

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

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NCA&T University Physics Colloquium
8 April 2026

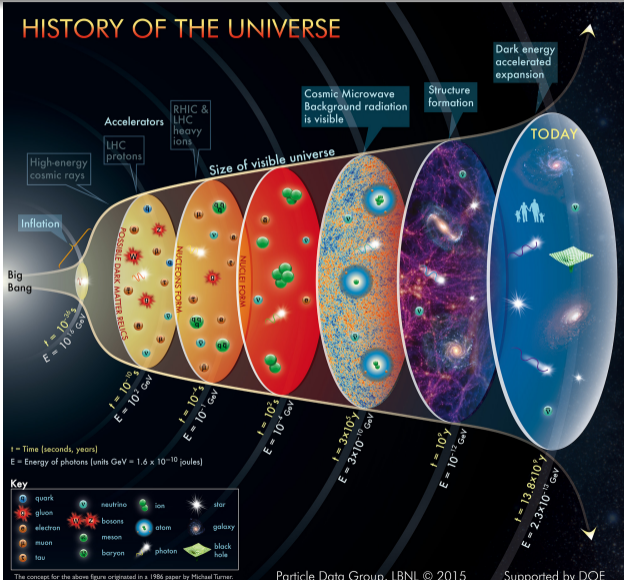


Quick outline

- 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

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 = 1.673×10^{-27} kg
- Typical energy = 1 GeV = 1.602×10^{-10} J
- Typical momentum = 1 GeV = 5.344×10^{-19} kg m/s
- Typical size = 1 fm = 10^{-15} m
- Typical time = 1 fm = 3.336×10^{-24} s

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$$T \sim \frac{\Lambda_{\text{QCD}}}{k_B} = 200 \text{ MeV} = 2.3 \times 10^{12} \text{ K}$$

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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

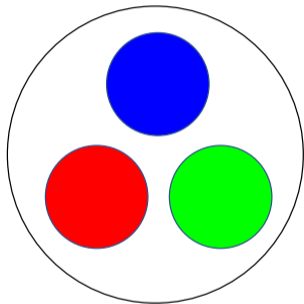
$$B \sim \frac{\gamma c \mu_0 e}{4\pi r^2} = 4.8 \times 10^{14} \text{ T (RHIC)}, 1.4 \times 10^{16} \text{ T (LHC)}$$

QCD as explained by approximate analogy to QED

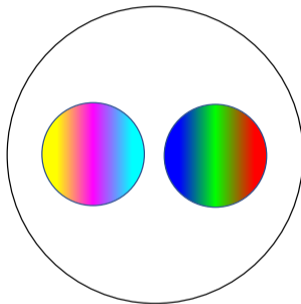
QED		QCD	
electric charge	\leftrightarrow	color charge	coupling
electrons	\leftrightarrow	quarks	matter fermions
photons	\leftrightarrow	gluons	exchange bosons
atoms	\leftrightarrow	nucleons	(stable) bound states
molecules	\leftrightarrow	nuclei	compound states

- 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

Baryon

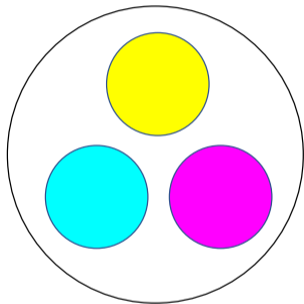


Meson

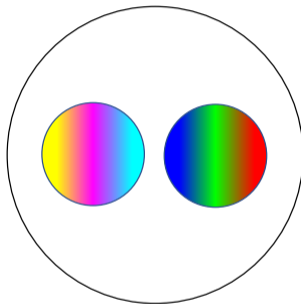


- Color-charged particles (quarks and gluons) are generically called **partons**
- QCD bound states are generically called **hadrons**, divided into **baryons** and **mesons**
- All observables must be in color singlet state—no partons can be found in isolation in nature

Antibaryon



Antimeson

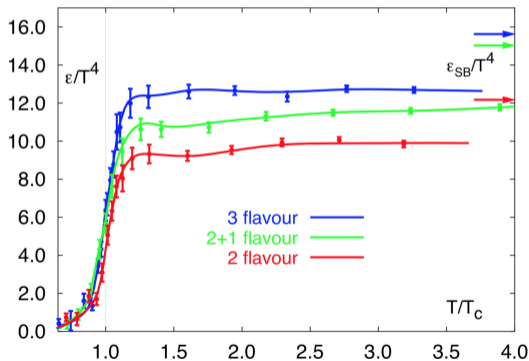


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Phases of QCD matter

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



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

- 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)

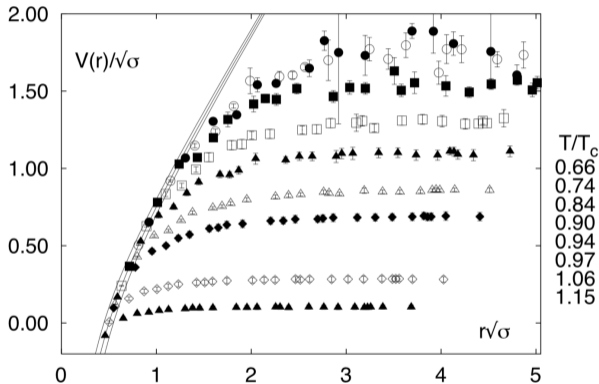
- The QED potential

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

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

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

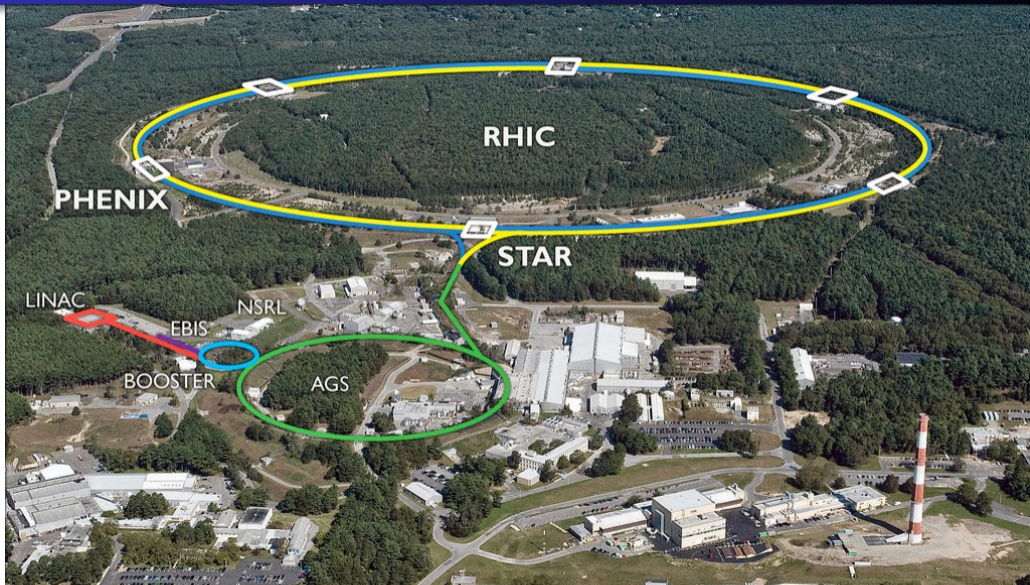
- Coulomb part and confining part



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

Basics of high energy nuclear collisions

The Relativistic Heavy Ion Collider



The Relativistic Heavy Ion Collider

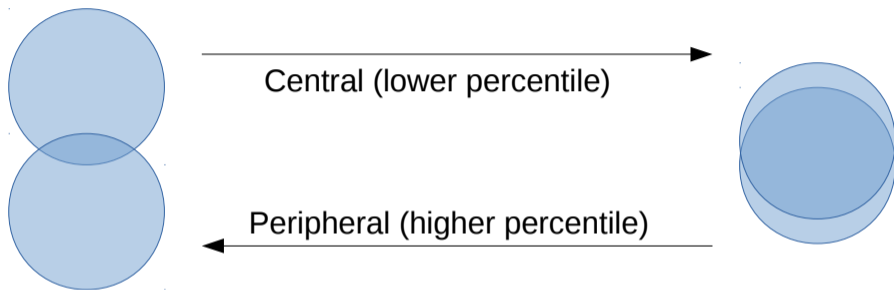
- RHIC is the only polarized proton collider in the world (Cold QCD)
- RHIC is one of two heavy ion colliders in the world (Hot QCD)

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
O+O	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, 9.8, 7.7, 7.3, 5.8, 5.2, 5, 4.6, 4.5, 4.2, 3.85 ...
U+U	193

Final RHIC collisions were earlier this year, the end of an era...

Full history: <https://www.agsrhichome.bnl.gov/RHIC/Runs/>

Centrality



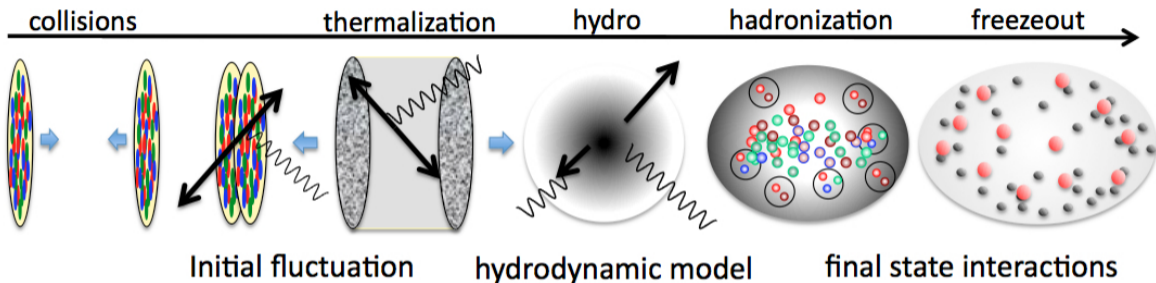
Central collisions: more overlap means more participating nucleons (N_{part})

—Larger volume, longer lifetime

Peripheral collisions: less overlap means fewer participating nucleons

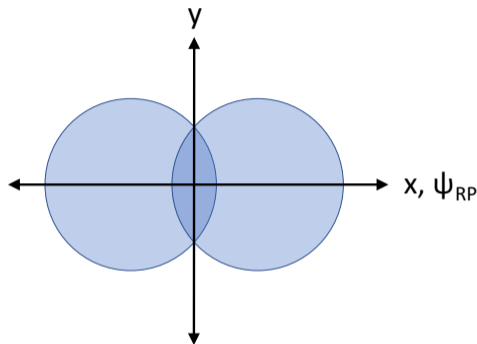
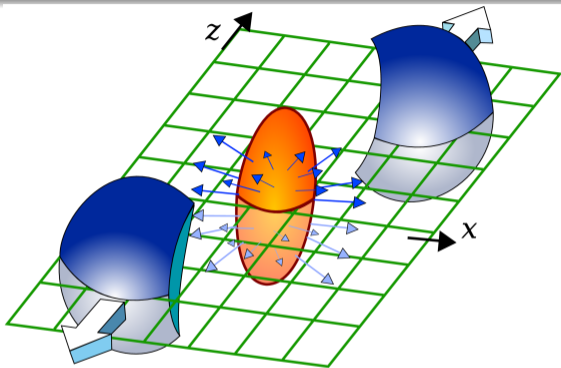
—Smaller volume, shorter lifetime

Standard model of heavy ion physics



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

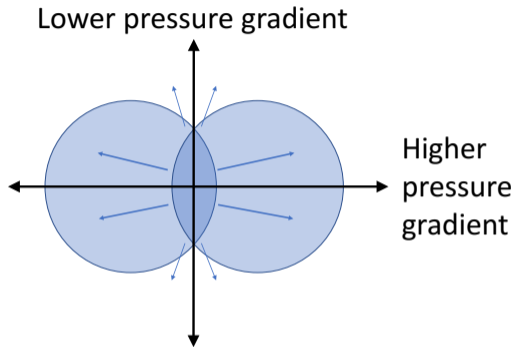
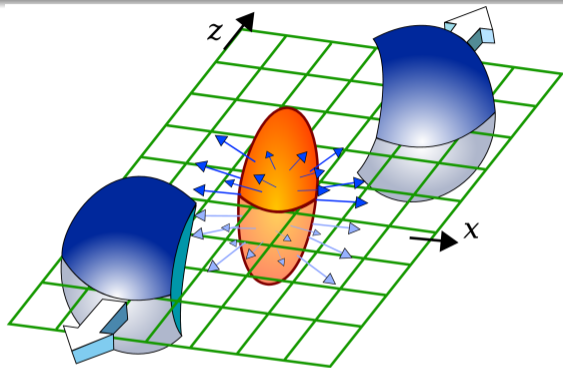
Azimuthal anisotropy measurements



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

- Hydrodynamics translates initial shape (including fluctuations) into final state distribution
- In $A+A$, the shape is mostly elliptical, so $n = 2$ dominates

Azimuthal anisotropy measurements

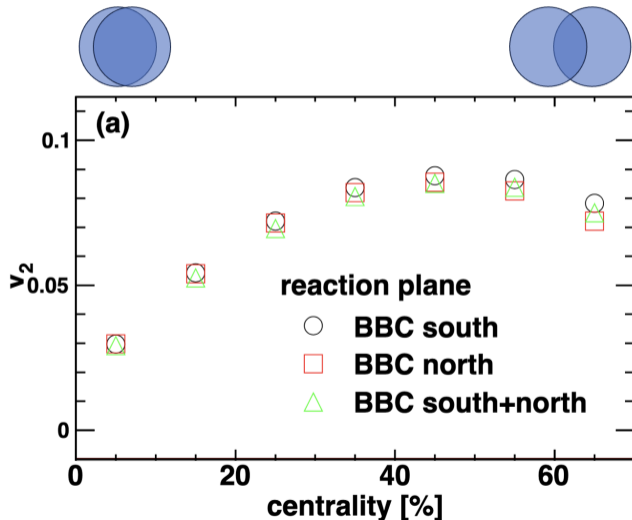


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v_2 vs Centrality

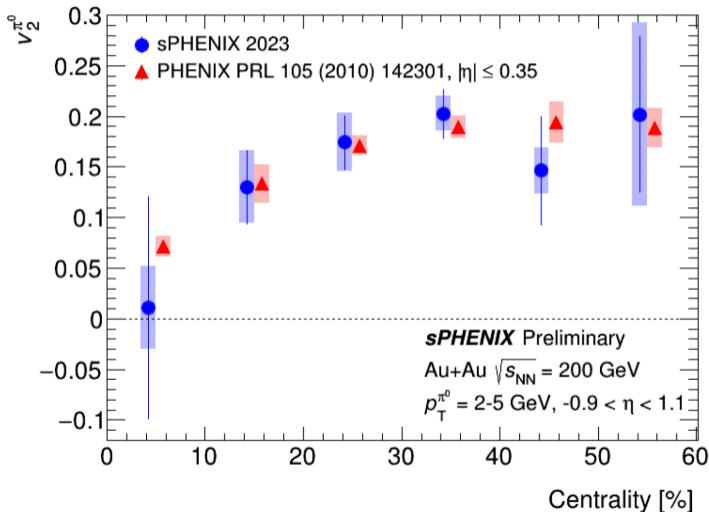
PHENIX, Phys. Rev. C 92, 034913 (2015)



- Non-monotonic behavior because of competing effects
- More peripheral = higher eccentricity \rightarrow higher v_2
- More peripheral = smaller system size \rightarrow lower v_2

π^0 v_2 vs Centrality

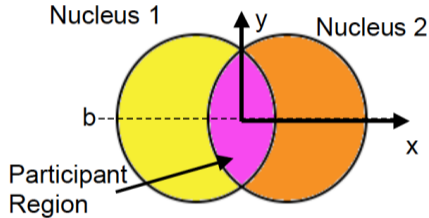
- Successful extraction of π^0 v_2 from sPHENIX Run 2023 Commissioning dataset with very limited statistics
- Excellent agreement to PHENIX measurement for all centralities



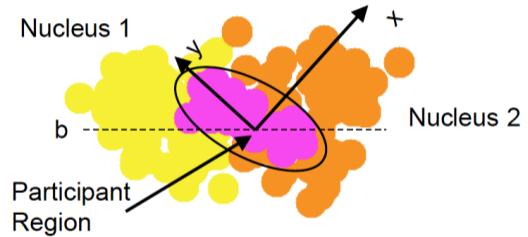
Important discovery in 2005

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

Standard Eccentricity



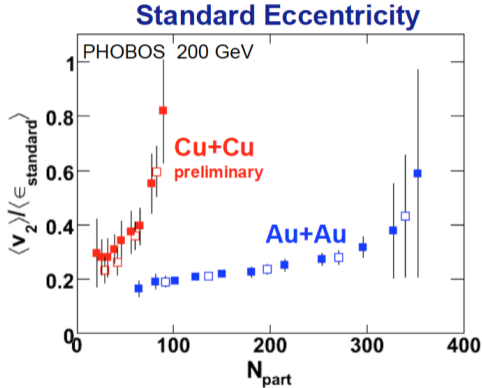
Participant Eccentricity



A nucleus isn't just a sphere

Important discovery in 2005

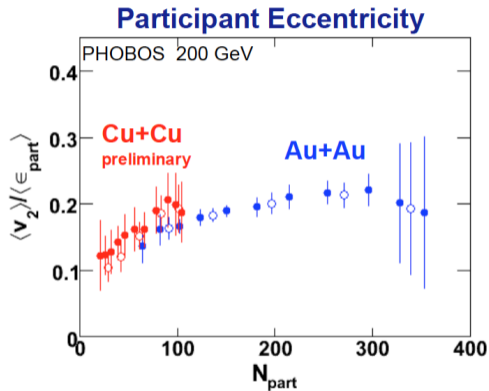
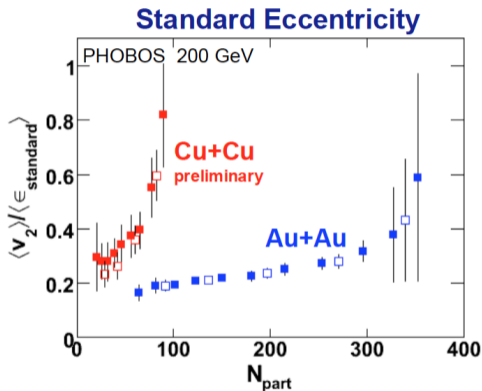
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Important discovery in 2005

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

NeXSPheRIO results on elliptic flow at RHIC and connection with thermalization

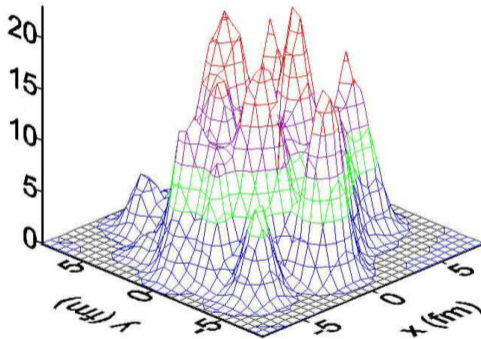
R.Andrade¹, F.Grassi¹, Y.Hama¹, T.Kodama², O.Socolowski Jr.³, and B.Tavares²

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

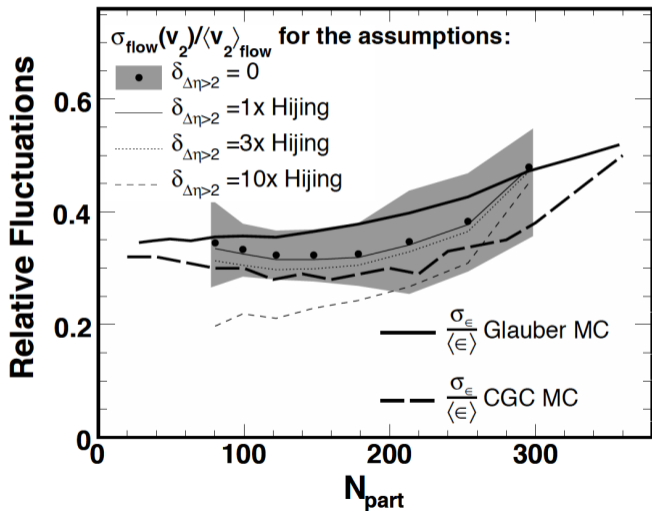
Received 1 January 2004



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

Fluctuations in large systems

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



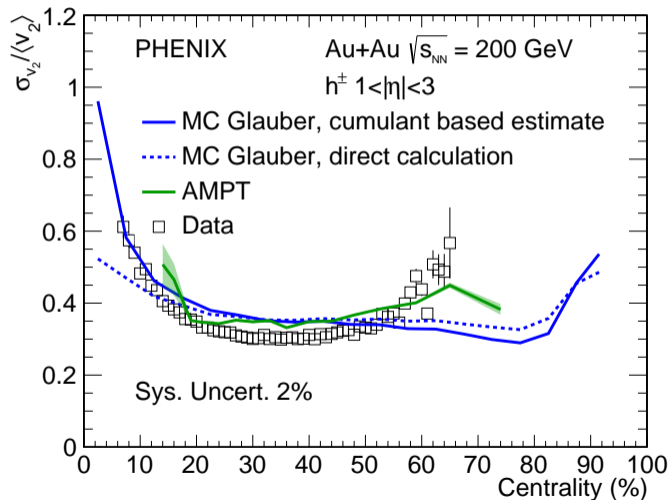
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2 \rangle$

$$|\eta| < 1$$

Generally good agreement with models of initial geometry

Fluctuations in large systems

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



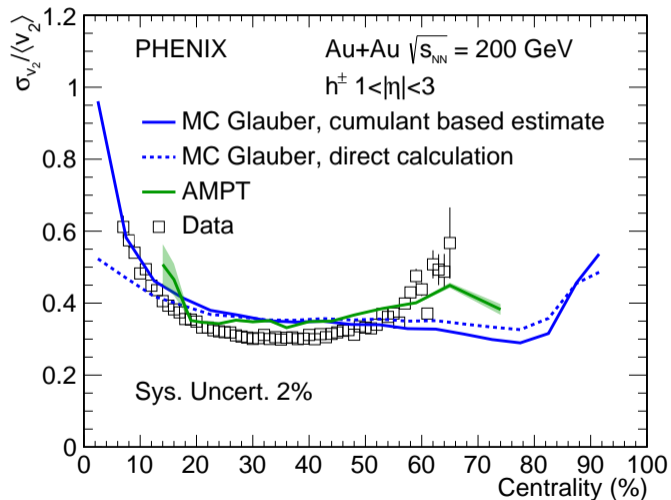
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2 \rangle$

$$1 < |\eta| < 3$$

Generally good agreement with models of initial geometry

Fluctuations in large systems

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



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

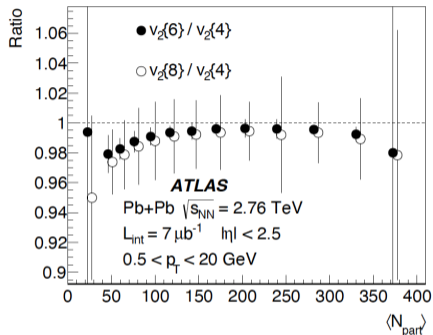
$$1 < |\eta| < 3$$

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

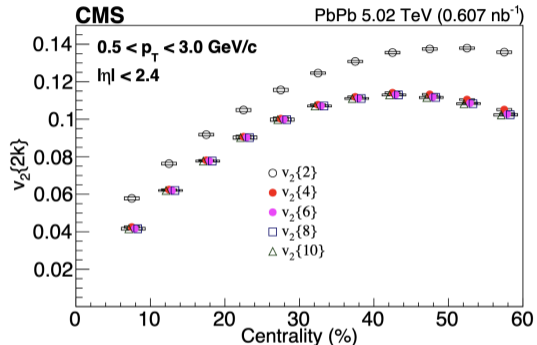
Peripheral: non-linearity in hydro response (e.g. J. Noronha-Hostler et al Phys. Rev. C 93, 014909 (2016))

Flow measurements in Au+Au

ATLAS Eur. Phys. J. C (2014) 74: 3157



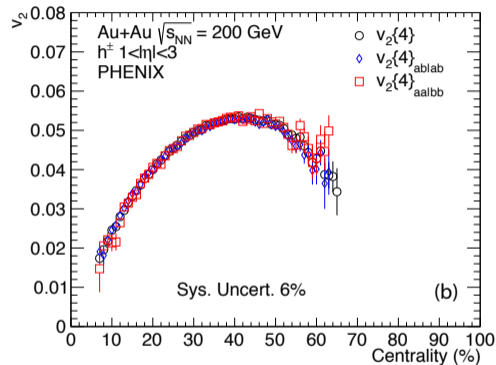
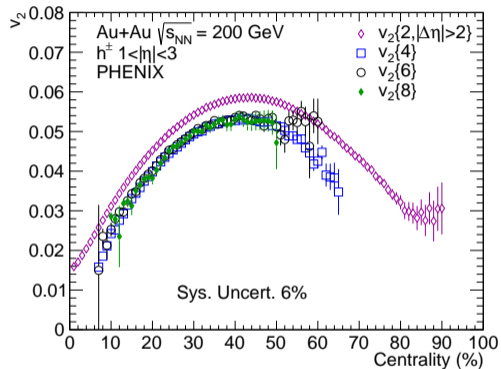
CMS JHEP 02, 106 (2024)



- sPHENIX can measure $v_2\{2, 4, 6, 8\}$ with very high precision
 - Roughly, $v_2\{2\} = \sqrt{v_2^2 + \sigma^2}$ and $v_2\{4, 6, 8\} \approx \sqrt{v_2^2 - \sigma^2}$
 - Deviations of ratios from unity give insights into higher moments of v_2 distribution
- Can definitely measure $v_2\{10\}$, but not clear (yet) what level of sensitivity can be obtained

Flow measurements in Au+Au

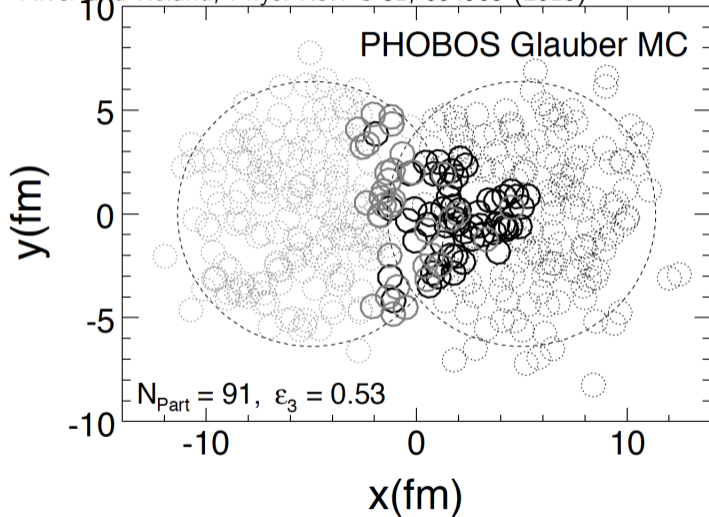
PHENIX, Phys. Rev. C 99, 024903 (2019)



- You can do a lot with ~ 1 billion events...
- ...so you can do a lot more with ≈ 40 billion events!

Important discovery in 2010

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



Nucleon fluctuations can produce non-zero ε_n for odd n

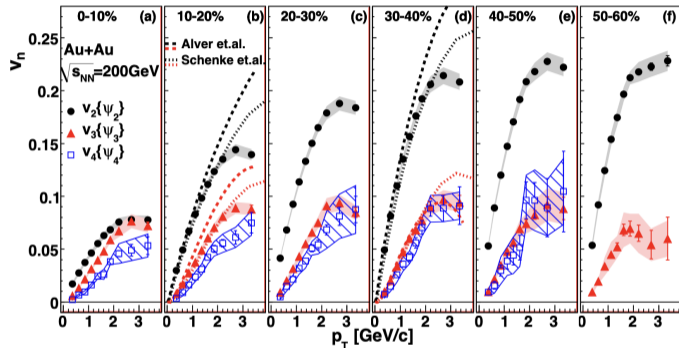
Symmetry planes ψ_n can be different for different harmonics

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

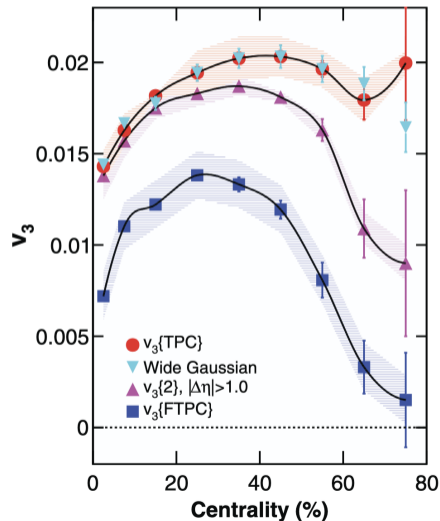
v_3 in Au+Au collisions

PHENIX, Phys. Rev. Lett. 107, 252301 (2011)

STAR, Phys. Rev. C 88, 014904 (2013)

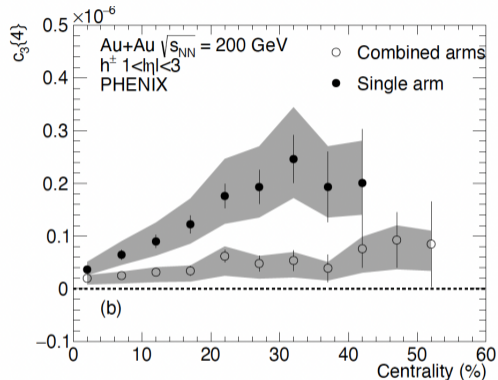
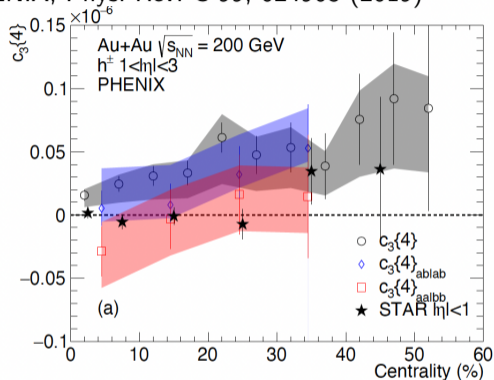


Sure enough, v_3 isn't zero



v_3 in Au+Au collisions

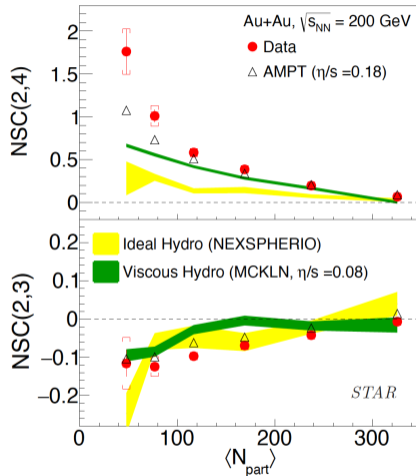
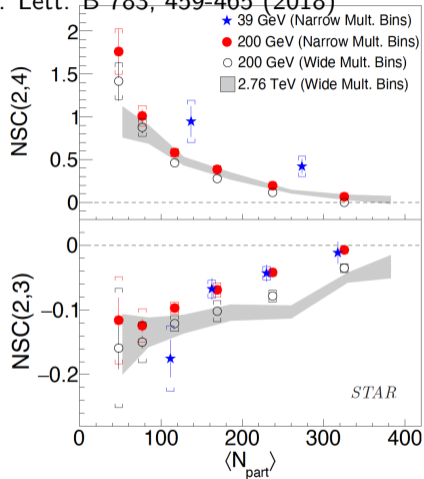
PHENIX, Phys. Rev. C 99, 024903 (2019)



- Previous observation of interesting rapidity dependence of $c_3\{4\} = -v_3^4\{4\}$ comparing STAR $|\eta| < 1$ and PHENIX $1 < |\eta| < 3$
- sPHENIX can do high precision measurement with $|\eta| < 1.1$ (central barrel) and $2.0 < |\eta| < 4.9$ (sEPD)

Harmonic correlations in Au+Au

STAR, Phys. Lett. B 783, 459-465 (2018)



- NSC(n,m) gives correlations between n -th and m -th harmonics
- sPHENIX can improve these with more statistics, add higher harmonics, etc

Small systems

PHYSICAL REVIEW LETTERS

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Exploiting Intrinsic Triangular Geometry in Relativistic $^3\text{He} + \text{Au}$ 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

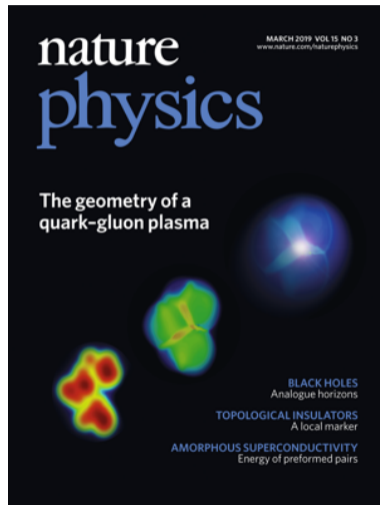
naturephysics

Letter | Published: 10 December 2018

Creation of quark–gluon plasma droplets with three distinct geometries

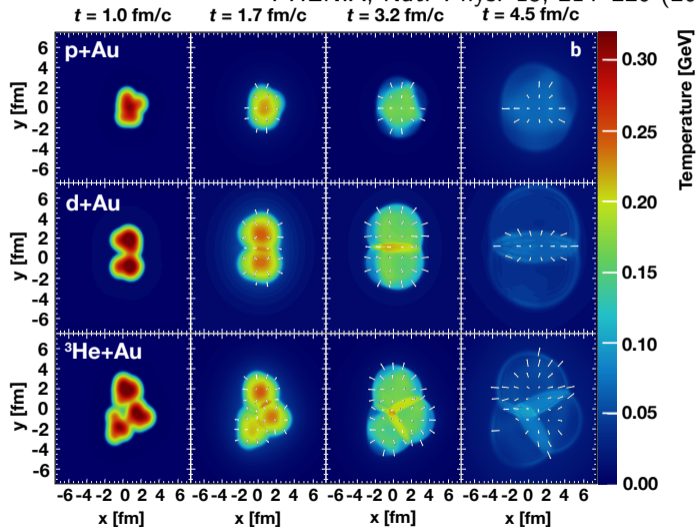
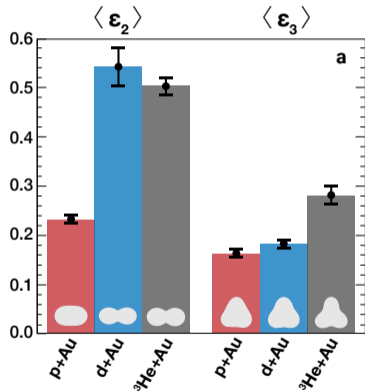
PHENIX Collaboration

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



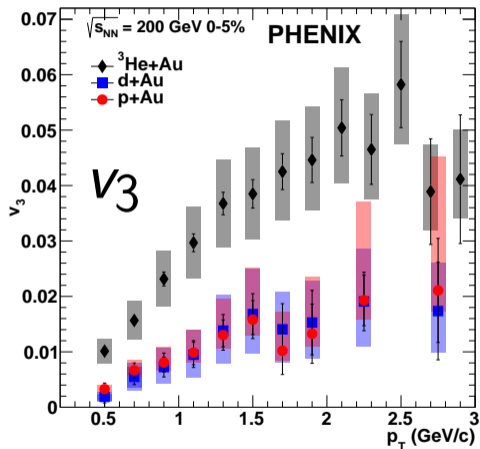
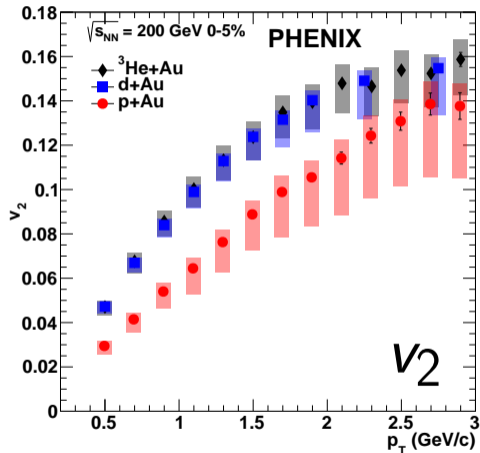
Small systems geometry scan

PHENIX, Nat. Phys. 15, 214–220 (2019)



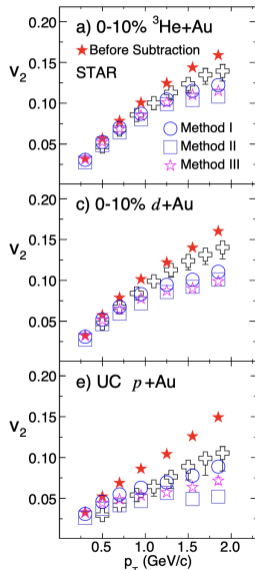
Small systems geometry scan

PHENIX, Nat. Phys. 15, 214–220 (2019)



- v_2 and v_3 ordering matches ε_2 and ε_3 ordering in all three systems

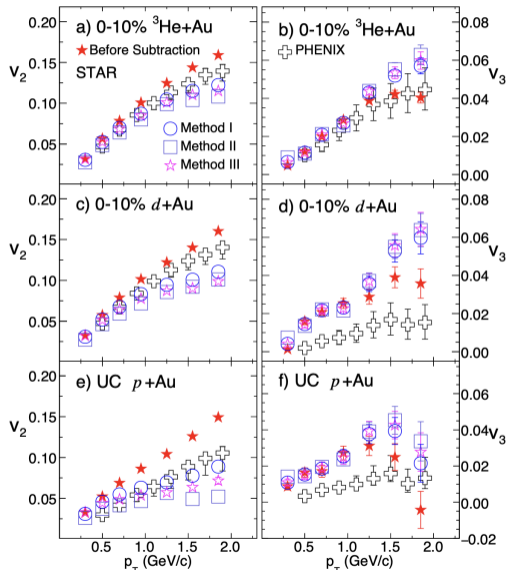
Comparisons with STAR



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

Good agreement between STAR and PHENIX for v_2

Comparisons with STAR



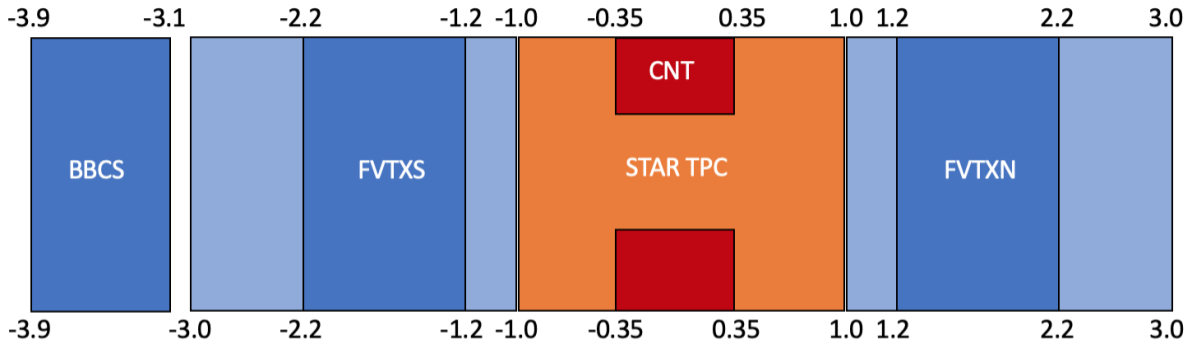
STAR, Phys. Rev. Lett. 130, 242301 (2023)

Good agreement between STAR and PHENIX for v_2

Large difference between STAR and PHENIX for v_3 in $p+\text{Au}$ and $d+\text{Au}$

The kinematic acceptance between the two experiments is very different, and longitudinal dynamics plays a big role in the observables

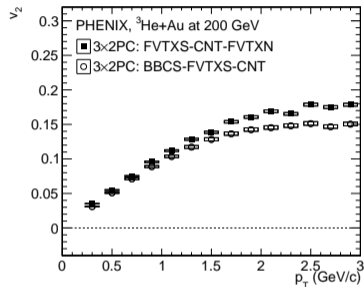
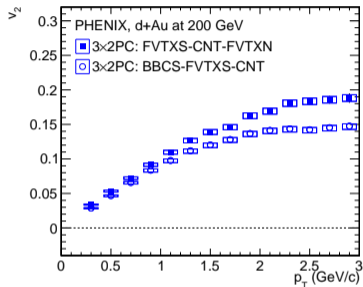
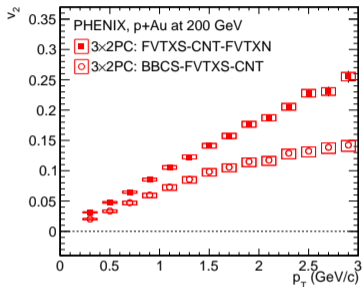
STAR and PHENIX detector comparison



- 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*

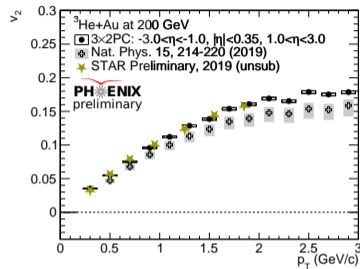
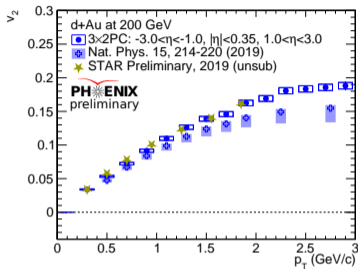
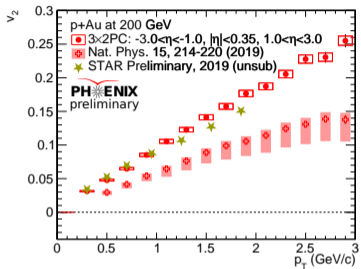
More STAR and PHENIX data comparisons

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



More STAR and PHENIX data comparisons

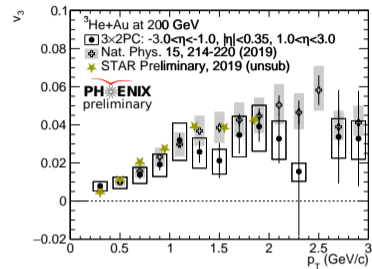
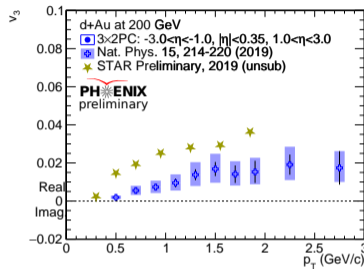
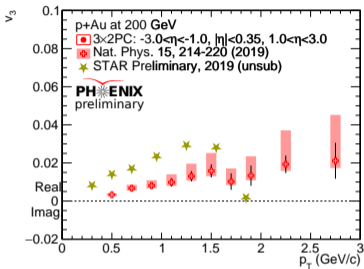
PHENIX, Phys. Rev. C 105, 024901 (2022)



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

More STAR and PHENIX data comparisons

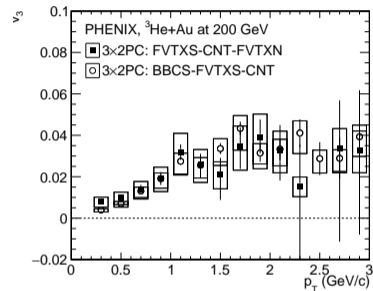
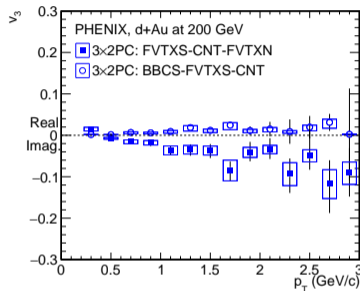
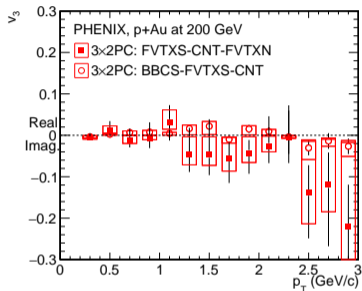
PHENIX, Phys. Rev. C 105, 024901 (2022)



- 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 much stronger for v_3 than v_2

More STAR and PHENIX data comparisons

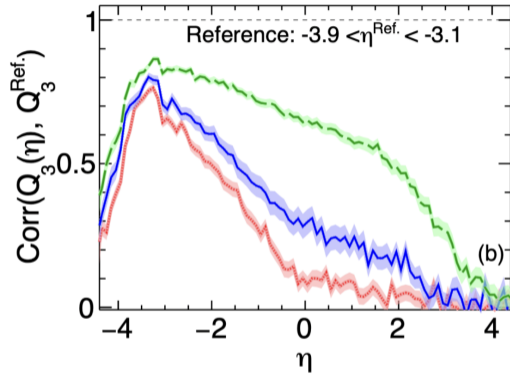
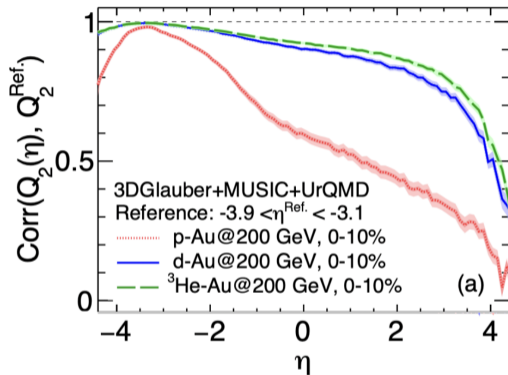
PHENIX, Phys. Rev. C 105, 024901 (2022)



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Pseudorapidity dependence in small systems

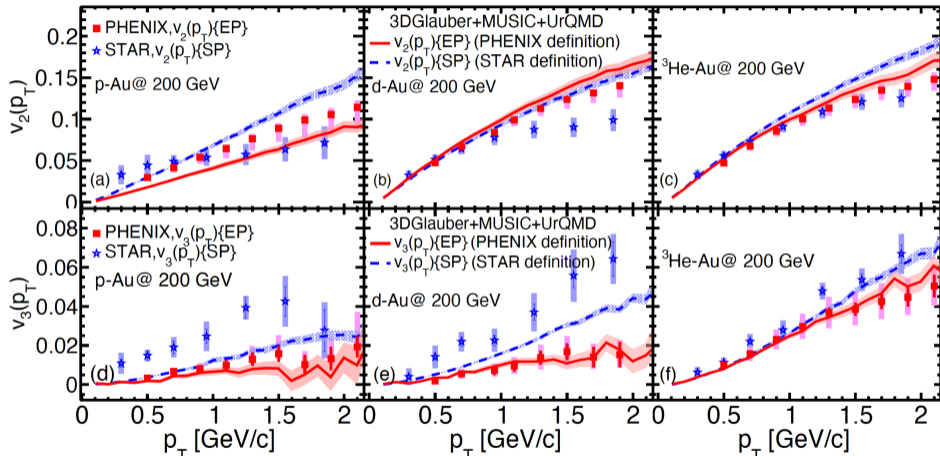
W. Zhao et al, Phys. Rev. C 107, 014904 (2023)



- 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...

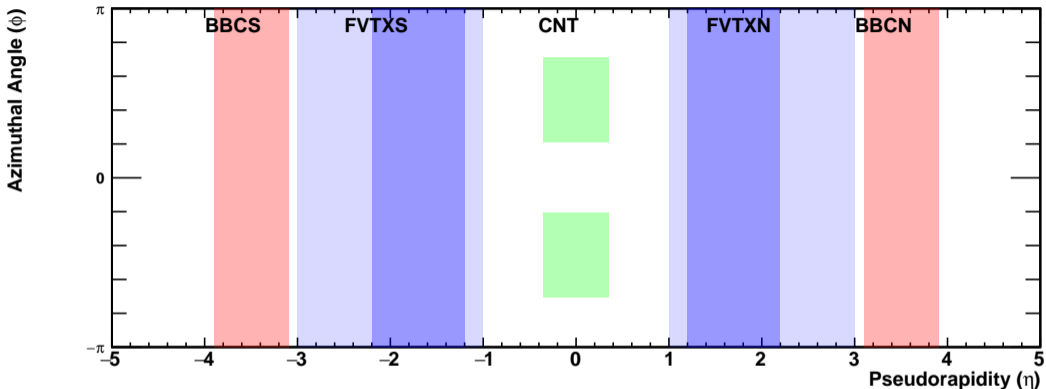
Pseudorapidity dependence in small systems

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



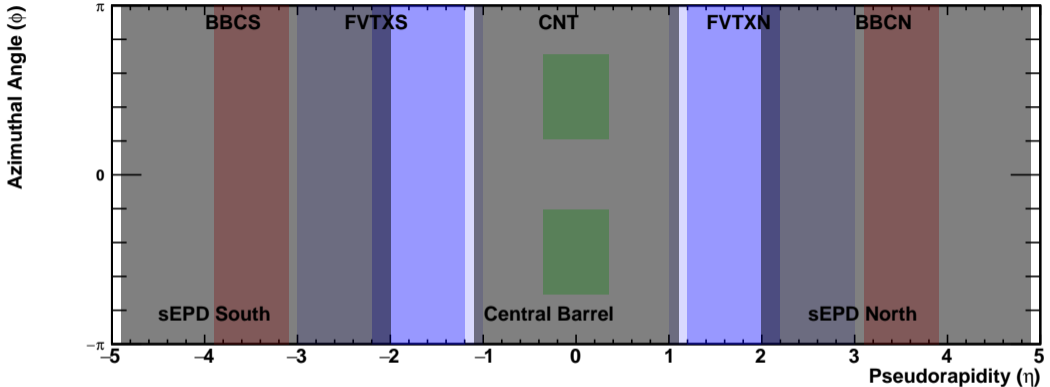
- Flow decorrelations lead to larger v_3 for STAR, explaining $\sim 50\%$ of the difference between the experiments in this particular model

(Missed) Opportunity for sPHENIX



- Thanks to large acceptance and high data rate, sPHENIX can make a major contribution
- The central barrel can match the STAR measurement
- The sEPD can extend the PHENIX measurement to even larger pseudorapidity separation
- Unfortunately, for... reasons... sPHENIX is over and will never collect p +Au data

(Missed) Opportunity for sPHENIX



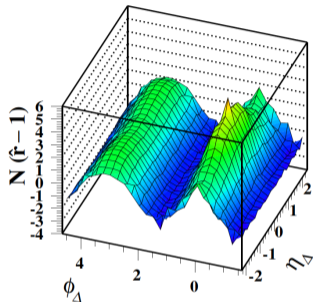
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The ridge is a signature of flow

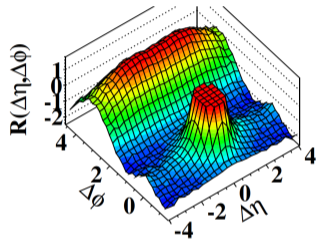
STAR, PRC 73, 064907 (2006)

CMS, JHEP 1009, 091 (2010)

CMS, PLB 718, 795 (2013)



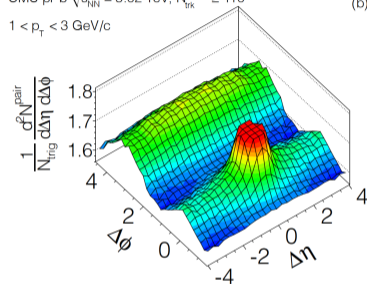
(d) CMS $N \geq 110$, $1.0 \text{ GeV}/c < p_{\perp} < 3.0 \text{ GeV}/c$



CMS pPb $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, $N_{\text{trk}}^{\text{offline}} \geq 110$

$1 < p_{\perp} < 3 \text{ GeV}/c$

(b)

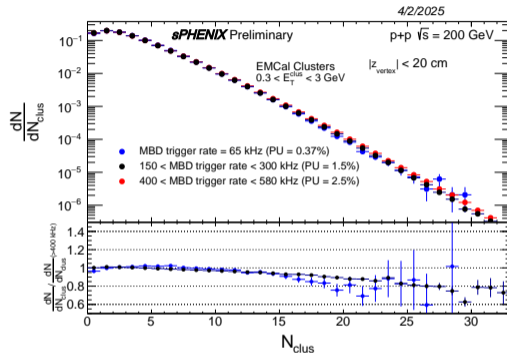
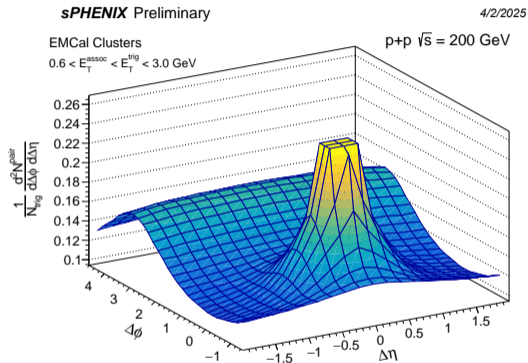


Extended structure away from near-side jet peak interpreted as collective effect due to presence of QGP

- 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))

The ridge is a signature of flow

sPHENIX performance plots



- Is there a p+p ridge at RHIC? The hunt is on!
- The current analysis uses about 1% at most of the total data, using the full dataset acquired via streaming readout will allow further study of high-multiplicity events

The ridge is a signature of flow

sPHENIX performance plots

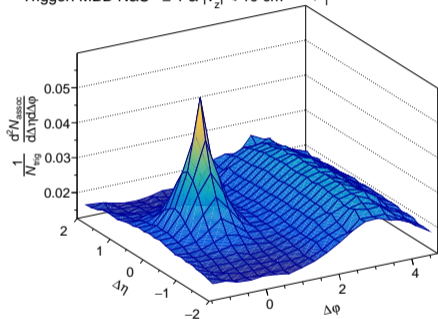
sPHENIX Preliminary

p+p $\sqrt{s} = 200$ GeV

Trigger: MBD N&S ≥ 1 & $|v_z| < 10$ cm $p_T > 1$ GeV/c

4/2/2025

$N_{\text{Silicon Tracklet}} > 0$



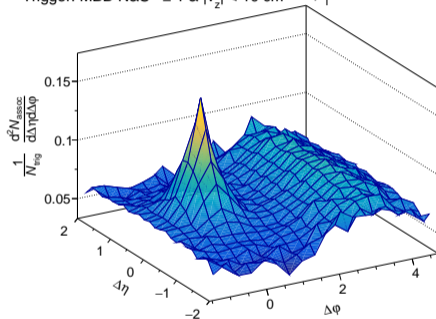
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Trigger: MBD N&S ≥ 1 & $|v_z| < 10$ cm $p_T > 1$ GeV/c

4/2/2025

$N_{\text{Silicon Tracklet}} > 10$ (top 1% HM)



- Is there a p+p ridge at RHIC? The hunt is on!
- The current analysis uses about 1% at most of the total data, using the full dataset acquired via streaming readout will allow further study of high-multiplicity events

The Story So Far

- 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

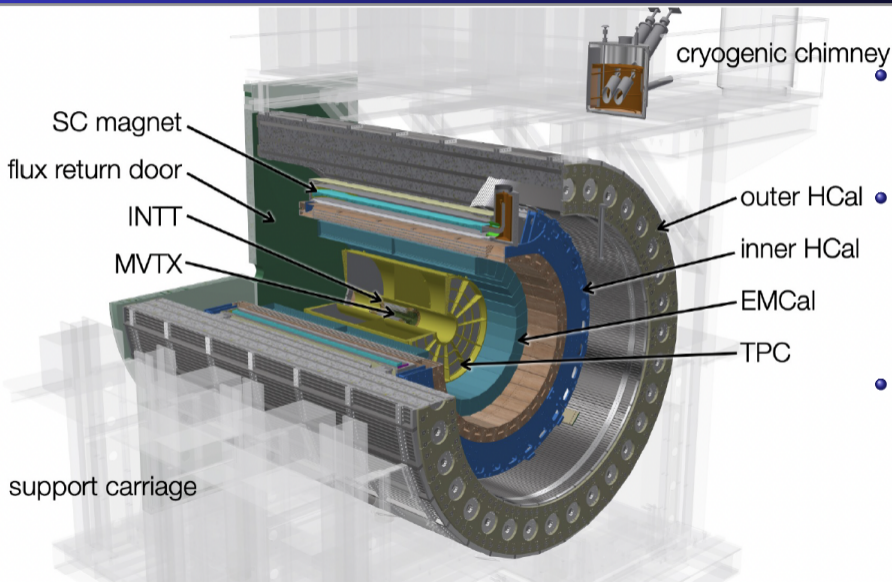
sPHENIX Run25 at a glance

OR

A brief summary of the last year-and-a-half of my life



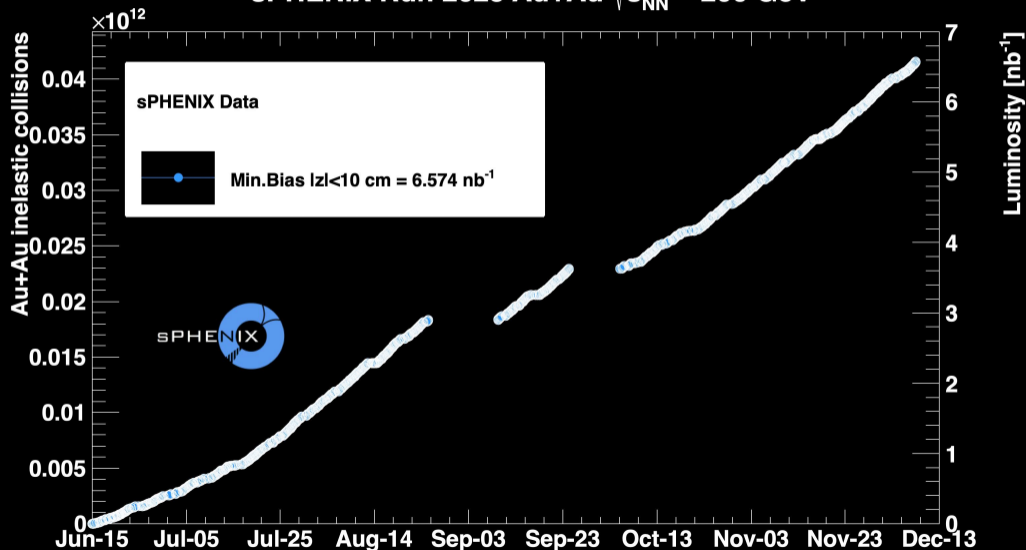
- Conceived in 2012, sPHENIX was identified in the 2015 DOE Nuclear Physics Long Range Plan as essential for achieving the goal of studying the microscopic properties of the QGP
- With assembly completed in 2023, sPHENIX is a state-of-the-art jet and upsilon detector
- In overall design, it closely resembles general purpose particle physics detectors like CMS and ATLAS —First and only detector at RHIC with hadronic calorimetry
- Completed data taking earlier this year, “R&R” now ongoing



- Full calorimetry (i.e. both electromagnetic and hadronic)
- High-precision tracking (3 layers of Si pixels, 2 layers of Si strips, time projection chamber and TPC outer tracker)
- Event characterization (min bias detector, event plane detector, zero degree calorimeter)

sPHENIX Luminosity: Au+Au at $\sqrt{s_{NN}} = 200$ GeV

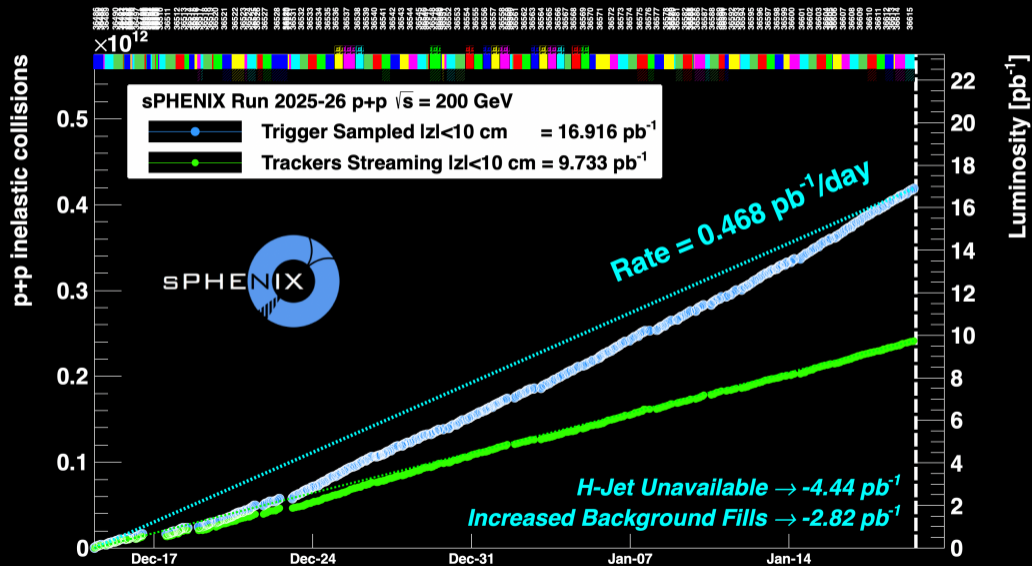
sPHENIX Run 2025 Au+Au $\sqrt{s_{NN}} = 200$ GeV



sPHENIX Run25 Au+Au Summary

- 182 days from first Au+Au collisions on June 9 to final Au+Au collisions on December 8
 - Blue cold hipot failure March 26 led to nine weeks of delay
 - Squirrel incident followed immediately by damaged power line cross arm led to about one week of delay
 - Vacuum loss and window damage from unexpected abort led to about one week of delay
- All subsystem triggered data: 6.574 nb^{-1}
 - 93% of Run25 goal
 - Decision was made to end Au+Au at a specified date to get started on p+p
- None of this spectacular success would have been possible without the tireless efforts of shift crew members, subsystem experts, and technicians, all of whom worked long hours for a very long time

sPHENIX Luminosity: p+p at $\sqrt{s} = 200$ GeV



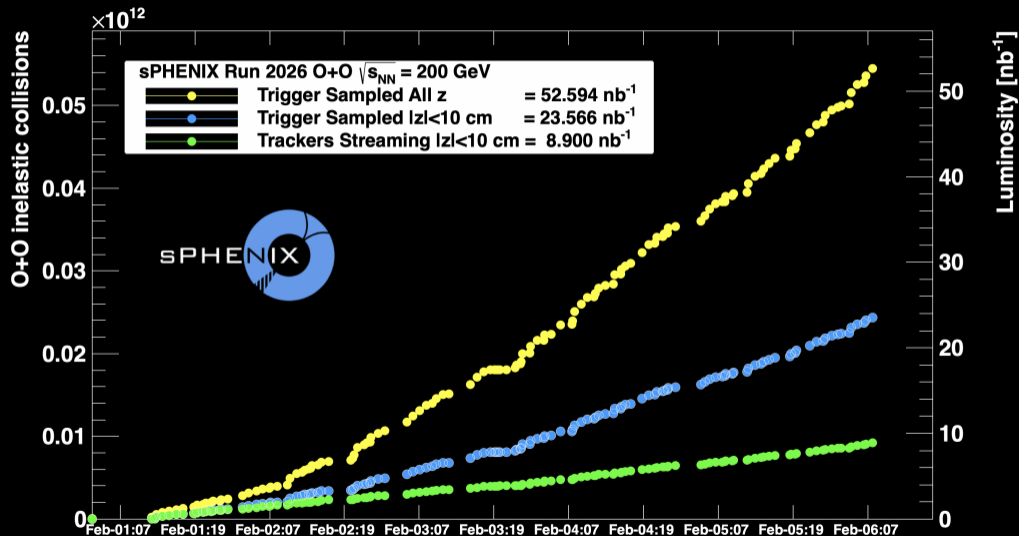
sPHENIX Run25 p+p Summary

- All subsystem triggered data: 16.9 pb^{-1}
 - 130% of Run25 goal
 - Program total of $30.2 \text{ pb}^{-1} = 67\%$ of program goal
- All tracker streaming data: 9.7 pb^{-1}
 - 216% of program goal
 - Program total of $12.6 \text{ pb}^{-1} = 280\%$ of program goal
- All subsystem triggered data with known polarization (viz. functioning H-Jet polarimeter): 12.5 pb^{-1}
 - 96% of Run25 goal
 - Program total of $25.8 \text{ pb}^{-1} = 57\%$ of program goal
- None of this spectacular success would have been possible without the tireless efforts of shift crew members, subsystem experts, and technicians, all of whom worked some combination of nights, weekends, Christmas, and New Year's

Final p+p collisions: Tuesday 2026-01-20 at 08:10 EST



sPHENIX Luminosity: O+O at $\sqrt{s_{NN}} = 200$ GeV



sPHENIX Run25 O+O Summary

- Our original program goal was 13 nb^{-1} in two weeks of running
 - Our “conservative estimate of what we thought we could achieve” was stated to be “at least 4 nb^{-1} ”
 - Me at the January 23 GM: “I want 5 nb^{-1} , and I think we can do it”
 - sPHENIX: “hold my beer”
- The total run time was 5.33 days
- All subsystem triggered data: 23.6 nb^{-1}
 - 182% of program goal
- All tracker streaming data: 8.9 nb^{-1}
 - 228% of program goal
 - Original goal 3.9 nb^{-1} assuming 30% streaming on 13 nb^{-1} trigger sampled
- All vertex calo-only data: 52.6 nb^{-1}
 - 404% of program goal
- What could you call this other than a spectacular success?

Final RHIC Collisions Ever: Friday 2026-02-06 at 09:08 EST



Summary

- It was totally awesome, man
- 369 shift change meetings
- 182 days of Au+Au, 6.6 nb^{-1} , 93% of goal
- 41 days of p+p, 16.7 pb^{-1} , 130% of goal
- 5.3 days of O+O, 23.6 nb^{-1} , 181% of goal
- Every ending is a new beginning, welcome to the sPHENIX analysis era!

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

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

A brief history of heavy ion physics

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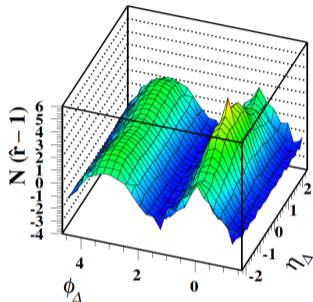
“Twenty years ago, the challenge in heavy ion physics was to find the QGP. Now, the challenge is to not find it.” —Jürgen Schukraft, QM17

The ridge is a signature of flow

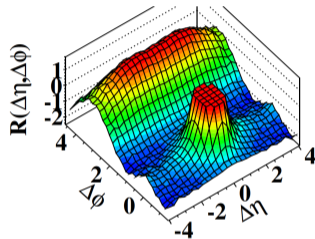
STAR, PRC 73, 064907 (2006)

CMS, JHEP 1009, 091 (2010)

CMS, PLB 718, 795 (2013)



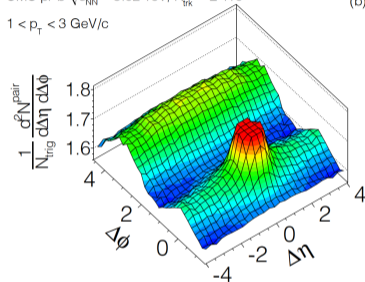
(d) CMS $N \geq 110$, $1.0 \text{ GeV}/c < p_{\perp} < 3.0 \text{ GeV}/c$



CMS pPb $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, $N_{\text{trk}}^{\text{offline}} \geq 110$

$1 < p_{\perp} < 3 \text{ GeV}/c$

(b)

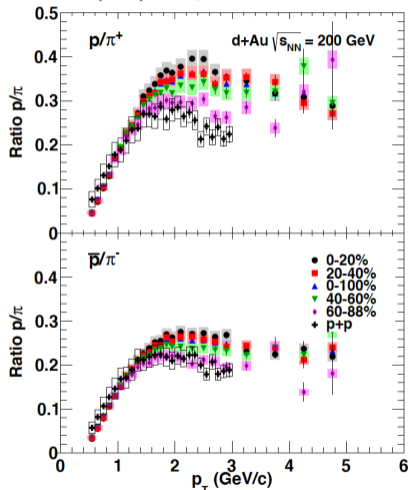


Extended structure away from near-side jet peak interpreted as collective effect due to presence of QGP

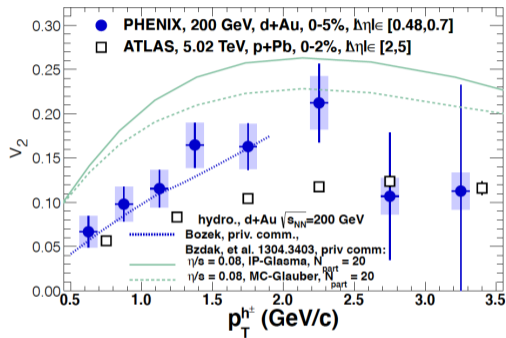
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- Realized by STAR to be flow in 2009 (PRL 105, 022301 (2010))
- First found in small systems by CMS (JHEP 1009, 091 (2010) and PLB 718, 795 (2013))

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)

Small systems geometry scan

PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press About 

Exploiting Intrinsic Triangular Geometry in Relativistic $^3\text{He} + \text{Au}$ 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

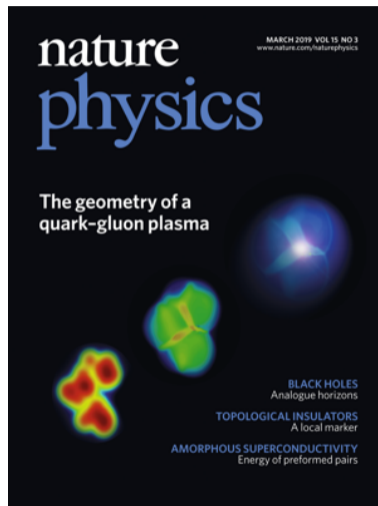
naturephysics

Letter | Published: 10 December 2018

Creation of quark–gluon plasma droplets with three distinct geometries

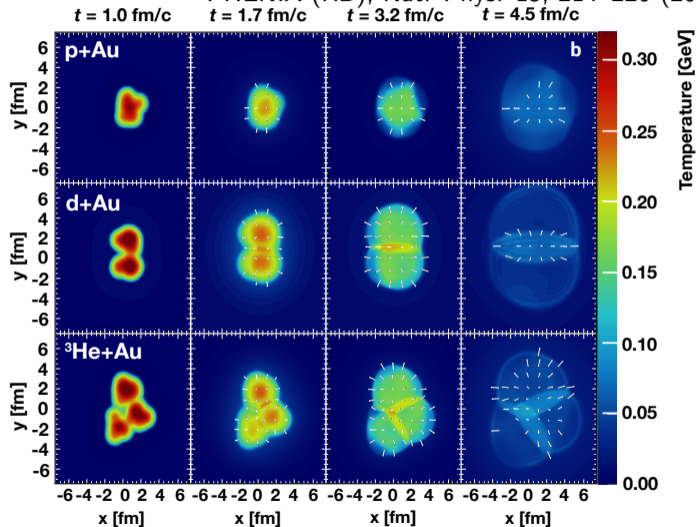
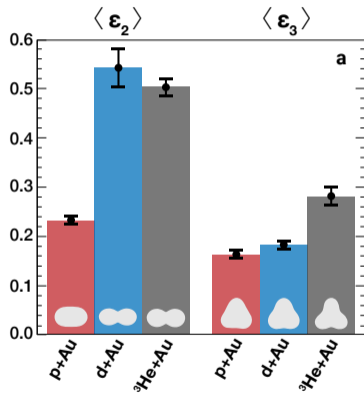
PHENIX Collaboration

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



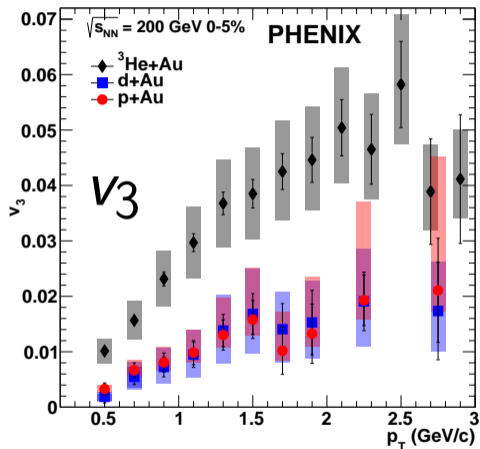
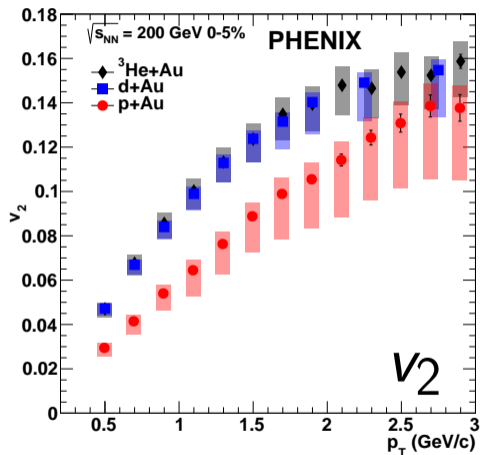
Small systems geometry scan

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



Small systems geometry scan

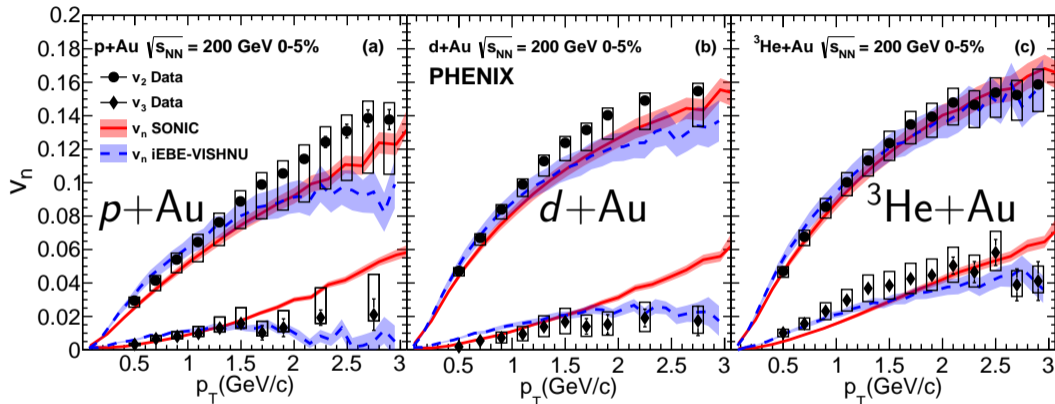
PHENIX (RB), Nat. Phys. 15, 214–220 (2019)



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

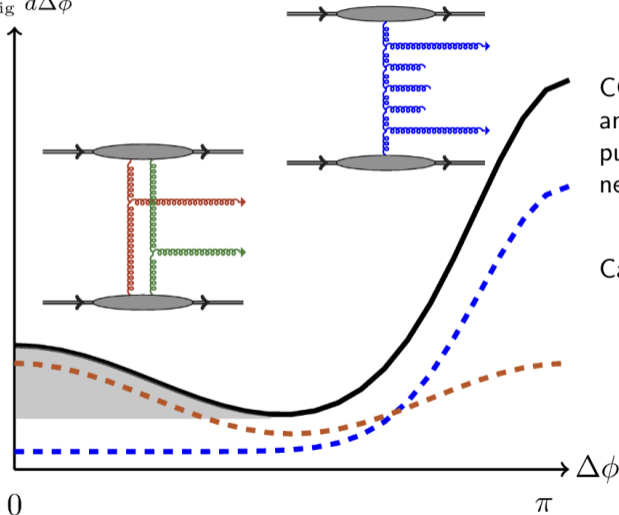


- v_2 and v_3 vs p_T predicted or described very well by hydrodynamics in all three systems
 - All predicted (except v_2 in $d+Au$) in J.L. Nagle et al, PRL 113, 112301 (2014)
 - v_3 in $p+Au$ and $d+Au$ predicted in C. Shen et al, PRC 95, 014906 (2017)

Can initial state effects explain the data?

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

$$\frac{1}{N_{\text{Trig}}} \frac{d^2 N}{d\Delta\phi}$$

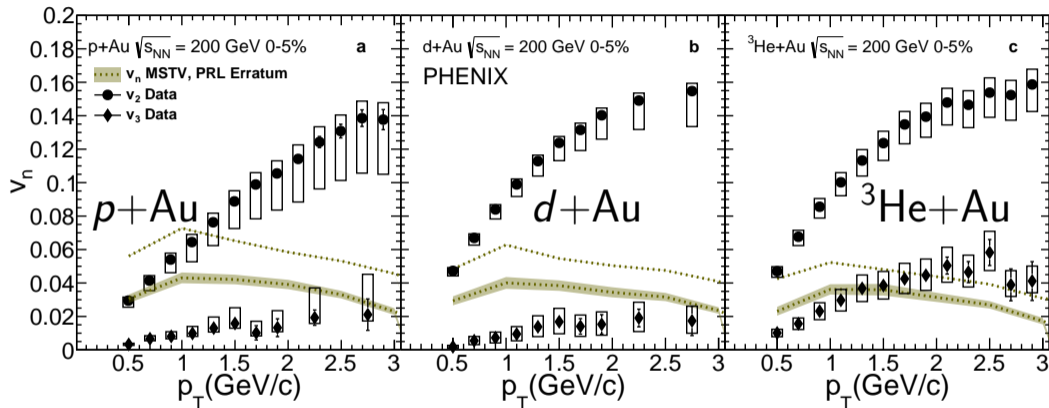


CGC framework: glasma diagrams produce angular correlations like the ridge and v_n purely from initial state correlations, with no need for final state interactions (hydro)

Can they explain the data?

Initial state effects cannot explain the data

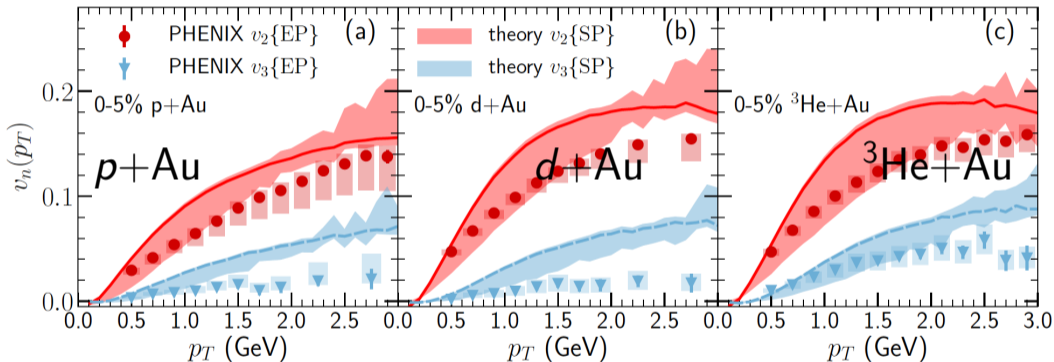
PHENIX (RB), Nat. Phys. 15, 214–220 (2019)



- 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?

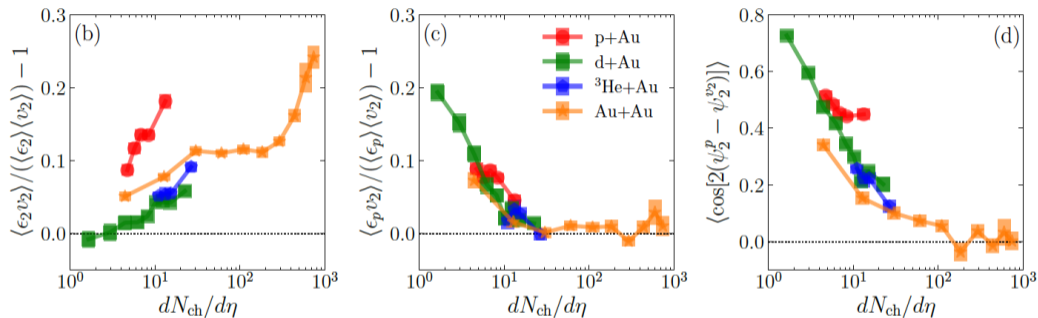
B. Schenke et al, Phys. Lett. B 803, 135322 (2020)



- 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?

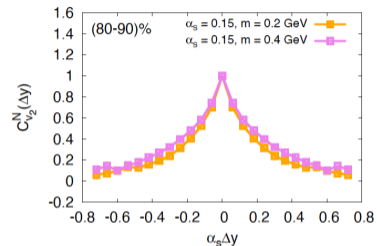
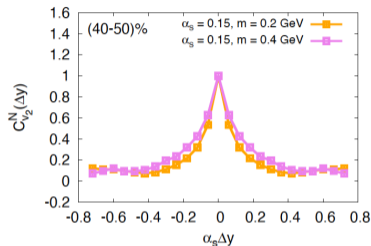
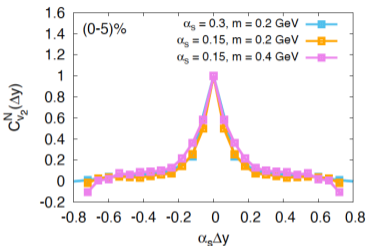
B. Schenke et al, Phys. Lett. B 803, 135322 (2020)



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

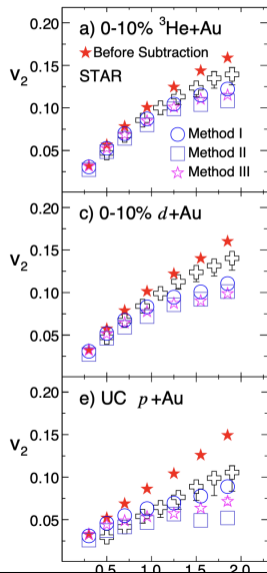
How important are initial state effects?

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

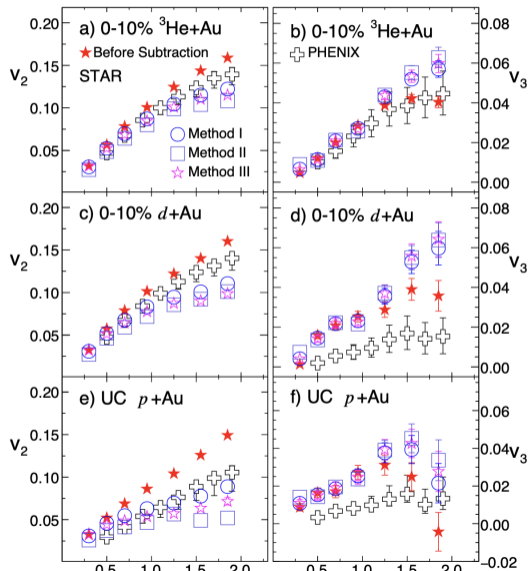
Comparisons with STAR



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

Good agreement between STAR and PHENIX for v_2

Comparisons with STAR

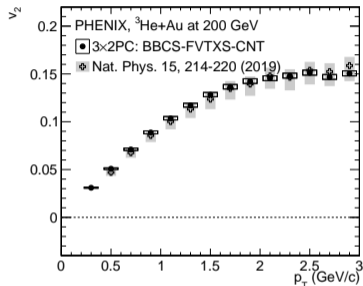
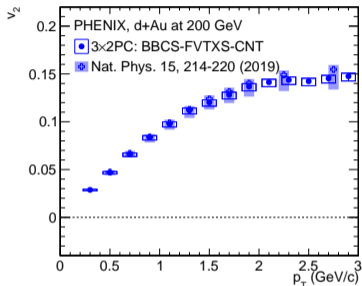
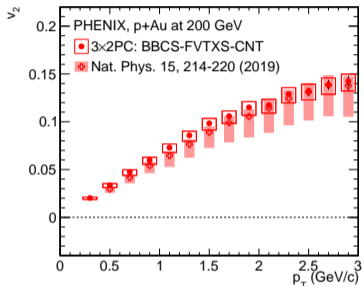


STAR, Phys. Rev. Lett. 130, 242301 (2023)

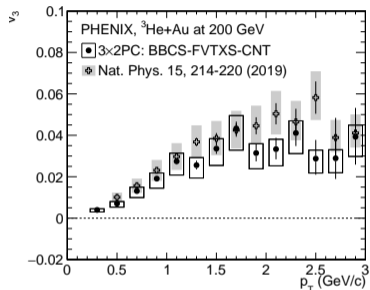
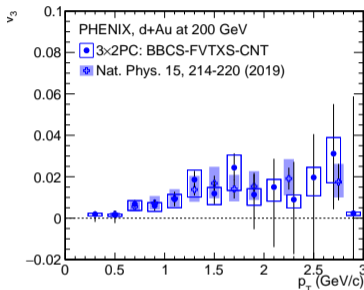
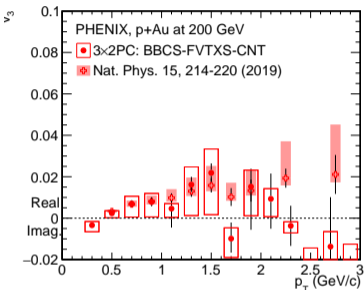
Good agreement between STAR and PHENIX for v_2

Large difference between STAR and PHENIX for v_3 in $p+\text{Au}$ and $d+\text{Au}$

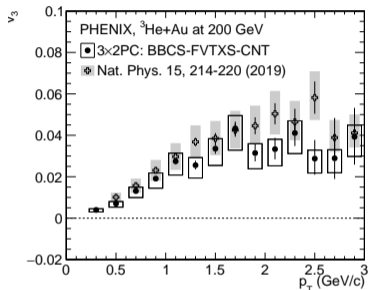
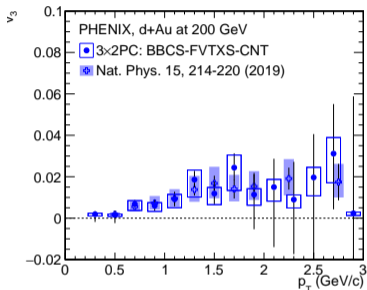
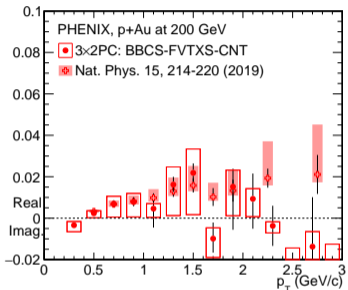
Large subnucleonic fluctuations can overwhelm the intrinsic geometry in some models, leading to similar ε_3 for all systems



- 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)

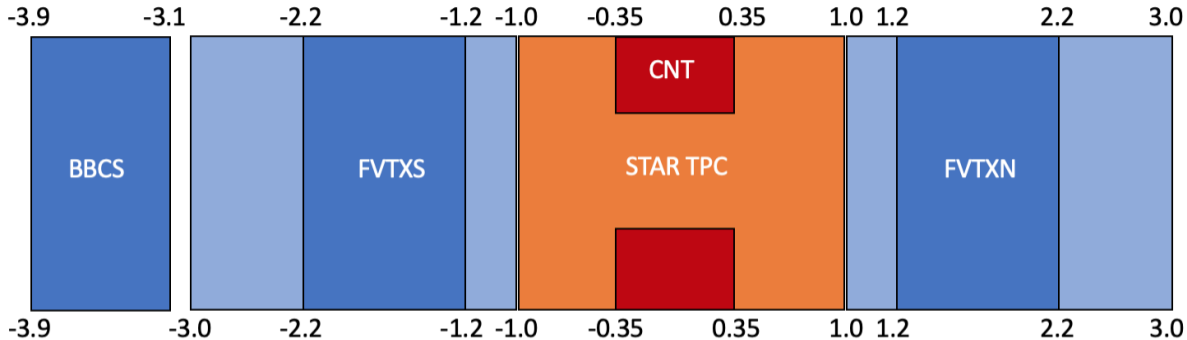


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- All new analysis using two-particle correlations with event mixing instead of event plane method
 - Completely new and separate code base
 - Very different sensitivity to key experimental effects (beam position, detector alignment)
- It's essential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

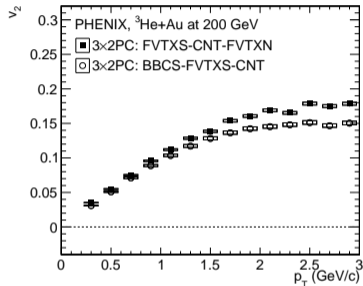
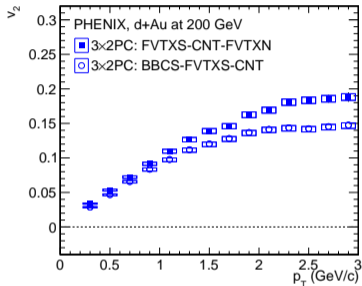
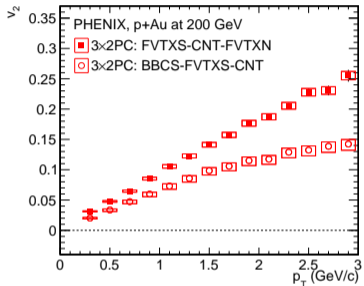
STAR and PHENIX detector comparison



- 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*

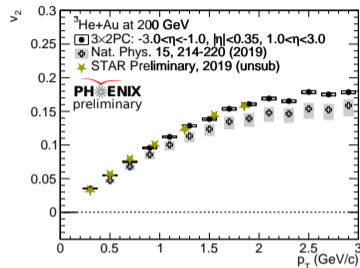
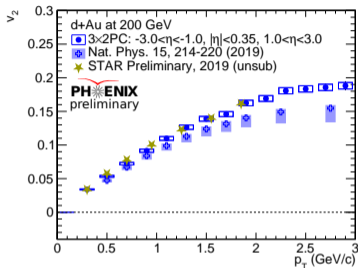
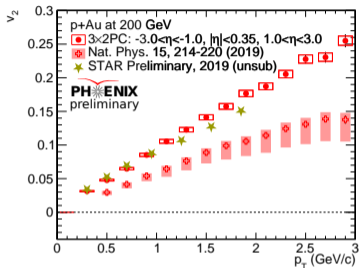
More STAR and PHENIX data comparisons

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



More STAR and PHENIX data comparisons

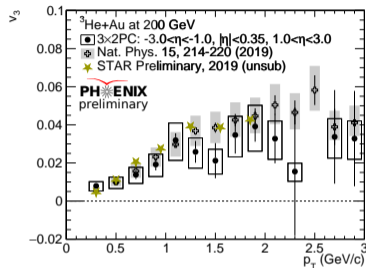
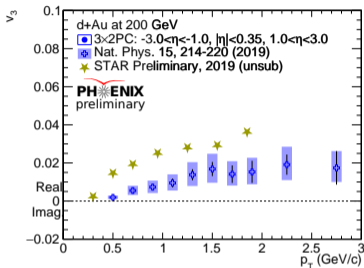
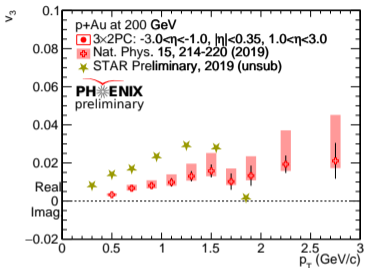
PHENIX (RB), Phys. Rev. C 105, 024901 (2022)



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

More STAR and PHENIX data comparisons

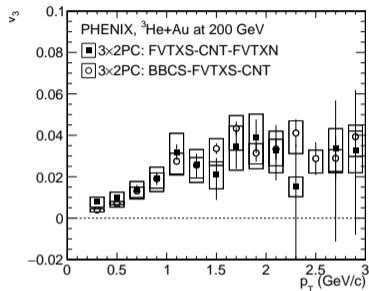
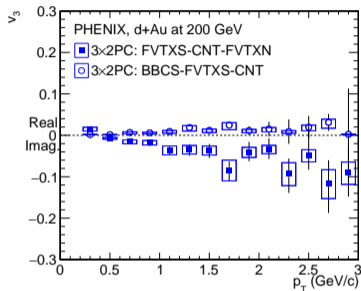
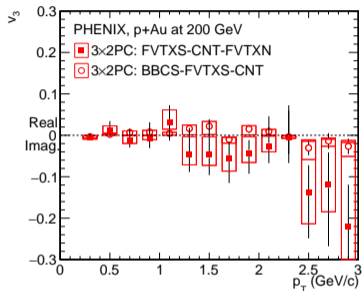
PHENIX (RB), Phys. Rev. C 105, 024901 (2022)



- 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

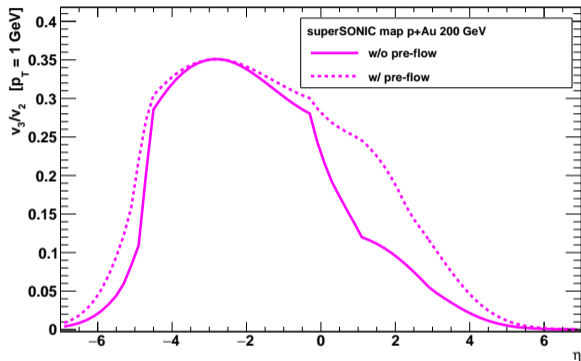
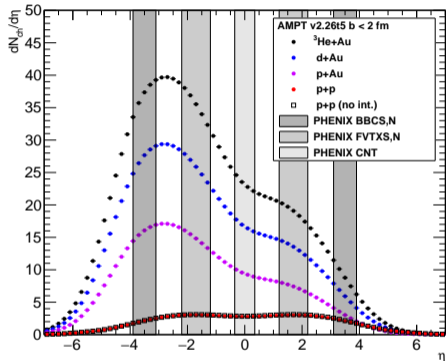
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Pseudorapidity dependence in small systems

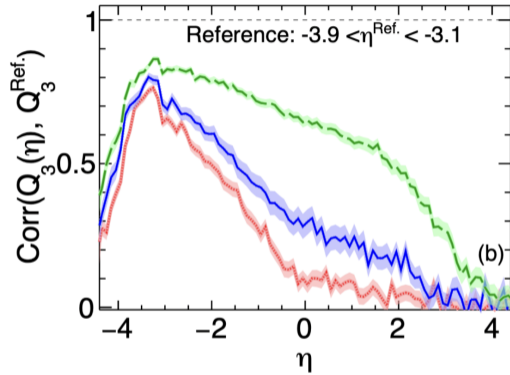
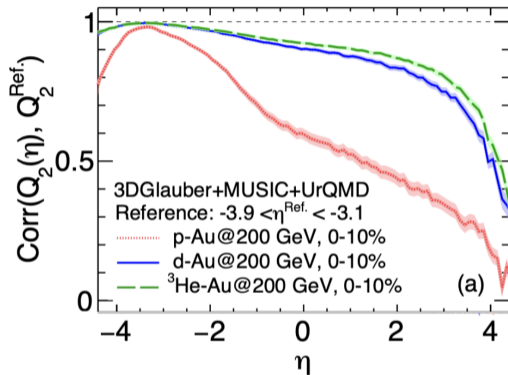
J.L. Nagle et al (RB), Phys. Rev. C 105, 024906 (2022)



- $dN_{ch}/d\eta$ 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

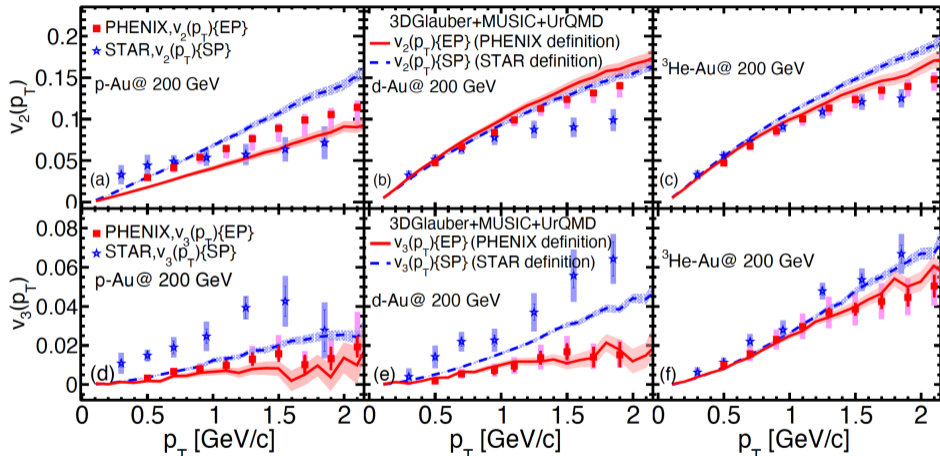
W. Zhao et al, Phys. Rev. C 107, 014904 (2023)



- 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

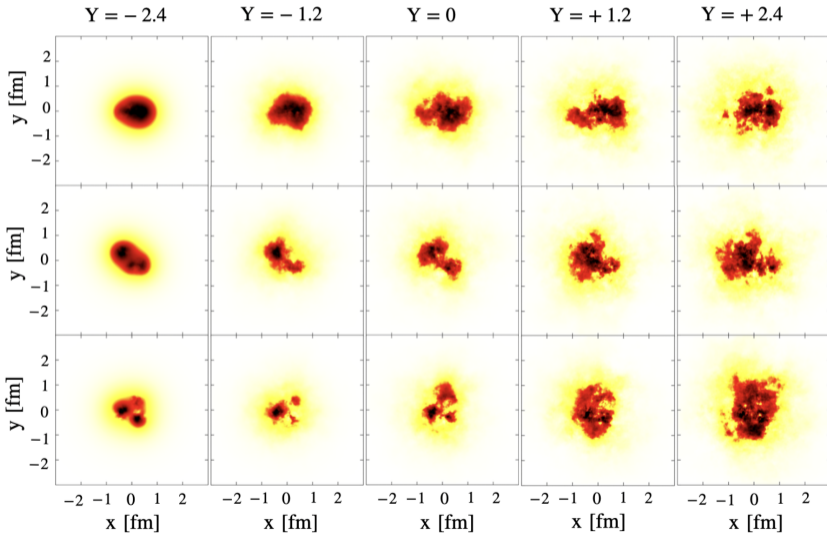
W. Zhao et al, Phys. Rev. C 107, 014904 (2023)



- Flow decorrelations lead to larger v_3 for STAR, explaining $\sim 50\%$ 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

Summary and Outlook

- Lots of exciting opportunities for very interesting flow measurements with sPHENIX!
- While flow measurements are a bonus rather than the core sPHENIX science mission, the PAC24 report clearly highlights the potential opportunities for new flow measurements
 - “The PAC recommends a Au+Au run in which sPHENIX collects at least 7 nb^{-1} of data as the highest priority for Run 25.”
 - This corresponds to about 50 billion events
 - “The PAC has received beam use requests for running pp, p+Au, and O+O collision systems. The PAC sees all three of these proposed runs as fully aligned with RHIC’s core scientific mission, and in fact as key elements of completing that mission. Each of these three proposed runs is necessary to address central open RHIC Science questions in a decisive way.”
 - More p+p needed for Upsilon program
 - Exciting prospects for more small systems measurements