Recent Results from PHENIX

Ron Belmont, University of North Carolina at Greensboro

A. Gáspár: Calculate the Entropy XIV

23rd ZIMÁNYI SCHOOL

WINTER WORKSHOP

ON HEAVY ION PHYSICS

December 4-8, 2023

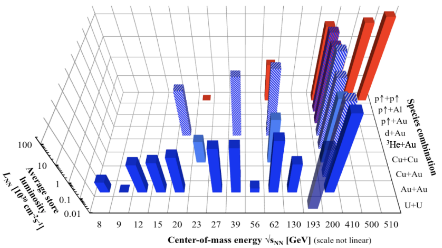
Budapest, Hungary

József Zimányi (1931 - 2006)

Data collected

Run	Species	Energy $\sqrt{s_{NN}}$ (GeV)	Integrated Luminosity (mb^{-1})
1 (2000)	Au+Au	56	1.0E-6
2 (2001/2002)	Au+Au	200	2.4E-5
	p+p	200	1.5E+5
3 (2003)	d+Au	200	2.7E+3
	p+p	200	3.5E+5
4 (2004)	Au+Au	200	2.4E+2
	Au+Au	62.4	9.0E+0
5 (2005)	Cu+Cu	200	3.0E+3
	Cu+Cu	62.4	1.9E+2
	Cu+Cu	22.4	2.7E+3
	p+p	200	3.4E+6
6 (2006)	p+p	200	7.5E+6
	p+p	62.4	8.0E+4
7 (2007)	Au+Au	200	8.1E+2
8 (2008)	d+Au	200	8.0E+4
	p+p	200	5.2E+6
9 (2009)	p+p	500	1.4E+7
	p+p	200	1.6E+7
10 (2010)	Au+Au	200	1.5E+3
	Au+Au	62.4	1.1E+2
	Au+Au	39	4.0E+4
	Au+Au	7.7	3.0E+2

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

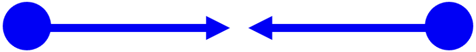


Completed taking data in 2016
Many high impact analyses ongoing

Run	Species	Energy $\sqrt{s_{NN}}$ (GeV)	Integrated Luminosity (mb^{-1})
11 (2011)	p+p	500	1.8E+7
	Au+Au	19.6	2.0E+0
	Au+Au	200	1.7E+3
	Au+Au	27	7.0E+0
12 (2012)	p+p	200	1.0E+7
	p+p	510	3.2E+7
	U+U	193	2.0E+2
	Cu+Au	200	5.0E+3
13 (2013)	p+p	510	1.6E+8
14 (2014)	Au+Au	14.6	4.0E+0
	Au+Au	200	7.5E+3
	^{3}He+Au	200	2.4E+4
15 (2015)	p+p	200	6.0E+7
	p+Au	200	2.0E+5
	p+Al	200	5.0E+5
16 (2016)	Au+Au	200	7.0E+3
	d+Au	200	5.0E+4
	d+Au	62.4	5.0E+3
	d+Au	19.6	8.0E+1
	d+Au	39	2.0E+3

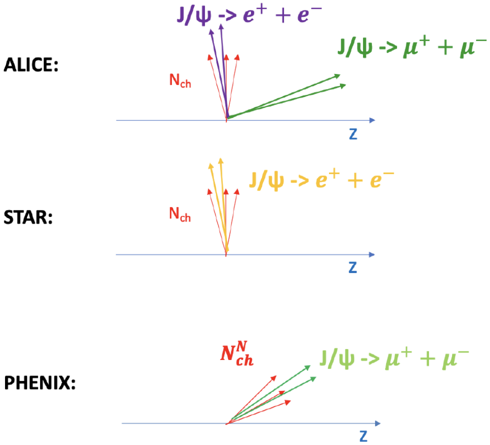
Recent Papers

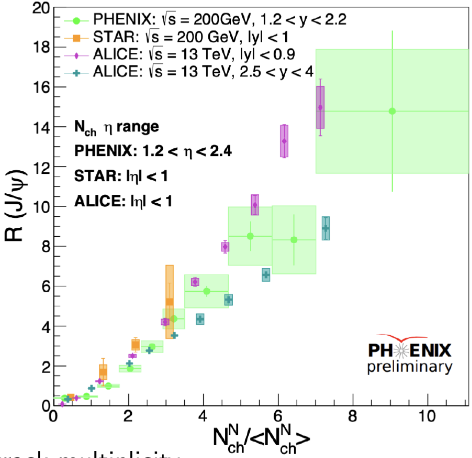
- PRL130, 251901 (2023) Direct γ cross section in p+p $\sqrt{s} = 510$ GeV
- PRD107, 112004 (2023) Transverse spin asymmetry of π^0, η in p+Al and p+Au $\sqrt{s_{NN}} = 200$ GeV
- PRD107, 052012 (2023) Transverse spin asymmetry of heavy flavor decay electrons
- PRC107, 024907 (2023) Flow in p+p, p+Al, d+Au, ^{3}He+Au $\sqrt{s_{NN}} = 200$ GeV
- PRC107, 024914 (2023) Low p_T γ in Au+Au at $\sqrt{s_{NN}} = 39$ and 62.4 GeV
- PRC107, 014907 (2023) ϕ in Cu+Au and U+U $\sqrt{s_{NN}} = 200$ GeV
- PRC106, 014908 (2022) ϕ in p+p, p+Al, d+Au, ^{3}He+Au $\sqrt{s_{NN}} = 200$ GeV
- PRC105, 064912 (2022) $\psi(2S)$ in p+p, p+Al, and p+Au $\sqrt{s_{NN}} = 200$ GeV
- arXiv:2303.12899 Suppression of high p_T π^0 relative to direct γ in central d+Au $\sqrt{s_{NN}} = 200$ GeV
- arXiv:2303.07191 Transverse spin asymmetry of $h^\pm$ in p+p, p+Al, and d+Au $\sqrt{s_{NN}} = 200$ GeV
- arXiv:2203.17187 Non-prompt γ in Au+Au $\sqrt{s_{NN}} = 200$ GeV
- arXiv:2203.17058 Charm and bottom production in Au+Au $\sqrt{s_{NN}} = 200$ GeV



p+p

J/ψ yield in $p+p$





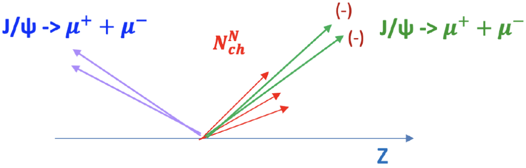
- J/ψ yield exhibits large dependence on local track multiplicity
—Usually attributed to multi-parton interactions

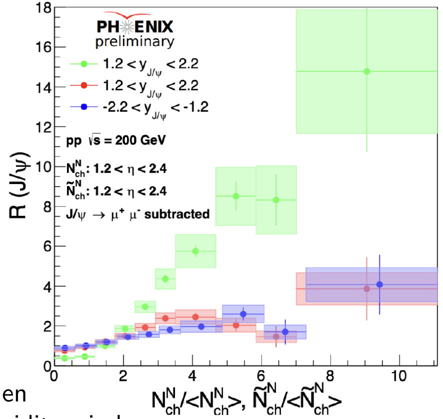
J/ψ yield in $p+p$

J/ψ and tracks in the same rapidity

J/ψ and tracks in the opposite rapidity

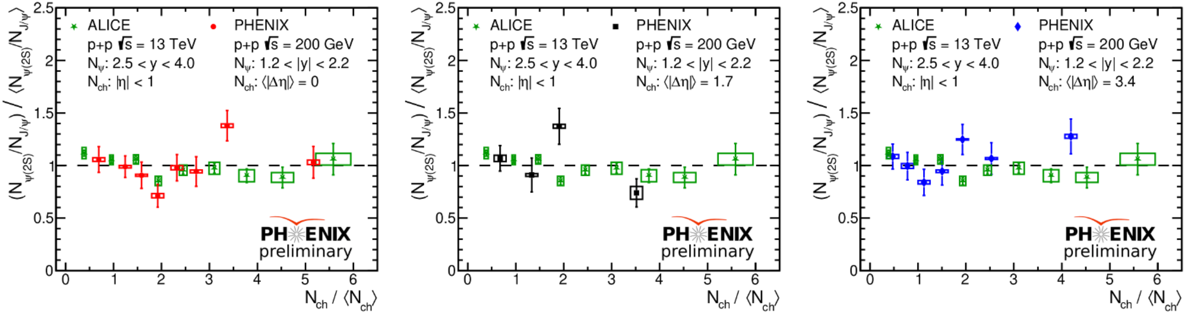
J/ψ and tracks in the same rapidity, tracks from J/psi removed from track count





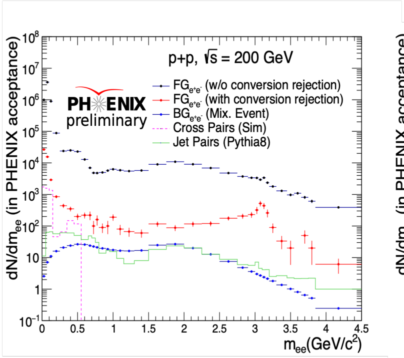
- J/ψ yield vs multiplicity significantly reduced when
  - —Looking at J/ψ and multiplicity in separate rapidity windows
  - —Looking at J/ψ and multiplicity in the same rapidity window but removing the $\mu^+\mu^-$ from the multiplicity
- Important implications for MPI picture

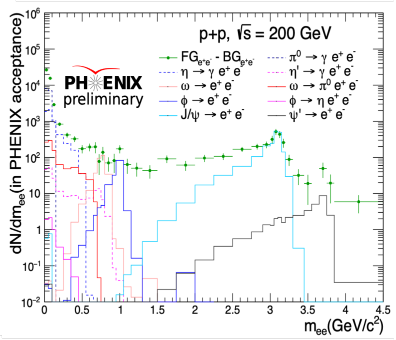
$\psi(2S)$ to J/ψ ratio in $p+p$

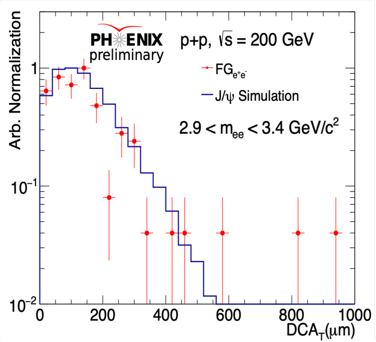


- Multiplicity-dependent studies can be used as test for onset of QGP-like signatures
- PHENIX results match ALICE results, double ratio consistent with unity for all multiplicity

Delipton invariant mass in $p+p$

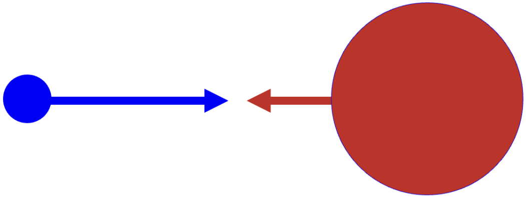






- Measurements of intermediate mass dilepton pairs
- Separation of semi-leptonic decay and prompt pairs

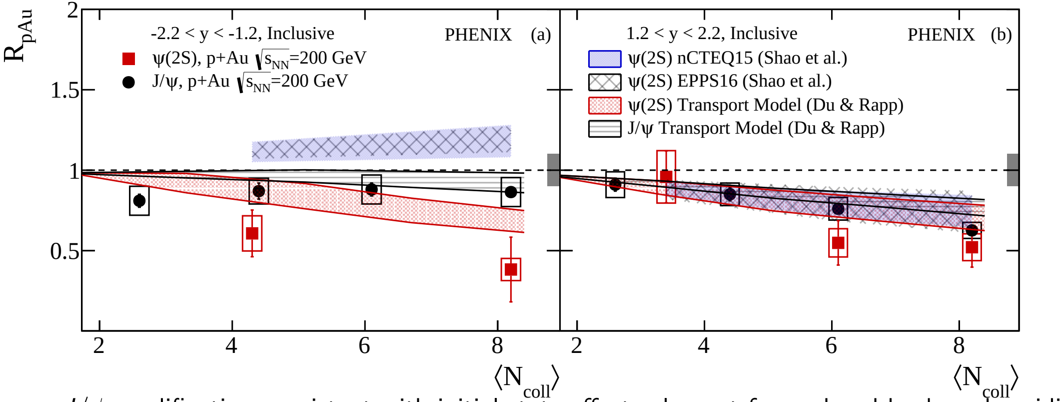
Intermission



p,d,^{3}He+Au

J/ψ and $\psi(2S)$ in small systems

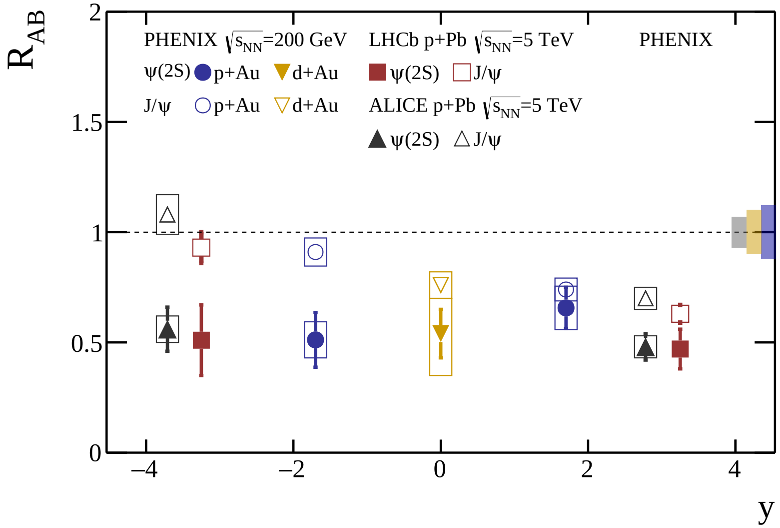
Phys. Rev. C 105, 064912 (2023)



- 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
  —Presence of co-movers? QGP?

J/ψ and $\psi(2S)$ in small systems

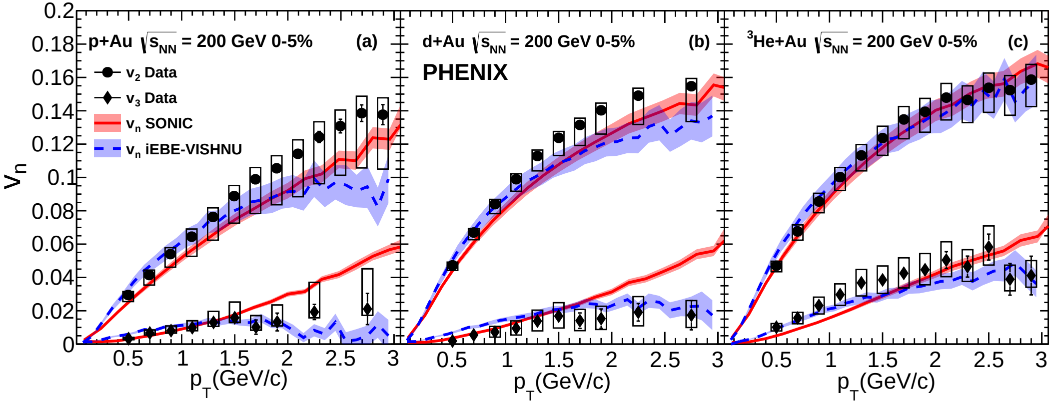
Phys. Rev. C 105, 064912 (2023)



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

v_n in small systems

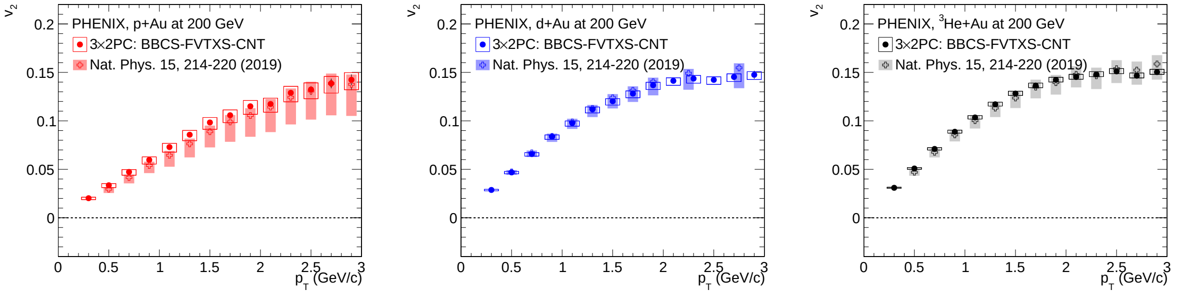
Nat. Phys. 15, 214–220 (2019)



- v_2 and v_3 vs p_T predicted or described very well by hydrodynamics in all three systems
  —All predicted (except v_2 in d+Au) in J.L. Nagle et al, PRL 113, 112301 (2014)
  —v_3 in p+Au and d+Au predicted in C. Shen et al, PRC 95, 014906 (2017)

v_n in small systems

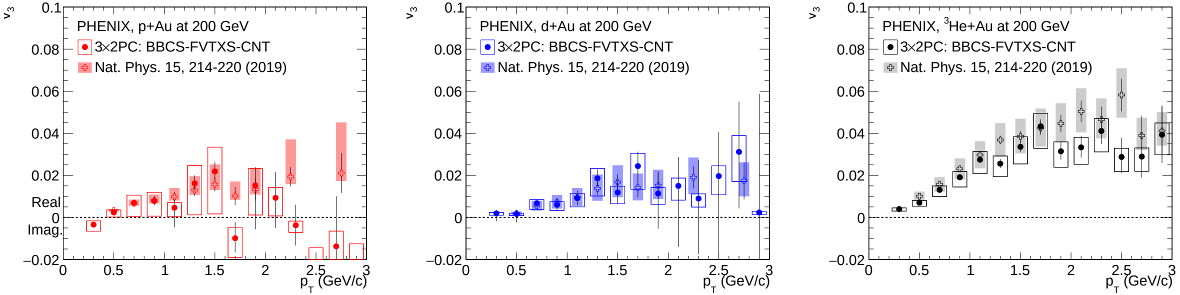
Phys. Rev. C 105, 024901 (2022)



- All new analysis using two-particle correlations with event mixing instead of event plane method used in Nature Physics publication
  —Very different sensitivity to key experimental effects (beam position, detector alignment)
- Uses same detector combination as used in Nature Physics publication

v_n in small systems

Phys. Rev. C 105, 024901 (2022)



- All new analysis using two-particle correlations with event mixing instead of event plane method used in Nature Physics publication
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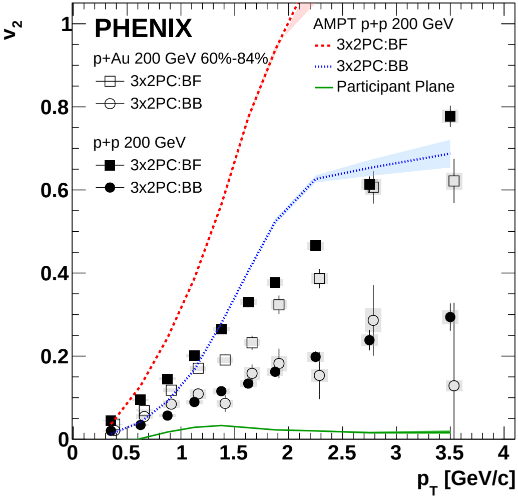
v_2 in small systems

Phys. Rev. C 107, 024907 (2023)

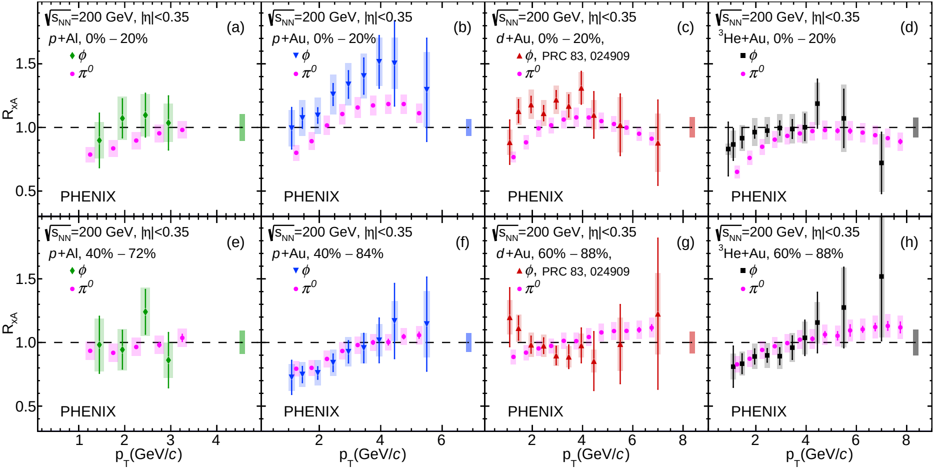


Systematic study of v_2 in small systems
—$p+p$, $p+$Au, $d+$Au, ^{3}He+Au
—Centrality dependence
—Multiple detector combinations

AMPT exhibits little or no collectivity but large v_2 due to non-flow correlations
Also shows similar relative pattern between backward-backward (BB) and backward-forward (BF)

ϕ meson in small systems

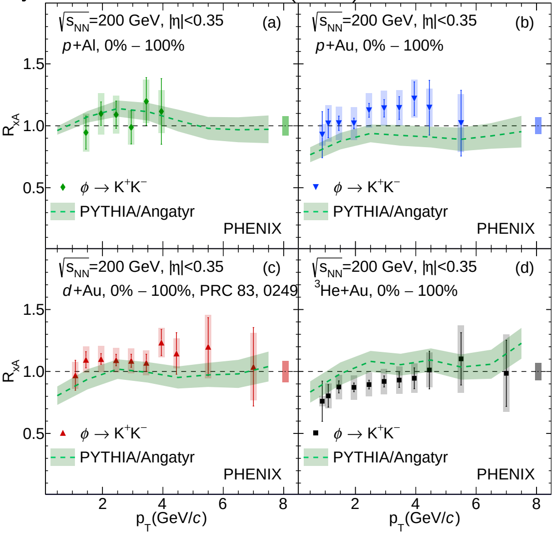
Phys. Rev. C 106, 014908 (2022)



- ϕ similar to π^0 with a few hints of a slight enhancement relative to π^0

ϕ meson in small systems

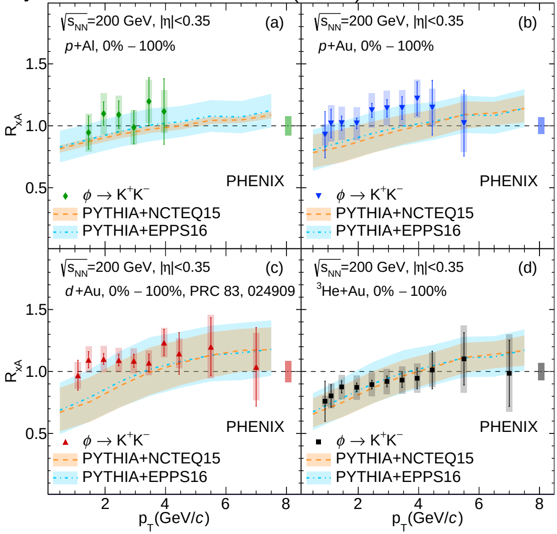
Phys. Rev. C 106, 014908 (2022)



ϕ nuclear modification reasonably well-described by PYTHIA/Angantyr, but overall system size ordering is missed

ϕ meson in small systems

Phys. Rev. C 106, 014908 (2022)

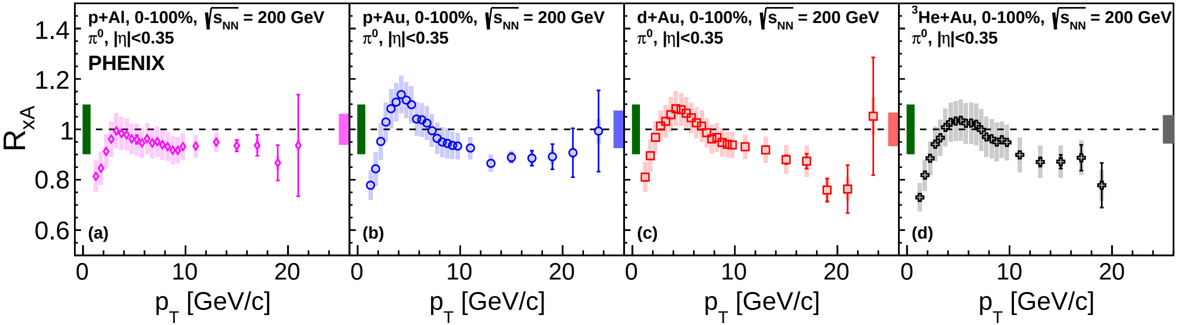


ϕ nuclear modification reasonably well-described by PYTHIA/Angantyr, but overall system size ordering is missed

Also reasonably well-described by PYTHIA with nPDFs, but overall system size ordering is missed

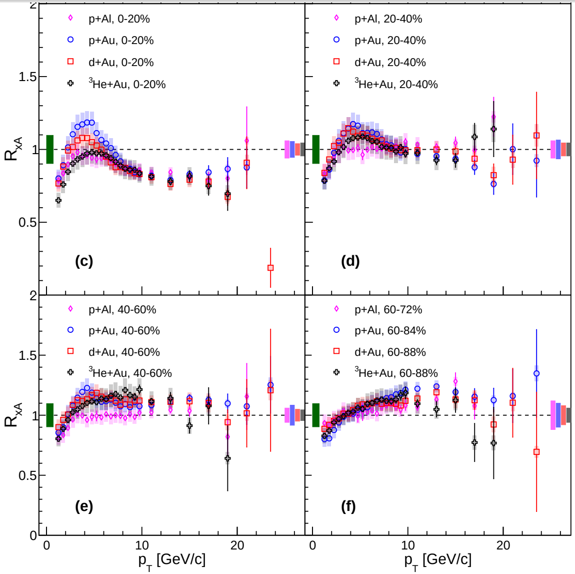
Nuclear modification of π^0 in small systems

Phys. Rev. C 105, 064902 (2022)



- Minimum bias collisions shown
- Cronin enhancement at intermediate p_T
  —Lighter target shows smaller enhancement (p+Al $<$ p+Au)
  —Heavier projectile shows smaller enhancement (^{3}He+Au $<$ d+Au $<$ p+Au)

Nuclear modification of π^0 in small systems



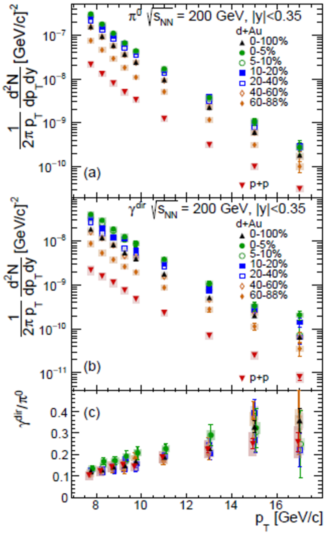
Phys. Rev. C 105, 064902 (2022)

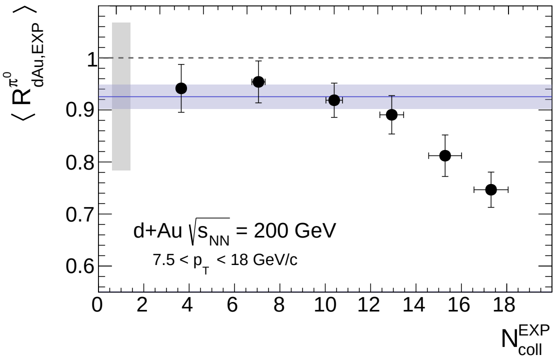
Considerable centrality dependence—suppression in central, enhancement in peripheral

Peripheral enhancement not new, but still difficult to understand...

Experimental measure of N_{coll} in small systems

arXiv:2303.12899 (submitted to Phys.Rev.C)

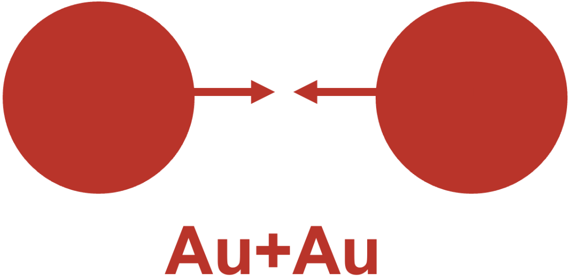




- Use electroweak probes (photons in this case) to directly measure N_{coll}
- No enhancement in peripheral
- Modest suppression in central

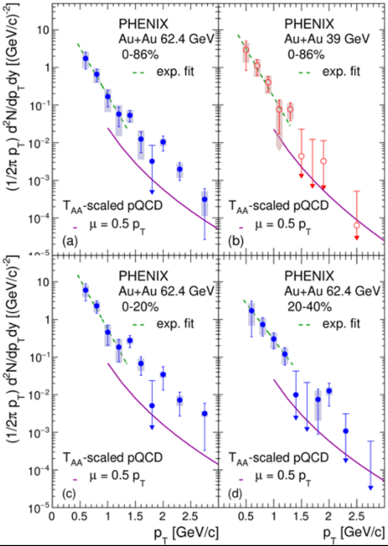
$$N^{EXP}_{coll} = \frac{Y^{\text{direct photons}}_{dAu}}{Y^{\text{direct photons}}_{pp}}$$

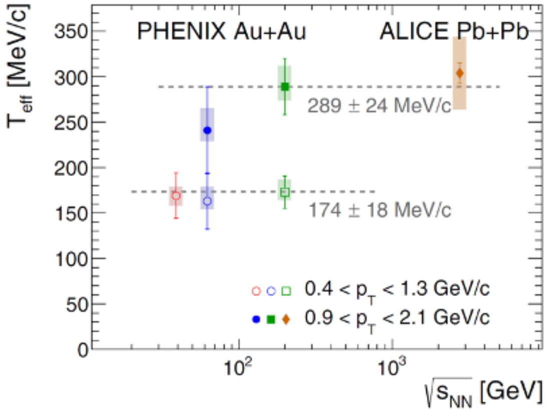
Intermission



Low p_T direct photons in Au+Au

Phys. Rev. C 107, 024914 (2023)

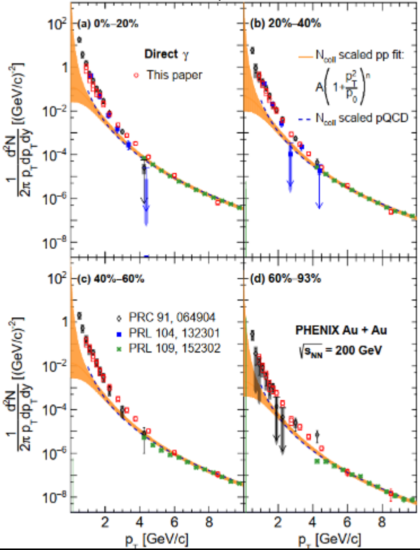




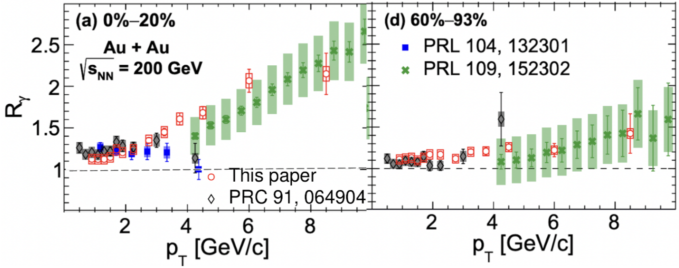
- Systematic measurement of direct photon in various systems and beam energy in wide p_T range

Direct photons in Au+Au

arXiv:2203.17187 (submitted to Phys. Rev. C)

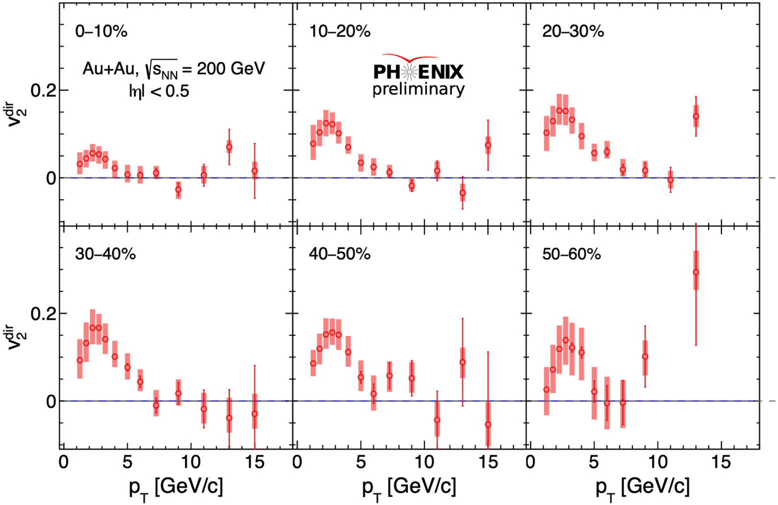


$$R_\gamma = \frac{\gamma_{inclusive}}{\gamma_{decay}}$$



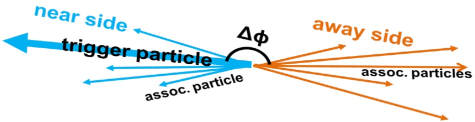
- 10x higher statistics
- Agreement with previous results
- $R_\gamma > 1 \rightarrow$ excess direct photons

Direct photon v_2 in Au+Au

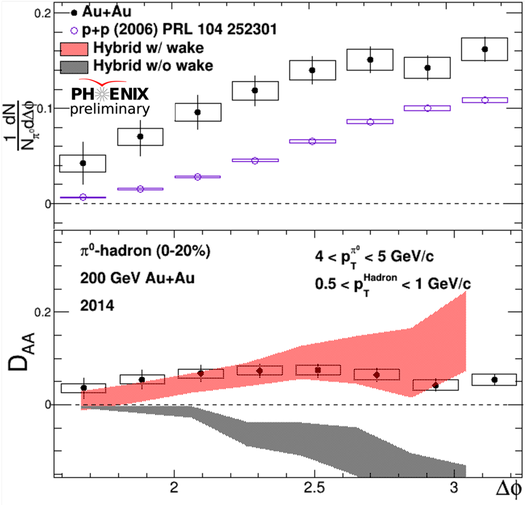


- Significant reduction in statistical and systematic uncertainties over previous measurement
- Results consistent with zero at high p_T

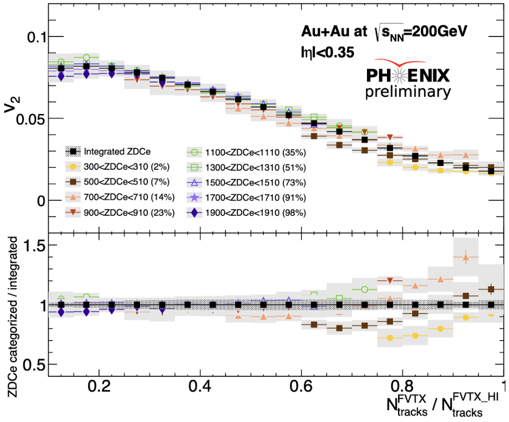
Medium response to jets in Au+Au



- Enhancement of low p_T hadrons quantified with $D_{AA} = Y_{AA} - Y_{pp}$
- Hybrid model with wake consistent with PHENIX π^0-h correlations
- Progressing towards γ^{direct}-h correlations in high statistics Au+Au data sets (2014 and 2016)

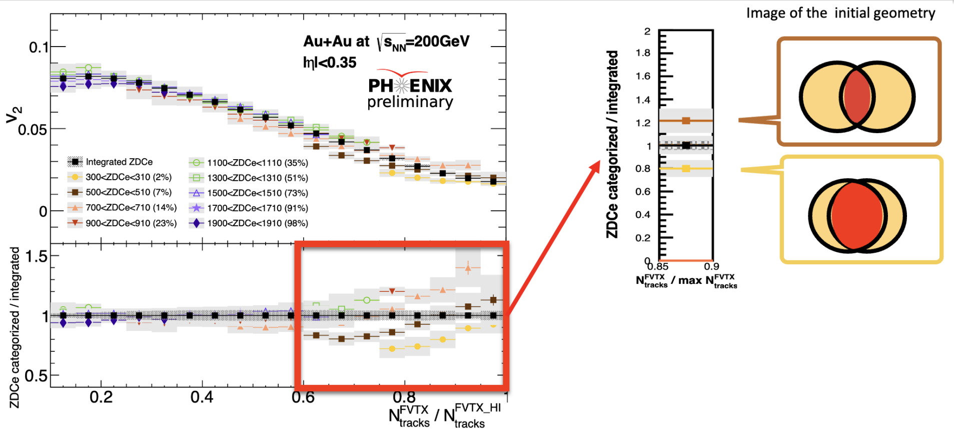


Multiplicity dependence of v_2 in different event categories in Au+Au



- Narrow selection in ZDC energy approximately fixes N_{part}
- Comparison of v_2 with same multiplicity but different ZDC energy allows study of geometry dependence—not the same as event-shape engineering, but a related idea

Multiplicity dependence of v_2 in different event categories in Au+Au



- Narrow selection in ZDC energy approximately fixes N_{part}
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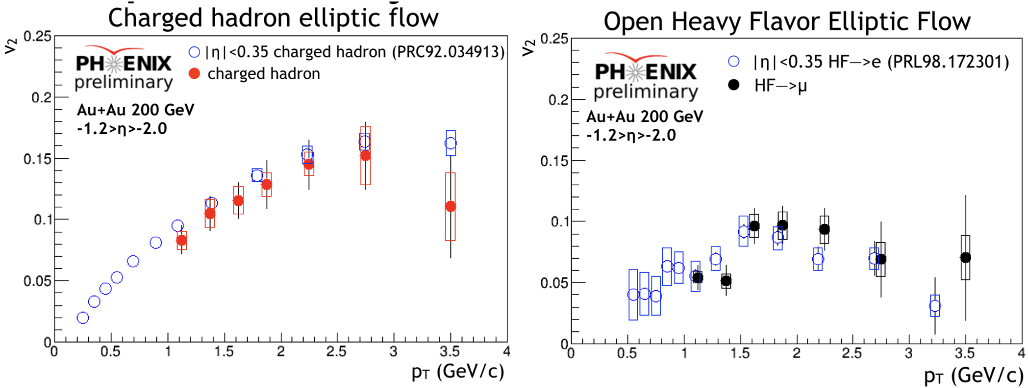
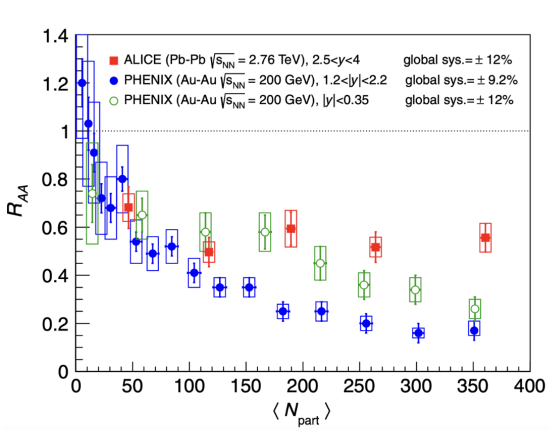
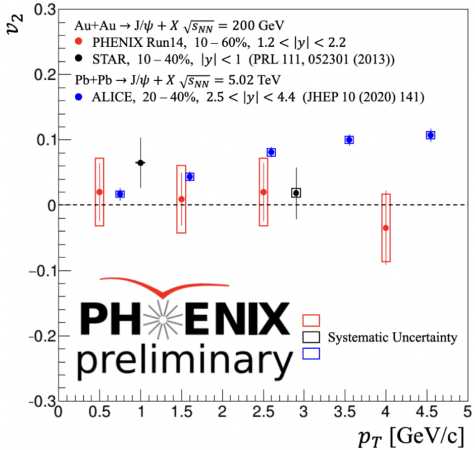
Open heavy flavor v_2 in Au+Au



- First-ever RHIC measurement of open heavy flavor elliptic flow at forward rapidity
- Mass ordering apparent

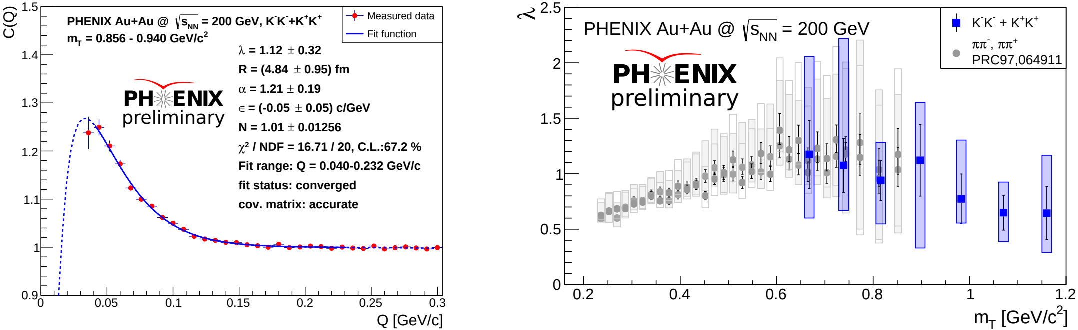
J/ψ in Au+Au





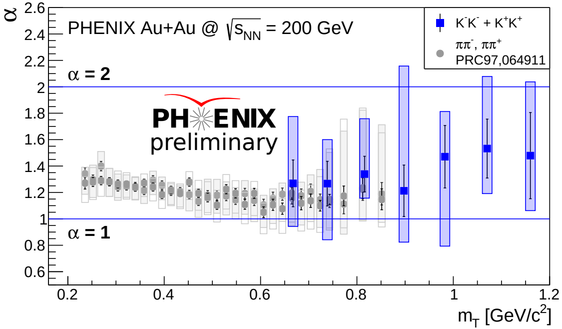
- PHENIX J/ψ shows stronger suppression at both forward and mid-rapidity compared to ALICE
- PHENIX J/ψ v_2 consistent with zero, while clearly non-zero in ALICE data
- At RHIC energies, regeneration not as significant

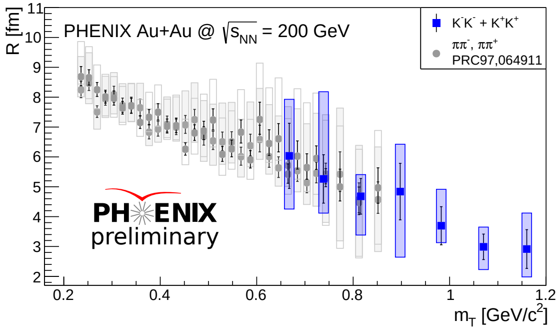
Kaon femtoscopy in Au+Au



- Femtoscopy with $K^{\pm}$ and assuming Lévy source
- λ describes strength of correlation
- α describes shape of distributions—$\alpha = 2$ is Gaussian, $\alpha = 1$ is Cauchy
- R is width parameter (similar to but not same as standard Gaussian radius)

Kaon femtoscopy in Au+Au





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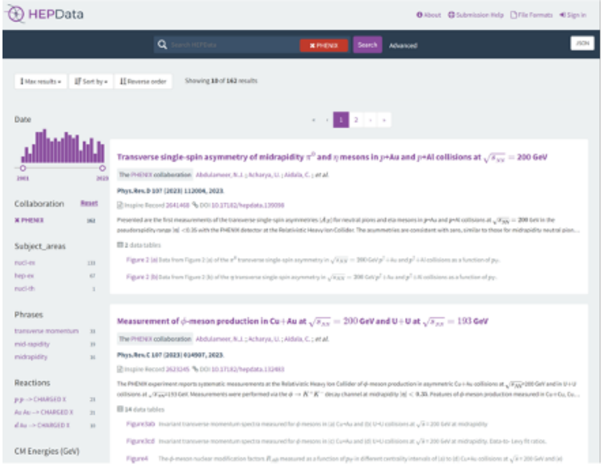
- 192/218 PHENIX papers on HEPData
- REANA is a framework of analysis preservation
- Analysis environment (libraries, etc) are in container (Docker)
- Workflow in YAML
- π^0 and direct γ d+Au analyses implemented



Brief summary and outlook

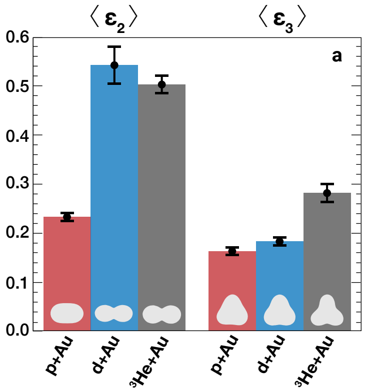
- Evidence of final state effects in charmonium production in small systems at RHIC
- Evidence of centrality determination bias in high-p_T particle R_{xA} in small systems, can use direct photons to correct for this bias
  —No enhancement in peripheral collisions
  —Suppression in central collisions
- Comprehensive set of small systems flow measurements
- First measurement of open heavy flavor v_2
- Zero v_2 for J/ψ (and stronger suppression compared to LHC)
  —Regeneration less important RHIC energies
- New results on femtoscopy with charged kaons
- More interesting and important measurements from PHENIX coming soon!

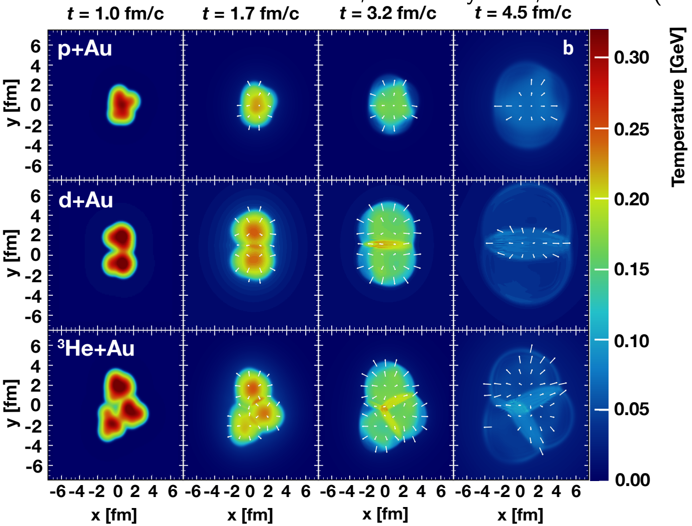
Additional Material

Additional Material

Small systems geometry scan

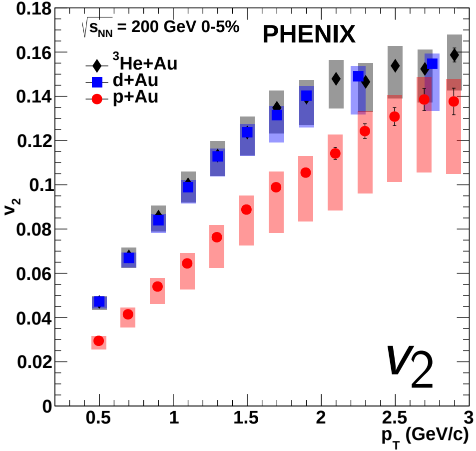
PHENIX, Nat. Phys. 15, 214–220 (2019)

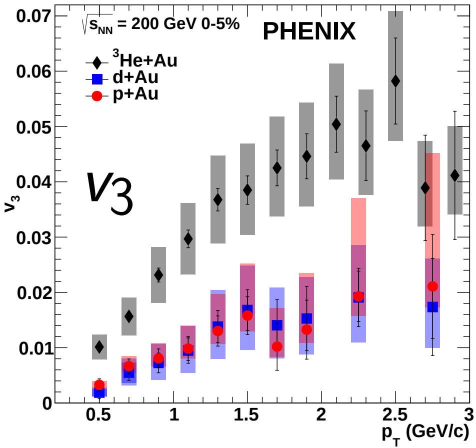




Small systems geometry scan

PHENIX, Nat. Phys. 15, 214–220 (2019)

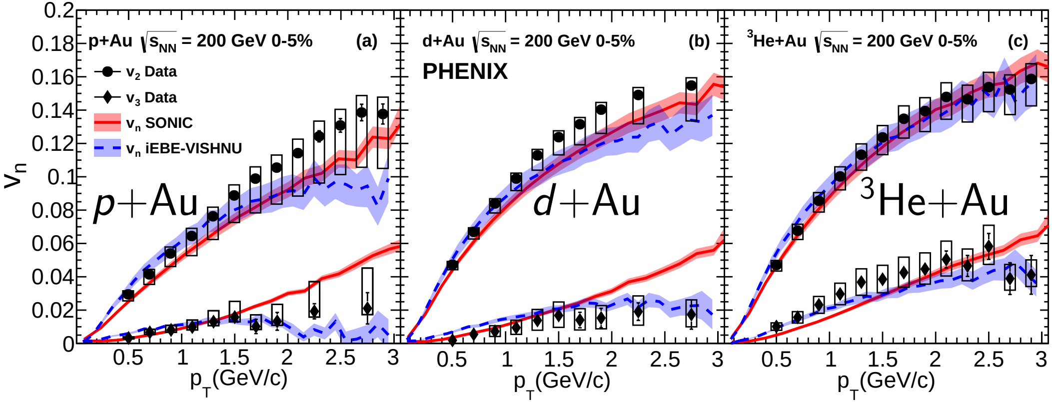




- v_2 and v_3 ordering matches ε_2 and ε_3 ordering in all three systems
  —Collective motion of system translates the initial geometry into the final state

Small systems geometry scan

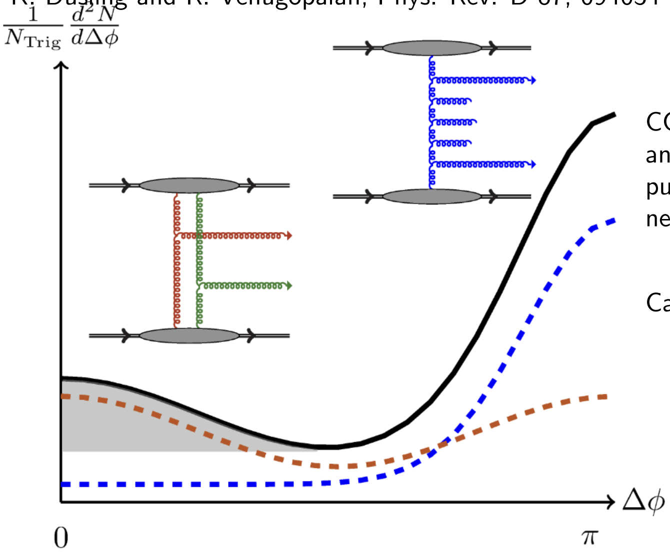
PHENIX, Nat. Phys. 15, 214–220 (2019)



- v_2 and v_3 vs p_T predicted or described very well by hydrodynamics in all three systems
  —All predicted (except v_2 in d+Au) in J.L. Nagle et al, PRL 113, 112301 (2014)
  —v_3 in p+Au and d+Au predicted in C. Shen et al, PRC 95, 014906 (2017)

Can initial state effects explain the data?

K. Dusling and R. Venugopalan, Phys. Rev. D 87, 094034 (2013)

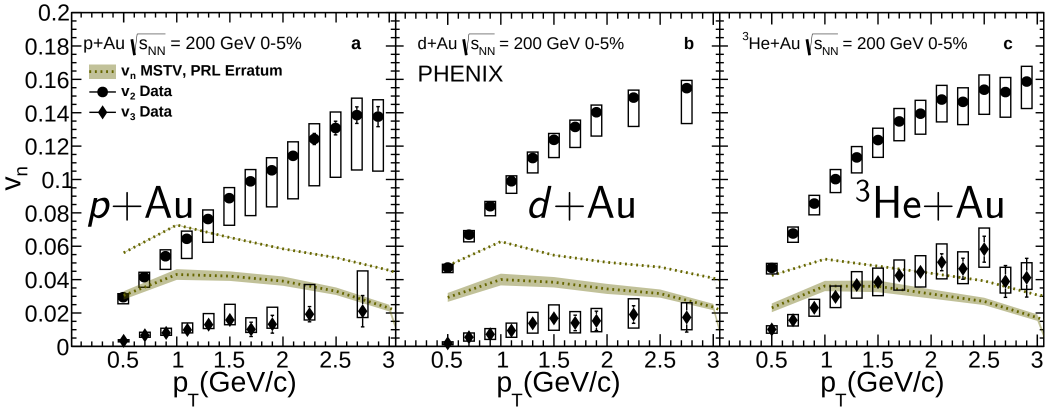


CGC framework: glasma diagrams produce angular correlations like the ridge and v_n purely from initial state correlations, with no need for final state interactions (hydro)

Can they explain the data?

Initial state effects cannot explain the data

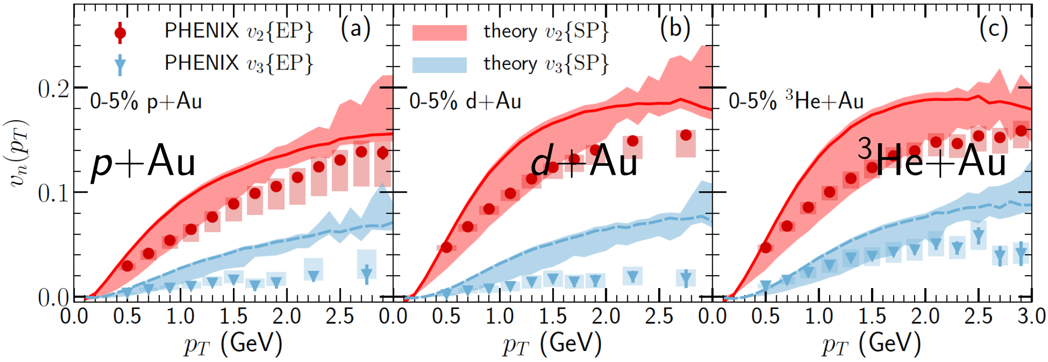
PHENIX, Nat. Phys. 15, 214–220 (2019)



- Initial state effects (CGC/Glasma) alone do not describe the data —Phys. Rev. Lett. 123, 039901 (Erratum) (2019)

How important are initial state effects?

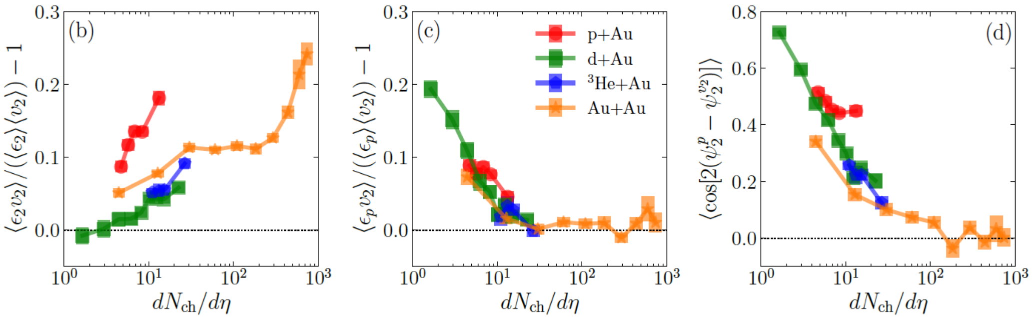
B. Schenke et al, Phys. Lett. B 803, 135322 (2020)



- Initial state effects important for theory, but make little contribution for central collisions
- Overestimation of data assumed to be related to fluid choice parameters and/or longitudinal dynamics

How important are initial state effects?

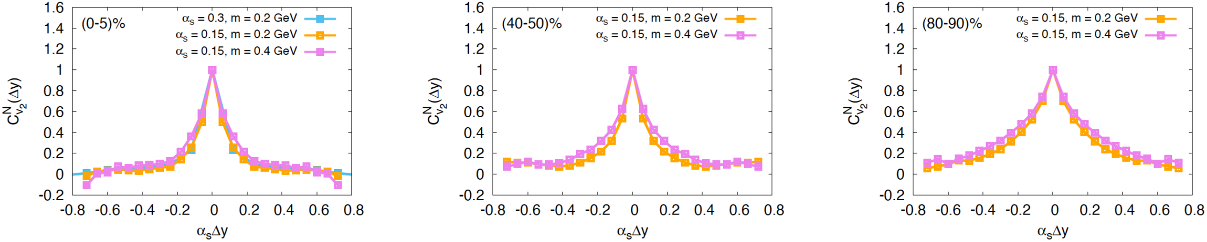
B. Schenke et al, Phys. Lett. B 803, 135322 (2020)



- For central p+Au, modest correlation between ε_p and v_2
- For central d+Au and ^{3}He+Au, no correlation between ε_p and v_2

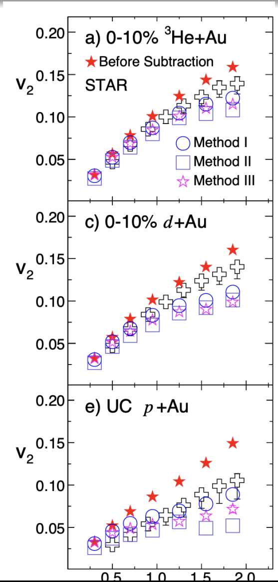
How important are initial state effects?

B. Schenke et al, Phys. Rev. D 105, 094023 (2022)



- The CGC/Glasma correlations appear to be too narrow in (pseudo)rapidity to have any significant impact on the data
  —The PHENIX data are measured with three detectors spanning $-3.9 < \eta < +0.35$
- We'll talk more about the importance of the pseudorapidity acceptance of experiments soon

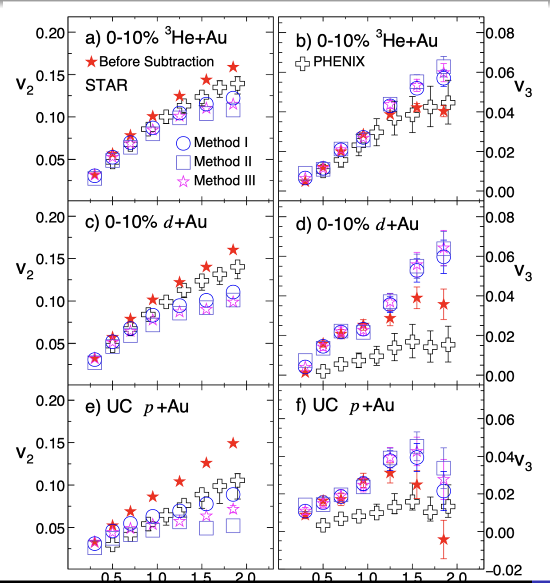
Comparisons with STAR



STAR, Phys. Rev. Lett. 130, 242301 (2023)

Good agreement between STAR and PHENIX for v_2

Comparisons with STAR



STAR, Phys. Rev. Lett. 130, 242301 (2023)

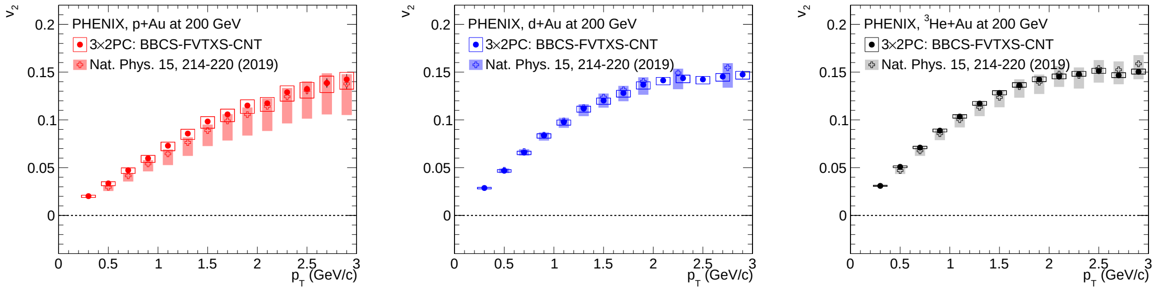
Good agreement between STAR and PHENIX for v_2

Large difference between STAR and PHENIX for v_3 in p+Au and d+Au

Large subnucleonic fluctuations can overwhelm the intrinsic geometry in some models, leading to similar ε_3 for all systems

PHENIX data update

PHENIX, Phys. Rev. C 105, 024901 (2022)



- PHENIX has completed a new analysis confirming the results published in Nature Physics
- All new analysis using two-particle correlations with event mixing instead of event plane method
  —Completely new and separate code base
  —Very different sensitivity to key experimental effects (beam position, detector alignment)

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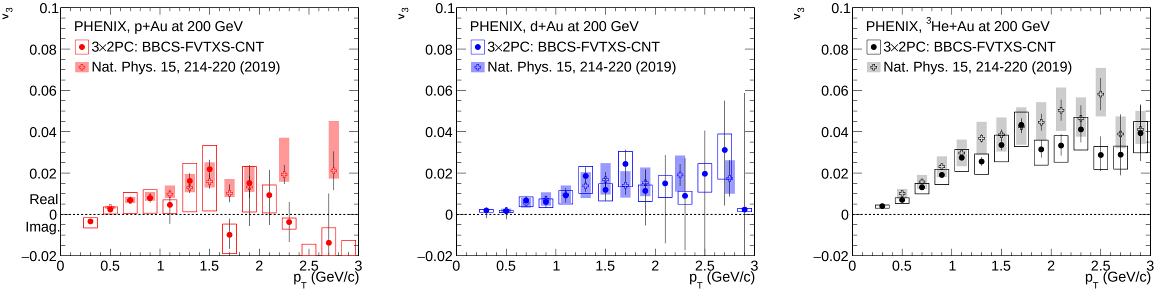

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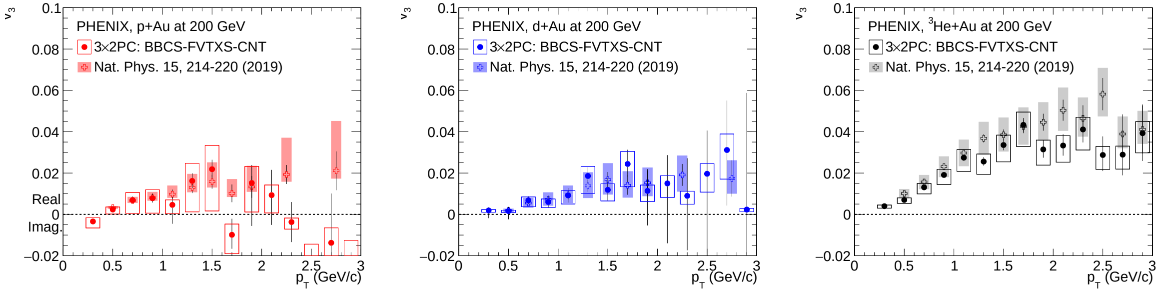

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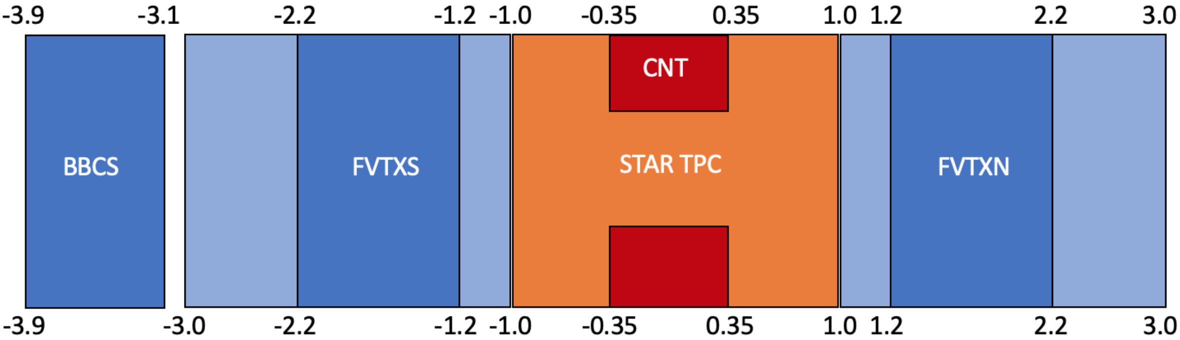
- All new analysis using two-particle correlations with event mixing instead of event plane method
  —Completely new and separate code base
  —Very different sensitivity to key experimental effects (beam position, detector alignment)
- It's essential to understand the two experiments have very different acceptance in pseudorapidity
  —STAR-PHENIX difference actually reveals interesting physics

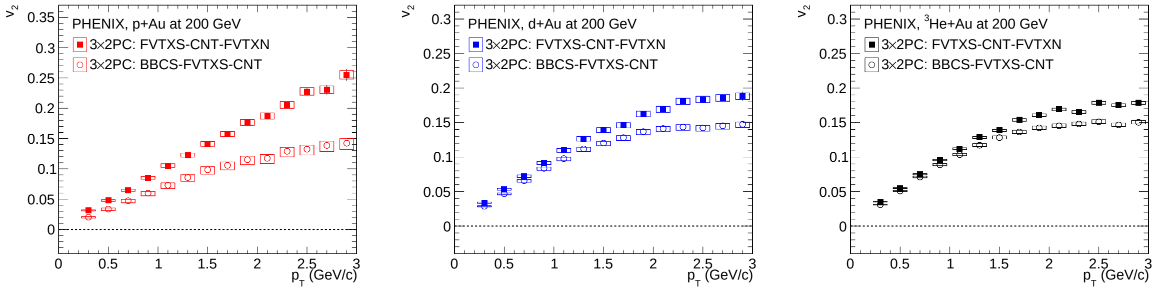
STAR and PHENIX detector comparison



- The PHENIX Nature Physics paper uses the BBCS-FVTXS-CNT detector combination
  —This is very different from the STAR analysis (TPC only)
- We can try to use FVTXS-CNT-FVTXN detector combination to better match STAR
  —Closer, and "balanced" between forward and backward, *but still different*

More STAR and PHENIX data comparisons

PHENIX, Phys. Rev. C 105, 024901 (2022)



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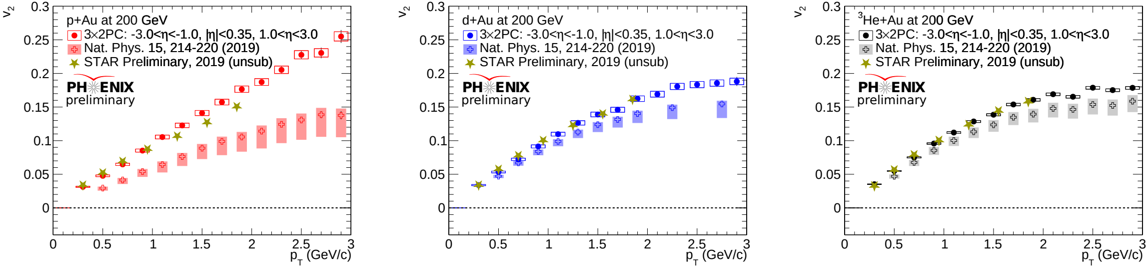
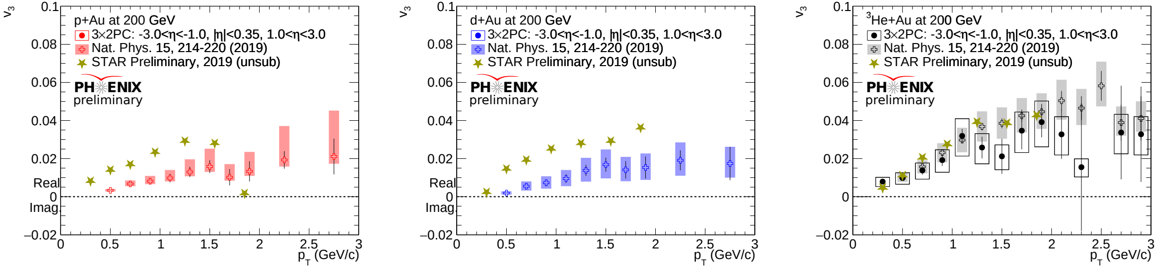


- Good agreement with STAR for v_2
  —Similar physics for the two different pseudorapidity acceptances

More STAR and PHENIX data comparisons

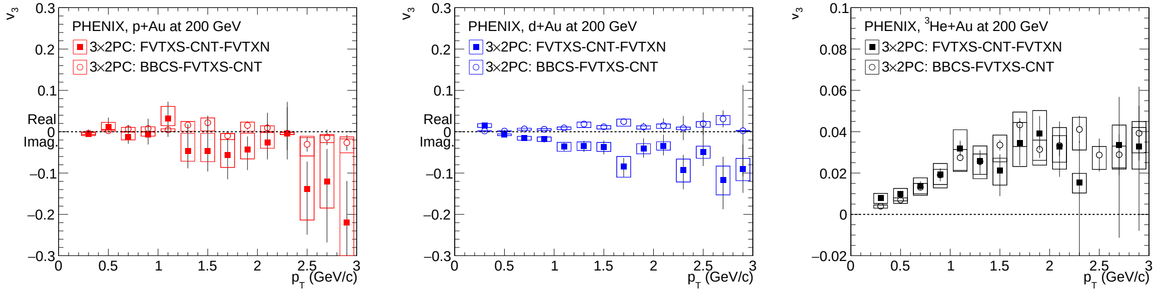
PHENIX, Phys. Rev. C 105, 024901 (2022)



- Good agreement with STAR for v_2
  —Similar physics for the two different pseudorapidity acceptances
- Strikingly different results for v_3
  —Rather different physics for the two different pseudorapidity acceptances
  —Longitudinal effects apparently much stronger for v_3 than v_2

More STAR and PHENIX data comparisons

PHENIX, Phys. Rev. C 105, 024901 (2022)



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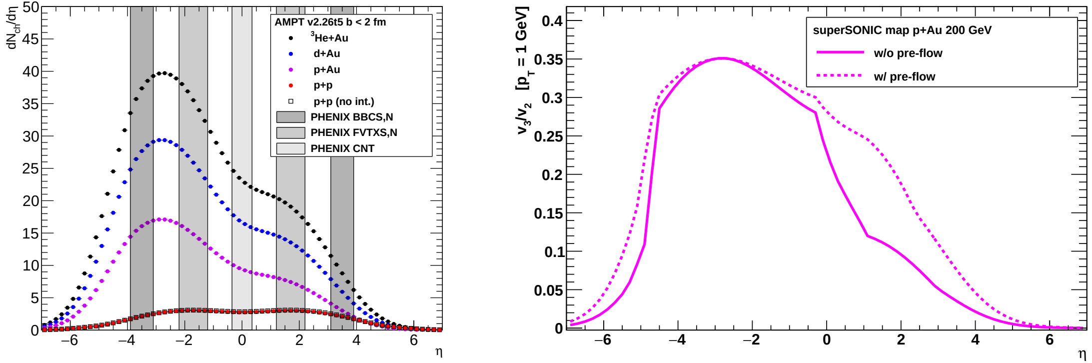
Pseudorapidity dependence in small systems

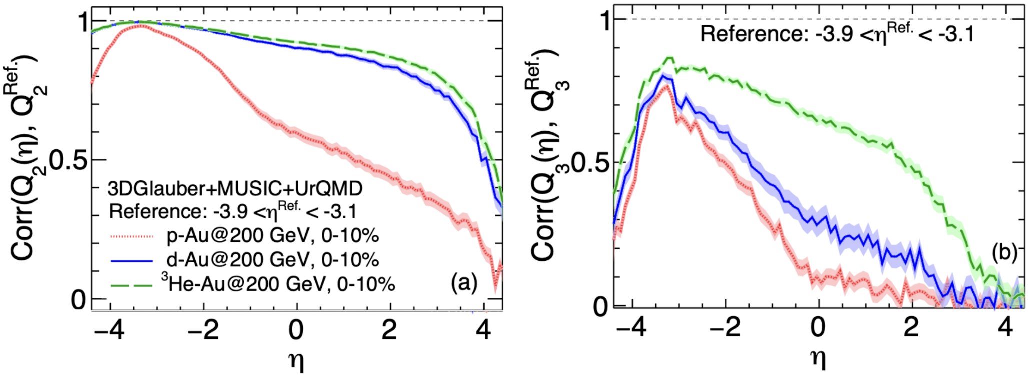
J.L. Nagle et al, Phys. Rev. C 105, 024906 (2022)



- $dN_{ch}/d\eta$ from AMPT, $v_3(\eta)$ from (super)SONIC
- The likely much stronger pseudorapidity dependence of v_3 compared to v_2 is an essential ingredient in understanding different measurements

Pseudorapidity dependence in small systems

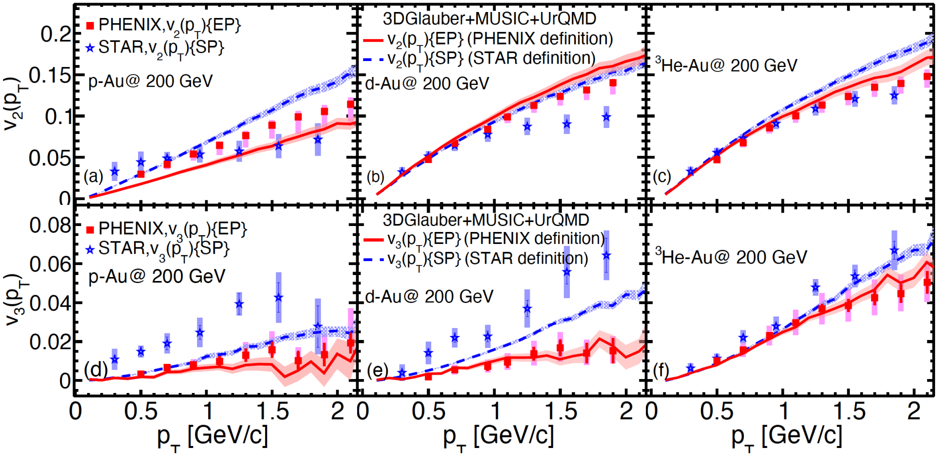
W. Zhao et al, Phys. Rev. C 107, 014904 (2023)



- Flow vectors become decorrelated with increasing pseudorapidity separation
  —The effect is much stronger for v_3 than for v_2
- The hierarchy of the measured v_n depends on that of the geometry *and* decorrelations
  —Interesting that the decorrelation hierarchy matches that of the geometry...

Pseudorapidity dependence in small systems

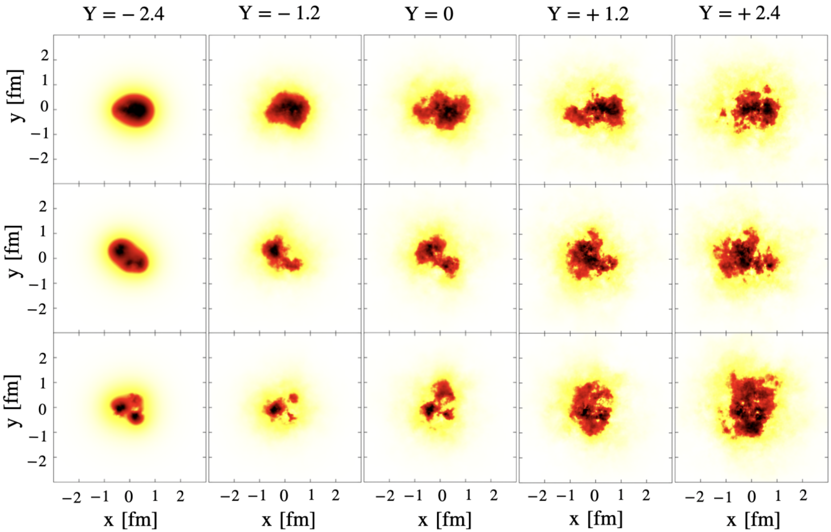
W. Zhao et al, Phys. Rev. C 107, 014904 (2023)



- Flow decorrelations lead to larger v_3 for STAR, explaining ∼50% of the difference between the experiments in this particular model

Pseudorapidity dependence in small systems

B. Schenke et al, Phys. Rev. D 105, 094023 (2022)



- Intrinsic geometry likely persists over all pseudorapidity ranges
- Fluctuations in the geometry vary as a function of rapidity (p from a p+Pb collision shown)
- PHENIX data follow intrinsic geometry, STAR data follow subnucleonic fluctuations