PHENIX Highlights

What's the new results since last RHIC/AGC Users' meeting,

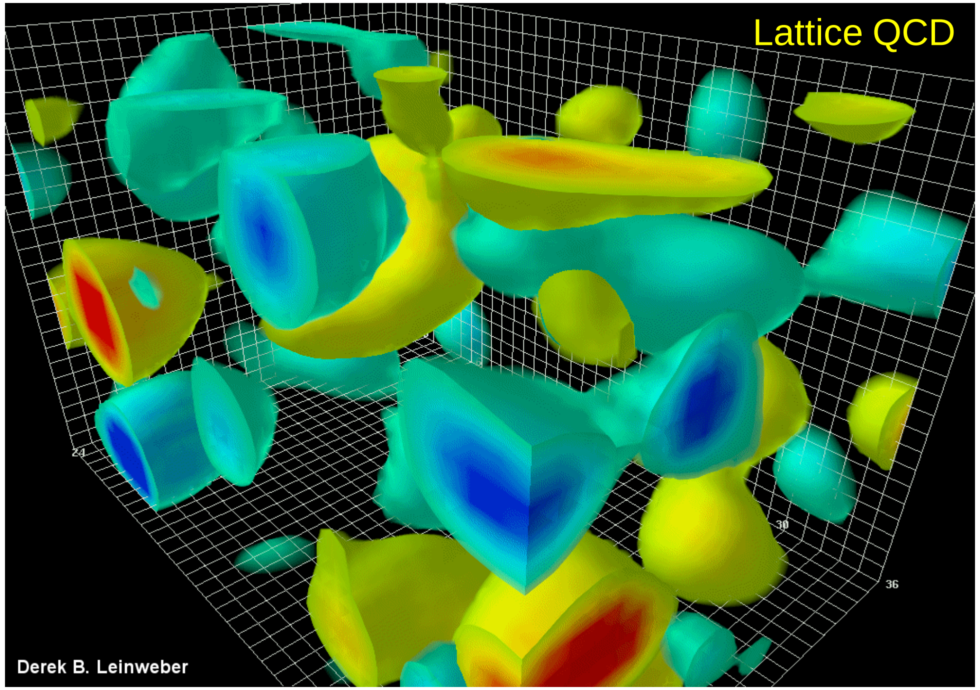
and what have we learned?

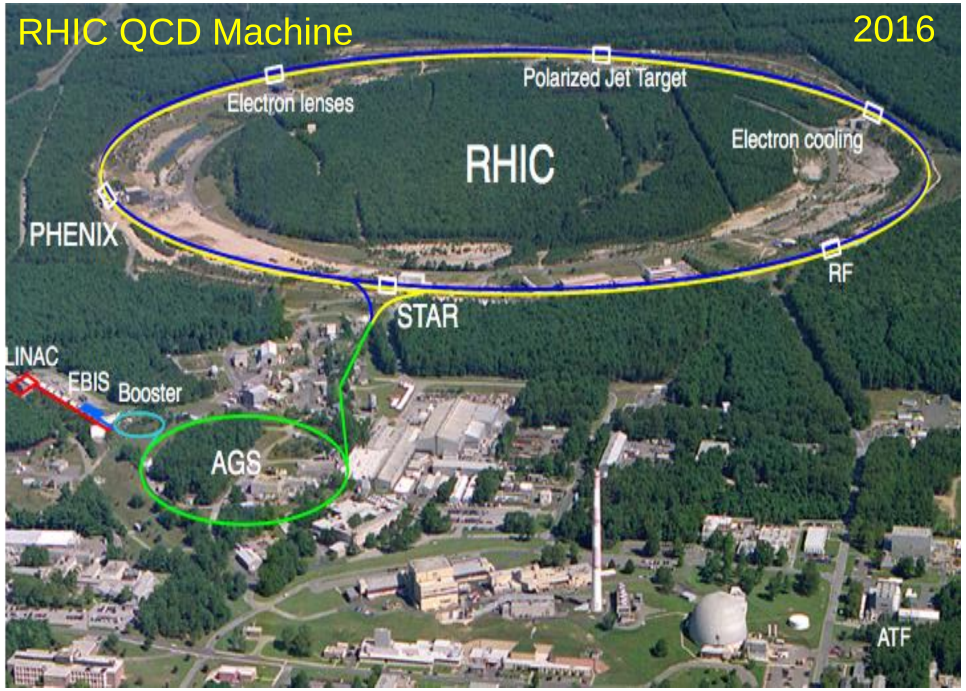
Rachid Nouicer, for the PHENIX Collaboration

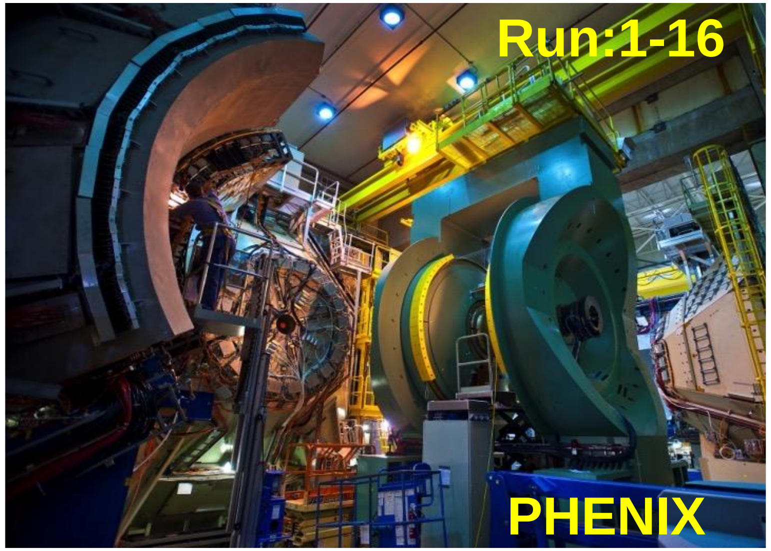
Brookhaven National Laboratory

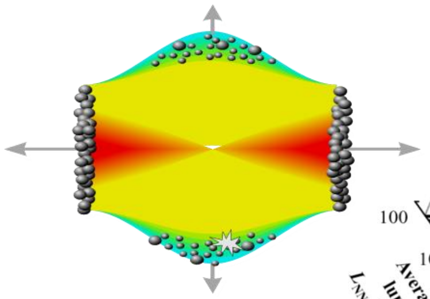
U.S. DEPARTMENT OF ENERGY

RHIC Amazing QCD Machine: Many Species and Energies

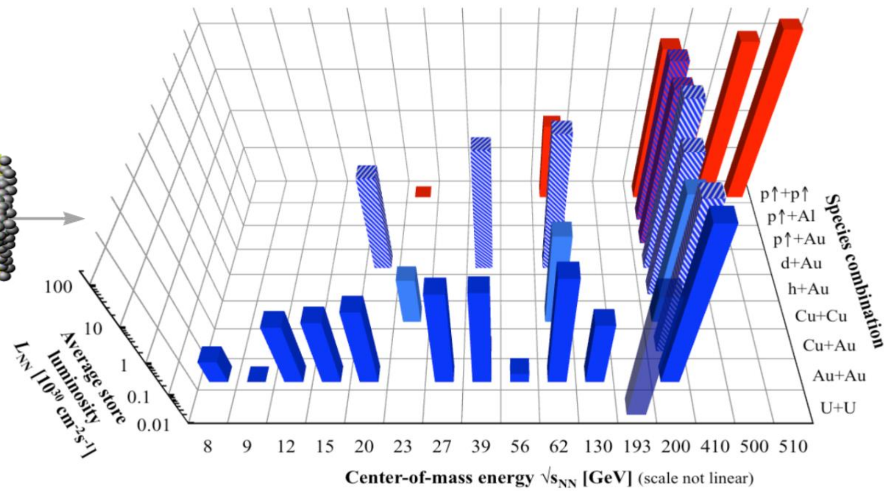








RHIC energies, species combinations and luminosities (Run-1 to 16)



PHENIX Collected and Enjoying Every Bit of RHIC Data

- 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

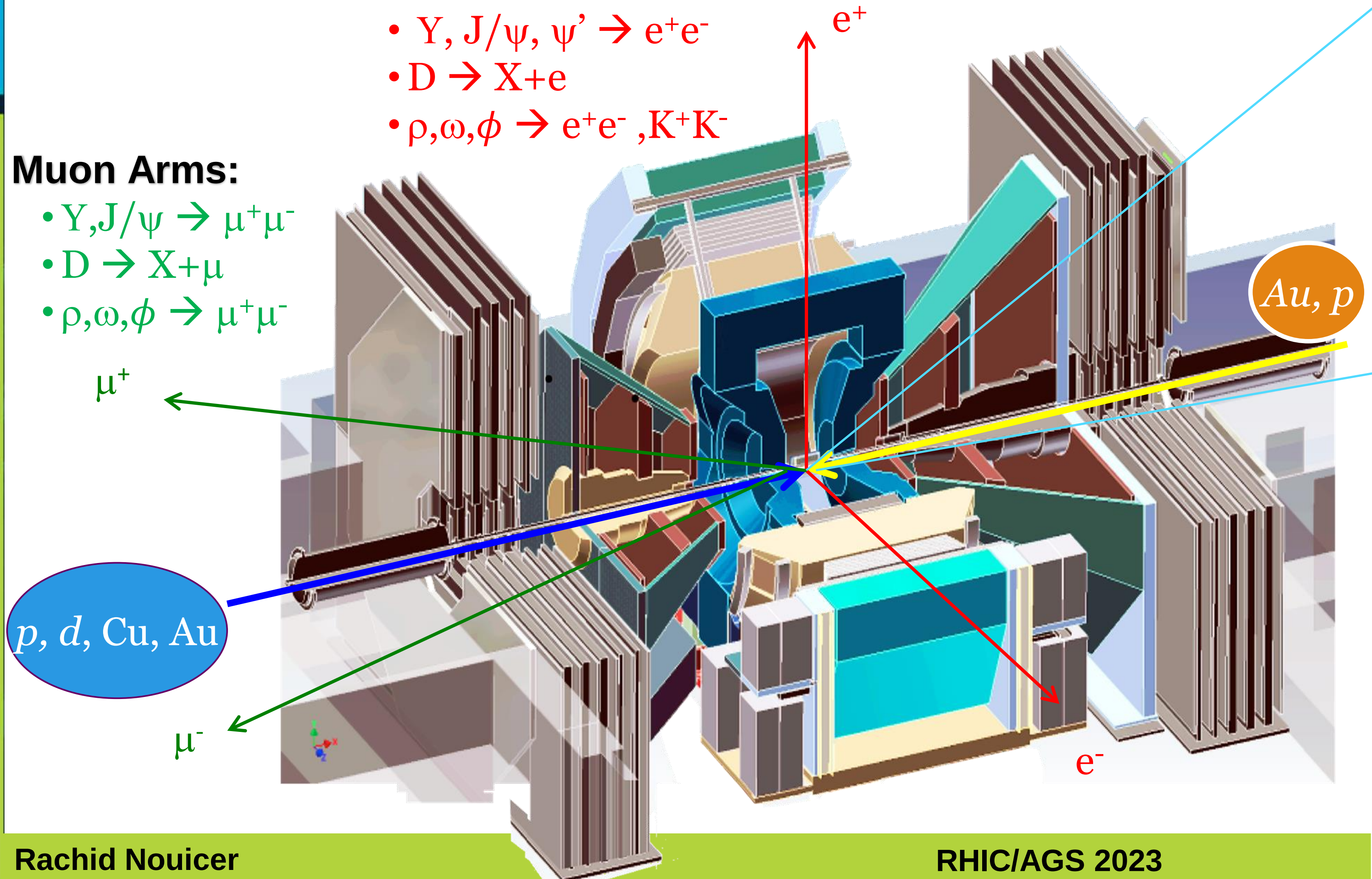
Run	Species	Total particle energy [GeV/nucleon]	Total delivered luminosity [mb^{-1}]
IX (2009)	p+p +p	500 200	110x10^{-6} 114x10^{-6}
X (2010)	Au+Au Au+Au Au+Au Au+Au Au+Au	200 62.4 39 7.7 11.5	10.3x10^{-3} 544 206 4.23 7.8
XI (2011)	p+p Au+Au Au+Au Au+Au	500 19.6 200 27	166x10^{-6} 33.2 9.79x10^{-3} 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}

PHENIX Detector: Collected Data from 2000 to 2016

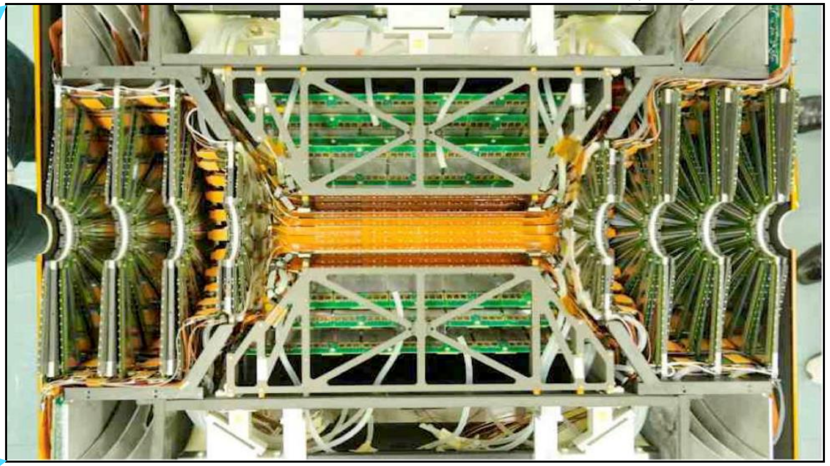
- PHENIX was optimized to measure leptons: rapidity coverage: 1.2<|y|<2.2 and |y|<0.35

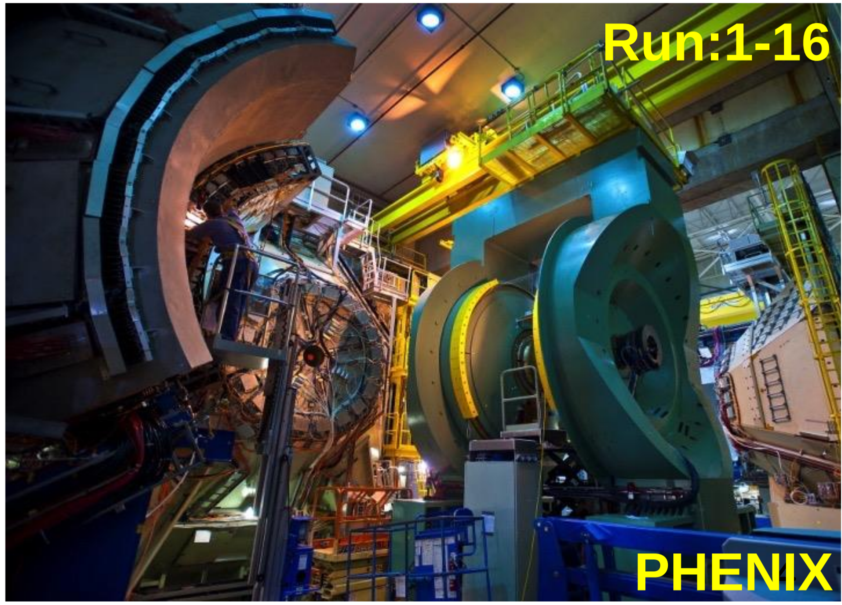
Central Arms:
- Υ, J/ψ, ψ' → e^+e^-
- D → X+e
- ρ,ω,ϕ → e^+e^- ,K^+K^-

Muon Arms:
- Υ,J/ψ → $\mu^+\mu^-$
- D → X+μ
- ρ,ω,ϕ → $\mu^+\mu^-$



2012: upgraded with Silicon detector VTX/FVTX for HF physics





Outline

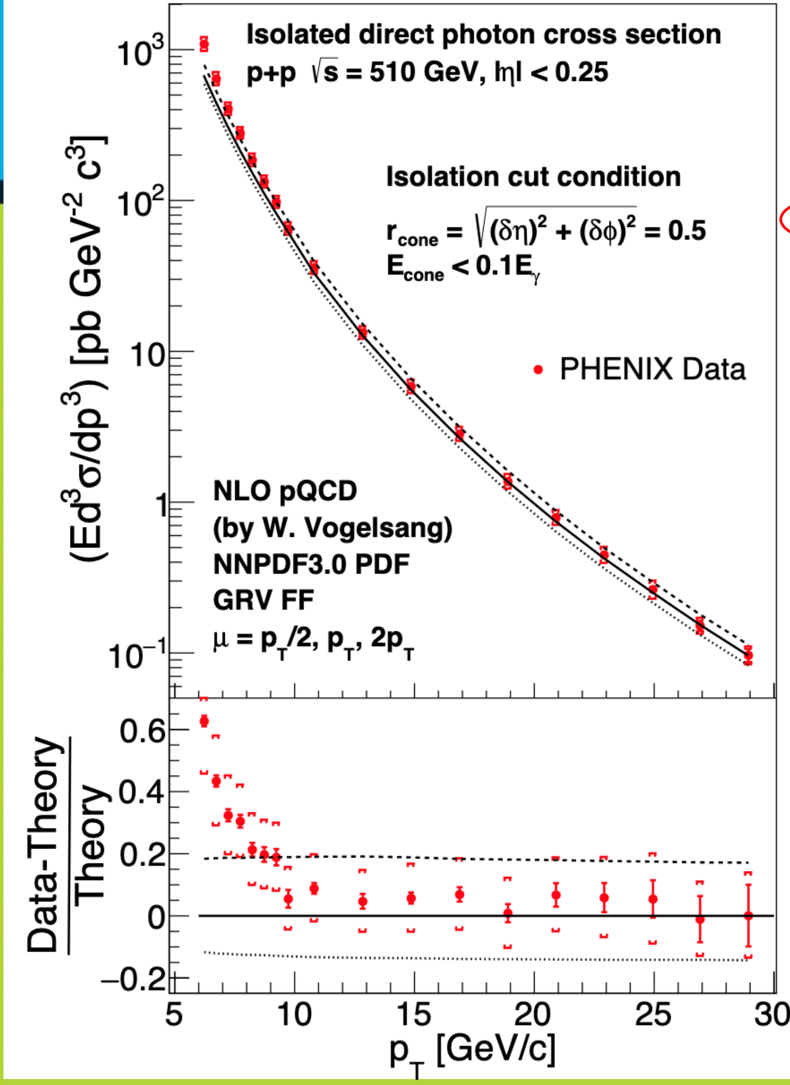
1. Spin Results
   a) Direct γ in Polarized p+p (BNL Recent News)
   b) A_N Heavy Flavor Decay Electrons
   c) High Precision Measurements of A_N of π^0 and η
2. Direct γ in Large System Au+Au at 39, 62.4, and 200 GeV
3. Hint of QGP Droplets in Small Systems
   a) Independent Measurements of Flow v2 and v3
   b) Direct γ and π^0 Production
   c) Suppression of π^0 Relative to Direct γ First Hint of Energy Loss
   d) Nuclear Modification Factors for J/ψ and ψ(2S) vs Rapidity

This is a short list from PHENIX recent findings

PHENIX on the News: Direct Photon in Polarized p+p at 510 GeV

Measurement of Direct-Photon Cross Section and Double-Helicity Asymmetry at $\sqrt{s} = 510$ GeV in $\vec{p}+\vec{p}$ Collisions

N. J. Abdulameer *et al.* (PHENIX Collaboration)
Phys. Rev. Lett. **130**, 251901 – Published 21 June 2023



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Direct Photons Point to Positive Gluon Polarization

Results from 'golden measurement' at RHIC's PHENIX experiment show the spins of gluons align with the spin of the proton they're in

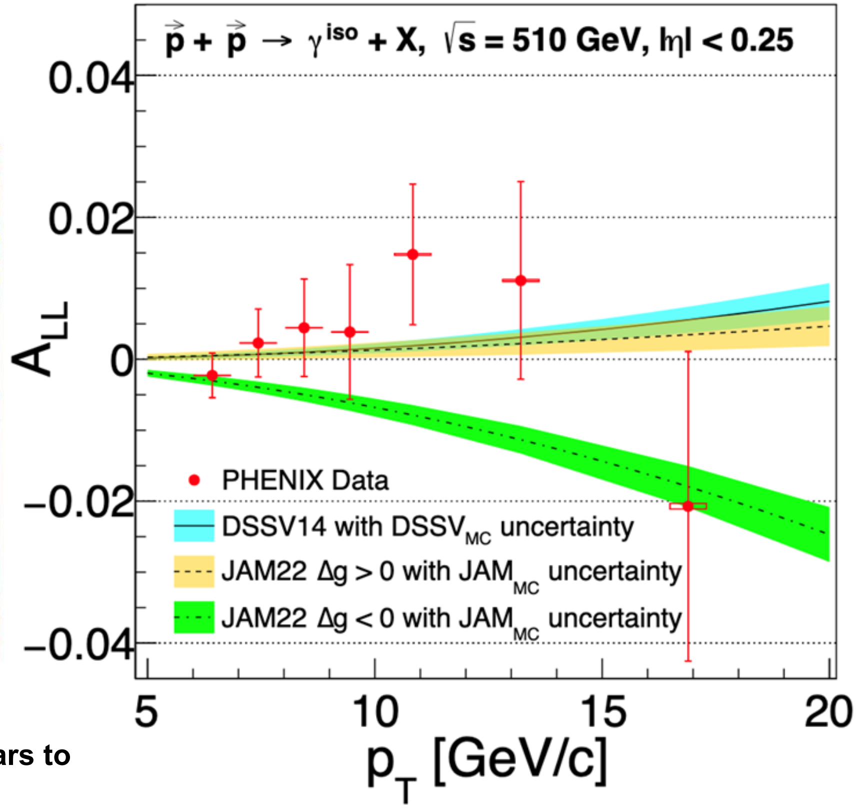
June 21, 2023

"Golden" measurements
Proposed in the RHIC physics spin program

Direct photon is clean measurements

Dedication: "In the end, it took five students over 15 years to complete this analysis"

- **Double helicity asymmetry isolated direct photons**



❖ First measurement directly sensitive to sign of Δg
➢ Δg<0 excluded at 2.8 σ level

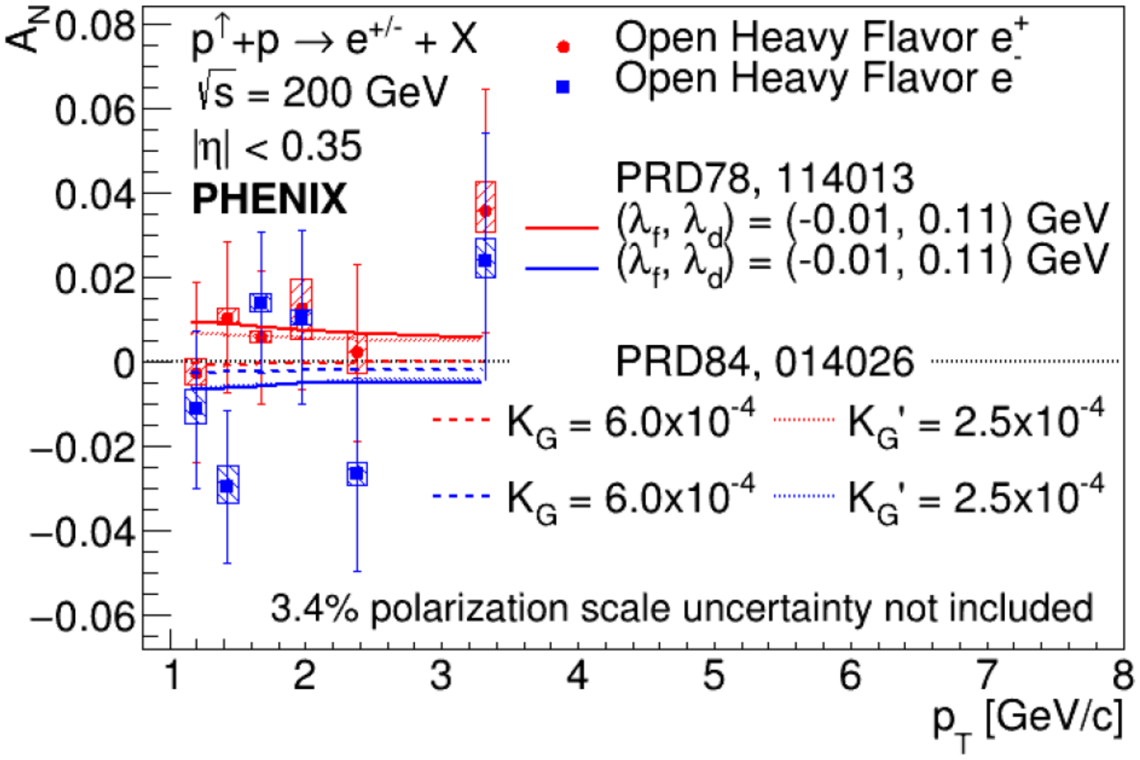
Spin Results

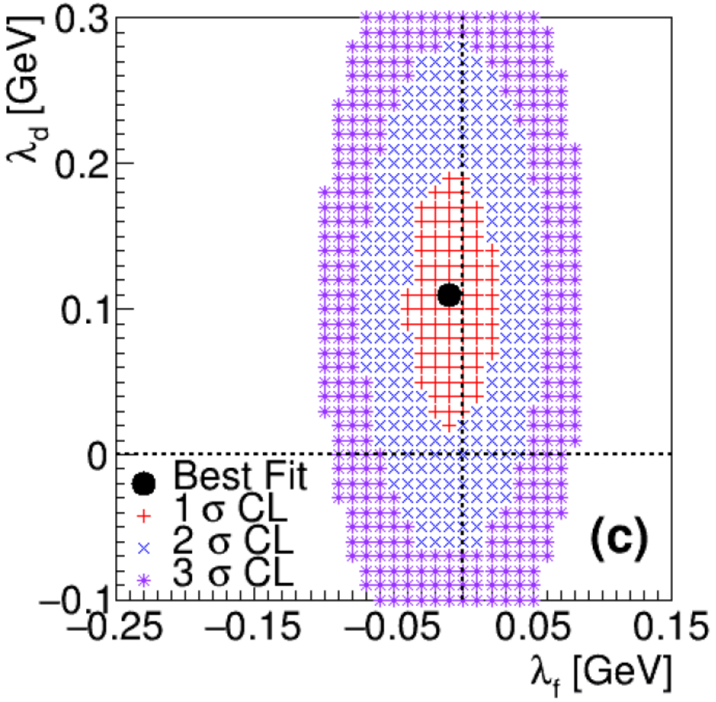
Improving constraints on gluon spin-momentum correlations in transversely polarized protons via midrapidity open-heavy-flavor electrons in $p^{\uparrow}+p$ collisions at $\sqrt{s}=200$ GeV

N. J. Abdulameer *et al.* (PHENIX Collaboration)
Phys. Rev. D **107**, 052012 – Published 29 March 2023

Measurement of A_N of heavy-flavor decay electrons

- **Transverse Single Spin Asymmetries**





$A_N(p^{\uparrow}+p \rightarrow HF(e^{+/-}) + X)$

$\sqrt{s}$ = 200 GeV

$|\eta|$ < 0.35

PHENIX

Theory: PRD78, 114013

$A_N^{D^0/\bar{D}^0 \rightarrow e^{+/-}}(\lambda_f,\lambda_d)$

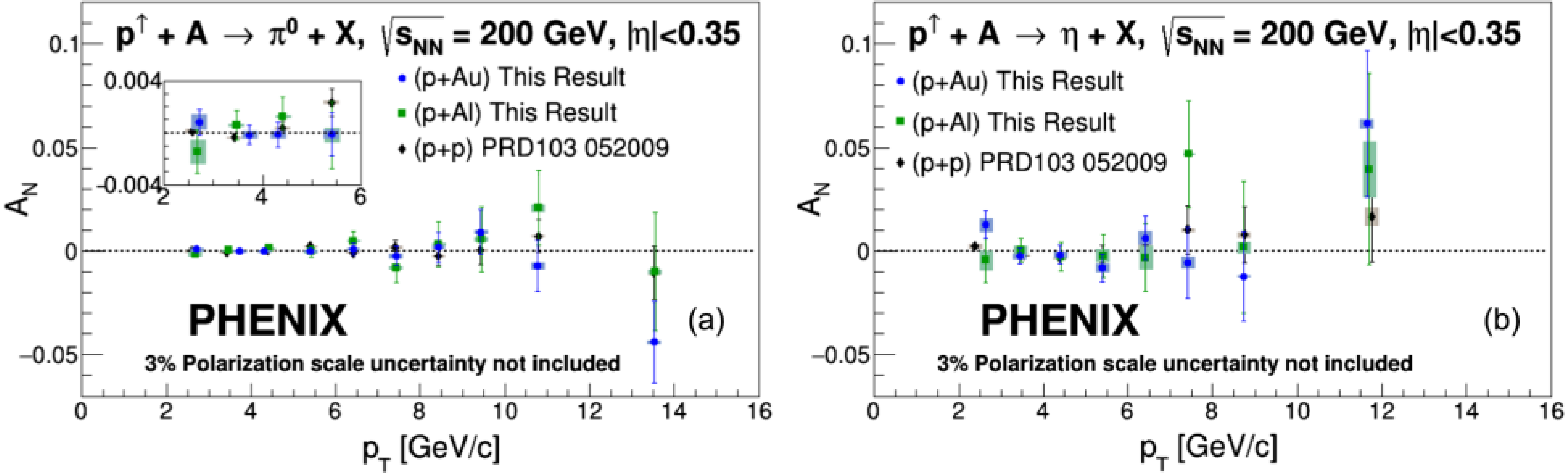
- Constraints on parameters of Tri-Gluon model by Z.Kang and J.W.Qiu
  - The first measurement on the parameters (λ_f, λ_d) of the model.

Spin Results

Transverse single-spin asymmetry of midrapidity π^0 and η mesons in $p + \mathrm{Au}$ and $p + \mathrm{Al}$ collisions at $\sqrt{s_{NN}} = 200$ GeV

N. J. Abdulameer *et al.* (PHENIX Collaboration)
Phys. Rev. D **107**, 112004 – Published 9 June 2023

First measurements of the transverse single-spin asymmetries (A_N) for neutral pions and eta mesons in p + Au and p + Al collisions at 200 GeV



- High precision measurements of the transverse single-spin asymmetries (A_N):
  - The measured asymmetries are consistent with zero up to very high precision in both collision systems for both meson species (π^0 and η).
  - Measurements show no evidence of additional effects that could potentially arise from the more partonic environments present in proton-nucleus collisions.

Direct Photon

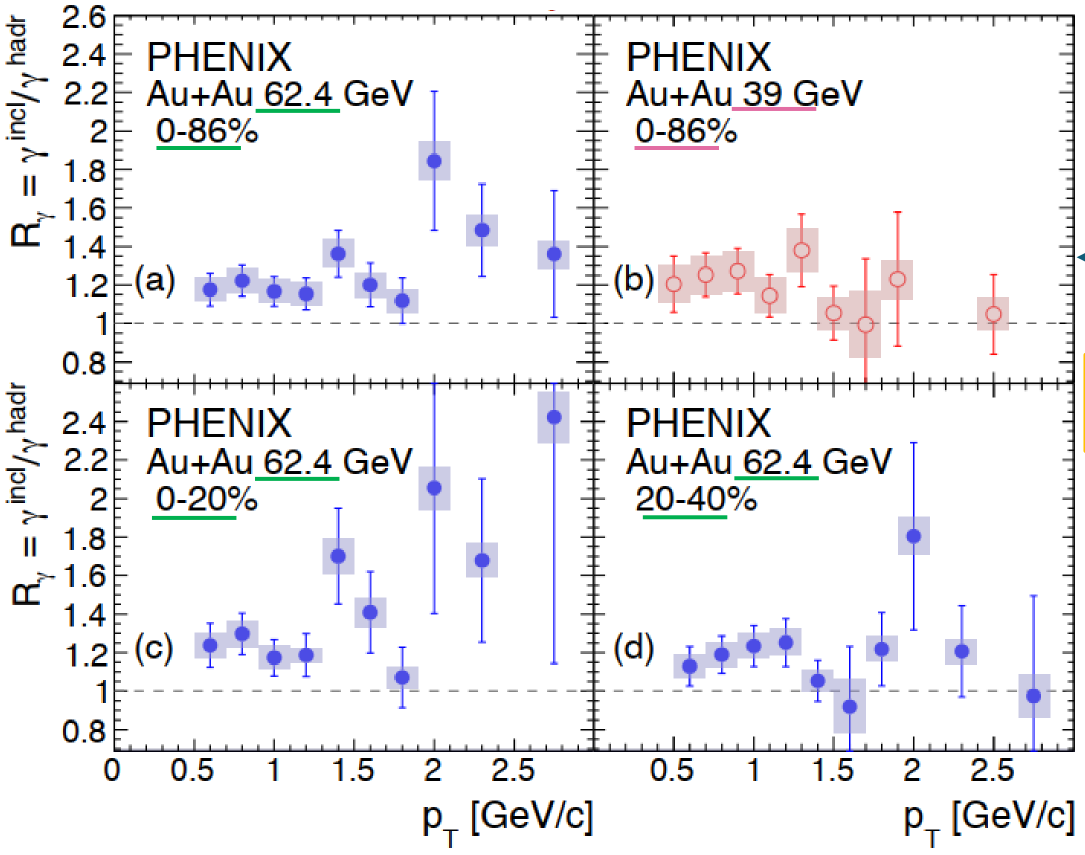
Published recently

PRC Editors' Suggestion

Low-p_T direct-photon production in Au + Au collisions at $\sqrt{s_{NN}}$ = 39 and 62.4 GeV

N. J. Abdulameer *et al.* (PHENIX Collaboration)

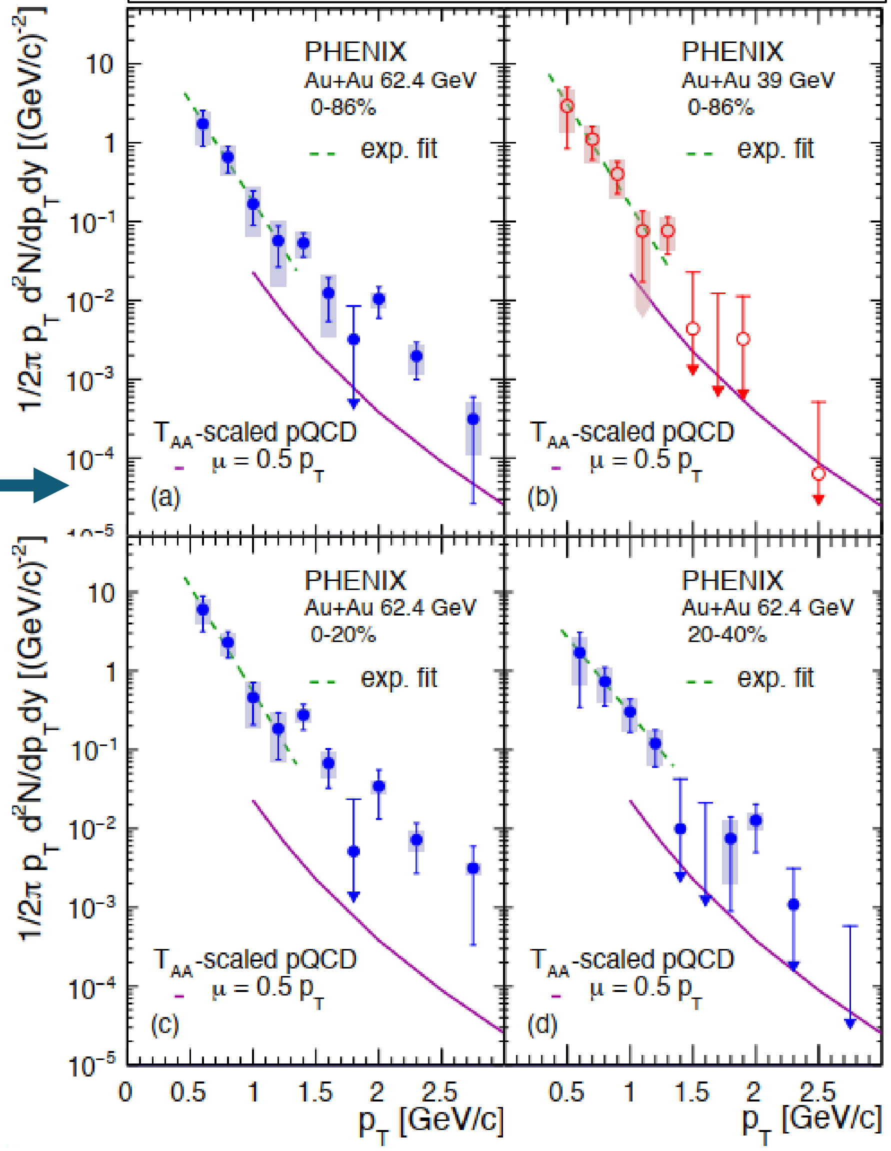
Phys. Rev. C **107**, 024914 (2023) - Published 24 February 2023



$$R_\gamma = \frac{\gamma_{inclusive}}{\gamma_{decay}}$$

$$\gamma_{direct} = (R_\gamma - 1)\,\gamma_{hadron}$$

Direct Photons: AuAu at 39 and 62.4 GeV



- ❖ Observed significant direct photon yield relative to those from hadron decays in both energies in Au+Au collisions.

Direct Photon

Published recently

PRC Editors' Suggestion

Low-p_T direct-photon production in Au + Au collisions at $\sqrt{s_{NN}} = 39$ and 62.4 GeV

N. J. Abdulameer *et al.* (PHENIX Collaboration)

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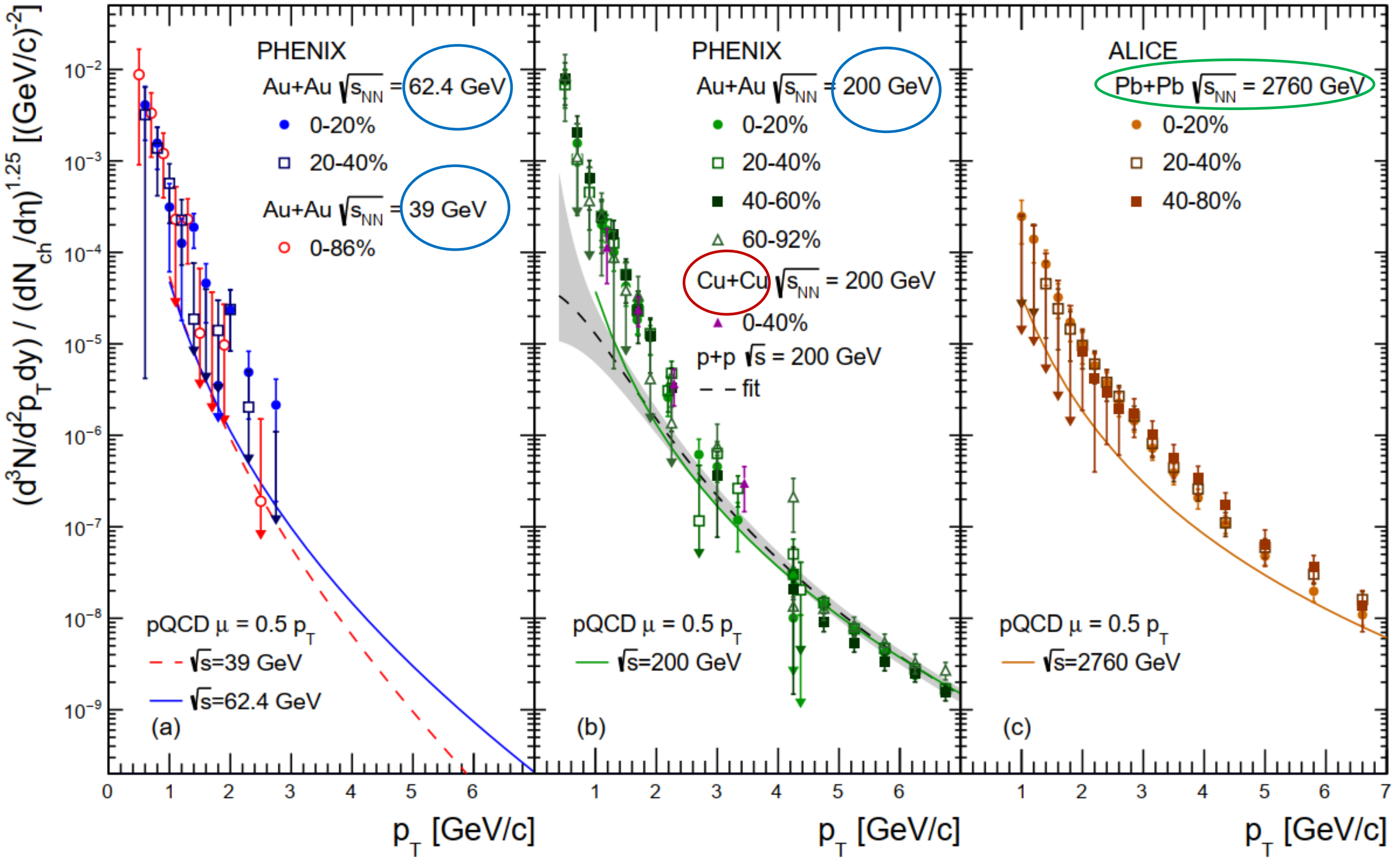
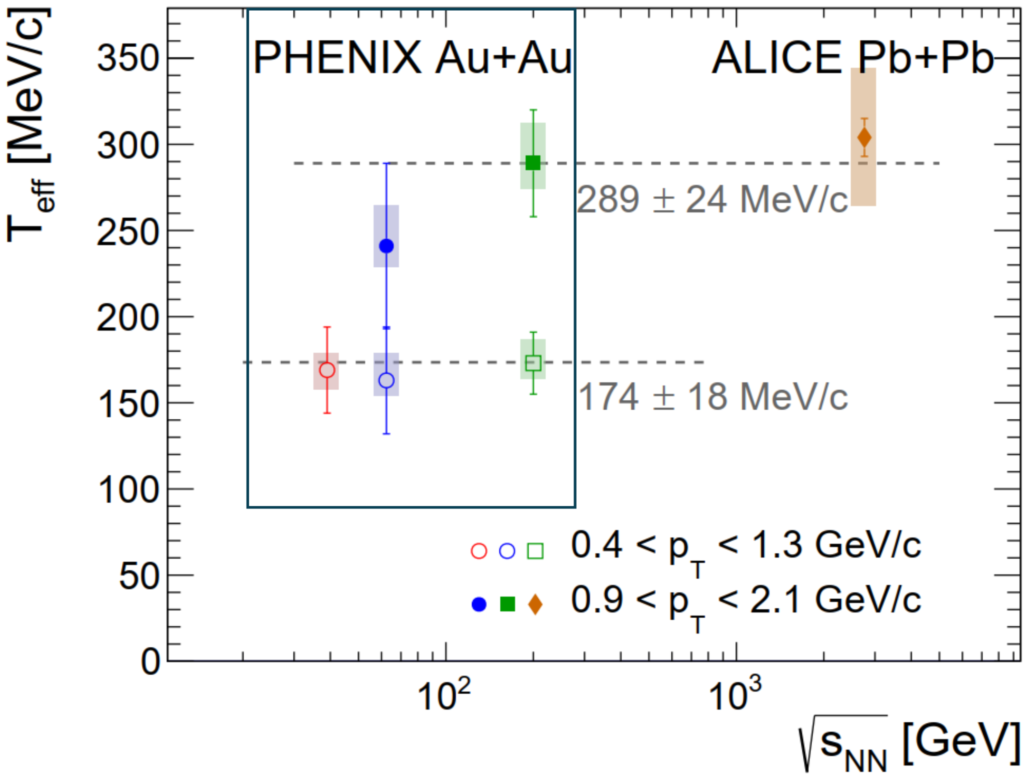
Direct Photon p_T-spectra



The similarity of T_{eff} at low p_T suggests a common source of direct γ from RHIC to LHC energies



- Direct photons with p_T of up to a few GeV/c are expected to be dominantly of thermal origin
- These photons are radiated from a thermalized hot fireball of quark-gluon plasma
  - Results from a fit to lowest p_T direct photon yields indicate $T_{eff} = 174 \pm 18$ MeV

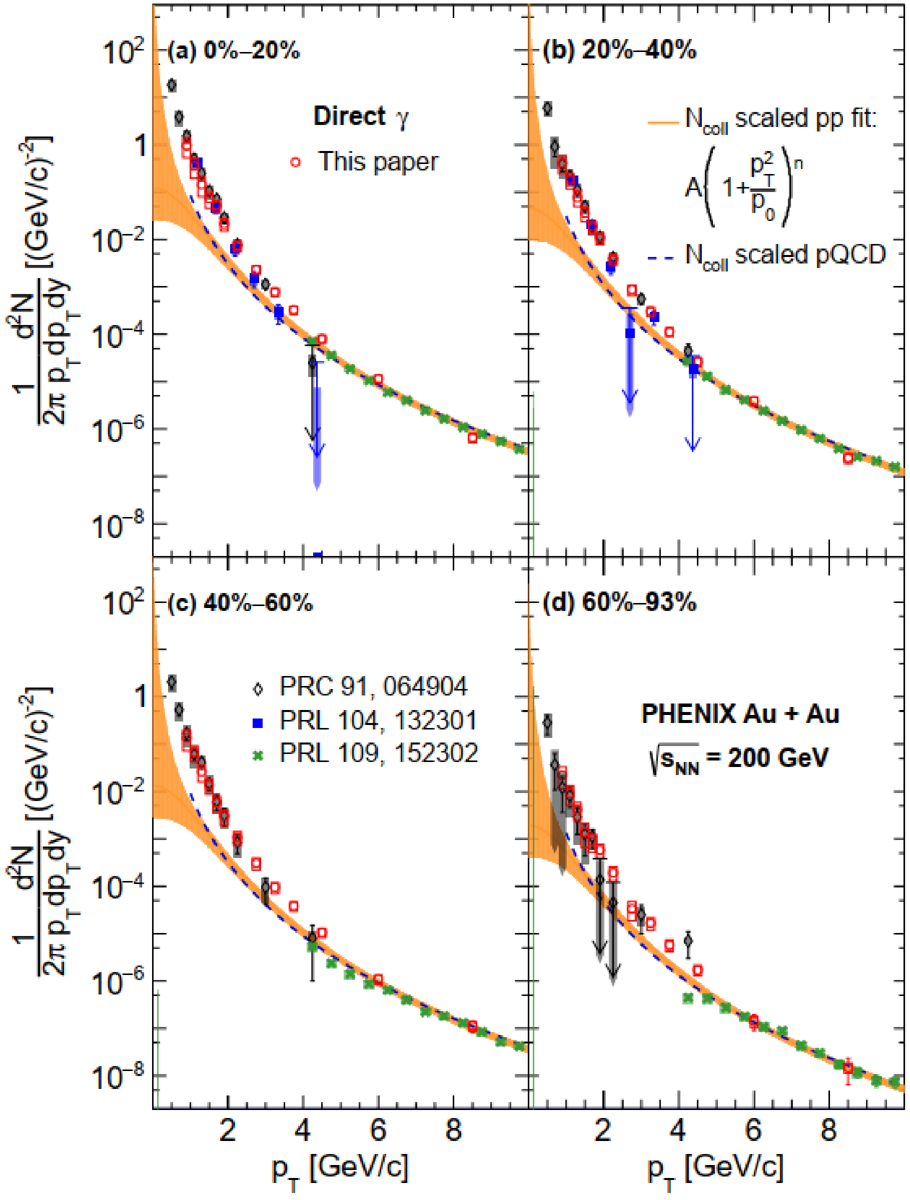
Direct Photon

Nonprompt direct-photon production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

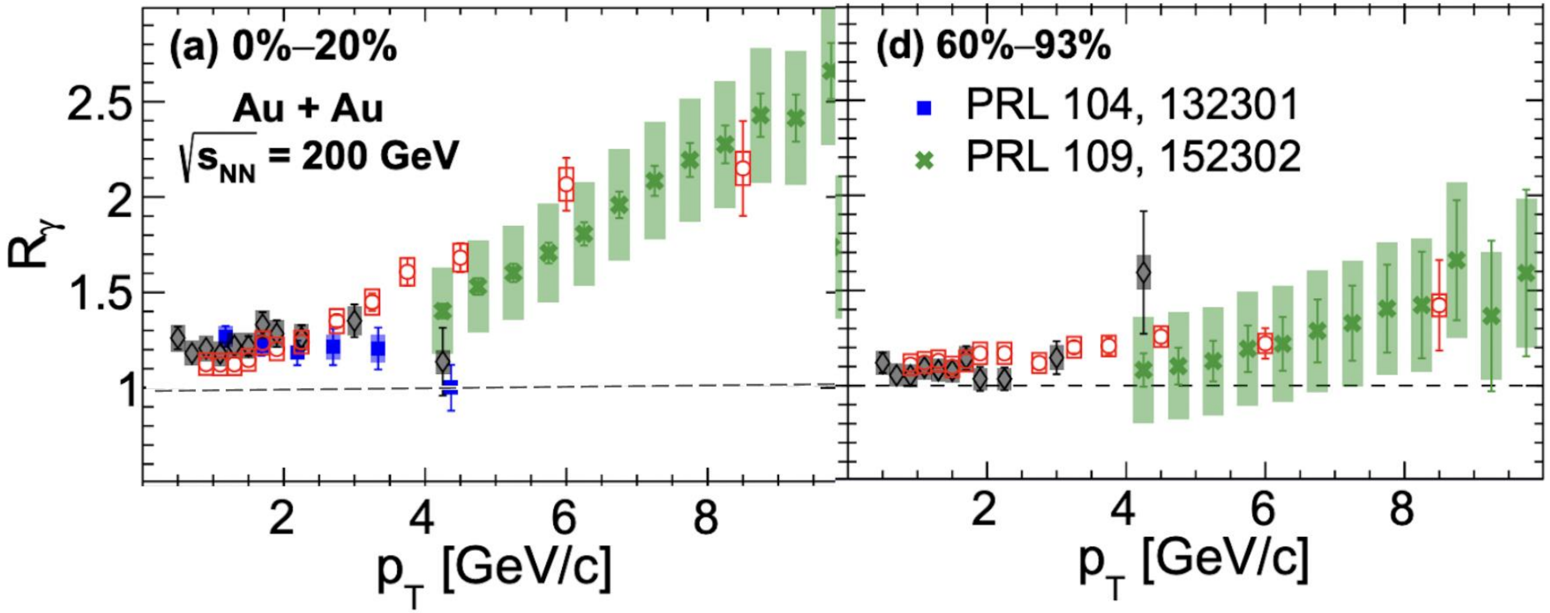
U.A. Acharya,[21] A. Adare,[12] C. Aidala,[42] N.N. Ajitanand,[60,*] Y. Akiba,[55,56,†] M. Alfred,[23] N. Apadula,[28,61]

Submitted for publication in PRC

arXiv > nucl-ex > arXiv:2203.17187



$$R_\gamma = \frac{\gamma_{\text{inclusive}}}{\gamma_{\text{decay}}}$$



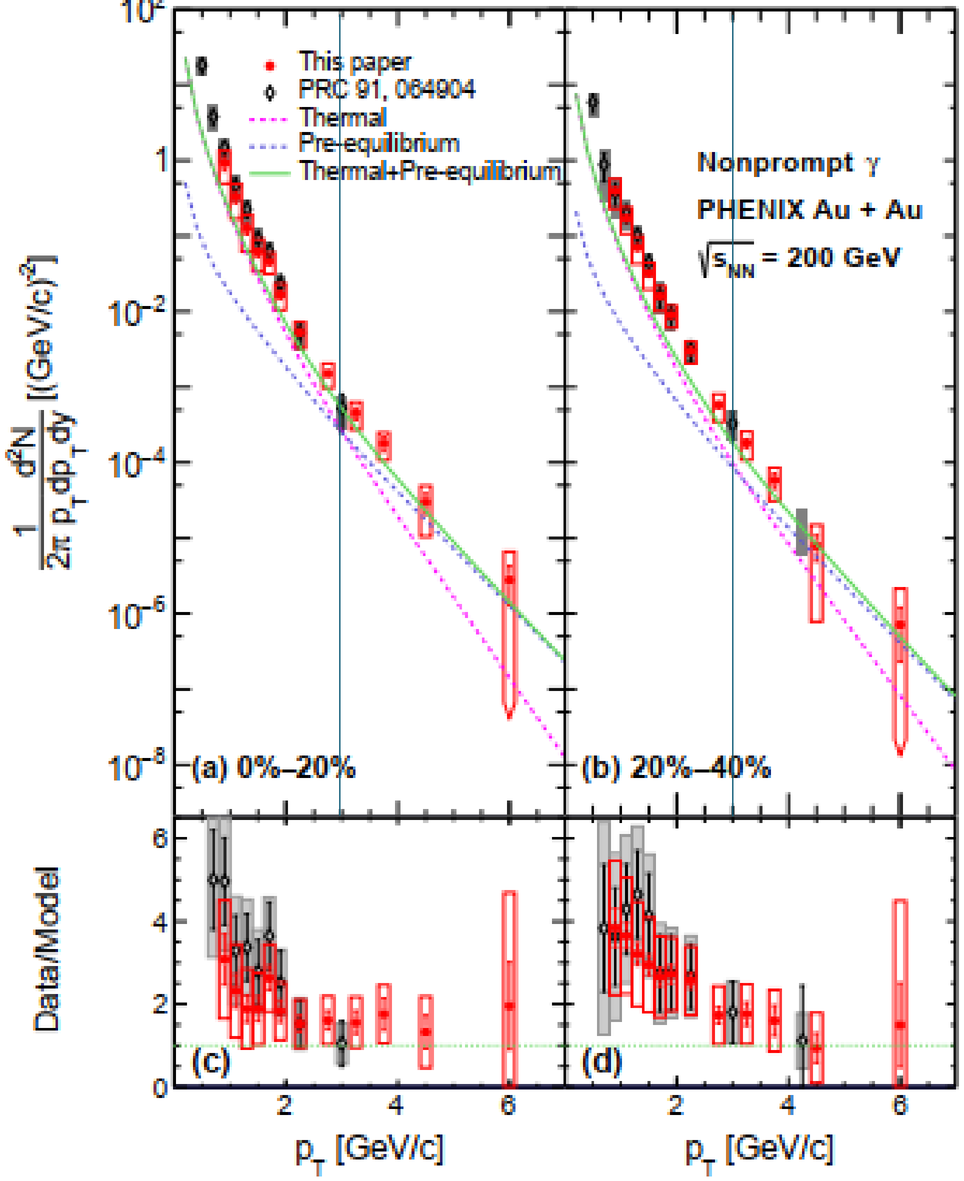
- Current external photon conversion measurements (red) use data set with ~10× more statistics than previous published data.
- Comparison with previous methods for direct photon measurements show good agreement → results are very robust
  - For most central collisions, *Rγ* > 1, indicating excess direct photon yield

Direct Photon

Nonprompt direct-photon production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

arXiv > nucl-ex > arXiv:2203.17187

U.A. Acharya,[21] A. Adare,[12] C. Aidala,[42] N.N. Ajitanand,[60,*] Y. Akiba,[55,56,†] M. Alfred,[23] N. Apadula,[28,61]



PHENIX Nonprompt Direct Photon vs theory

Multimessenger heavy-ion collision physics

Charles Gale, Jean-François Paquet, Björn Schenke, and Chun Shen
Phys. Rev. C **105**, 014909 – Published 14 January 2022

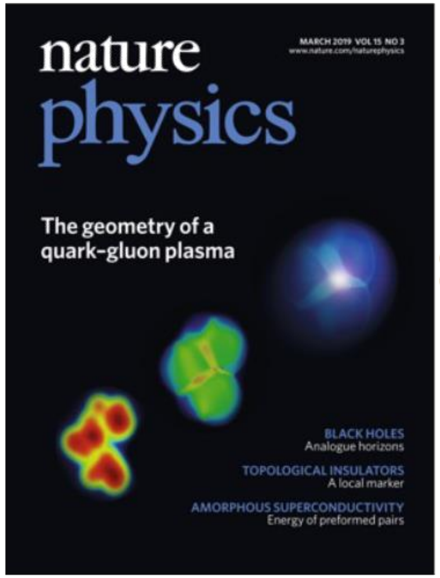
" The hybrid model used here describes all stages of relativistic heavy-ion collisions. Chronologically, those are an initial state reflecting the collision of nuclei described within the color glass condensate effective theory; a pre-equilibrium phase based on nonequilibrium linear response; relativistic viscous hydrodynamics, and a hadronic afterburner. The effect of the pre-equilibrium phase on both photonic and hadronic observables is highlighted for the first time. "

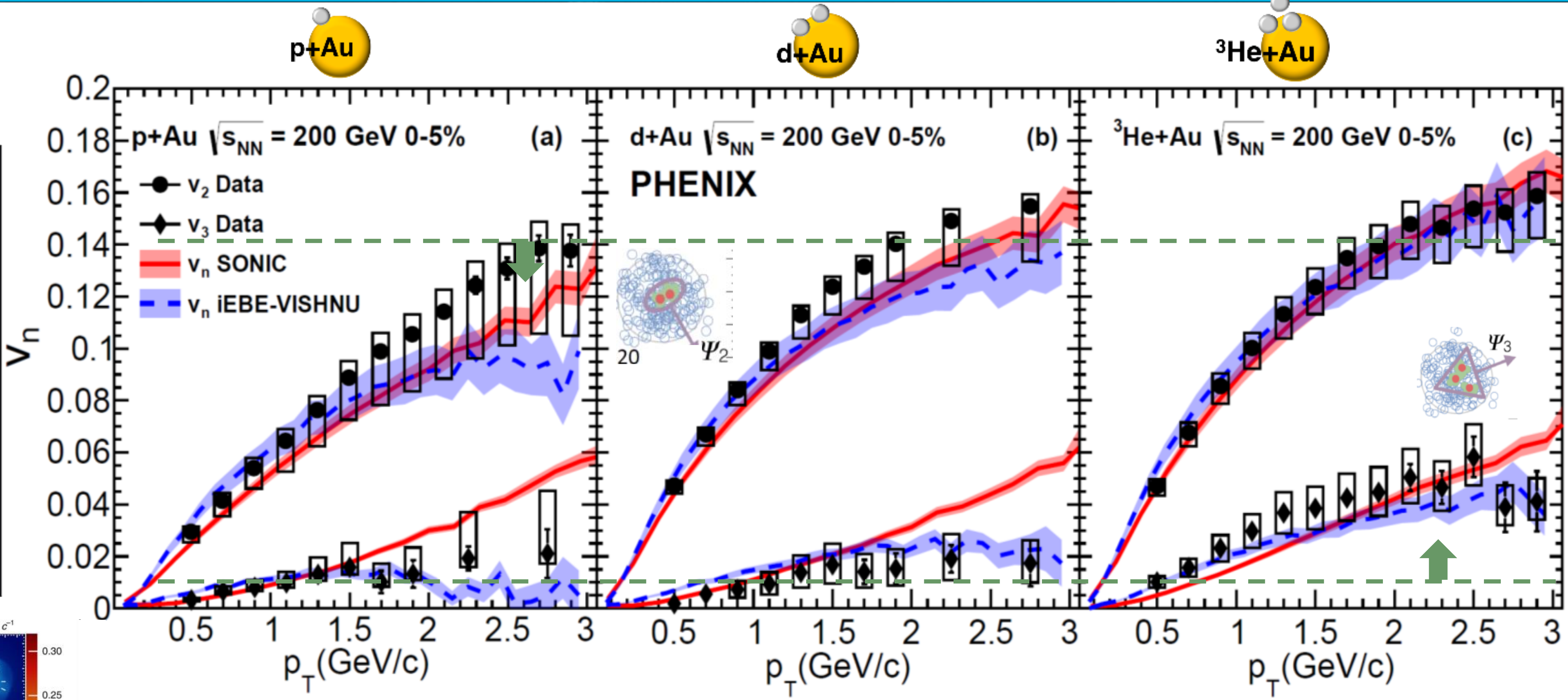
What have we learned?

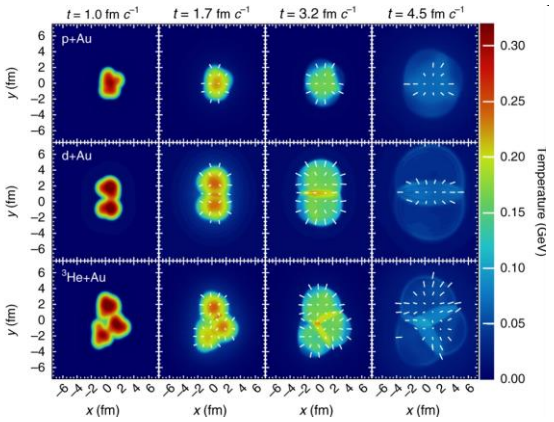
- Dominant contribution from pre-equilibrium above 3 GeV/c in the model seems to align well with the data
- Overall yield falls short, especially below 2 GeV/c.

Evidence of Formation of Small Droplets of QGP in Small Systems

PHENIX:
Nature Phys. 15 (2019) 214







- Geometrical ordering as expected from hydrodynamical models
  - v_2 p+Au < d+Au ~ ^{3}He+Au
  - v_3 p+Au ~ d+Au < ^{3}He+Au

Anisotropy of charged particle production consistent with hydrodynamic expansion

Kinematic dependence of azimuthal anisotropies in $p + \mathrm{Au}$, $d + \mathrm{Au}$, and $^{3}\mathrm{He} + \mathrm{Au}$ at $\sqrt{s_{NN}} = 200$ GeV

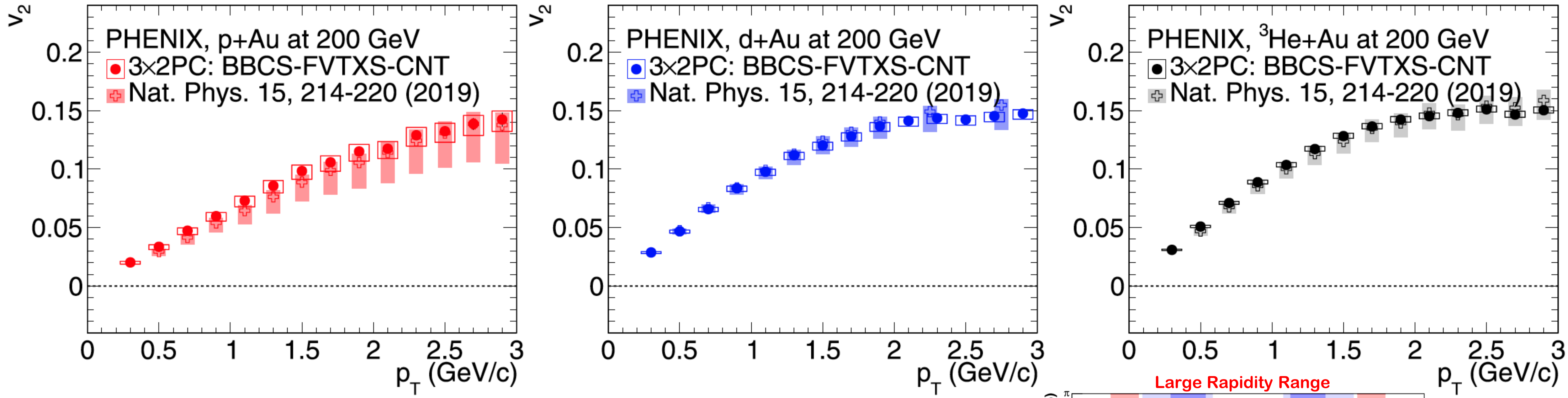
U. A. Acharya *et al.* (PHENIX Collaboration)
Phys. Rev. C **105**, 024901 – Published 3 February 2022

Measurements of second-harmonic Fourier coefficients from azimuthal anisotropies in $p + p$, $p + \mathrm{Au}$, $d + \mathrm{Au}$, and $^{3}\mathrm{He} + \mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV

N. J. Abdulameer *et al.* (PHENIX Collaboration)
Phys. Rev. C **107**, 024907 – Published 9 February 2023

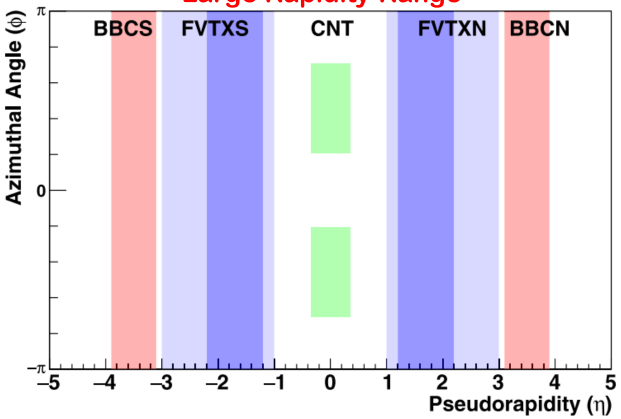
New Cross Checks

Independent Study of Elliptic Flow v_2



- <u>Using two particle correlations over large rapidity range</u>
  - Different systematics, different sensitivity to non flow effects
  - Consistent v_2

Large Rapidity Range



Kinematic dependence of azimuthal anisotropies in $p+\mathrm{Au}$, $d+\mathrm{Au}$, and $^3\mathrm{He}+\mathrm{Au}$ at $\sqrt{s_{NN}} = 200$ GeV

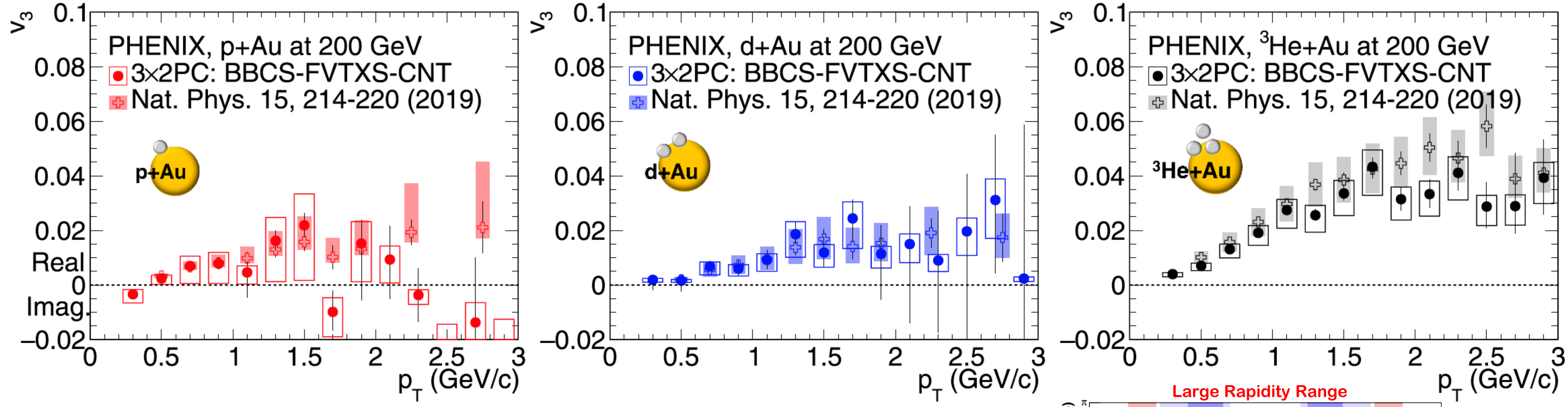
U. A. Acharya *et al.* (PHENIX Collaboration)
Phys. Rev. C **105**, 024901 – Published 3 February 2022

Measurements of second-harmonic Fourier coefficients from azimuthal anisotropies in $p+p$, $p+\mathrm{Au}$, $d+\mathrm{Au}$, and $^3\mathrm{He}+\mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV

N. J. Abdulameer *et al.* (PHENIX Collaboration)
Phys. Rev. C **107**, 024907 – Published 9 February 2023

New Cross Checks

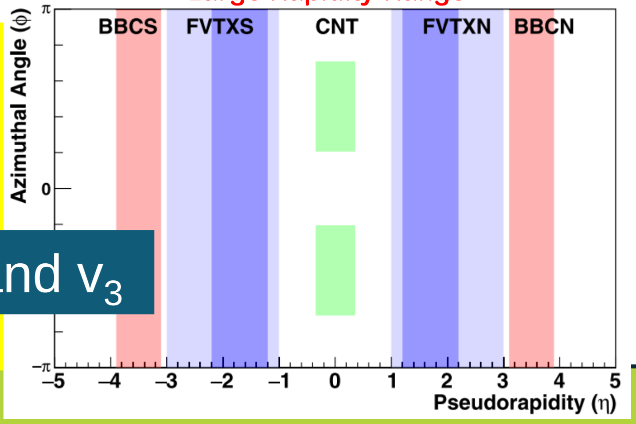
Independent Study of Triangular Flow v_3



- Using two particle correlations over large rapidity range
  - Different systematics, different sensitivity to non flow effects
  - Consistent v_2
  - Consistent v_3

Confirm geometrical ordering of v_2 and v_3

Large Rapidity Range



Kinematic dependence of azimuthal anisotropies in $p + \mathrm{Au}$, $d + \mathrm{Au}$, and $^3\mathrm{He} + \mathrm{Au}$ at $\sqrt{s_{NN}} = 200$ GeV

U. A. Acharya *et al.* (PHENIX Collaboration)
Phys. Rev. C **105**, 024901 – Published 3 February 2022

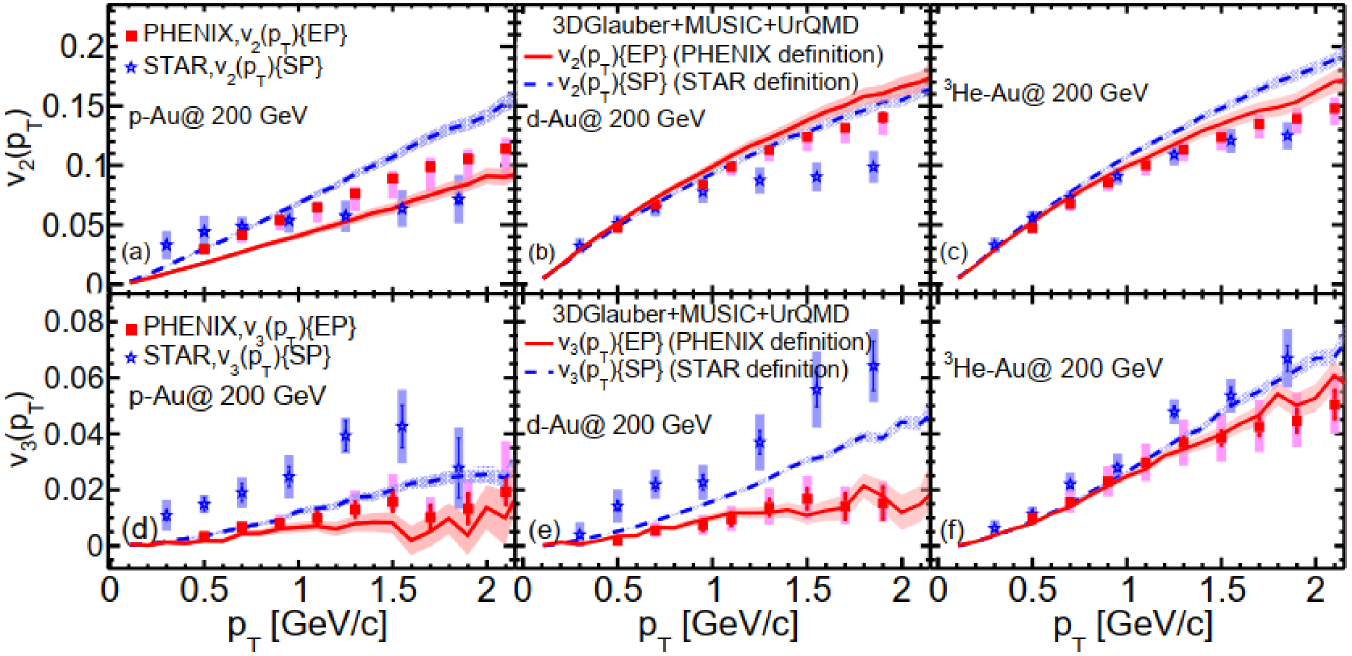
Measurements of second-harmonic Fourier coefficients from azimuthal anisotropies in $p + p$, $p + \mathrm{Au}$, $d + \mathrm{Au}$, and $^3\mathrm{He} + \mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV

N. J. Abdulameer *et al.* (PHENIX Collaboration)
Phys. Rev. C **107**, 024907 – Published 9 February 2023

PHENIX data well reproduced by the recent theoretical calculations

3D structure of anisotropic flow in small collision systems at energies available at the BNL Relativistic Heavy Ion Collider

Wenbin Zhao, Sangwook Ryu, Chun Shen, and Björn Schenke
Phys. Rev. C **107**, 014904 – Published 6 January 2023

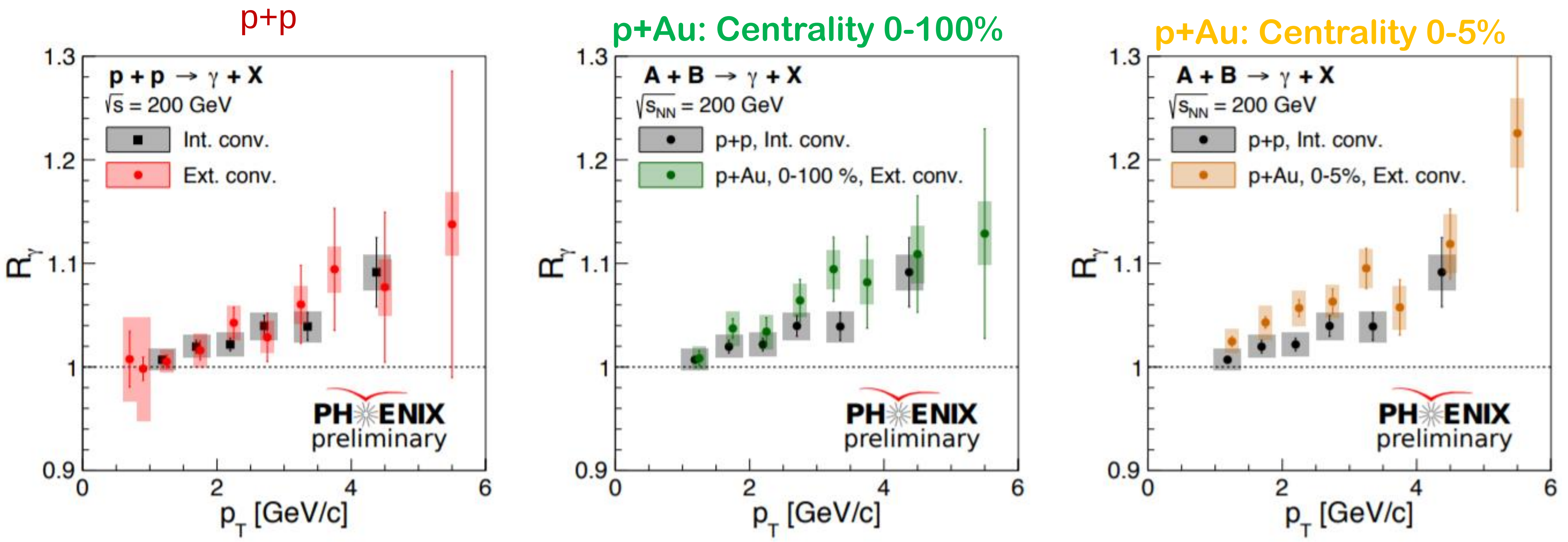


3D-GLAUBER + MUSIC+URQMD: dynamical initial state model coupled to (3+1)D viscous relativistic hydrodynamics

Importance of the longitudinal flow decorrelations in anisotropic flow measurements asymmetric nuclear collisions.

"Fig. 5 shows that the 3d glauber+music+urqmd model gives an overall good description of the PHENIX $v_n(p_T)$ data for d+Au and 3He+Au collisions. We underestimate the $v_2(p_T)$ in p+Au collisions by about 20-30%, possibly because of a too large longitudinal flow decorrelation in the model. " ✓

Direct photon measurements in p+p, p+Au collisions at 200 GeV

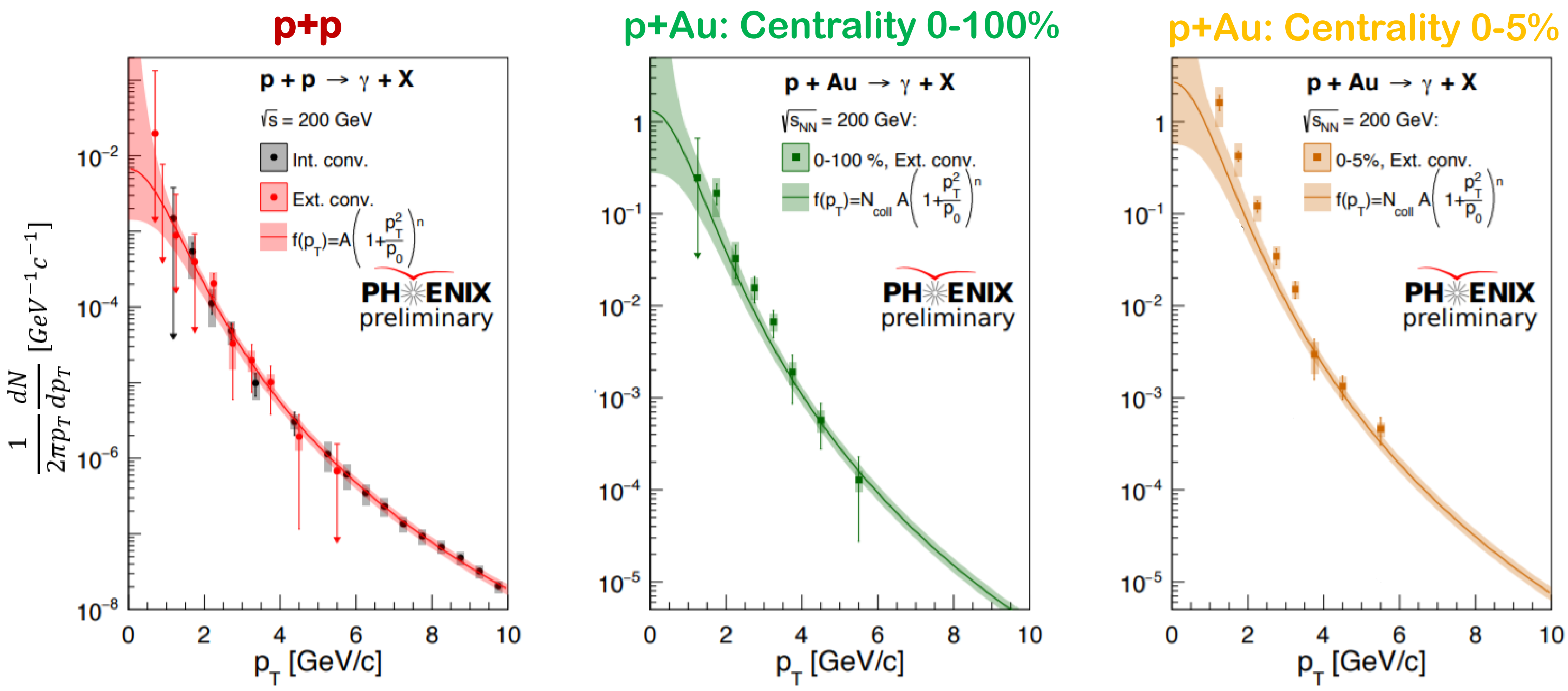


$$R_\gamma = \frac{\gamma_{\text{inclusive}}}{\gamma_{\text{decay}}}$$

❖ Observed significant direct photon yield relative to those from hadron decays in small systems

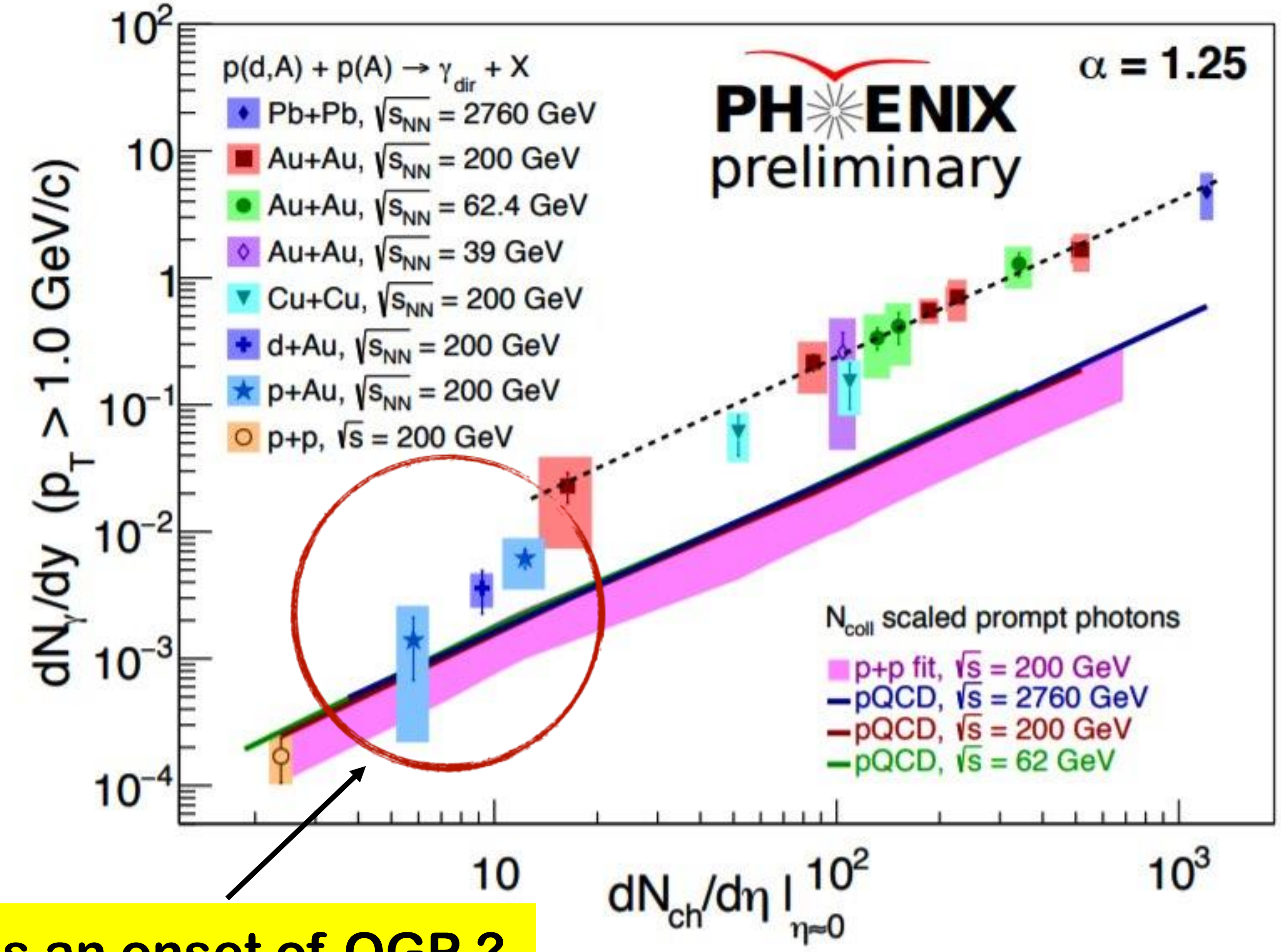
Direct photon measurements in p+p, p+Au collisions at 200 GeV

Direct photon p_T-spectra → T_{eff}



New Analysis Results (Preliminary)

Direct photon measurements in p+p, p+Au collisions at 200 GeV



Is this an onset of QGP ?

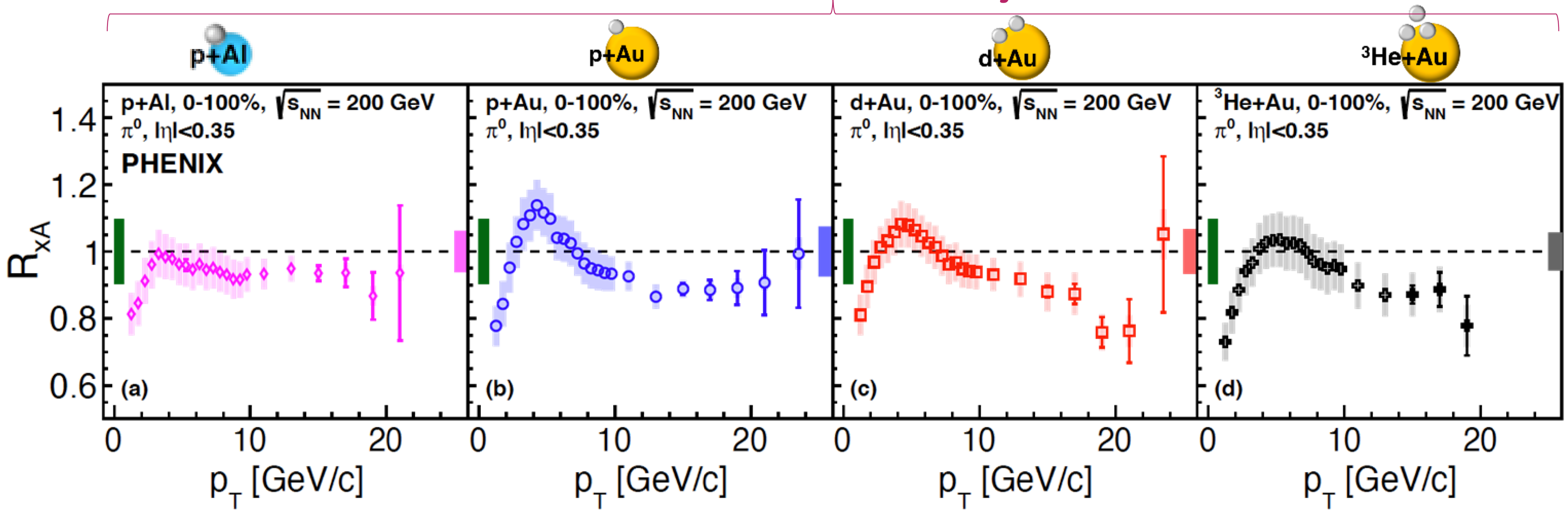
Hint of QGP Droplets in Small Systems

π^0 measurements in p+Al, p+Au , d+Au, He+Au collisions at 200 GeV

Systematic study of nuclear effects in $p + \mathrm{Al}$, $p + \mathrm{Au}$, $d + \mathrm{Au}$, and $^3\mathrm{He} + \mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV using π^0 production

U. A. Acharya *et al.* (PHENIX Collaboration)
Phys. Rev. C **105**, 064902 – Published 6 June 2022

Minimum Bias: 0- 100% centrality Class



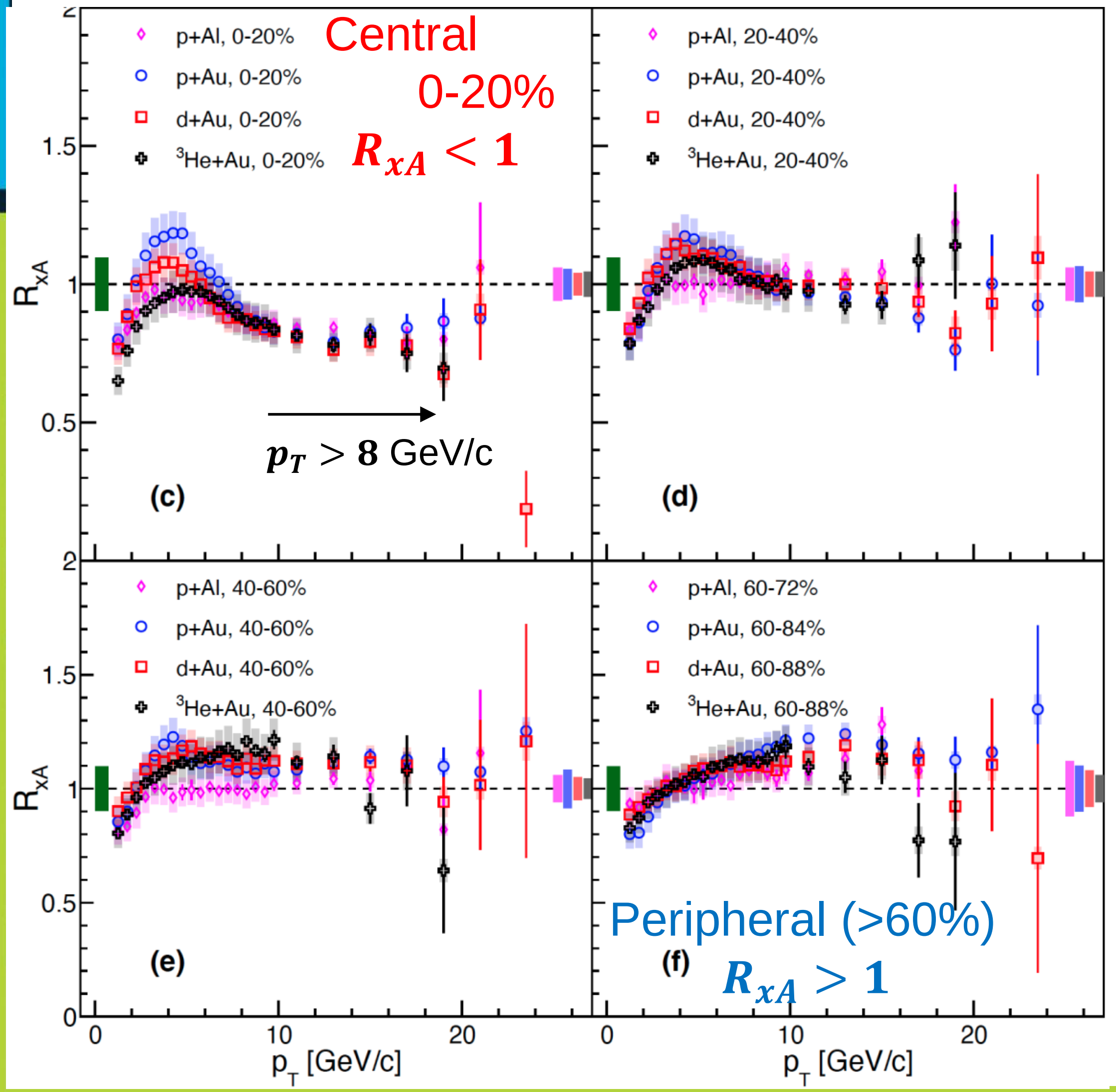
Obtained from measurements of Invariant Yield of π^0

$$R_{xA}(p_T) = \frac{Y_{xA}(p_T)}{\langle N_{coll}\rangle\, Y_{pp}(p_T)}$$

- **Cronin peak in intermediate range $2 < p_T < 6$ GeV/c**
  - **Peak increase with "target" A in p+A**
  - **Broadening/decrease/shift of peak with increasing "projectile" p+Au → d+Au → ³He+Au**

Hint of QGP Droplets in Small Systems

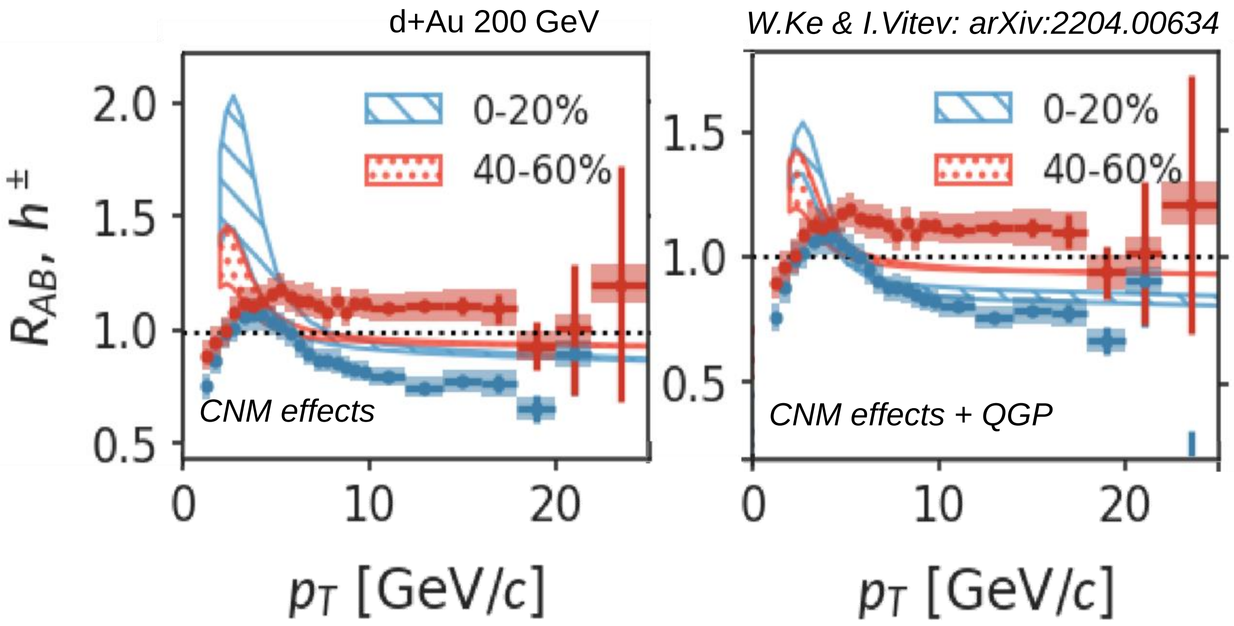
Systematic study of nuclear modification factor of inclusive π^0 in small systems in different centralities.



Systematic study of nuclear effects in $p+\mathrm{Al}$, $p+\mathrm{Au}$, $d+\mathrm{Au}$, and $^3\mathrm{He}+\mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV using π^0 production

U. A. Acharya *et al.* (PHENIX Collaboration)
Phys. Rev. C **105**, 064902 – Published 6 June 2022

- π^0 R_{xA} from pAu, dAu, ³HeAu
  - Central: 20% suppression - consistent with energy loss
  - Peripheral: 15 % enhancement - unexplained, likely due to selection bias



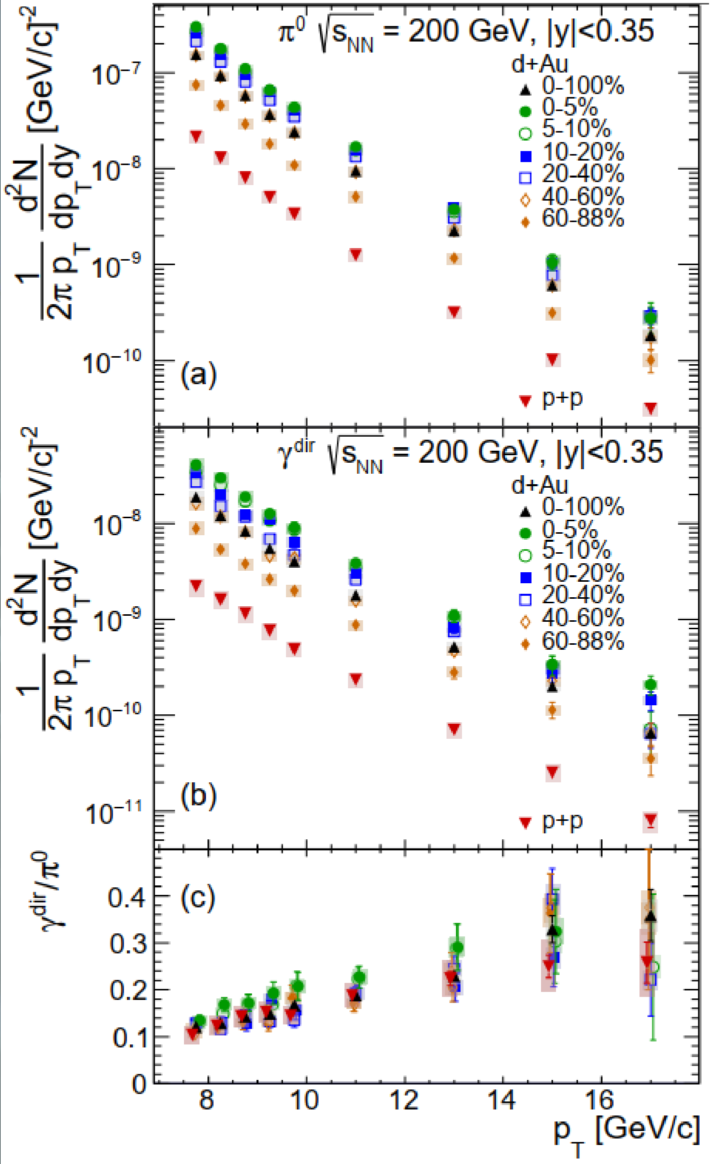
- **Similar observations at RHIC & LHC**

Inconclusive R_{xA} for high p_T in small systems
bias or final state effects?

Hint of QGP Droplets in Small Systems

Disentangling centrality bias and final-state effects in the production of high-p_T π^0 using direct γ in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

π^0 / γ^{dir} p_T-spectra



Search for final state effects simultaneous measure direct γ and π^0

- **No nuclear modification of direct γ**
  - Au+Au direct γ scale with N_{coll}

$$R_{AB}^{\gamma^{dir}}(p_T) = \frac{Y_{AB}^{\gamma^{dir}}(p_T)}{N_{coll}\, Y_{pp}^{\gamma^{dir}}(p_T)} \sim 1$$

- Use direct γ to measure factor "N_{coll}" to scale hard scattering processes

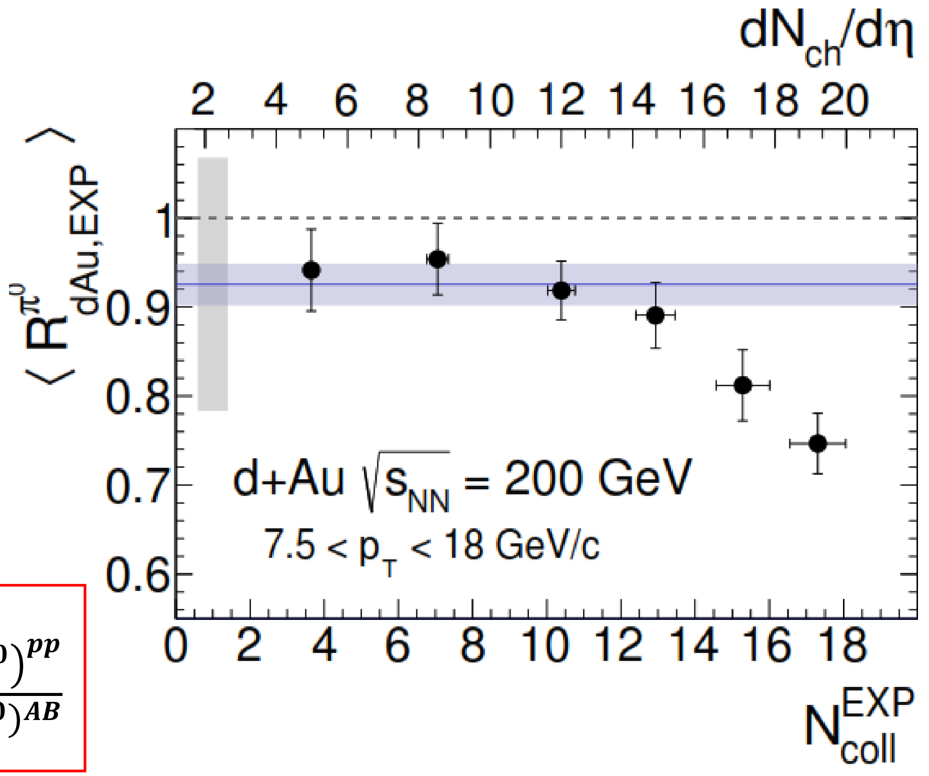
$$N_{coll}^{EXP} = \frac{Y_{AB}^{\gamma^{dir}}(p_T)}{Y_{pp}^{\gamma^{dir}}(p_T)}$$

- Redefine Nuclear Modification Factor

$$R_{AB,EXP}^{\pi^0}(p_T) = \frac{Y_{AB}^{\pi^0}(p_T)}{Y_{pp}^{\pi^0}(p_T)} \times \frac{Y_{pp}^{\gamma^{dir}}(p_T)}{Y_{AB}^{\gamma^{dir}}(p_T)} = \frac{(\gamma^{dir}/\pi^0)^{pp}}{(\gamma^{dir}/\pi^0)^{AB}}$$

arXiv > nucl-ex > arXiv:2303.12899

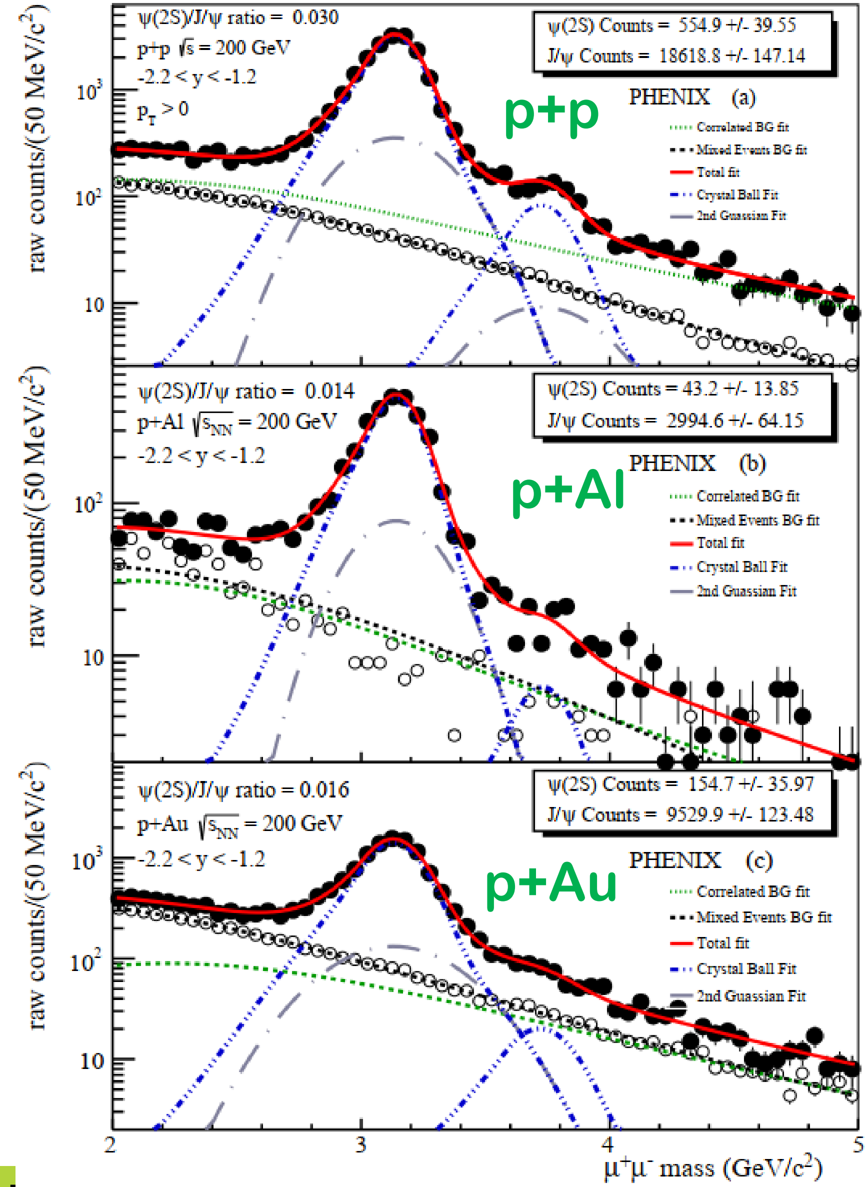
Submitted for Publication in PRL



- ❖ First evidence for significant 20% final state suppression of high p_T π^0 (7.5 to 18 GeV/c) in central 0–5% d+Au collisions
- ❖ Previously observed enhancement of π^0 R_{dAu} in peripheral events due to event selection bias
  - ➢ Experimental determination of N_{coll} removes event selection bias
- ❖ Suppression of π^0 in most central collisions suggests possible energy loss due to QGP formation.

Hint of QGP Droplets in Small Systems

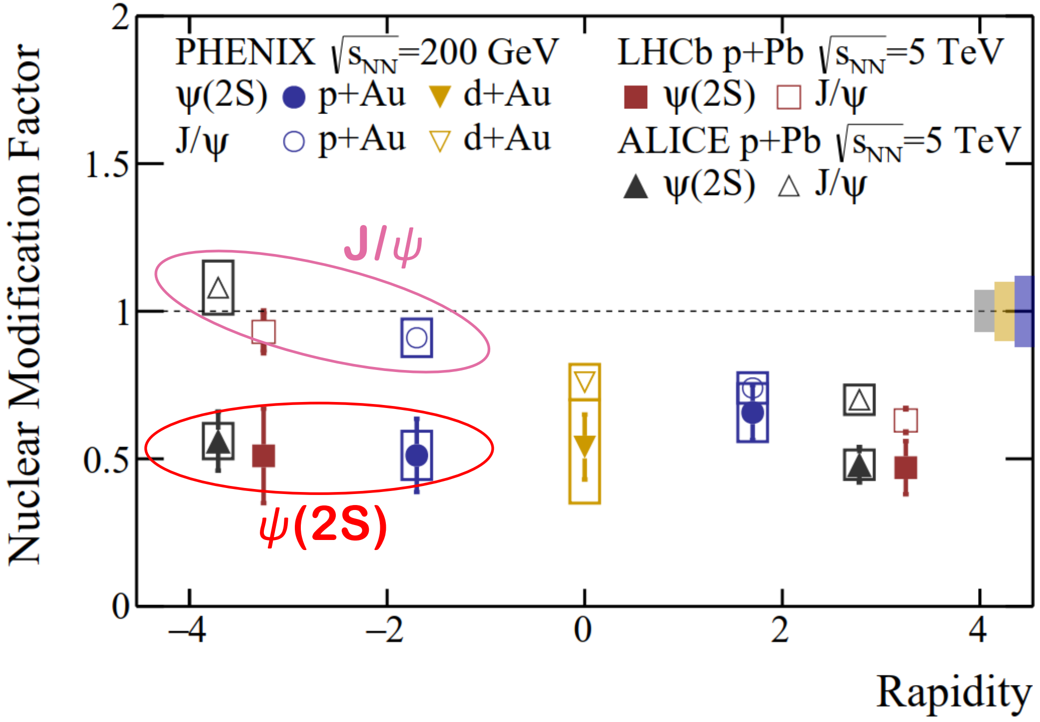
Invariant mass spectra



Editors' Suggestion

Measurement of $\psi(2S)$ nuclear modification at backward and forward rapidity in $p+p$, $p+\mathrm{Al}$, and $p+\mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV

U. A. Acharya *et al.* (PHENIX Collaboration)
Phys. Rev. C **105**, 064912 – Published 29 June 2022



- J/ψ and ψ(2S) modification similar at forward rapidity:
  → Hint initial state effects dominate charmonium production
- PHENIX, LHCb, and ALICE at backward rapidity:
  - ψ(2S) is more suppressed than J/ψ: $R_{AB}(J/\psi) > R_{AB}(\psi(2S))$.

Summary

- Without doubt RHIC is amazing QCD machine
  - Many species, many energies, high luminosity, and very stable beam
- Spin Physics Results
  - Isolated direct photons measurements show Δg is positive in polarized p+p collisions
  - Prob gluon dynamics through A_N(HF) measurements in p+p collisions
  - High precision $A_N(\pi^0,\eta)$ at mid-rapidity: no nuclear modification in p+Al and p+Au collisons
- Large System AuAu at 200 GeV
  - Nonprompt γ^{dir} directly sensitive to early emission prior to hadron gas formation
- Small systems p+Al, p+Au, d+Au, ^{3}He+Au at 200 GeV
  - v_2/v_3 consistent with geometrical ordering expected from hydro expansion and well reproduced by the recent theoretical model calculations.
  - First evidence for significant 20% final state suppression of high p_T π^0 (7.5 to 18 GeV/c) in 0-5% d+Au
  - Suppression ψ(2S) at backward rapidity indication final state effect in p+Au collisions
- PHENIX is using Golden data (runs-12-16 high statistic); heavy flavor physics is under exploration. Careful analysis with new approaches are ongoing and many preliminary results will be submitted for publication soon.

Thank you!

Auxiliaries Slides

ϕ Production

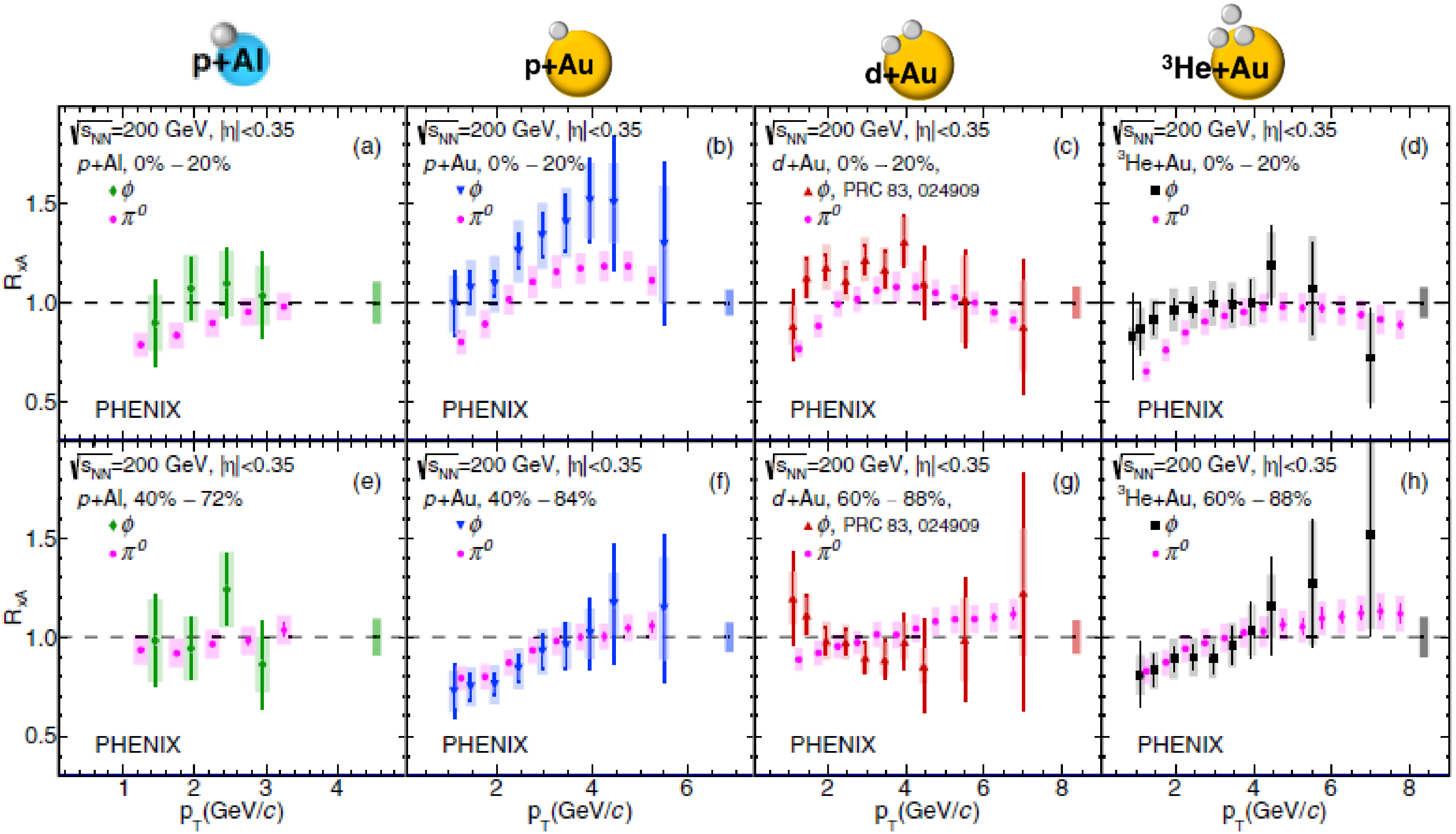
ϕ meson production in $p+\mathrm{Al}$, $p+\mathrm{Au}$, $d+\mathrm{Au}$, and $^3\mathrm{He}+\mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV

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

Strangeness (ϕ Meson) Production in Small System

Remarks on ϕ production:

➢ In the early state of high-energy collisions, strangeness is produced in flavor creation (gg→ss, qq→ss) and flavor excitation (gs→gs, qs→qs). Strangeness is also created during the subsequent partonic evolution via gluon splittings (g→ss). These processes tend to dominate the production of high-p_T strange hadrons.



- The ϕ meson production in the most central collisions shows a trend to less suppression than the π^0 meson production at moderate p_T.

- The *RxA* for both mesons are in agreement within uncertainties.

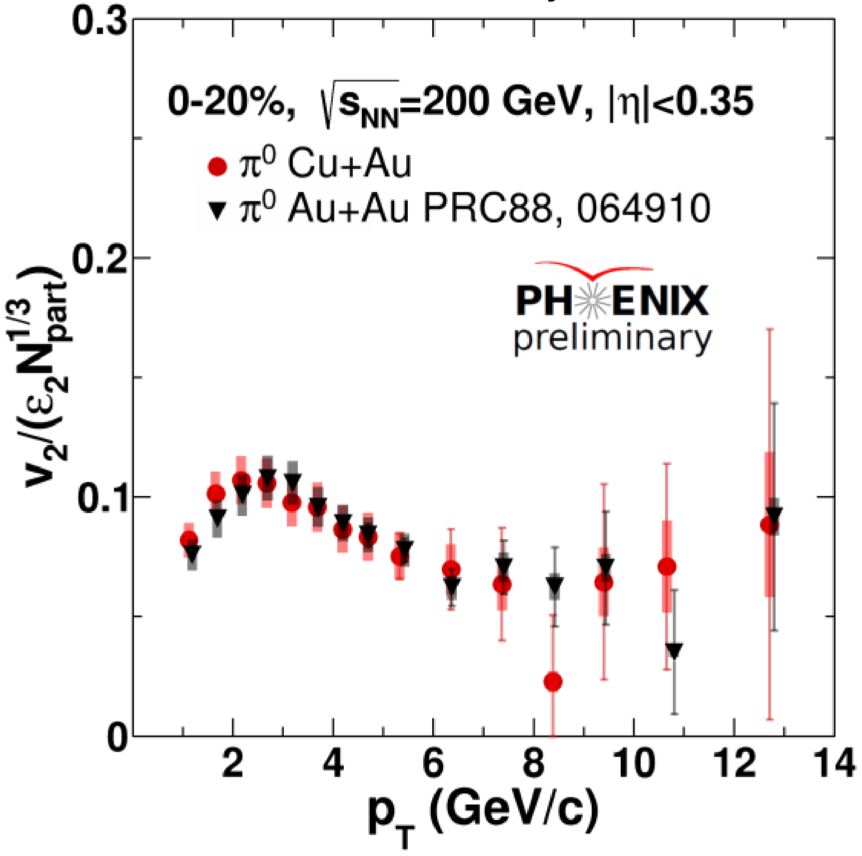
Within present statistic, comparison of ϕ (s, $\bar{s}$) to π^0 (u, d) shows no clear strangeness enhancement.

PHENIX New Analysis Results (Preliminary)

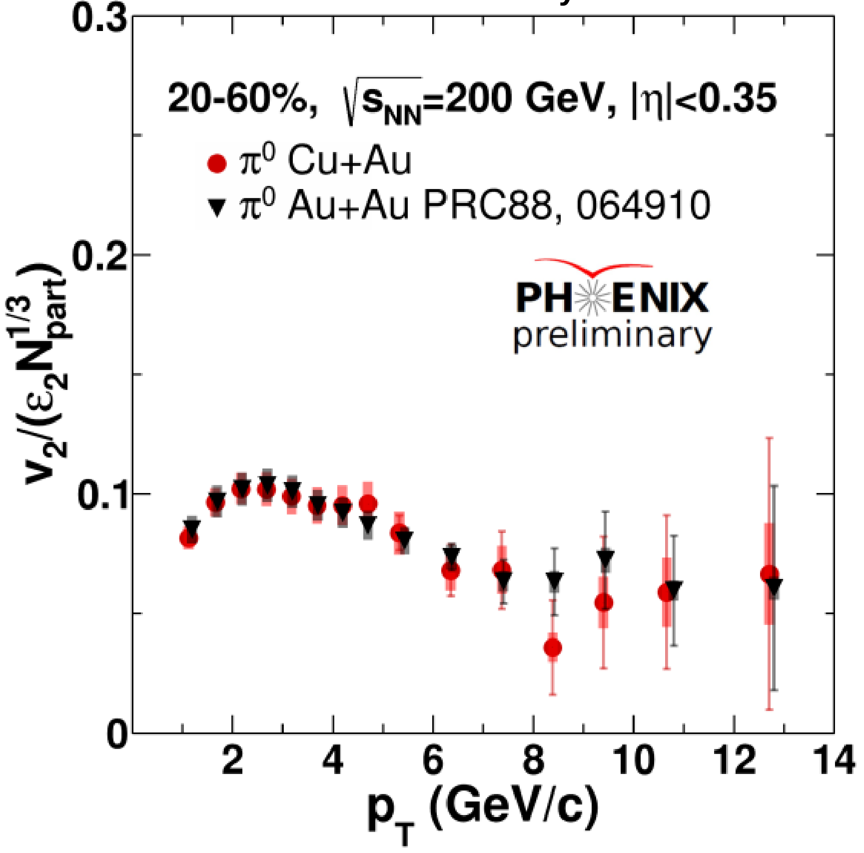
What else about π^0 ?

π^0 flow vs p_T in Cu+Au vs Au+Au

0-20% centrality Class



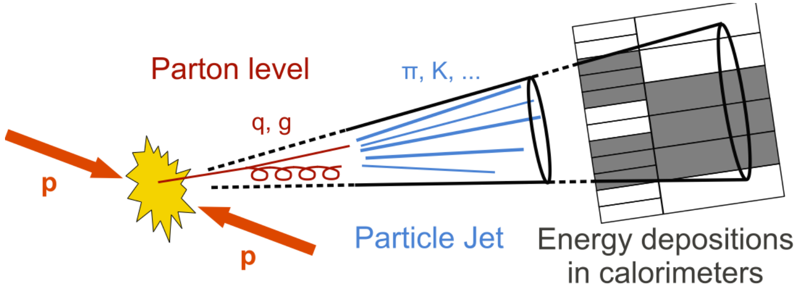
20-60% Centrality Class



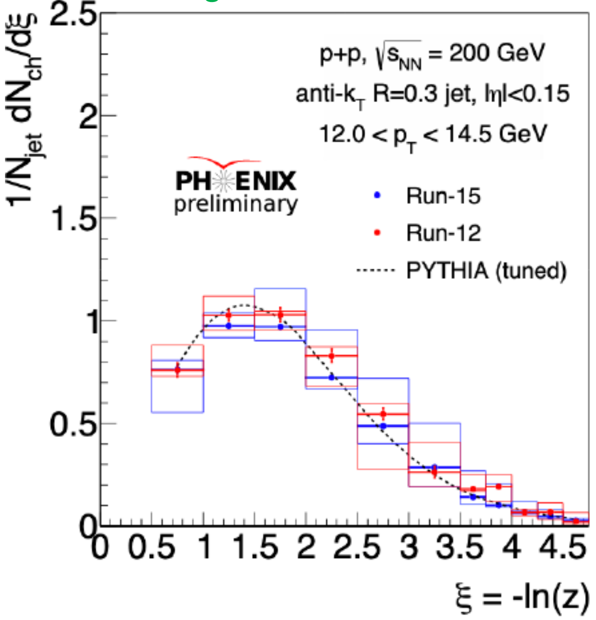
- In both system at the same energy, v_2 scales with eccentricity * system size (ε_2 * $(N_{part})^{1/3}$) even at high p_T, where this is not hydro…

PHENIX New Analysis Results (Preliminary)

Jet substructure in p+p collisions

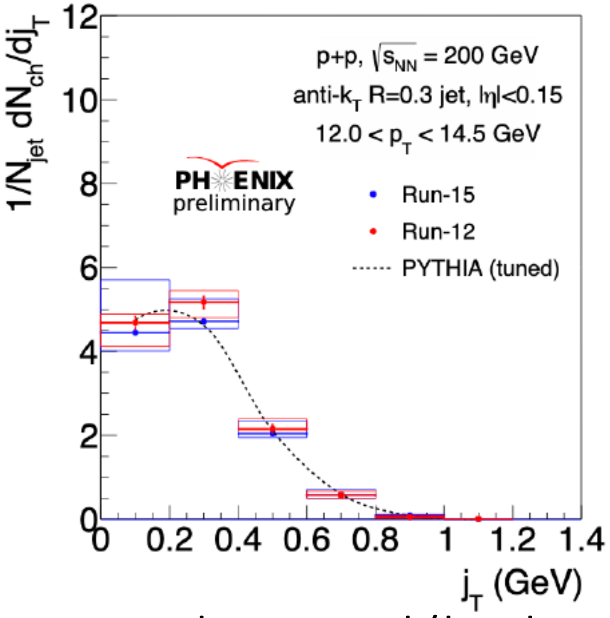


Fragmentation function



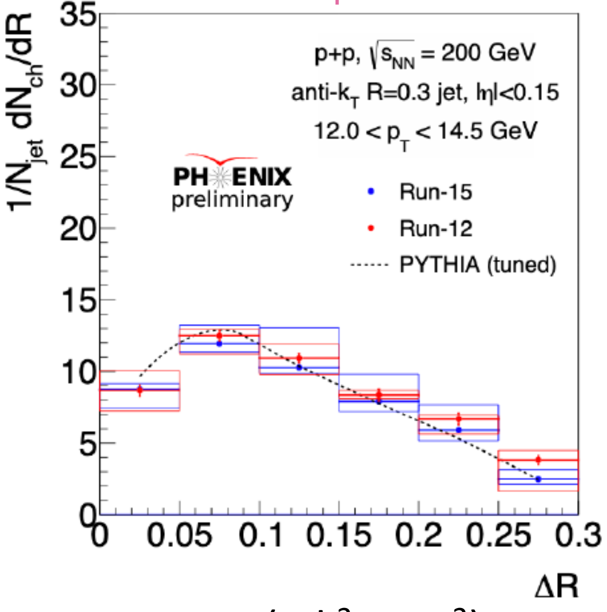
$\xi = -\ln(z) = \ln(p_{T,jet}/p_{T,h})$

Transverse fragmentation



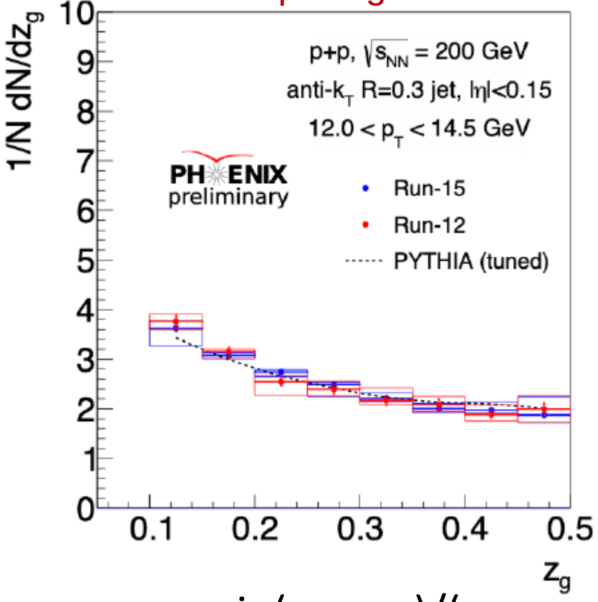
$j_T = |p_{jet} \times p_{track}| / |p_{jet}|$

Radial profile



$\Delta R = \sqrt{(\Delta\phi^2 + \Delta\eta^2)}$

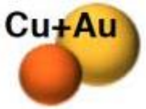
Jet splitting function



$z_g = \min(p_{T1}, p_{T2})/(p_{T1} + p_{T2})$

- PHENIX measured jet substructure in pp (shown for $12 < p_T < 14.5$ GeV jets)
- pp data from Run 12, 15 ; 2D unfolding and tuned PYTHIA (dashed lines)
- Baseline for ongoing jet substructure measurements in p+A and A+A

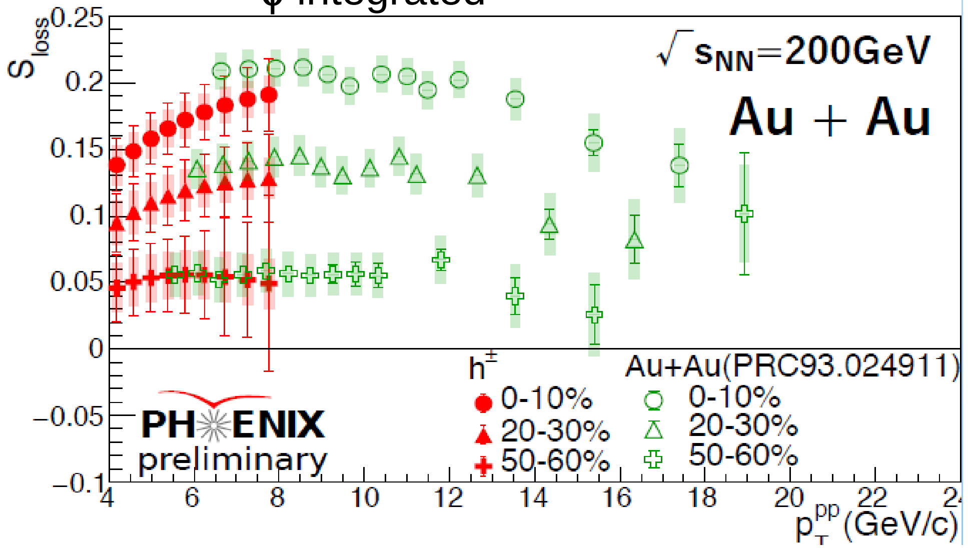
PHENIX New Analysis Results (Preliminary)



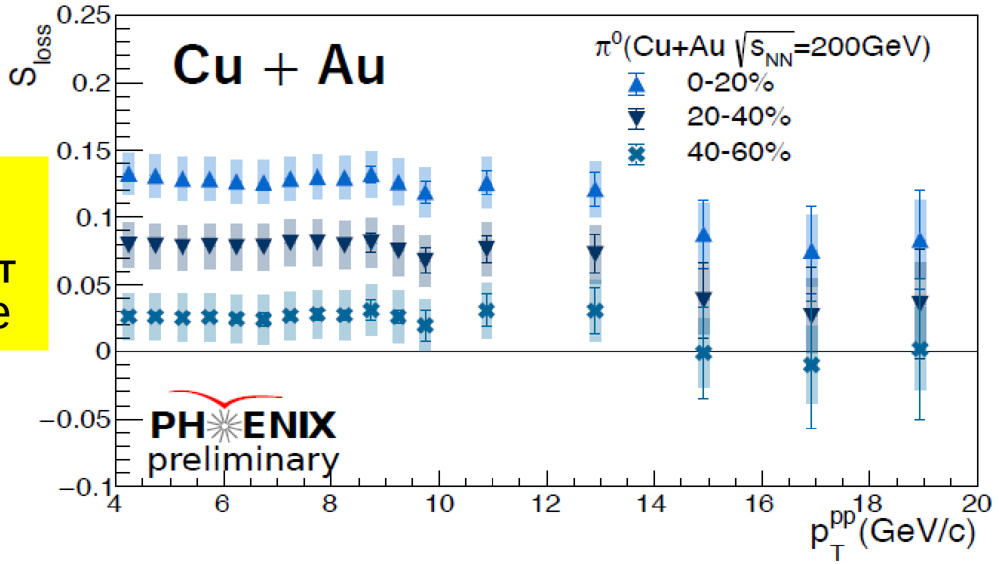
Charged hadron S_{loss} vs reaction plane in A+B

$$S_{loss} \equiv \delta p_T / p_T = \frac{p_T^{pp} - p_T^{AA}}{p_T^{pp}}$$

ϕ-integrated

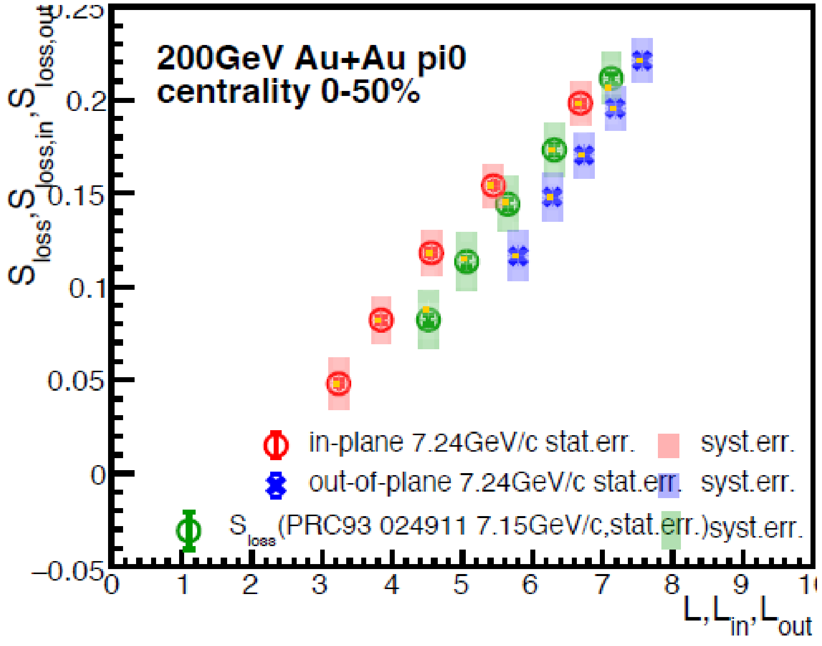


π^0 and h similar



π^0 only
No strong p_T dependence

ϕ-differential (in-plane, out-of-plane)



Different values and evolution with L in-plane and out-of-plane