Creating droplets of the early universe in the laboratory with nuclear collisions

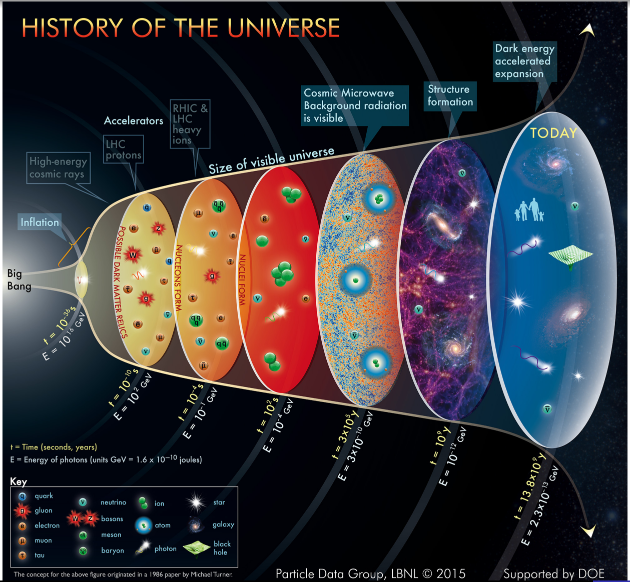
Ron Belmont
University of North Carolina at Greensboro

East Carolina University Physics Colloquium
15 March 2024

Quick outline

- Introduction and motivation
- Some basics of high energy nuclear physics ("heavy ion physics")
- Small systems
- A brief look towards the future...

The history of the universe



- The early universe (few microseconds) was a quark-gluon plasma (QGP)
- The QGP is a system of deconfined quarks and gluons
- We can recreate the QGP in the lab in collisions of nuclei at relativistic energies
- Goal of high energy nuclear physics: create, identify, and study the QGP

Connections to other fields and reasons for general interest

Key questions that are broadly applicable in physics

- At what scale do emergent phenomena become measureable?
  —E.g. how small of a system can be described by hydrodynamics?
- How do emergent phenomena arise?
  —E.g. how do we get from the QCD Lagrangian to relativistic hydrodynamics?
- How do we understand collective motion of strongly coupled systems?
  —QGP, superconductors, topological materials, degenerate fermi gases, etc.

Connections to other fields and reasons for general interest

Cosmology and astrophysics

- Early universe was a QGP
- Light nucleus formation in collisions may be related to big bang nucleosynthesis
- Lots of cross-talk between neutron star astrophysics and high energy nuclear physics
  —Connection between neutron star equation of state and QGP equation of state
  —Neutron star mergers: truly gigantic nuclear collisions
  —Quark stars: stars with QGP at center

Particle physics and fundamental symmetries

- High energy nuclear collisions can be used to search for P- and CP-violation in QCD
  —Distinct from but related to searches for neutron EDM
- Many applications of string theory (especially AdS/CFT) in theoretical calculations
  —E.g. the KSS-bound for the viscosity to entropy density ratio of the QGP

Typical sizes and scales for heavy ion physics

- Mass of proton $= 938.3$ MeV $= 1.007$ amu $= 1.673 \times 10^{-27}$ kg
- Typical energy $= 1$ GeV $= 1.602 \times 10^{-10}$ J
- Typical momentum $= 1$ GeV $= 5.344 \times 10^{-19}$ kg m/s
- Typical size $= 1$ fm $= 10^{-15}$ m
- Typical time $= 1$ fm $= 3.336 \times 10^{-24}$ s

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- Largest magnetic field in known universe: about 10^{19} to 10^{21} times Earth's magnetic field; 10^3 to 10^5 times larger than the field of magnetars

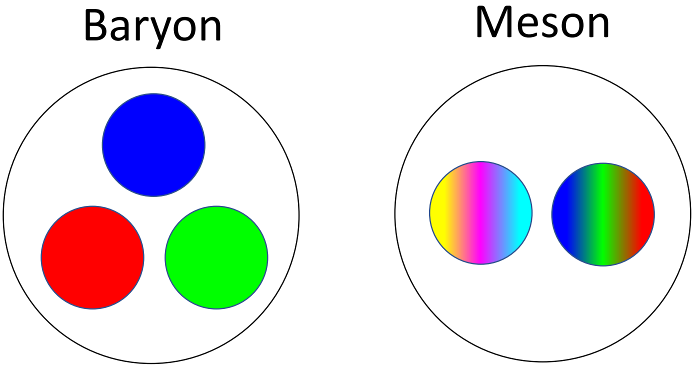
$$B \sim \frac{\gamma c \mu_0 e}{4\pi r^2} = 4.8 \times 10^{14} \text{ T (RHIC)}, \; 1.4 \times 10^{16} \text{ T (LHC)}$$

QCD as explained by approximate analogy to QED

QED		QCD	
electric charge	$\leftrightarrow$	color charge	coupling
electrons	$\leftrightarrow$	quarks	matter fermions
photons	$\leftrightarrow$	gluons	exchange bosons
atoms	$\leftrightarrow$	nucleons	(stable) bound states
molecules	$\leftrightarrow$	nuclei	compound states

- One kind of electric charge, three kinds of color charge
- Photons do not have electric charge, gluons do have color charge
- Only one photon, eight different gluons

QCD bound states



- Color-charged particles (quarks and gluons) are generically called **partons**
- QCD bound states are generically called **hadrons**, divided into **baryons** and **mesons**
- All observables must be in color singlet state—no partons can be found in isolation in nature

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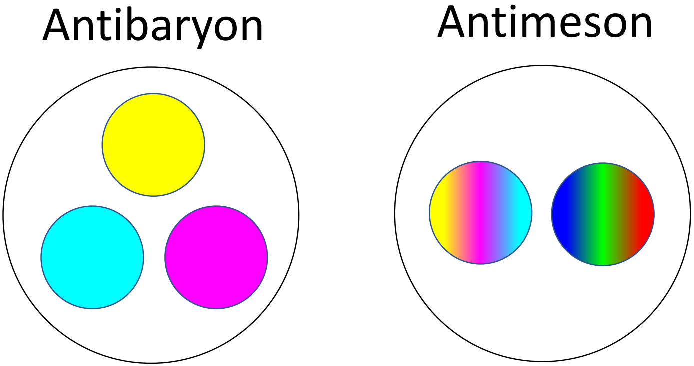

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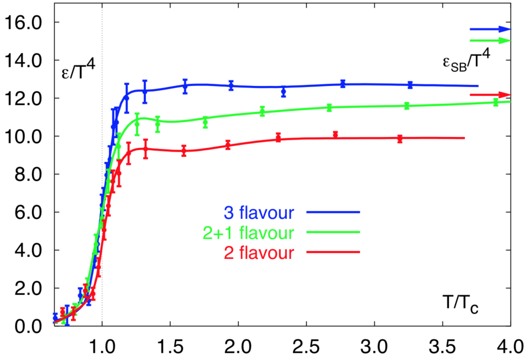
Phases of QCD matter

F. Karsch, Lect. Notes Phys. 583, 209-249 (2002)

- Lattice QCD predicts a phase transition from nuclear matter to QGP
- Large increase energy density at $T_C \approx 155$ MeV due to large increase in number of degrees of freedom



$$\varepsilon_{SB} = g\frac{\pi^2}{30}T^4$$

- Below T_C: g = 3
  3 pions with spin 0
- Above T_C: g = 37
  8 gluons with spin 1,
  2 (anti)quarks with spin 1/2

Phases of QCD matter

F. Karsch, Lect. Notes Phys. 583, 209-249 (2002)

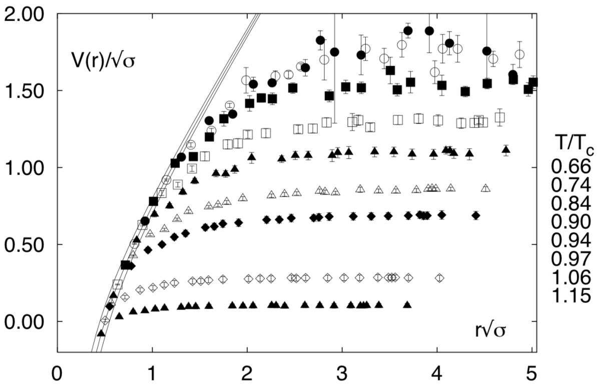
- The QED potential

$$V(r) = -\frac{\alpha_{EM}}{r}$$

- The QCD potential for $q\bar{q}$

$$V(r) = -\frac{4}{3}\frac{\alpha_S}{r} + kr$$

- Coulomb part and confining part

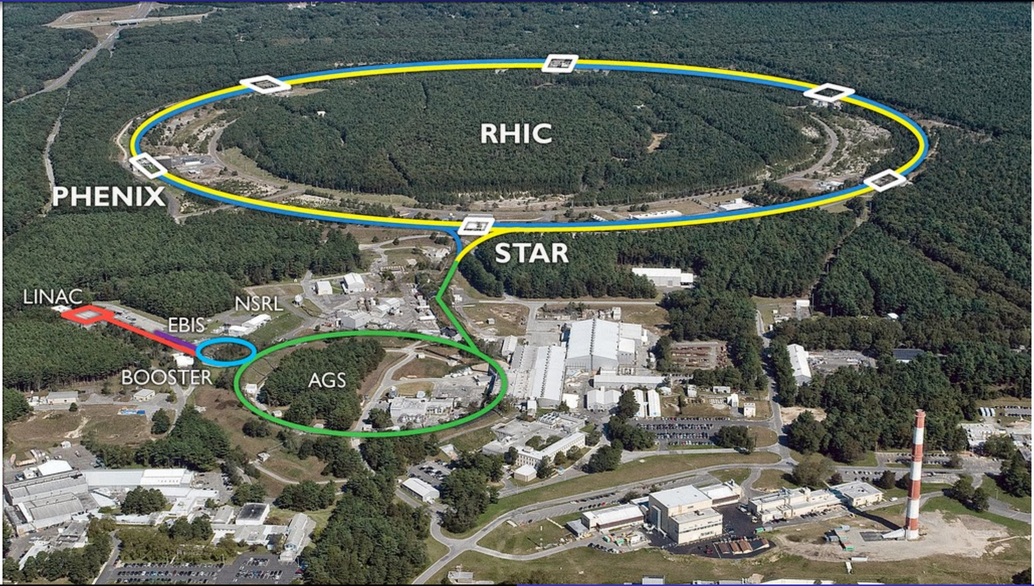


- The confining part of gets weaker with increasing temperature
- More or less gone at the critical temperature ($T_C \approx 155$ MeV)

Intermission

Basics of high energy nuclear collisions

The Relativistic Heavy Ion Collider



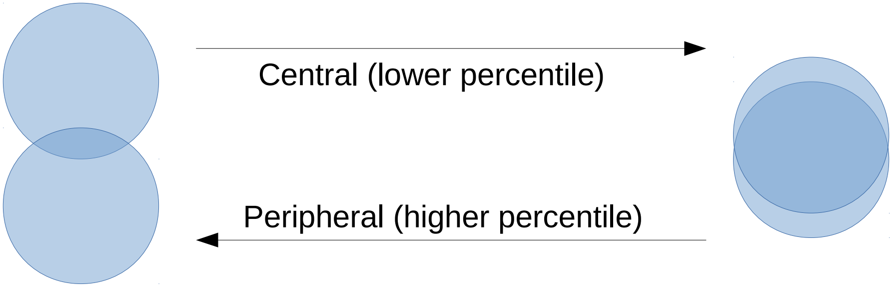
The Relativistic Heavy Ion Collider

- RHIC is the only polarized proton collider in the world (Cold QCD)
- RHIC is one of two heavy ion colliders in the world (Hot QCD)

Collision Species	Collision Energies (GeV)
p↑+p↑	510, 500, 200, 62.4
p+Al	200
p+Au	200
d+Au	200, 62.4, 39, 19.6
^{3}He+Au	200
Cu+Cu	200, 62.4, 22.5
Cu+Au	200
Ru+Ru	200
Zr+Zr	200
Au+Au	200, 130, 62.4, 56, 39, 27, 19.6, 15, 11.5, 7.7, 5, ...
U+U	193

And more to come!

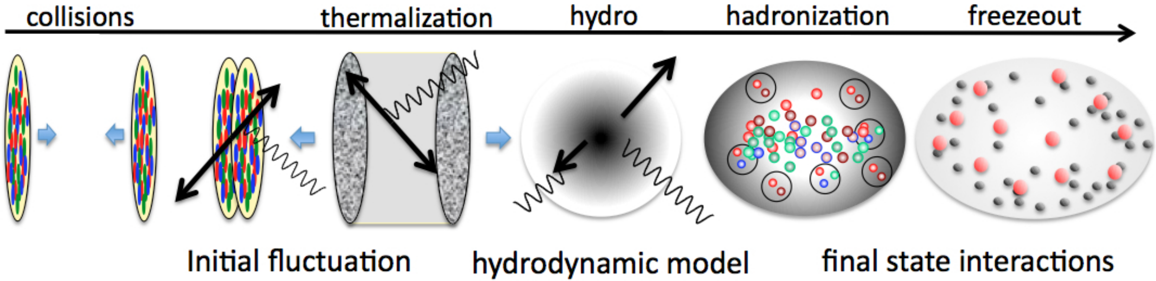
Centrality



Central collisions: more overlap means more participating nucleons (N_{part})
—Larger volume, longer lifetime

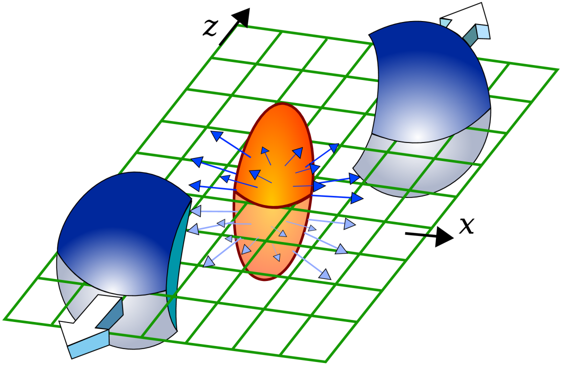
Peripheral collisions: less overlap means fewer participating nucleons
—Smaller volume, shorter lifetime

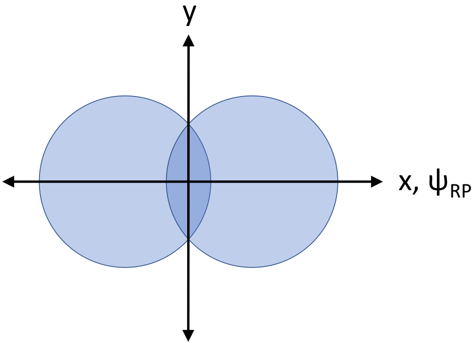
Standard model of heavy ion physics



Based on developments in hydro theory over the last few years, we might replace "thermalization" with "hydrodynamization"

Azimuthal anisotropy measurements

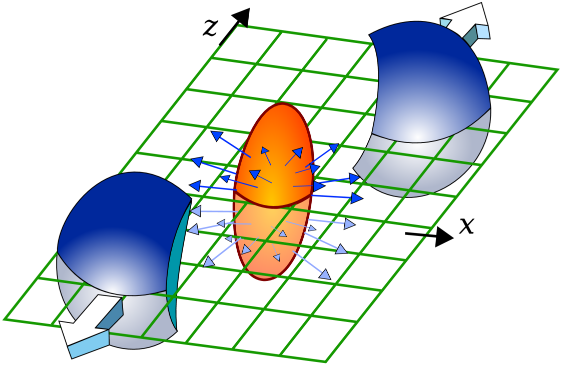


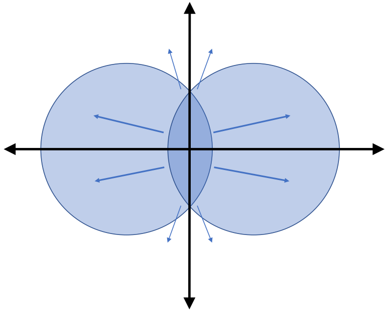


$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^n \cos n\varphi \rangle + \langle r^n \sin n\varphi \rangle}}{\langle r^n \rangle}$$

- Hydrodynamics translates initial shape (including fluctuations) into final state distribution

Azimuthal anisotropy measurements





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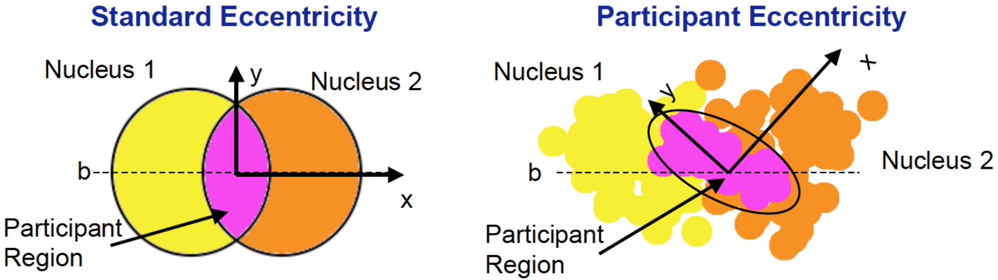
Important discovery in 2005

PHOBOS Plenary, Quark Matter 2005 (see also Phys.Rev.C 77, 014906 (2008))



A nucleus isn't just a sphere

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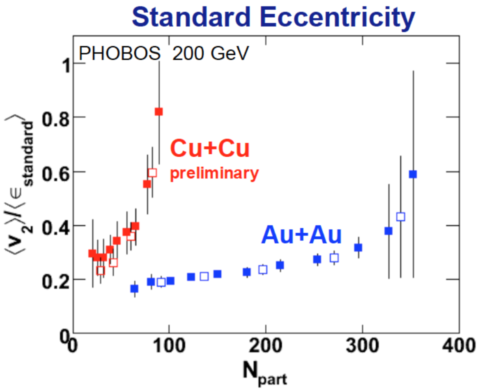

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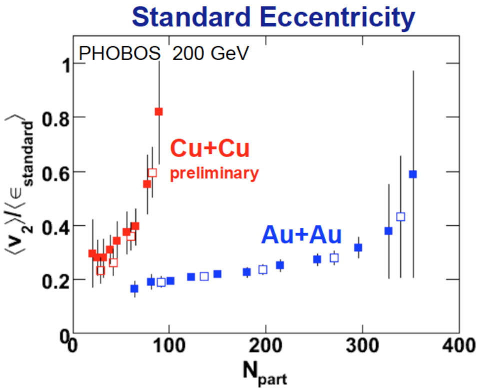
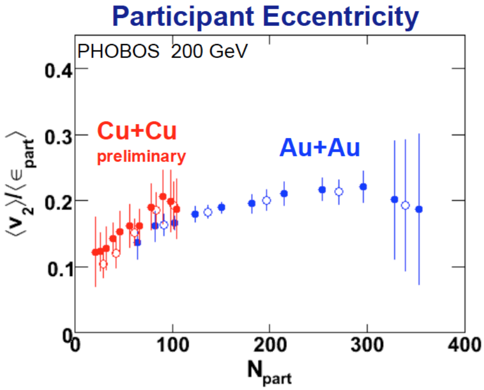




A nucleus isn't just a sphere

Important discovery in 2005

R. Andrade et al, Eur. Phys. J. A 29, 23-26 (2006)

NeXSPheRIO results on elliptic flow at RHIC and connection with thermalization

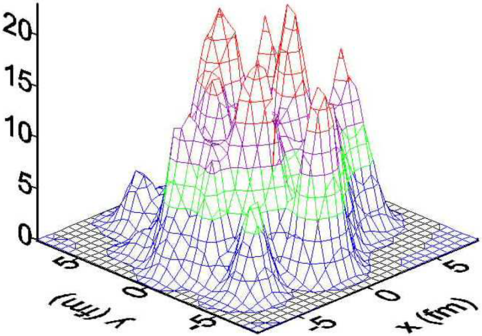
R.Andrade[1], F.Grassi[1], Y.Hama[1], T.Kodama[2], O.Socolowski Jr.[3], and B.Tavares[2]

[1] Instituto de Física, USP,
C. P. 66318, 05315-970 São Paulo-SP, Brazil

[2] Instituto de Física, UFRJ,
C. P. 68528, 21945-970 Rio de Janeiro-RJ , Brazil

[3] CTA/ITA,
Praça Marechal Eduardo Gomes 50, CEP 12228-900 São José dos Campos-SP, Brazil

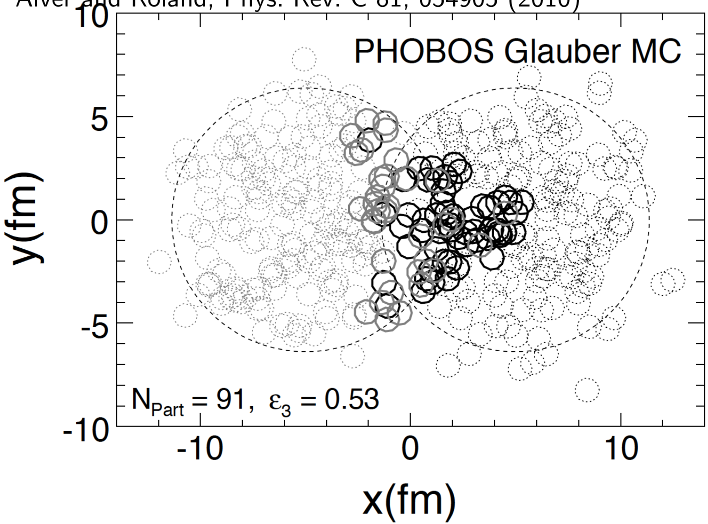
Received 1 January 2004



Worth noting that lumpy initial conditions were predicted some time in 2003

Important discovery in 2010

Alver and Roland, Phys. Rev. C 81, 054905 (2010)



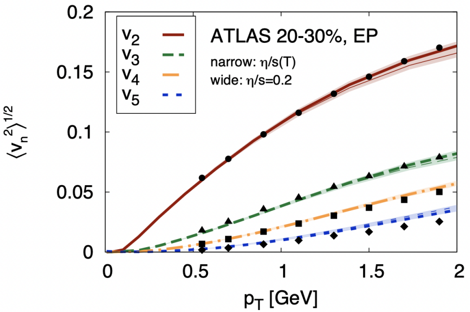
Nucleon fluctuations can produce non-zero ε_n for odd n

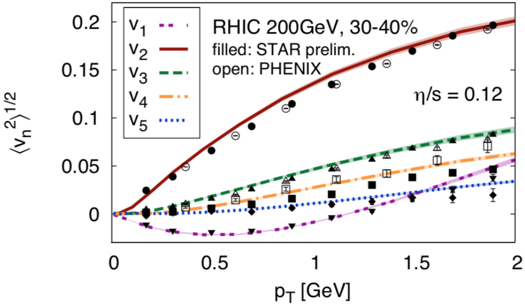
Symmetry planes ψ_n can be different for different harmonics

$$\varphi = \phi_{lab} - \psi_n$$

Data and theory for v_n

Gale et al, Phys. Rev. Lett. 110, 012302 (2013)

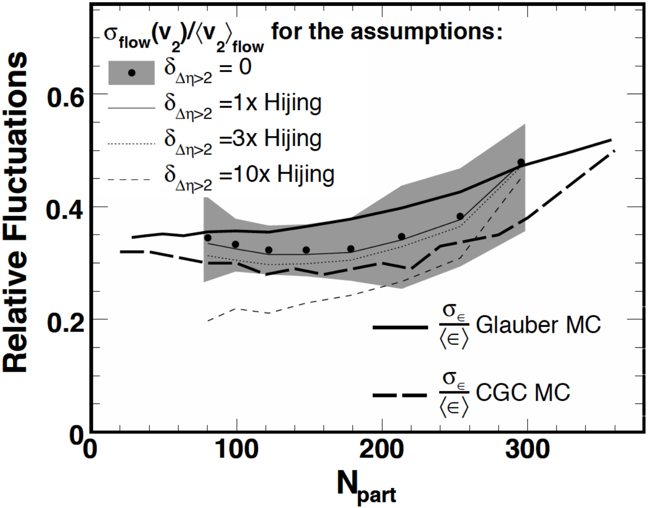




$$\frac{dN}{d\varphi} \propto 2v_1 \cos\varphi + 2v_2 \cos 2\varphi + 2v_3 \cos 3\varphi + 2v_4 \cos 4\varphi + 2v_5 \cos 5\varphi$$

Fluctuations in large systems

PHOBOS, Phys. Rev. C 81, 034915 (2010)



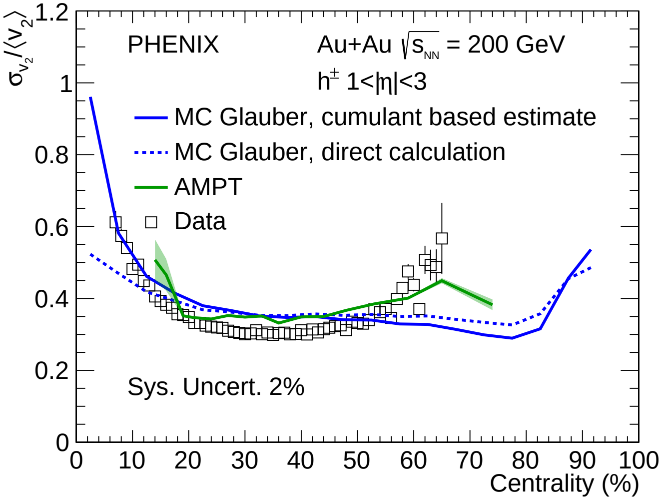
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2\rangle$

$|\eta| < 1$

Generally good agreement with models of initial geometry

Fluctuations in large systems

PHENIX (RB), Phys. Rev. C 99, 024903 (2019)



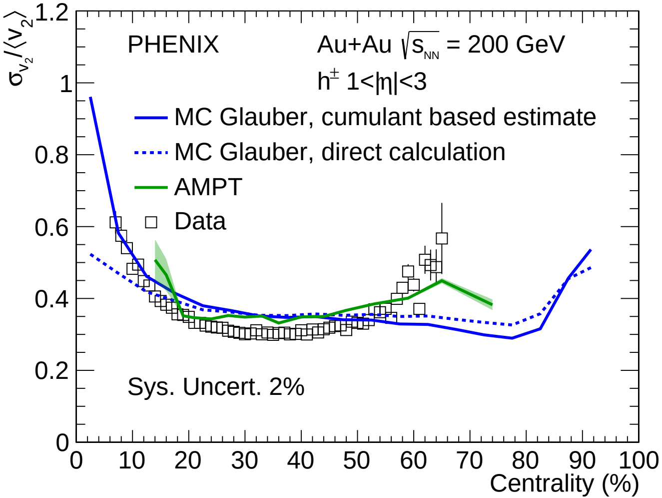
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2\rangle$

$1 < |\eta| < 3$

Generally good agreement with models of initial geometry

Fluctuations in large systems

PHENIX (RB), Phys. Rev. C 99, 024903 (2019)



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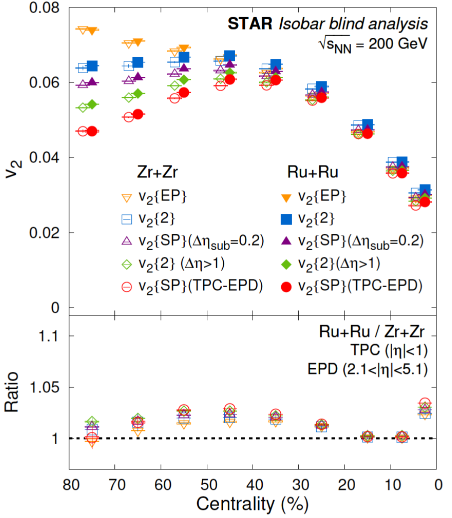
Central: breakdown of small-variance limit (assumed in data and solid line)

Peripheral: non-linearity in hydro response (e.g. J. Noronha-Hostler et al Phys. Rev. C 93, 014909 (2016))

Geometry engineering and nuclear structure

STAR, Phys. Rev. C 105, 014901 (2022)



Exquisite new data from STAR shows percent-level sensitivity to nuclear structure

J. Jia, Phys. Rev. C 105, 044905 (2022) proposes to use flow and nuclear structure to inform each other

Intermission

Small systems

A brief history of heavy ion physics

- 1980s and 1990s—AGS and SPS... QGP at SPS!
- Early 2000s—QGP at RHIC! No QGP at SPS. d+Au as control.
- Mid-late 2000s—Detailed, quantitative studies of strongly coupled QGP. d+Au as control.
- 2010—Ridge in high multiplicity p+p (LHC)! Probably CGC!
- Early 2010s—QGP in p+Pb!
- Early 2010s—QGP in d+Au!
- Mid 2010s to present—QGP almost everywhere

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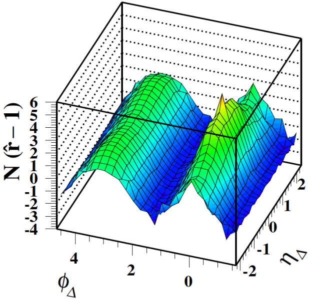
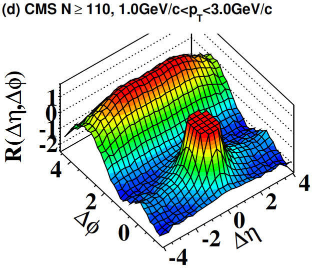
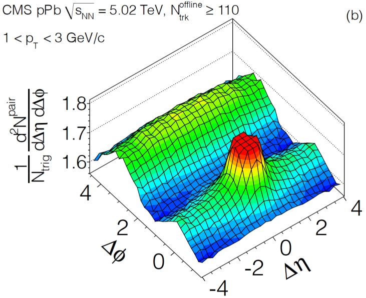
"Twenty years ago, the challenge in heavy ion physics was to find the QGP. Now, the challenge is to not find it." —Jürgen Schukraft, QM17

The ridge is a signature of flow

STAR, PRC 73, 064907 (2006) CMS, JHEP 1009, 091 (2010) CMS, PLB 718, 795 (2013)





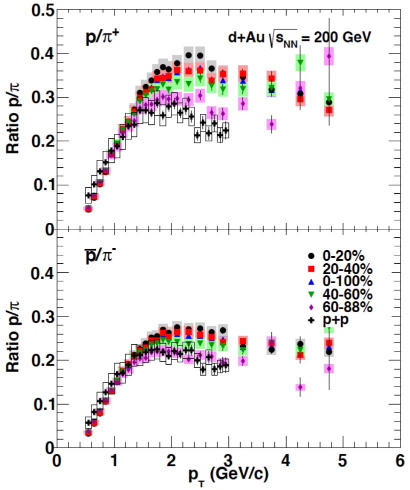


Extended structure away from near-side jet peak interpreted as collective effect due to presence of QGP

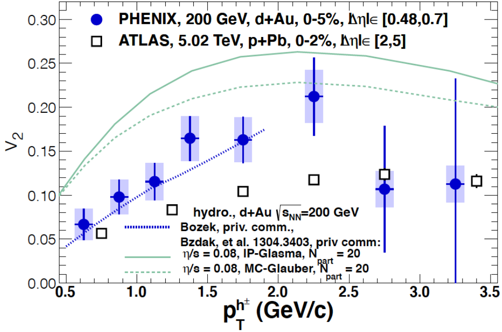
- Discovered by STAR in Au+Au in 2004 (PRC 73, 064907 (2006) and PRL 95, 152301 (2005))
- Realized by STAR to be flow in 2009 (PRL 105, 022301 (2010))
- First found in small systems by CMS (JHEP 1009, 091 (2010) and PLB 718, 795 (2013))

First results at RHIC

PHENIX (RB), Phys. Rev. C 88, 024906 (2013)



PHENIX, Phys. Rev. Lett. 111, 212301 (2013)



- Right around the same time as the p+Pb ridge:
  —First paper measuring v_2 in d+Au at RHIC
  —Measurement of baryon enhancement in d+Au (RB PhD thesis)

Intermission

Small systems geometry scan

Small systems geometry scan

PHYSICAL REVIEW LETTERS

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Exploiting Intrinsic Triangular Geometry in Relativistic $^{3}\mathrm{He}+\mathrm{Au}$ Collisions to Disentangle Medium Properties

J. L. Nagle, A. Adare, S. Beckman, T. Koblesky, J. Orjuela Koop, D. McGlinchey, P. Romatschke, J. Carlson, J. E. Lynn, and M. McCumber

Phys. Rev. Lett. **113**, 112301 – Published 12 September 2014

- Collective motion translates initial geometry into final state distributions
- To determine whether small systems exhibit collectivity, we can adjust the geometry and compare across systems
- We can also test predictions of hydrodynamics with a QGP phase

Small systems geometry scan

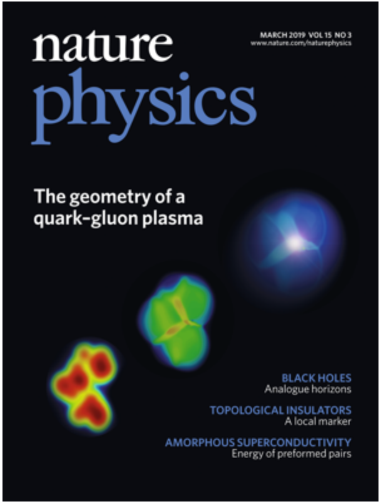
nature physics

Letter | Published: 10 December 2018

Creation of quark–gluon plasma droplets with three distinct geometries

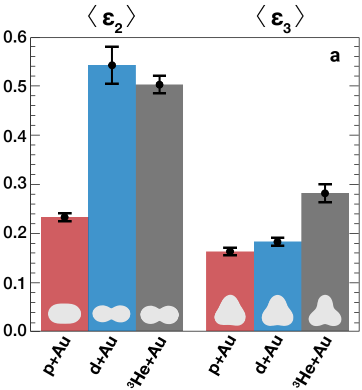
PHENIX Collaboration

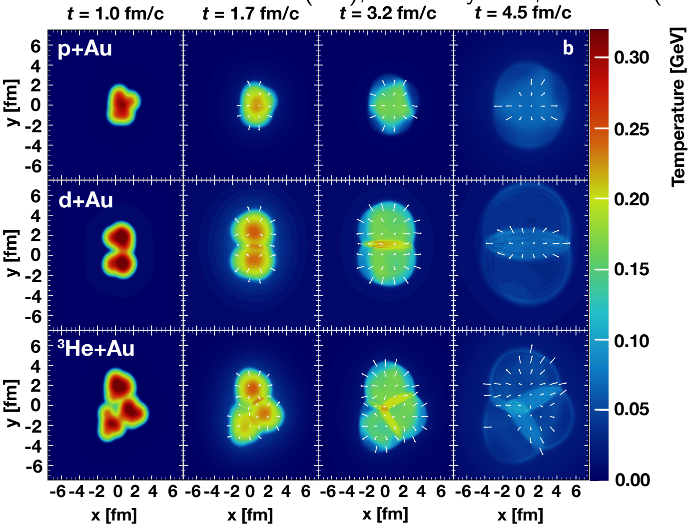
Nature Physics **15**, 214–220(2019) | Cite this article



Small systems geometry scan

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





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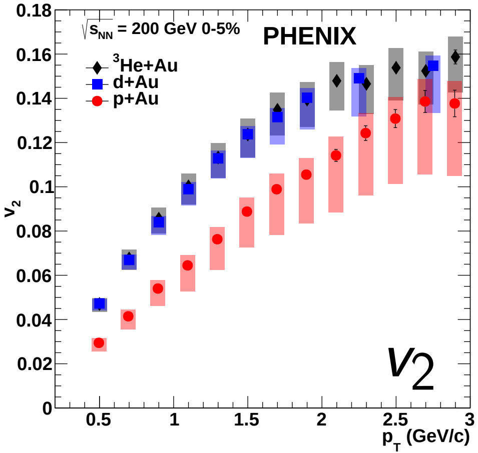
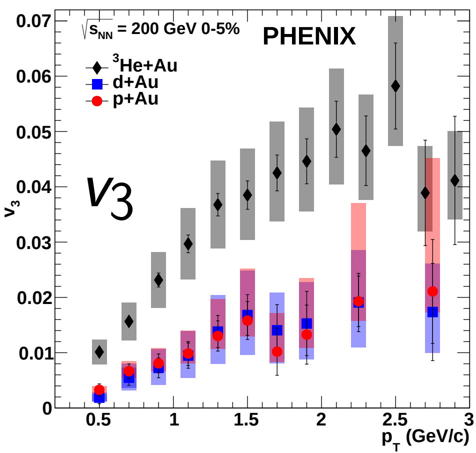
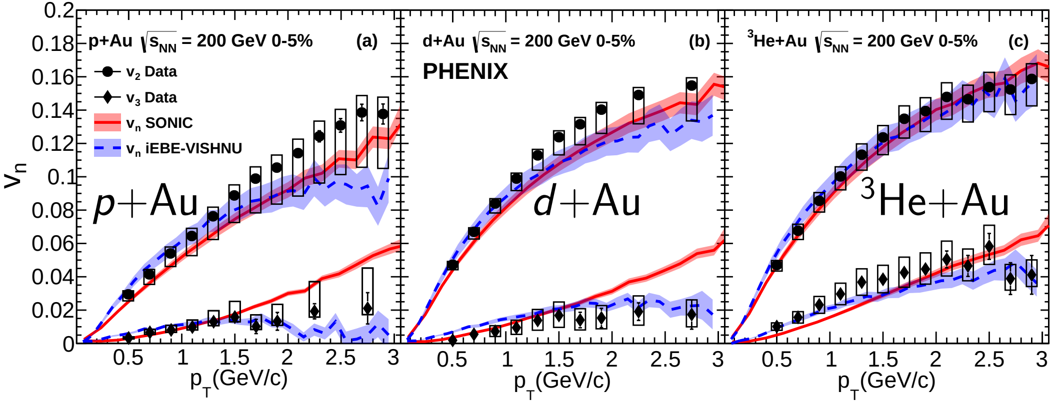




- v_2 and v_3 ordering matches ε_2 and ε_3 ordering in all three systems
  —Collective motion of system translates the initial geometry into the final state

Small systems geometry scan

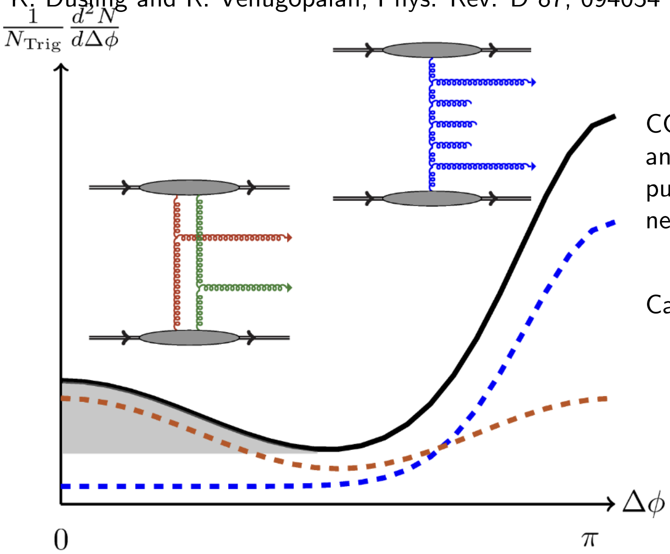
PHENIX (RB), Nat. Phys. 15, 214–220 (2019)



- 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)

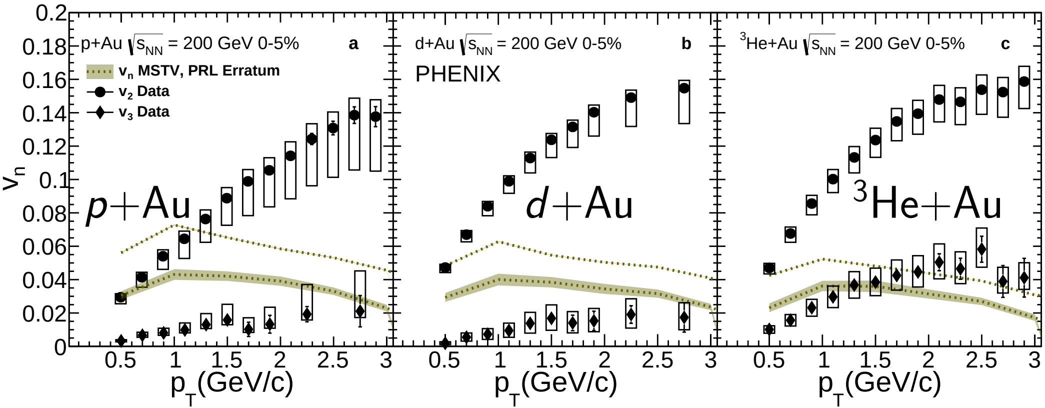


CGC framework: glasma diagrams produce angular correlations like the ridge and v_n purely from initial state correlations, with no need for final state interactions (hydro)

Can they explain the data?

Initial state effects cannot explain the data

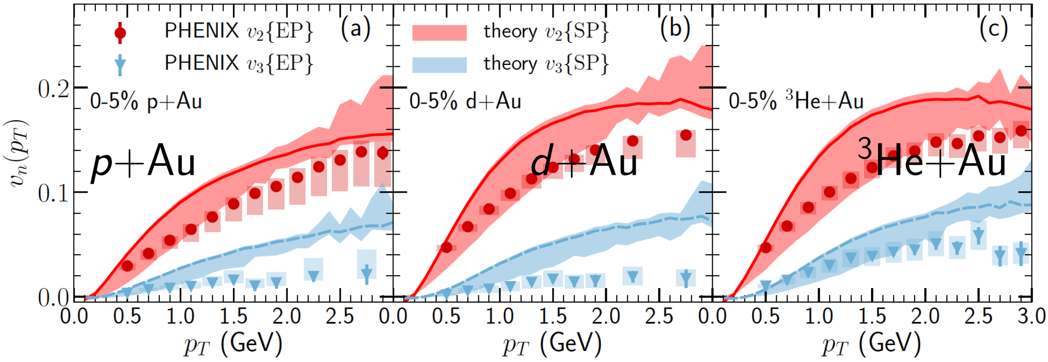
PHENIX (RB), Nat. Phys. 15, 214–220 (2019)



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

How important are initial state effects?

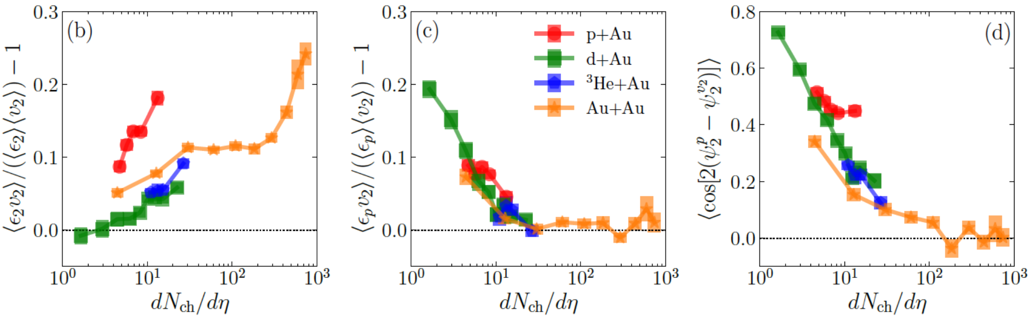
B. Schenke et al, Phys. Lett. B 803, 135322 (2020)



- 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?

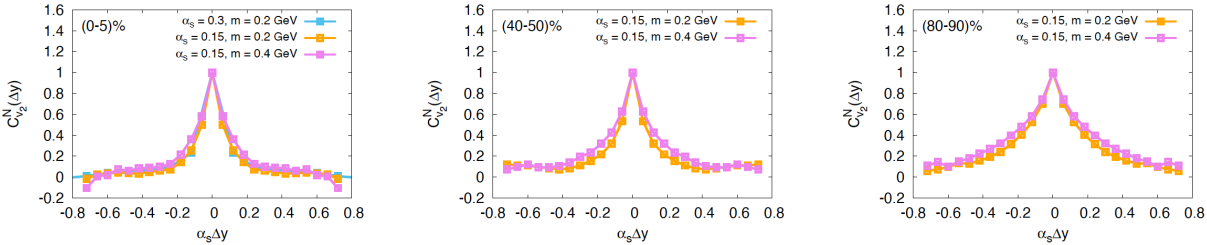
B. Schenke et al, Phys. Lett. B 803, 135322 (2020)



- 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

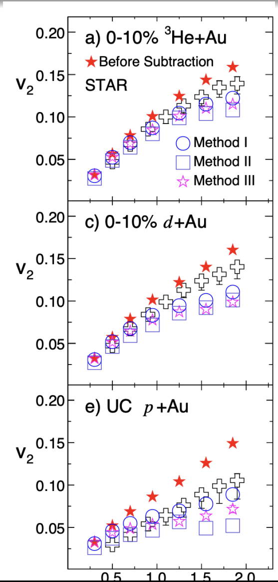
How important are initial state effects?

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

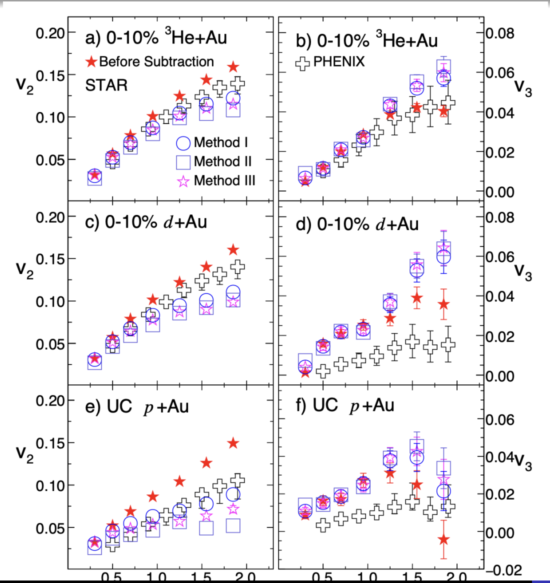
Comparisons with STAR



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)

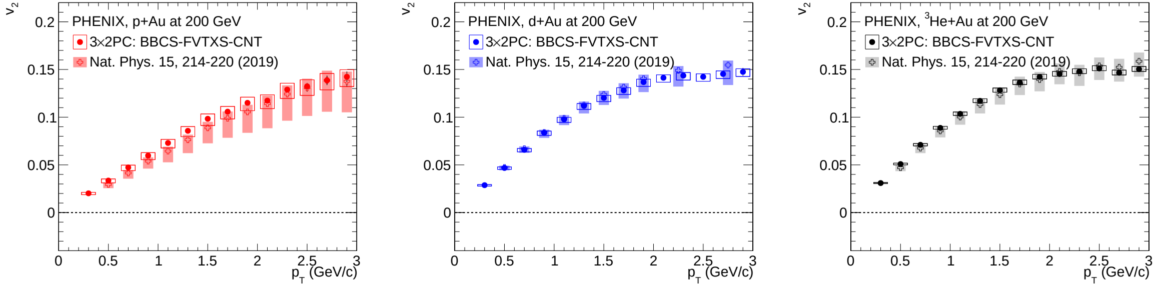
Good agreement between STAR and PHENIX for v_2

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 (RB), 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)

PHENIX data update

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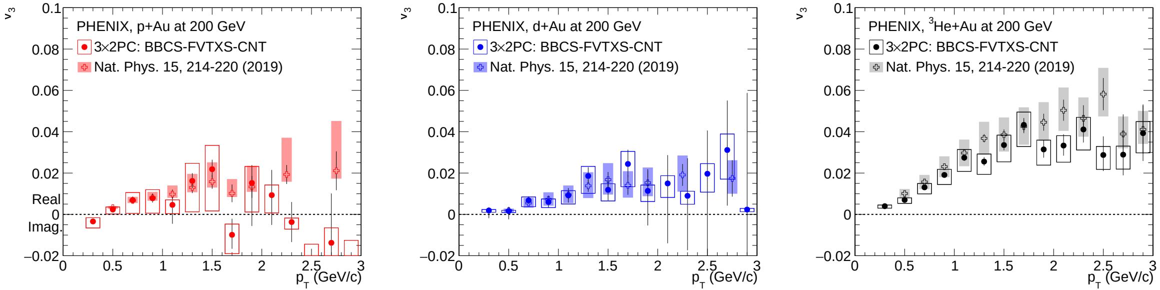

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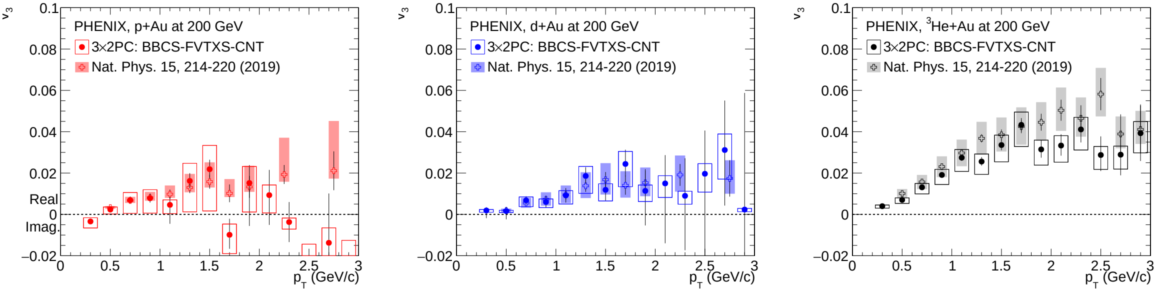
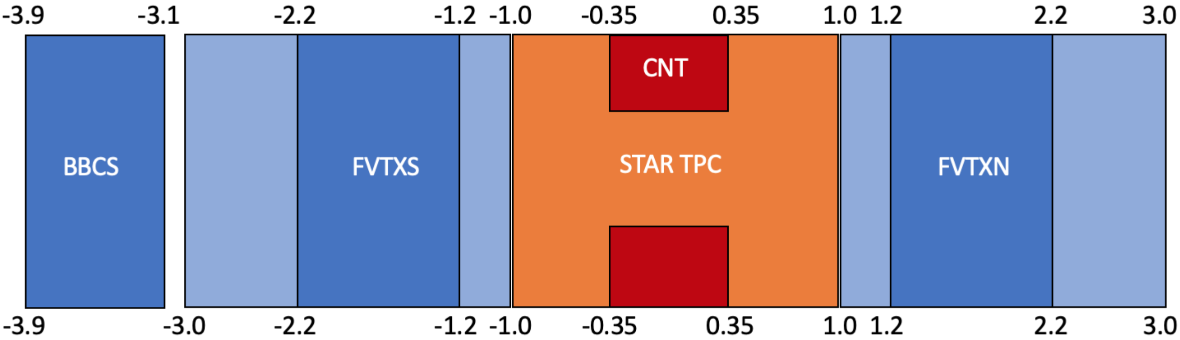


- PHENIX has completed a new analysis confirming the results published in Nature Physics
- All new analysis using two-particle correlations with event mixing instead of event plane method
  —Completely new and separate code base
  —Very different sensitivity to key experimental effects (beam position,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

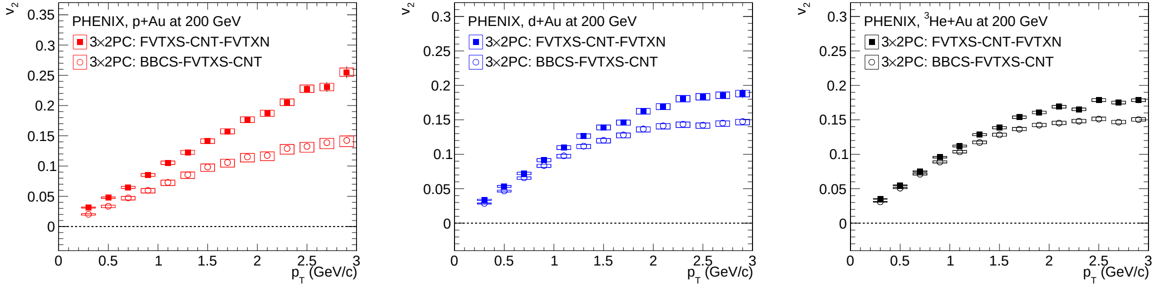
STAR and PHENIX detector comparison



- 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 (RB), Phys. Rev. C 105, 024901 (2022)



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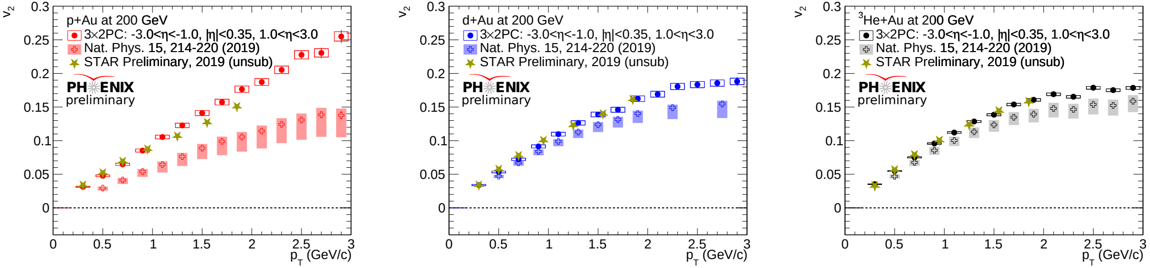

- Good agreement with STAR for v_2

  —Similar physics for the two different pseudorapidity acceptances

More STAR and PHENIX data comparisons

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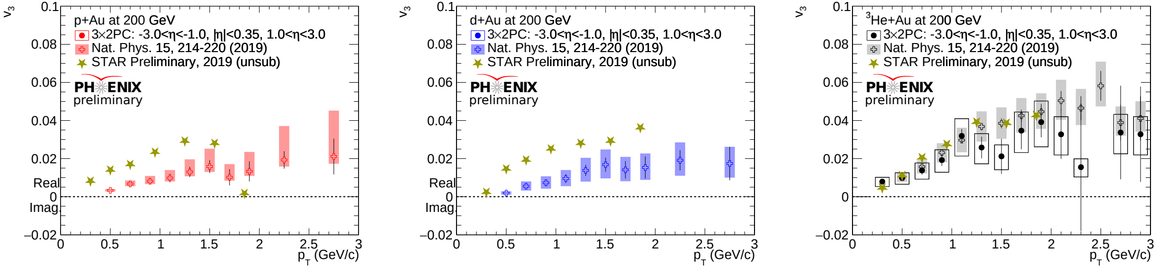

- Good agreement with STAR for v_2
  —Similar physics for the two different pseudorapidity acceptances
- Strikingly different results for v_3
  —Rather different physics for the two different pseudorapidity acceptances
  —Longitudinal effects apparently much stronger for v_3 than v_2

More STAR and PHENIX data comparisons

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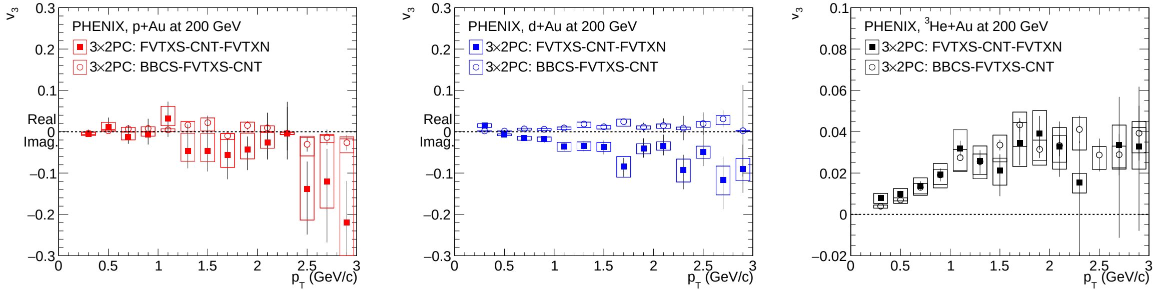

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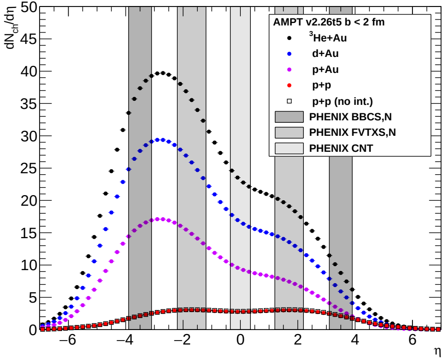
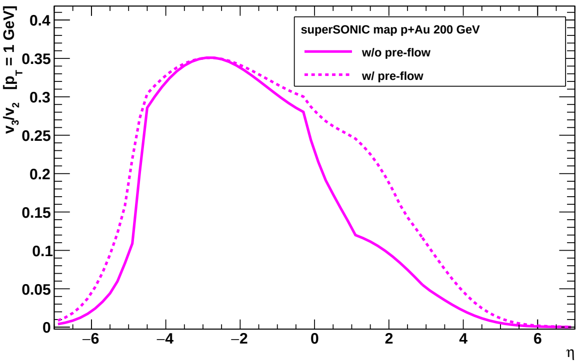
Pseudorapidity dependence in small systems

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

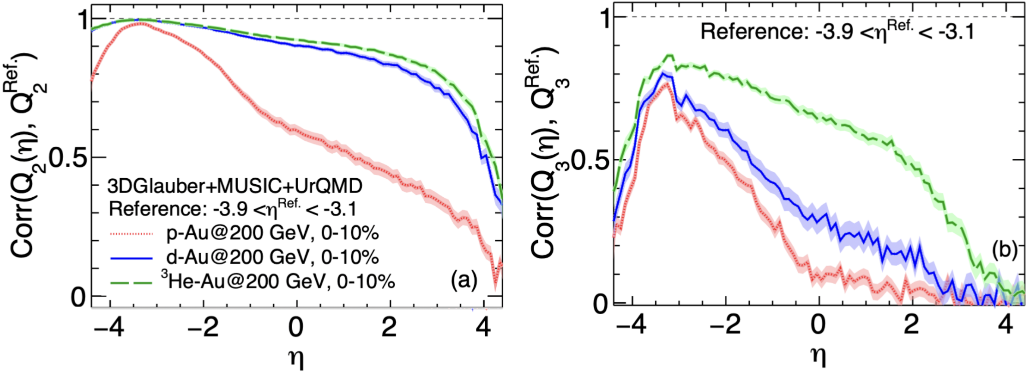




- $dN_{ch}/d\eta$ from AMPT, $v_3(\eta)$ from (super)SONIC
- The likely much stronger pseudorapidity dependence of v_3 compared to v_2 is an essential ingredient in understanding different measurements

Pseudorapidity dependence in small systems

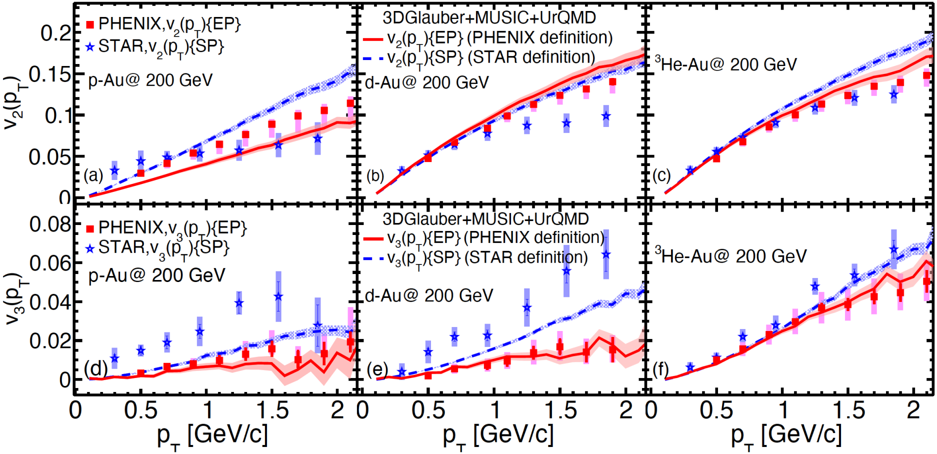
W. Zhao et al, Phys. Rev. C 107, 014904 (2023)



- 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

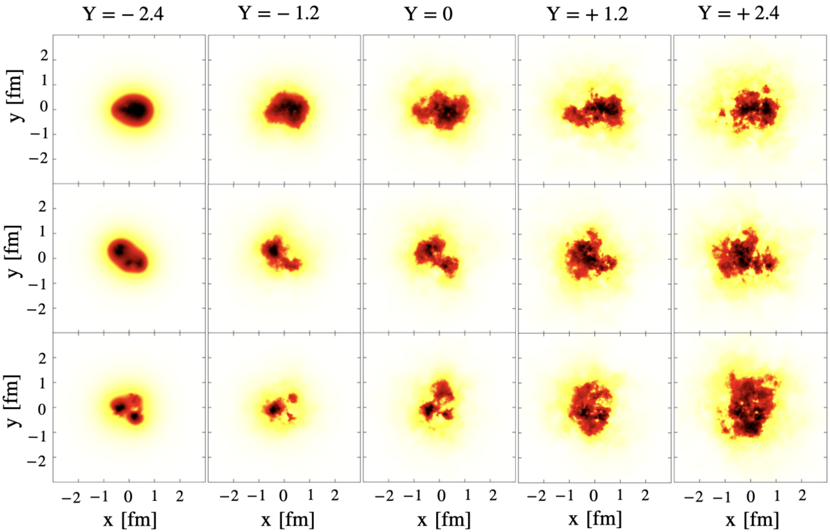
W. Zhao et al, Phys. Rev. C 107, 014904 (2023)



- 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

Brief Summary

- Long established role of geometry and hydrodynamics in large systems
- Role of geometry and hydrodynamics in small systems also now established
- Understanding the pseudorapidity dependence is an essential part of understanding the overall dynamics
  —Longitudinal decorrelation leads to major differences between measurements
  —The intrinsic geometry likely persists over long ranges in pseudorapidity
  —Fluctuations in the geometry vary over pseudorapidity
- Initial state effects, though important from a theoretical standpoint, have minimal impact on the measured v_n
  —This is in part due to their rather small range in pseudorapidity
- We've learned a lot from 2+1D hydro, but we have ever-increasing need for 3+1D hydro

Intermission

The future

The future

- Unfortunately, UNCG has decided there is no future
  —Astronomy courses discontinued starting Fall 2024
  —Program and department to be dissolved by the end of Spring 2029 (or sooner)

The future

- Academic Portfolio Review is a tool—like any tool it is not inherently good or bad; it can be used for good or bad aims
- The UNCG administration has used APR to make destructive curriculum changes (and violated numerous principles of shared governance in the course of doing so)
- No explanations or justifications have been given for any program discontinuations, including a strong Anthropology department and a thriving Computational Math PhD program
- Despite numerous claims of budget and enrollment issues, no financial analysis justifying the cuts has been given, and program discontinuations often lead to further enrollment decline
- The Math & Stats department has produced a detailed review, indicating huge losses
- Astronomy courses bring in $1 million in revenue per academic year, which fully covers the cost of our department; they also fulfill key general education requirements for non-science majors, and there isn't infinite capacity to just shift those students around

The future

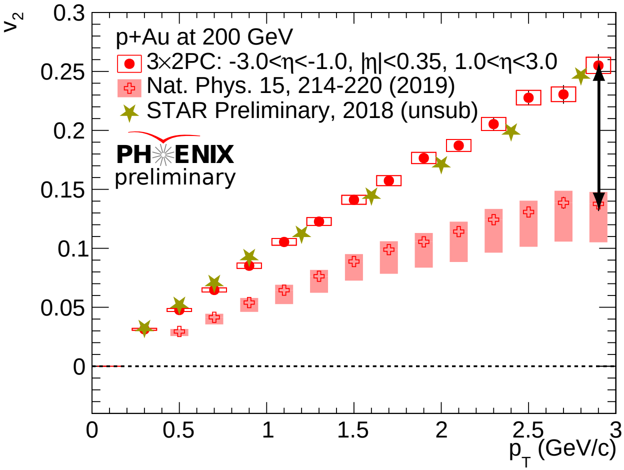
- There's bad news and good news
  - Academic Portfolio Review is going to become a permanent fixture in the UNC system, and it will not be used for good
  - But you—we—can fight back when they try to hurt our universities
  - Donors have the biggest impact; votes of no confidence and negative press coverage can be very helpful
- Some friendly suggestions for you to consider
  - Read local news, especially alts, and become familiar certain reporters and their work—they can be great allies
  - Pay careful attention to administrative actions, especially regarding faculty contracts and curriculum changes; take and keep notes for yourself
  - Join your local AAUP chapter, it's cheap ($20/yr at UNCG), it's fun, it's people you know and care about

Extra material

Intermission

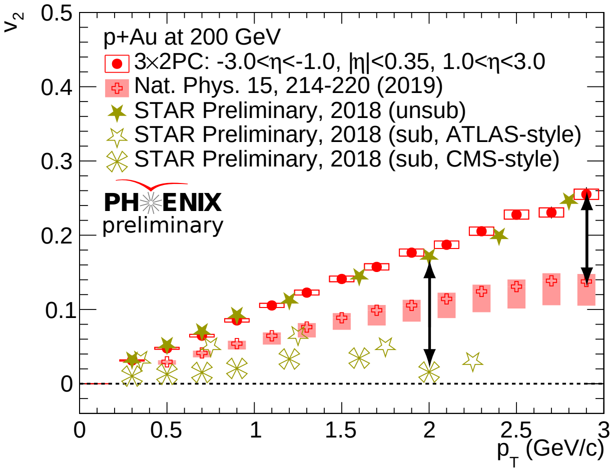
Understanding the non-flow contributions

Understanding the nonflow contribution: v_2 in p+Au as a case study



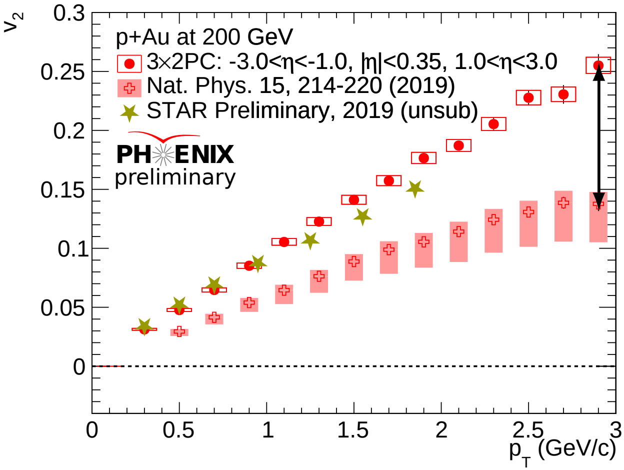
- The large difference between the PHENIX published and STAR preliminary in this case is nonflow
- PHENIX suppresses nonflow via kinematic selection

Understanding the nonflow contribution: v_2 in p+Au as a case study



- The large difference between the PHENIX published and STAR preliminary in this case is nonflow
- PHENIX suppresses nonflow via kinematic selection
- STAR applies non-flow subtraction procedure
- One needs to be careful about the risk of over-subtraction methods—S. Lim, et al (RB), Phys. Rev. C 100, 024908 (2019)

Understanding the nonflow contribution: v_2 in p+Au as a case study



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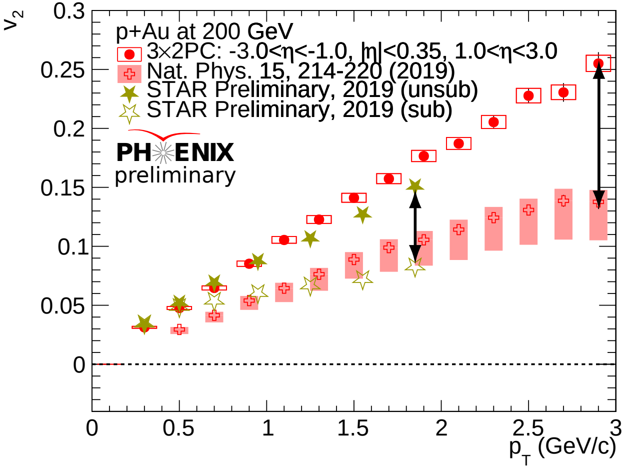


- The large difference between the PHENIX published and STAR preliminary in this case is nonflow
- PHENIX suppresses nonflow via kinematic selection
- STAR applies non-flow subtraction procedure
- Considerable improvement in nonflow subtraction in STAR 2019 preliminary, reasonable agreement with PHENIX

Additional non-flow studies using published data tables

- To enable additional study, the new PHENIX (RB) publication (arXiv:2017.06634, sub'd to PRC) includes the complete set of $\Delta\phi$ correlations and extracted coefficients c_1, c_2, c_3, c_4

Additional non-flow studies using published data tables

Checking Non-Flow Assumptions and Results via PHENIX Published Correlations in p+p, p+Au, d+Au, ^{3}He+Au at $\sqrt{s_{NN}}$ = 200 GeV

J.L. Nagle,[1] R. Belmont,[2] S.H. Lim,[3] and B. Seidlitz[1]

[1] *University of Colorado, Boulder, Colorado 80309, USA*
[2] *University of North Carolina, Greensboro, North Carolina 27413, USA*
[3] *Pusan National University, Busan, 46241, South Korea*

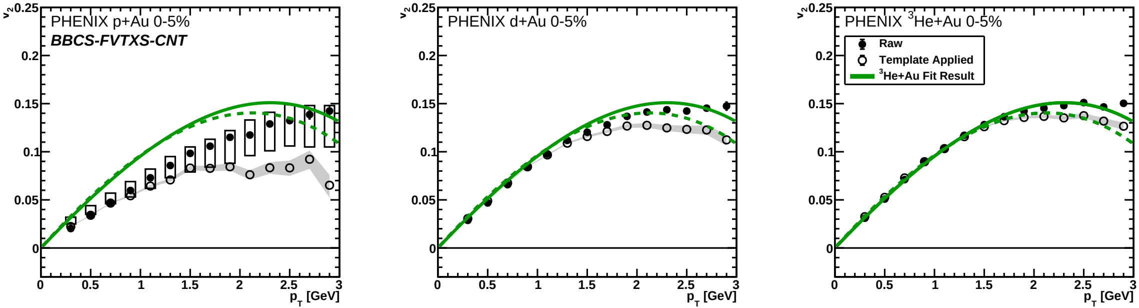
(Dated: July 16, 2021)

https://arxiv.org/abs/2107.07287

- To enable additional study, the new PHENIX (RB) publication (arXiv:2017.06634, sub'd to PRC) includes the complete set of $\Delta\phi$ correlations and extracted coefficients c_1, c_2, c_3, c_4
- A new paper uses these data tables to explore non-flow subtraction of these data as well as to assess the degree of (non-)closure of non-flow subtraction methods

Additional non-flow studies using published data tables

J.L. Nagle et al (RB), arXiv:2107.07287 (submitted to PRC)



- The BBCS-FVTXS-CNT combination minimizes non-flow, so subtraction doesn't make too much difference

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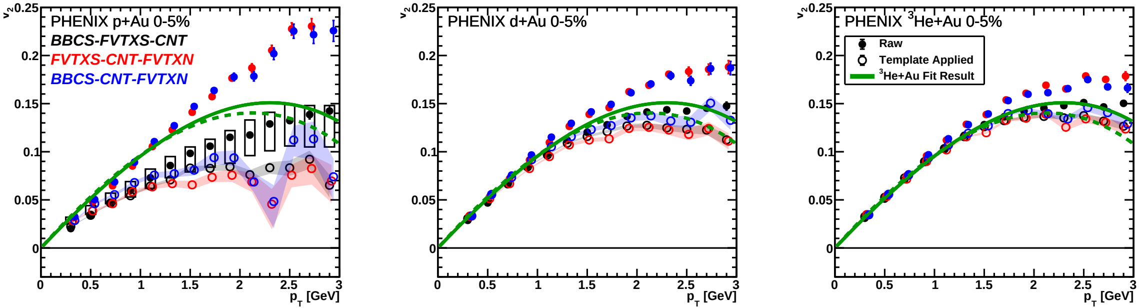

- The BBCS-FVTXS-CNT combination minimizes non-flow, so subtraction doesn't make too much difference
- The FVTXS-CNT-FVTXN combination has more non-flow, and the subtraction does much more
- That the three different combinations all line up after non-flow subtraction seems to lend some credence thereto, but one must be careful...

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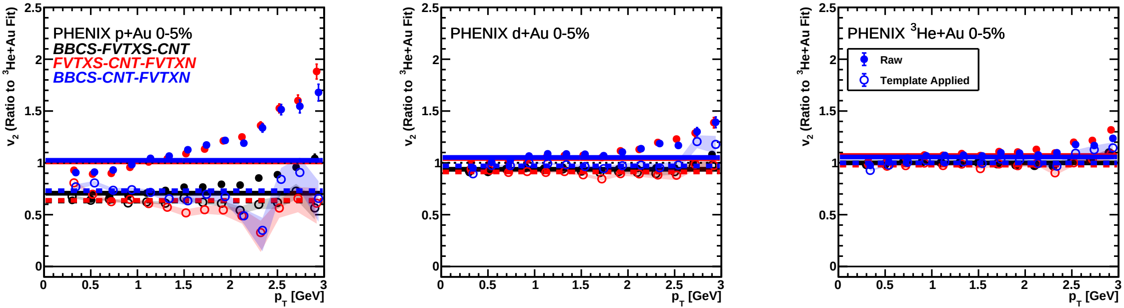

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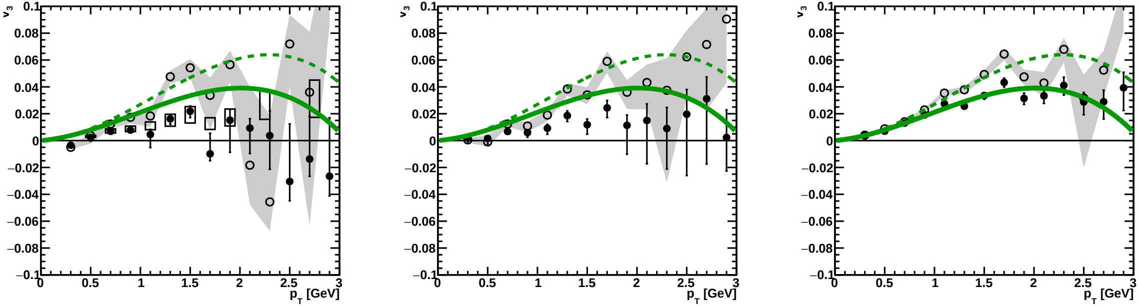

- There's a larger relative change for v_3 compared to v_2, but the smaller value of v_3 makes the non-flow subtraction more sensitive to non-closure

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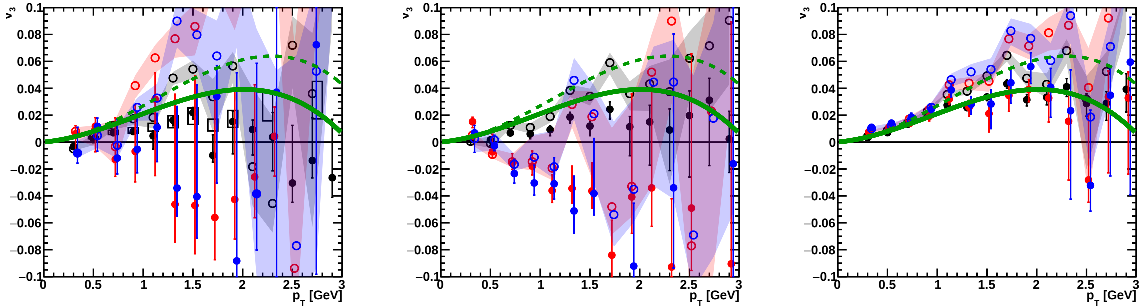

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- For the combinations with more non-flow, where the v_3 is imaginary in p+Au and d+Au, the non-flow subtraction is completely uncontrolled

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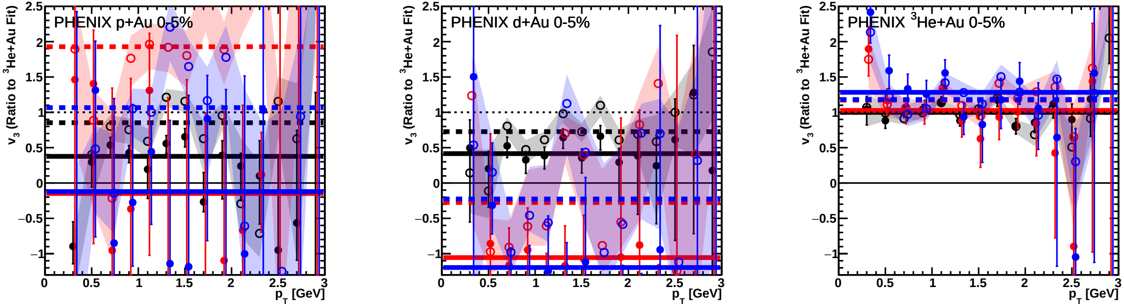

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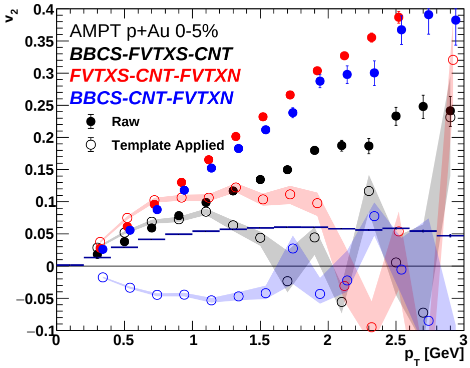

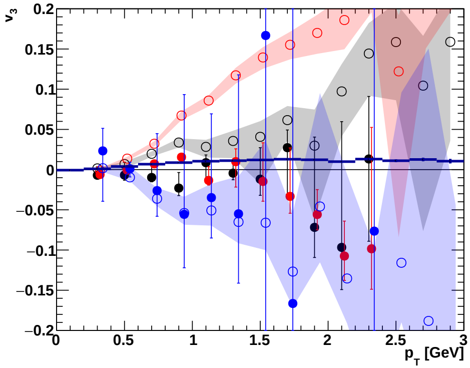

- Closure is considerably violated in AMPT

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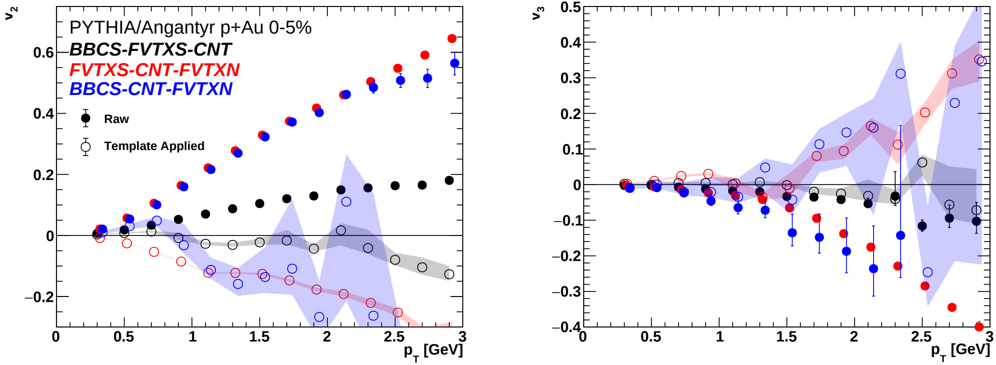

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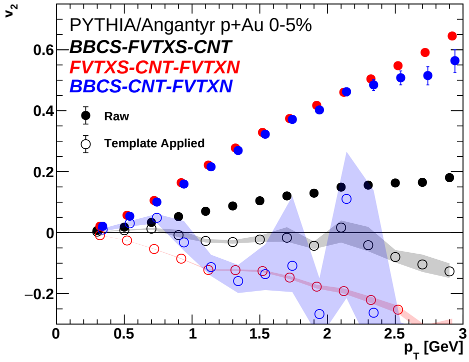
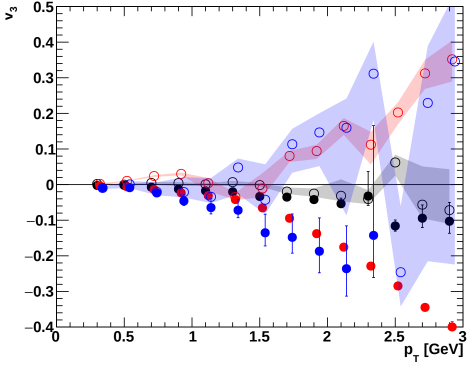
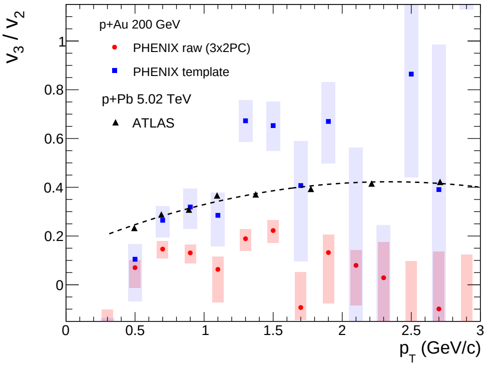




- Closure is considerably violated in AMPT and PYTHIA/Angantyr
- Since AMPT has too much non-flow and PYTHIA doesn't have any flow, the degree of overcorrection in real data is likely not as bad as it is with these generators

Additional non-flow studies using published data tables

J.L. Nagle et al (RB), arXiv:2107.07287 (submitted to PRC)



- The standard PHENIX v_3/v_2 is lower than the ATLAS, while the non-flow corrected is above

Additional non-flow studies using published data tables

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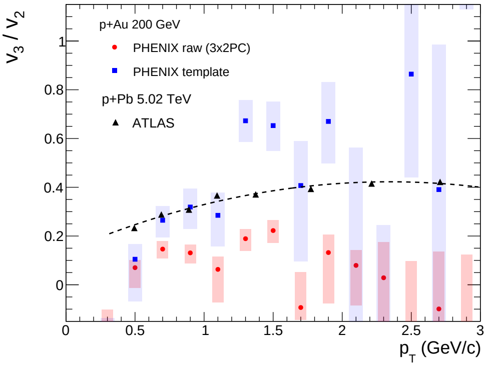

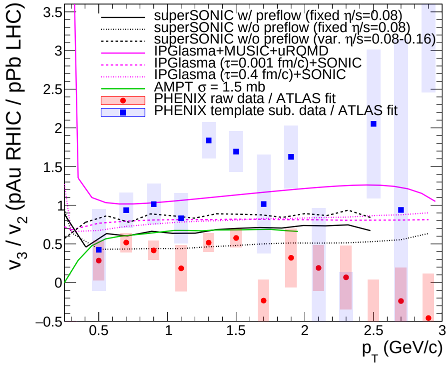

- The standard PHENIX v_3/v_2 is lower than the ATLAS, while the non-flow corrected is above
- The ratio is expected to be lower for lower collision energies in almost all physics scenarios
  —Lower energy, shorter lifetime, more damping of higher harmonics

Additional non-flow studies using published data tables

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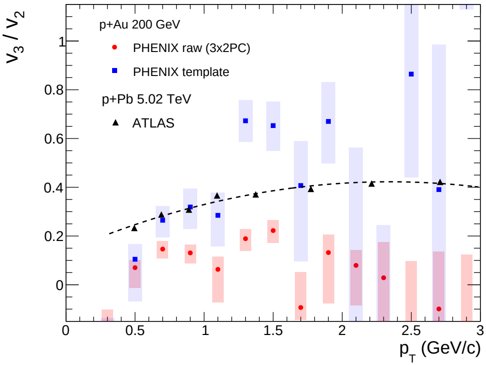

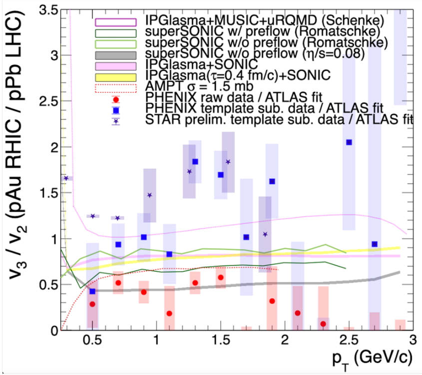

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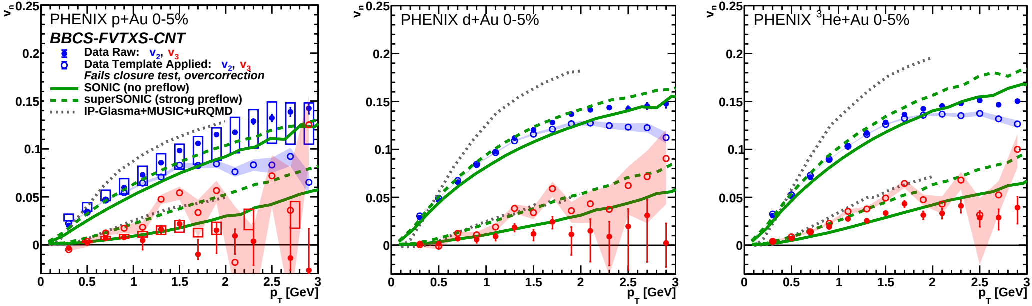
- The ratio is expected to be lower for lower collision energies in almost all physics scenarios
  —Lower energy, shorter lifetime, more damping of higher harmonics
- The STAR v_3/v_2 is very similar to the non-flow corrected PHENIX ratio

Additional non-flow studies using published data tables

J.L. Nagle et al (RB), arXiv:2107.07287 (submitted to PRC)



- Since the template method over-corrects the raw BBCS-FVTXS-CNT v_3, the truth is likely in between
- A firm understanding of this could shed a lot of light on various physics scenarios...

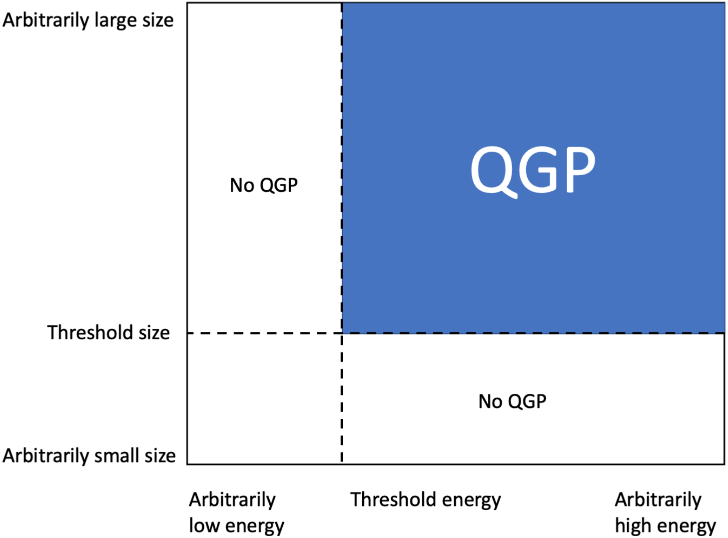
Intermission

Extremely small systems

Intermission

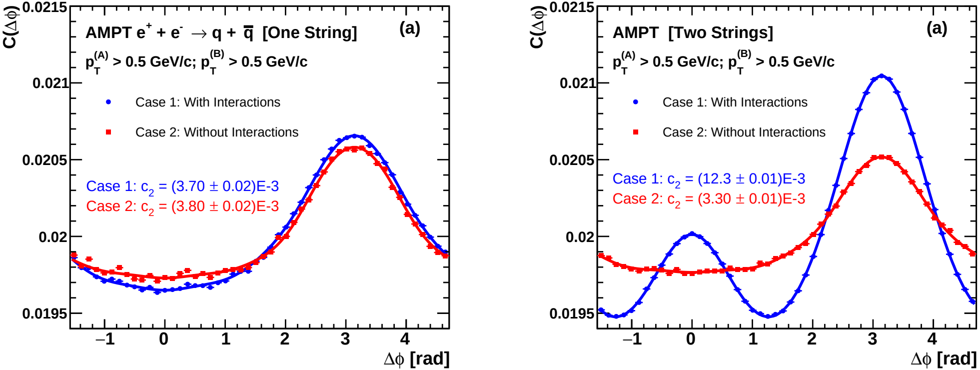
Can we turn the QGP off?

Let's have a look at *extremely* small systems



Extremely small systems in AMPT

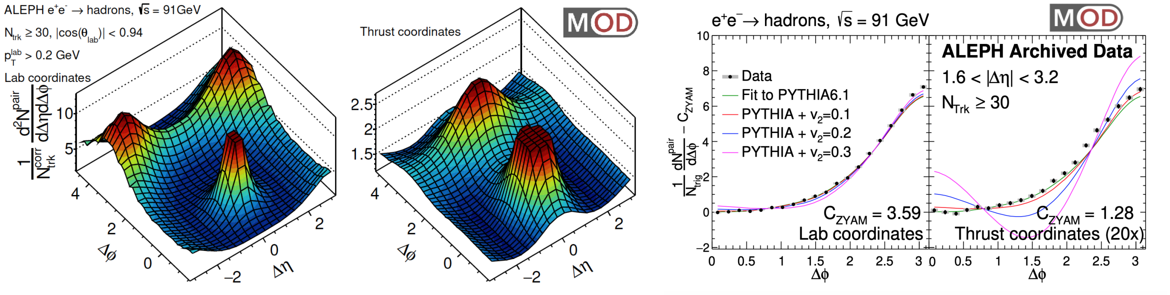
J.L. Nagle et al, Phys. Rev. C 97, 024909 (2018)



- A single color string ($e^+ + e^-$ collisions) shows no sign of collectivity
- Two color strings shows collectivity
  —In AMPT, $p+p$ has two strings and $p/d/^3$He+Au have more

Extremely small systems at LEP

Badea et al, Phys. Rev. Lett. 123, 212002 (2019)

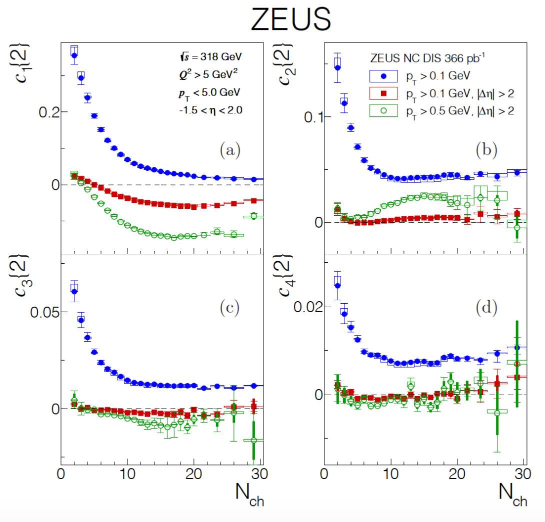


No apparent collectivity in ALEPH $e^+ + e^-$ data

- Brought up as a possibility in e.g. P. Romatschke, EPJC 77, 21 (2017)
- Not expected in parton escape picture (see previous slide)
- Not expected (below $\sqrt{s} \approx 7$ TeV) in e.g. P. Castorina et al, EPJA 57, 111 (2021)

Extremely small systems at HERA and the EIC

Abt et al, JHEP 04, 070 (2020)



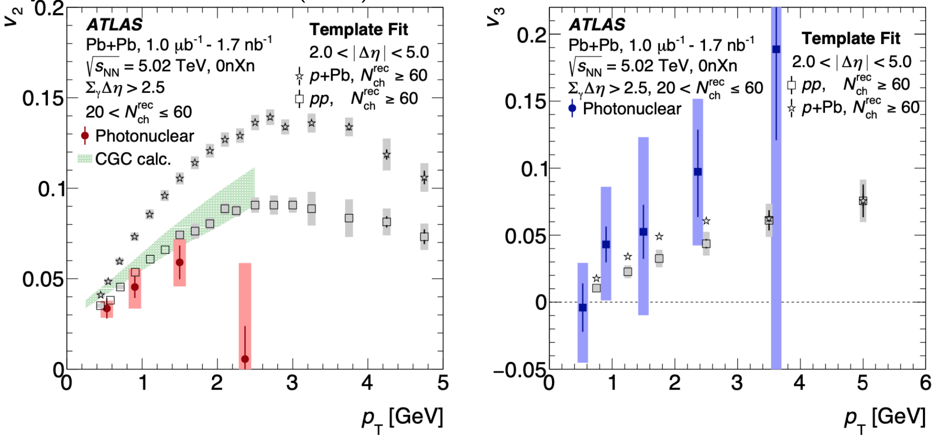
"The correlations observed here do not indicate the kind of collective behaviour recently observed at the highest RHIC and LHC energies in high-multiplicity hadronic collisions."

No collectivity in e+p collisions at HERA $\rightarrow$
Not likely to find collectivity in e+p collisions at EIC
But what about e+A collisions?

Considerable interest in this topic within EIC community (see talks by R. Milner, E. Ferreiro, others...)

Extremely small systems at the LHC

ATLAS, Phys. Rev. C 104, 014903 (2021)



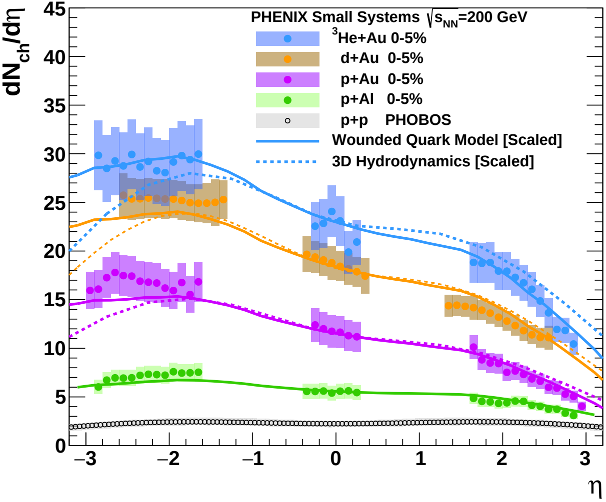
- Observation of collectivity in photonuclear collisions
- Collective picture: photon fluctuates into a vector meson (e.g. ρ), not so different from p+Pb
- Initial state picture: CGC calculation in good agreement, further investigation needed

Intermission

Pseudorapidity dependence in small systems as a prelude to the geometry scan

Pseudorapidity dependence in small systems

PHENIX (RB), Phys. Rev. Lett. 121, 222301 (2018)



p+Al, *p*+Au, *d*+Au, ^{3}He+Au

Good agreement with wounded quark model (M. Barej et al, Phys. Rev. C 97, 034901 (2018))

Good agreement with 3D hydro (P. Bozek et al, Phys. Lett. B 739, 308 (2014))

Pseudorapidity dependence in small systems

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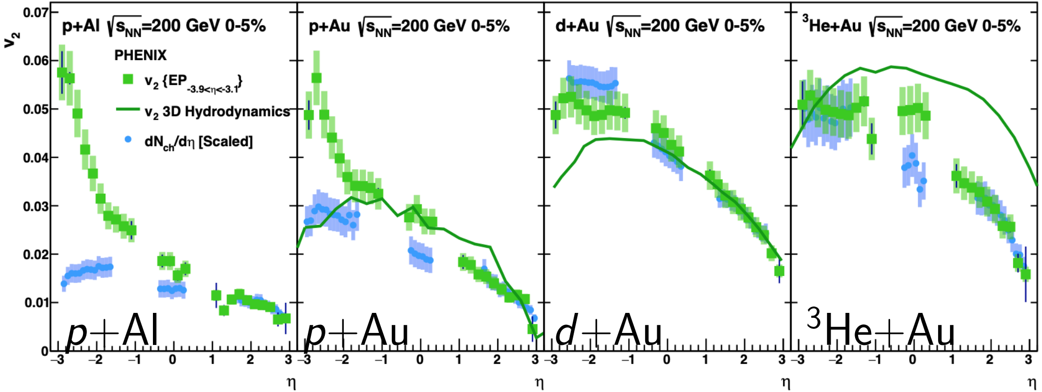

- v_2 vs η in p+Al, p+Au, d+Au, and ^{3}He+Au
- Good agreement with 3D hydro for p+Au and d+Au (Bozek et al, PLB 739, 308 (2014))

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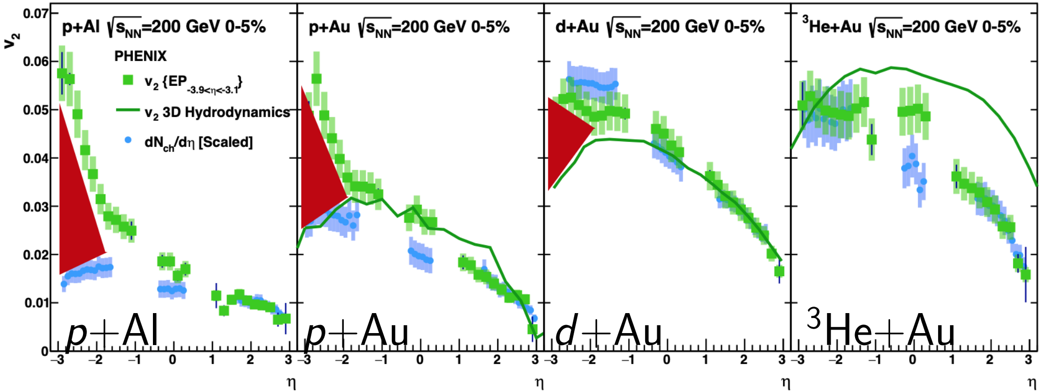

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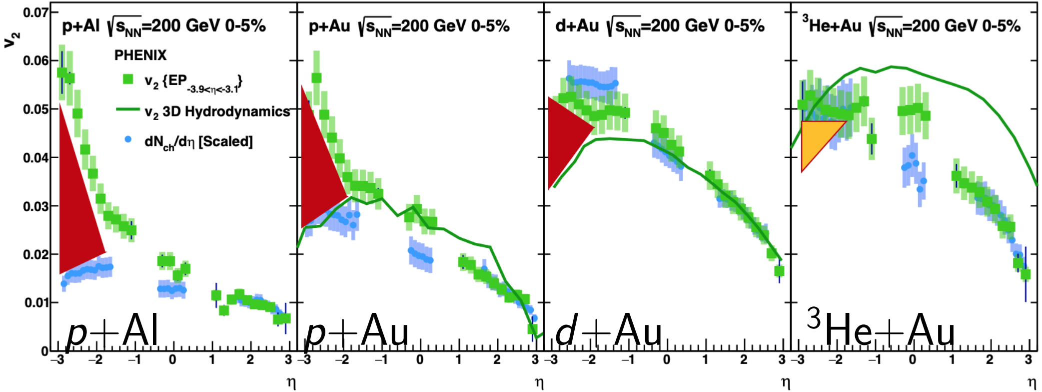
Pseudorapidity dependence in small systems

PHENIX (RB), Phys. Rev. Lett. 121, 222301 (2018)



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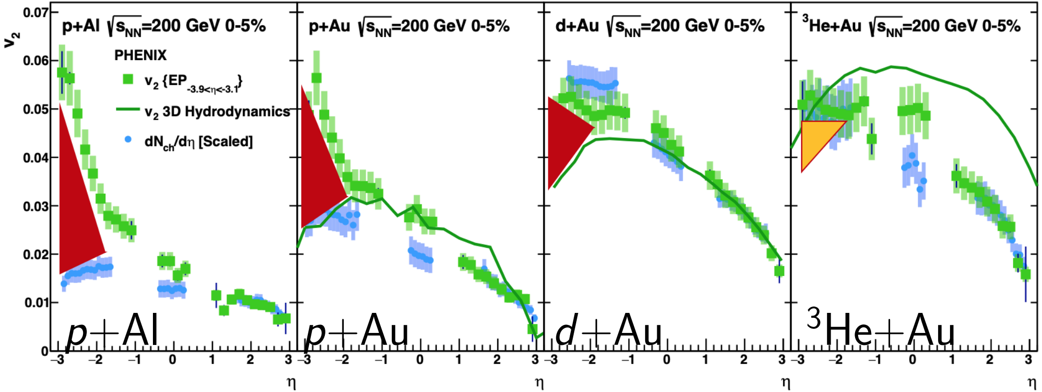


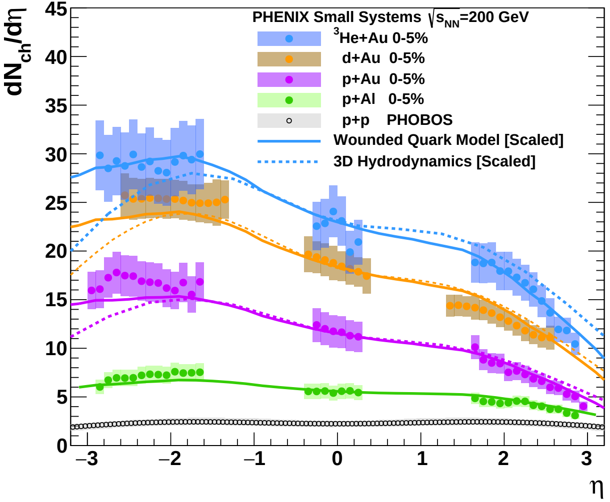
- It would be nice to know $v_3(\eta)$, but very hard to measure

Intermission

Pseudorapidity dependence in small systems

Pseudorapidity dependence in small systems

Phys. Rev. Lett. 121, 222301 (2018)



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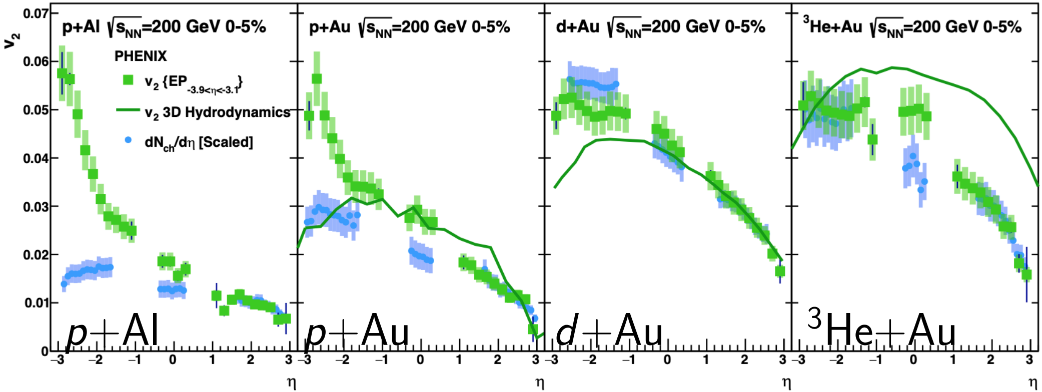

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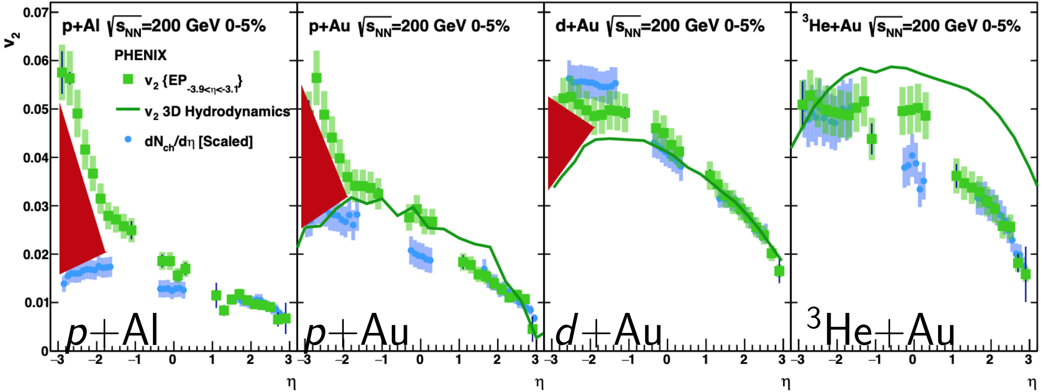

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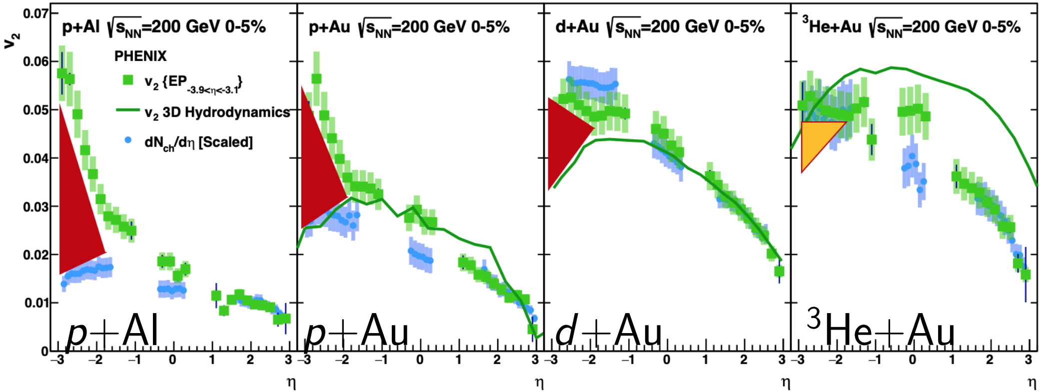

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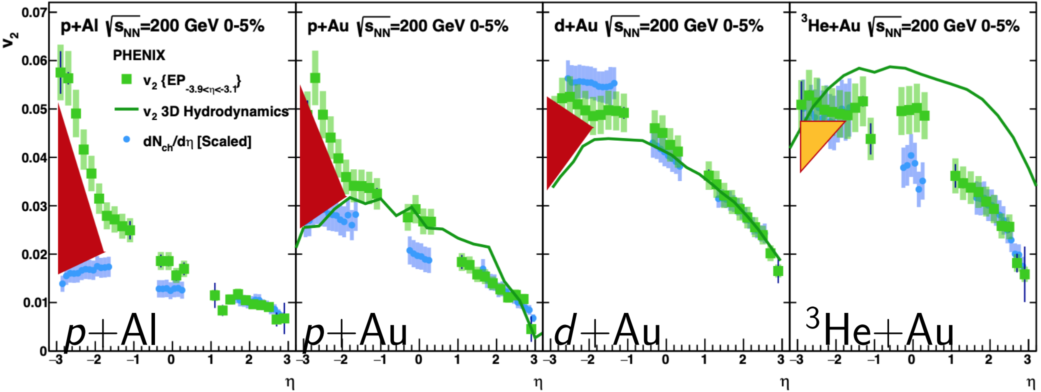

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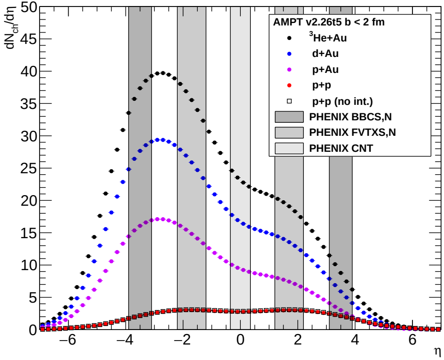
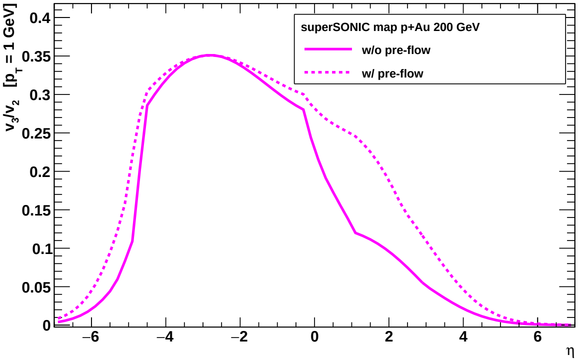
Pseudorapidity dependence in small systems

J.L. Nagle et al, arXiv:2107.07287 (submitted to PRC)





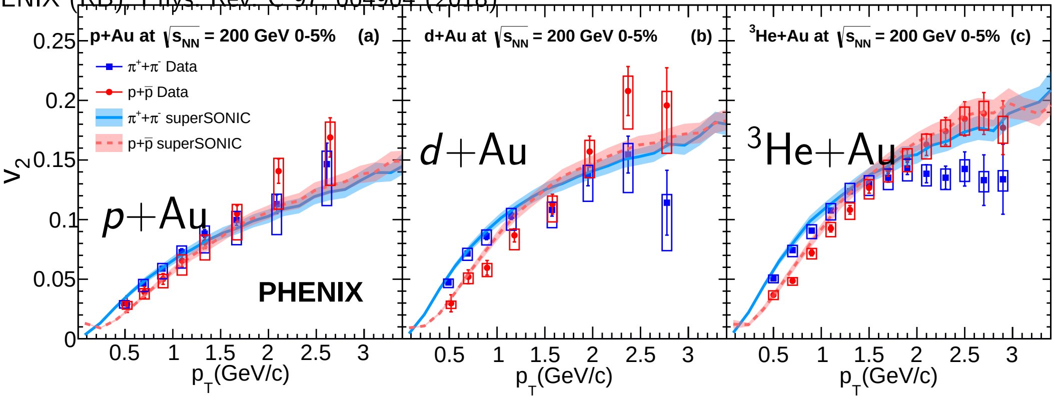
- $dN_{ch}/d\eta$ from AMPT, $v_3(\eta)$ from (super)SONIC
- The likely much stronger rapidity dependence of v_3 compared to v_2 is an essential ingredient in understanding different measurements

Intermission

Small systems geometry scan

Small systems geometry scan

PHENIX (RB), Phys. Rev. C 97, 064904 (2018)



- Identified particle v_2 vs p_T in p+Au, d+Au, and ^{3}He+Au
  —Low p_T mass ordering well-described by hydro
  —Hydro doesn't have enough splitting at mid-p_T (hadronization by Cooper-Frye)

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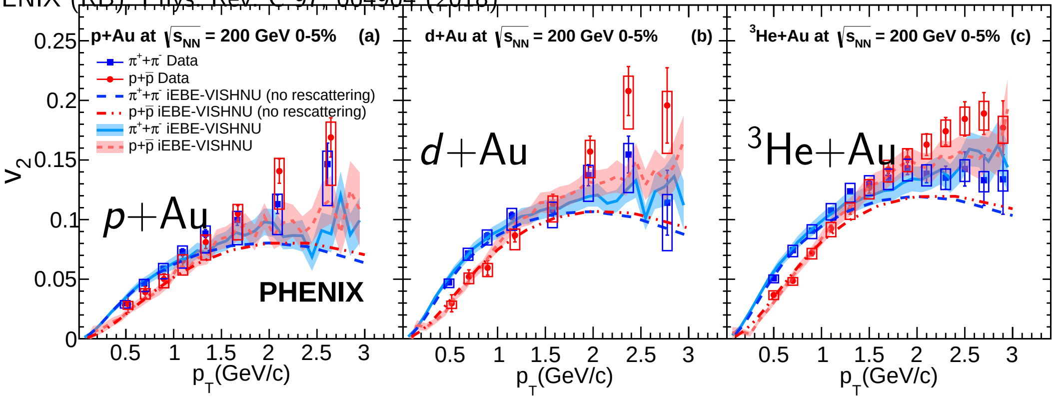

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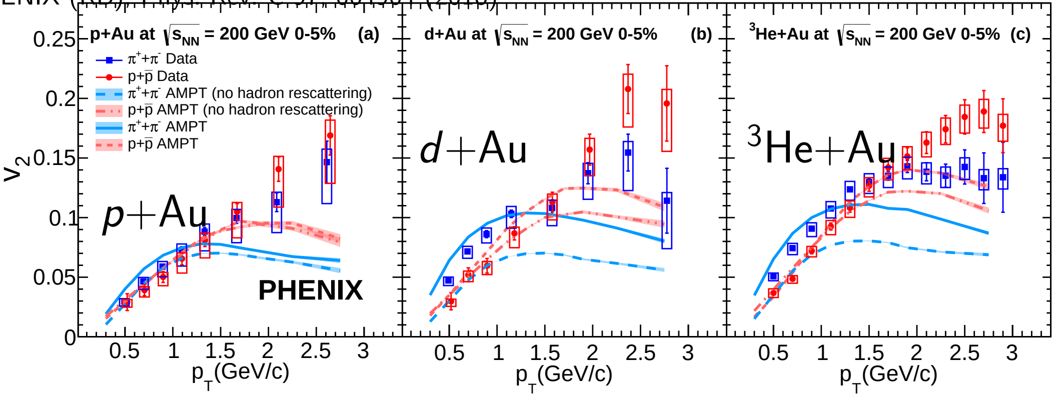

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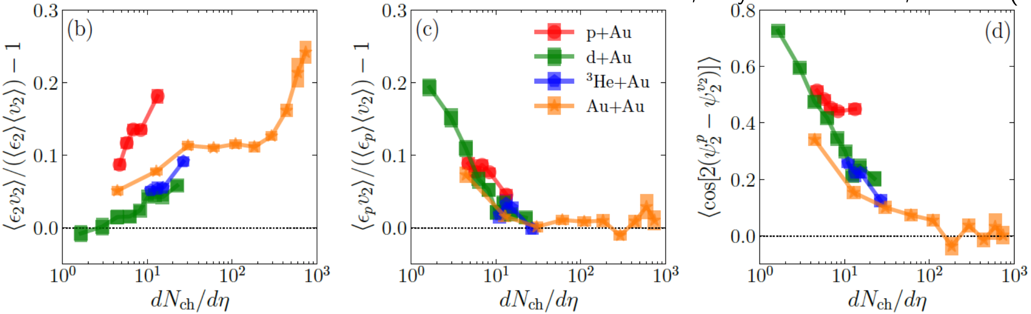
  —Low p_T mass ordering well-described by hydro
  —Hydro doesn't have enough splitting at mid-p_T (hadronization by Cooper-Frye)
- AMPT gets mid-p_T separation because of the more realistic hadronization (coalescence)

How important are initial state effects?

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



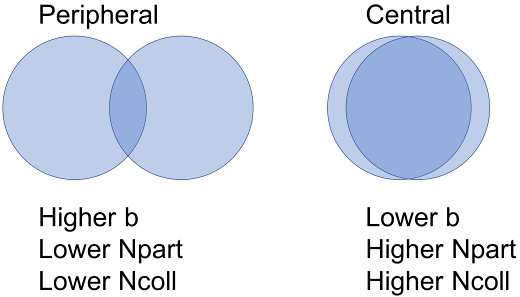
- For central p+Au, modest correlation between ε_p and v_2 but fairly strong correlation between ψ_2^p and $\psi_2^{v_2}$
- For central d+Au and ^{3}He+Au, no correlation between ε_p and v_2, modest correlation between ψ_2^p and $\psi_2^{v_2}$

Intermission

Event characterization

Centrality

- b (impact parameter)—separation between the centers of the two nuclei
- N_{part}—number of nucleons in the overlap region
- N_{coll}—number of nucleon-nucleon collisions



Centrality	$\langle N_{coll} \rangle$	$\langle N_{part} \rangle$
Au+Au		
0-10%	960.2	325.8
10-20%	609.5	236.1
20-40%	300.8	141.5
40-60%	94.2	61.6
60-92%	14.8	14.7
d+Au		
0-20%	15.1	15.3
20-40%	10.2	11.1
0-100%	7.6	8.5
40-60%	6.6	7.8
60-88%	3.1	4.3
p+p	$\equiv 1$	$\equiv 2$

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- b (impact parameter)—separation between the centers of the two nuclei
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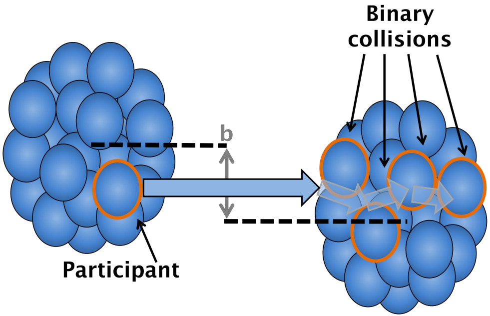

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Intermission

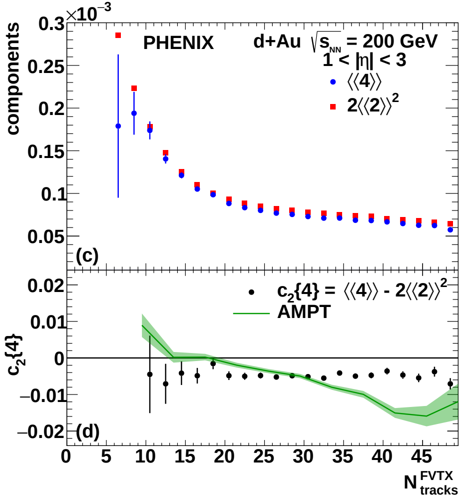
Multiparticle correlations

Components and cumulants in p+Au and d+Au at 200 GeV

Phys. Rev. Lett. 120, 062302 (2018)

$$v_2\{4\} = (-c_2\{4\})^{1/4}$$

Negative $c_2\{4\}$ means real $v_2\{4\}$



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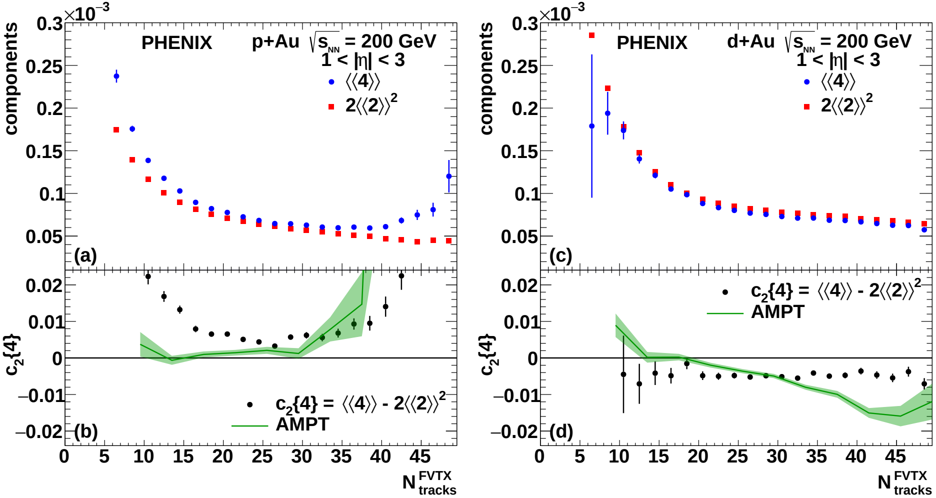

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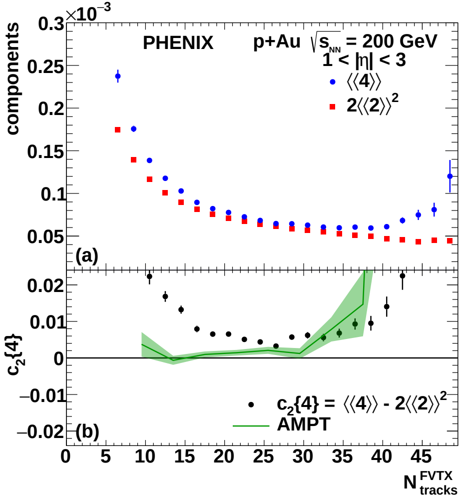
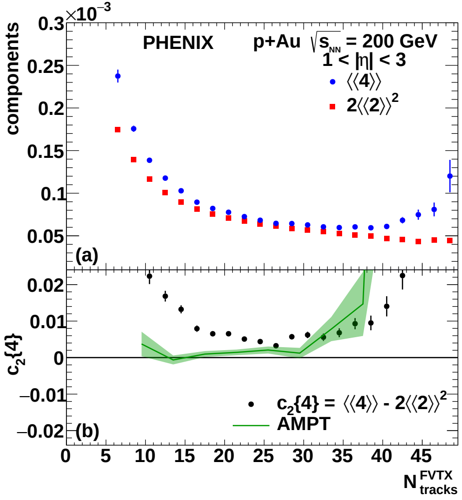


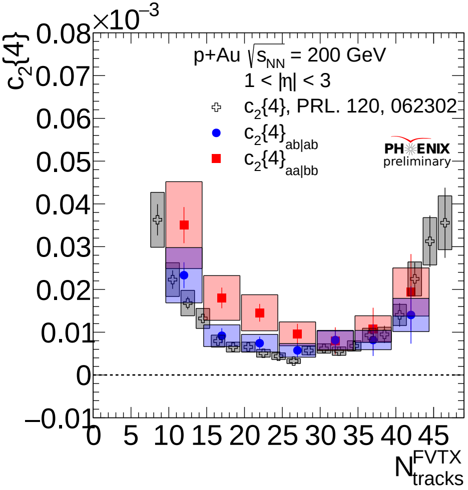
$c_2\{4\}$ is positive in p+Au

Can we blame this on nonflow?

Components and cumulants in p+Au and d+Au at 200 GeV

Phys. Rev. Lett. 120, 062302 (2018)



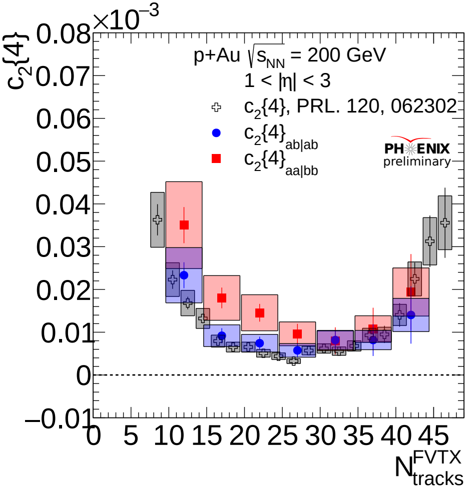


Components and cumulants in p+Au and d+Au at 200 GeV

Phys. Rev. Lett. 120, 062302 (2018)

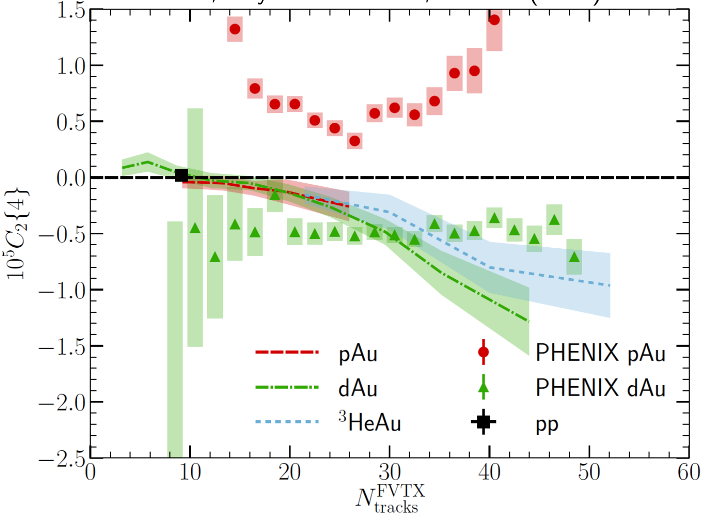
Use of subevents further suppresses nonflow

Positive $c_2\{4\}$ in p+Au doesn't seem to be related to nonflow



Cumulants in p+Au and d+Au at 200 GeV

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



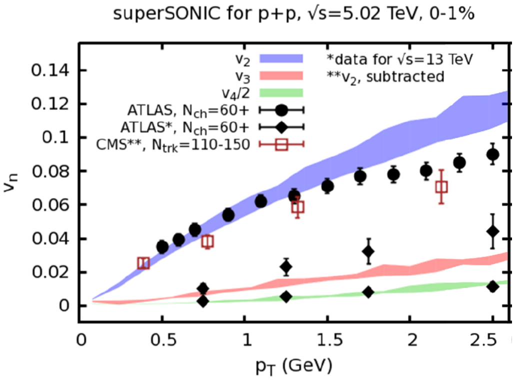
Cumulants are computationally expensive in hydro theory, so not as well-studied

This particular calculation doesn't show the strong geometry dependence seen in the data

Important to note this is 2+1D hydro, so the kinematics can't match the data

$p+p$ collisions at the LHC

Weller & Romatschke, PLB 774, 351 (2017)



- Hydro does a good job of $v_n\{2\}$...

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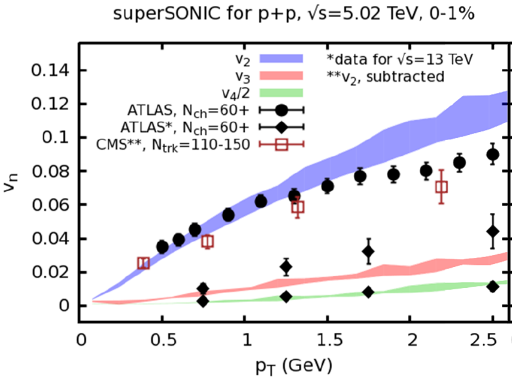
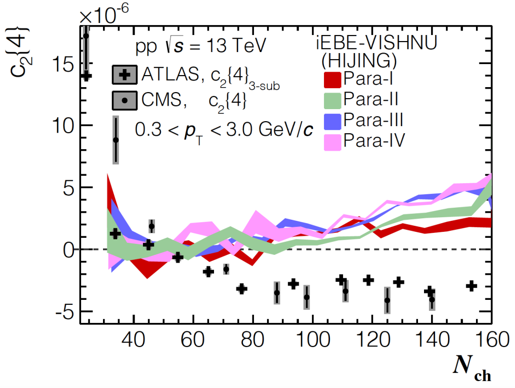


W. Zhao et al, PLB 780, 495 (2018)



- Hydro does a good job of $v_n\{2\}$...
- ...but hydro cannot even get the correct sign of $c_2\{4\}$

Intermission

Initial eccentricities

Initial eccentricities

Table compiled by J.L. Nagle

System	Nagle Nucleons w/o NBD fluctuations	Welsh Nucleons w/ NBD fluctuations	Welsh Quarks w/ NBD and Gluon fluctuations	IPGlasma w/ Nucleons t=0	IP-Glasma w/ 3 Quarks t=0
ε_2 p+Au	0.23	0.32	0.38	**0.10**	**0.50**
ε_2 d+Au	0.54	0.48	0.51	**0.58**	**0.73**
ε_2 ^{3}He+Au	0.50	0.50	0.52	**0.55**	**0.64**
ε_3 p+Au	0.16	0.24	0.30	**0.09**	**0.32**
ε_3 d+Au	0.18	0.28	0.31	**0.28**	**0.40**
ε_3 ^{3}He+Au	0.28	0.32	0.35	**0.34**	**0.46**

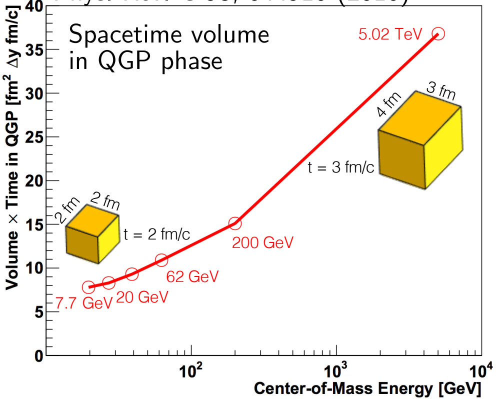
- Nagle et al: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.113.112301
- Welsh et al: https://journals.aps.org/prc/abstract/10.1103/PhysRevC.94.024919
- IP-Glasma run by S. Lim using publicly available code (thanks to B. Schenke)

Intermission

Small systems beam energy scan

Testing hydro by controlling system size and life time

J.D. Orjuela Koop et al (RB)
Phys. Rev. C 93, 044910 (2016)

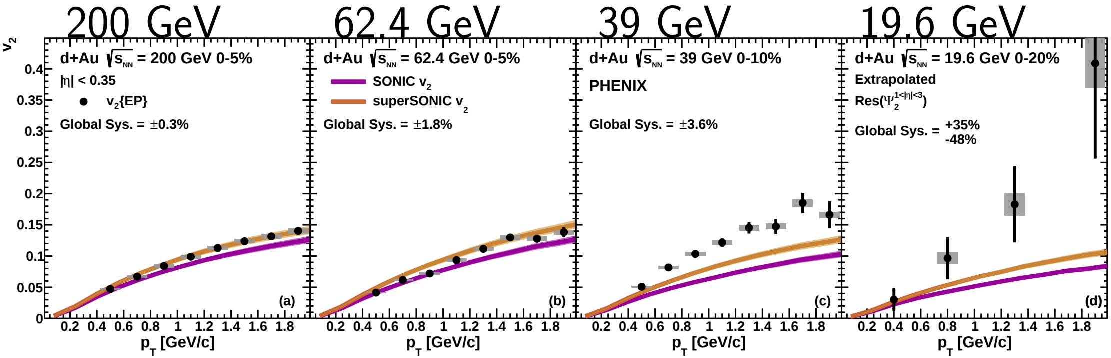


Geometry in d+Au collisions dominated by deuteron shape, thus largely independent of collision energy

Spacetime volume of system in QGP phase decreases with decreasing collision energy

d+Au beam energy scan

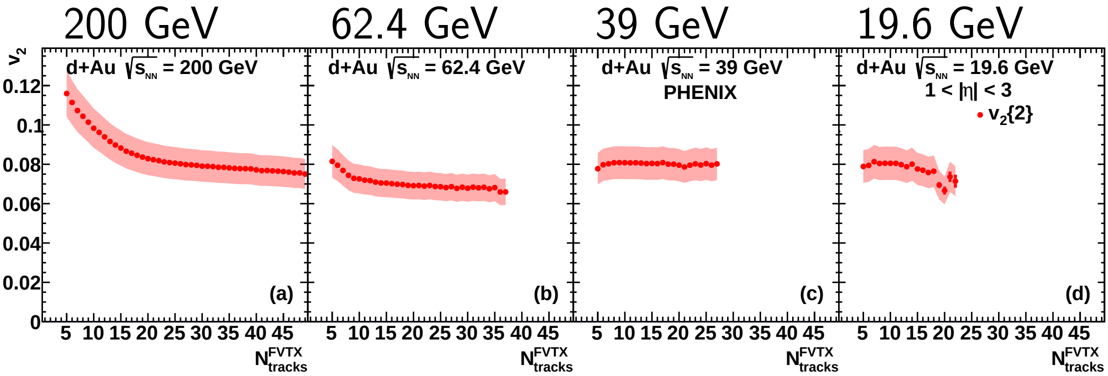
PHENIX (RB), Phys. Rev. C 96, 064905 (2017)



- Hydro theory agrees with higher energies very well, underpredicts lower energies
- Likely need different EOS for lower energies; influence of conserved charges likely more important at lower energies (see e.g. J. Noronha-Hostler et al, 1911.10272, 1911.12454)
- Nonflow likelier to be an issue due to lower multiplicity at lower energies

d+Au beam energy scan

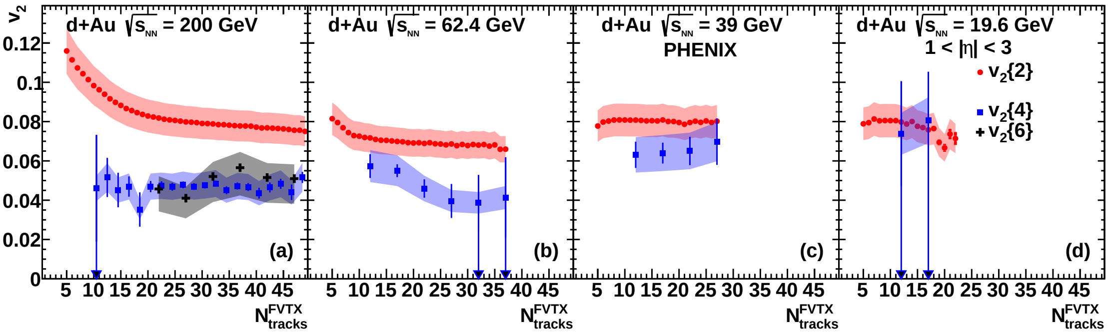
PHENIX (RB), Phys. Rev. Lett. 120, 062302 (2018)



d+Au beam energy scan

PHENIX (RB), Phys. Rev. Lett. 120, 062302 (2018)

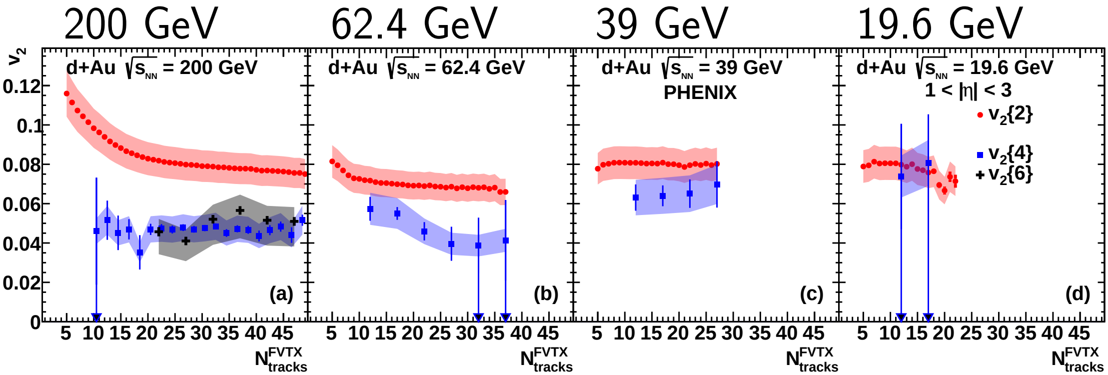
200 GeV 62.4 GeV 39 GeV 19.6 GeV



- Measurement of $v_2\{6\}$ in d+Au at 200 GeV and $v_2\{4\}$ in d+Au at all energies

d+Au beam energy scan

PHENIX (RB), Phys. Rev. Lett. 120, 062302 (2018)



- Measurement of $v_2\{6\}$ in d+Au at 200 GeV and $v_2\{4\}$ in d+Au at all energies
- Multiparticle correlations can be a good indicator of collectivity, but beware caveats

Testing hydro by controlling system geometry

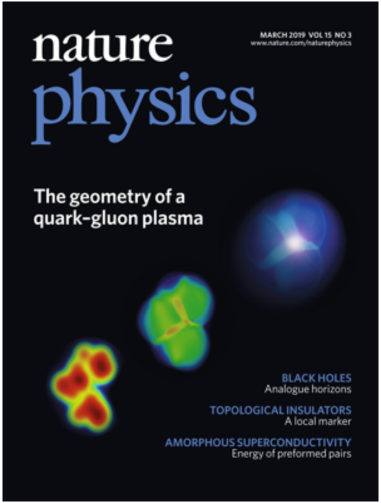
A marquee result of the RHIC program

Major interest in and out of field—174 citations

Creation of quark–gluon plasma droplets with three distinct geometries

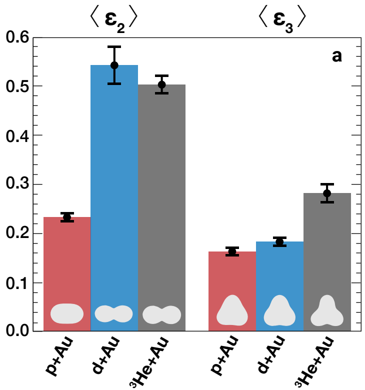
PHENIX Collaboration

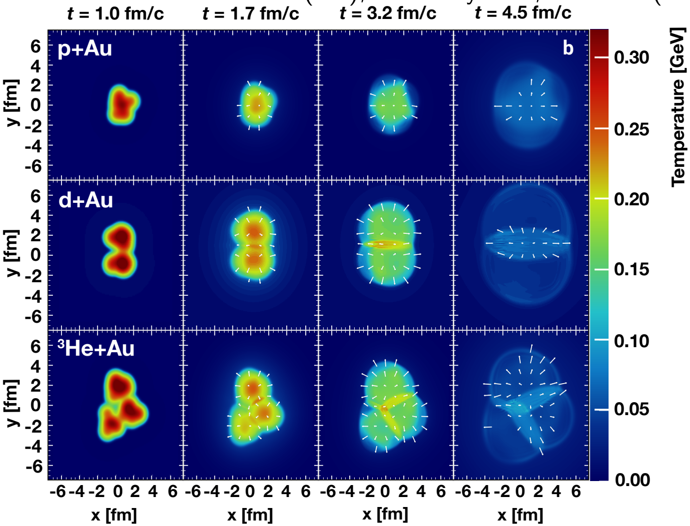
Nature Physics **15**, 214–220(2019) | Cite this article



Testing hydro by controlling system geometry

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





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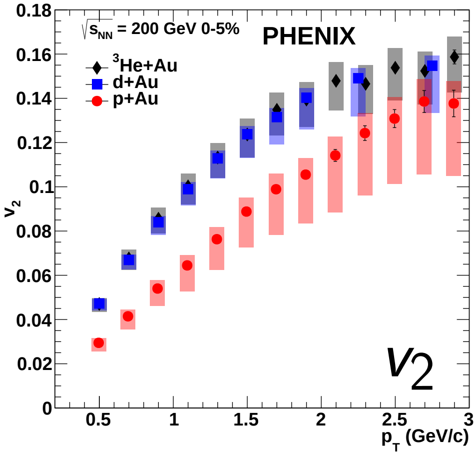
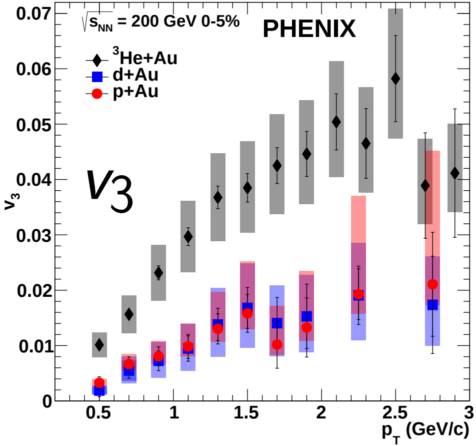
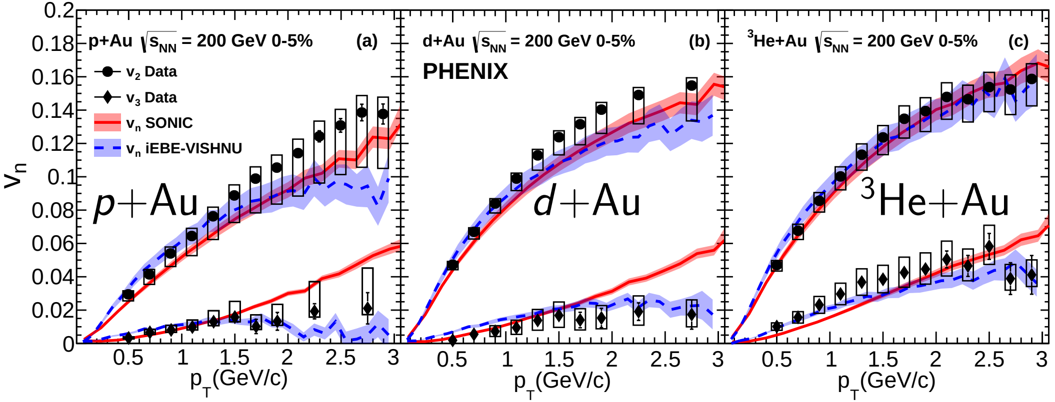




- v_2 and v_3 ordering matches ε_2 and ε_3 ordering in all three systems
  —Collective motion of system translates the initial geometry into the final state

Testing hydro by controlling system geometry

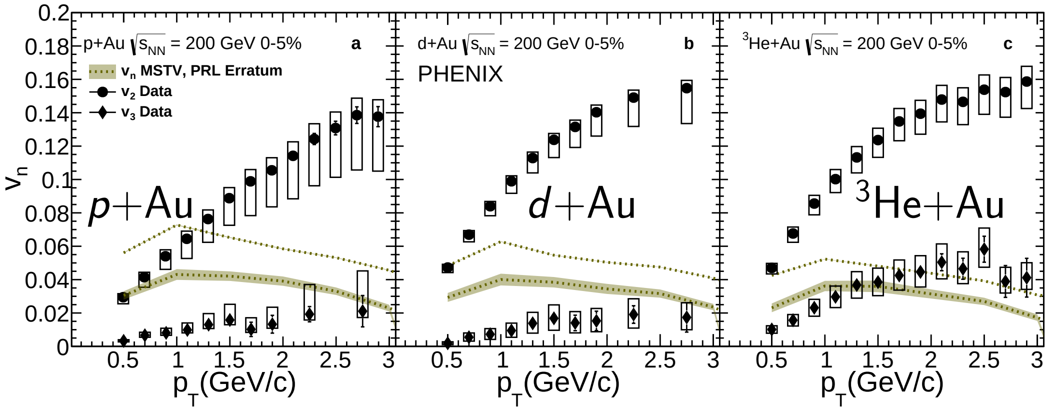
PHENIX (RB), Nat. Phys. 15, 214–220 (2019)



- 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)

Testing hydro by controlling system geometry

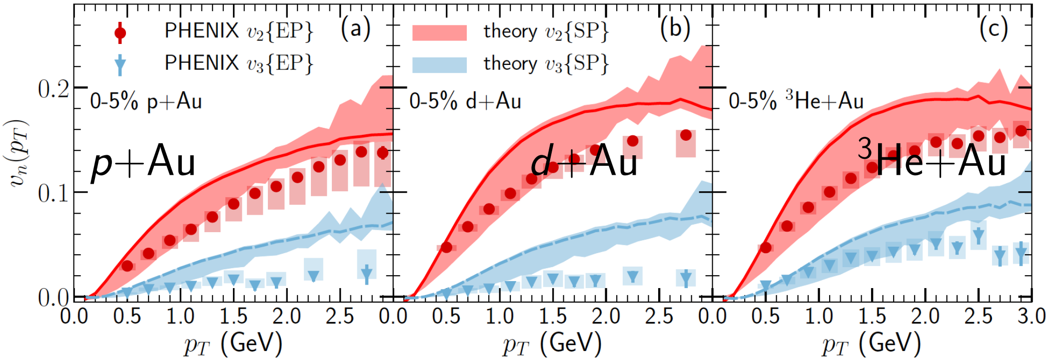
PHENIX (RB), Nat. Phys. 15, 214–220 (2019)



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

Testing hydro by controlling system geometry

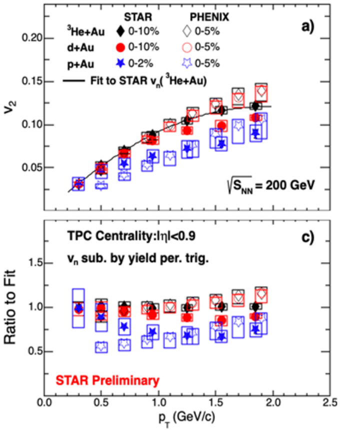
PHENIX (RB), Nat. Phys. 15, 214–220 (2019)



- Inclusion of initial state effects is important, but not a big contribution for central collisions —B. Schenke et al, Phys. Lett. B 803, 135322 (2020)

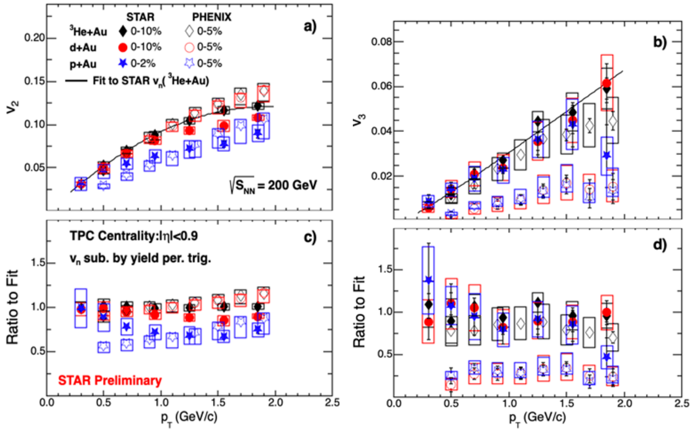
Comparisons with STAR

STAR, Quark Matter 2019



Good agreement between STAR and PHENIX for v_2

STAR, Quark Matter 2019

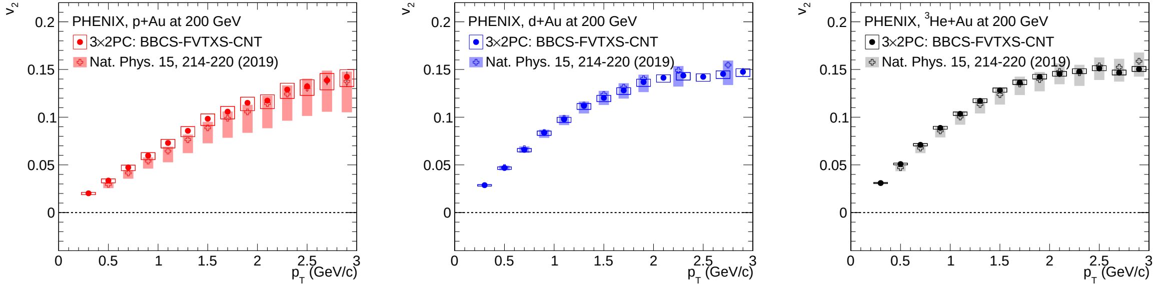


Good agreement between STAR and PHENIX for v_2

Large discrepancy between STAR and PHENIX for v_3

PHENIX data update

PHENIX (RB), arXiv:2107.06634 (accepted by Phys. Rev. C)



- 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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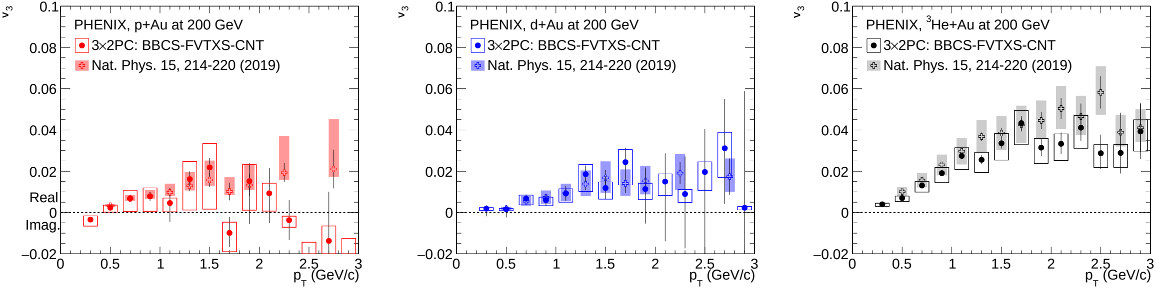

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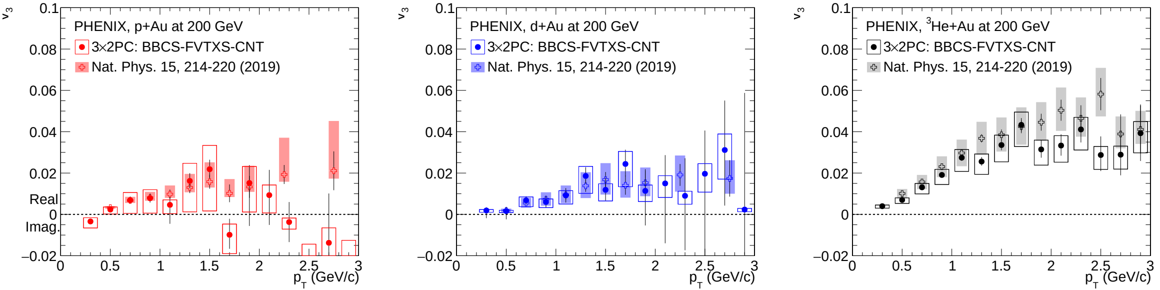

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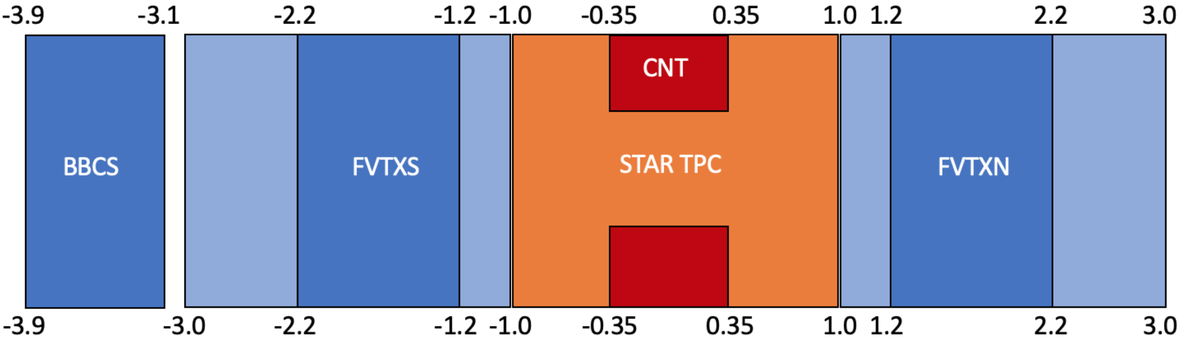
- All new analysis using two-particle correlations with event mixing instead of event plane method
  —Completely new and separate code base
  —Very different sensitivity to key experimental effects (beam position, detector alignment)
- It's essential to understand the two experiments have very different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

STAR and PHENIX detector comparison



- The PHENIX Nature Physics paper uses the BBCS-FVTXS-CNT detector combination
  —Very different kinematic acceptance compared to STAR
- We can try to use FVTXS-CNT-FVTXN detector combination to better match STAR
  —Closer, and “balanced” between forward and backward

More STAR and PHENIX data comparisons

PHENIX (RB), arXiv:2107.06634 (accepted by Phys. Rev. C)

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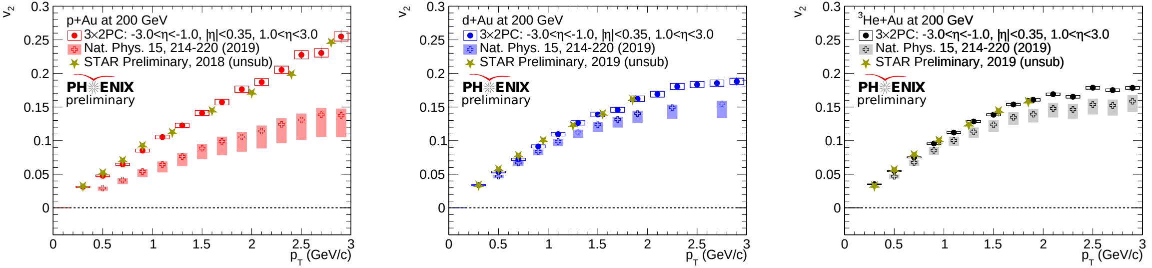

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  —Similar physics for the two different pseudorapidity acceptances

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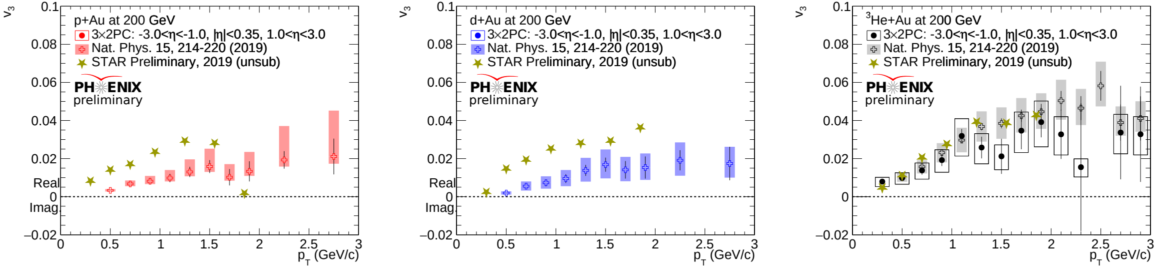

- Good agreement with STAR for v_2
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- Strikingly different results for v_3
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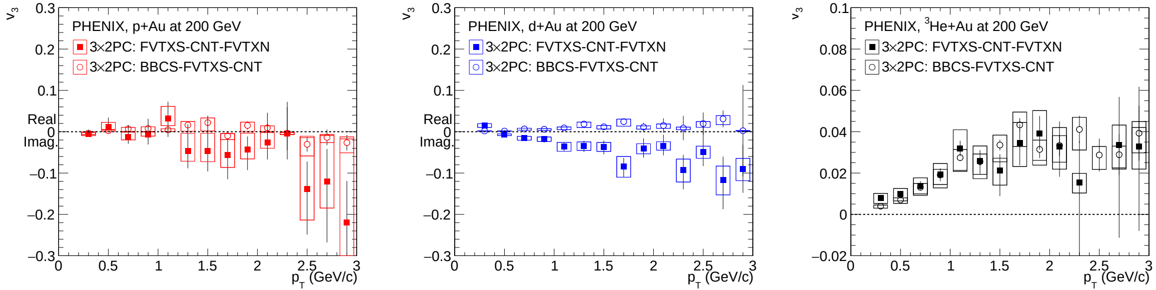

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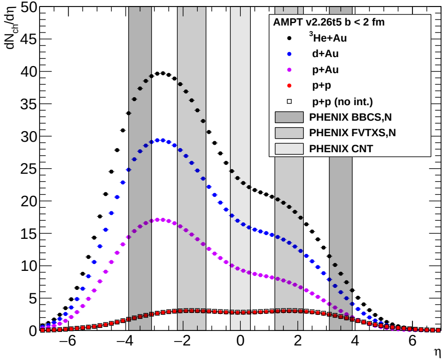
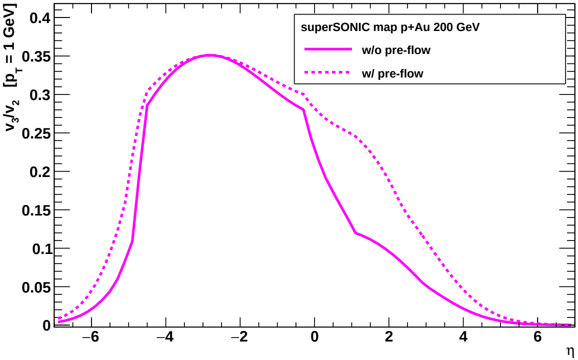
Longitudinal dynamics in small systems

J.L. Nagle et al (RB), arXiv:2107.07287 (submitted to PRC)

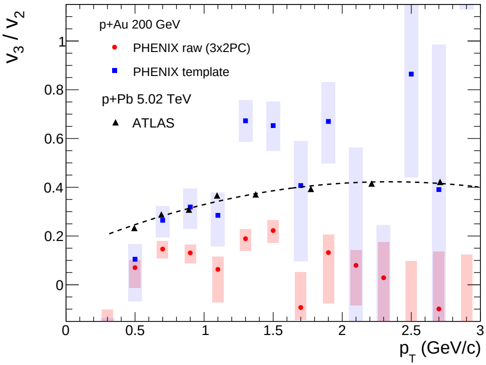


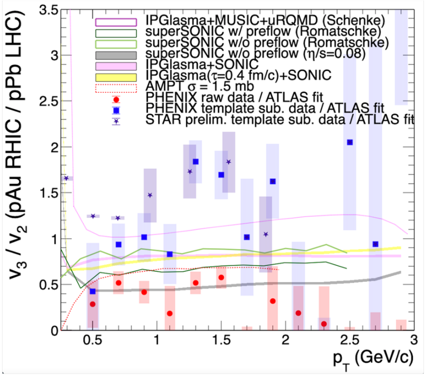


- $dN_{ch}/d\eta$ from AMPT, $v_3(\eta)$ from (super)SONIC
- The likely much stronger pseudorapidity dependence of v_3 compared to v_2 is an essential ingredient in understanding different measurements

Additional non-flow studies using published data tables

J.L. Nagle et al (RB), arXiv:2107.07287 (submitted to PRC)





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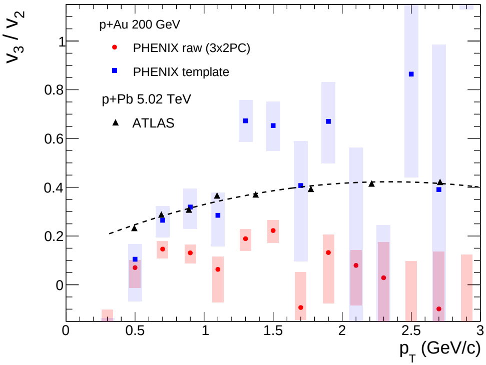
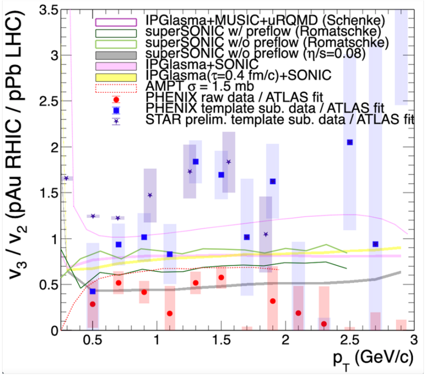
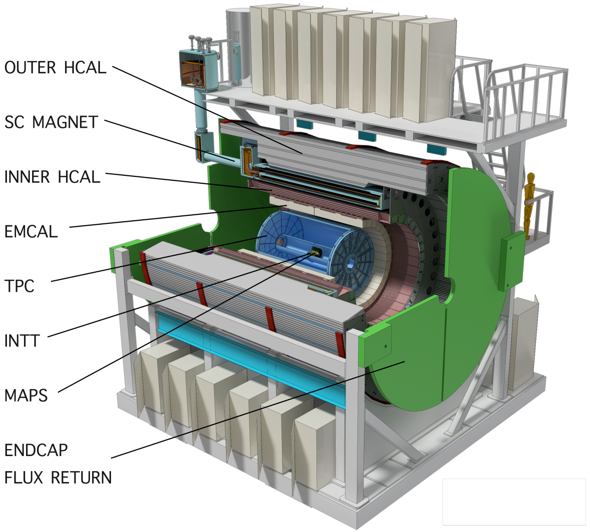




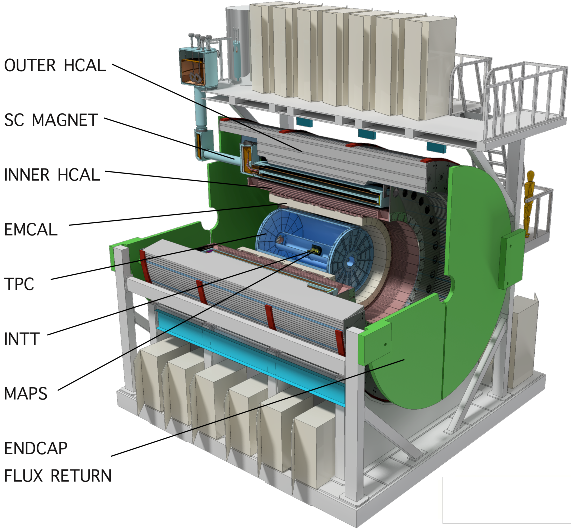
- v_3/v_2 expected be lower for lower collision energy due to shorter lifetime —STAR data may have unphysically large v_3/v_2
- Application of "non-flow subtraction" to remove contamination can lead to significant over-correction; see also S. Lim, et al (RB), Phys. Rev. C 100, 024908 (2019)

sPHENIX: QGP microscope



From the 2015 DOE Nuclear Physics Long Range Plan: **[The goal is to] probe the inner workings of QGP by resolving its properties at shorter and shorter length scales.... essential to this goal... is a state-of-the-art jet detector at RHIC, called sPHENIX.**

sPHENIX: QGP microscope



Resolving power $d \propto \lambda$

de Broglie wavelength $\lambda = h/p$

p	λ
2.5 eV	500 nm
100 keV	12 pm
200 MeV	6.2 fm
1 GeV	1.2 fm
10 GeV	0.12 fm
50 GeV	0.025 fm

sPHENIX: timeline

Past and present

- Magnet purchase — July 2013
- Magnet delivery — April 2015
- DOE OPA CD-0 — September 2016
- Order for Outer HCal steel — March 2018
- DOE OPA CD-1/CD-3a — August 2018
- DOE OPA PD-2/PD-3 Review — May 2019
- Authorization for PD-2/PD-3 — September 2019
- Fabrication orders — September 2019 (ongoing)
- Assembly and installation begins — April 2021 (ongoing)

Future

- Completion of assembly and installation, initial commissioning — September 2022
- First collisions — January 2023

sPHENIX: magnet

STANDARD FORM 122
JUNE 1974
GENERAL SERVICES ADMINISTRATION
FPMR (41 CFR) 101-32.306
FPMR (41 CFR) 101-43.315

TRANSFER ORDER
EXCESS PERSONAL PROPERTY

1. ORDER NO. SLAC 2013-07-18

2. DATE July 18, 2013

3. TO: GENERAL SERVICES ADMINISTRATION*

4. ORDERING AGENCY (Full name and address)*
Brookhaven National Lab
Attention: John Haggerty; haggerty@bnl.gov
Upton, NY 11973-5000

5. HOLDING AGENCY (Name and address)*
SLAC National Accelerator Laboratory
2575 Sand Hill Road, MS 85A
Menlo Park, CA 94025

6. SHIP TO (Consignee and destination)*
Same as block 4

7. LOCATION OF PROPERTY
SLAC National Accelerator Laboratory
C/O Mike Racine
2575 Sand Hill Road, MS 53
Menlo Park, CA 94025
650 926-3543 racine@slac.stanford.edu

8. SHIPPING INSTRUCTIONS
BNL to arrange for shipping

9. ORDERING AGENCY APPROVAL
A. SIGNATURE
B. DATE 7-19-13
C. TITLE Property Manager

10. APPROPRIATION SYMBOL AND TITLE
transfer from DE-AC02-76SFO0515
transfer to DE-AC02-98CH10886

11. ALLOTMENT

12. GOVERNMENT B/L NO.

13. PROPERTY ORDERED

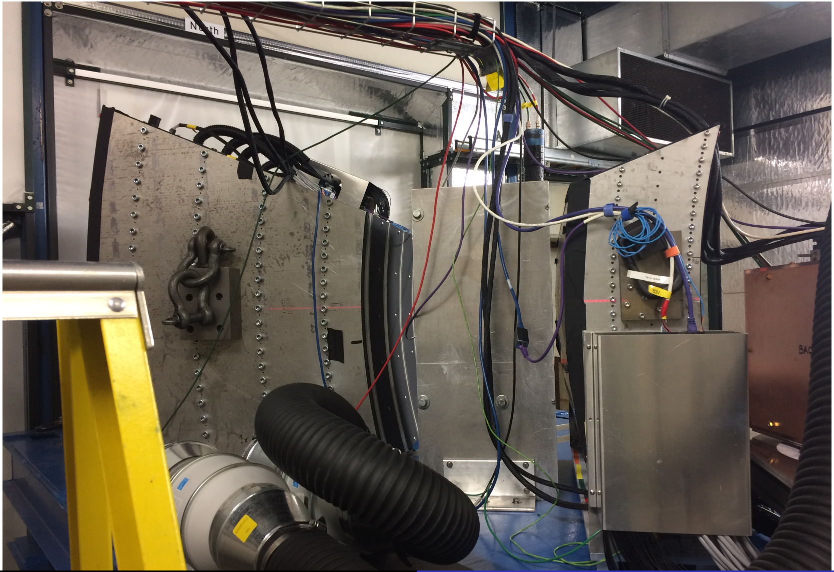
GSA AND HOLDING AGENCY NOS. (a)	ITEM NO. (b)	DESCRIPTION (Include noun name, FSC Group and Class, Condition Code and if available, National Stock Number) (c)	UNIT (d)	QUANTITY (e)	ACQUISITION COST UNIT (f)	ACQUISITION COST TOTAL (g)
		Administrative Transfer				
	1	BaBar Solenoid and Components Date of Mfr: 1996 (See attached list)	ea	1	12,000,000.00	$ 12,000,000.00

sPHENIX: magnet

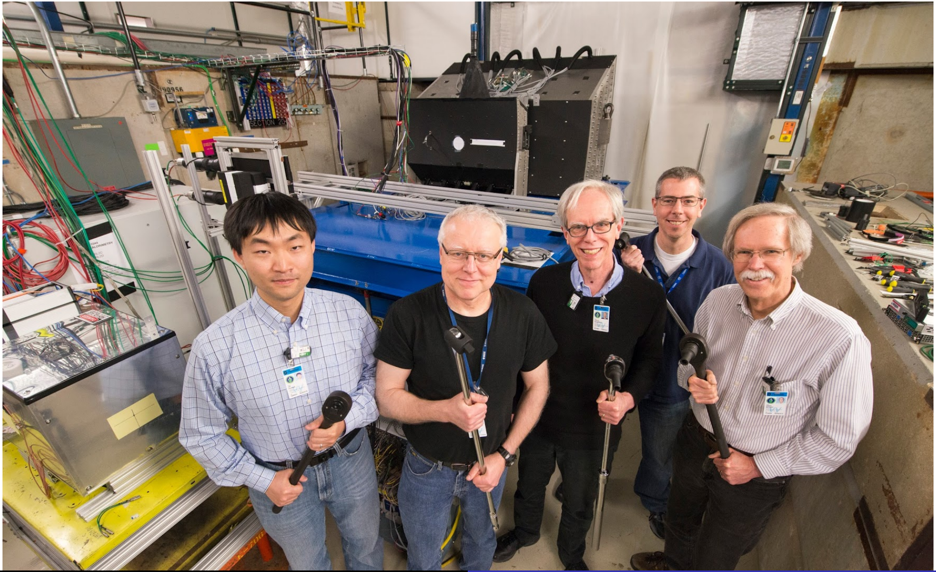
sPHENIX: magnet

sPHENIX: beam tests

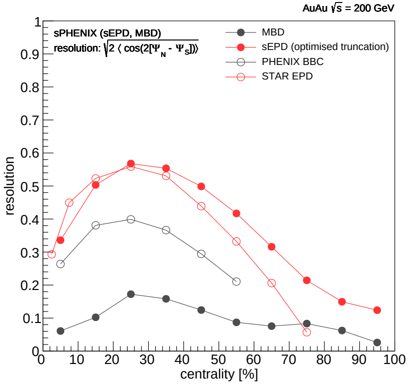
sPHENIX: beam tests

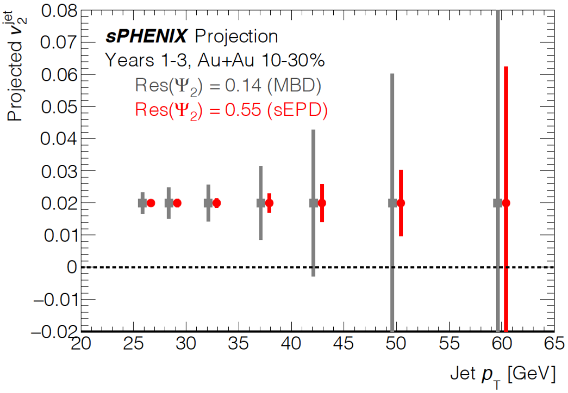


sPHENIX: beam tests



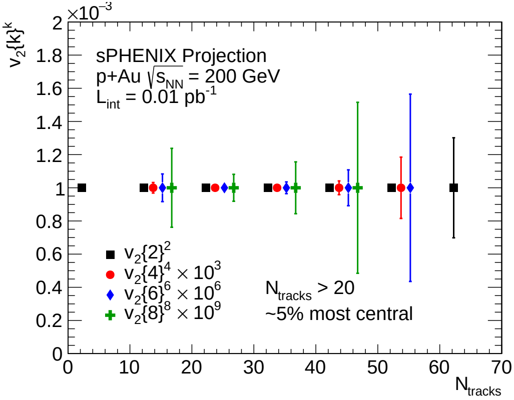
sPHENIX: event plane detector as day one "upgrade"

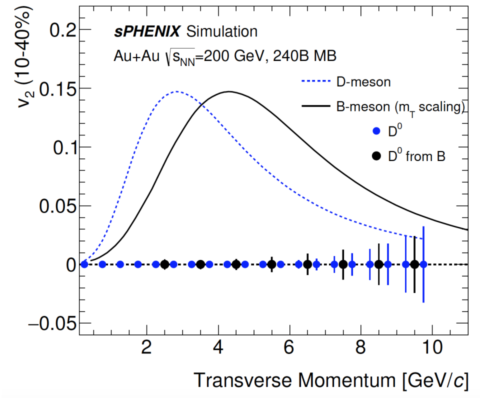




- Lots of core sPHENIX measurements need flow expertise
- RB co-I on NSF MRI for event plane detector
  —Funds disbursed August 2021, construction ongoing (at Lehigh U)

sPHENIX: projections





- Multi-particle correlations are very sensitive to the underlying distribution
- Heavy quark flow provides major insights into transport coefficients