Heavy Ion Physics in the EIC Era

PHENIX Highlights

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Outline

Heavy ion collisions:

Direct photons

Heavy flavor

Light flavor hadrons

Small systems:

Heavy flavor

Light flavor hadrons

p+p collisions:

Heavy flavor

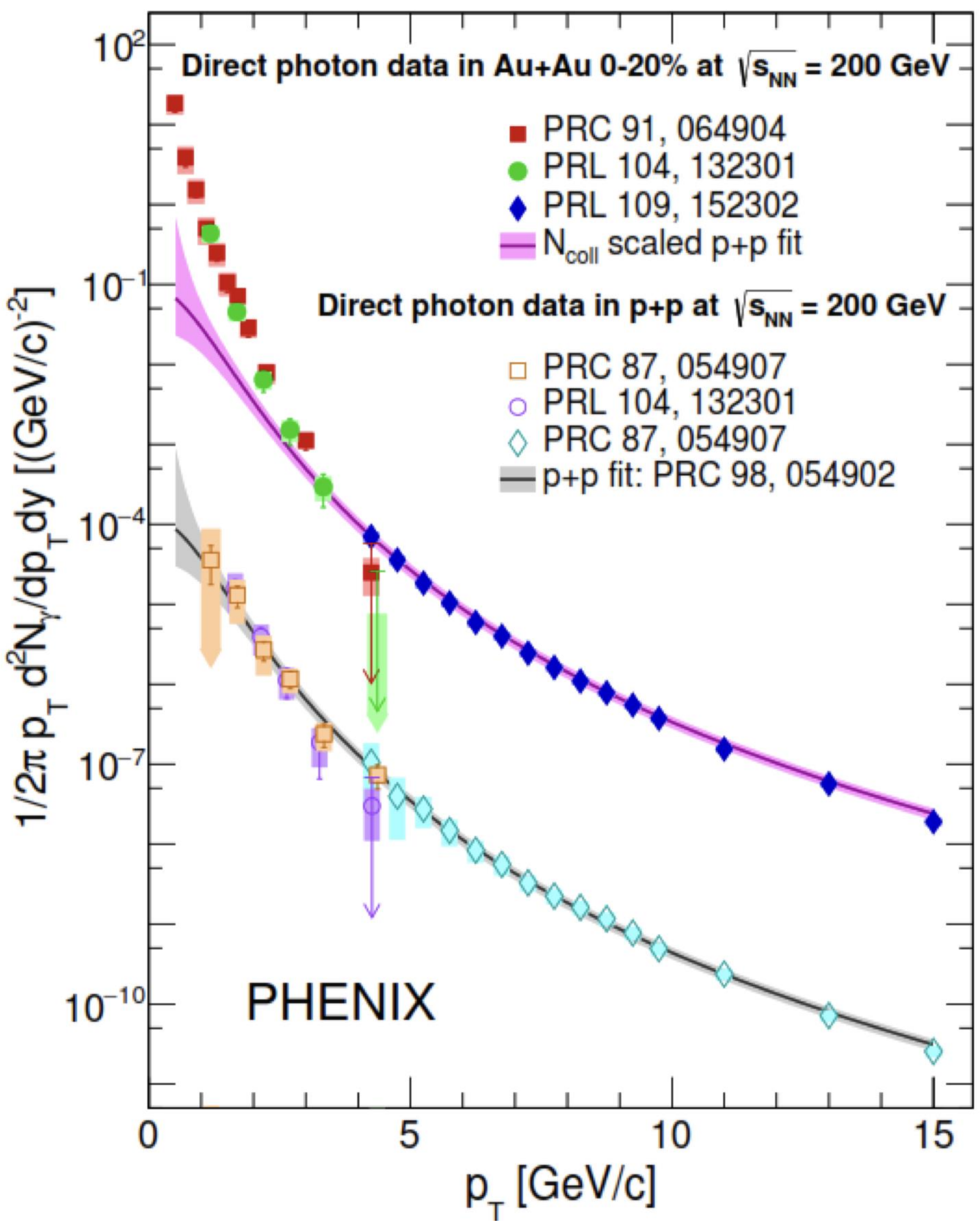
Direct photons and hadrons

Heavy Ion Collisions

Direct Photons

Direct photons in p+p & Au+Au at 200 GeV

PHENIX: PRC 107 (2023) 2, 024914



Direct γ yields are well established

p+p consistent with pQCD

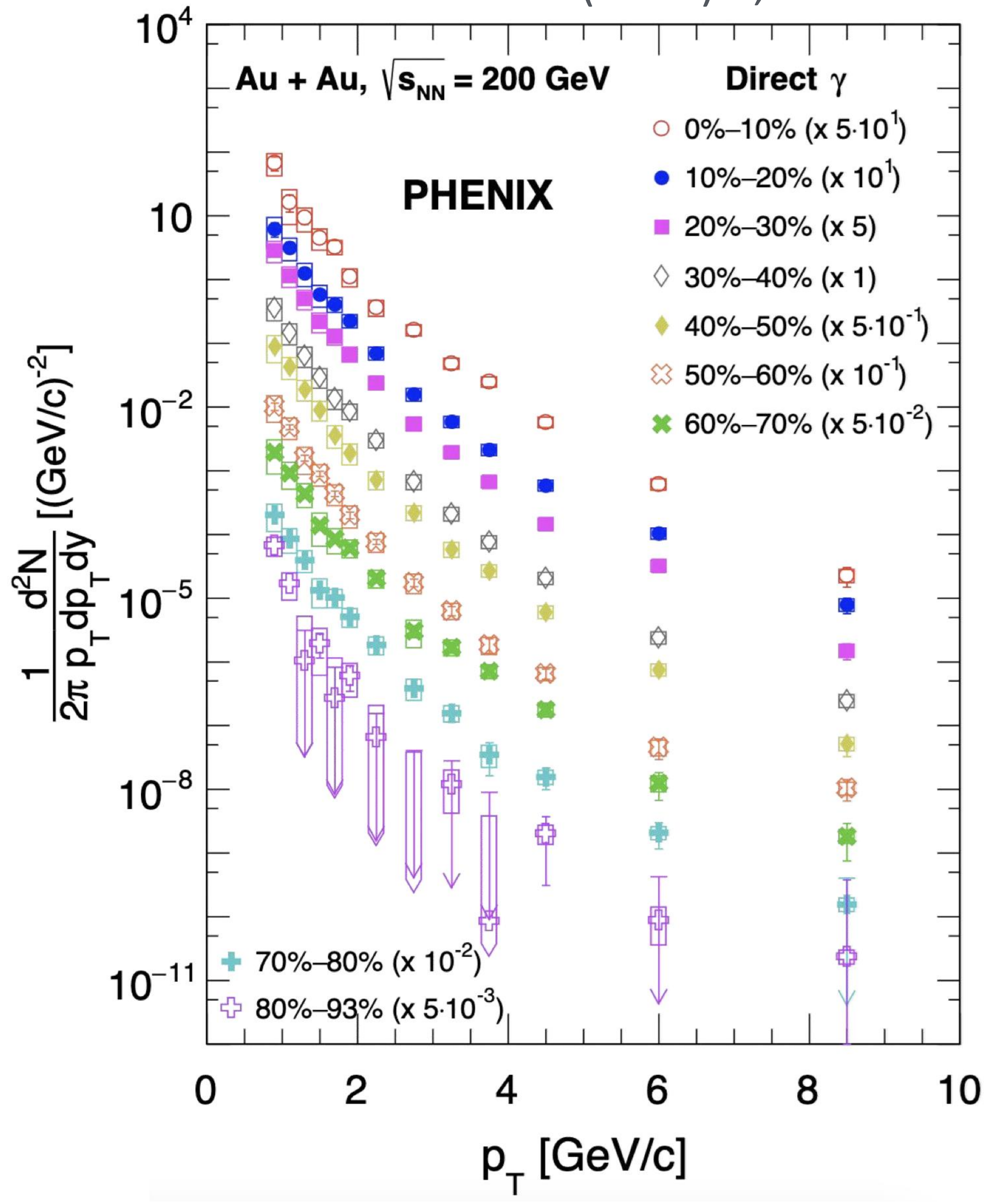
Au+Au follows N_{coll} scaled *p+p* above 4 GeV

Significant excess below 3 GeV in Au+Au

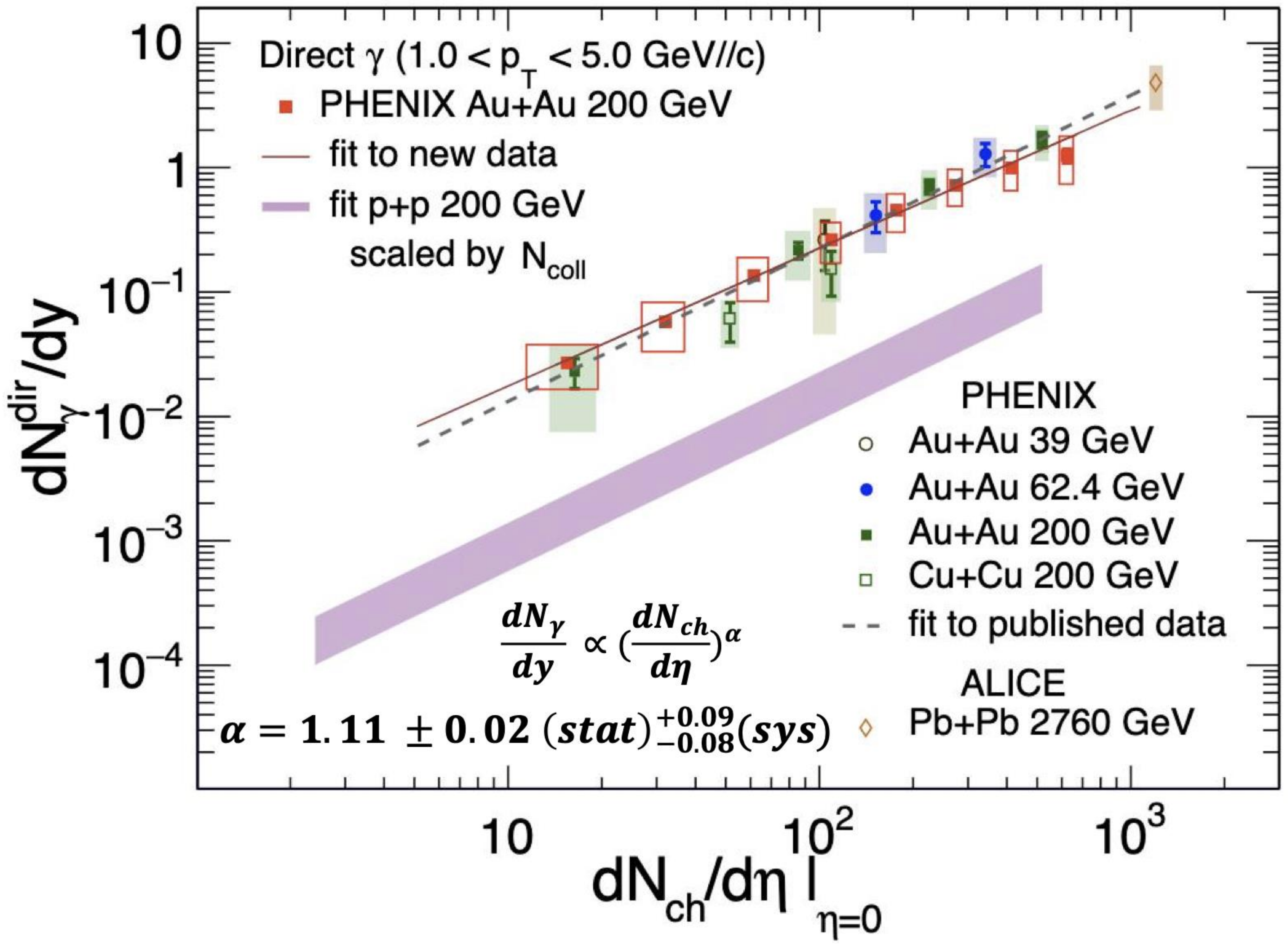
Excess has close to $e^{-p_T/T_{eff}}$ shape with T_{eff} ~ 240 MeV

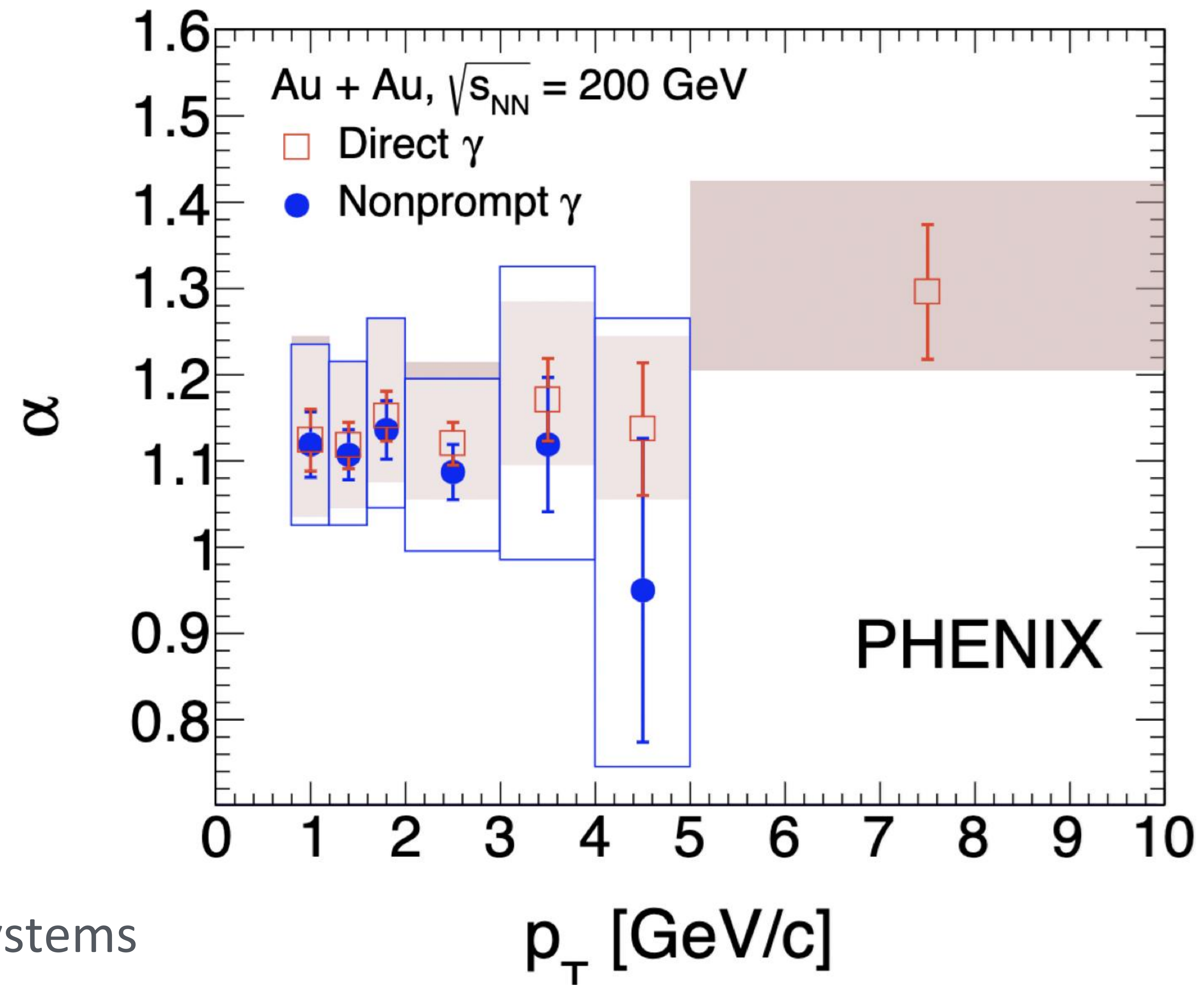
New high statistics Au+Au results reveal universal features

PHENIX: PRC 109 (2024) 4, 044912



System Size and Energy Dependence of Direct Photon Yield





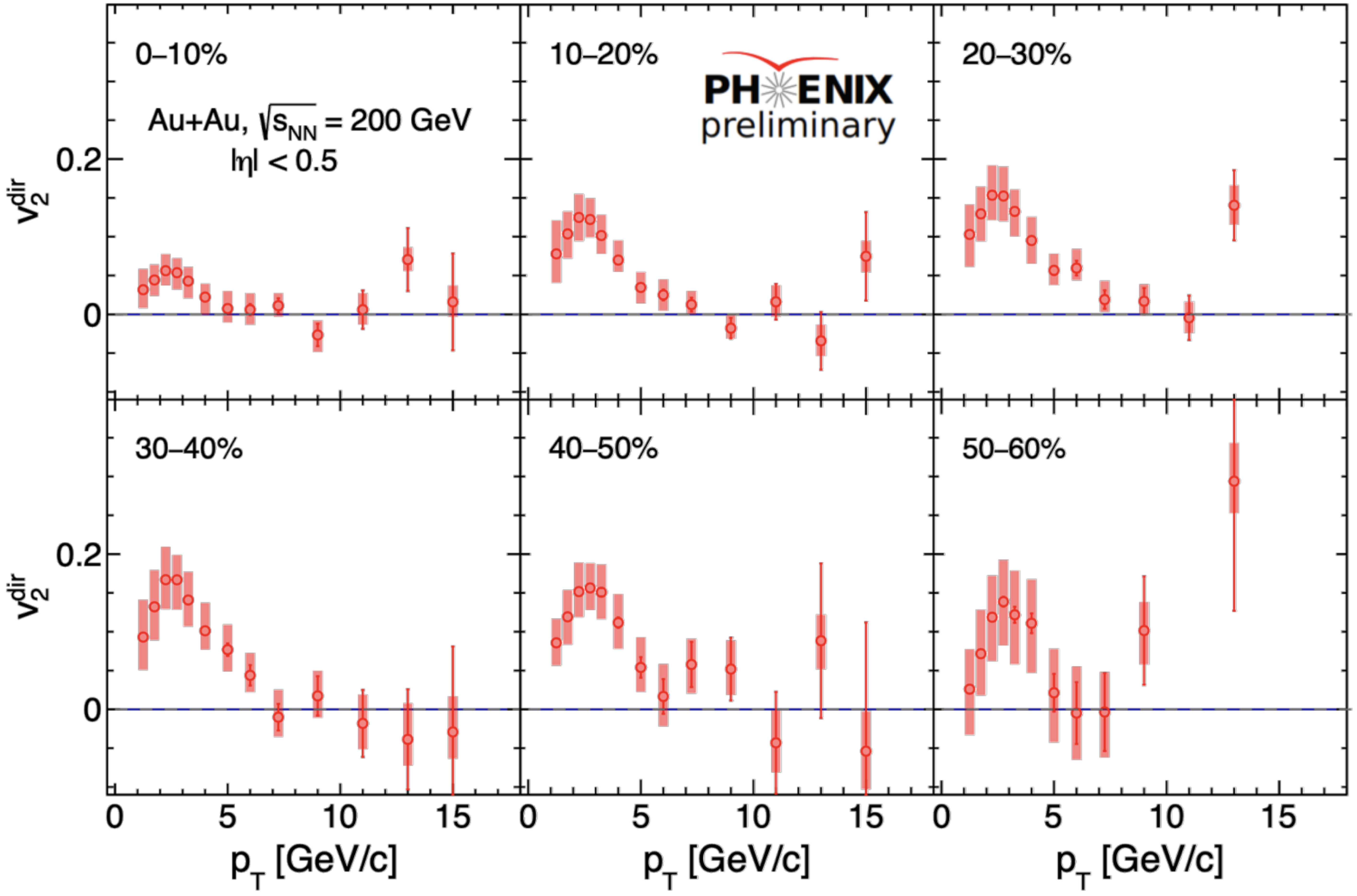
Universal scaling behavior of direct γ yields in all A+A systems

α only reaches 1.11

With no obvious α dependence on p_T

PHENIX: Phys. Rev. C 109 (2024) 4, 044912
PHENIX: Phys. Rev. C 107 (2023) 2, 024914
ALICE: Phys. Lett. B 754 (2016) 235-248

Direct photon azimuthal anisotropy



Significant anisotropy for p_T < 5 GeV/c

Similar to hadrons

Maximum around 2-3 GeV/c

Clear centrality dependence

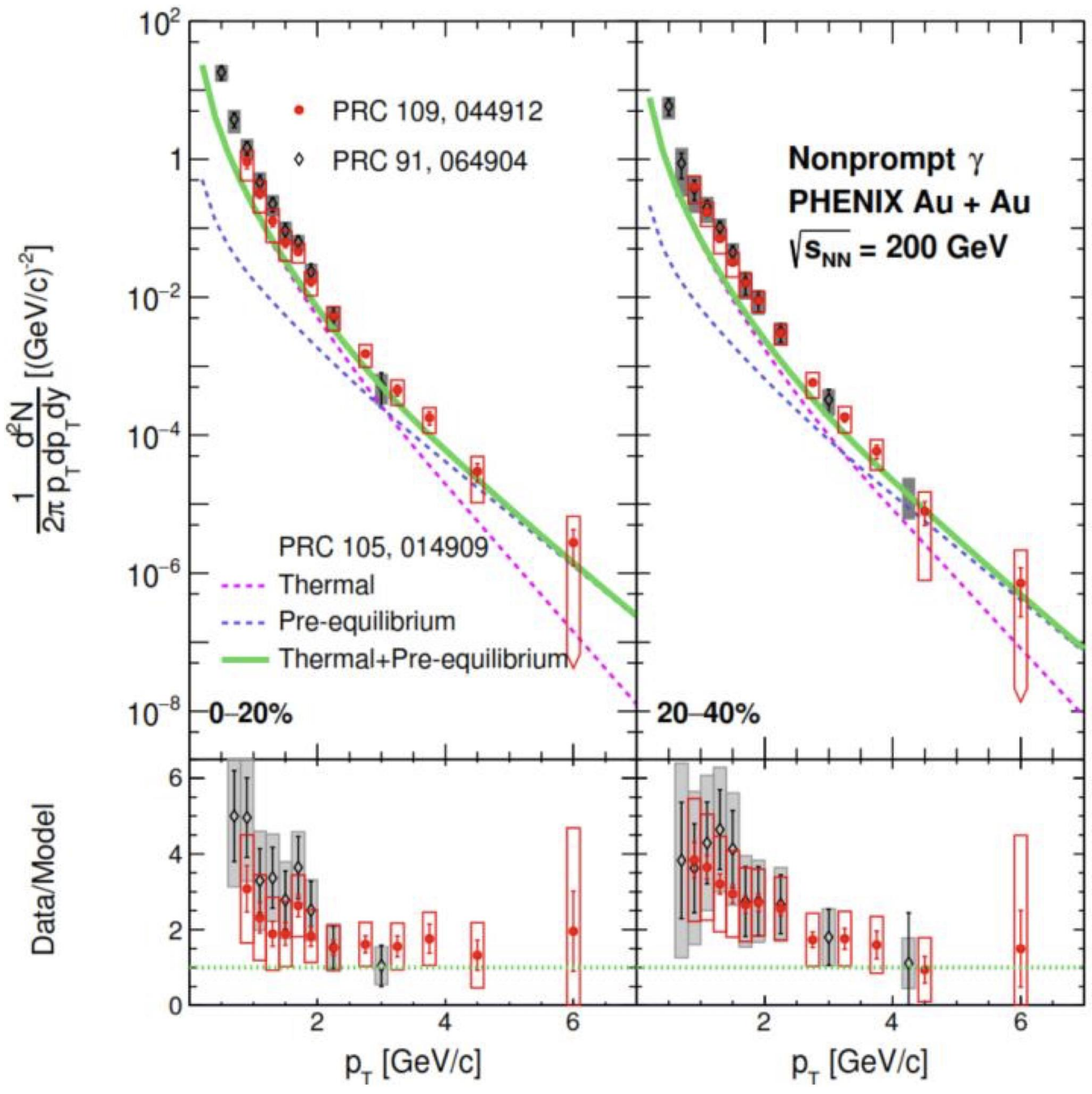
High p_T dominated by prompt photon emission

v_2 consistent with zero

No centrality dependence

Thermal photon model calculations

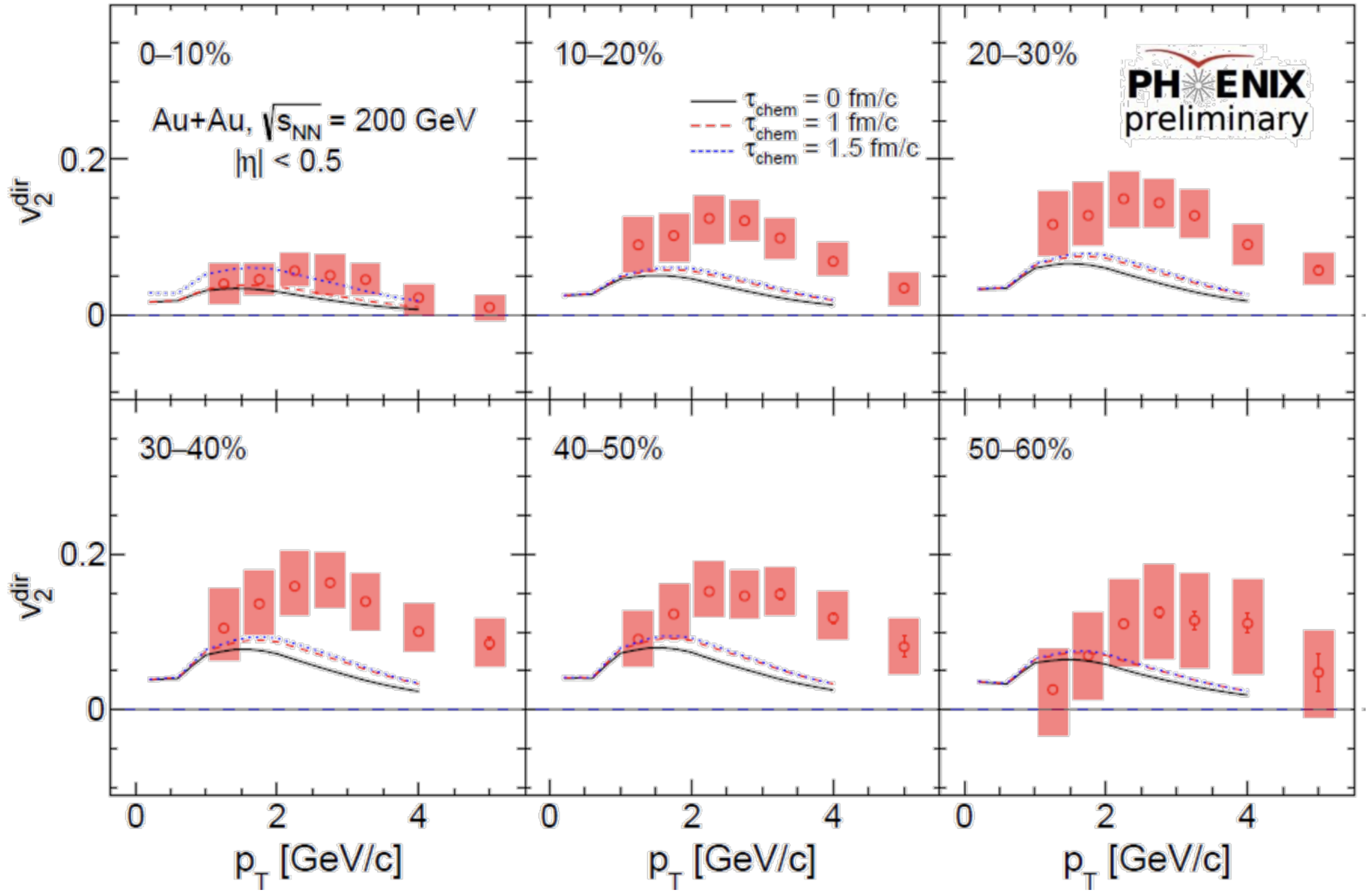
C. Gales et. al. PRC 105 014909 (2022)



Multi-messenger heavy-ion physics

Hybrid model for all stages of heavy-ion collisions

Effect of pre-equilibrium phase for photons and hadrons

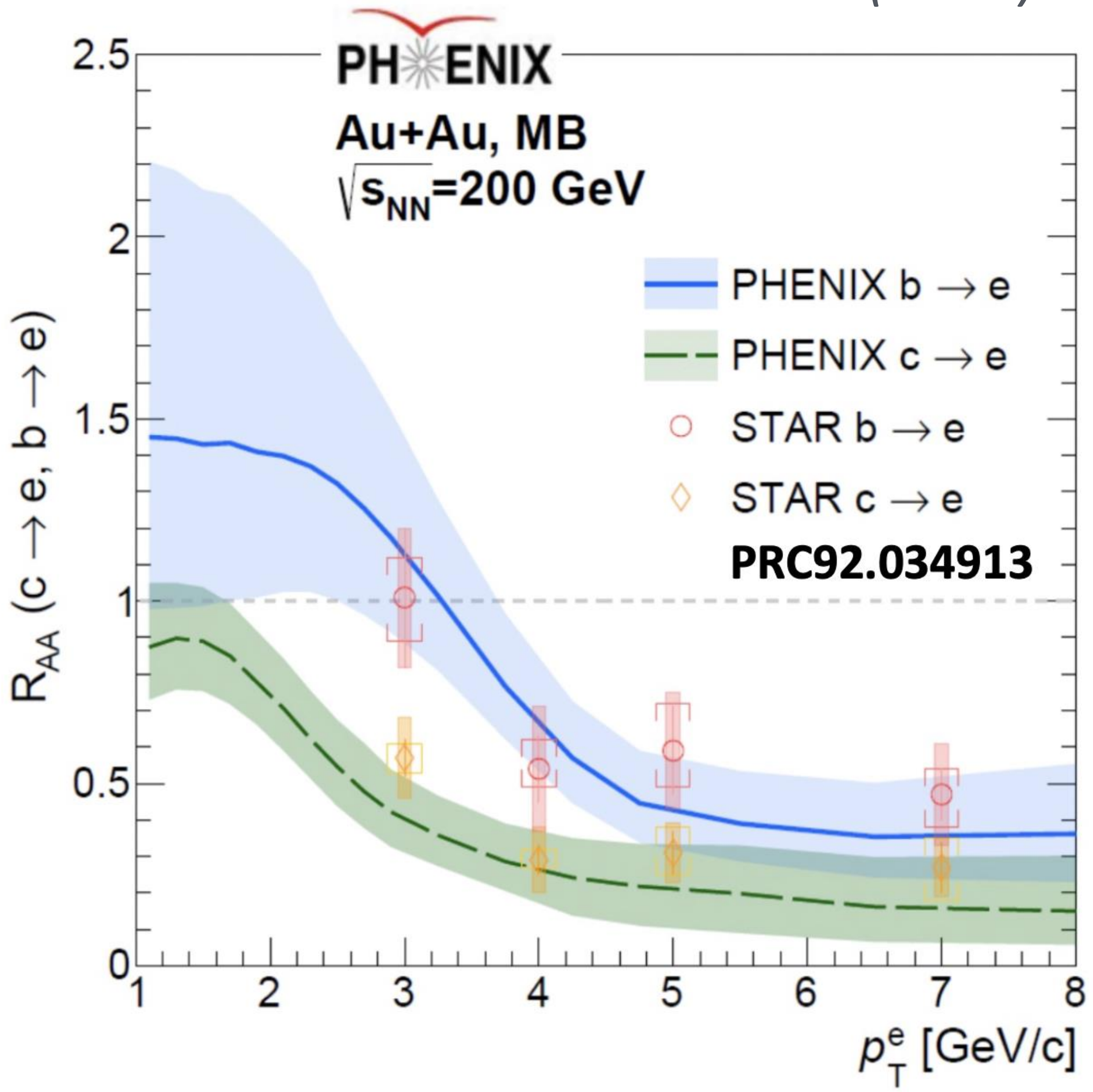


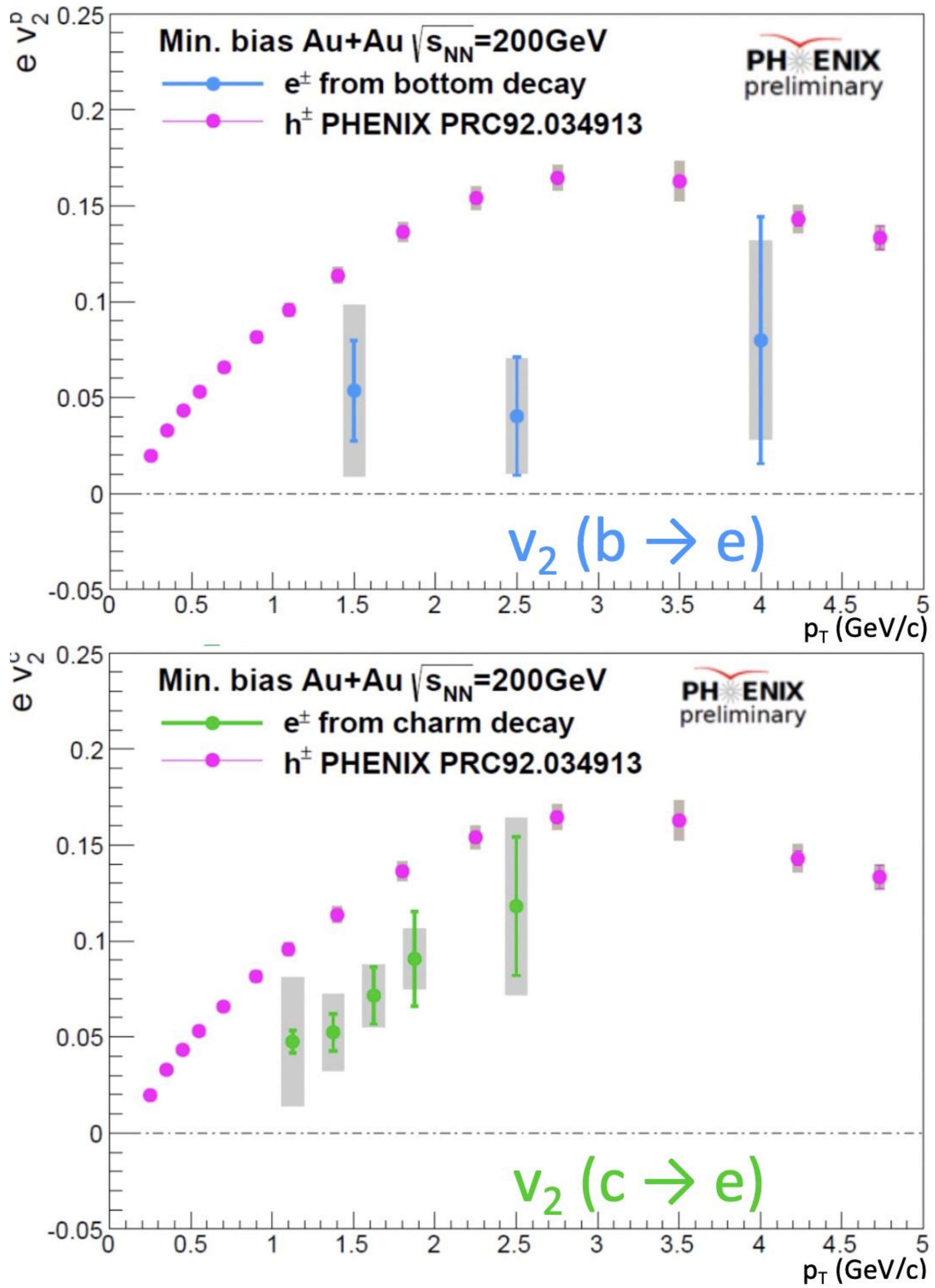
Model calculations qualitatively reproduce shape, but falls short quantitatively

Heavy Flavor

Separated Charm and Bottom R_{AA} and v_2

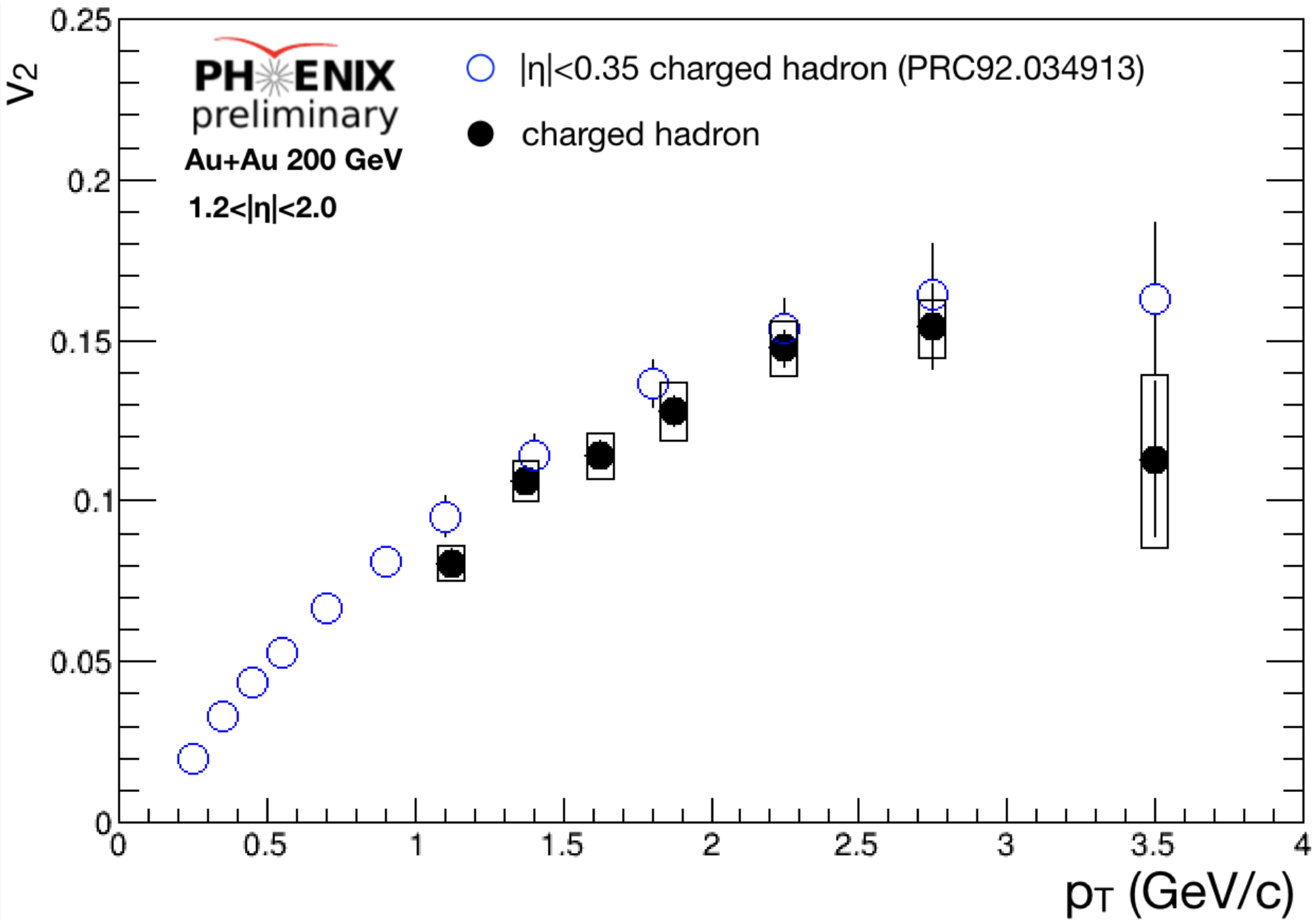
PHENIX: PRC 109 044907 (2024)





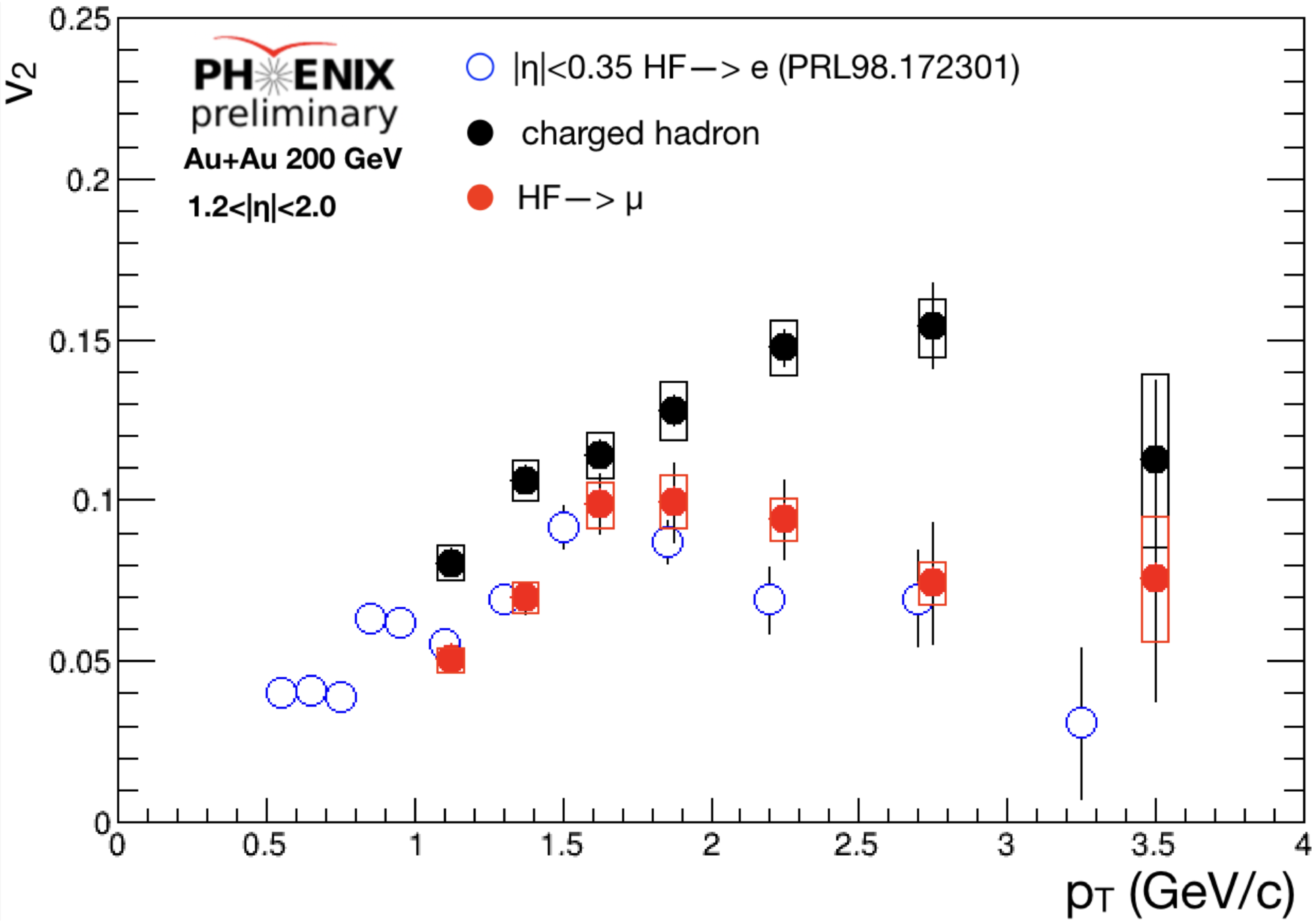
Clear mass ordering observed between
$(b \to l)$ & $(c \to l)$ at RHIC for both R_{AA} & v_2
Similar patterns are observed
Interplay of energy loss and hydro at mid-p_T?

Heavy Flavor v_2 Measurement



Hint of rapidity-dependence of charged hadron v_2

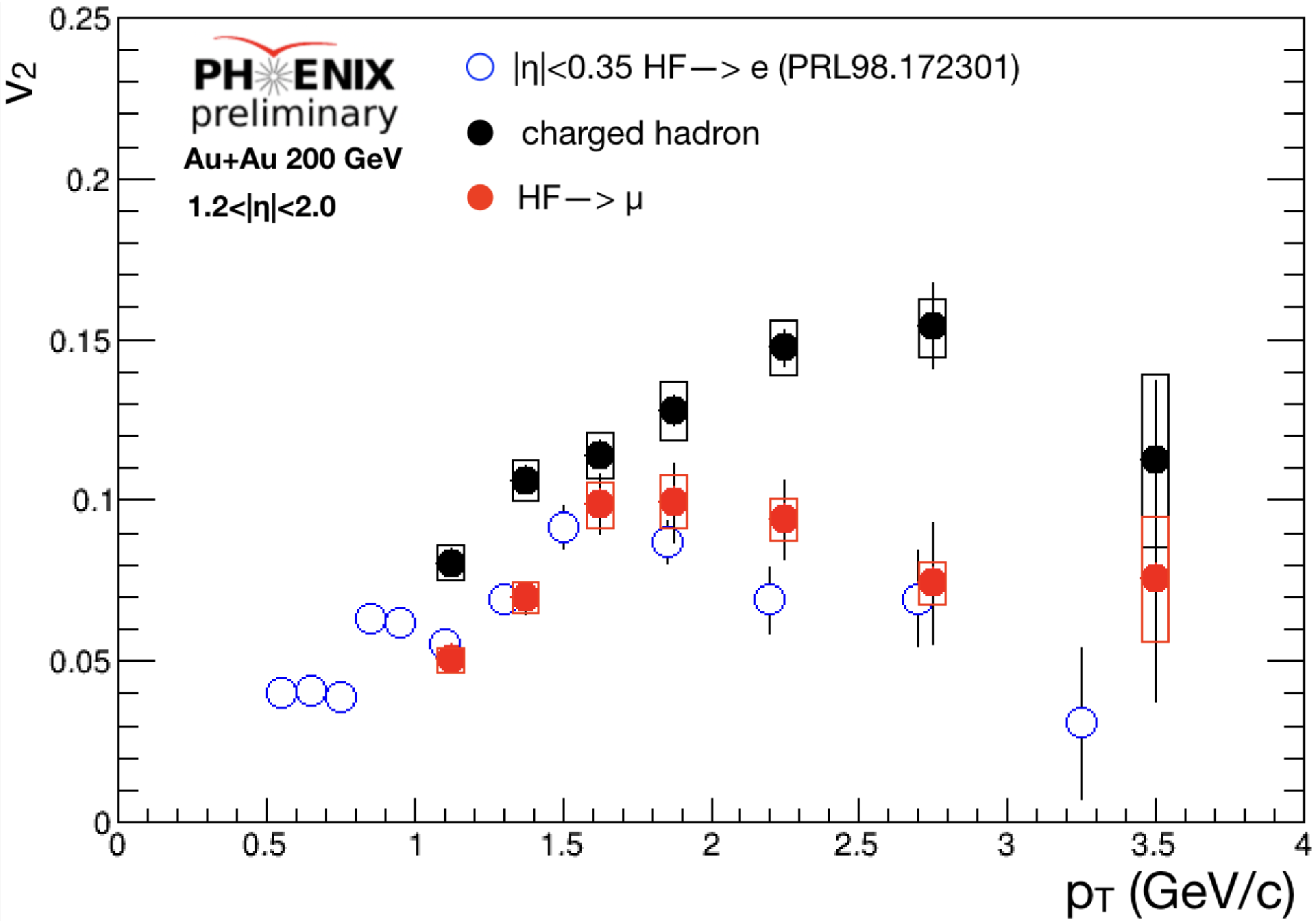
Heavy Flavor v_2 Measurement



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

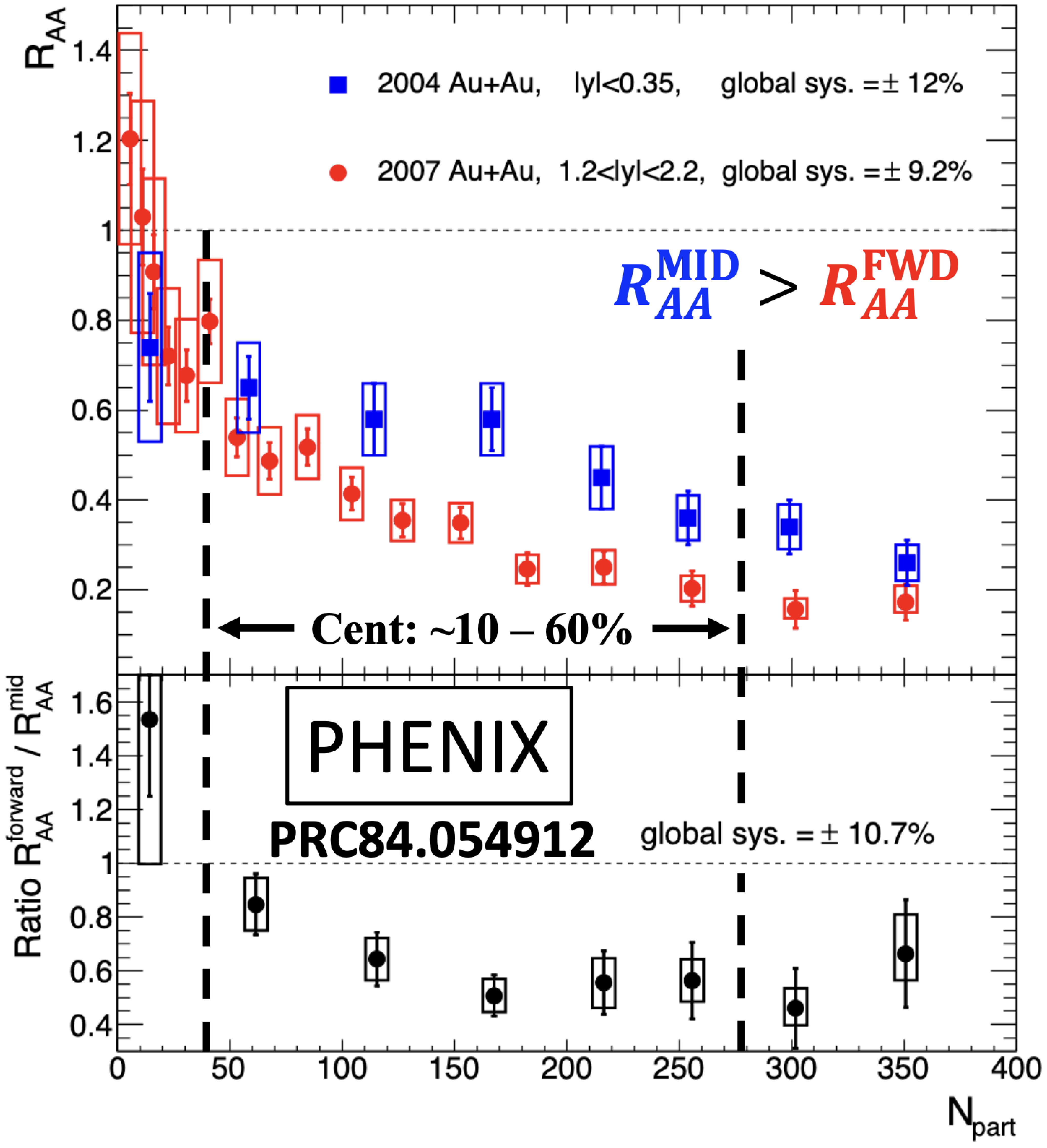


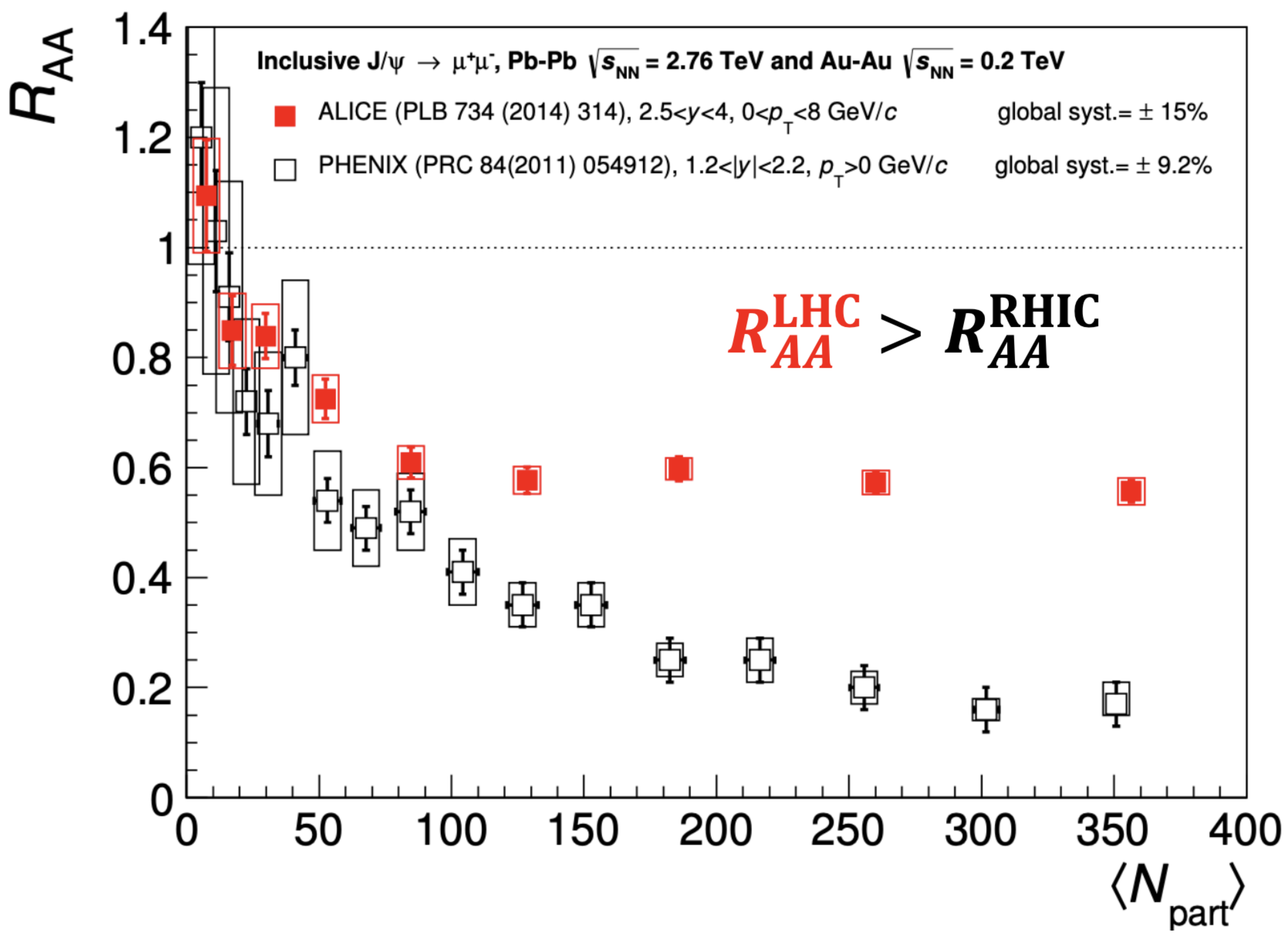
Hint of rapidity-dependence of charged hadron v_2

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})

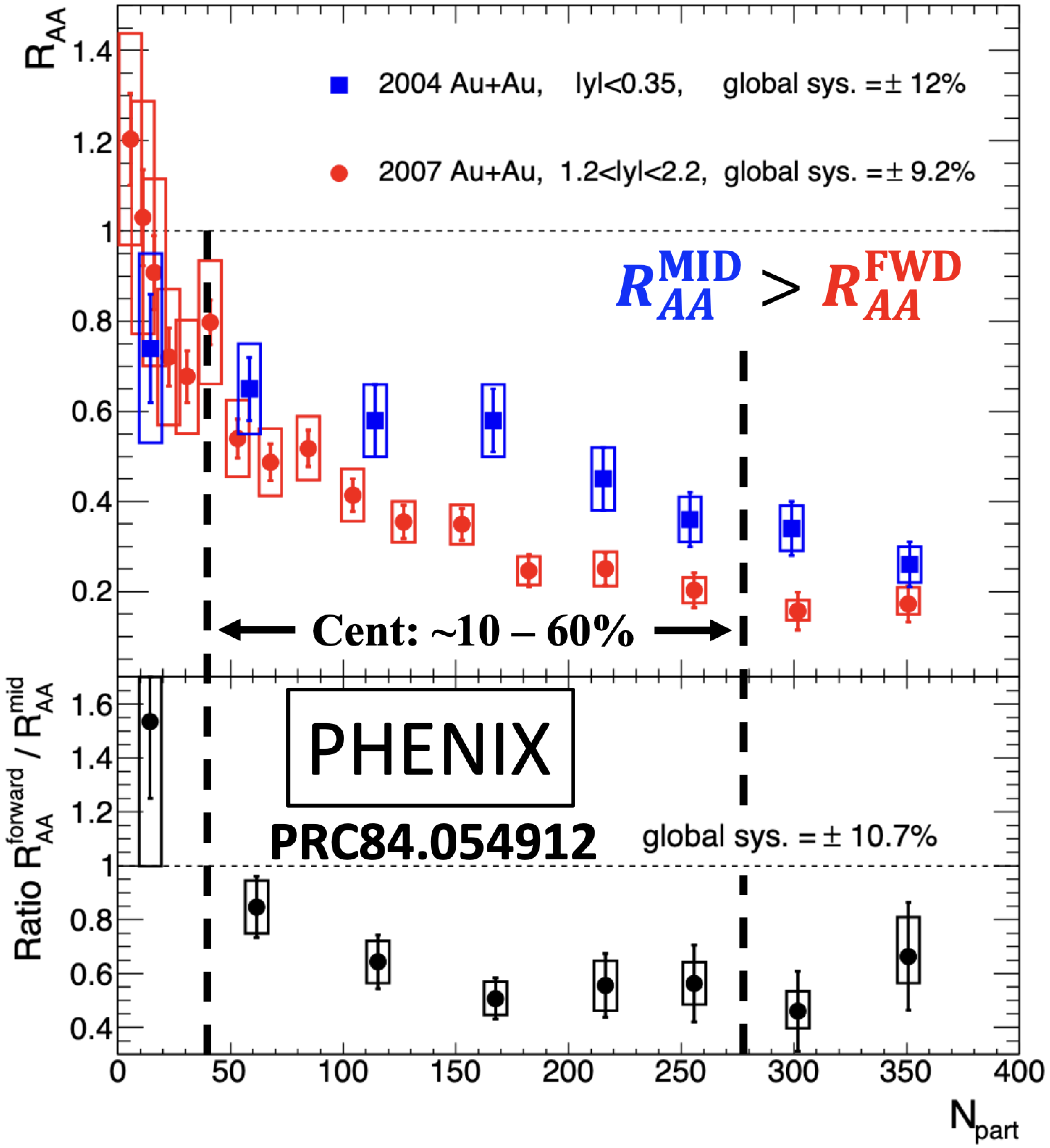


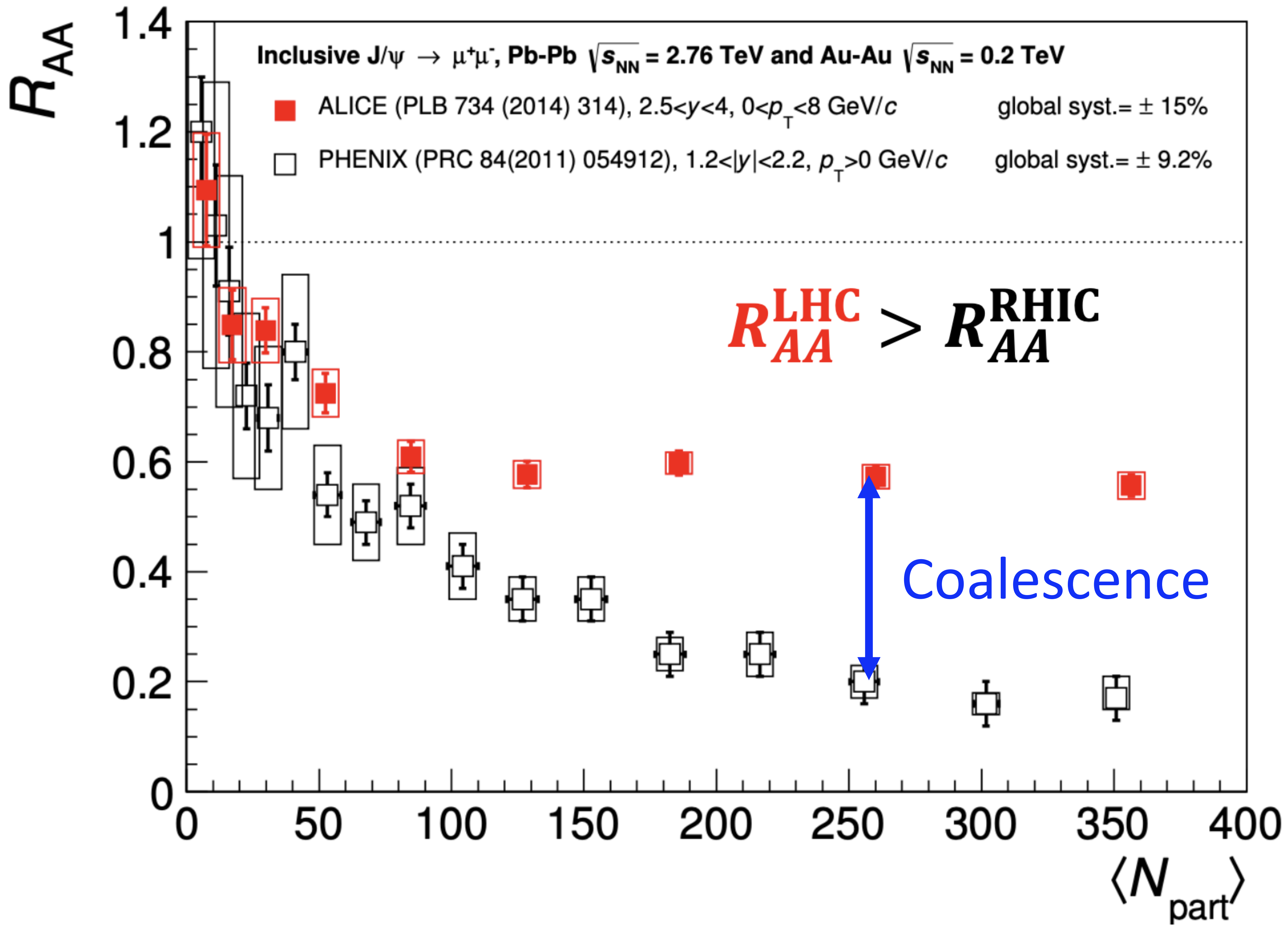


RHIC: $R_{AA}^{MID} > R_{AA}^{FWD}$

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

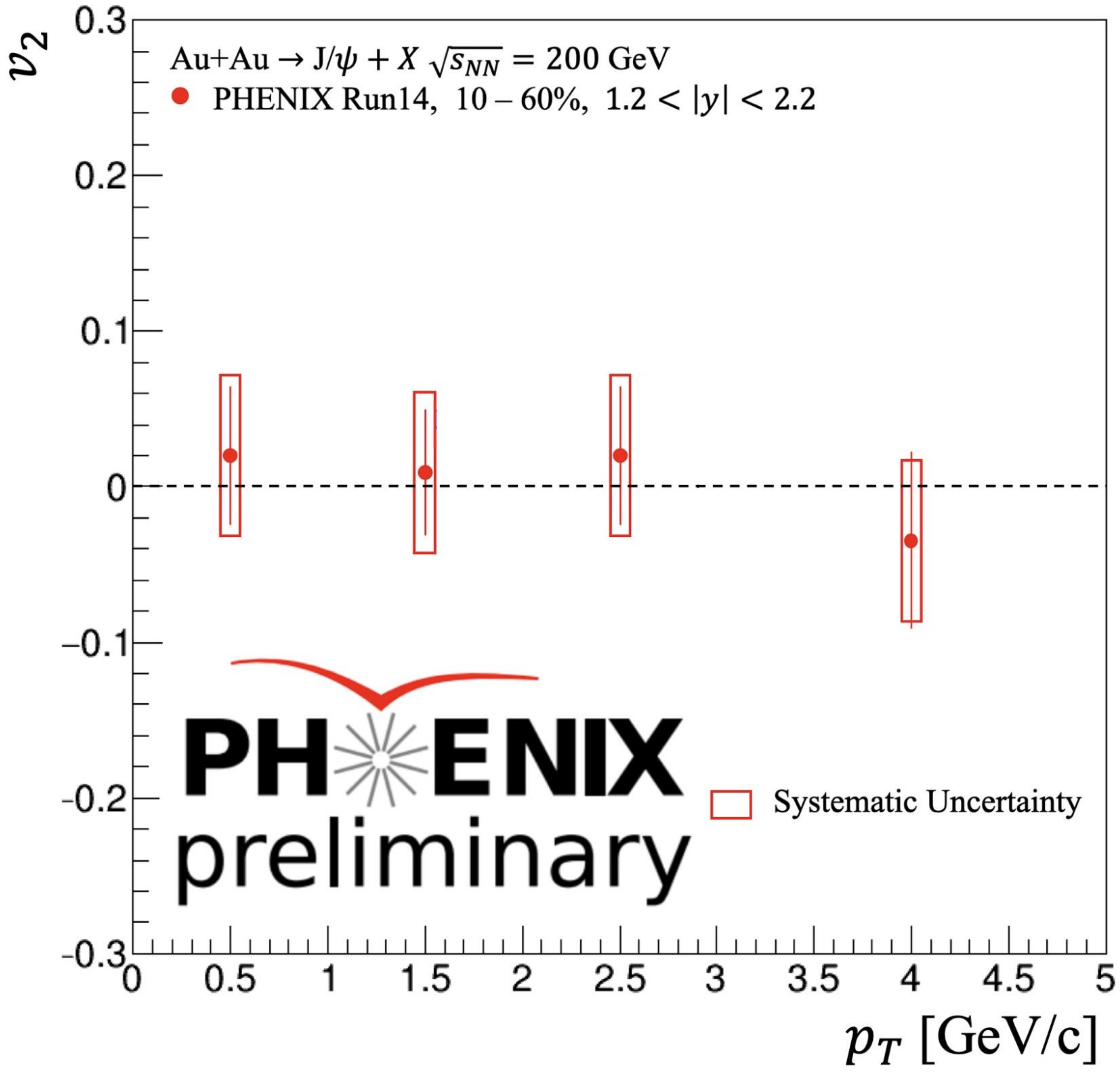
J/ψ Nuclear Modification (R_{AA})





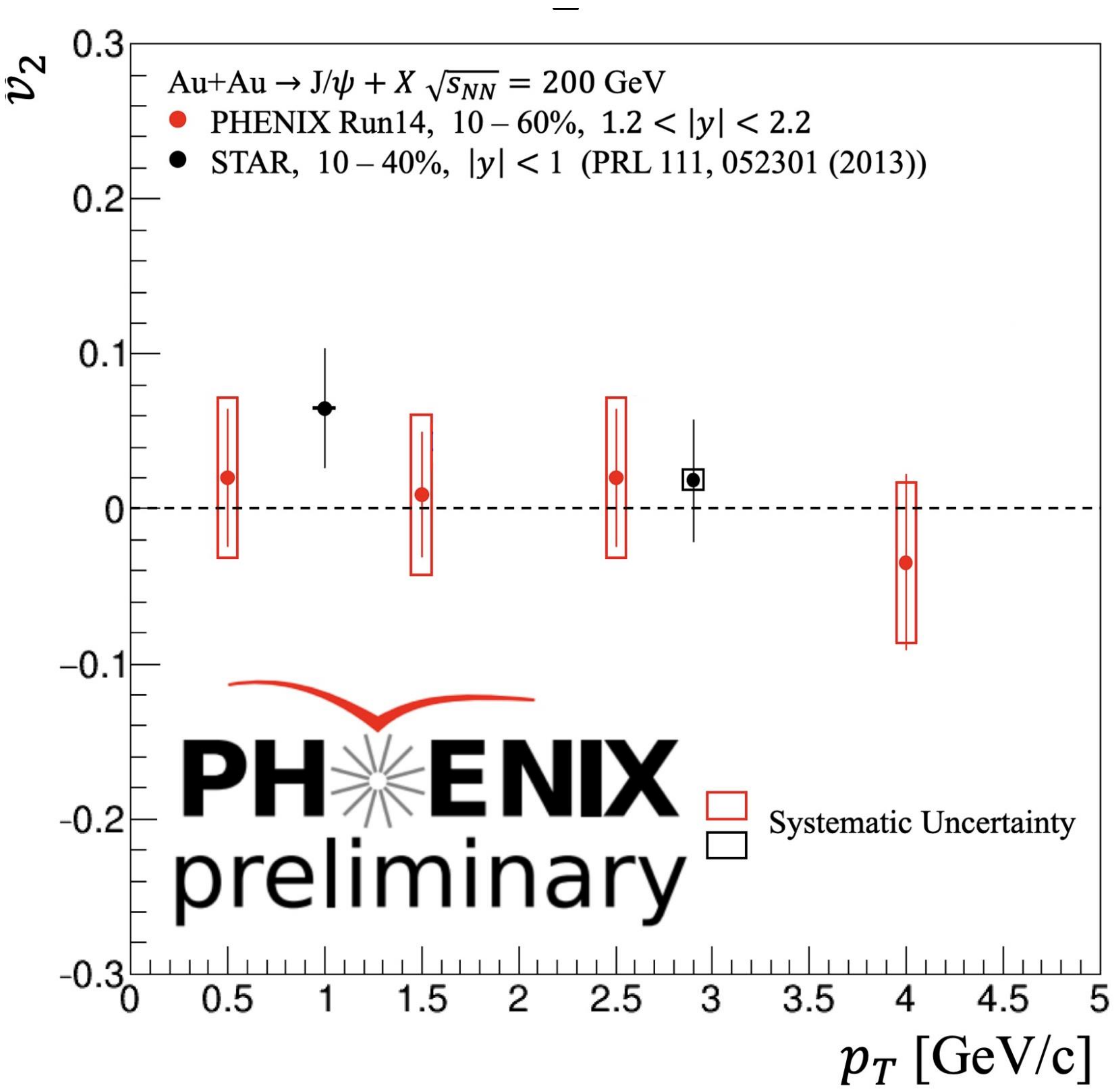
Coalescence effect between charm quark and antiquark leads to J/ψ regeneration at LHC

J/ψ Elliptic Flow Measurement



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

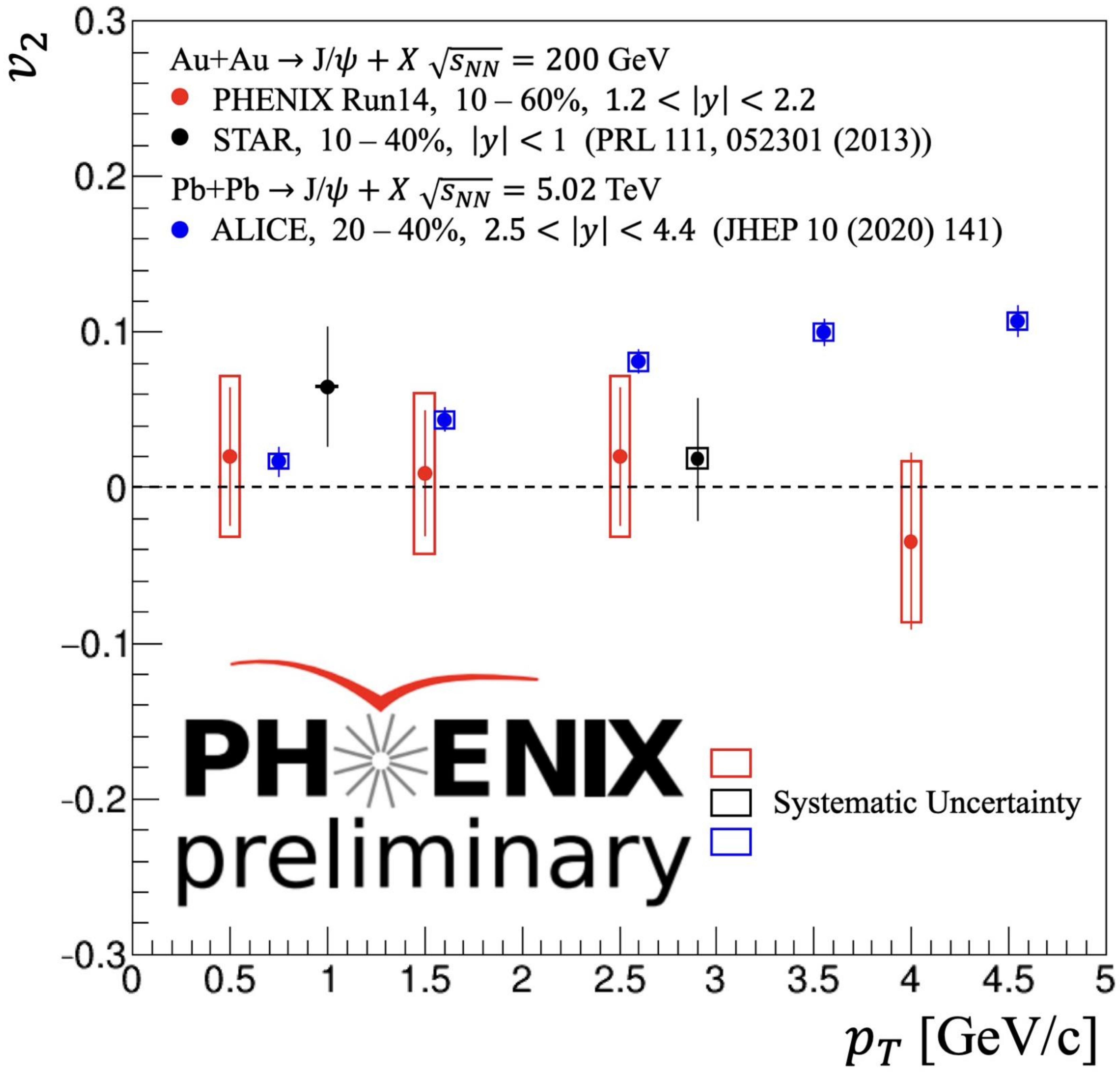
J/ψ Elliptic Flow Measurement



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

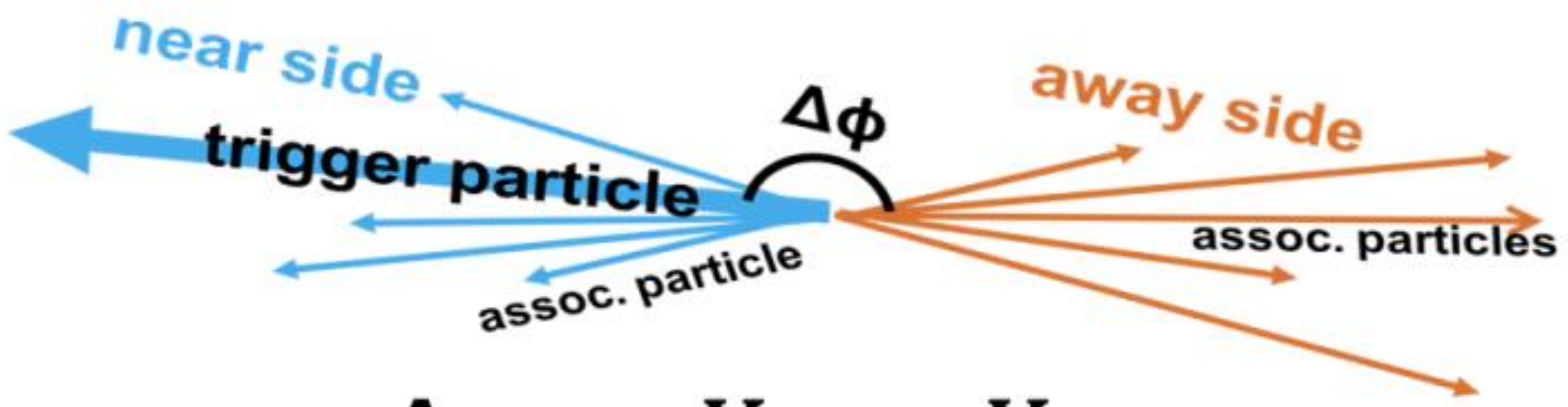
Not enough energy at RHIC for J/ψ regeneration to become noticeable?

Light Flavor Hadrons

Medium response to jets in Au+Au

Transition from enhancement for low p_T to suppression for high p_T associated hadrons

Trend is reproduced with Hybrid model with medium response

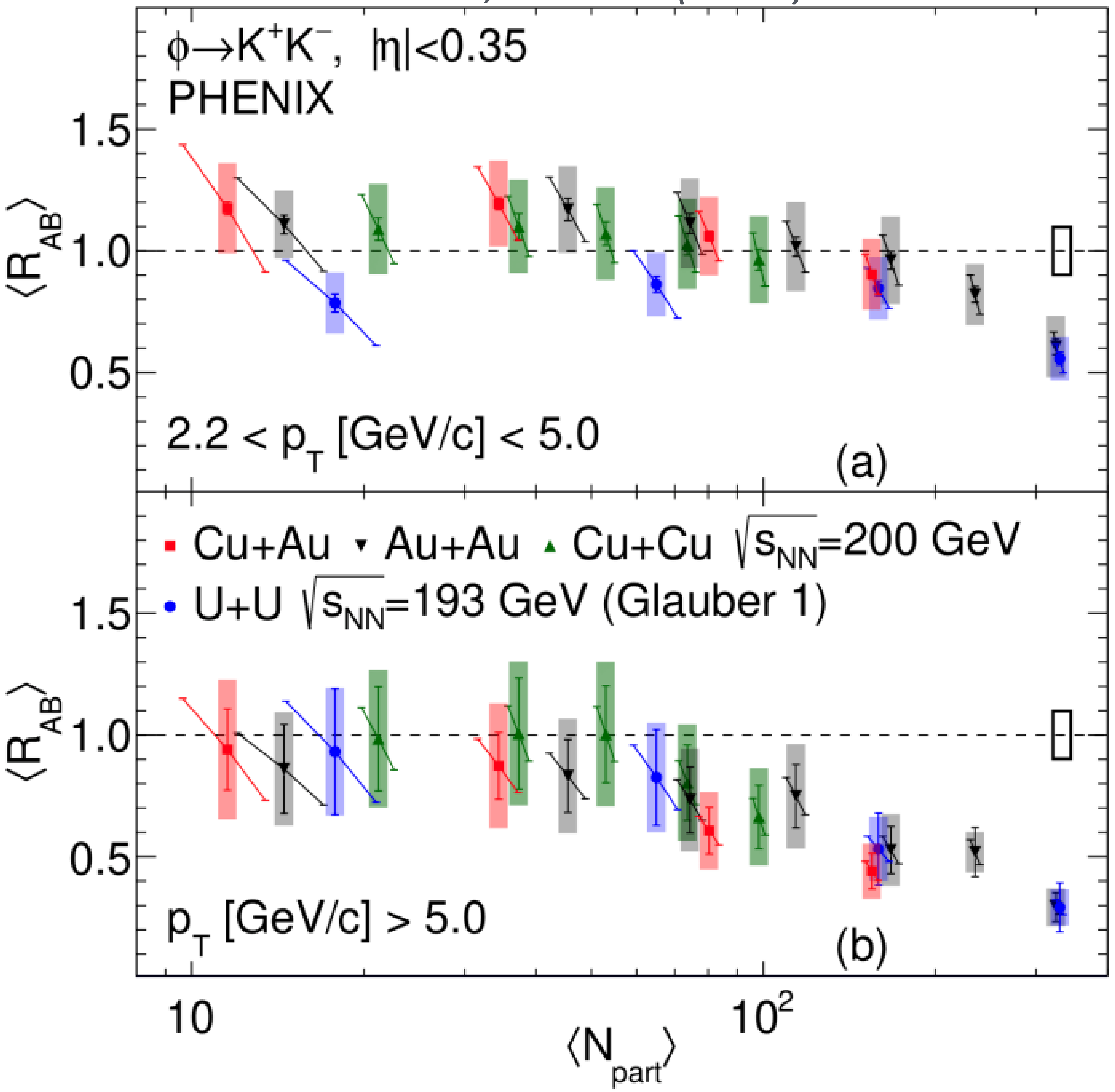


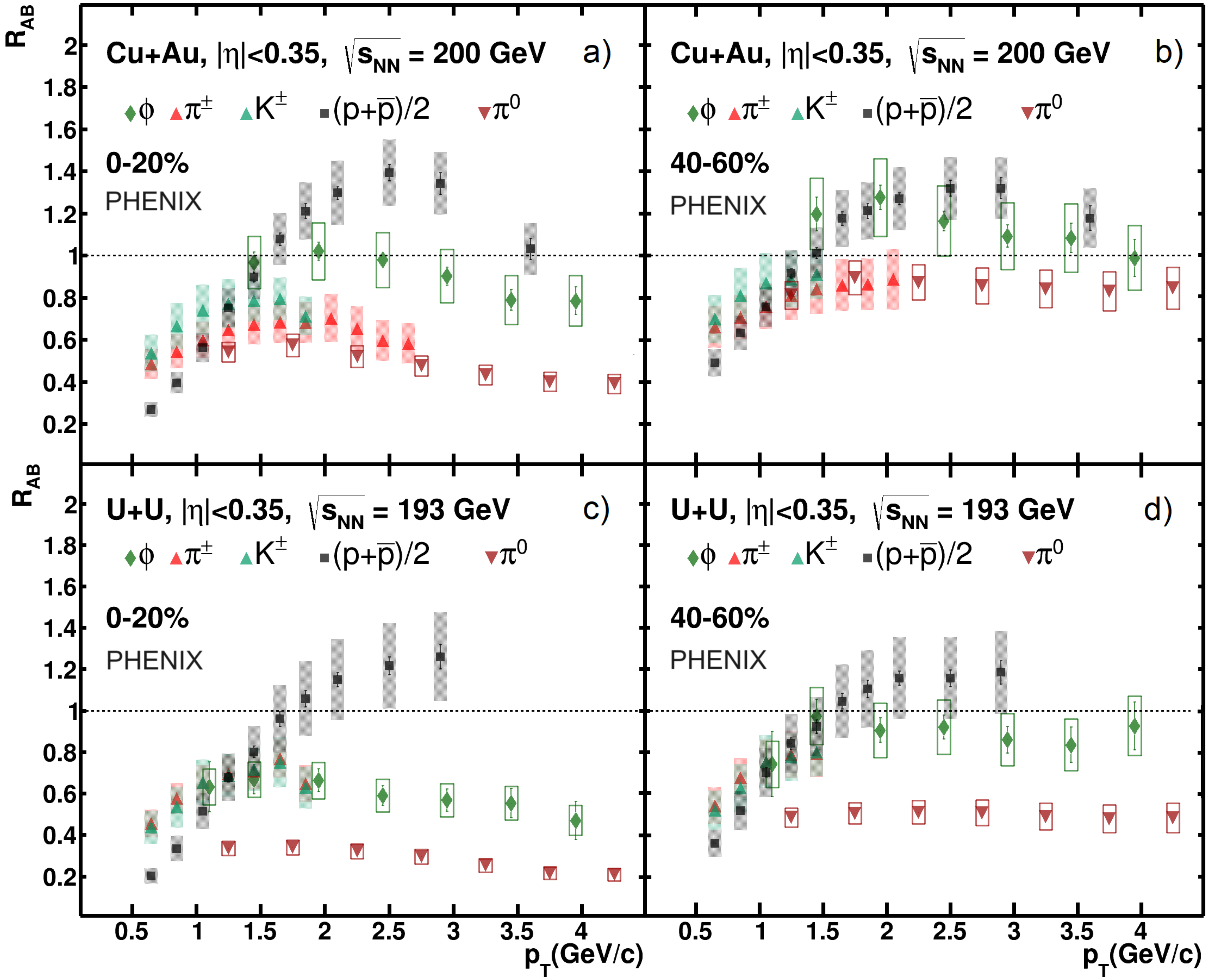
$$\Delta_{AA} = Y_{AA} - Y_{pp}$$

PHENIX: arXiv:2406.08301

Light Flavor Hadron Production

PHENIX: PRC 107, 014907 (2023)

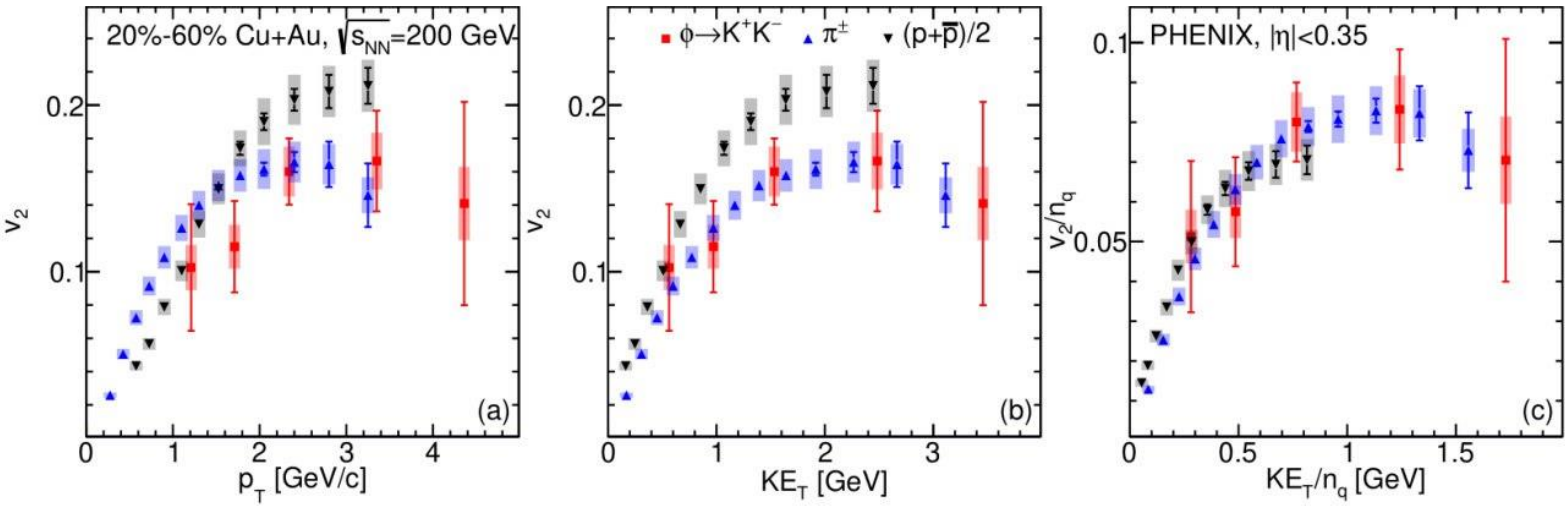




Scaling with nuclear overlap size and dependence on number and flavor of valence quarks

ϕ, $\pi^{\pm}$, and proton v_2

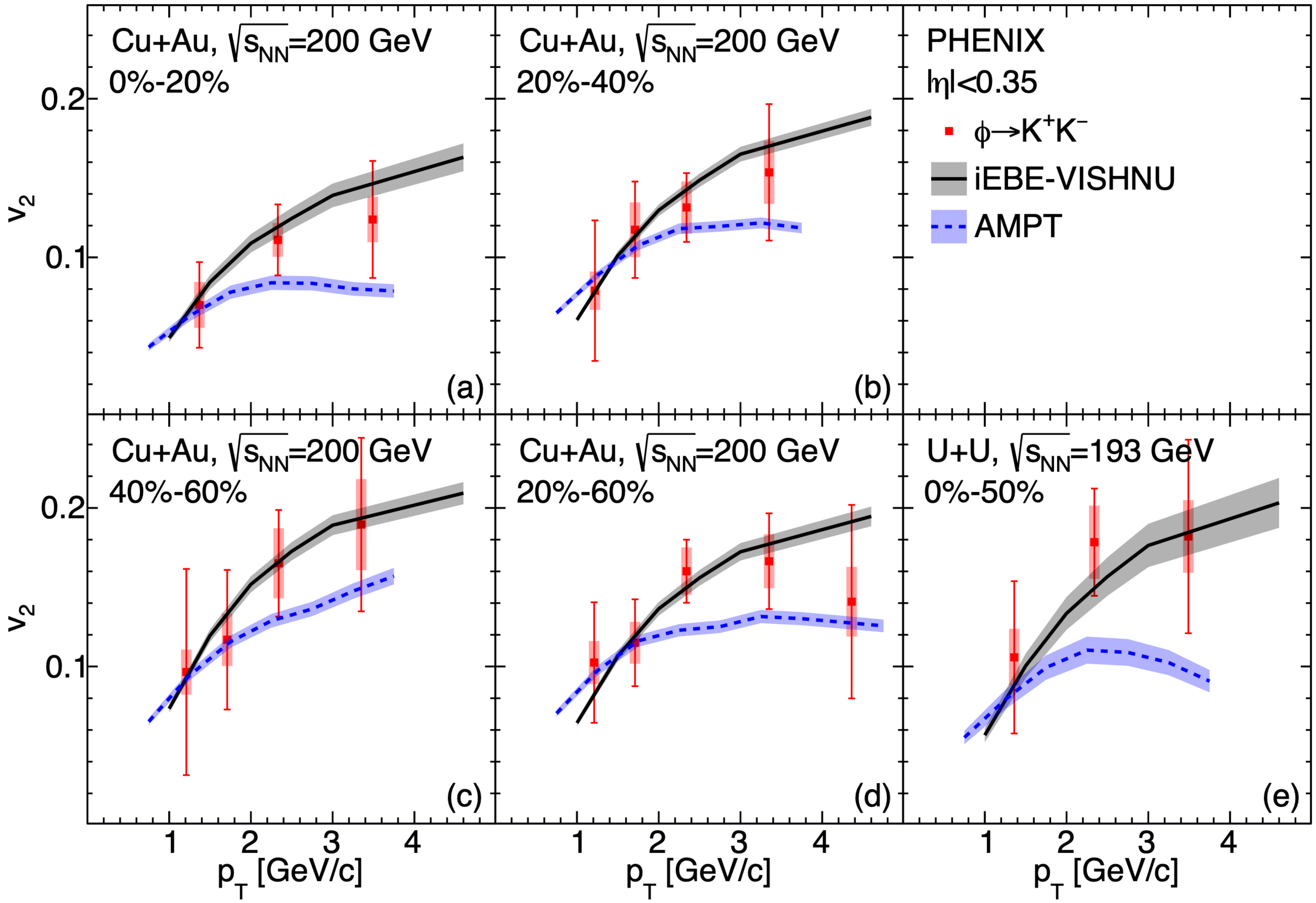
PHENIX: PRC 107, 014907 (2023)



- 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

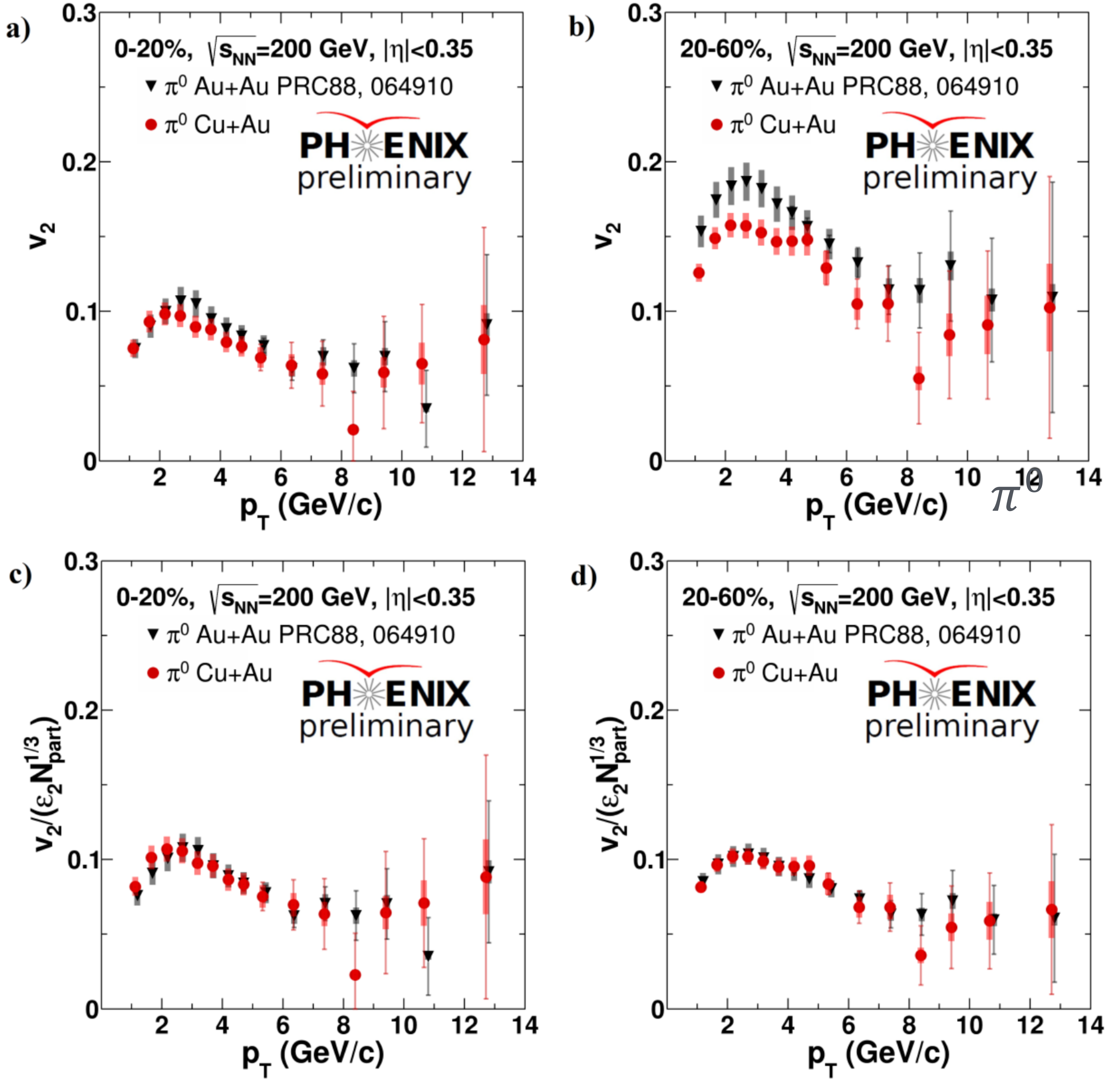
ϕ meson Elliptic Flow vs Models

PHENIX: PRC 107, 014907 (2023)



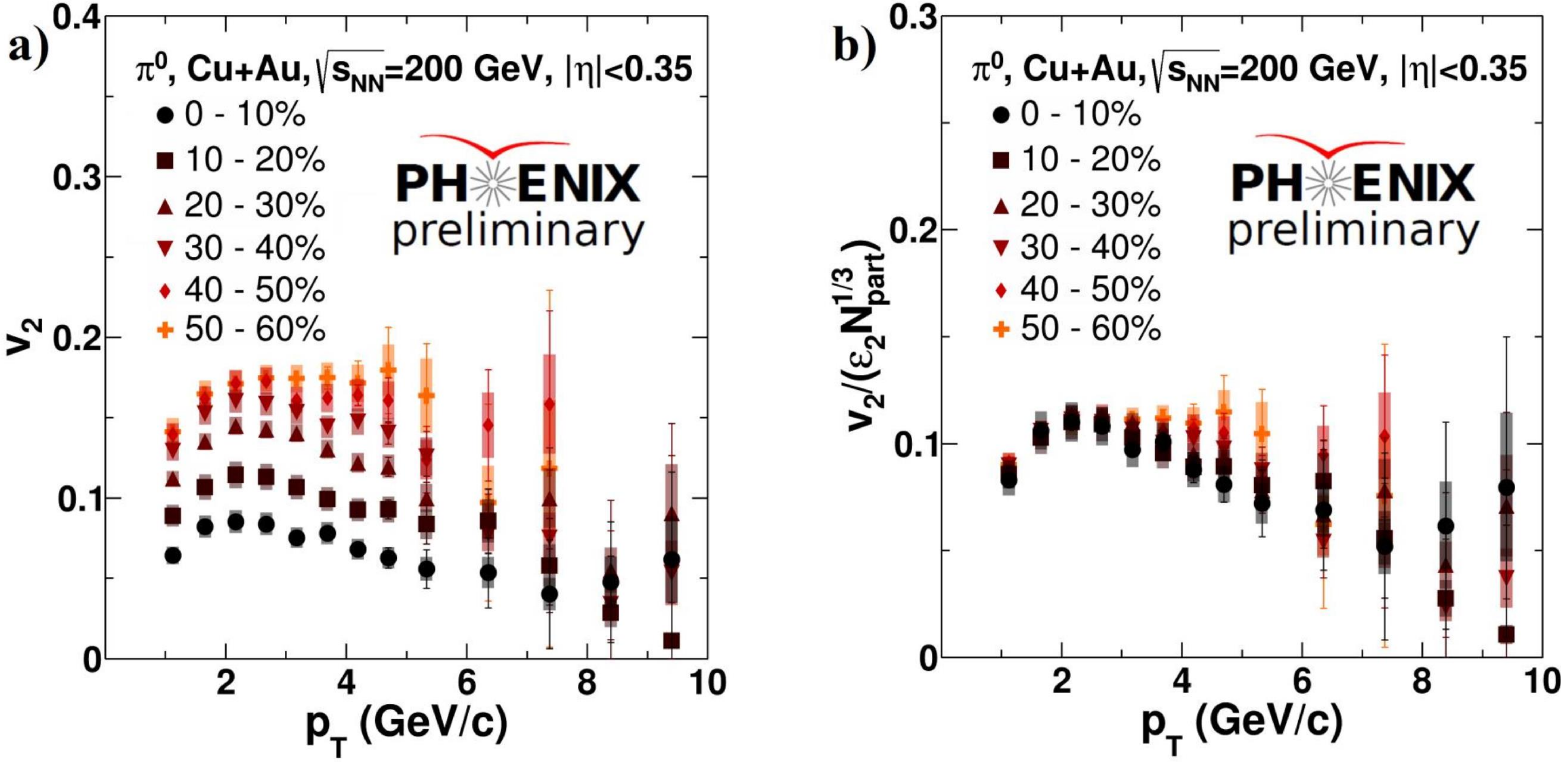
ϕ meson elliptic flow is well described by hydrodynamic model iEBE-VISHNU and transport model AMPT

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?

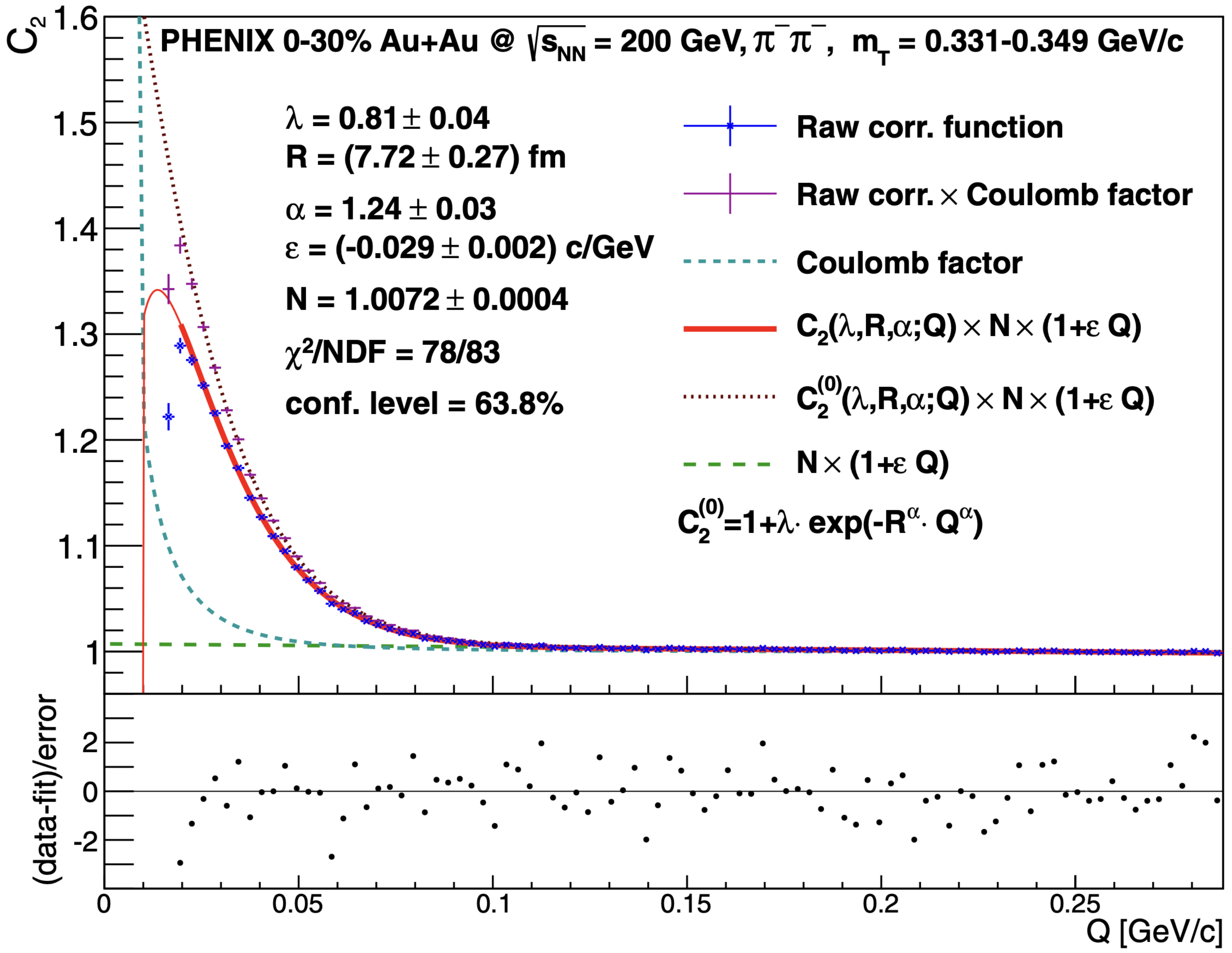
π^0 Elliptic Flow Measurement



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

$\pi^{\pm}\pi^{\pm}$ Bose-Einstein correlations

PHENIX: arxiv:2407.08586



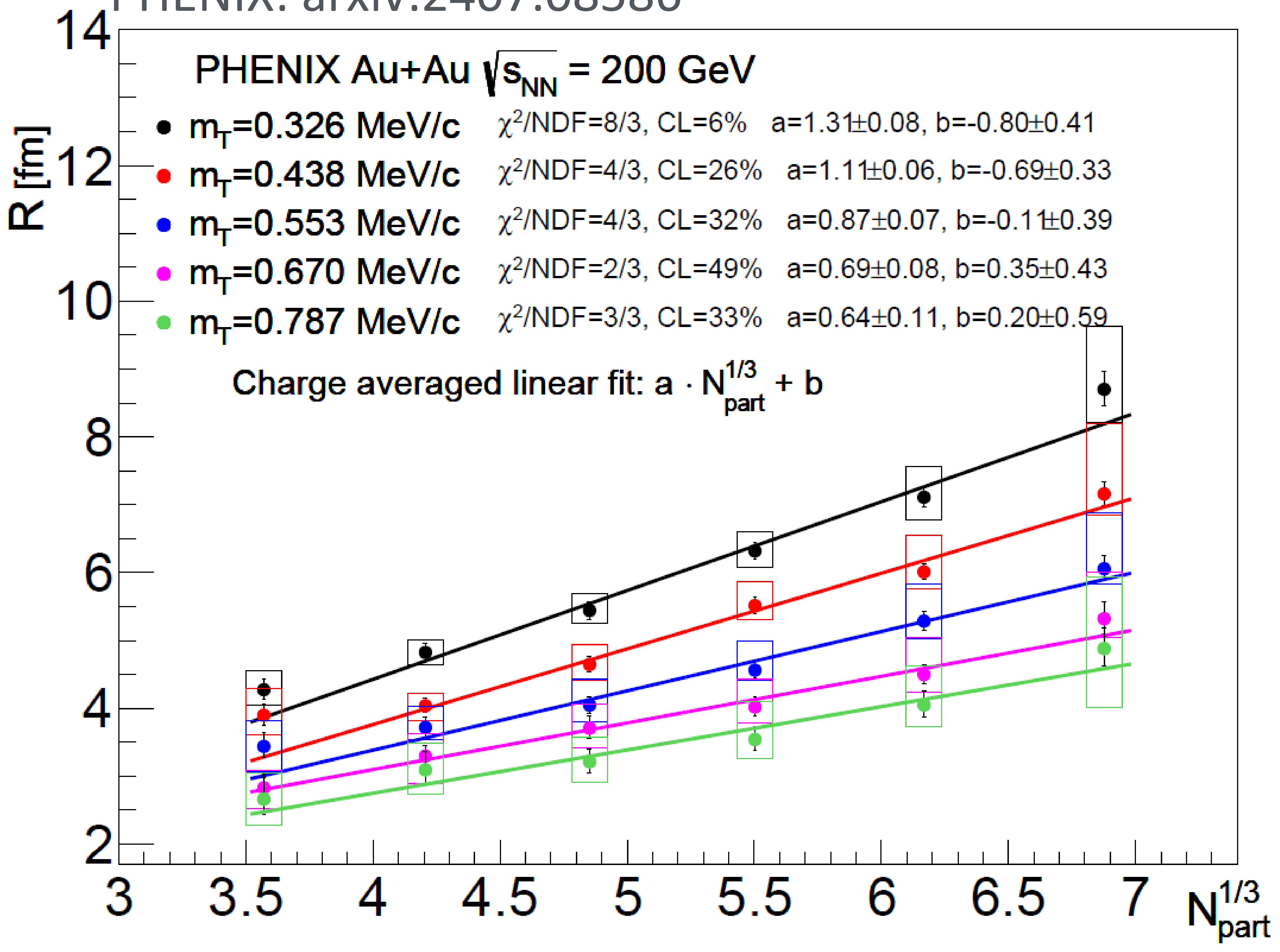
Examples of the measured Coulomb-distorted two-pion Bose-Einstein correlation function, the Coulomb correction factor, and the resulting Coulomb-corrected two-pion

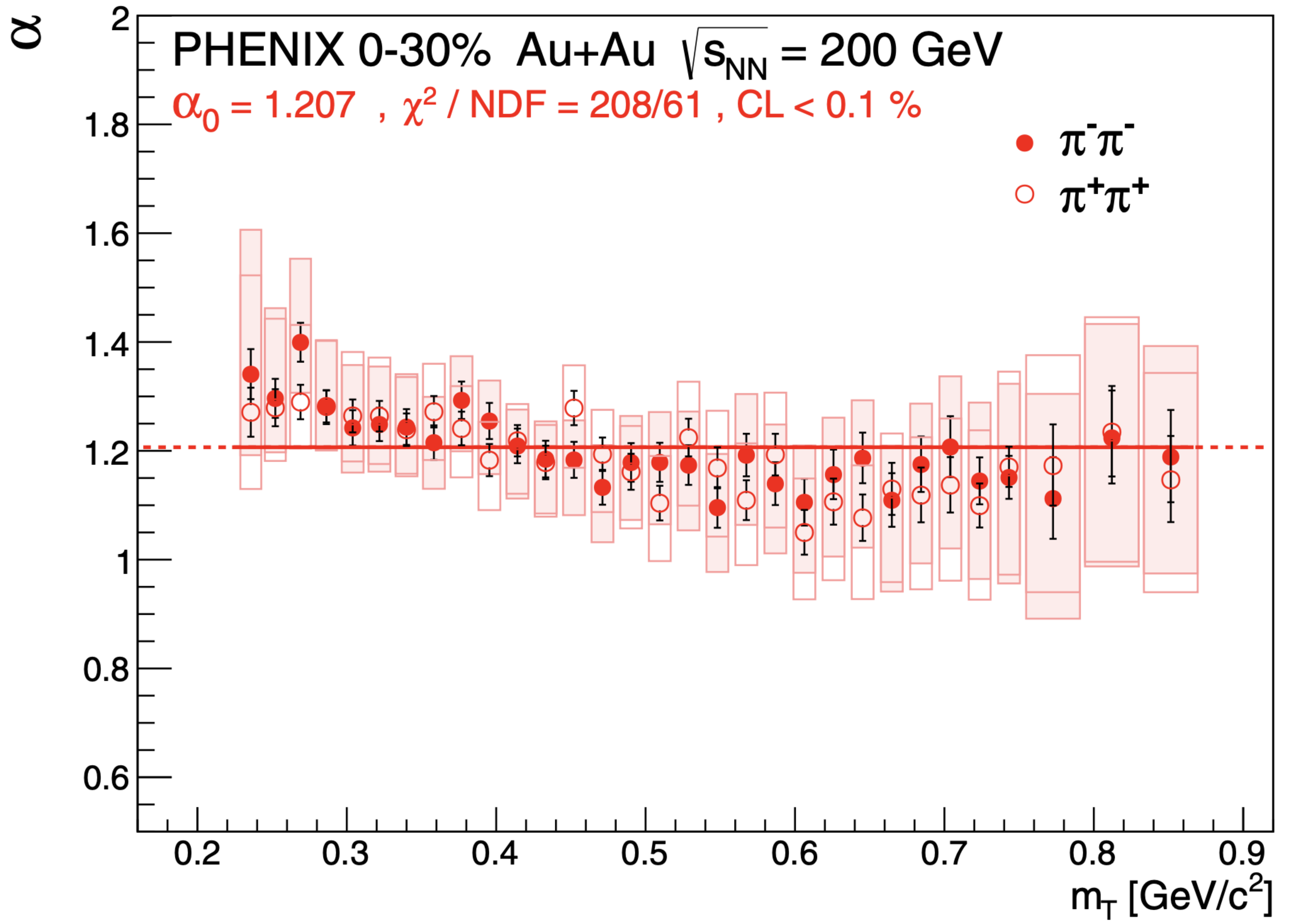
Bose-Einstein correlation functions Fits that define the parameters of the Levy-stable Bose-Einstein correlation functions

λ, R, α – strength, length-scale, and shape factors are studied as function of m_T and centrality

$\pi^{\pm}\pi^{\pm}$ Bose-Einstein correlations

PHENIX: arxiv:2407.08586

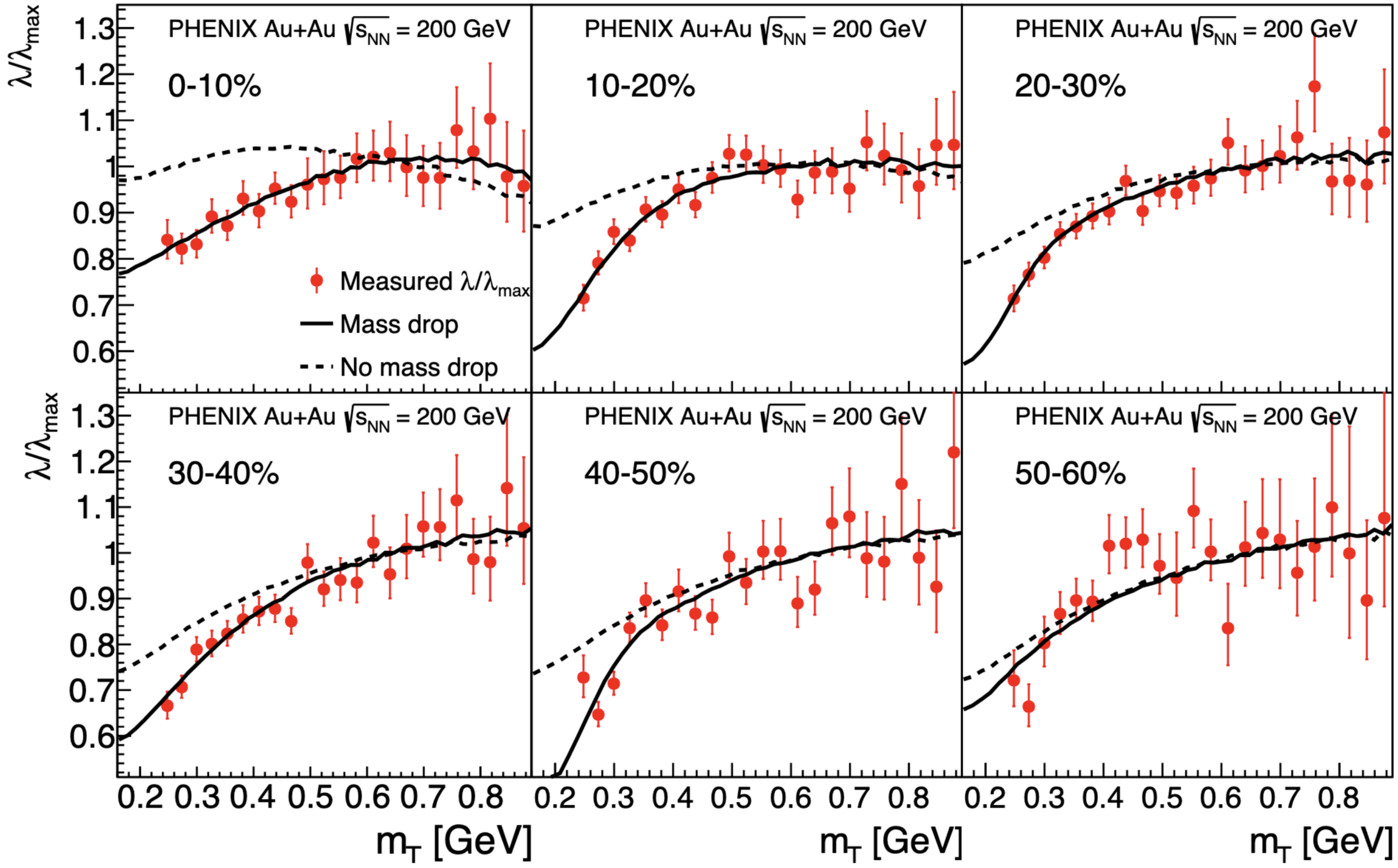




Measured R is proportional to $N_{part}^{1/3}$, which is proportional to length-scale of QGP.
The values of $\alpha(m_T) \approx 1.2$ are significantly below the Gaussian limit of 2 and scale with m_T differently than $v_2(m_T)$

$\pi^{\pm}\pi^{\pm}$ Bose-Einstein correlations

PHENIX: arxiv:2407.08586



Comparison of the data to both the optimal fits and the case that lacks the in-medium mass modification of the η' meson

For $m_T \geq 500$ MeV no significant difference between the optimal fit and the assumption of no modification case.

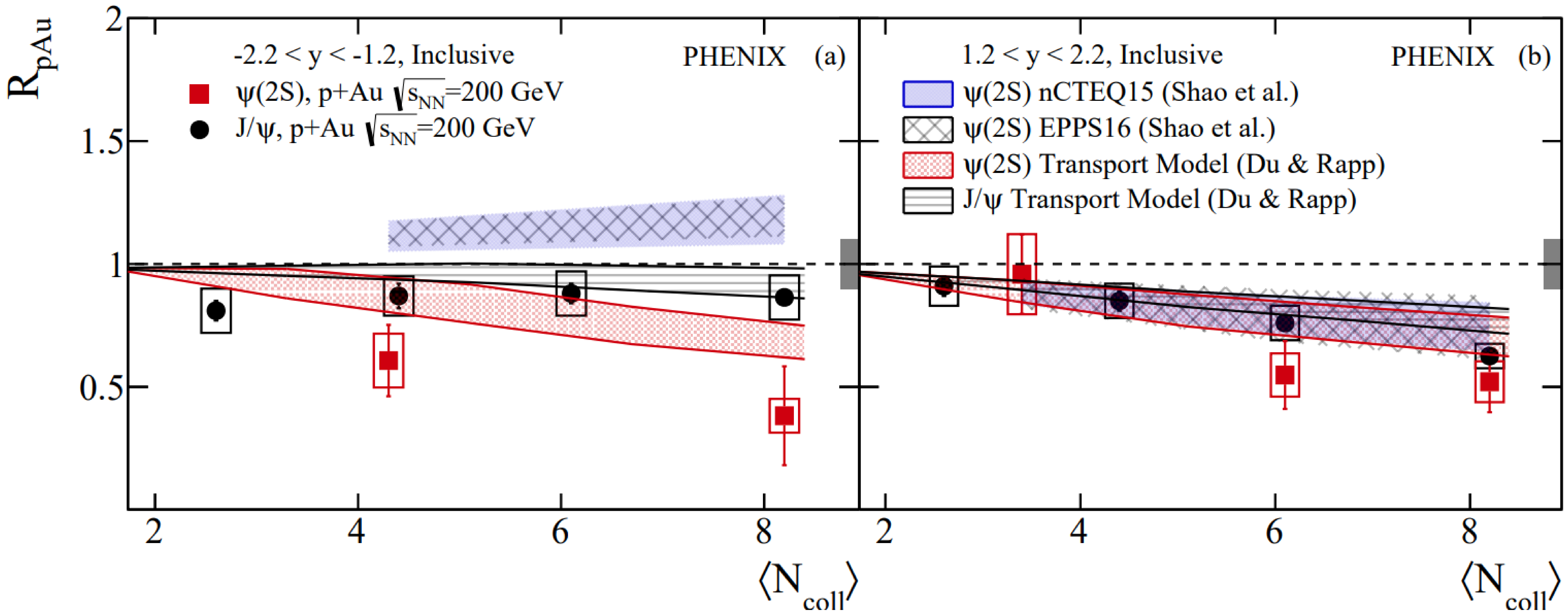
At low m_T no modification seems to be disfavored

Small Systems

Heavy Flavor

J/ψ and $\psi(2S)$ in small systems

PHENIX, PRC 105, 064912 (2023)

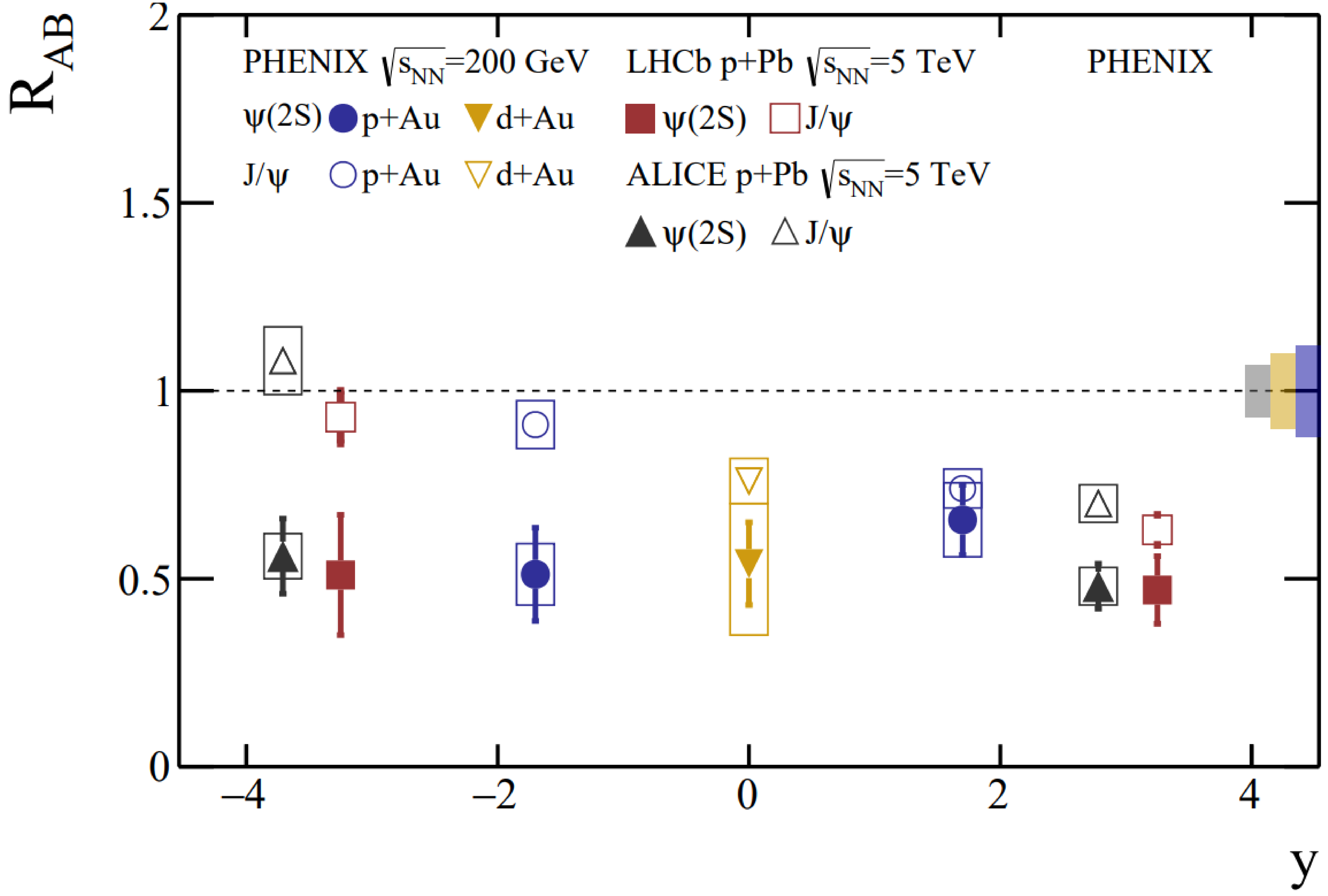


J/ψ modification consistent with initial state effects alone at forward and backward rapidity

$\psi(2S)$ modification indicates presence of final state effects at backward rapidity

J/ψ and $\psi(2S)$ in small systems

PHENIX, PRC 105, 064912 (2023)

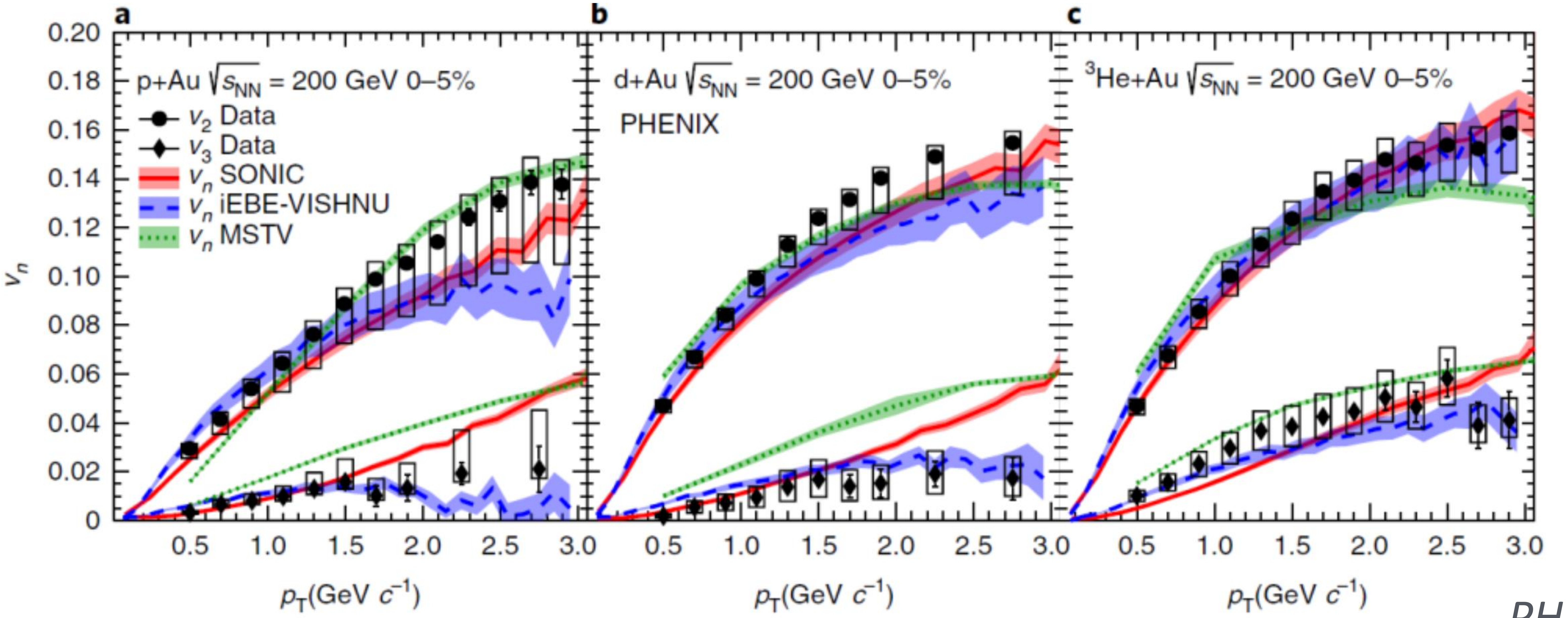


Similar patterns for J/ψ and $\psi(2S)$ found at RHIC and LHC

Light Flavor Hadrons

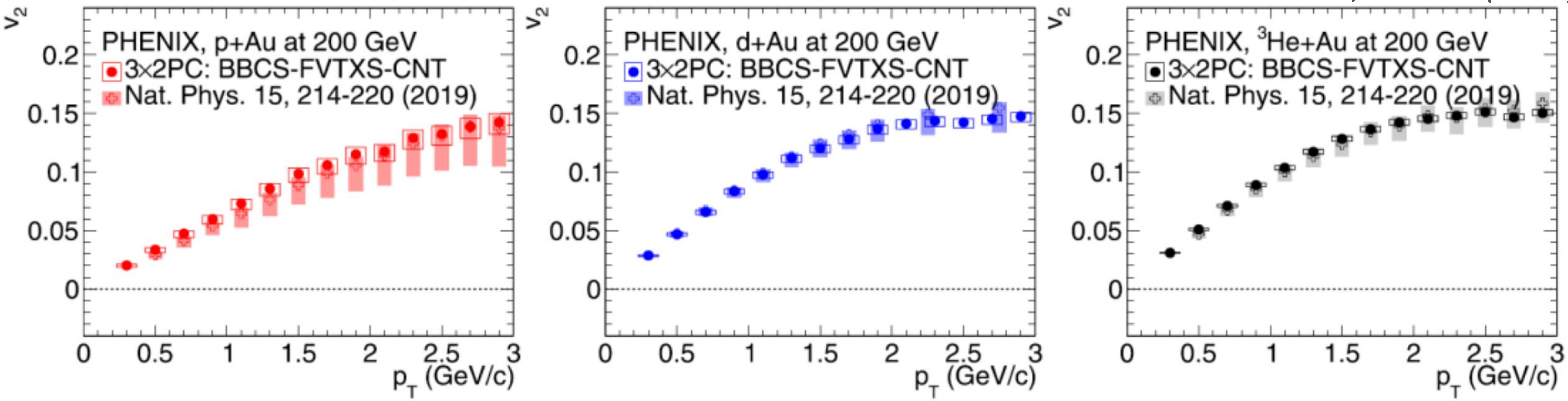
Elliptic flow in small systems

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

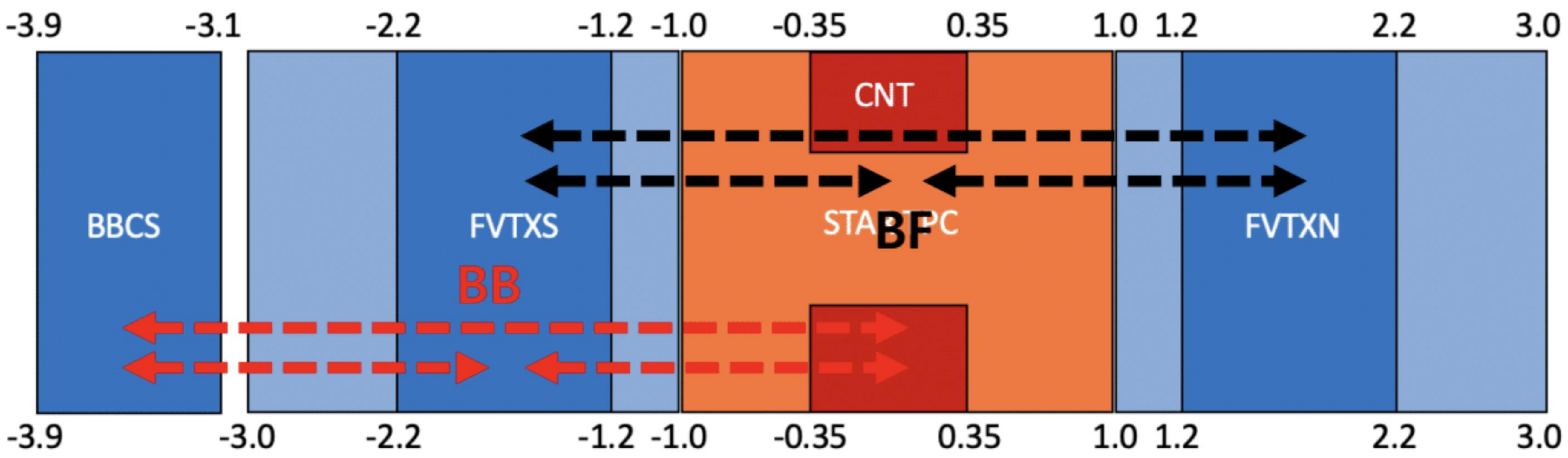


Nature physics results were confirmed

PHENIX: PRC 105, 024901 (2022)

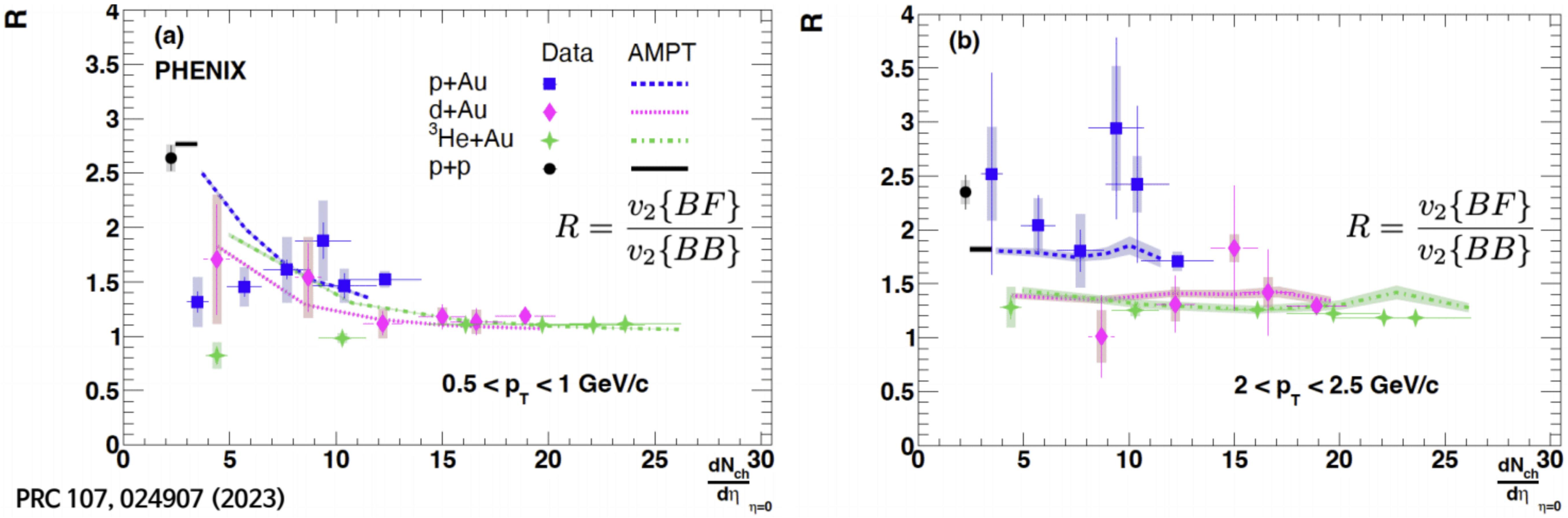


Multiplicity dependence

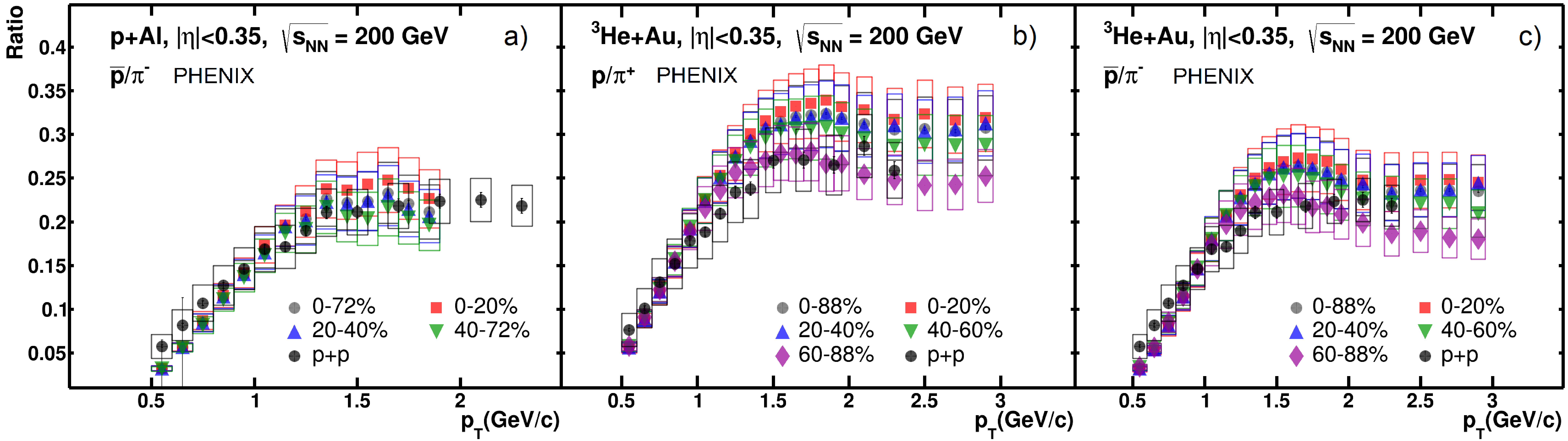


Please try to calculate observables in models as close to experimental ones as possible!

PHENIX: PRC 107 024907 (2023)

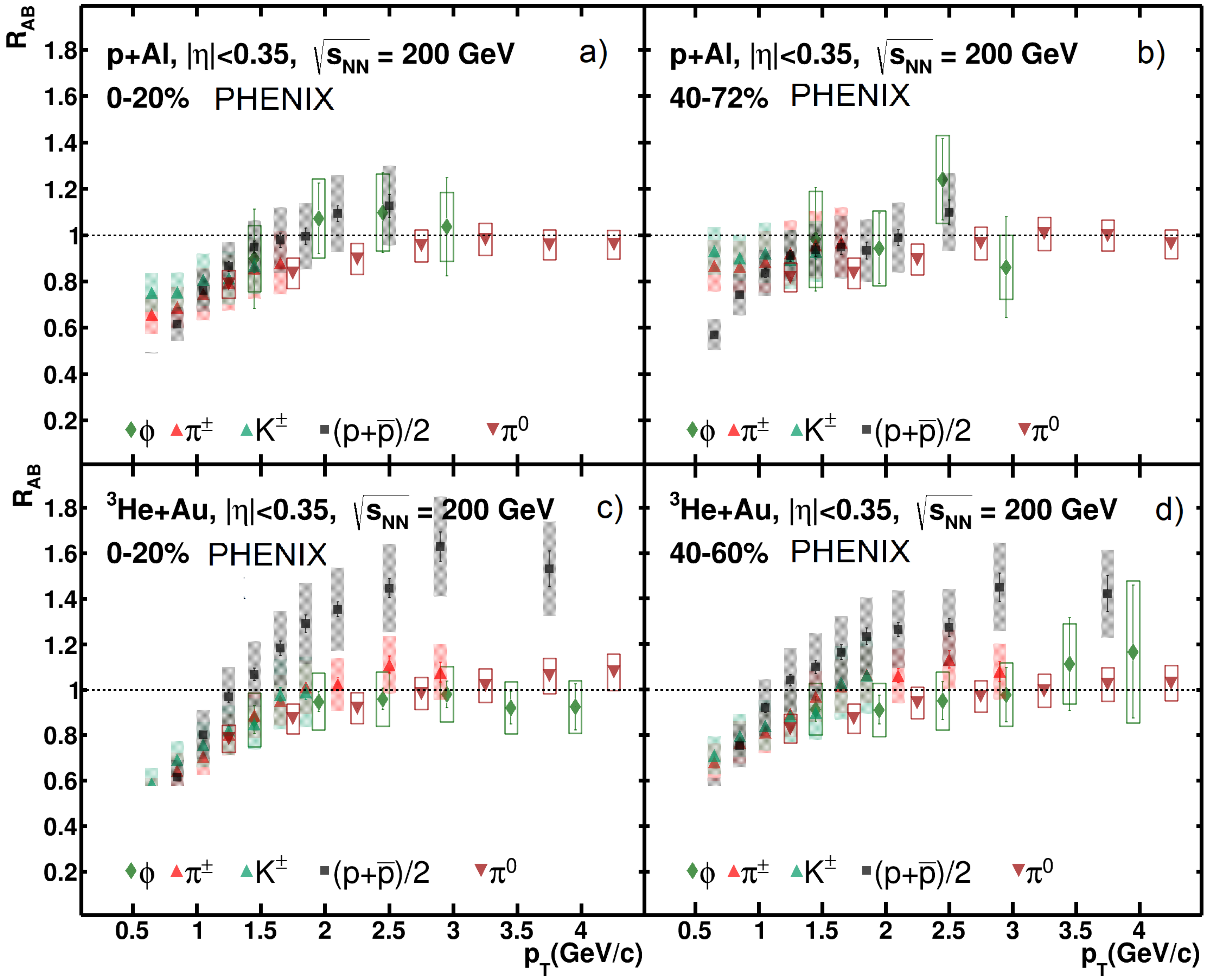


Light Hadron Production



Centrality dependence of baryon to meson ratio is observed in small systems at PHENIX

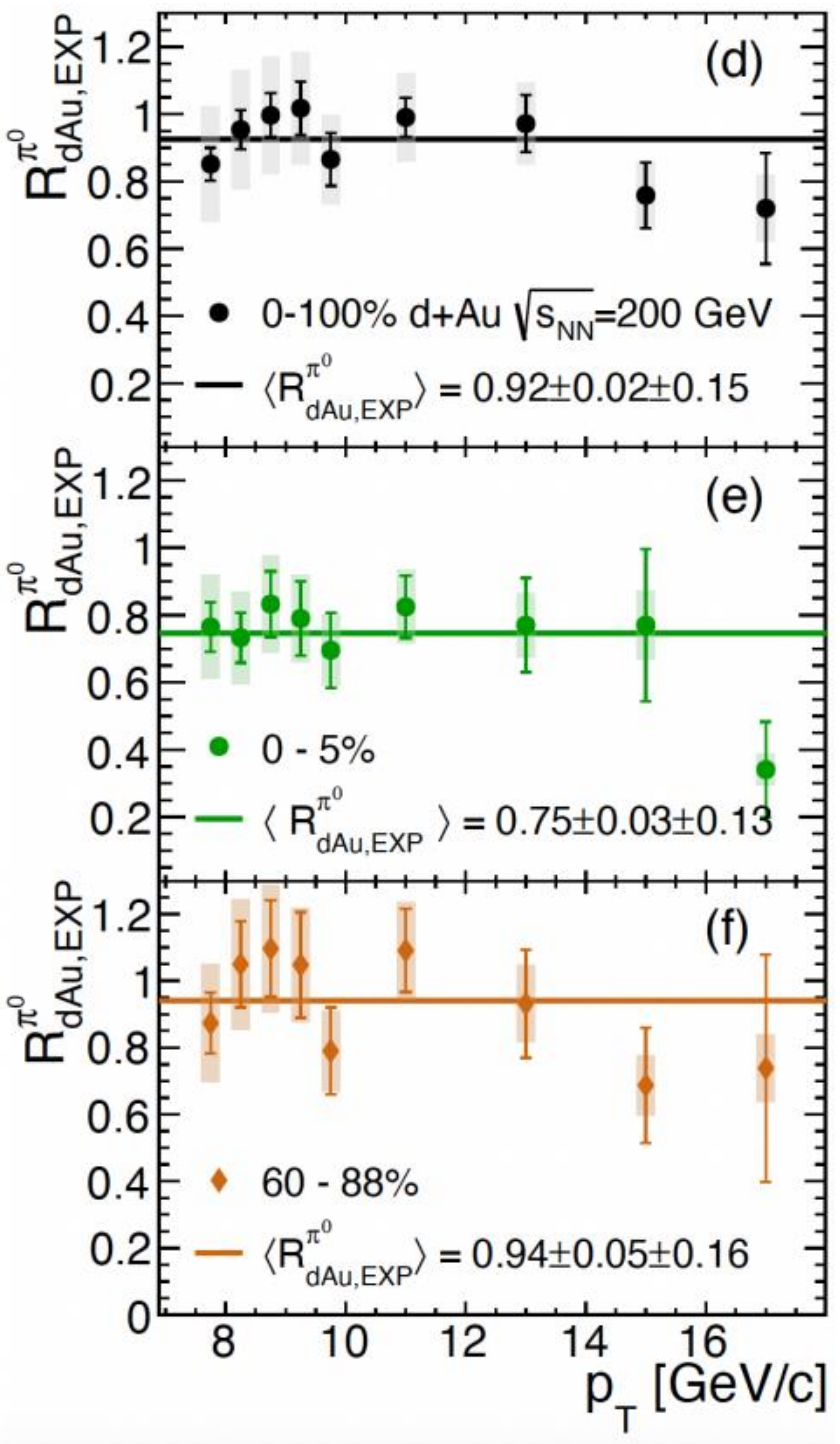
Light Hadron Production



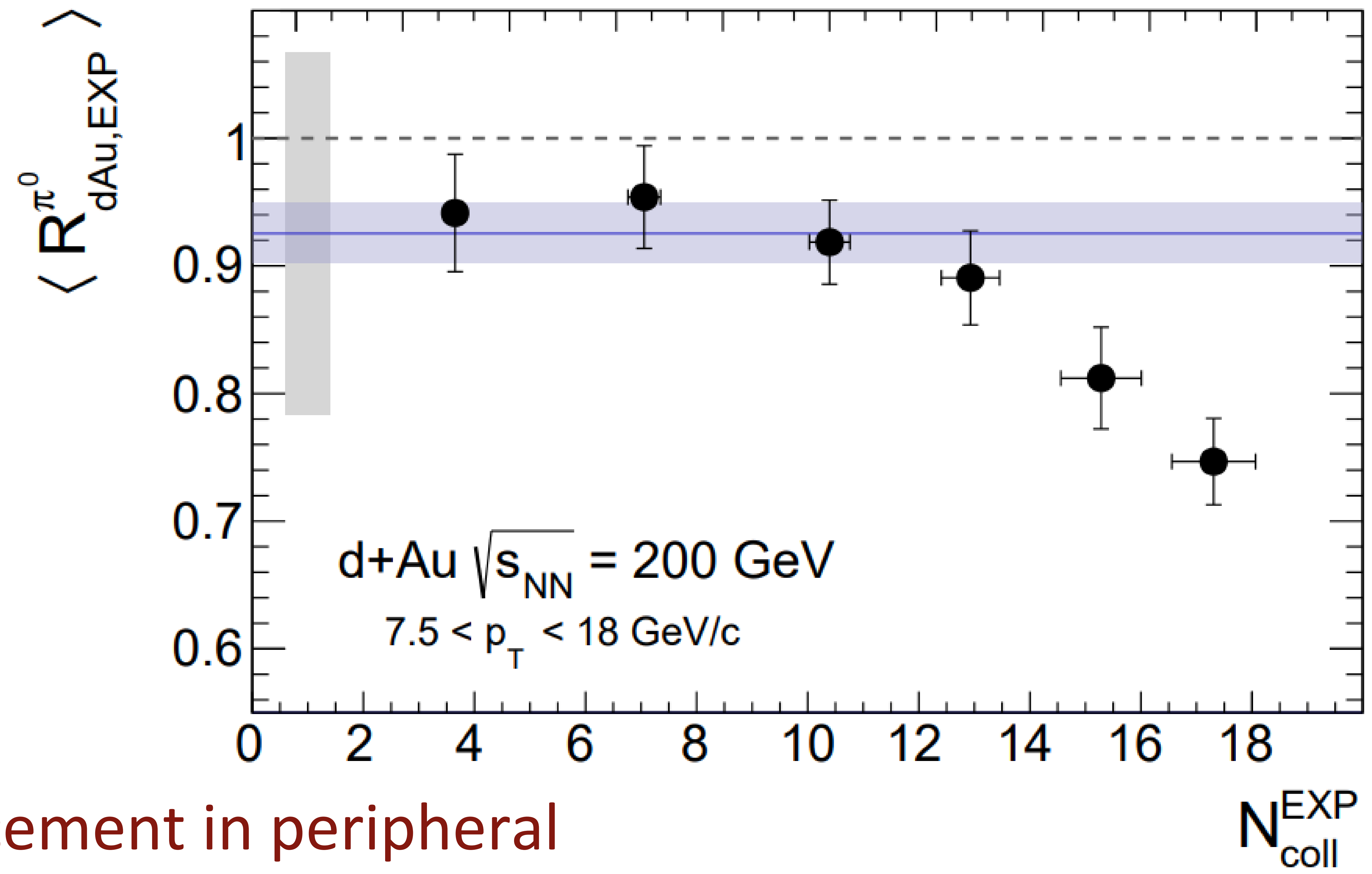
In ^{3}He+Au collisions proton yields are enhanced in comparison to meson yields

ϕ meson follows the same pattern as light flavored mesons

γ_{dir} and π^0 spectra in *d*+Au



PHENIX: arXiv:2303.12899



No enhancement in peripheral

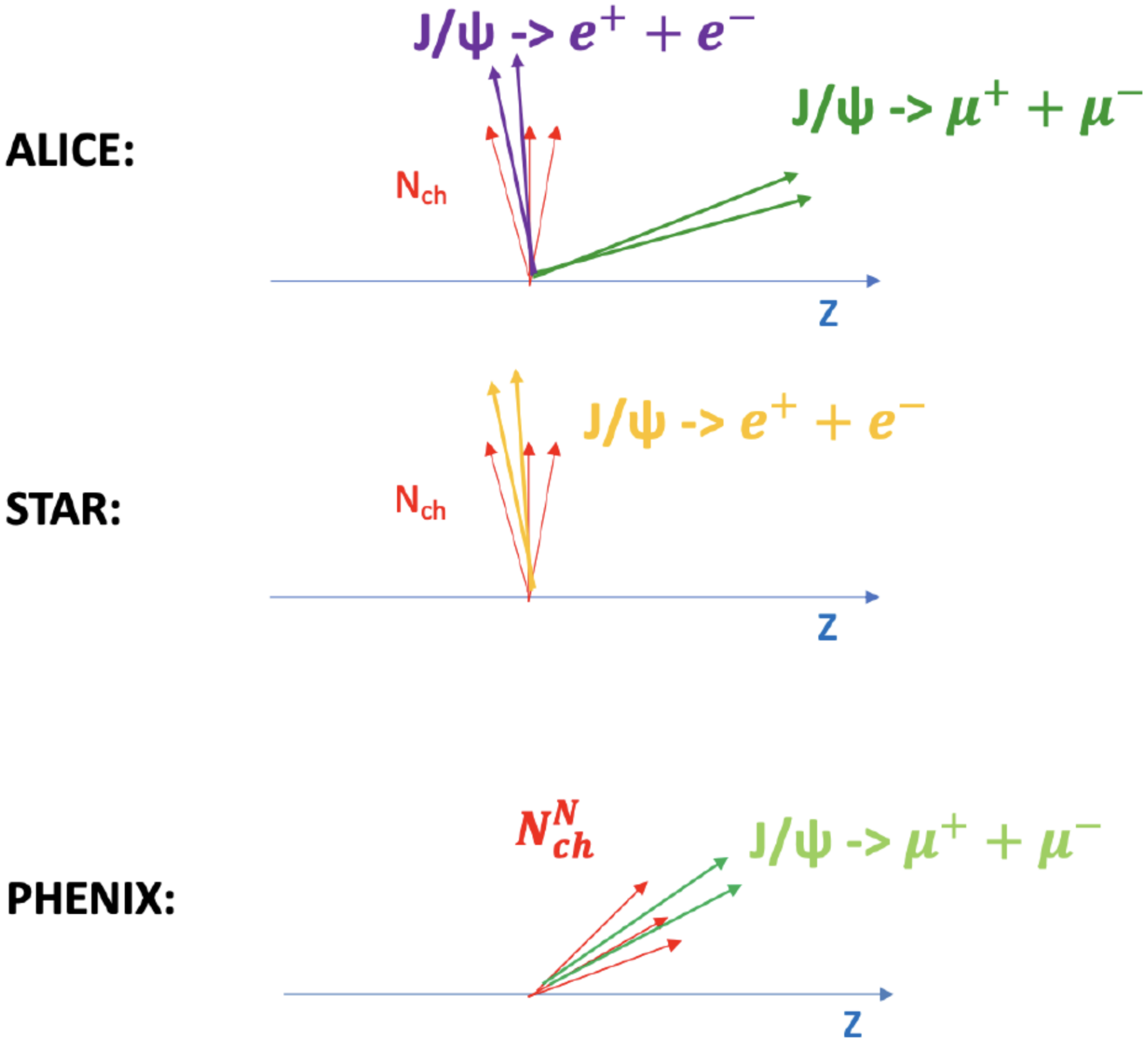
Modest suppression

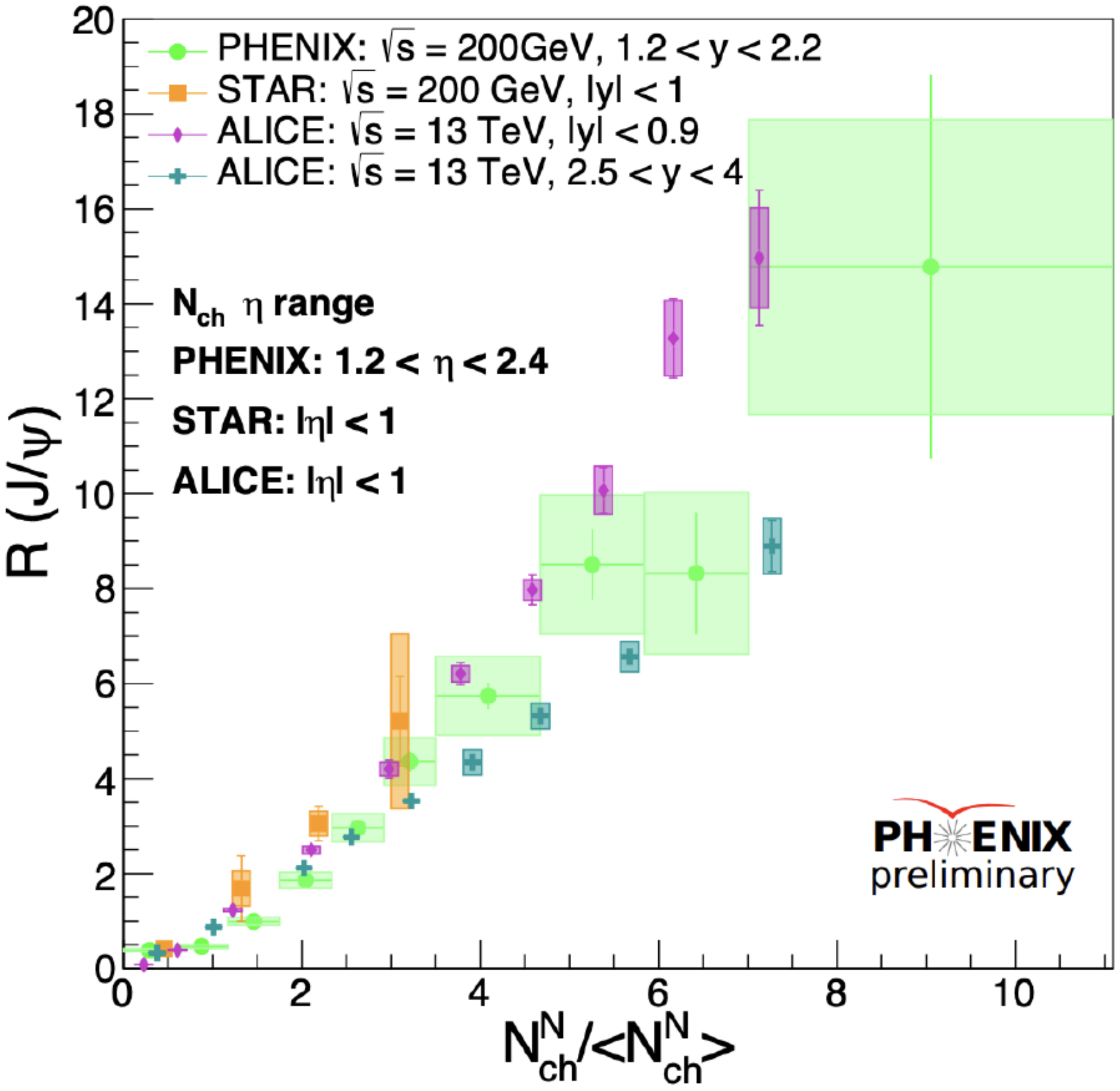
In central Suppression pattern not necessarily indicative of final state effects

see e.g. D.V. Perepelitsa PRC 110 (2024) 011901

Proton-proton collisions

J/ψ yield in p+p



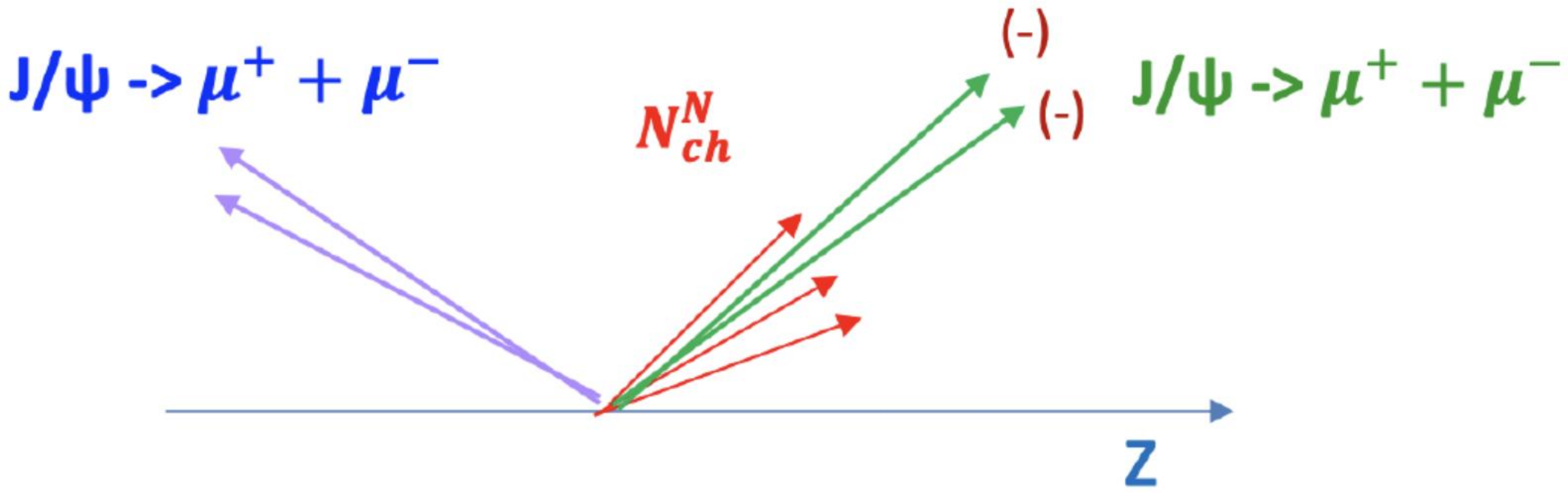


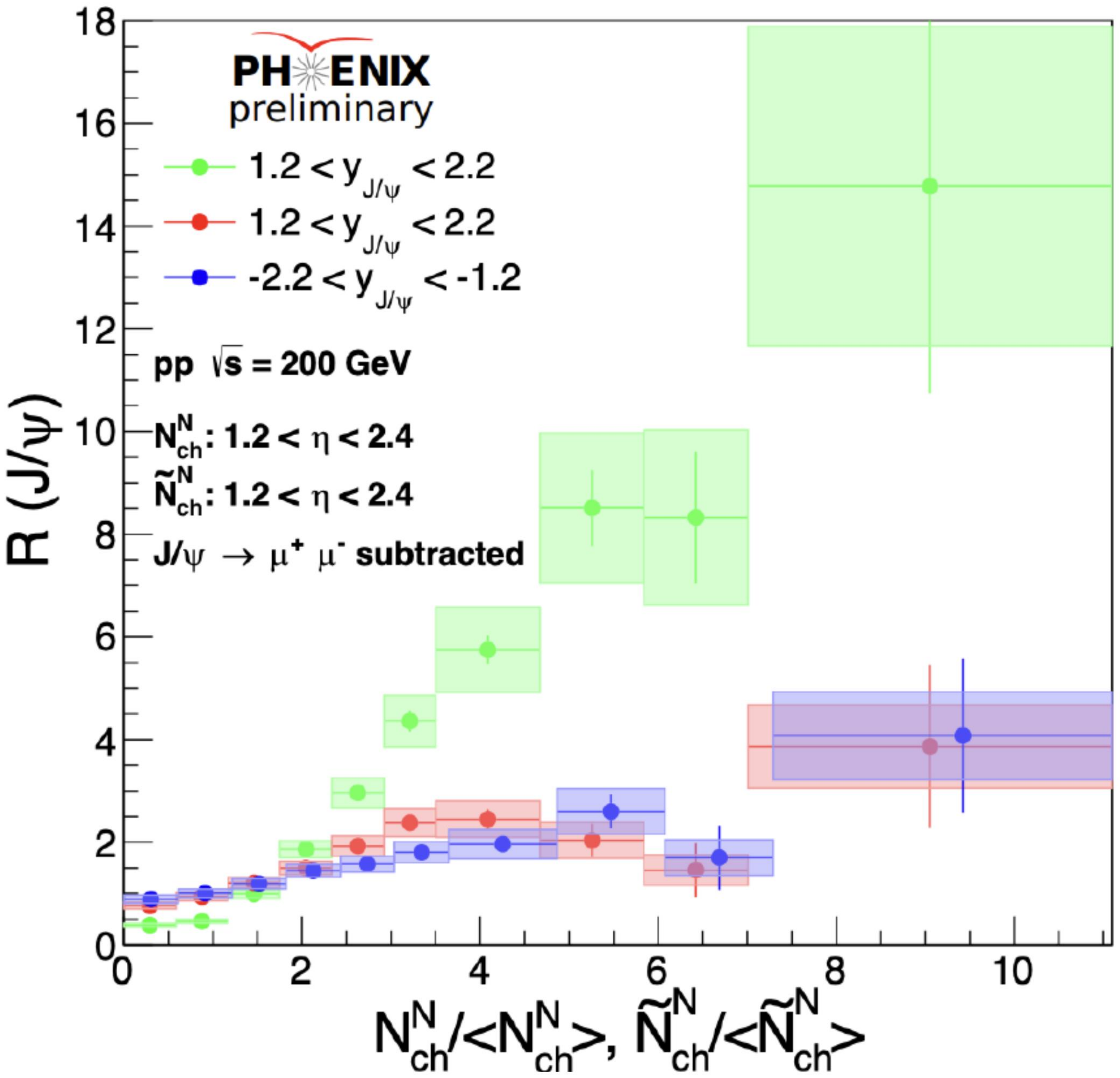
J/ψ yield exhibits large dependence on local track multiplicity

Usually attributed to multi-parton interactions

J/ψ yield in p+p

J/ψ and tracks in the same rapidity
J/ψ and tracks in the opposite rapidity
J/ψ and tracks in the same rapidity, tracks from J/ψ removed from tracks count



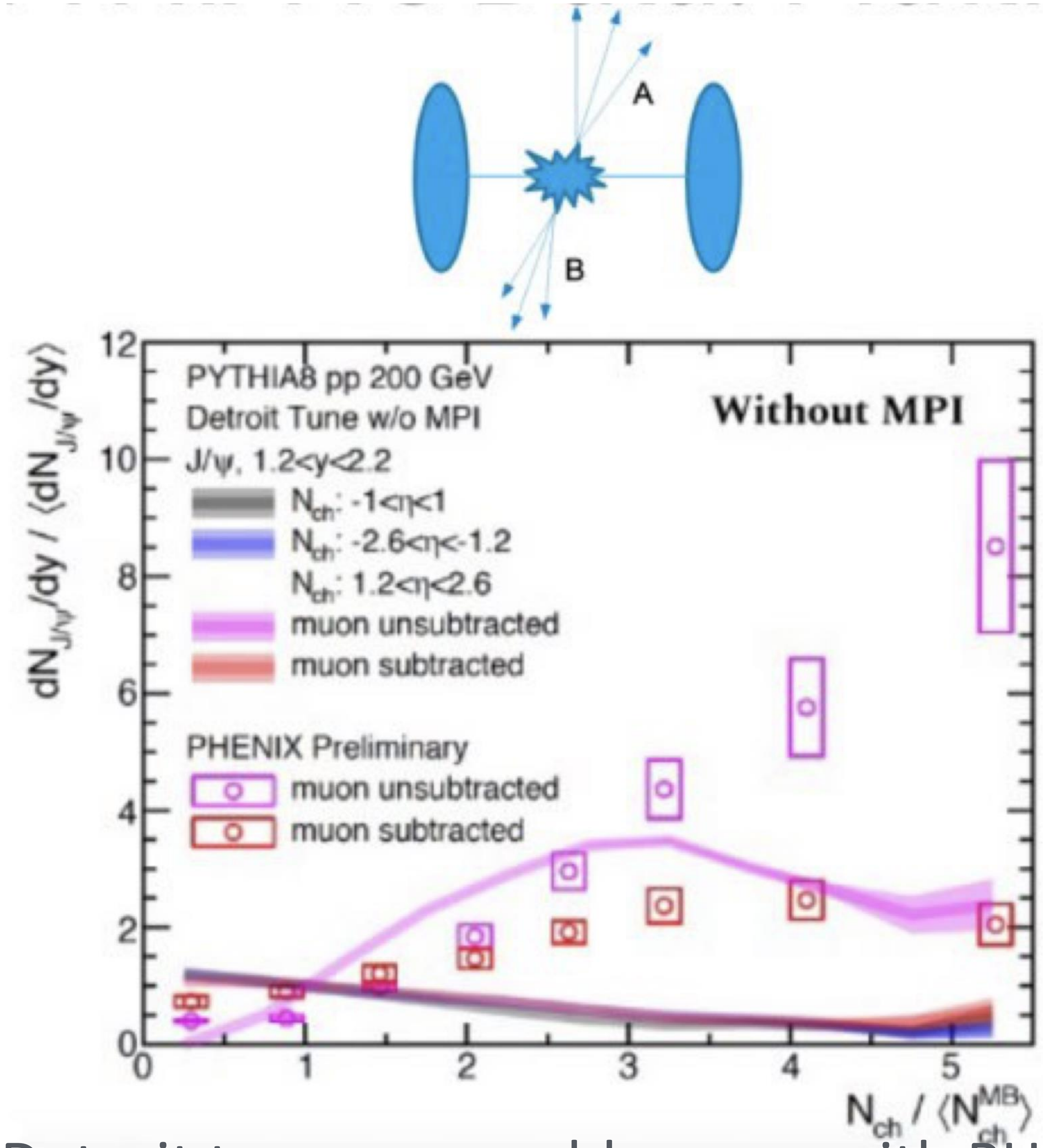


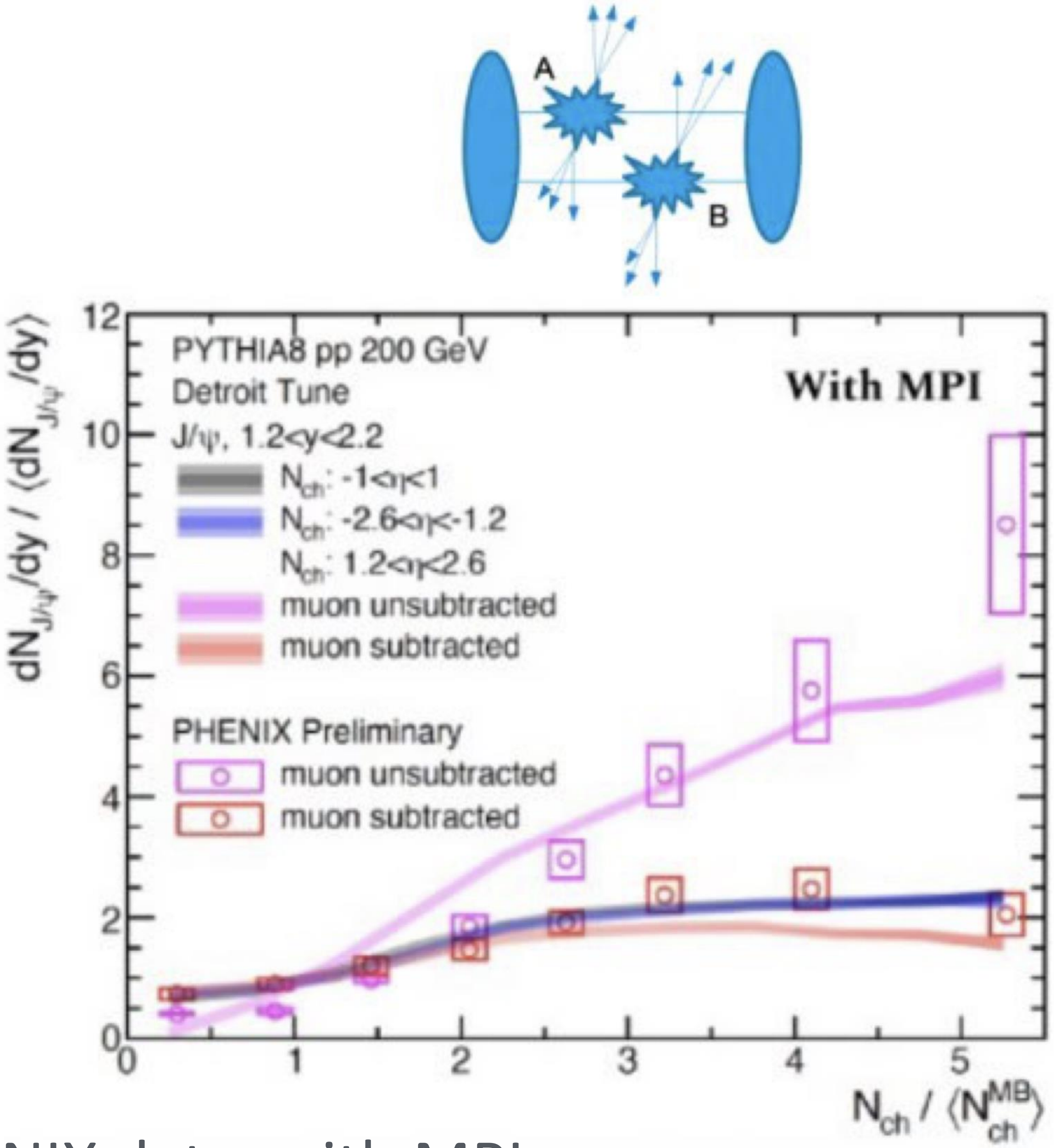
J/ψ yields vs multiplicity significantly reduced when

- Looking at J/ψ and multiplicity in separate rapidity windows
- Looking at J/ψ and multiplicity in the same rapidity window but removing the $\mu^+\mu^-$

Important implications for MPI picture

PYTHIA vs Data: Multi-Parton-Interactions

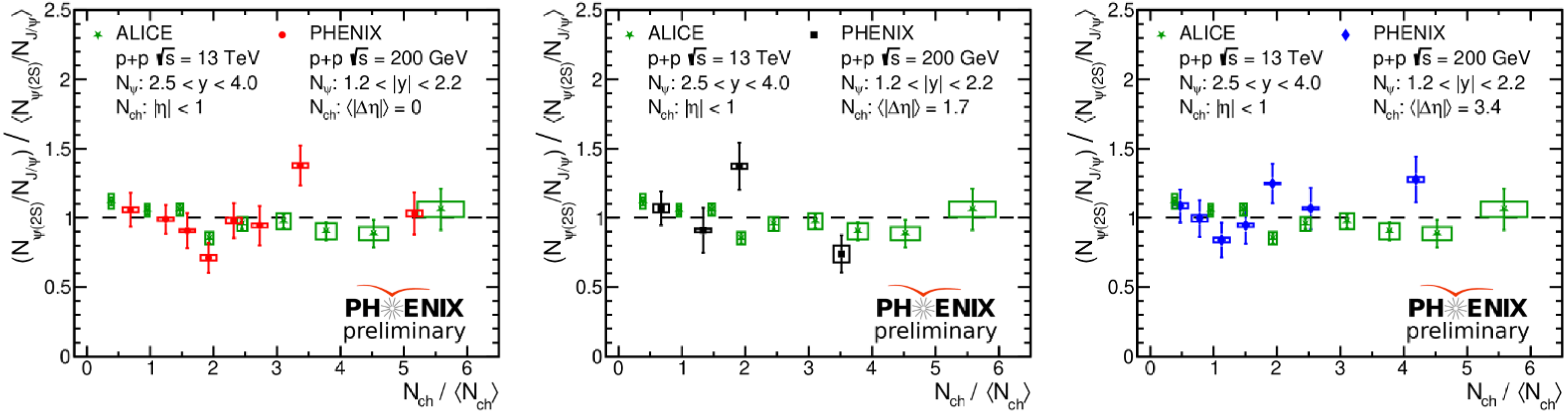




PYTHIA8 Detroit tune reasonably agree with PHENIX data, with MPI
w/o MPI, fit failed badly

Proper understanding of the Underline Events is important

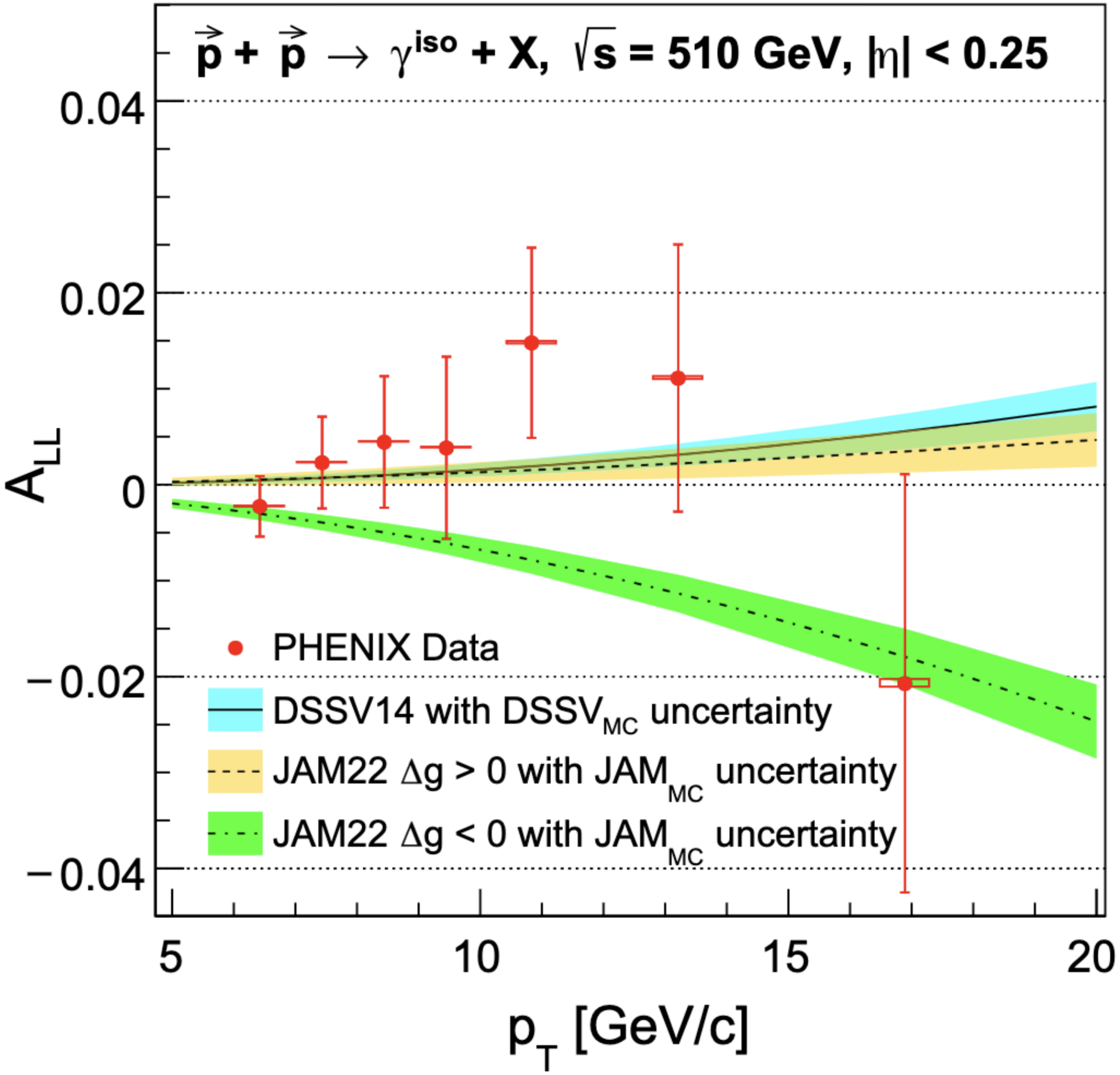
$\psi(2S)$ to J/ψ ratio in *p+p*



Multiplicity-dependent studies can be used as test for onset of QGP-like signatures
PHENIX results match ALICE results, double ratio consistent with unity for all multiplicity

A_{LL} of direct photons

PHENIX: PRL 130, 251901 (2023)



Polarized gluon PDF Δ_g had sign ambiguity in previous results

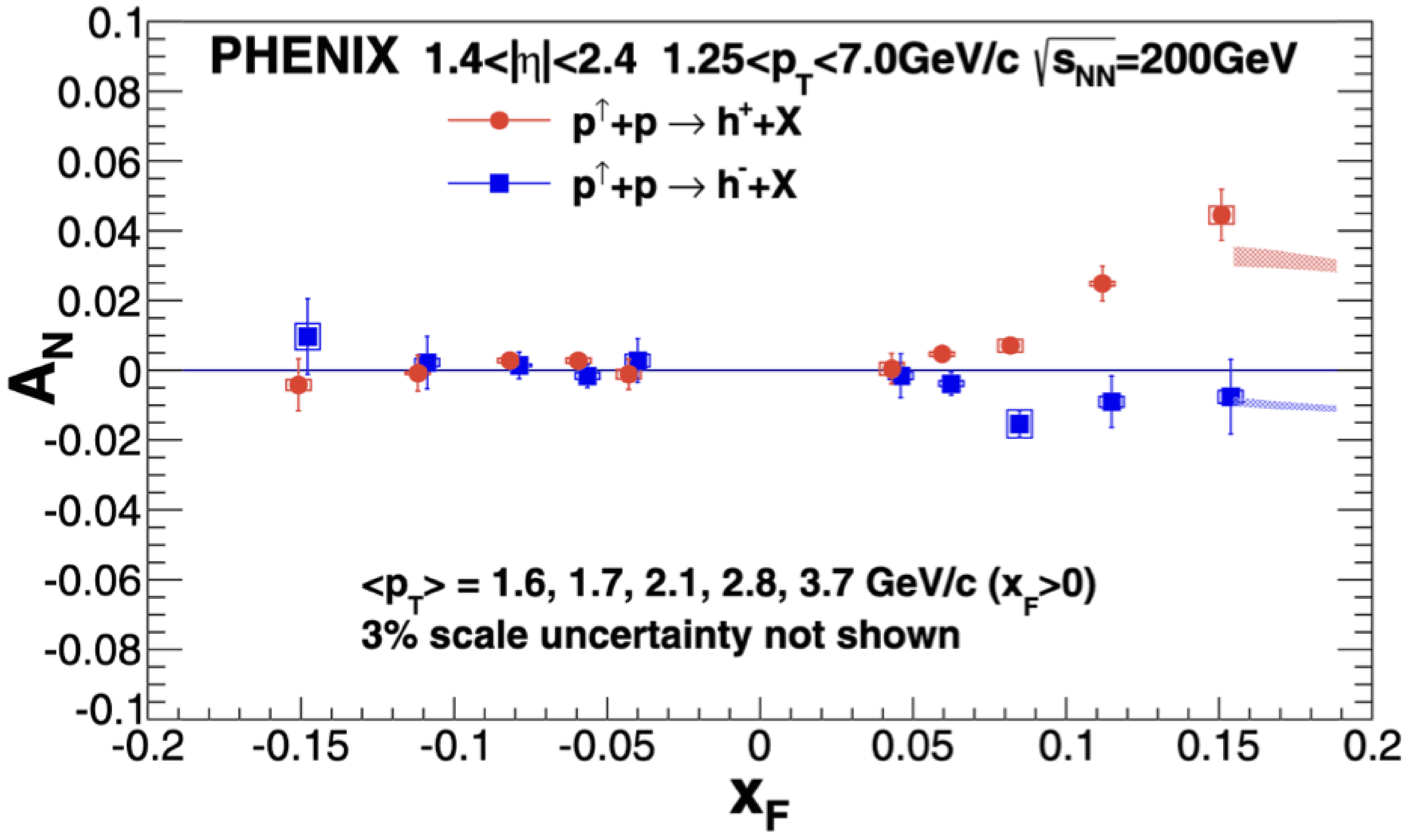
JAM Collaboration, PRD105 074022 (2022)

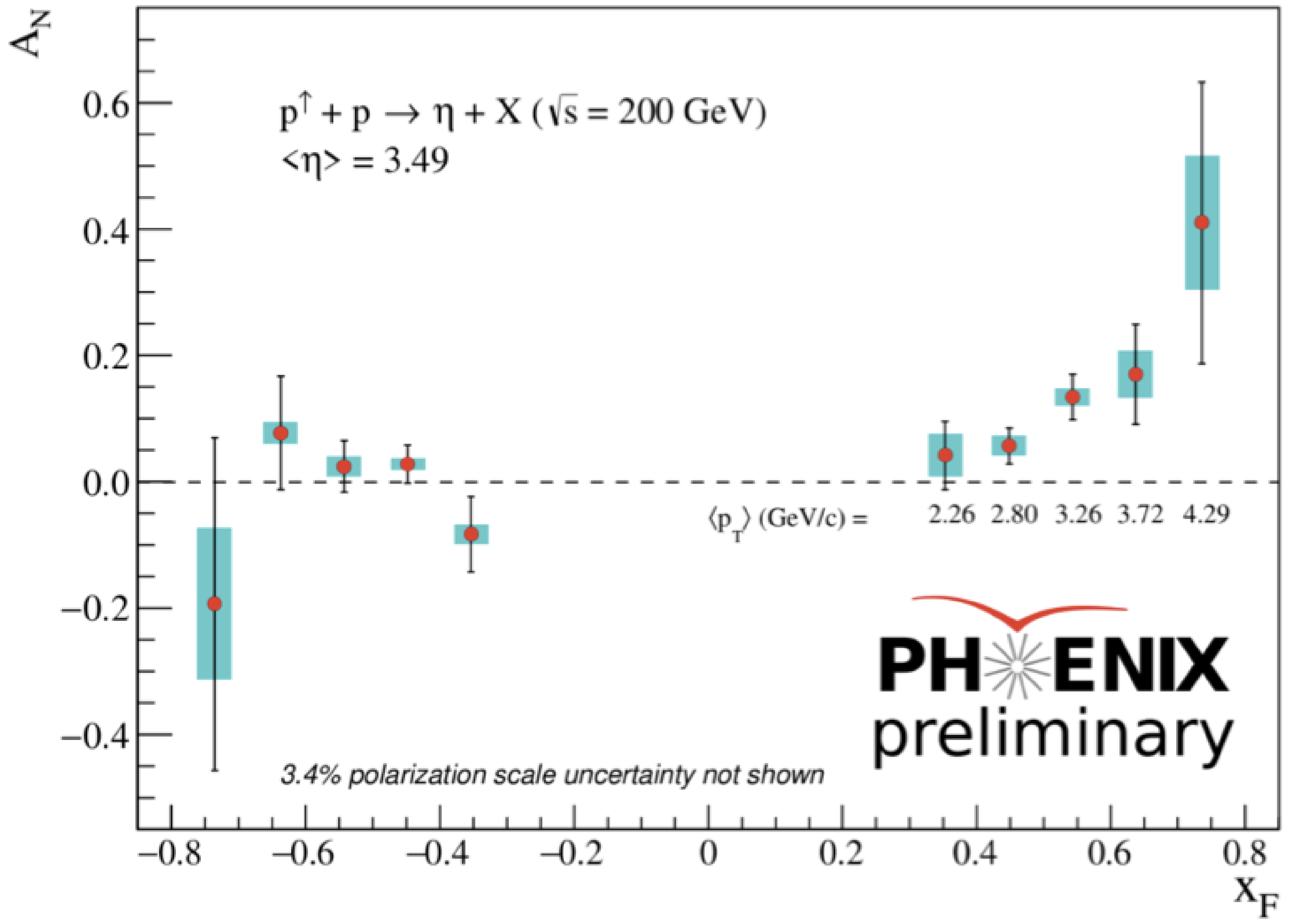
JAM Collaboration, PRD106 L031502 (2022)

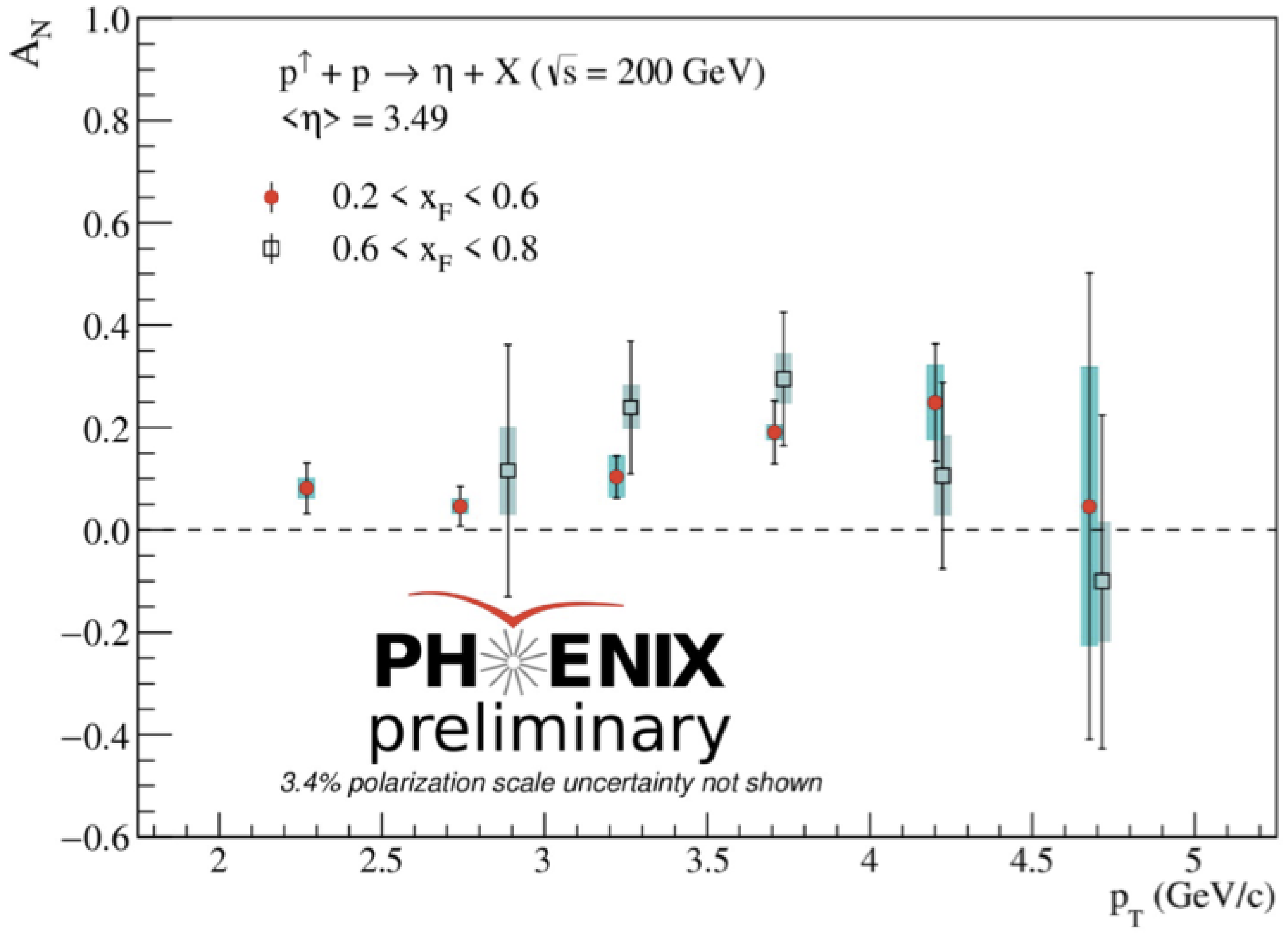
PHENIX results indicate $\Delta_g > 0$ at 2.8σ level

A_N of hadrons

PHENIX: PRD 108, 072016 (2023)







h^+: large positive asymmetries

h^- : mix of negative π and positive K asymmetries

η: large asymmetries at high x_F

SUMMARY

Possible Answers in Large Systems:

High-p_T direct photons flow is zero and yields follows N_{coll} scaled p+p, whereas at high $p_T - \pi^0$ flows and its yields are suppressed – partonic energy loss?

Open Heavy flavor flow and suppression shows mass ordering – energy loss?

Suppression of hard jet particles and enhancement of soft jet particles – energy loss?

Light flavored hadrons – coalescence is a main mechanics for flow transition from partonic level and for baryon and strangeness enhancement at hadron level?

Charmonium – not enough energy for heavy flavor recombination to become noticeable at forward rapidity?

SUMMARY

PHENIX Stony Brook University

Challenges and Questions in Large Systems:

Low-p_T photon "puzzle" remains unsolved

Universal scaling behavior of direct γ yields needs further investigations

Does $\varepsilon_2 N_{part}^{1/3}$ scaling work even for high-p_T π^0 v_2 and if so – why?

Is chiral symmetry restored in Au+Au?

Does charm regeneration occurs in Au+Au at mid-rapidity?

SUMMARY

Small Systems:

Do we see same patterns in heavy ion?
Is effect in small system "smaller"?
When do CNM effects end and QGP begin?

Excited Charmonium is suppressed in *p*+Au

High-p_T π^0 yields are suppressed in central *d*+Au (Modify Glauber?)

Light hadron flow follows nuclear overlap geometry in $p/d/^3$He+Au

Baryon to meson yields are enhanced $p/d/^3$He+Au

Modification of J/ψ consistent with initial state effects and strangeness is not enhanced

SUMMARY

p+p:

PHENIX results indicate $\Delta_g > 0$ at 2.8σ level

Large hadron A_N

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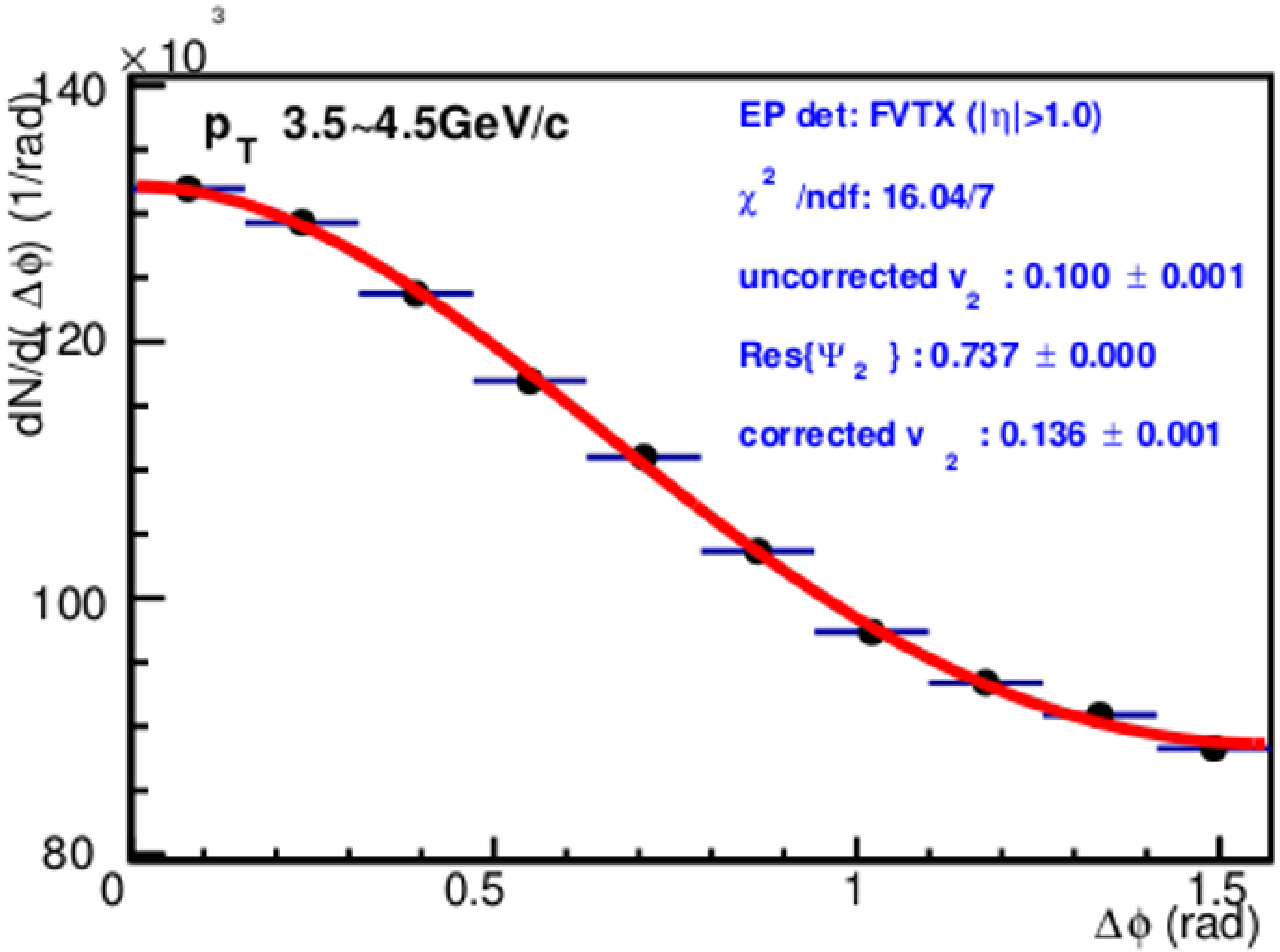
Thank you for attention!

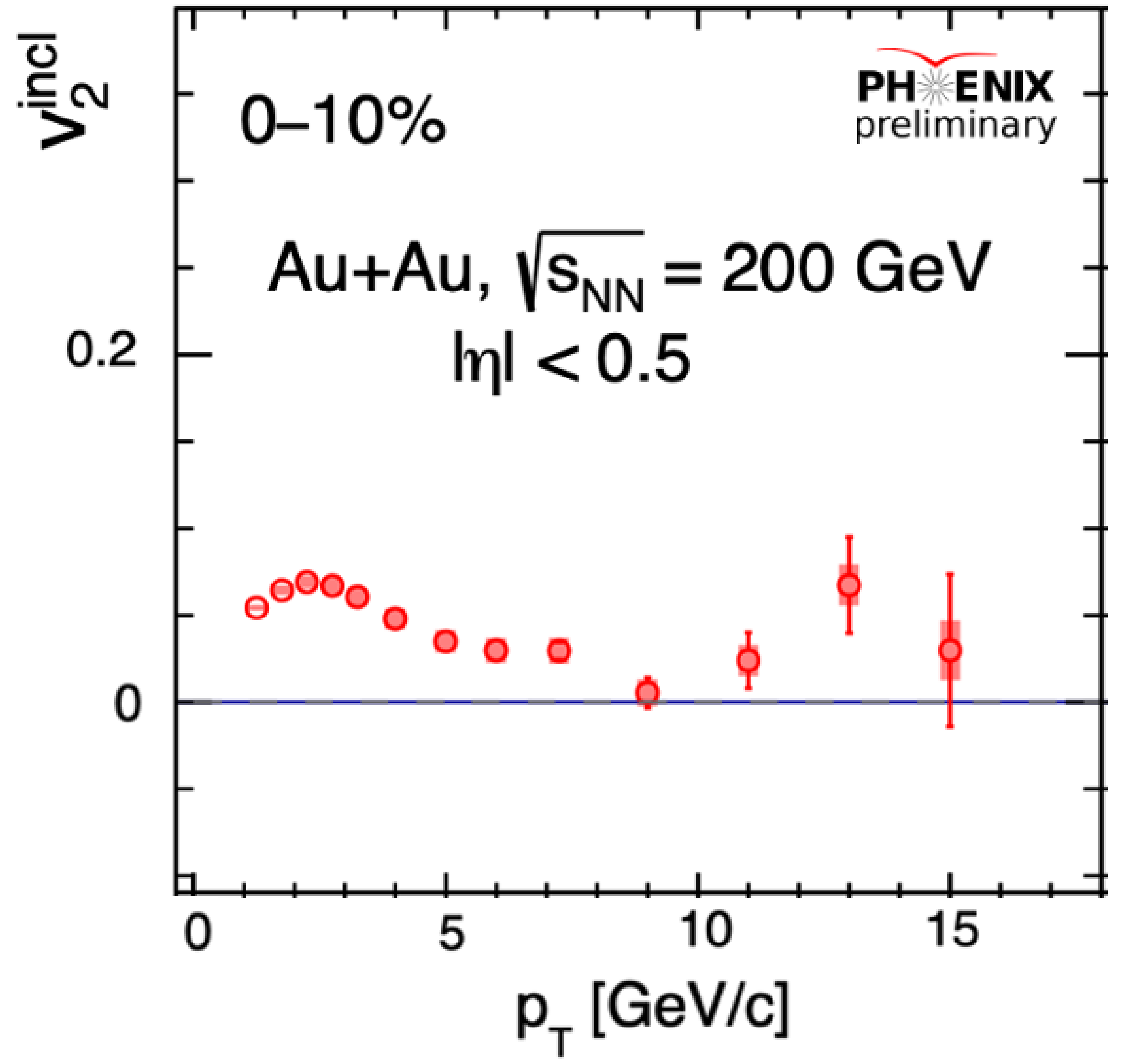
BACK UP

Photon Flow Extraction

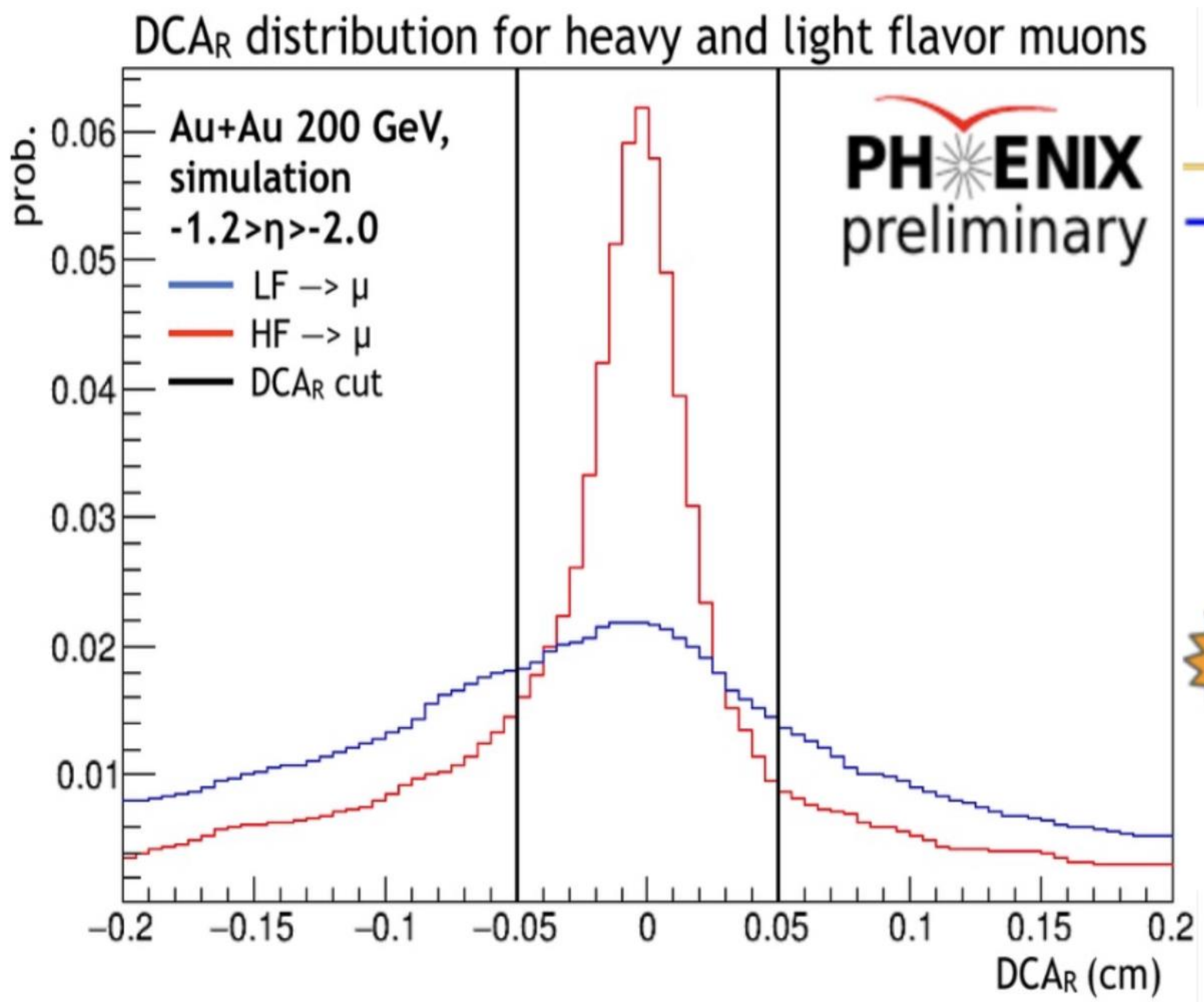
$$\frac{dN}{d(\Delta\phi)} = A(1 + 2v_2cos(2\Delta\phi) + 2v_4cos(4\Delta\phi))$$

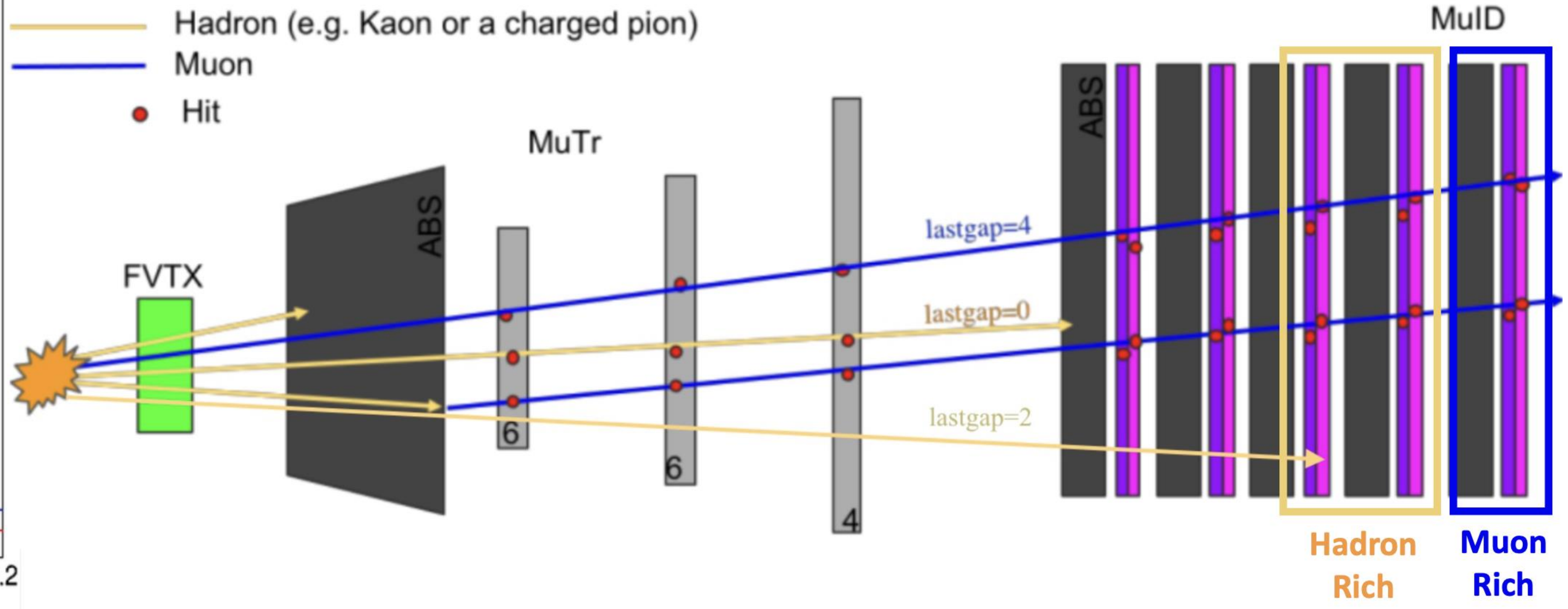
$$v_2^{dir} = \frac{R_\gamma v_2^{incl} - v_2^{dec}}{R_\gamma - 1}$$



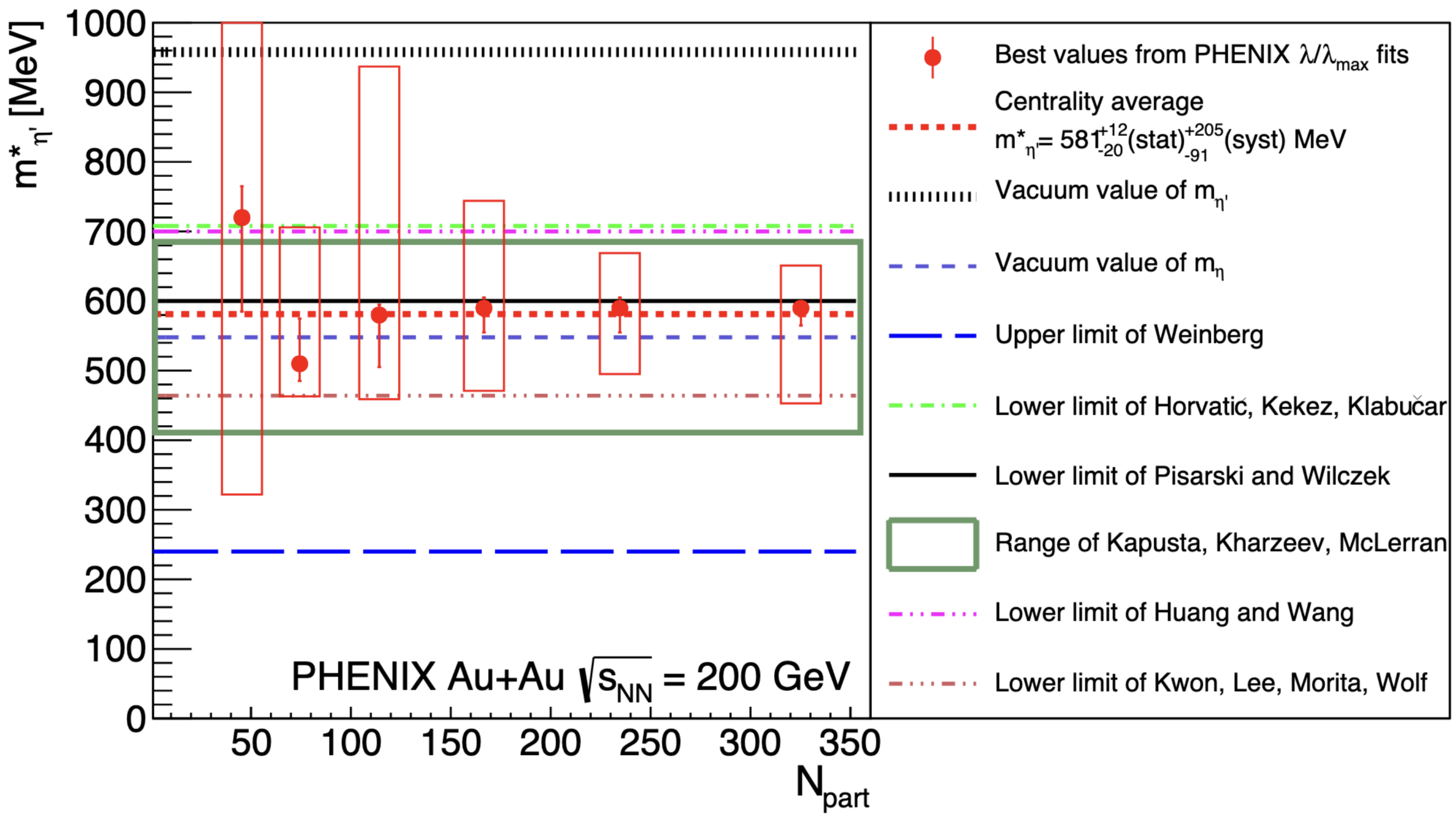


Single Muon Analysis

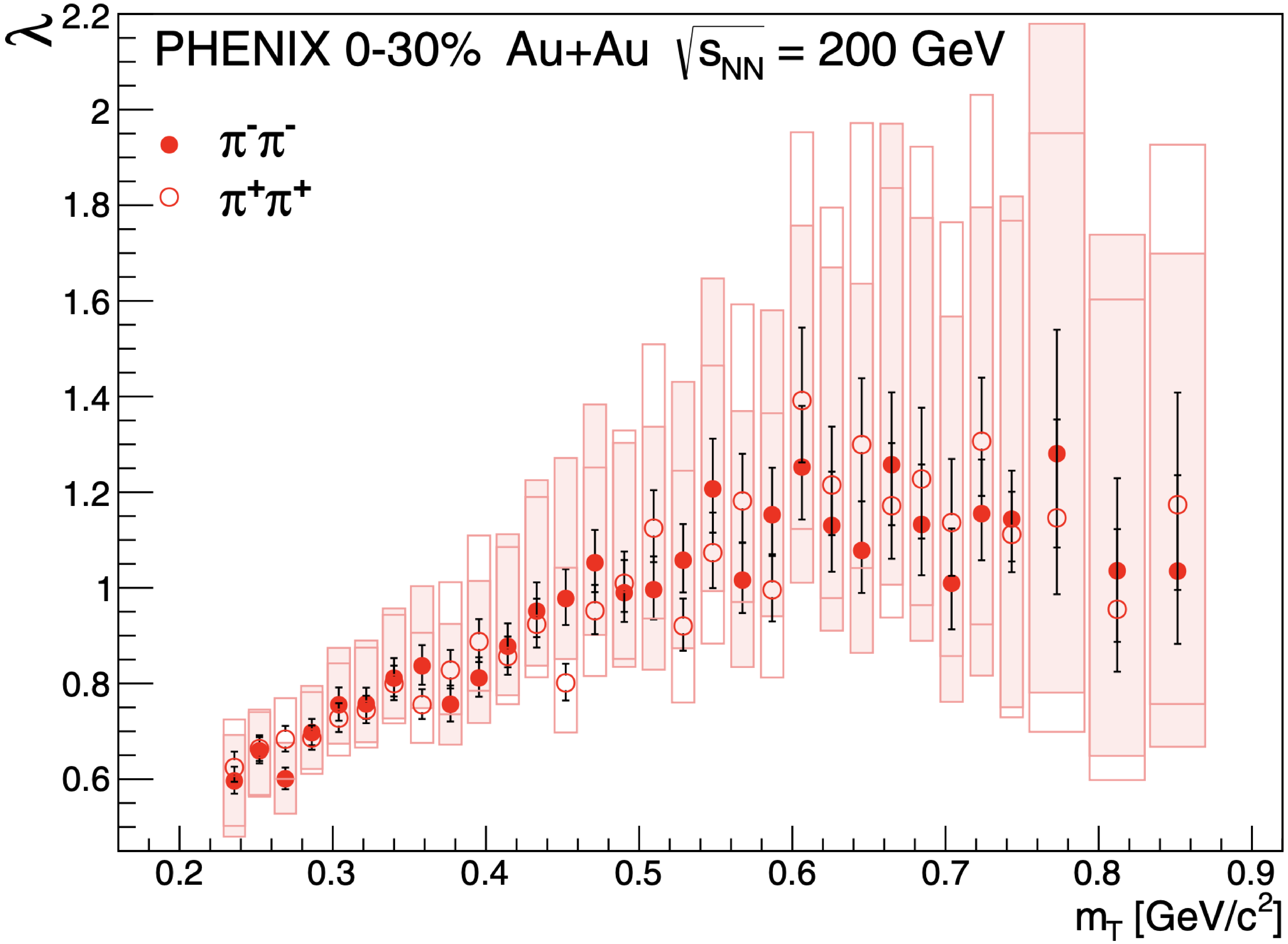




- Track quality cuts to purify muons from heavy flavor
- Extract v_2 for hadrons and inclusive muons
- Tuned MC simulating precise particle ratios to separate muons from light and heavy flavor decays

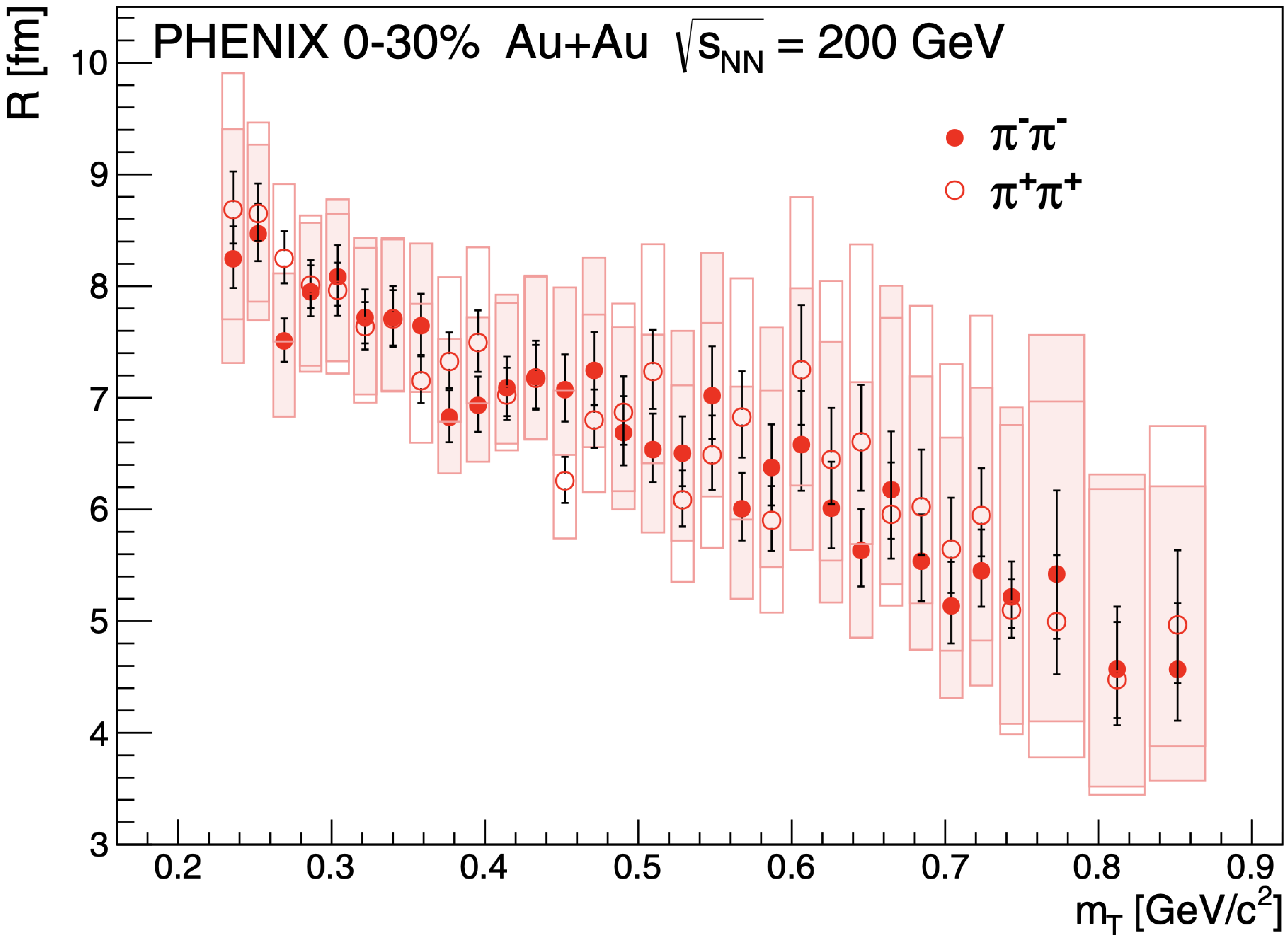


- The optimal values of and $m^*_{\eta'}$ as function of N_{part}



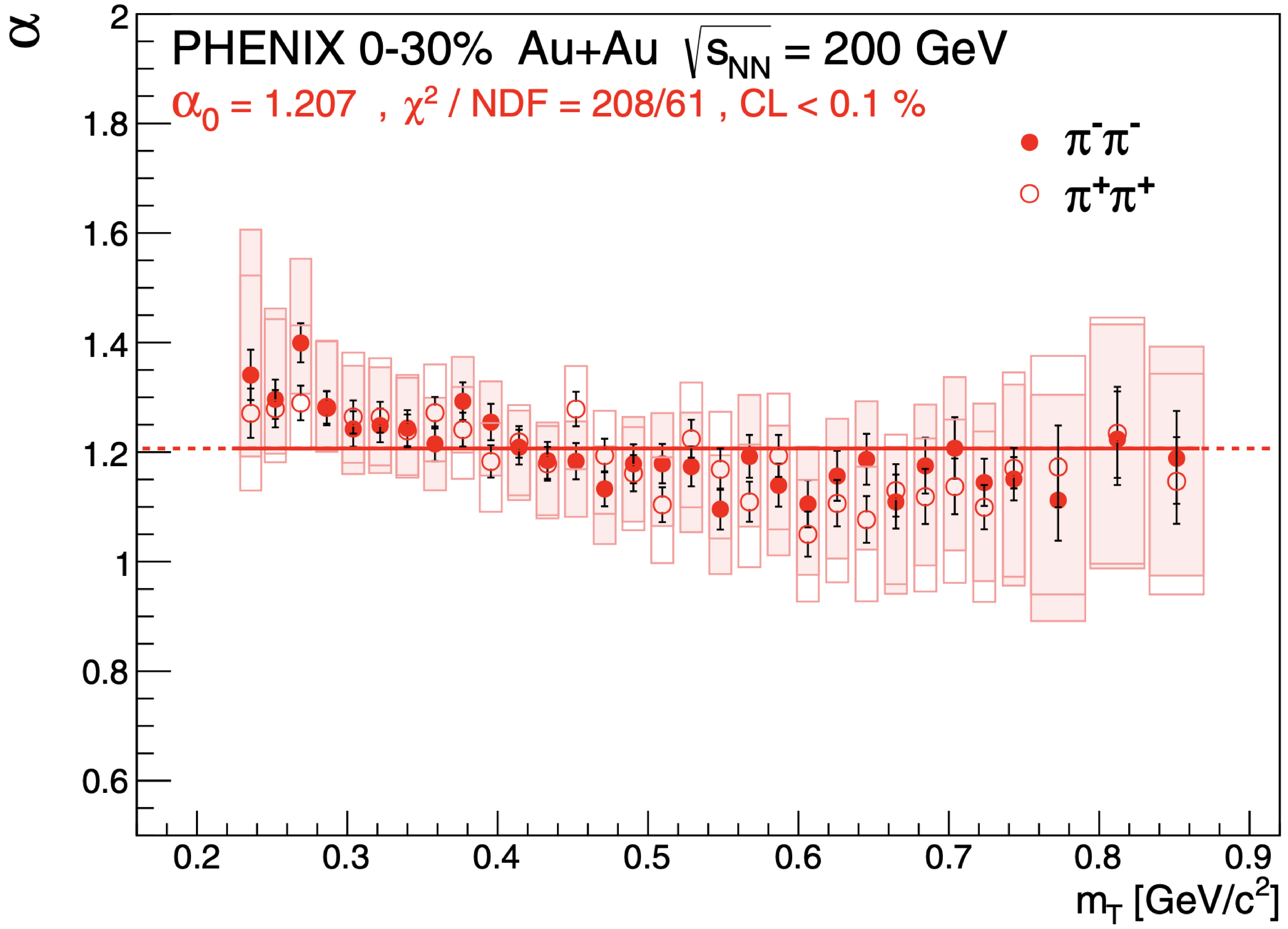
λ – correlation-strength parameter

- Correlation strength parameter λ vs average m_T of the pair, for 0–30% centrality collisions
- The intercept parameter λ seems to saturate at high m_T
- A decrease of $\lambda(m_T)$ is clearly visible at low values of the average transverse mass m_T



R – Lévy scale parameter

- $\boldsymbol{R}$ vs average $\boldsymbol{m_T}$ of the pair
- A characteristic decreasing trend
- Similar to the decrease predicted by hydrodynamical calculations of a three-dimensionally expanding source for the $\boldsymbol{\alpha} = \mathbf{2}$ Gaussian case
- For $\alpha < 2$ we are not aware of any theoretical predictions for the $\boldsymbol{m_T}$ dependence of the Levy scale parameter R



α – Lévy index parameter

- $\boldsymbol{\alpha}$ vs average $\boldsymbol{m_T}$ of the pair
- The values of $\boldsymbol{\alpha(m_T)}$ are significantly below the Gaussian limit of 2
- If the $\boldsymbol{\alpha = 2}$ Gaussian approximation fails, the $\boldsymbol{\alpha = 1}$ exponential approximation is attempted
- $\boldsymbol{\alpha}$ are systematically above 1
- Although the case of $\alpha = 1$ is closer to the measured α values than the case of $\alpha = 2$