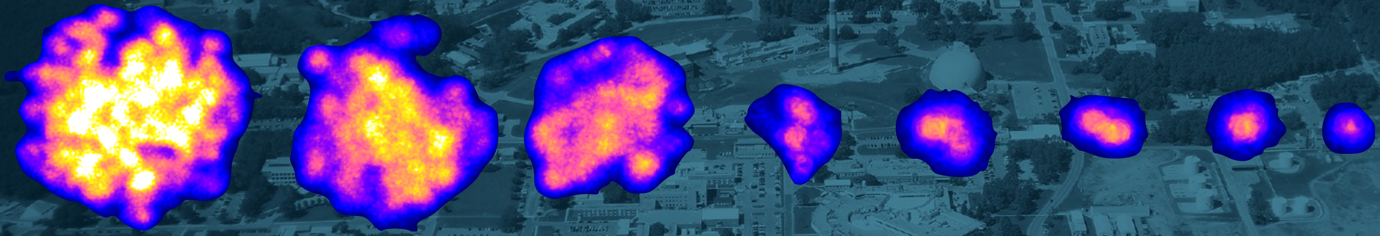
Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY



A brief review on collectivity in small collision systems

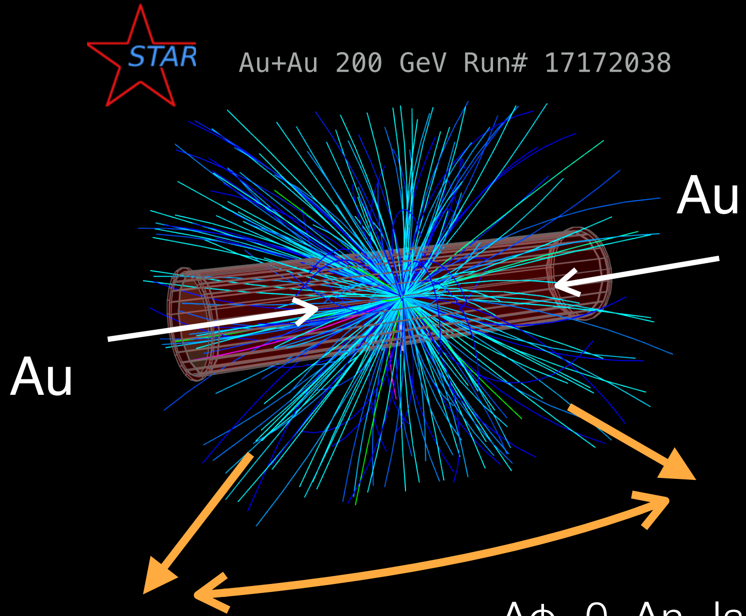
Prithwish Tribedy
(Brookhaven National Laboratory)

A Virtual Tribute to Quark Confinement and the Hadron Spectrum 2021
August 2-6, 2021

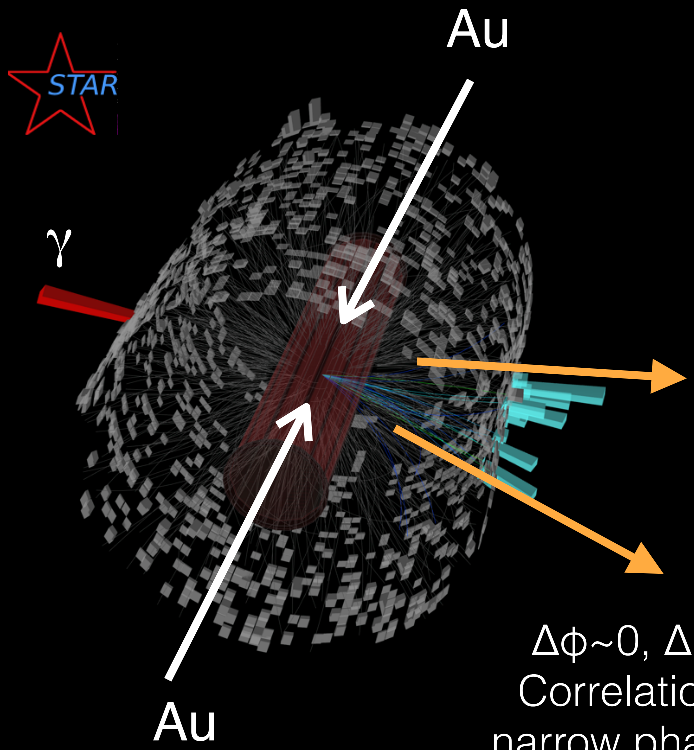
Outline

- Introduction
  - My definition of collectivity & why it is interesting
- What drives collectivity in small collision systems ?
  - Key players in the game
- Pinning down the origin of collectivity with RHIC small system scan
  - Predictions from initial state (CGC) and final state (Hydrodynamics)
- The hybrid framework to study collectivity in small systems
  - Framework combining CGC + Hydro. and predictions
- Strong acceptance dependence and puzzle with triangular flow
  - Where do we see shape engineering works?
- Further attempts to distinguish initial & final state effects
  - Correlation between transverse momentum and anisotropy harmonics
- Most recent venture: Collectivity in Photon included collisions
  - Collectivity search & building a bridge between RHIC/LHC and EIC

Pattern of particle emission



Δϕ~0, Δη~large
(Correlation pattern repeated
over wide phase space)

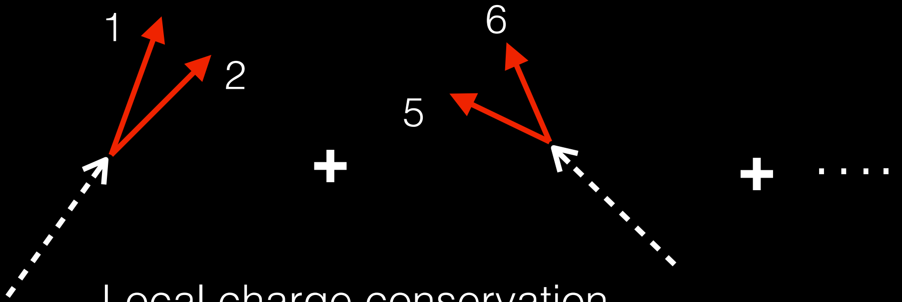


Δϕ~0, Δη~small
Correlation over a
narrow phase space

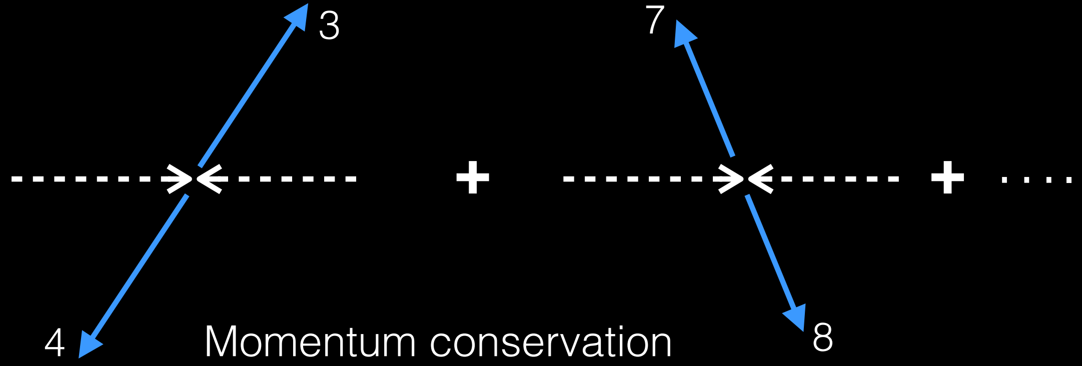
In collisions very often a pattern of particle emission is observed that span over a wide phase space

What is collectivity ?

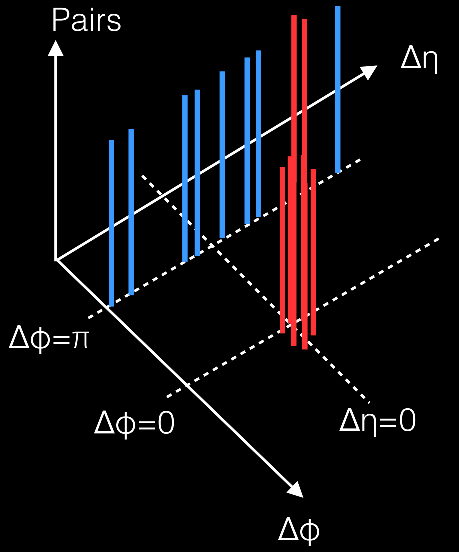
At fundamental levels conservation laws determine correlation among few particles



Local charge conservation



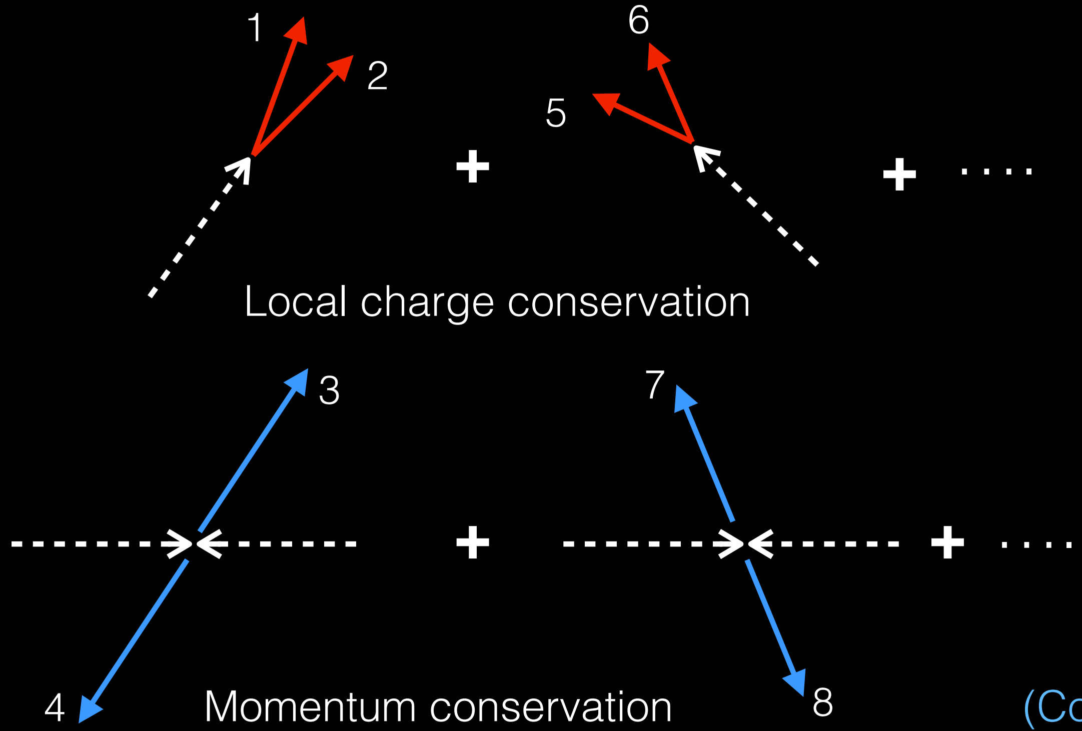
Momentum conservation

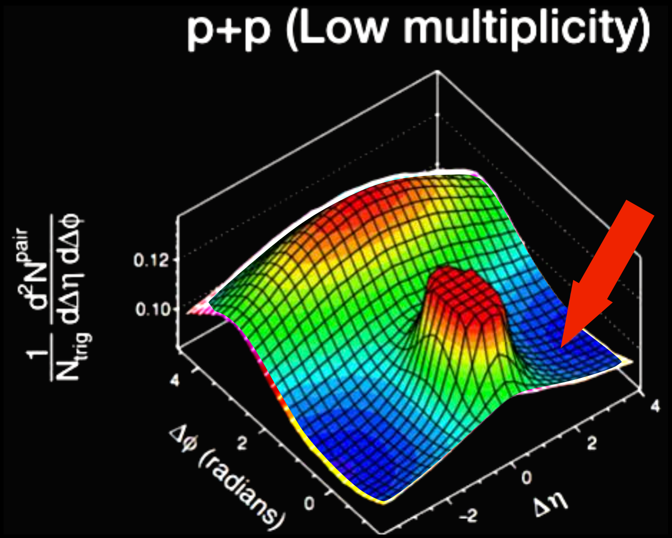


These correlations will not fill the full-phase space

What is collectivity ?

At fundamental levels conservation laws determine correlation among few particles



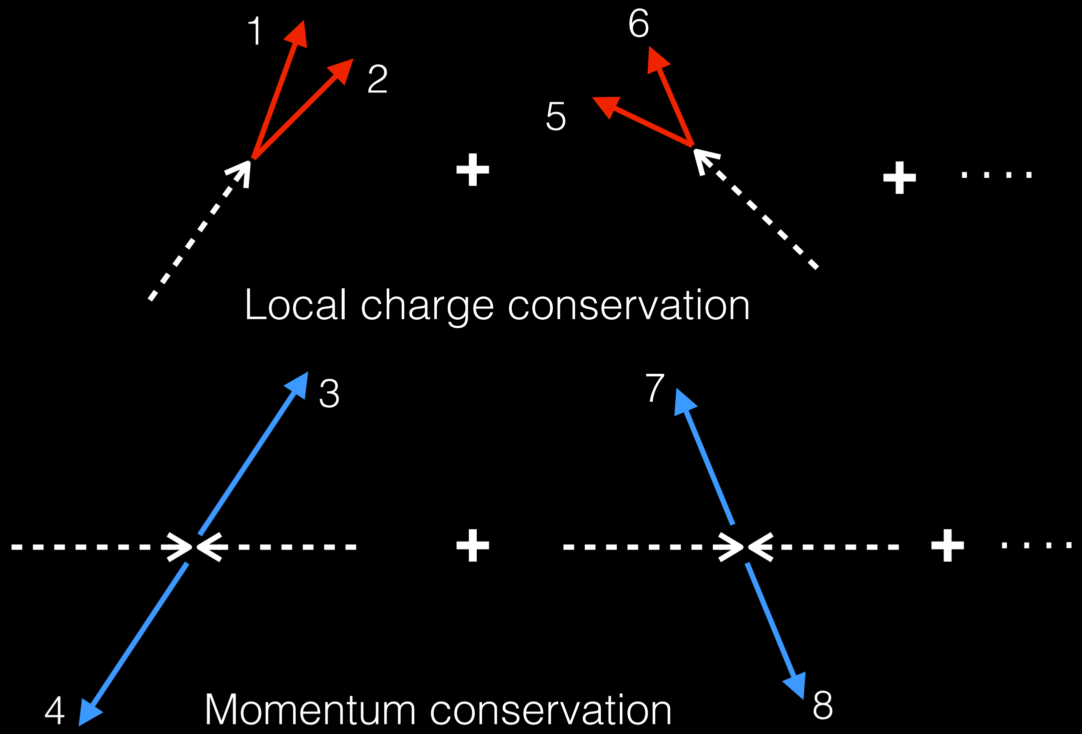


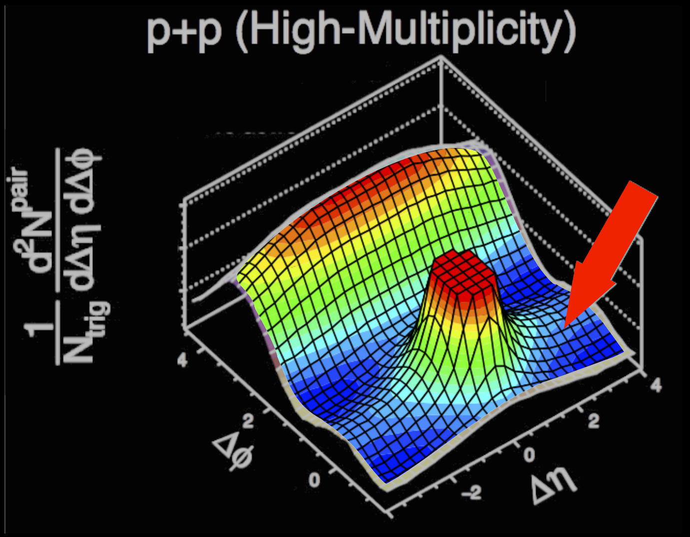
These correlations will not fill the full-phase space (Seen in experiment)

(Conservation $\Longrightarrow$ perfect configurations)

What is collectivity ?

At fundamental levels conservation laws determine correlation among few particles

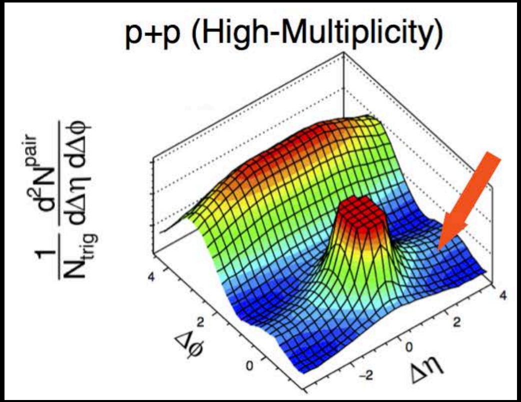


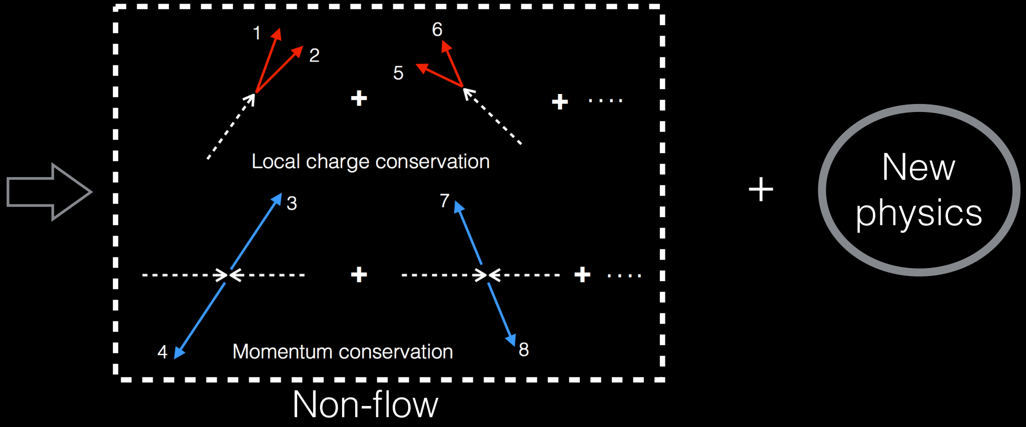


Violation from such scenario is striking

What is collectivity ?

Deviations from these perfect configurations or correlation among few particles ⟹ Important physics at play (often non-perturbative)





Collectivity ⟹ observation of a specific pattern or behavior that is followed by most of its constituents in a system

Observing correlations among many must be accompanied by a large scale deviation ⟹ interesting to study with decreasing system size

Au+Au → p+A → p+p → e(γ)+A → e(γ)+p → e+e

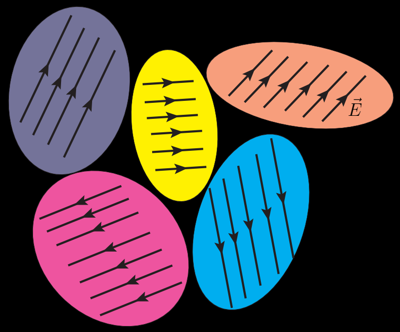
What drives collectivity in small collision systems ?

Origin of collectivity: initial state correlations from CGC

Quantum correlations due to
Bose enhancement / Glasma graphs

Enhanced probability to find two gluons with the same transverse momentum.

Classical correlations due to
local anisotropy 1/Qs

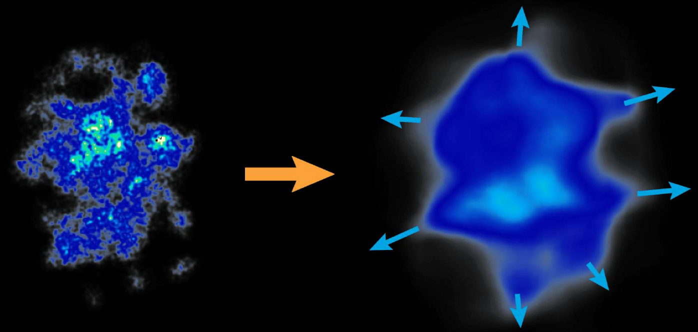


Gluons hitting the same domain in target get scatter in the same direction

Gelis,Lappi Venugopalan PRD 78 054020 (2008), PRD 79 094017 (2009); Dumitru, Gelis, McLerran,Venugopalan NPA810, 91 (2008); Dumitru, Jalilian-Marian PRD 81 094015 (2010); Dusling, Venugopalan PRD 87 (2013); A. Dumitru, A.V. Giannini, Nucl.Phys.A933 (2014) 212; V. Skokov. Phys.Rev.D91 (2015) 054014; T. Lappi, B. Schenke, S. Schlichting, R. Venugopalan, JHEP 1601 (2016) 061; Kovner, Skokov, Phys.Rev. D98 (2018) no.1, 014004

Origin of collectivity: final state correlations from hydro

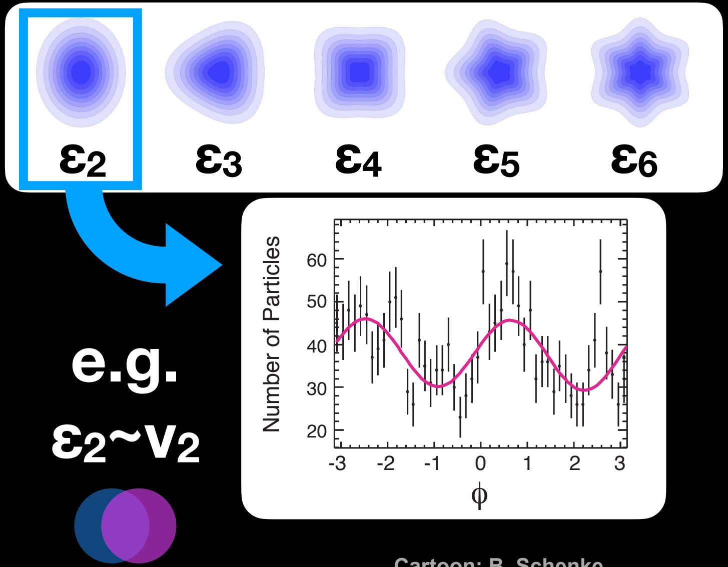
Azimuthal momentum anisotropy generated by medium response to the initial transverse geometry: Pressure gradients drive expansion



Initial energy density distribution

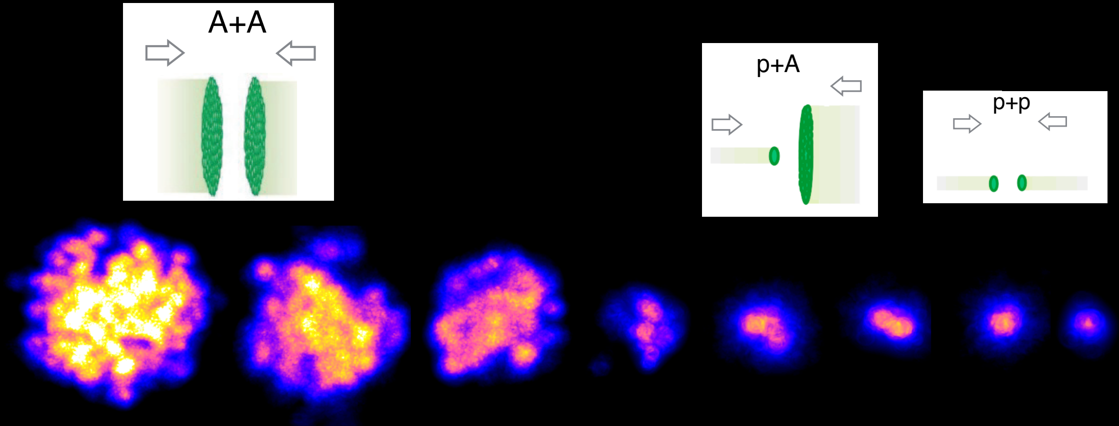
Hydrodynamic expansion

Fourier components of initial geometry



Cartoon: B. Schenke

Collectivity across systems



U+U Au+Au Ru+Ru O+O ^{3}He+Au d+Au p+Au p+p

fig: Chun Shen QM19

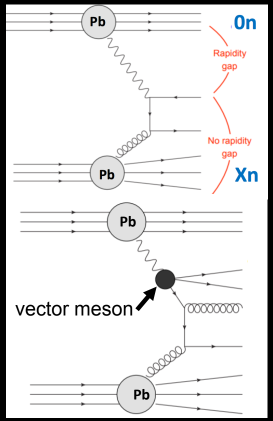
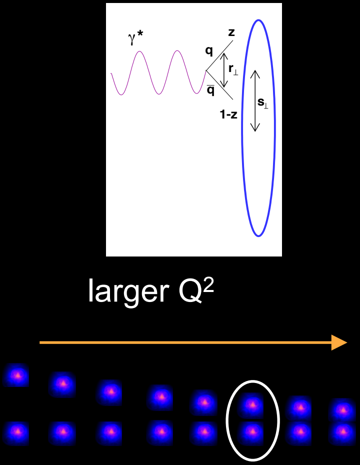
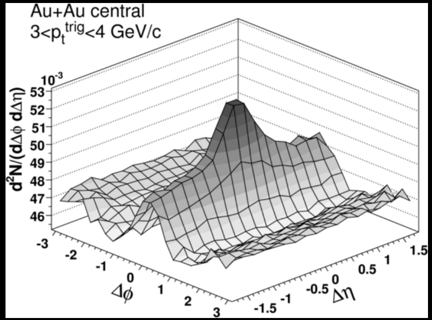


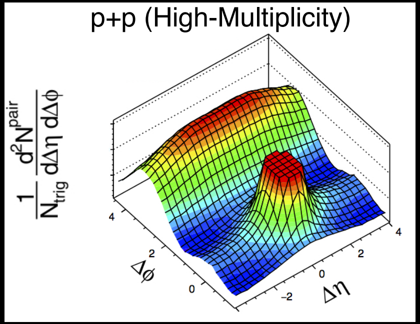
Photo-nuclear



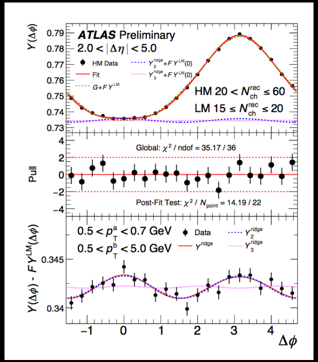
dipole+A (EIC)



STAR collaboration, Phys. Rev. Lett. 95, 152301
Phys. Rev. C 80 (2009) 64912



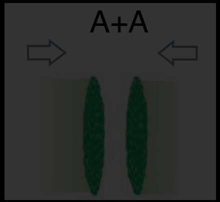
CMS collab., JHEP 1009:091,2010

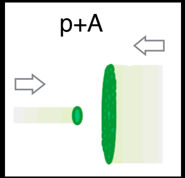


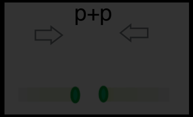
ATLAS collab.,
Phys. Rev. C 104, 014903 (2021)

Will γ*+A be the next small system ?

What drives collectivity in small systems ?







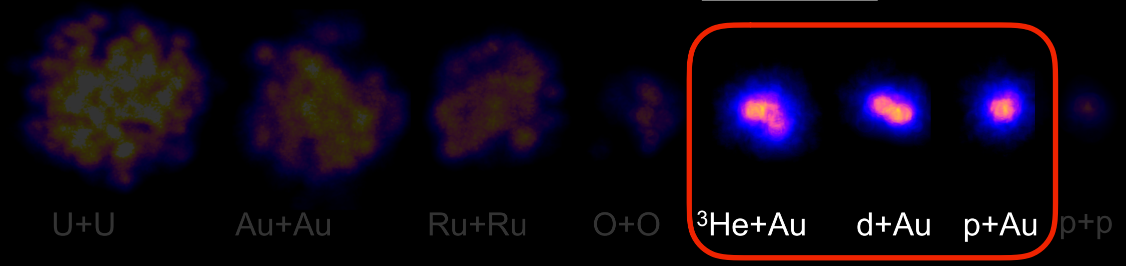


fig: Chun Shen QM19

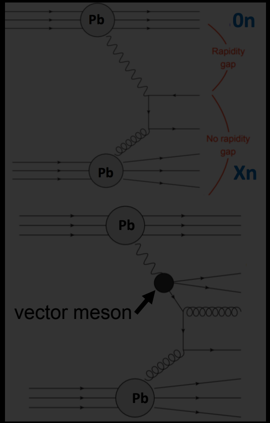
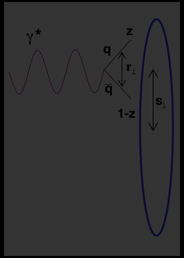
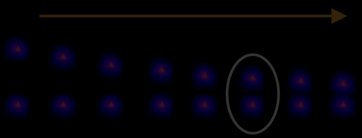


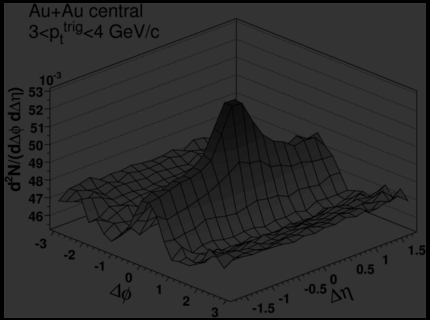
Photo-nuclear



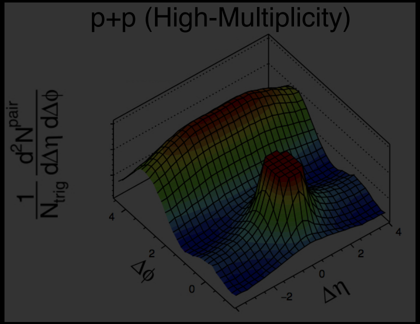
larger Q



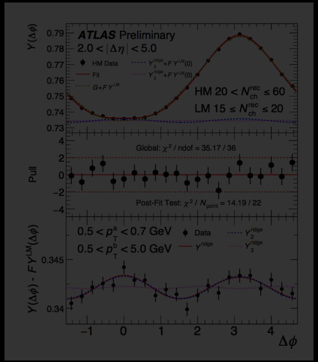
dipole+A (EIC)



STAR collaboration, Phys. Rev. Lett. 95, 152301
Phys. Rev. C 80 (2009) 64912



CMS collab.,



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

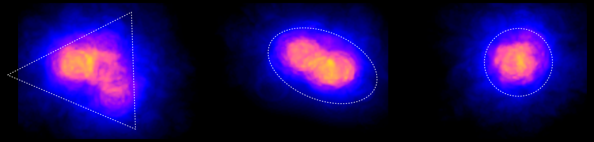
Will γ*+A be the next small system ?

Pinning down the origin of collectivity with RHIC small system scan

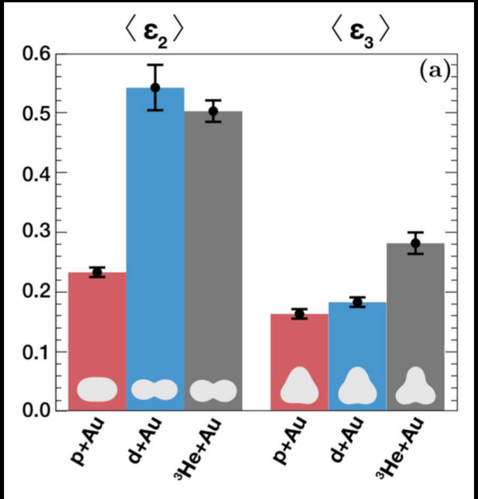
Event Engineering using different light ions

Shape engineering:

^{3}He+Au → Triangular
d+Au → Elliptical
p+Au → Circular



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



PHENIX collab., arXiv: 2107.06634v1
Nagle et. al., Phys. Rev. Lett. 113, 112301

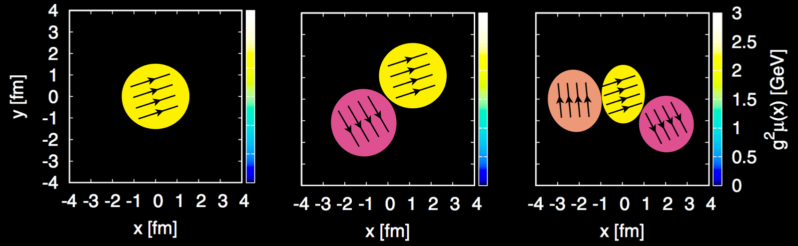
$\langle\varepsilon_{2,3}\rangle$	Collision system	Nucl. w/o NBD Fluc.	Nucl. w/ NBD Fluc.	Quarks w/ NBD Fluc.	IP-G w/ Nucl.	IP-G w/ Quarks
$\langle\varepsilon_2\rangle$	p+Au	0.23	0.32	0.38	0.10	0.50
	d+Au	0.54	0.48	0.51	0.58	0.73
	^{3}He+Au	0.50	0.50	0.52	0.55	0.64
$\langle\varepsilon_3\rangle$	p+Au	0.16	0.24	0.30	0.09	0.32
	d+Au	0.18	0.28	0.31	0.28	0.40
	^{3}He+Au	0.28	0.32	0.35	0.34	0.46

A primary motivation of the RHIC small system scan

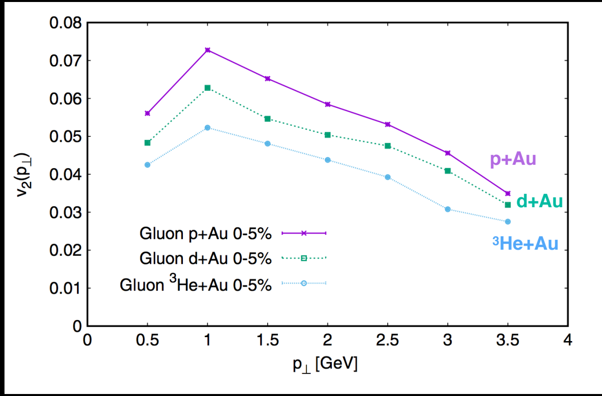
The ordering of v_3 is more decisive (v_2 ordering → stronger final state effect)

What drives collectivity in small systems ?

Color Glass Condensate (oversimplified)

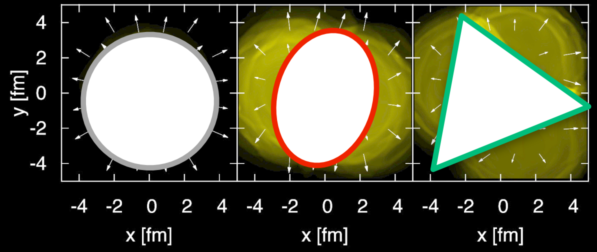


v_2(p+Au) > v_2(d+Au) > v_2(^{3}He+Au)

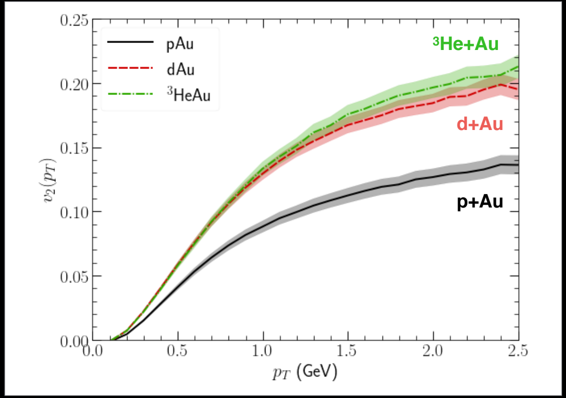


Mace, Skokov, PT, Venugopalan, Phys. Rev. Lett. Erratum 123, 039901(E) (2019)

Relativistic Hydrodynamics (oversimplified)



v_2(p+Au) < v_2(d+Au) ~ v_2(^{3}He+Au)



Schenke, Shen, PT, Phys. Rev. C 102, 044905 (2020)

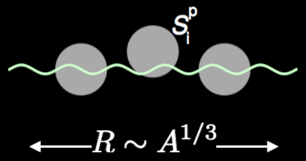
Two possible mechanisms, qualitatively different predictions

The hybrid framework to study collectivity in small systems

Initial state model based on CGC: IP-Glasma

Kowalski, Teaney hep-ph/0304189v3

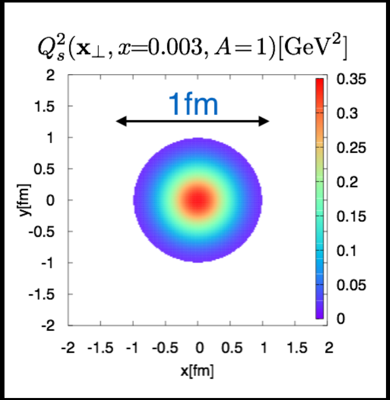
Schenke, PT, Venugopalan Phys. Rev. Lett. 108 (2012) 252301, Phys. Rev. C 86, 034908 (2012)



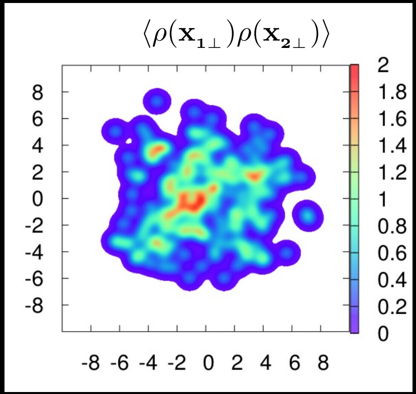
$$[D_\mu, F^{\mu\nu}] = J^\nu$$

$$A^i = A^i_{(A)} + A^i_{(B)}$$

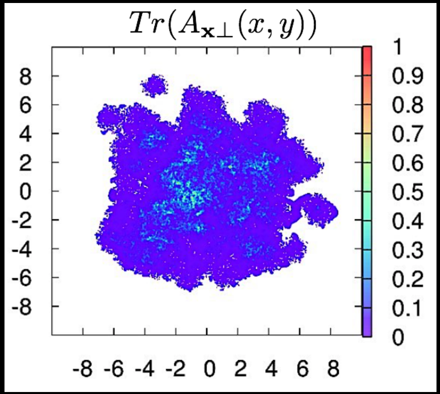
$$A^\eta = \frac{ig}{2}\left[A^i_{(A)}, A^i_{(B)}\right]$$



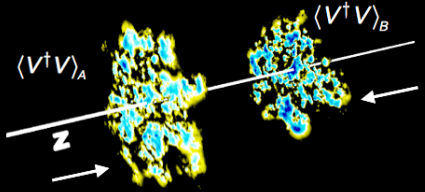
A saturation model of proton



Build a saturation model of nucleus



Estimate the color fields inside nucleus



Compute & evolve the color fields after collisions

Stress-Energy tensor: $T^{\mu\nu} = -g^{\mu\alpha}g^{\nu\beta}g^{\gamma\delta}F_{\alpha\gamma}F_{\beta\delta} + \frac{1}{4}g^{\mu\nu}g^{\alpha\gamma}g^{\beta\delta}F_{\alpha\beta}F_{\gamma\delta}$

Hybrid framework combining CGC + Hydro

Schenke, Shen, PT, Phys. Rev. C 102, 044905 (2020)

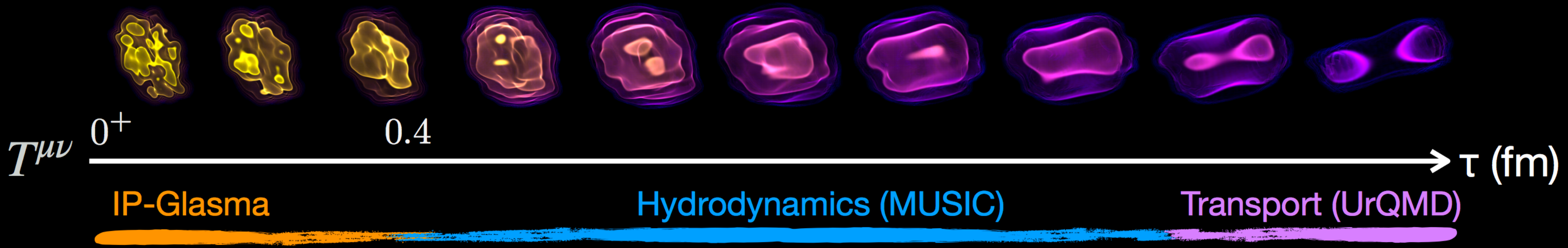


Fig: Chun Shen (different calculation)

$$T^{\mu\nu}_{\rm CYM} = T^{\mu\nu}_{\rm hydro} \longrightarrow u_\mu T^{\mu\nu}_{\rm hydro} = e u^\nu$$

$$\pi^{\mu\nu} = T^{\mu\nu}_{\rm CYM} - \frac{4}{3} e u^\mu u^\nu + \frac{e}{3} g^{\mu\nu}$$

$$\Pi = \frac{e}{3} - P(e)$$

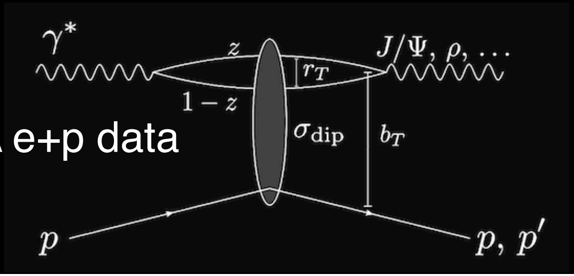
Smooth matching between CGC and Hydro

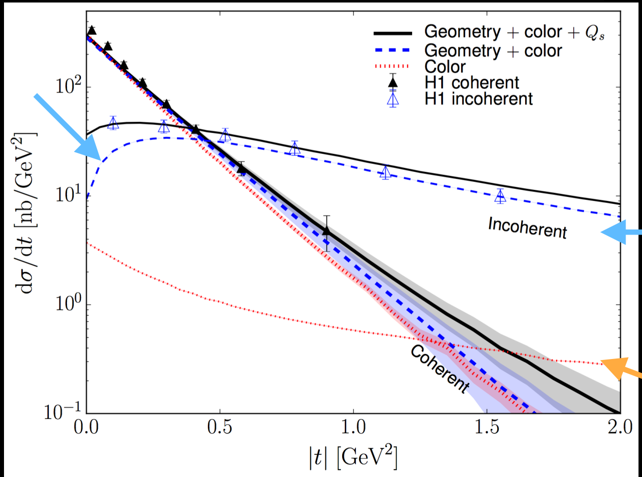
+ Landau Matching with lattice EoS

Cooper-Frye particlization

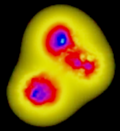
Independent constrains from Global data

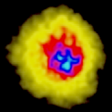
HERA e+p data

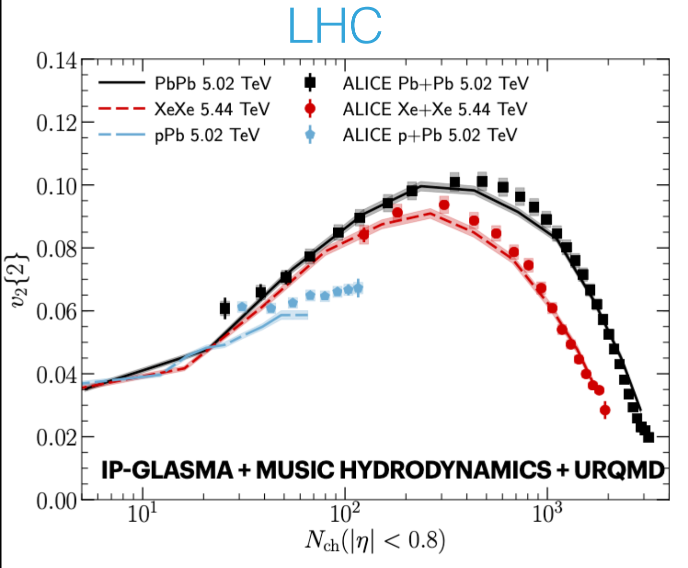




Mantysaari, Schenke, Phys. Rev. Lett. 117, 052301 (2016), Phys.Rev. D94 (2016) 034042



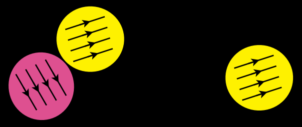




Before simulating hadronic collisions IP-Glasma is constrained by photon-induced collision data

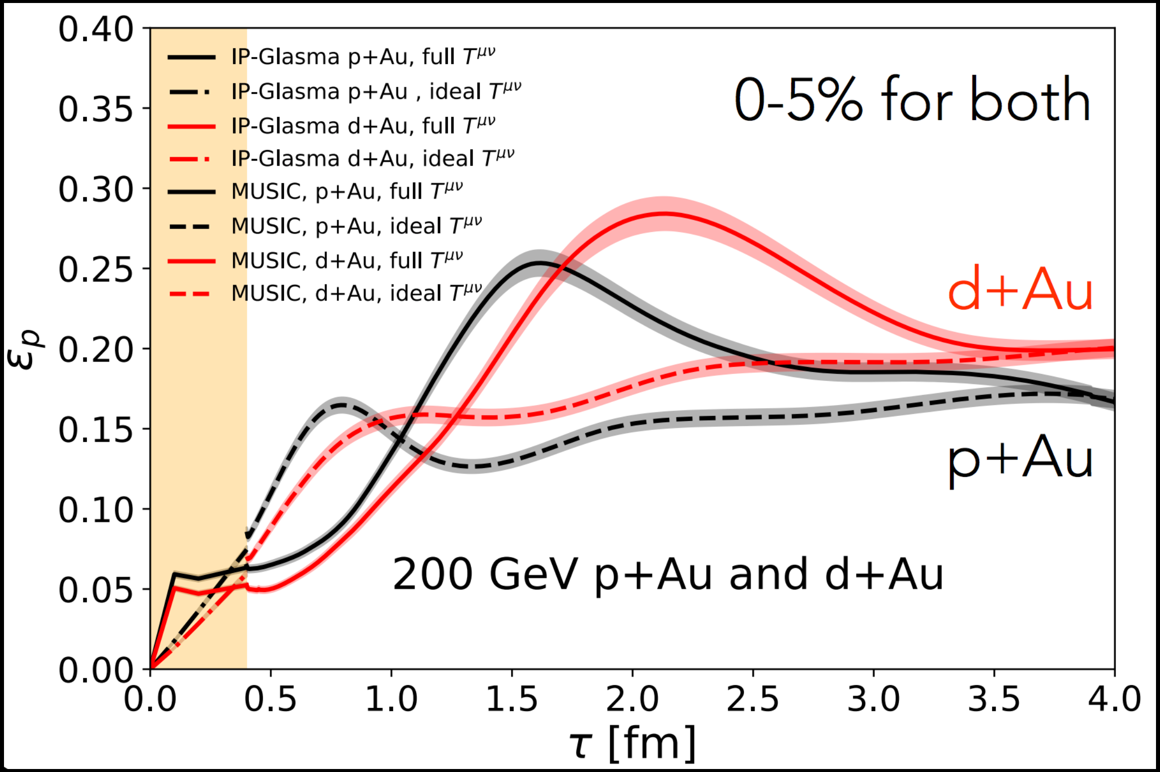
Using single set of parameters we fit bulk observables in different collision system

What drives collectivity in small systems ?

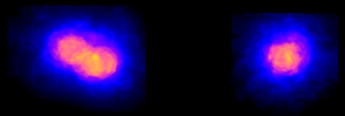


v_2(d+Au)<v_2(p+Au)

Early Time
(pre-equilibrium
CGC-dynamics
dominate)



Schenke, Shen, PT, Phys. Lett. B, 135322

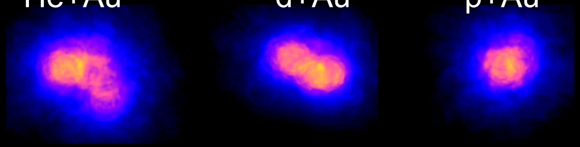


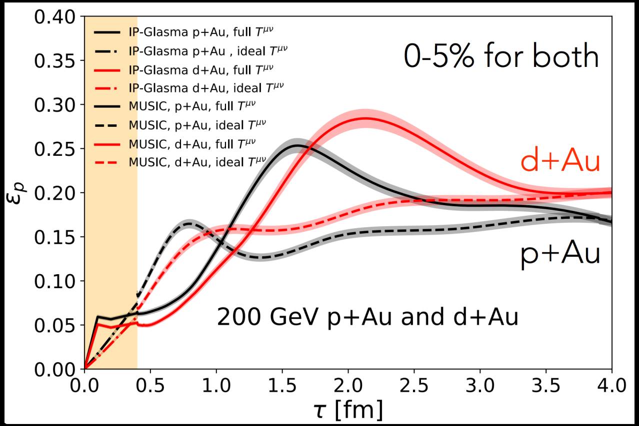
v_2(d+Au)>v_2(p+Au)

Late Time
(Final state/hydro
dominates)

What drives collectivity in small systems ?

^{3}He+Au d+Au p+Au





v_2(d+Au) < v_2(p+Au)

Early Time (pre-equilibrium CGC-dynamics dominate)

Schenke, Shen, PT, Phys. Lett. B, 135322

v_2(d+Au) > v_2(p+Au)

Late Time (Hydrodynamics dominate)

nature physics

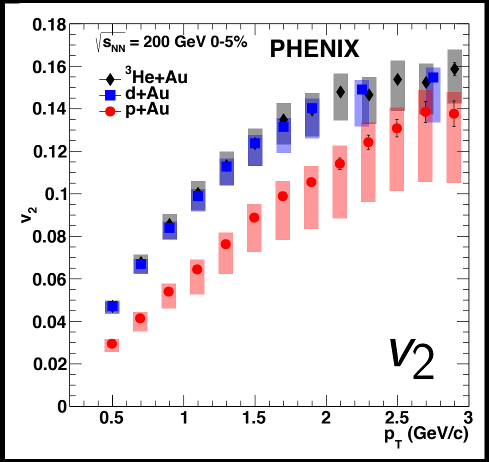
Creation of quark–gluon plasma droplets with three distinct geometries

PHENIX Collaboration

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

12k Accesses | **76** Citations | **227** Altmetric | Metrics

$v_2(^{3}\text{He+Au}) \sim v_2(\text{d+Au}) > v_2(\text{p+Au})$



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

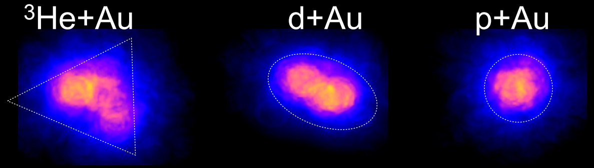
PHENIX results decisively establishes role of final state driving collectivity
our framework provides deeper insight on how it happens

Strong acceptance dependence and puzzle with triangular flow

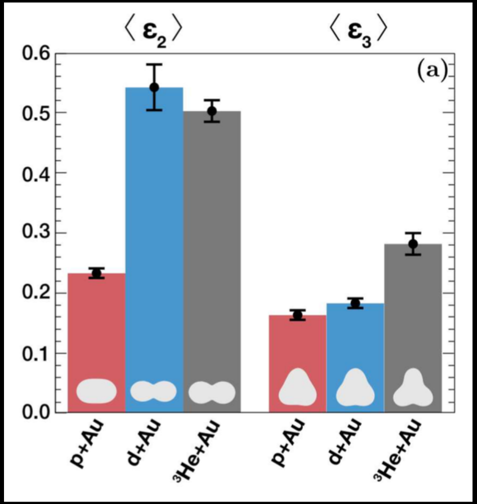
Puzzle with triangular flow in small systems

Shape engineering:

^{3}He+Au → Triangular
d+Au → Elliptical
p+Au → Circular



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



PHENIX collab., arXiv: 2107.06634v1
Nagle et. al., Phys. Rev. Lett. 113, 112301

$\langle\varepsilon_{2,3}\rangle$	Collision system	Nucl. w/o NBD Fluc.	Nucl. w/ NBD Fluc.	Quarks w/ NBD Fluc.	IP-G w/ Nucl.	IP-G w/ Quarks
$\langle\varepsilon_2\rangle$	p+Au	0.23	0.32	0.38	0.10	0.50
	d+Au	0.54	0.48	0.51	0.58	0.73
	^{3}He+Au	0.50	0.50	0.52	0.55	0.64
$\langle\varepsilon_3\rangle$	p+Au	0.16	0.24	0.30	0.09	0.32
	d+Au	0.18	0.28	0.31	0.28	0.40
	^{3}He+Au	0.28	0.32	0.35	0.34	0.46

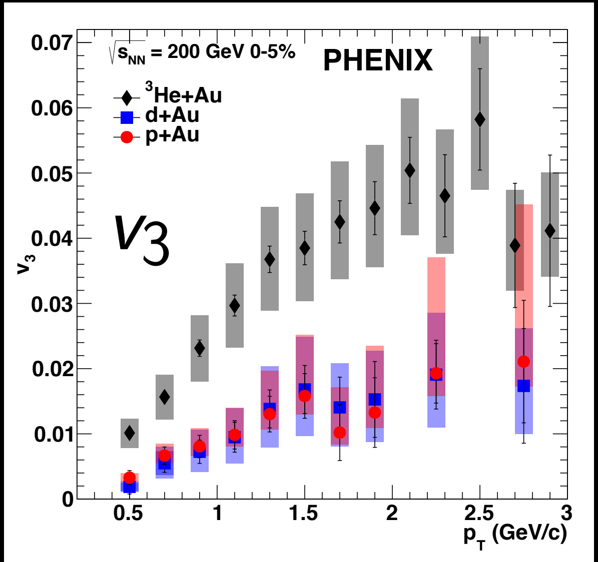
A primary motivation of the RHIC small system scan, confirmed by PHENIX data

The ordering of v_3 is more decisive (v_2 ordering → stronger final state effect)

Puzzle with triangular flow in small systems

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

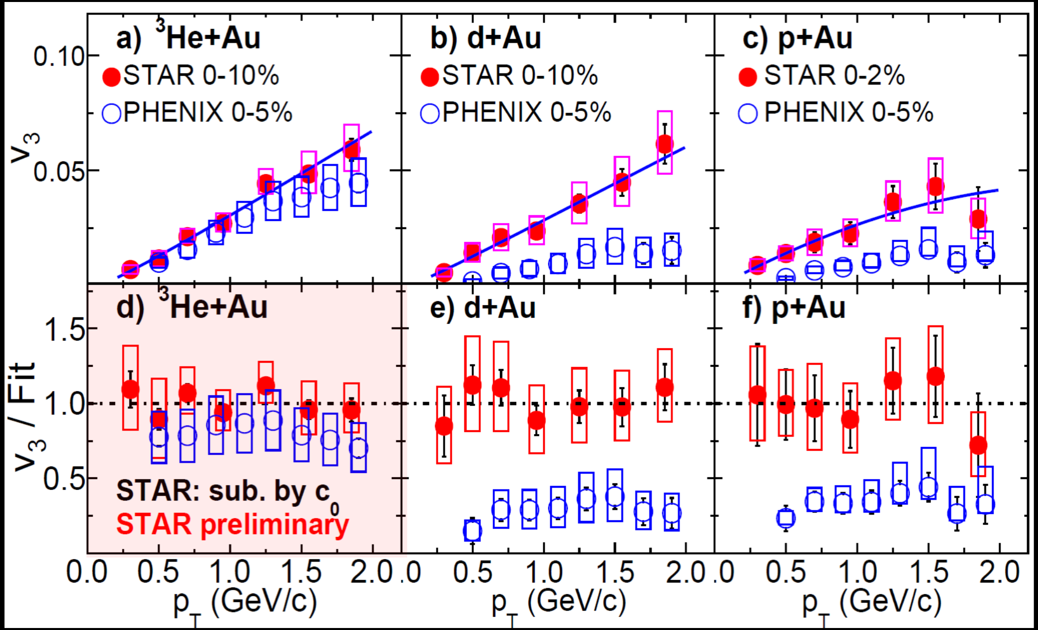
$v_3(^3He+Au) > v_3(d+Au) \sim v_3(p+Au)$



PHENIX results are compatible with shape engineering

$v_3(^3He+Au) \sim v_3(d+Au) \sim v_3(p+Au)$

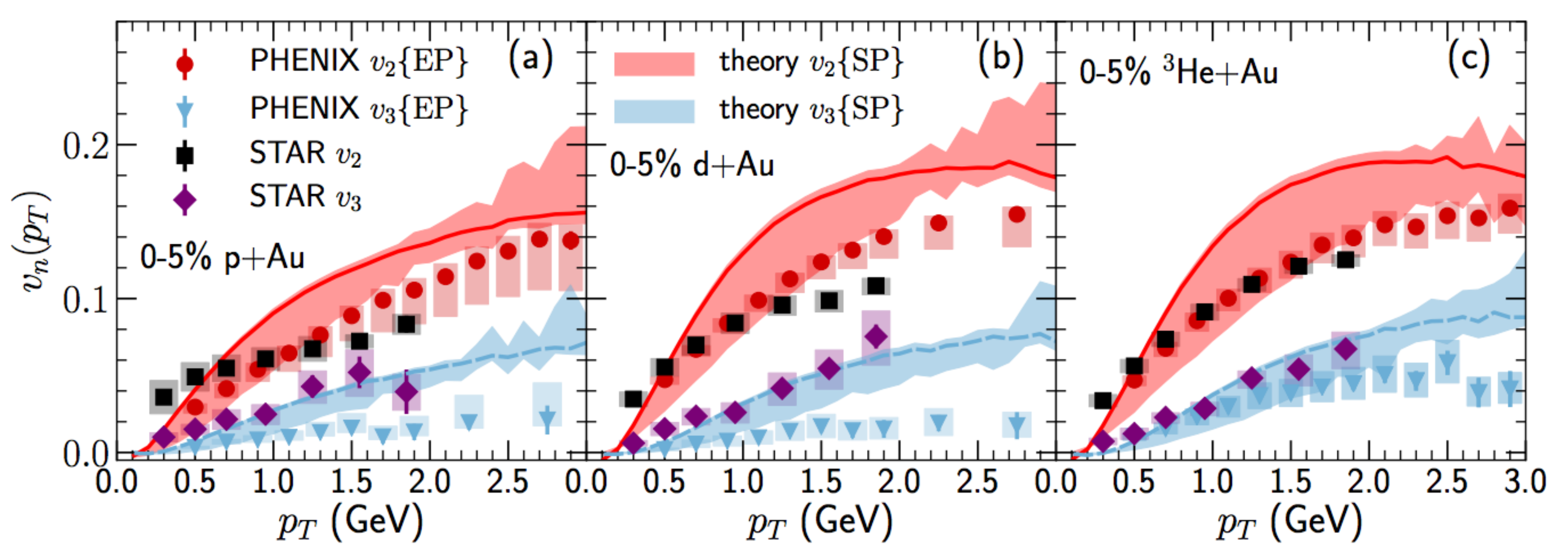
Shengli Huang, IS 2021



STAR mid-rapidity results seem to be not compatible with shape engineering expectations

Puzzle with triangular flow in small systems

B. Schenke, C. Shen, P. Tribedy, Phys.Lett.B 803 (2020) 135322; Data: C. Aidala et al. (PHENIX), Nature Phys. 15, 214 (2019) , STAR Preliminary data: Roy Lacey (QM2019)



Hydrodynamic simulations: describes small system v_2 well but also do not show strong evidence of shape engineering in terms of v_3

(Our framework is boost invariant, data have strong acceptance dependence)

Strong acceptance dependence of (raw) harmonic coefficients

PHENIX (3x2PC,EP)
$v_2(^3He+Au) \sim v_2(d+Au) > v_2(p+Au)$ ☺
$v_3(^3He+Au) > v_3(d+Au) \sim v_3(p+Au)$ ☺

PHENIX collab, Nature Phys. 15, 214–220 (2019)

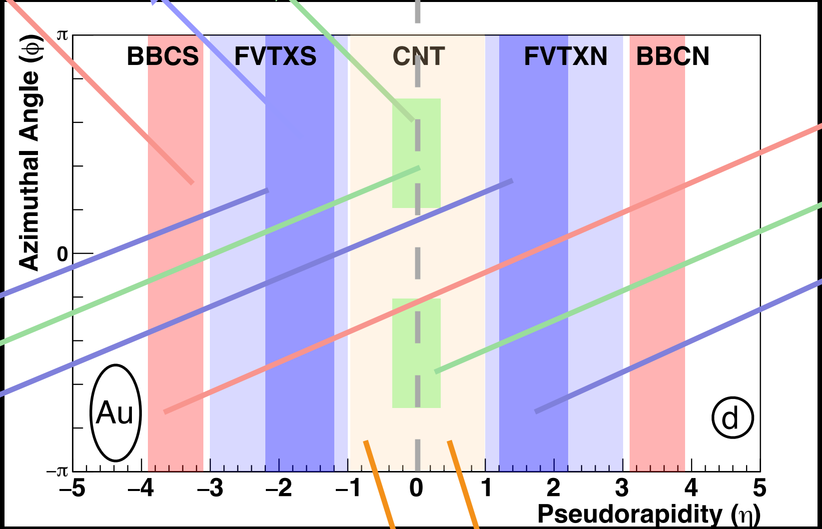
CGC+Hydro (Boost invariant)
$v_2(^3He+Au) \sim v_2(d+Au) > v_2(p+Au)$ ☺
$v_3(^3He+Au) \sim v_3(d+Au) \sim v_3(p+Au)$ ☹

Schenke, Shen, PT, Phys.Lett.B 803 (2020) 135322

PHENIX (3x2PC)
$v_2(p+Au) \geq v_2(d+Au) \geq v_2(^3He+Au)$ ☹

$v_3(^3He+Au) > 0$
$v_3(d+Au) = ?$
$v_3(p+Au) = ?$ ☹

PHENIX collab., arXiv: 2107.06634v1, Nagle et. al, arXiv:2107.07287



PHENIX (3x2PC)
$v_2(p+Au) \geq v_2(d+Au) \geq v_2(^3He+Au)$ ☹

$v_3(^3He+Au) > 0$
$v_3(d+Au) = ?$
$v_3(p+Au) = ?$ ☹

PHENIX collab., arXiv: 2107.06634v1
Nagle et. al, arXiv:2107.07287

STAR TPC (2PC)
$v_2(^3He+Au) \sim v_2(d+Au) > v_2(p+Au)$ ☺
$v_3(^3He+Au) \sim v_3(d+Au) \sim v_3(p+Au)$ ☹

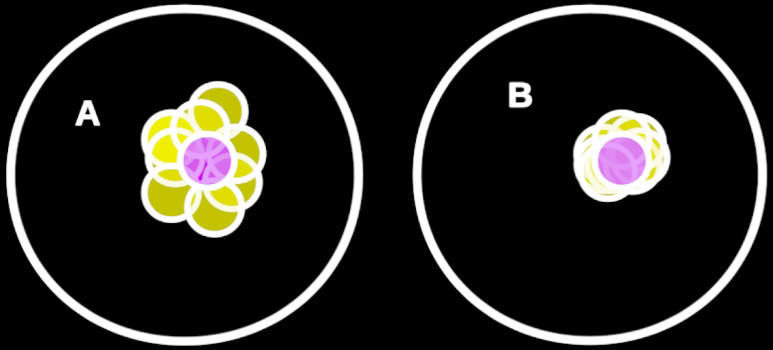
Shengli Huang, IS 2021

☺ Shape engineering works
☹ Doesn't work (or can't be checked)

Further attempts to distinguish initial & final state effects

If final state effects (hydro) dominates

G. Giacalone, B. Schenke and C. Shen, Phys. Rev. Lett. 125, 192301 (2020)



Event-by-event correlation between v2 and ⟨pT⟩

$$\hat{\rho}_2(v_2^2, \langle p_T \rangle) = \frac{\langle \hat{\delta} v_2^2 \hat{\delta} \langle p_T \rangle \rangle}{\sqrt{\langle (\hat{\delta} v_2^2)^2 \rangle \langle (\hat{\delta} \langle p_T \rangle)^2 \rangle}}$$

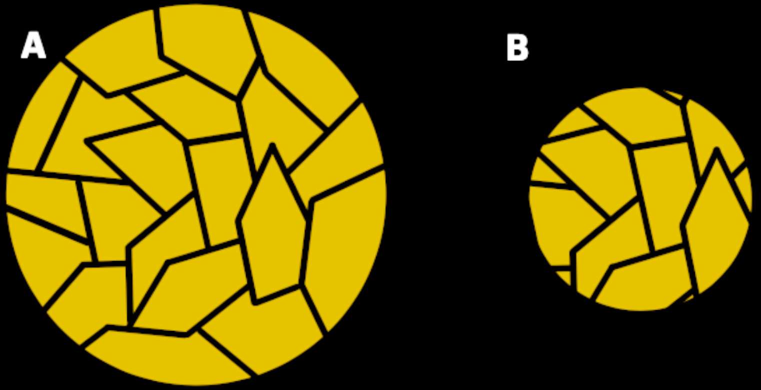
$R(A) > R(B)$ ➡ $\langle p_T \rangle (A) < \langle p_T \rangle (B)$

$\varepsilon_2(A) > \varepsilon_2(B)$ ➡ $v_2(A) > v_2(B)$

➡ v_2 and $\langle p_T \rangle$ are anti-correlated

If initial state effects (hydro) dominates

G. Giacalone, B. Schenke and C. Shen, Phys. Rev. Lett. 125, 192301 (2020)



Event-by-event correlation between v2 and ⟨pT⟩

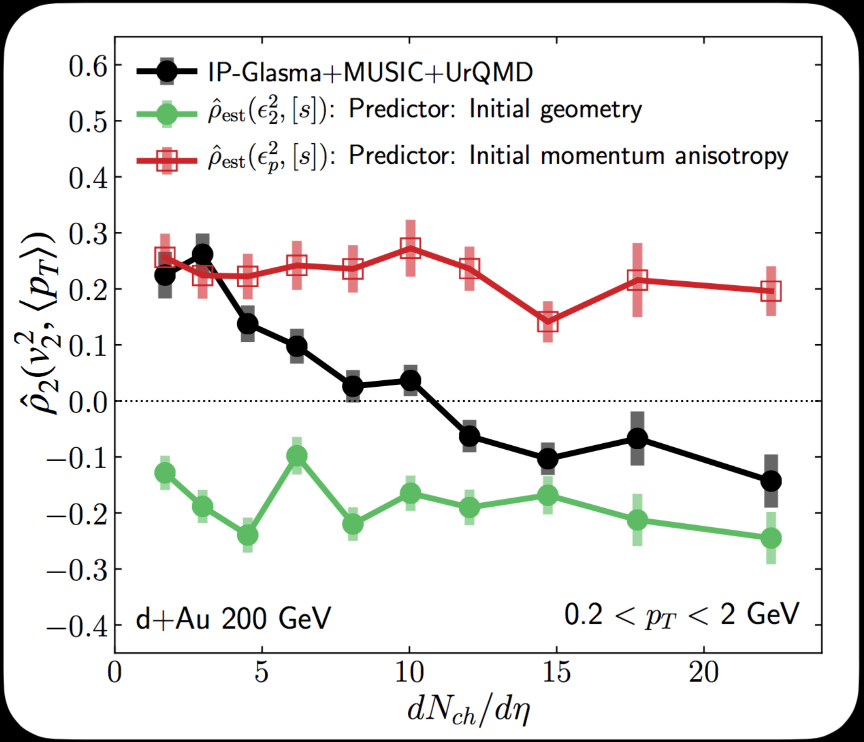
$$\hat{\rho}_2(v_2^2, \langle p_T \rangle) = \frac{\langle \hat{\delta} v_2^2 \hat{\delta} \langle p_T \rangle \rangle}{\sqrt{\langle (\hat{\delta} v_2^2)^2 \rangle \langle (\hat{\delta} \langle p_T \rangle)^2 \rangle}}$$

$R(A) > R(B)$ → $\langle p_T \rangle(A) < \langle p_T \rangle(B)$

$\varepsilon_p(A) < \varepsilon_p(B)$ → $v_2(A) < v_2(B)$

→ v_2 and $\langle p_T \rangle$ are correlated

Correlation between initial and final anisotropy



G. Giacalone, B. Schenke and C. Shen, Phys. Rev. Lett. 125, 192301 (2020)

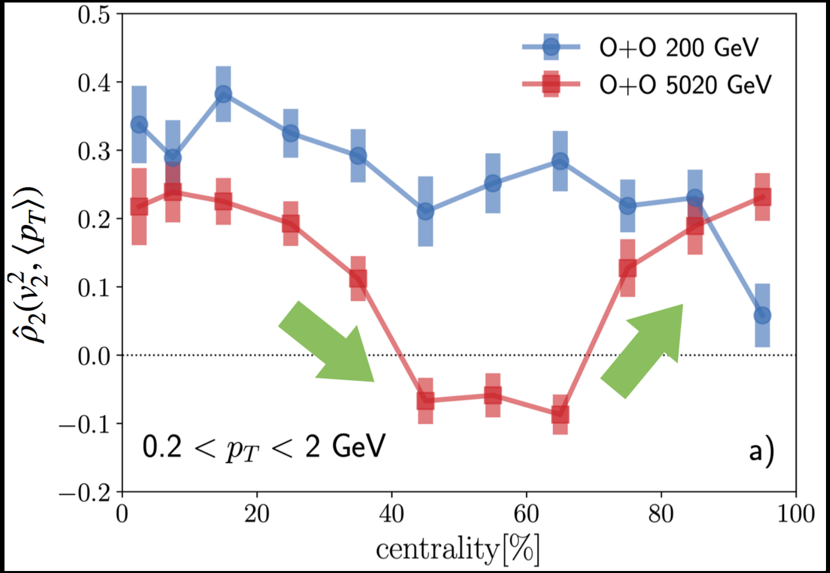
Event-by-event correlation between v2 and ⟨pT⟩

$$\hat{\rho}_2(v_2^2, \langle p_T \rangle) = \frac{\langle \hat{\delta} v_2^2 \hat{\delta} \langle p_T \rangle \rangle}{\sqrt{\langle (\hat{\delta} v_2^2)^2 \rangle \langle (\hat{\delta} \langle p_T \rangle)^2 \rangle}}$$

For $dN_{ch}/d\eta \approx 10$, switches from initial state correlation to final state correlation

Correlation between initial and final anisotropy

G. Giacalone, B. Schenke and C. Shen, Phys. Rev. Lett. 125, 192301 (2020), Lim, Nagle, Phys. Rev. C 103, 064906 (2021), Zhang et. al., arXiv:2103.01348

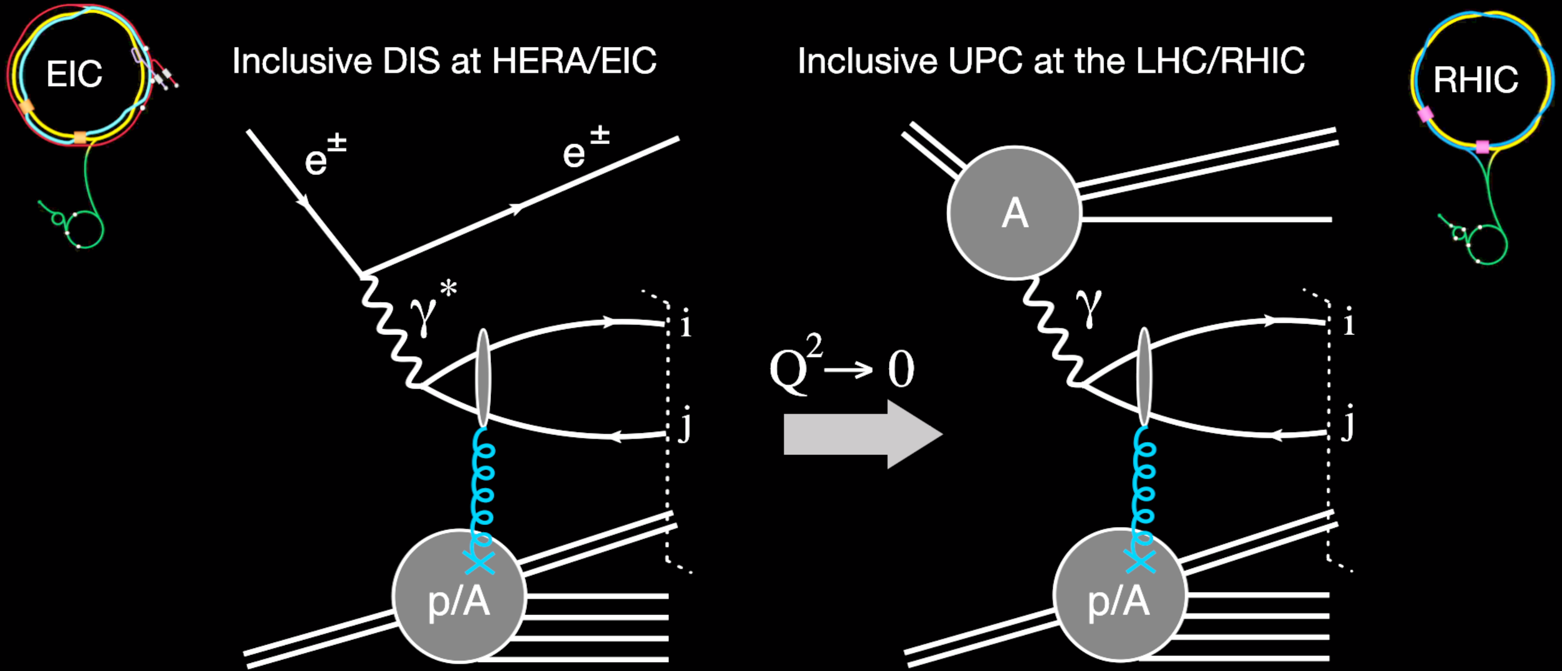


Double sign change @ LHC energy, No sign change @ RHIC energy

Opportunity: RHIC just took O+O data with wide acceptance STAR detector
Caution: This observable will be plagued by non-flow (conservation) effects

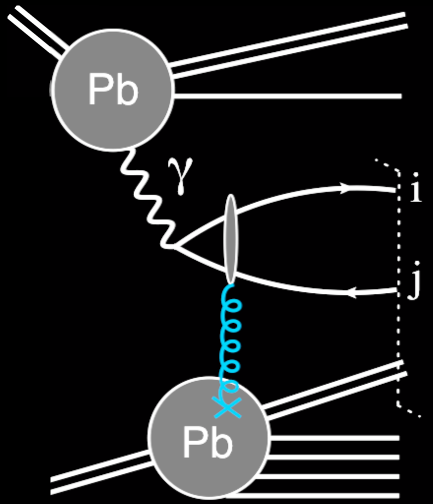
Most recent venture: Collectivity in Photon included collisions

Search for collectivity in photon induced collisions

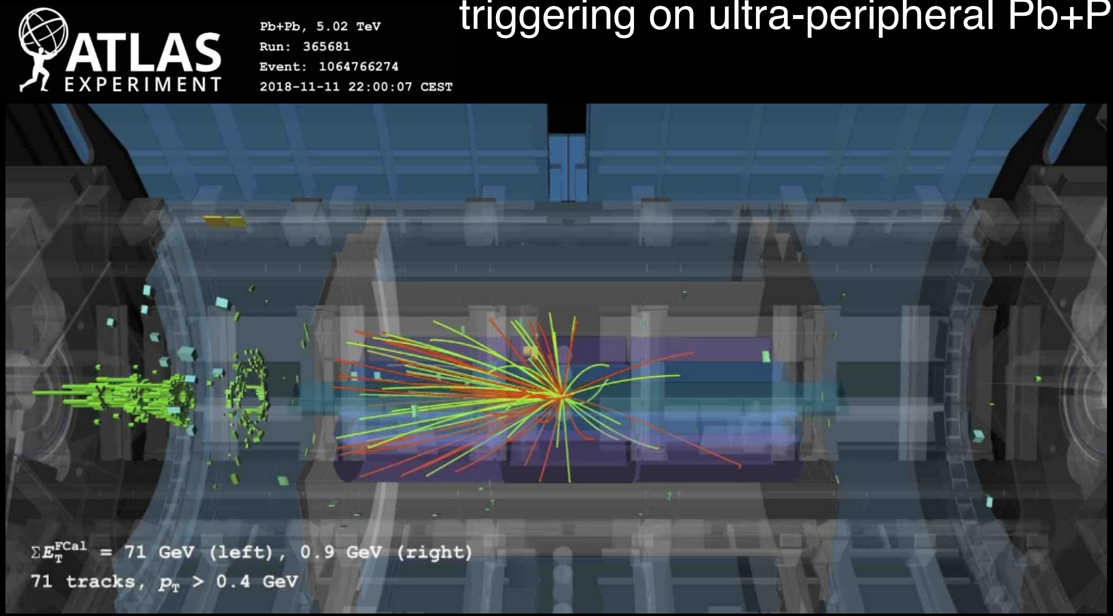


e+p/A DIS (Q^2 >1 GeV^2), most events have $Q^2 \rightarrow 0$, called photoproduction processes
Until the EIC is built ultra-peripheral p/A+A collisions → opportunity to study photoproduction

Search for collectivity UPC collisions at the LHC



ATLAS collect γ+Pb collisions by triggering on ultra-peripheral Pb+Pb



$Q^2 \sim (\hbar c/R_A)^2 \to 0$, γ^L(p, LHC)=6.51e3,

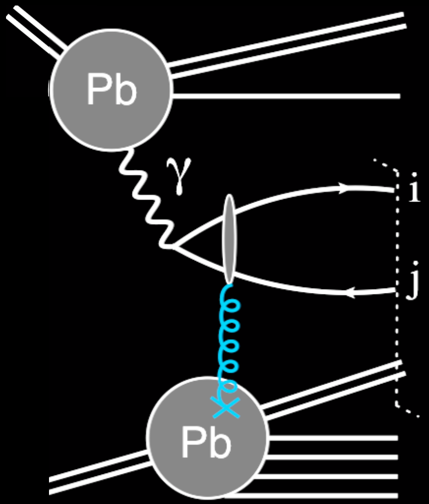
E_γ (LHC) ~ γ^L $(\hbar c/R_A)$ ~71 GeV

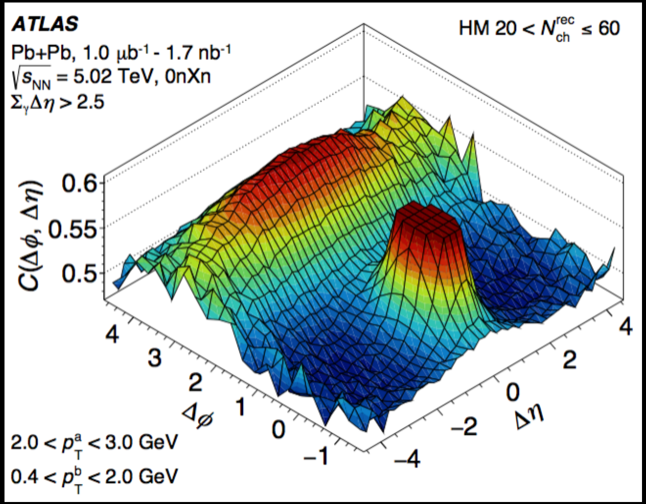
$W_{\gamma Pb}$ (LHC) ~ 844 GeV, $dN_{trk}/d\eta$ (HM) > 10

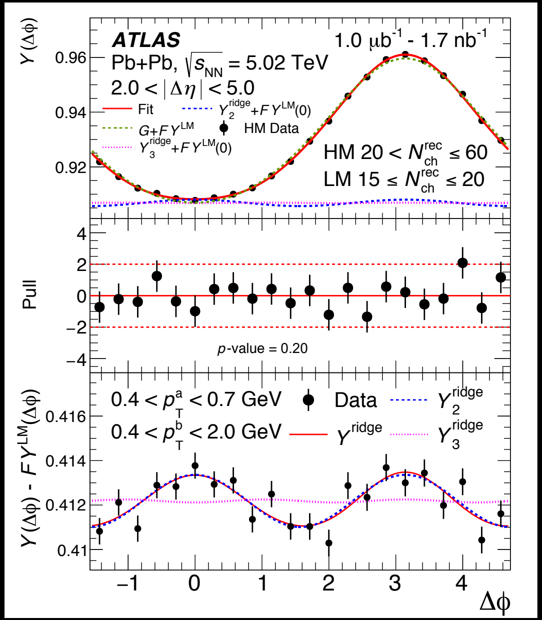
ATLAS collaboration performed this pioneering measurements of collectivity in γ+Pb collisions

Search for collectivity UPC collisions at the LHC

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







$$Y(\Delta\phi, 2<|\Delta\eta|<5) = \frac{1}{N_{\rm trig}}\frac{d^2N_{\rm pair}}{d\Delta\phi} = \frac{N_{\rm asco}}{2\pi}\left(1+\sum_n 2a_n\cos(n\Delta\phi)\right)$$

$$Y(\Delta\phi)^{\rm template}(HM) = FY(\Delta\phi)(LM) + Y(\Delta\phi)^{\rm ridge}(HM)$$

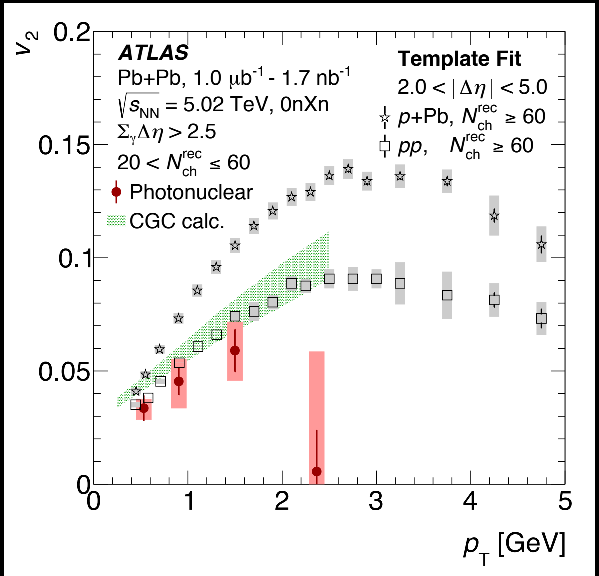
$$Y(\Delta\phi)^{\rm ridge}(HM) = G\{1+2a_2\cos(2\Delta\phi)+2a_3\cos(3\Delta\phi)+2a_4\cos(4\Delta\phi)\}$$

Template fitting of di-hadron correlations

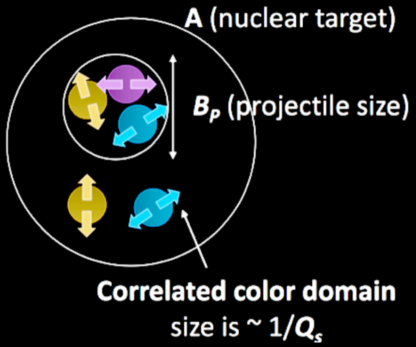
High activity γ+Pb events can accommodate a long-range ridge component (related to collectivity)

Search for collectivity UPC collisions at the LHC

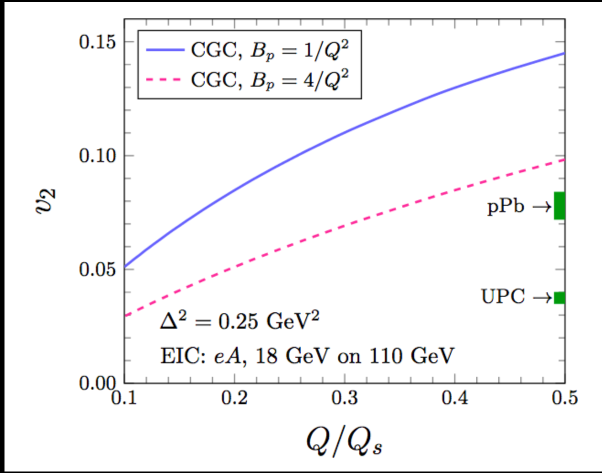
ATLAS collab., Phys. Rev. C 104, 014903 (2021)



Cartoon: Blair Seidlitz, IS2021



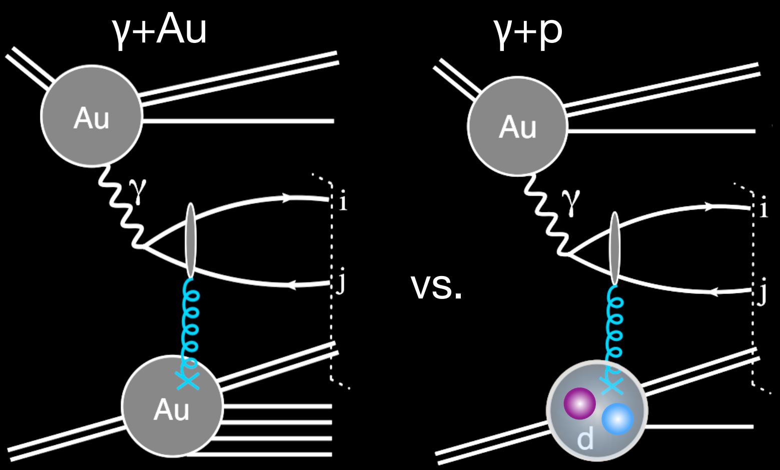
Shi et. al.,Phys. Rev. D 103, 054017 (2021)



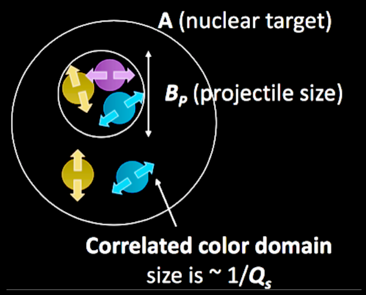
Elliptic anisotropy is lower in γ+Pb than in p+Pb

CGC calculations provide an explanation based on color domain picture.

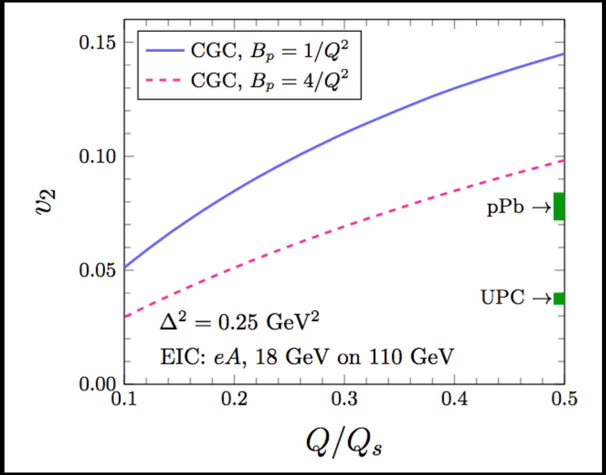
What can we do at RHIC Au+Au(γ) vs d+Au(γ)



Cartoon: Blair Seidlitz, IS2021



Shi et. al.,Phys. Rev. D 103, 054017 (2021)



$$Q^2_{S,A} = Q^2_{s,p} \times A^{1/3}$$

$$v_2^{\gamma+Au} \propto \frac{Q}{Q_{S,A}} = \frac{Q}{Q_{S,p} \times A^{1/6}} \approx \frac{v_2^{\gamma+p}}{A^{1/6}}$$

$$\left.\frac{v_2^{\gamma+p}}{v_2^{\gamma+Au}}\right|_{Q^2=\text{fixed}} \propto A^{1/6} > 1$$

If the domain picture holds we should be able to see this ordering by triggering photonuclear processes in ultra-peripheral Au+Au and p/d+Au at RHIC 200 GeV collisions

At EIC we can test this with much better control

Summary

Collectivity in small systems:

RHIC small system collision has been very successful
Hybrid framework combining CGC + Hydro can provide many insights
Challenges to understand acceptance dependence and non-flow
New observables are under investigation and scrutiny
UPC can be a doorway to study collectivity at the future EIC

Many exciting new possibilities

1. RHIC took data this year on O+O, possible O+O run at the LHC
2. RHIC just took d+Au data with the STAR detector (wide acceptance measurements)
3. Anticipated Au+Au 200 GeV run of RHIC (2023, 2025) sPHENIX & STAR with forward upgrade

Thanks