Searching for the smallest droplets of the early universe: heavy-ion physics with small systems

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Physics Department Seminar
Urbana-Champaign, IL
15 February 2021

Утро в сосновом лесу

Утро в сосновом лесу

Historical Perspective

"Those who do not remember George Santayana are condemned to paraphrase him." - Unknown

- 400 BCE Democritus hypothesizes atoms
- 1687 Newton publishes *Philosophiae Naturalis Principia Mathematica*
- 1900 Planck's Law
- 1905 Einstein's 4 papers
- 1911 Rutherford scattering
- 1913 Bohr atom
- 1924 de Broglie wavelength
- 1925 Heisenberg's Matrix mechanics
- 1926 Schrödinger equation
- 1927 Dirac's relativistic quantum mechanics

Historical Perspective

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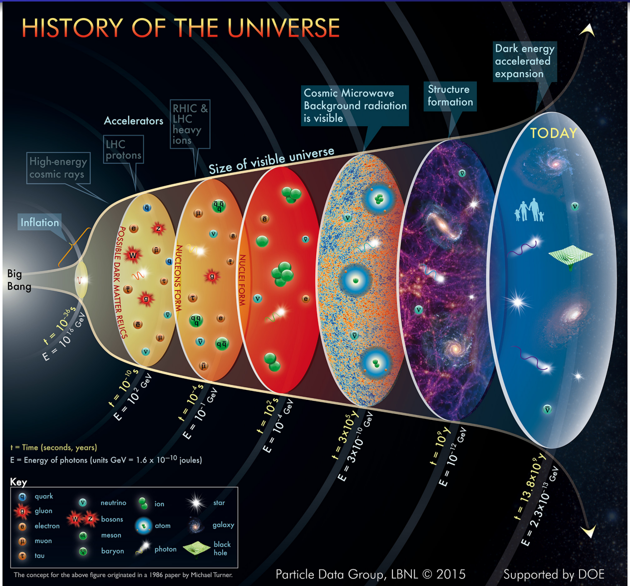
- 1963 Gell-Mann's Quark Model (particle zoo)
- 1965 Additional degree of freedom postulated for quarks by Han and Nambu
- 1969 Deep inelastic scattering experiments prove the existence of quarks
- 1972 Color charge and basic framework of **quantum chromodynamics**
- 1973 Asymptotic Freedom discovered by Gross, Politzer, and Wilczek
- 1975 Collins and Perry formulate a QCD plasma
- 1980 Shuryak coins term quark-gluon plasma (QGP)
- 2000 RHIC is operational
- 2010 First heavy ion collisions at LHC

The history of the universe

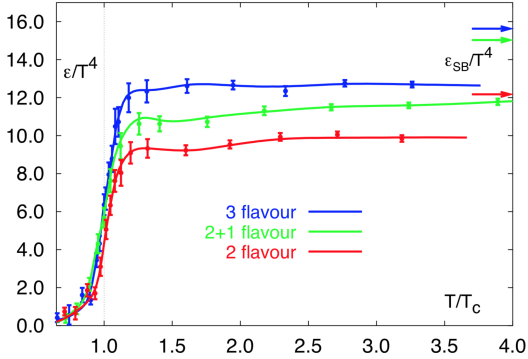


- The early universe (few microseconds) was a quark-gluon plasma (QGP)
- The QGP is a system of deconfined quarks and gluons
- We can recreate the QGP in the lab in collisions of heavy nuclei at relativistic speeds
- Goal of heavy-ion physics: create, identify, and study the QGP

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)

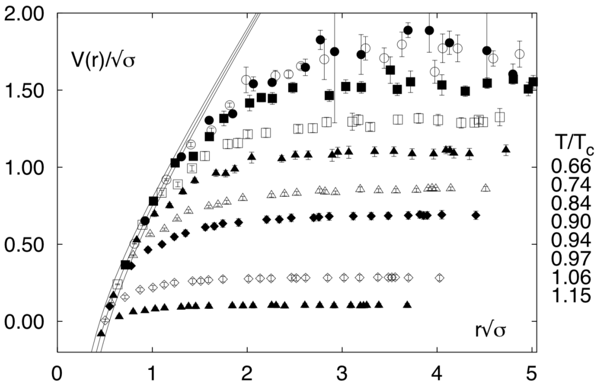
- The QED potential

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

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

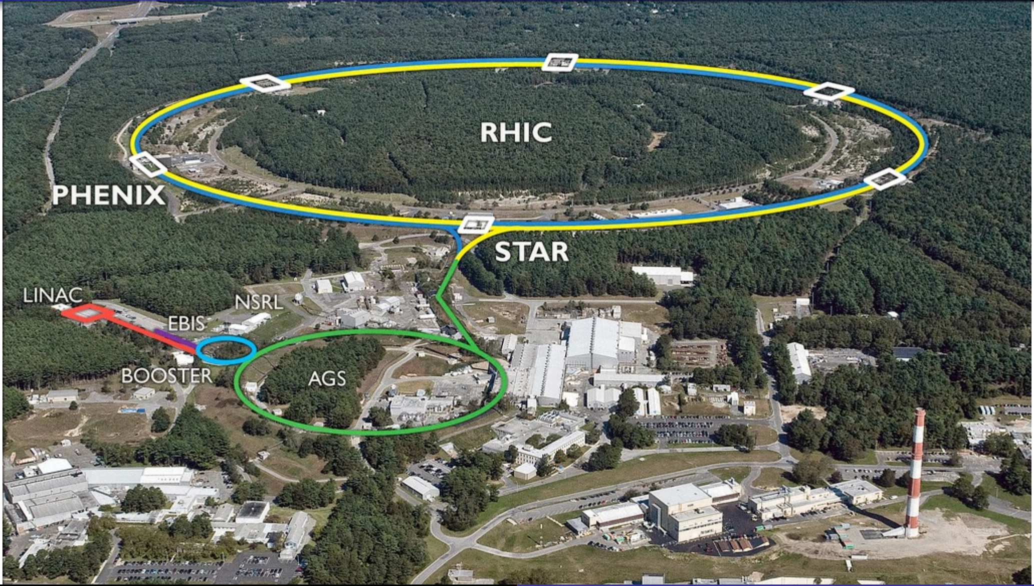
$$V(r) = -\frac{4}{3}\frac{\alpha_S}{r} + kr$$

- 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)

The Relativistic Heavy Ion Collider



The Relativistic Heavy Ion Collider

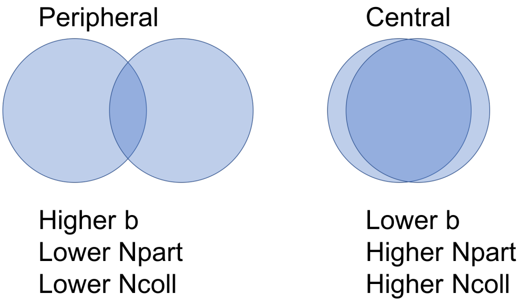
- RHIC is the only polarized proton collider in the world
- RHIC is one of two heavy ion colliders, the other being the LHC

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

- 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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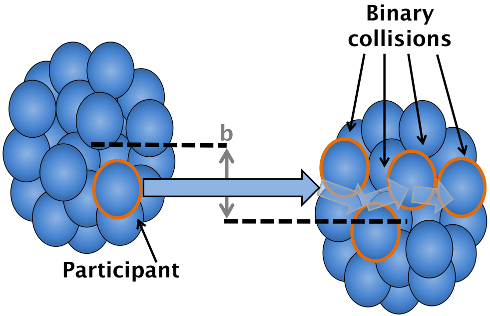

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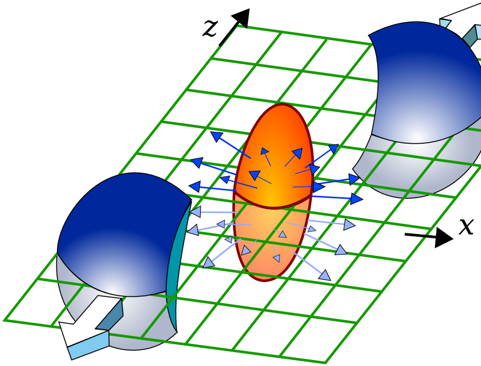
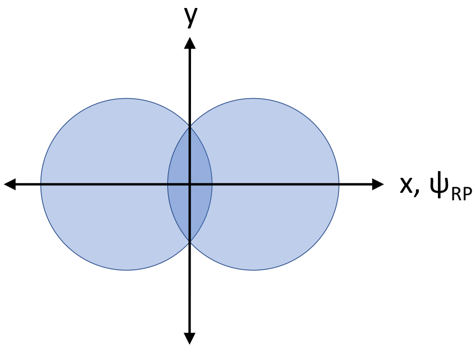
Azimuthal anisotropy measurements

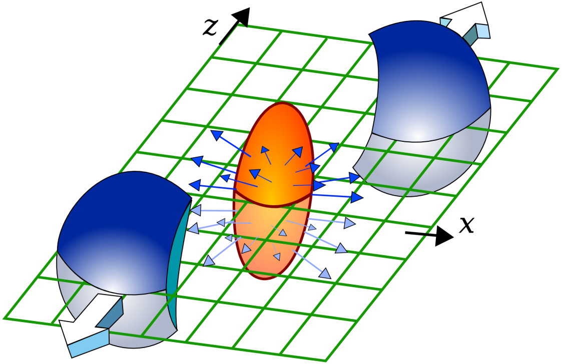


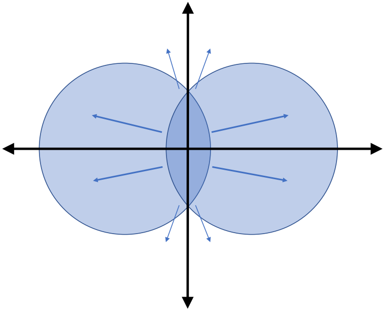


$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^n \cos n\varphi \rangle + \langle r^n \sin n\varphi \rangle}}{\langle r^n \rangle}$$

- Hydrodynamics translates initial shape (including fluctuations) into final state distribution
- $\varphi = \phi_{lab} - \psi_{RP}$

Azimuthal anisotropy measurements





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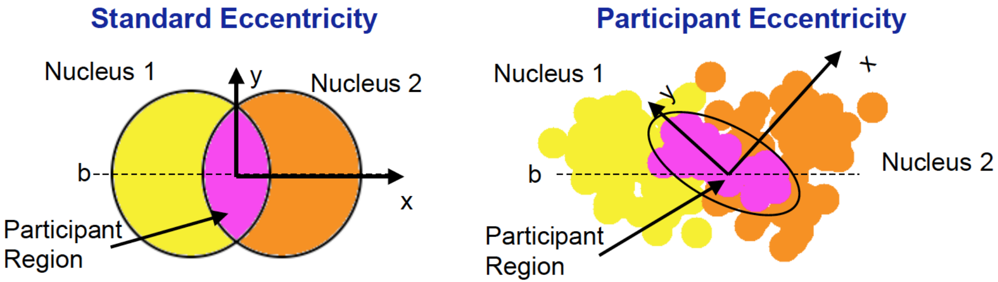
Important discovery in 2005

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



A nucleus isn't just a sphere

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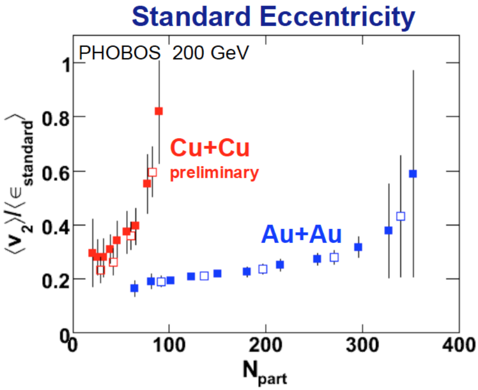

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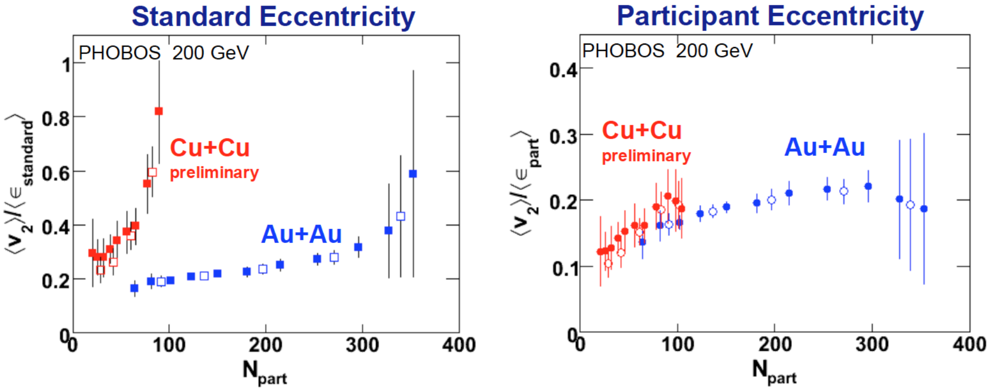


A nucleus isn't just a sphere

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

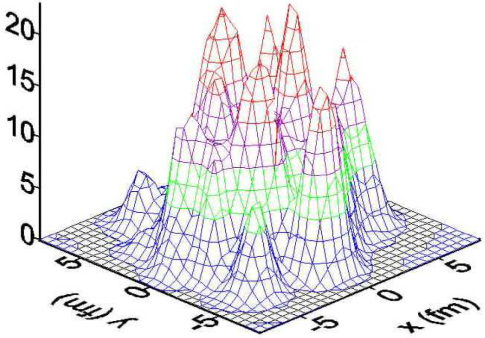
R.Andrade[1], F.Grassi[1], Y.Hama[1], T.Kodama[2], O.Socolowski Jr.[3], and B.Tavares[2]

[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

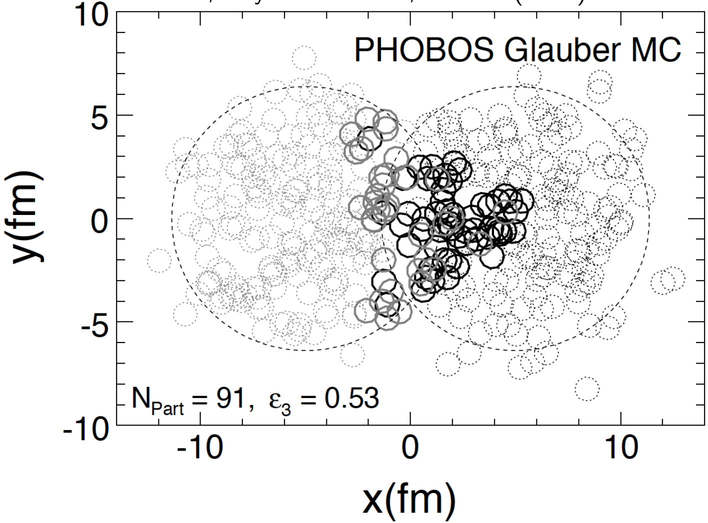
Received 1 January 2004



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)



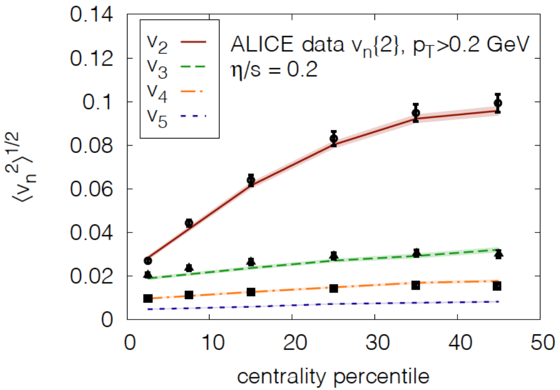
Nucleon fluctuations can produce non-zero ε_n for odd n

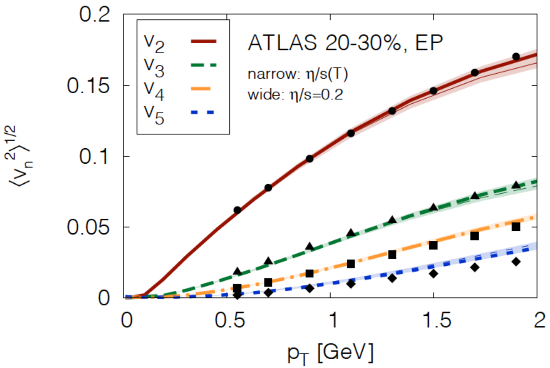
Symmetry planes ψ_n can be different for different harmonics

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

Data and theory for v_n

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

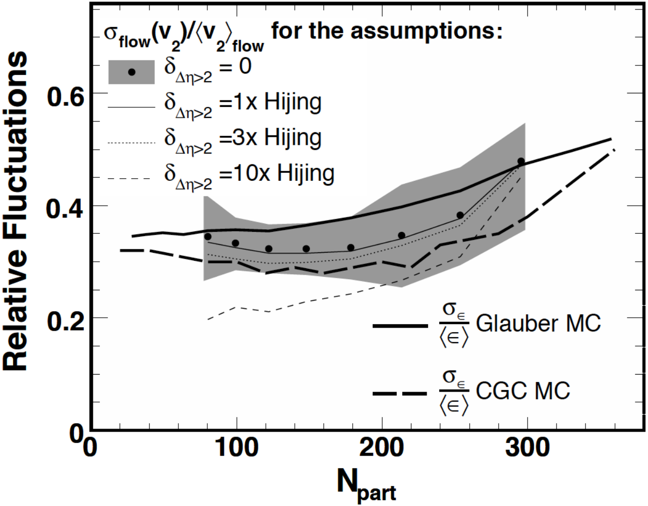




$$\frac{dN}{d\varphi} \propto 2v_2 \cos 2\varphi + 2v_3 \cos 3\varphi + 2v_4 \cos 4\varphi + 2v_5 \cos 5\varphi$$

Fluctuations in large systems

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



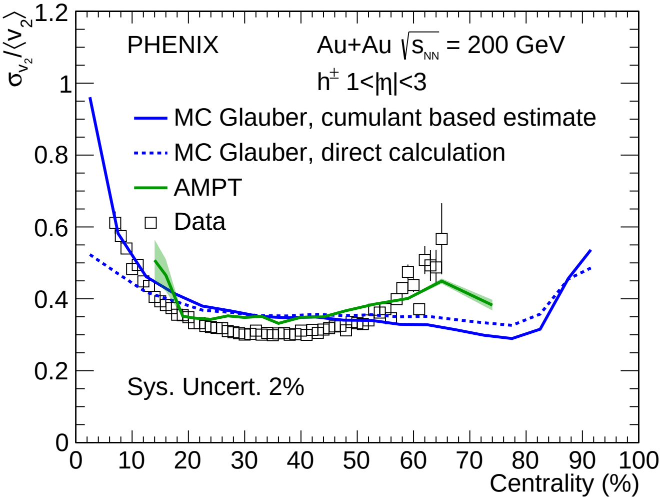
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2 \rangle$

$|\eta| < 1$

Generally good agreement with models of initial geometry

Fluctuations in large systems

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



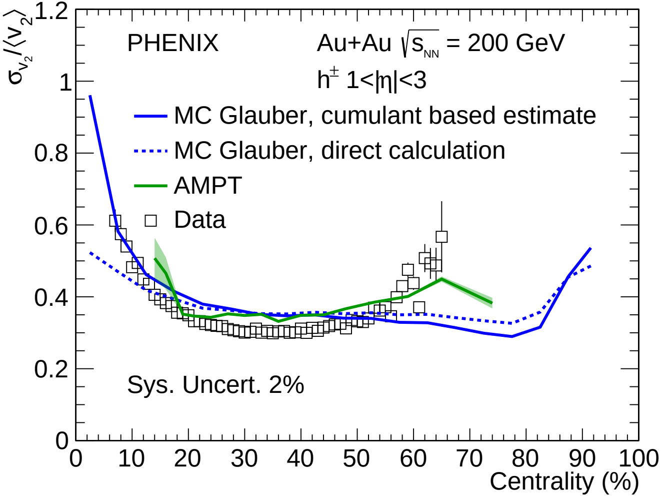
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2\rangle$

$1 < |\eta| < 3$

Generally good agreement with models of initial geometry

Fluctuations in large systems

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



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$1 < |\eta| < 3$

Central: breakdown of small-variance limit

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

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 and now-ish—QGP in high multiplicity p+p? QGP in mid-multiplicity p+p?? QGP in d+Au even at low energies???

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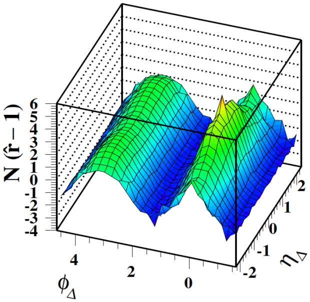
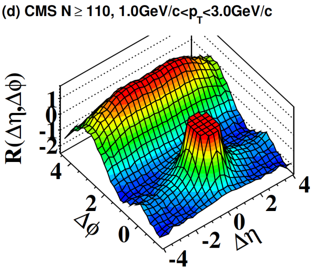
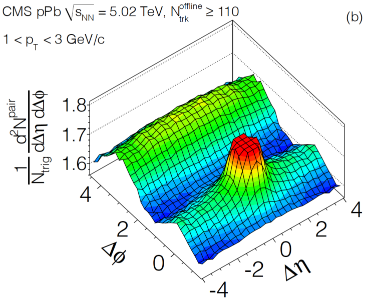
"Twenty years ago, the challenge in heavy ion physics was to find the QGP. Now, the challenge is to not find it." —Jürgen Schukraft, QM17

The ridge is a signature of flow

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





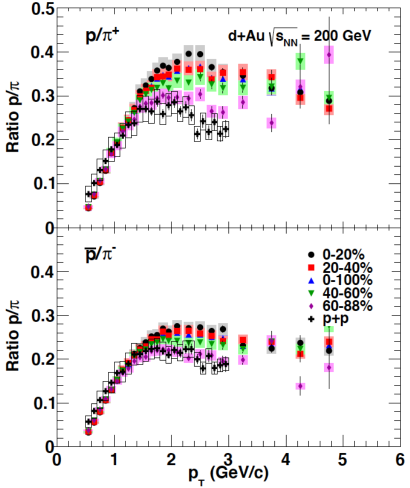


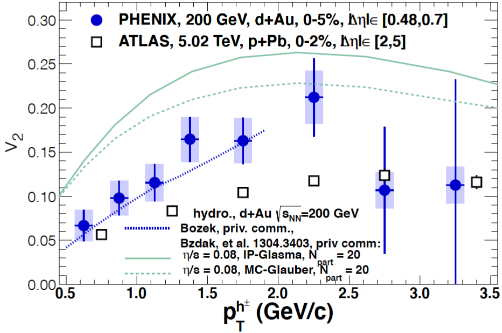
Extended structure away from near-side jet peak interpreted as collective effect due to presence of QGP

- First 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 (AS), Phys. Rev. Lett. 111, 212301 (2013)





- First paper measuring v_2 in d+Au at RHIC by Anne!
- Paper based on my PhD thesis found baryon enhancement in d+Au similar to that in Au+Au

Intermission

Small systems geometry scan

Adjusting nuclear species to access different geometries

Testing hydro by controlling system geometry

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

Testing hydro by controlling system geometry

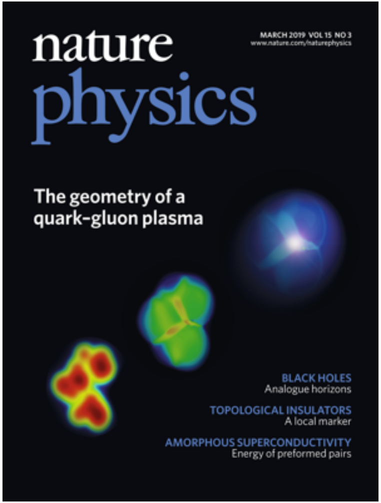
nature physics

Letter | Published: 10 December 2018

Creation of quark–gluon plasma droplets with three distinct geometries

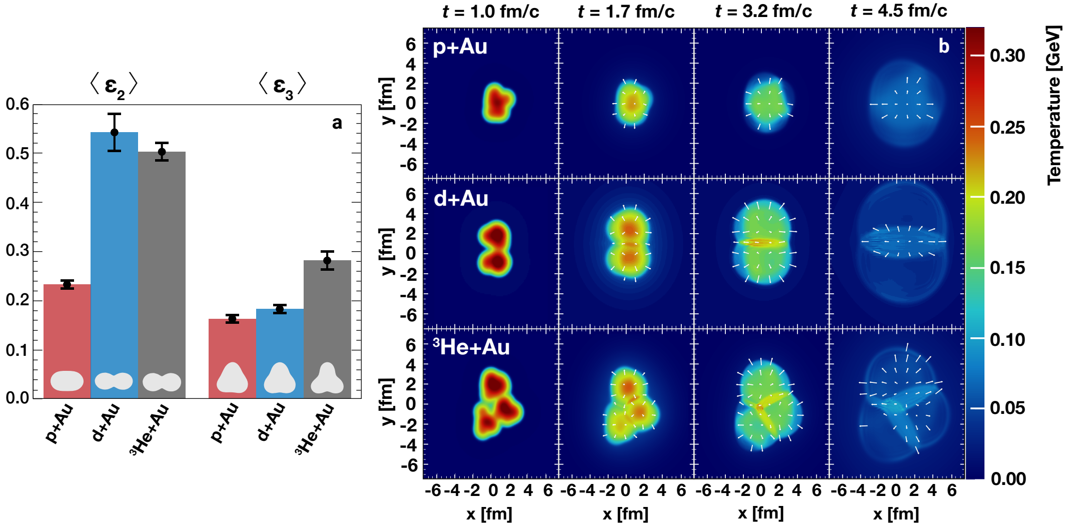
PHENIX Collaboration

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



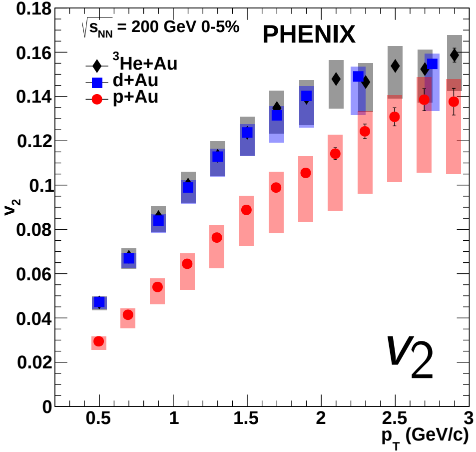
Testing hydro by controlling system geometry

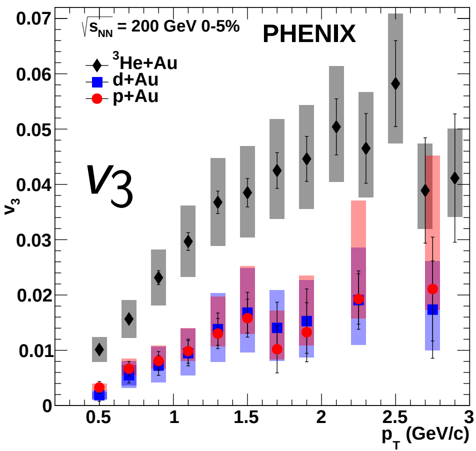
PHENIX (RB), Nature Physics 15, 214–220 (2019)



Testing hydro by controlling system geometry

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



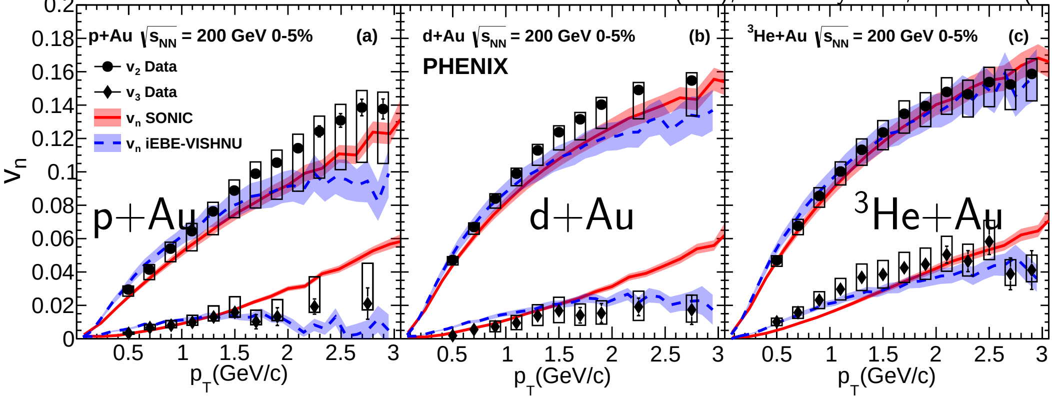


- v_2 and v_3 ordering matches ε_2 and ε_3 ordering in all three systems

  —Collective motion of system translates the initial geometry into the final state

Testing hydro by controlling system geometry

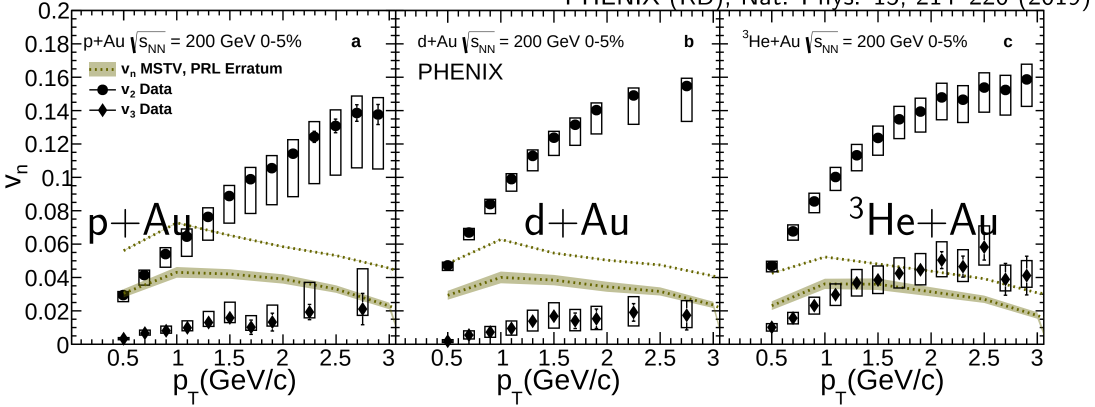
PHENIX (RB), Nat. Phys. 15, 214–220 (2019)



- 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

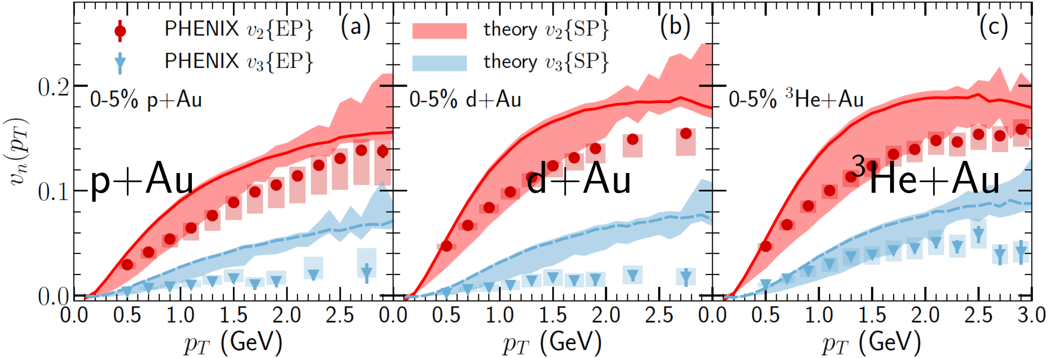
PHENIX (RB), Nat. Phys. 15, 214–220 (2019)



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

Testing hydro by controlling system geometry

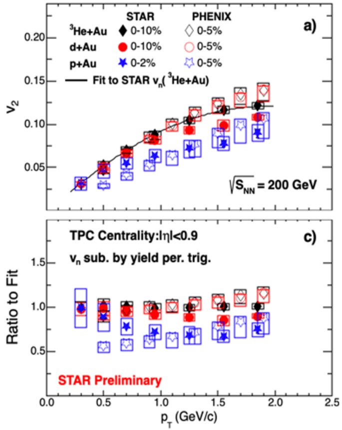
PHENIX (RB), Nat. Phys. 15, 214–220 (2019)



- Important to include initial state effects
  —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

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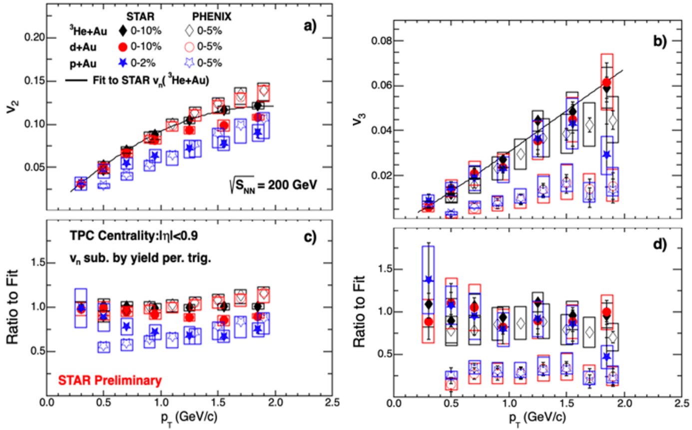
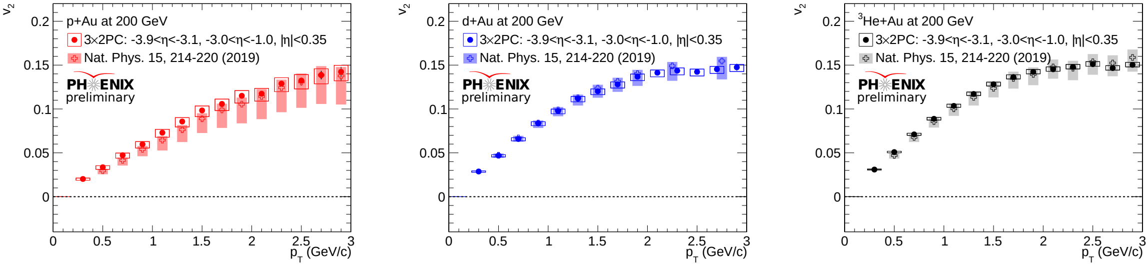


Good agreement between STAR and PHENIX for v_2

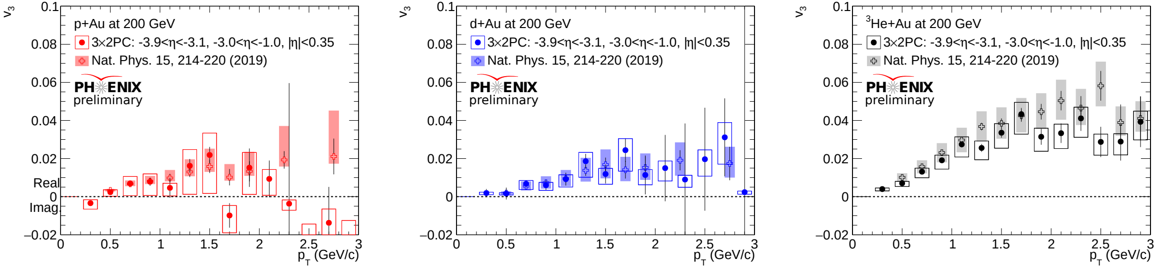
Large discrepancy between STAR and PHENIX for v_3

PHENIX data update



- 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
- Measurement error ruled out—discrepancy must be due to physics

PHENIX data update



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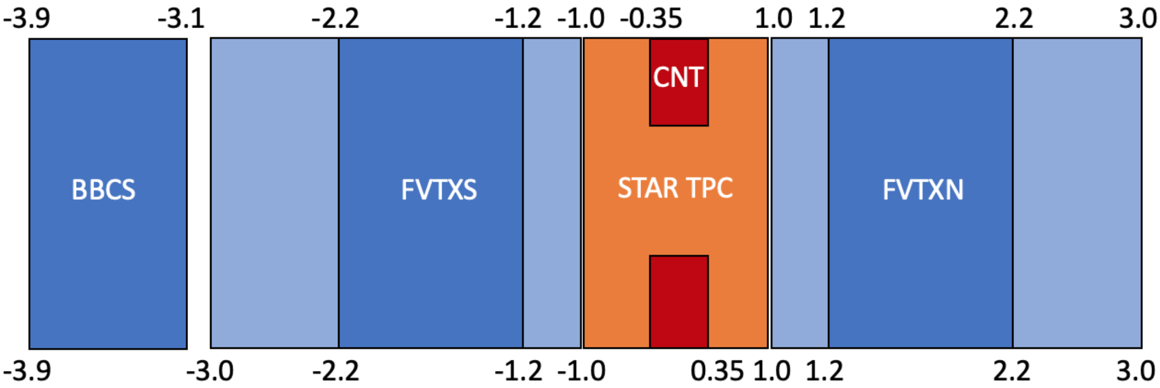
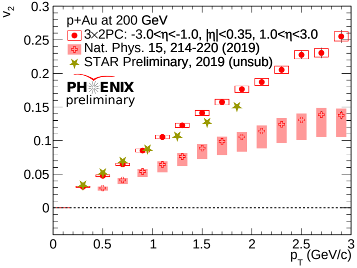
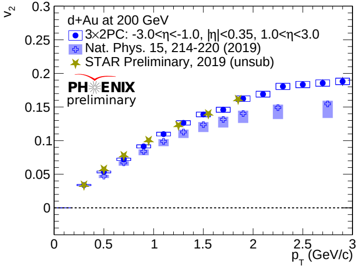
STAR and PHENIX detector comparison

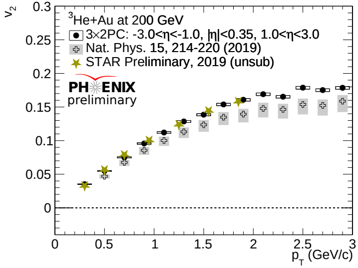


- The Nature Physics paper uses the BBCS-FVTXS-CNT detector combination
  —This is very different from the STAR analysis
- We can try to use FVTXS-CNT-FVTXN detector combination to better match STAR
  —Closer, and "balanced" between forward and backward, *but still different*

More STAR and PHENIX data comparisons

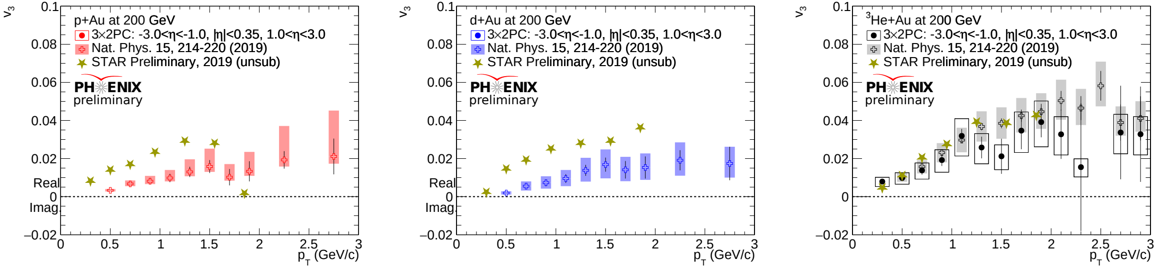






- Good agreement with STAR for v_2
  —Similar physics for the two different pseudorapidity acceptances

More STAR and PHENIX data comparisons



- Good agreement with STAR for v_2
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- Strikingly different results for v_3
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  —Decorrelation effects much stronger for v_3 than v_2

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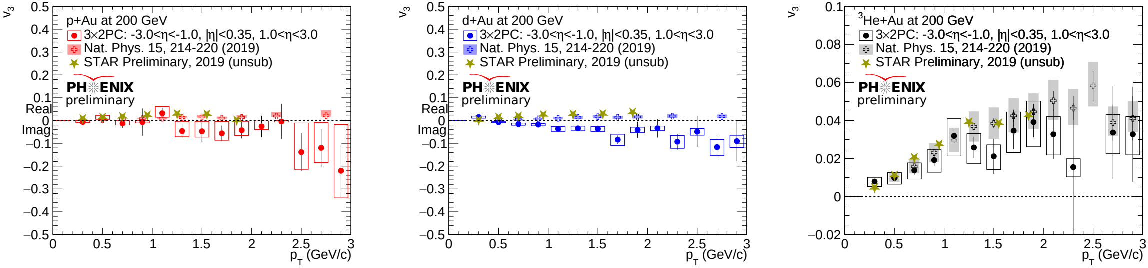

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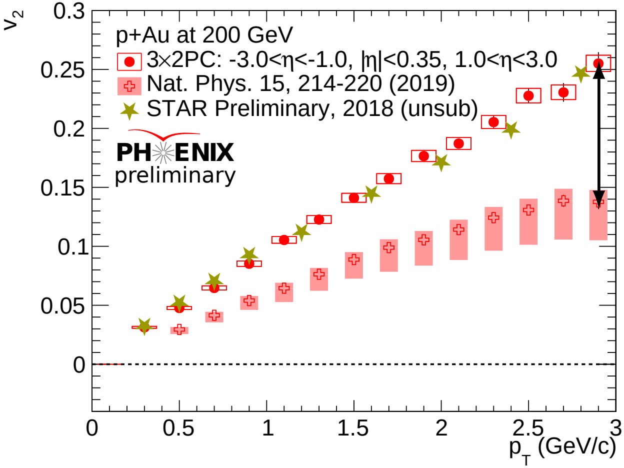
Understanding the nonflow contribution: v_2 in p+Au as a case study

RB, Initial Stages 2021



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

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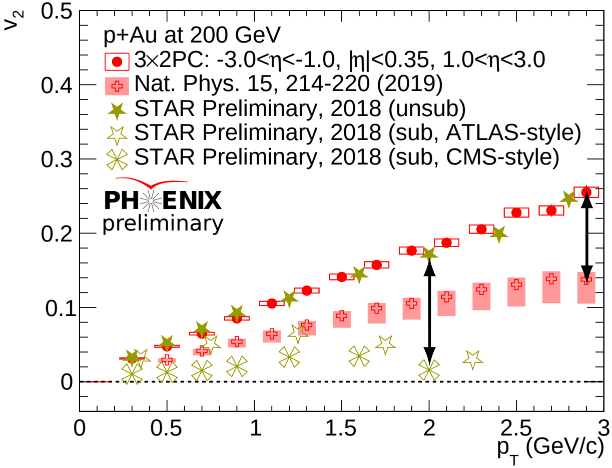
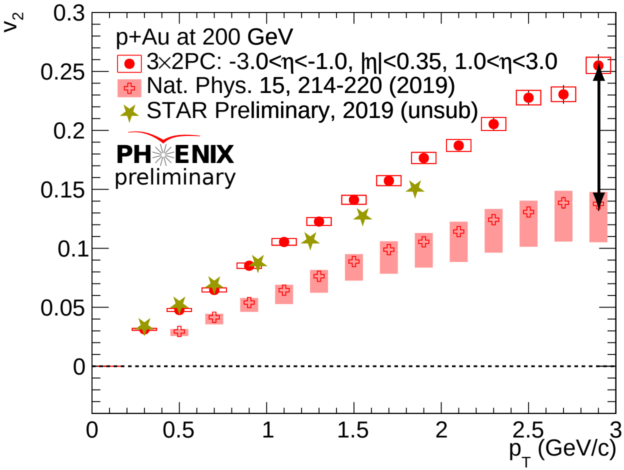


- The large difference between the PHENIX published and STAR preliminary in this case is nonflow
- PHENIX suppresses nonflow via kinematic selection
- STAR applies non-flow subtraction procedure
- One needs to be careful about the risk of over-subtraction methods—S. Lim et al (RB), Phys. Rev. C 100,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

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

RB, Initial Stages 2021



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

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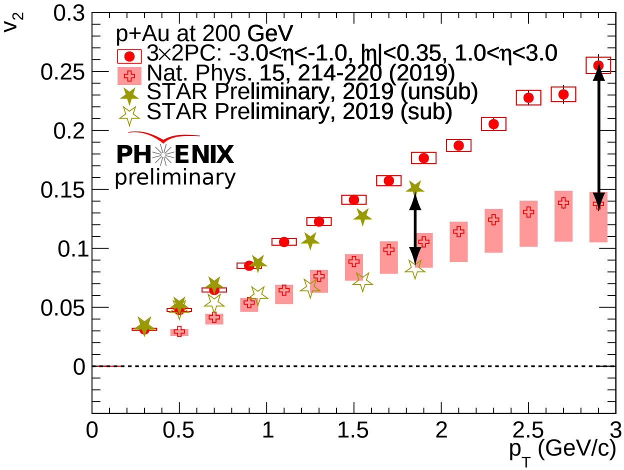


- The large difference between the PHENIX published and STAR preliminary in this case is nonflow
- PHENIX suppresses nonflow via kinematic selection
- STAR applies non-flow subtraction procedure
- Considerable improvement in nonflow subtraction in STAR 2019 preliminary, reasonable agreement with PHENIX

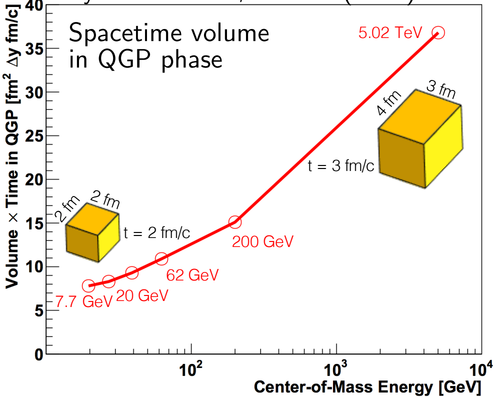
Intermission

Small systems beam energy scan

Fix the geometry, vary the collision energy

Testing hydro by controlling system size and life time

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

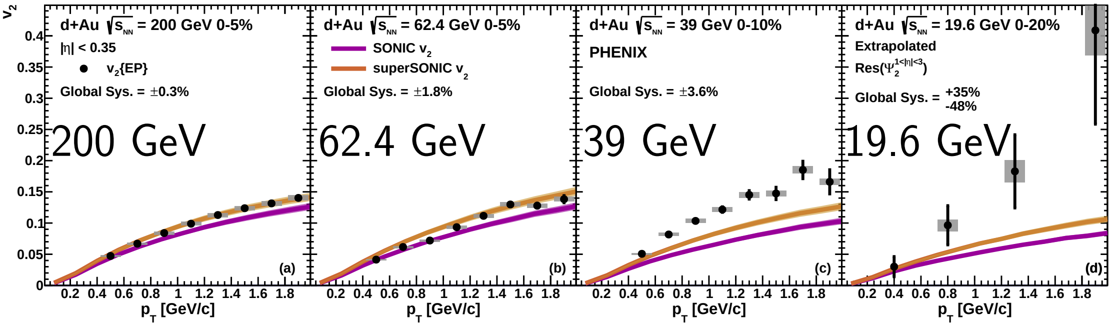


Geometry in d+Au collisions dominated by deuteron shape, thus largely independent of collision energy

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

d+Au beam energy scan

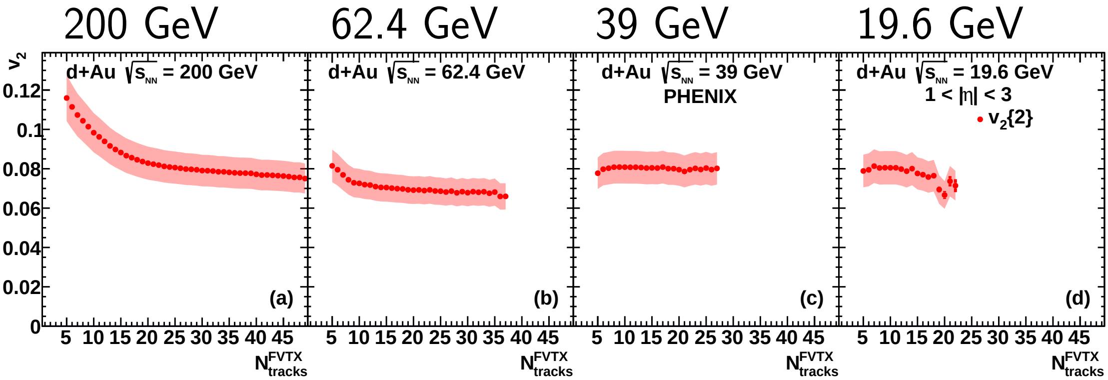
PHENIX (RB), Phys. Rev. C 96, 064905 (2017)



- 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. M. Martinez et al, arXiv: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

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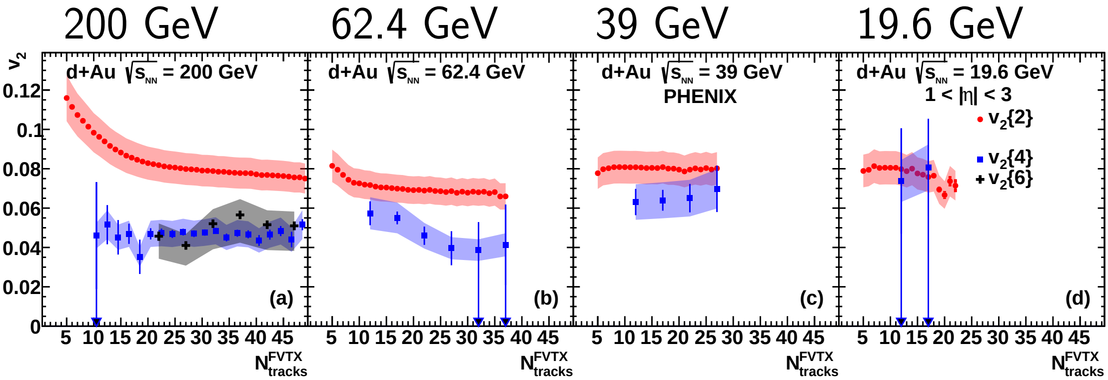
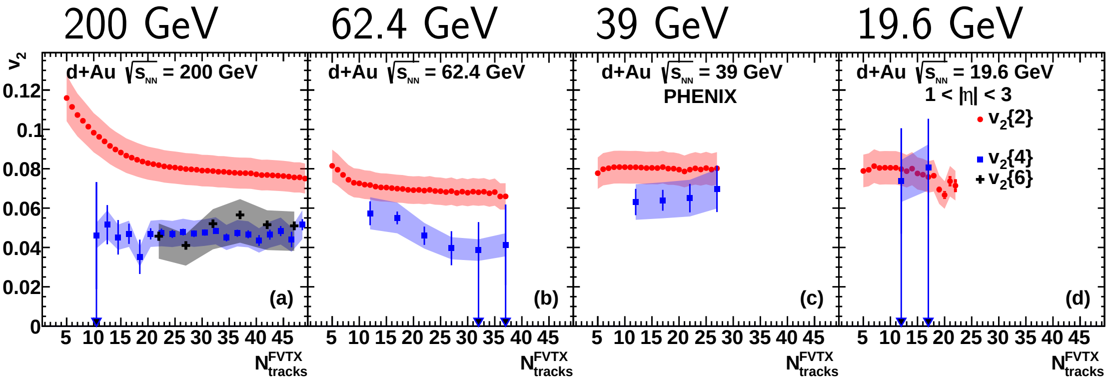


- Measurement of $v_2\{6\}$ in d+Au at 200 GeV and $v_2\{4\}$ in d+Au at all energies

d+Au beam energy scan

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



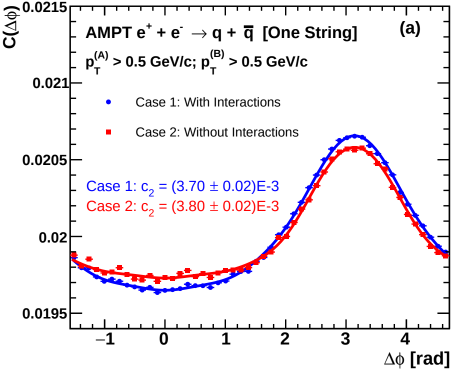
- Measurement of $v_2\{6\}$ in d+Au at 200 GeV and $v_2\{4\}$ in d+Au at all energies
- Multiparticle correlations can be a good indicator of collectivity

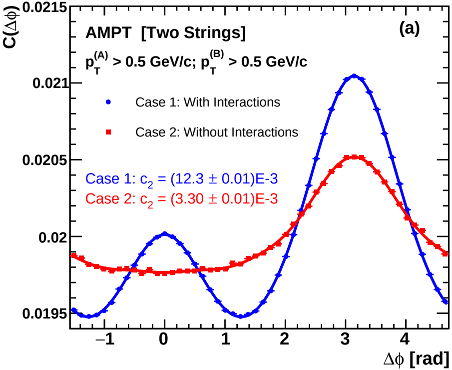
Intermission

How about *extremely* small systems?

Extremely small systems in AMPT

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

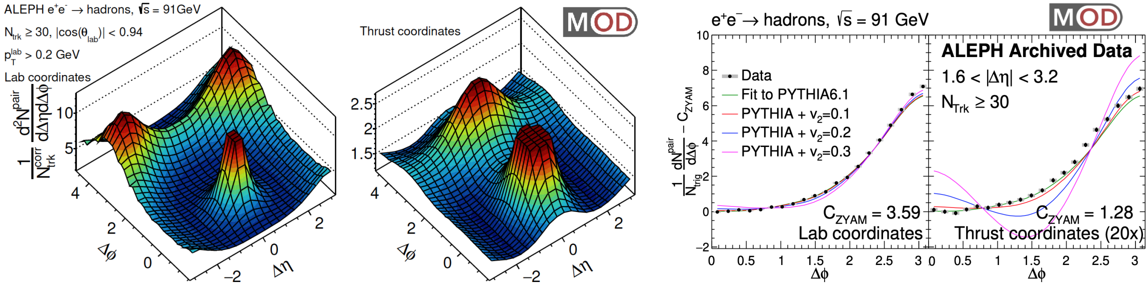




- A single color string ($e^+ + e^-$ collisions) shows no sign of collectivity
- Two color strings shows collectivity
  —In AMPT, $p+p$ has two strings and $p/d/^3$He+Au have more

Extremely small systems at LEP

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

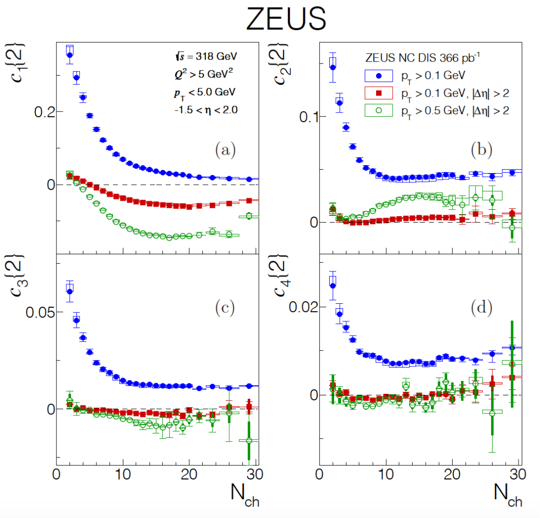


No apparent collectivity in ALEPH $e^{+}+e^{-}$ data

- Brought up as a possibility in e.g. P. Romatschke, Eur. Phys. J. C 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, arXiv:2011.06966

Extremely small systems at HERA and the EIC

Abt et al, JHEP 04, 070 (2020)



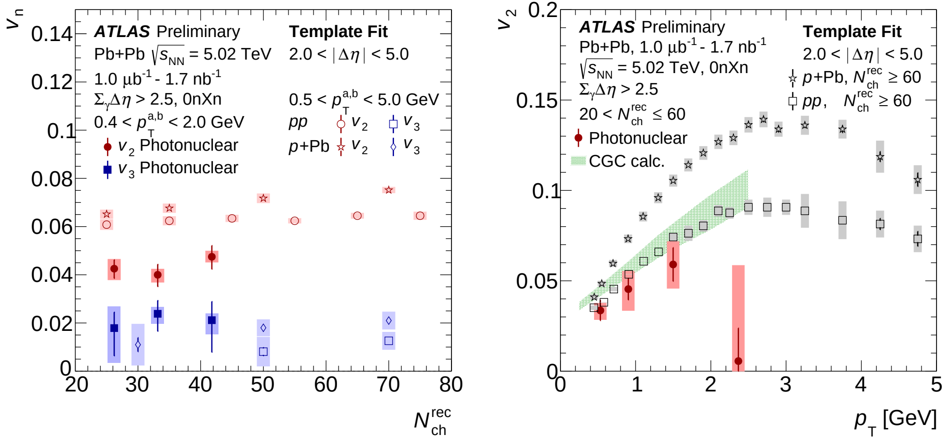
"The correlations observed here do not indicate the kind of collective behaviour recently observed at the highest RHIC and LHC energies in high-multiplicity hadronic collisions."

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 Preliminary, Initial Stages 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

Part III: the future

The 2015 Long Range Plan for Nuclear Science

https://www.science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

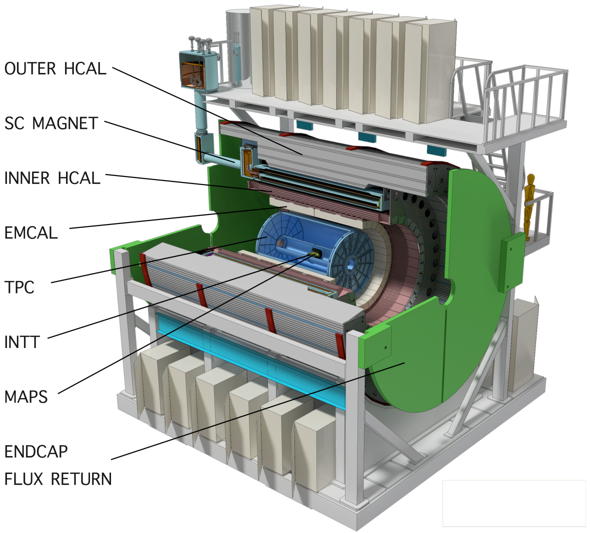
Recommendation I: The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.
—CEBAF, FRIB, Symmetries & Neutrinos, **RHIC** (BES II & **sPHENIX**)

Recommendation II: We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

Recommendation III: We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

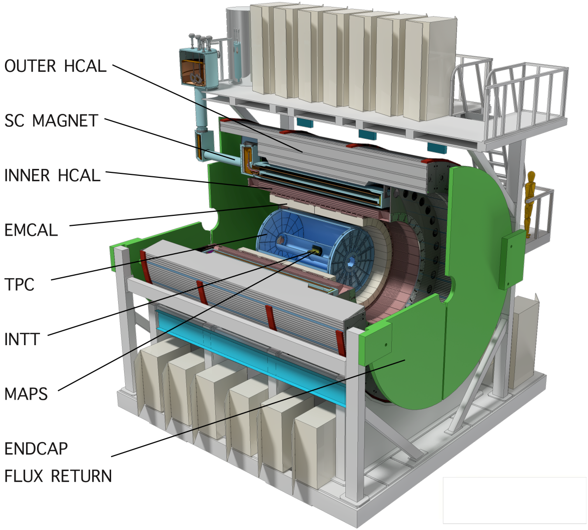
Recommendation IV: We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

sPHENIX: QGP microscope



From the LRP: **[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)

Future

Installation begins	April 2021
Installation complete	July 2022
Initial commissioning complete	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 [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

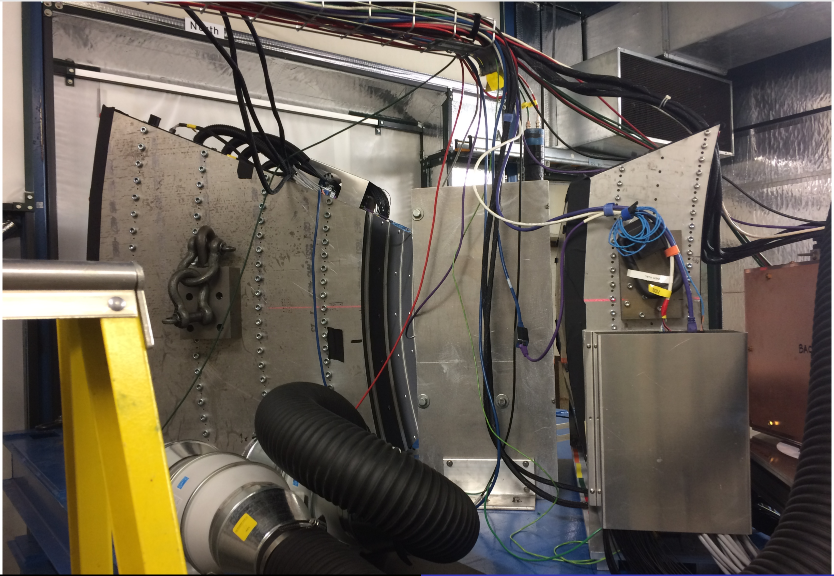
GSA AND HOLDING AGENCY NOS. (a)	ITEM NO. (b)	DESCRIPTION (Include noun name, FSC Group and Class, Condition Code and if available, National Stock Number) (c)	UNIT (d)	QUANTITY (e)	ACQUISITION COST UNIT (f)	ACQUISITION COST TOTAL (g)
		Administrative Transfer				
	1	BaBar Solenoid and Components Date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

sPHENIX: magnet

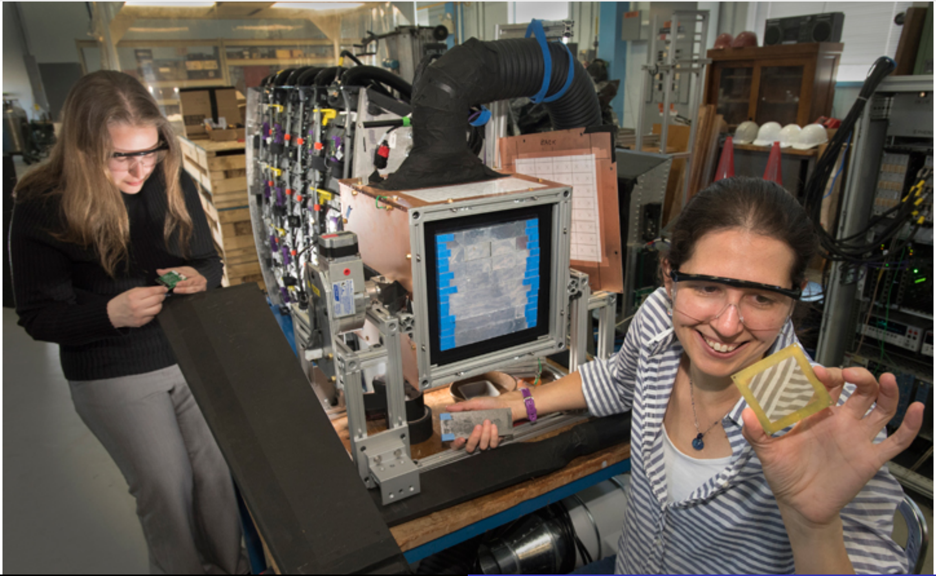
sPHENIX: magnet

sPHENIX: beam tests

sPHENIX: beam tests



sPHENIX: beam tests



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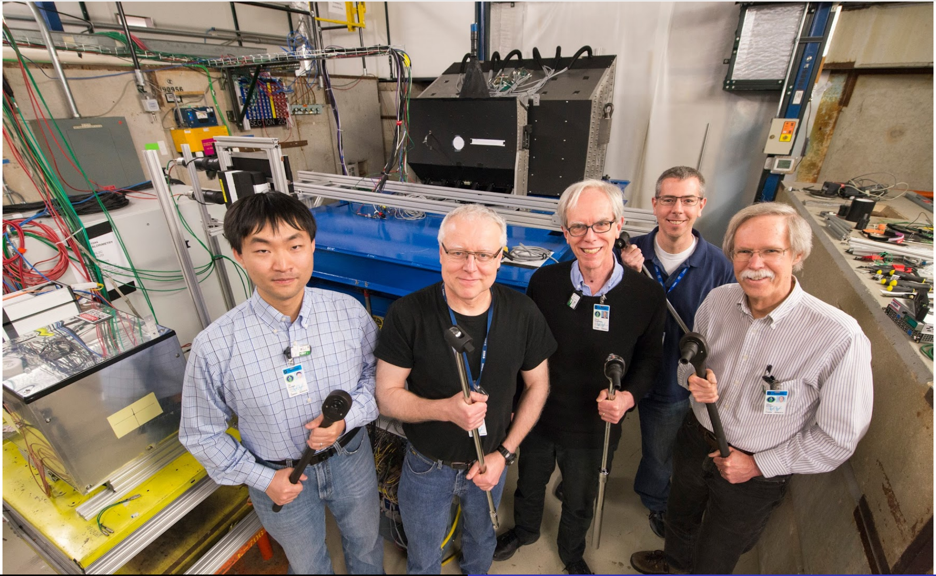
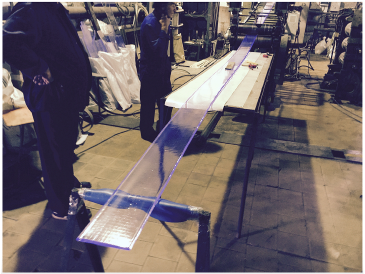
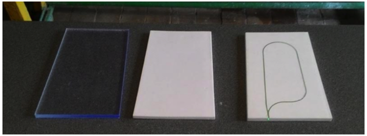
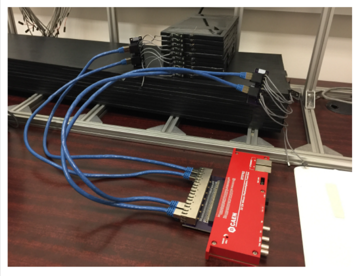
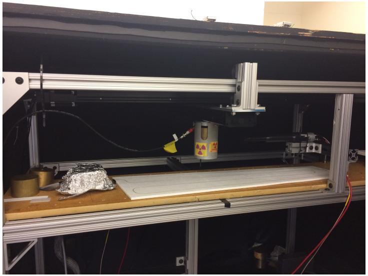


sPHENIX: HCal tiles





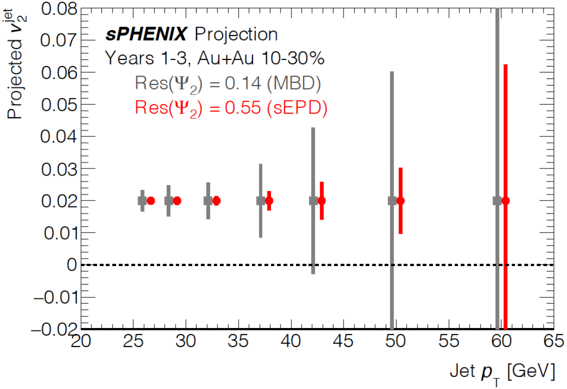


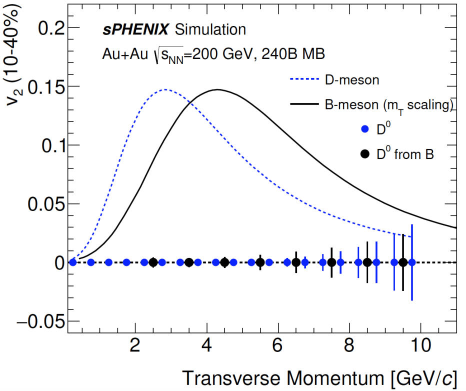


sPHENIX: jets!

sPHENIX: heavy flavor!

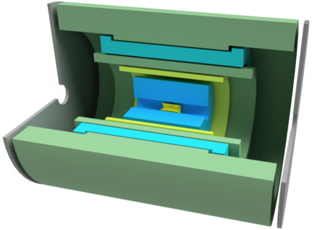
sPHENIX: projections



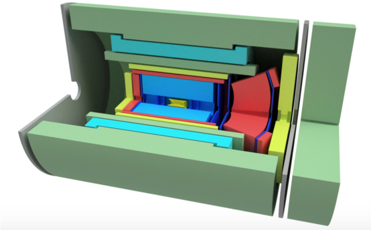


- Lots of core sPHENIX measurements need flow expertise
- RB involved in recent NSF MRI for event plane detector

sPHENIX: day one EIC detector



sPHENIX EIC proposal: arXiv:1402.1209



An EIC Detector Built Around The sPHENIX Solenoid

A Detector Design Study

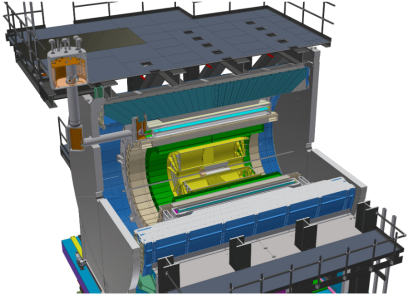
sPHENIX: day one EIC detector

Recently formed ECCE consortium dedicated to repurposing sPHENIX

Existing Infrastructure

- Existing BaBar solenoid (1.5T), flux return and cradle
  - Substantial investment/risk reduction
- IP8 infrastructure
  - Cryogenic connection to RHIC
  - Racks, mechanical, safety, electrical, etc.
- Potential re-use/refurbish existing sPHENIX detectors as appropriate
- ECCE consortium has considerable recent DOE project experience

Currently under construction, sPHENIX represents a $27M investment by DOE (MIE)



Summary and outlook

- We can recreate the early universe in the lab using collisions of large nuclei
- Small systems have had a lot of surprises for us—definitely not a control experiment
- The key tool we've used is having a variety of nuclear species to control the collision geometry
  —The geometry scan used projectiles to compare intrinsic geometry with fluctuations
  —The beam energy scan used the same projectile to compare intrinsic geometry with fluctuations
- QGP droplet formation is on a strong footing
  —Experimental results inspiring lots of progress in hydro theory
- It's an exciting time for nuclear physics in the US

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"The optimist regards the future as uncertain."—Eugene Wigner

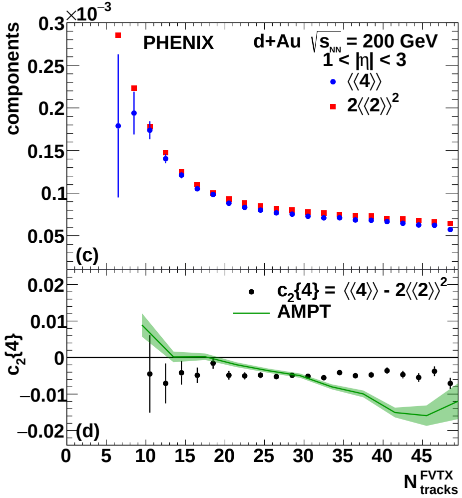
Extra material

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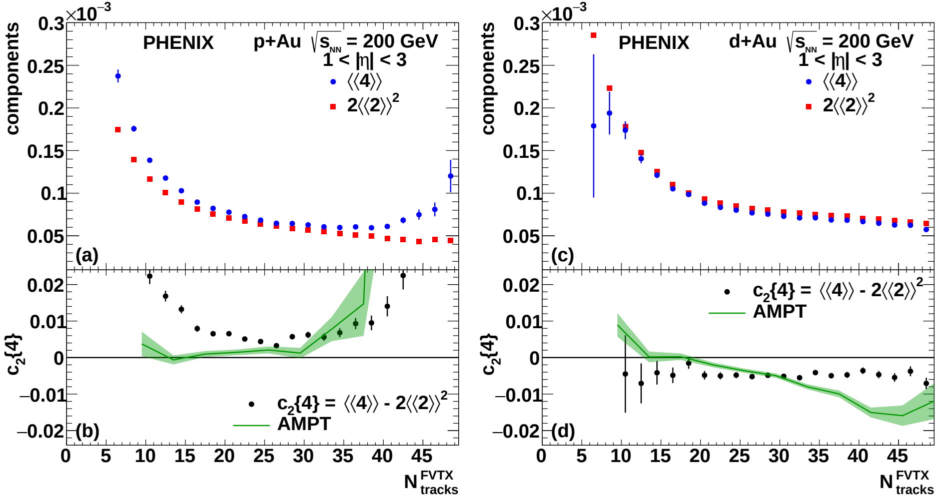
Phys. Rev. Lett. 120, 062302 (2018)



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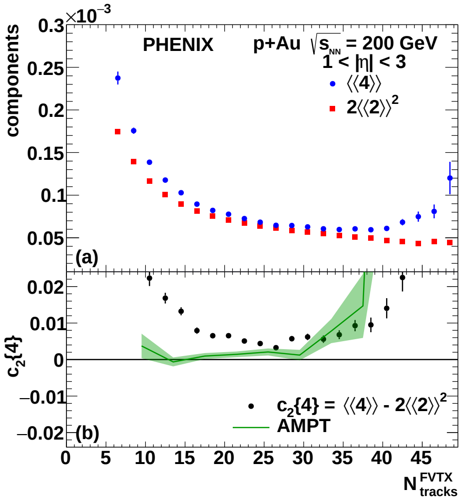
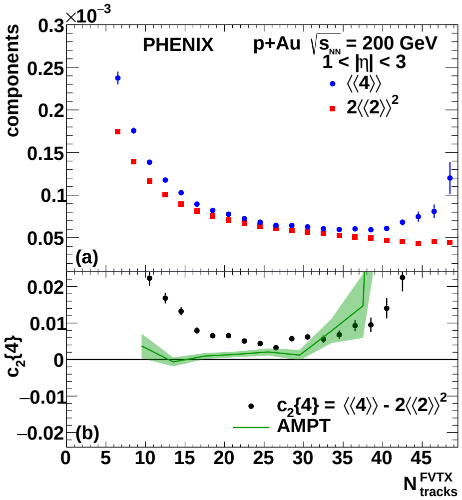


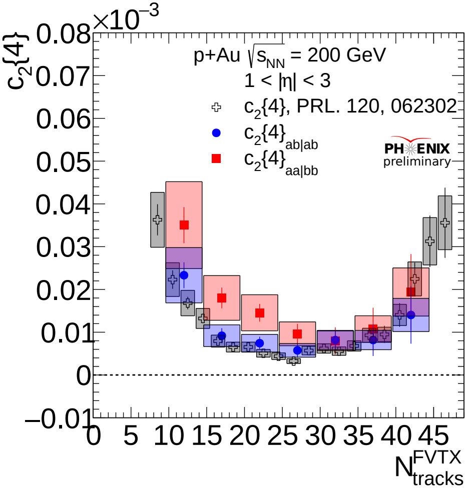
$c_2\{4\}$ is positive in p+Au

Can we blame this on nonflow?

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

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

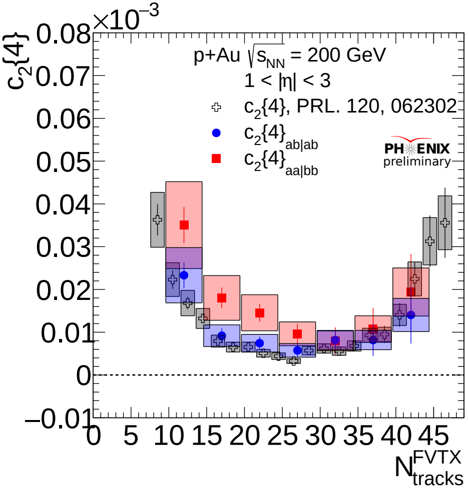




Components and cumulants in p+Au and d+Au at 200 GeV

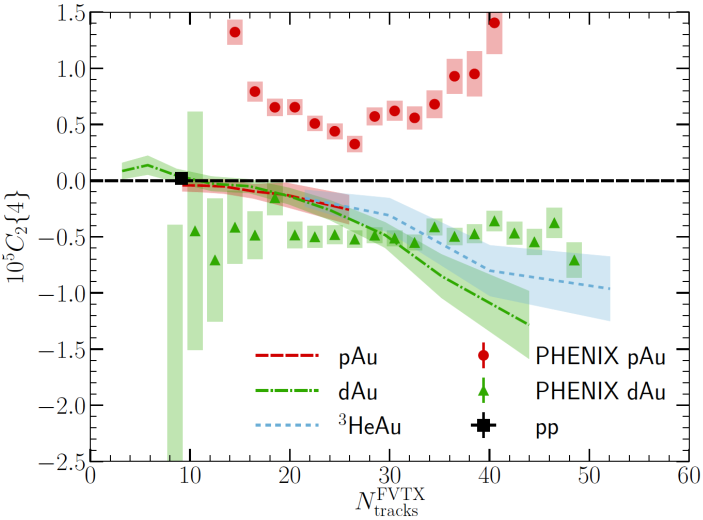
Use of subevents further suppresses nonflow

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, arXiv:1908.06212



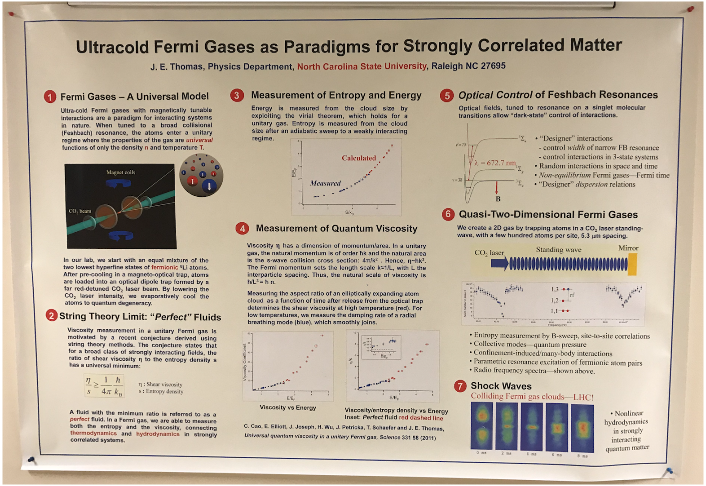
Cumulants are computationally expensive in hydro theory, so not as well-studied

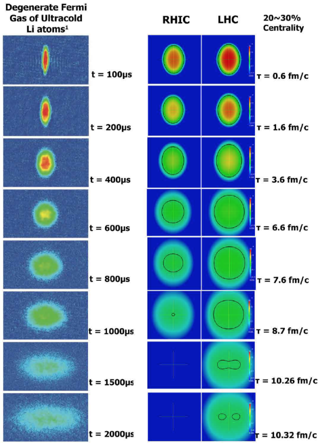
This particular calculation doesn't show the strong geometry dependence seen in the data

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

Ultracold Fermi Gas

J. Thomas et al, NCSU





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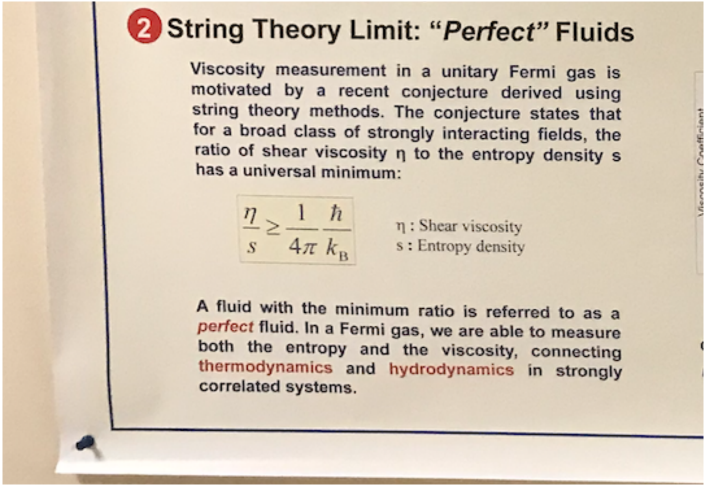
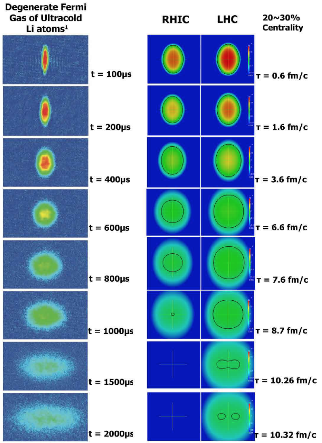
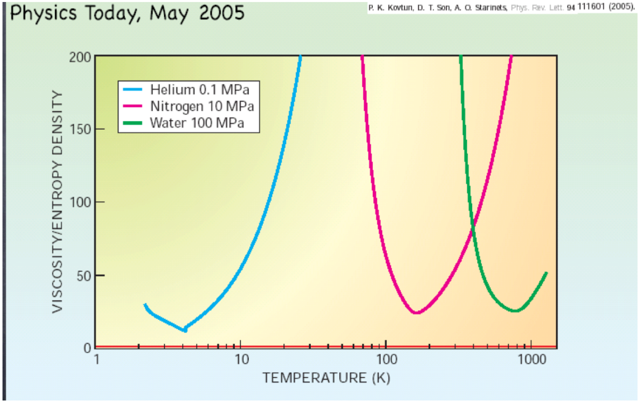




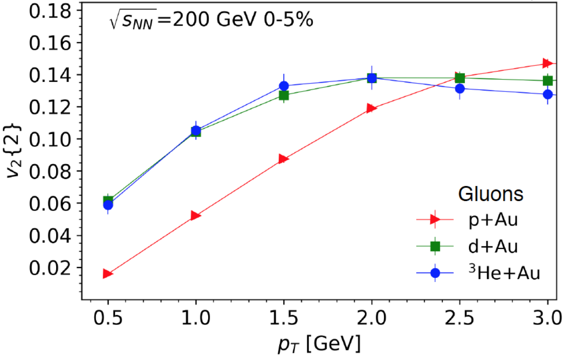
Viscosity (over entropy density)

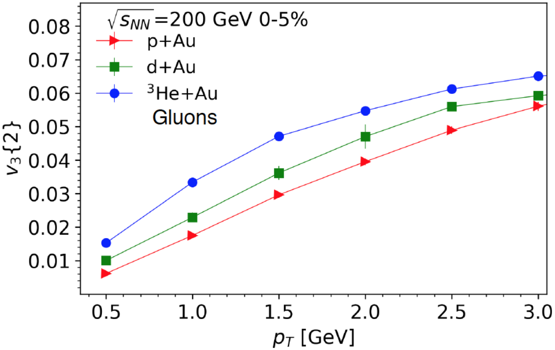


Ultracold Fermi gases: few times the lower bound
Quark-gluon plasma: very close to the lower bound

CGC results on small systems

M. Mace et al, Phys. Rev. Lett. 121, 052301 (2018)





- New for QM18: v_2 and v_3 for small systems

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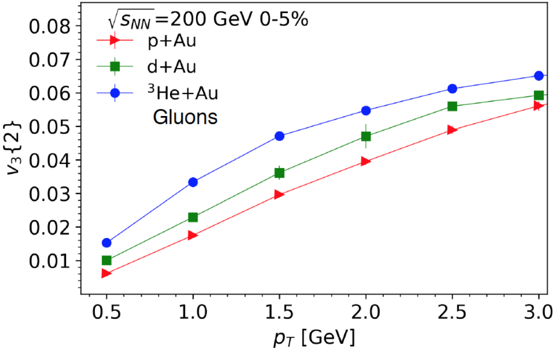
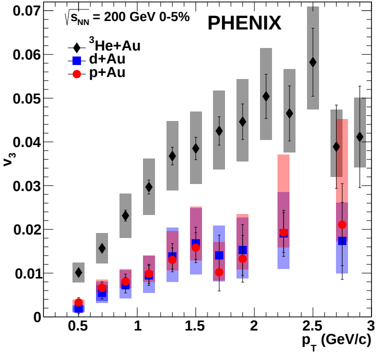
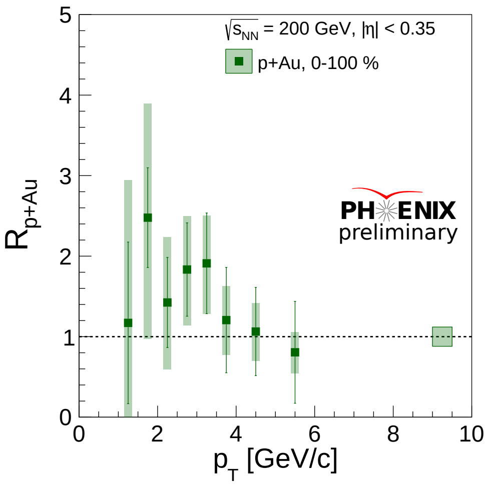




- New for QM18: v_2 and v_3 for small systems
- v_3 ordering is wrong in CGC
  —CGC: p+Au $<$ d+Au $<$ ^{3}He+Au
  —Data: p+Au $\approx$ d+Au $<$ ^{3}He+Au

Photons in small systems



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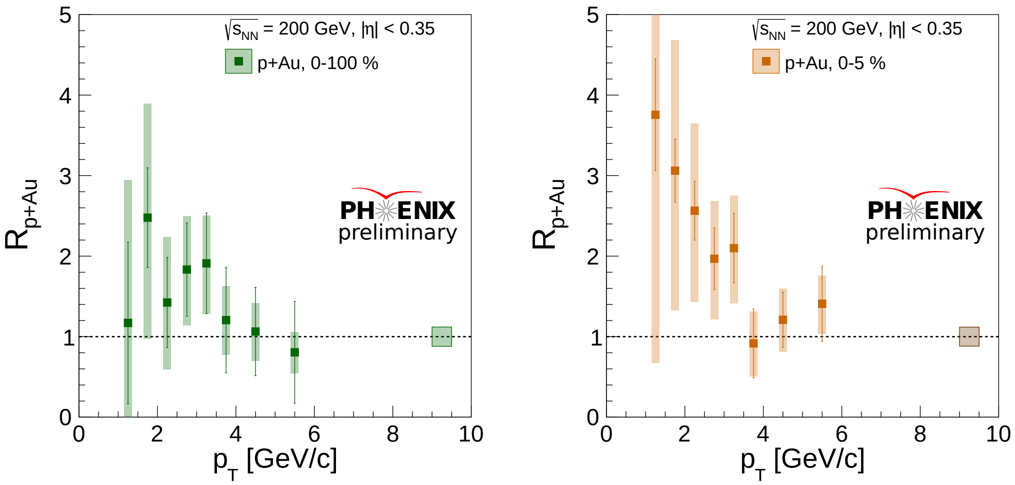
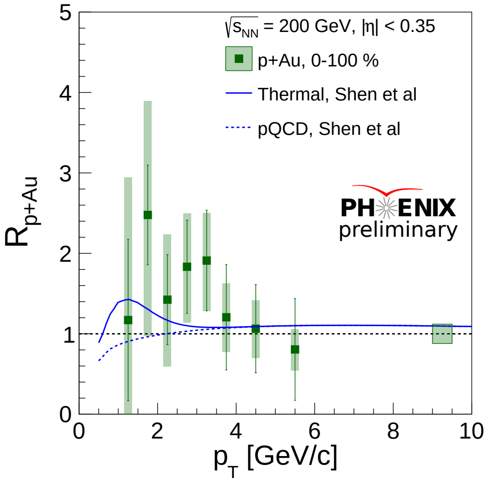
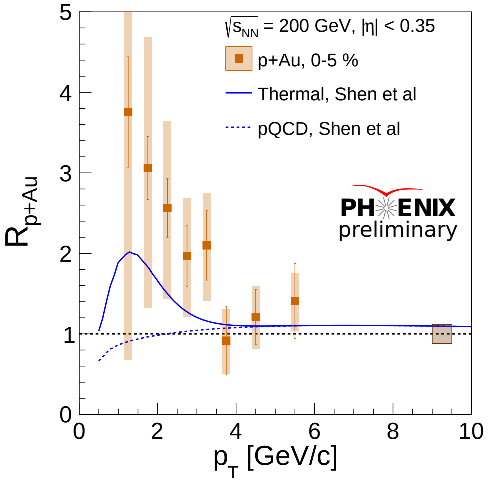


- Thermal photons in p+Au?

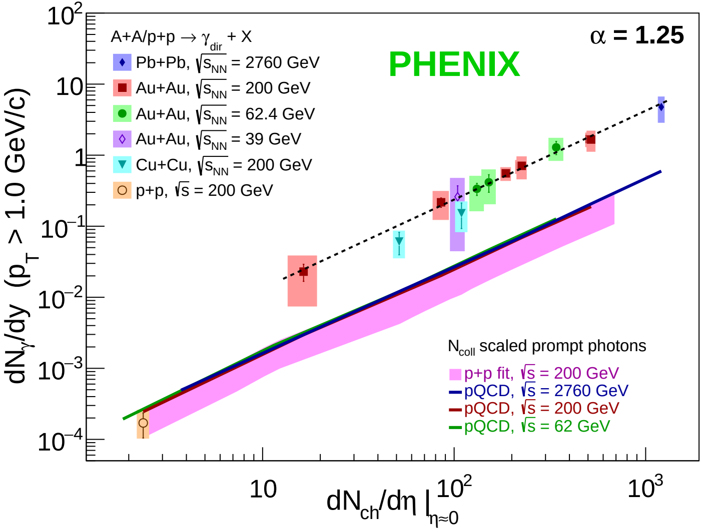
Photons in small systems





- Thermal photons in p+Au? Theory from Phys. Rev. C 95, 014906 (2017)

Photon yields



Common scaling for Au+Au and Pb+Pb at different energies; very different from N_{coll}-scaled $p+p$

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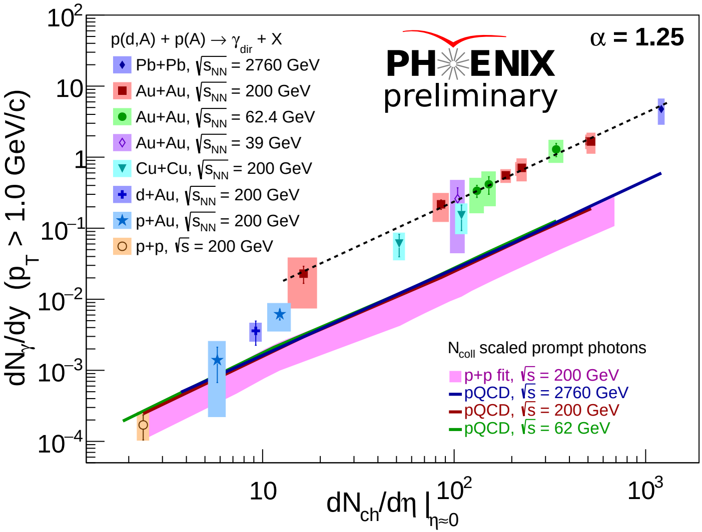
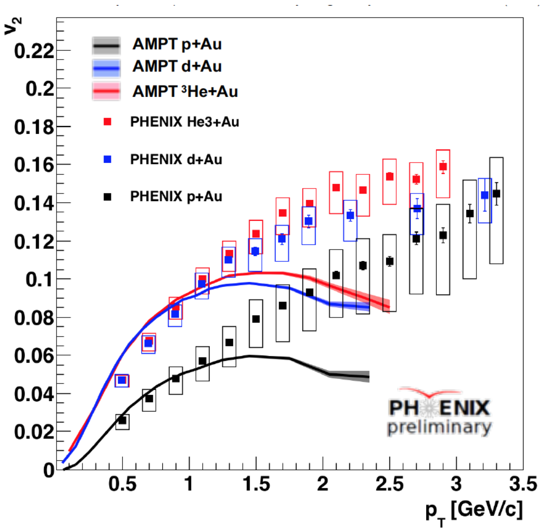


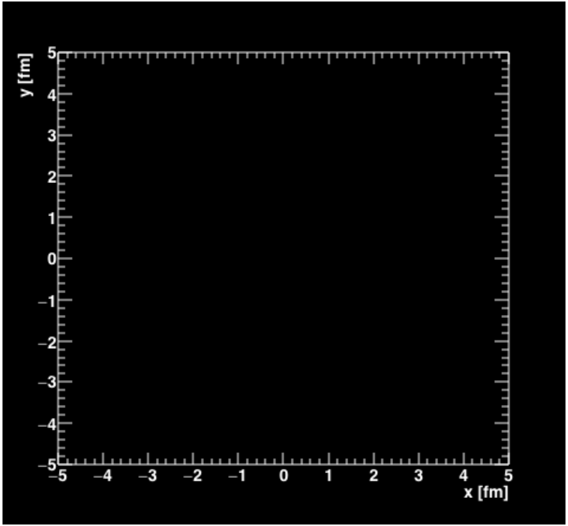
Common scaling for Au+Au and Pb+Pb at different energies; very different from N_{coll}-scaled $p+p$

p+Au and d+Au in between

AMPT



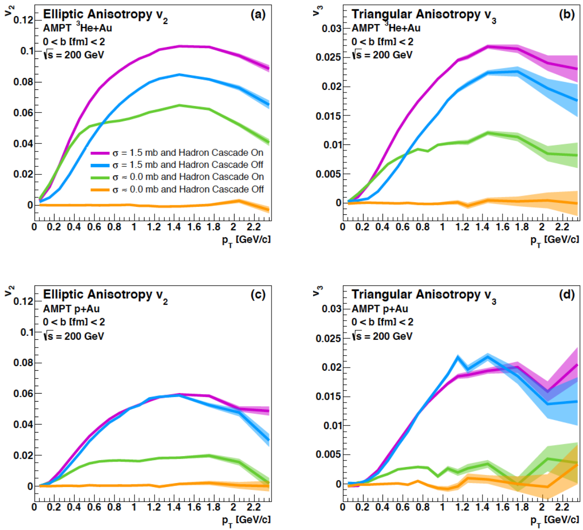
v_2
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.5
1
1.5
2
2.5
3
3.5
p_T [GeV/c]
AMPT p+Au
AMPT d+Au
AMPT ^{3}He+Au
PHENIX He3+Au
PHENIX d+Au
PHENIX p+Au
PHENIX
preliminary



y [fm]
x [fm]
5
4
3
2
1
0
−1
−2
−3
−4
−5

AMPT with no scattering

J.D. Orjuela Koop et al Phys. Rev. C 92, 054903 (2015)



- Turn off scattering in AMPT—remove all correlations with initial geometry $\sigma_{parton} = 0$ and $\sigma_{hadron} = 0$
- Participant plane v_2 goes to zero
- Other sources of correlation remain—non-flow

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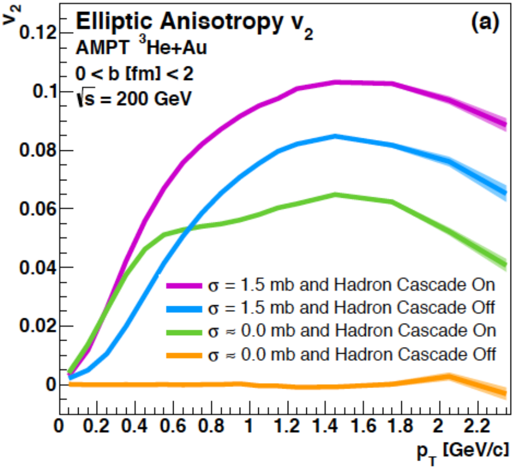

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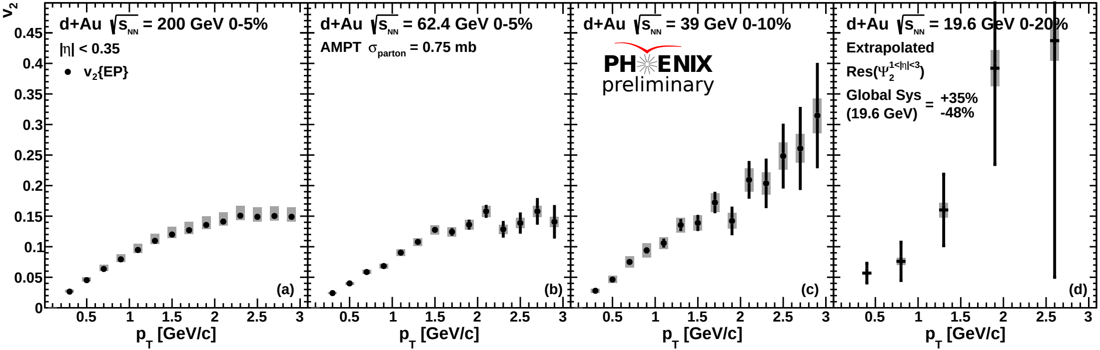
v_2 vs p_T, comparisons to AMPT

Phys. Rev. C 96, 064905 (2017)



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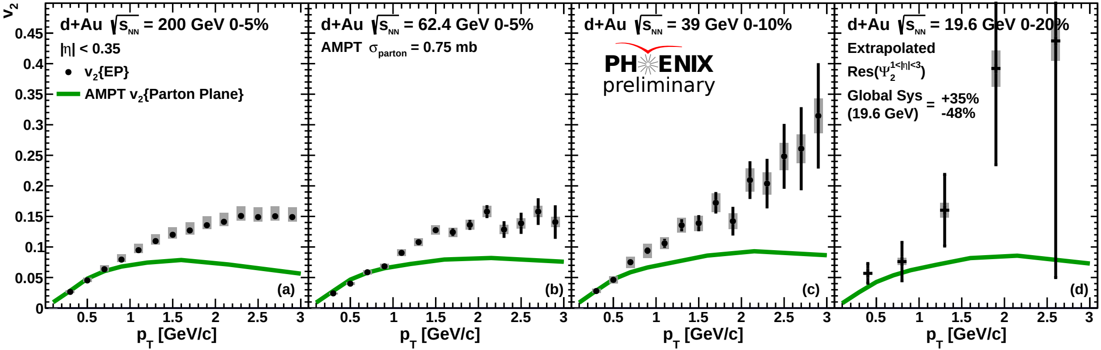
Phys. Rev. C 96, 064905 (2017)



- AMPT flow only shows good agreement at low p_T and all energies

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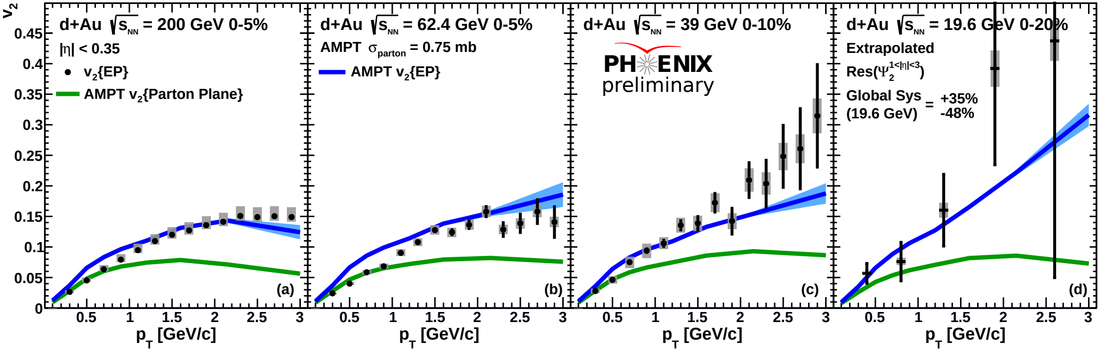
Phys. Rev. C 96, 064905 (2017)



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- AMPT flow+non-flow shows reasonable agreement for all p_T and all energies

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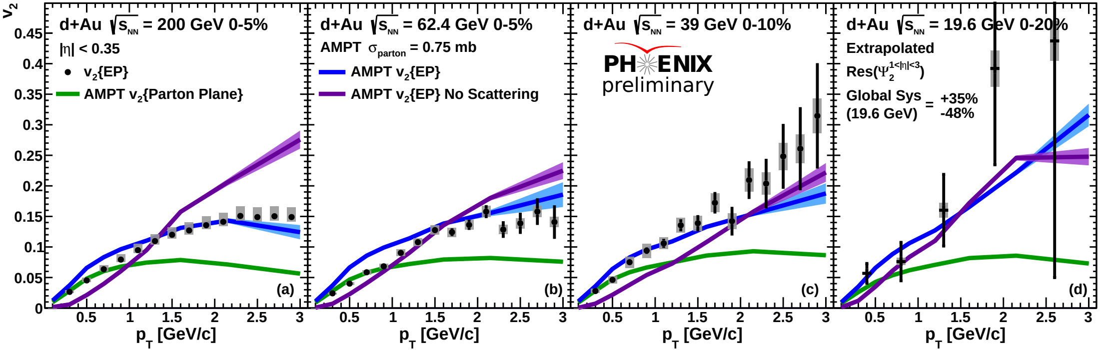
Phys. Rev. C 96, 064905 (2017)

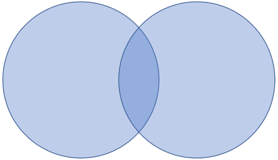


- AMPT flow only shows good agreement at low p_T and all energies
- AMPT flow+non-flow shows reasonable agreement for all p_T and all energies
- AMPT non-flow only far under-predicts for low p_T, too high for high p_T

Centrality

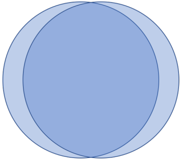
- Need to characterize the overlap of the two nuclei
- b (impact parameter)—separation between the centers of the two nuclei
- N_{part}—number of nucleons in the overlap region
- N_{coll}—number of nucleon-nucleon collisions

Peripheral



Higher b
Lower Npart
Lower Ncoll

Central



Lower b
Higher Npart
Higher Ncoll

Centrality	$\langle N_{\mathrm{part}} \rangle$	$\langle N_{\mathrm{coll}} \rangle$
Pb+Pb		
0-5%	382.7 ± 5.1	1685 ± 190
5-10%	329.7 ± 4.6	1316 ± 140
10-20%	260.5 ± 4.4	921 ± 96
20-30%	186.4 ± 3.9	556 ± 55
30-40%	128.9 ± 3.3	320 ± 32
40-50%	85.0 ± 2.6	171 ± 16
50-60%	52.8 ± 2.0	84.3 ± 7
60-70%	30.0 ± 1.3	37.9 ± 3
70-80%	15.8 ± 0.6	15.6 ± 1
p+p	$\equiv 2$	$\equiv 1$

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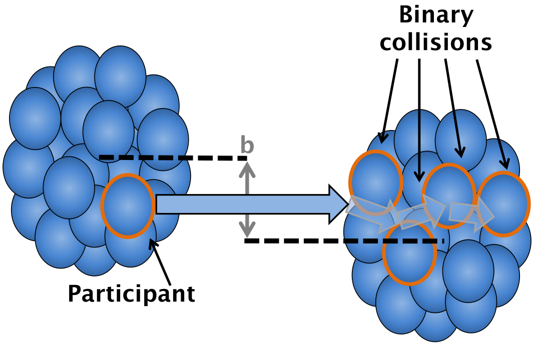

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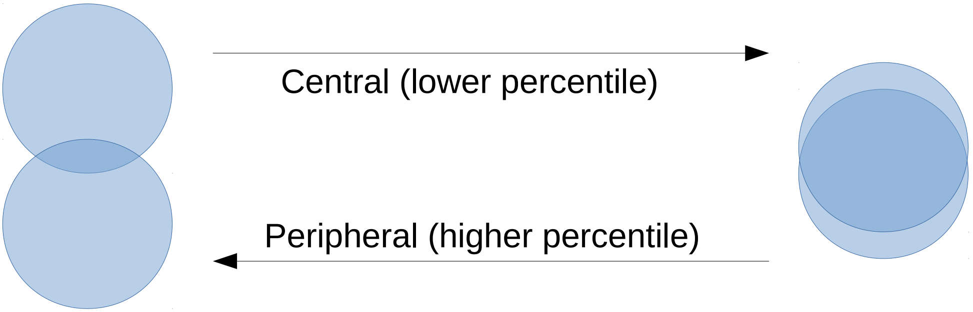

The six flavors of quarks

flavor	charge	mass
down	-1/3 e	3.0–7.0 MeV
up	2/3 e	1.5–3.0 MeV
strange	-1/3 e	95 $\pm$ 25 MeV
charm	2/3 e	1.25 $\pm$ 0.09 GeV
bottom	-1/3 e	4.70 $\pm$ 0.07 GeV
top	2/3 e	174.2 $\pm$ 3.3 GeV

- No bound states with top quarks
  (so heavy they decay weakly before a bound state can be formed)
- All others can form bound states
  —Any combination of quarks you can imagine is allowed
  —Though some have to be part of a linear combination
  —Sometimes a single combination can be more than one particle

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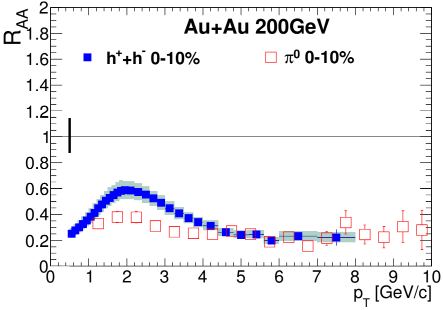
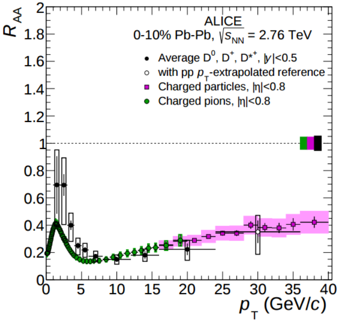
A few examples

- $p = uud$, $n = udd$
- $\pi^+ = u\bar{d}$, $\pi^- = \bar{u}d$, $\pi^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$
- $\Lambda^0 = uds$, $\Lambda_c^+ = udc$, $\Lambda_b^0 = udb$
- $K^- = \bar{u}s$, $D^+ = \bar{d}c$, $B^- = \bar{u}b$
- $c\bar{c} = \eta_c, J/\psi, \chi_c, h_c$

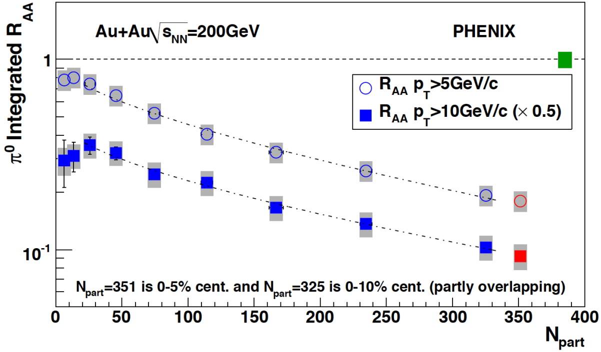
Suppression of high energy particles





- $R_{AA} = \frac{N^{A+A}_{particles}}{N^{p+p}_{particles} \times N_{coll}}$
- $R_{AA} < 1$ means particles are suppressed

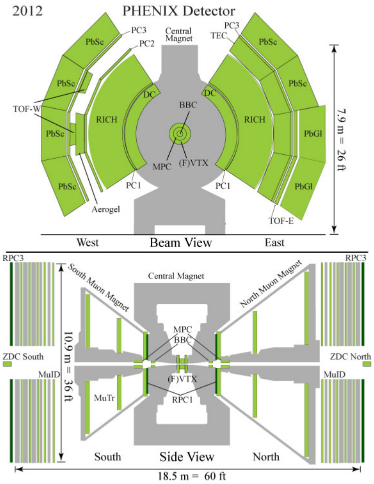
Suppression of high energy particles



- R_{AA} decreases (more suppression) with increasing N_{part} (bigger system)
- More medium → more stuff in the way → more suppresssion
- System size/geometry important aspect of suppression

PHENIX

- Weighs approximately 3000 tons
- Three separate magnet systems (Central Arms and Muon North and South) weighing 1700 tons alone
- 16 detector subsystems and about 5,000,000 (silicon) plus 300,000 (other) electronics channels
- 30 feet tall, 40 feet wide, 60 feet long
- Very fast DAQ system—7 kHz, 1 GB/s
- Ideally suited for measurements of rare probes, electrons, muons, high p_T photons, etc.



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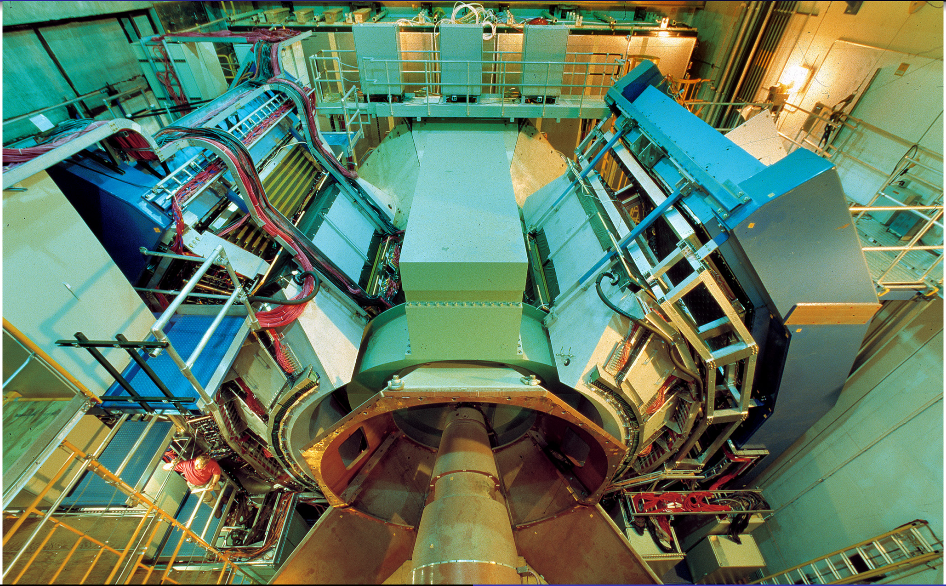
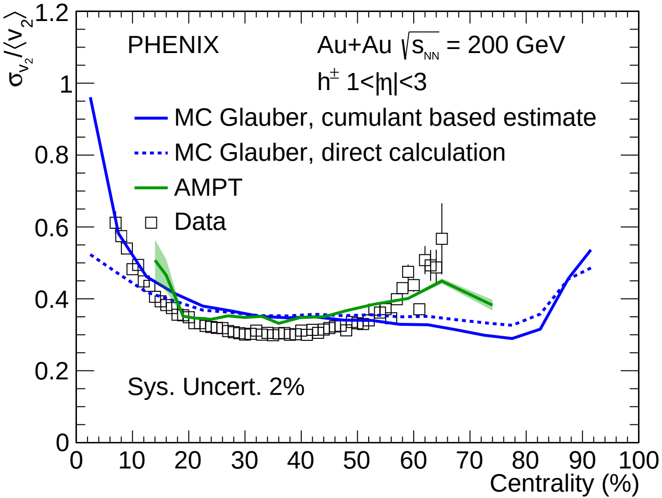


Collectivity in large systems

arXiv:1804.10024 (submitted to Phys. Rev. C)



$1 < |\eta| < 3$

$\sigma_{v_2} / \langle v_2 \rangle$

Central: breakdown of small-variance limit

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

Collectivity in large systems

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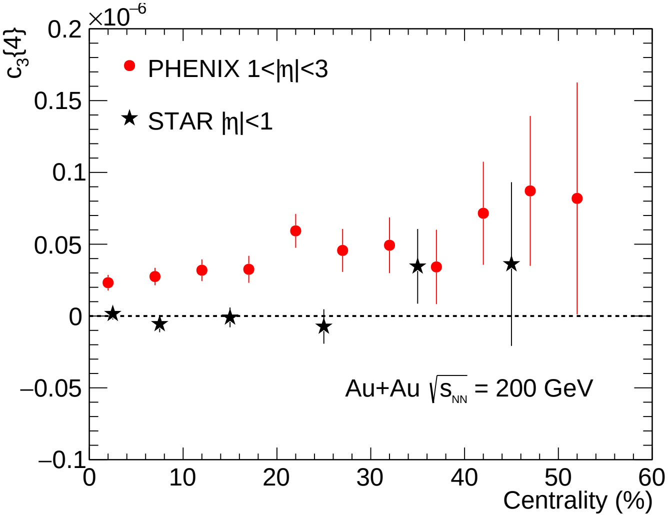

$1 < |\eta| < 3$

Cannot extract

$\sigma_{v_3} / \langle v_3 \rangle$

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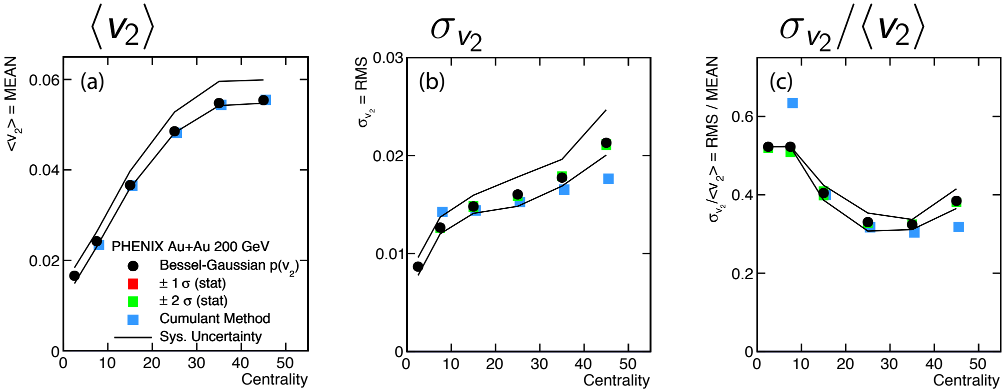

- Can extract $\langle v_2 \rangle$ and σ_{v_2} separately using forward-fold

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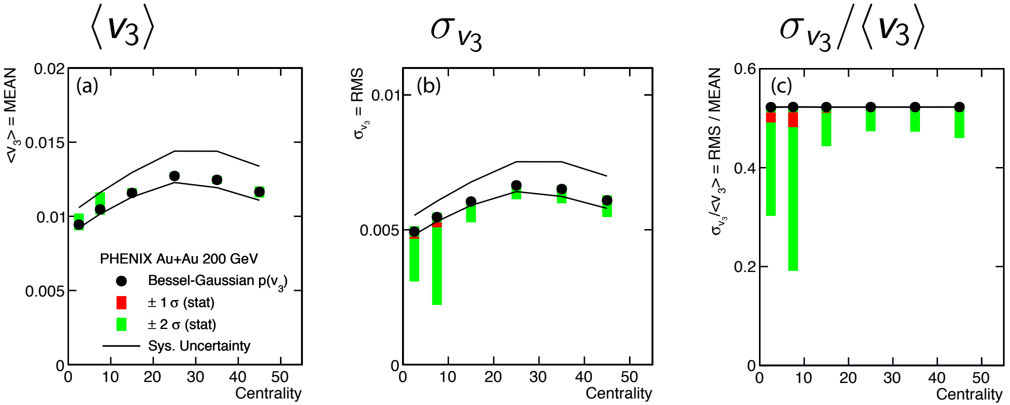

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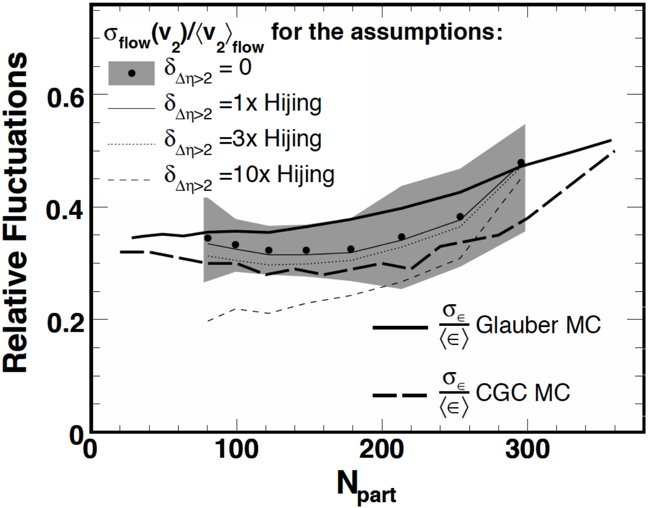
Fluctuations in large systems

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



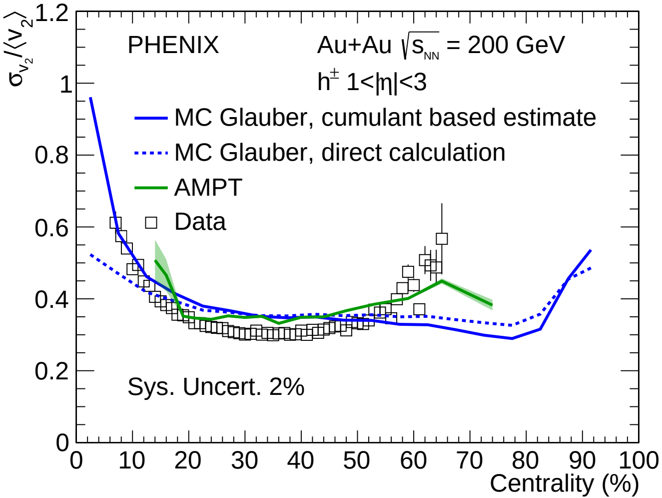
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2\rangle$

$|\eta| < 1$

Generally good agreement with models of initial geomtry

Fluctuations in large systems

PHENIX, arXiv:1804.10024 (submitted to Phys. Rev. C)



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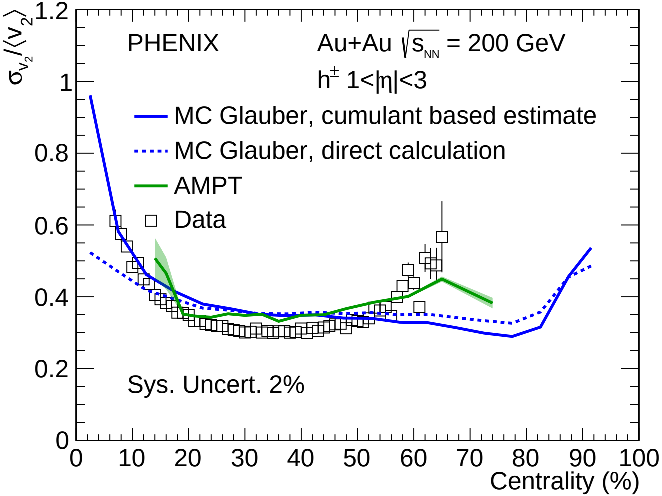

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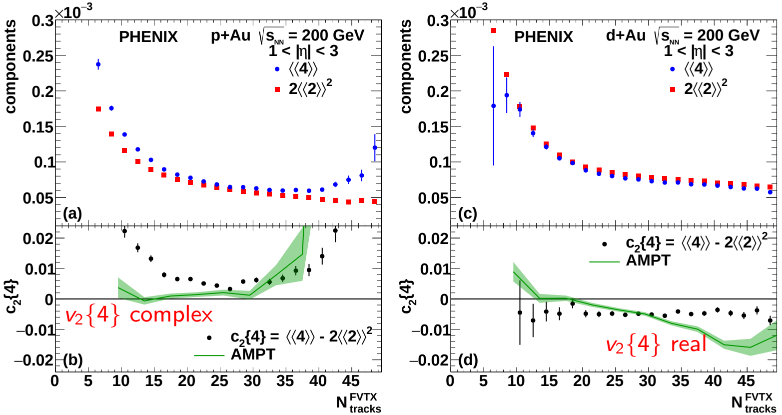
Central: breakdown of small-variance limit

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

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

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



- Is the sign of $c_2\{4\}$ a good indicator of collectivity? No.
- Fluctuations could dominate in the p+Au...

Back to basics (a brief excursion)

The (raw) moments of a probability distribution function $f(x)$:

$$\mu_n = \langle x^n \rangle \equiv \int_{-\infty}^{+\infty} x^n f(x) dx$$

The moment generating function:

$$M_x(t) \equiv \langle e^{tx} \rangle = \int_{-\infty}^{+\infty} e^{tx} f(x) dx = \int_{-\infty}^{+\infty} \sum_{n=0}^{\infty} \frac{t^n}{n!} x^n f(x) dx = \sum_{n=0}^{\infty} \mu_n \frac{t^n}{n!}$$

Moments from the generating function:

$$\mu_n = \left. \frac{d^n M_x(t)}{dt^n} \right|_{t=0}$$

Key point: the moment generating function uniquely describe $f(x)$

Back to basics (a brief excursion)

Can also uniquely describe $f(x)$ with the cumulant generating function:

$$K_x(t) \equiv \ln M_x(t) = \sum_{n=0}^{\infty} \kappa_n \frac{t^n}{n!}$$

Cumulants from the generating function:

$$\kappa_n = \left.\frac{d^n K_x(t)}{dt^n}\right|_{t=0}$$

Since $K_x(t) = \ln M_x(t)$, $M_x(t) = \exp(K_x(t))$, so

$$\mu_n = \left.\frac{d^n \exp(K_x(t))}{dt^n}\right|_{t=0}, \quad \kappa_n = \left.\frac{d^n \ln M_x(t)}{dt^n}\right|_{t=0}$$

End result: (details left as an exercise for the interested reader)

$$\mu_n = \sum_{k=1}^{n} B_{n,k}(\kappa_1, ..., \kappa_{n-k+1}) \qquad = B_n(\kappa_1, ..., \kappa_{n-k+1})$$

$$\kappa_n = \sum_{k=1}^{n} (-1)^{k-1}(k-1)! B_{n,k}(\mu_1, ..., \mu_{n-k+1}) \quad = L_n(\kappa_1, ..., \kappa_{n-k+1})$$

Back to basics (a brief excursion)

Evaluating the Bell polynomials gives

$$\begin{aligned}
\langle x \rangle &= \kappa_1 \\
\langle x^2 \rangle &= \kappa_2 + \kappa_1^2 \\
\langle x^3 \rangle &= \kappa_3 + 3\kappa_1\kappa_2 + \kappa_1^3 \\
\langle x^4 \rangle &= \kappa_4 + 4\kappa_1\kappa_3 + 3\kappa_2^2 + 6\kappa_1^2\kappa_2 + \kappa_1^4
\end{aligned}$$

One can tell by inspection (or derive explicitly) that κ_1 is the mean, κ_2 is the variance, etc.

Back to basics (a brief excursion)

Subbing in $x = v_n$, $\kappa_2 = \sigma^2$, we find

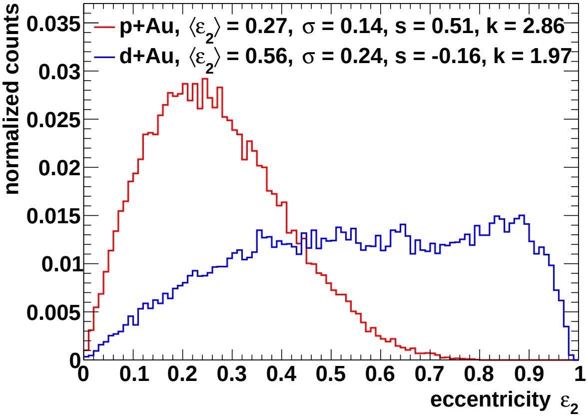
$$\left(\langle v_n^4 \rangle = v_n^4 + 6v_n^2\sigma^2 + 3\sigma^4 + 4v_n\kappa_3 + \kappa_4\right)$$
$$-\left(2\langle v_n^2 \rangle^2 = 2v_n^4 + 4v_n^2\sigma^2 + 2\sigma^4\right)$$
$$\rightarrow$$
$$\langle v_n^4 \rangle - 2\langle v_n^2 \rangle^2 = -v_n^4 + 2v_n^2\sigma^2 + \sigma^4 + 4v_n\kappa_3 + \kappa_4$$

Skewness s: $\kappa_3 = s\sigma^3$
Kurtosis k: $\kappa_4 = (k-3)\sigma^4$

$$v_n\{2\} = (v_n^2 + \sigma^2)^{1/2}$$
$$v_n\{4\} = (v_n^4 - 2v_n^2\sigma^2 - 4v_n s\sigma^3 - (k-2)\sigma^4)^{1/4}$$

So the fully general form is a bit more complicated than we tend to think...

Eccentricity distributions and cumulants

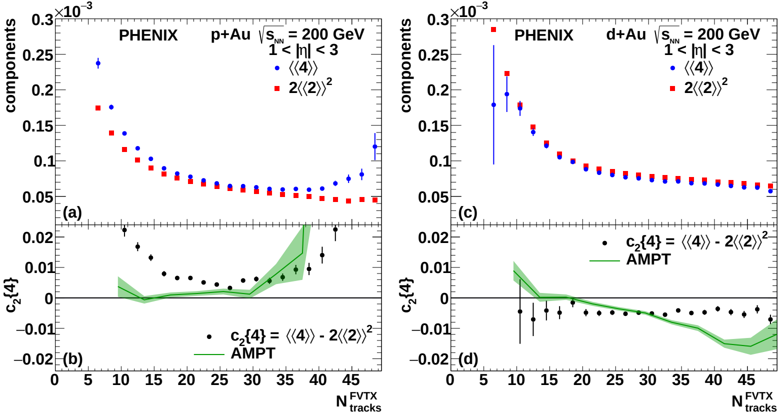


$$\varepsilon_2\{4\} = (\varepsilon_2^4 - 2\varepsilon_2^2\sigma^2 - 4\varepsilon_2 s\sigma^3 - (k-2)\sigma^4)^{1/4}$$

	p+Au	d+Au
ε_2^4	0.00531	0.0983
$2\varepsilon_2^2\sigma^2$	0.00277	0.0370
$4\varepsilon_2 s\sigma^3$	0.00147	-0.0053
$(k-2)\sigma^4$	0.00031	-0.0001

- the variance brings $\varepsilon_2\{4\}$ down (this term gives the usual $\sqrt{v_2^2 - \sigma^2}$)
- positive skew brings $\varepsilon_2\{4\}$ further down, negative skew brings it back up
- kurtosis > 2 brings $\varepsilon_2\{4\}$ further down, kurtosis < 2 brings it back up
  —recall Gaussian has kurtosis $= 3$

Eccentricity distributions and cumulants



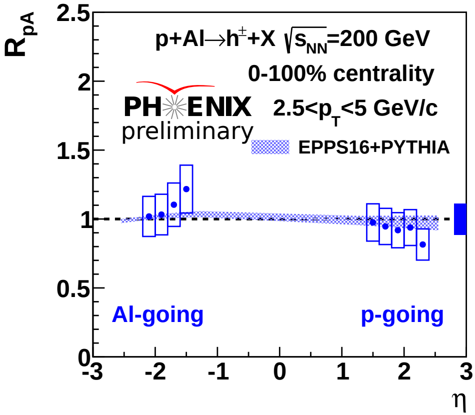
$$v_2\{4\} = \left(v_2^4 - 2v_2^2\sigma^2 - 4v_2 s\sigma^3 - (k-2)\sigma^4\right)^{1/4}$$

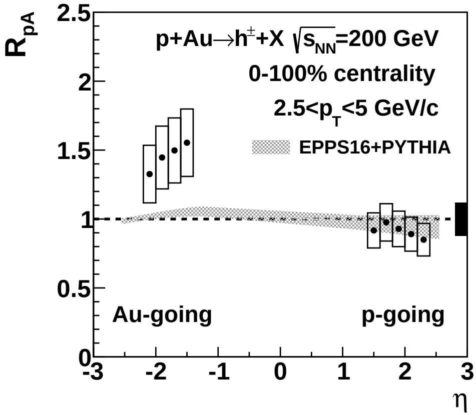
- Eccentricity fluctuations alone go a long way towards explaining this
- Additional fluctuations in the (imperfect) translation of ε_2 to v_2?

Intermission

Particle production in small systems

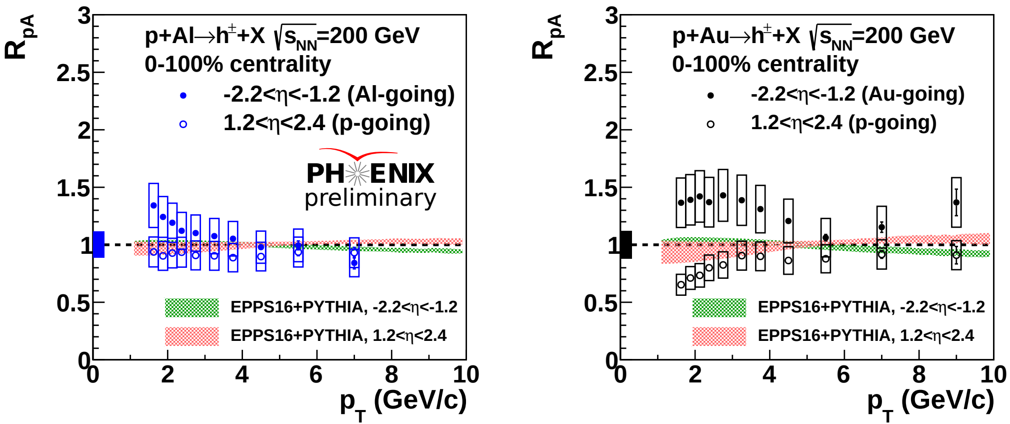
Small systems nuclear modification





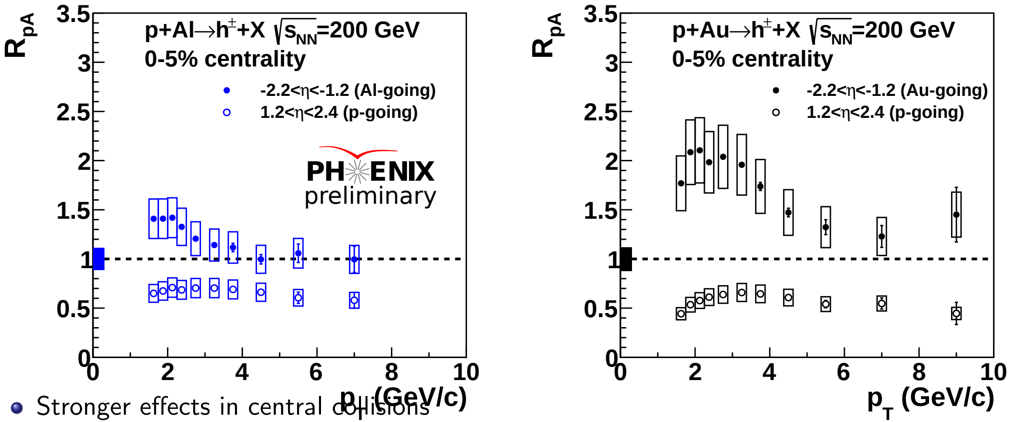
- Forward modification consistent with nPDF effects (EPPS16)

Small systems nuclear modification



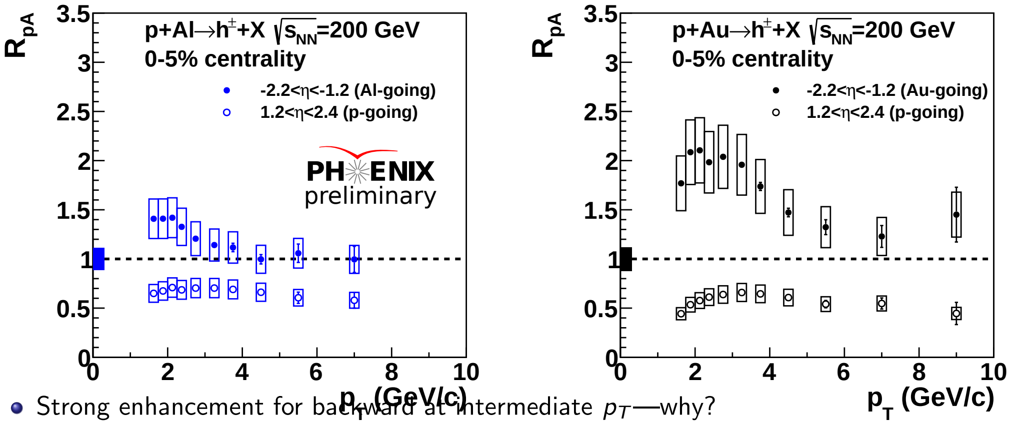
- High-p_T modification consistent with nPDF effects (EPPS16)

Small systems nuclear modification



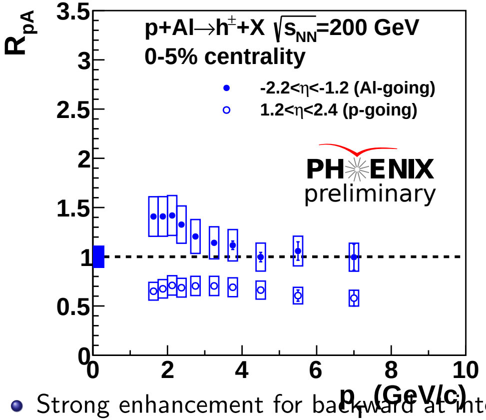
- Stronger effects in central collisions

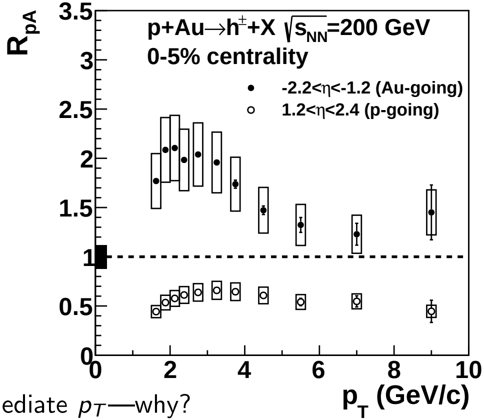
Small systems nuclear modification



- Strong enhancement for backward at intermediate p_T—why?

Small systems nuclear modification





- Strong enhancement for backward at intermediate p_T—why?
- Don't forget: particle species dependence of Cronin! There must be final state effect(s)...

Particle species dependence of “Cronin enhancement”

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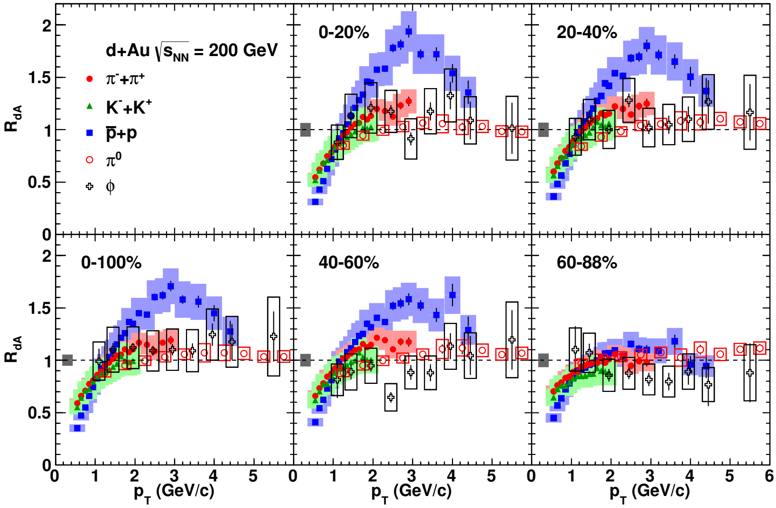

π^+, π^-, π^0,

K^+, K^-,

p, $\bar{p}$,

ϕ

Protons much more strongly modified than pions

ϕ mesons confusing as always...