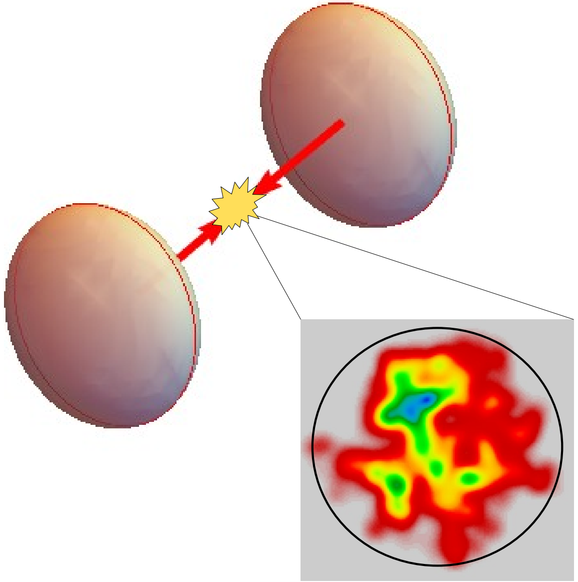
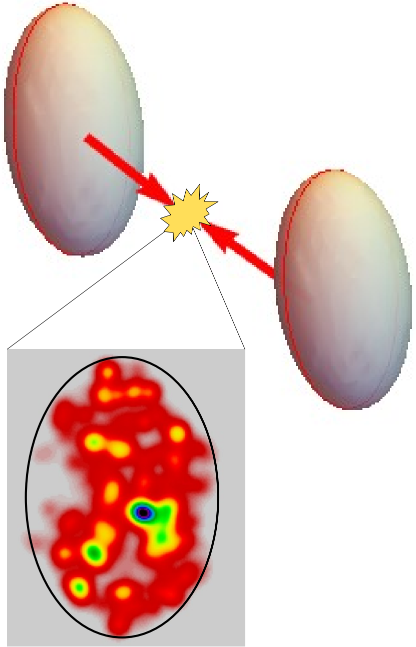
Observing the structure of atomic nuclei at high-energy colliders



by

Giuliano Giacalone

11 / 02 / 2022



UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

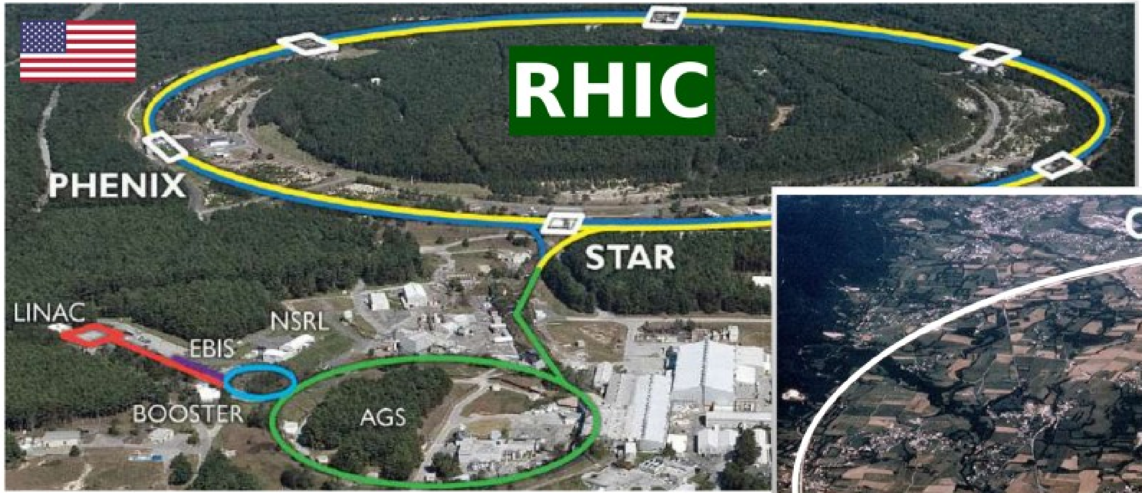
isoQuant SFB1225

OUTLINE

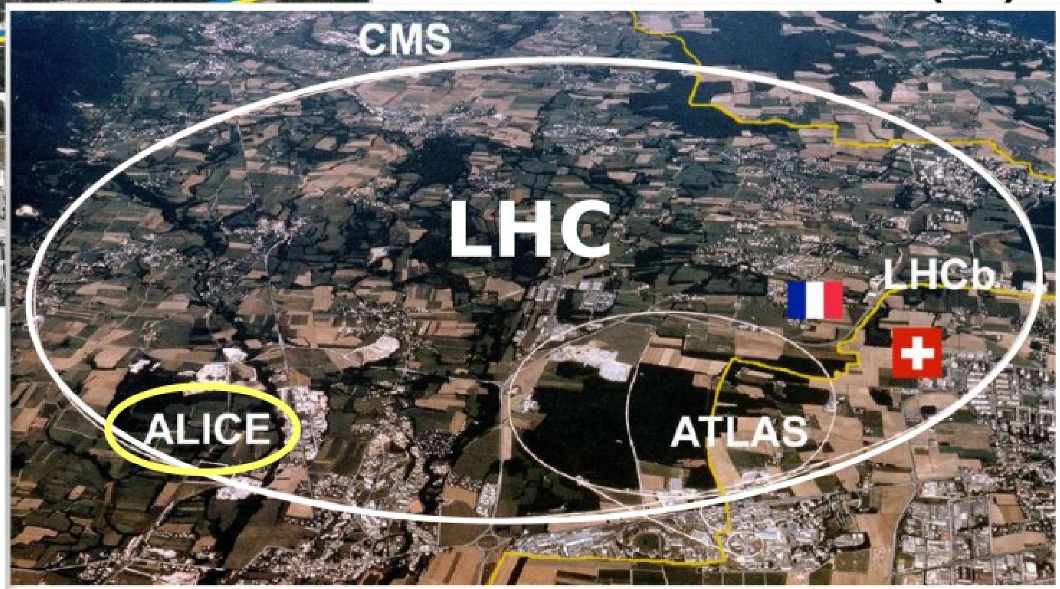
- 1. Heavy-ion collisions.
- 2. Anisotropic flow.
- 3. Modeling (deformed) nuclei at high energy.
- 4. Nuclear deformation in the data (pre-2021).
- 5. Collisions of isobars: the 2021 breakthrough.

1. Heavy-ion collisions.

Long Island (NY)



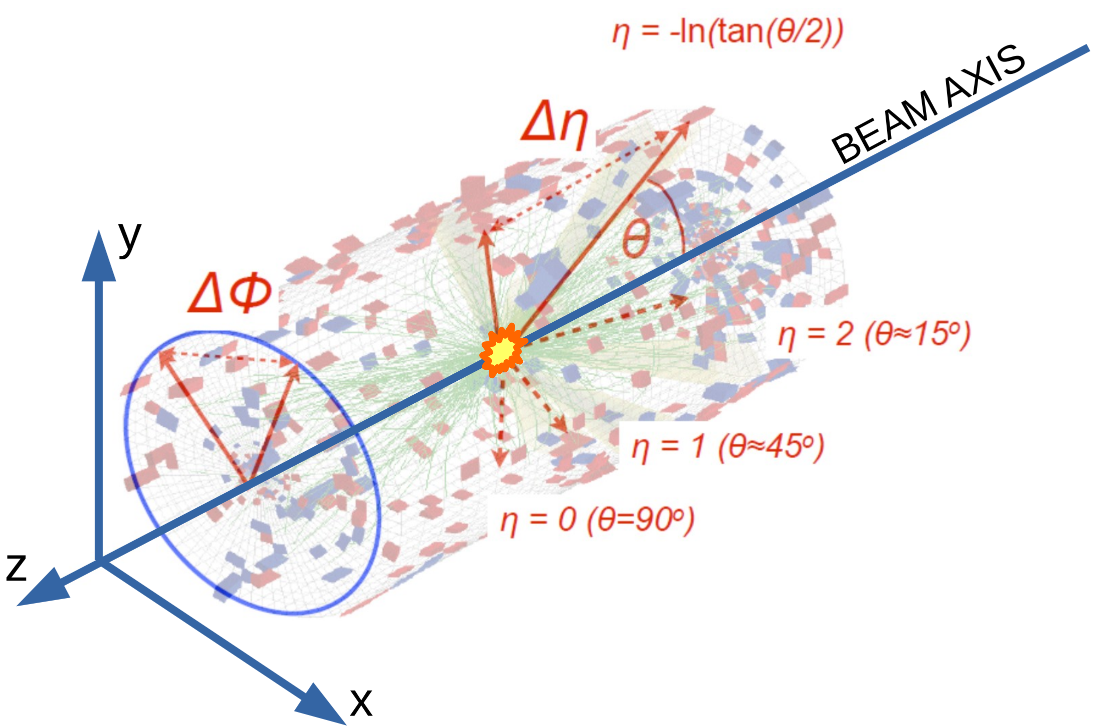
Geneva (CH)



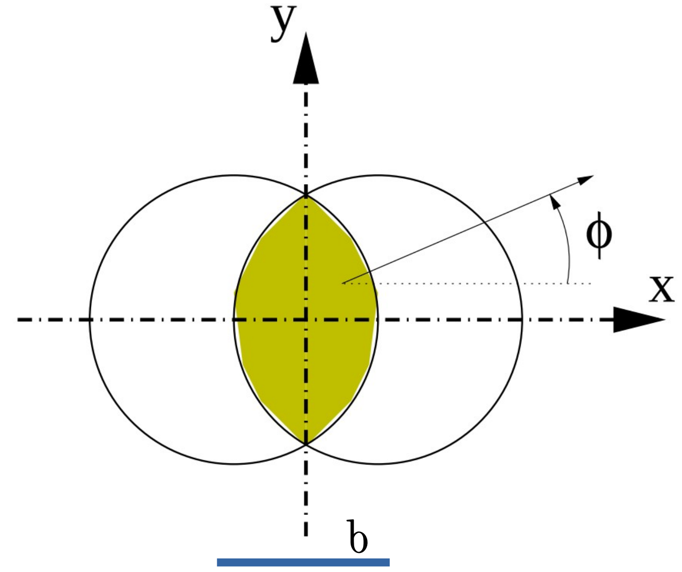
- Great experimental program of high-energy nuclear collisions.
  (~2k experimentalists involved)

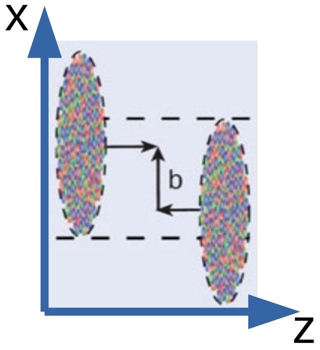
- Nuclei collided ~1 month/year @ LHC.
  RHIC is dedicated to nuclear collisions. (shutdown ~2026)

COLLISION GEOMETRY



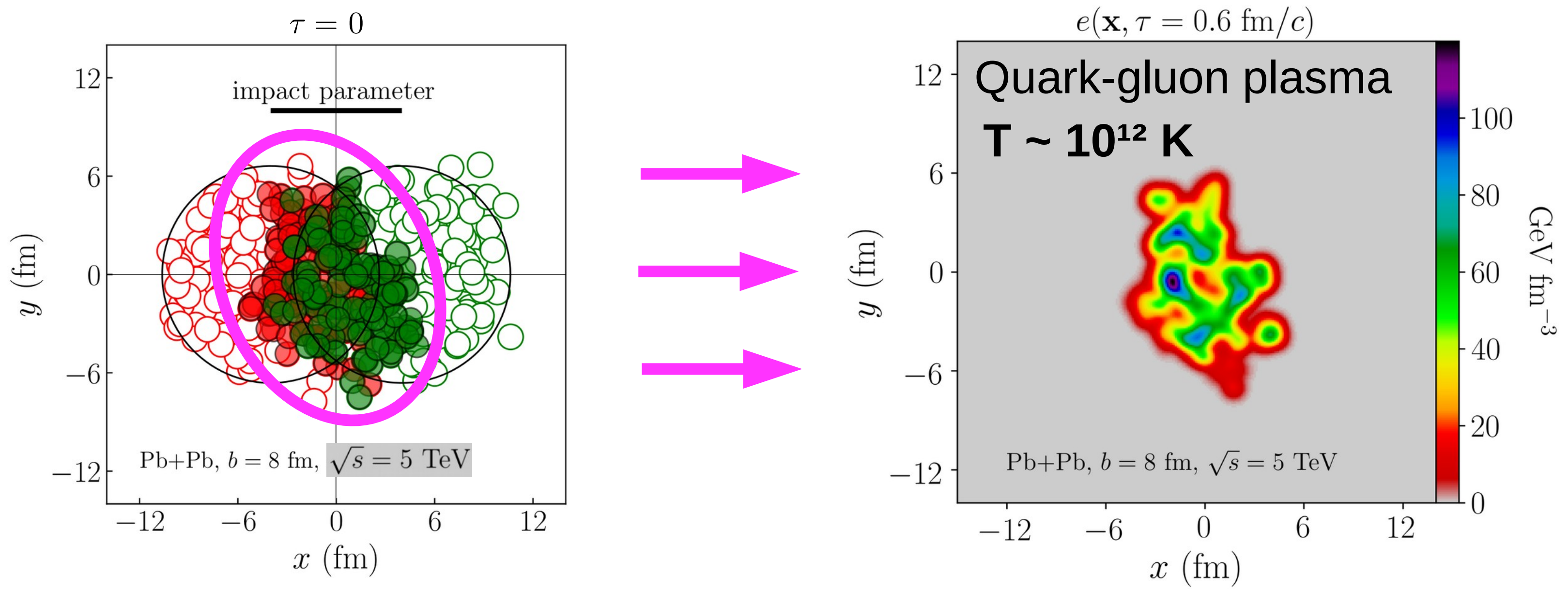
Plane transverse to the beam:





Nuclei are “pancakes” in the lab frame

REPRODUCING THE EARLY UNIVERSE IN THE LAB



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

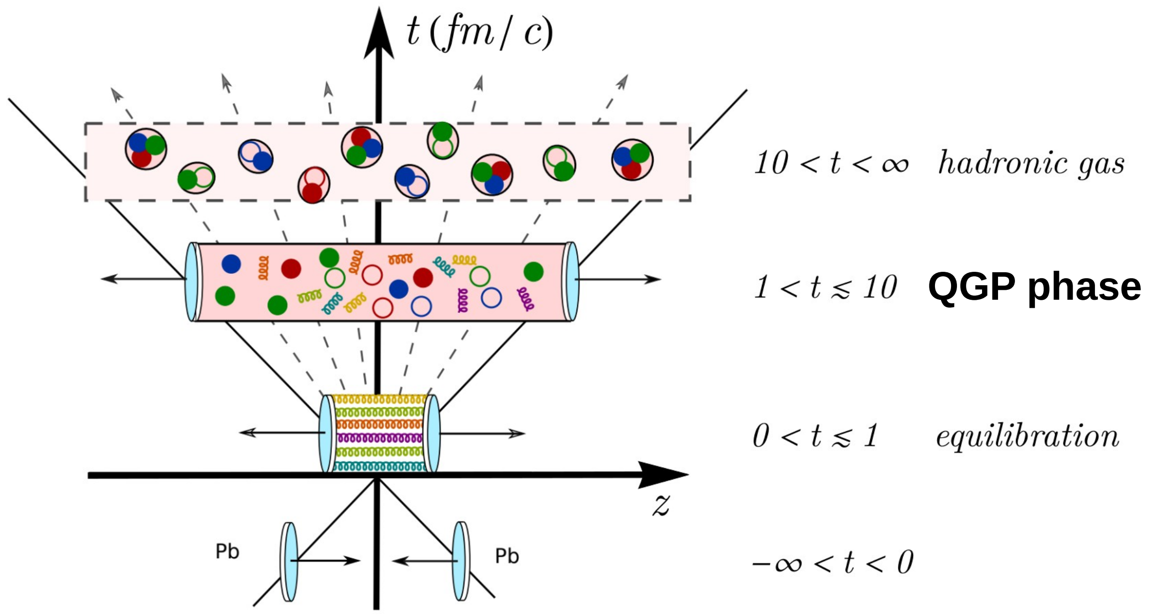
$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$$ + viscous corrections ($\eta/s, \zeta/s$, ...)

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

[HotQCD collaboration, 1407.6387]

Main goals: understanding the initial condition and the transport properties.

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



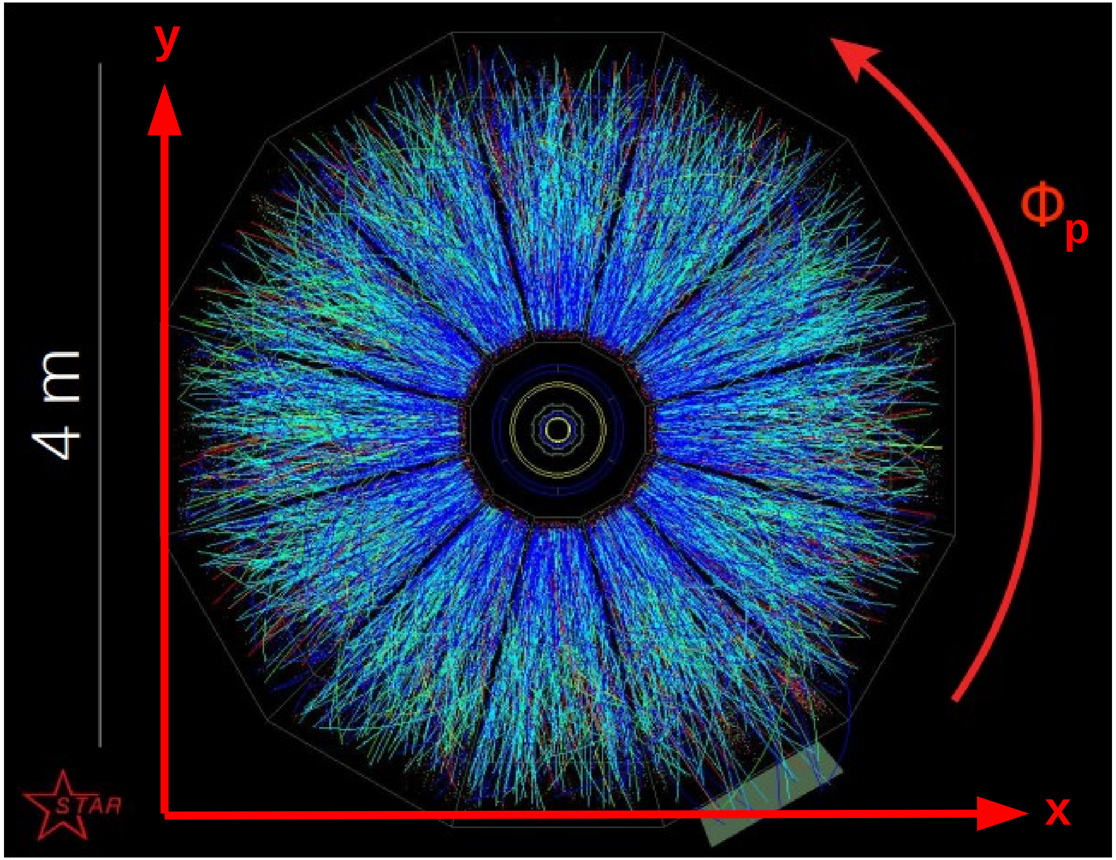
t = ∞

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

Reconstruct information from "observables", functions of the spectrum, e.g.,

$$N = \int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} \;, \quad V_n = \frac{1}{N}\int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-in\phi_p} \;, \quad \langle p_t \rangle = \frac{1}{N}\int_{\mathbf{p}_t} p_t \frac{dN}{d^2\mathbf{p}_t} \quad \ldots$$

2. Anisotropic flow.



Are particles emitted isotropically in the transverse plane?

Fourier decomposition of the azimuthal distribution of particles.

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

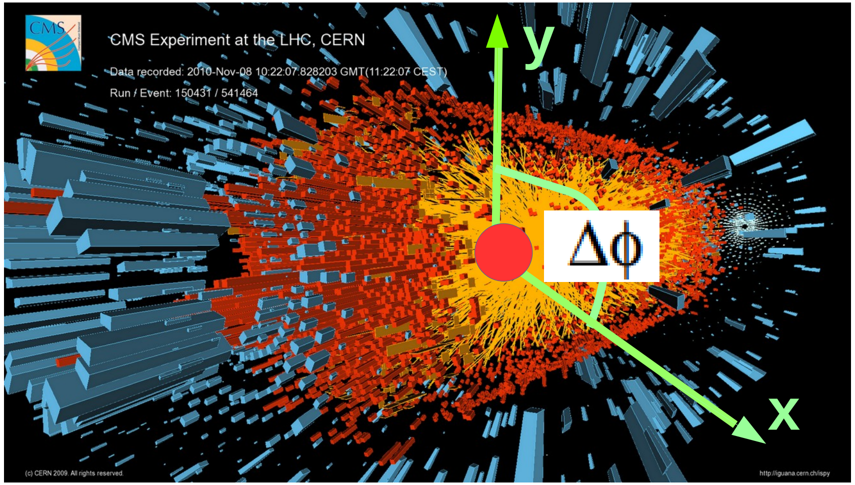
$$v_n = |V_n|$$

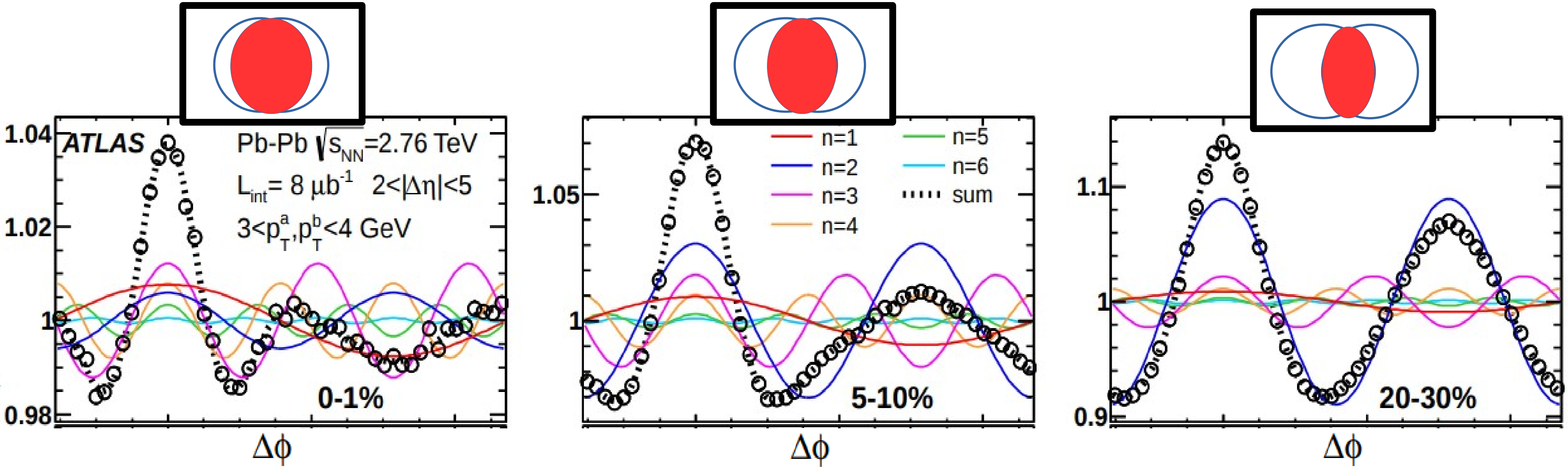
anisotropic flow coefficients

Experimentally, anisotropy is observed.

Measurable up to n~10.

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

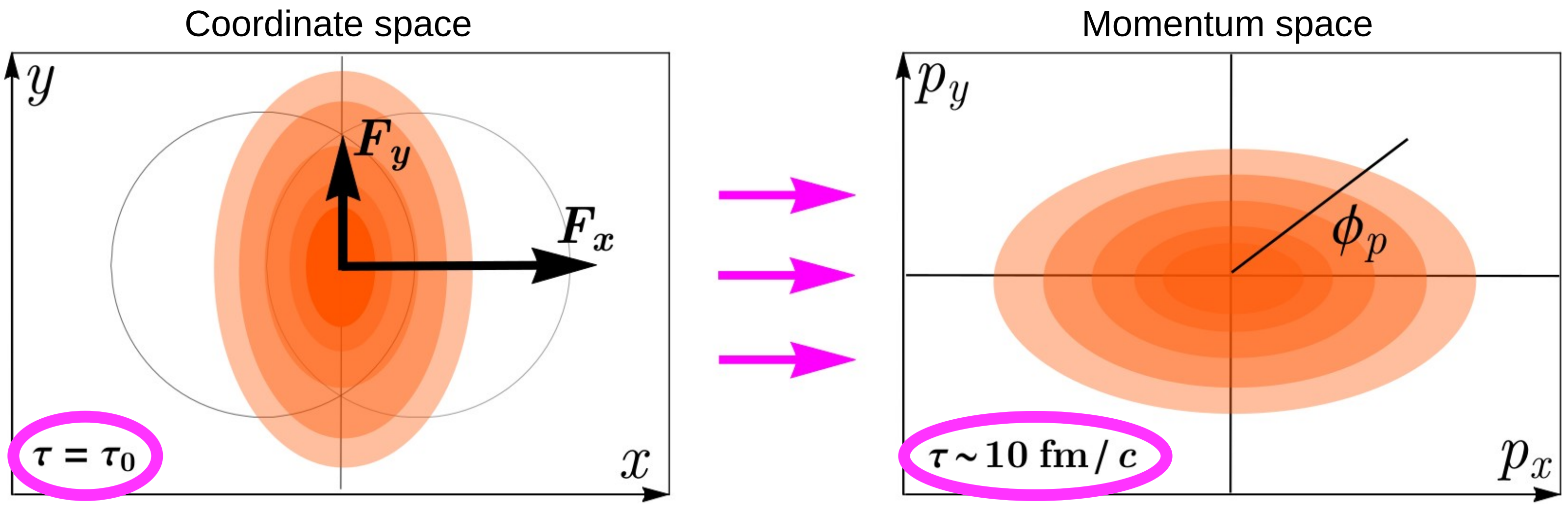




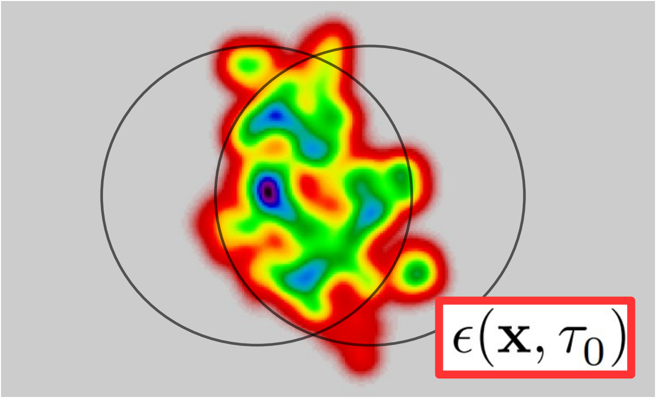
Anisotropic flow from spatial anisotropy. $F = -\nabla P$

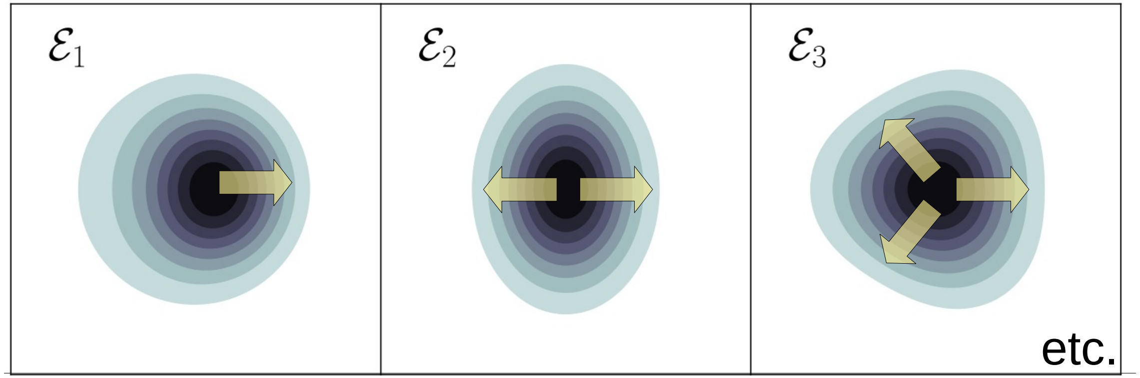
Elliptic flow, the 2nd harmonic.
Dynamical response to elliptical geometry. $\longrightarrow$ $V_2 = \frac{1}{N}\int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-i2\phi_p}$

[Ollitrault, 1992]



QGP is not a smooth object due to the nucleons.
Deformations yield flow harmonics via pressure gradients.





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

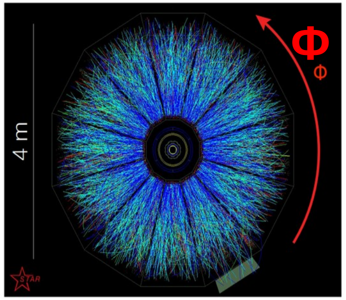
$$\mathcal{E}_n = -\frac{\int r dr d\phi \; r^n e^{in\phi} \epsilon(r,\phi)}{\int r dr d\phi \; r^n \epsilon(r,\phi)} \quad \Longrightarrow \quad V_n \propto \mathcal{E}_n$$

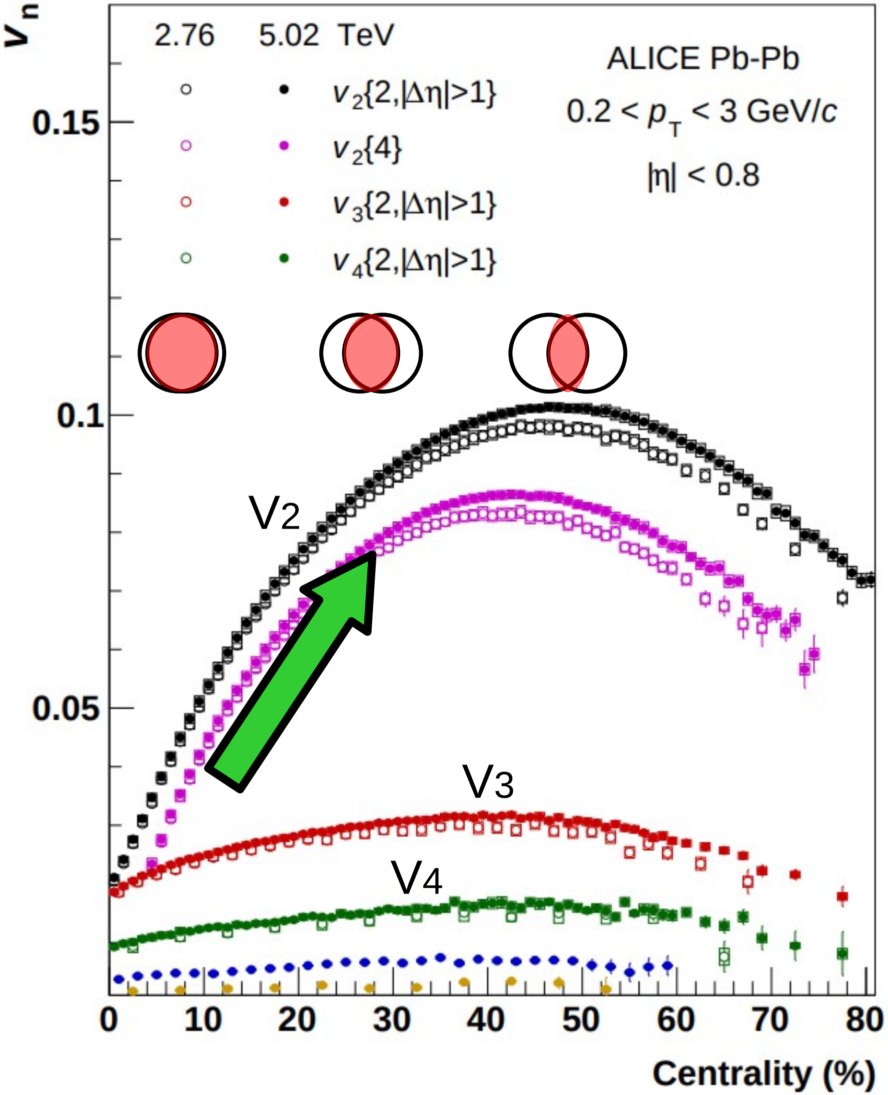
[Teaney, Yan, 1010.1876]

Recent measurements.

[ALICE collaboration, 1804.02944]

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



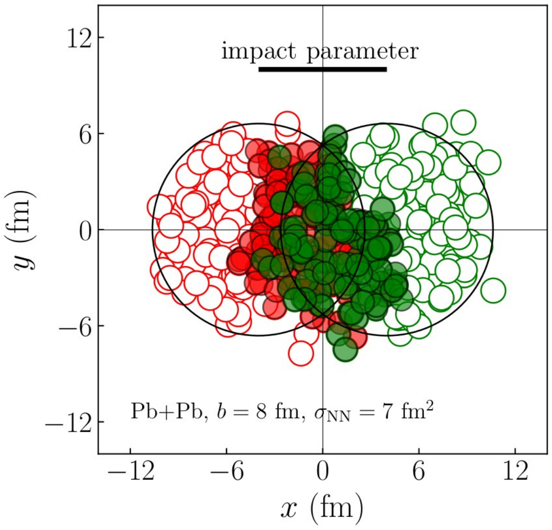


Strong enhancement of V_2 as the system becomes more elliptical.

Other coefficients depend little on centrality. Still nonzero.

How do we model the initial condition?

3. Modeling nuclei at high energy.



Initial geometry determined by impact parameter + nucleons.

Glauber Monte Carlo approach. Nucleons sampled independently from Woods-Saxon profile for each nucleus.

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

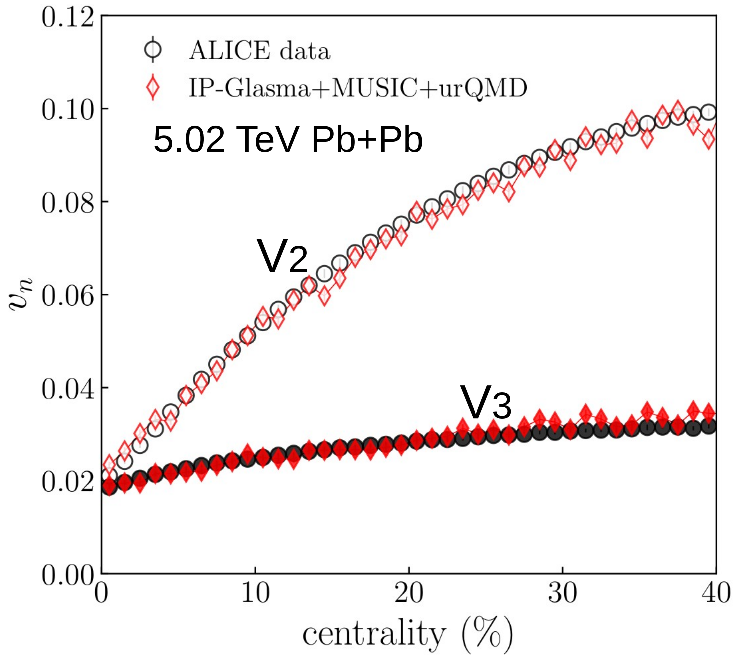
$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-R}{a}\right)}$$

R → half-width radius

a → diffusivity

Couple with a model of QGP evolution.
(e.g. IP-Glasma+MUSIC+UrQMD).

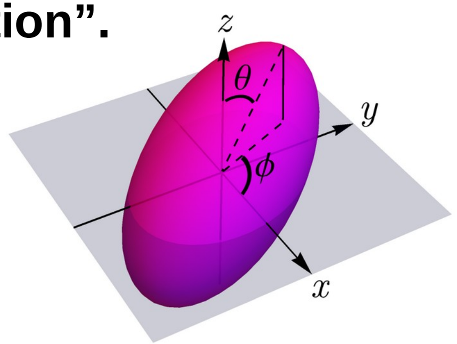
[Schenke, Shen, Tribedy, 2005.14682]



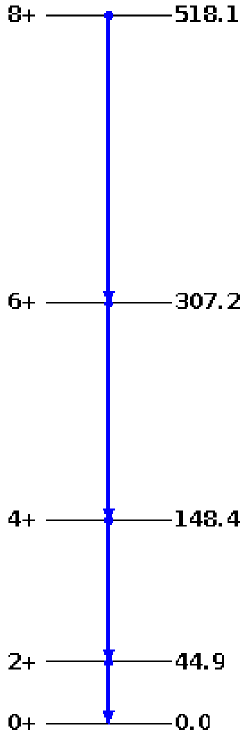
Anisotropies are captured.
This “mean field” approach is very powerful.

Important ingredient missing. Nuclei are strongly correlated and collective.

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



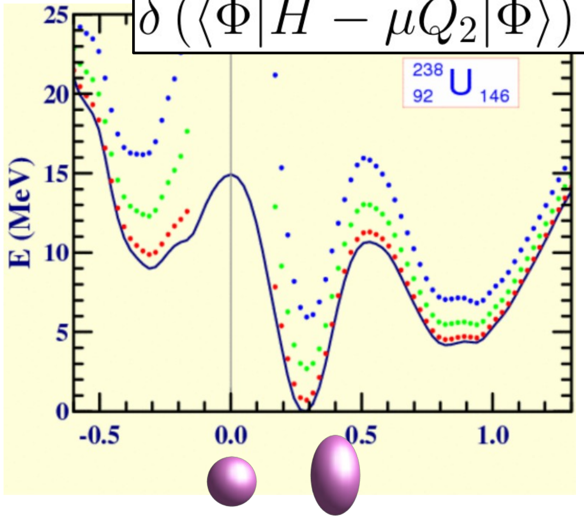
$^{238}_{92}\mathrm{U}$ **E = B J(J+1)**



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

Microscopic origin:
Very complicated.
“Spontaneous breaking”
of rotational symmetry
in Hartreee-Fock approach.

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



State-of-the-art for large nuclei. Guiding principle: symmetry.

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

Capture correlations through "symmetry-breaking" intrinsic shapes (HFB states).

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

Slater determinant

e.g. quadrupole deformation

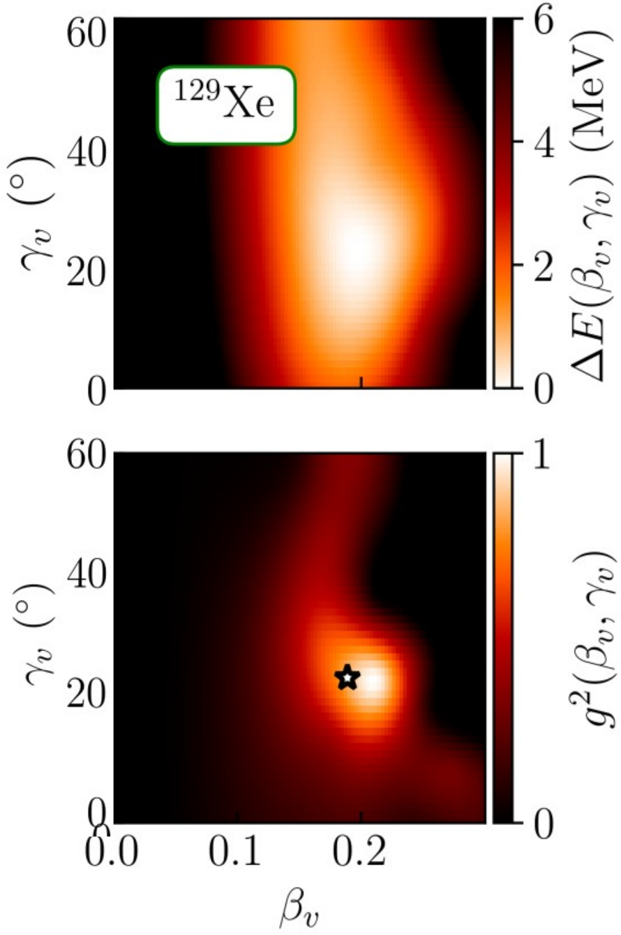
Restore symmetry via enriched variational Ansatz. Projected generator coordinate method, e.g.,

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

weights projections HFB states

Fix the weights via additional variational equation

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

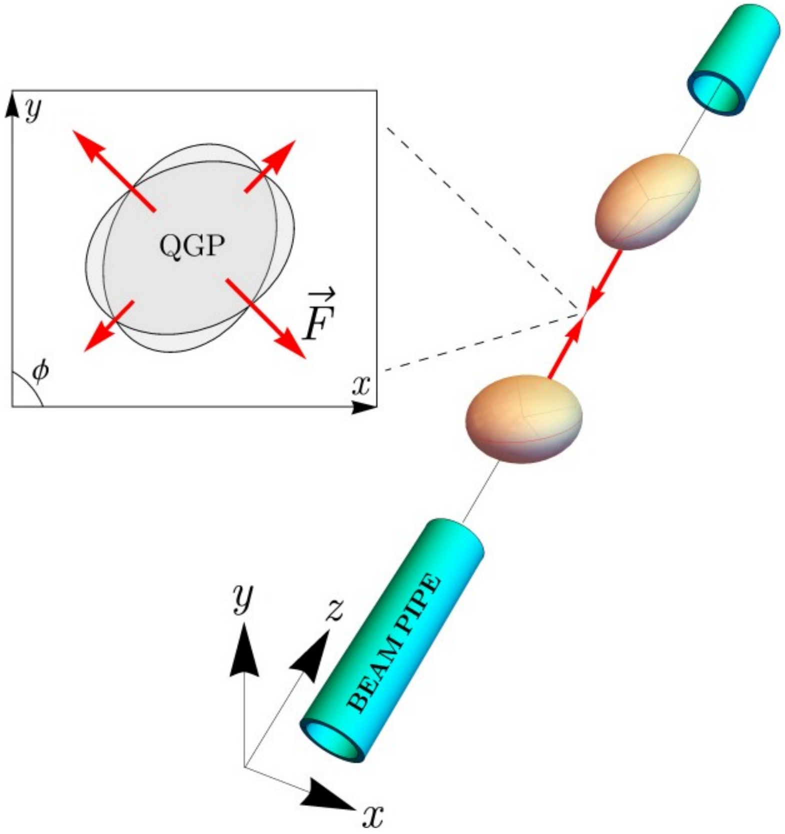


Intrinsic shapes are non-observable for direct measurements, but they leave their fingerprint on virtually all nuclear observables and phenomena

Michael Bender – RBRC Workshop Jan 2021

They will show up as well at high energy.

THIS TALK!



Collide nuclei with intrinsic deformations.

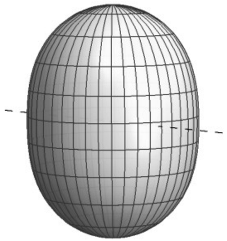
The configuration of nucleons is deformed and acquires a random orientation.

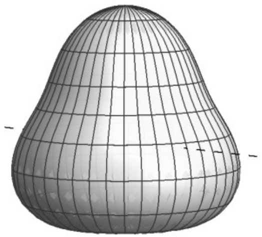
Generalize the Woods-Saxon profile to include intrinsic deformations:

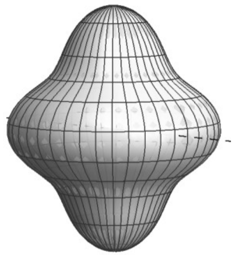
$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r-R(\Theta,\Phi)\right]/a\right)} \;, \quad R(\Theta,\Phi) = R_0\left[1+\underline{\beta_2}\left(\cos\gamma Y_{20}(\Theta)+\sin\underline{\gamma}Y_{22}(\Theta,\Phi)\right)+\underline{\beta_3}Y_{30}(\Theta)+\underline{\beta_4}Y_{40}(\Theta)\right]$$

Deformation coefficients are associated with the multipole moments of the density:

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

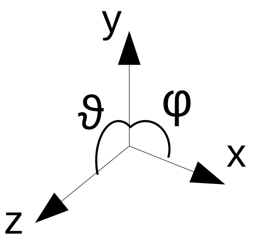


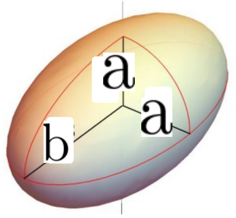




For $\beta_2>0$, the nucleus is prolate ($\gamma=0$), triaxial ($\gamma=30^0$), or oblate ($\gamma=60^0$).

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

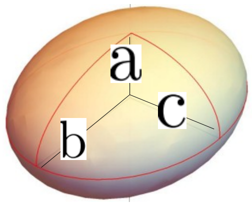




$\gamma = 0$

$r_1 = r_2 < r_3$

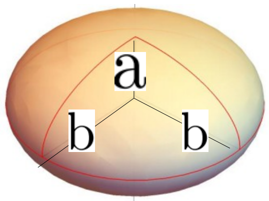
prolate



$\gamma = 30^\circ$

$r_1 \neq r_2 \neq r_3$

triaxial

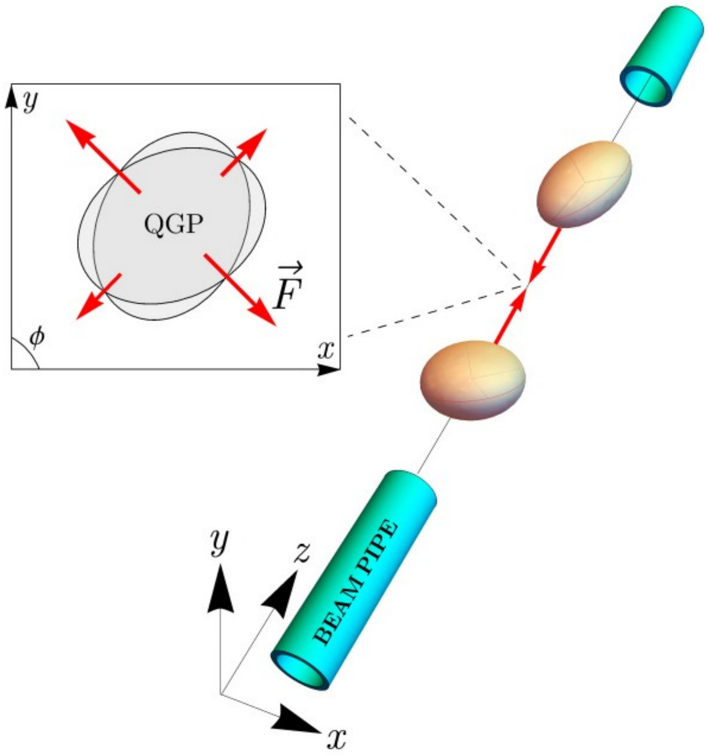


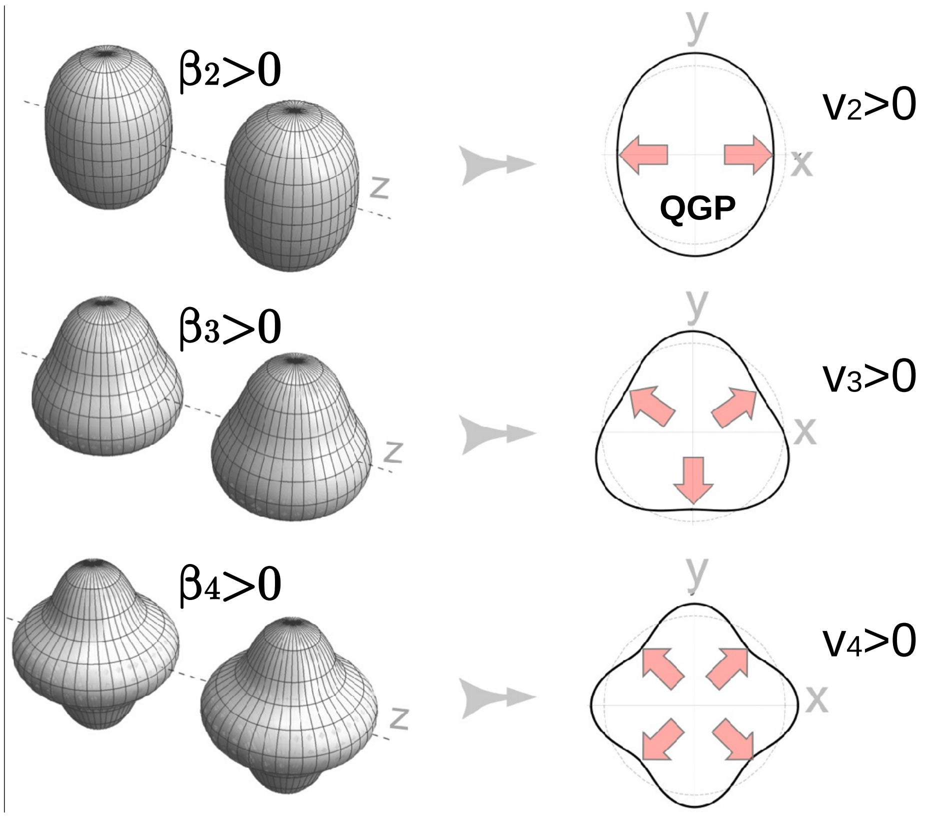
$\gamma = 60^\circ$

$r_1 < r_2 = r_3$

oblate

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





from [Jia, 2106.08768]

If true, very straightforward method to see deformations in an experiment.

4. Nuclear deformation in the data (pre-2021).

@RHIC. Precision data from STAR.

[STAR collaboration, 1505.07812]

Leading corrections to the fluctuations of elliptic flow coefficient:

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

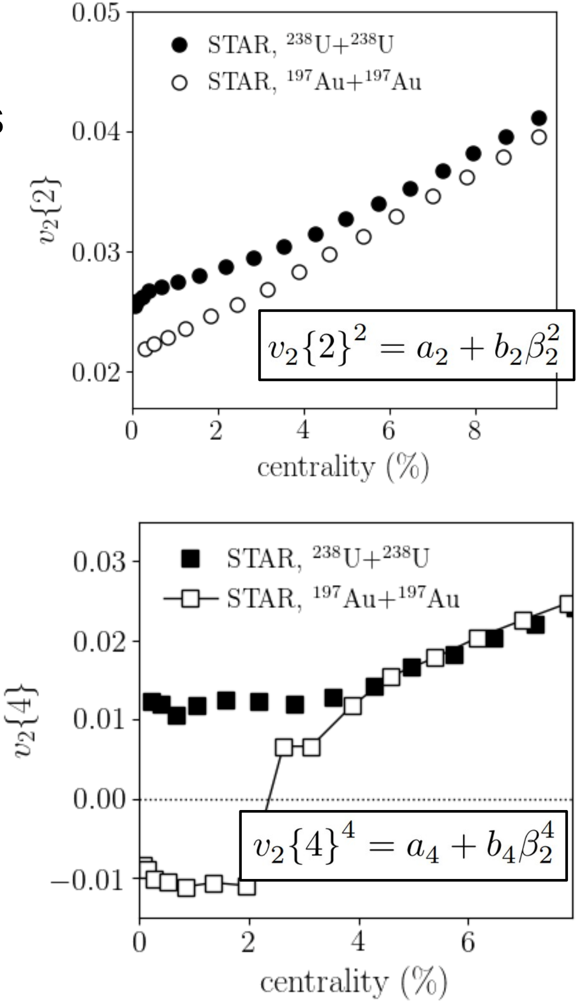
VARIANCE

$$v_2\{4\}^4 = a_4 + b_4\beta_2^4$$

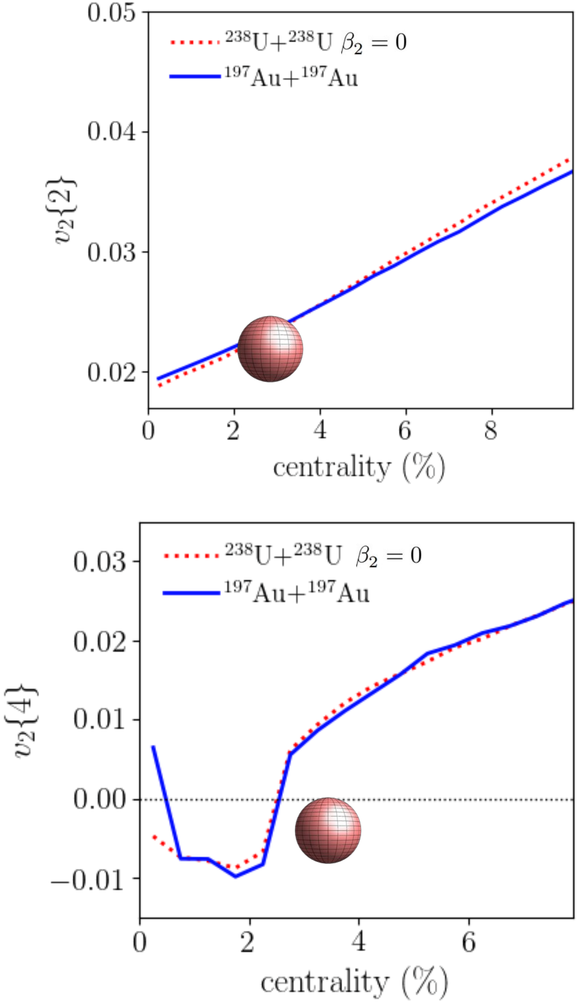
KURTOSIS

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

STAR data



theory estimate



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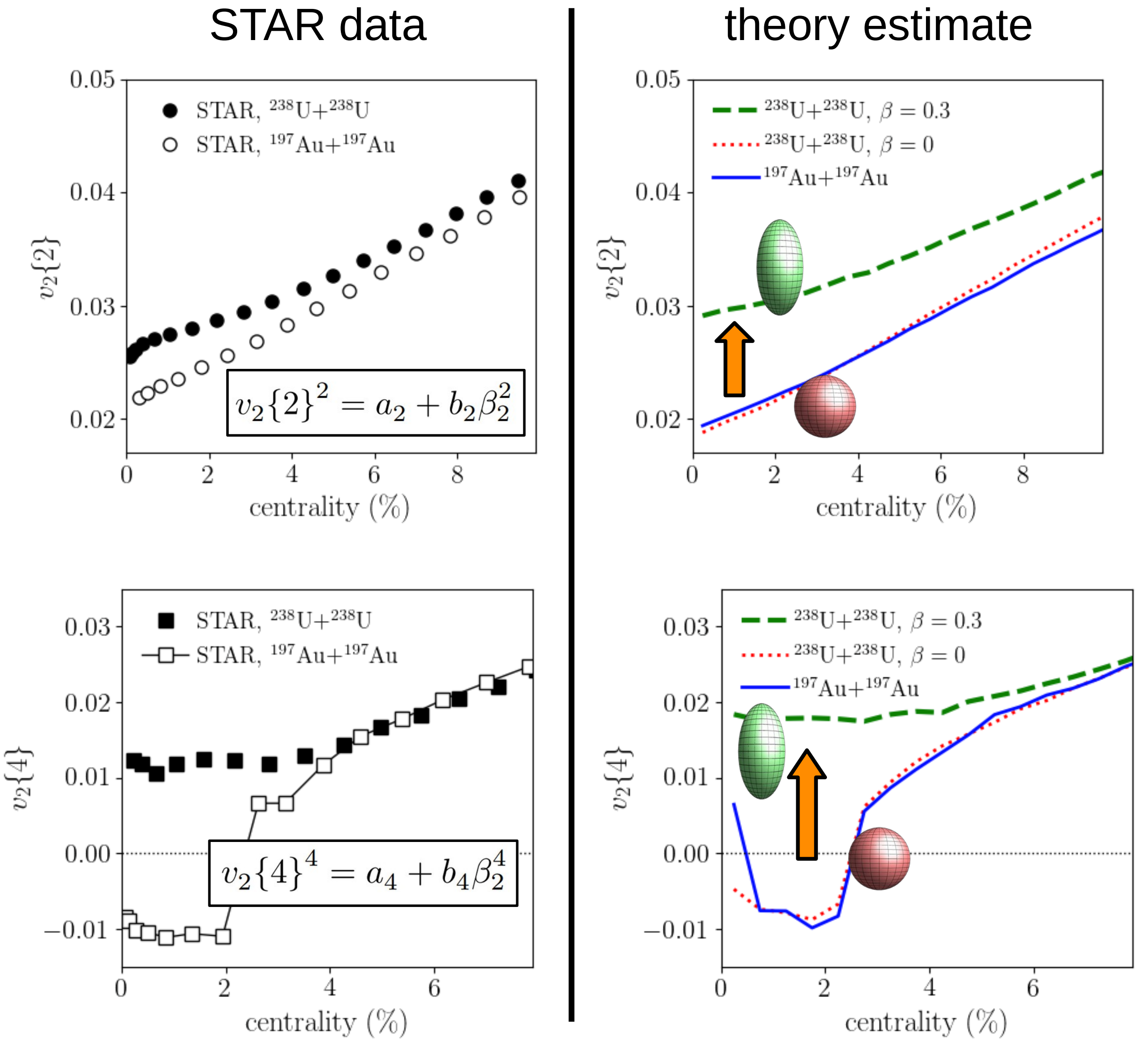
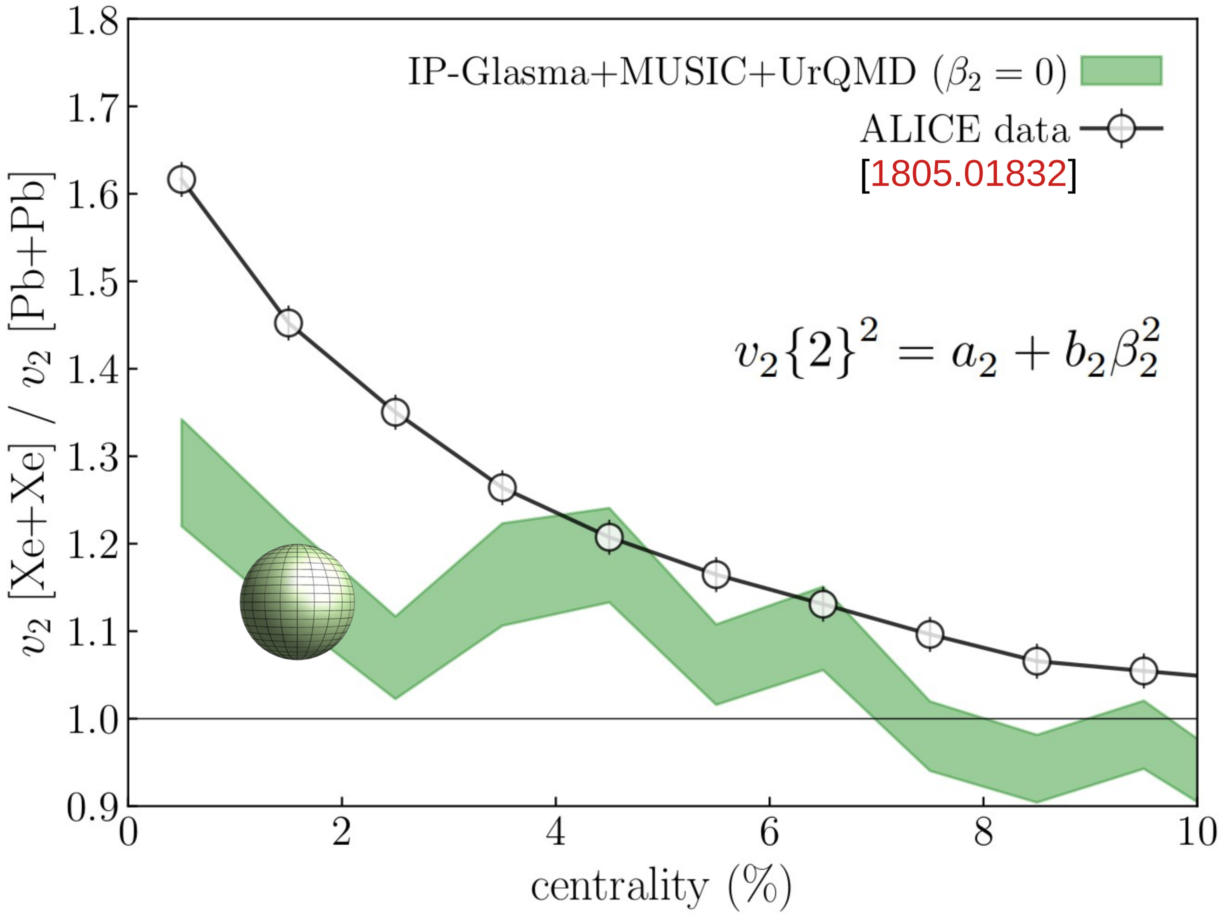
KURTOSIS

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

Deformation explains the data!

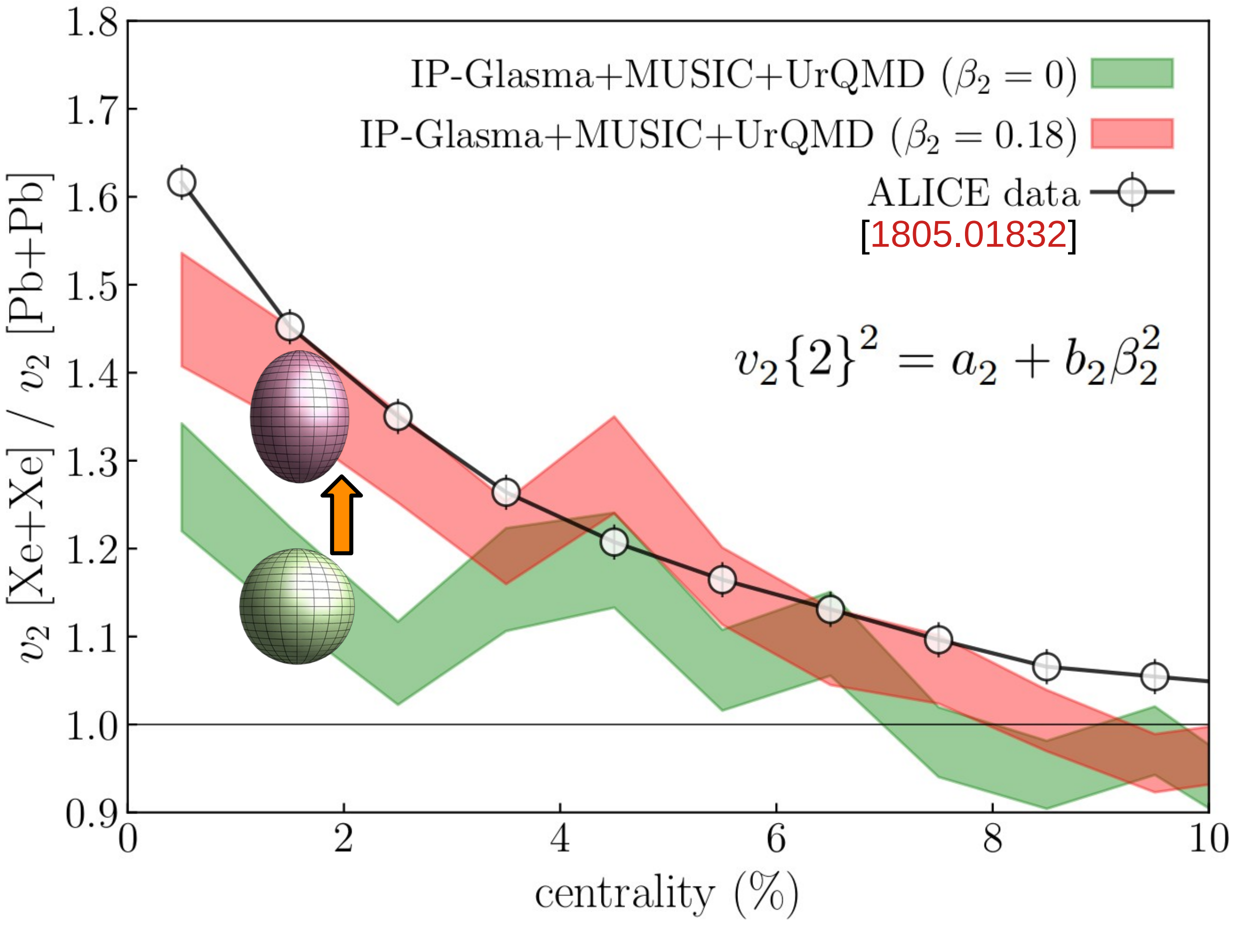


@ **LHC.** Enhanced elliptic flow in Xe-Xe collisions.



Model fails with spherical 129Xe.

Moving to LHC. Enhanced elliptic flow in Xe-Xe collisions.



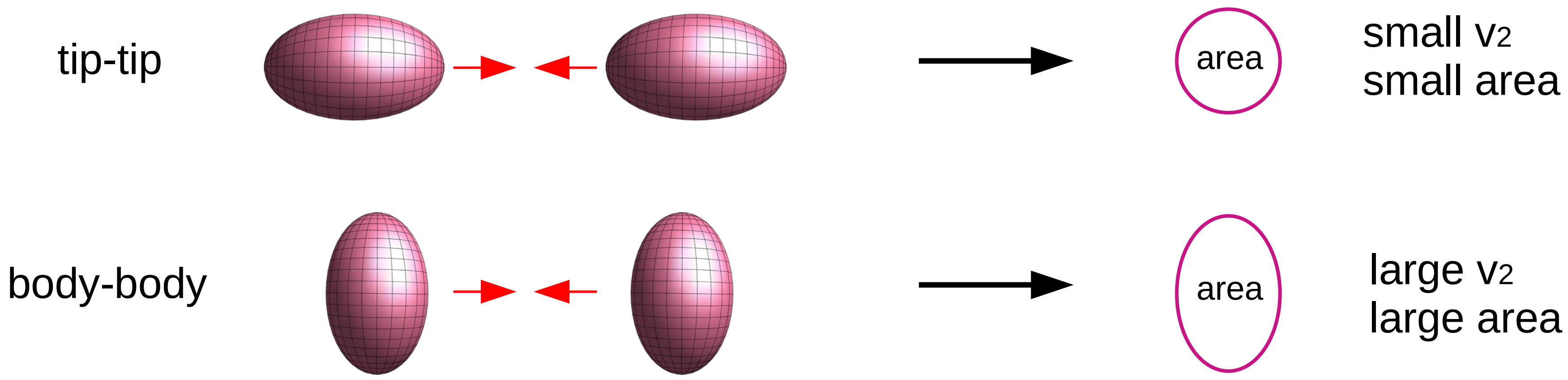
Dramatic improvement with deformed 129Xe.

NB: value of β2 of 129Xe recently evaluated and is ≈0.21.

See also [Giacalone, Luzum, Noronha-Hostler, Ollitrault, 1711.08499]

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

[Giacalone, 1910.04673]



Area of overlap to control the relative orientation of the colliding ions.

In experiments, area is anti-correlated with the mean momentum: $\langle p_t \rangle = \frac{1}{N} \int_{\mathbf{p}_t} p_t \frac{dN}{d^2\mathbf{p}_t}$

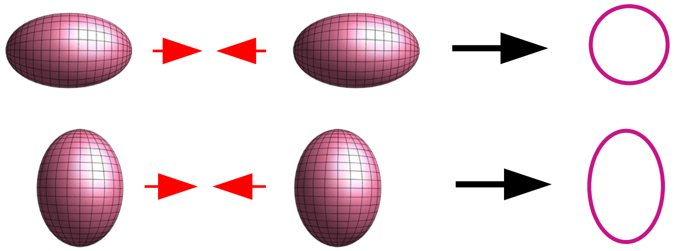
[Broniowski, Chojnacki, Obara, 0907.3216]
[Bozek, Broniowski,1701.09105]

Correlation between v_2 and $[p_t]$:

$$\rho_2 \equiv \rho(v_2^2, [p_t]) = \frac{\langle \delta v_2^2 \delta [p_t] \rangle}{\sqrt{\langle (\delta v_2^2)^2 \rangle \langle (\delta [p_t])^2 \rangle}}$$

[Bozek,1601.04513]

For central collisions of well-deformed nuclei:



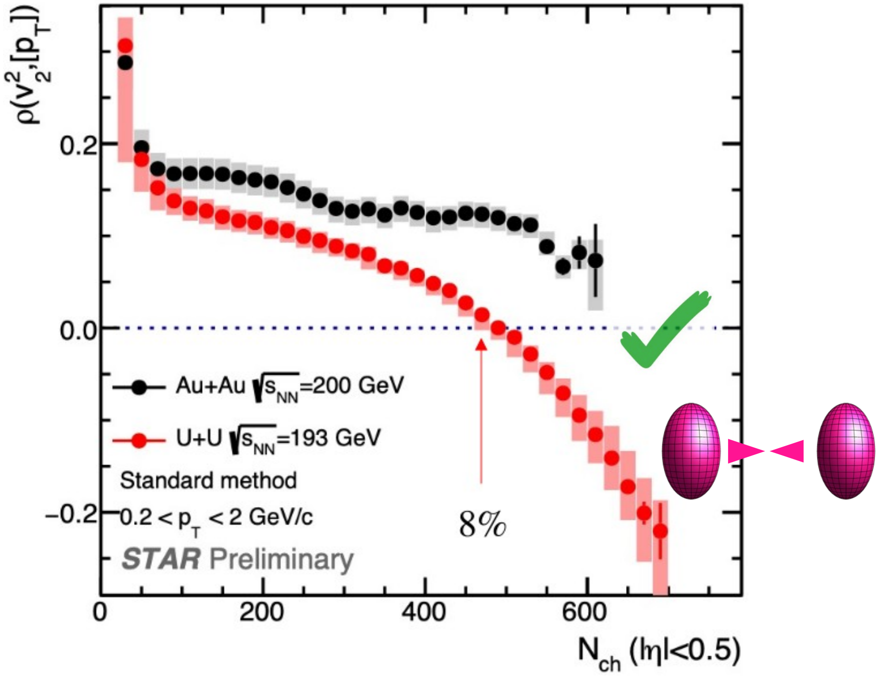
small v_2
large $[p_t]$

large v_2
small $[p_t]$

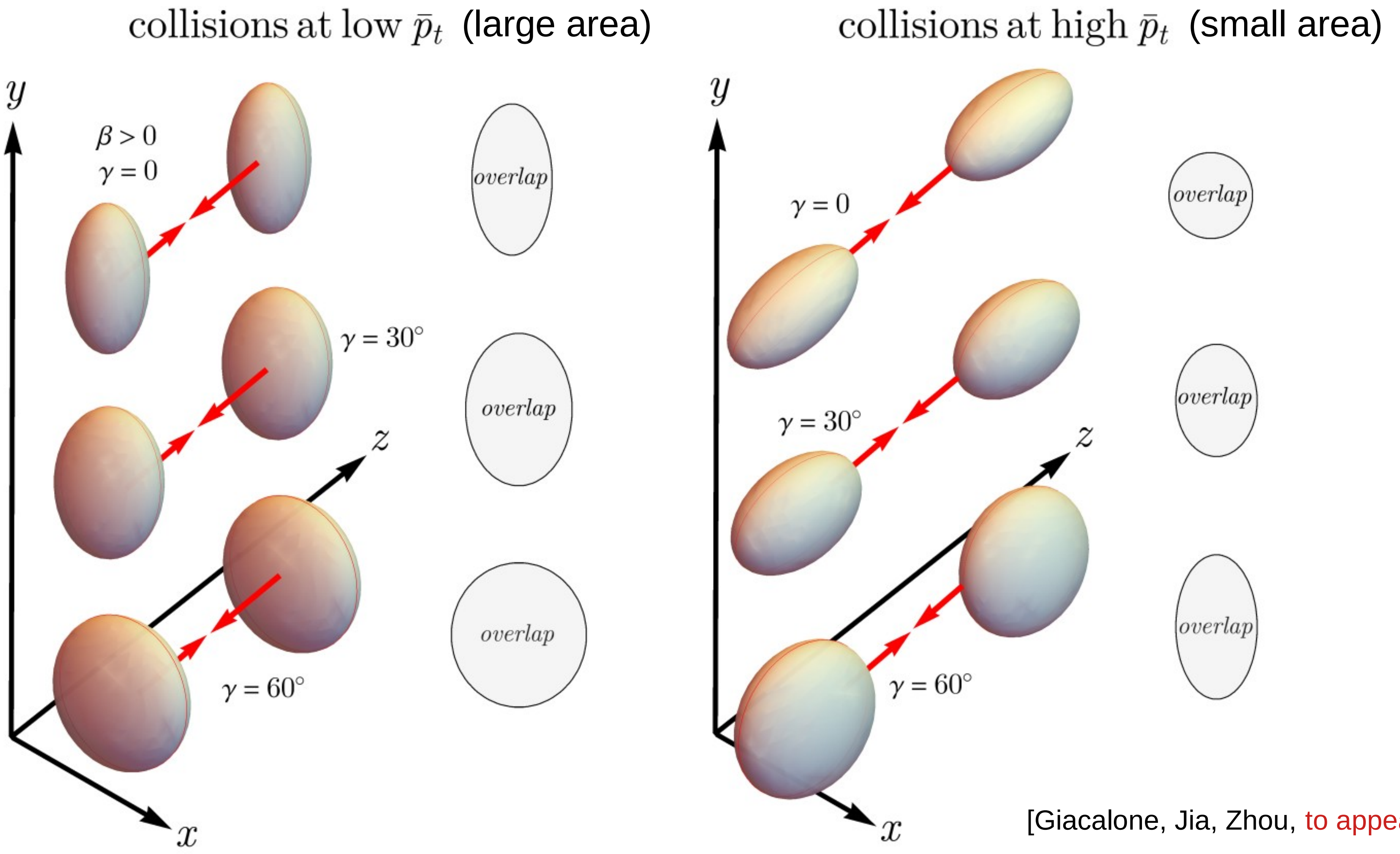
$$\boxed{\rho_2 < 0}$$

[Giacalone, 2004.14463]

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

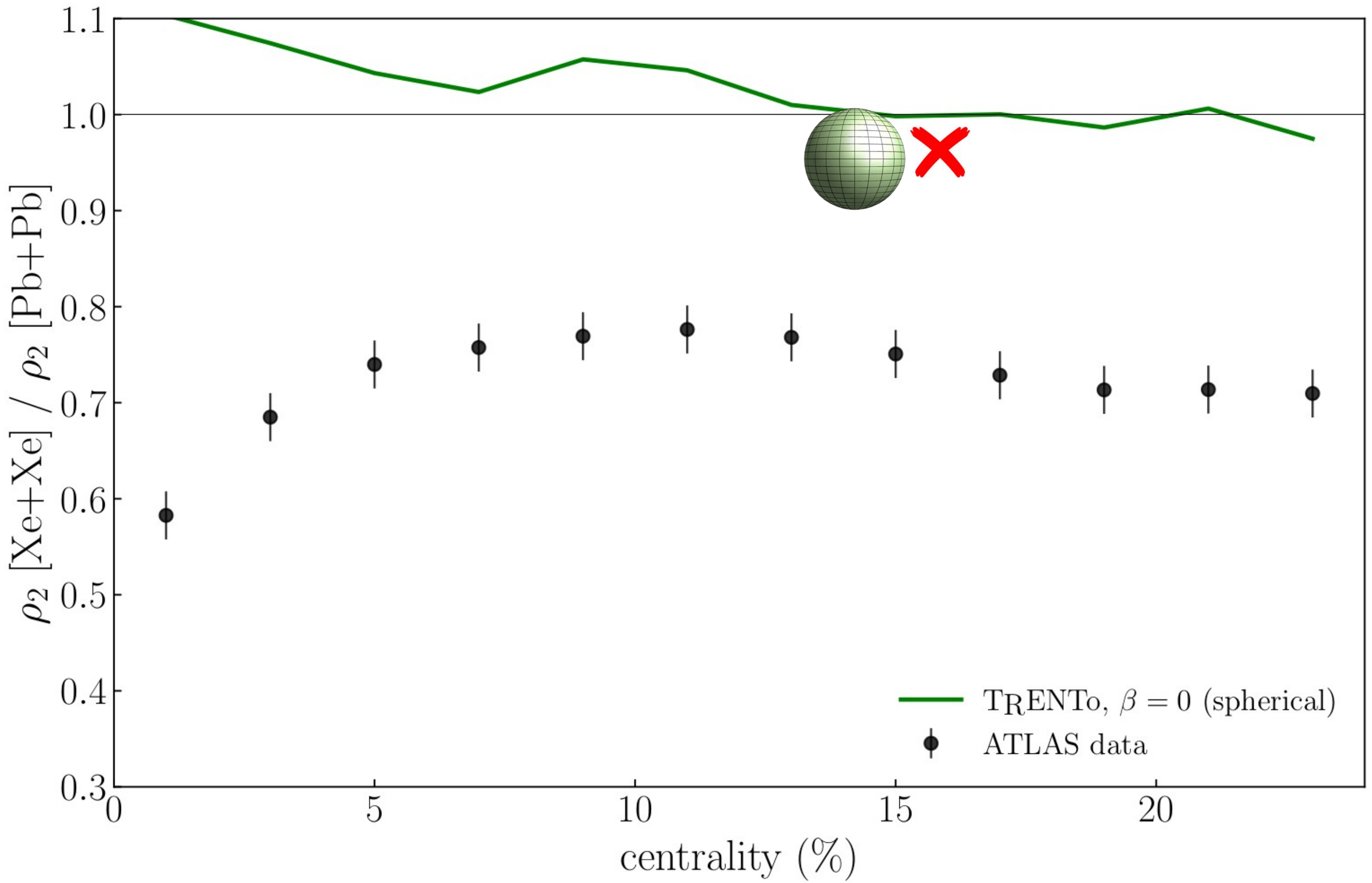


The ellipticity of the ‘maximal area of overlap’ depends on the triaxiality.



[Giacalone, Jia, Zhou, to appear]

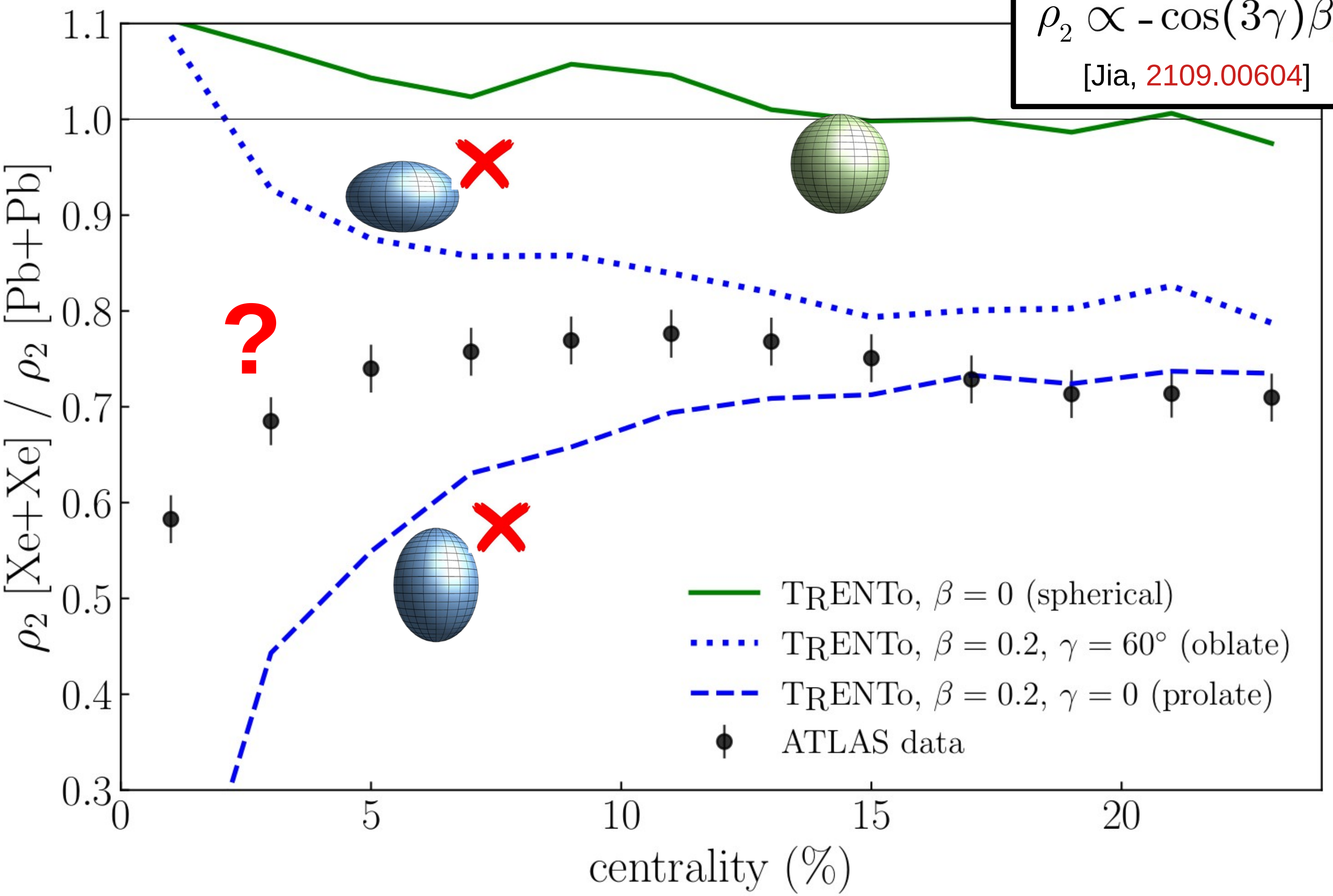
We know 129Xe is triaxial, what happens to the observable ρ_2?



We know 129Xe is triaxial, what happens to the observable ρ_2?

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

[Jia, 2109.00604]



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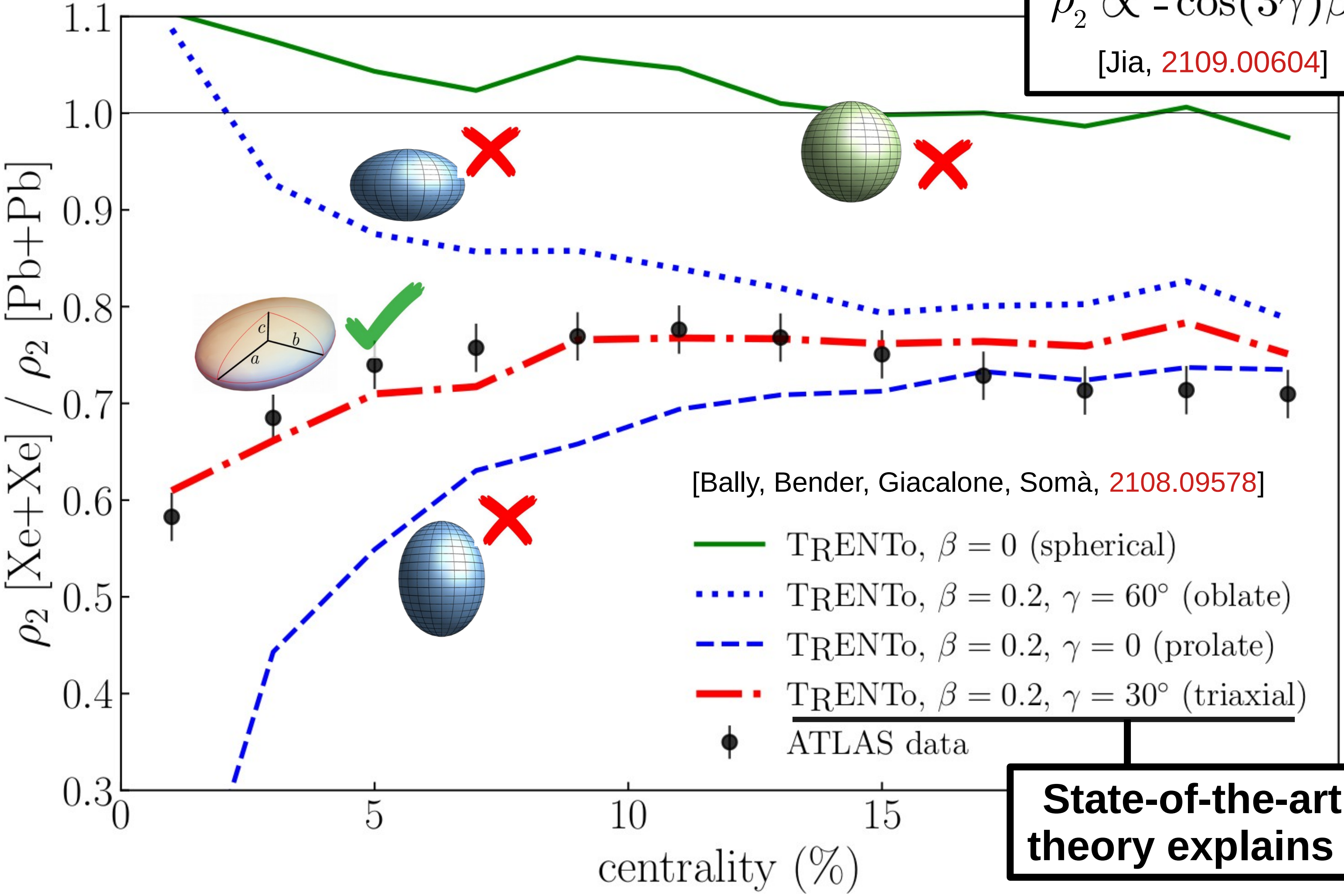


State-of-the-art nuclear theory explains LHC data

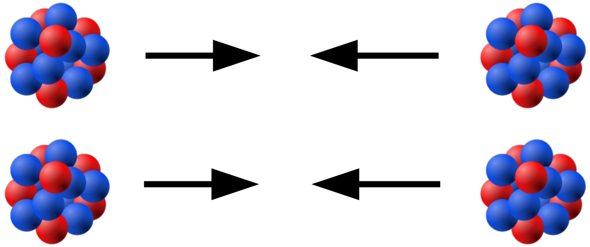
5. Collisions of isobars: the 2021 breakthrough.

Collisions of isobars performed in 2018 at RHIC to study magnetic fields.

[STAR collaboration, 2109.00131]

A=96 96Ru

A=96 96Zr



96Ru

96Zr

If X and Y are isobars, then X+X produces same QGP as Y+Y.

Ratios of observables is unity?

$$\frac{\mathcal{O}_{\mathrm{X+X}}}{\mathcal{O}_{\mathrm{Y+Y}}} \stackrel{?}{=} 1$$

[Giacalone, Jia, Somà, 2102.08158]

Departure from unity only comes from nuclear structure.

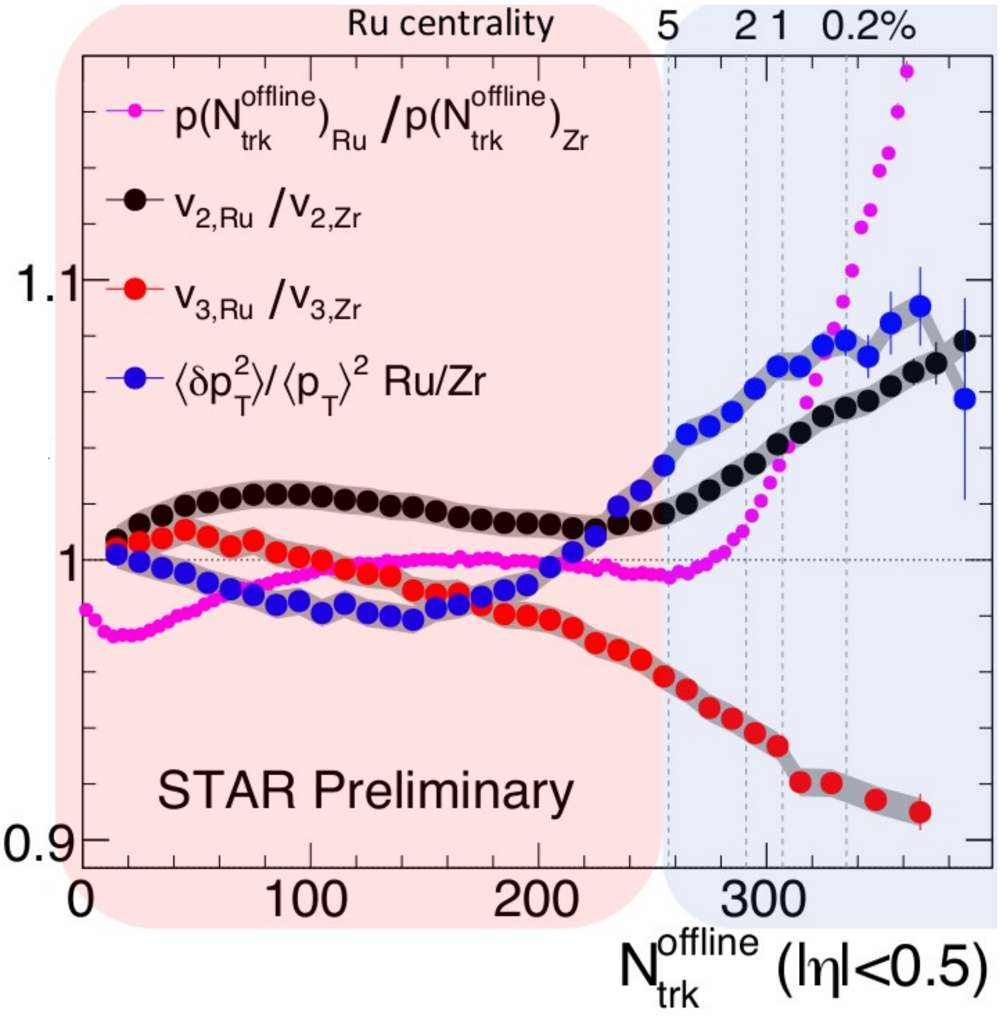
Dramatic advantages of this method:

1) Theory uncertainty from high-energy side is minimized.

2) Experimental error is only statistical in isobar running mode!

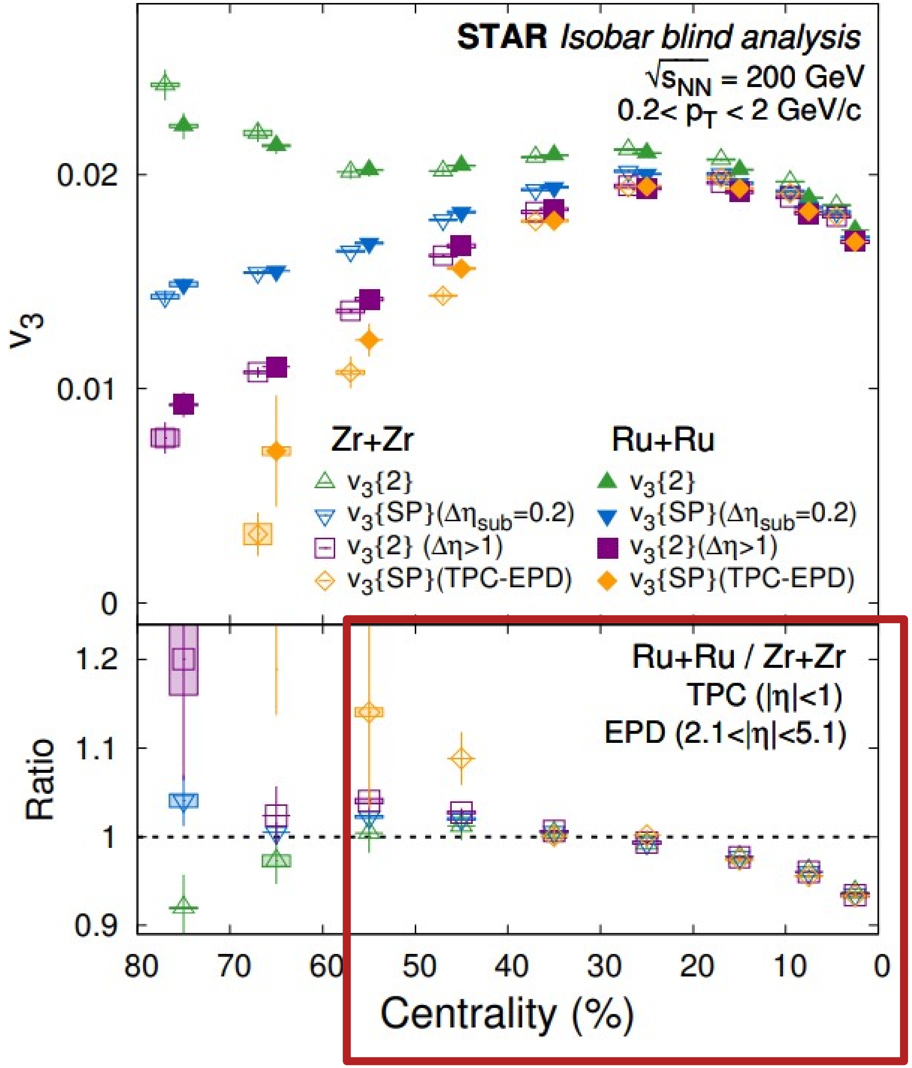
[STAR collaboration, 2109.00131]
[see e.g. Zhang, APS DNP fall meeting 2021]

$$\frac{\mathcal{O}_{X+X}}{\mathcal{O}_{Y+Y}} \stackrel{?}{=} 1 \longrightarrow$$ **NO!**

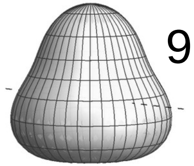


The two systems produce different observables.

Fully-fledged nuclear shape phenomenology.



Incredible outcome: octupole deformation in 96Zr.



Low-lying 3⁻ state identified for this nucleus.

[Iskra et al., PLB 788 (2019) 396-400]

However, theory has not yet clarified if there is a static octupole deformation.

recent attempt [Rong, Lu, 2201.02114]

Nuclear physics does not have a clear explanation for this observation.

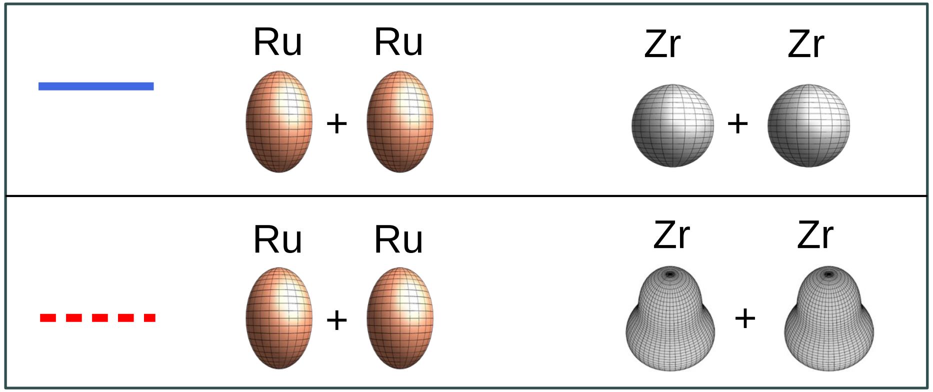
My understanding: it is simply inaccessible via low-energy experiments.

Now assume a static octupole deformation.

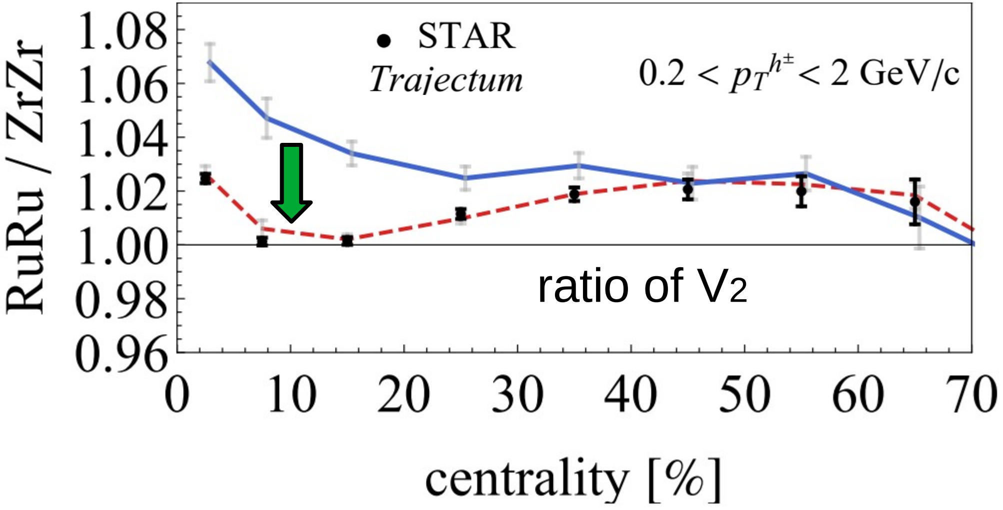
Unambiguous signatures at high energy.

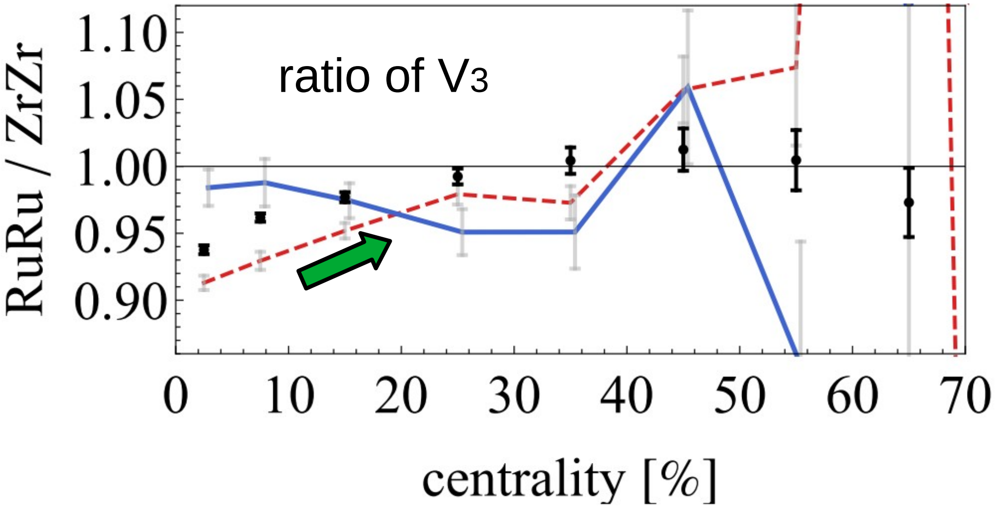
Suggests $\beta_3 \approx 0.15$.

LEGEND:



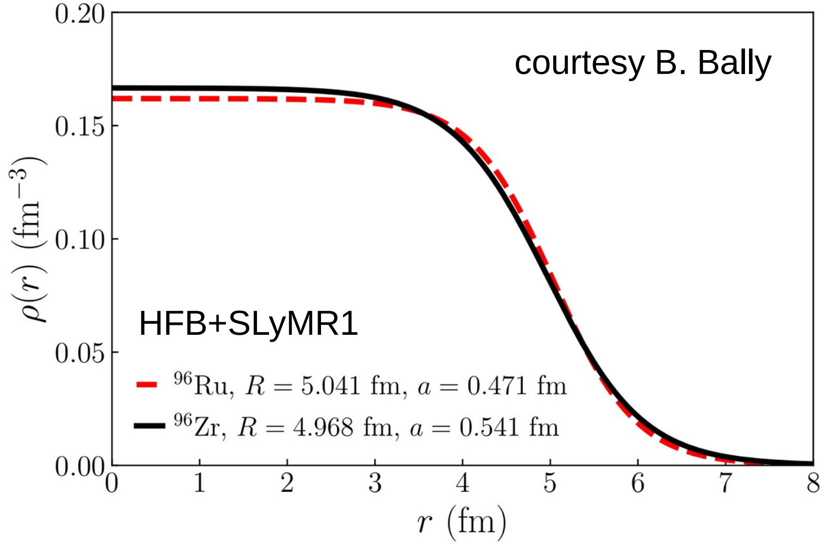
[Nijs, van der Schee, 2112.13771]





[see also Zhang, Jia, 2109.01631, 2111.15559]

Bonus from isobars. Accessing the neutron skin difference. Neutrons matter!

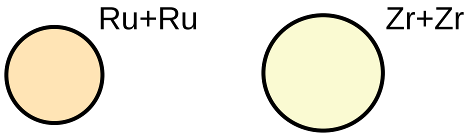


Radial profiles are different:

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

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

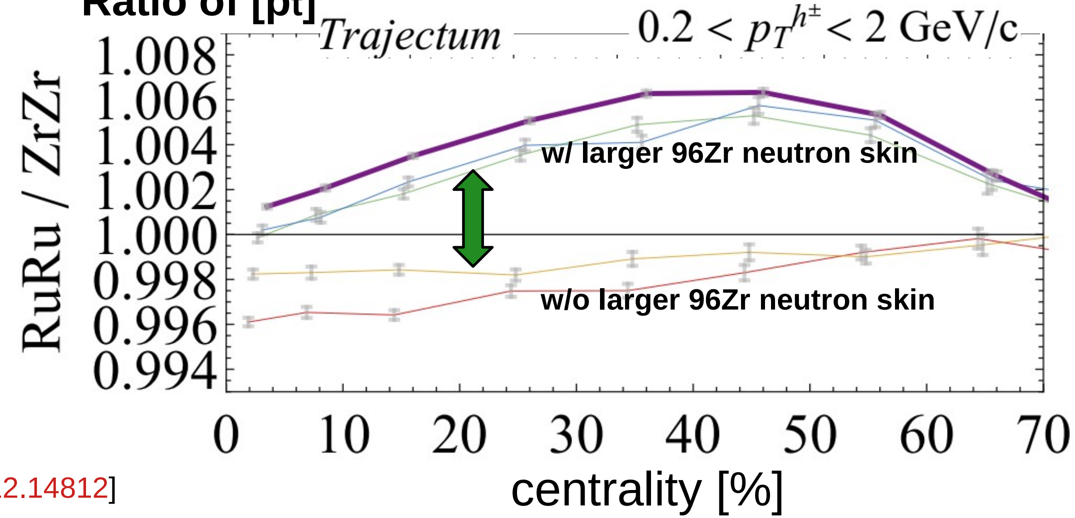
Due to the smaller neutron skin,
Ru+Ru systems are more compact.



[pt] is enhanced.

[Nijs, van der Schee, 2112.13771]
[Xu, Zhao, Li, Zhou, Chen, Wang, 2112.14812]

Ratio of [pt]



RECAP

- Manifestation of intrinsic nuclear shapes in the collective flow of the quark-gluon plasma.
- Evidence of **axial and triaxial quadrupole**, **axial octupole**, and **neutron skin** effects.
- Isobars give the cleanest access to ground-state nuclear shapes via high energy collisions. There are over 100 pairs of stable isobars.
- What next?

Intersection of nuclear structure and high-energy nuclear collisions

Organizers:
Jiangyong Jia (Stony Brook & BNL)
Giuliano Giacalone (ITP Heidelberg)
Jacquelyn Noronha-Hostler (Urbana-Champaign)
Dean Lee (Michigan State & FRIB)
Matt Luzum (São Paulo)
Fuqiang Wang (Purdue)

Jan 23rd - Feb 24th 2023

INSTITUTE for NUCLEAR THEORY

Deciphering nuclear phenomenology across energy scales

https://esnt.cea.fr/Phocea/Page/index.php?id=107

Organizers:
Giuliano Giacalone (ITP Heidelberg)
Jean-Yves Ollitrault (IPhT Saclay)
You Zhou (Niels Bohr Institute)

Sep 20th - Sep 23rd 2022

Extreme Me Matter Institute EMMI

EMMI

Nuclear physics confronts relativistic collisions of isobars

May 30th - Jun 3rd 2022
Oct 12th - Oct 14th 2022

Organizers:
Giuliano Giacalone (ITP Heidelberg)
Jiangyong Jia (Stony Brook & BNL)
Vittorio Somà (IRFU Saclay)
You Zhou (Niels Bohr Institute)