2024 RHIC/AGS Annual Users' Meeting

Highlights from the PHENIX experiment on flow measurements

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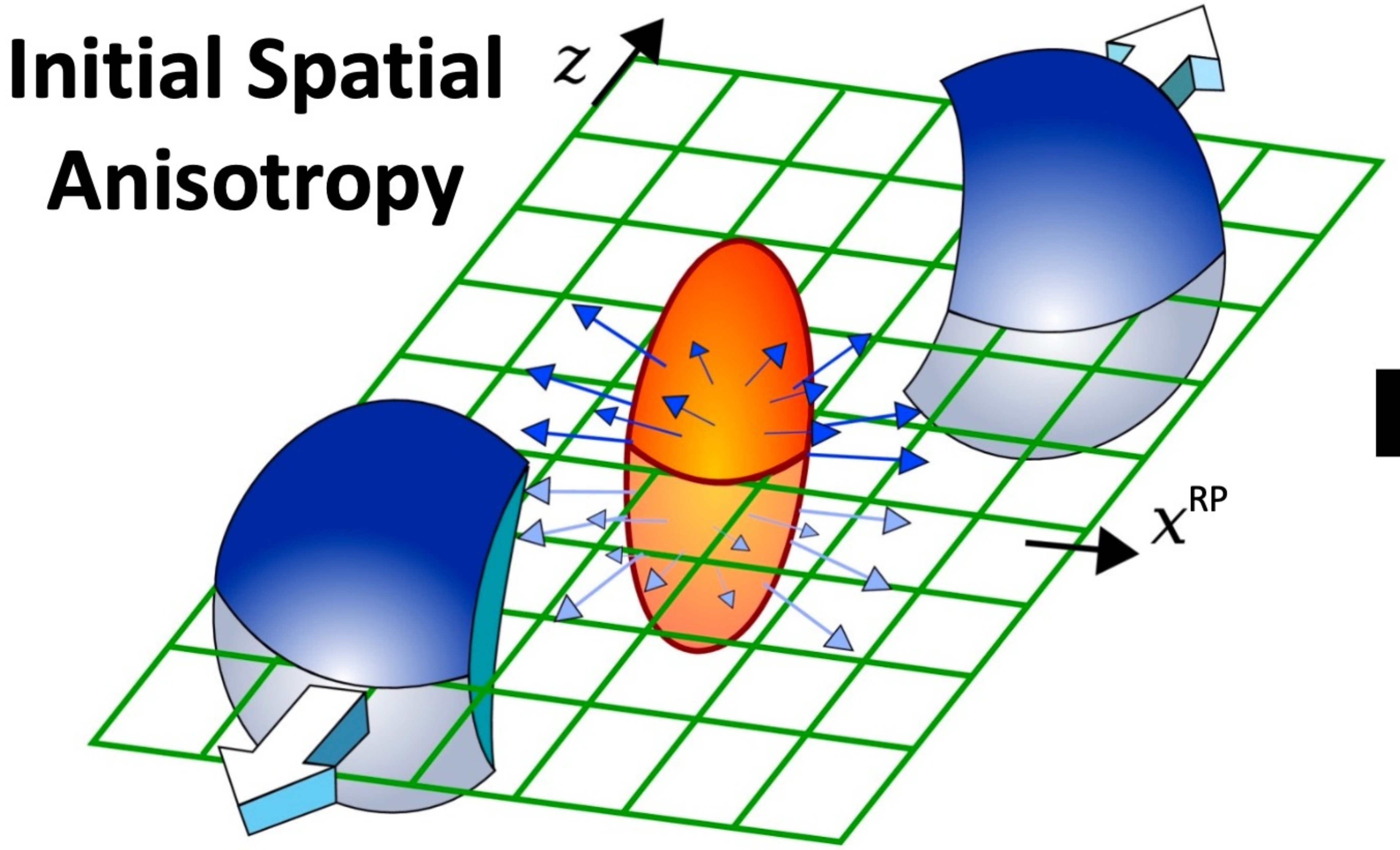
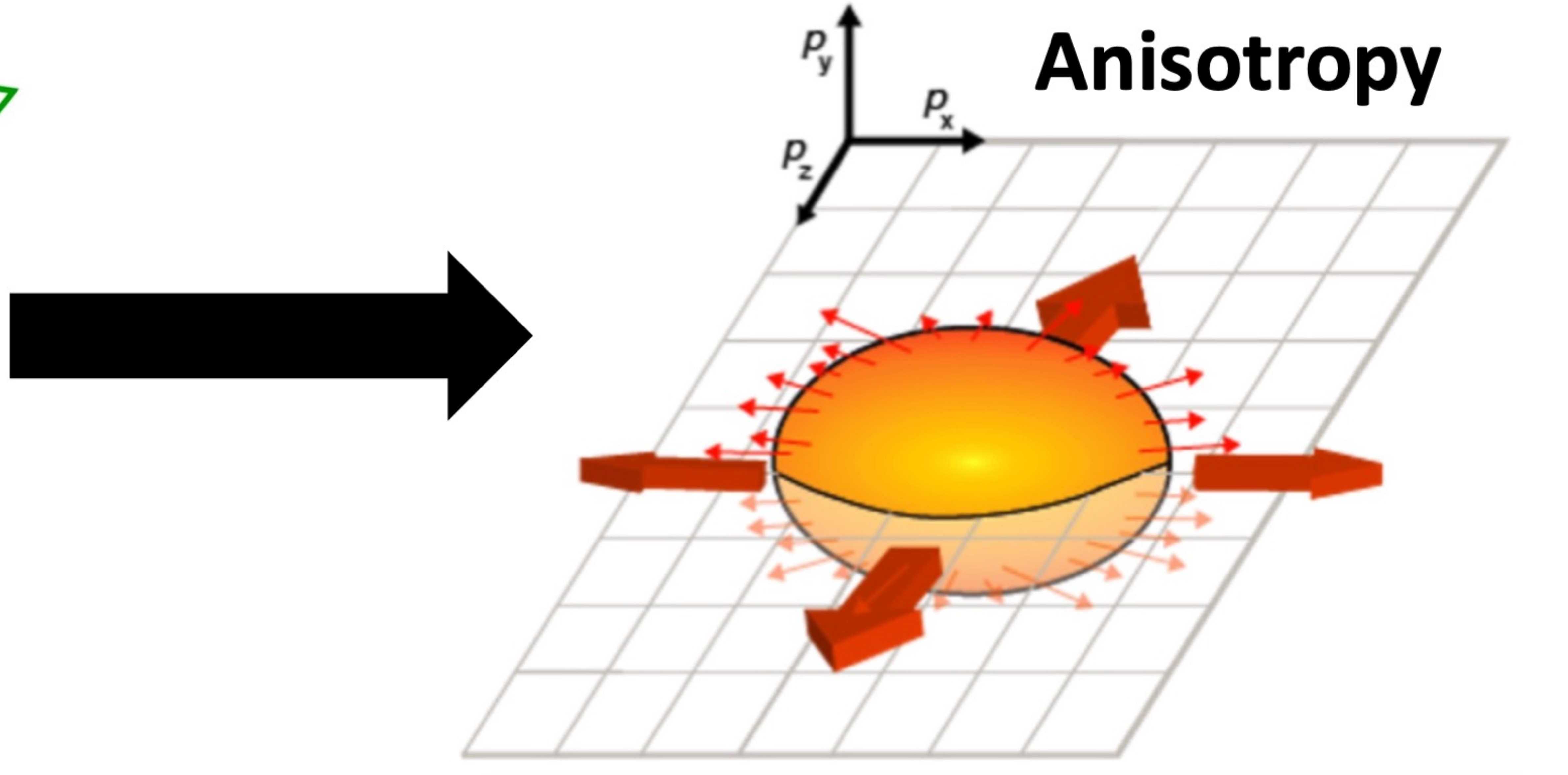
11 June 2024

Flow Studies

- From initial conditions to final state particle momentum anisotropy
- Hydrodynamic expansion, Energy loss, Non-flow





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

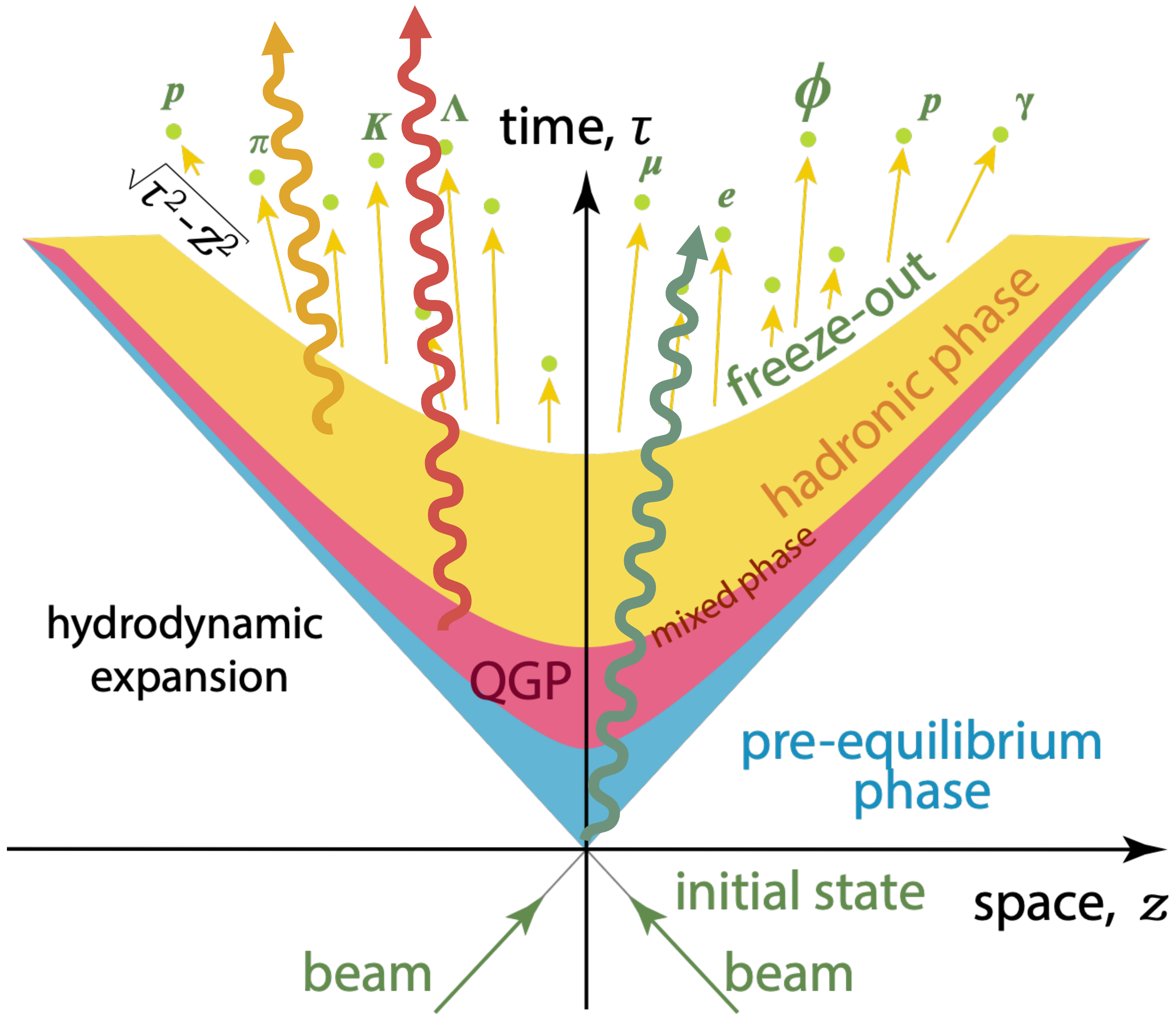
$$v_2 = \langle \cos(2(\phi_i - \Psi_2)) \rangle$$

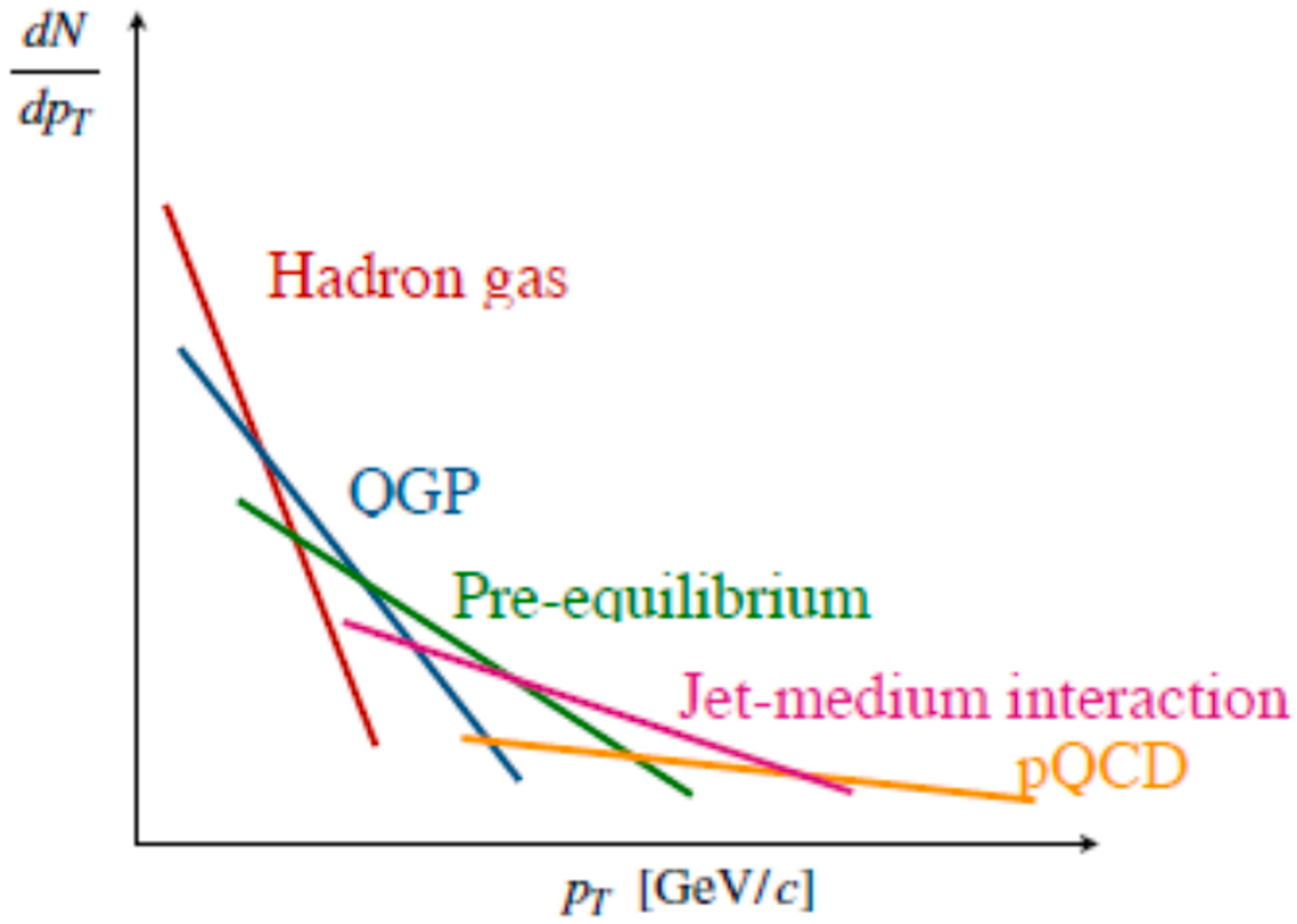
Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

Direct Photons

Direct photons

- Created all the time from initial hard scattering to kinetic freeze-out
- Hard to measure and to disentangle the different sources





Inclusive and decay photon v_2

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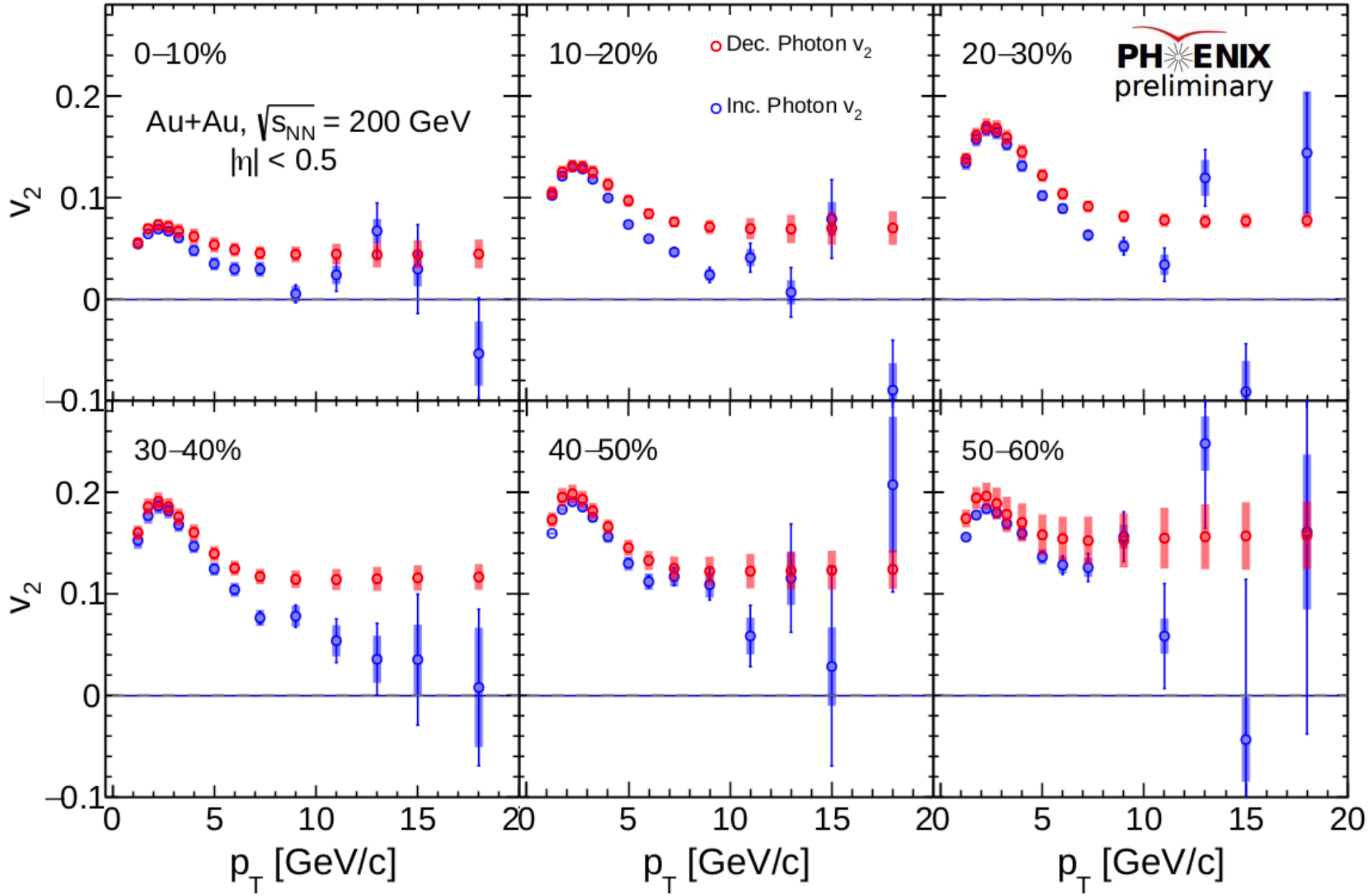
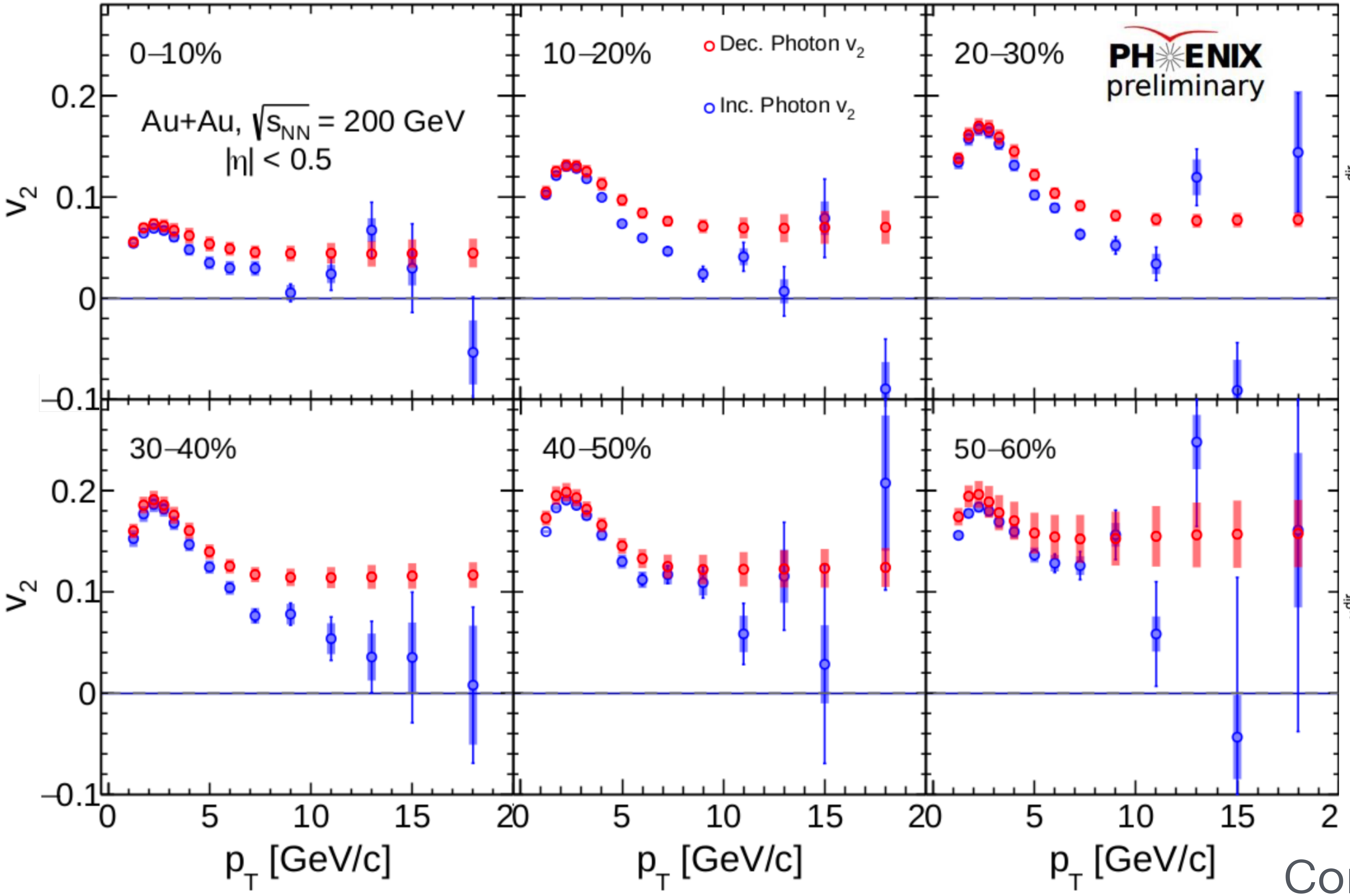
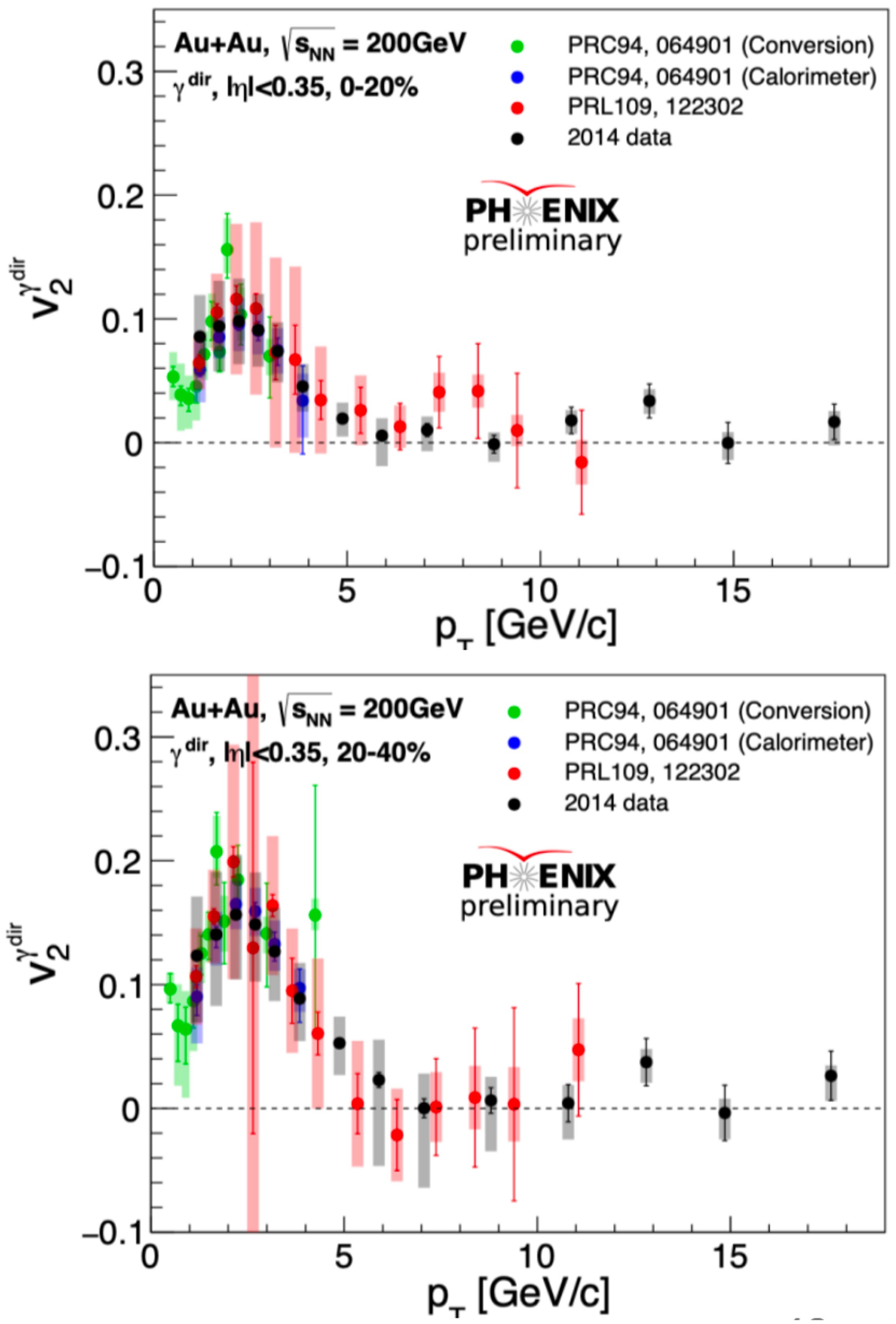


- Inclusive photons: direct + decay
- Decay photon: dominated by π^0 → mirrors hadron flow
- At high p_T direct photons dominate (γ/π^0 increases)

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

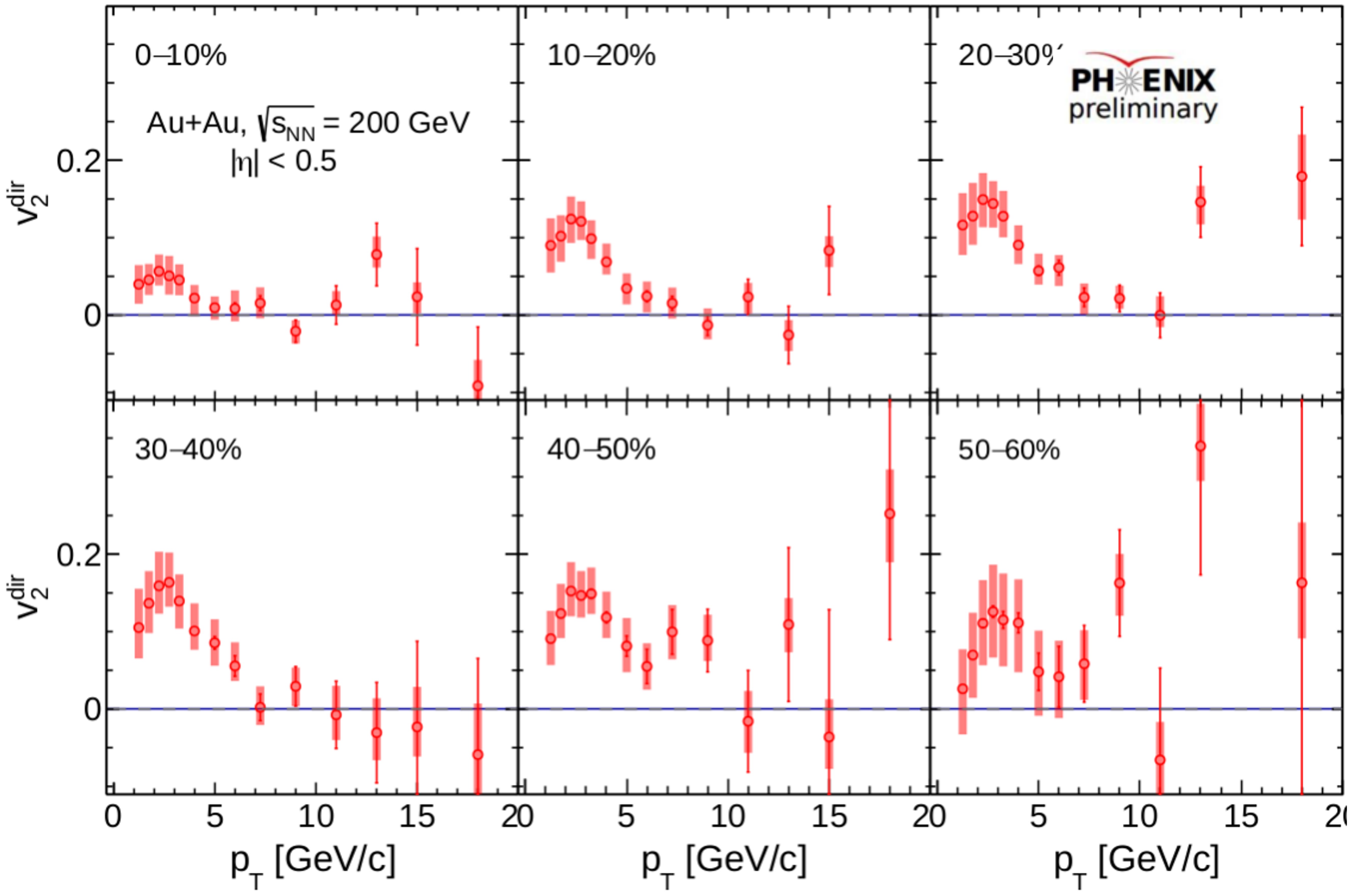
Direct and decay photon v_2





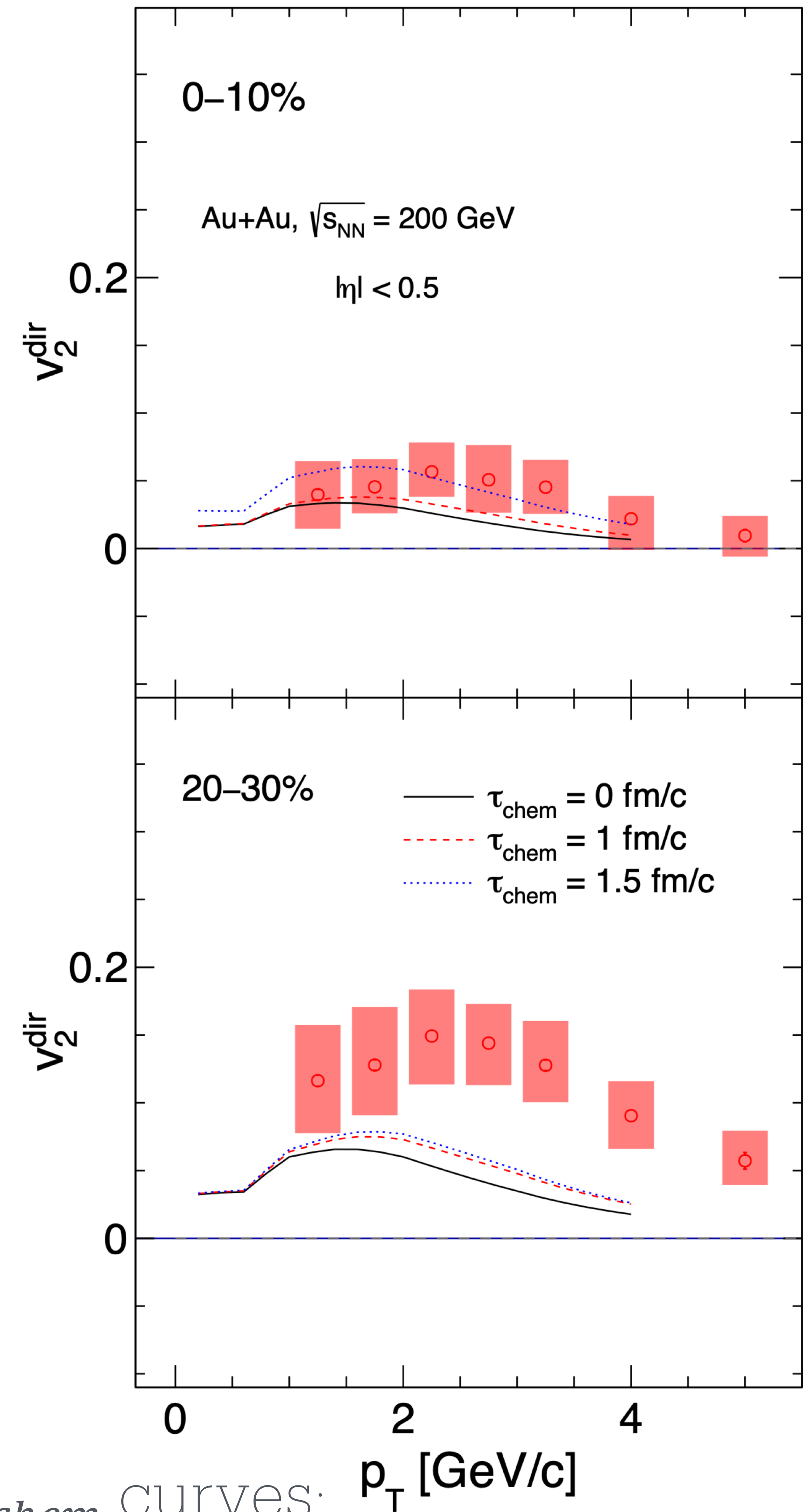
Consistent with earlier findings

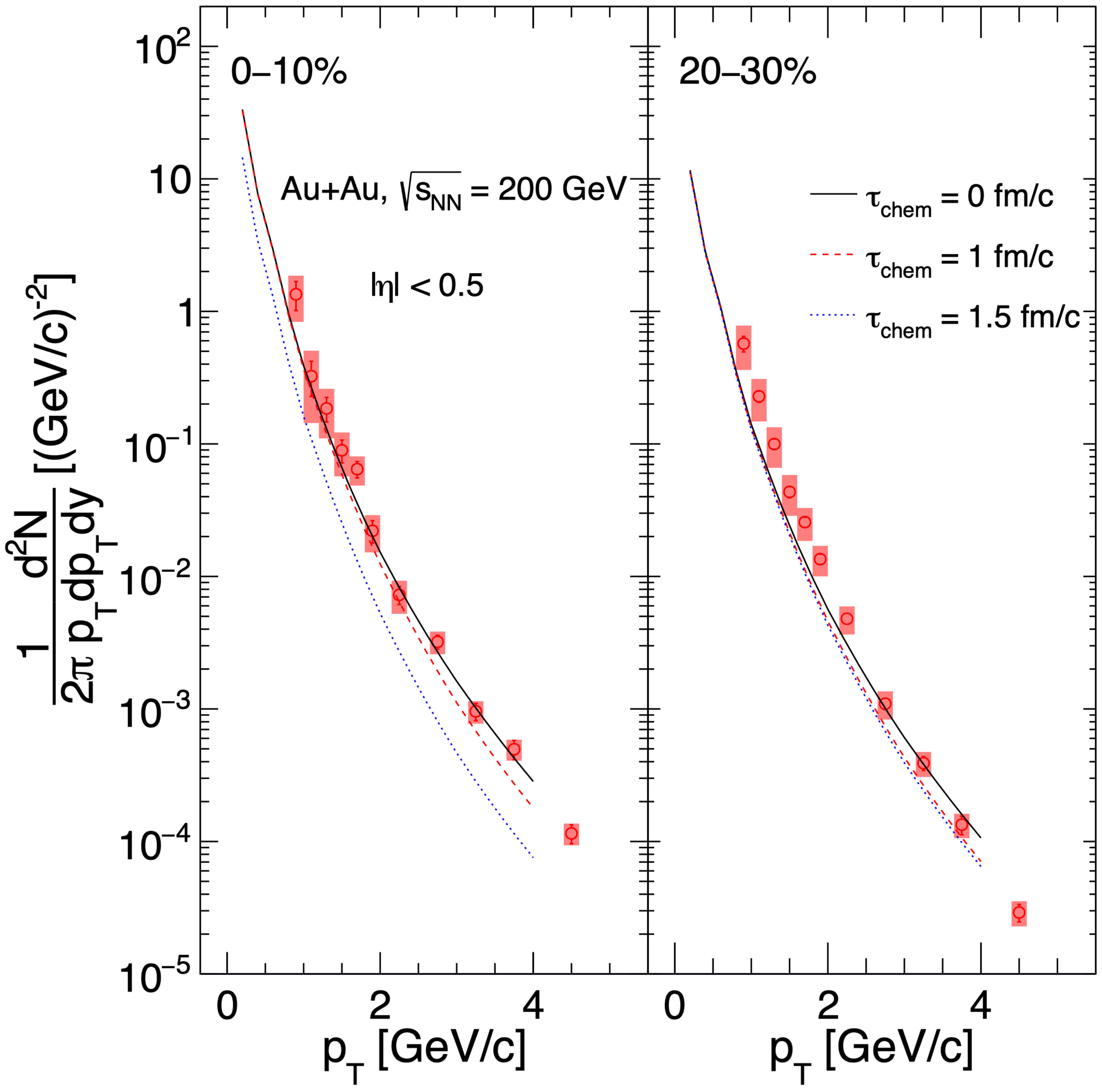
Direct Photon Flow



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

v_2 at low and high p_T





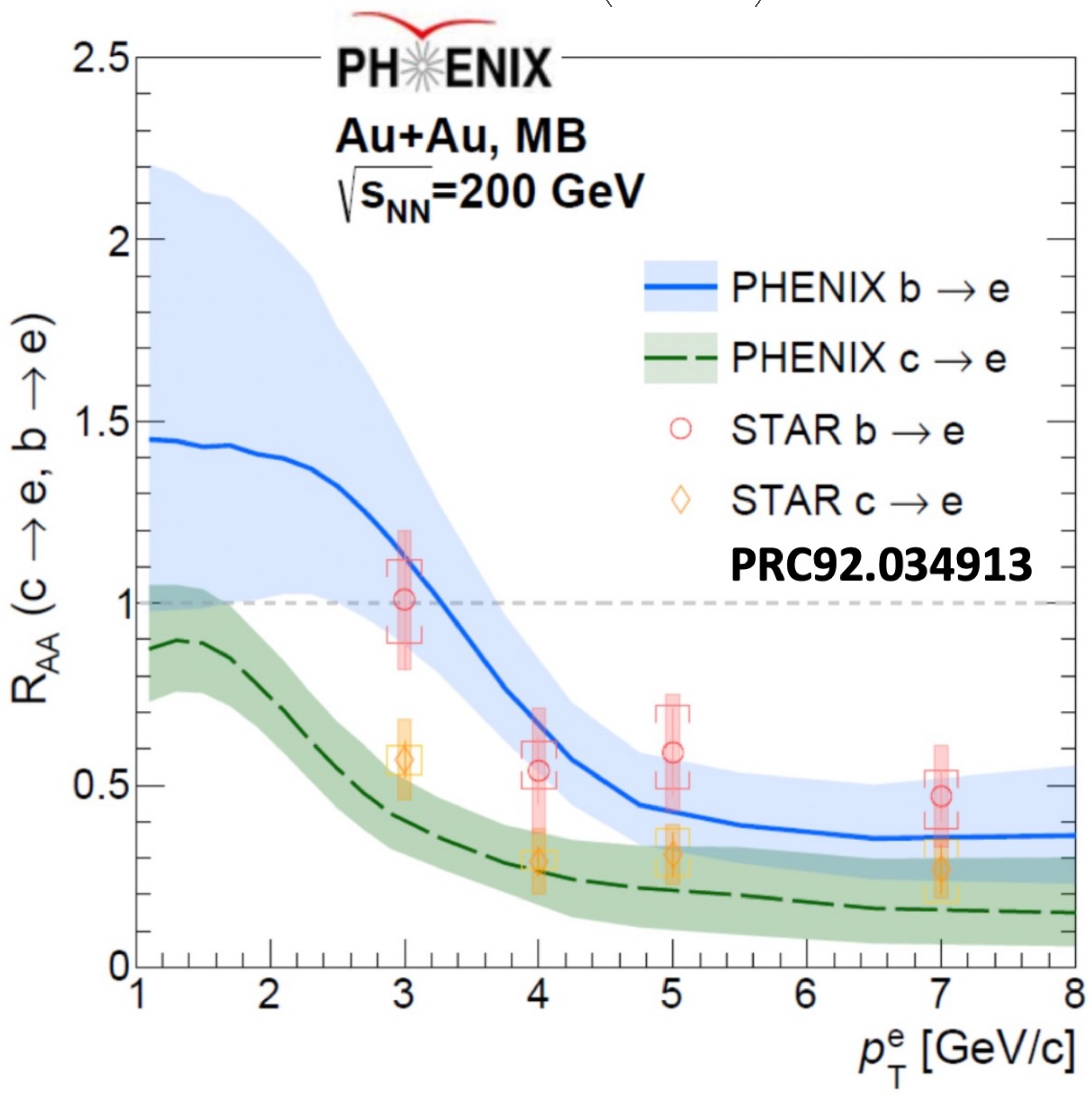
Larger time of quark production and equilibration in initial purely gluonic system t_{chem} is preferred, but still fails above 2 GeV/c

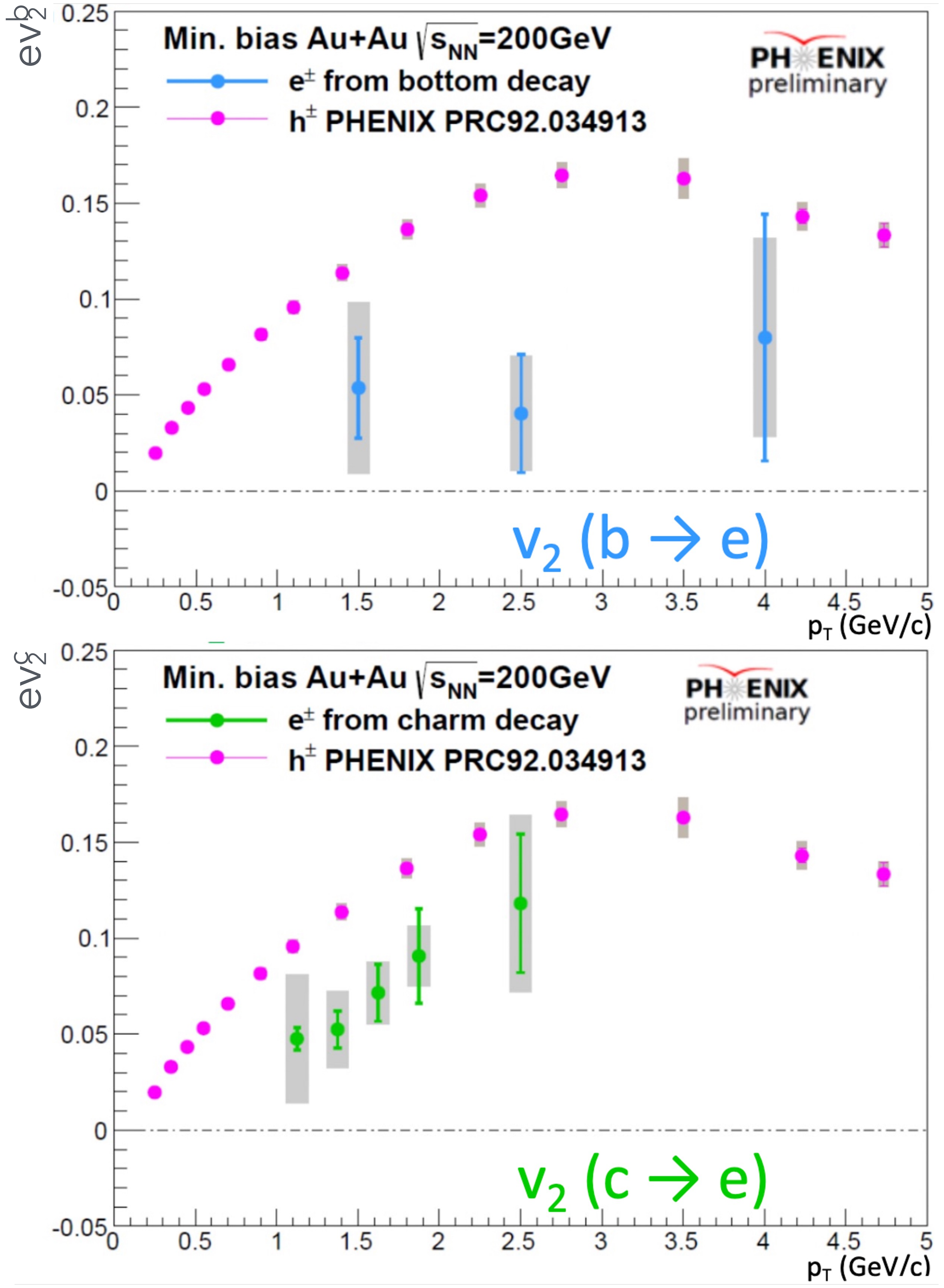
t_{chem} curves:
PRC 106, 014909 (2022)

Heavy Flavor

Separated Charm and Beauty R_{AA} and v_2

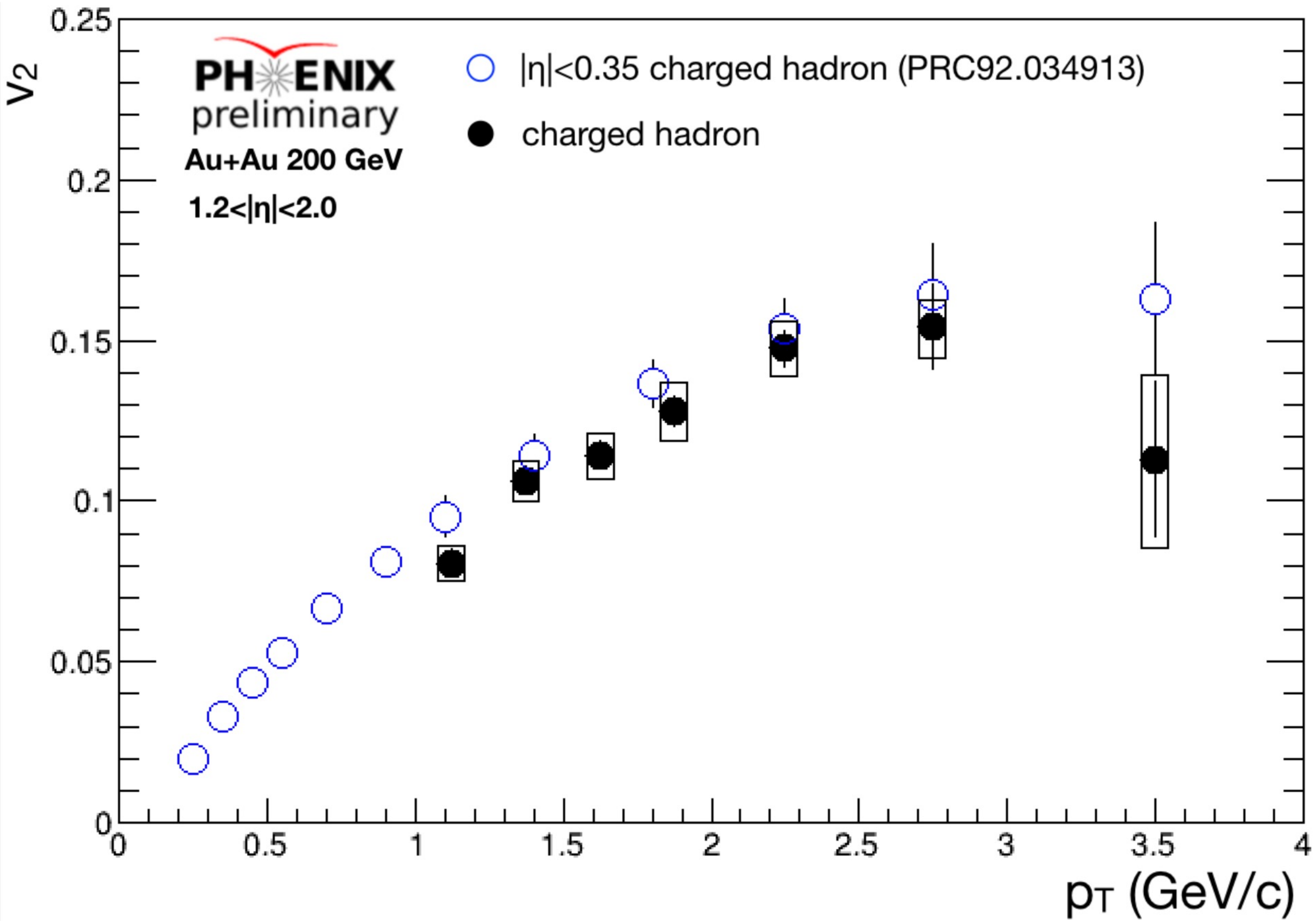
PRC 109 044907 (2024)





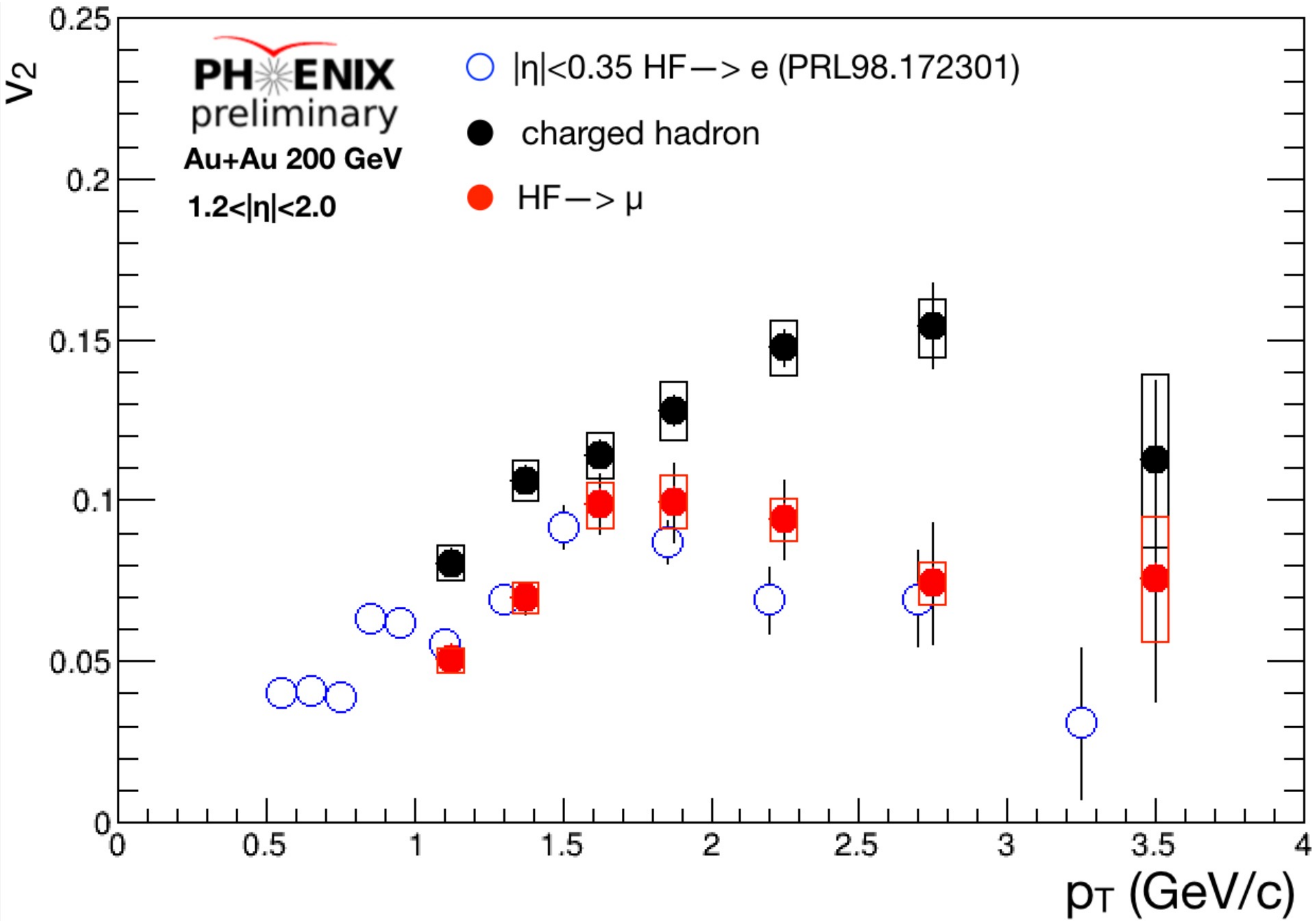
- Clear mass ordering observed between $(b \to l)$ and $(c \to l)$ at RHIC for both R_{AA} and v_2
- Interplay of energy loss and hydro at mid-p_T?

Heavy Flavor v_2 Measurement



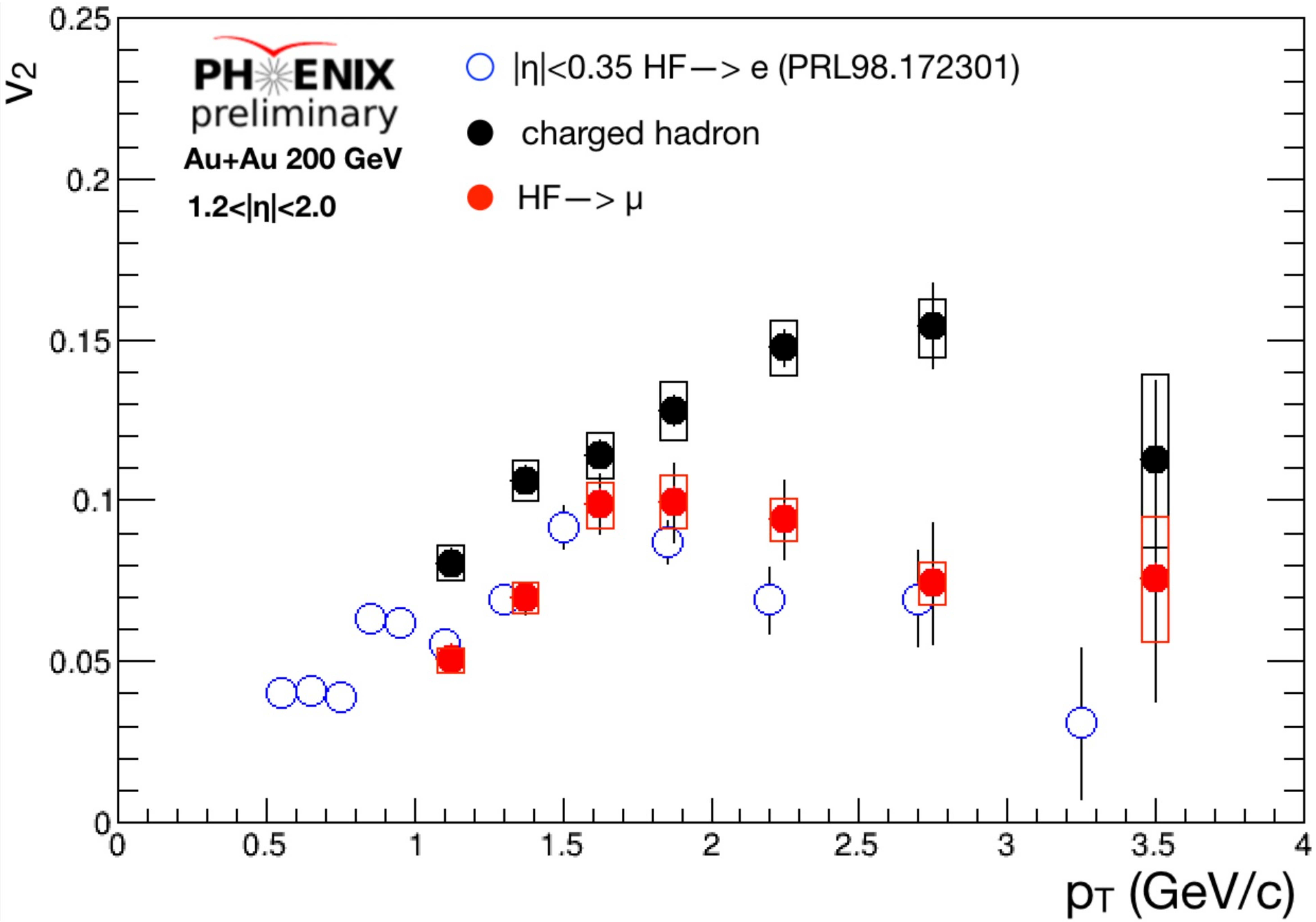
- Hint of rapidity-dependence of charged hadron v_2

Heavy Flavor v_2 Measurement



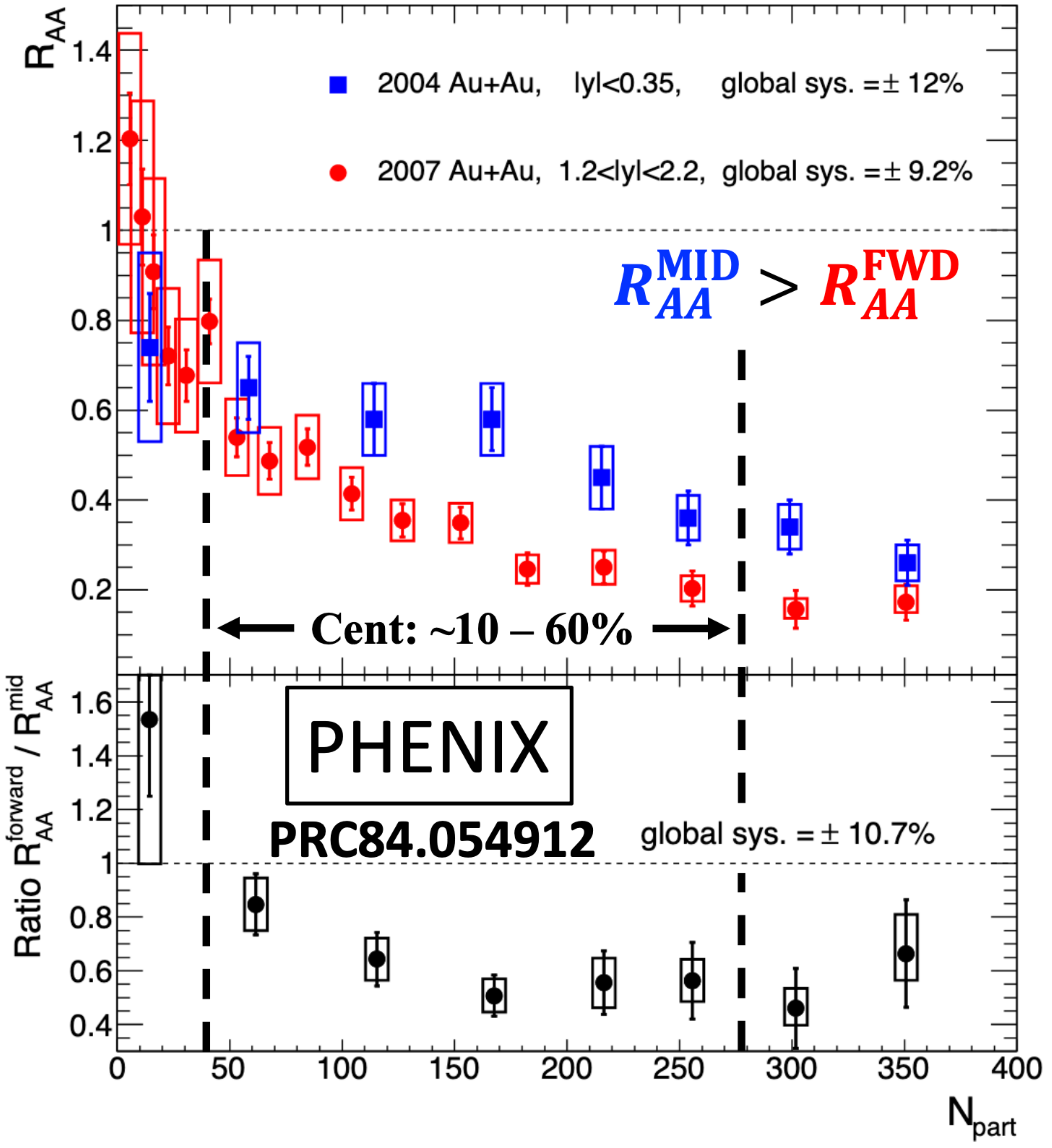
- Hint of rapidity-dependence of charged hadron v_2
- Open HF v_2 is consistent with previous PHENIX results at mid-rapidity

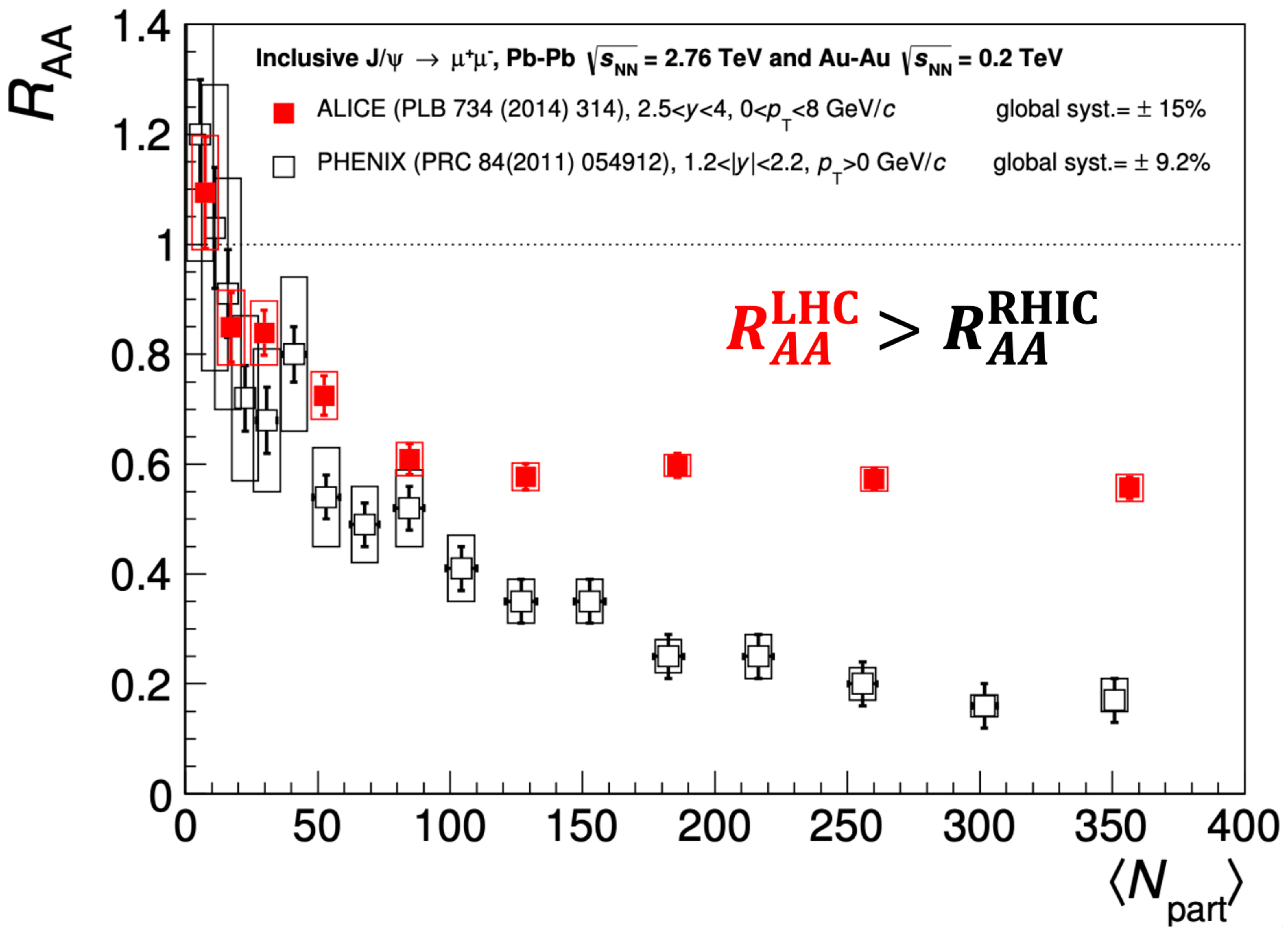
Heavy Flavor v_2 Measurement



- Hint of rapidity-dependence of charged hadron v_2
- Open HF v_2 is consistent with previous PHENIX results at mid-rapidity
- HF particles flow with the QGP, but less than charged hadrons

J/ψ Nuclear Modification (R_{AA})

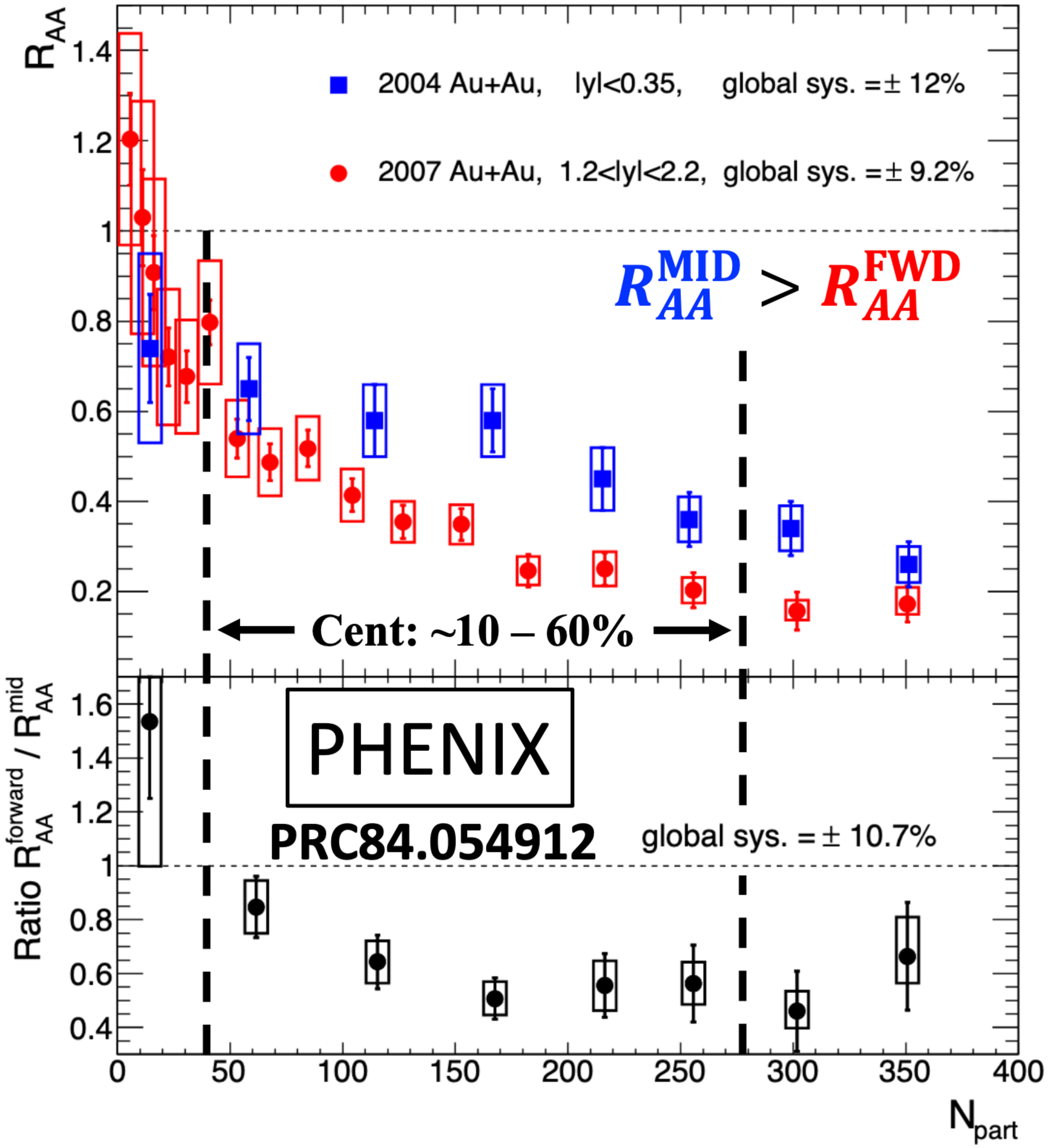


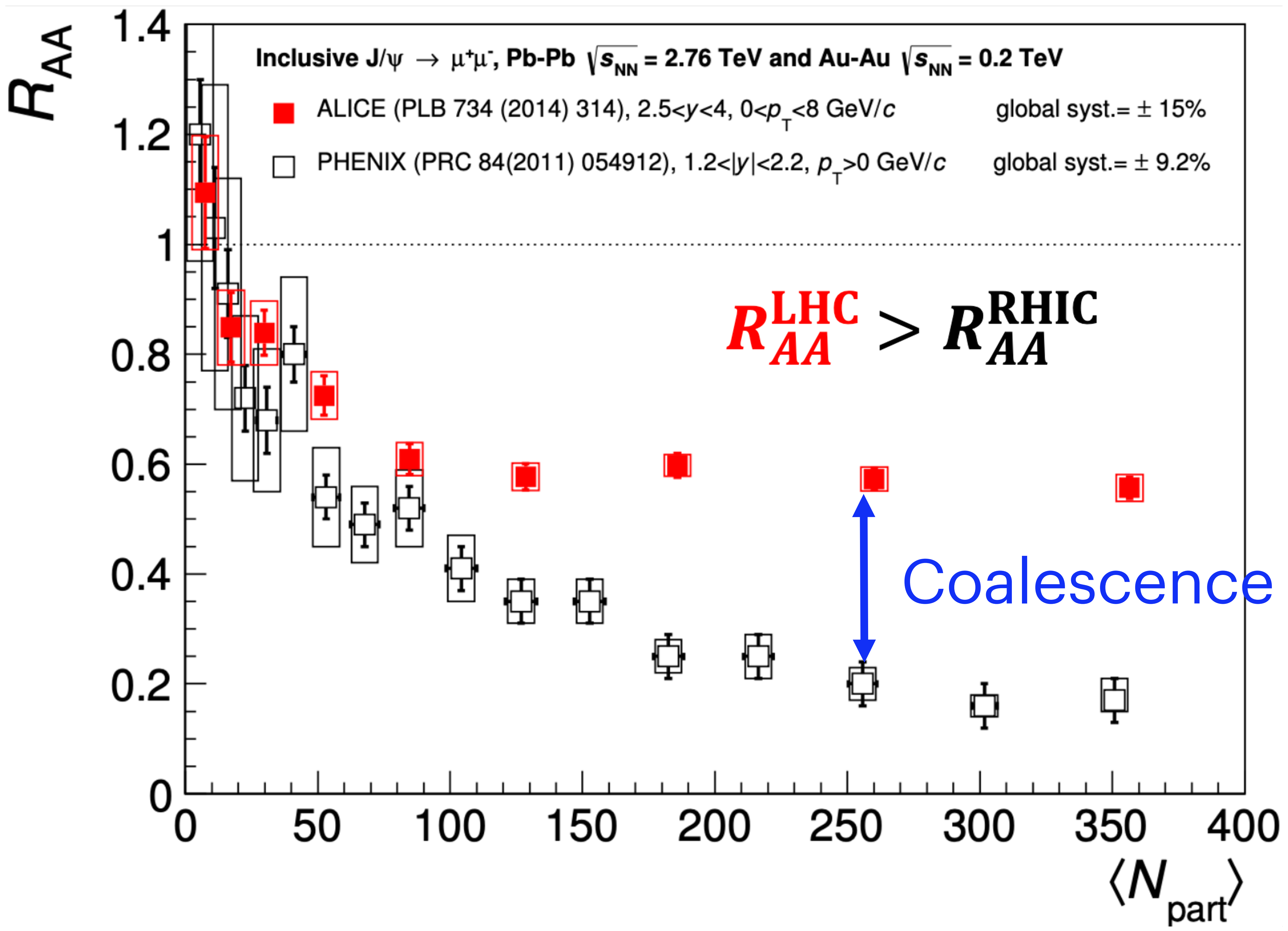


RHIC: $R_{AA}^{MID} > R_{AA}^{FWD}$

Forward: $R_{AA}^{LHC} > R_{AA}^{RHIC}$

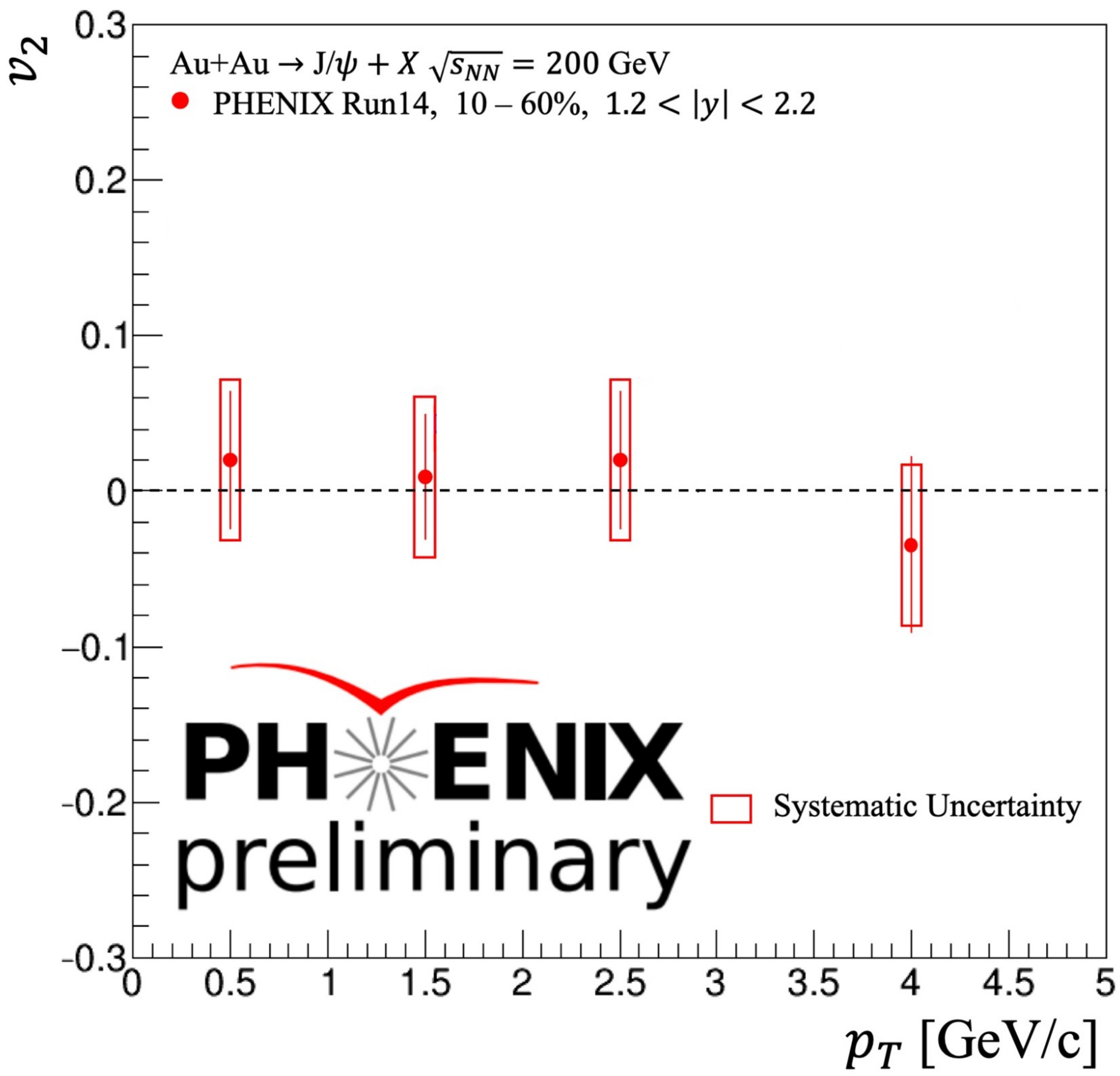
J/ψ Nuclear Modification (R_{AA})





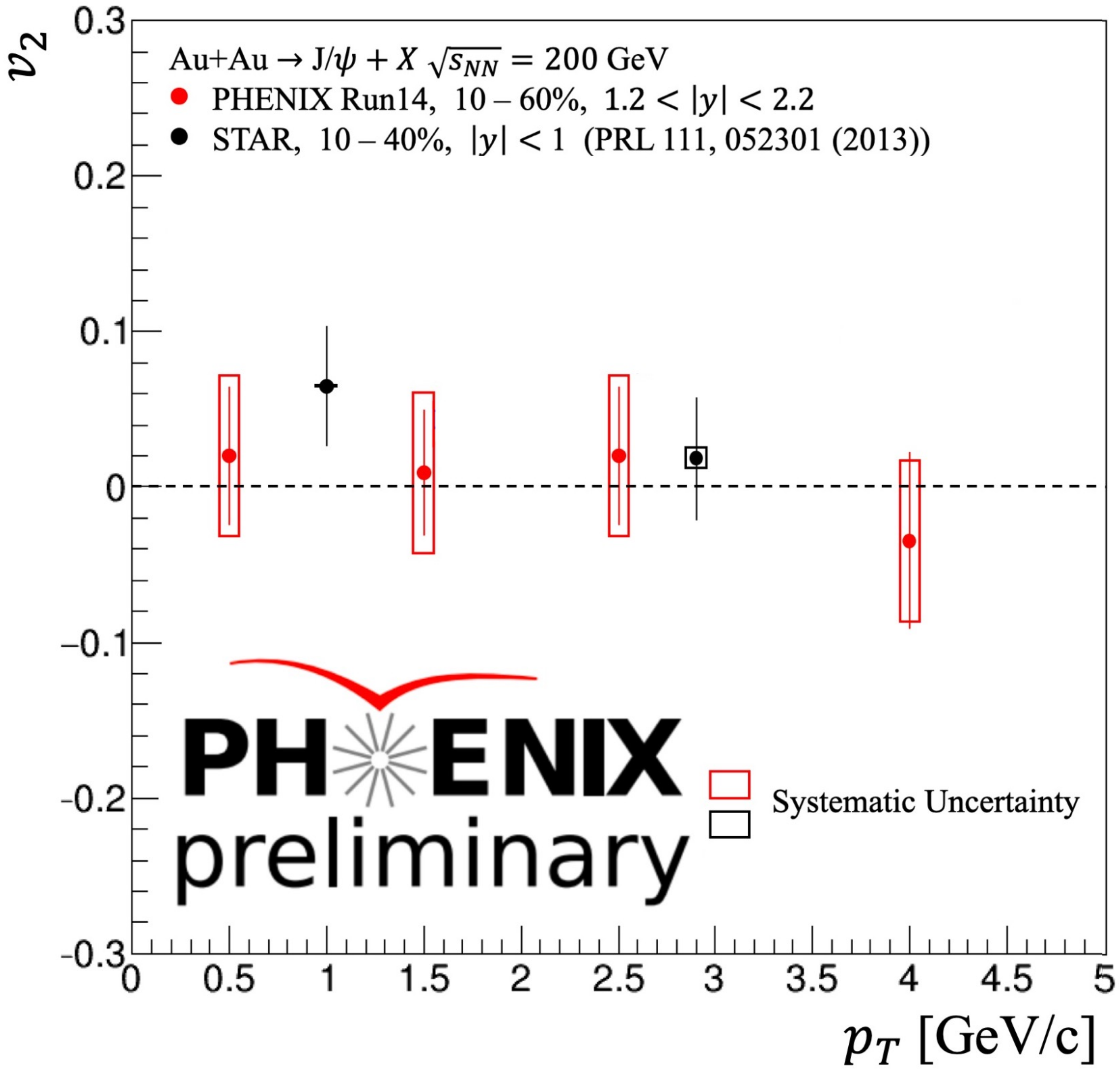
Coalescence effect between charm quark and antiquark leads to J/ψ regeneration at LHC

J/ψ Elliptic Flow Measurement



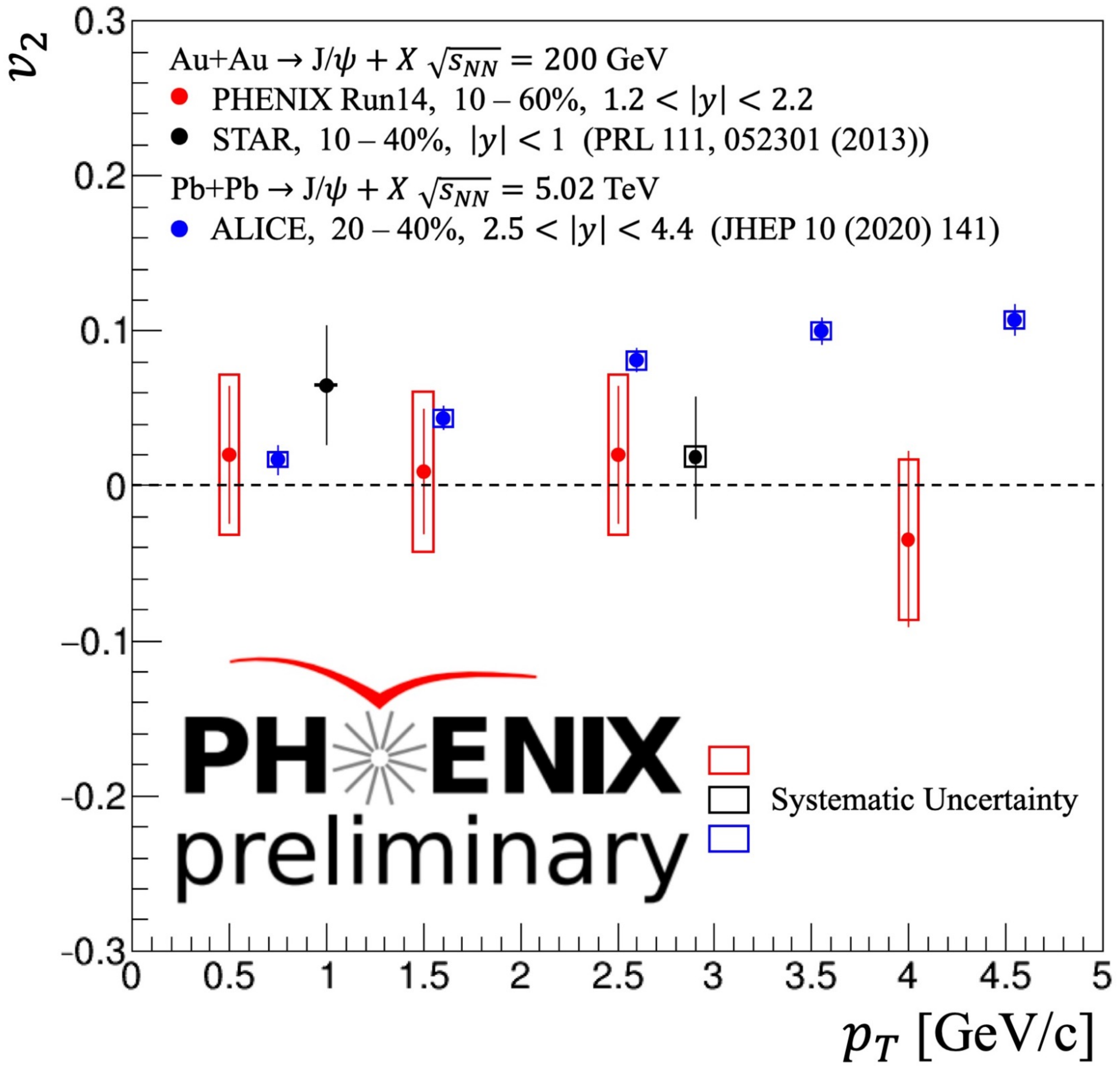
- PHENIX J/ψ $v_2$at forward rapidity is consistent with 0

J/ψ Elliptic Flow Measurement



- PHENIX J/ψ v_2 at forward rapidity is consistent with 0
- Forward and mid-rapidity results at RHIC are consistent, but the uncertainties are large

J/ψ Elliptic Flow Measurement



- PHENIX J/ψ v_2 at forward rapidity is consistent with 0
- Forward and mid-rapidity results at RHIC are consistent, but the uncertainties are large
- The ALICE nonzero result is different from our measurement
- Not enough energy at RHIC for J/ψ regeneration to become noticeable?

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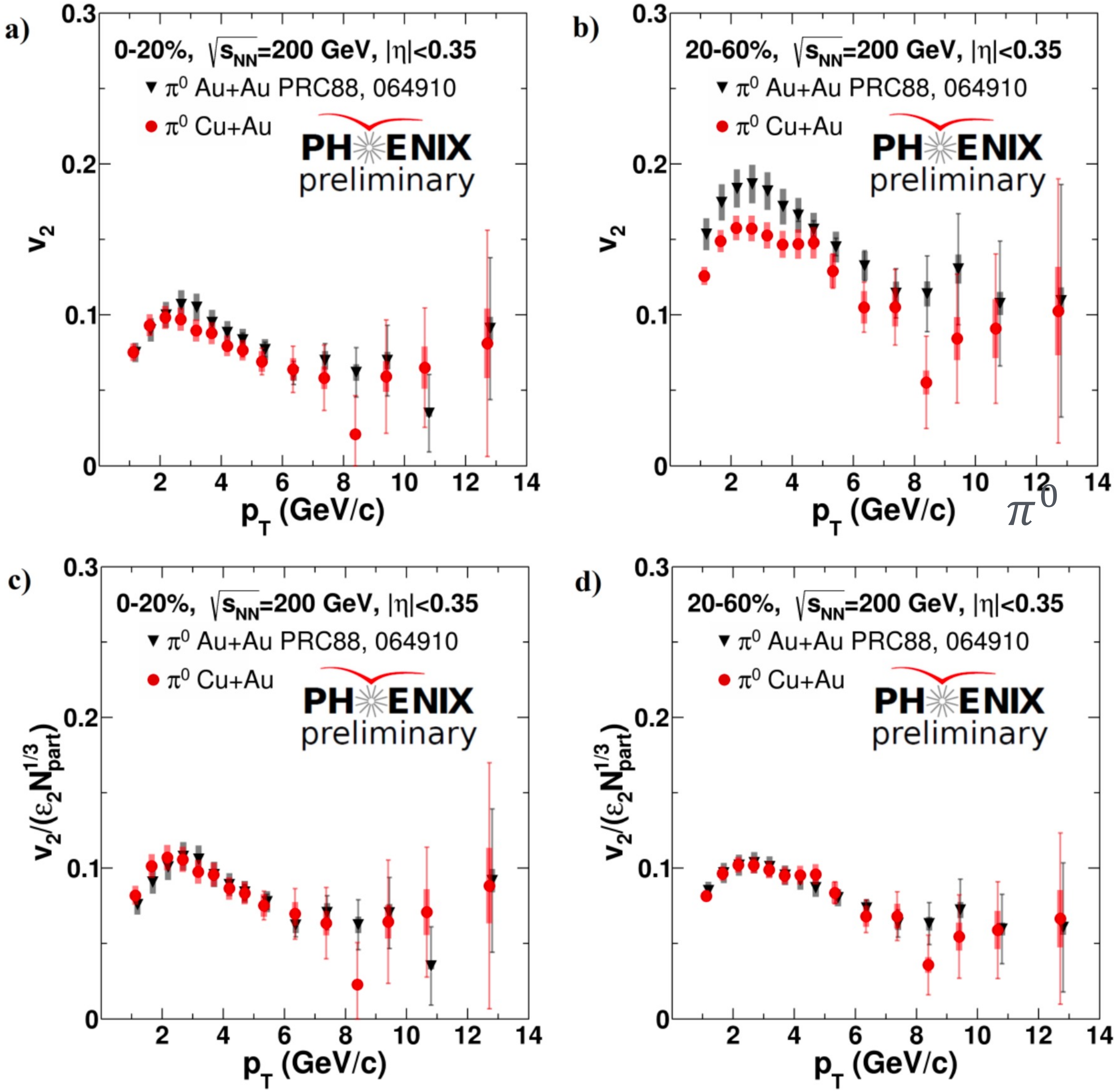
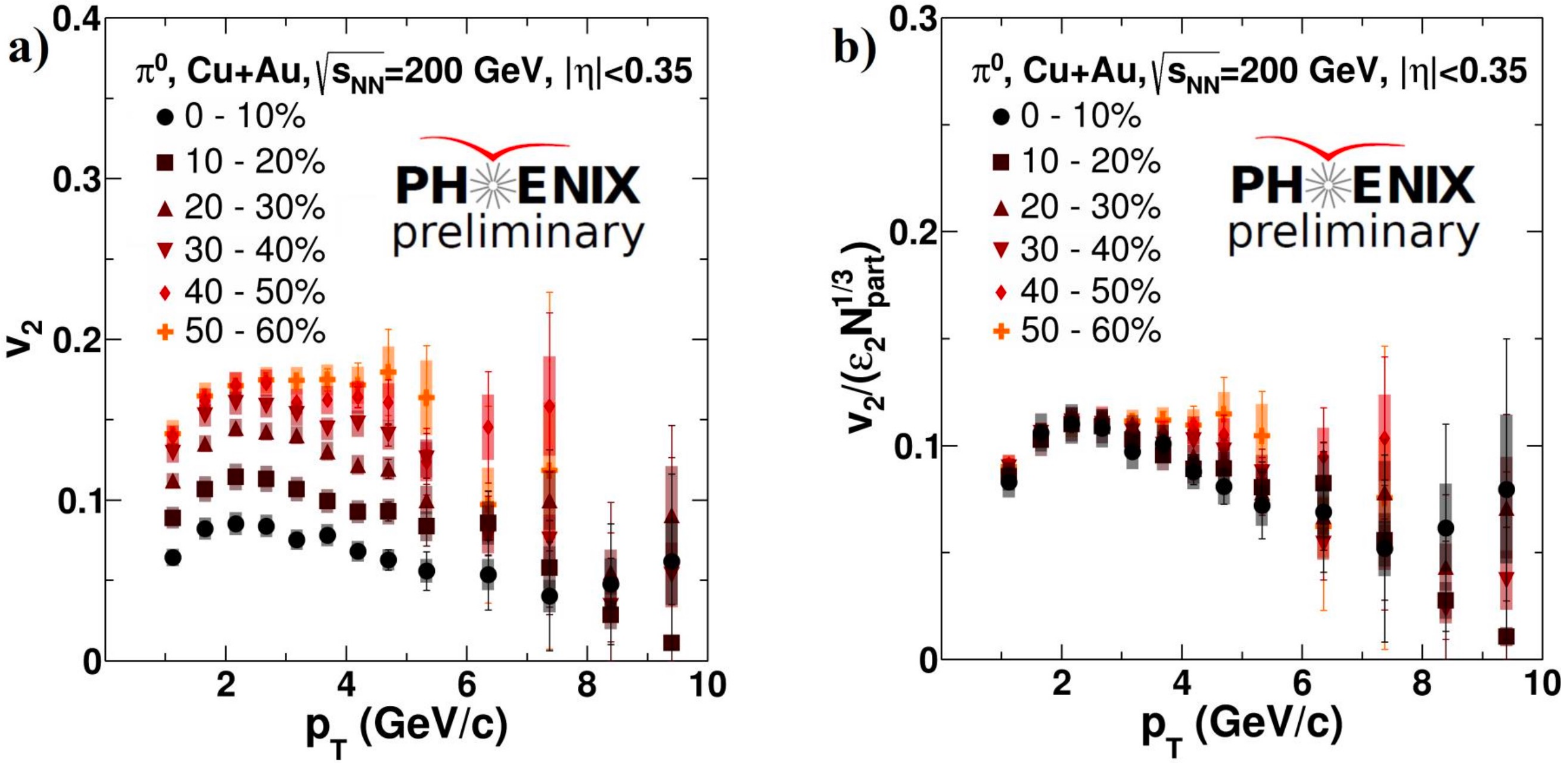
Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

π^0 Elliptic Flow Measurement



- The $v_2/\left(\varepsilon_2 N_{part}^{1/3}\right)$ are consistent within uncertainties in Cu+Au and Au+Au collisions
- The elliptic flow values are nonzero at $p_T > 5$ GeV/c
- Does $\varepsilon_2 N_{part}^{1/3}$ scaling work even at high-p_T?

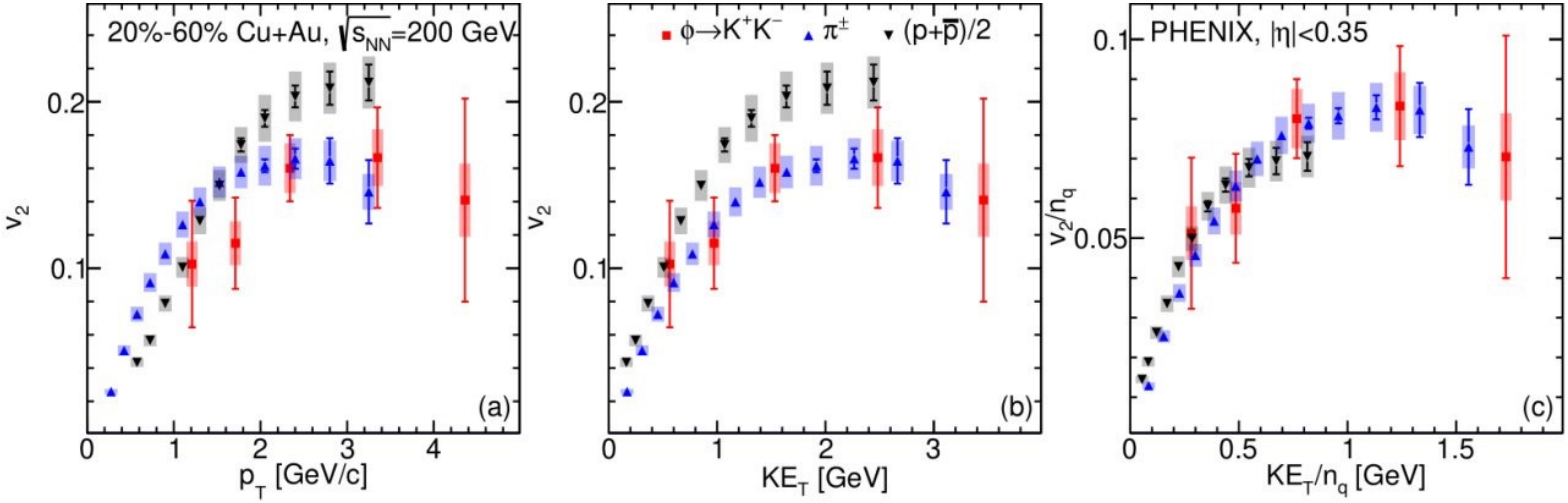
π^0 Elliptic Flow Measurement



The $v_2/\left(\varepsilon_2 N_{part}^{1/3}\right)$ are consistent within uncertainties in all centralities in Cu+Au collisions

$\phi, \pi^{\pm}$,and proton v_2

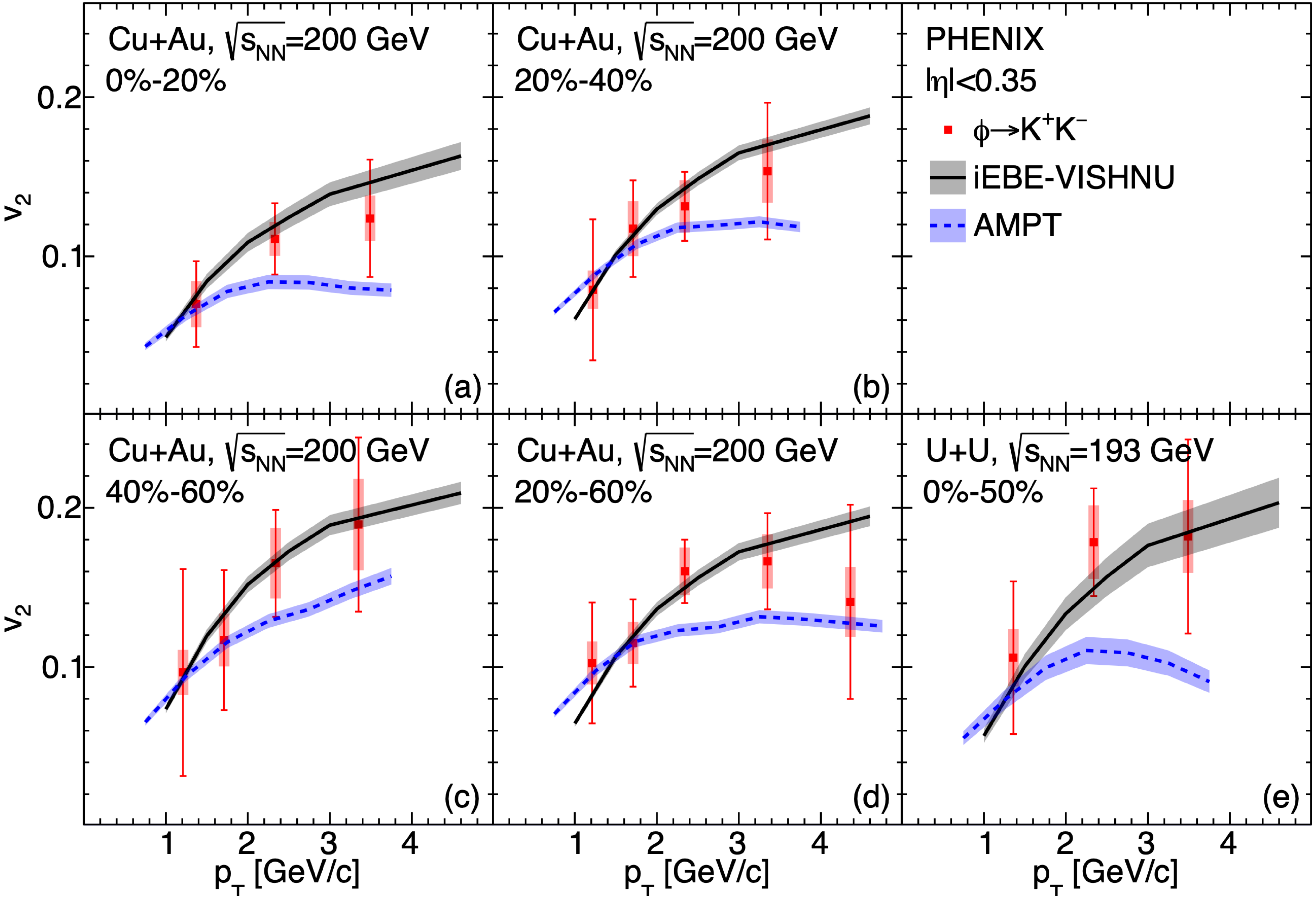
PRC 107, 014907 (2023)



- Scaling v_2 with n_q and kE_T/n_q
- Scaling with n_q - quark-coalescence models
- ϕ mesons - smaller rescattering cross section in comparison to $\pi^{\pm}$ and (anti)protons may indicate that the elliptic flow develops prior to hadronization

ϕ meson Elliptic Flow vs Models

PRC 107, 014907 (2023)

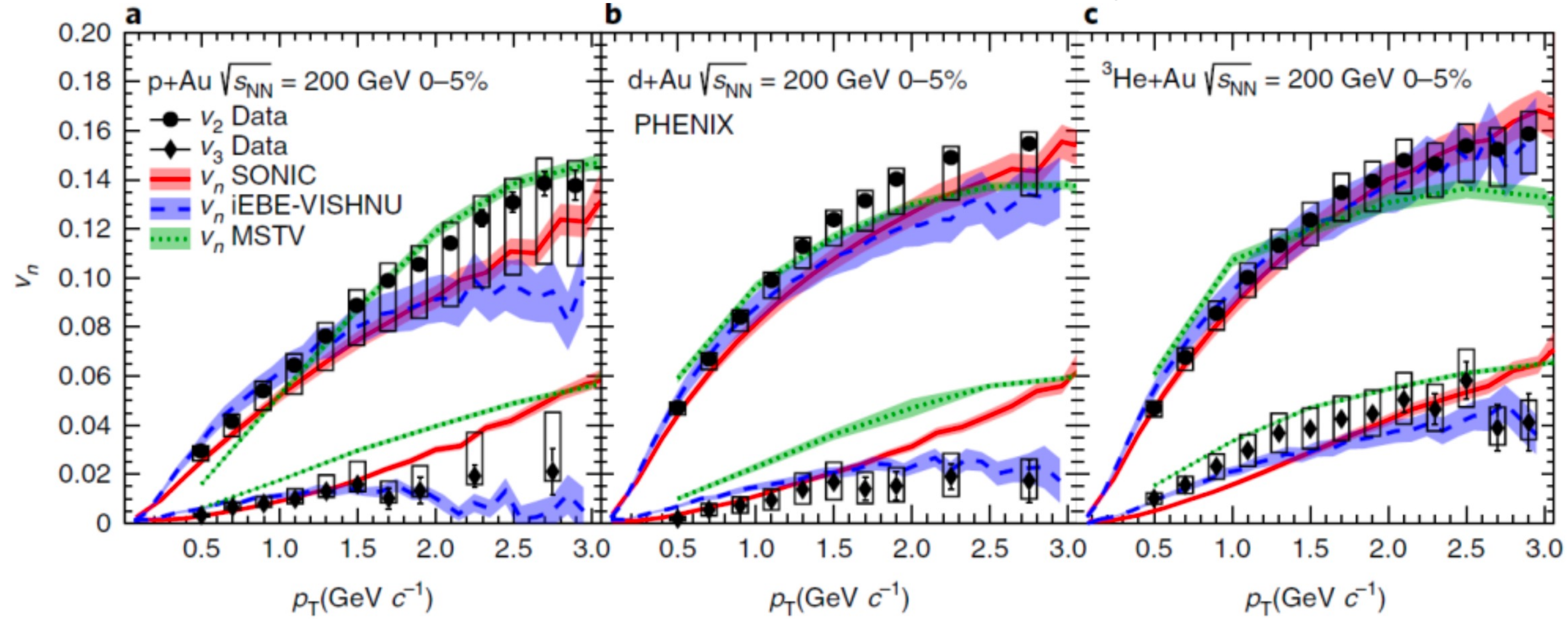


ϕ meson elliptic flow is well described by hydrodynamic model iEBE-VISHNU and transport model AMPT

Small Systems

Elliptic flow in small systems

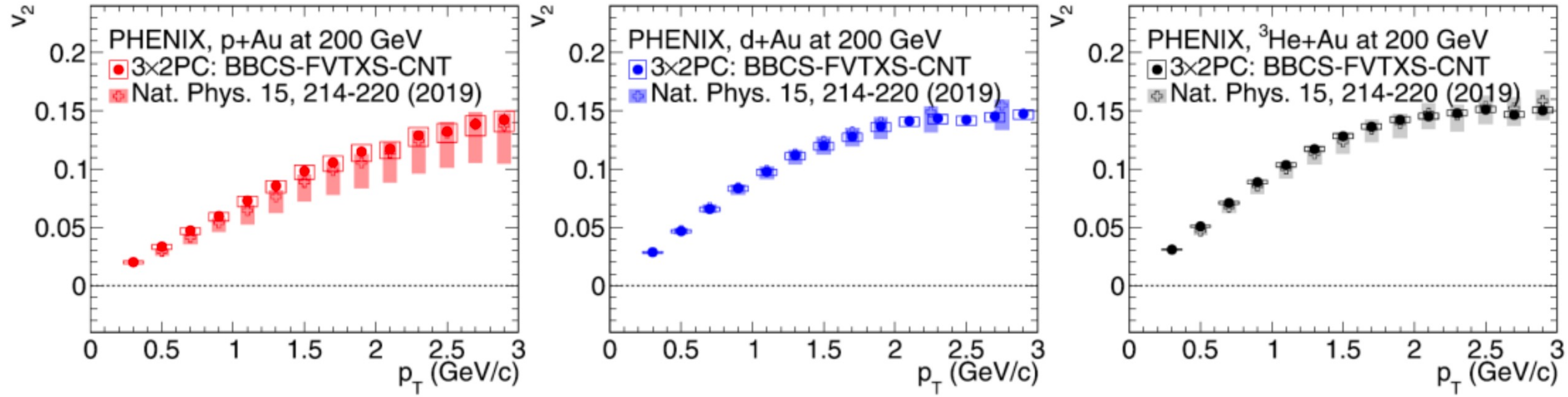
Nat. Phys. 15 (2019) 3, 214-220



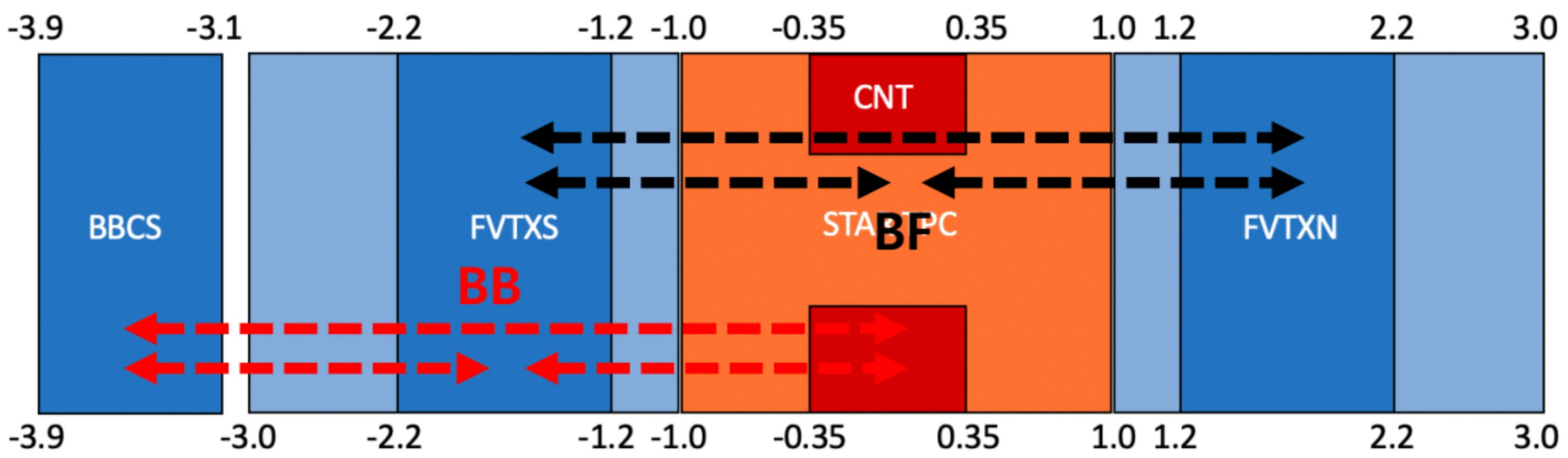
Nature Physics results were confirmed

Talk by Sanghoon Lim

PRC 105, 024901 (2022)

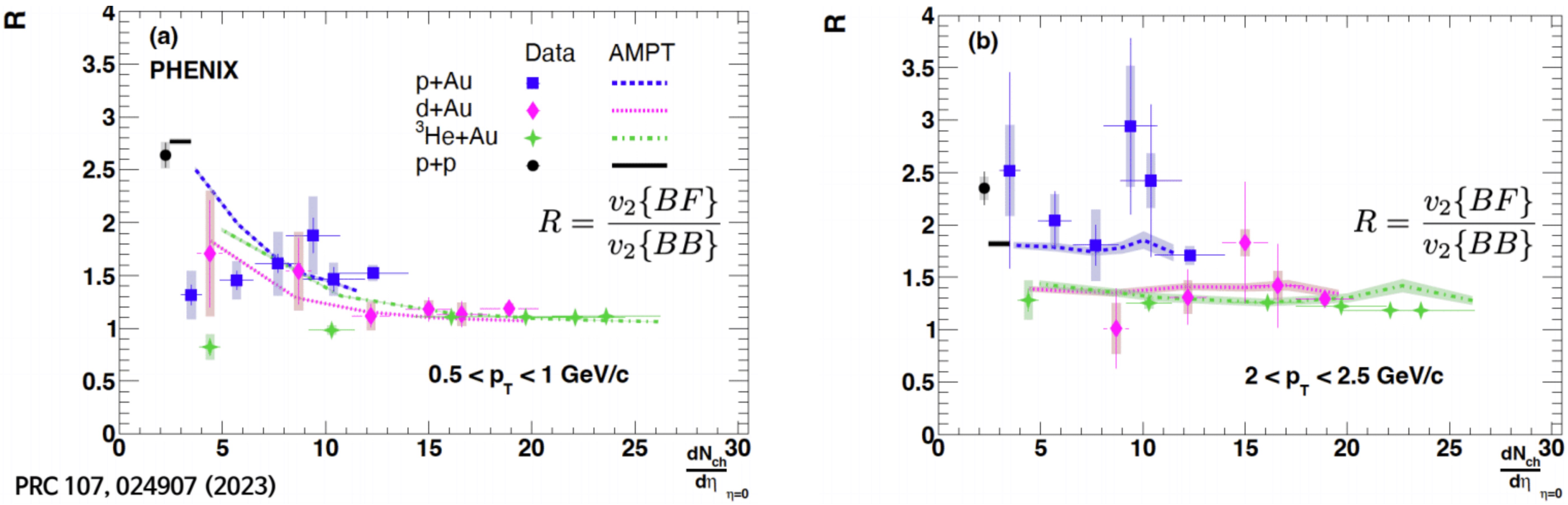


Multiplicity dependence



Talk by Sanghoon Lim

PRC 107 024907 (2023)



SUMMARY

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Large Systems:

- Low- p_T photon "puzzle" remains unsolved
- High-p_T direct photons flow is zero, π^0 flows at high p_T - partonic energy loss?
- Light and Heavy flavors flow at mid p_T - hydro + energy loss?:
  - Light flavored hadrons - coalescence is a main mechanics for flow transition from partonic level
  - J/Psi - not enough energy for heavy flavor recombination to become noticeable

Detailed study of small systems flow in next section (stay tuned)

SUMMARY

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Thank you for attention!

BACK UP

Heavy-Flavor Extraction

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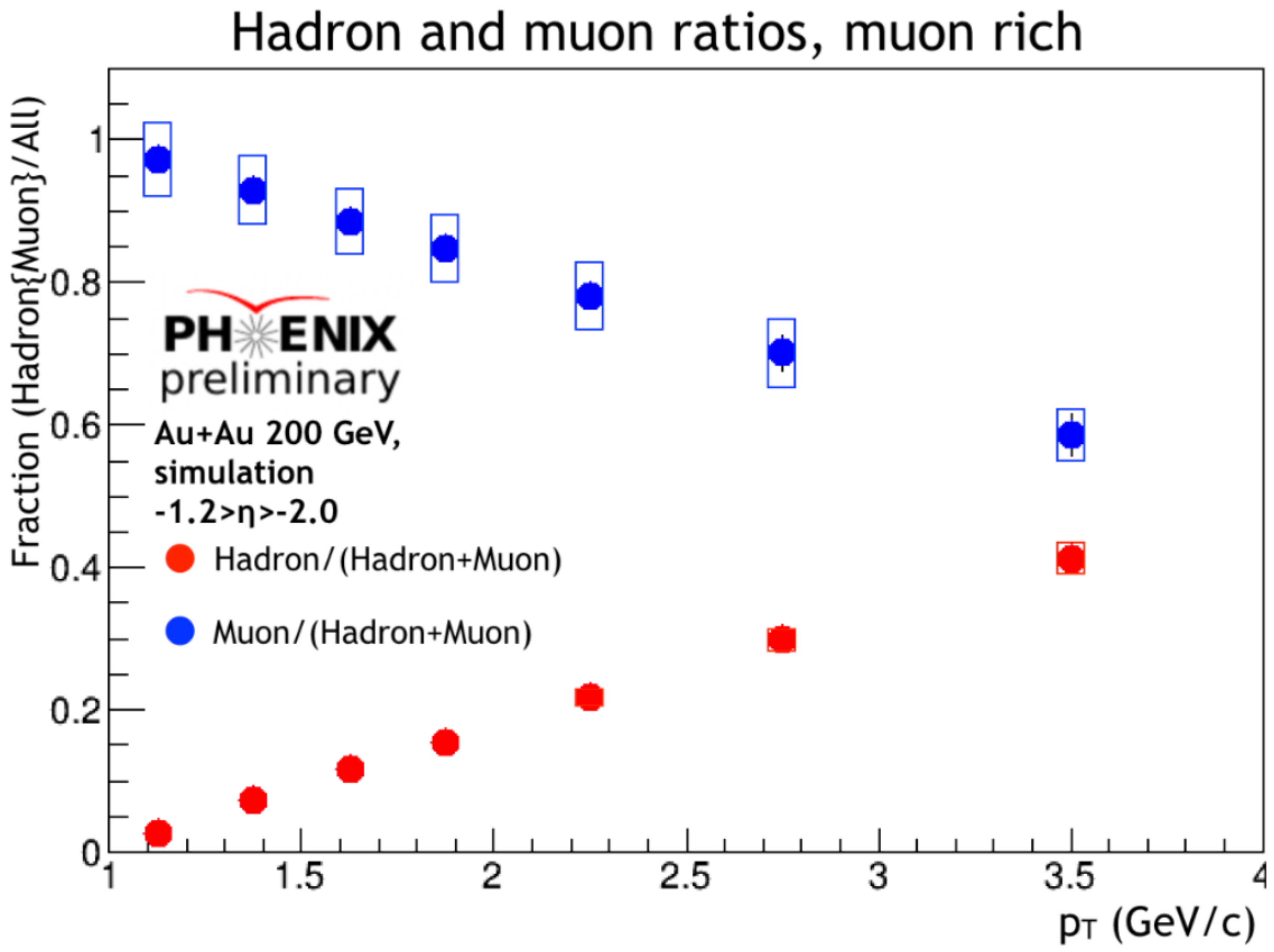
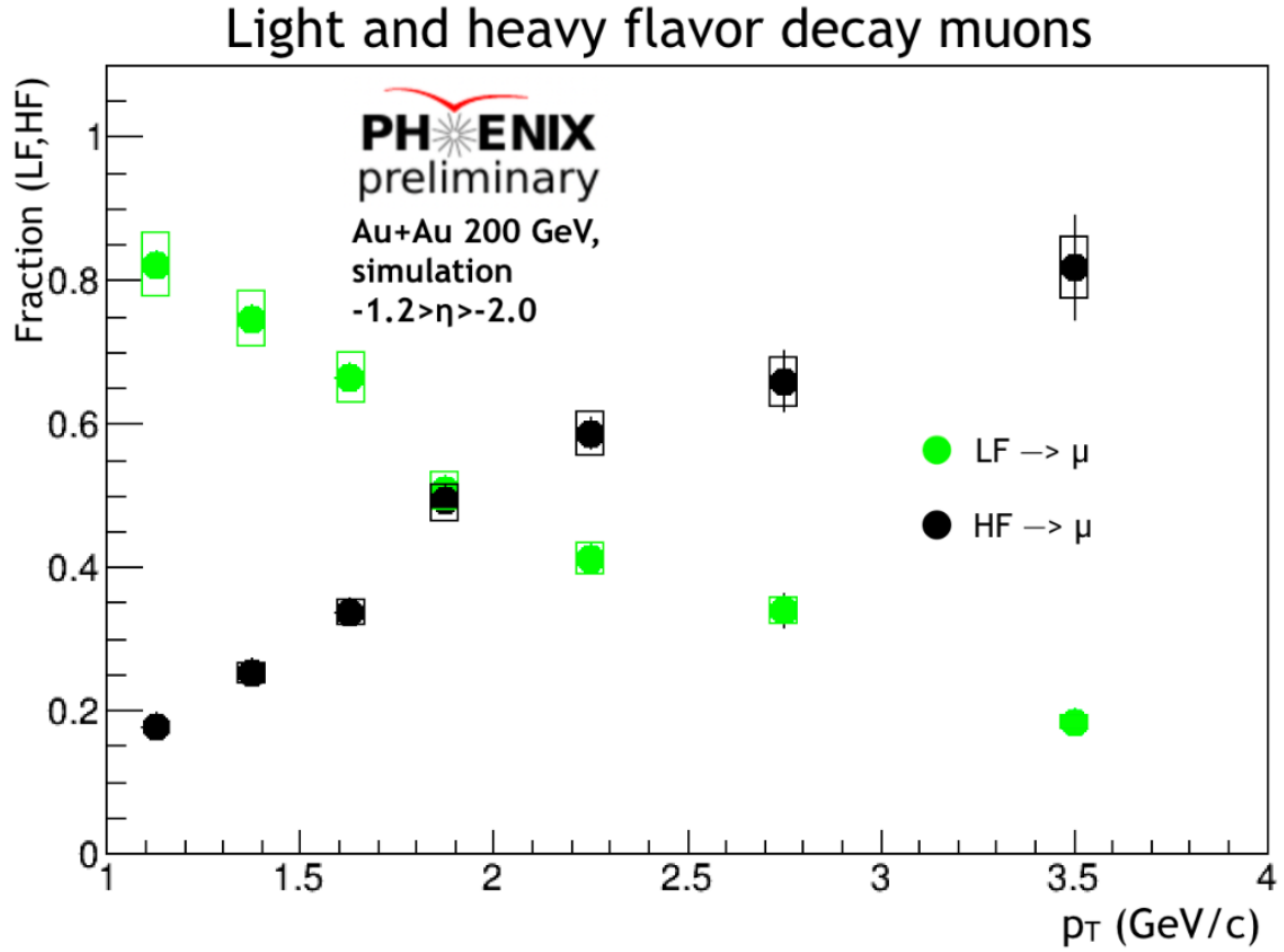
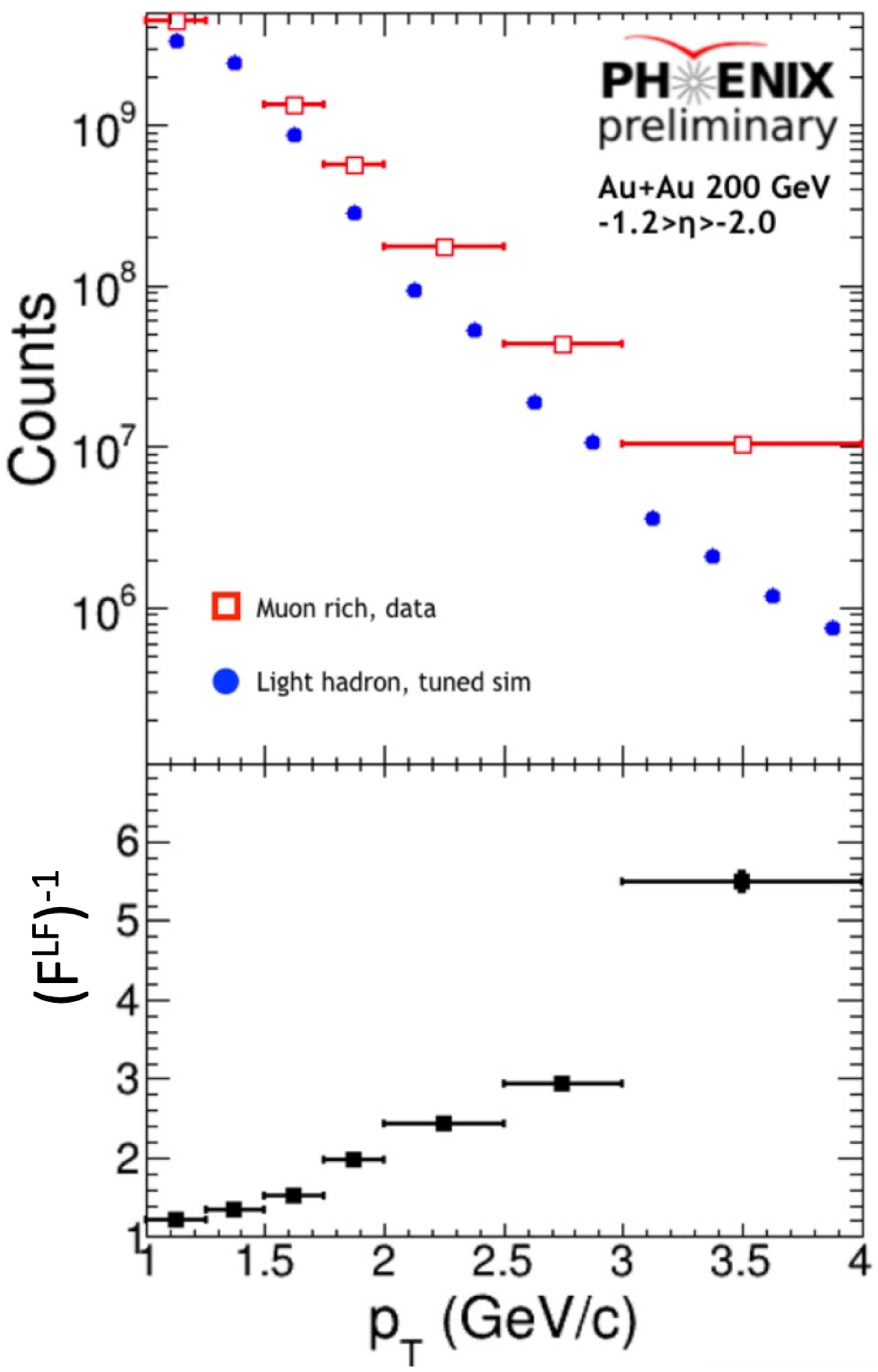




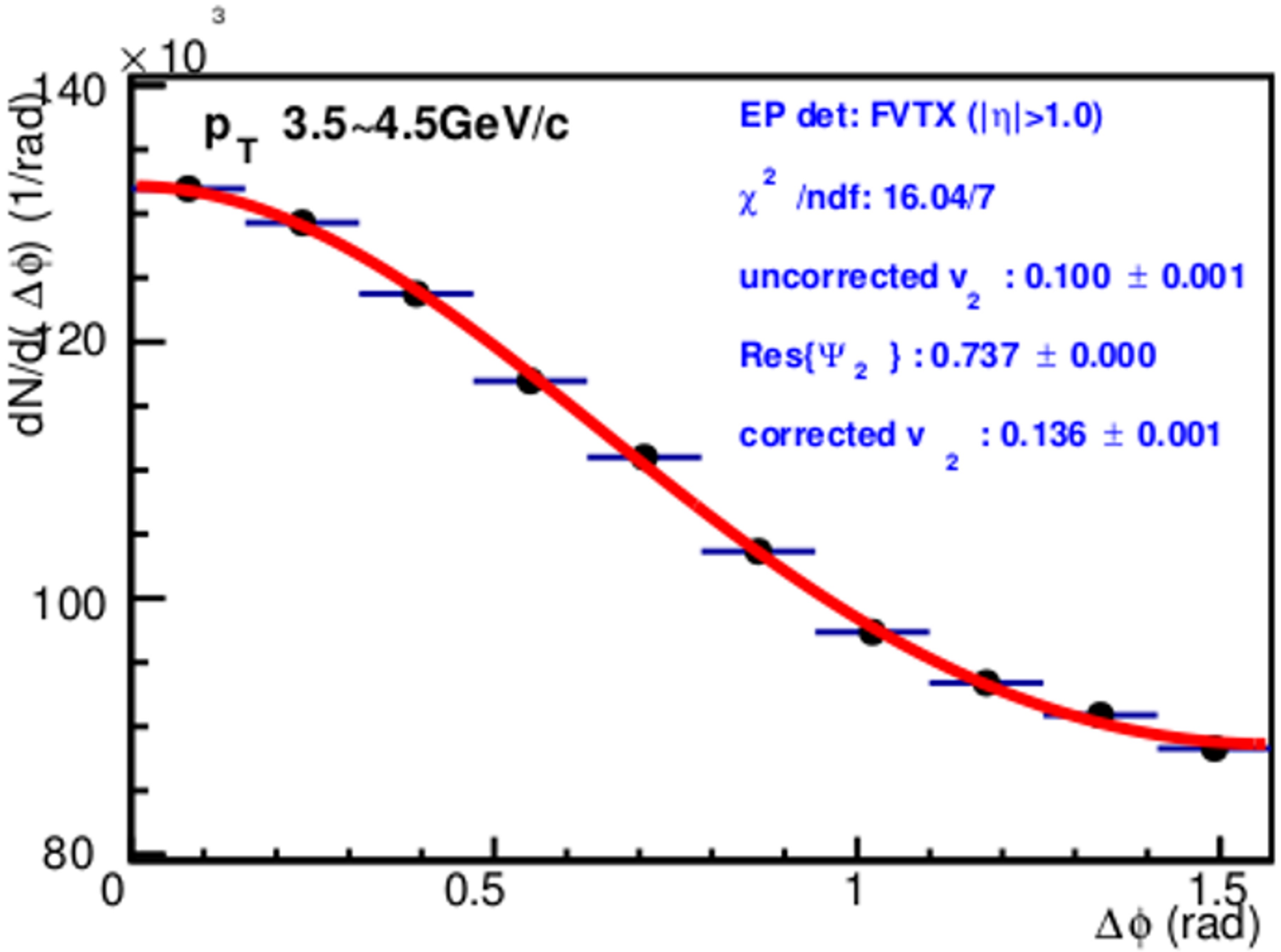


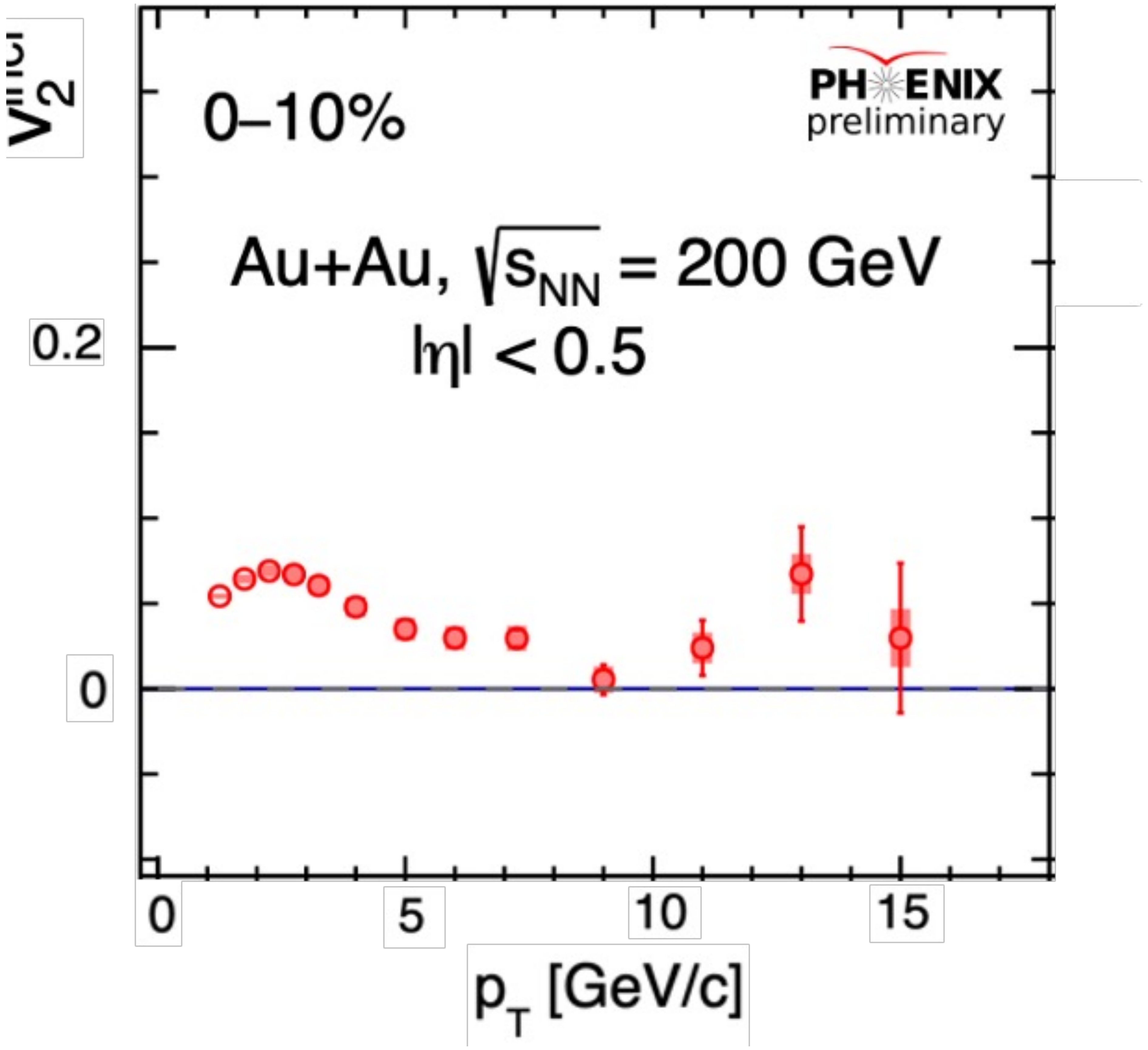
- Using tuned PYTHIA+GEANT4 embedded in real Au+Au events we can extract the inclusive muon fraction
- Extract the HF muon fraction by comparing data to tuned simulation with HF contribution excluded
- Determine heavy flavor muon v_2 in the inclusive muon sample:
- $v_2^{HF} = \frac{1}{F^{HF}}\left(v_2^{\mu}(1 - F^{HF})v_2^{LF}\right); \quad F^{HF} = 1 - F^{LF}$

Photon Flow Extraction

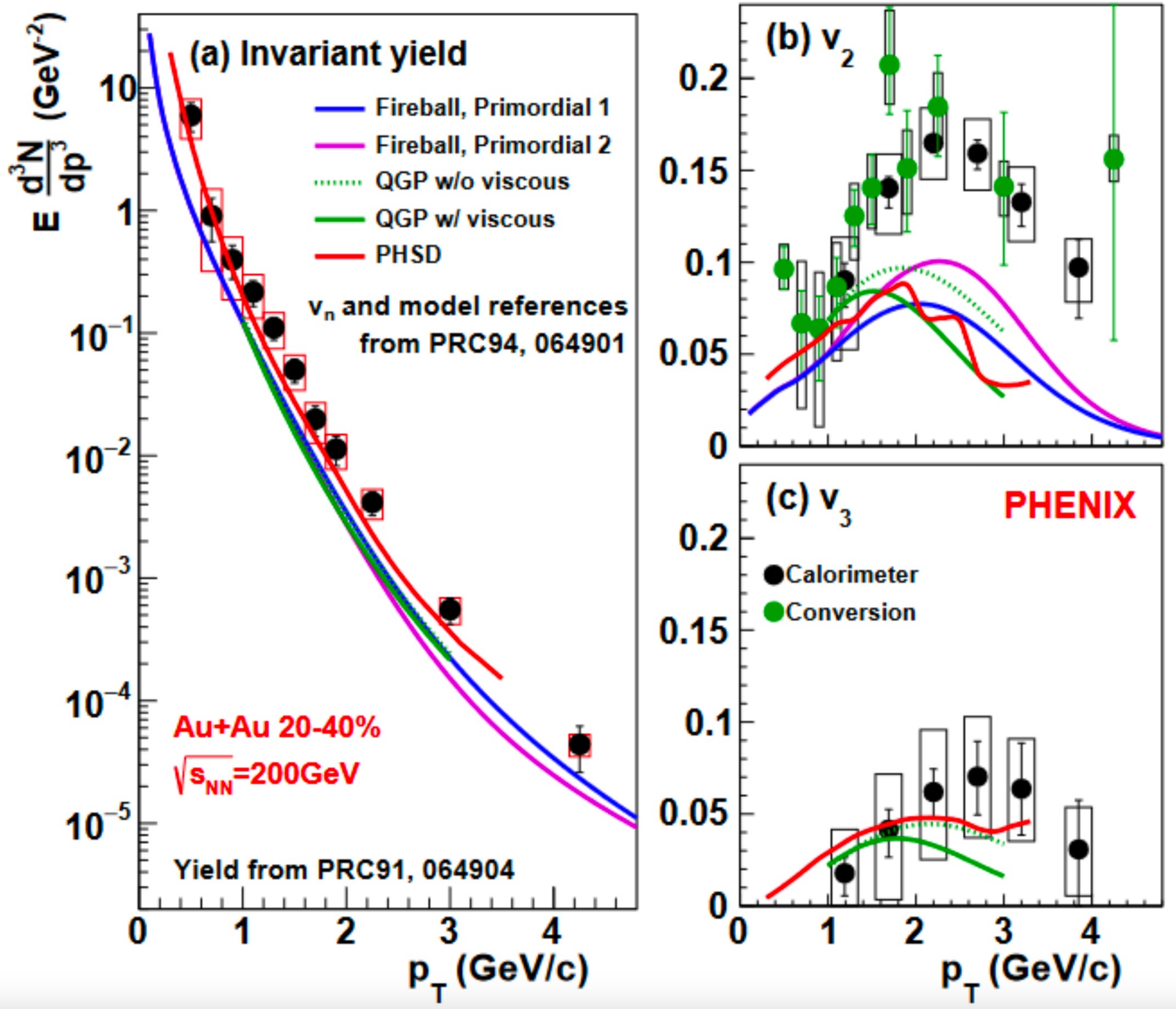
$$\frac{dN}{d(\Delta\phi)} = A(1 + 2v_2cos(2\Delta\phi) + 2v_4cos(4\Delta\phi))$$

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





Direct photon puzzle– a decade ago



OBSERVED:

High yield and high v_2 at the same time
(azimuthal anisotropy in p_T)
Incompatible with the old paradigm:

- high yield → high T → early emission
- high v_2 → late emission (low T, v_2 needs time to build up)

Challenge to models, but also to experiment!

Multi-messenger photons: penetrating and soft

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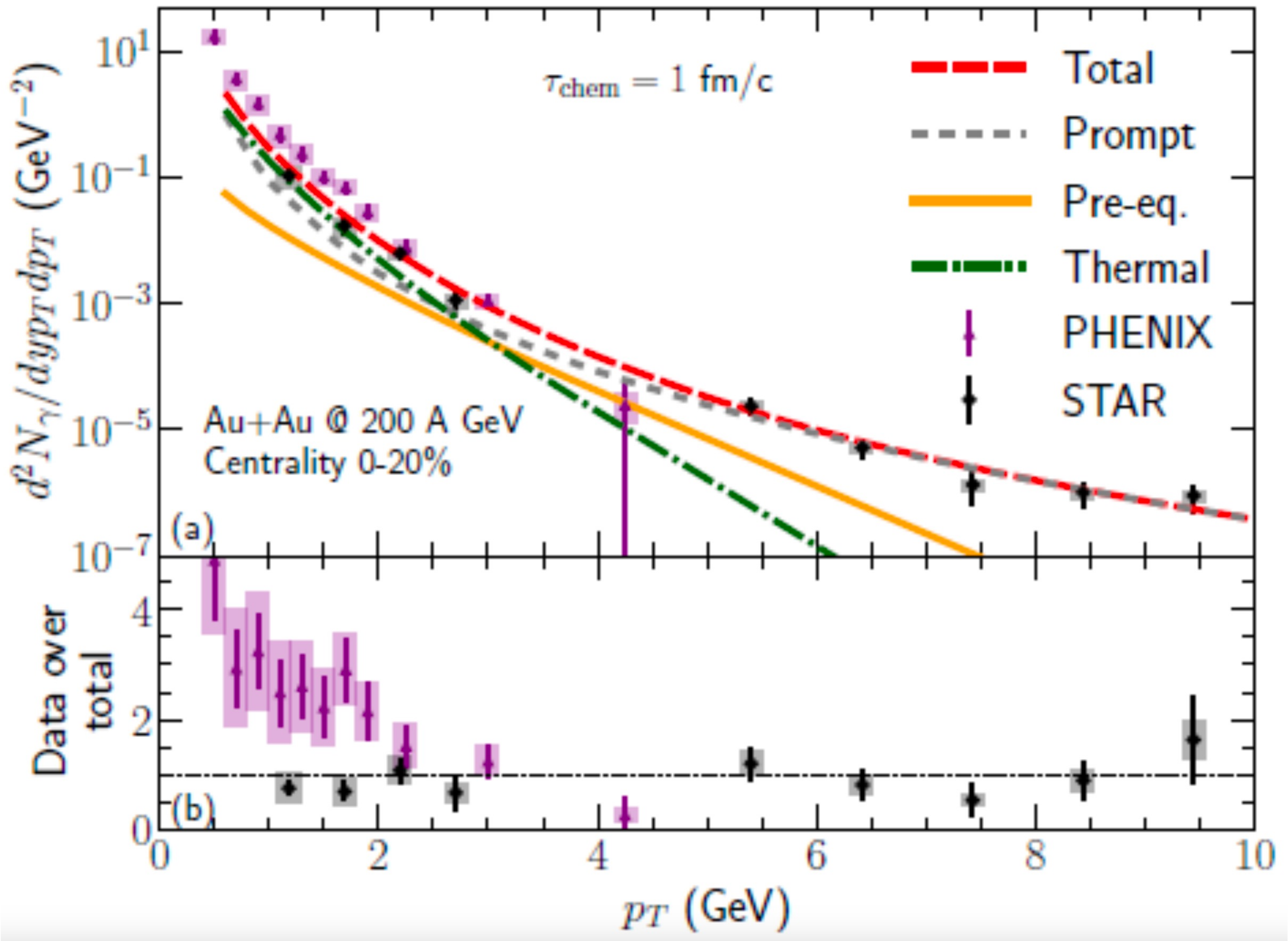

Hadronic and e.m. simultaneously
Pre-hydro: KoMPoST
Pre-eq takes over only at 3 GeV
(and prompt already dominant there)
Observed flow max around 2 GeV,
but still too small

Much has been written about "the photon v_2 puzzle" [55, 71]. In a nutshell, the puzzle stems from the fact that the measured direct photon elliptic flow has been found to be as large as that of hadrons, in the region $p_T < 4$ GeV/c, as is also clear from the data shown in this paper. The majority of theoretical models currently underpredict the photon spectrum and elliptic flow. No approach with realistic dynamics can both reproduce photon spectrum and elliptic flow, and this situation has not been modified because of the inclusion of a pre-hydrodynamic phase like KøMPøST.

Issues remain even after pre-hydro

Multi-messenger compared to previous results

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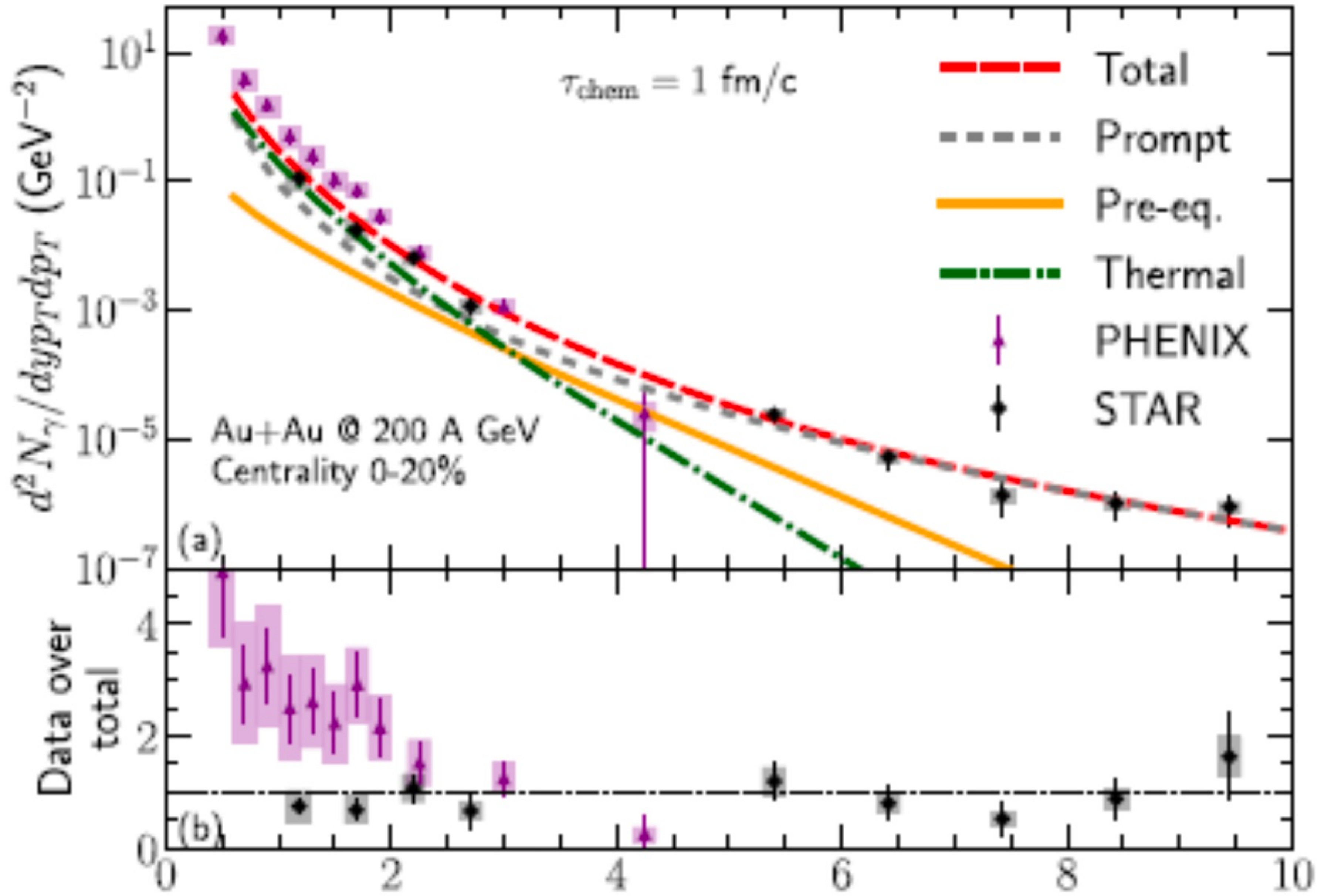


PRC 105, 014909 (2022)

FIG. 6. (a) The yield of direct photons in Au + Au collisions at maximum RHIC energy, in the 0%–20% centrality class. The different channels are enumerated in the text. Here, $\tau_{chem} = 1$ fm/c. We compare with experimental data from the PHENIX [60] and STAR [61] Collaborations. (b) The ratio of experimental data over the total calculated photon yield.

Pre-equilibrium photons:
not a solution, neither for yield nor for v_2
Discrepancy at low p_T (as opposed to STAR)

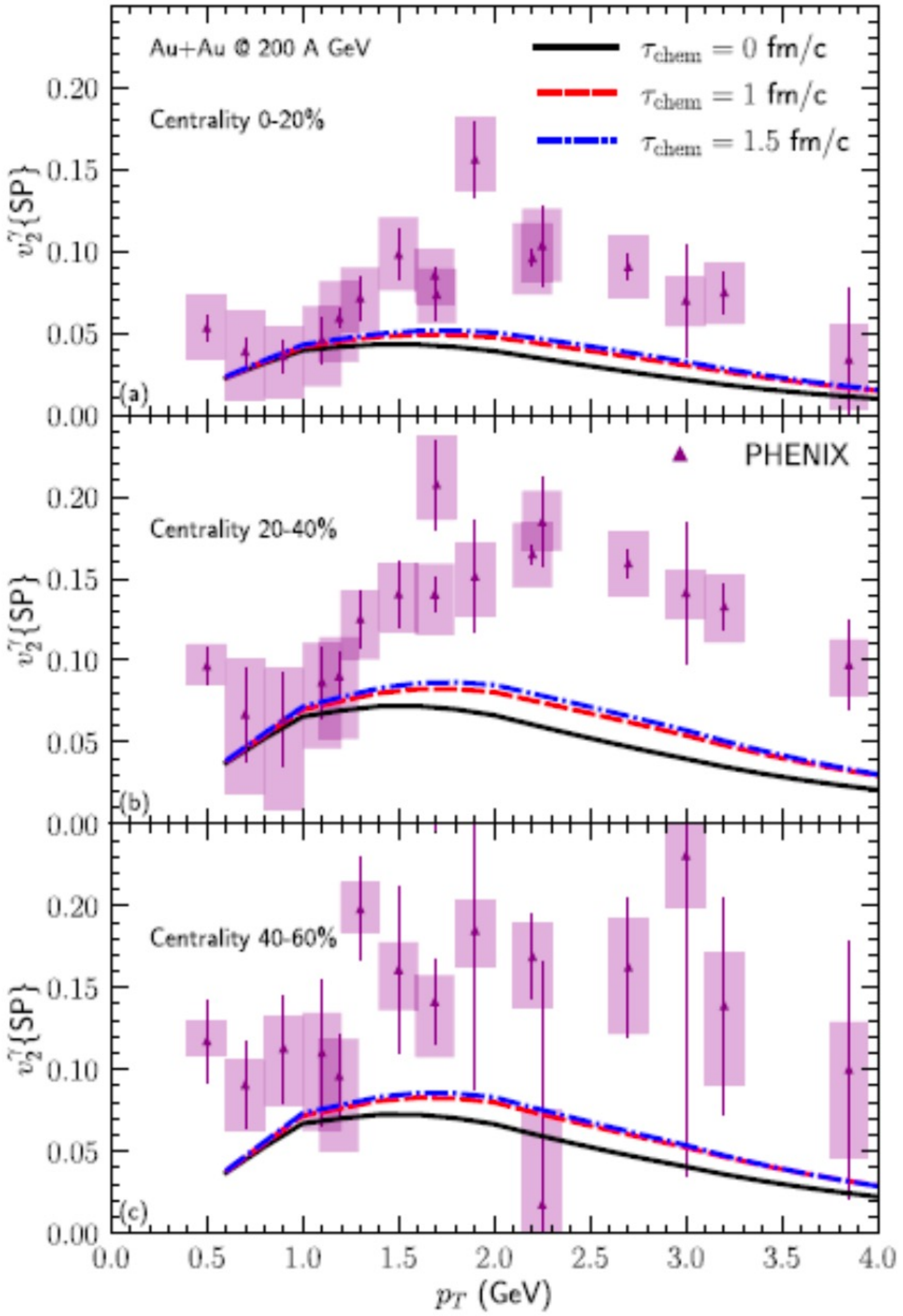
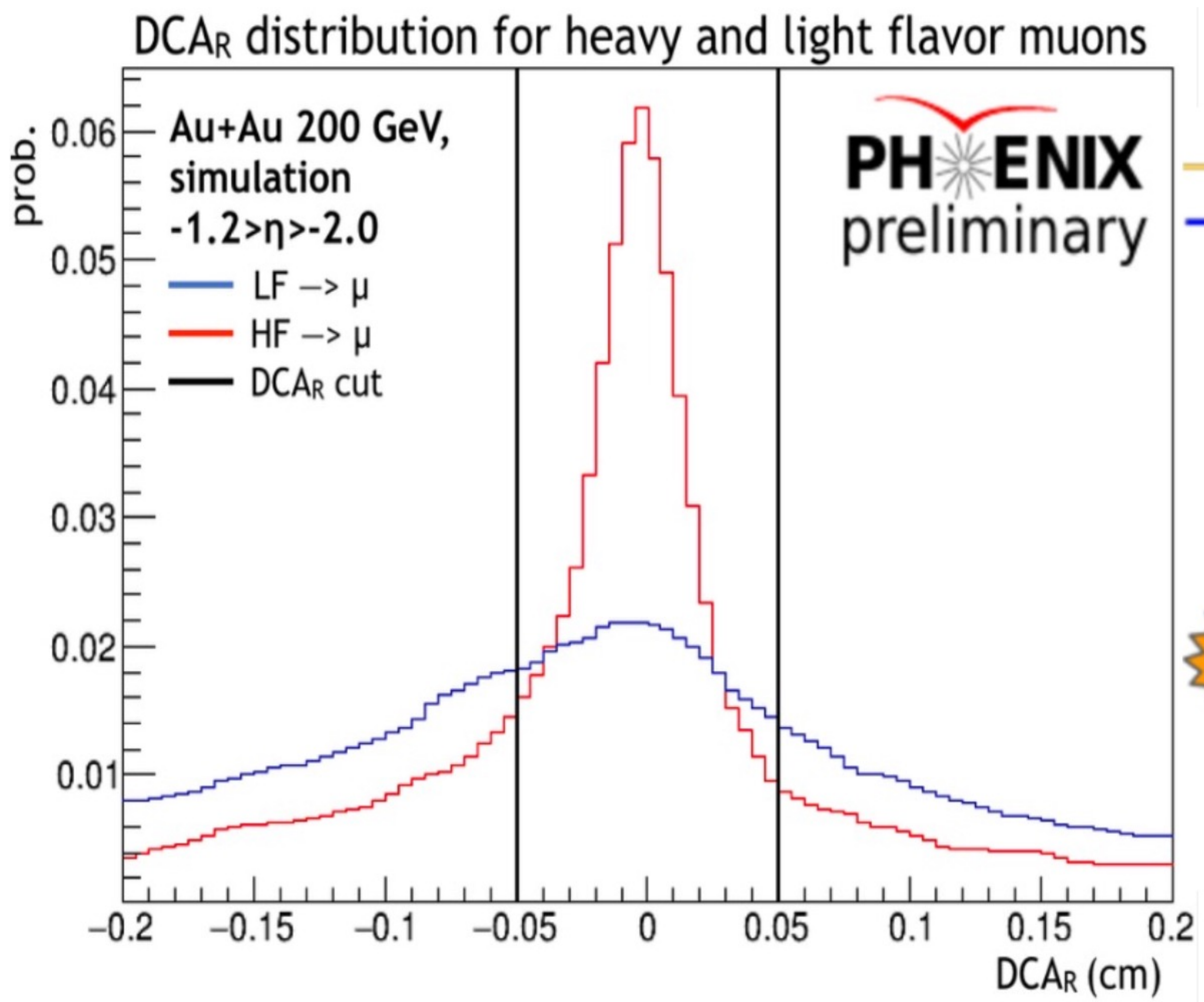


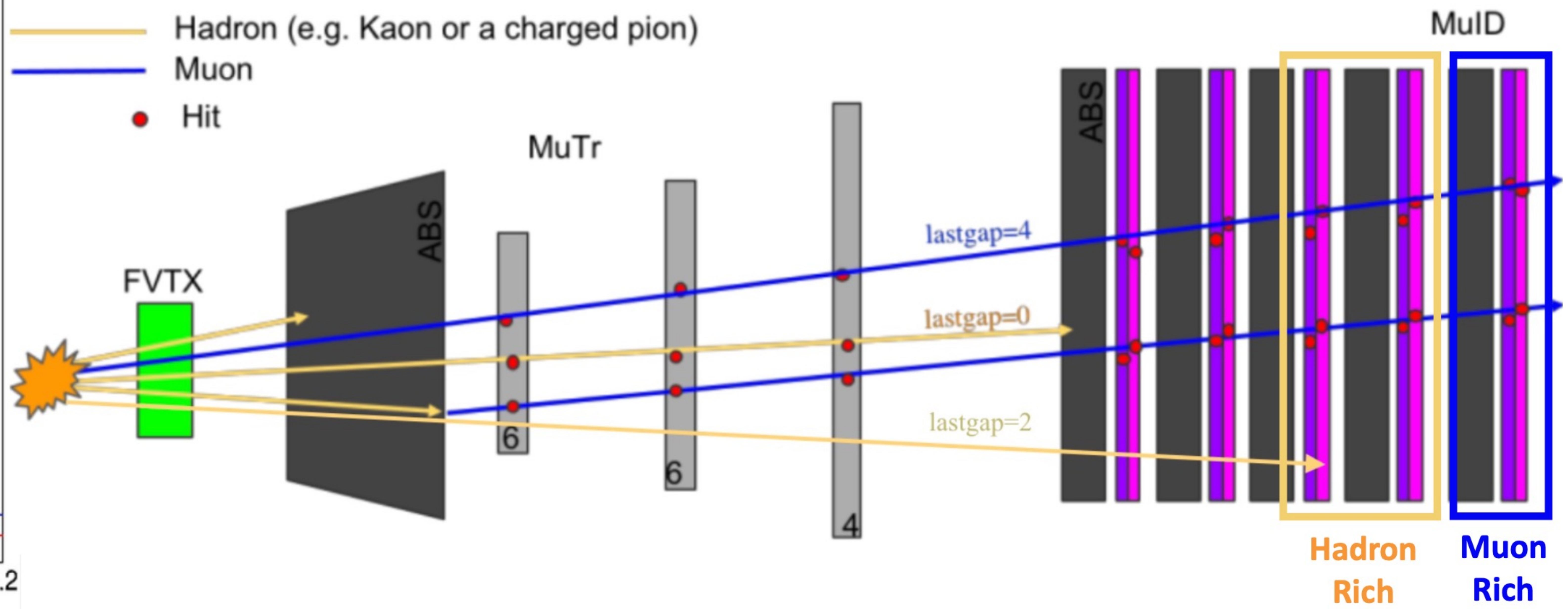
FIG. 8. Same caption as for Fig. 7, but for the direct photon $v_2^\gamma\{SP\}$. Data are from Ref. [62].

Consistent at low p_T, fails at "medium"

- τ_{chem} → time when quarks are produced and equilibrate in an initially purely gluonic system
- Large τ_{chem} → suppression of early photon emission rate

Single Muon Analysis

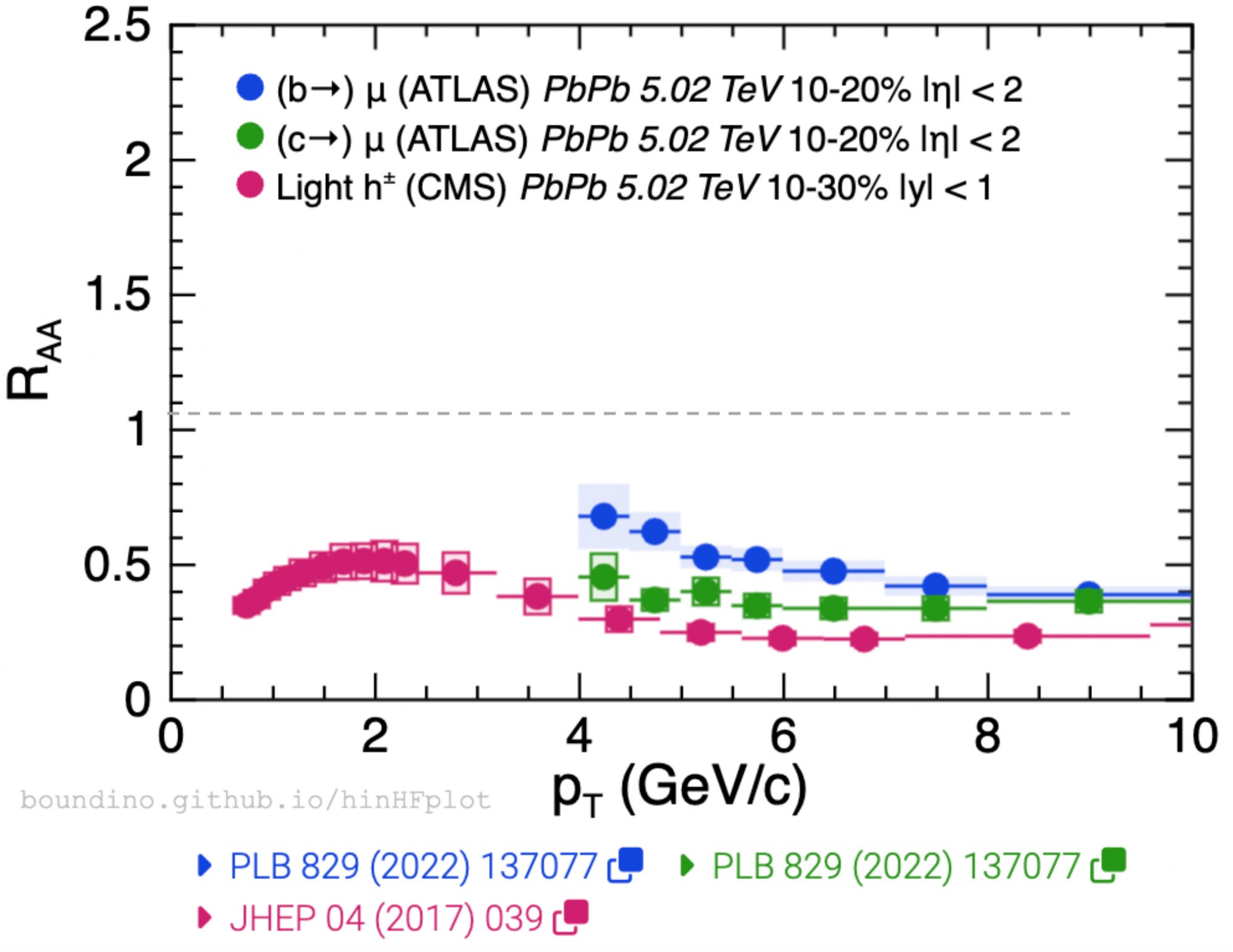




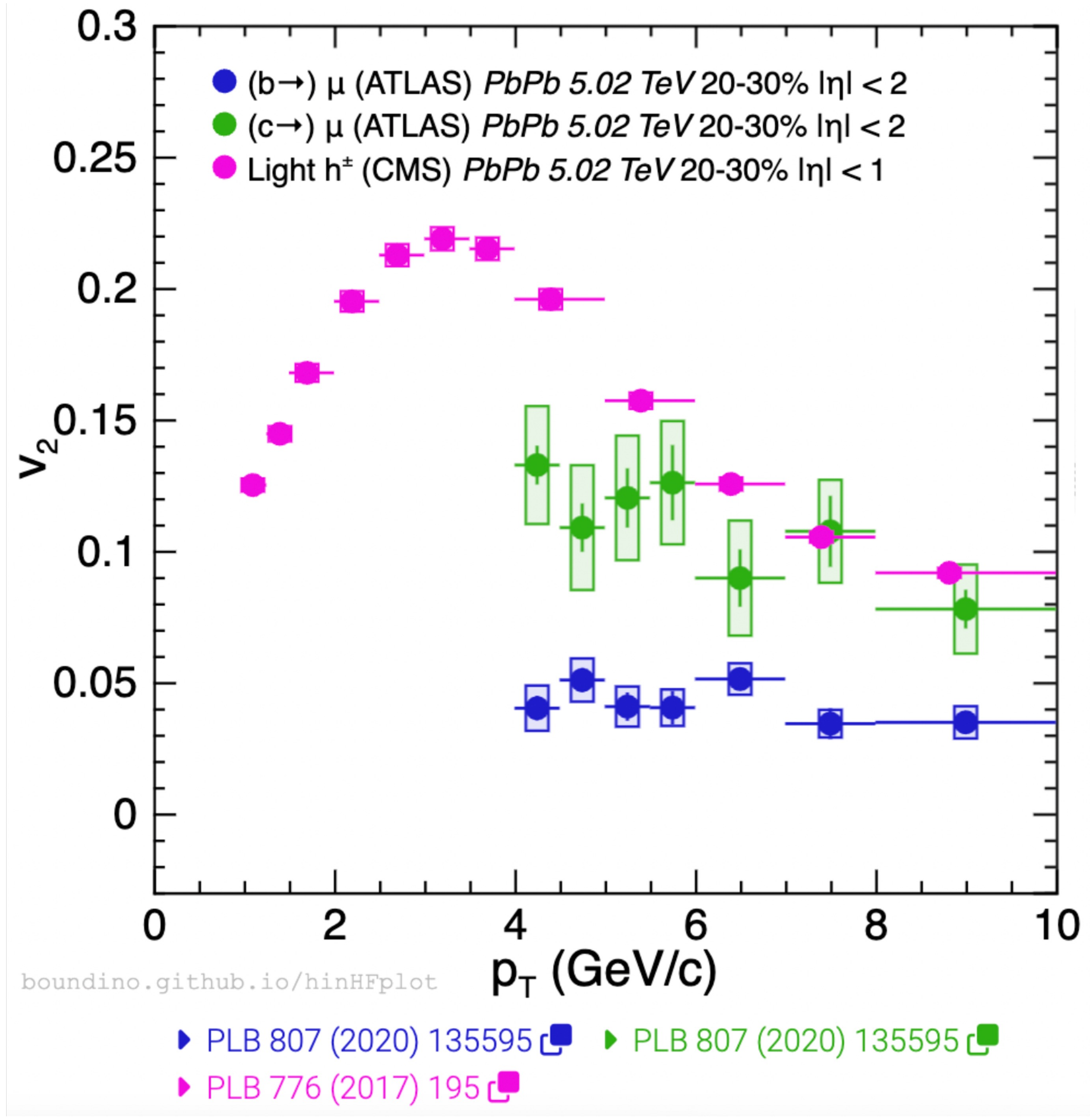
- Track quality cuts to purify muons from heavy flavor
- Extract v_2 for hadrons and inclusive muons
- Tuned MC simulating precise particle ratios to separate muons from light and heavy flavor decays

Charm and Beauty

R_{AA} of separated charm and beauty



v_2 of separated charm and beauty



Measurement methods of v_2

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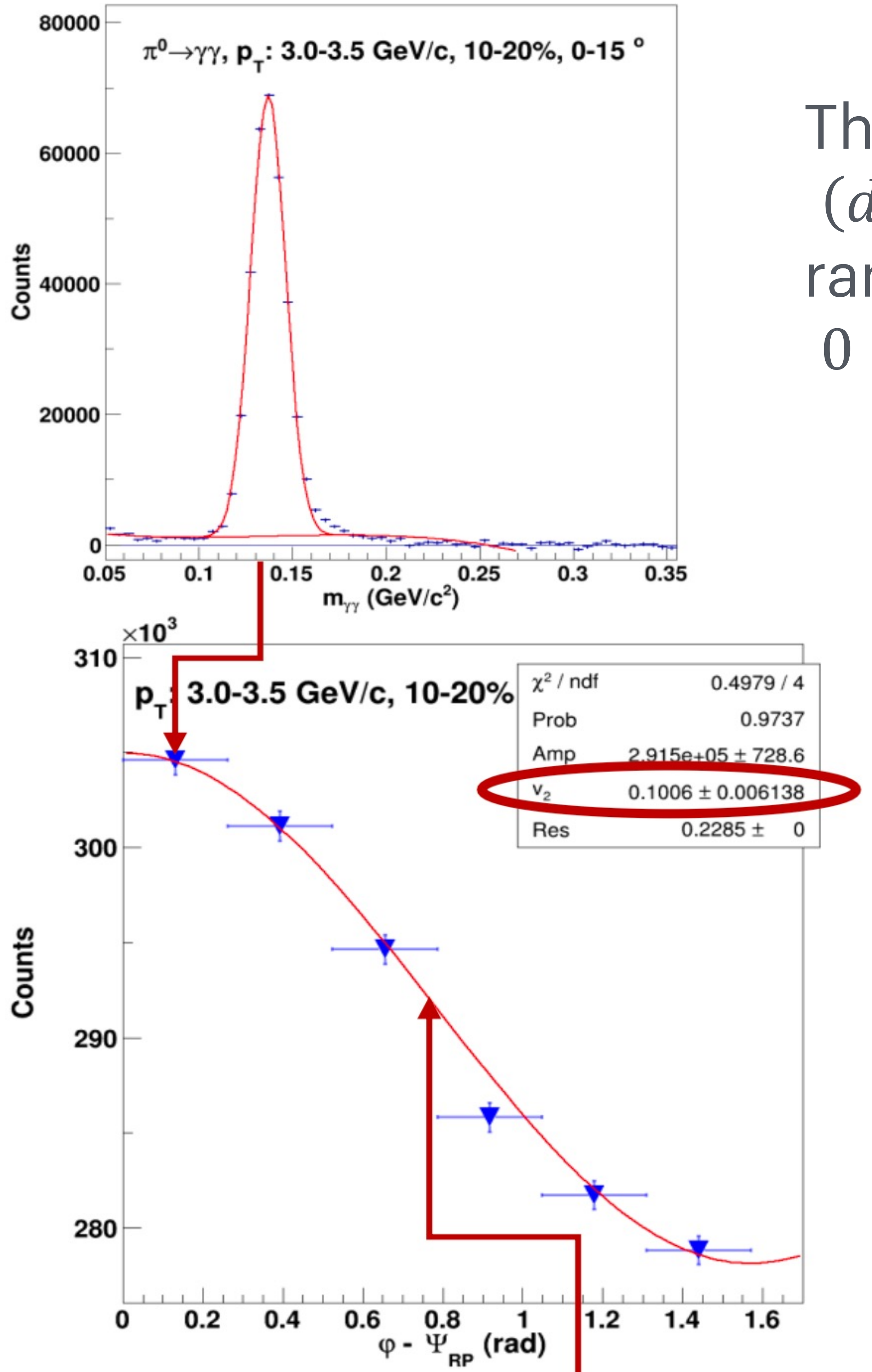
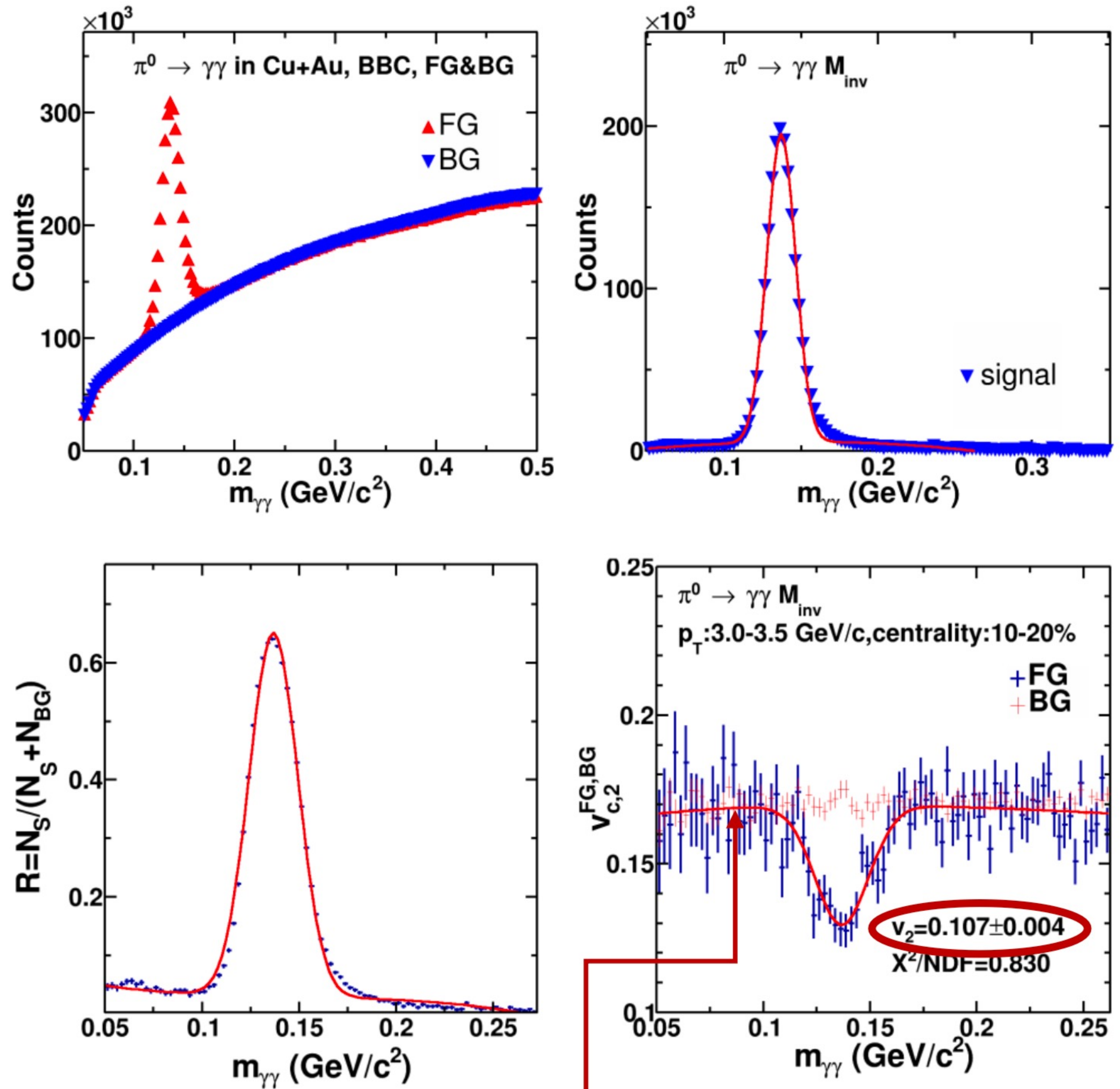
Subtraction method



The yields of $\gamma\gamma$ $(dN/(\phi - \Psi))$ in 6 ranges:
$0 < \phi - \Psi < \pi/2$

$$d\,N/(\varphi - \Psi) = N(1 + 2v_2 \cos[2(\varphi - \Psi)])$$

Invariant mass fit method



$$v_2^{\text{pair}}(\mathrm{M_{inv}}) = v_2^{\text{signal}} N_{\text{signal}}/N_{\text{pair}}(\mathrm{M_{inv}}) + v_2^{\text{BG}}(1 - R(\mathrm{M_{inv}}))$$