Flow signals and physics in small-system collisions

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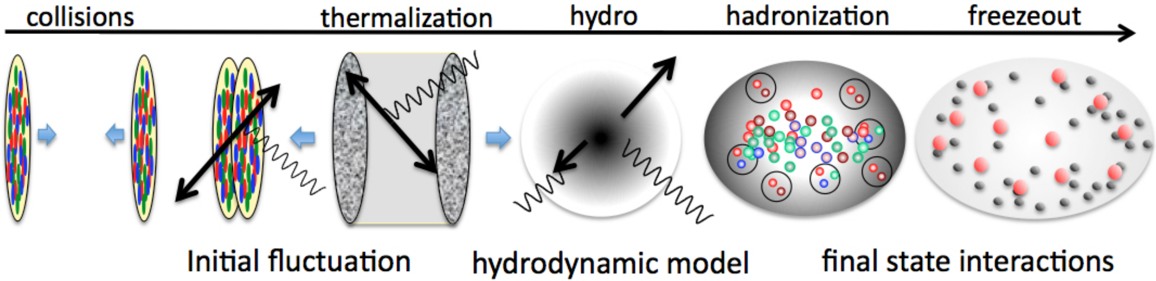
University of North Carolina at Greensboro

Center for Frontiers in Nuclear Science workshop
RHIC Science Programs Informative Toward EIC in the Coming Years
The Internet
24 May 2021

UNC GREENSBORO

Standard model of heavy ion physics



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

Quick outline

- Identified particles
- Thermal photons
- Flow correlations

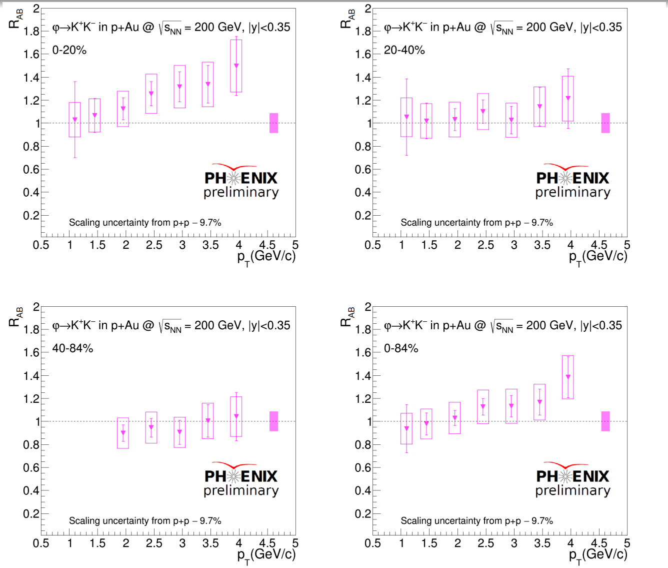
Intermission

Identified particles

Reminder: the nuclear modification factor is

$$R_{AB} = \frac{\text{Yield in AB collisions}}{\text{Yield in pp collisions} \cdot \text{Number of binary collisions}}$$

Identified hadron nuclear modification factors in p+Au



ϕ meson in p+Au

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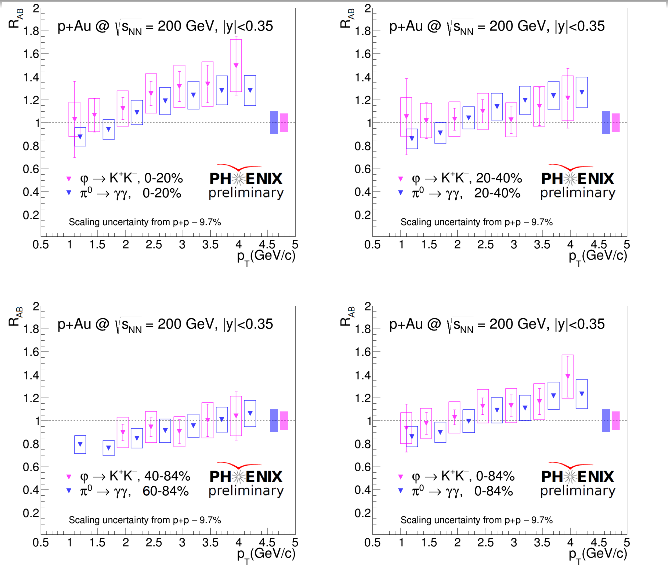
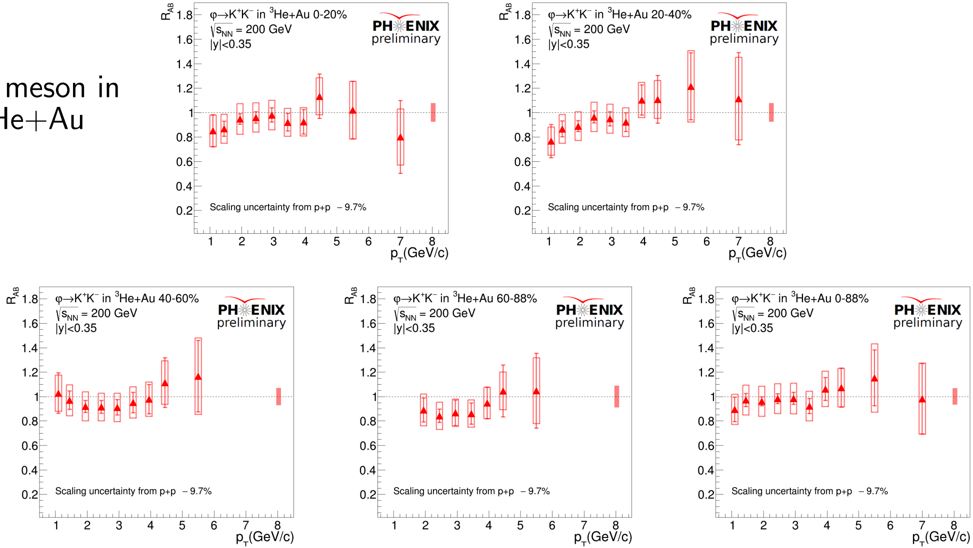


ϕ meson in p+Au

ϕ shows similar modification to π^0 in p+Au despite different mass and strangeness content

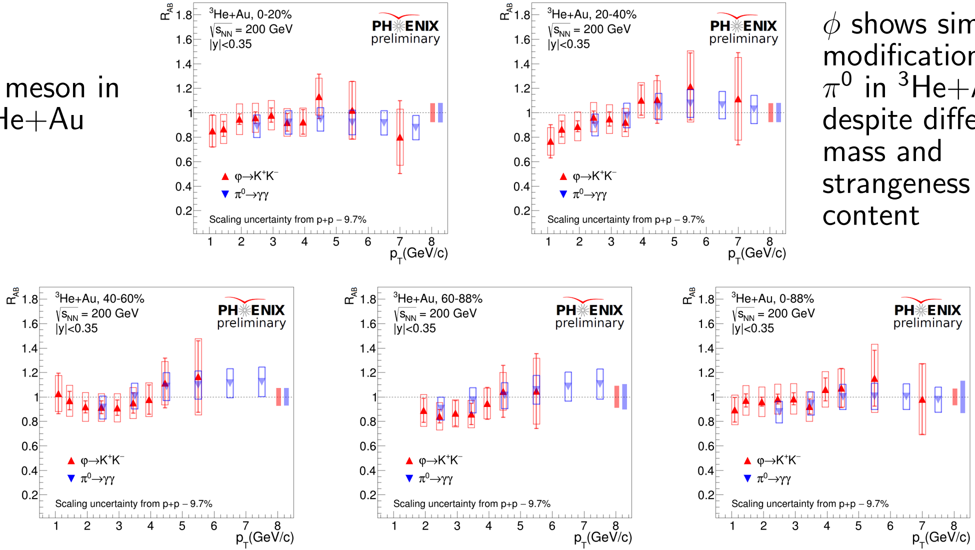
Identified hadron nuclear modification factors in ^{3}He+Au

ϕ meson in ^{3}He+Au



Identified hadron nuclear modification factors in ^{3}He+Au

ϕ meson in ^{3}He+Au



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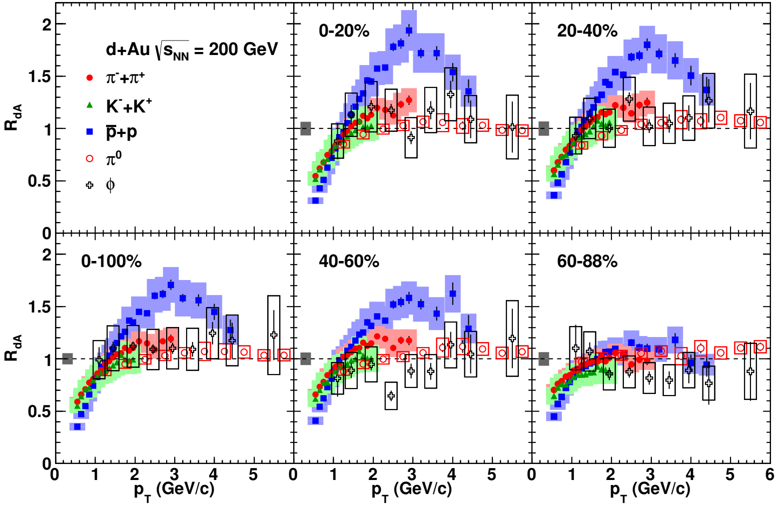
Particle species dependence of “Cronin enhancement”

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



π^+, π^-, π^0,
K^+, K^-,
$p, \bar{p}$,
ϕ

Particle species dependence of "Cronin enhancement"

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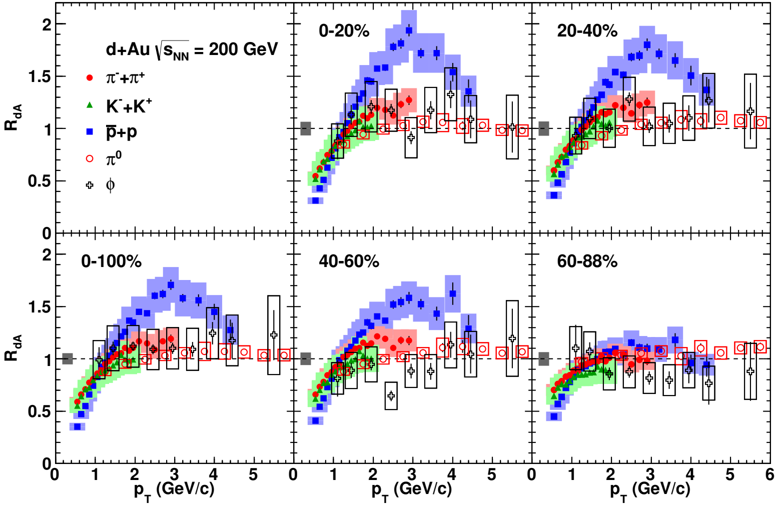
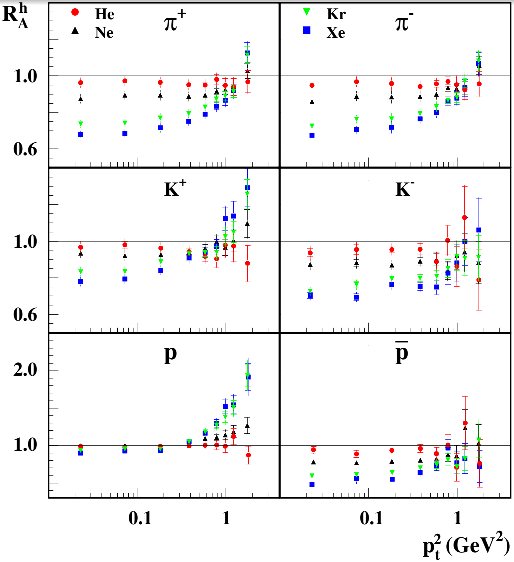


π^+, π^-, π^0,
K^+, K^-,
p, $\bar{p}$,
ϕ

Baryons strongly different from mesons, as found in large systems

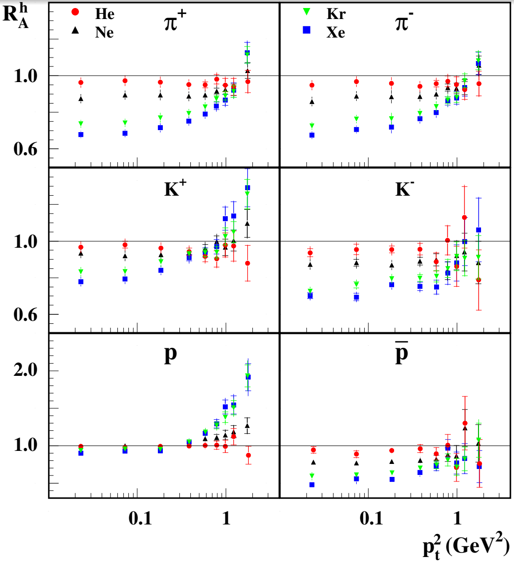
Hadronization in $e+p/d/A$ collisions



HERMES, Phys. Lett. B 780, 1 (2007)

Hadronization is modified in $e+A$ relative to $e+d$

Hadronization in $e+p/d/A$ collisions



HERMES, Phys. Lett. B 780, 1 (2007)

Hadronization is modified in $e+A$ relative to $e+d$

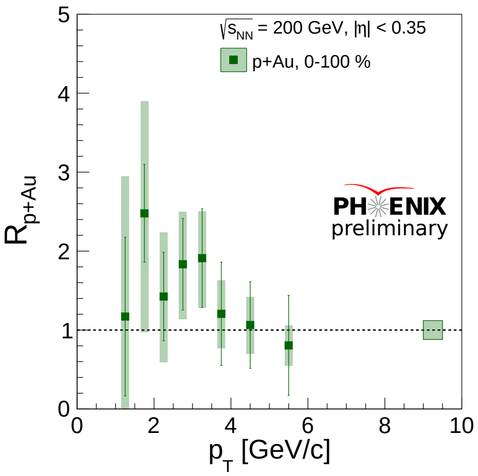
Any connections between modifications in $e+A$ and heavy ions?

Opportunities for further hadronization studies at the EIC

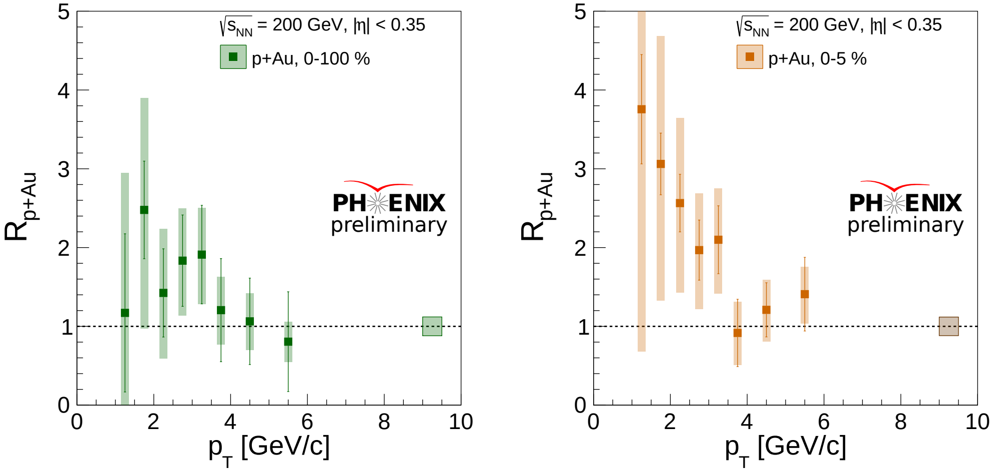
Intermission

Thermal photons

Nuclear modification of photons

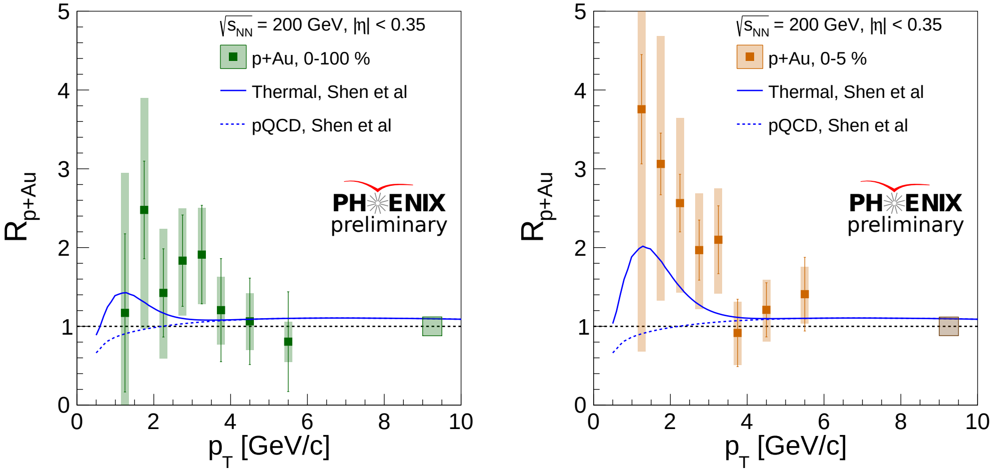


Nuclear modification of photons



- Thermal photons in *p*+Au?

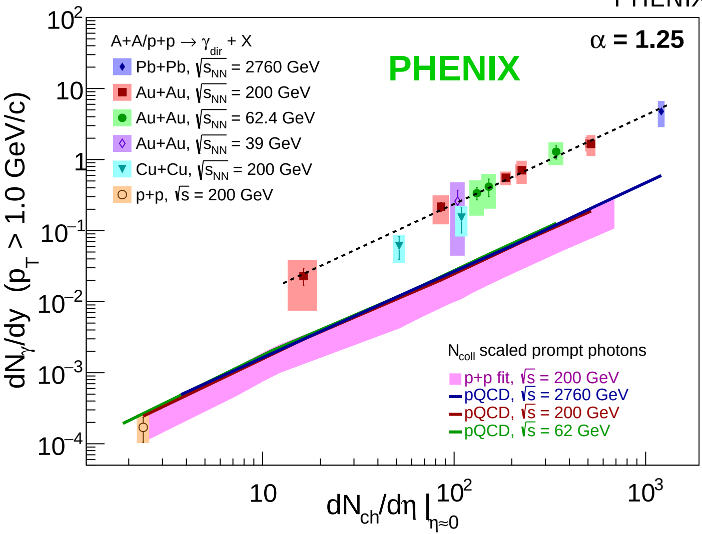
Nuclear modification of photons



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

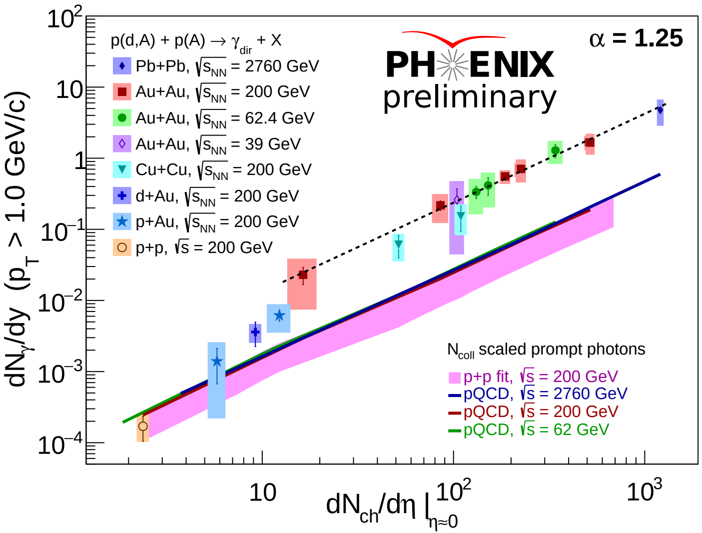
Photon yields

PHENIX, Phys. Rev. Lett. 123, 022301 (2019)



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

Photon yields



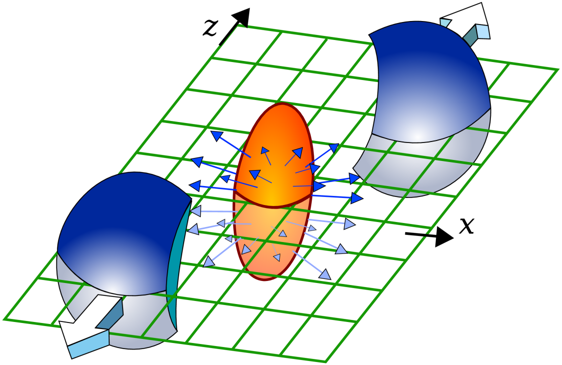
Common scaling for Au+Au and Pb+Pb at different energies; very different from N_{coll}-scaled $p+p$

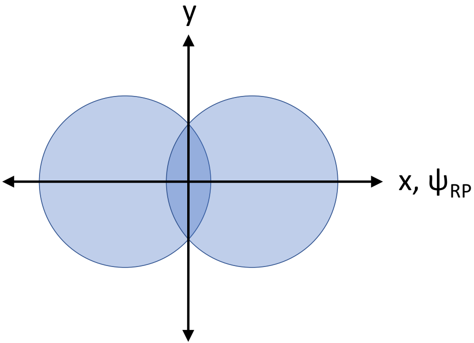
p+Au and d+Au in between, indicating a possible turn-on of thermal photons

Intermission

Flow correlations

Azimuthal anisotropy measurements

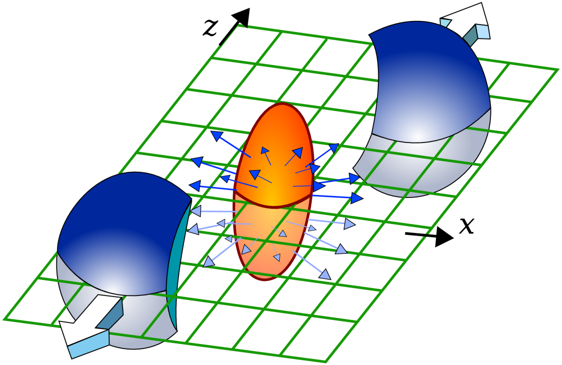


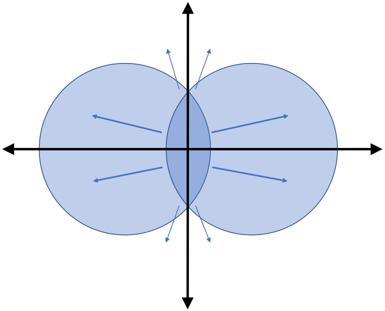


$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^n \cos n\varphi \rangle + \langle r^n \sin n\varphi \rangle}}{\langle r^n \rangle}$$

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

Azimuthal anisotropy measurements





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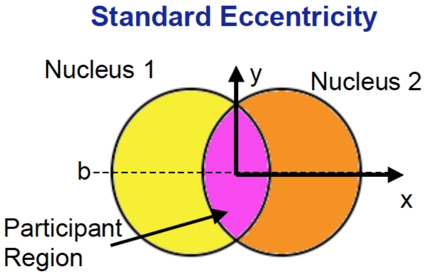
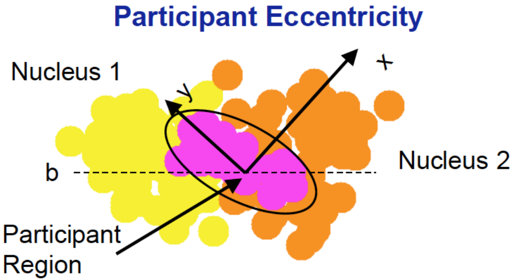
Important discovery in 2005

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





A nucleus isn't just a sphere

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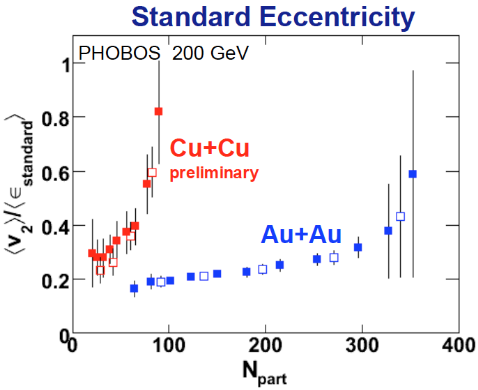

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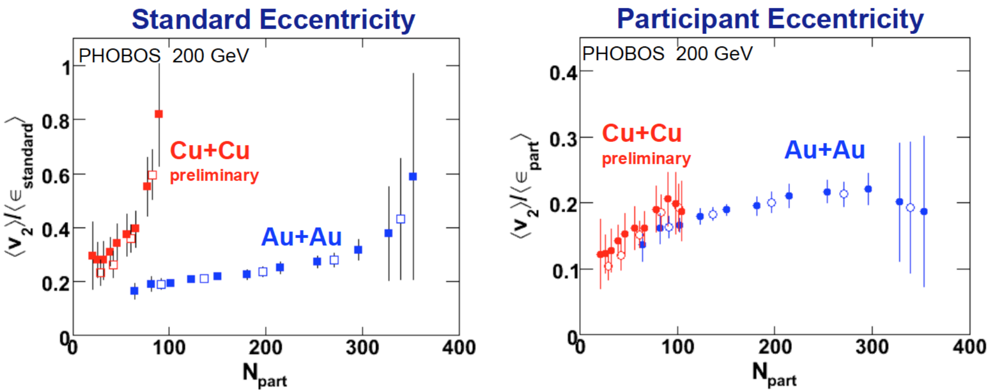


A nucleus isn't just a sphere

Important discovery in 2005

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

NeXSPheRIO results on elliptic flow at RHIC and connection with thermalization

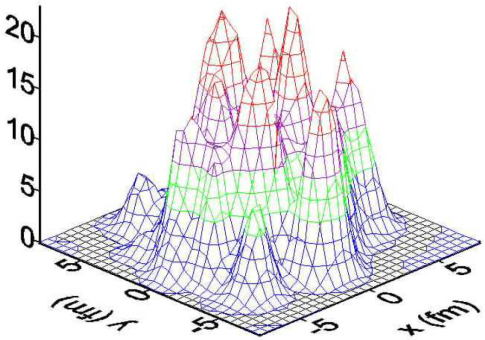
R.Andrade[1], F.Grassi[1], Y.Hama[1], T.Kodama[2], O.Socolowski Jr.[3], and B.Tavares[2]

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

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

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

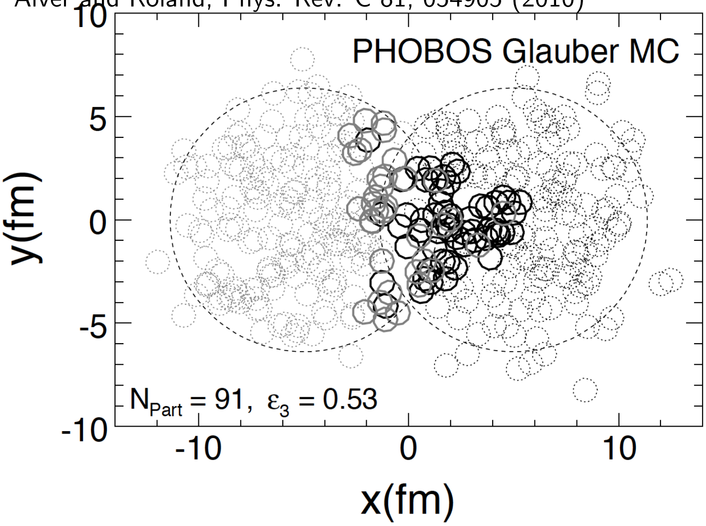
Received 1 January 2004



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

Important discovery in 2010

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



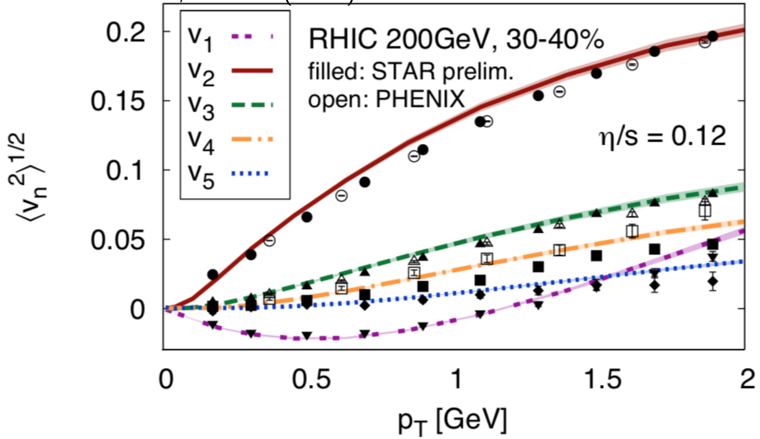
Nucleon fluctuations can produce non-zero ε_n for odd n

Symmetry planes ψ_n can be different for different harmonics

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

Data and theory for v_n

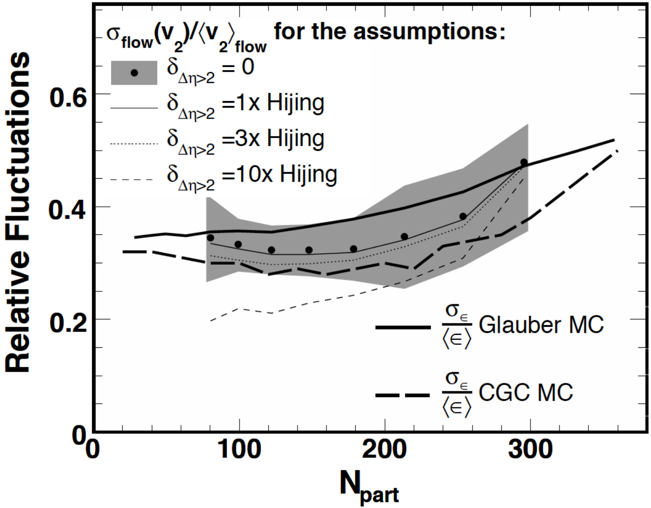
Gale et al, Phys. Rev. Lett. 110, 012302 (2013)



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

Fluctuations in large systems

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



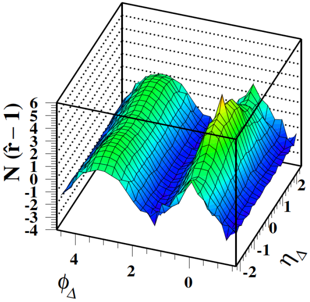
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2 \rangle$

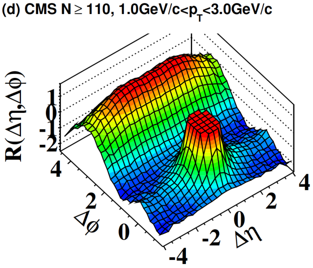
$|\eta| < 1$

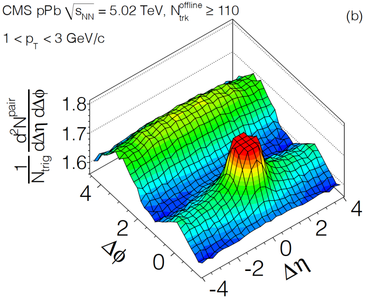
Generally good agreement with models of initial geometry

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))

Testing hydro by controlling system geometry

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

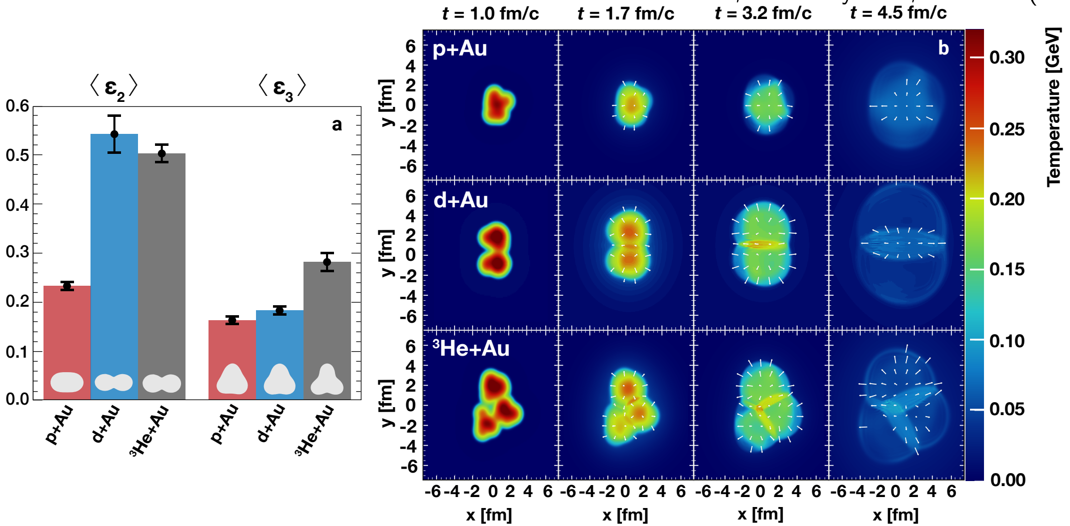
J. L. Nagle, A. Adare, S. Beckman, T. Koblesky, J. Orjuela Koop, D. McGlinchey, P. Romatschke, J. Carlson, J. E. Lynn, and M. McCumber

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

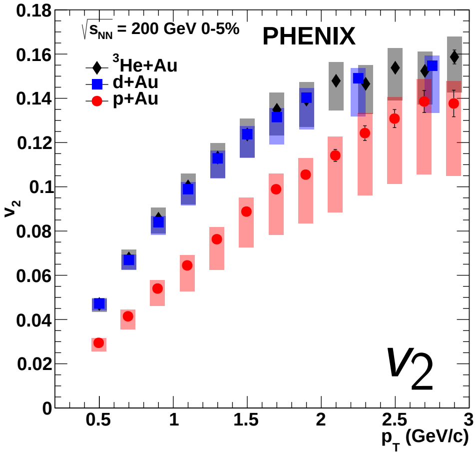
Testing hydro by controlling system geometry

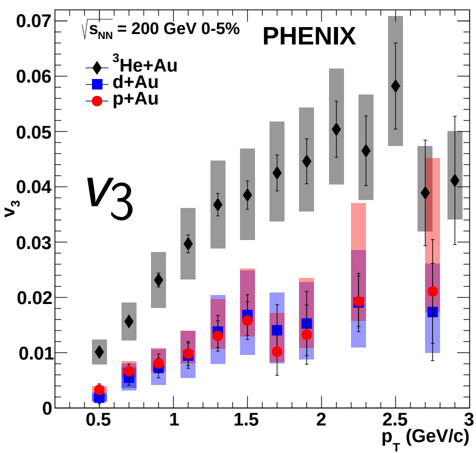
PHENIX, Nat. Phys. 15, 214–220 (2019)



Testing hydro by controlling system geometry

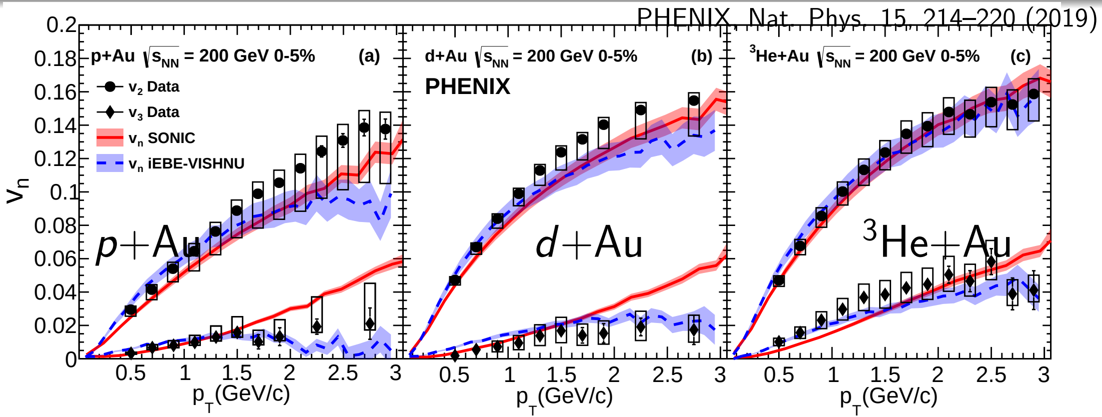
PHENIX, Nat. Phys. 15, 214–220 (2019)





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

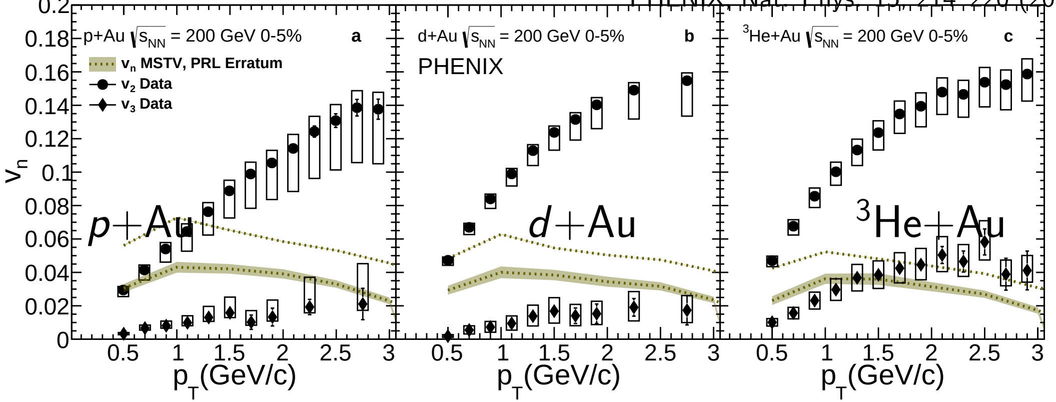
Testing hydro by controlling system geometry



- 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

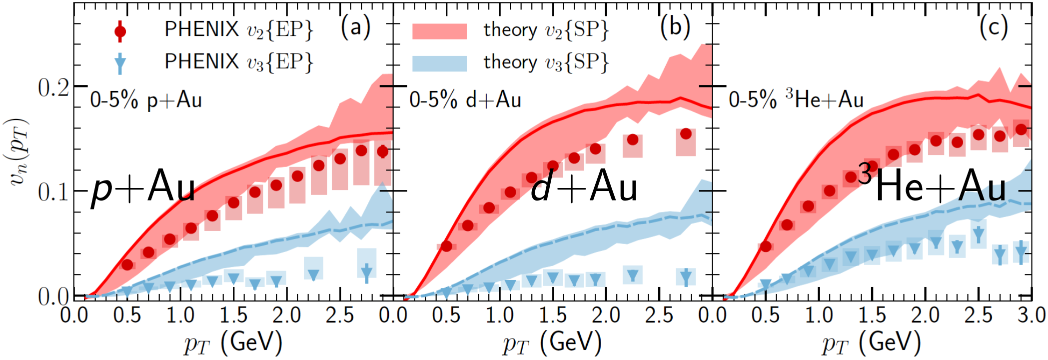
PHENIX, Nat. Phys. 15, 214–220 (2019)



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

Testing hydro by controlling system geometry

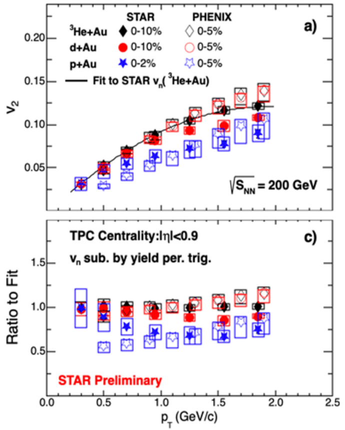
PHENIX, Nat. Phys. 15, 214–220 (2019)



- 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

Comparisons with STAR

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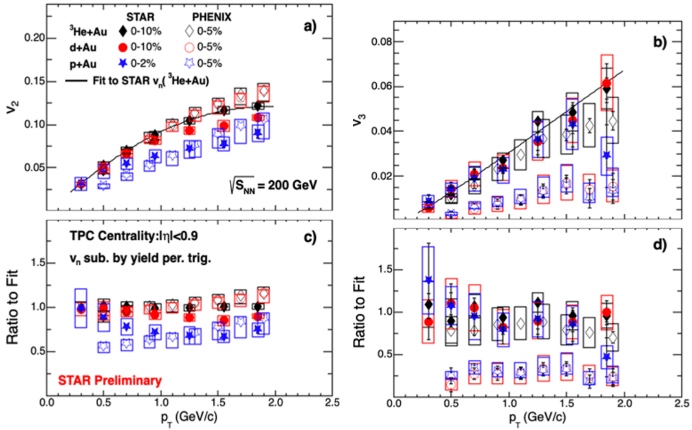
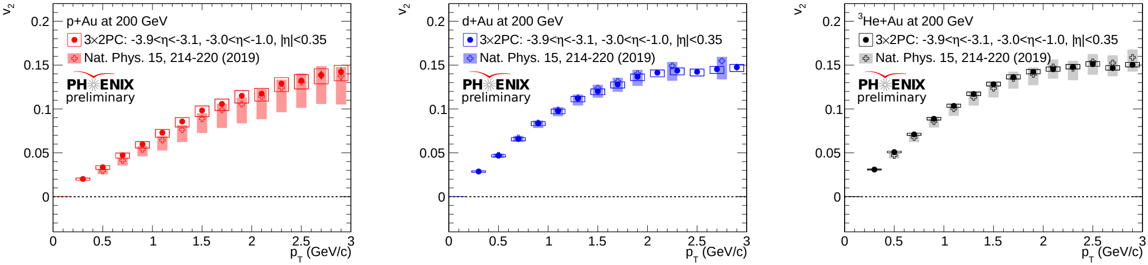


Good agreement between STAR and PHENIX for v_2

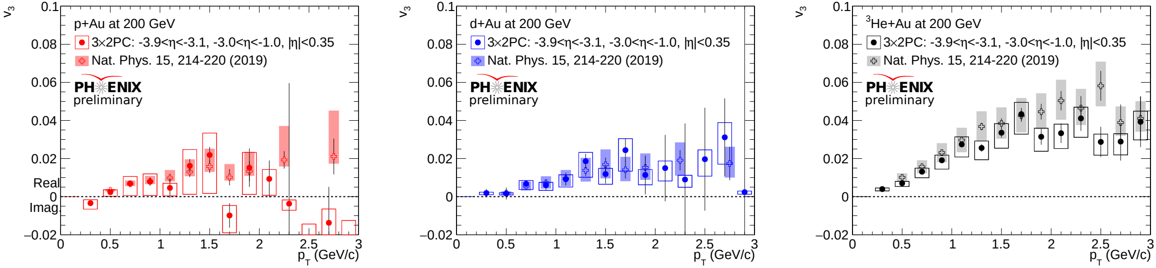
Large discrepancy between STAR and PHENIX for v_3

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
  —Very different sensitivity to key experimental effects (beam position, detector alignment)

PHENIX data update



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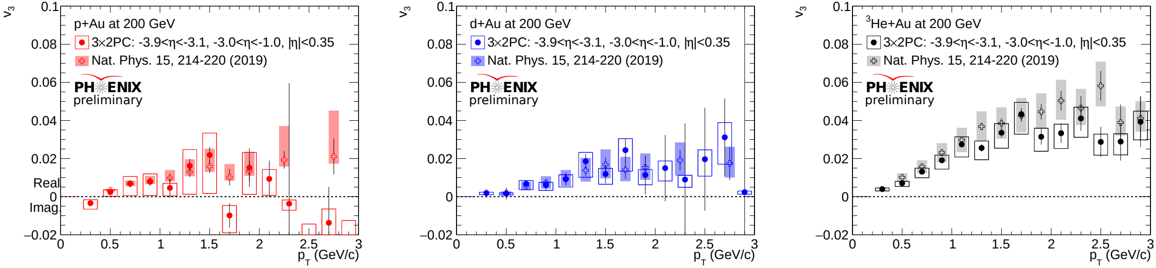

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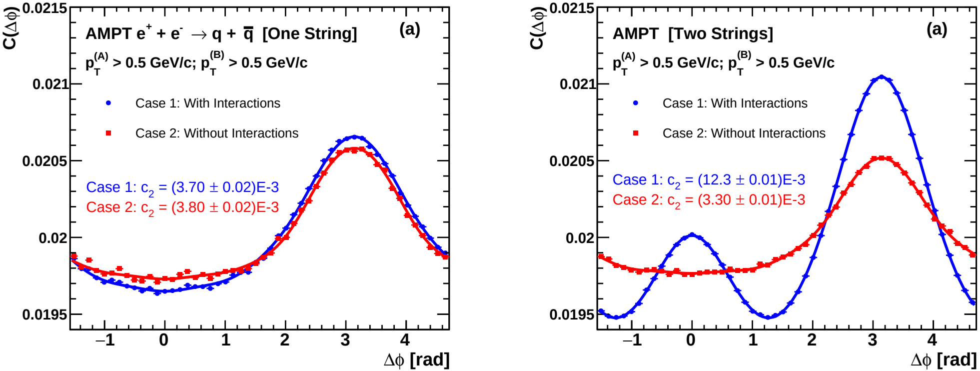
- All new analysis using two-particle correlations with event mixing instead of event plane method
  —Completely new and separate code base
  —Very different sensitivity to key experimental effects (beam position, detector alignment)
- It's essential to understand the two experiments have very different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

Intermission

How about *extremely* small systems?

Extremely small systems in AMPT

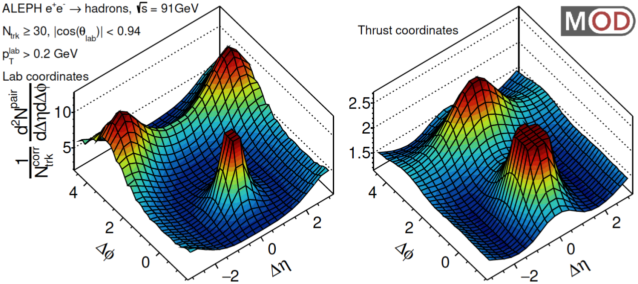
J.L. Nagle et al, Phys. Rev. C 97, 024909 (2018)

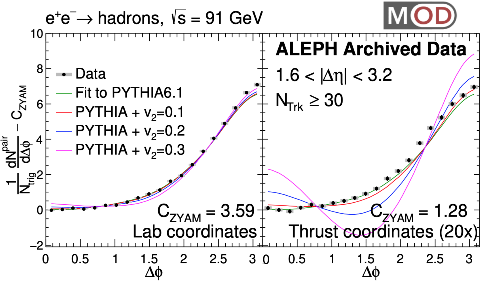


- A single color string ($e^+ + e^-$ collisions) shows no sign of collectivity
- Two color strings shows collectivity
  —In AMPT, $p+p$ has two strings and $p/d/^3$He+Au have more

Extremely small systems at LEP

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



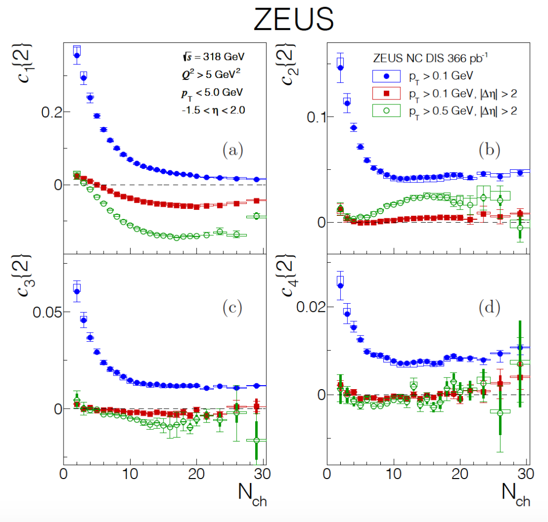


No apparent collectivity in ALEPH $e^+ + e^-$ data

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

Extremely small systems at HERA and the EIC

Abt et al, JHEP 04, 070 (2020)



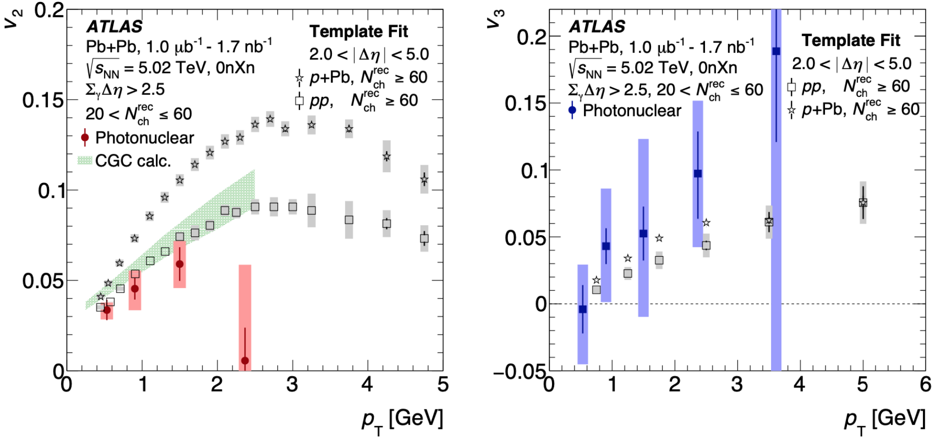
"The correlations observed here do not indicate the kind of collective behaviour recently observed at the highest RHIC and LHC energies in high-multiplicity hadronic collisions."

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

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

Extremely small systems at the LHC

ATLAS, arXiv:2101.10771



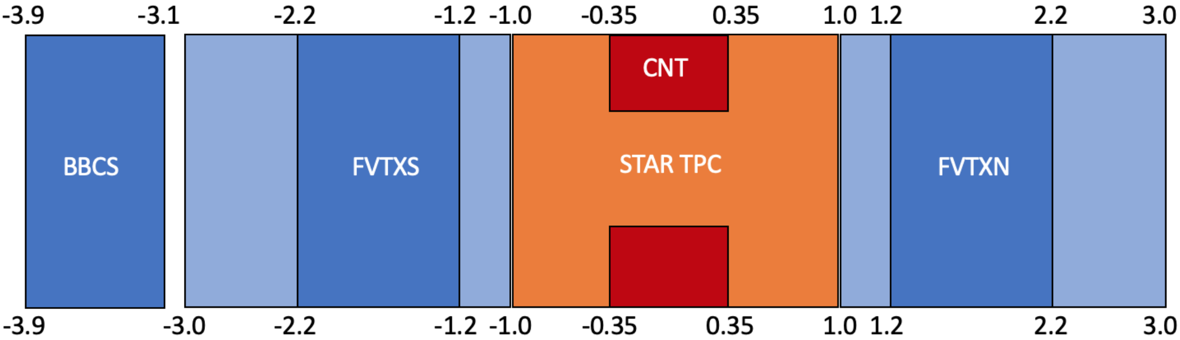
- Observation of collectivity in photonuclear collisions
- Collective picture: photon fluctuates into a vector meson (e.g. ρ), not so different from p+Pb
- Initial state picture: CGC calculation in good agreement, further investigation needed

Brief summary and outlook

- Identified particles in small systems
  —Minimal sensitivity to mass and strangeness
  —Strong sensitivity to baryon vs meson
  —Hadronization (likely via parton coalescence) plays a key role in system dynamics and observables
- Photons in small systems
  —Excess in photon R_{pA} at low p_T may indicate presence of thermal photons
  —Scaled photon yields may show turn-on of thermal photons from p+p to small systems to large systems
- Apparent (near-) universality of collectivity in hadronic collisions
  —Collectivity observed in photonuclear collisions (which may be purely hadronic)
- Apparent absence of collectivity in leptonic and semi-leptonic collisions
- Possibility for future observation of collectivity in (semi-) leptonic collisions?
  —Both interest and opportunity in e+A collisions at the EIC
  —Far-future e^{+}+e^{-} colliders *might* reach necessary conditions for collectivity

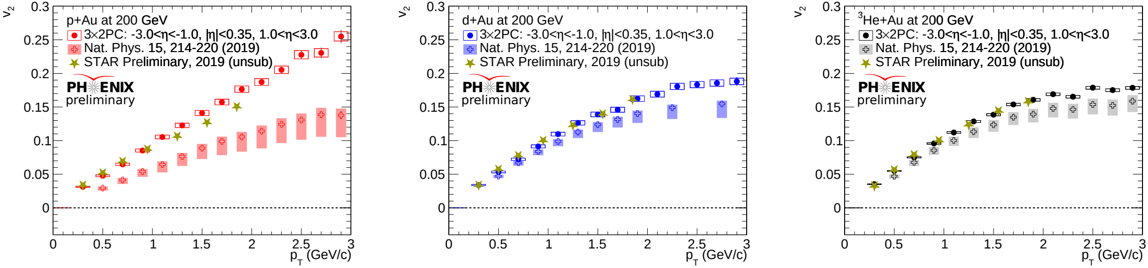
Extra material

STAR and PHENIX detector comparison

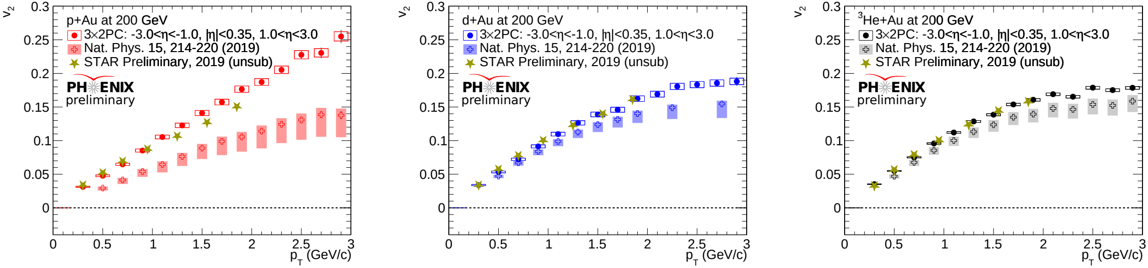


- The Nature Physics paper uses the BBCS-FVTXS-CNT detector combination
  —This is very different from the STAR analysis
- We can try to use FVTXS-CNT-FVTXN detector combination to better match STAR
  —Closer, and "balanced" between forward and backward, *but still different*

More STAR and PHENIX data comparisons



More STAR and PHENIX data comparisons



- Good agreement with STAR for v_2
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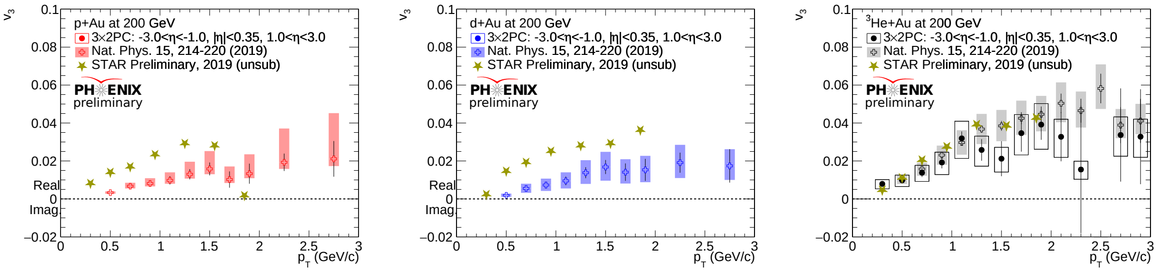

- Good agreement with STAR for v_2
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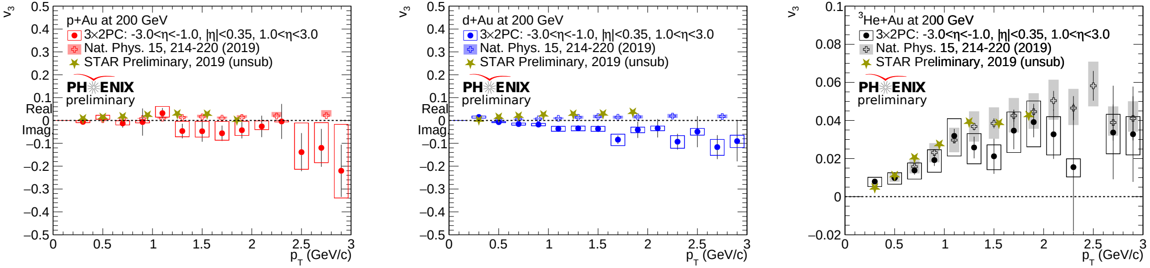
- Strikingly different results for v_3
  —Rather different physics for the two different pseudorapidity acceptances
  —Decorrelation effects much stronger for v_3 than v_2

More STAR and PHENIX data comparisons



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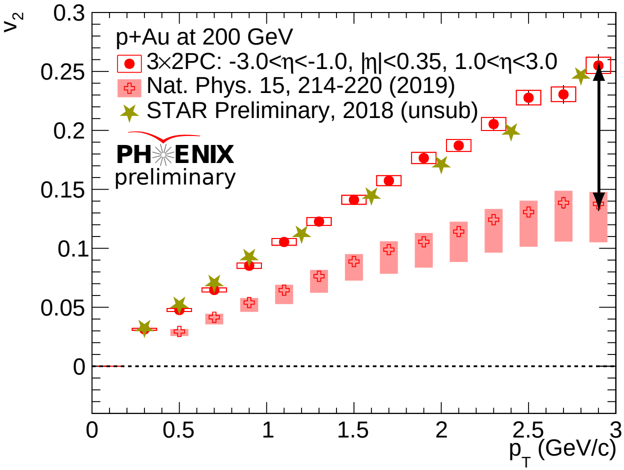
Understanding the nonflow contribution: v_2 in p+Au as a case study



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

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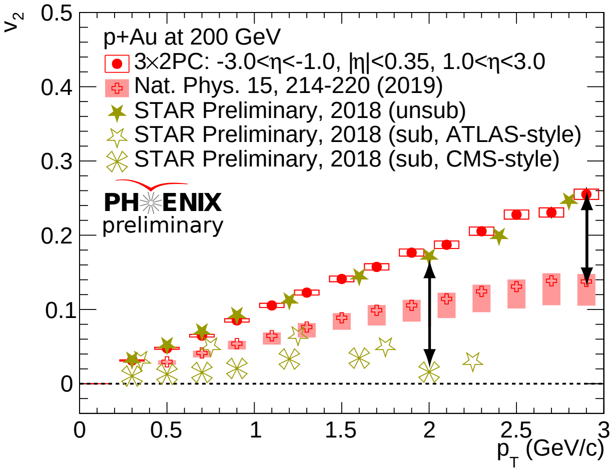
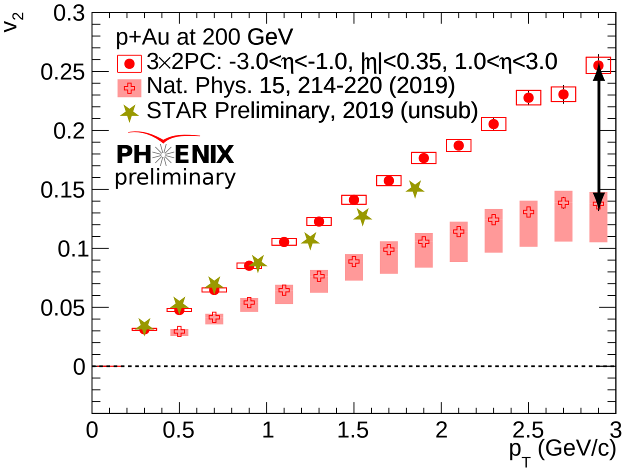


- The large difference between the PHENIX published and STAR preliminary in this case is nonflow
- PHENIX suppresses nonflow via kinematic selection
- STAR applies non-flow subtraction procedure
- One needs to be careful about the risk of over-subtraction methods—S. Lim et al, Phys. Rev. C 100, 024908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

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



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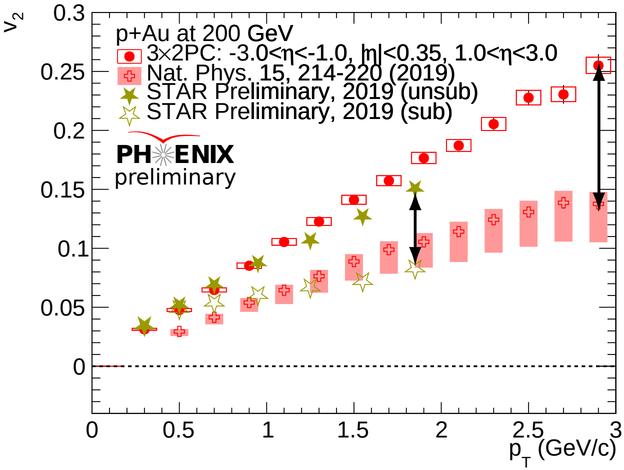
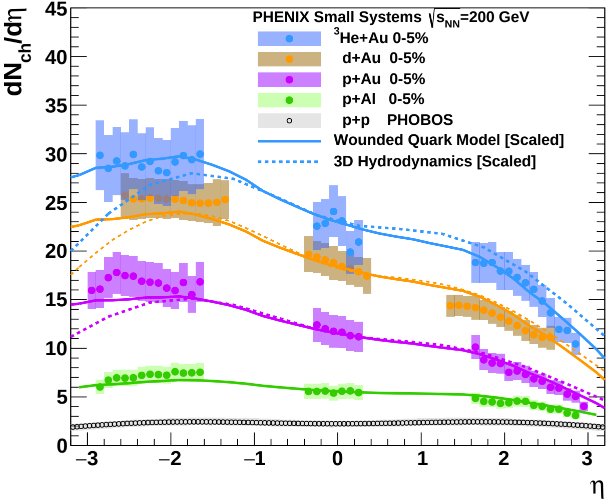


- The large difference between the PHENIX published and STAR preliminary in this case is nonflow
- PHENIX suppresses nonflow via kinematic selection
- STAR applies non-flow subtraction procedure
- Considerable improvement in nonflow subtraction in STAR 2019 preliminary, reasonable agreement with PHENIX

Longitudinal dynamics in small systems

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



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

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

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

Longitudinal dynamics in small systems

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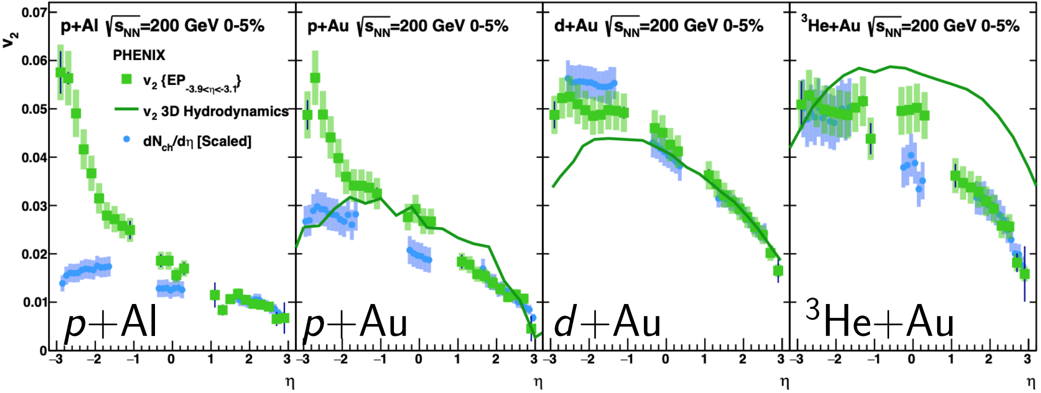

- v_2 vs η in p+Al, p+Au, d+Au, and ^{3}He+Au
- Good agreement with 3D hydro for p+Au and d+Au (Bozek et al, PLB 739, 308 (2014))

Longitudinal dynamics in small systems

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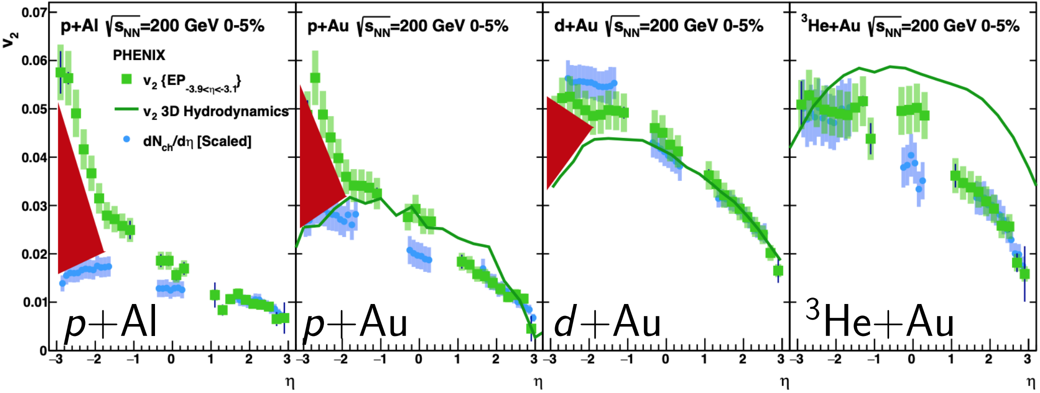

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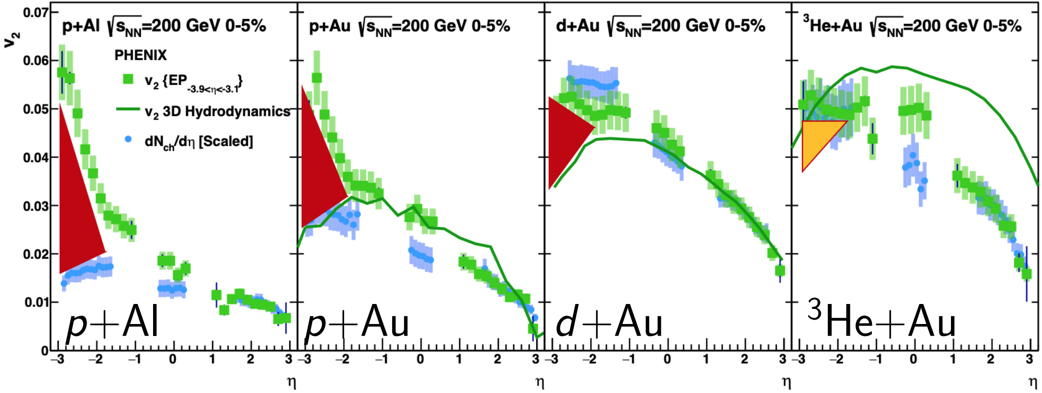

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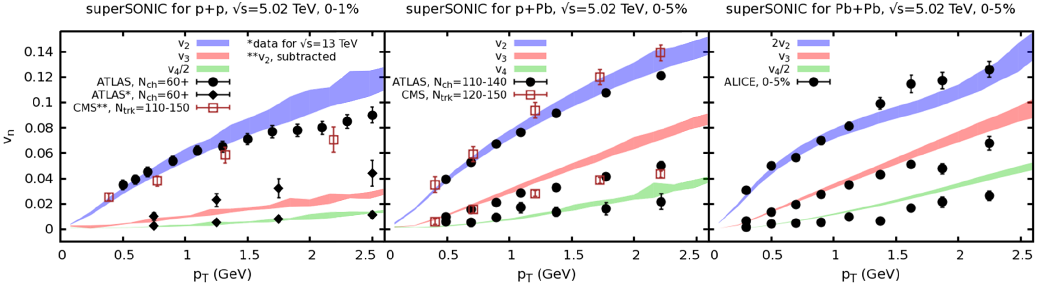
Azimuthal anisotropy measurements

Weller & Romatschke, Phys. Lett. B 774, 351 (2017)

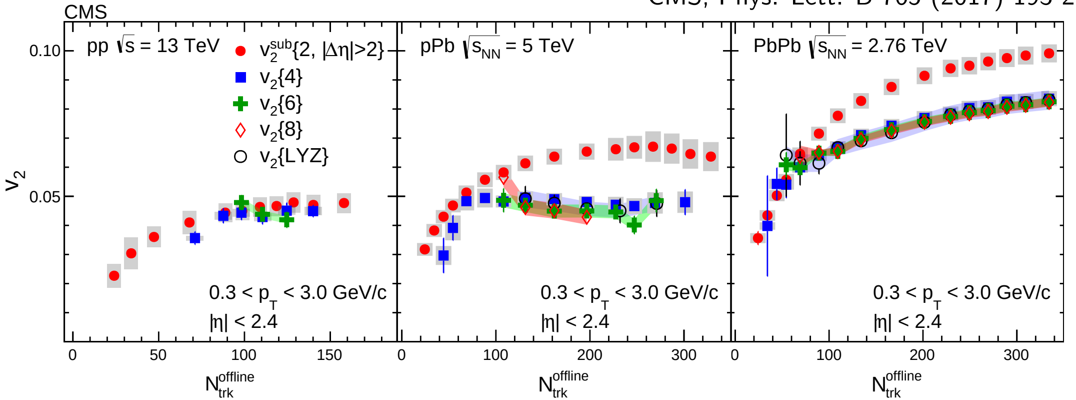


- Hydrodynamics provides simultaneous description of v_2, v_3, v_4 in p+p, p+Pb, Pb+Pb

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

Multiparticle Correlations

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

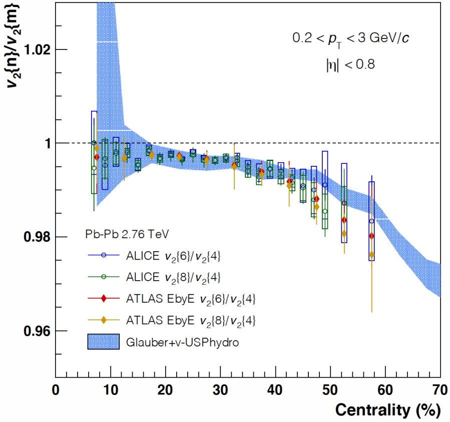


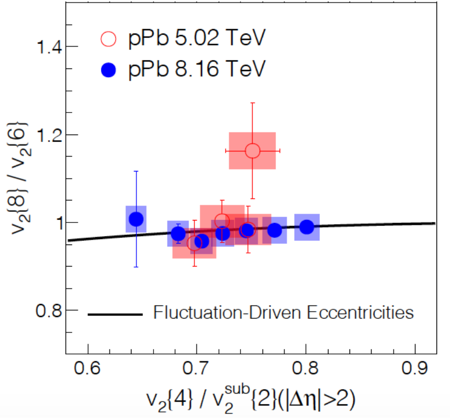
- Fluctuations are very important and manifest in multiparticle correlations $v_2\{2, |\Delta\eta| > 2\} = \sqrt{v_2^2 + \sigma^2},\ v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx \sqrt{v_2^2 - \sigma^2}$

Multiparticle Correlations

ALICE, JHEP 1807, 103 (2018)

CMS, Phys. Rev. C 101, 014912 (2020)



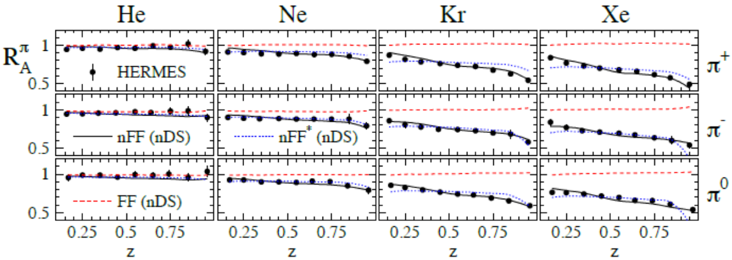


Ratios $(v_n\{j\}/v_n\{k\}) \rightarrow$ insights into fluctuations via probability dist $P(v_n)$

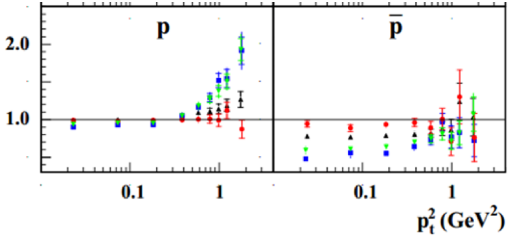
p+Pb data exhibit expected patterns based on geometry

Hadronization at the EIC

HERMES, Eur. Phys. J. A 47, 113 (2011)



HERMES, Phys. Lett. B 780, 1 (2007)



- Hadronization is modified in *e*+*A* collisions relative to *e*+*d*
- Connection to modification observed in small/large heavy ion collisions?