Scaling Properties of ϕ-Meson and Light Charged Hadron Production in Small and Large Systems at PHENIX

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Outline

PHENIX established a comprehensive physics program to study ϕ-meson and light charged hadron production in Small (pAl, pAu, dAu, ^{3}HeAu), and Large (CuAu, AuAu, UU) systems:

ϕ meson production in $p+\mathrm{Al}$, $p+\mathrm{Au}$, $d+\mathrm{Au}$, and $^3\mathrm{He}+\mathrm{Au}$ collisions at $\sqrt{s_{NN}}=200$ GeV

U. Acharya *et al.* (PHENIX Collaboration)
Phys. Rev. C **106**, 014908 – Published 26 July 2022

Measurement of ϕ-meson production in $\mathrm{Cu}+\mathrm{Au}$ collisions at $\sqrt{s_{NN}}=200$ GeV and $\mathrm{U}+\mathrm{U}$ collisions at $\sqrt{s_{NN}}=193$ GeV

N. J. Abdulameer *et al.* (PHENIX Collaboration)
Phys. Rev. C **107**, 014907 – Published 13 January 2023

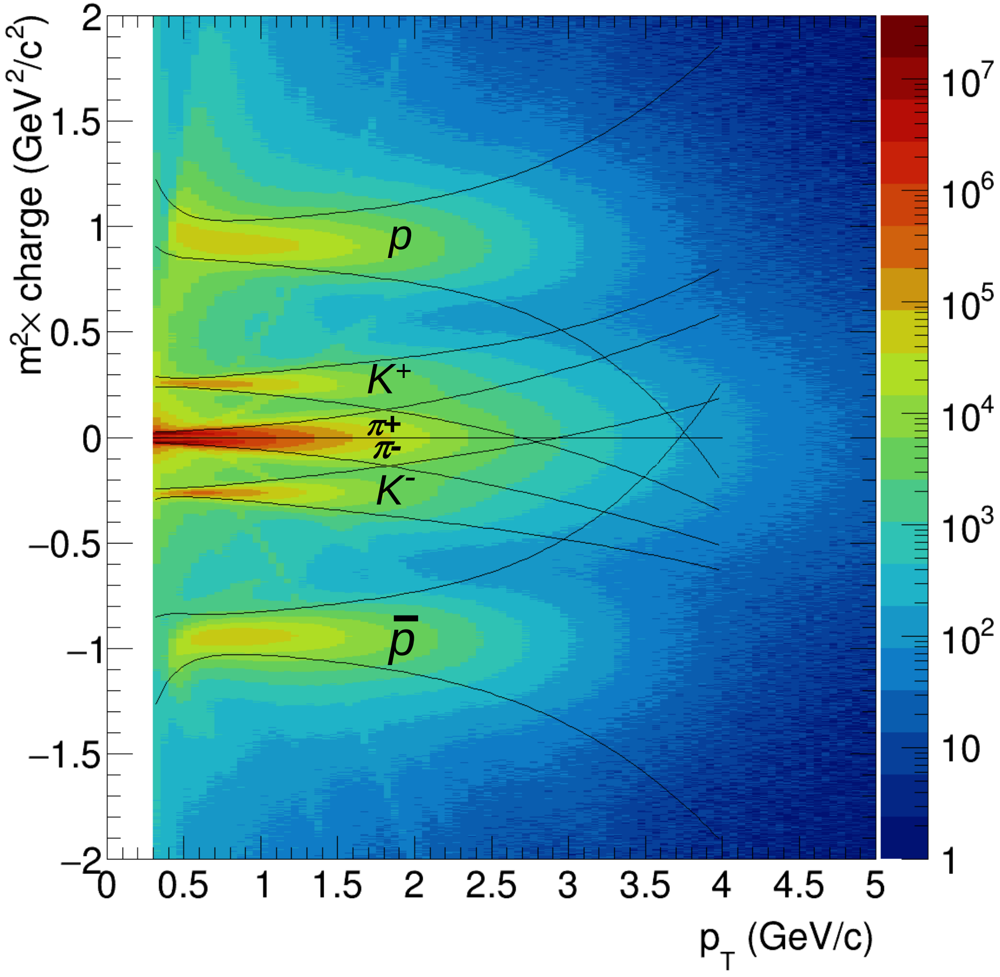
Identified charged-hadron production in $p+\mathrm{Al}$, $^3\mathrm{He}+\mathrm{Au}$, and $\mathrm{Cu}+\mathrm{Au}$ collisions at $\sqrt{s_{NN}}=200$ GeV and in $\mathrm{U}+\mathrm{U}$ collisions at $\sqrt{s_{NN}}=193$ GeV

N. J. Abdulameer *et al.* (PHENIX Collaboration)
Phys. Rev. C **109**, 054910 – Published 20 May 2024

1. Identified light charged hadrons production in small and large systems:
   - Freeze-out temperature, ratios, and nuclear modification factors
2. ϕ-Meson production in small and large systems:
   - nuclear modification factors, comparison to symmetric systems, and elliptic flow
3. Summary

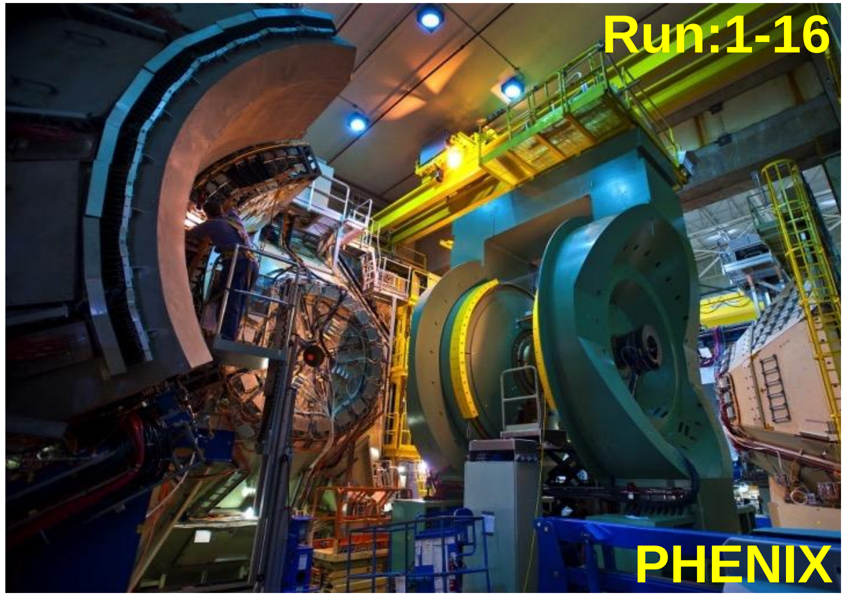
Charged Hadrons Identification in PHENIX

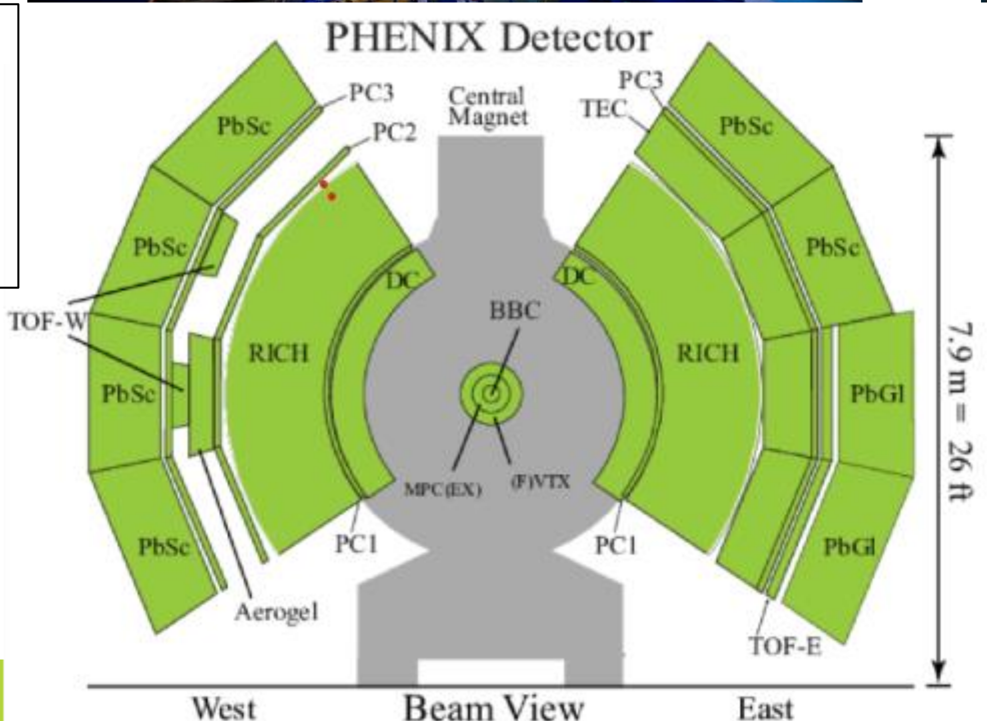
❖ Charged hadrons are detected in the TOF and the DC. The squared mass of the tracks is determined by:



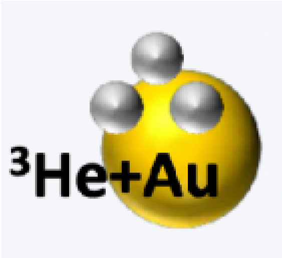
$$m^2 = \frac{p^2}{c^2}\left(\frac{t^2c^2}{L^2} - 1\right)$$

- *p: momentum (DC)*
- *L: particle flight path length (vertex to TOF Det.)*
- *t : time of flight measured in the TOF Det.*

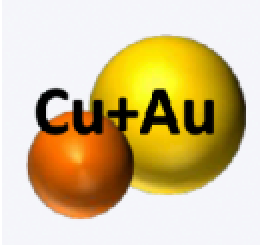


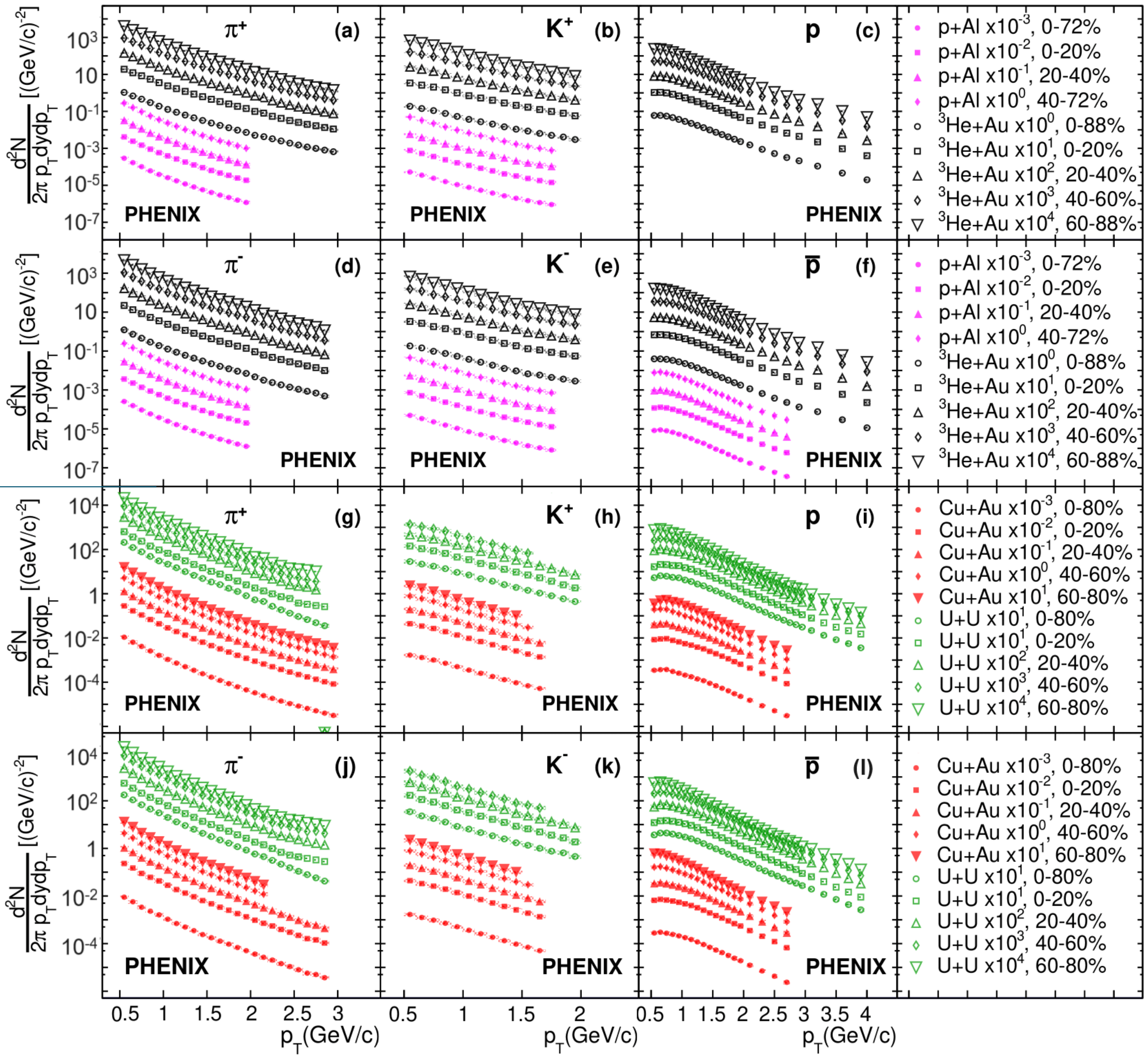


Invariant Transverse Momentum Spectra vs Centrality Classes



❖ **p, *K* , and *p* invariant p_T spectra exhibit different shapes.**





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Transverse Mass Spectra

π, *K* , and *p* spectra have different shapes

and in order to quantify these differences, we look at the transverse-mass spectra.

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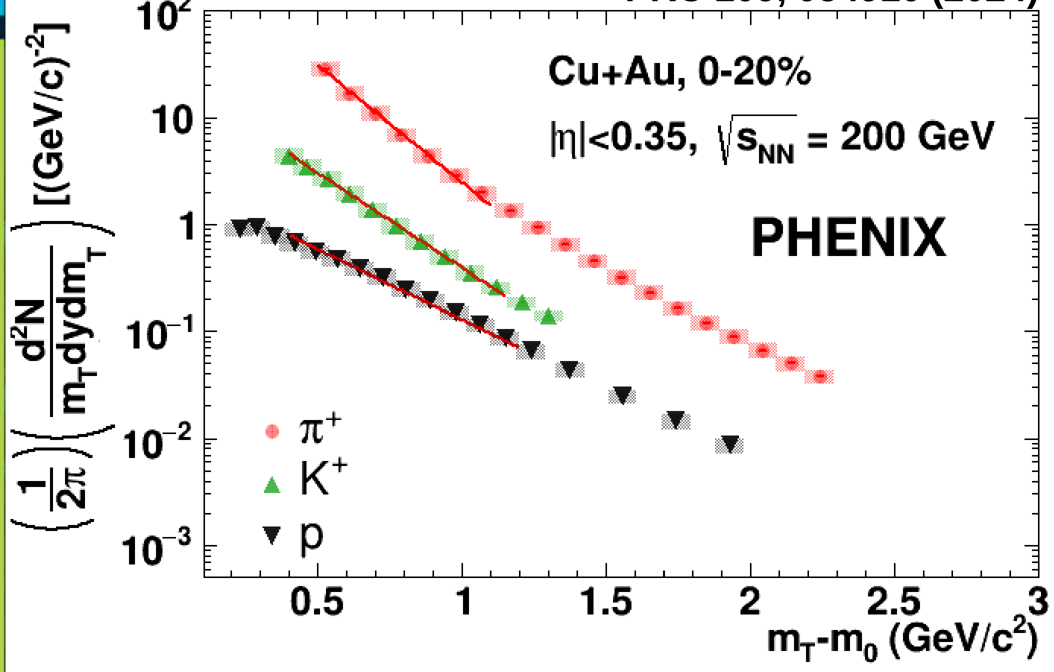

$$\frac{1}{2\pi m_T}\frac{d^2N}{dm_T dy} = \frac{A}{2\pi T(T+m_0)}\exp\left(-\frac{m_T - m_0}{T}\right)$$

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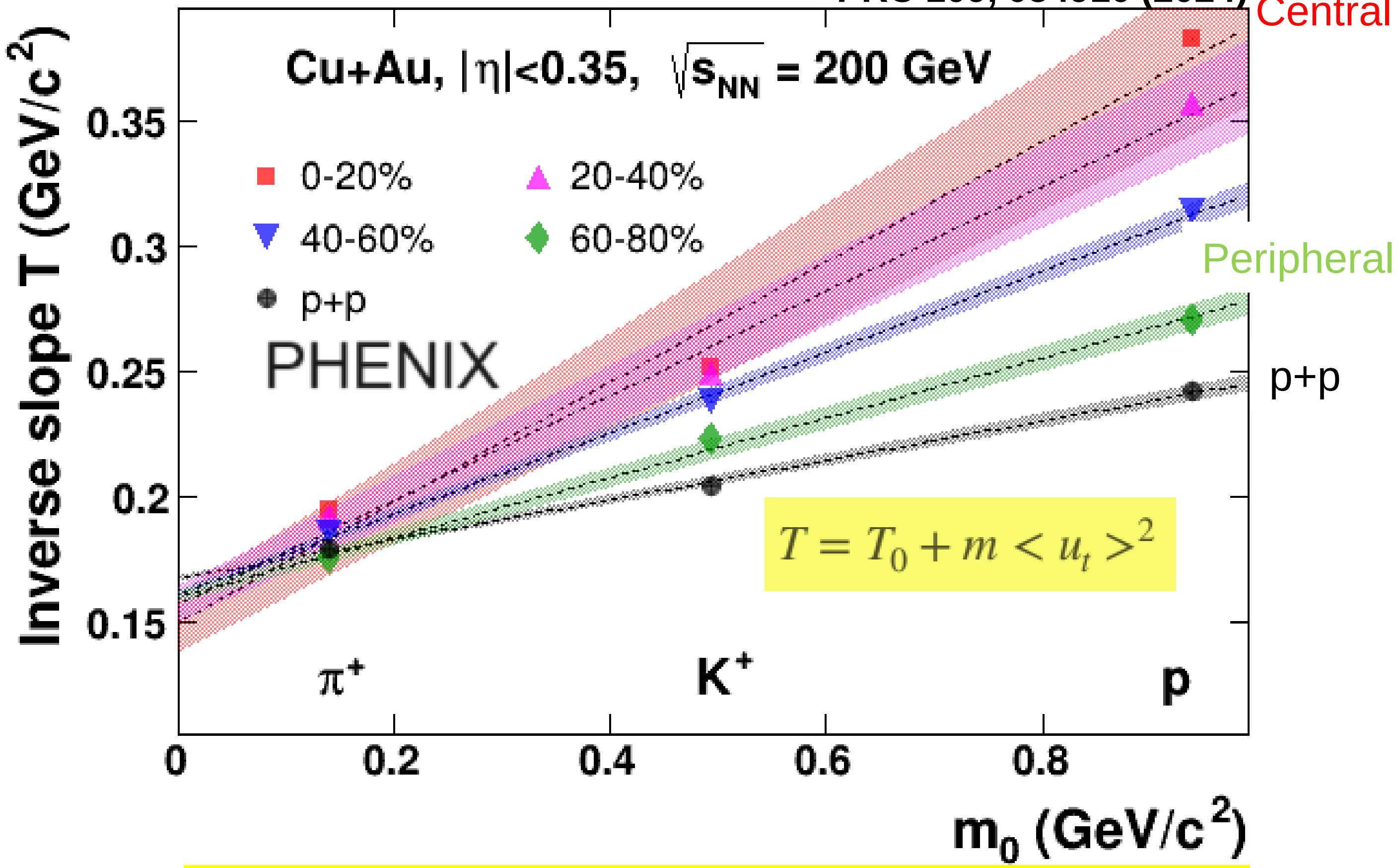

$$T = T_0 + m < u_t >^2$$

The inverse slope parameter exhibits a dependence on the hadron mass!

Freeze-out Temperature and Average Collective Velocity of all Particle Species

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Can be interpreted as the freeze-out temperature

$$T = T_0 + m < u_t >^2$$

Average collective velocity for all particle species

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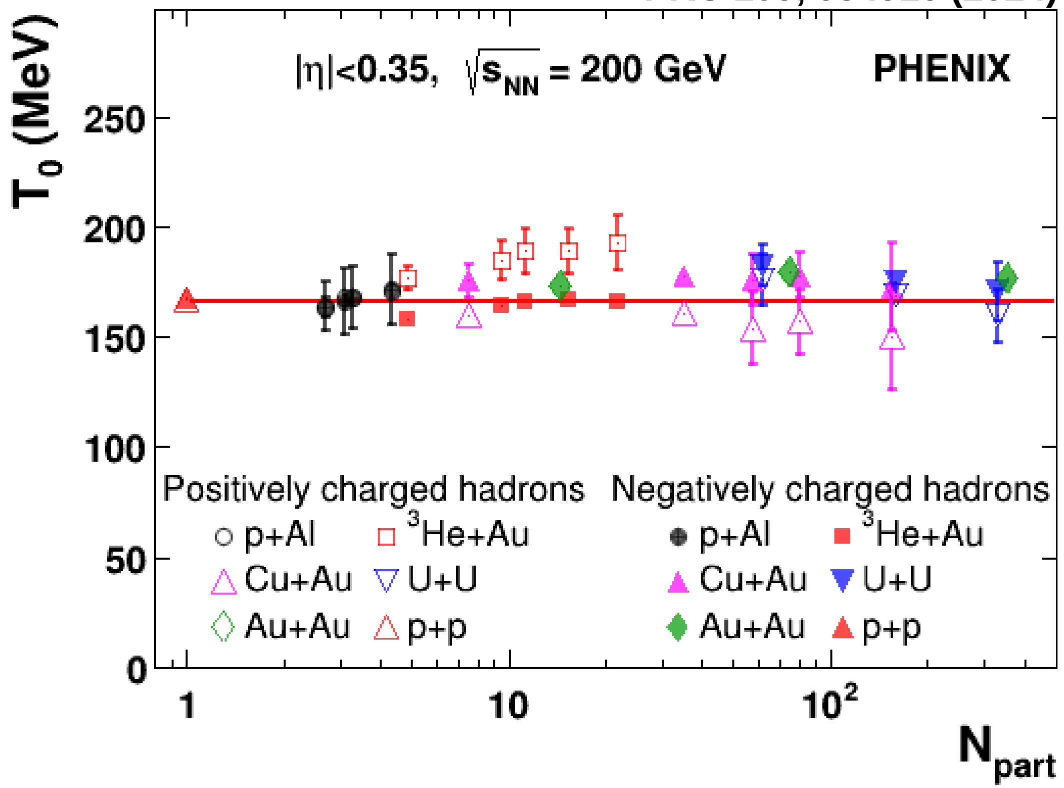

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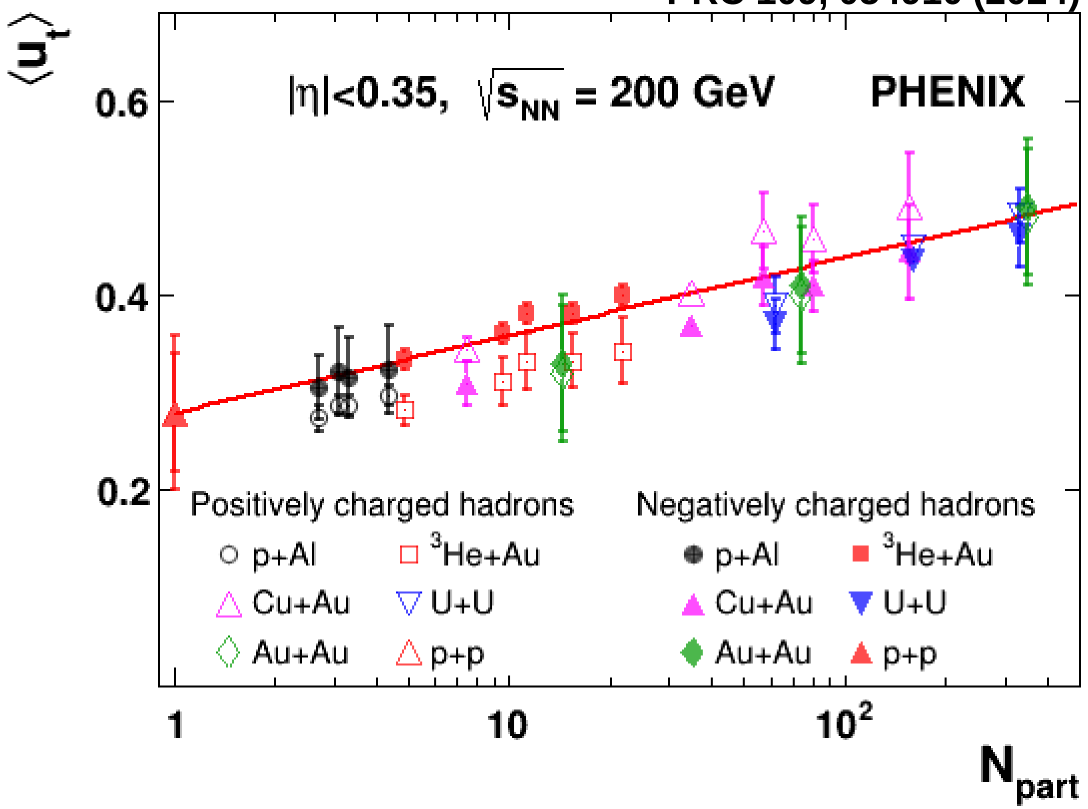
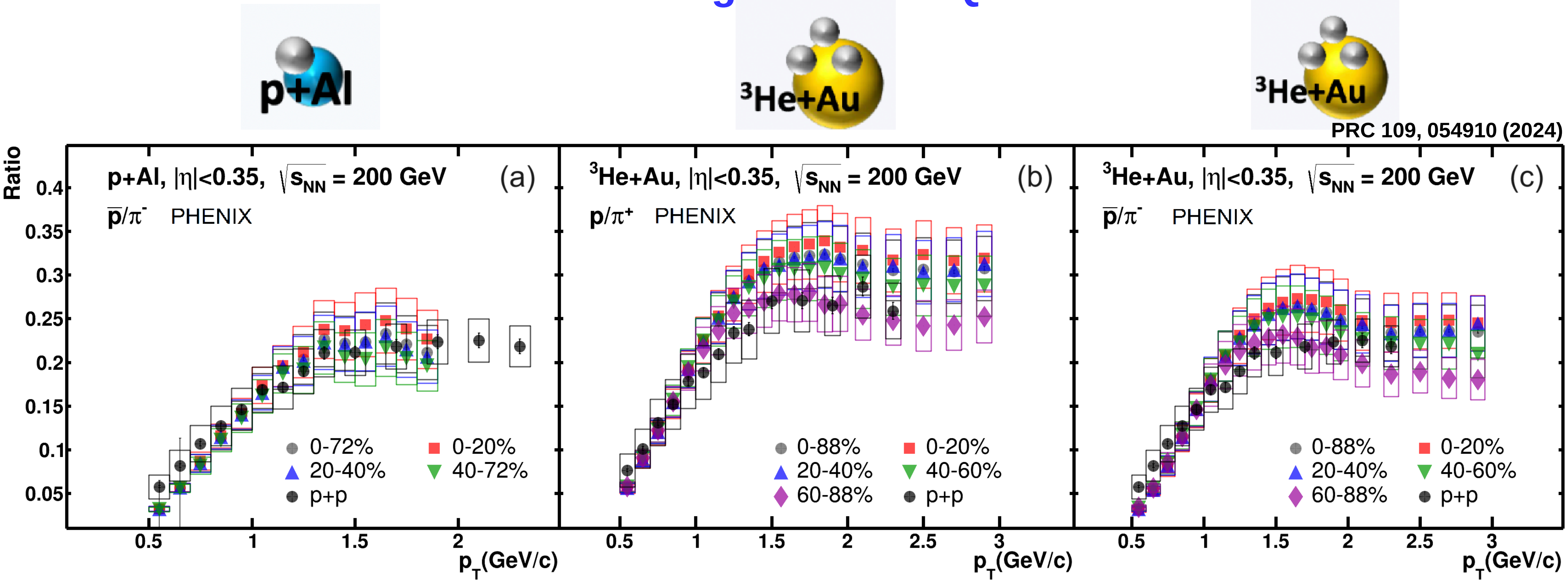


The freeze-out temperature is approximately independent of centralities and collision system size within uncertainties!

Collective effects are more pronounced in collisions characterized by large N_{part}

p/π - Ratio in Small Collision Systems

Enhancement of baryon production in nucleus-nucleus collisions is considered to be one of the signatures of QGP formation



- **In small collision systems (p+Al, ^{3}He+Au), the values of p/π ratios in all centrality classes are similar to those measured in p+p collisions within uncertainties.**

p/π - Ratio in Large Collision Systems

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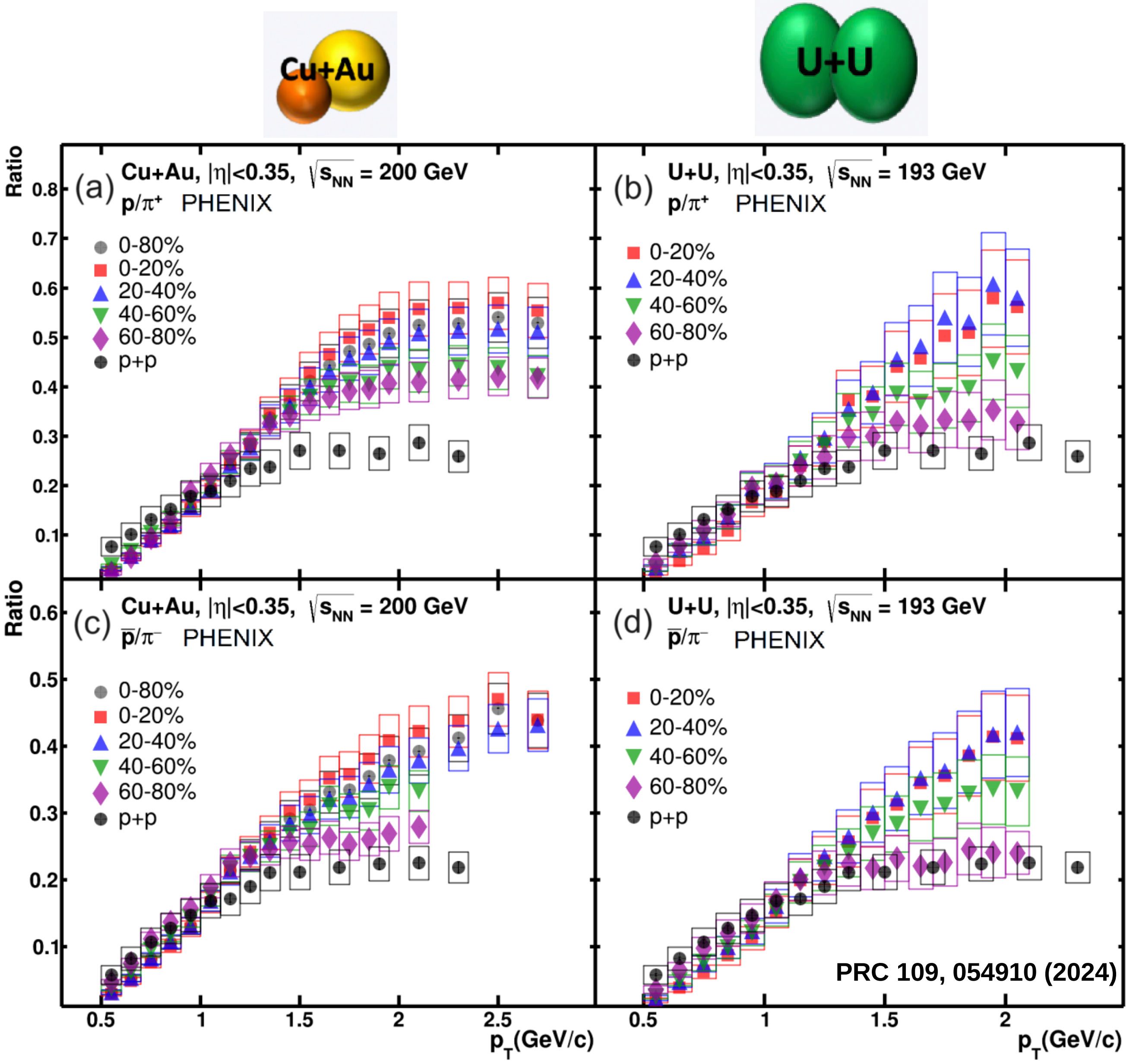
Enhancement of baryon production in nucleus-nucleus collisions is considered to be one of the signatures of QGP formation

- In collision systems with large $\langle N_{part} \rangle$ values p/π ratios reach the values of ≈ 0.6, which is ≈2 times larger than (p/π) p+p.



Nuclear Modification Factor in Small Collision Systems

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Comparisons of identified charged-hadron R_{AB} values as a function of p_T in central and peripheral

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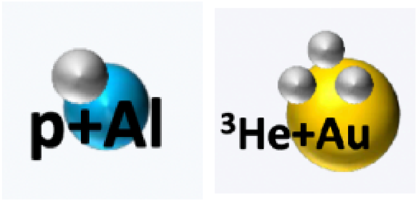
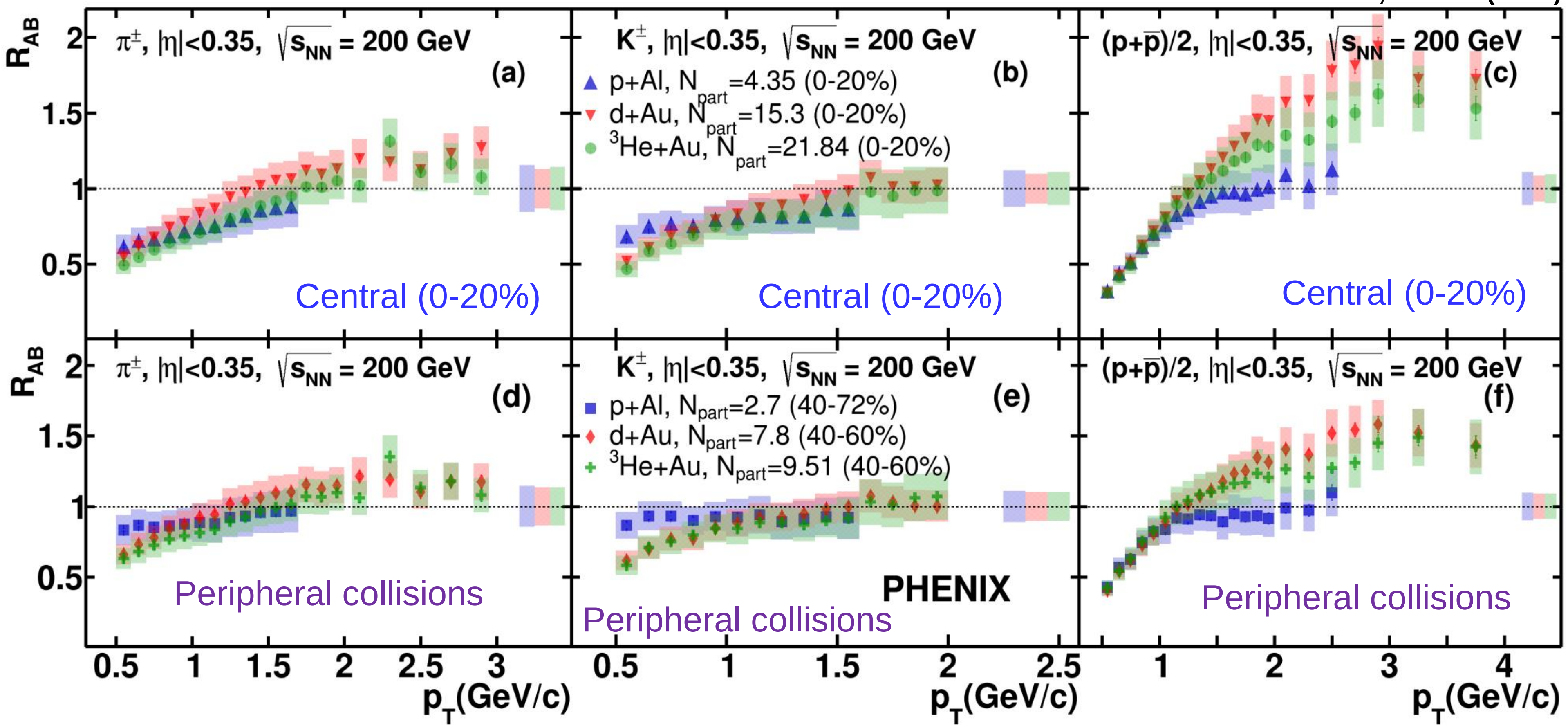
Small systems



$R_{AB}(\pi, K) \sim 1$



- Proton R_{AB} values in p+Al collisions at the intermediate p_T range (1.0 GeV/c < pT < 2.5 GeV/c) are equal to unity, while in d/^{3}He+Au collisions proton R_{AB} is above unity → this difference btw p+Al and d/^{3}He+Au might be caused by the size of the p+Al system being insufficient to observe an increase in proton production.

Nuclear Modification Factor in Large Collision Systems

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Comparisons of identified charged-hadron R_{AB} values as a function of p_T in central and peripheral

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Large systems

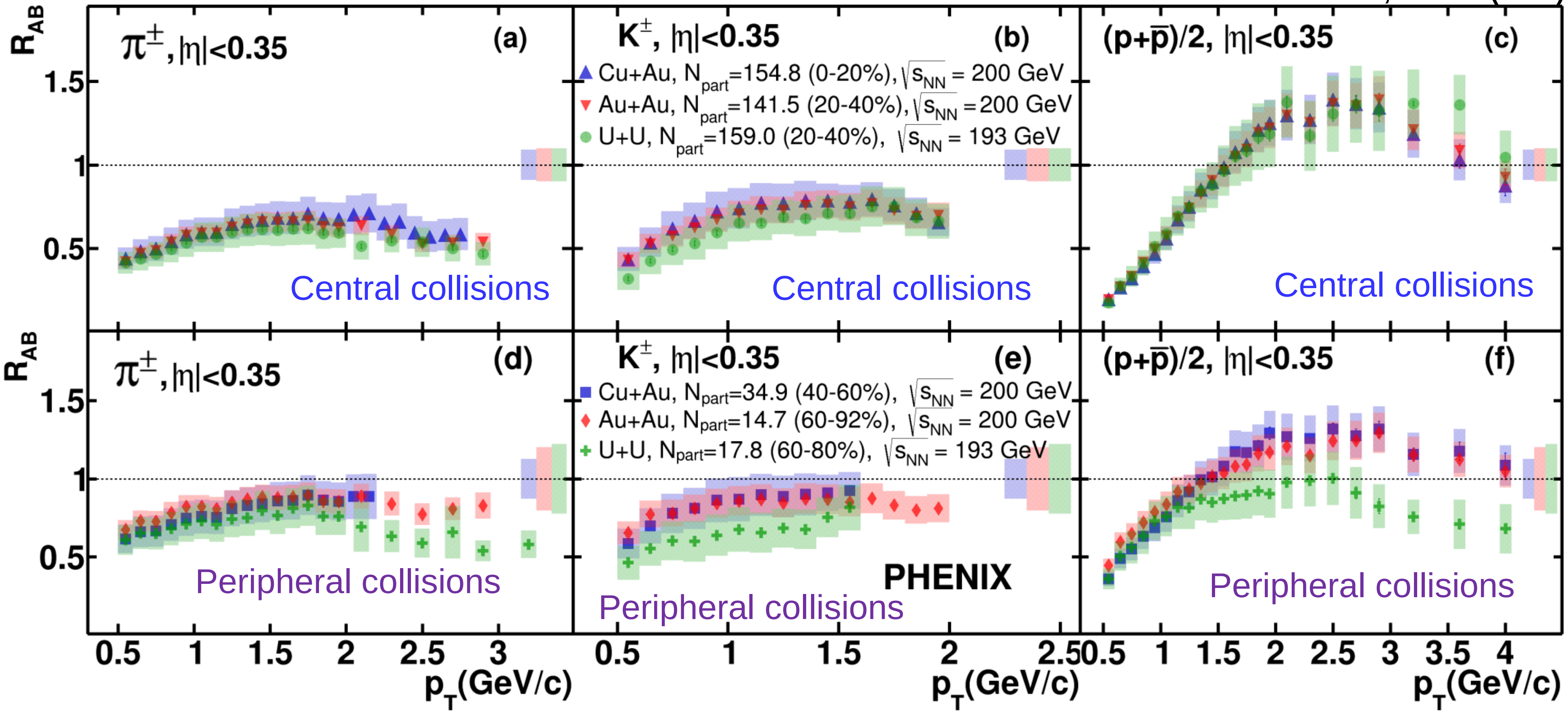
Cu+Au,

Au+Au,

U+U

Central Collisions

$R_{AB}(\pi, K) < 1$



- The R_{AB} values are found to be in agreement in collisions with different geometries, but with the same $< N_{part}>$ values, indicating that identified charged-hadron production depends only on system size and not geometry.

ϕ-Meson Production in Small and Large Collision Systems

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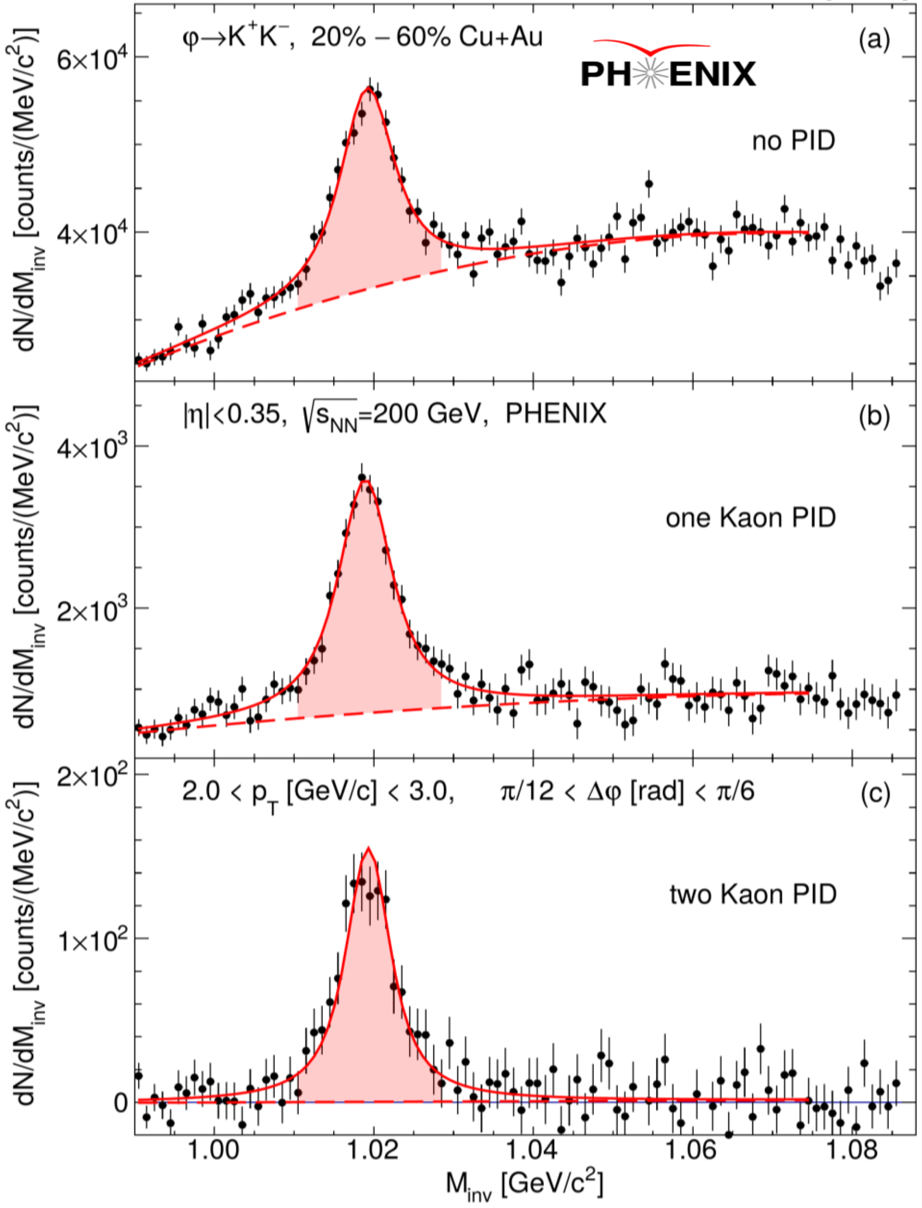
- In large systems (CuAu, Au+Au, and U+U):
  ϕ-meson production is an excellent probe for studying QGP - sensitive to several aspects of the collision, including modifications of strangeness production in bulk matter.

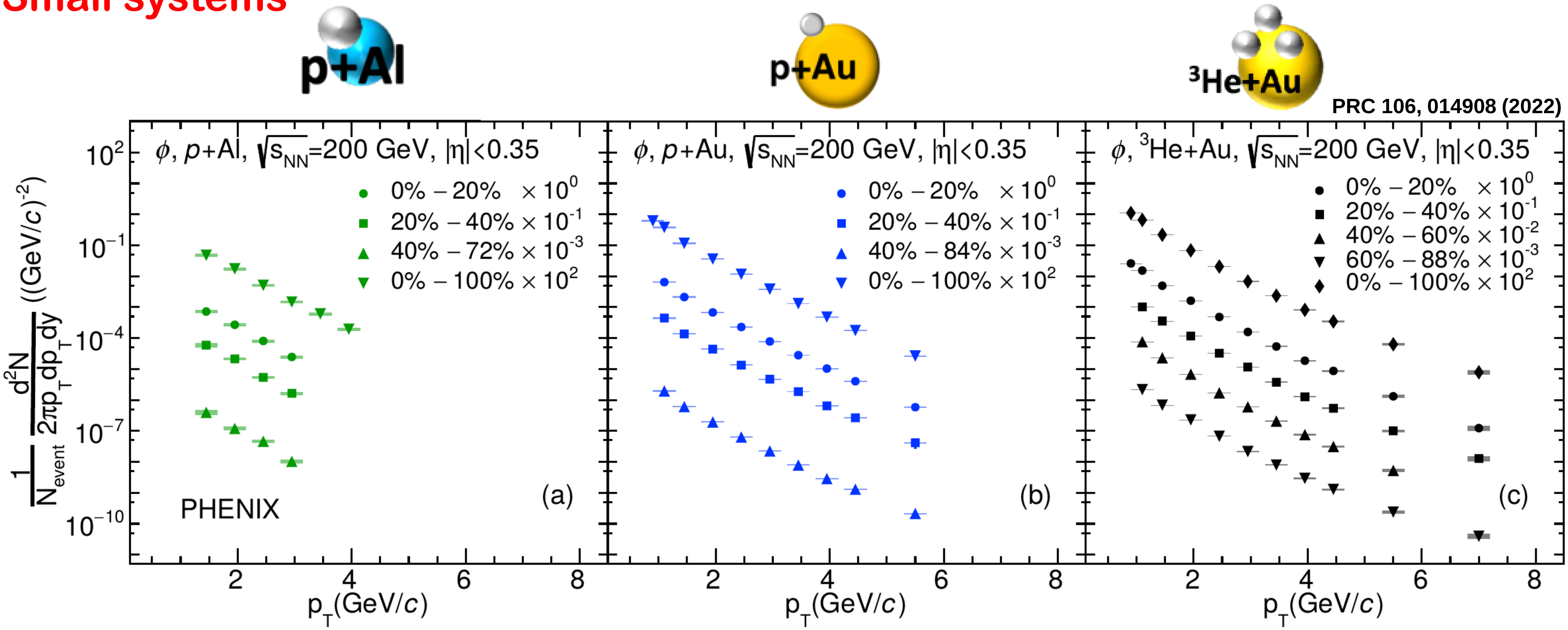
- In small systems (p+Al, p+Au, d+Au, ^{3}He+Au):
  ϕ-meson production is a good probe to study cold nuclear matter effects in order to disentangle hot nuclear (QGP related) and cold nuclear matter (modification of the production cross section in a nuclear target) effects exiting in A+B collisions.

- $\phi \rightarrow K^+K^-$ with a branching ratio of 48.9 0.5 %



ϕ-Meson Invariant Transverse Momentum Spectra

Small systems

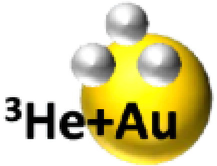


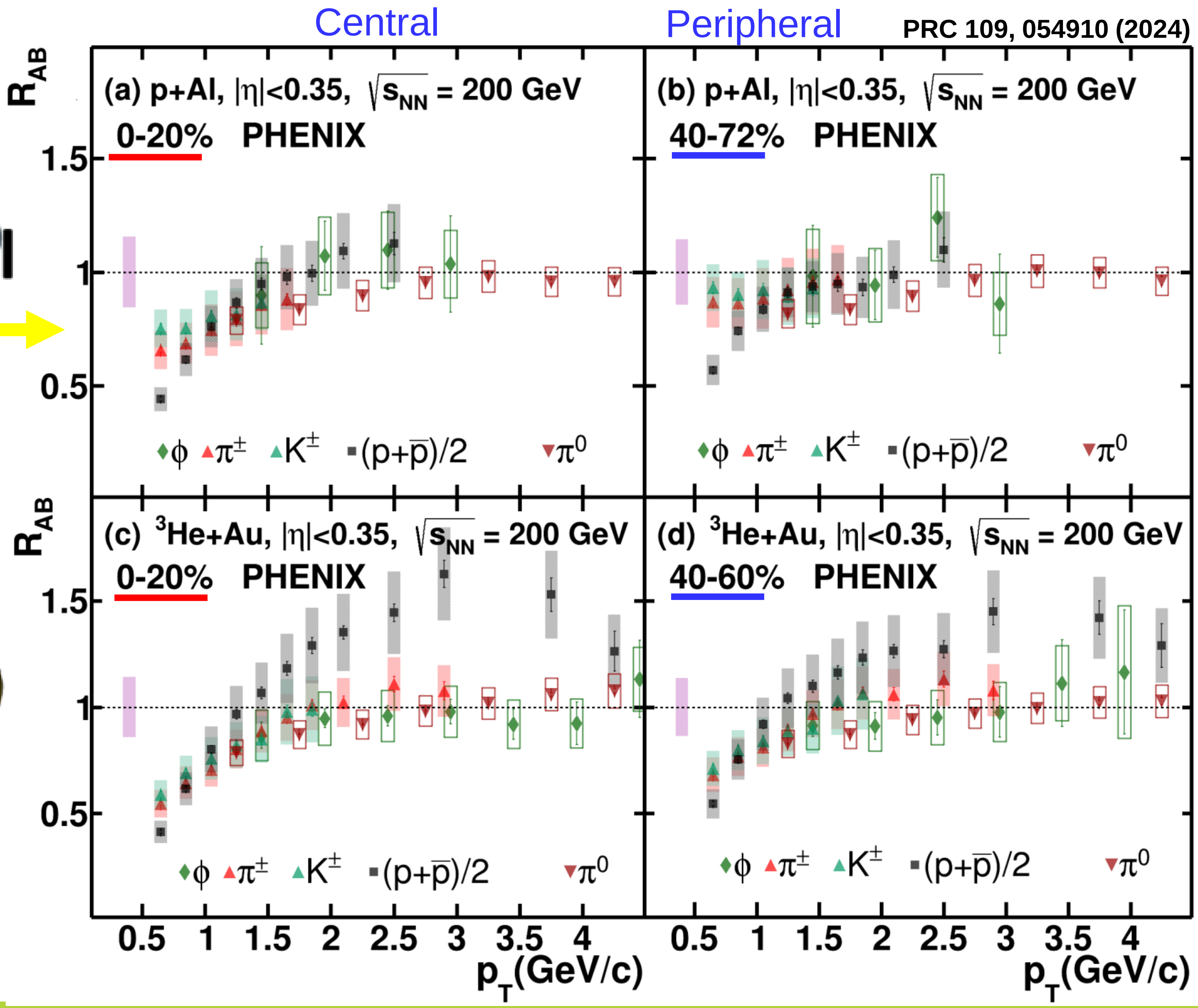
ϕ-Meson Nuclear Modification Factor in Small Systems

Small systems

p+Al collision system: R_{AB} *of protons and* all mesons are in agreement within uncertainties, which shows zero enhancement in proton to φ-meson production.

^{3}He+Au collision system:
proton R_{AB} values are enhanced over all meson R_{AB} values.





ϕ-Meson Invariant Transverse Momentum Spectra

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Large systems

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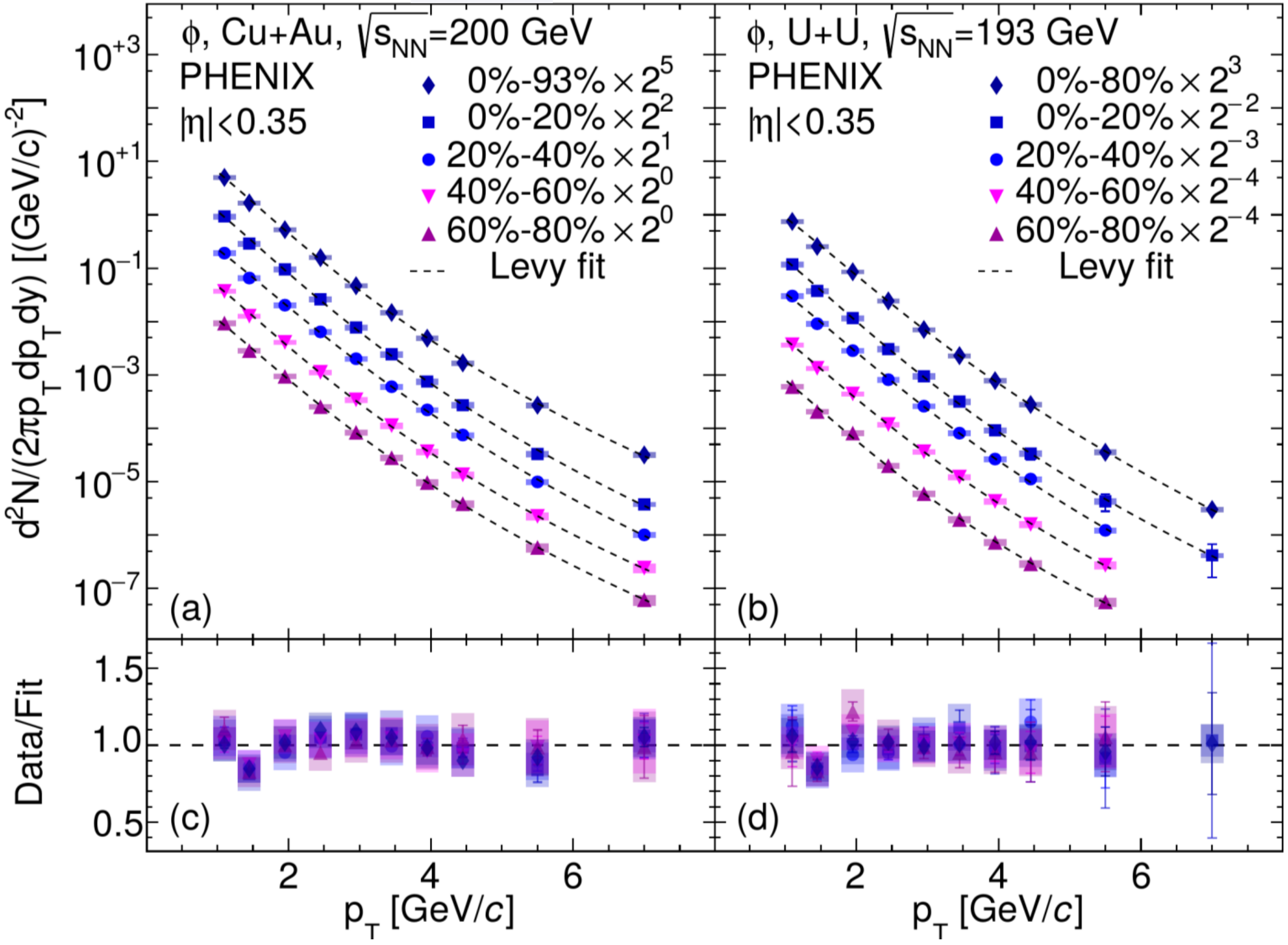


- Utilizing the $\phi \to K^+K^-$ with the Kaon identification using DC and TOF in the East Arm.
- The dashed lines represent the Levy-function fits

$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} = \frac{1}{2\pi}\frac{dN}{dy}\frac{(n-1)(n-2)}{nT(nT+m_\phi(n-2))} \times$$

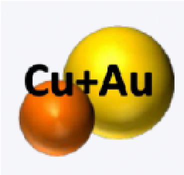
$$\times \left(1 + \frac{\sqrt{{p_T}^2 + m_\phi^2} - m_\phi}{nT}\right)^{-n}$$

ϕ-Meson Nuclear Modification Factor in Large Systems

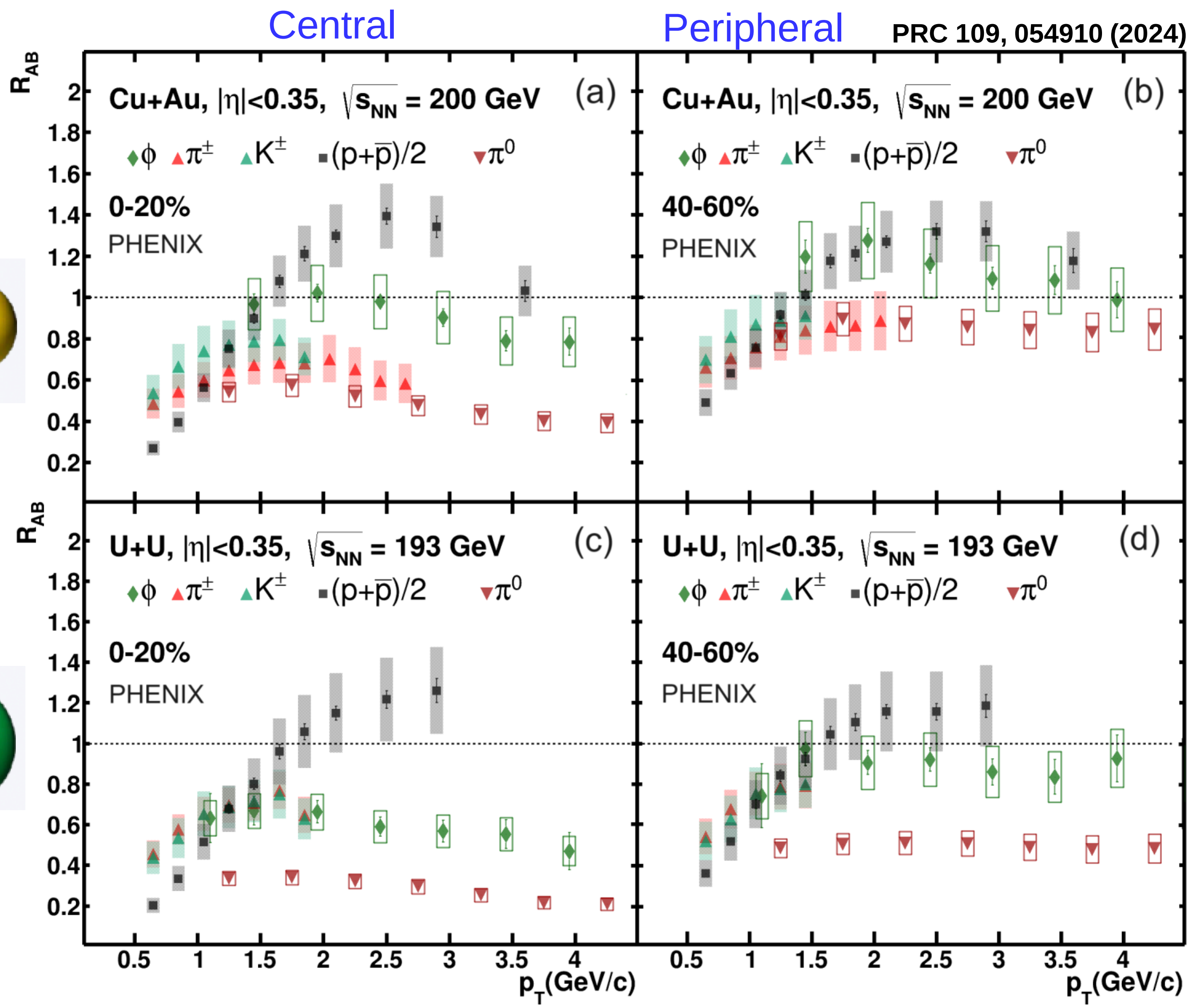
Large systems

Observations:

1) in central collisions: proton R_{AB} values are enhanced over all meson R_{AB} values. m_{ϕ} =1019 MeV/c^2 is similar to m_p=938 MeV/c^2, therefore the enhancement of proton R_{AB} values over ϕ-meson R_{AB} values suggests differences in baryon versus meson production instead of a simple mass dependence.



2) in peripheral collisions:
R_{AB} (proton) and R_{AB} (ϕ-meson) are in good agreement within uncertainties.



ϕ-Meson: Comparison with the Symmetric Systems

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- In order to better understand the features of ϕ-meson production, the integrated nuclear modification factors $\langle R_{AB} \rangle$ for ϕ-mesons as a function of $\langle N_{part} \rangle$ for different collision systems: **Cu+Au, Cu+Cu, Au+Au, and U+U collisions.**

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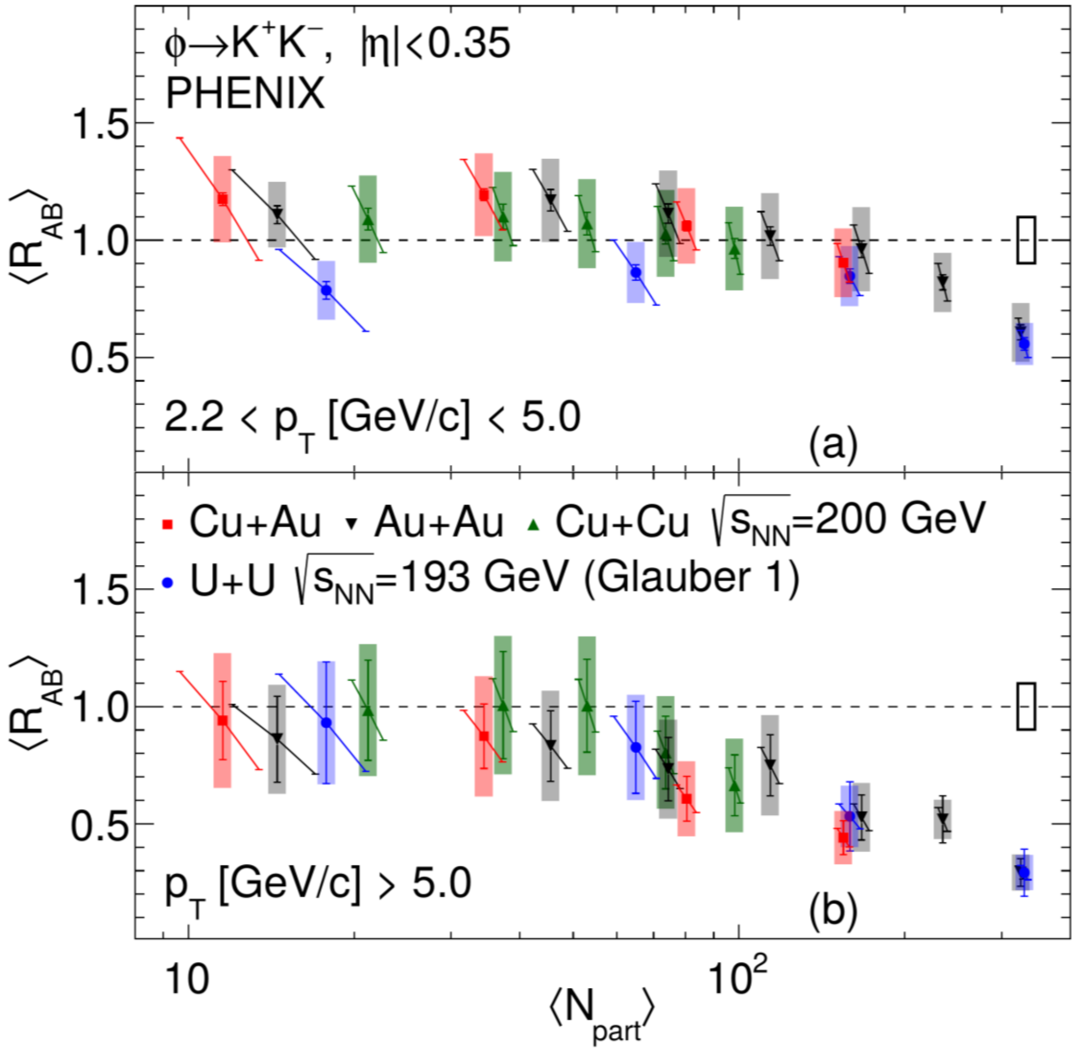
Large systems

- The $\langle R_{AB} \rangle$ values for ϕ-mesons vs. $\langle N_{part} \rangle$ obtained in the large collision systems are consistent within uncertainties

- The obtained $\langle R_{AB} \rangle$ results suggest the scaling of ϕ-meson production with the average nuclear overlap size, regardless of the collision geometry



Elliptic Flow v_2 of ϕ-Meson

Large Systems: Cu+Au, U+U, and Au+Au

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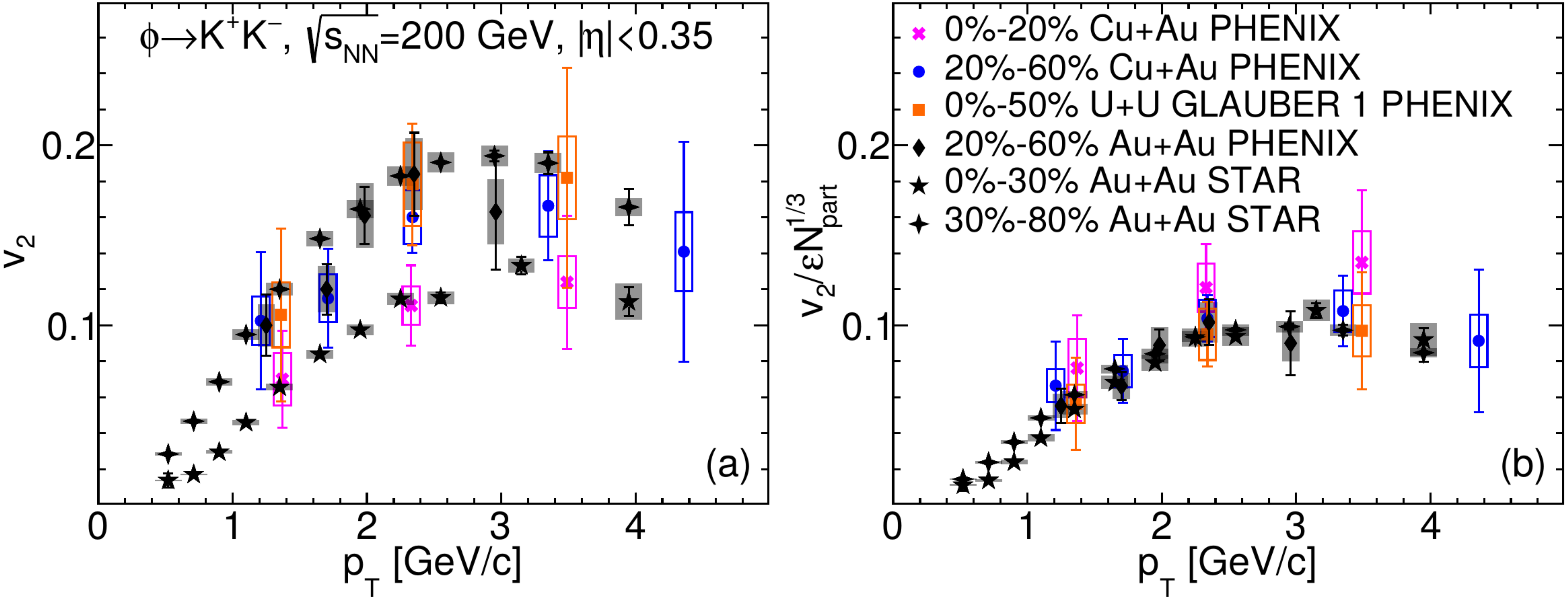

The comparison of elliptic flow for ϕ-mesons in symmetric and asymmetric collision systems suggests that the v_2 values follow common empirical scaling with $\varepsilon N_{part}^{1/3}$

Summary

Few bullets to remember from these measurements:

- The freeze-out temperature (T_0) is approximately independent of centralities and collision system size
- In small systems (p+Al, ^{3}He+Au): p/π ratios in all centrality classes are similar to those measured in p+p
- In large systems (Cu+Au, U+U), p/π ratios reach ≈ 2 times larger than (p/p) in p+p
- ϕ-meson meson production in p+Al collision system: R_{AB} of protons and all mesons are in agreement within uncertainties, which shows zero enhancement in proton to ϕ-meson production.

Thank you!

Auxiliaries Slides

K/π Ratio in Small and Large Collision Systems

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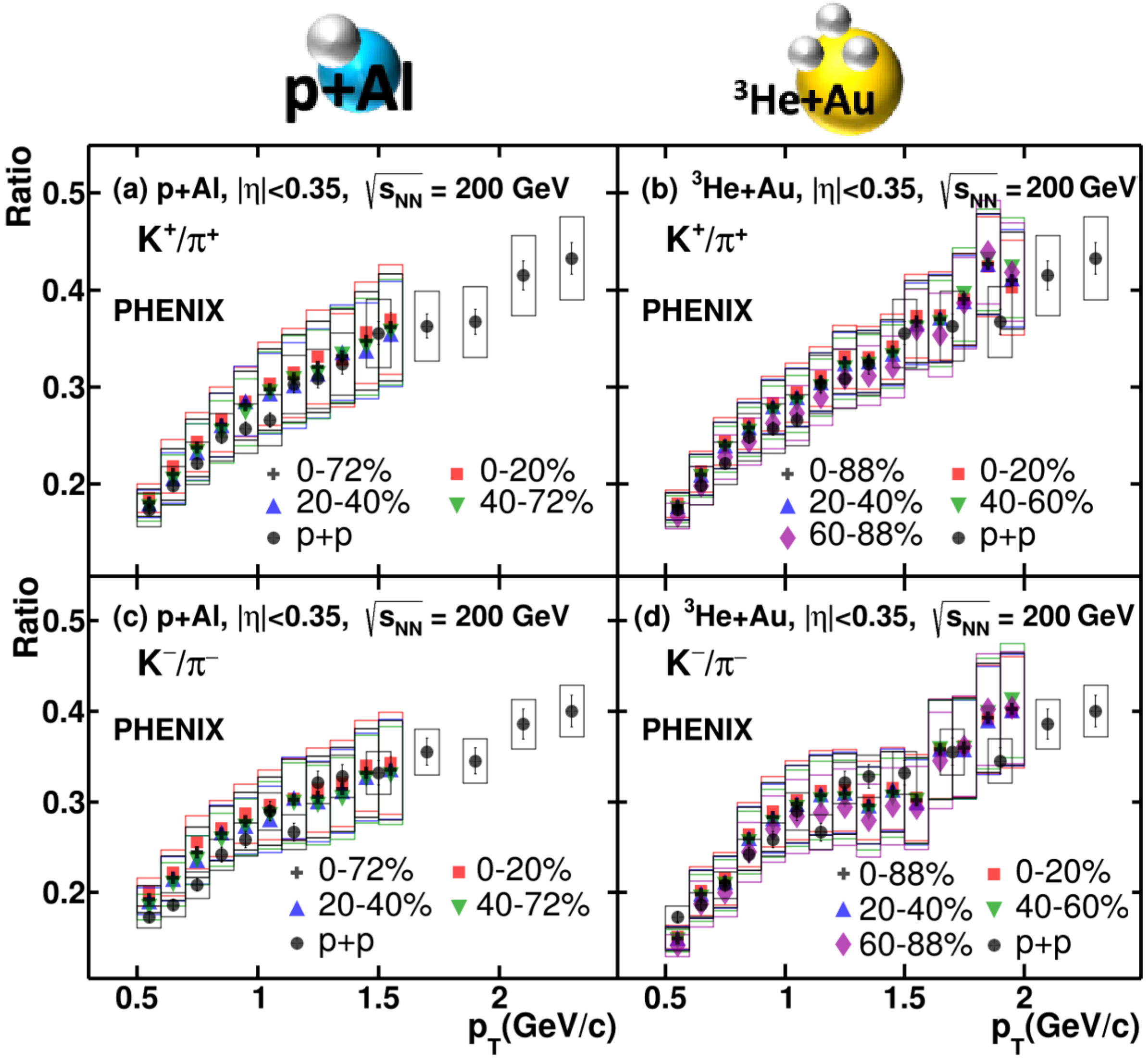

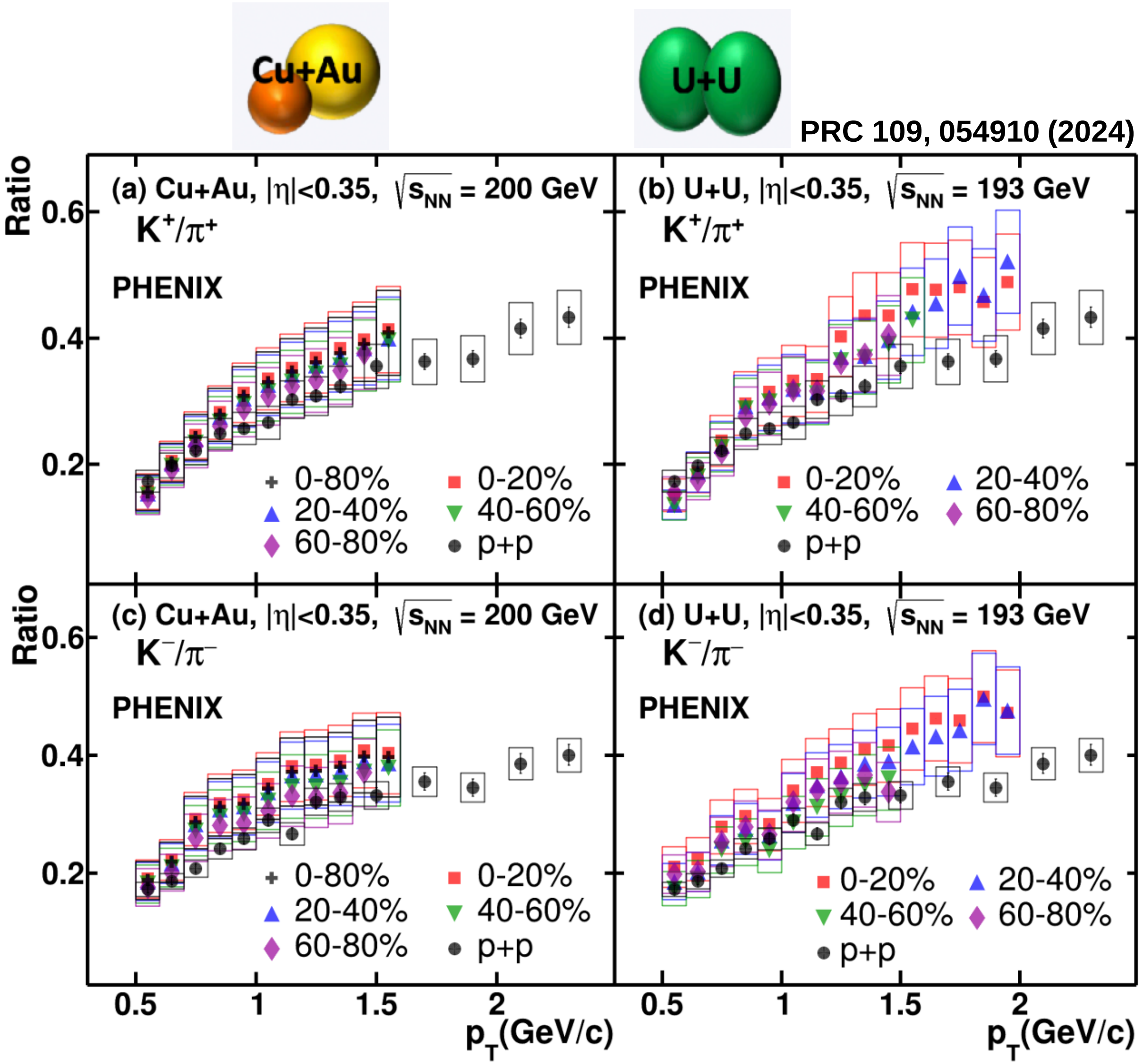

PHENIX Collected and Enjoying Every Bit of RHIC Data

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- Analyzing and publishing all these very interesting scientific data takes time, manpower, and resources. PHENIX Collaboration is on the right path to achieve these goals, and seek for a new discovery (ies) about the properties of QCD Matter at RHIC.
- To maintain this momentum, Data and Analysis Preservation (DAP) is critical.

Run	Species	Total particle energy [GeV/nucleon]	total delivered Luminosity [mb^{-1}]
I (2000)	Au+Au Au+Au	56 130	< 0.001 20
II (2001/2002)	Au+Au Au+Au p+p	200 19.6 200	25.8 0.4 1.4x10^{-6}
III (2003)	d+Au p+p	200 200	73x10^{-3} 5.5x10^{-6}
IV(2004)	Au+Au Au+Au p+p	200 62.4 200	3.53x10^{-3} 67 7.1x10^{-6}
V (2005)	Cu+Cu Cu+Cu Cu+Cu p+p p+p	200 62.4 22.4 200 410	42.1x10^{-3} 1.5x10^{-3} 0.02x10^{-3} 29.5x10^{-6} 0.1x10^{-6}
VI (2006)	p+p p+p	200 62.4	88.6x10^{-6} 1.05x10^{-6}
VII (2007)	Au+Au Au+Au	200 9.2	7.25x10^{-3} Small
VIII (2008)	d+Au p+p Au+Au	200 200 9.6	437x10^{-3} 38.4x10^{-6} Small

Run	Species	Total particle energy [GeV/nucleon]	Total delivered luminosity [mb^{-1}]
IX (2009)	p+p +p	500 200	110x10^{-6} 114x10^{-6}
X (2010)	Au+Au Au+Au Au+Au Au+Au Au+Au	200 62.4 39 7.7 11.5	10.3x10^{-3} 544 206 4.23 7.8
XI (2011)	p+p Au+Au Au+Au Au+Au	500 19.6 200 27	166x10^{-6} 33.2 9.79x10^{-3} 63.1
XII (2012)	p+p p+p U+U Cu+Au	200 510 193 200	74x10^{-6} 283x10^{-6} 736 27x10^{-3}
XIII (2013)	p+p	510	1.04x10^{-9}
XIV (2014)	Au+Au Au+Au ^{3}He+Au	14.6 200 200	44.2 43.9x10^{-3} 134x10^{-3}
XV (2015)	p+p p+Au p+Al	200 200 200	282x10^{-6} 1.27x10^{-6} 3.97x10^{-6}
XVI (2016)	Au+Au d+Au d+Au d+Au d+Au	200 200 62.4 19.6 39	52.2x10^{-3} 46.1x10^{-3} 44.0x10^{-3} 7.2x10^{-3} 19.5x10^{-3}