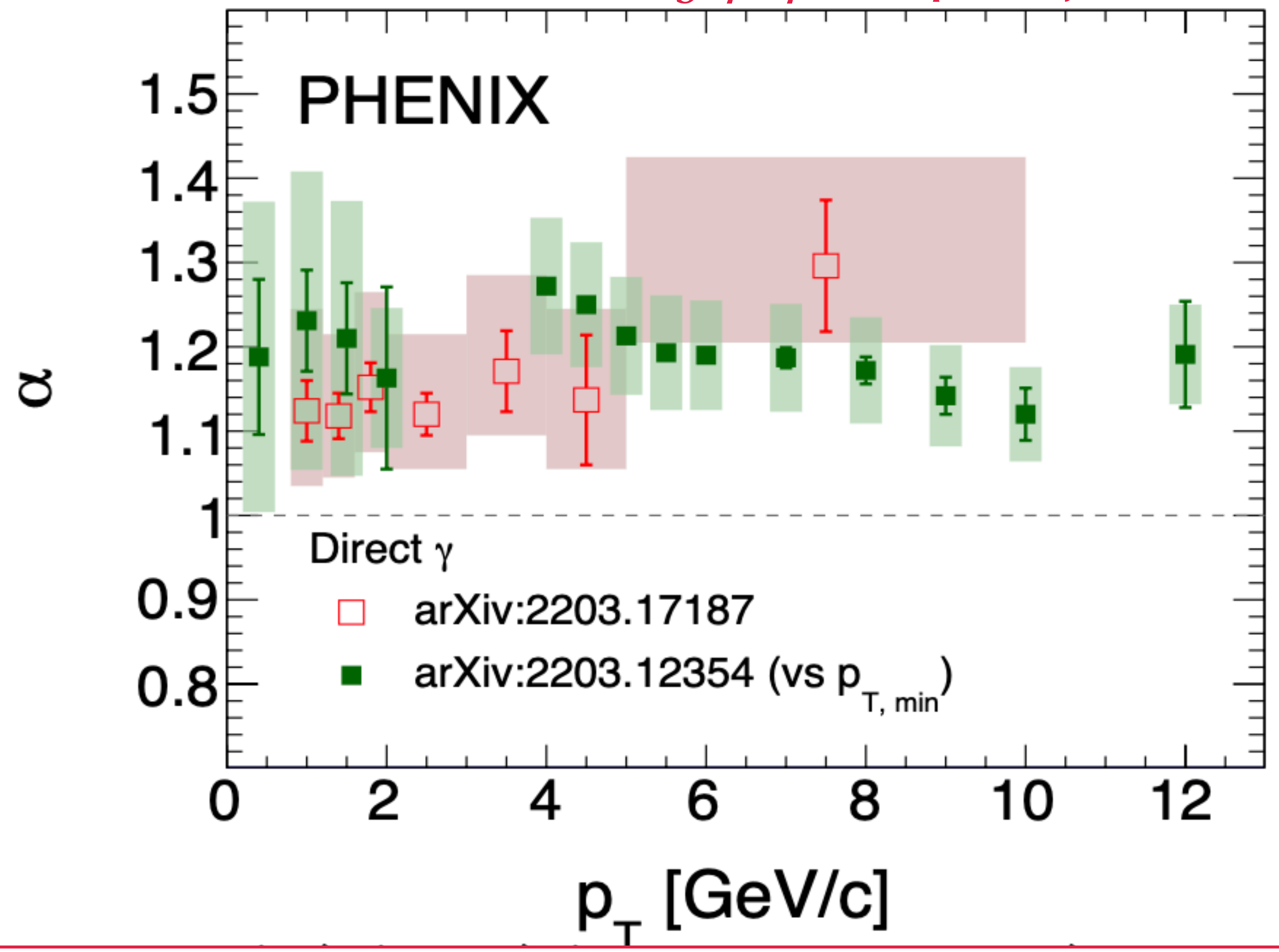
Universal Scaling of Direct γ Yields

arXiv:2203.17187 (Accepted by PRC)



arXiv:2203.17187 (Accepted by PRC)

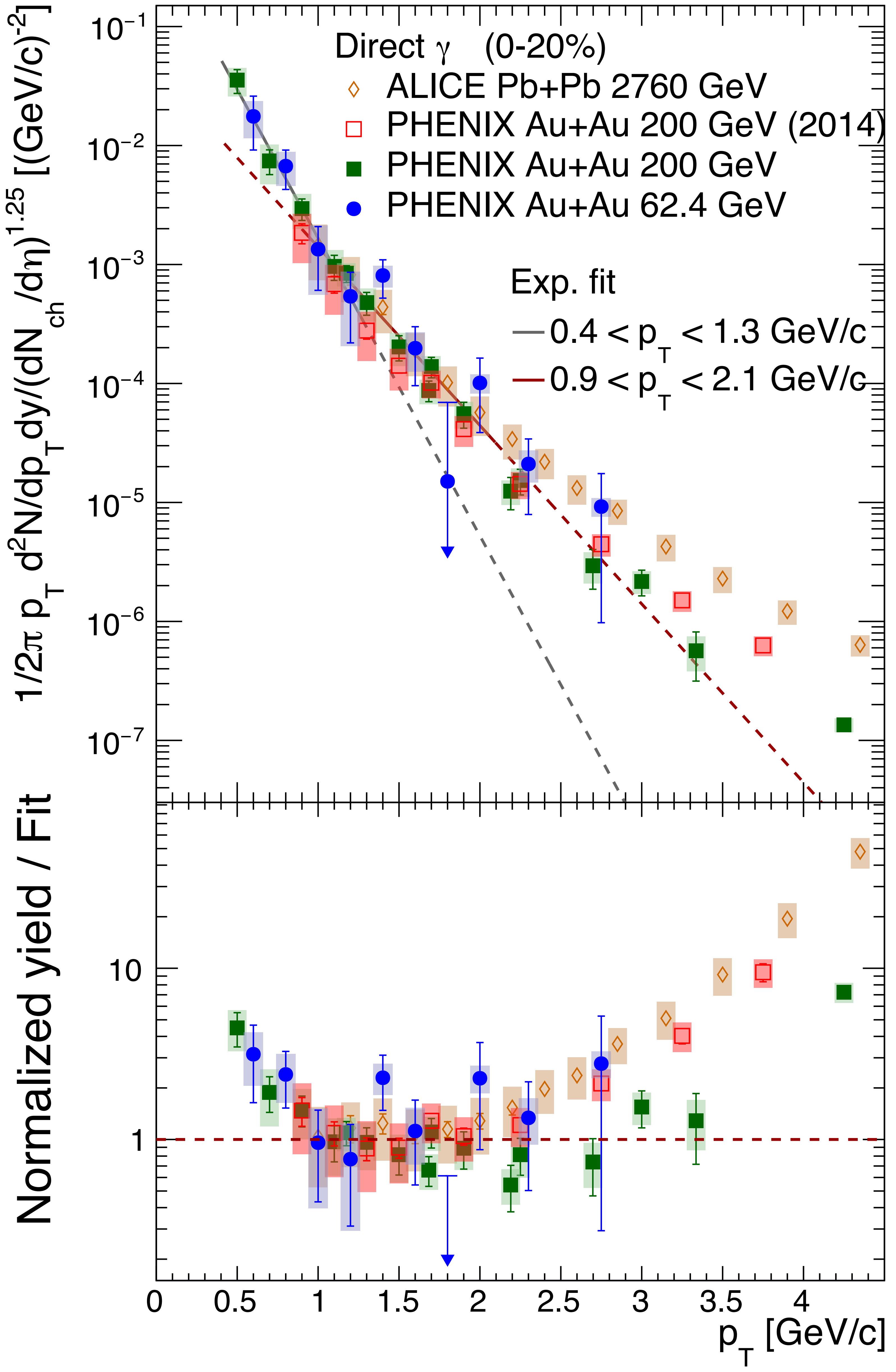


$$\frac{dN_\gamma}{dy} = A \times \left(\frac{dN_{ch}}{d\eta}\right)^\alpha$$

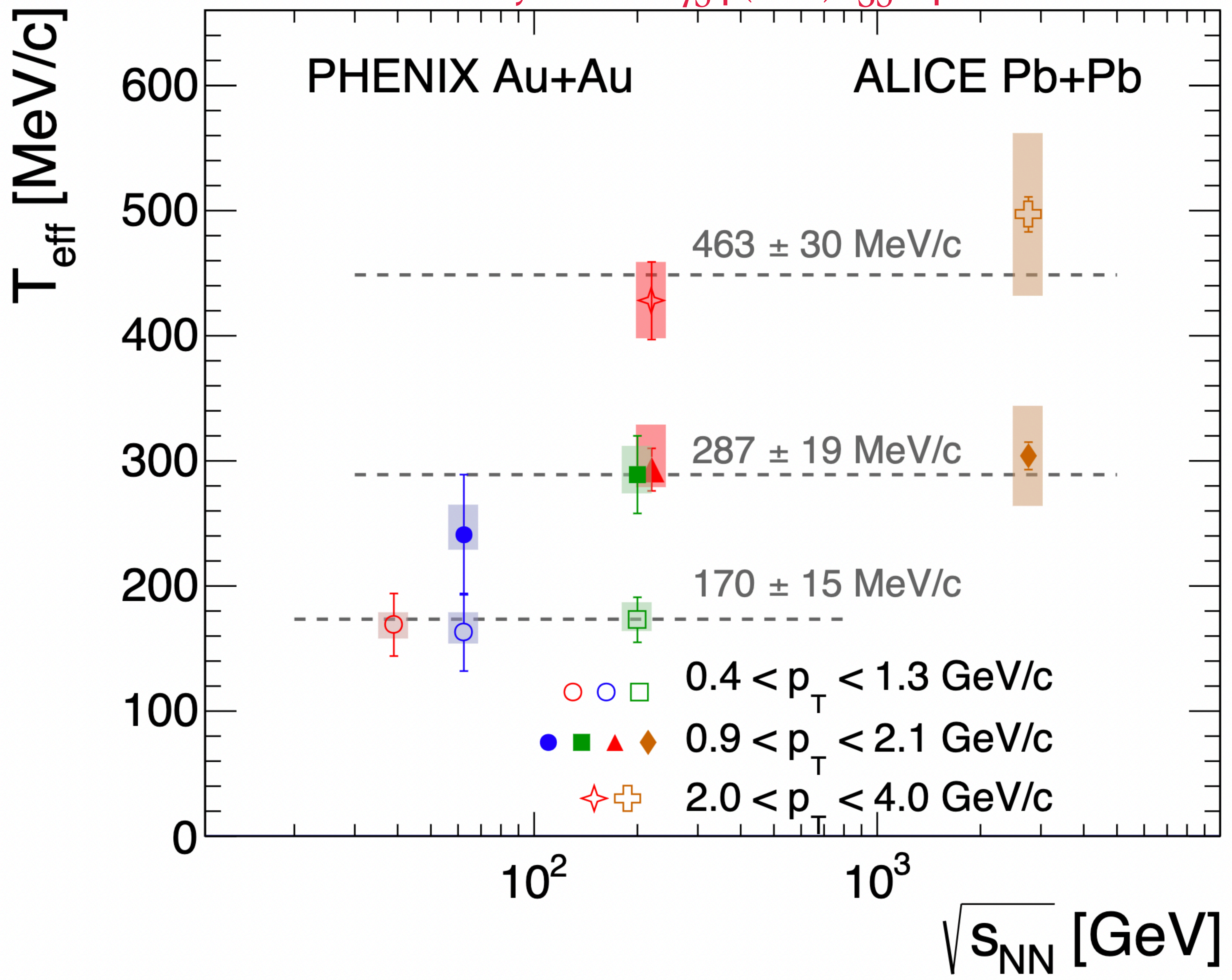
Universal scaling behaviour of direct photon yields in all A+A systems.

- **α** >1 and independent of p_T
- Hydro Model: Different dependence on $dN_{ch}/d\eta$ for QGP, HG and prompt component.

T_{eff} From Direct γ

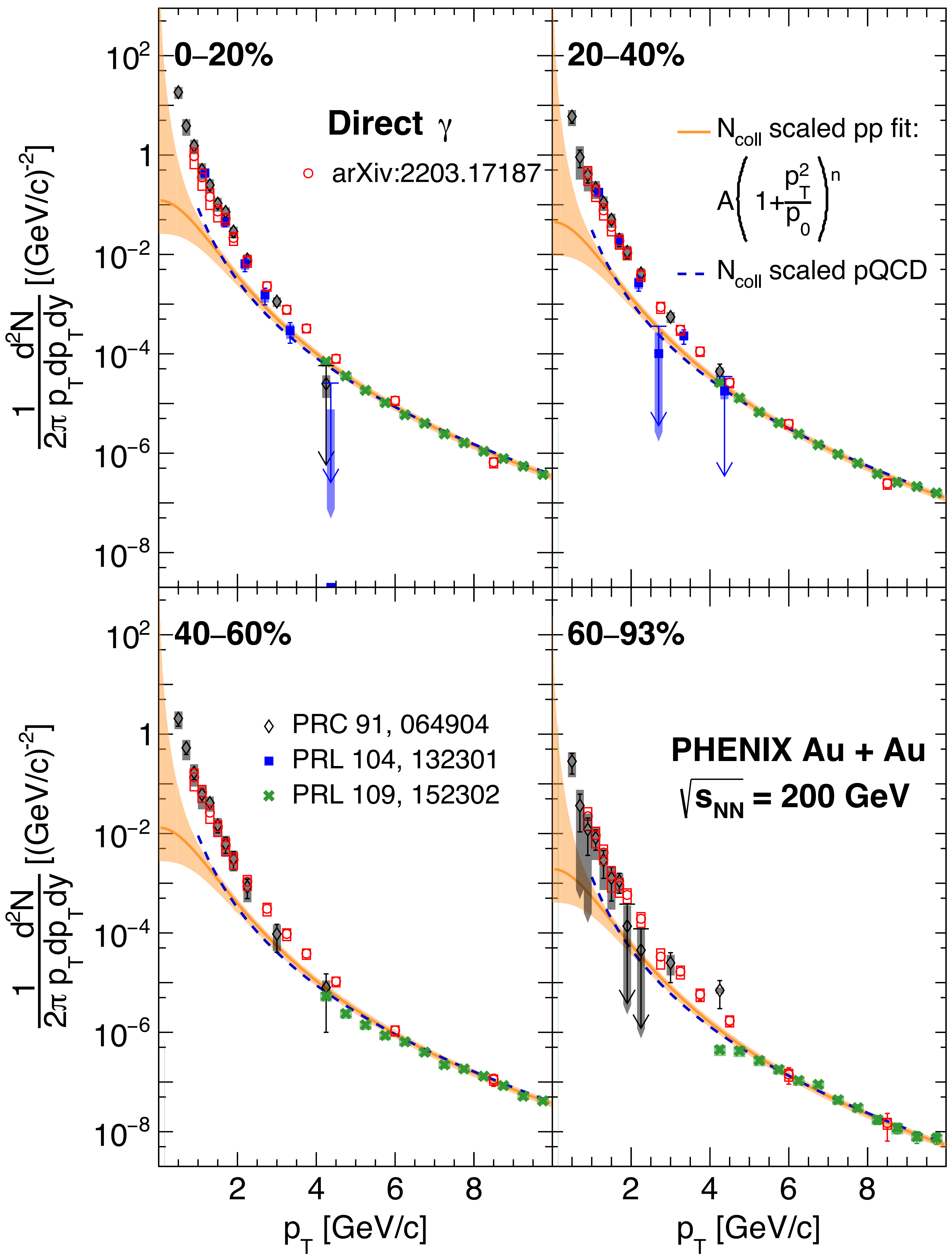


arXiv:2203.17187
Phys. Rev. C107, 024914 (2023)
Phys. Lett. B 754 (2016) 235-248



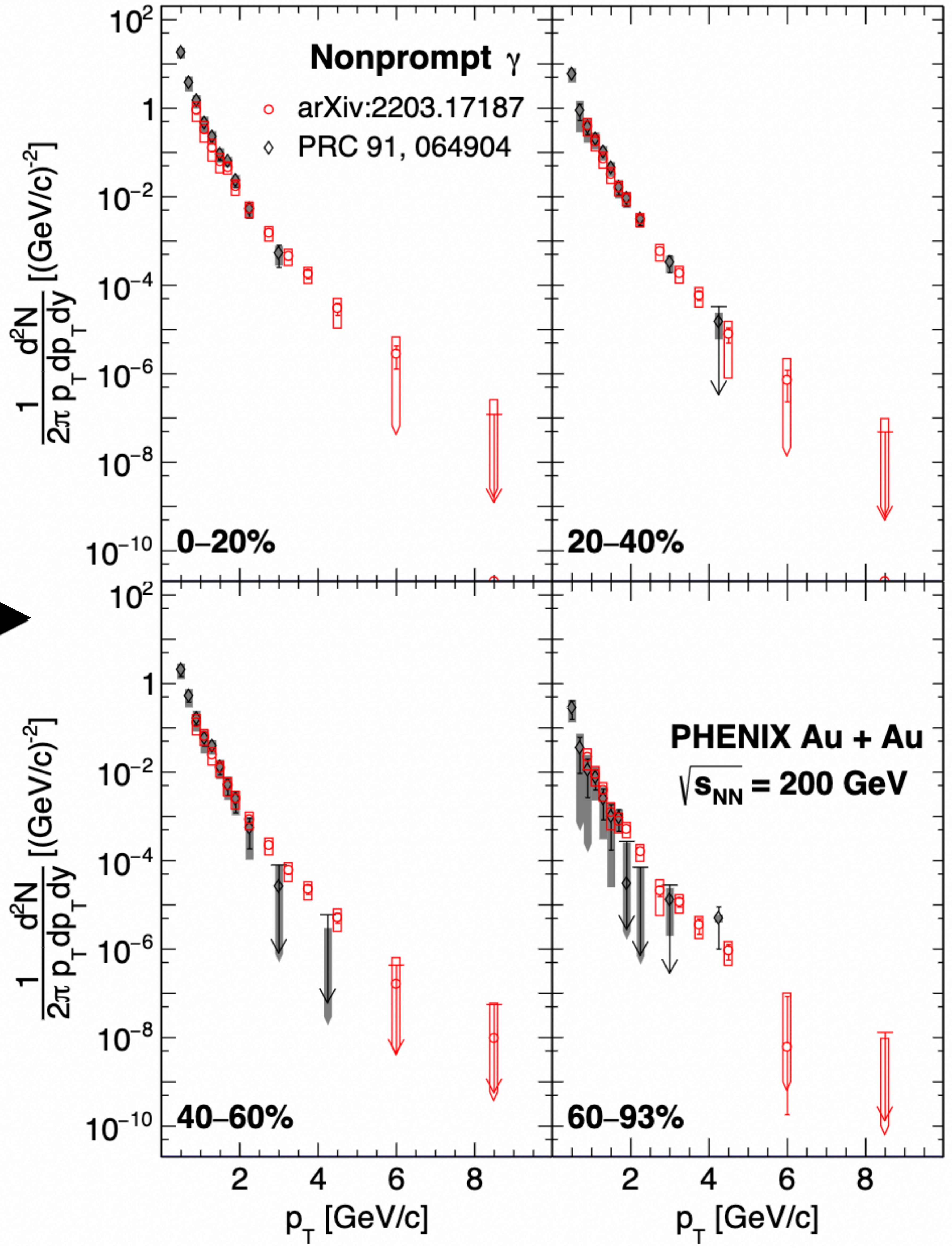
Similar spectra around 2 GeV/c -common source of photon production independent of $\sqrt{s_{NN}}$

Non-prompt Direct γ at Au+Au at 200 GeV



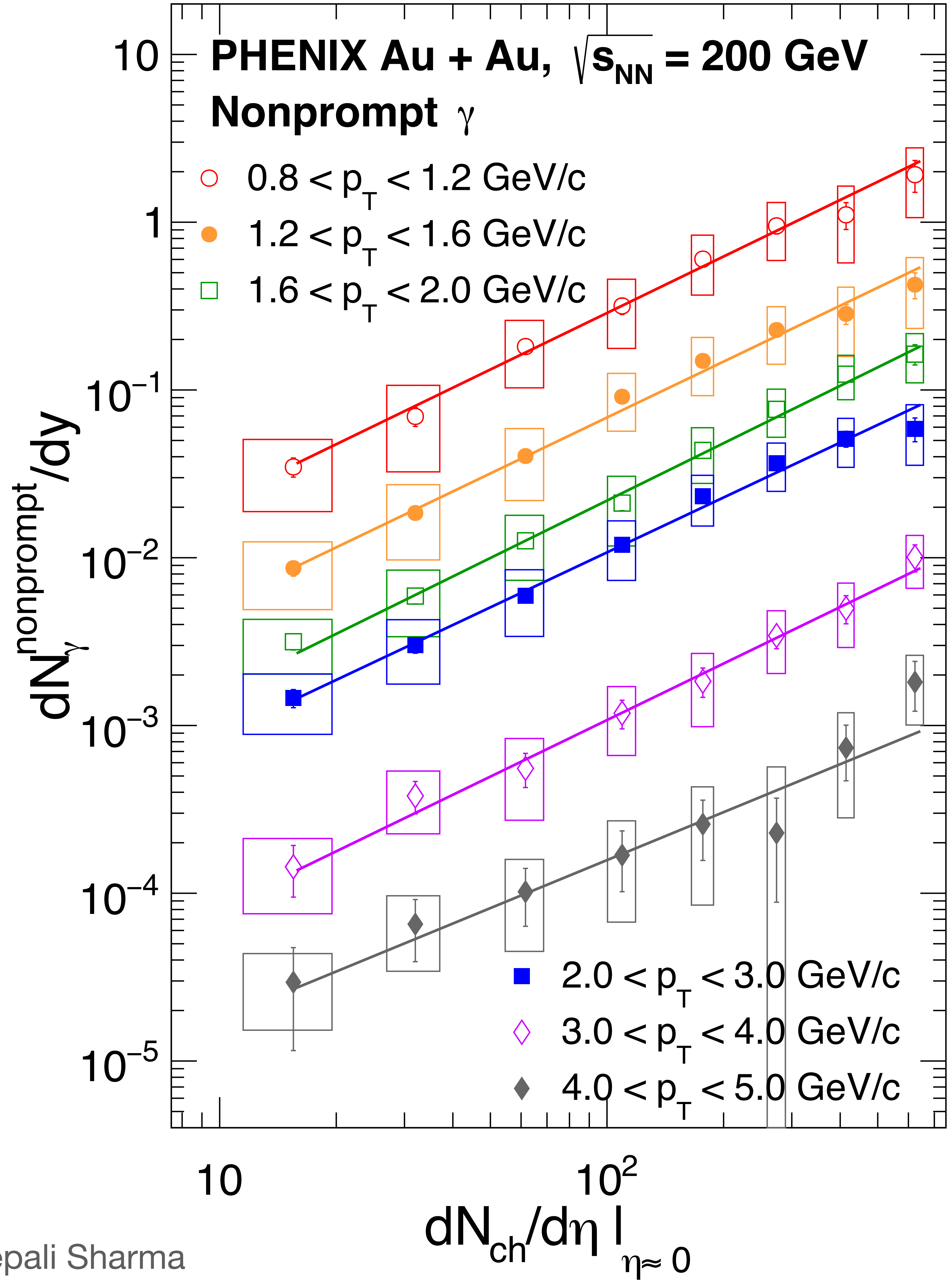
— N_{coll} scaled
p+p fit

Non-prompt direct photons

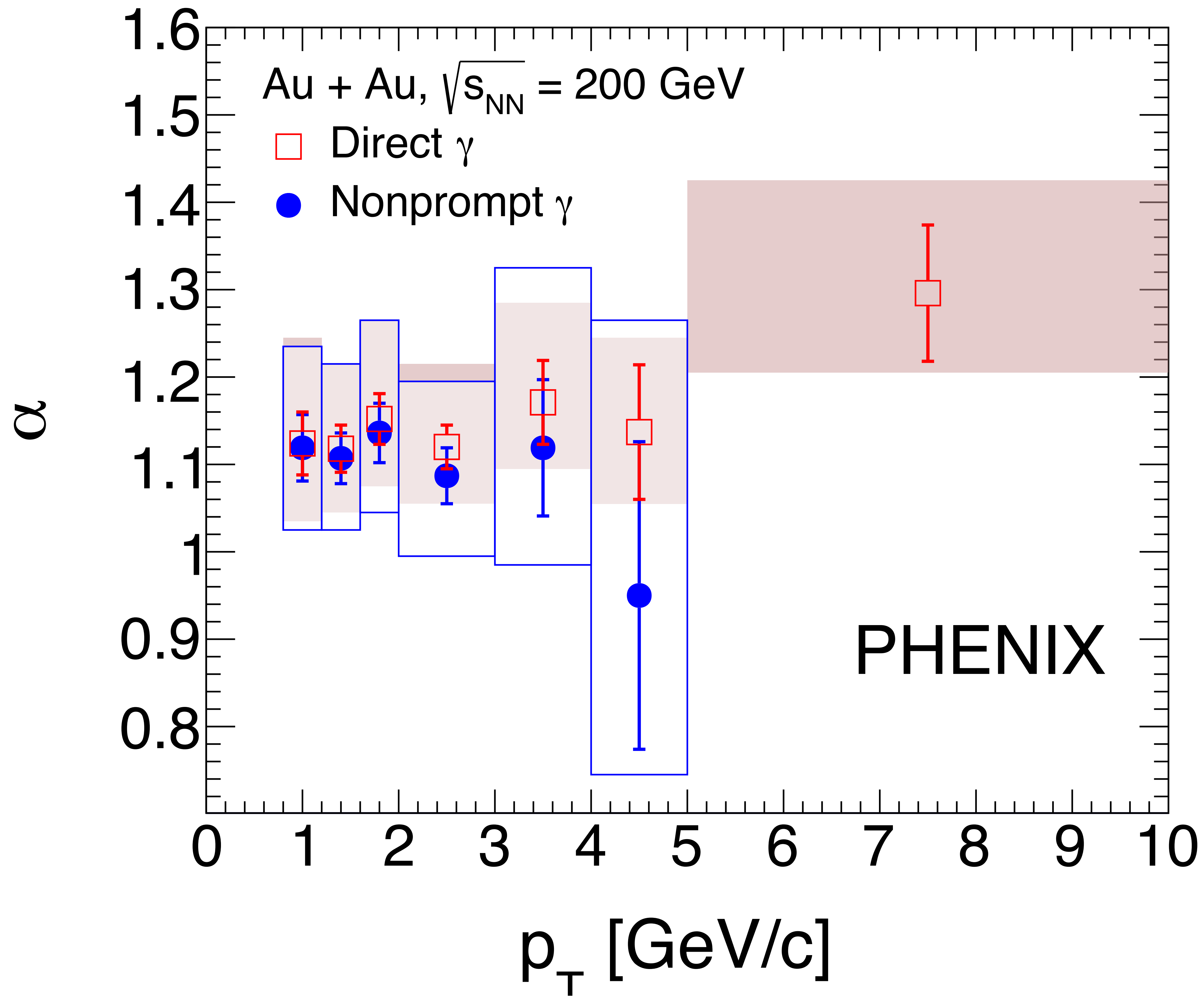


Scaling of Non-prompt Direct γ with $dN_{ch}/d\eta$

arXiv:2203.17187 (Accepted by PRC)



arXiv:2203.17187 (Accepted by PRC)



α independent of p_T for direct photons and non-prompt photons

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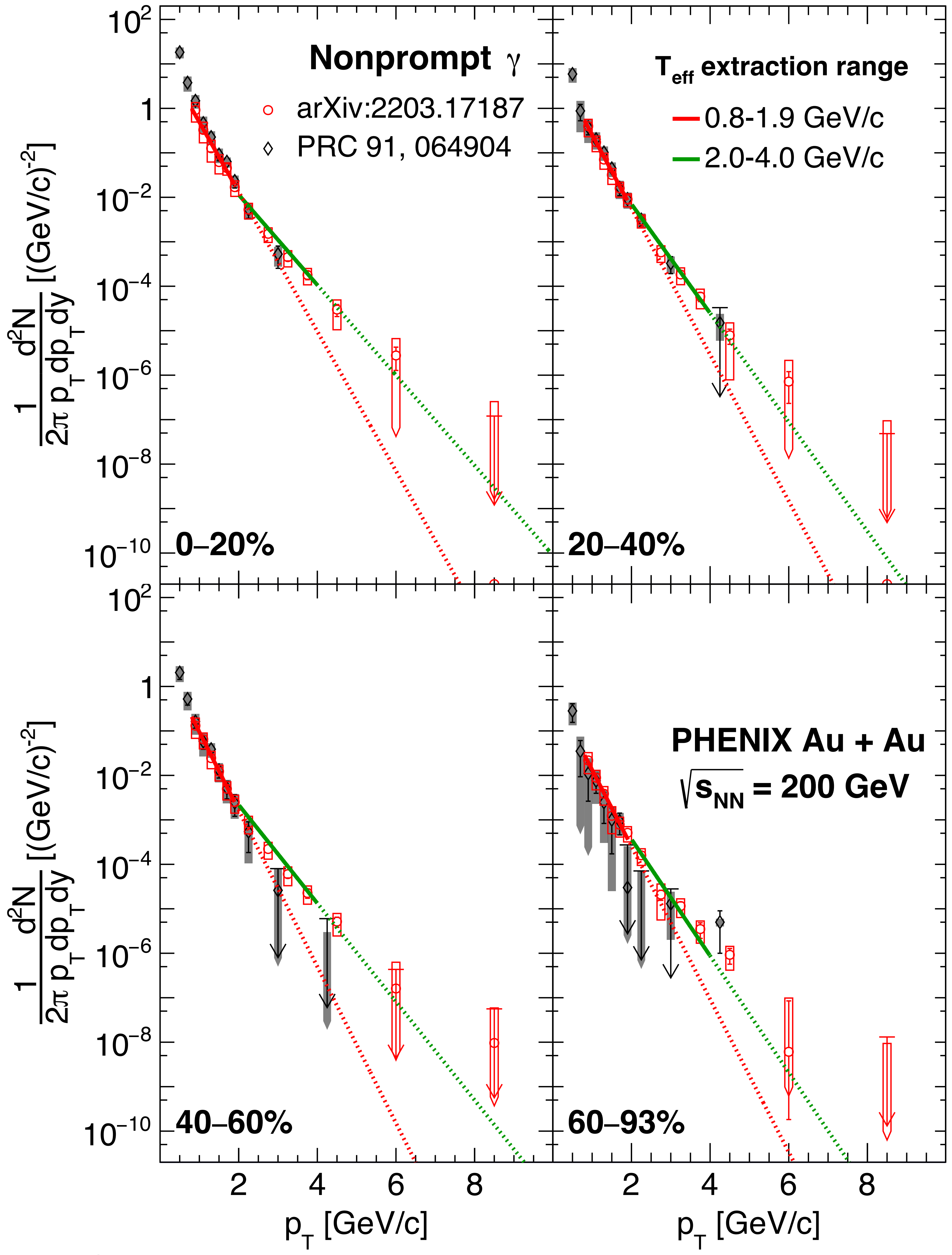
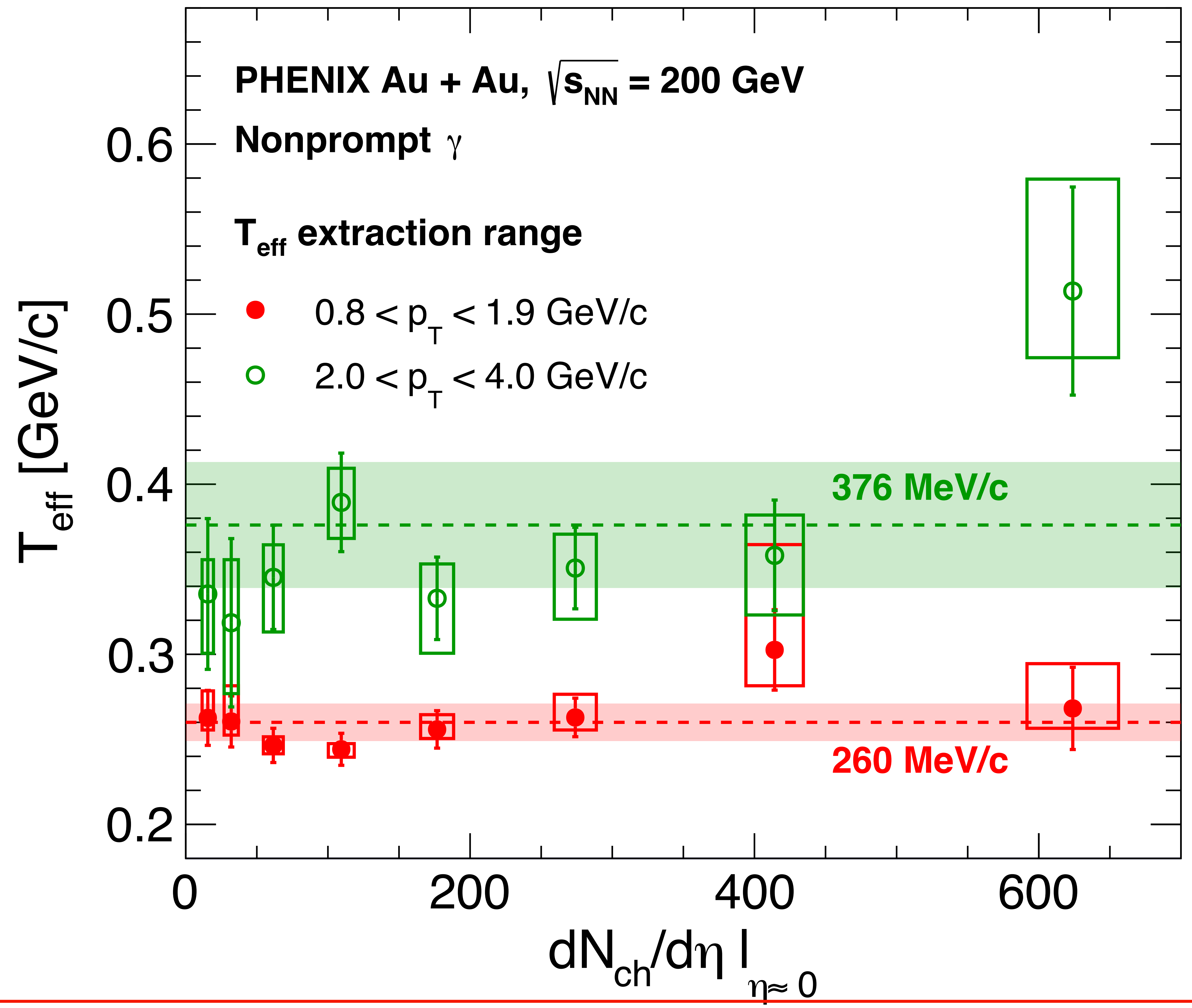
T_{eff} for Non-prompt Direct γ

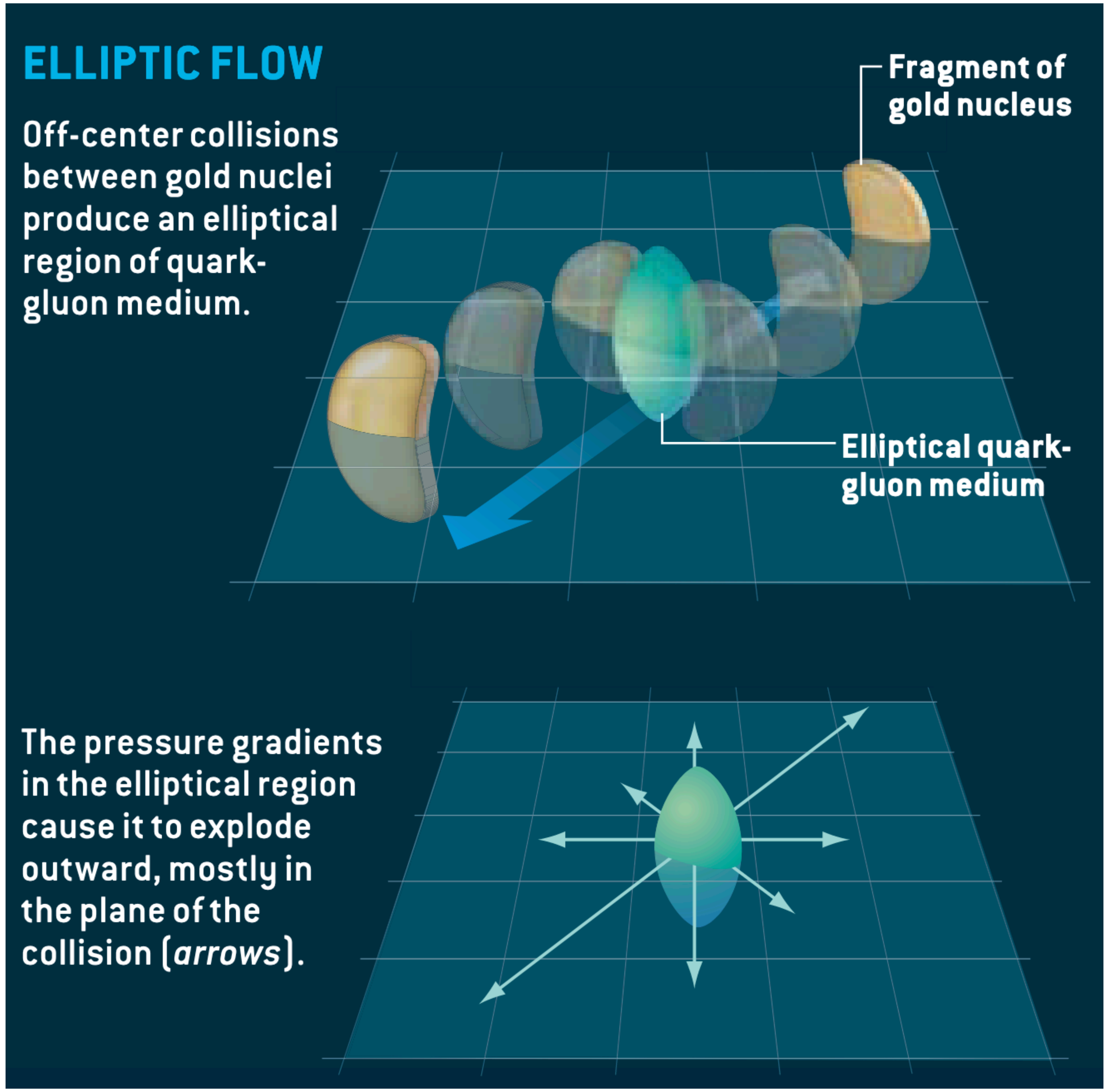
arXiv:2203.17187 (Accepted by PRC)





- No obvious system size dependence of T_{eff}
- Increasing inverse slope (>350 MeV/c) with p_T suggests contributions from sources beyond those from Hadron Gas

Elliptic Flow of Direct Photons



- Quantified by the second Fourier moment of the particle azimuthal distribution with respect to the reaction plane.

$$\frac{dN}{d\phi} = N_0[1 + 2v_2 \cos(2\phi)]$$

- In the analysis, v_2 is calculated using the following equation

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

- We measure the anisotropy in the azimuthal distribution of photons with respect to the reaction plane determined by the forward vertex detector $1.5 < |\eta| < 2.9$.

Direct Photons v_2 (R_γ Calculation)

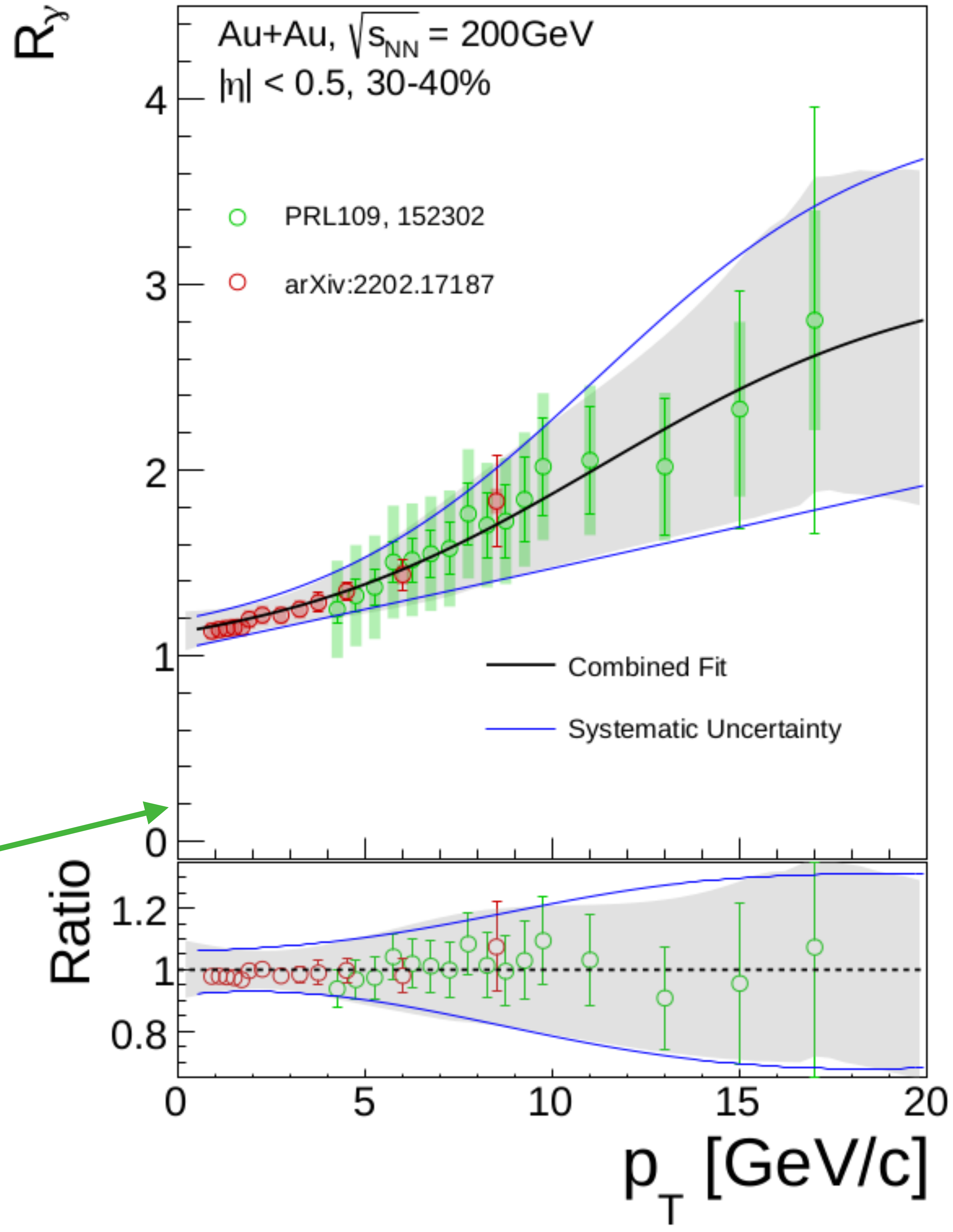
v_2^{incl} of all the photons measured by the EMCal (from data)

v_2^{dec} of all the photons coming from hadron decays (comes from cocktail)

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

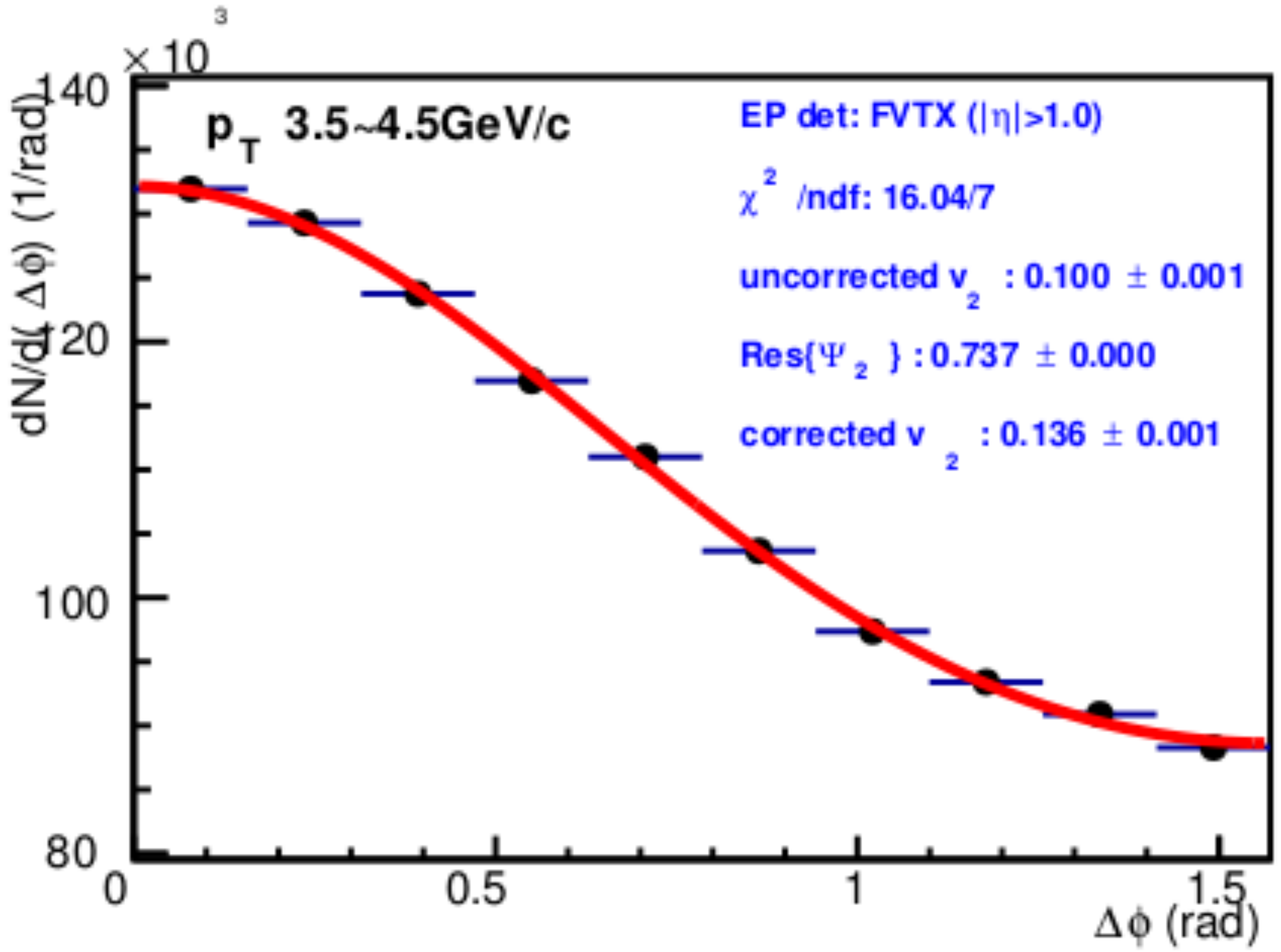
R_γ of direct photons (measured from data)

Calculating R_γ for flow extraction

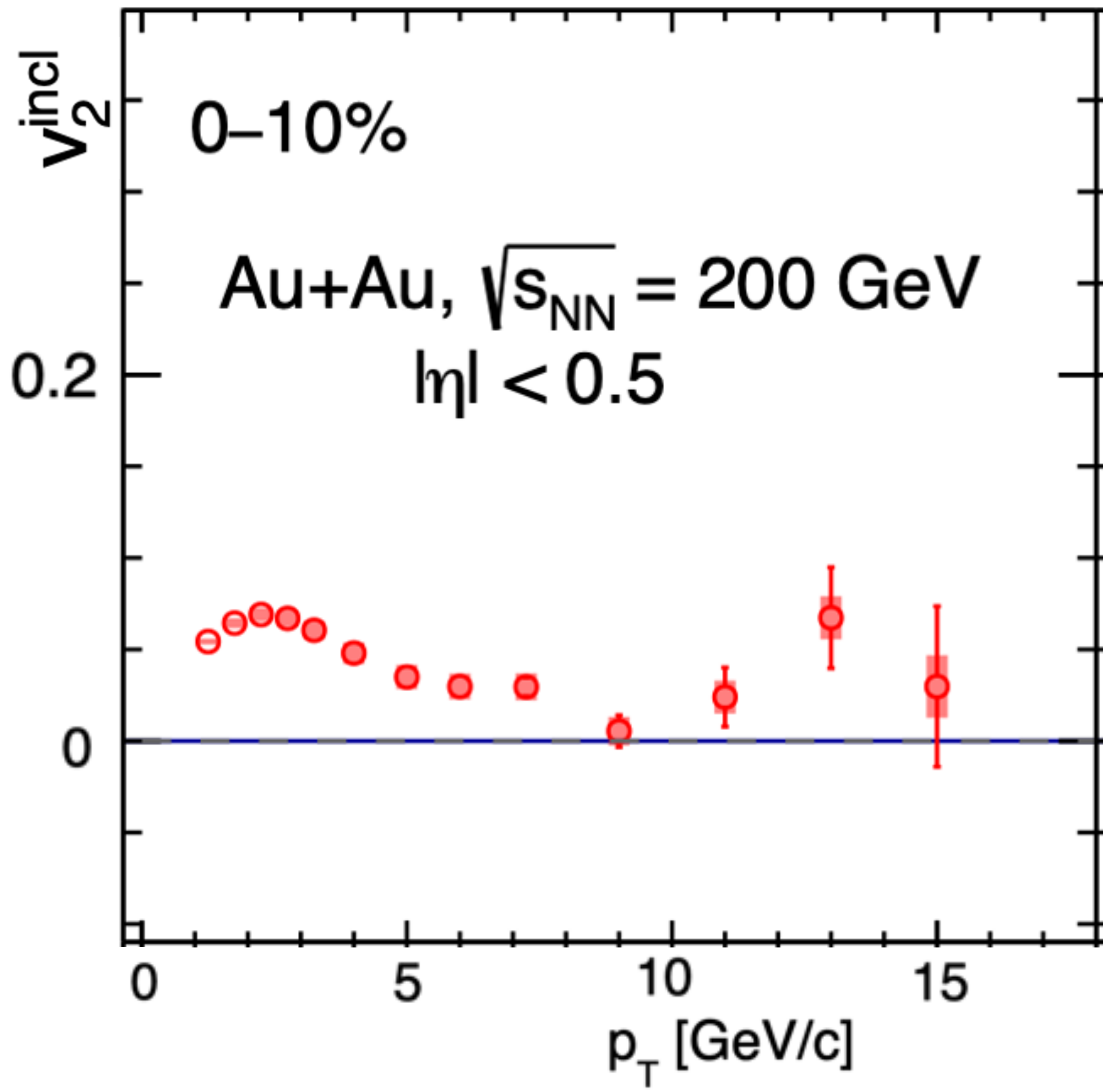


Inclusive Photon Flow (v_2^{incl}) Extraction

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



Repeat fit over all pT bins



Fit $\Delta\phi$ distribution for a given p_T bin to

$$\frac{dN}{d\Delta\phi} = A(1 + 2v_2\cos(2\Delta\phi) + 2v_4 cos(4\Delta\phi))$$

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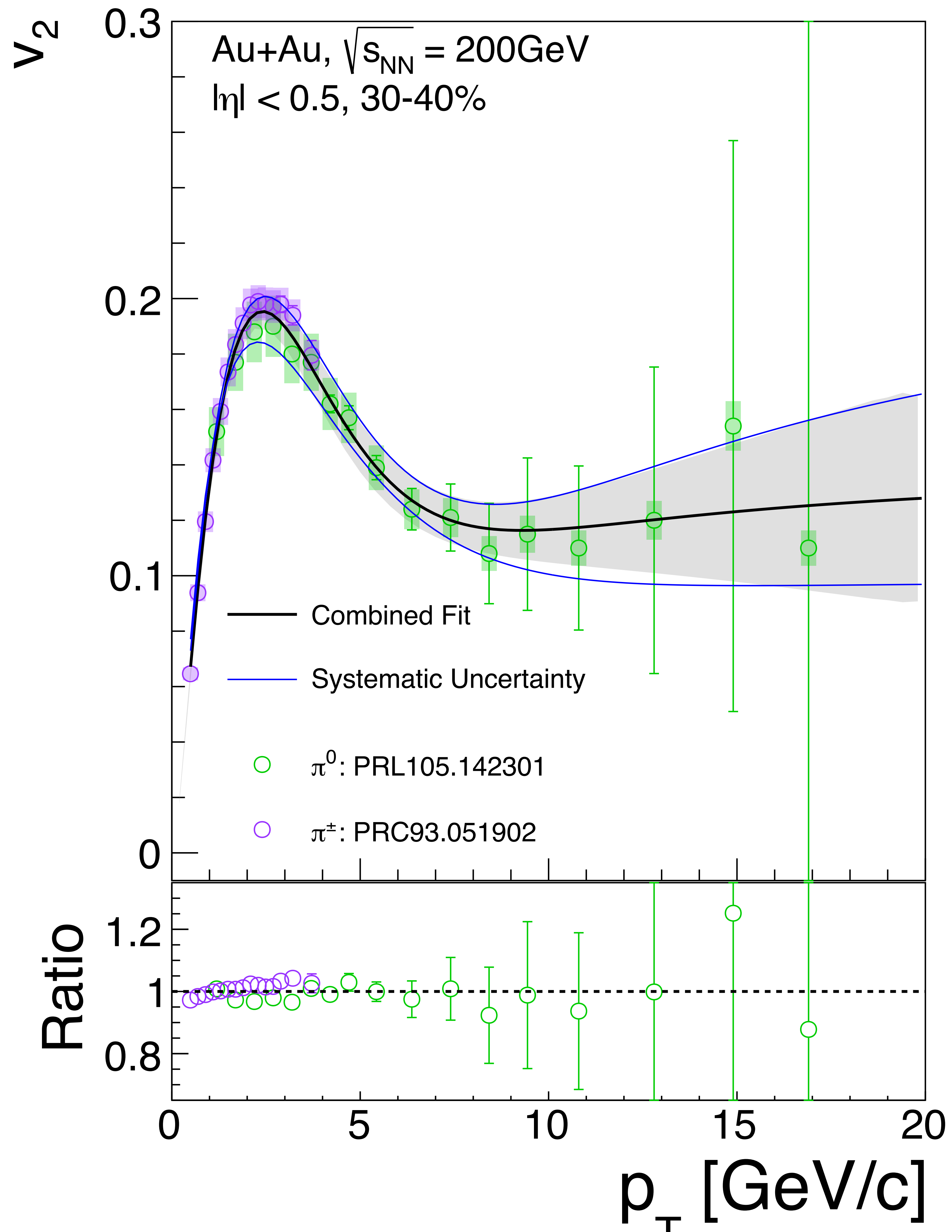
Hadron Decay Photon Flow (v_2^{dec}) Extraction

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

- A combined fit to multiple measurements of $\pi^0, \pi^\pm$ v_2
- Fit is used as input into the simulations to calculate decay photon v_2
- Contributions of other mesons estimated by scaling KE_T
    - $v_2^{\pi}(KE_T) = v_2^{allmesons}(KE_T)$
    - $KE_T = \sqrt{p_T^2 + m^2} - m$



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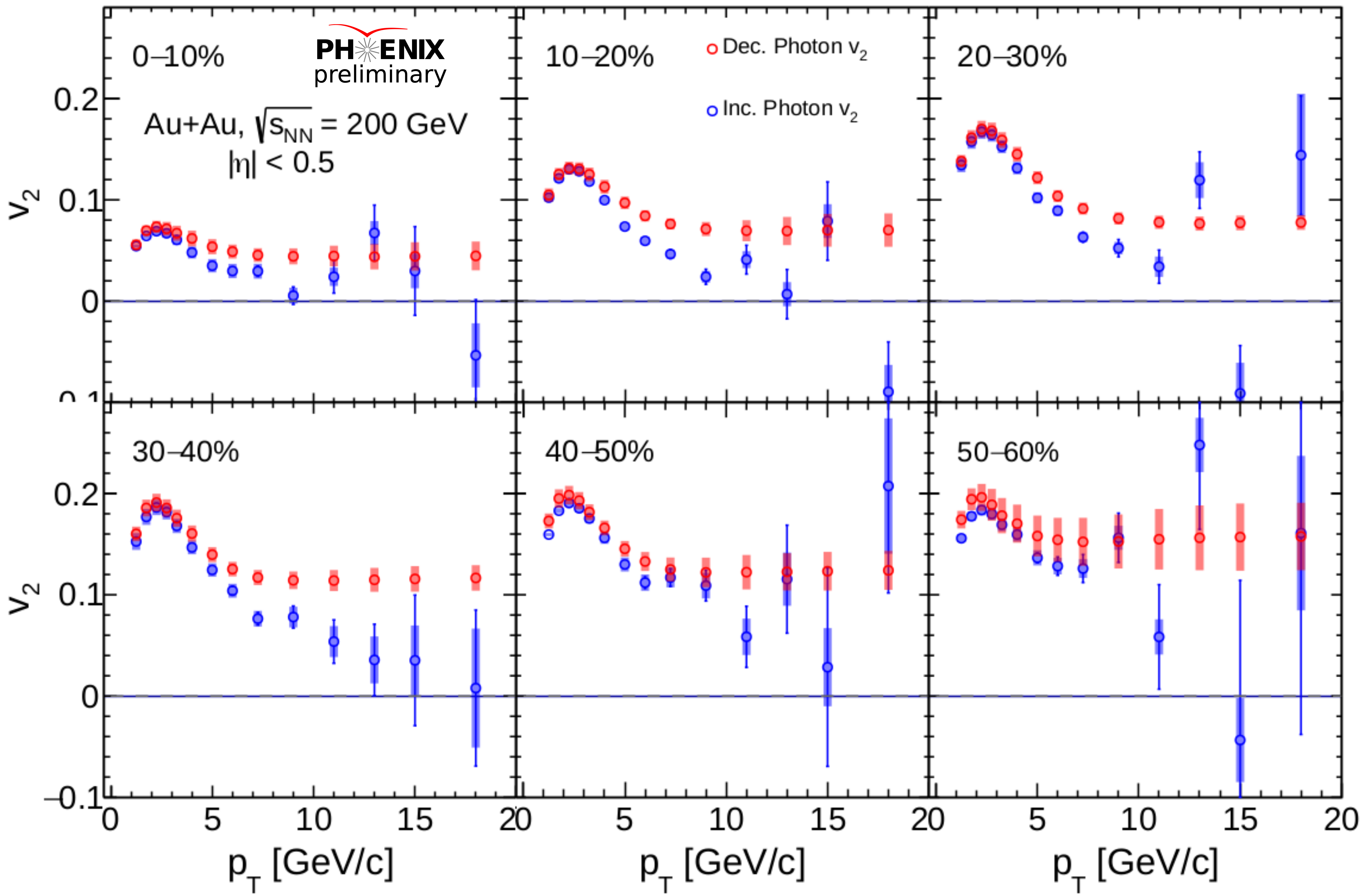
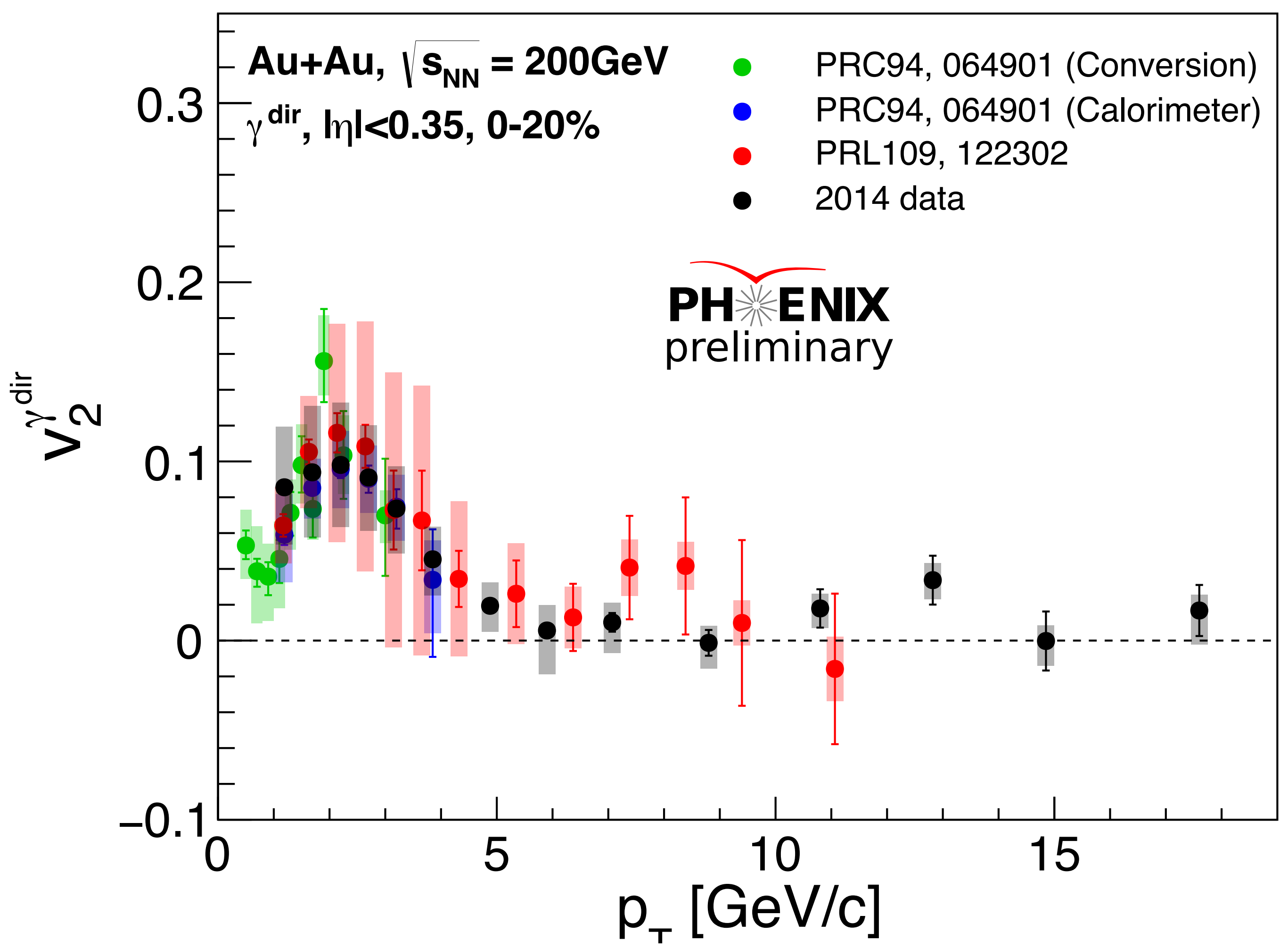
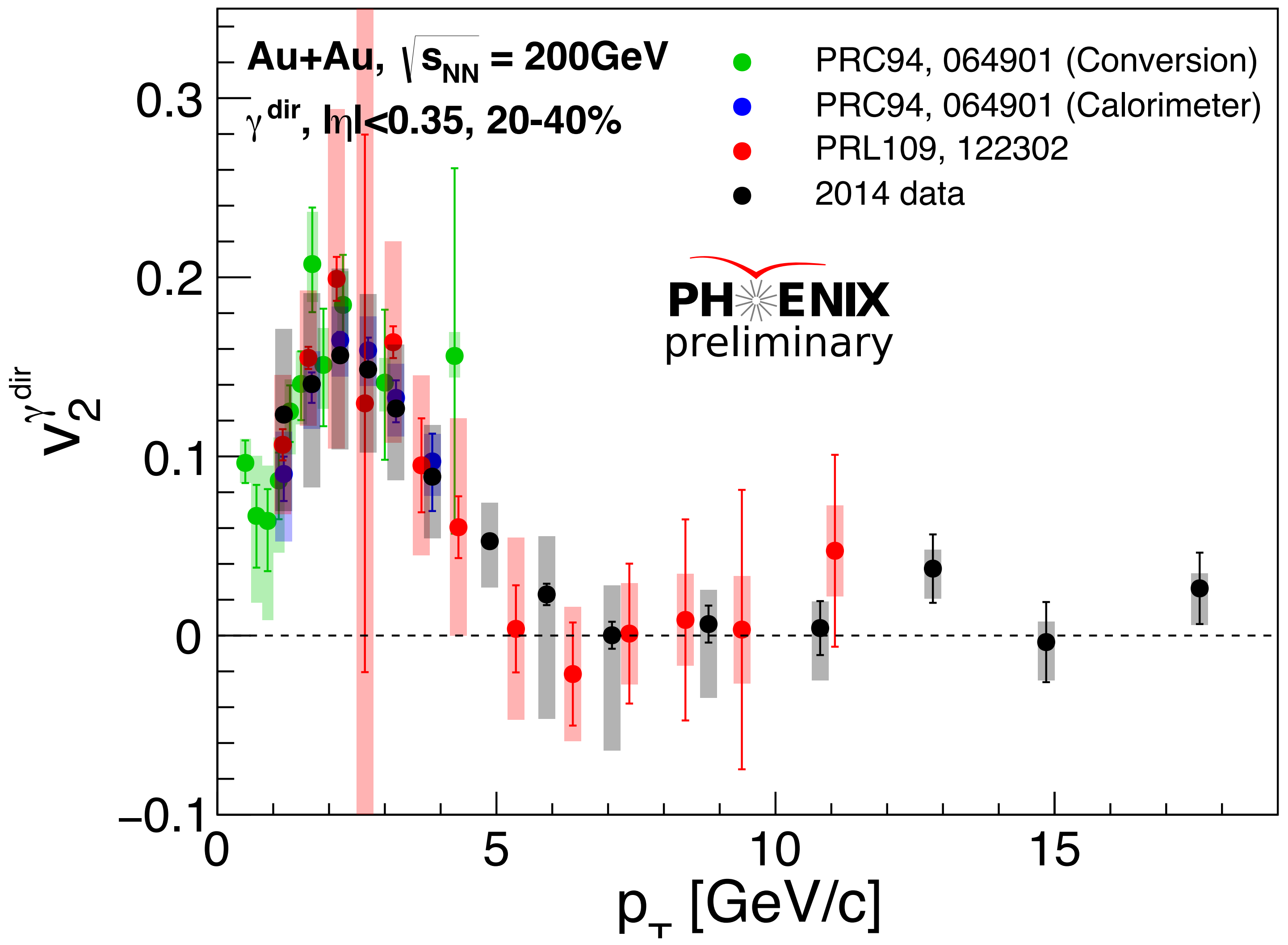
Inclusive (v_2^{incl}) and Decay Photon (v_2^{dec})Flow



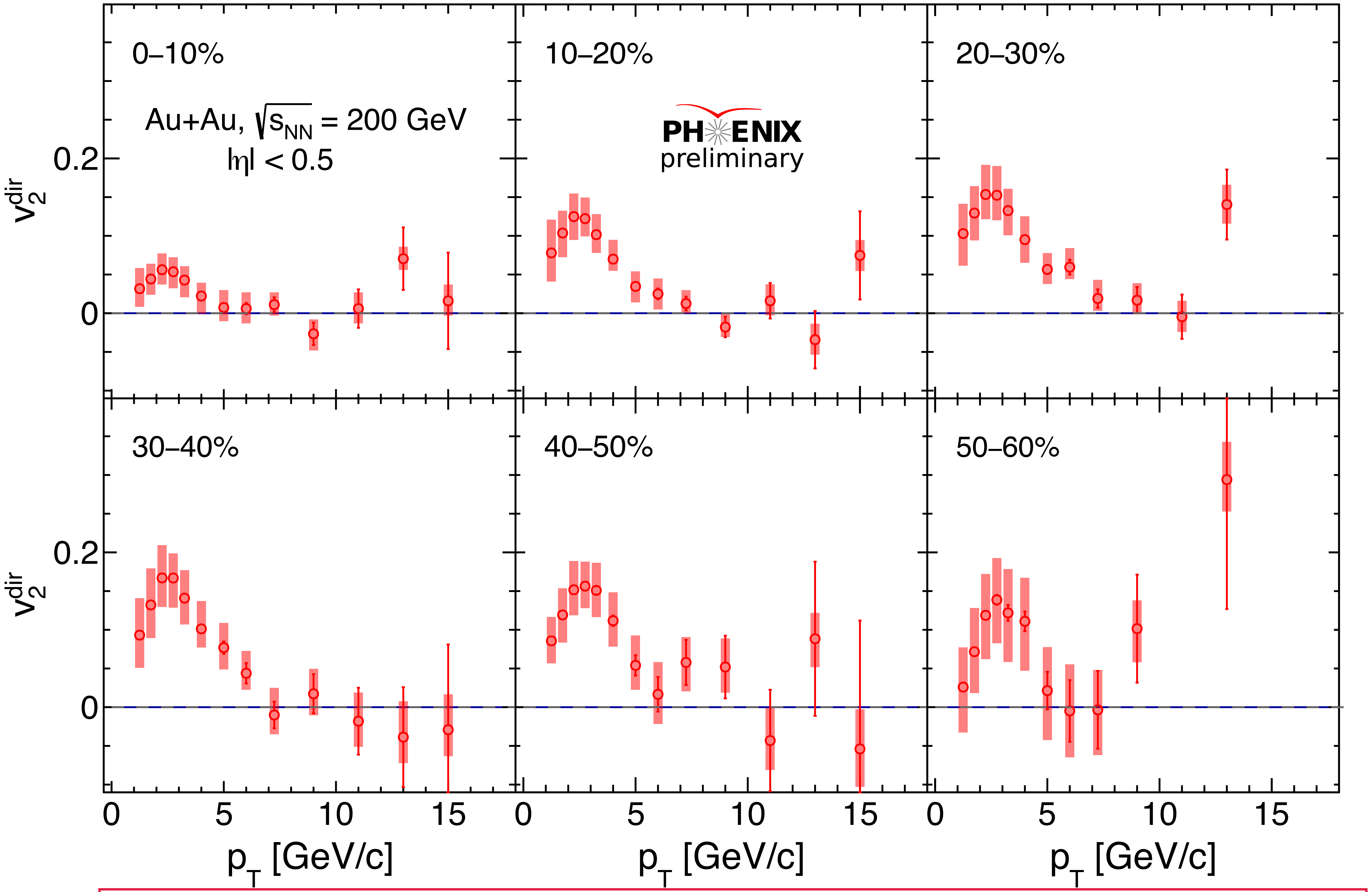
- Low p_T region— Decay and inclusive photon flow are comparable
- High p_T region — inclusive and decay photon flow are constant with decay slightly larger than inclusive for all centralities

Direct Photons Flow



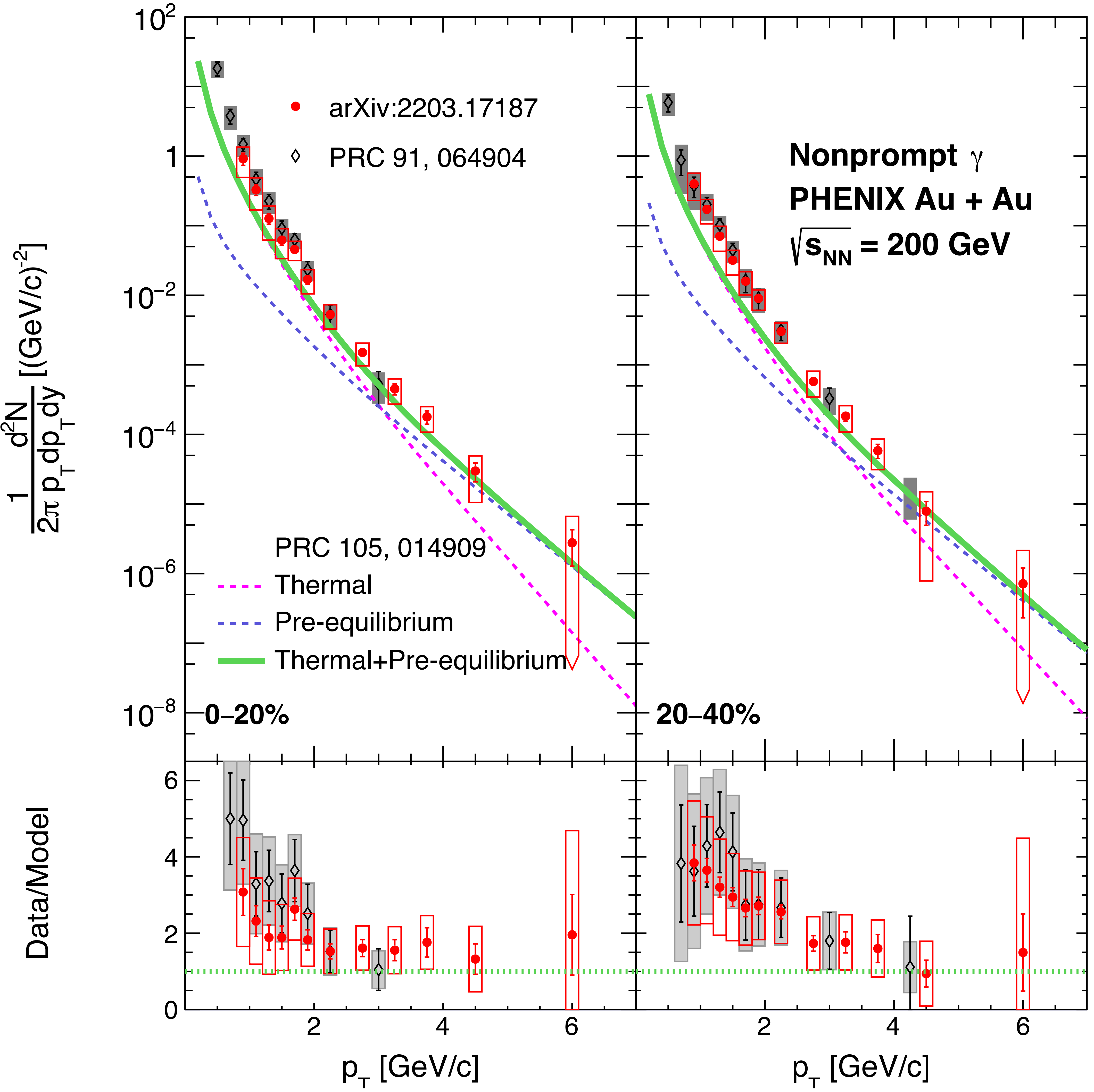


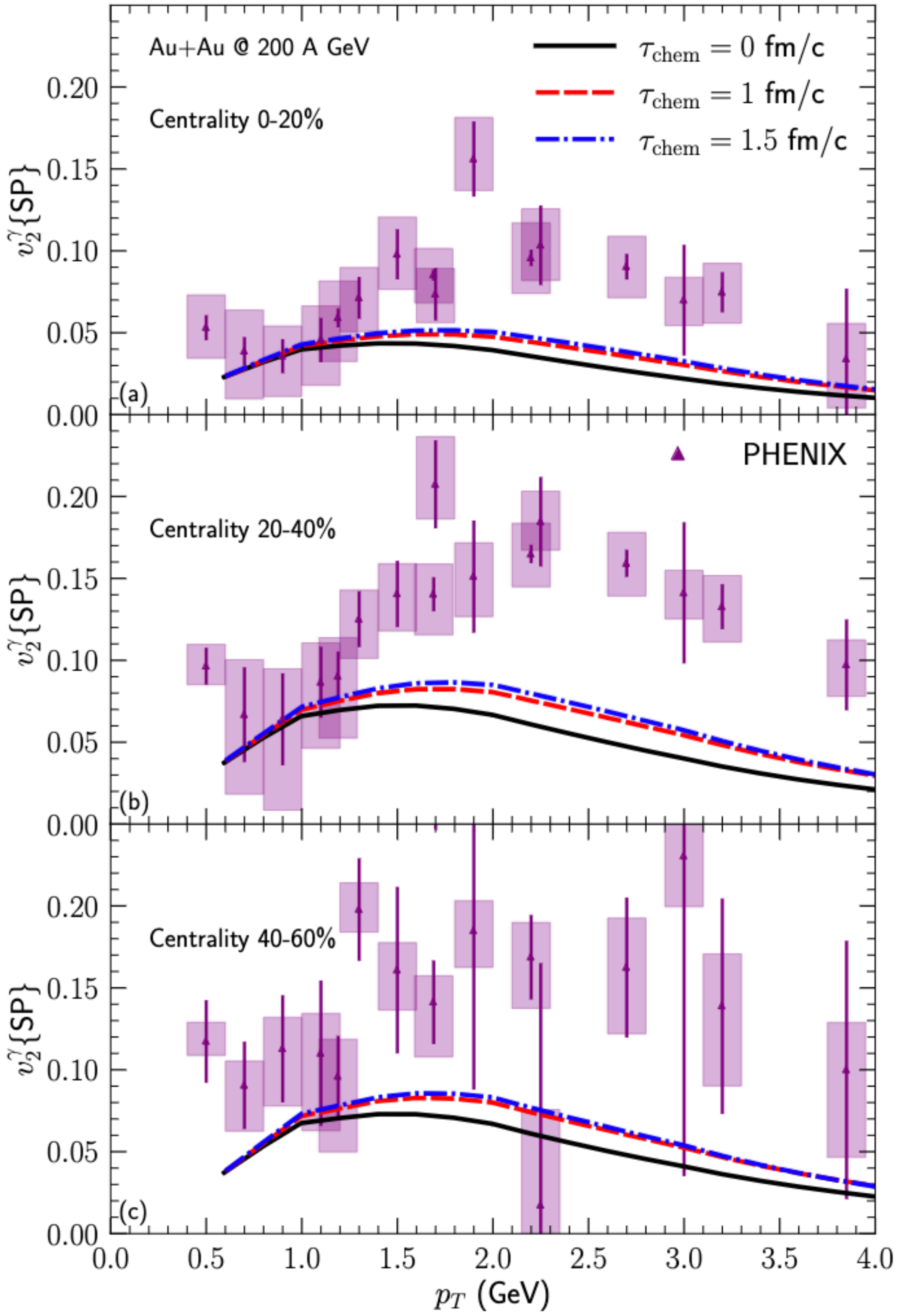
Consistent with previous results



Direct photons v_2 in the high p_T region is consistent with zero within uncertainties.

Comparison with Theory





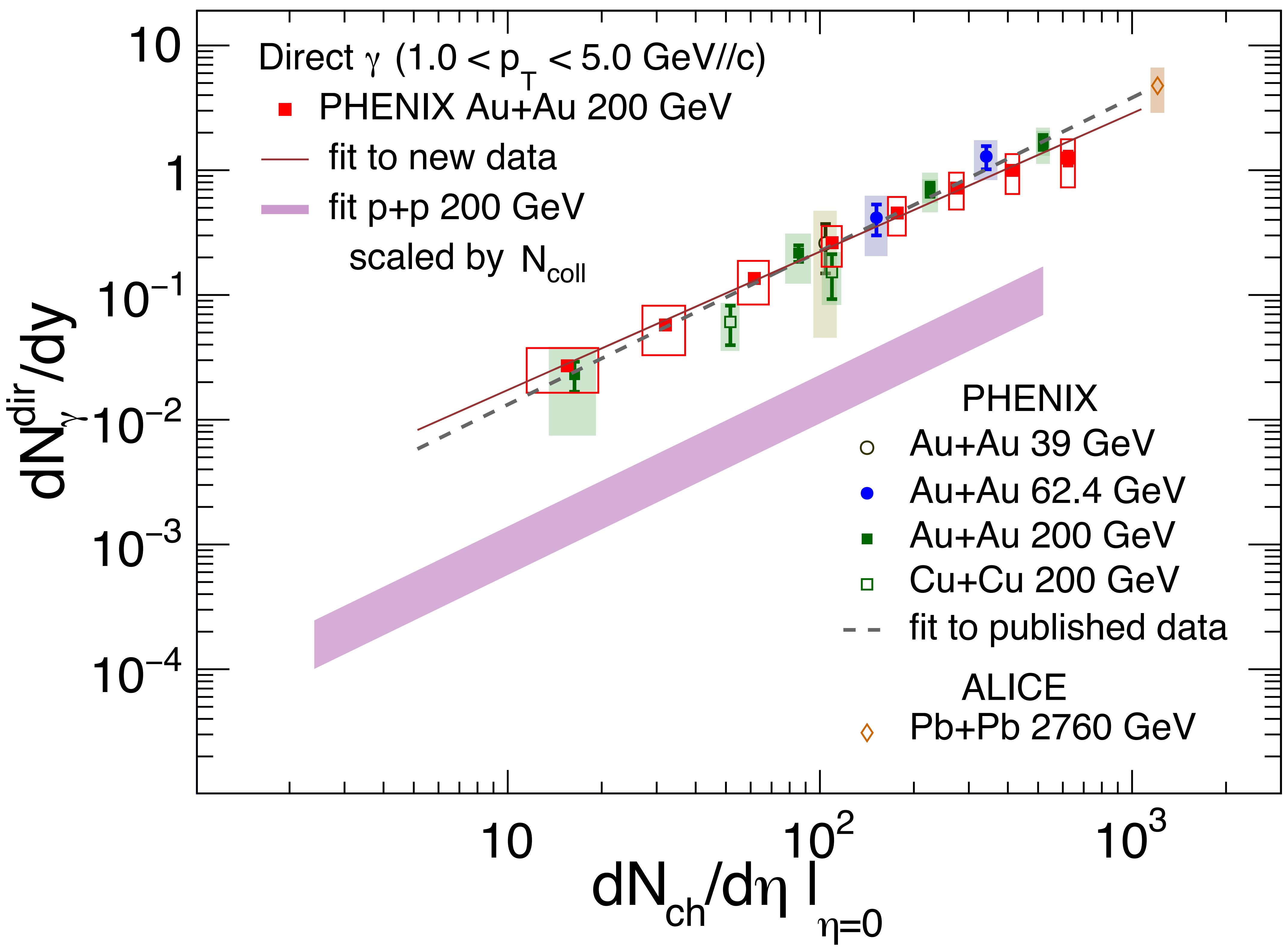
C. Gale, J.-F. Paquet, B. Schenke & C. Shen
Phys. Rev. C 105 (2022) 014909

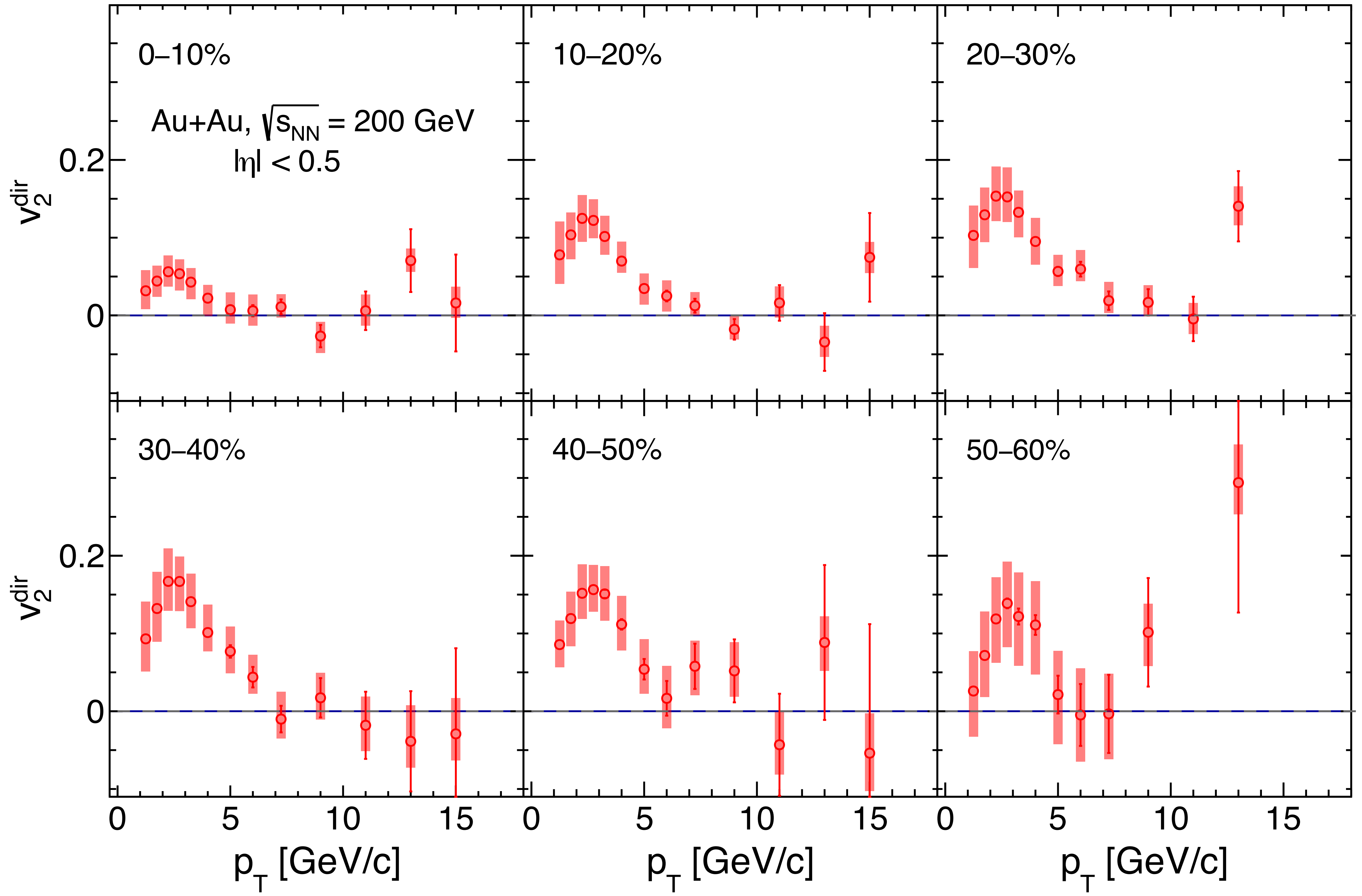
Multi-messenger heavy-ion physics

- Hybrid model that describes all stages of relativistic heavy-ion collisions
- Effect of pre-equilibrium phase on both photonic and hadronic observables highlighted.

- Dominant contribution from pre-equilibrium above 3 GeV/c in the model seems to align well with the data
- Overall yield falls short, especially below 2 GeV/c
- Quantitative disagreement with flow for all chemical equilibration times

Summary and Outlook





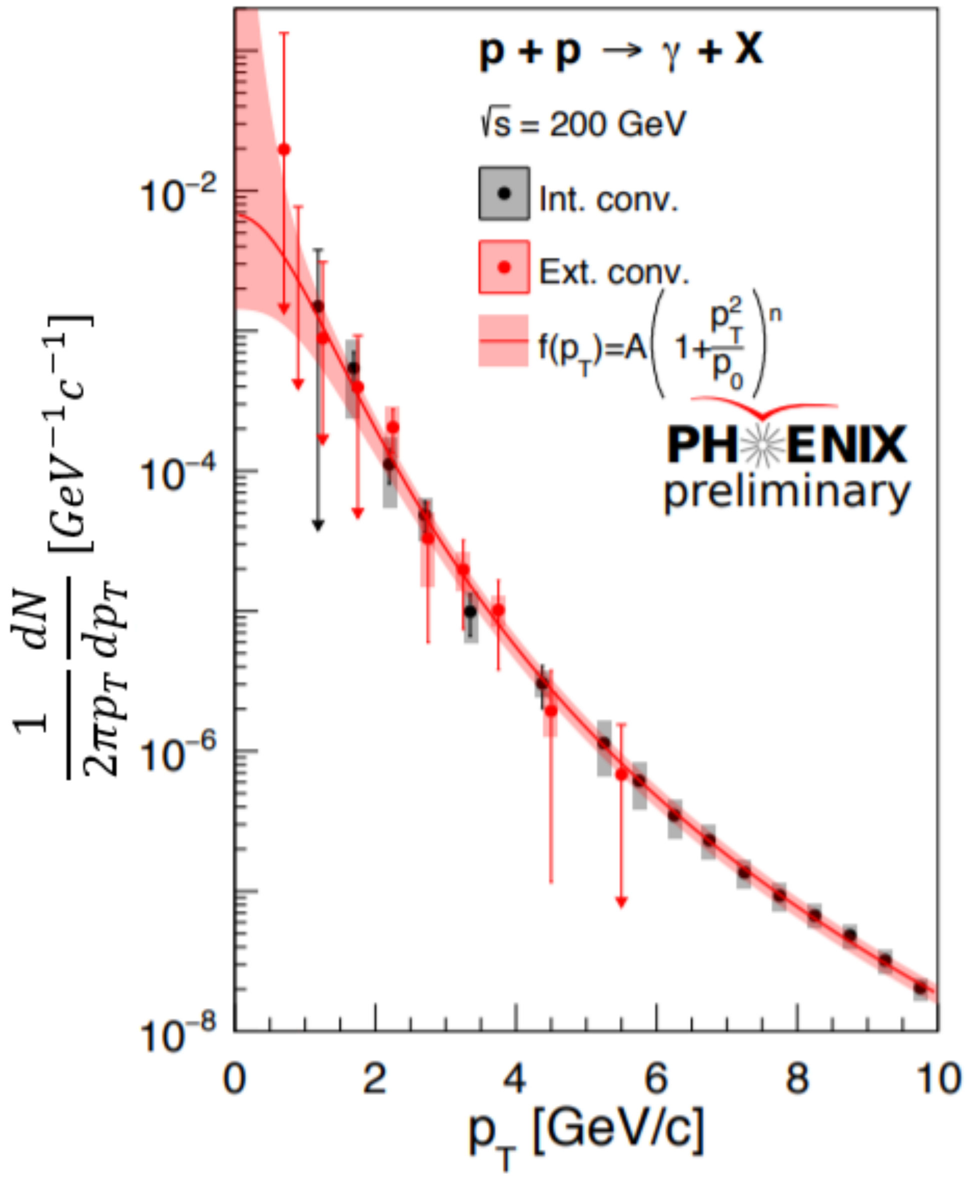
Double differential analysis of direct and non-prompt direct photons in p_T and $dN_{ch}/d\eta$ for shape of p_T spectra and rapidity density

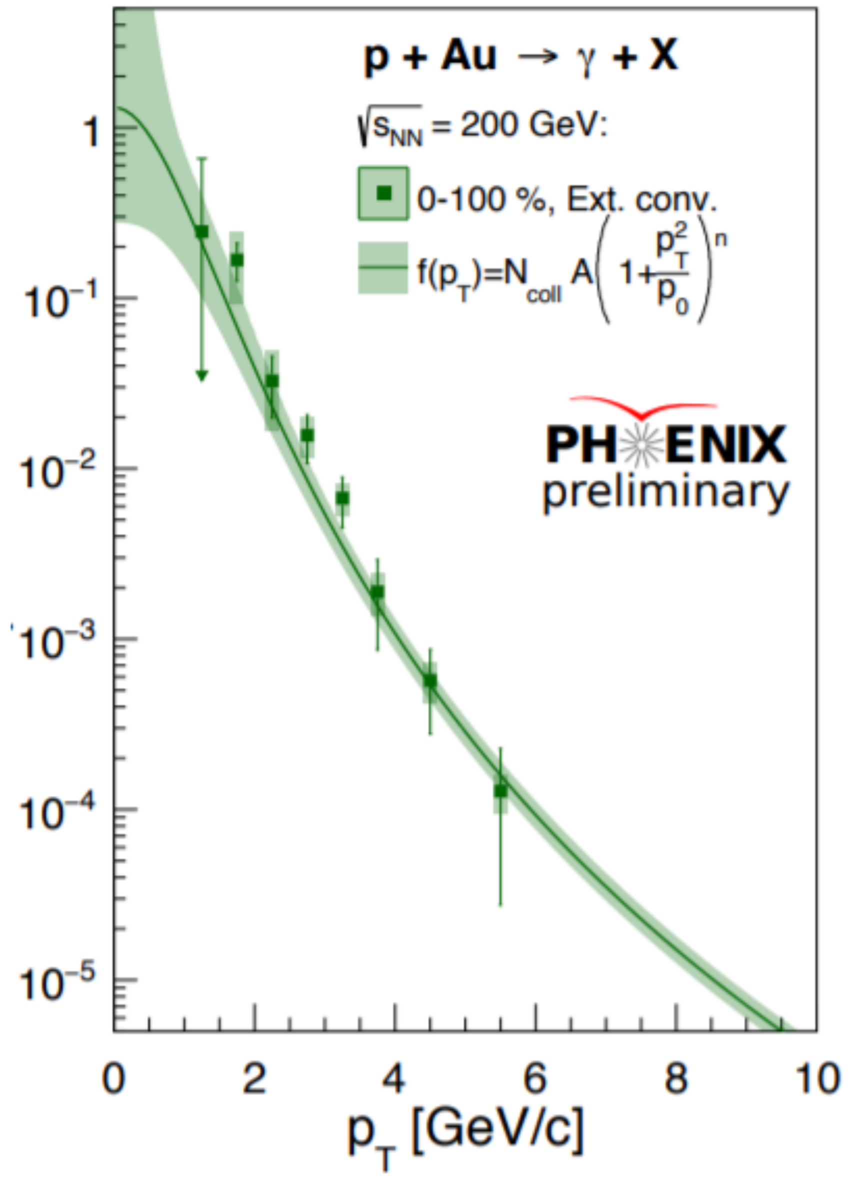
Flow results in Au+Au to be published soon!

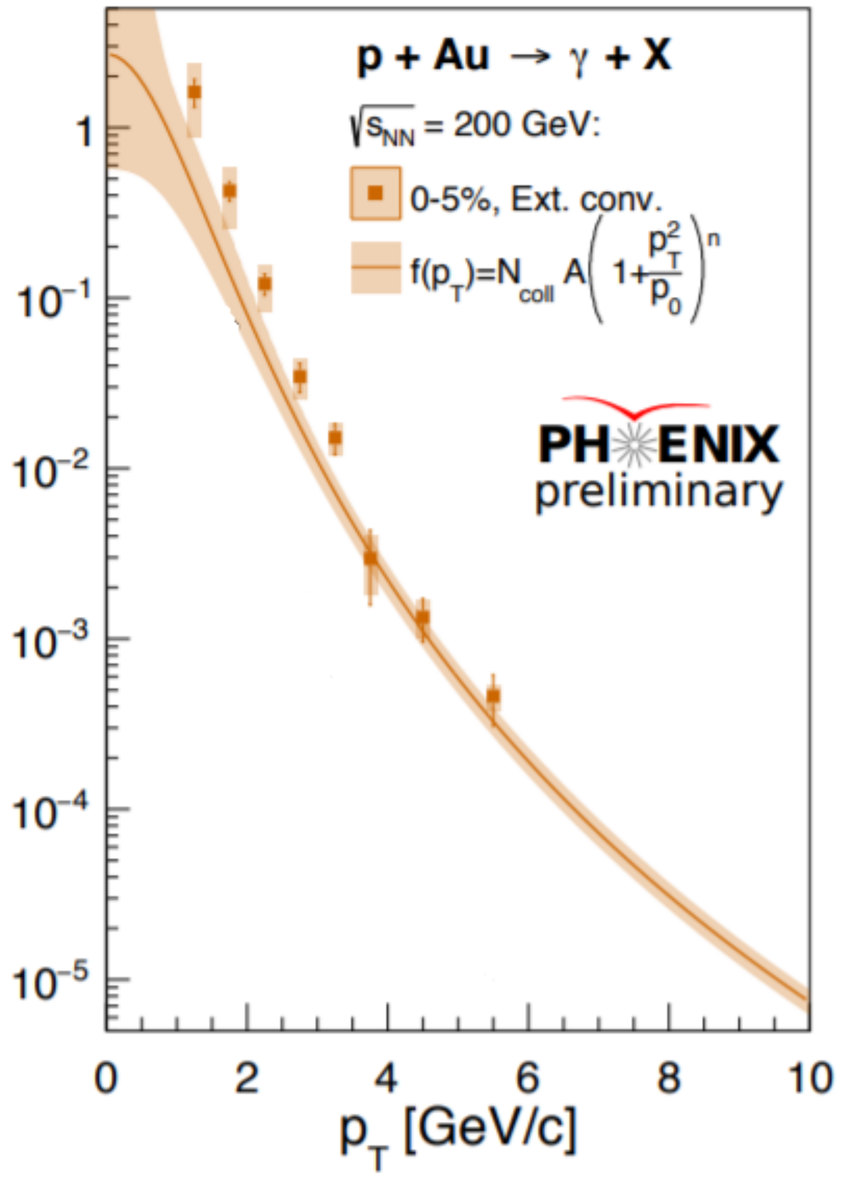
Results from Cu+Au analysis to come soon!

Thank You !

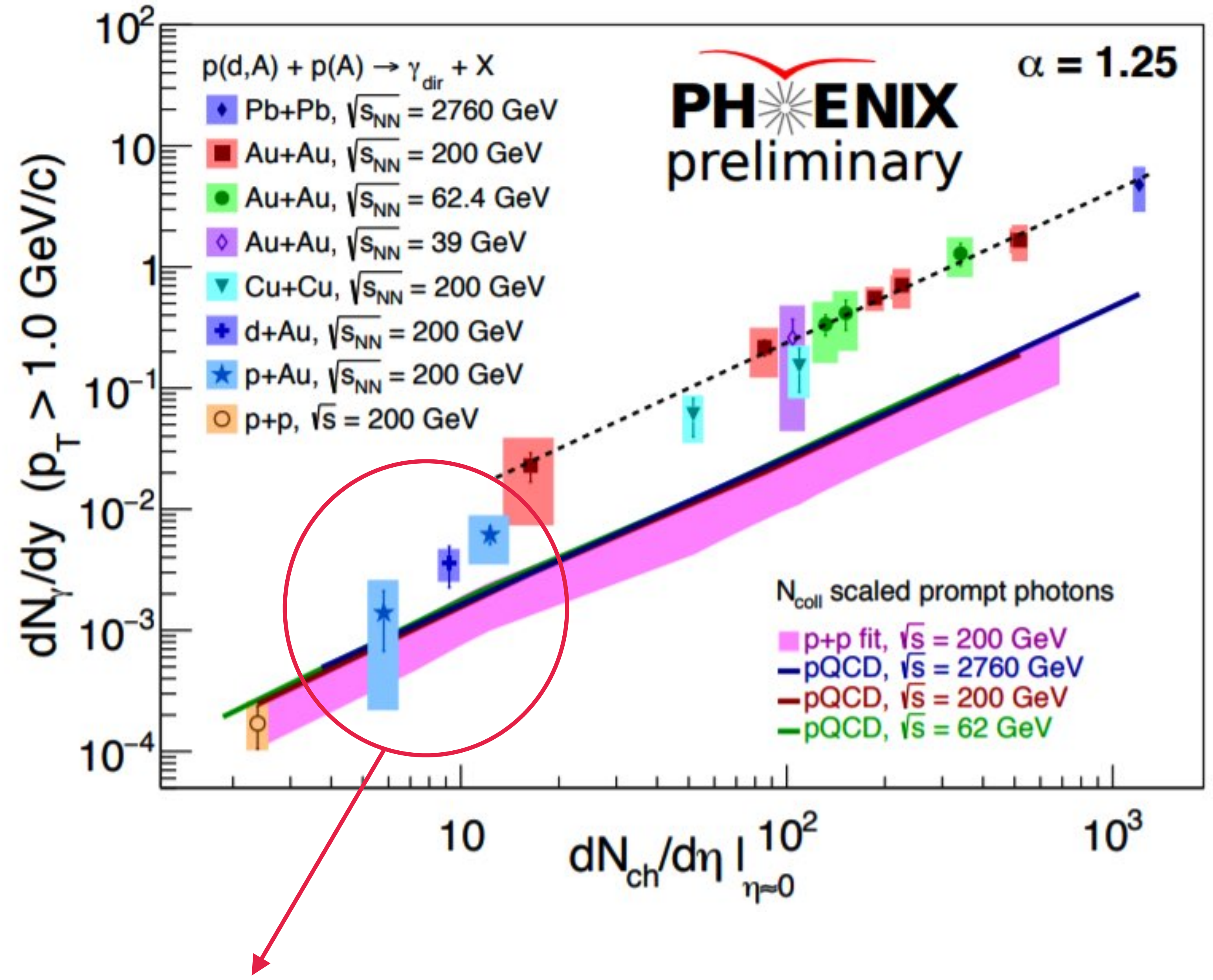
Direct γ in small systems







Bridging the gap



Onset of QGP?

$p+p$ Fit

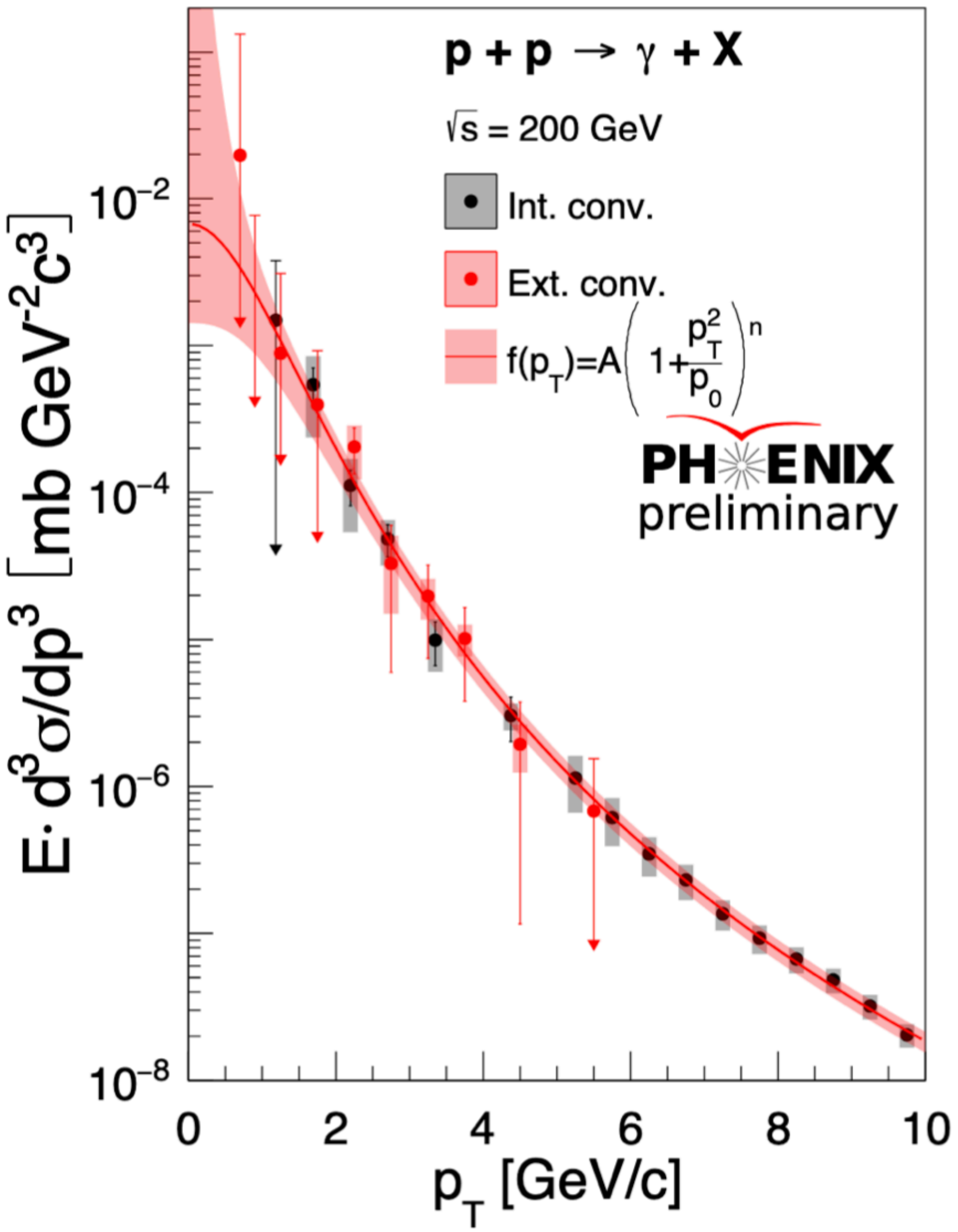
Functional form inspired by pQCD

Fit below 1 GeV/c motivated by Drell Yan measurements [Ito, et al, PRD23, 604 (1981)]

Systematic errors include the fit errors, different functional forms

$$\frac{dN}{dy} = a\left(1 + \frac{p_T^2}{b^2}\right)^c$$

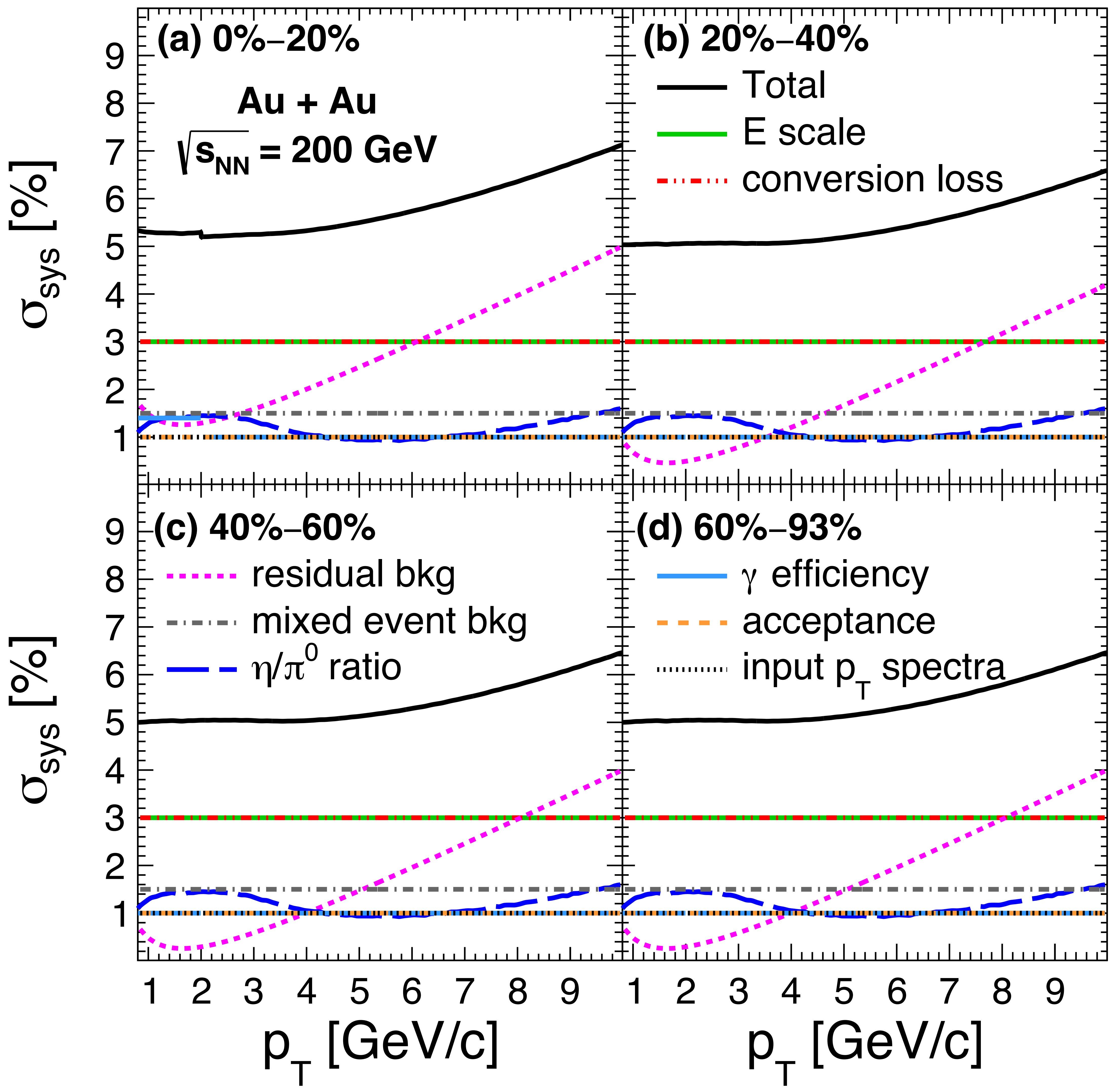
$a = 6.4 \times 10^3$ $\quad b = 1.45$ $\quad c = -3.30$



Systematic Uncertainties

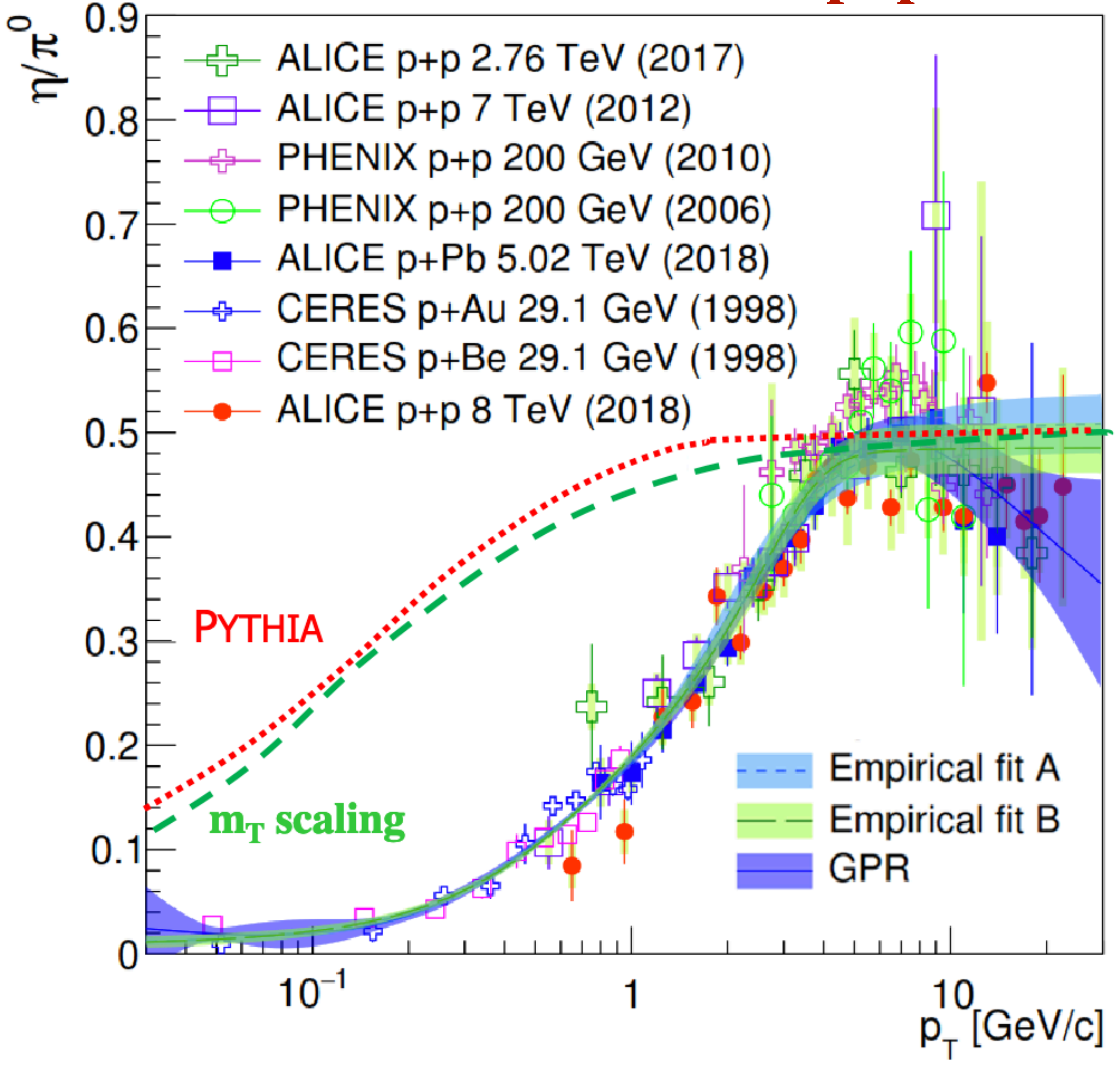
Systematic uncertainty source (39 GeV)	σ_{sys}/R_γ	Type
π^0 reconstruction		
tagged photon yield	8%	A
Conditional acceptance		
input Hagedorn p_T spectra and energy scale	8%	B
Cocktail ratio		
γ^{hadron}/π^0	2%	B

Systematic uncertainty source (62.4 GeV)	σ_{sys}/R_γ	Type
π^0 reconstruction		
tagged photon yield	5%	A
Conditional acceptance		
input Hagedorn p_T spectra and energy scale	5%	B
Cocktail ratio		
γ^{hadron}/π^0	2%	B



η/π^0 from world data

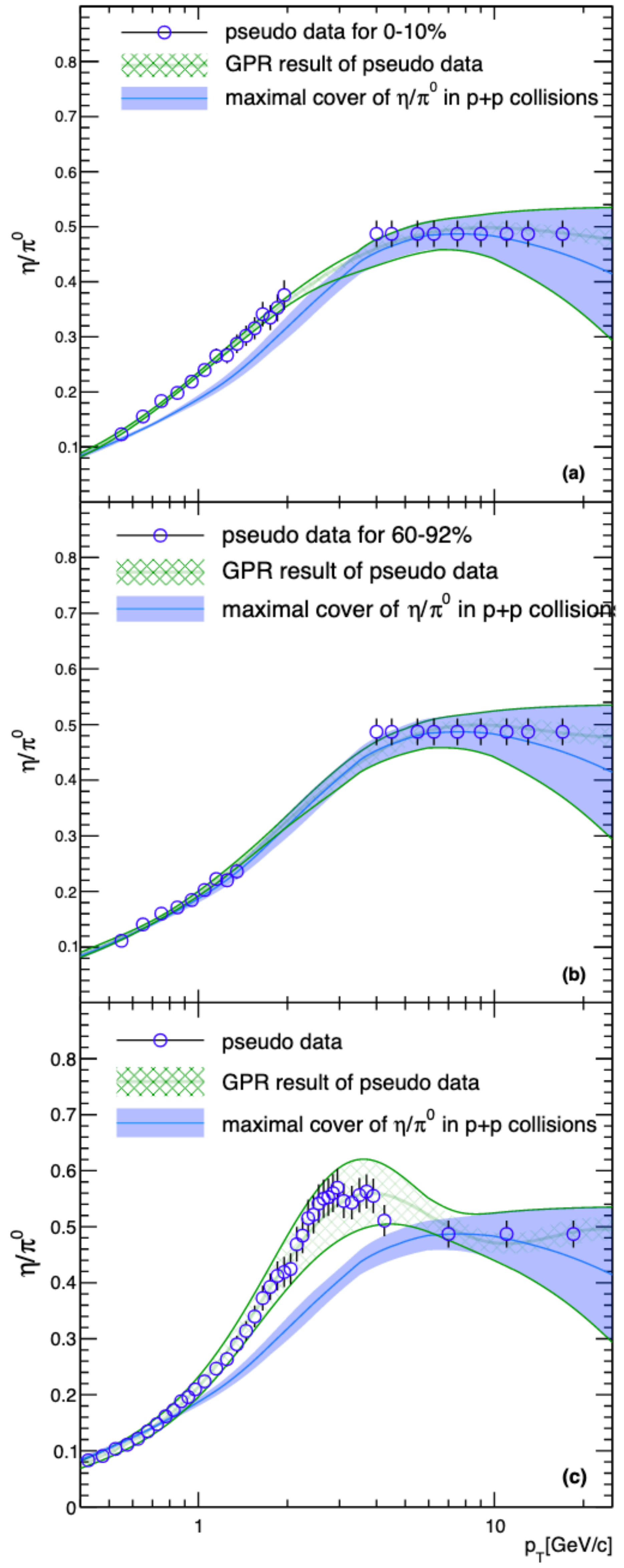
Universal ratio for p+p

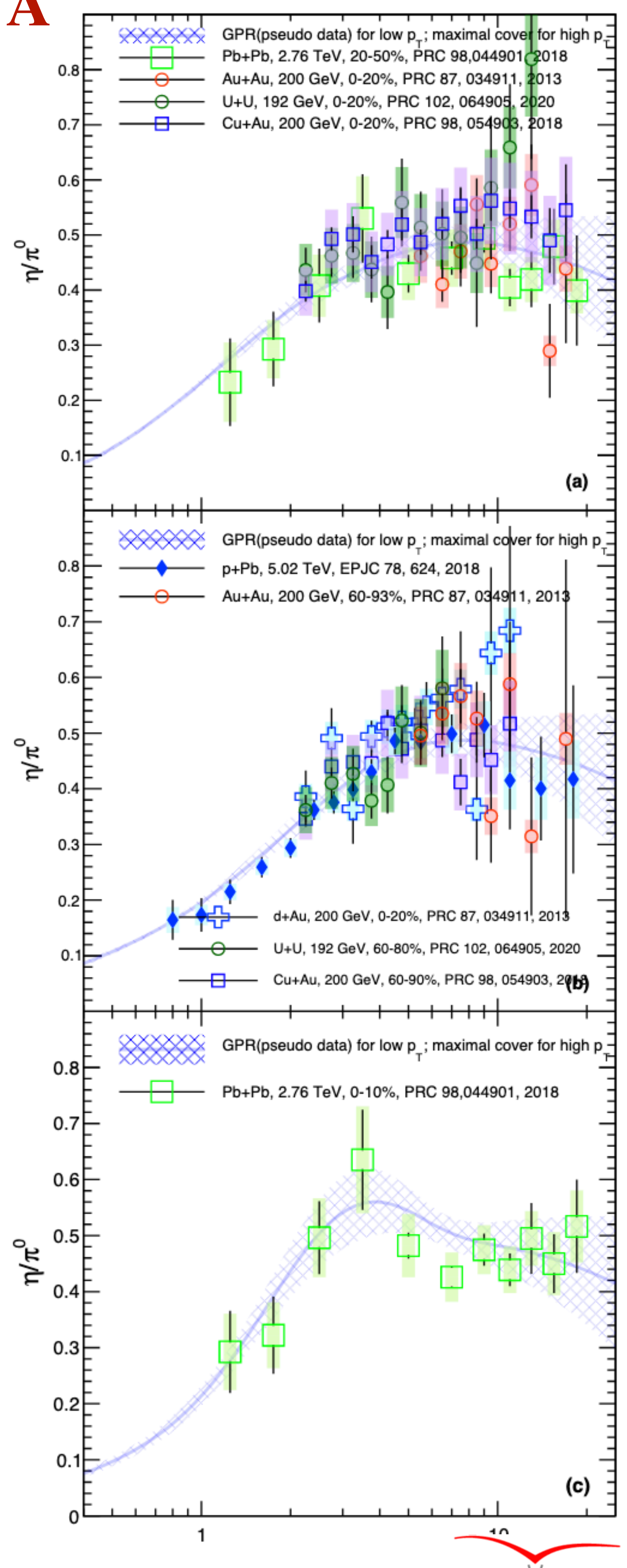


arXiv : 2102.05220

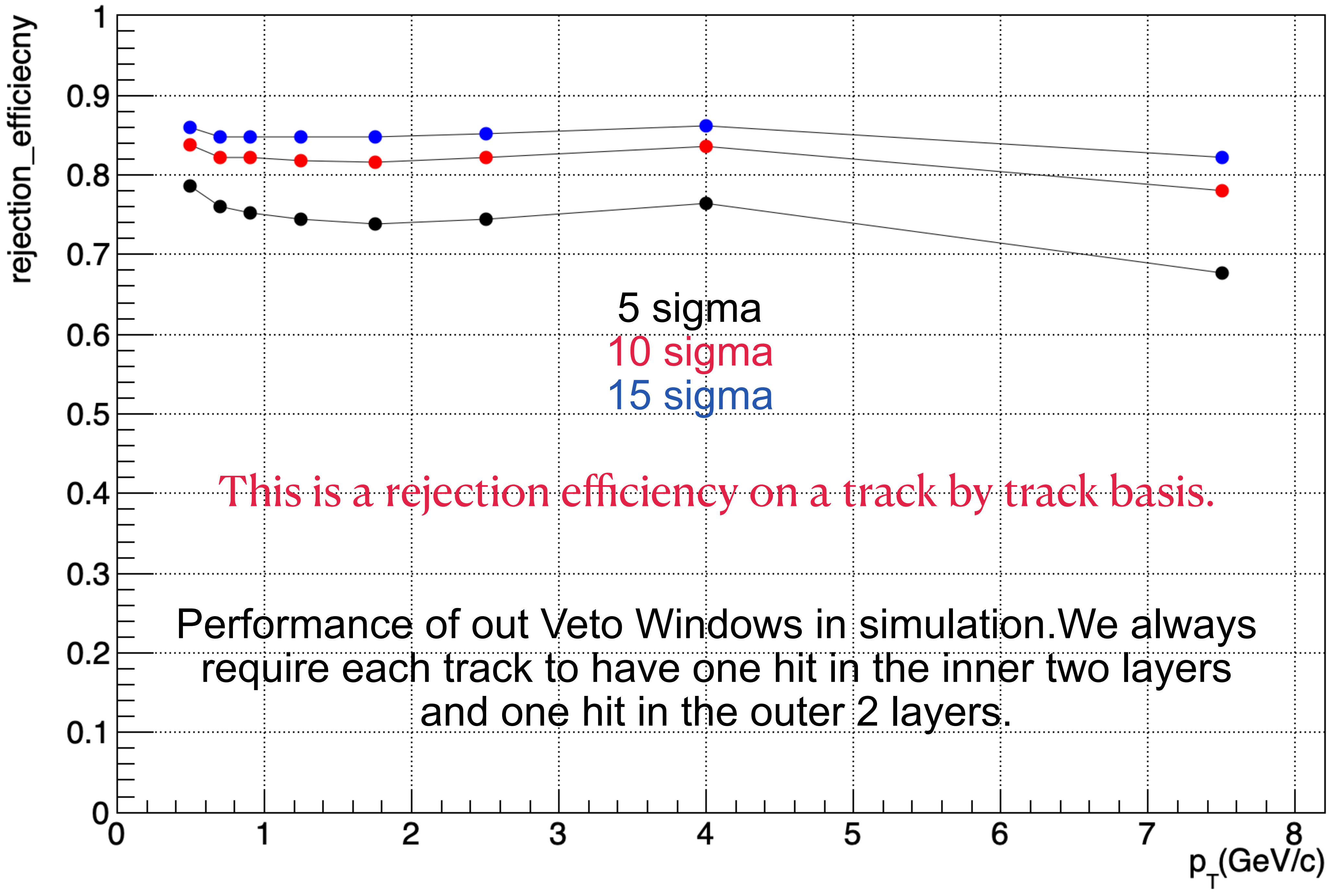
Accounting for effects of radial flow

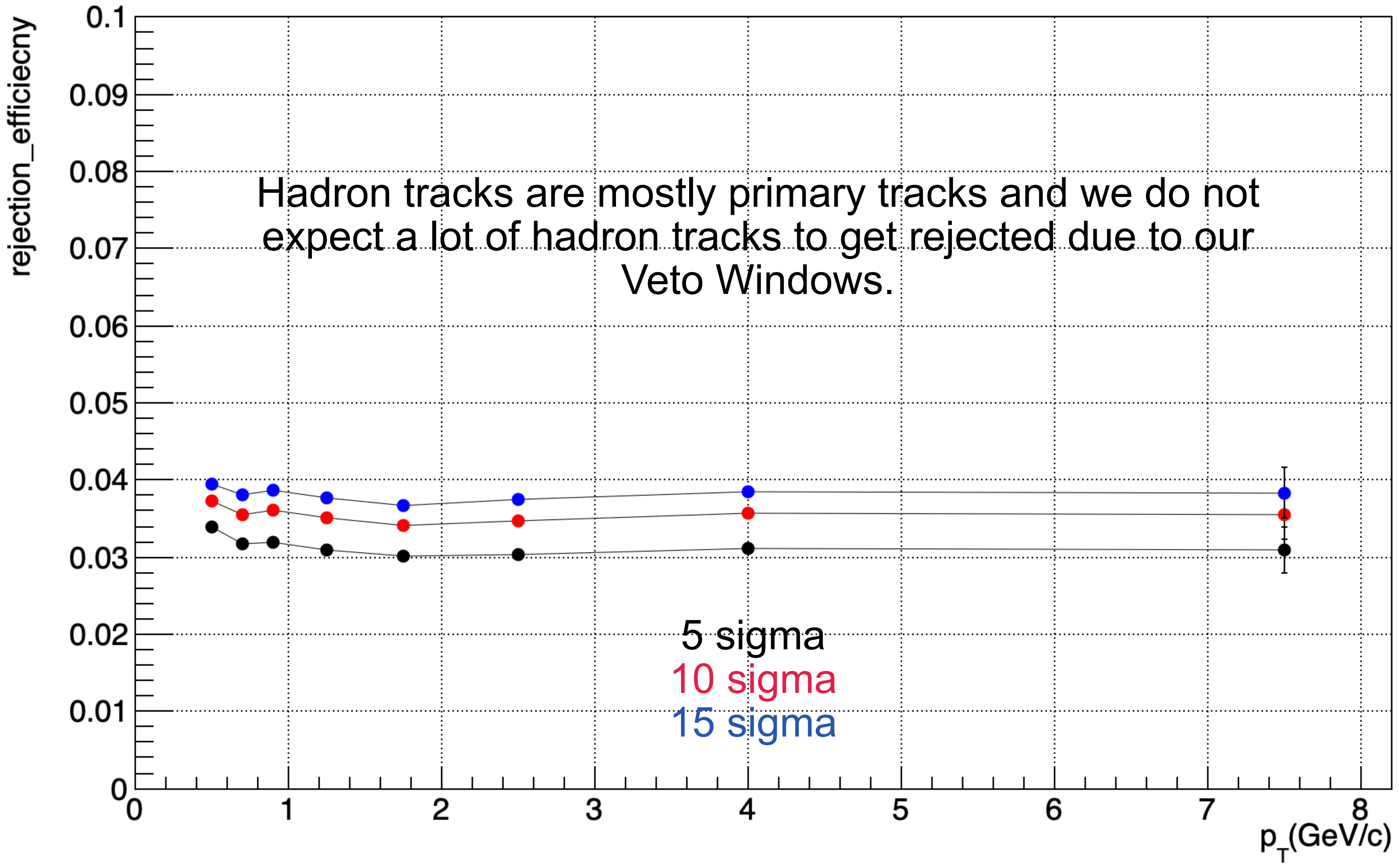
A + A





Performace of our rejection techniques





Sources of Direct Photons

Event Plane Measurement

$$\Psi_2 = \frac{1}{2}\tan^{-1}\left(\frac{Q_{2,y}}{Q_{2,x}}\right)$$

Where:

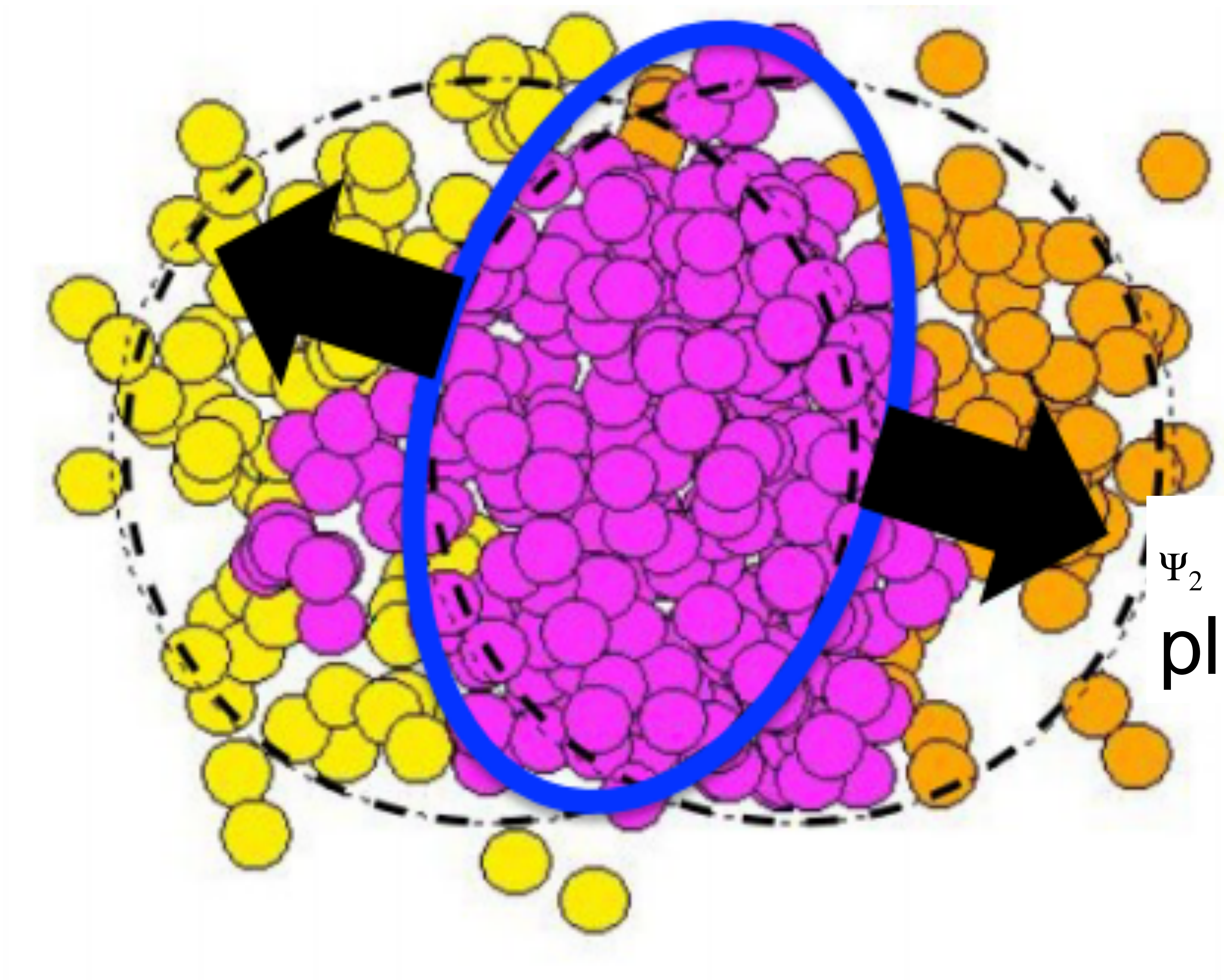
$$Q_{2,x} = \sum_i w_i \cos\left(2\phi_i\right) = Q_2\cos(2\Psi_2)$$

$$Q_{2,y} = \sum_i w_i \sin\left(2\phi_i\right) = Q_2\sin(2\Psi_2)$$

PMT index

charge detected in PMT i

Azimuthal angle corresponding to PMT i



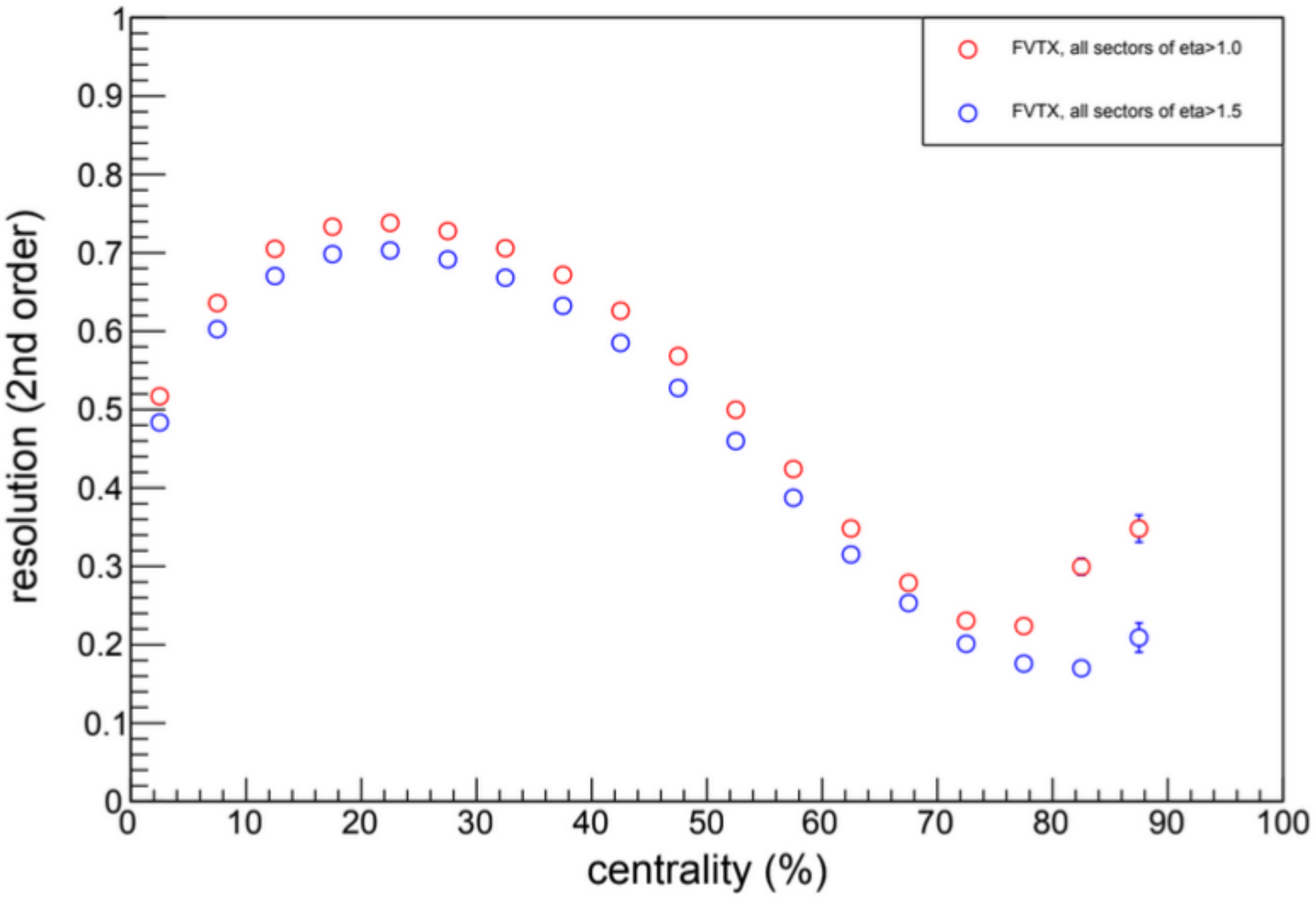
Ψ_2 event plane

Event plane is <u>estimated</u> based on charge deposited in FVTX detector

Event Plane Resolution

$$Res\left\{\Psi_2^{FVTX}\right\} = \frac{\left\langle \cos\left(2\left(\Psi_2^{FVTX} - \Psi_2^{BBC}\right)\right)\right\rangle \left\langle \cos\left(2\left(\Psi_2^{FVTX} - \Psi_2^{CNT}\right)\right)\right\rangle}{\left\langle \cos\left(2\left(\Psi_2^{BBC} - \Psi_2^{CNT}\right)\right)\right\rangle}$$

- FVTX has finite resolving power to estimate tl event plane
- The event plane resolution of the FVTX is calculated using the 3 sub-event method
  - *Average correlation functions over many events*
- Resolution correction: $v_{2,real}^{incl} = \dfrac{v_{2,obs}^{incl}}{Res\left\{\Psi_2\right\}}$



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Propagation of Uncertainties

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

- 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*

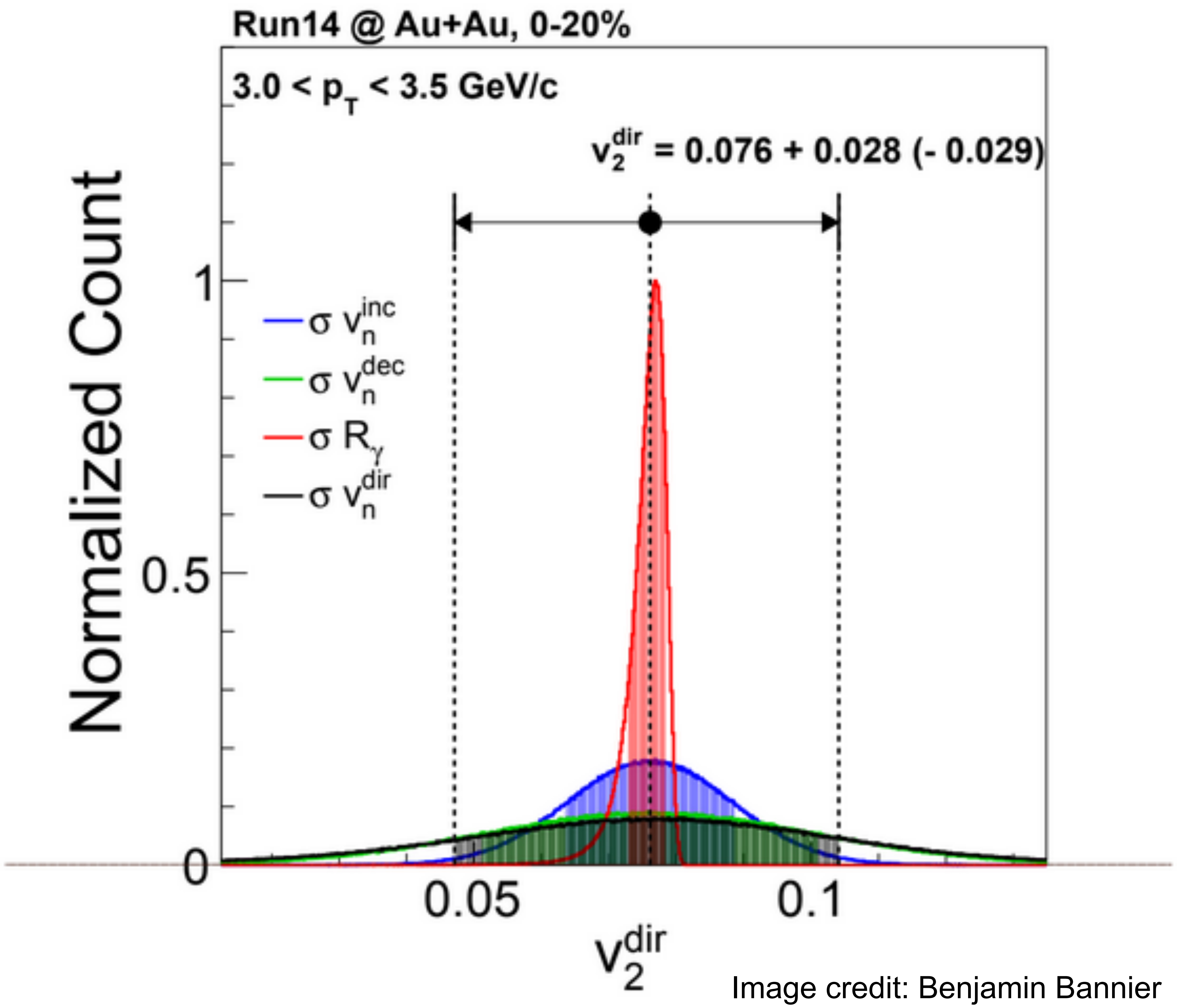
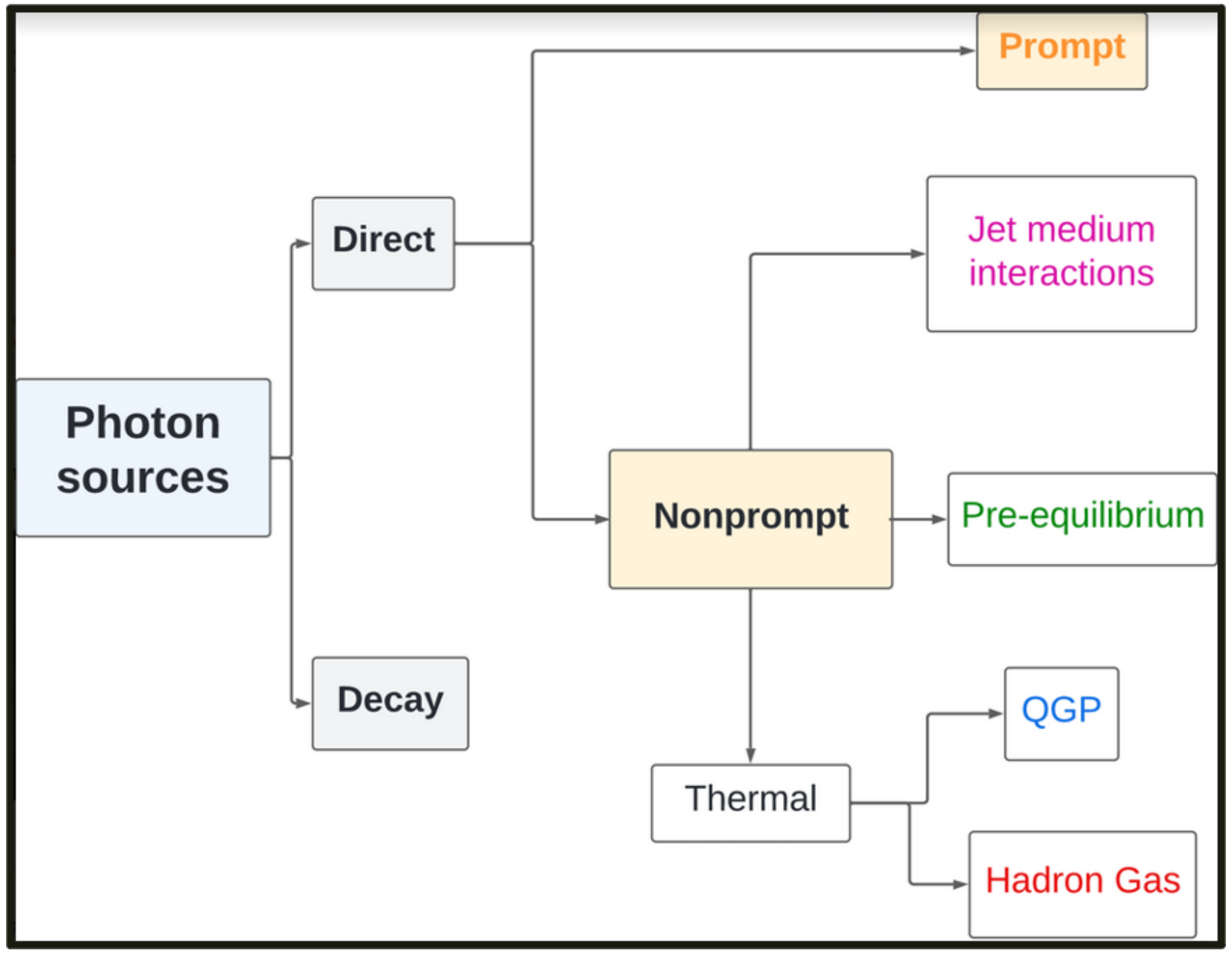
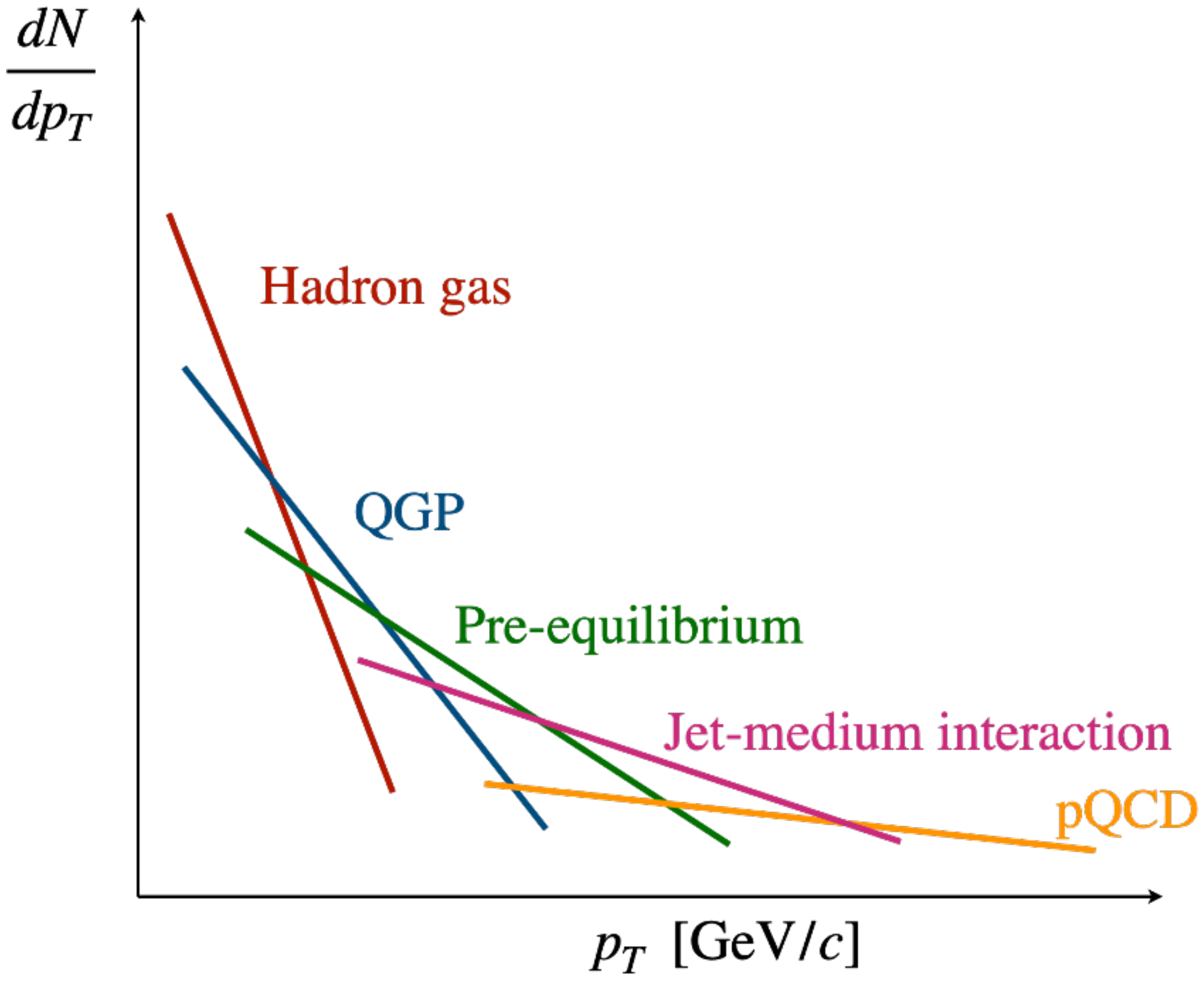


Image credit: Benjamin Bannier

Sources of Direct Photons

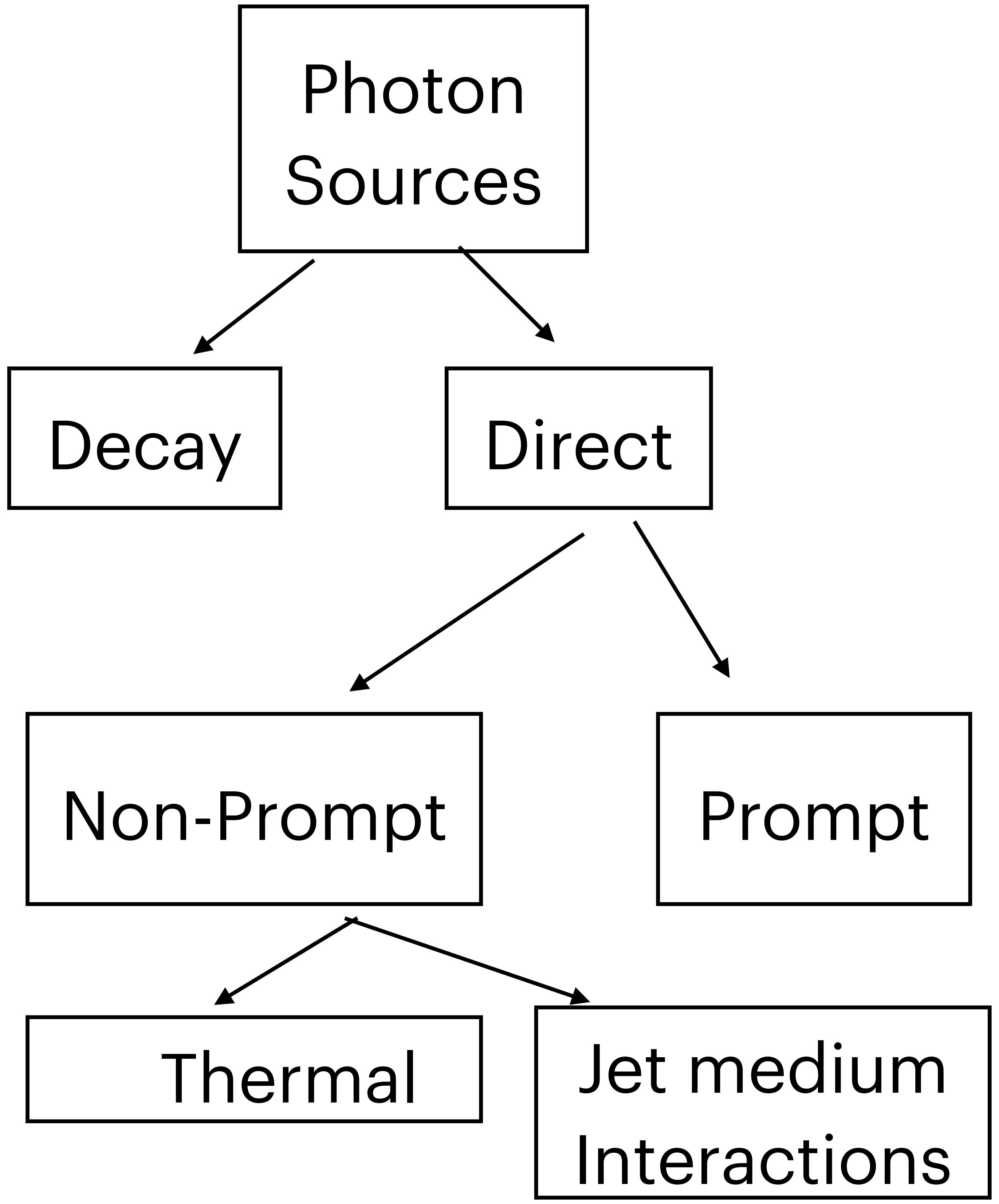


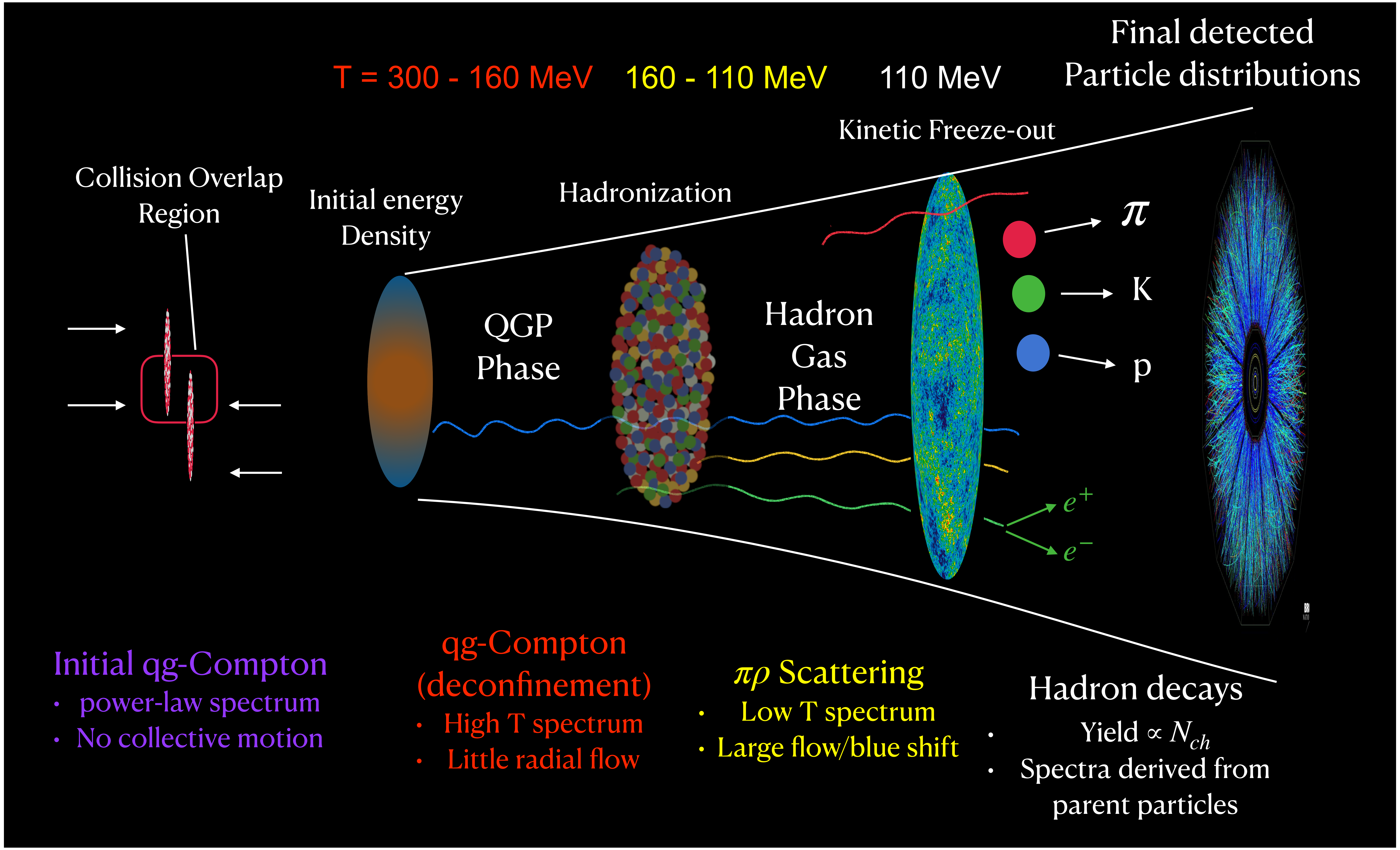


PHENIX

Why Photons ?

- Photons are color blind probes of Quark Gluon Plasma.





Photon Measurements in PHENIX

Calorimeter Method → Photons that directly deposit energy into EMCals.

Phys. Rev. Lett. 109, 152302 (2012)

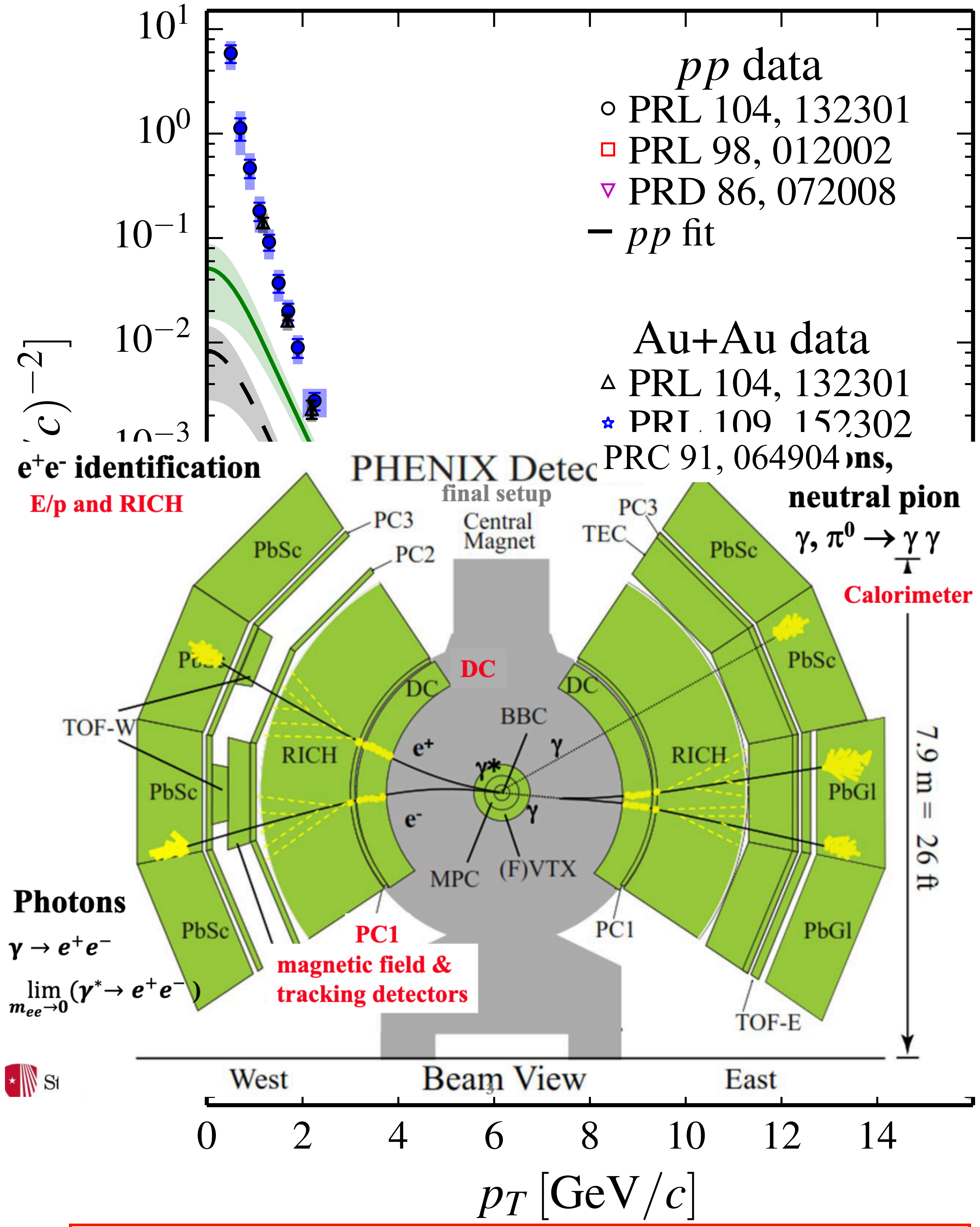
External Conversion Method → Photons that convert into e^+e^- pairs in the detector material. → Au+Au dataset at $\sqrt{s_{NN}} = 200$ GeV (2014)

arXiv:2203.17187
Phys. Rev. C 107, 024914 (2023)
Phys. Rev. C 91, 064904 (2015)

With the Silicon Vertex Detector (~ 13% X_0)

Internal Conversion Method → Virtual photons that internally convert into e^+e^- pairs.

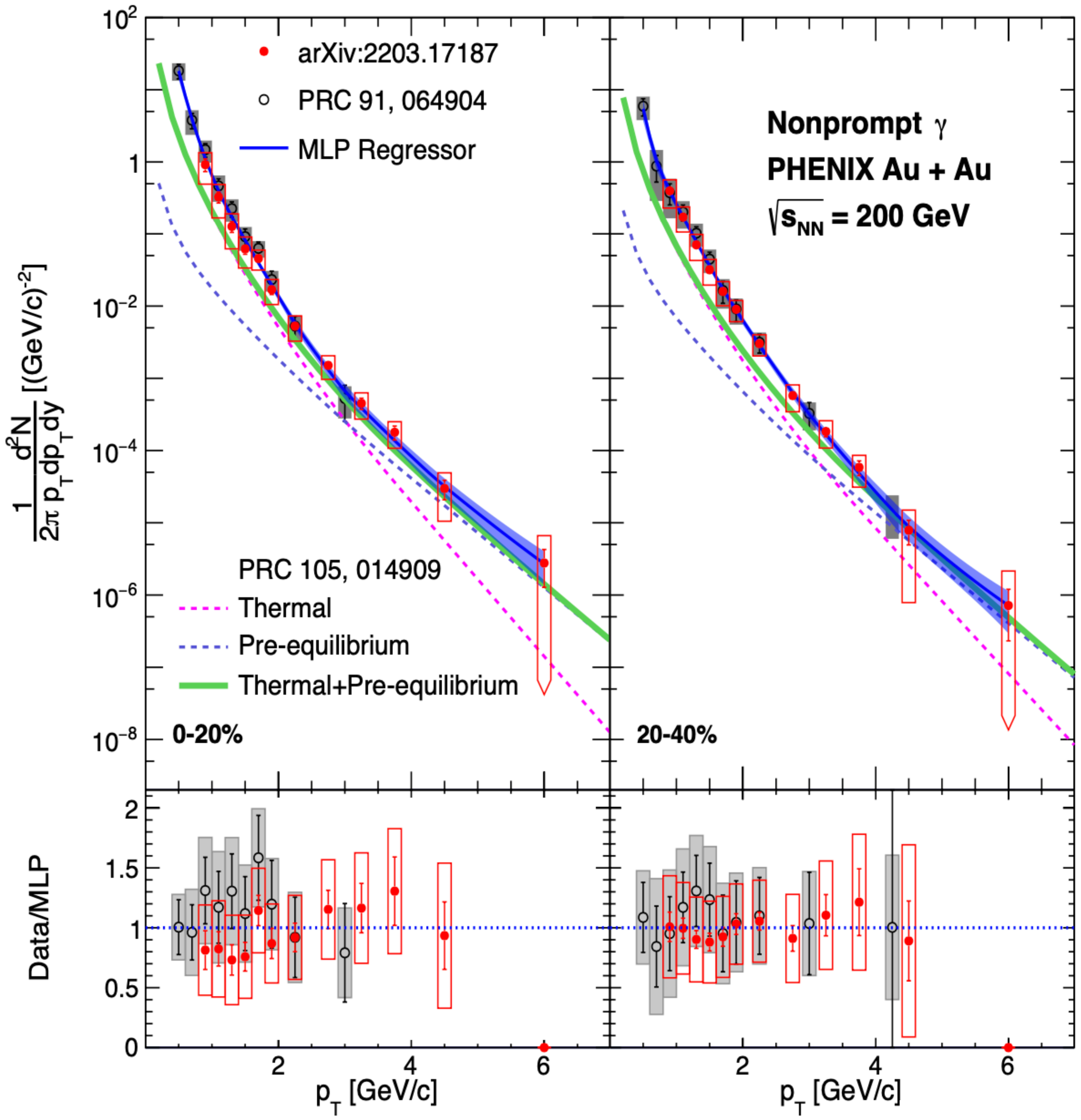
Phys. Rev. Lett. 104, 132301 (2010)

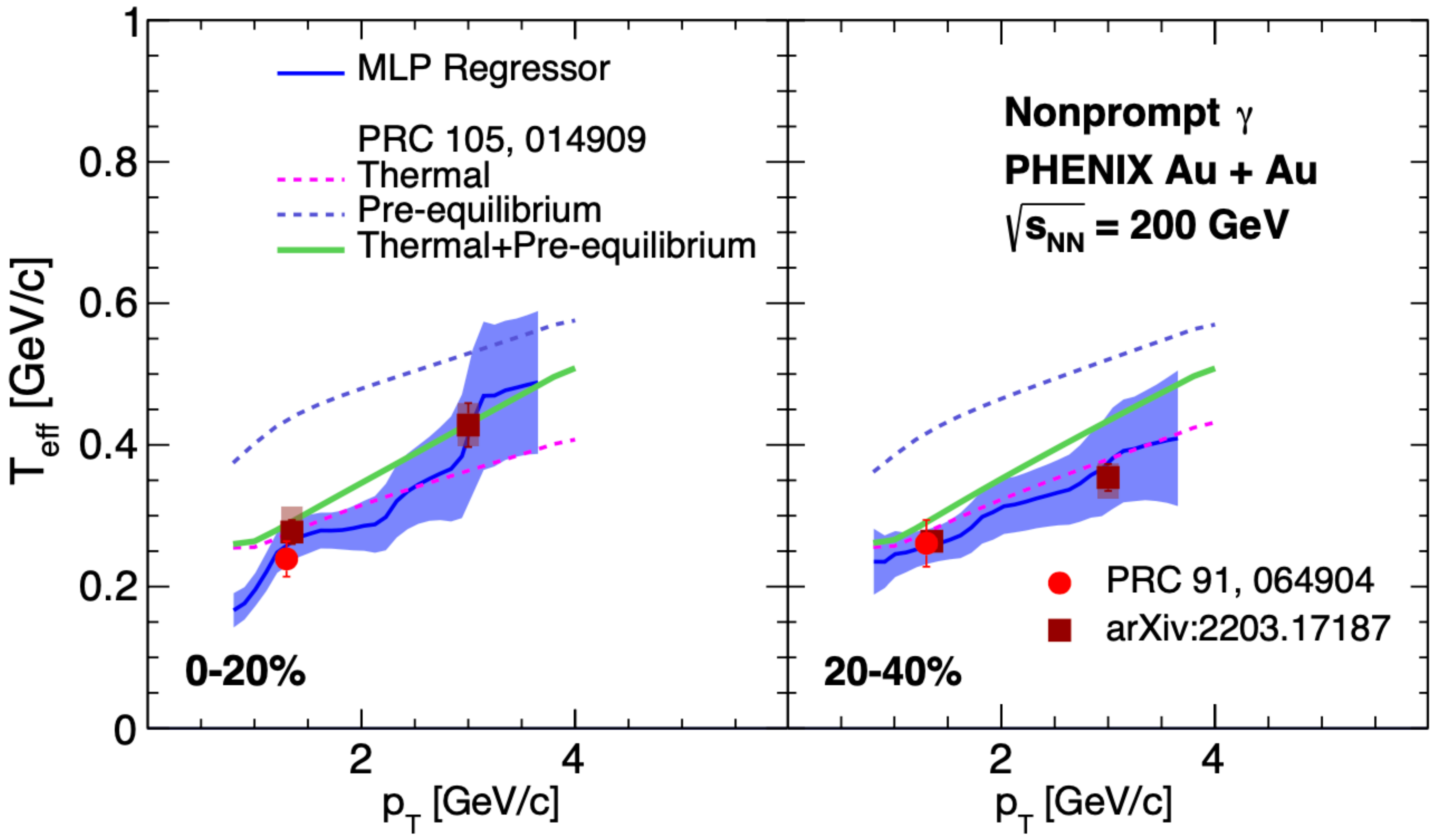


3 independent measurements in good agreement with each other

PHENIX

Comparison of Local Inverse Slopes





- Contributions from pre-equilibrium may be important at intermediate p_T