Small systems in heavy-ion collisions: creating droplets of the early universe?

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Physics Department Colloquium
North Carolina State University
Raleigh, NC
26 November 2018

Утро в сосновом лесу

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Outline

- Part 0: introduction
  —History lesson, units, physical constants, some basics
- Part I: the large
  —Overview of conventional heavy ion physics with large nuclei
- Part II: the small
  —Some recent results from heavy ion physics with small nuclei
- Part III: the future
  —A brief look at the next US-based experiment in heavy ions

Key points for Part 0

- A bit of a history lesson
- Natural units
- A basic sense of scale
- Fundamentals of quantum chromodynamics (QCD)
  —quarks
  —gluons
  —hadrons and confinement

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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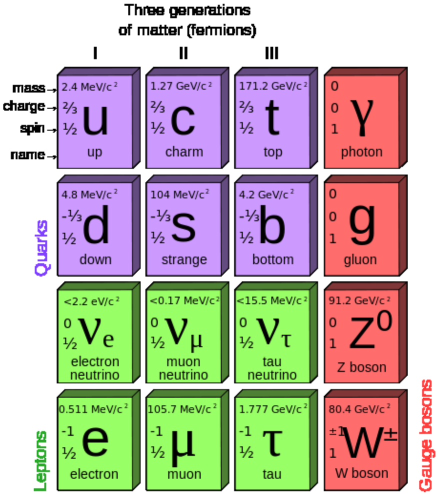
- 1963 Gell-Mann's Quark Model (particle zoo)
- 1965 Additional degree of freedom postulated for quarks by Han and Nambu
- 1969 Deep inelastic scattering experiments prove the existence of quarks
- 1972 Color charge and basic framework of **quantum chromodynamics**
- 1973 Asymptotic Freedom discovered 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

What we've learned so far



- **Electromagnetic force:** interactions among charged particles
- **Weak force:** flavor changes, e.g. lepton decays and nuclear beta decays
- **Strong force:** binds protons and neutrons together into nuclei (residual) and quarks together into hadrons (fundamental)
- **Gravitational force:** not part of the standard model

What we've learned so far

Which view of the world is the right one? It depends!

	slow	**fast**
large	**Classical Physics** (most of our daily life is here)	**Special Relativity** (effects noticeable in GPS and air travel)
small	**Quantum Mechanics** (solid state devices are based on small stuff)	**Quantum Field Theory** (only self-consistent way to combine QM and SR)

Note: GR effects **also** noticeable for GPS and air travel

Physical constants and units

- High energy physics makes physical constants very easy to remember!
- Planck's constant $\hbar = 1$
  —Shows up often quantum mechanics
- Speed of light $c = 1$
  —Shows up often in special relativity
- Boltzmann's constant $k_B = 1$
  —Shows up often in thermal physics and stat mech

Typical sizes and scales for heavy ion physics

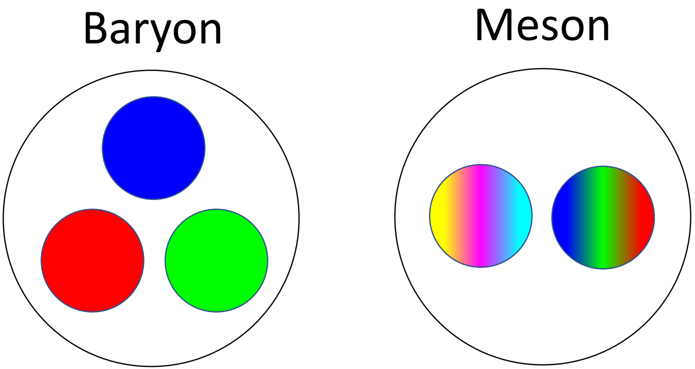
- Mass of proton $= 938.3$ MeV $= 1.007$ amu $= 1.673 \times 10^{-27}$ kg
- Typical energy $= 1$ GeV $= 1.602 \times 10^{-10}$ J
- Typical size $= 1$ fm $= 10^{-15}$ m
- Typical time $= 1$ fm $= 3.336 \times 10^{-24}$ s
- Typical temperature $= 200$ MeV $= 2.321 \times 10^{12}$ K

QCD as explained by approximate analogy to QED

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

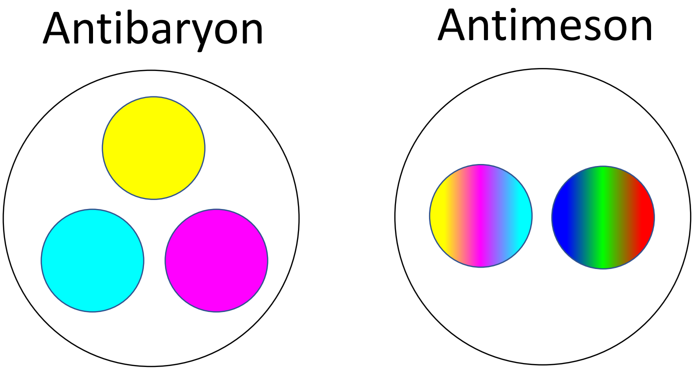
- One kind of electric charge, three kinds of color charge
- Photons do not have electric charge, gluons do have color charge
- Only one photon, eight different gluons

QCD bound states



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

QCD bound states



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QCD Potential and confinement

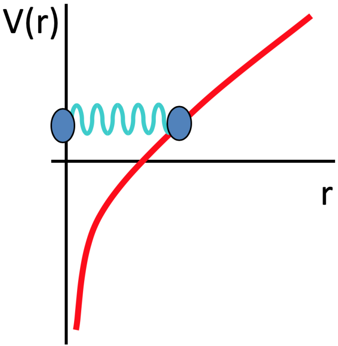
- The QED potential

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

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

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

- Coulomb part and confining part
- New pairs of quarks are created when energy exceeds mass



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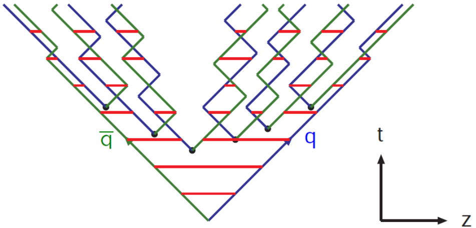
Motion of quarks and antiquarks in a q$\bar{\text{q}}$ system:



gives simple but powerful picture of hadron production

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

Summary for Part 0

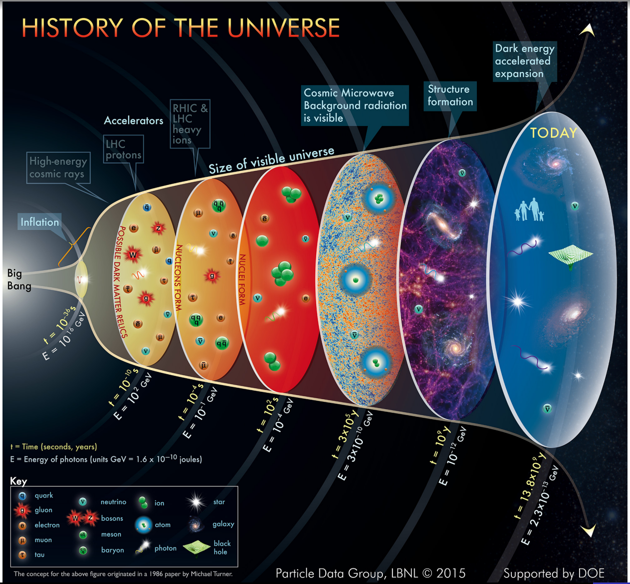
- QCD is the theory of strong interactions
- Quarks and gluons (partons) are the fundamental particles
- There are three colors (and eight kinds of gluon)
- QCD exhibits confinement, meaning can only be found in bound states (hadrons)

Key points for Part I

The quark gluon plasma:

- Is a phase of matter with deconfined quarks and gluons
- Existed in the very early universe
- Is created in the lab in collisions of large nuclei
  —Examples include $^{197}_{79}\mathrm{Au}+^{197}_{79}\mathrm{Au}$ and $^{208}_{82}\mathrm{Pb}+^{208}_{82}\mathrm{Pb}$
- Is hot and dense
- Behaves like a liquid
  —The initial-state geometry is translated into the final state

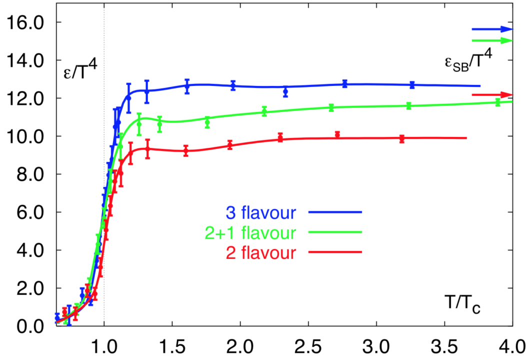
The history of the universe



- 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

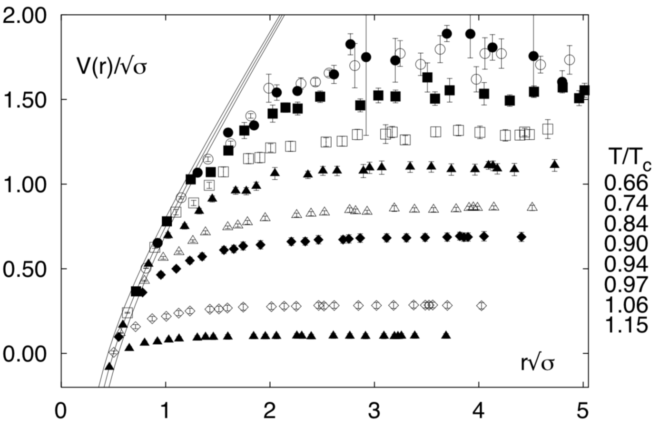
- Lattice QCD predicts a phase transition from nuclear matter to QGP
- Large increase energy density at $T_C \approx 155$ MeV due to large increase in number of degrees of freedom



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

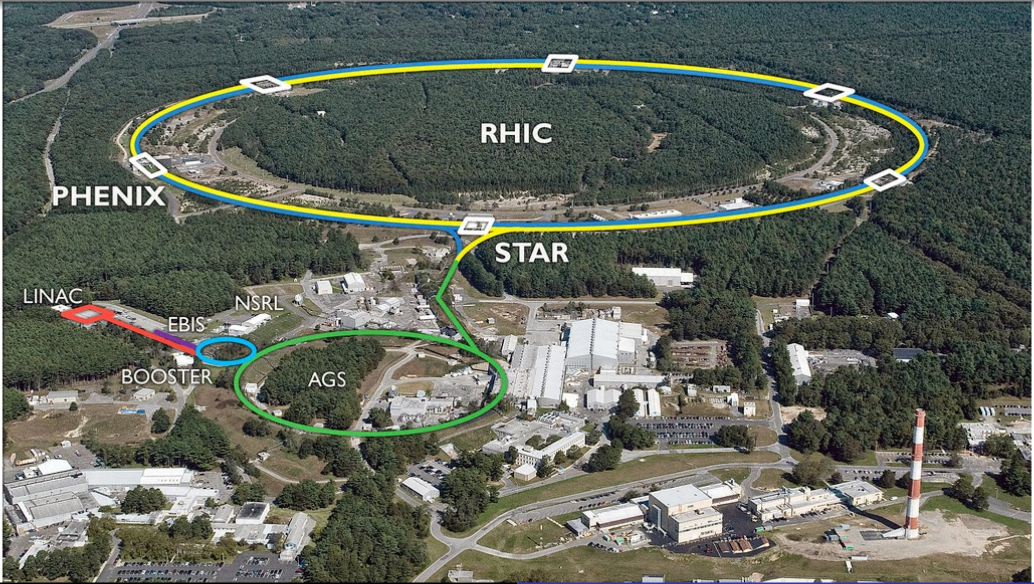
- Below T_C: g = 3
  3 pions with spin 0
- Above T_C: g = 37
  8 gluons with spin 1,
  2 (anti)quarks with spin 1/2

Phases of QCD matter



- 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



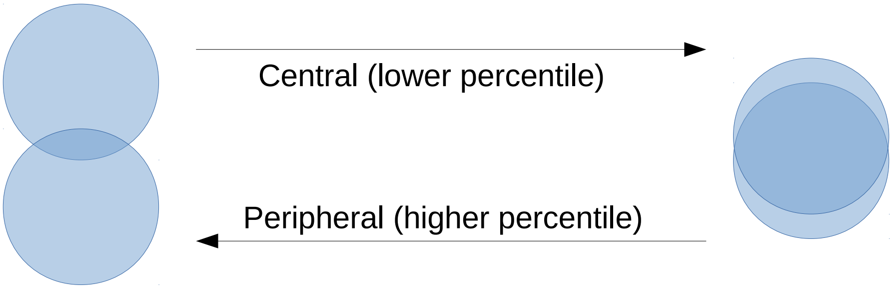
The Relativistic Heavy Ion Collider

- RHIC is the only polarized proton collider in the world
- RHIC is one of two heavy ion colliders, the other being the LHC
- RHIC is a dedicated ion collider and is designed to collide many different species of ions at many different energies—vastly more flexible than the LHC

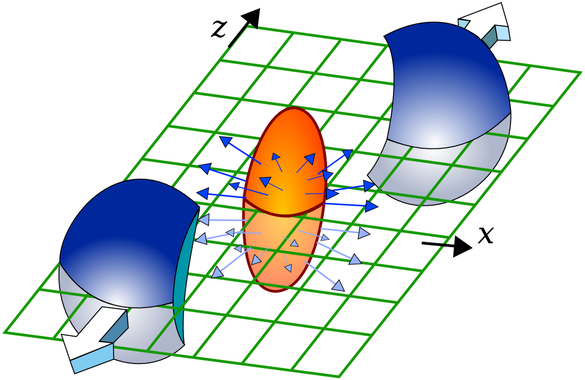
Collision Species	Collision Energies (GeV)
p↑+p↑	510, 500, 200, 62.4
p+Al	200
p+Au	200
d+Au	200, 62.4, 39, 19.6
^{3}He+Au	200
Cu+Cu	200, 62.4, 22.5
Cu+Au	200
Au+Au	200, 130, 62.4, 56, 39, 27, 19.6, 15, 11.5, 7.7, 5, ...
U+U	193

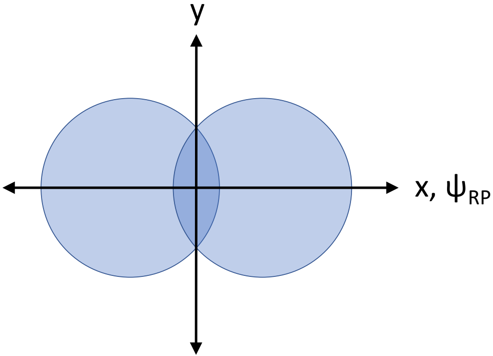
And lots more to come!

Centrality



Azimuthal anisotropy measurements

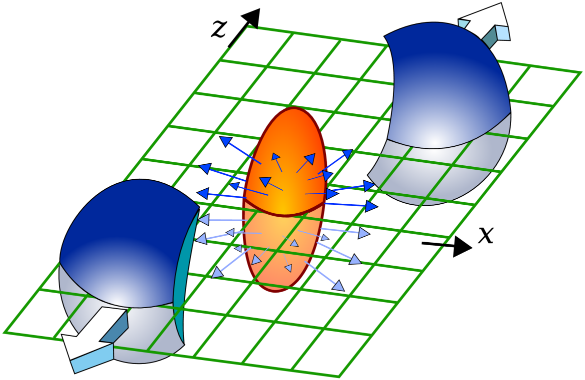


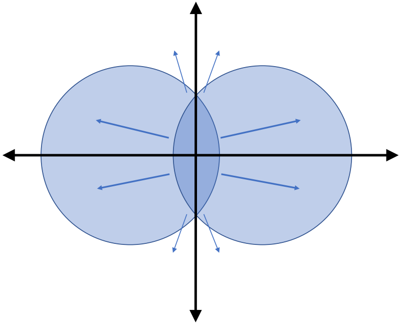


$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^2 \cos n\varphi \rangle + \langle r^2 \sin n\varphi \rangle}}{\langle r^2 \rangle}$$

- Hydrodynamics translates initial shape (ε_n) into final state distribution (v_n)
- Overlap shape approximately elliptical, expect v_2 to be the largest

Azimuthal anisotropy measurements





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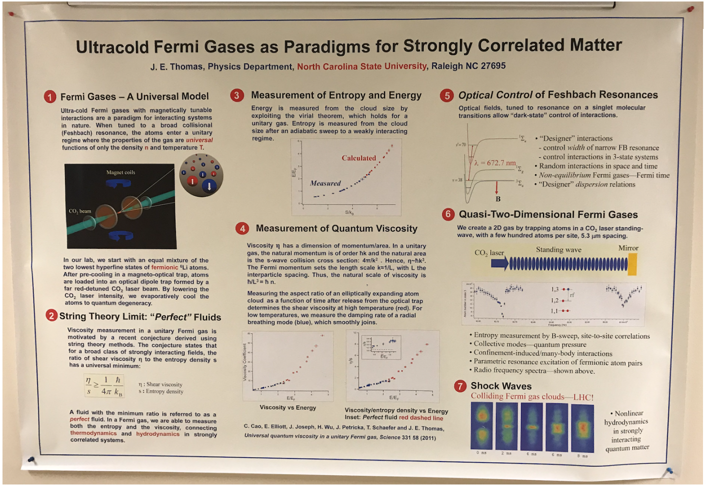
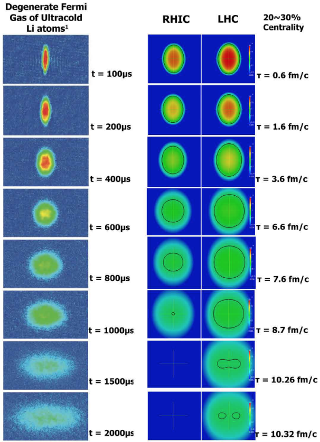
Ultracold Fermi Gas

J. Thomas et al, second floor





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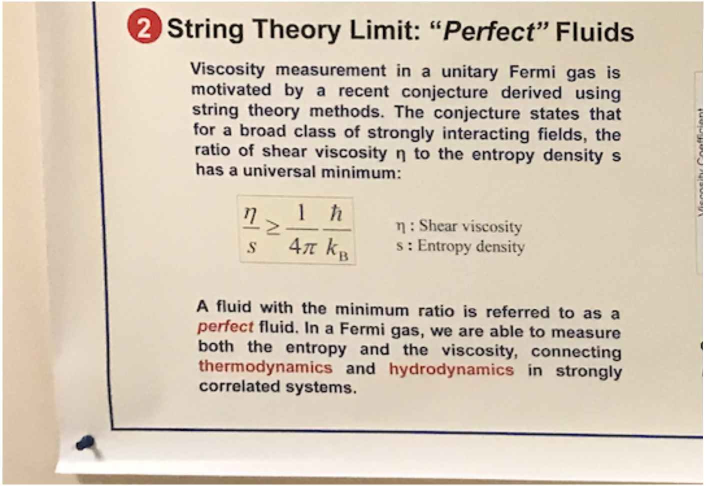


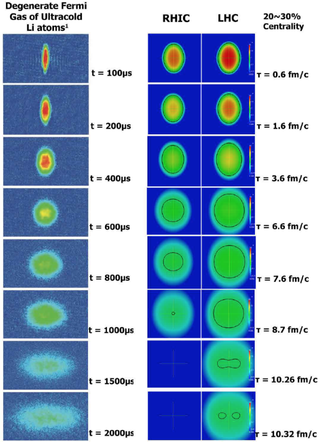
2 String Theory Limit: "*Perfect*" Fluids

Viscosity measurement in a unitary Fermi gas is motivated by a recent conjecture derived using string theory methods. The conjecture states that for a broad class of strongly interacting fields, the ratio of shear viscosity η to the entropy density s has a universal minimum:

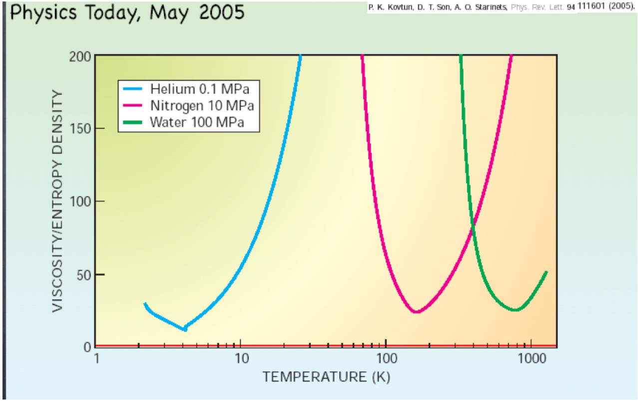
$$\frac{\eta}{s} \geq \frac{1}{4\pi}\frac{\hbar}{k_B}$$

η : Shear viscosity
s : Entropy density

A fluid with the minimum ratio is referred to as a *perfect* fluid. In a Fermi gas, we are able to measure both the entropy and the viscosity, connecting thermodynamics and hydrodynamics in strongly correlated systems.



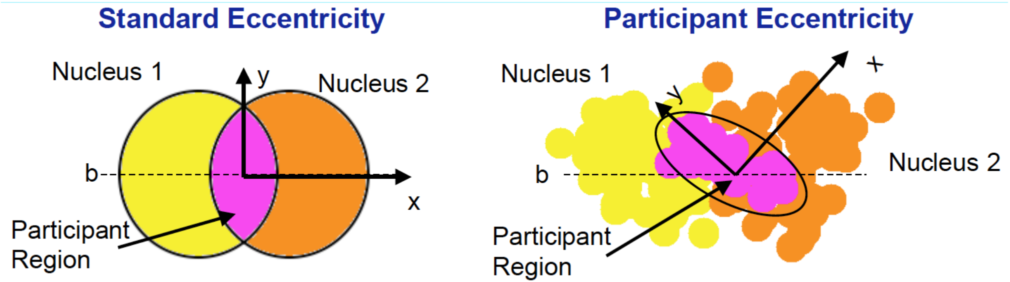
Viscosity (over entropy density)



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

Important discovery in 2005

G. Roland, PHOBOS Plenary, Quark Matter 2005



A nucleus isn't just a sphere

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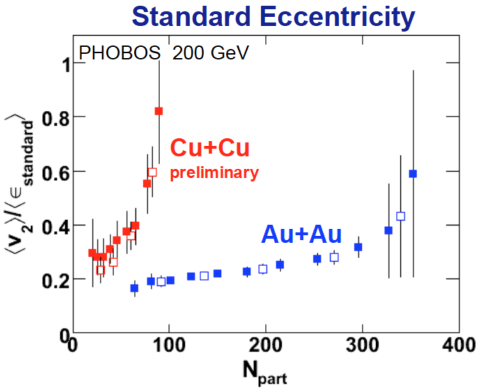

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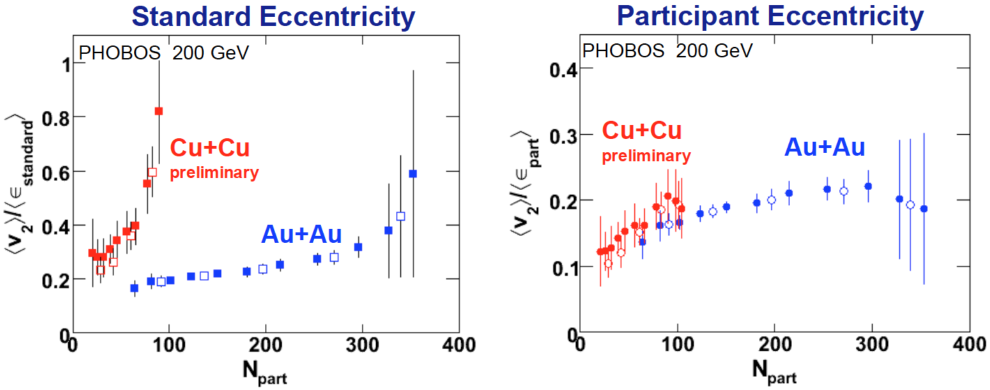
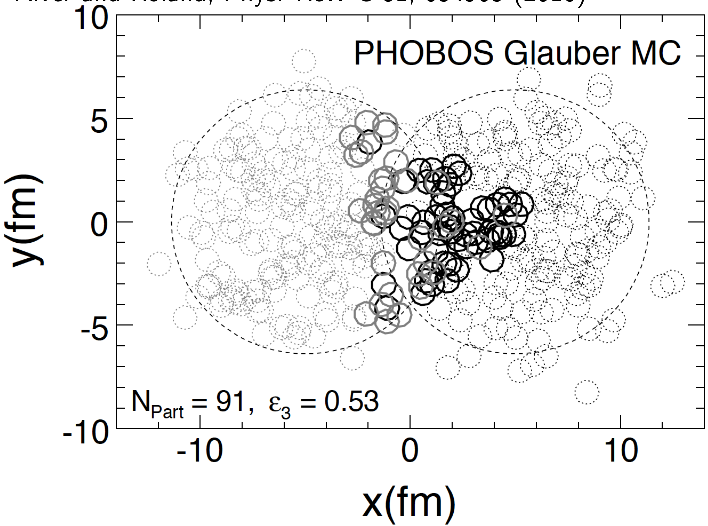


A nucleus isn't just a sphere

Important discovery in 2010

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



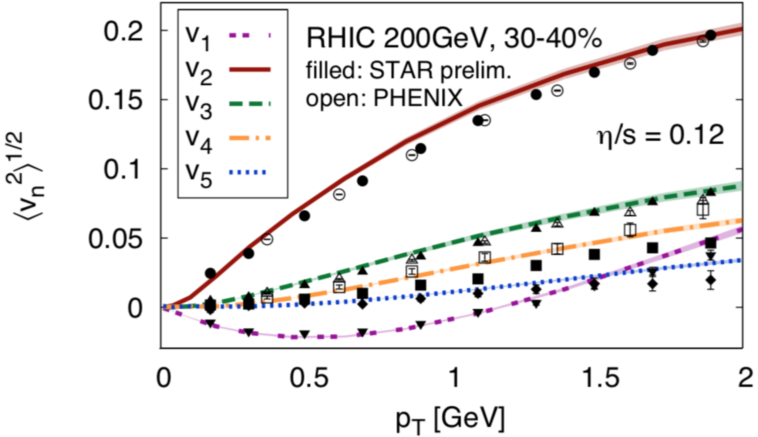
Nucleon fluctuations can produce non-zero ε_n for odd n

Symmetry planes ψ_n can be different for different harmonics

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

Data and theory for v_n

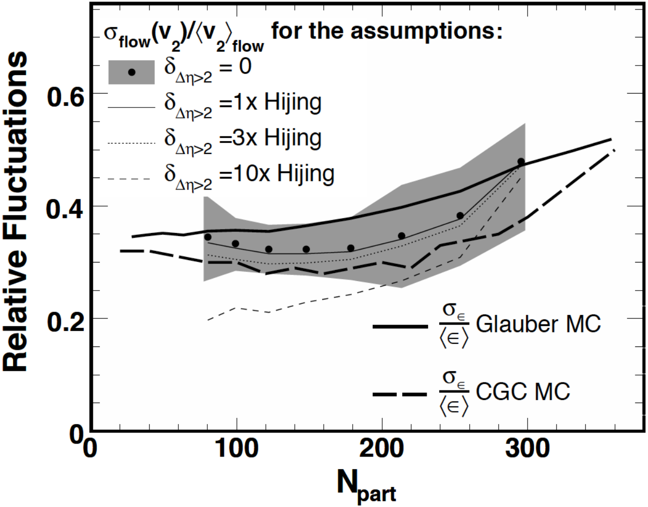
Gale et al, Phys. Rev. Lett. 110, 012302 (2013)



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

Fluctuations in large systems

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



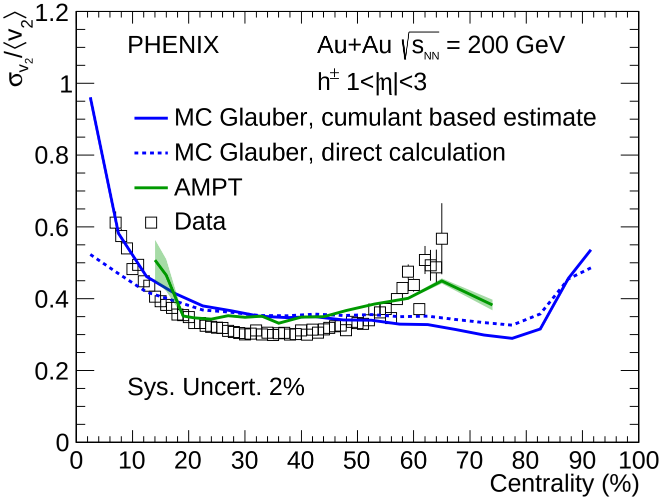
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2 \rangle$

$|\eta| < 1$

Generally good agreement with models of initial geomtry

Fluctuations in large systems

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



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

Summary for Part I

The quark-gluon plasma:

- Is a phase of matter with deconfined quarks and gluons
- Existed in the very early universe
- Is created in the lab in collisions of large nuclei
- Evolves hydrodynamically
  —The initial-state geometry is translated into the final state

Key points for Part II

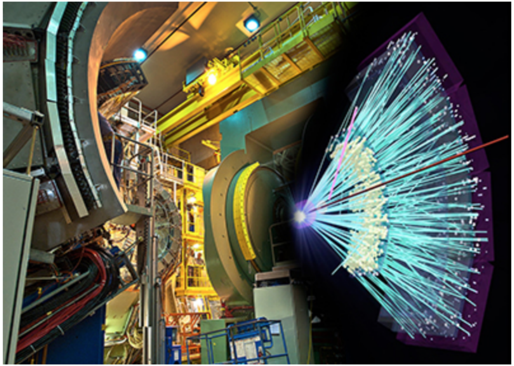
- A major component of heavy ion physics nowadays is “small systems”
  —Nuclear collisions of small+large or even small+small
  —Examples include d+Au, p+Pb, and even p+p
- The matter created in small systems looks a lot like the matter in large systems
- Roughly speaking, two competing pictures
  —QGP droplets being created in small systems
  —Initial state effects from color-glass condensate (CGC)

Media Attention

Physics World, September 22, 2017
Phys.org, September 18, 2017

Collider serves up drop of primordial soup

Sep 22, 2017



Tiny drop: PHENIX and reconstructed particle tracks from a QGP

PHENIX colleague Ron Belmont of the University of Colorado says it is still possible that the elliptical emission they have observed is due not to the formation of tiny QGPs but instead down to nuclear properties prior to collision. When accelerated close to light speed, time slows down for the heavy nuclei, which means, according to quantum chromodynamics, that they appear as a dense wall of gluons. The fact that these condensates are thicker in the centre of the nuclei might explain why particles generated in the collisions are not emitted in random directions, he says.

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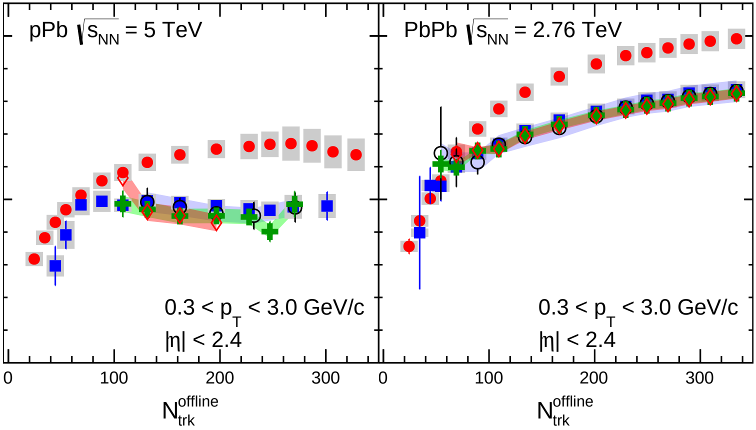
"Twenty years ago, the challenge in heavy ion physics was to find the QGP. Now, the challenge is to not find it." —Jürgen Schukraft, QM17

Multiparticle correlations in large and small systems

CMS, Phys. Lett. B 765 (2017) 193-220

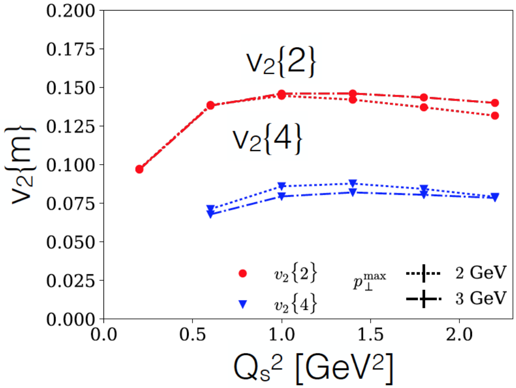


$$v_n^2\{2\} = \langle v_n \rangle^2 + \sigma^2$$
$$v_n^2\{4,6,8\} \approx \langle v_n \rangle^2 - \sigma^2$$

- Multiparticle correlations reflect global correlation from geometry in Pb+Pb, Au+Au, Cu+Cu, etc
- The p+Pb has a remarkably similar pattern as the Pb+Pb

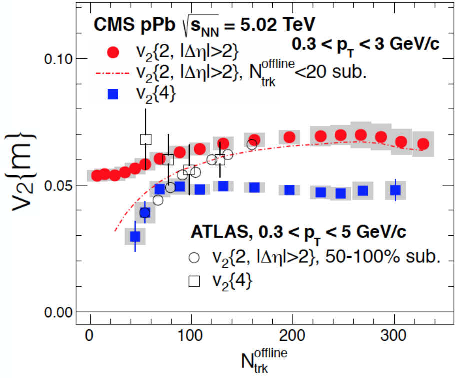
CGC results on small systems

Mark Mace, QM18



Dusling, MM, Venugopalan PRL 120 (2018)

Phys. Rev. Lett. 120, 042002 (2018)



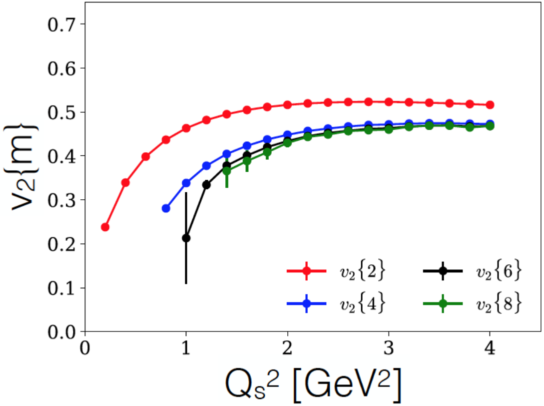
CMS PLB 724 (2013) 213

- Can reproduce $v_2\{2\}$ and $v_2\{4\}$
- Disagreement with data by a factor of 2, but qualitative features match

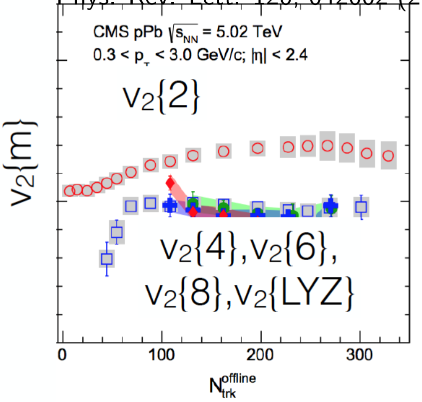
CGC results on small systems

Mark Mace, QM18

Phys. Rev. Lett. 120, 042002 (2018)



Dusling, MM, Venugopalan PRL 120 (2018)



CMS PRL 115 (2015) 012301

- Abelian calculations can produce $v_2\{2\}$, $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$
- Disagreement with data by factor of 5, but qualitative features match

Intermission

Small systems geometry scan

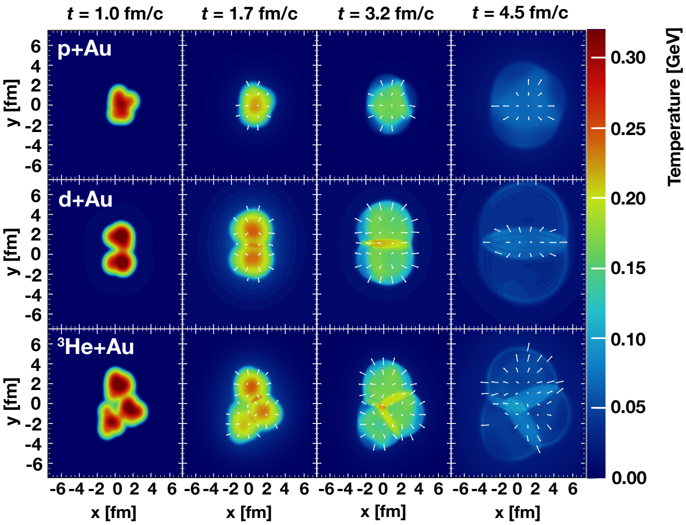
Testing hydro by controlling system geometry

arXiv:1805.02973, submitted to Nature Physics

- Hydrodynamics translates initial geometry into final state
- Test hydro hypothesis by varying initial geometry

	ε_2	ε_3
p+Au	0.24	0.16
d+Au	0.57	0.17
^{3}He+Au	0.48	0.23

- $\varepsilon_2^{p+Au} < \varepsilon_2^{d+Au} \approx \varepsilon_2^{3He+Au}$
- $\varepsilon_3^{p+Au} \approx \varepsilon_3^{d+Au} < \varepsilon_3^{3He+Au}$



Testing hydro by controlling system geometry

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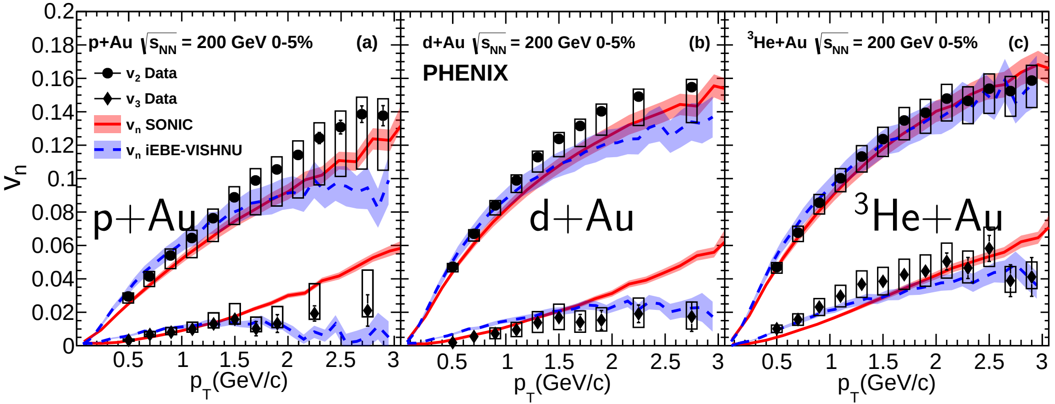
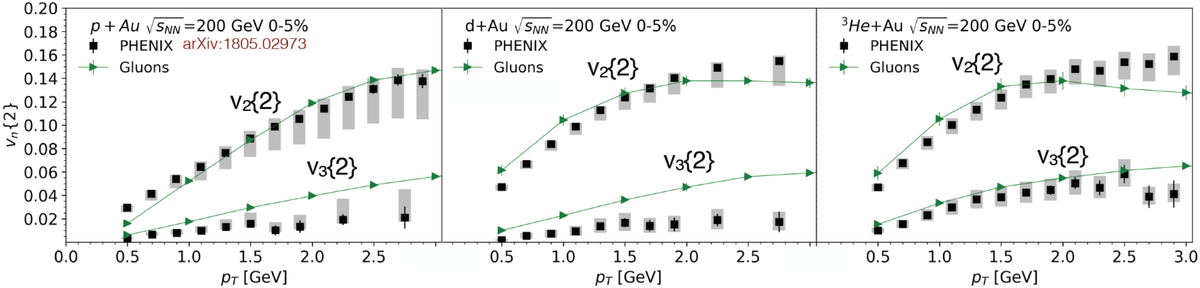


- v_2 and v_3 vs p_T described very well by hydro in all three systems
  —Suggests QGP droplets in hydro evolution(?)

CGC results on small systems

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

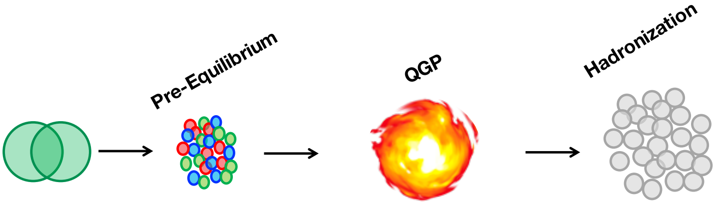


- v_2 is quite well-described
- v_3 is in the right ballpark, though hydro does better

Intermission

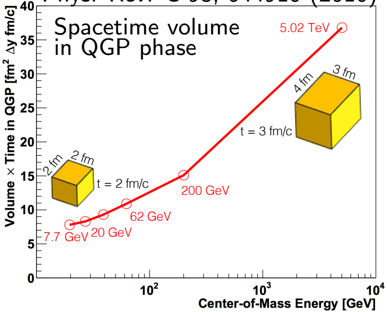
Small systems beam energy scan

Testing hydro by controlling system size and life time



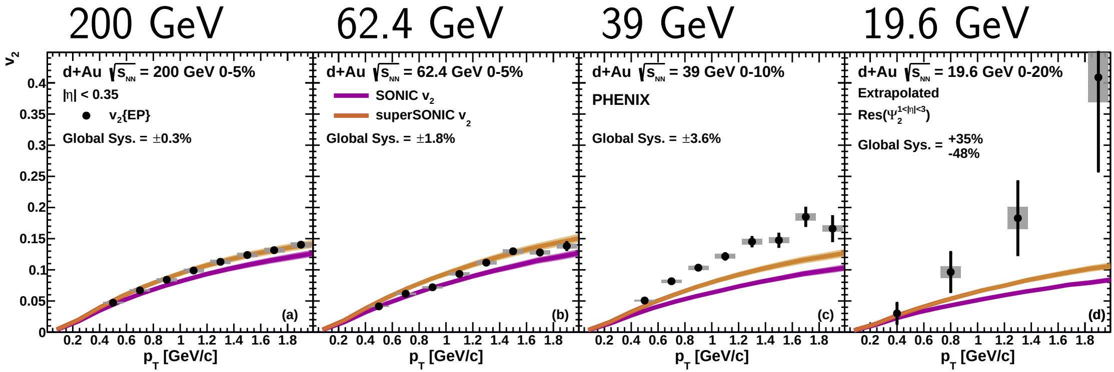
- Standard picture for A+A: QGP in hydro evolution
- What about small systems? And lower energies?
- Use collisions species and energy to control system size, test limits of hydro applicability

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



d+Au beam energy scan

Phys. Rev. C 96, 064905 (2017)

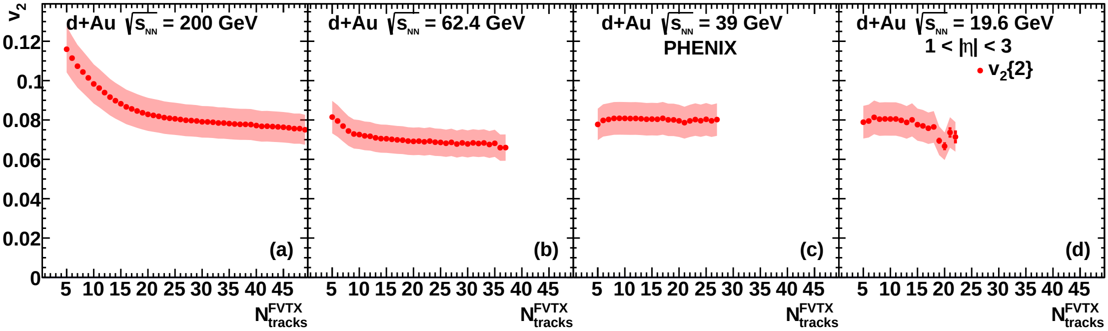


- Hydro theory agrees with higher energies very well, underpredicts lower energies
  —Breakdown of hydro?
  —Predominance of other correlations?

d+Au beam energy scan

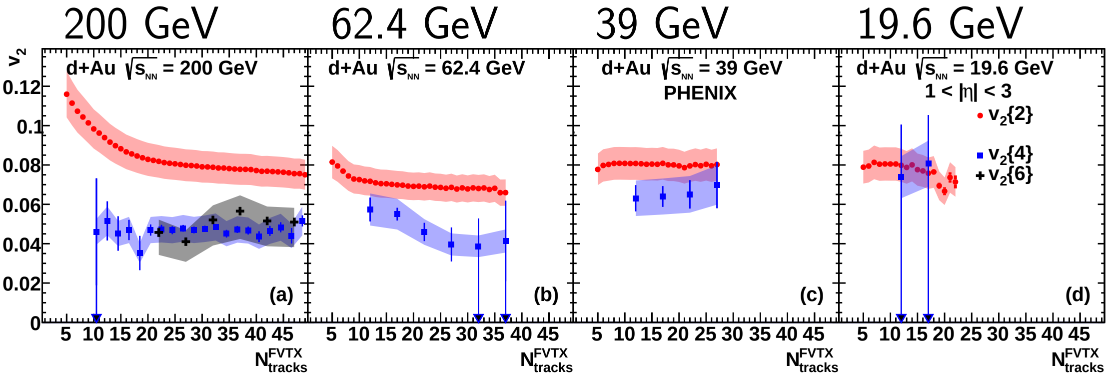
Phys. Rev. Lett. 120, 062302 (2018)

200 GeV 62.4 GeV 39 GeV 19.6 GeV



d+Au beam energy scan

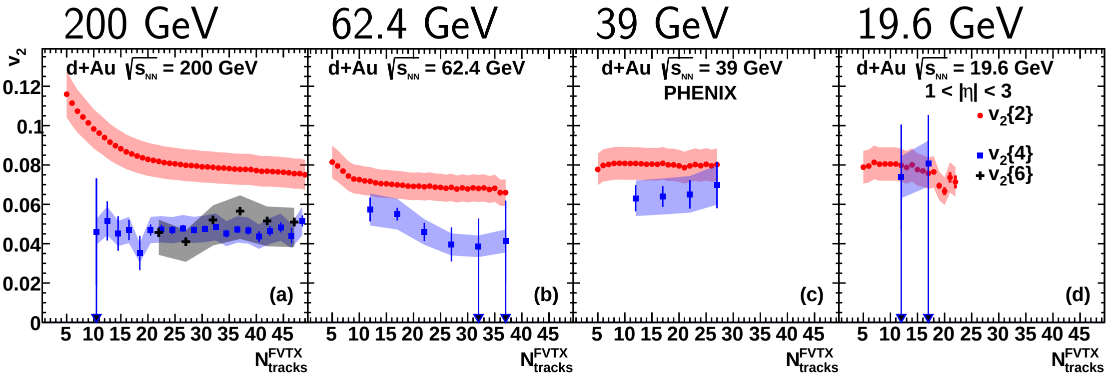
Phys. Rev. Lett. 120, 062302 (2018)



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

d+Au beam energy scan

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

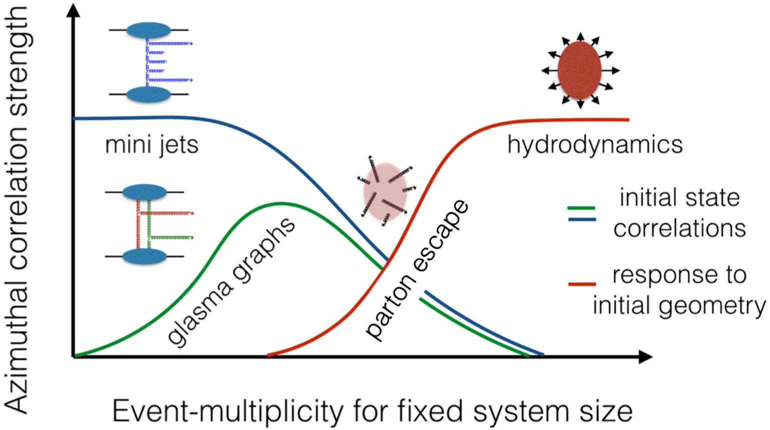


- Measurement of $v_2\{6\}$ in d+Au at 200 GeV and $v_2\{4\}$ in d+Au at all energies
- No theory comparisons available (yet...)

Competing theories

Where are we?

Figure: S. Schlitching, QM2015.



Summary for Part II

- Small systems is a hot topic in heavy ion physics
- We've even gotten some media attention for it
- The system created in small systems looks a like the one in large systems
- Two competing pictures: CGC and QGP
  —QGP picture ahead by points, but no knockout yet

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

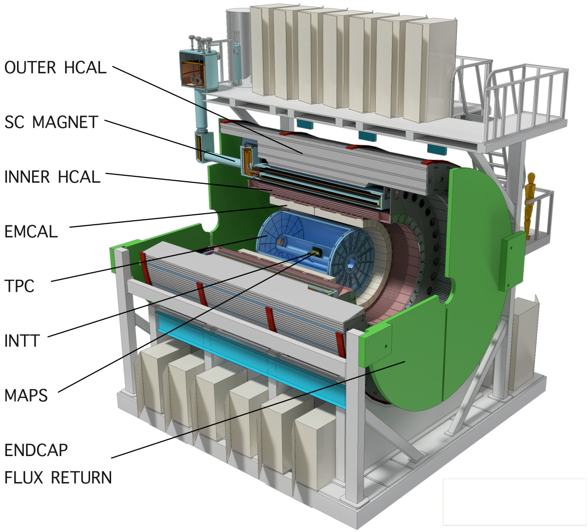
Recommendation I: The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.
—CEBAF, FRIB, Symmetries & Neutrinos, **RHIC** (BES II & **sPHENIX**)

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.

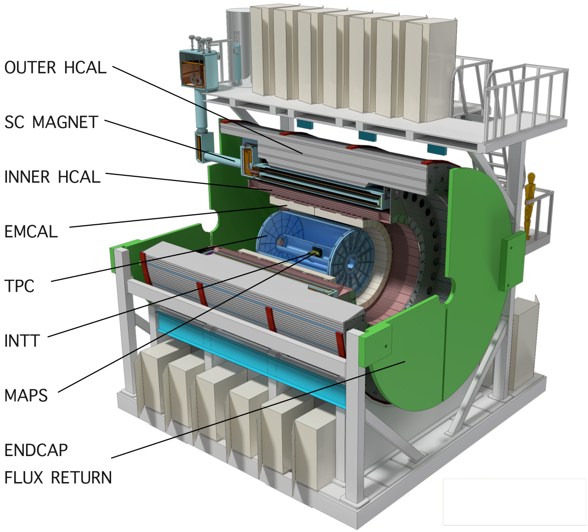
Recommendation IV: We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

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

Future

• DOE OPA CD-2/CD-3b Review	May 2019
• Authorization for CD-2/CD-3b	July 2019
• Fabrication orders	August 2019
• 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
B. DATE 7-19-13
C. TITLE Property Manager

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

11. ALLOTMENT

12. GOVERNMENT B/L NO.

13. PROPERTY ORDERED

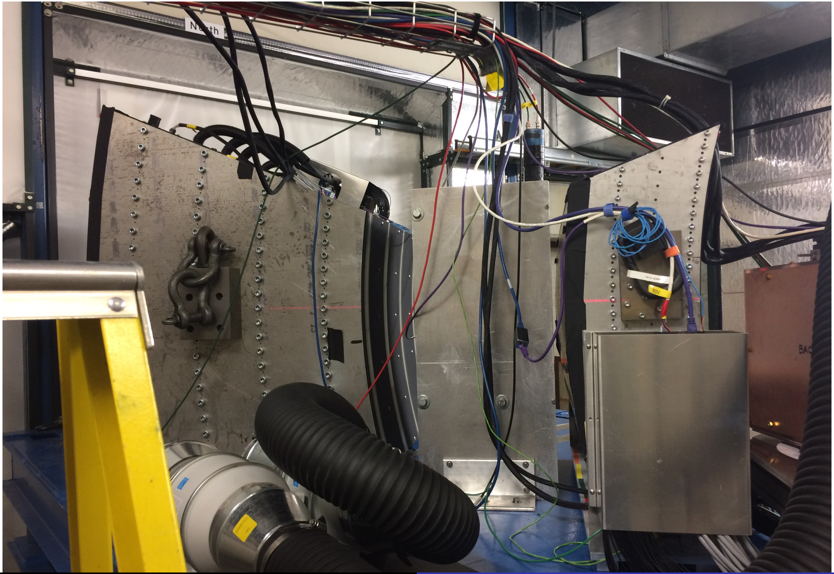
GSA AND HOLDING AGENCY NOS. (a)	ITEM NO. (b)	DESCRIPTION (Include noun name, FSC Group and Class, Condition Code and if available, National Stock Number) (c)	UNIT (d)	QUANTITY (e)	ACQUISITION COST UNIT (f)	ACQUISITION COST TOTAL (g)
		Administrative Transfer				
	1	BaBar Solenoid and Components Date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

sPHENIX: magnet

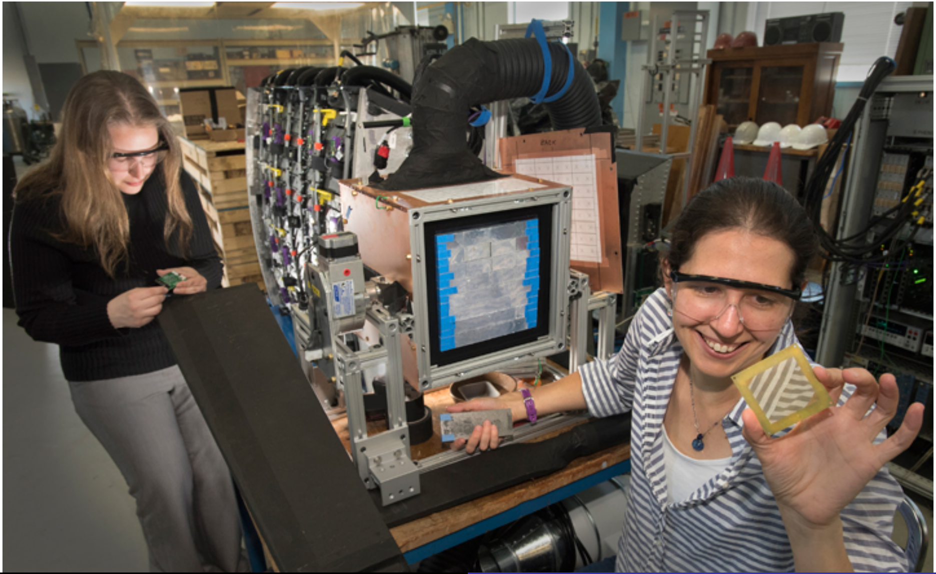
sPHENIX: magnet

sPHENIX: beam tests

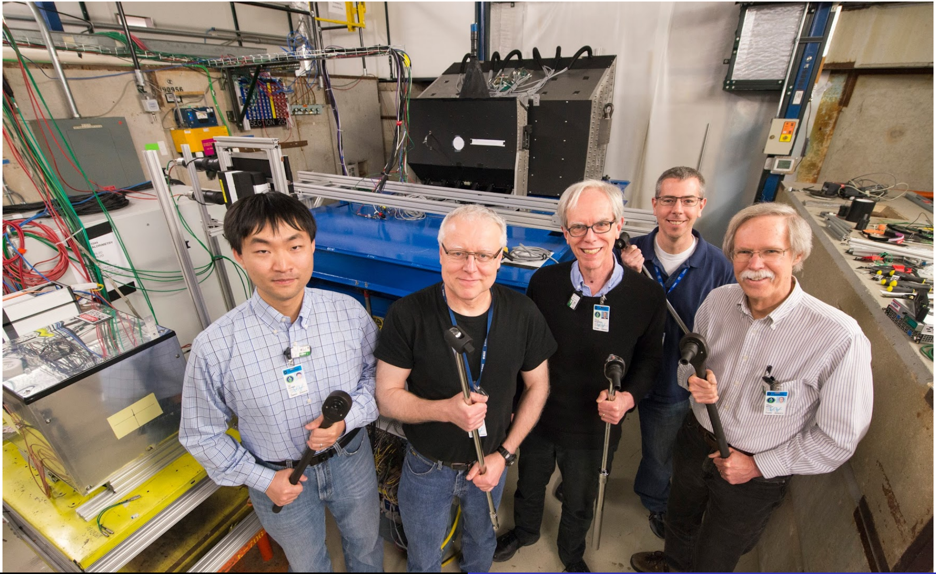
sPHENIX: beam tests



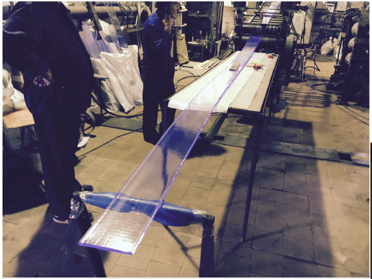
sPHENIX: beam tests

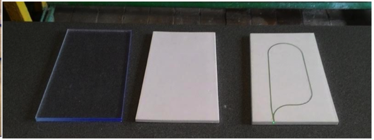


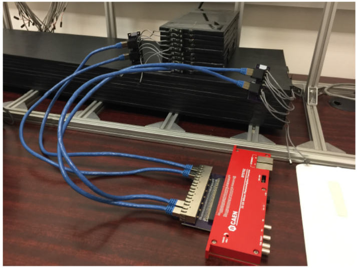
sPHENIX: beam tests

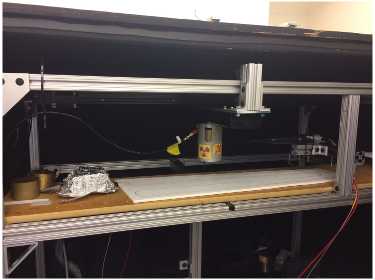


sPHENIX: HCal tiles





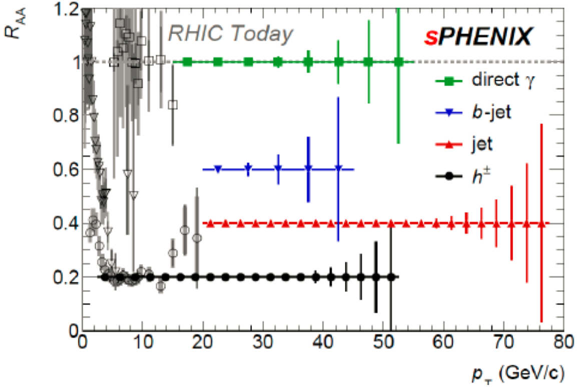


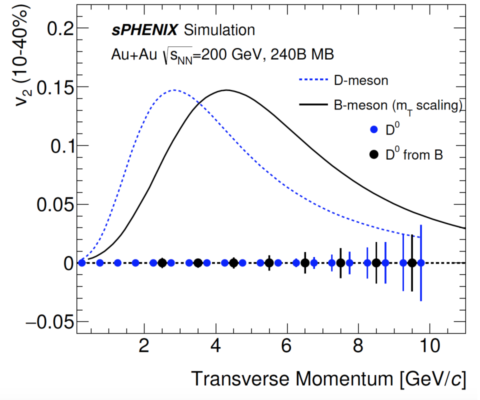


sPHENIX: jets!

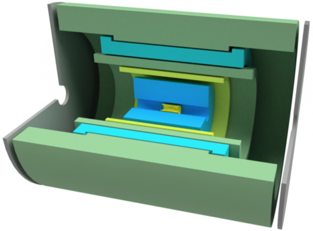
sPHENIX: heavy flavor!

sPHENIX: projections



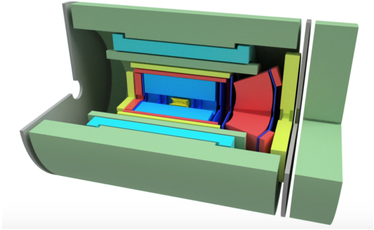


sPHENIX: day one EIC detector



EIC whitepaper: arXiv:1212.1701

sPHENIX EIC proposal: arXiv:1402.1209



An EIC Detector Built Around The sPHENIX Solenoid

A Detector Design Study

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
  —Many similarities to large systems, but theoretical picture less clear
  —How to disentangle CGC from QGP?
- It's an exciting time for nuclear physics in the US

Summary and outlook

- We can recreate the early universe in the lab using collisions of large nuclei
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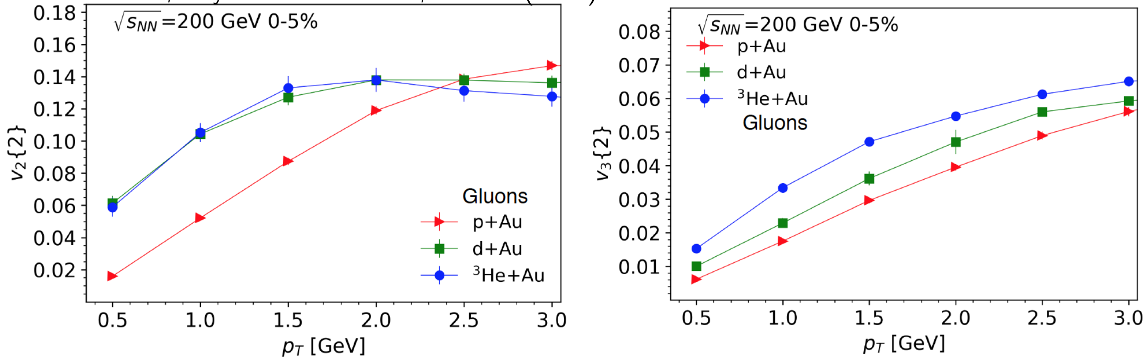
  —How to disentangle CGC from QGP?
- It's an exciting time for nuclear physics in the US

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

Extra material

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

CGC results on small systems

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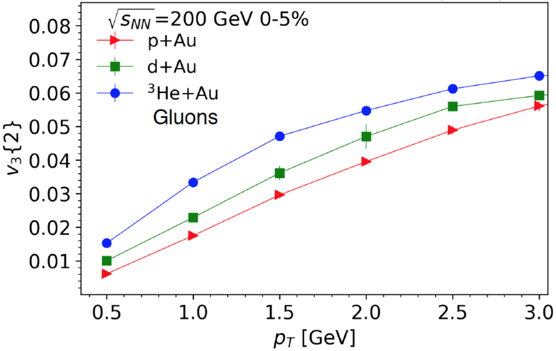
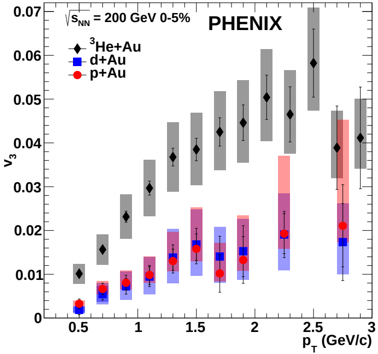
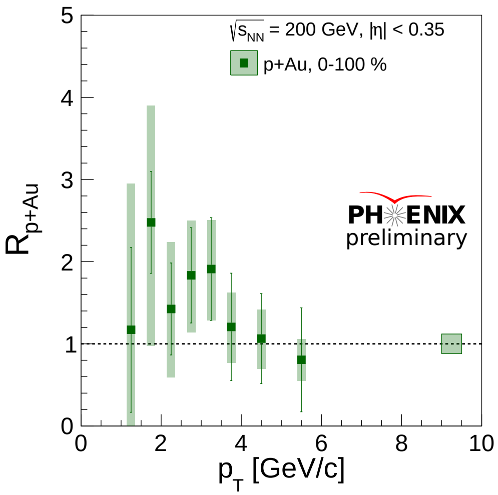


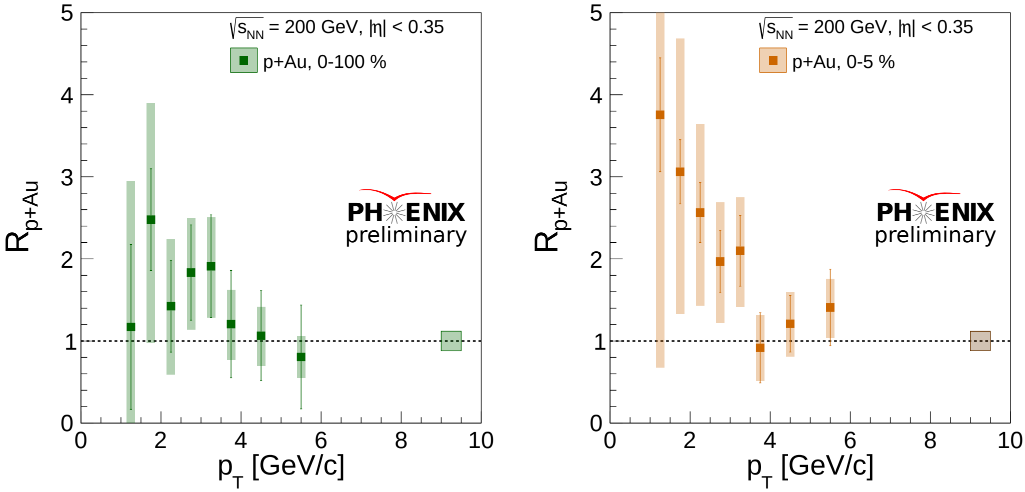


- New for QM18: v_2 and v_3 for small systems
- v_3 ordering is wrong in CGC
  —CGC: p+Au $<$ d+Au $<$ ^{3}He+Au
  —Data: p+Au $\approx$ d+Au $<$ ^{3}He+Au

Photons in small systems

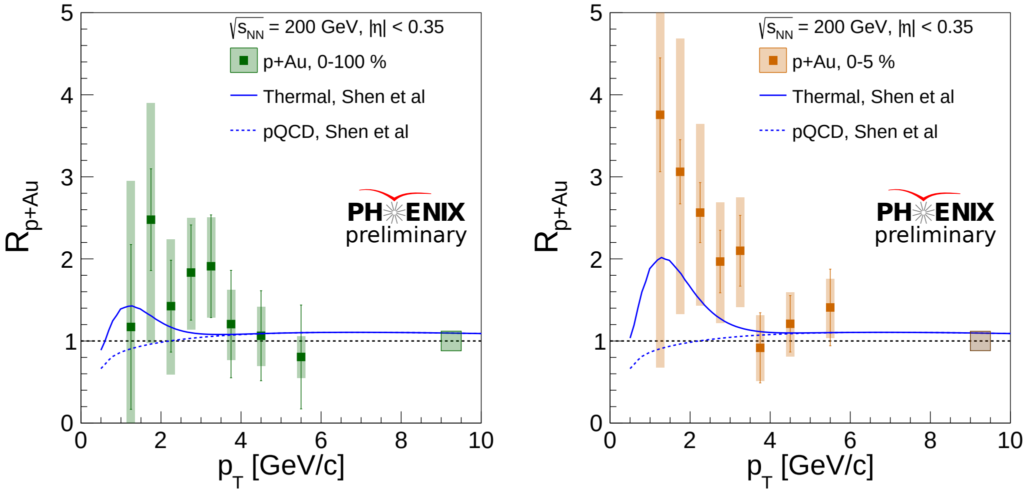


Photons in small systems



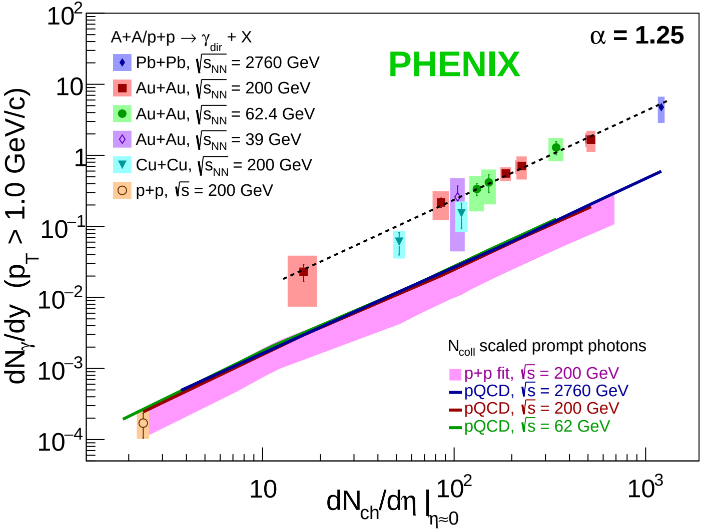
- Thermal photons in p+Au?

Photons in small systems



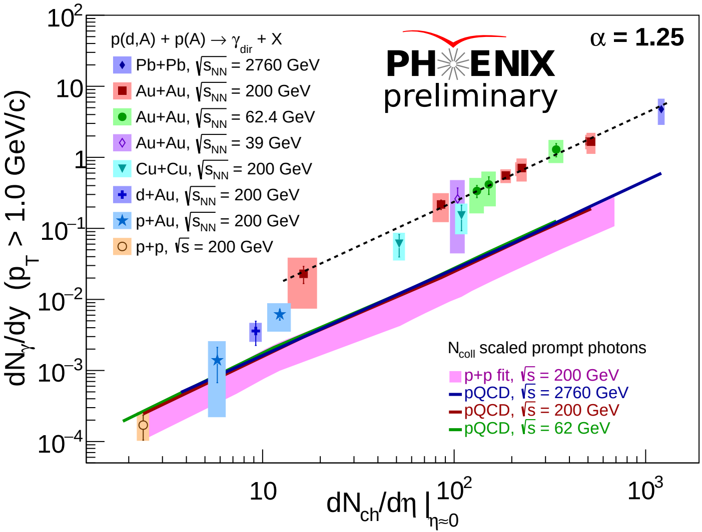
- Thermal photons in p+Au? Theory from Phys. Rev. C 95, 014906 (2017)

Photon yields



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

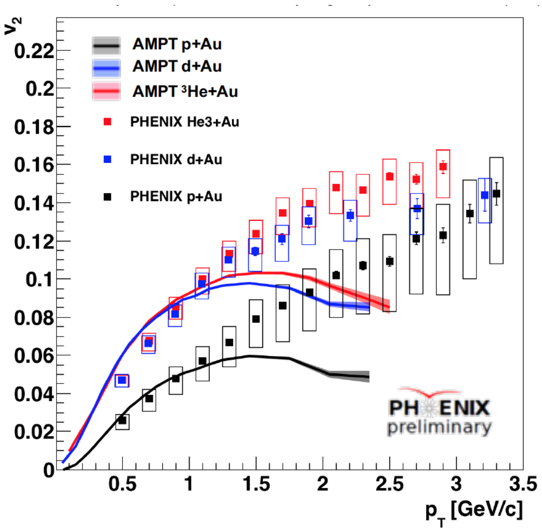
Photon yields



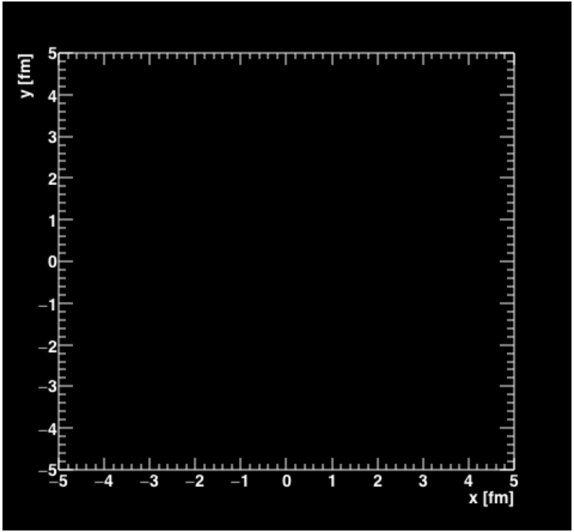
Common scaling for Au+Au and Pb+Pb at different energies; very different from N_{coll}-scaled $p+p$

p+Au and d+Au in between

AMPT



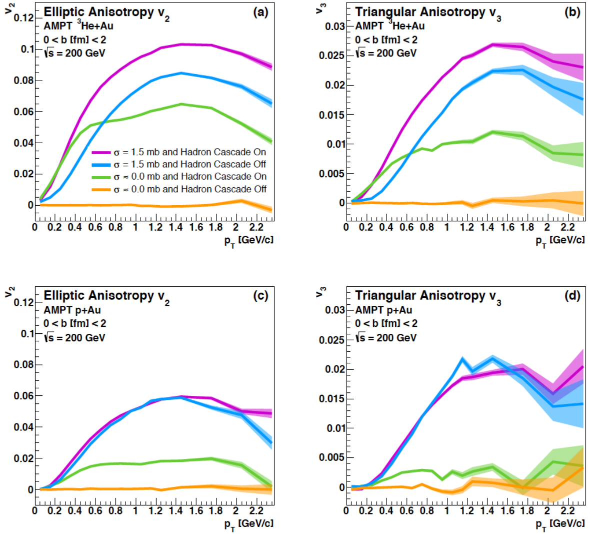
v_2
AMPT p+Au
AMPT d+Au
AMPT ³He+Au
PHENIX He3+Au
PHENIX d+Au
PHENIX p+Au
PHENIX
preliminary
p_T [GeV/c]



y [fm]
x [fm]

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

AMPT with no scattering

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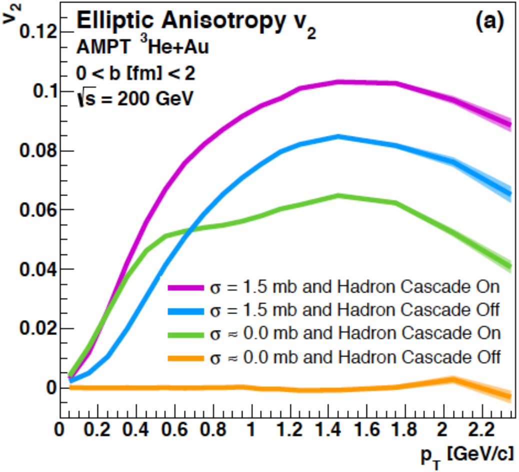

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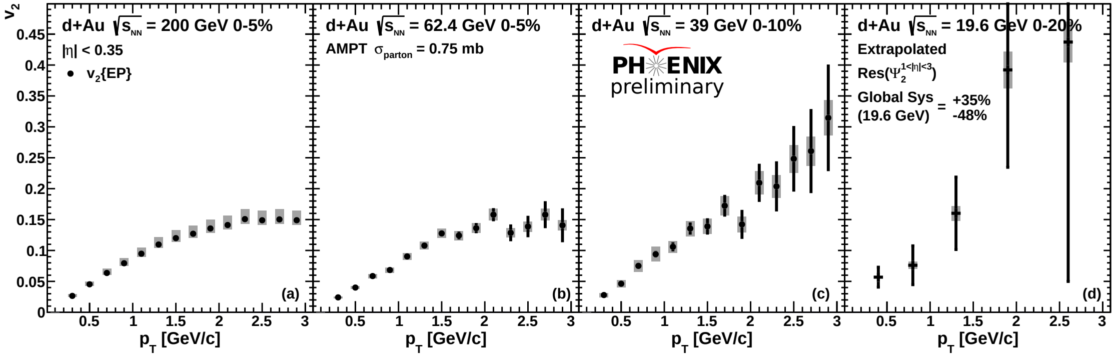
v_2 vs p_T, comparisons to AMPT

Phys. Rev. C 96, 064905 (2017)



v_2 vs p_T, comparisons to AMPT

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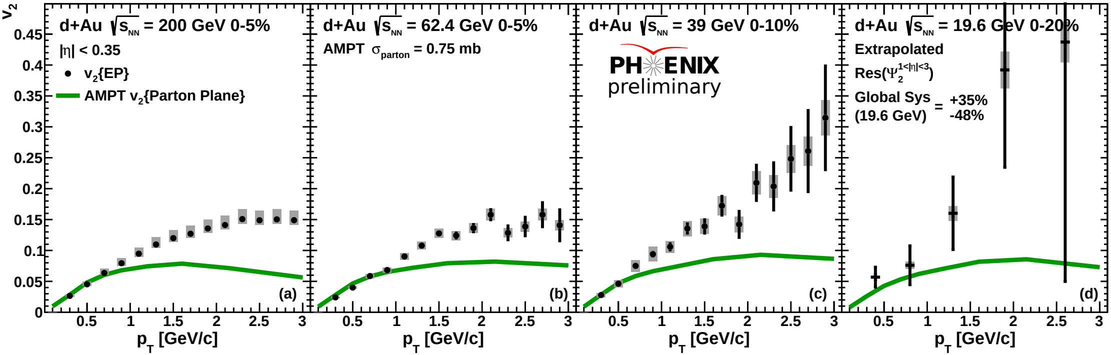
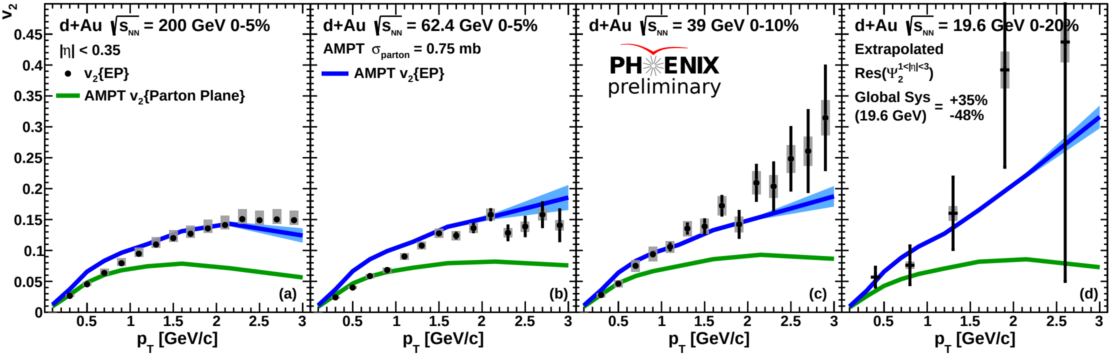


- AMPT flow only shows good agreement at low p_T and all energies

v_2 vs p_T, comparisons to AMPT

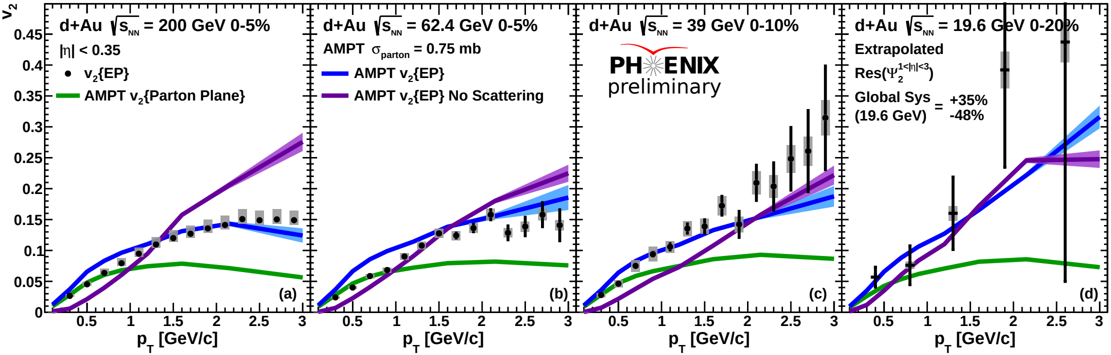
Phys. Rev. C 96, 064905 (2017)



- 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

v_2 vs p_T, comparisons to AMPT

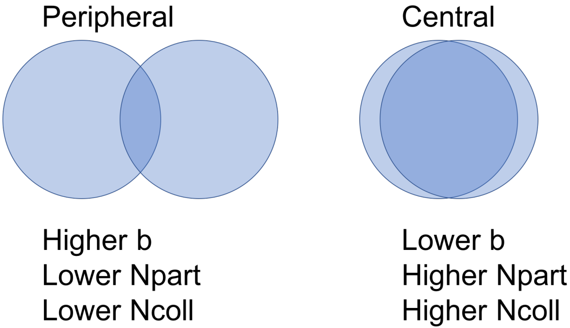
Phys. Rev. C 96, 064905 (2017)



- 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



Centrality	$\langle N_{\text{part}} \rangle$	$\langle N_{\text{coll}} \rangle$
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	≡ 2	≡ 1

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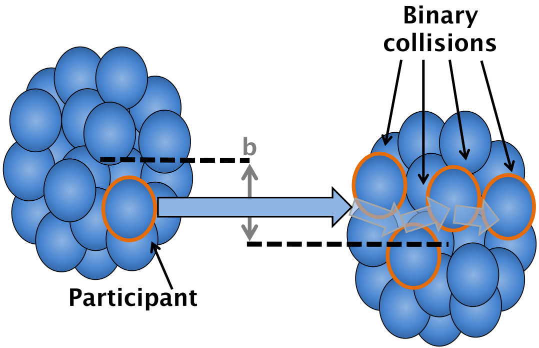

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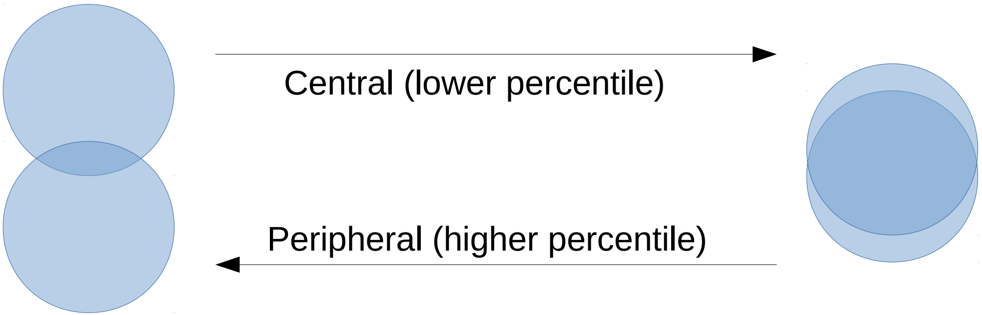

The six flavors of quarks

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 ± 25 MeV
charm	2/3 e	1.25 ± 0.09 GeV
bottom	-1/3 e	4.70 ± 0.07 GeV
top	2/3 e	174.2 ± 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

The six flavors of quarks

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strange	-1/3 e	95 ± 25 MeV
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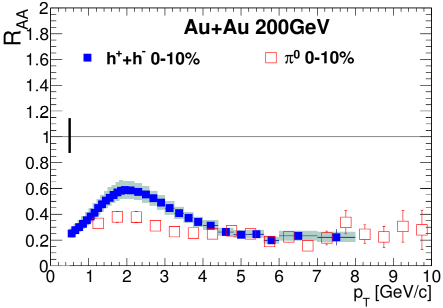
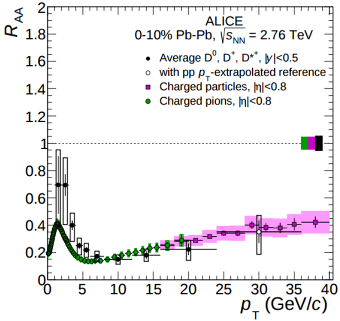
bottom	-1/3 e	4.70 ± 0.07 GeV
top	2/3 e	174.2 ± 3.3 GeV

A few examples

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

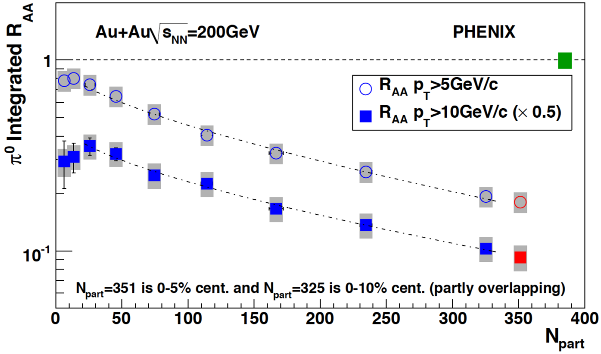
Suppression of high energy particles





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

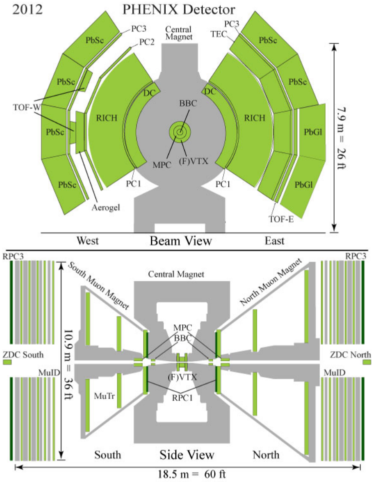
Suppression of high energy particles



- 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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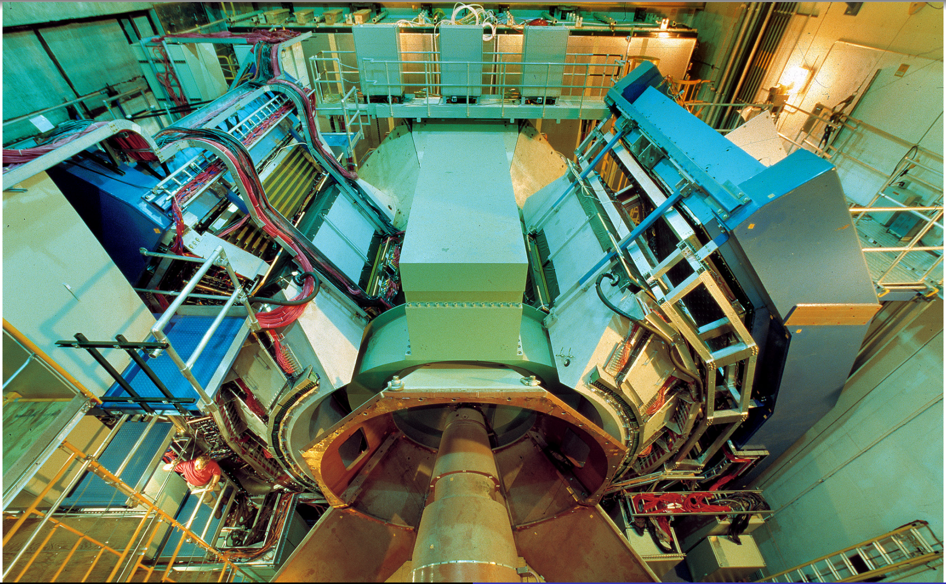
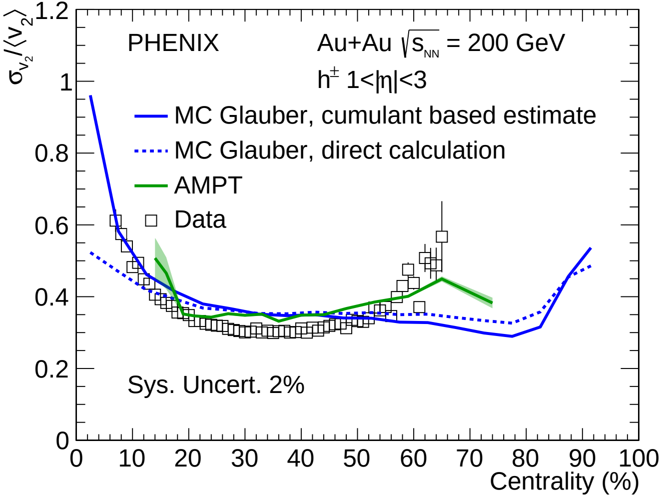


Collectivity in large systems

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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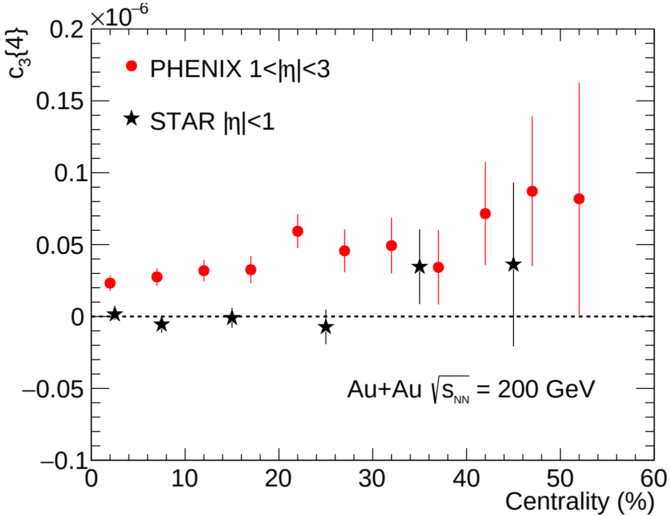

$1 < |\eta| < 3$

Cannot extract

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

Collectivity in large systems

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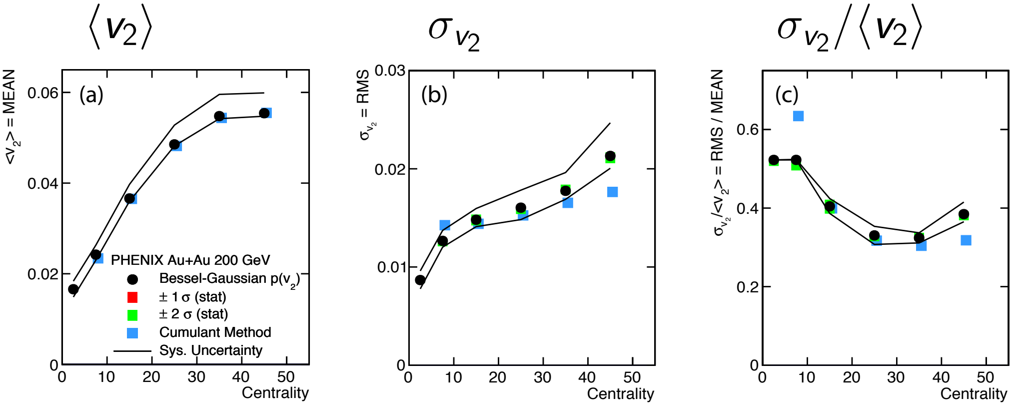

- Can extract $\langle v_2 \rangle$ and σ_{v_2} separately using forward-fold

Collectivity in large systems

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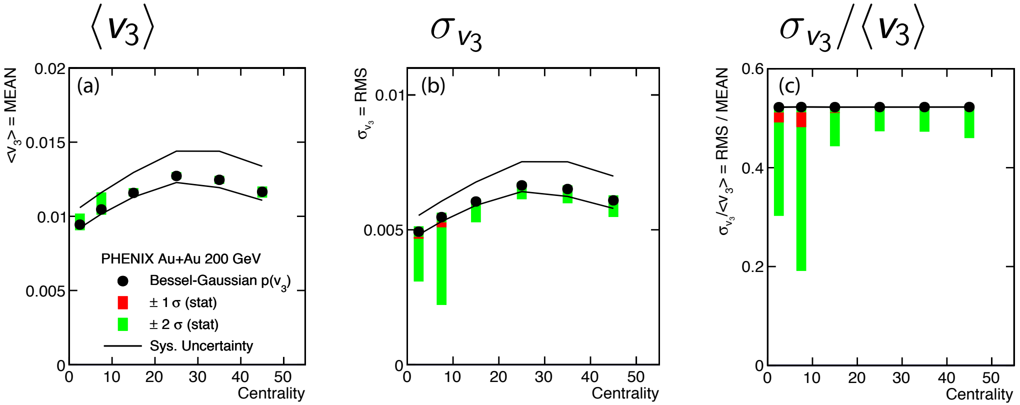
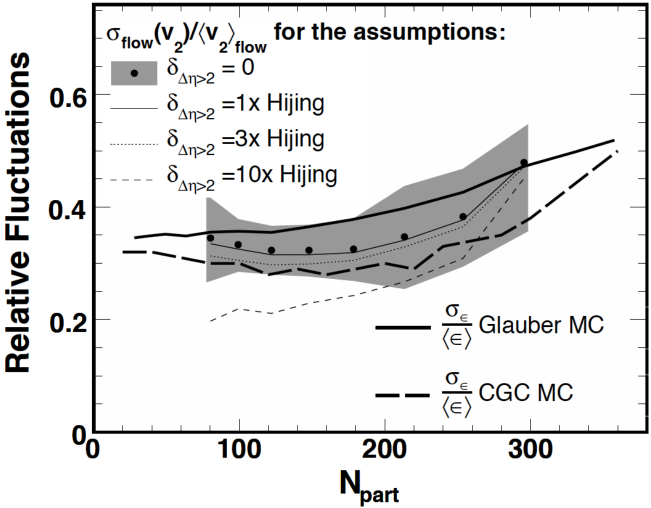


- Can extract $\langle v_3 \rangle$ and σ_{v_3} separately using forward-fold

Fluctuations in large systems

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



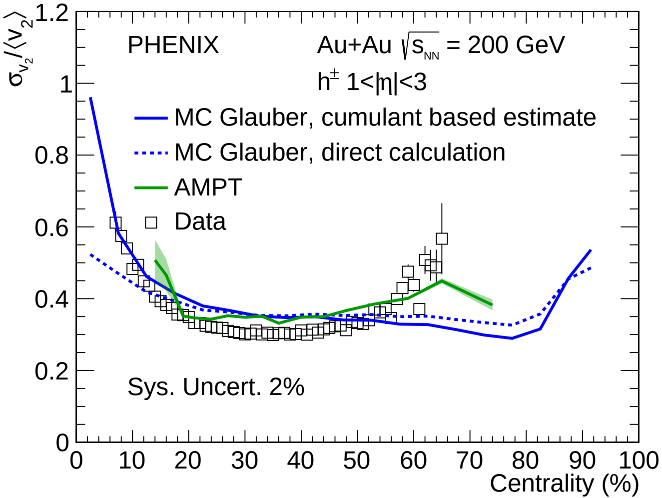
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2 \rangle$

$|\eta| < 1$

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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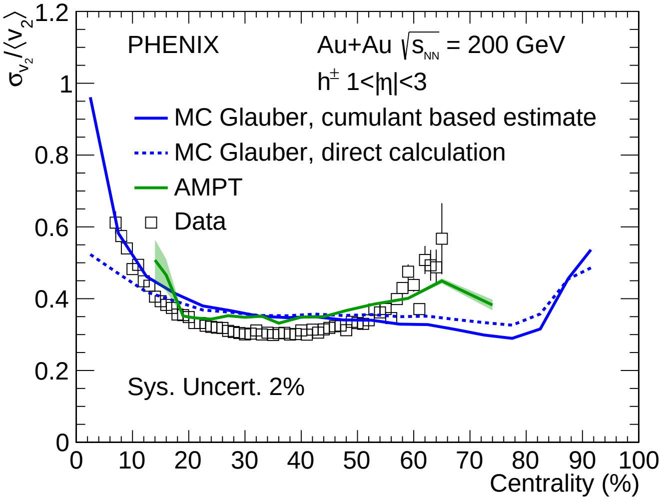


Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2\rangle$

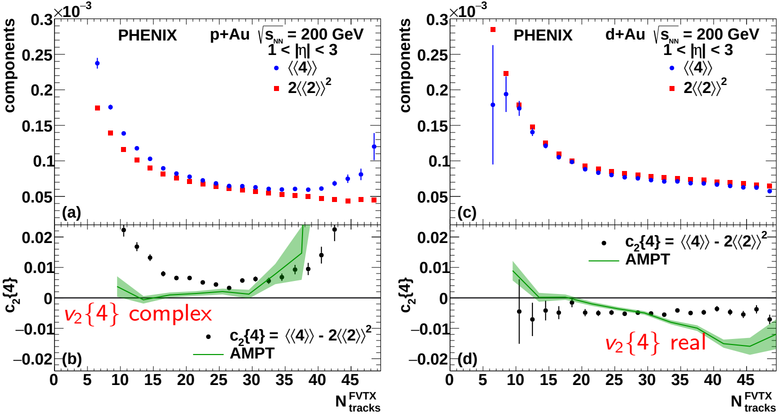
$1 < |\eta| < 3$

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))

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

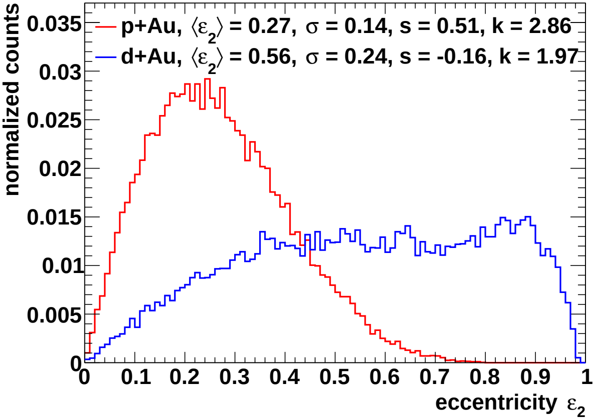
$$\left(\langle v_n^4\rangle = v_n^4 + 6v_n^2\sigma^2 + 3\sigma^4 + 4v_n\kappa_3 + \kappa_4\right)$$
$$-\left(2\langle v_n^2\rangle^2 = 2v_n^4 + 4v_n^2\sigma^2 + 2\sigma^4\right)$$
$$\rightarrow$$
$$\langle v_n^4\rangle - 2\langle v_n^2\rangle^2 = -v_n^4 + 2v_n^2\sigma^2 + \sigma^4 + 4v_n\kappa_3 + \kappa_4$$

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

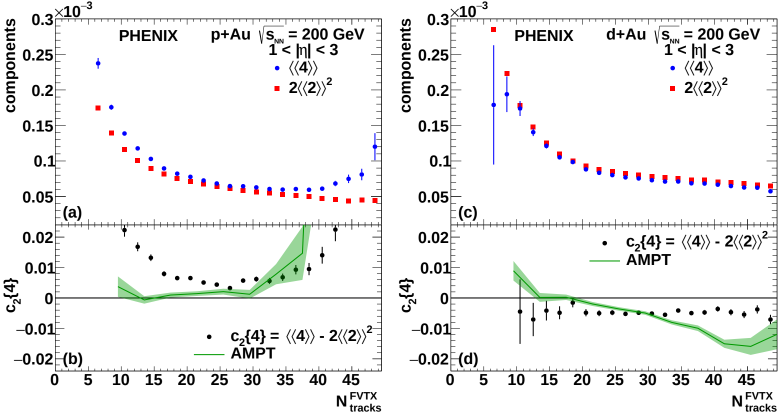


$$\varepsilon_2\{4\} = (\varepsilon_2^4 - 2\varepsilon_2^2\sigma^2 - 4\varepsilon_2 s\sigma^3 - (k-2)\sigma^4)^{1/4}$$

	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



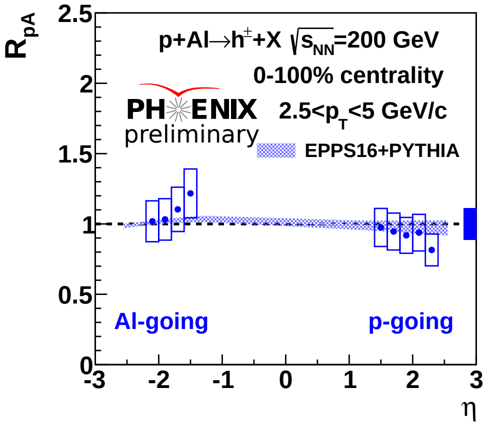
$$v_2\{4\} = \left(v_2^4 - 2v_2^2\sigma^2 - 4v_2 s\sigma^3 - (k-2)\sigma^4\right)^{1/4}$$

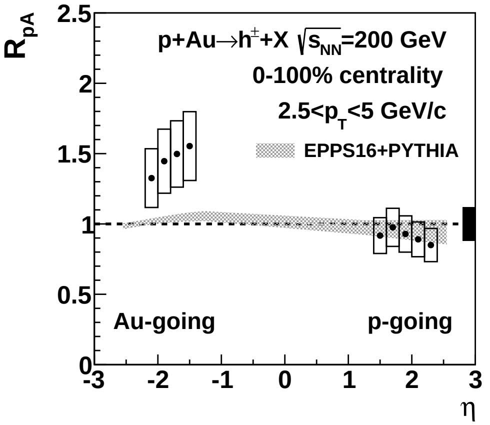
- Eccentricity fluctuations alone go a long way towards explaining this
- Additional fluctuations in the (imperfect) translation of ε_2 to v_2?

Intermission

Particle production in small systems

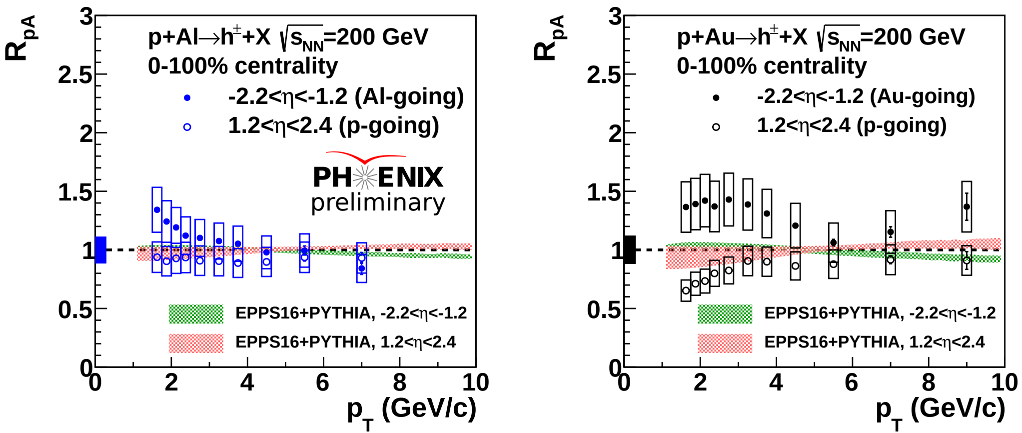
Small systems nuclear modification





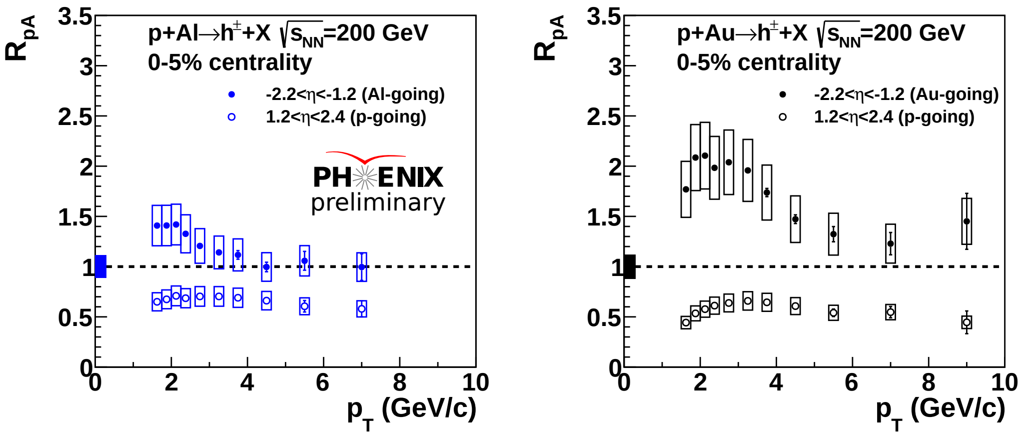
- Forward modification consistent with nPDF effects (EPPS16)

Small systems nuclear modification



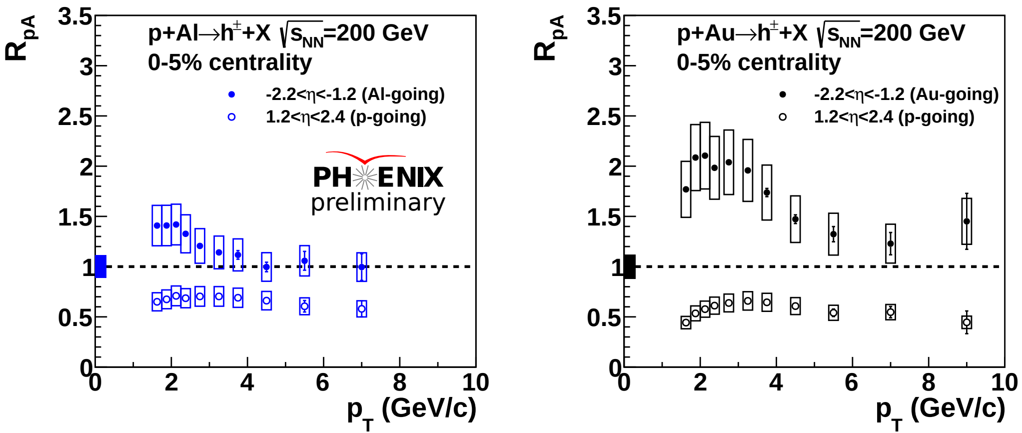
- High-p_T modification consistent with nPDF effects (EPPS16)

Small systems nuclear modification



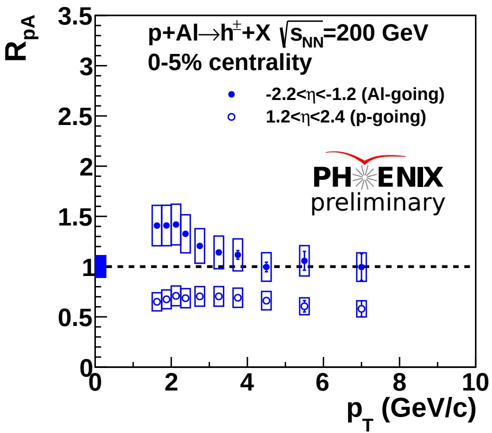
- Stronger effects in central collisions

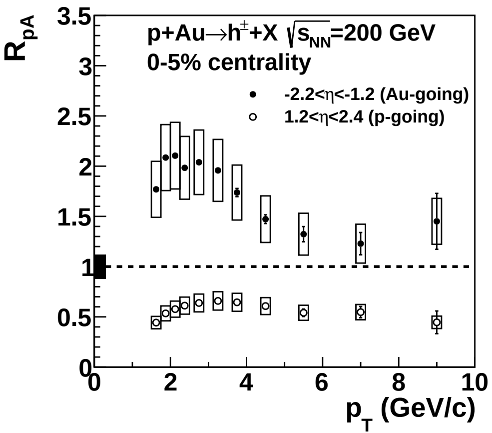
Small systems nuclear modification



- Strong enhancement for backward at intermediate p_T—why?

Small systems nuclear modification

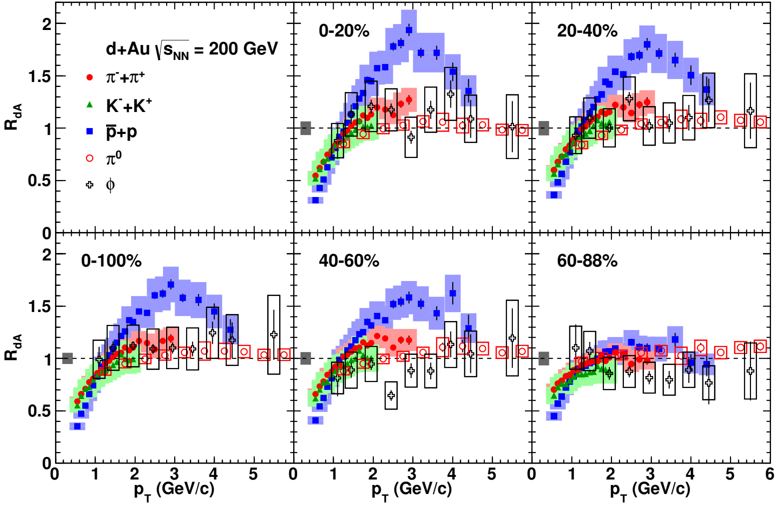




- Strong enhancement for backward at intermediate p_T—why?
- Don't forget: particle species dependence of Cronin! There must be final state effect(s)...

Particle species dependence of "Cronin enhancement"

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



π^+, π^-, π^0,

K^+, K^-,

p, $\bar{p}$,

ϕ

Protons much more strongly modified than pions

ϕ mesons confusing as always...