Nuclear structure and heavy-ion collisions

by

GIULIANO GIACALONE

30 / 05 / 2022

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

isoQuant
SFB1225

ExtreMe Matter Institute EMMI

EMMI Rapid Reaction Task Force

Nuclear Physics Confronts
Relativistic Collisions of Isobars

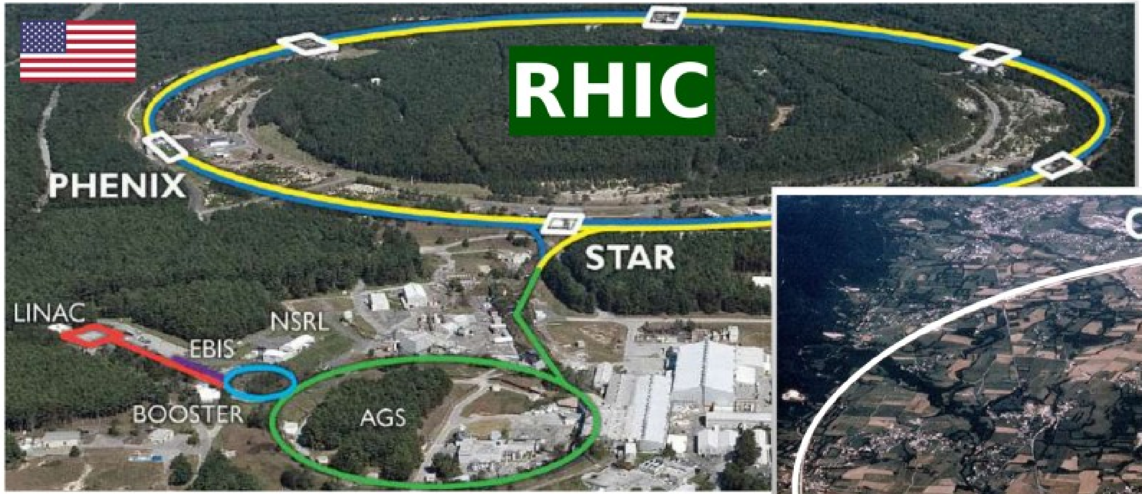
Open Symposium:
May 30, 2022, 1:45 p.m., Grosser Hoersaal, Heidelberg University,
Philosophenweg 12, 69120 Heidelberg/Germany

OUTLINE

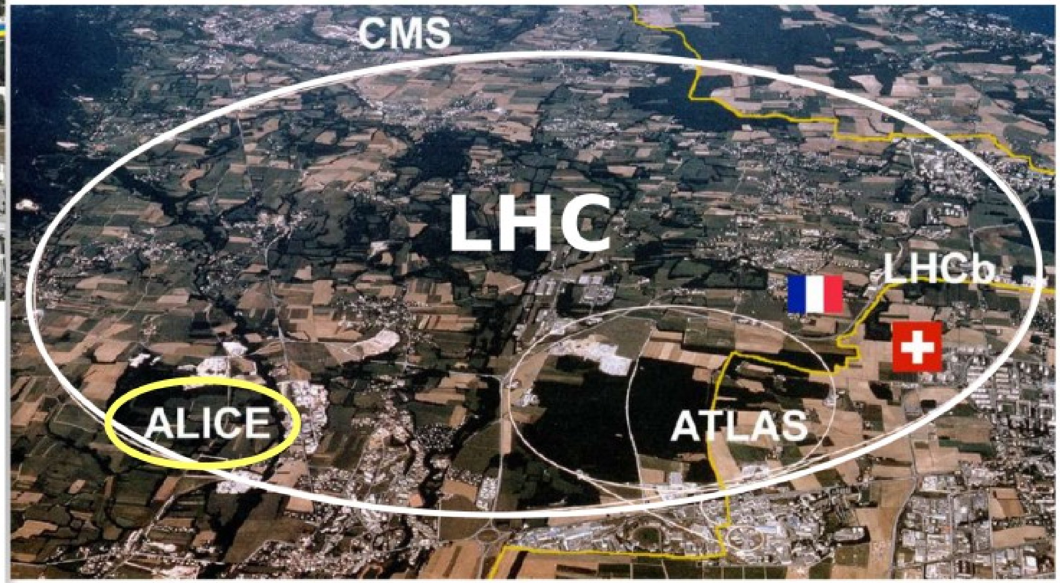
- 1. Heavy-ion collisions.
- 2. Anisotropic flow.
- 3. Modeling nuclei at high energy.
- 4. Nuclear deformation in elliptic flow data.
- 5. Nuclear deformation in shape-size correlations.
- Towards isobars.

1. Heavy-ion collisions.

Long Island (NY)



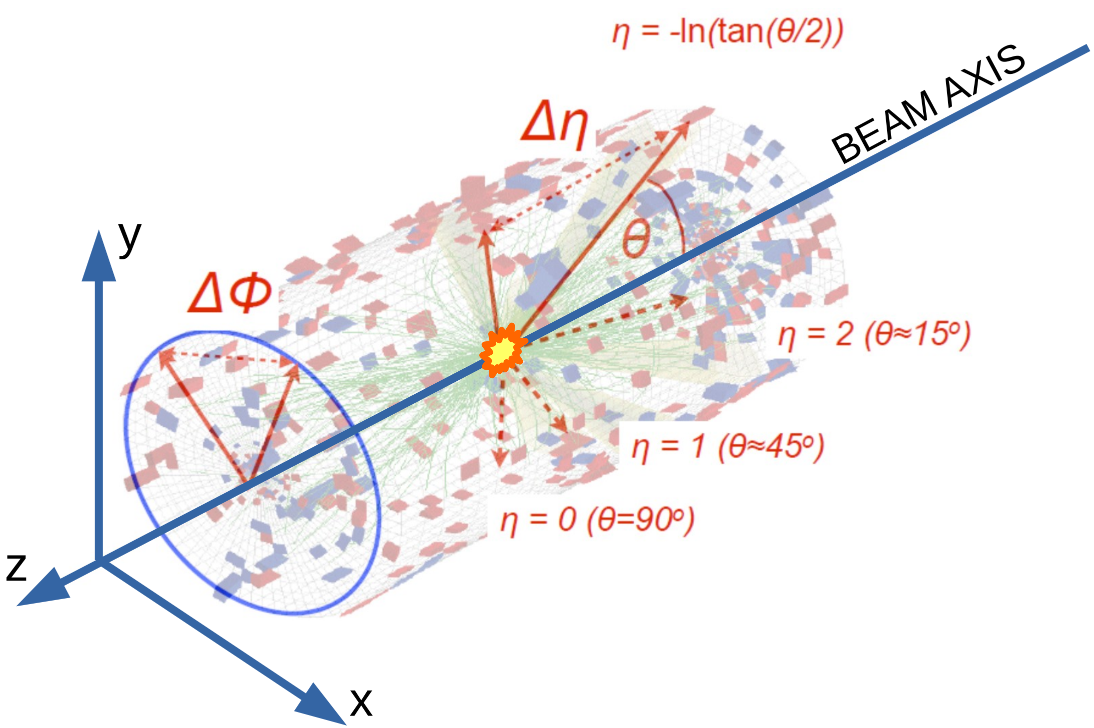
Geneva (CH)

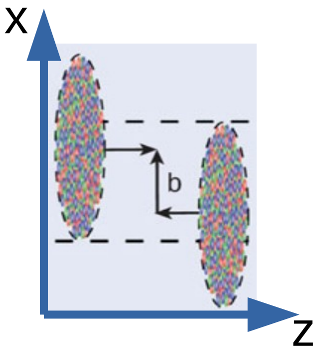


- Great experimental program of high-energy nuclear collisions.
  (~2k experimentalists involved)

- Nuclei collided ~1 month/year @ LHC.
  RHIC is dedicated to nuclear collisions. (shutdown 2026/2027)

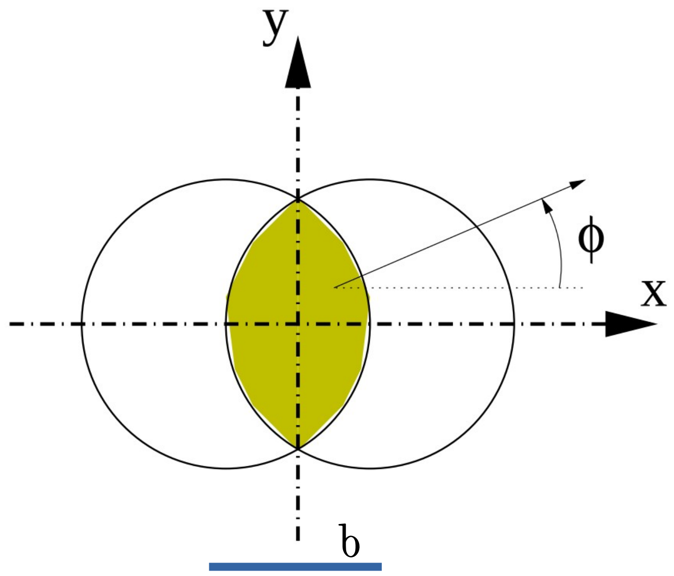
COLLISION GEOMETRY



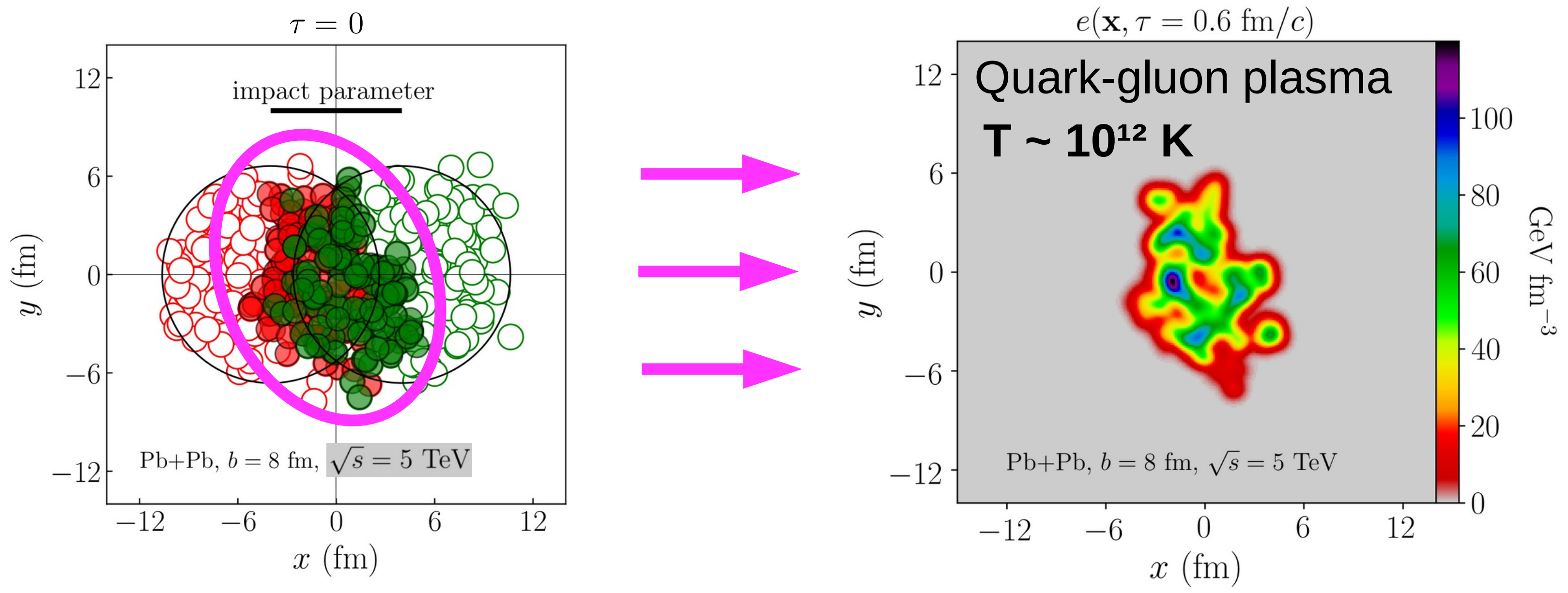


Nuclei are "pancakes" in the lab frame

Plane transverse to the beam:



REPRODUCING THE EARLY UNIVERSE IN THE LAB



$\Longrightarrow$ **Effective description: <u>relativistic fluid</u>.** [Romatschke & Romatschke, 1712.05815]

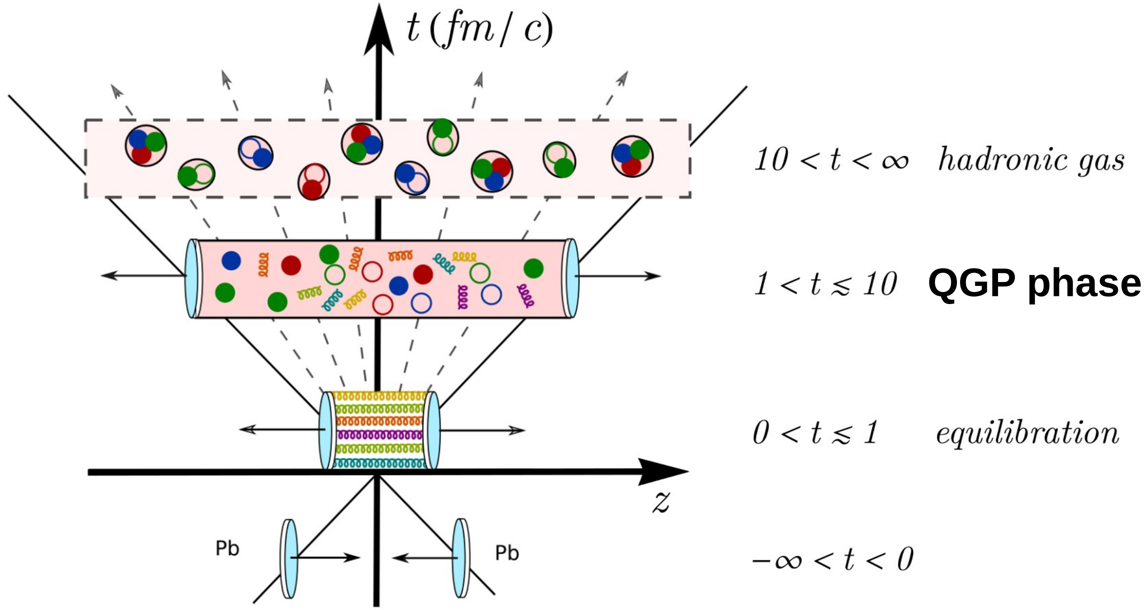
$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$$ + viscous corrections ($\eta/s, \zeta/s$, ...)

Equation of state from lattice QCD. Large number of DOF (~40): QGP.

[HotQCD collaboration, 1407.6387]

Main goals: understanding the <u>initial condition</u> and the transport properties.

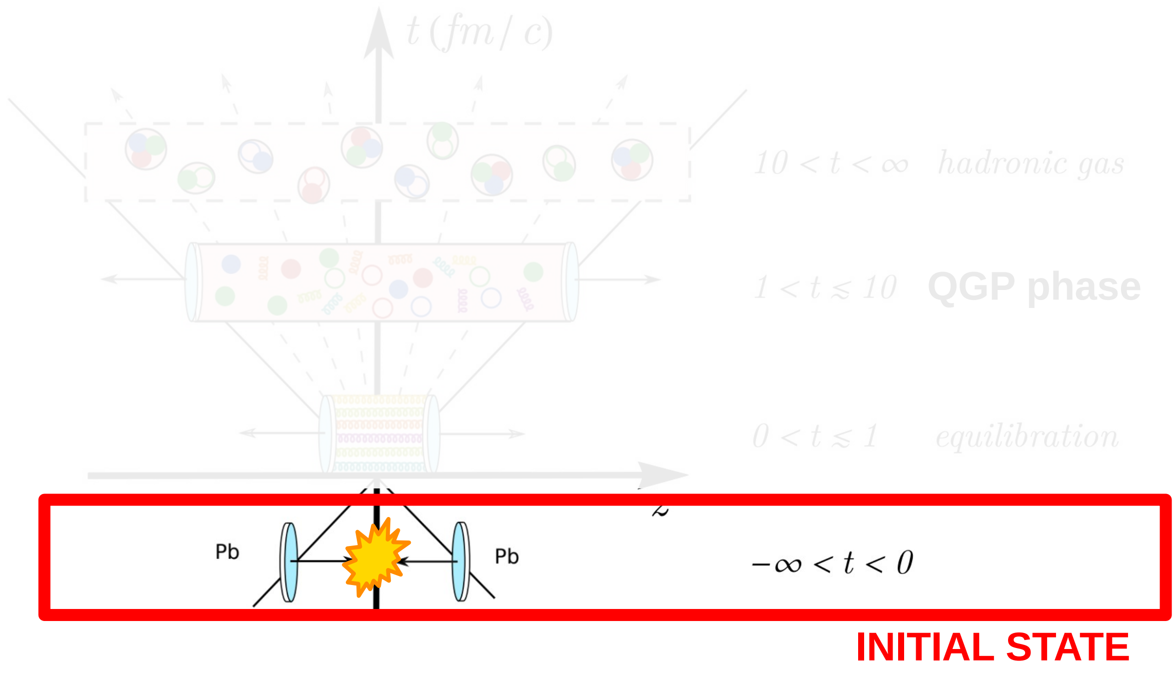
N.B. All we see is a spectrum of particles in momentum space.



t = ∞

$$\frac{dN}{d^3\mathbf{p}} = \frac{dN}{d\phi \; p_t dp_t \; d\eta}$$

N.B. All we see is a spectrum of particles in momentum space.

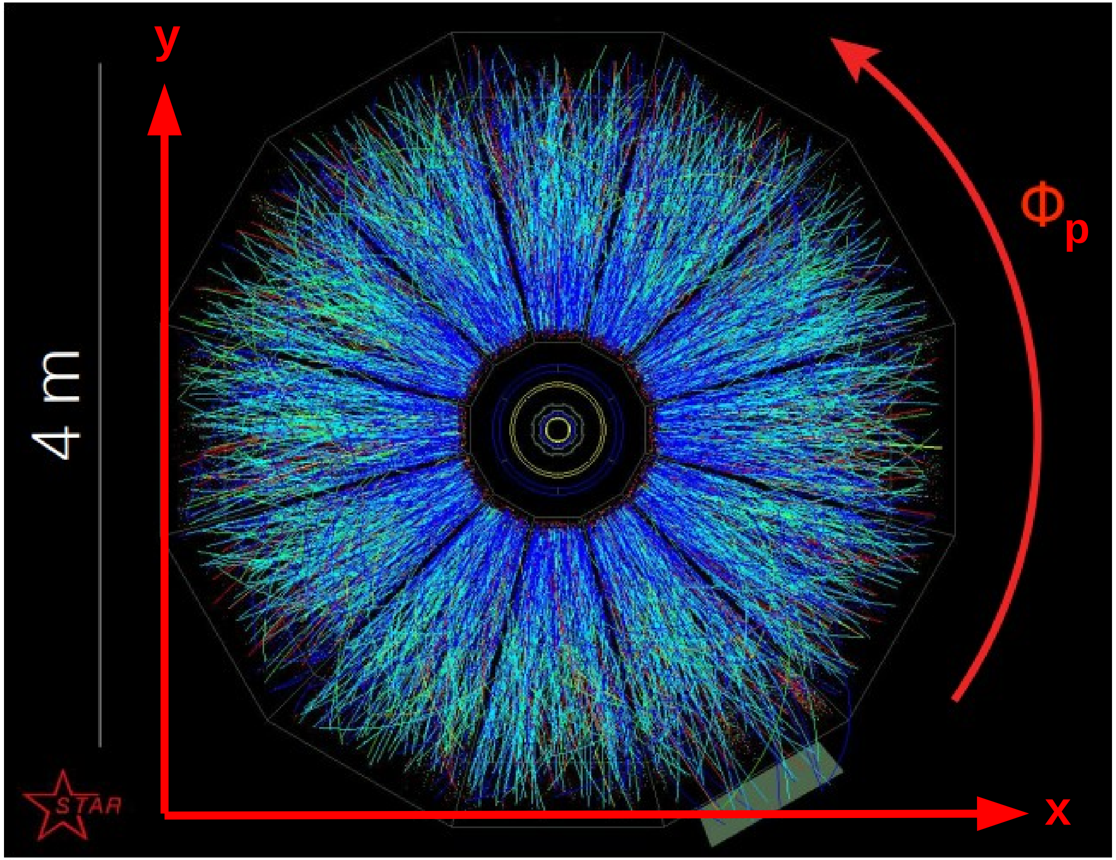


t = ∞

$$\frac{dN}{d^3\mathbf{p}} = \frac{dN}{d\phi\ p_t dp_t\ d\eta}$$

This talk: Can we “go back in time” and probe the initial condition?
Imprints of the colliding ions?

2. Anisotropic flow.



Are particles emitted isotropically in the transverse plane?

Fourier decomposition of the azimuthal distribution of particles.

$$V_n = \frac{1}{N}\int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-in\phi_p}$$

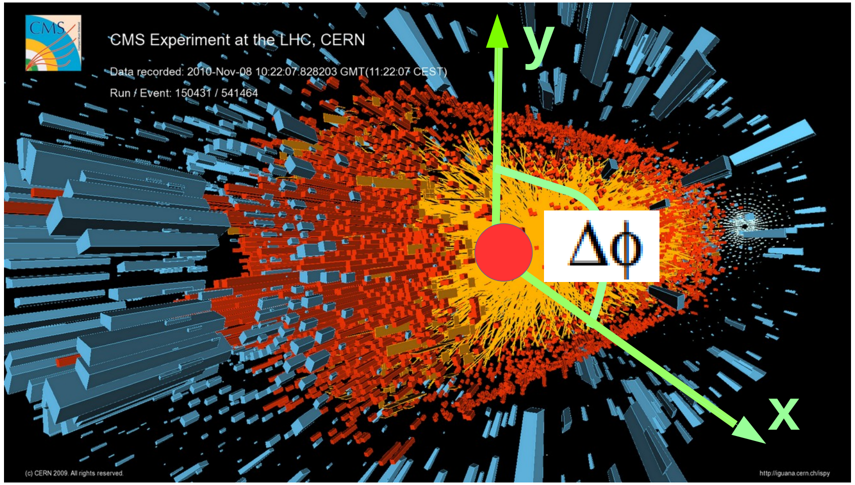
$$v_n = |V_n|$$

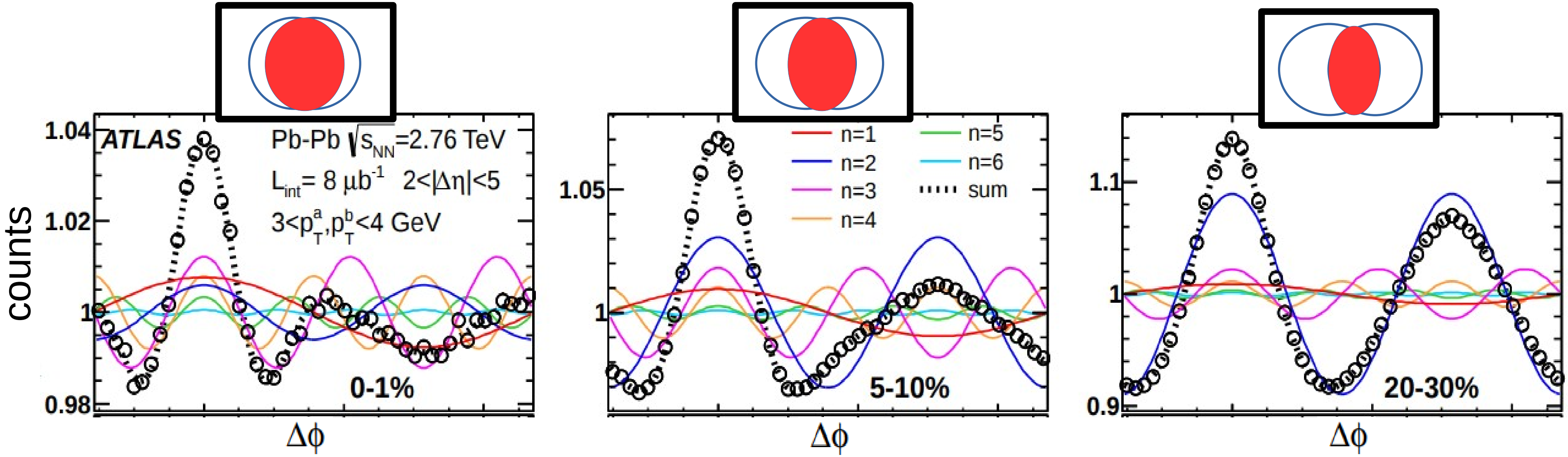
anisotropic flow coefficients

Experimentally, anisotropy is observed.

Measurable up to n~10.

Dominance of elliptical component (n=2) for off-central collisions. Why?

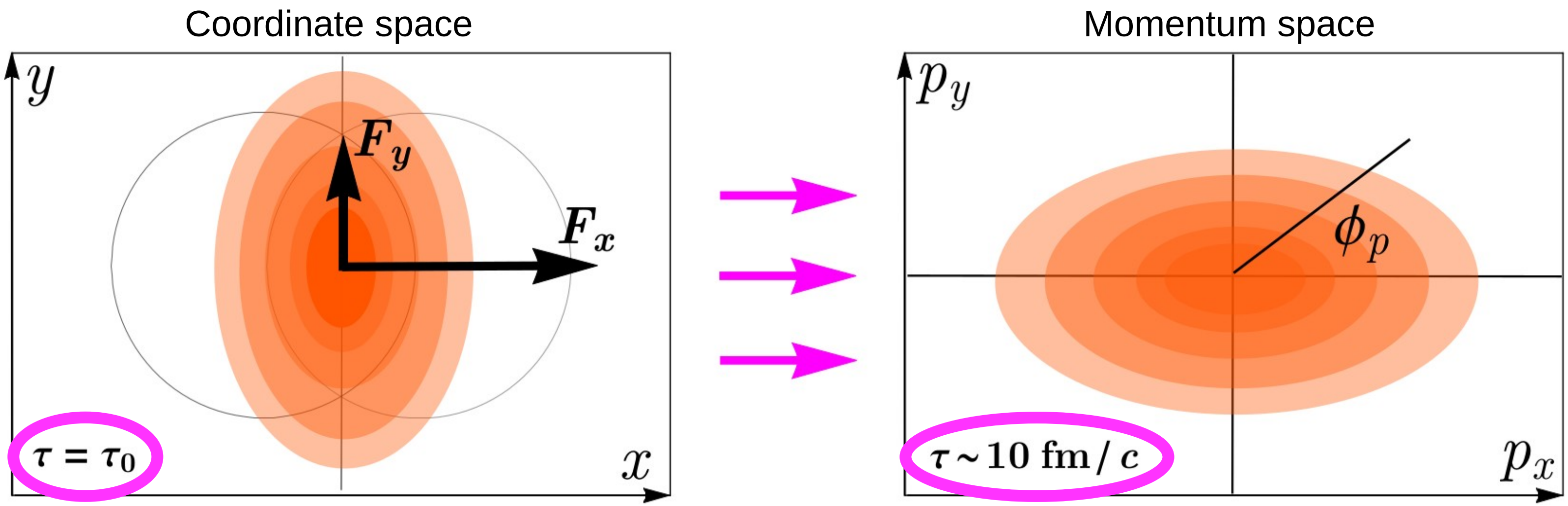




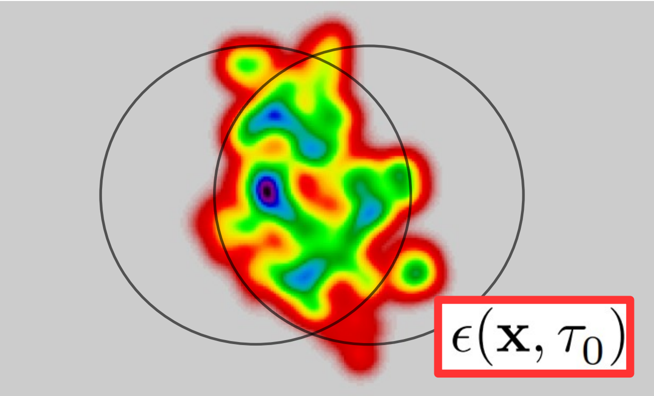
Anisotropic flow from spatial anisotropy. $F = -\nabla P$

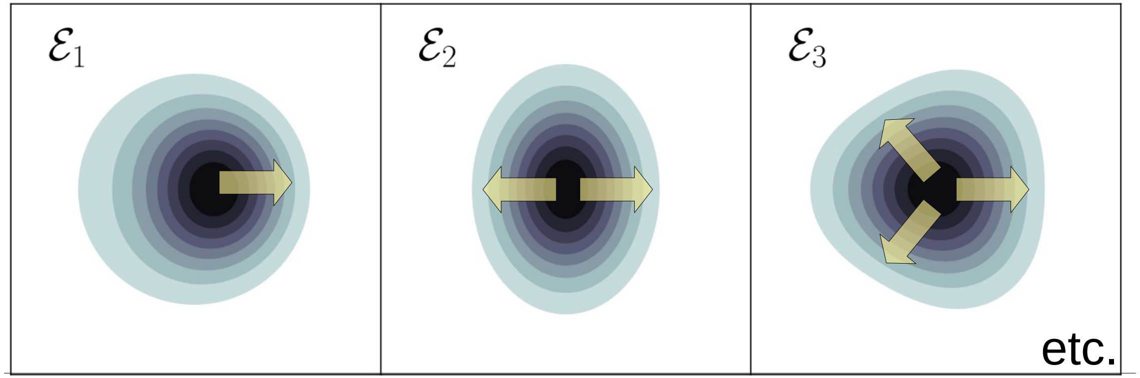
Elliptic flow, the 2nd harmonic.
Dynamical response to elliptical geometry. → $V_2 = \frac{1}{N}\int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-i2\phi_p}$

[Ollitrault, 1992]



QGP is not a smooth object.
Deformations yield flow harmonics via pressure gradients. $F = -\nabla P$





In a QGP, all multi-pole moments are nonzero:

$$\mathcal{E}_n = -\frac{\int r dr d\phi \; r^n e^{in\phi} \epsilon(r,\phi)}{\int r dr d\phi \; r^n \epsilon(r,\phi)}$$

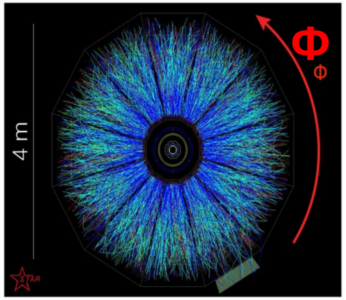
$$V_n \propto \mathcal{E}_n$$

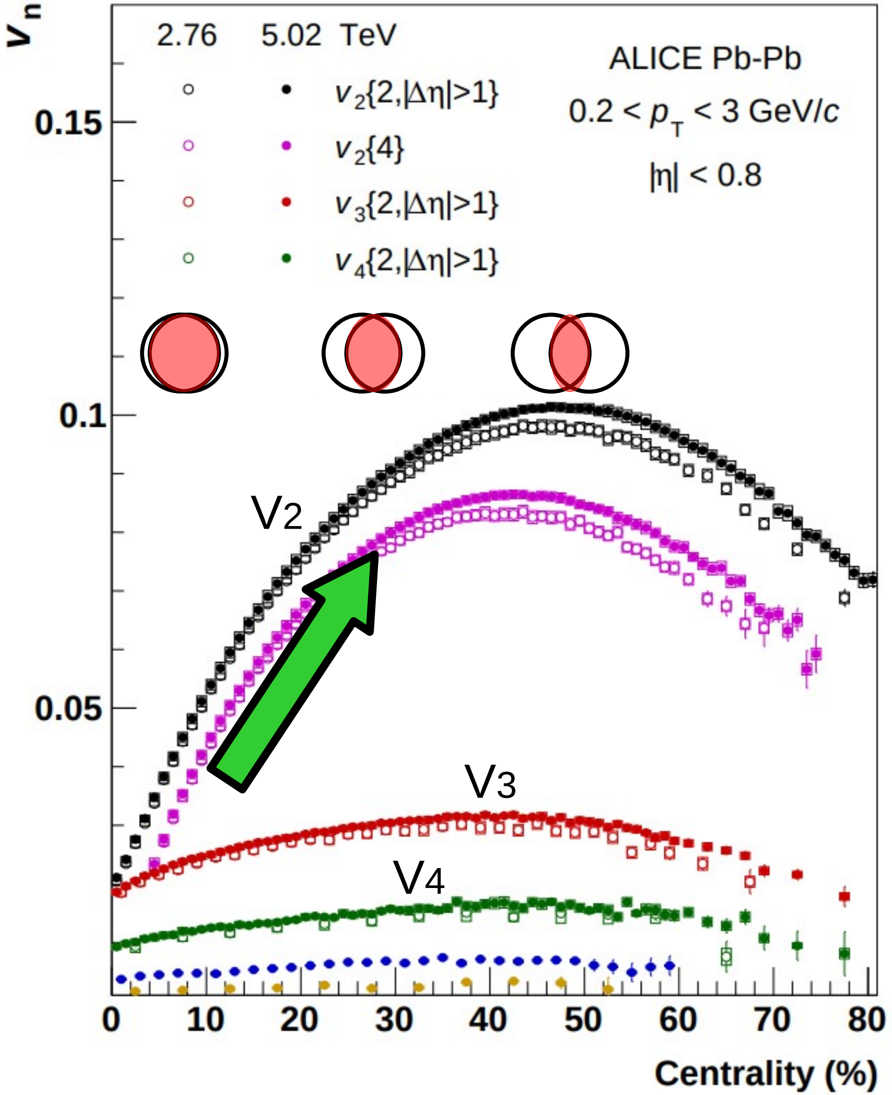
[Teaney, Yan, 1010.1876]

Recent measurements.

[ALICE collaboration, 1804.02944]

$$V_n = \frac{1}{N}\int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-in\phi_p}$$

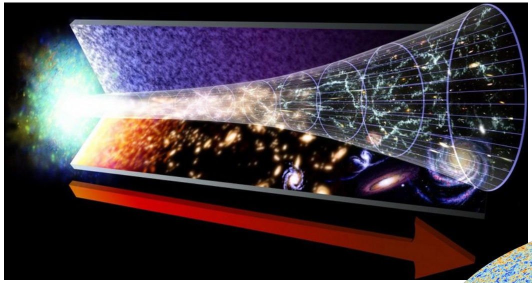


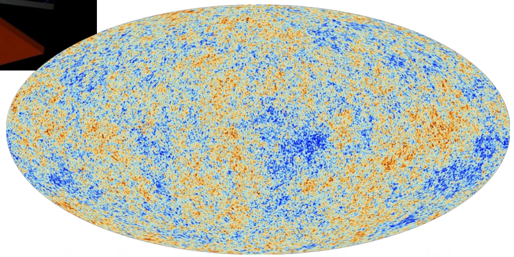


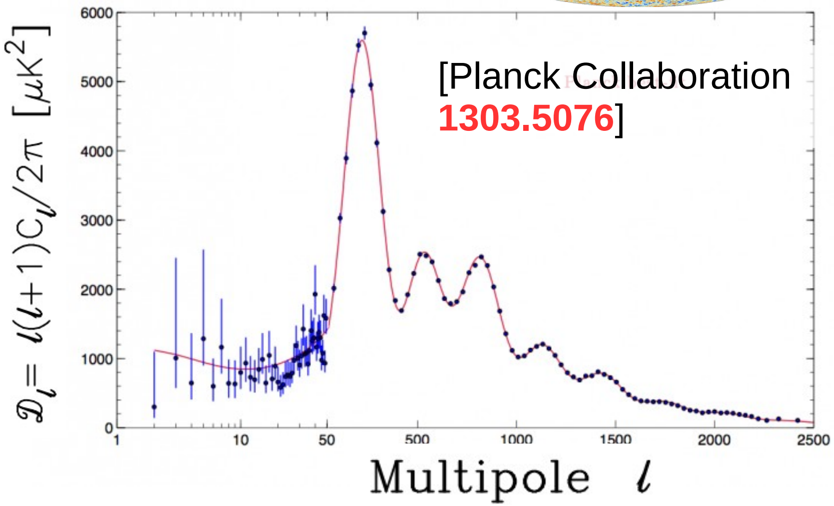
Strong enhancement of V_2 as the system becomes more elliptical. ✓

Other coefficients depend little on centrality. Still nonzero. ✓

The Big Bang

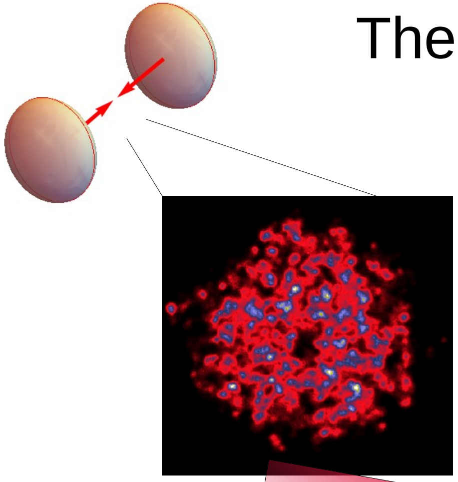


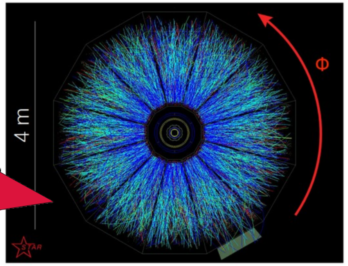


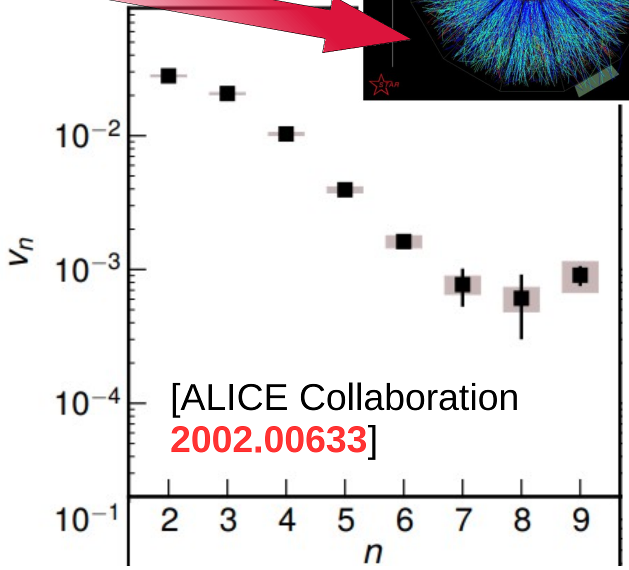


[Planck Collaboration 1303.5076]

The Little Bang(s)





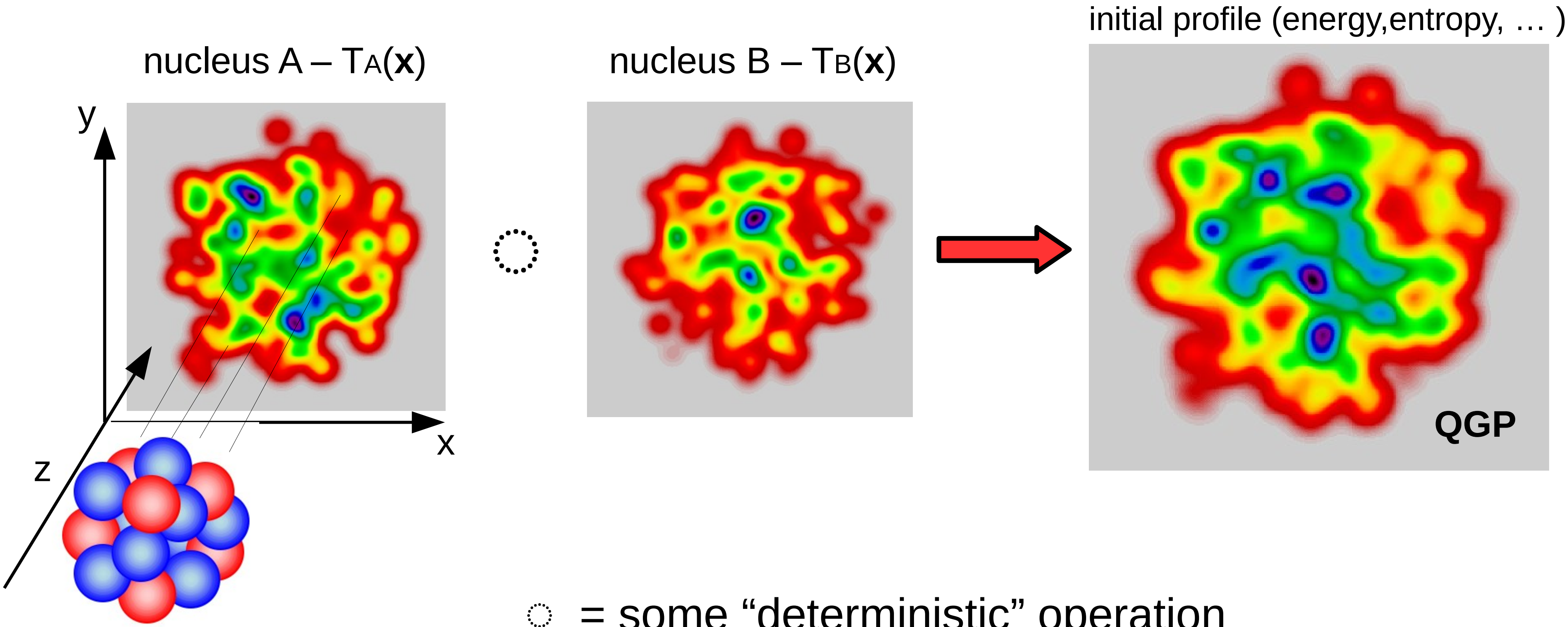


[ALICE Collaboration 2002.00633]

3. Modeling nuclei at high energy

Origin of primordial fluctuations?

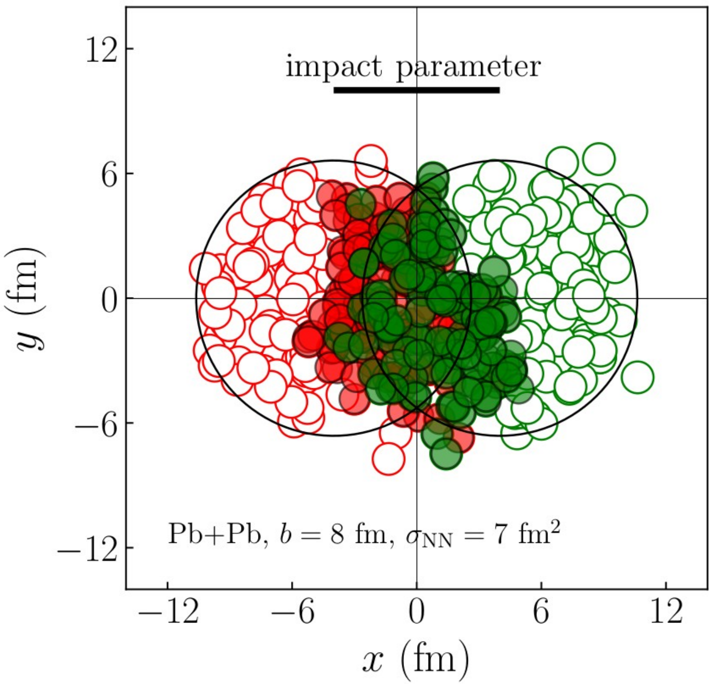
Encoded in the colliding ions (projected in 2D by Lorentz boost).



◌ = some “deterministic” operation

Inner structure of the colliding objects.

Starting point: Glauber Monte Carlo approach.

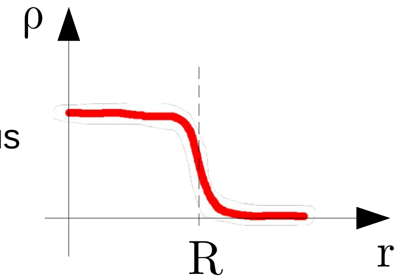


Independent nucleons in Woods-Saxon profile (ground state).

$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-R}{a}\right)}$$

R → half-width radius

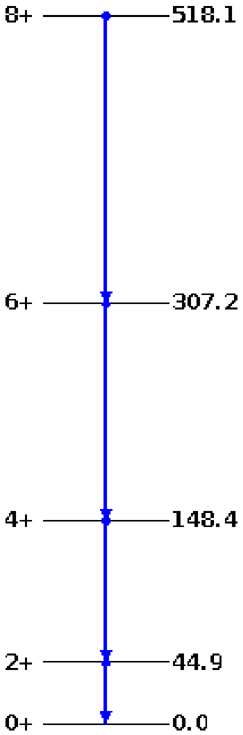
a → diffusivity



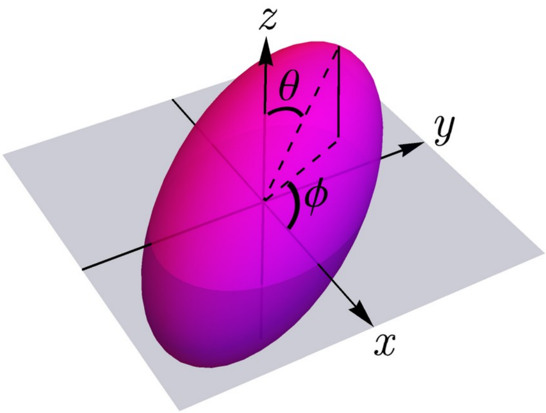
[Miller, Reygers, Sanders, Steinberg, nucl-ex/0701025]

Important ingredient required. Nucleons are strongly correlated and exhibit collective behavior.

$$^{238}_{92}\mathrm{U} \qquad E = B\,J(J+1)$$



Powerful approximation: “deformation”.
intrinsic deformed shape (nucleons)
with a random orientation.



From https://www.nndc.bnl.gov/nudat3/

Nuclear states from intrinsic shapes.

[Bender, Heenen, Reinhard, RMP 2003]
[Bender, Bally, 2010.15224]
[Bally, Bender, Giacalone, Somà, 2108.09578]

Capture correlations through “symmetry-breaking” intrinsic states (HFB states).

$$\delta\left(\langle\Phi|H-\mu Q_2|\Phi\rangle\right)=0$$

Slater determinant + pairing (Φ)

e.g. quadrupole deformation (Q_2)

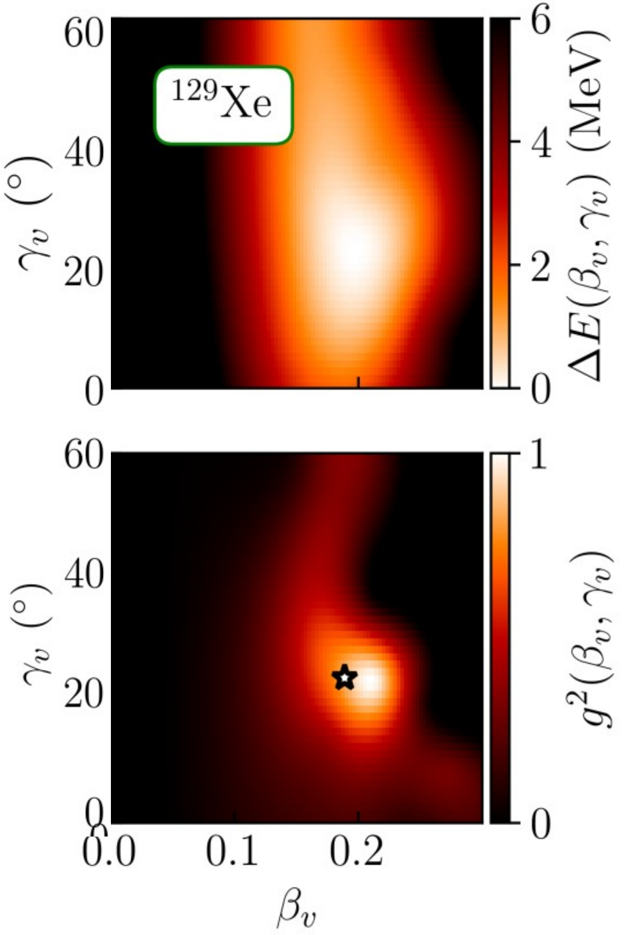
Restore symmetry via enriched variational Ansatz. Projected generator coordinate method, e.g.,

$$|\Psi\rangle=\sum_{(\beta_v,\gamma_v)K} f_{(\beta_v,\gamma_v)K}P^J_{MK}P^N P^Z|\Phi(\beta_v,\gamma_v)\rangle$$

weights — projections — HFB states

Fix the weights via additional variational equation

$$\delta\frac{\langle\Psi|H|\Psi\rangle}{\langle\Psi|\Psi\rangle}=0 \quad \text{to extract} \quad g^2\sim P(\beta,\gamma)$$



Intrinsic shapes are non-observable for direct measurements, but they leave their fingerprint on virtually all nuclear observables and phenomena

Michael Bender – RBRC Workshop Jan 2021

They will show up as well at high energy.

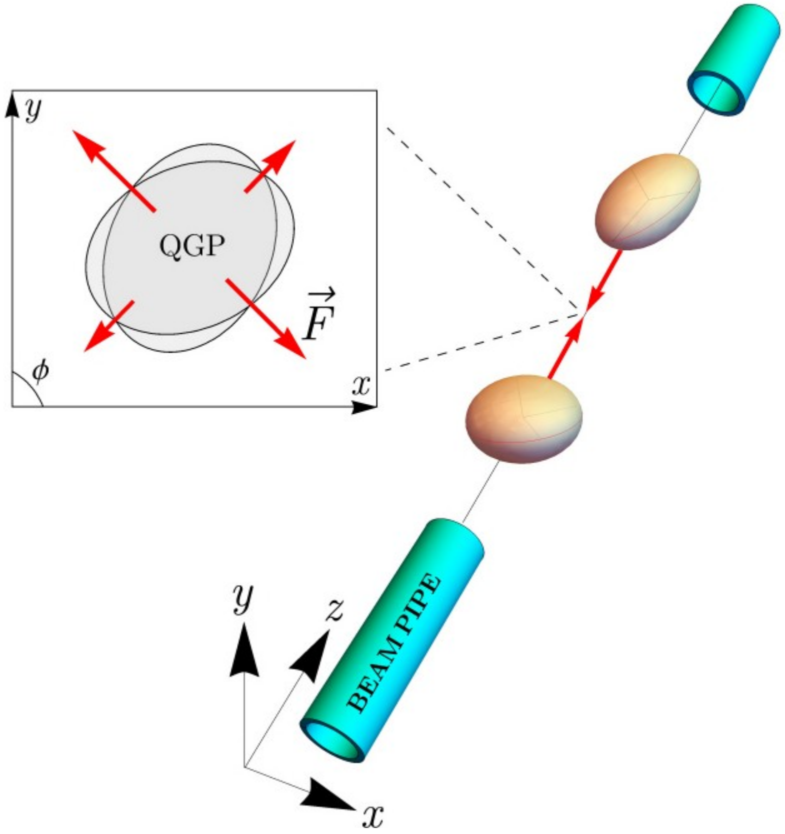
↓

OUR FOCUS!

Collide nuclei with intrinsic deformations.

↓

The configuration of nucleons is deformed with a random orientation.

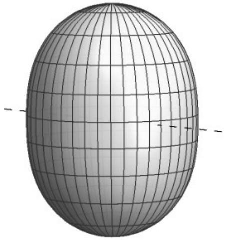


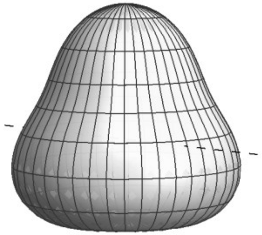
Generalize the Woods-Saxon profile:

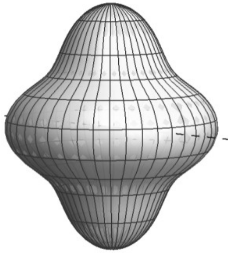
$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r-R(\Theta,\Phi)\right]/a\right)} \quad , \quad R(\Theta,\Phi) = R_0\left[1+\beta_2\left(\cos\gamma Y_{20}(\Theta)+\sin\gamma Y_{22}(\Theta,\Phi)\right)+\beta_3 Y_{30}(\Theta)+\beta_4 Y_{40}(\Theta)\right]$$

Deformation coefficients associated with the multipole moments of the density:

$$\beta_2 \to \int \rho(r,\Theta,\Phi) r^2 Y_{20}(\Theta) \qquad \beta_3 \to \int \rho(r,\Theta,\Phi) r^3 Y_{30}(\Theta) \qquad \beta_4 \to \int \rho(r,\Theta,\Phi) r^4 Y_{40}(\Theta)$$

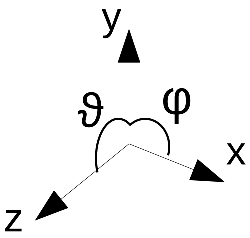


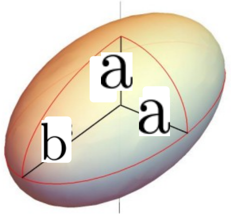




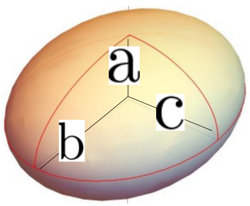
For $\beta_2>0$, the nucleus is prolate ($\gamma=0$), triaxial ($\gamma=30^0$), or oblate ($\gamma=60^0$).

$$Y_2^2(\theta,\varphi) = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\cdot\frac{(x+iy)^2}{r^2}$$

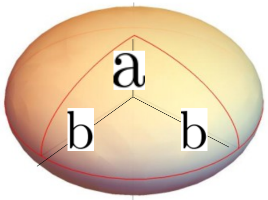




$\gamma = 0$
$r_1 = r_2 < r_3$
prolate

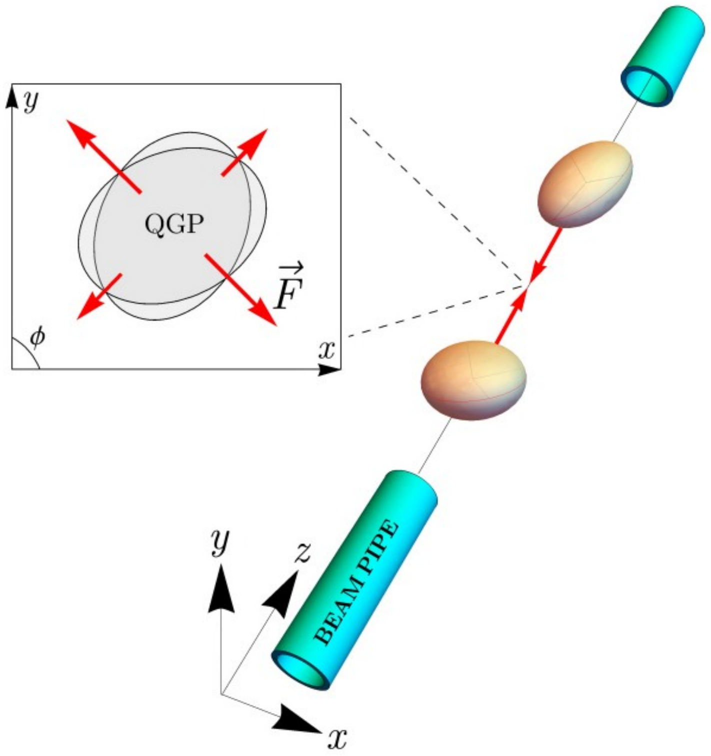


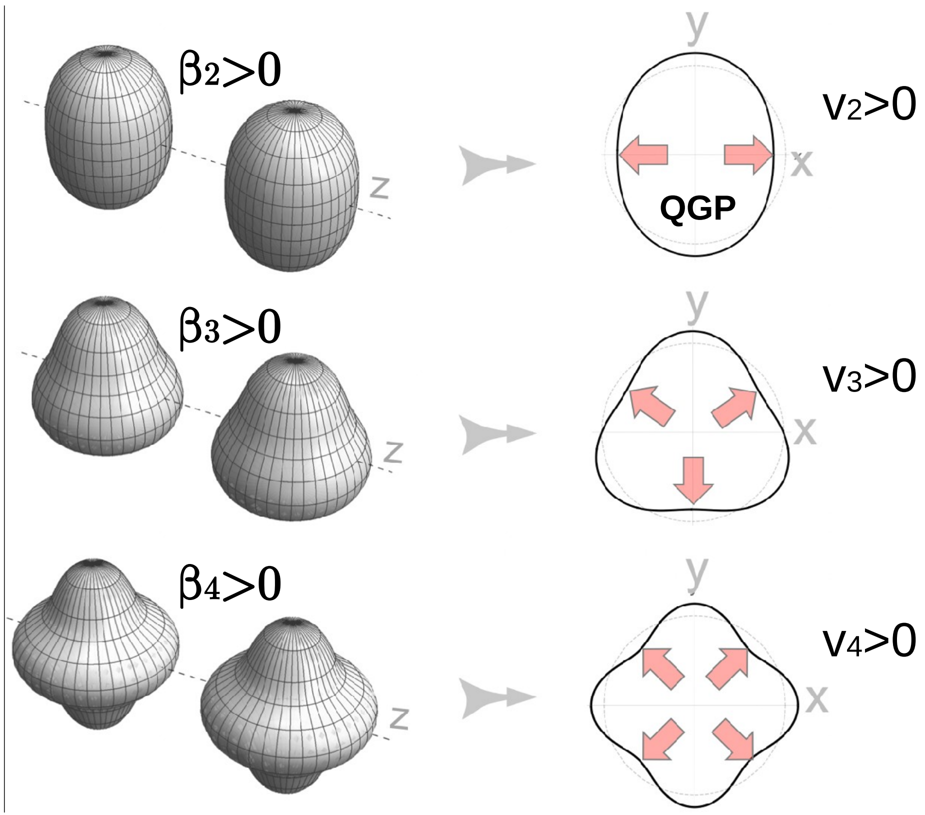
$\gamma = 30^\circ$
$r_1 \neq r_2 \neq r_3$
triaxial



$\gamma = 60^\circ$
$r_1 < r_2 = r_3$
oblate

Impact on QGP: additional sources of anisotropic flow for central collisions.





[Jia, 2106.08768]

Very straightforward method to “see” nuclear deformations.

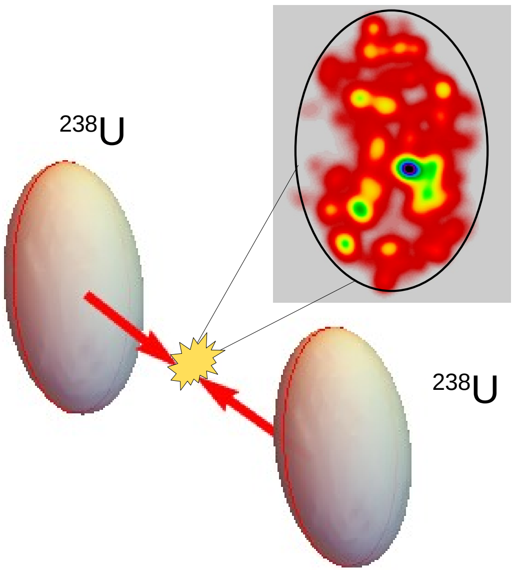
4. Nuclear deformation in elliptic flow data.

Standard measure is mean squared value.

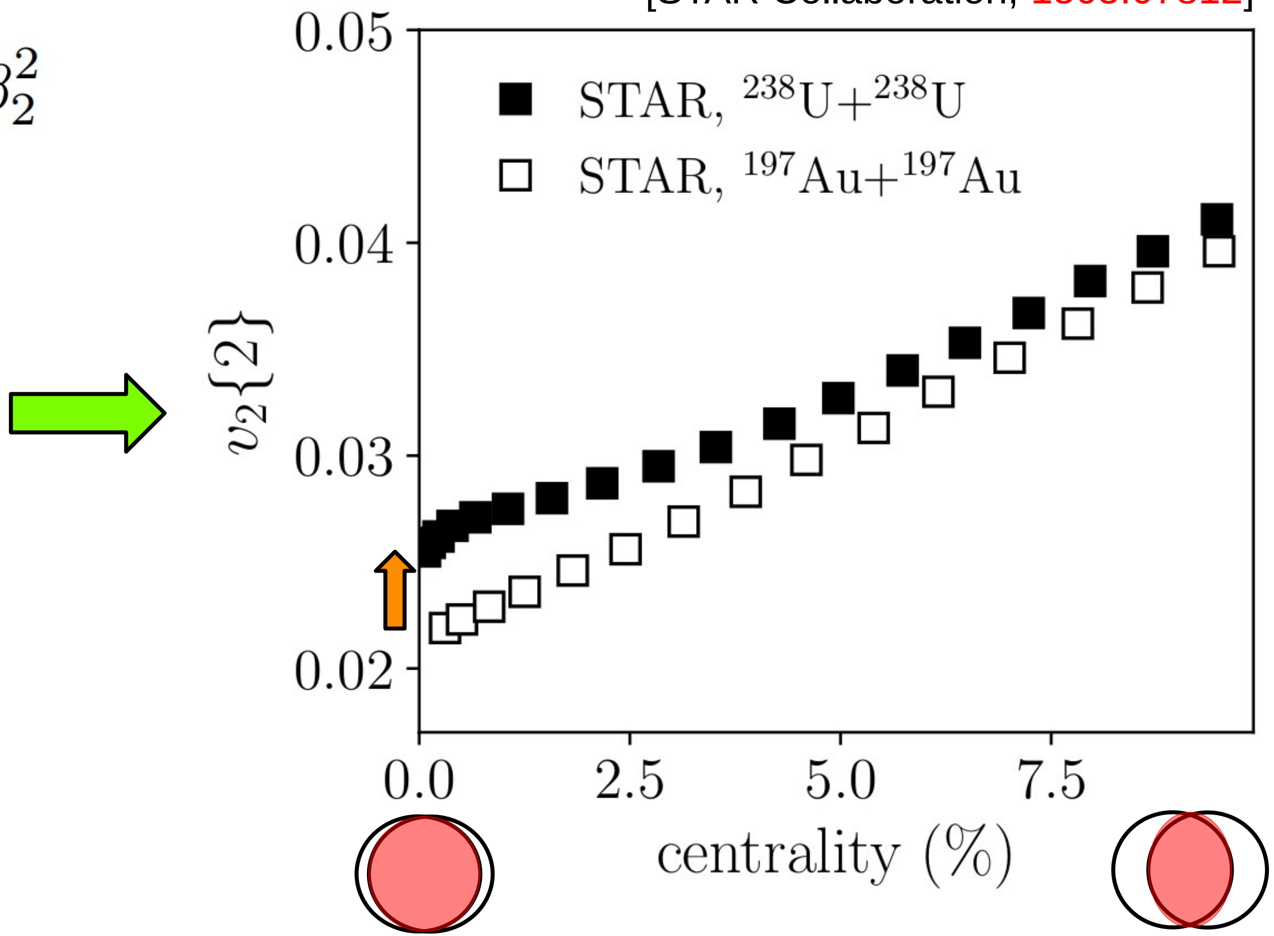
Robust leading dependence.

$$v_2\{2\}^2 \equiv \langle v_2^2 \rangle = a_2 + b_2\beta_2^2$$

[Giacalone, 1811.03959]
[Giacalone, Jia, Zhang, 2105.01638]
[Jia, 2106.08768]



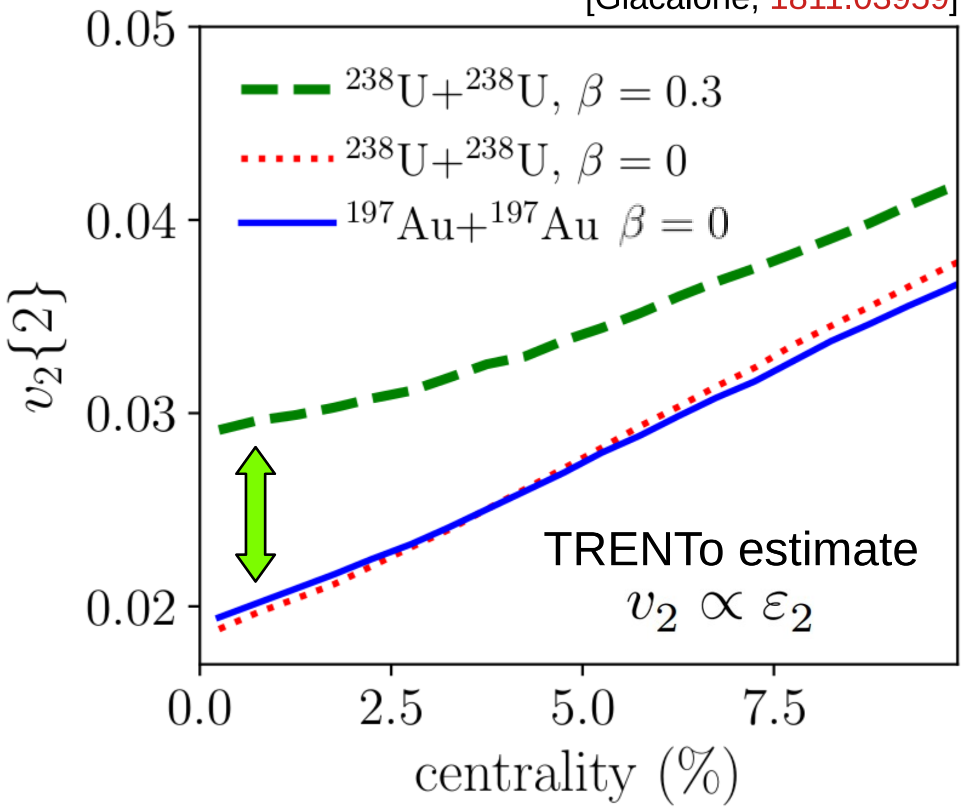
[STAR Collaboration, 1505.07812]



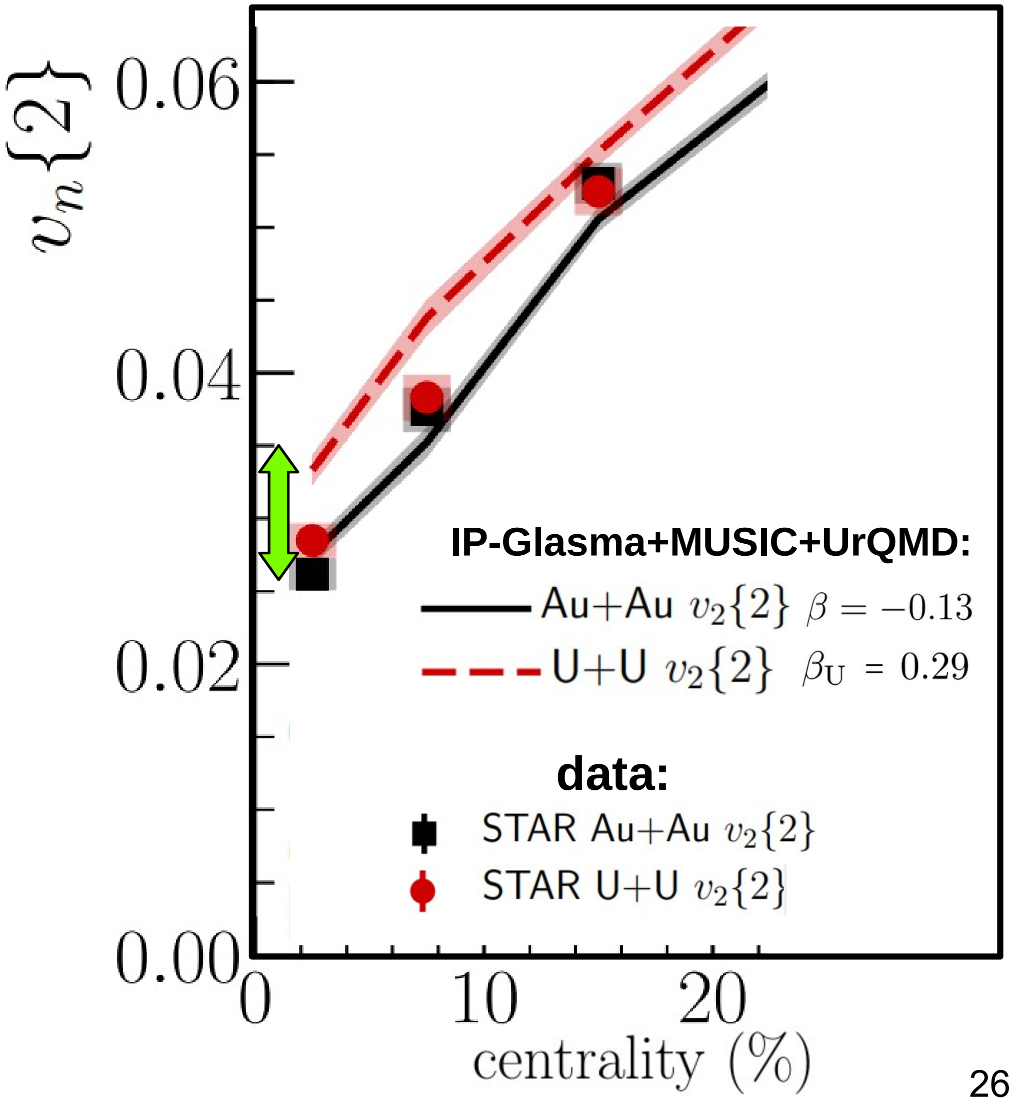
Issues on theory side.

Too large v_2 in U+U.

[Giacalone, 1811.03959]

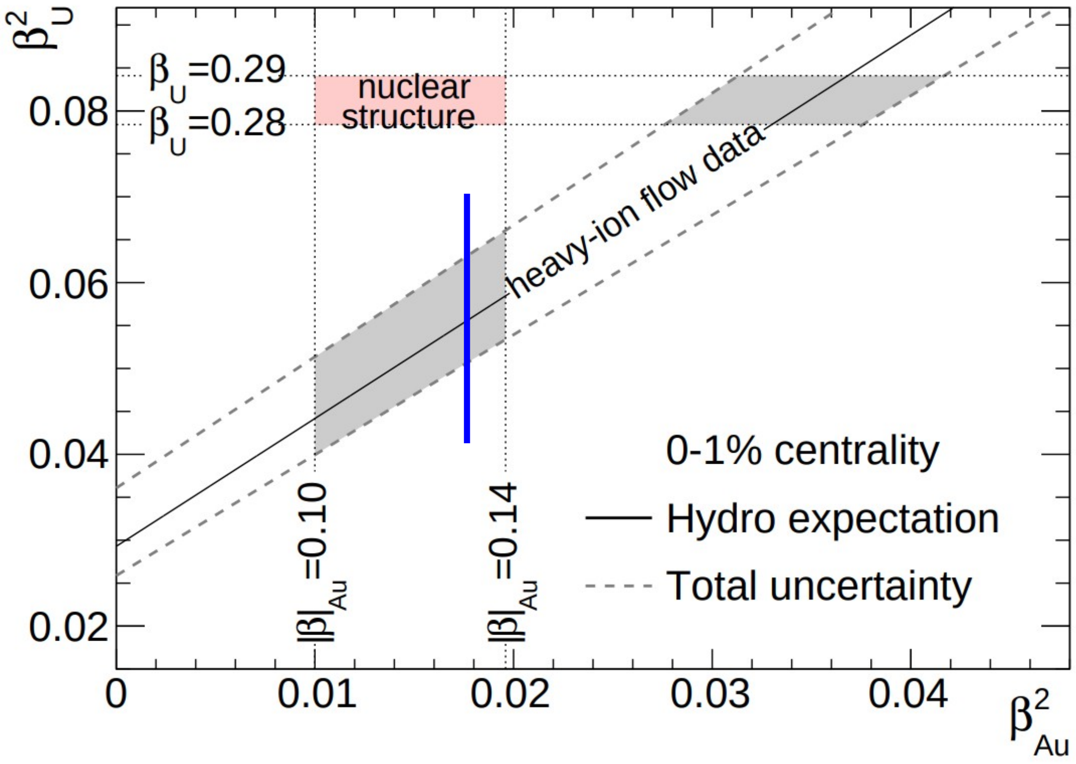


[Schenke, Shen, Tribedy, 2005.14682]



Systematic study within AMPT code. We need “less deformation” in ^{238}U. Why?

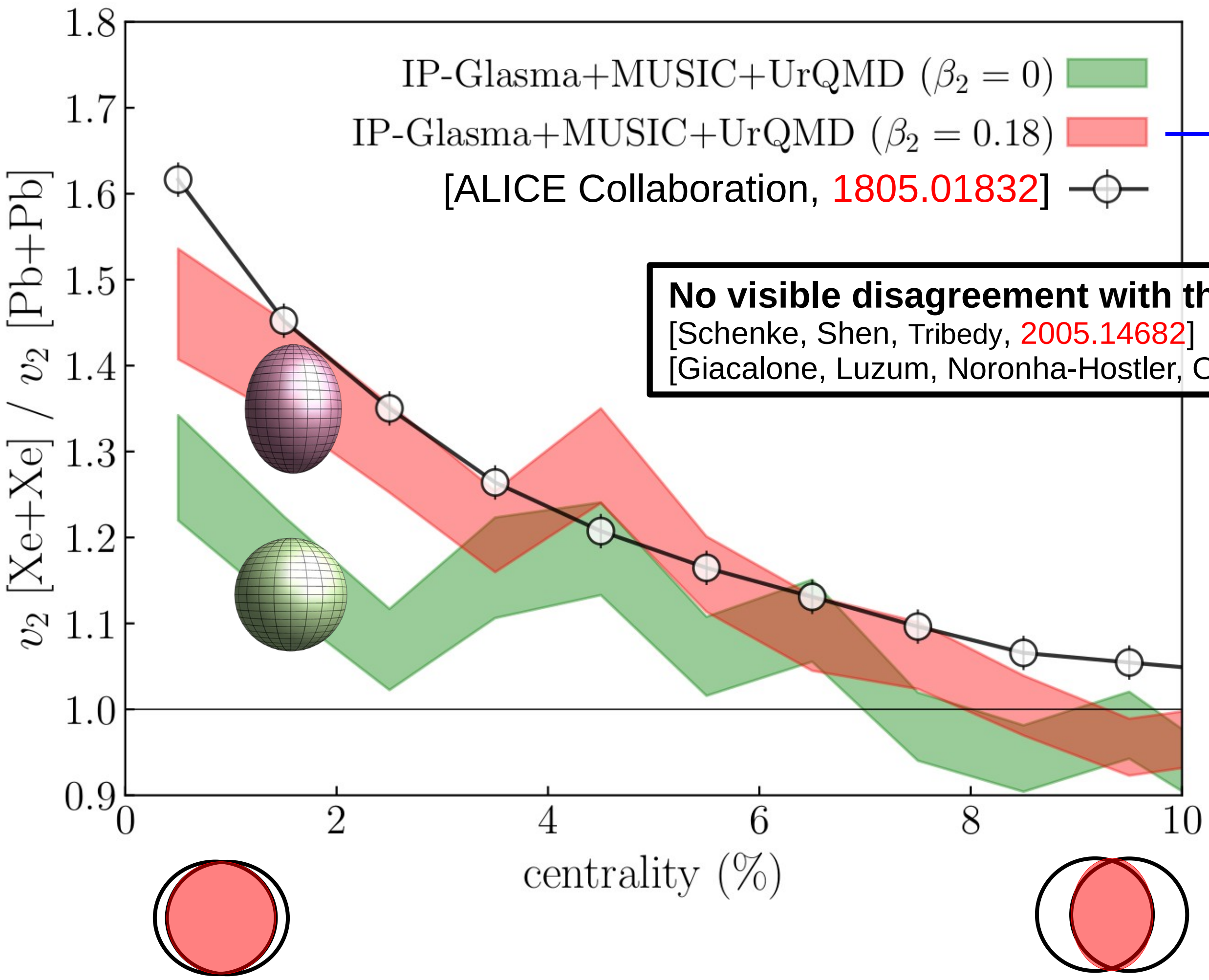
[Giacalone, Jia, Zhang **2105.01638**]



Spoiler: low-energy nuclear theory predicts β2 of ^{197}Au of about 0.13.

[Bally, Giacalone **in preparation**]

LHC: Enhanced flow in ^{129}Xe+^{129}Xe collisions compared to spherical baseline (^{208}Pb+^{208}Pb).

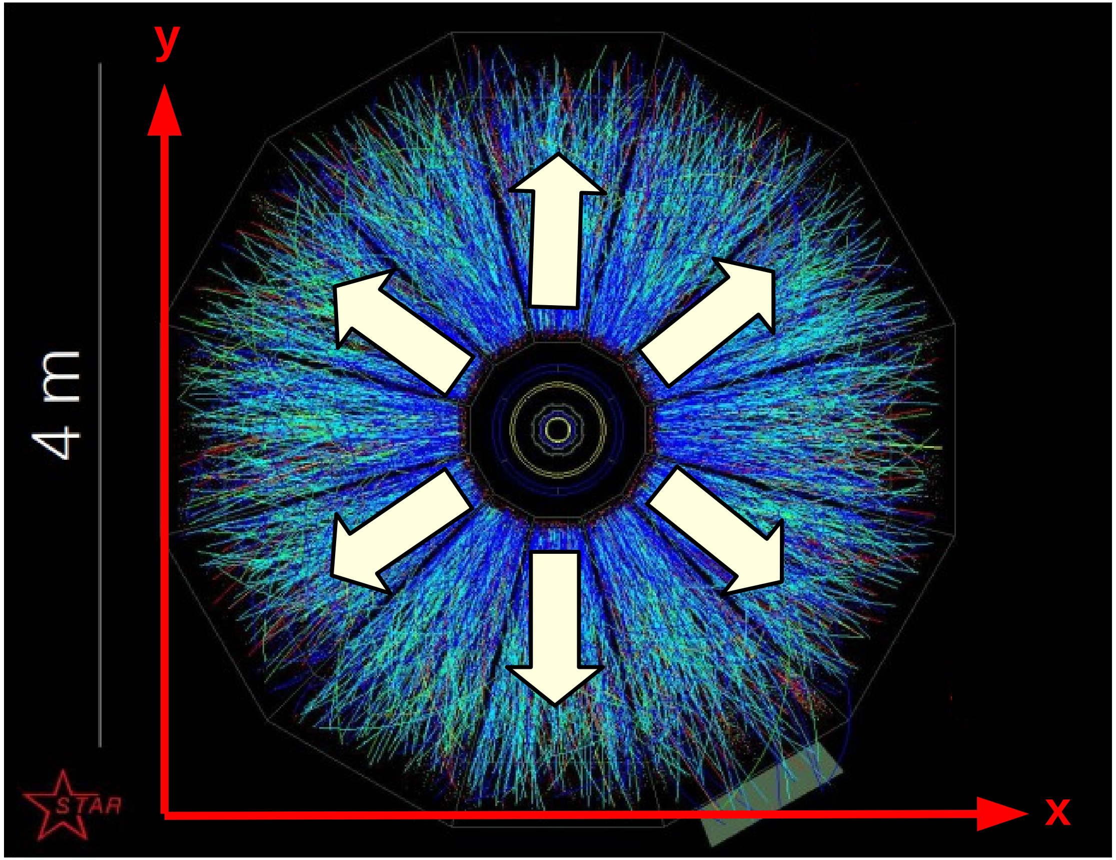


actual value is 0.2

No visible disagreement with theoretical calculations.
[Schenke, Shen, Tribedy, 2005.14682]
[Giacalone, Luzum, Noronha-Hostler, Ollitrault, 1711.08499]

4. Nuclear deformation in shape-size correlations.

Additional observable to access the initial condition.



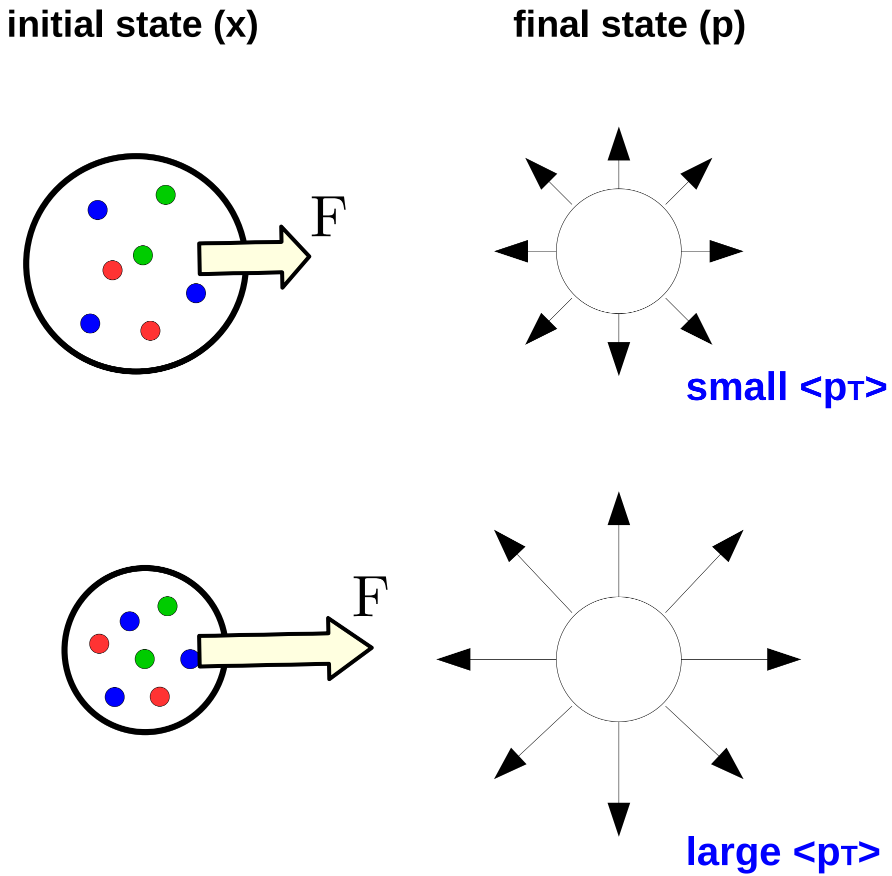
How much does it flow?

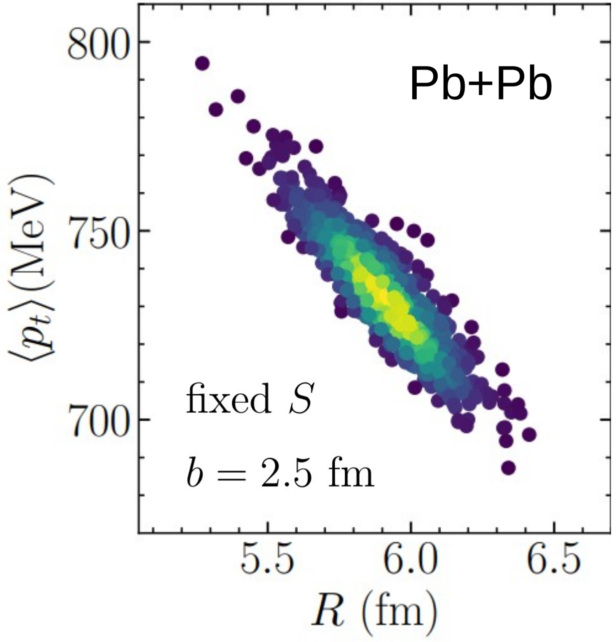
$$\langle p_t \rangle = \frac{1}{N} \int_{\mathbf{p}_t} p_t \frac{dN}{d^2\mathbf{p}_t}$$

Mean transverse momentum.

Energy per particle.

The “explosiveness” of the expansion from the initial system size.

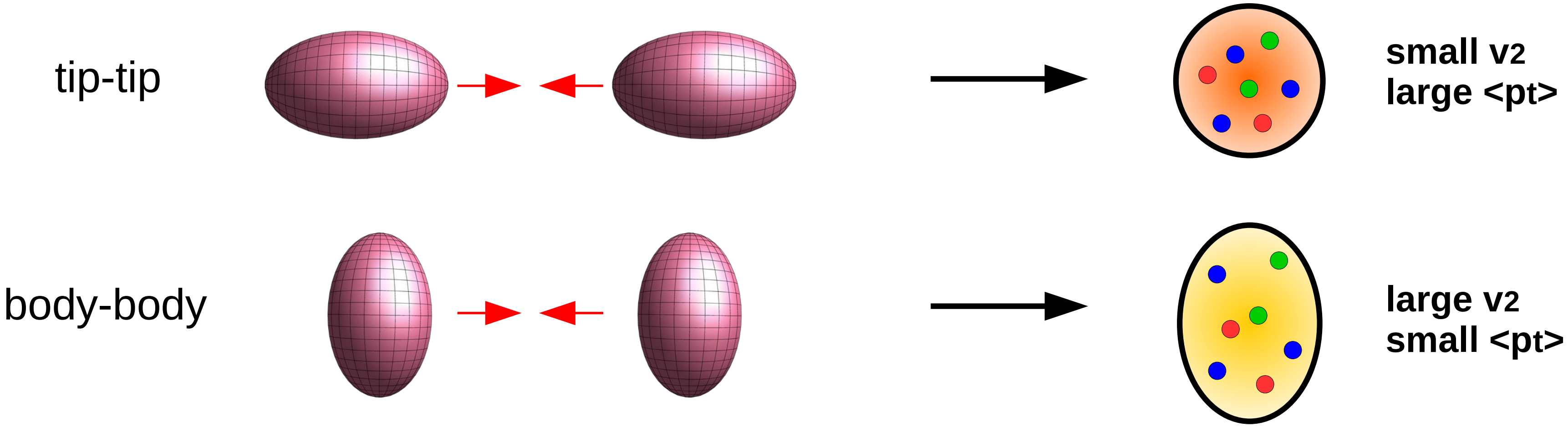




[Broniowski, Chojnacki, Obara, 0907.3216]
[Bozek, Broniowski, 1203.1810]
[Bozek, Broniowski, 1701.09105]

New “classical phenomenon”. What if we select events with a large overlap area?

[Giacalone, 1910.04673, 2004.14463]

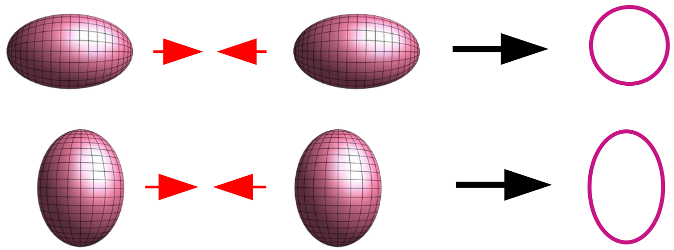


Correlation between v_2 and $[p_t]$ via Pearson coefficient: $$\rho_2 \equiv \rho(v_2^2, [p_t]) = \frac{\langle \delta v_2^2 \delta [p_t] \rangle}{\sqrt{\langle (\delta v_2^2)^2 \rangle \langle (\delta [p_t])^2 \rangle}}$$

Negative correlation from the quadrupole deformation.

[Bozek,1601.04513]

For central collisions of well-deformed nuclei:



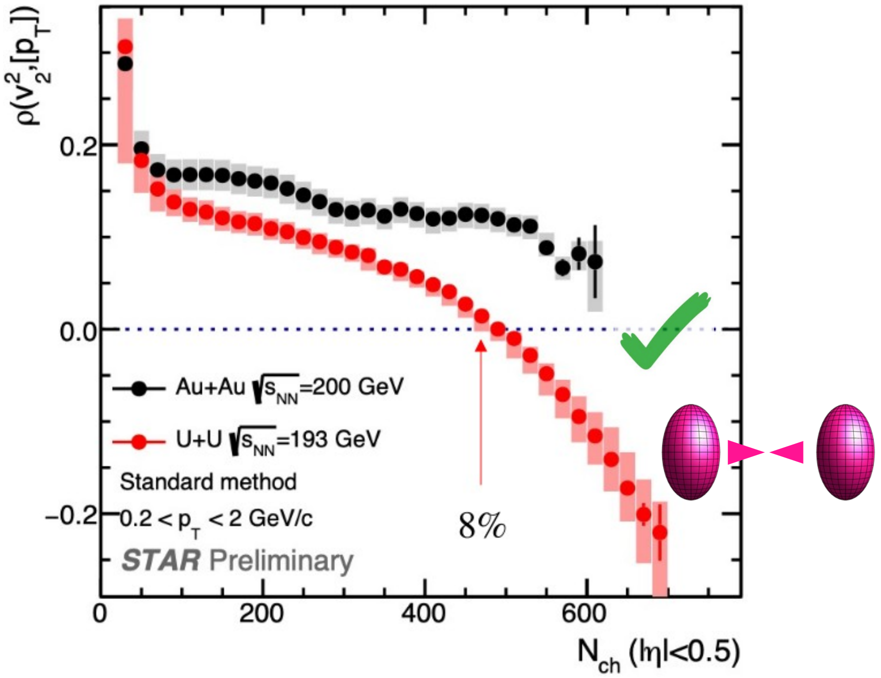
small v_2
large $[p_t]$

large v_2
small $[p_t]$

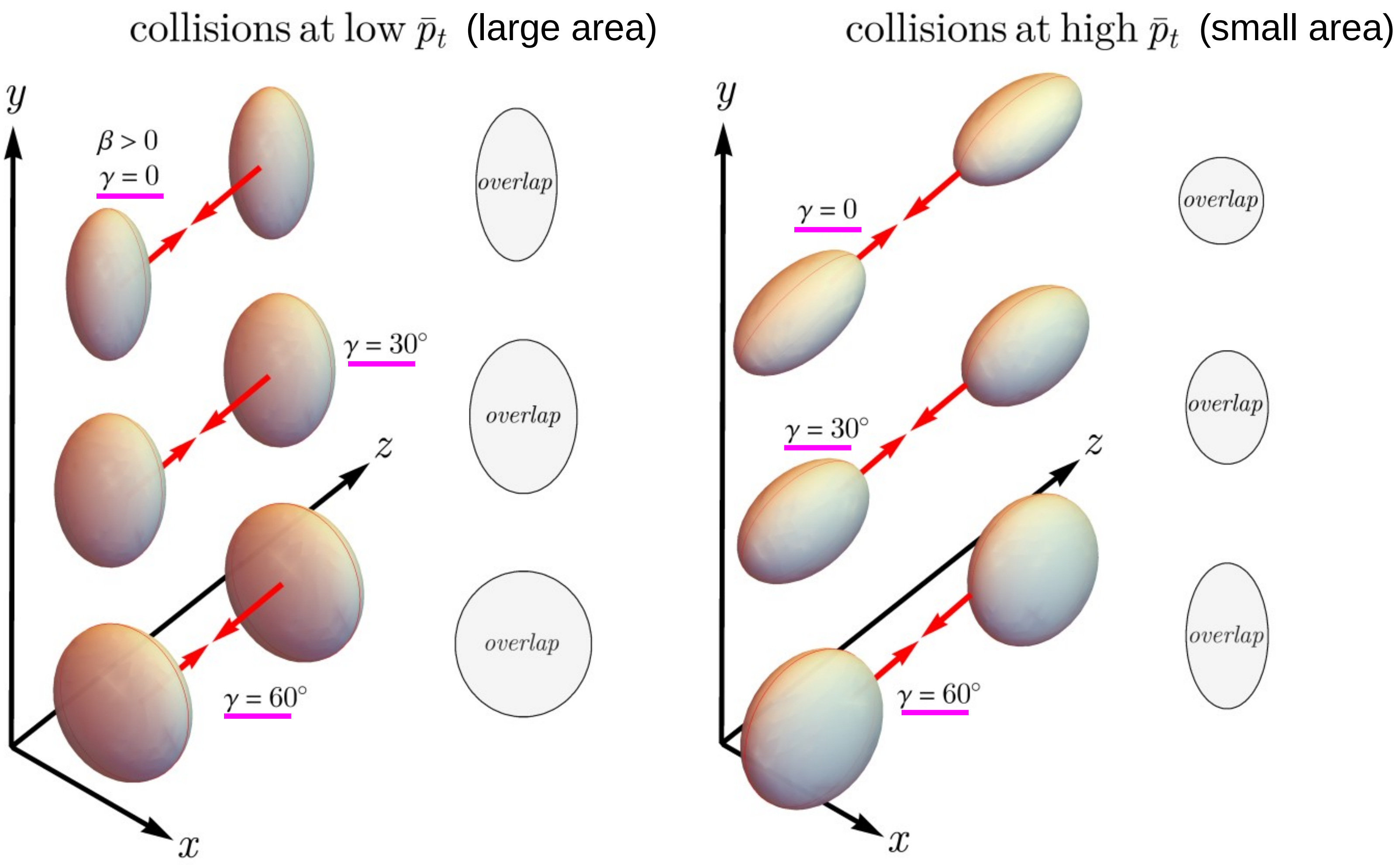
Correlation of the two observables is negative:

$$\rho_2 < 0$$

[see e.g. Jia, Initial Stages 21]



The ellipticity of the maximal area of overlap depends on the triaxiality.



Triaxiality @ LHC.
^{129}Xe predicted to be triaxial.

[Bally, Bender, Giacalone, Somà, 2108.09578]

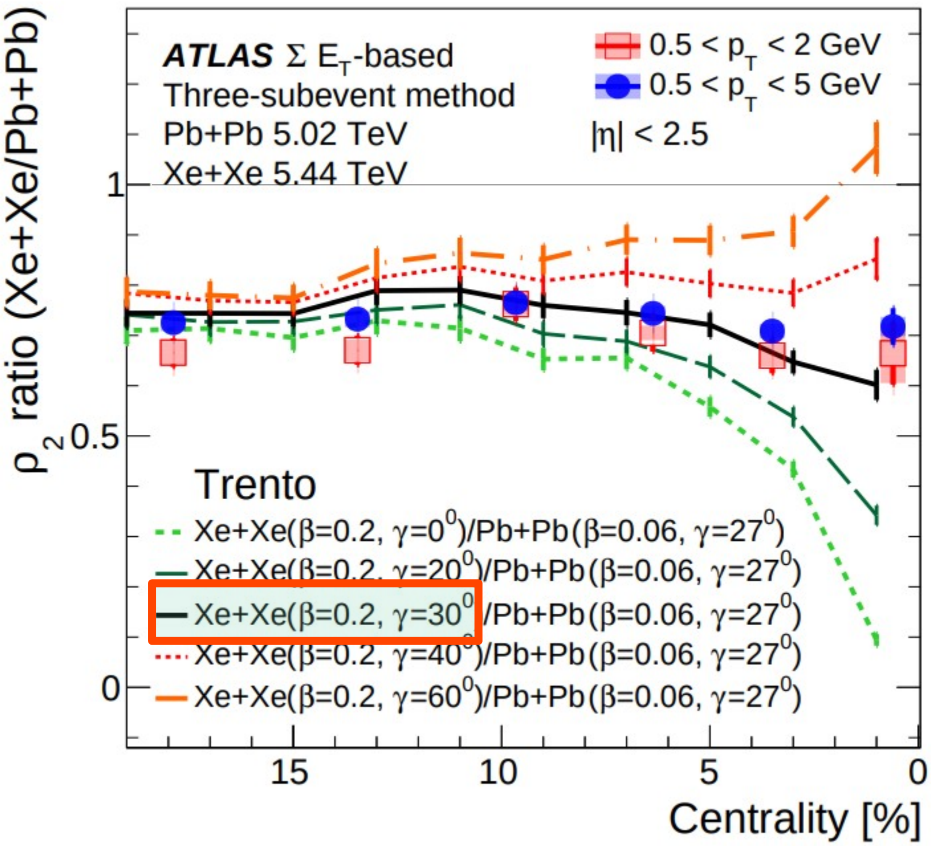
Compare to spherical baseline.
Simple leading dependence:

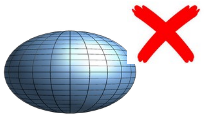
$$\rho_2 \propto -\cos(3\gamma)\beta_2^3$$

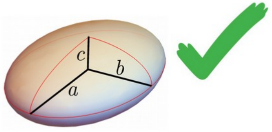
[Jia, 2109.00604]

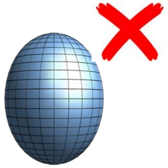
First experimental constraint on triaxiality of odd-mass ^{129}Xe.

[ATLAS Collaboration, 2205.00039]









Towards isobars.

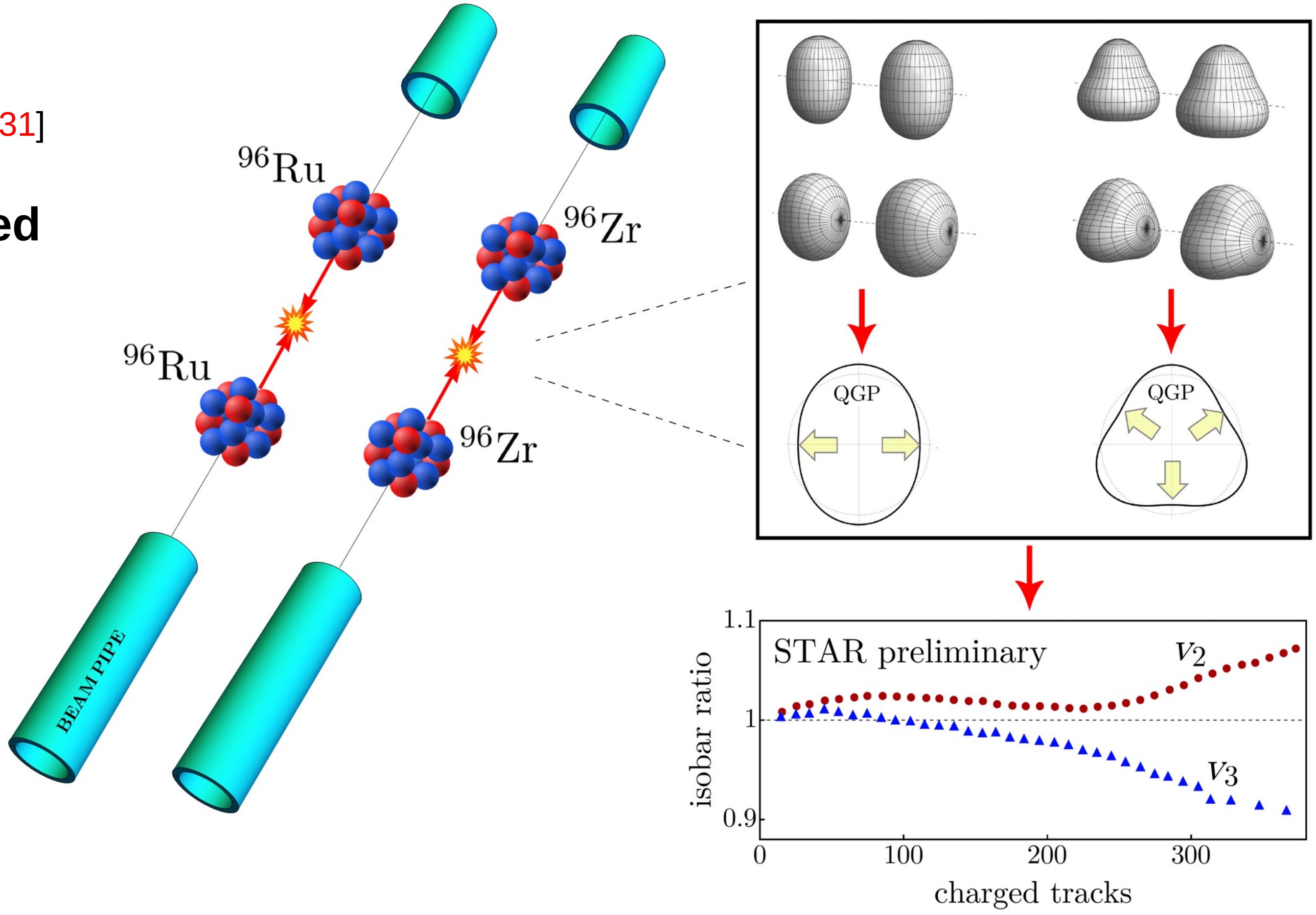
BREAKTHROUGH IN 2021

Isobar collisions @ RHIC.

[STAR collaboration, 2109.00131]

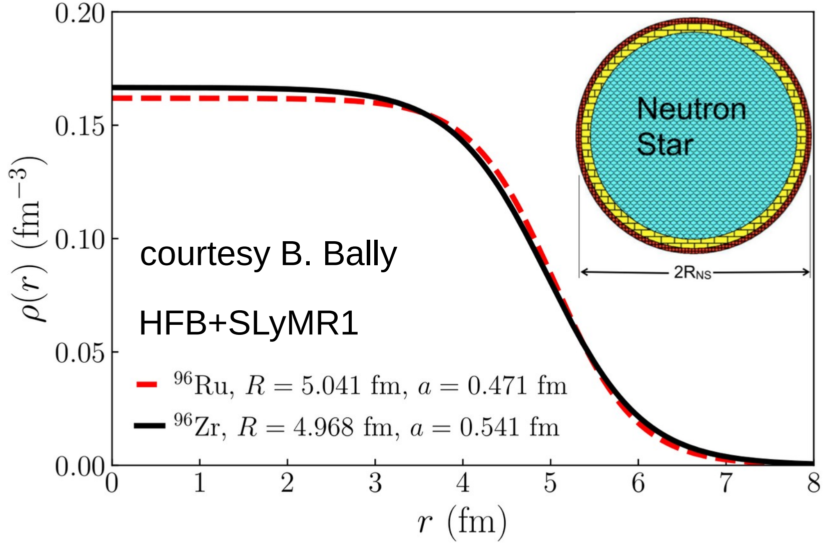
Octupole deformation observed in zirconium-96!

A tool for precision studies of nuclear shapes.



NEXT TALK BY J. JIA

Highlight: Neutrons matter!

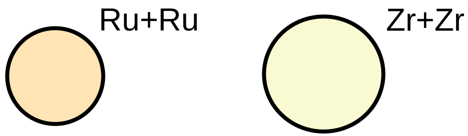


Radial profiles are different:

$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-R}{a}\right)}$$

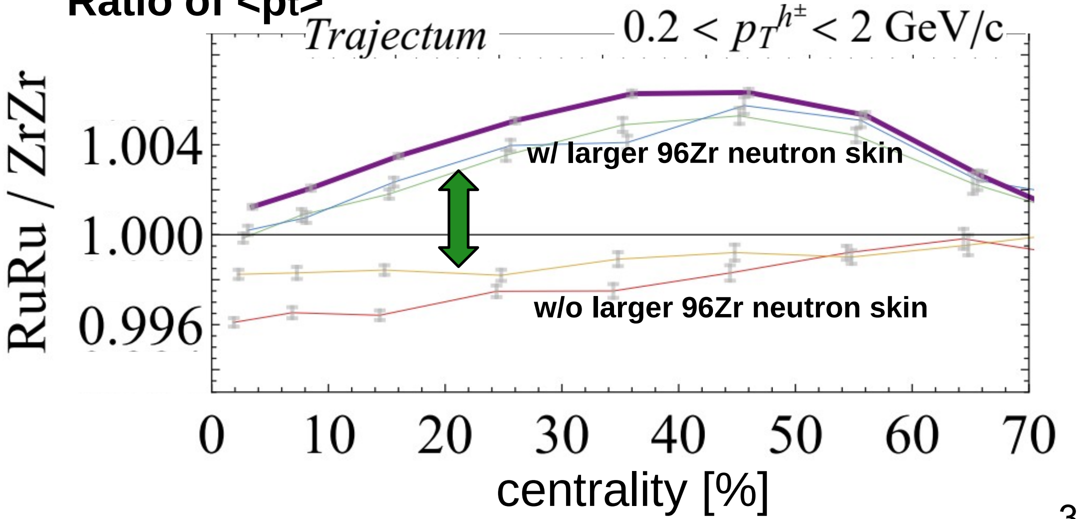
- 96Zr, more diffuse **due to larger N**.
- 96Ru, sharper surface.

Due to the smaller neutron skin, Ru+Ru systems are more compact.



<p_t> is enhanced.

Ratio of <p_t>



[Nijs, van der Schee, 2112.13771]
[Xu, Zhao, Li, Zhou, Chen, Wang, 2111.14812]
[Jia, Zhang, 2111.15559]

CONCEPTUAL QUESTIONS (to be discussed by the Task Force)

Unreasonable effectiveness of nuclear shapes?

Low-energy and high-energy approaches are consistent?

State-of-the-art low energy predictions match high-energy observations?

Would two communities benefit from collisions of extra species?

Exploiting isobars? (see next talk)

RECAP

- Manifestation of intrinsic nuclear shapes in the initial condition of the quark-gluon plasma.
- Evidence of **axial & triaxial quadrupole**, **axial octupole**, and **neutron skin** effects.
- ^{238}U appears to be less deformed in high-energy collisions than in low-energy calculations.
- Triaxial ^{129}Xe with β_2=0.20 naturally explains LHC data.
- Many conceptual questions to address in future. Isobars?