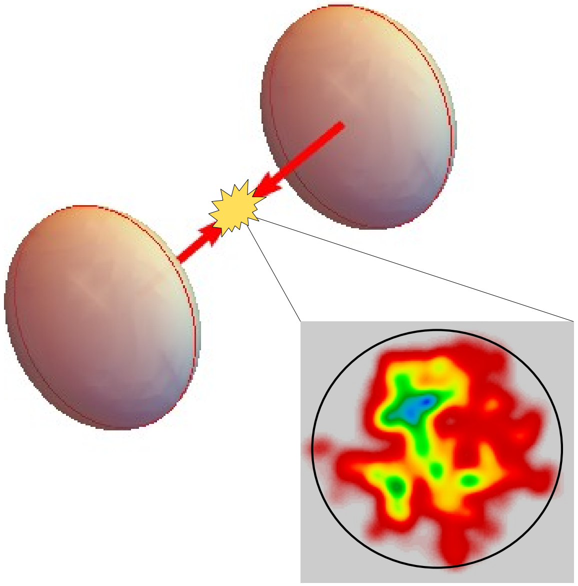
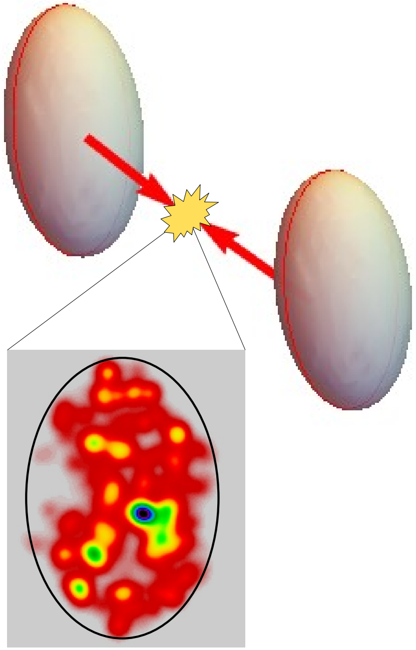
Imaging nuclear structure with hydrodynamics



by

GIULIANO GIACALONE

25 / 01 / 2022



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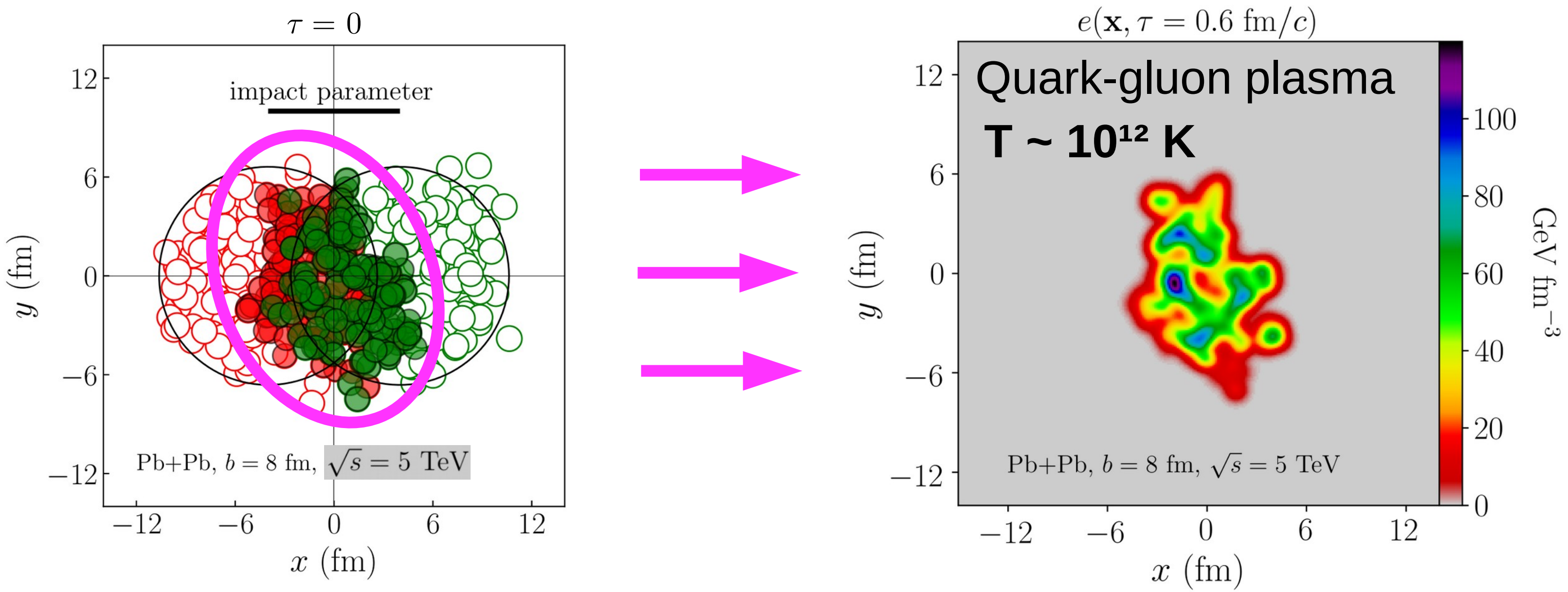
OUTLINE

- 1. Hydrodynamic flow and nuclear deformation.
- 2. Evidence of the quadrupole deformation at colliders.
- 3. Isobars: the ultimate tool.
- 4. Recap and future prospects.

1.

Hydrodynamic flow and nuclear deformation

HEAVY-ION COLLISIONS = THE EARLY UNIVERSE IN THE LAB



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

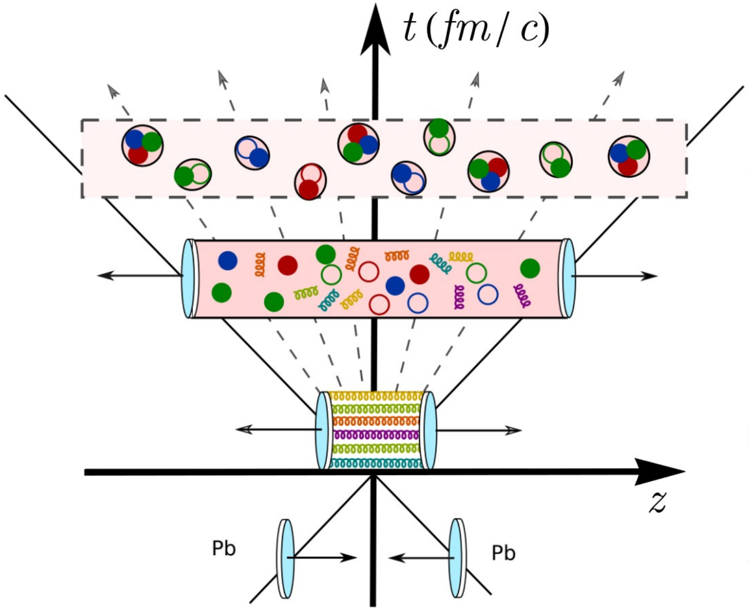
$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$$ + viscous corrections (η/s, ζ/s, ...)

Equation of state from lattice QCD (T > 156 MeV). Large number of DOF (~40): QGP.

[HotQCD collaboration, 1407.6387]

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

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



$t = \infty$

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

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

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

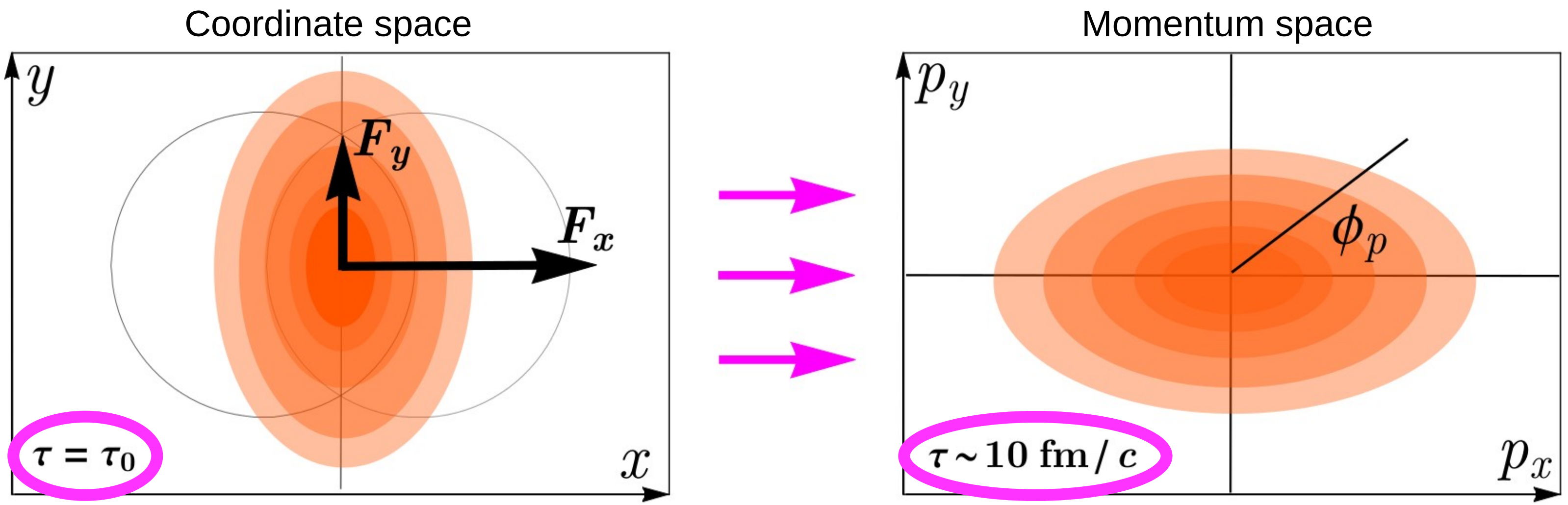
Powerful probe of fluid behavior.
Anisotropic flow from spatial anisotropy.

$$F = -\nabla P$$

Azimuthal anisotropy of particle emission.
Elliptic flow, the 2nd harmonic.

$$\longrightarrow \quad V_2 = \frac{1}{N} \int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-i2\phi_p}$$

[Ollitrault, **1992**]

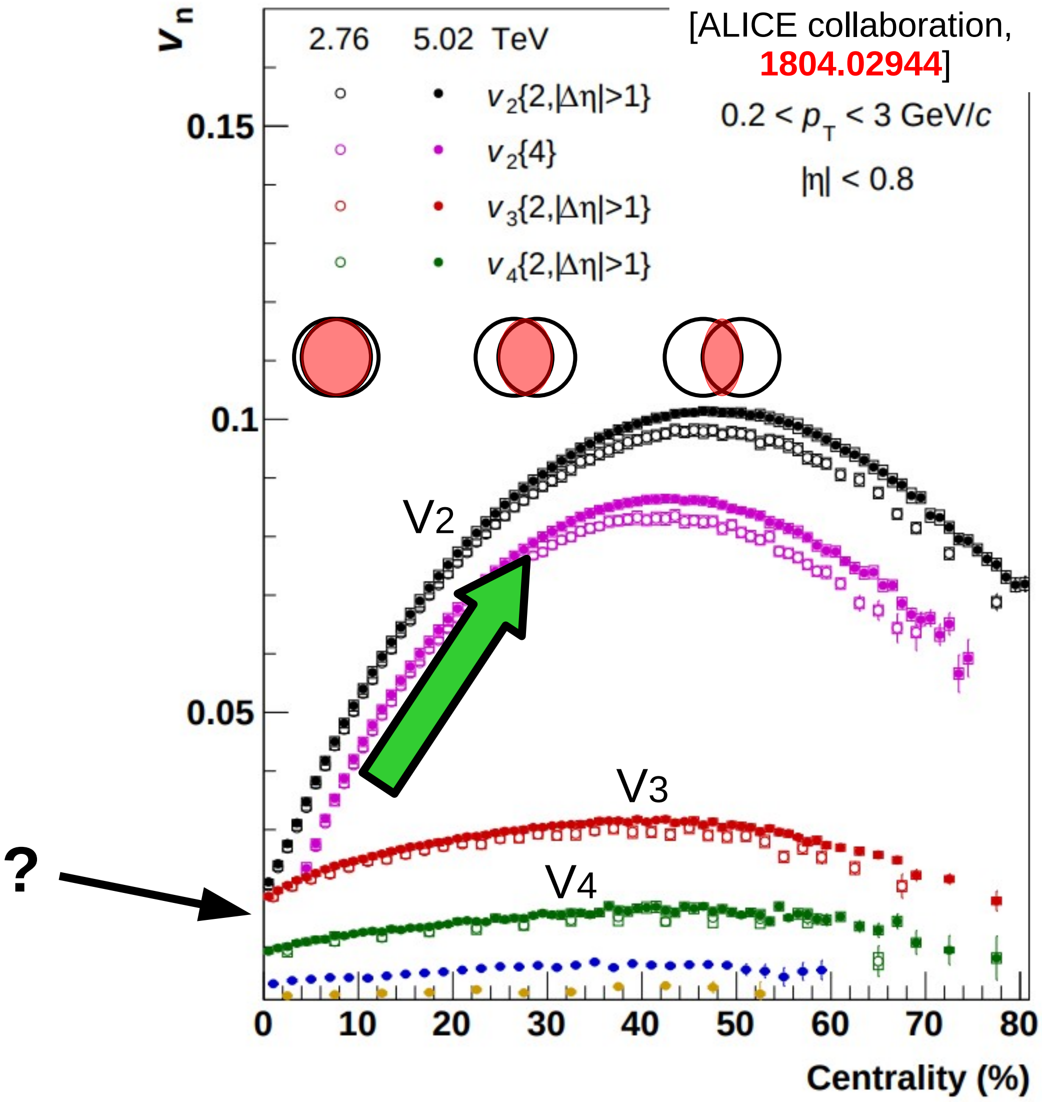


Strong enhancement of V_2 as the system becomes more elliptical.

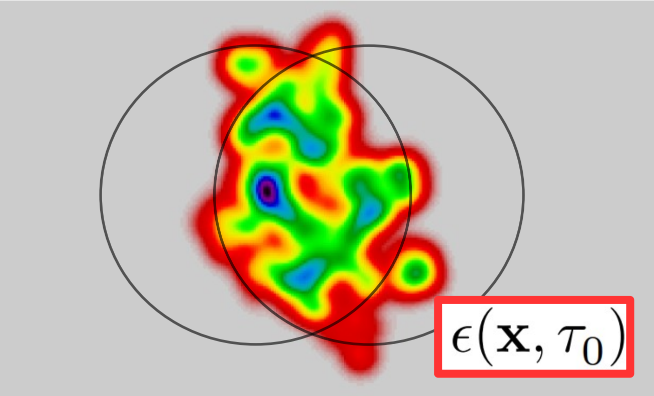
However, V_2 does not start at zero, along with the full spectrum of harmonics.

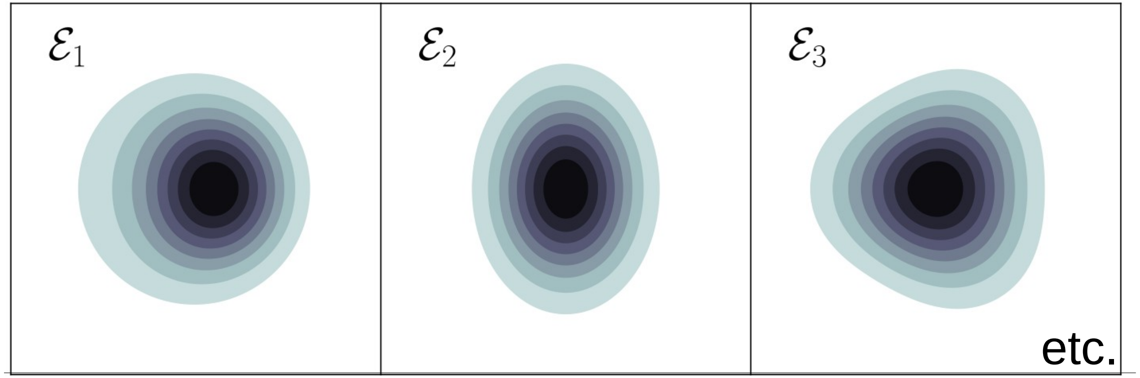
$$V_n = \frac{1}{N}\int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-in\phi_p}$$

Why?



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





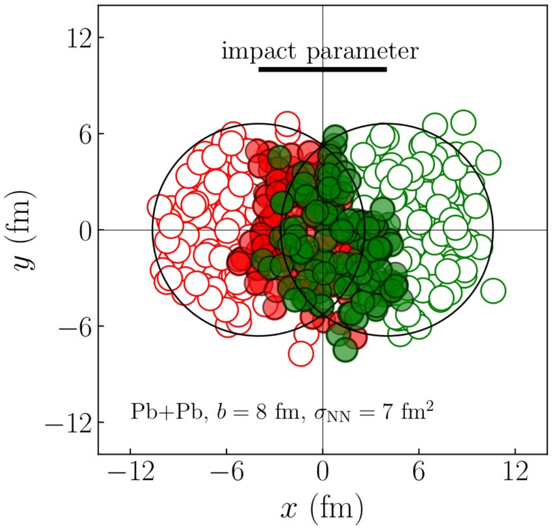
[Alver, Roland, **1003.0194**]

In a single 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**]

How do you get fluctuations that break symmetries?



Natural answer: nucleons. [Miller, Reygers, Sanders, Steinberg, nucl-ex/0701025]

Nucleons sampled from Woods-Saxon profile for each nucleus.

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

half-width radius

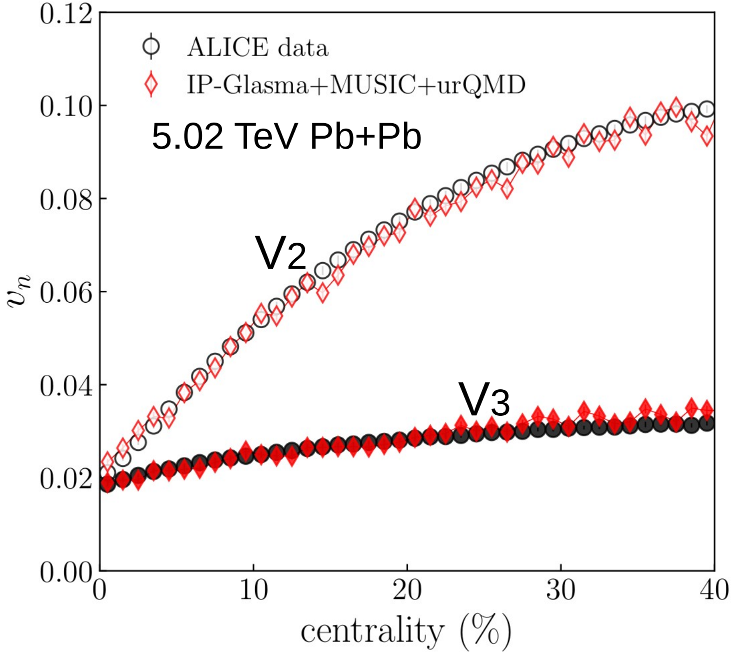
diffusivity

Short-range correlations typically from hard repulsive core.

talk by Massimiliano Alvioli

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

[Schenke, Shen, Tribedy, **2005.14682**]



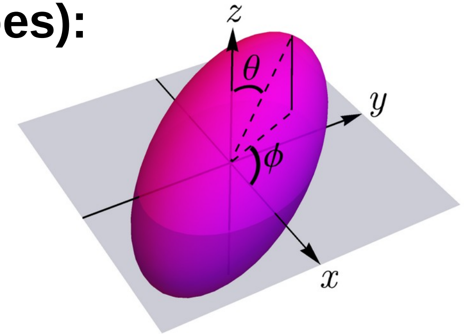
The great effectiveness of nucleons.

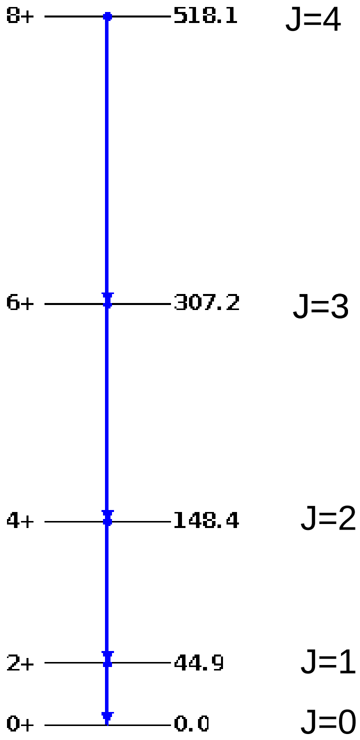
Important ingredient required. Most of nuclei are “deformed”.
For some nuclei, energy spectrum is that of a rigid rotor.

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

Powerful approximation (for certain isotopes):
intrinsic deformed shape (nucleons)
with a random orientation.

talk by Michael Bender



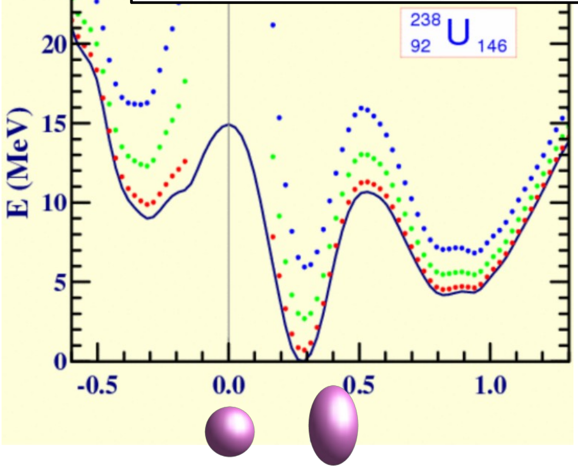


From https://www.nndc.bnl.gov/nudat3/

Microscopic origin:
Very complicated.
“Spontaneous breaking”
of rotational symmetry
at the mean-field level.
But <u>symmetry must be restored</u>.

talk by Benjamin Bally

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

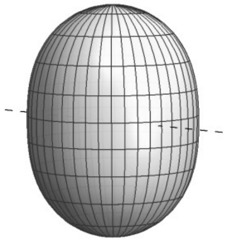


Generalize the Woods-Saxon profile to include intrinsic deformations:

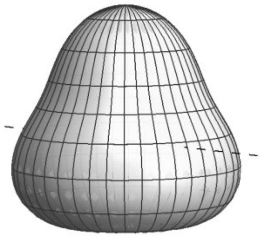
$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r-R(\Theta,\Phi)\right]/a\right)} \quad , \quad R(\Theta,\Phi) = R_0\left[1+\underline{\beta_2}\left(\cos\gamma Y_{20}(\Theta)+\sin\underline{\gamma} Y_{22}(\Theta,\Phi)\right)+\underline{\beta_3}Y_{30}(\Theta)+\underline{\beta_4}Y_{40}(\Theta)\right]$$

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

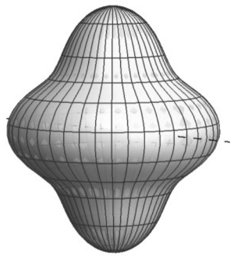
$$\beta_2 \to \int \rho(r,\Theta,\Phi) r^2 Y_{20}(\Theta)$$



$$\beta_3 \to \int \rho(r,\Theta,\Phi) r^3 Y_{30}(\Theta)$$

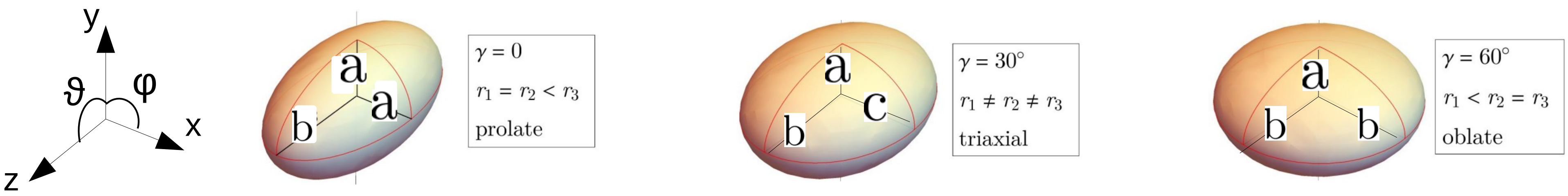


$$\beta_4 \to \int \rho(r,\Theta,\Phi) r^4 Y_{40}(\Theta)$$



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

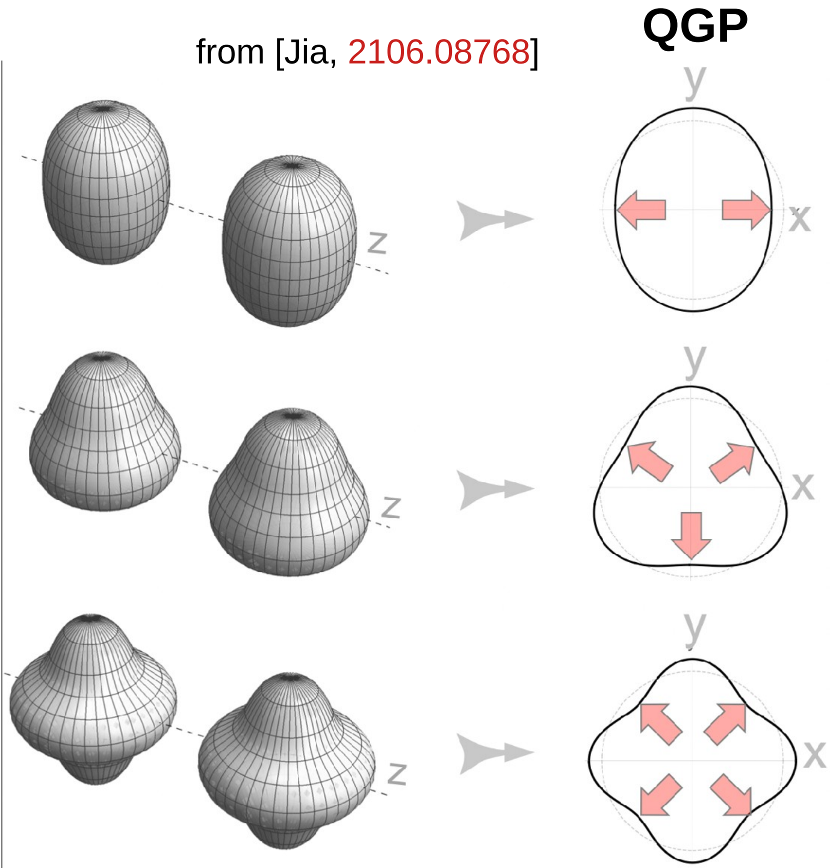
$$\boxed{Y_2^2(\theta,\varphi) = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\cdot\frac{(x+iy)^2}{r^2}}$$



Impact on anisotropy pointed out before RHIC program.

[Shuryak, PRC 61 034905, 2000] [Das Gupta, Gale, PRC 62 031901, 2000]
[Li, PRC 61 021903, 2000]

from [Jia, 2106.08768]



Possibilities discussed by several authors:

flow & jet quenching [Heinz, Kuhlman, nucl-th/0411054, nucl-th/0506088]

CME [Voloshin, 1006.1020]

impact on eccentricities [Filip, Lednicki, Masui, Xu, PRC 80 054903, 2009]
[Rybczynski, Broniowski, Stefanek, 1211.2537]

BREAKTHROUGH #1 – STAR 238U collision data in **2015**.

→ Failure of two-component model

→ Success of state-of-the-art models (IP-Glasma, Trento)

BREAKTHROUGH #2 – LHC 129Xe collision data in **2018**.

→ Deformation of odd-mass nucleus at the LHC

→ Success of state-of-the-art models

BREAKTHROUGH #3 – mean transverse momentum and isobar data in **2020/21**.

→ STAR U-U data on mean transverse momentum – elliptic flow correlations

→ Isobar data is released

2.

Evidence of the quadrupole deformation at colliders

(pre- isobar run)

Precision data from STAR.
$v_2\{4\}$ of opposite signs.

[STAR collaboration, 1505.07812]

Leading order corrections from β_2 :

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

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

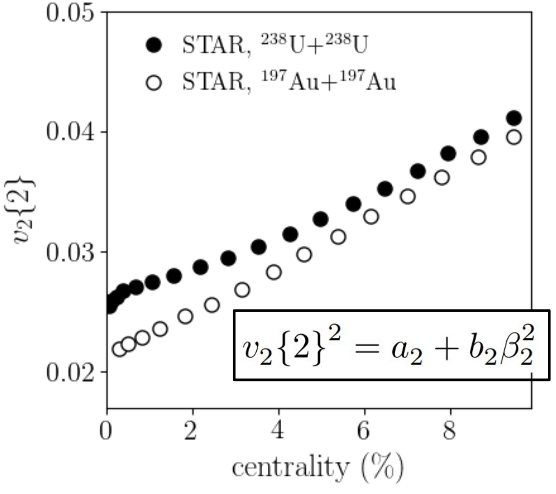
[Giacalone, 1811.03959]
[Giacalone, Jia, Zhang, 2105.01638]
[Jia, 2106.08768]

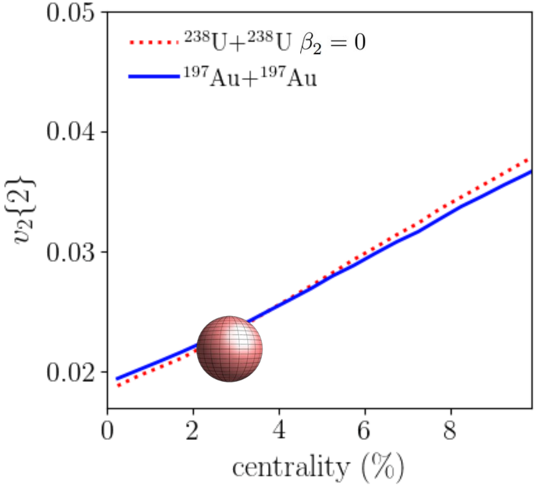
Estimates with TRENTo model.

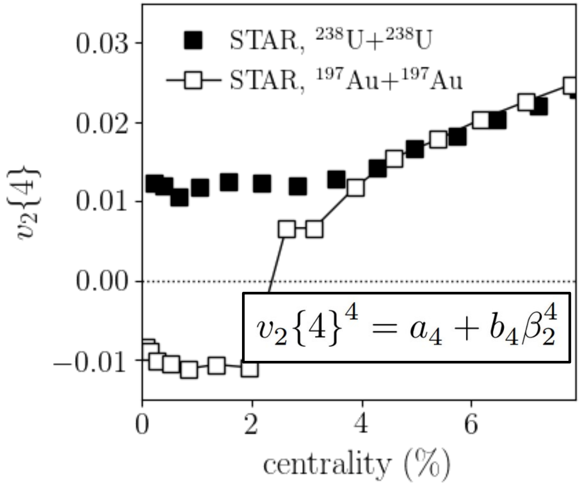
[Giacalone, 1811.03959]

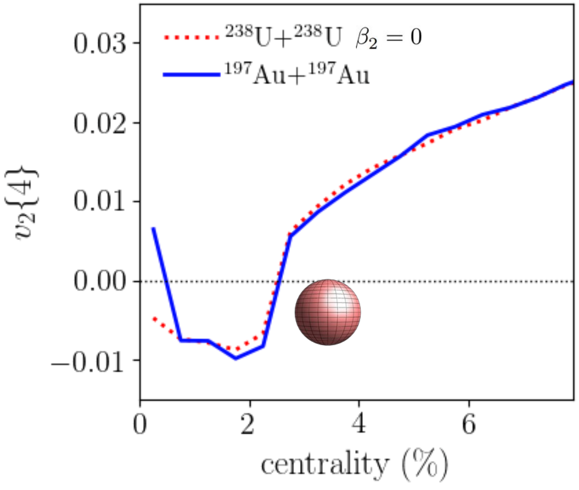
STAR data

TRENTo estimate









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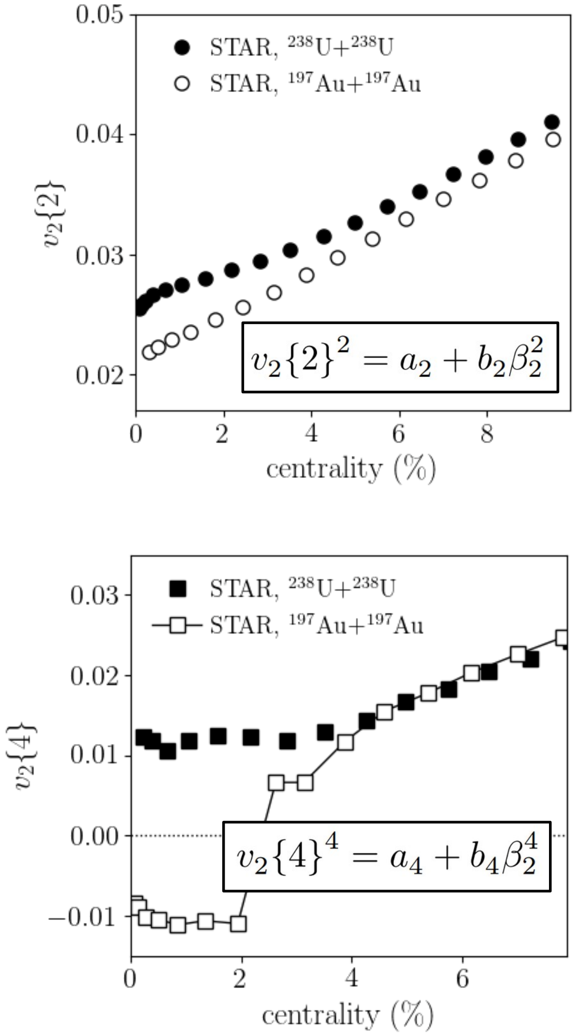
[Jia, 2106.08768]

Estimates with TRENTo model.

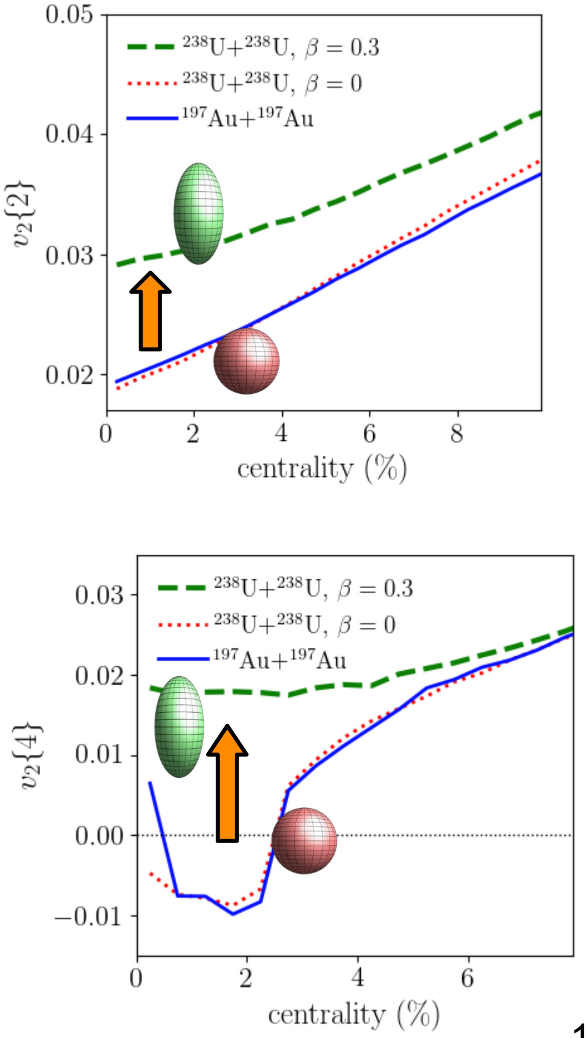
[Giacalone, 1811.03959]

Deformation explains the data!
Sign change of $v_2\{4\}$.

STAR data



TRENTo estimate



What if we select events with a large overlap area?

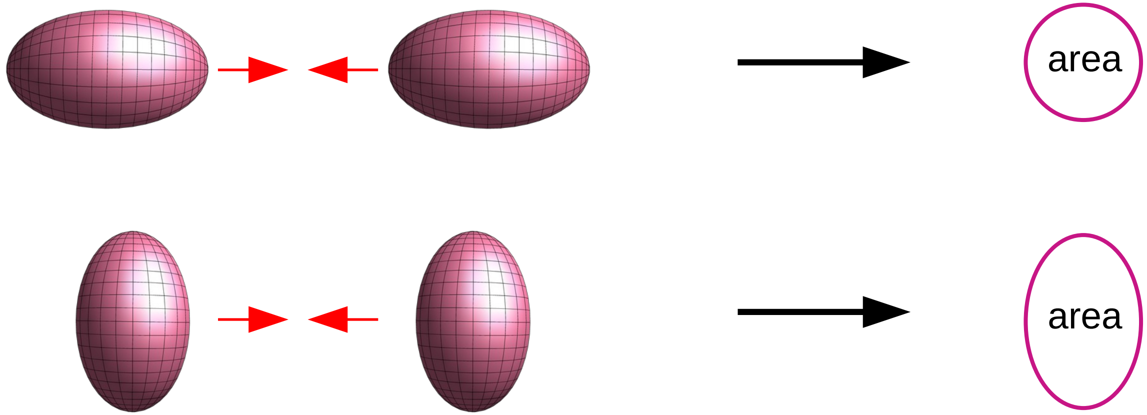
[Giacalone, 1910.04673, 2004.14463]

Area of overlap is in anti-correlated with the mean transverse 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]
[Schenke, Shen, Teaney, 2004.00690] [Gardim, Giacalone, Noronha-Hostler, Ollitrault 2004.01765]

tip-tip

body-body



<u>small v_2</u>
small area
<u>large $[p_t]$</u>

<u>large v_2</u>
large area
<u>small $[p_t]$</u>

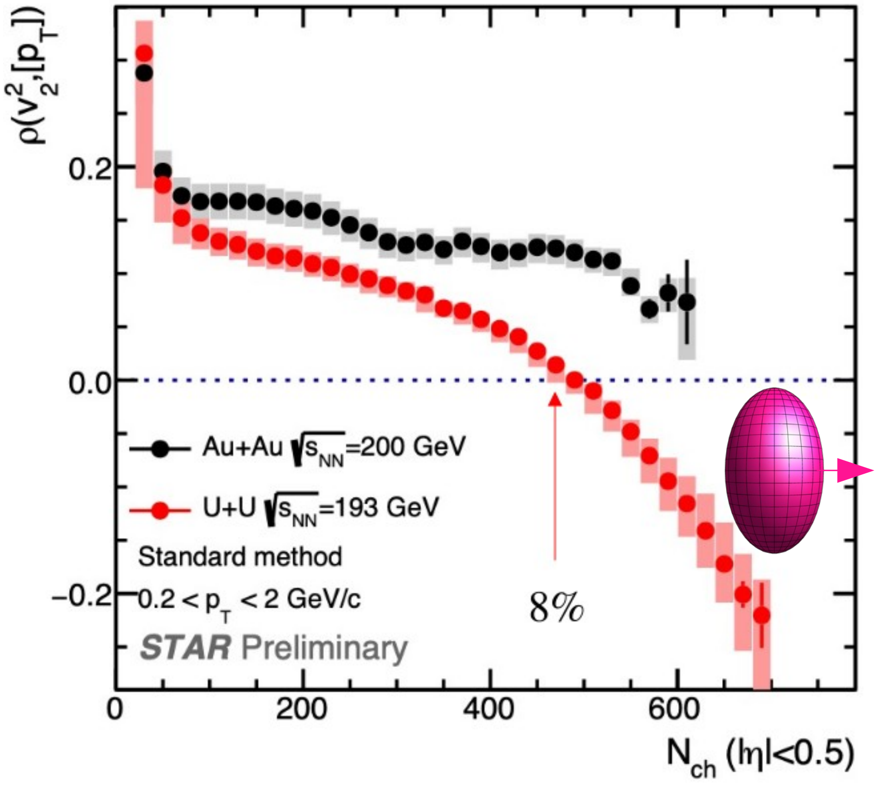
Correlation between v_2 and $[p_t]$ via Pearson coefficient: $$\rho_2 \equiv \rho(v_2^2, [p_t]) = \frac{\langle \delta v_2^2 \delta [p_t] \rangle}{\sqrt{\langle (\delta v_2^2)^2 \rangle \langle (\delta [p_t])^2 \rangle}}$$

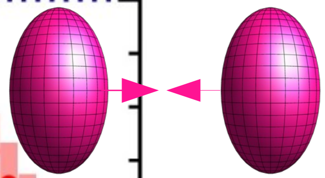
[Bozek,1601.04513]

For central collisions of large, well-deformed nuclei: $\boxed{\rho_2 < 0}$

Prediction confirmed. For central collisions of 238U nuclei: $\boxed{\rho_2 < 0}$

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





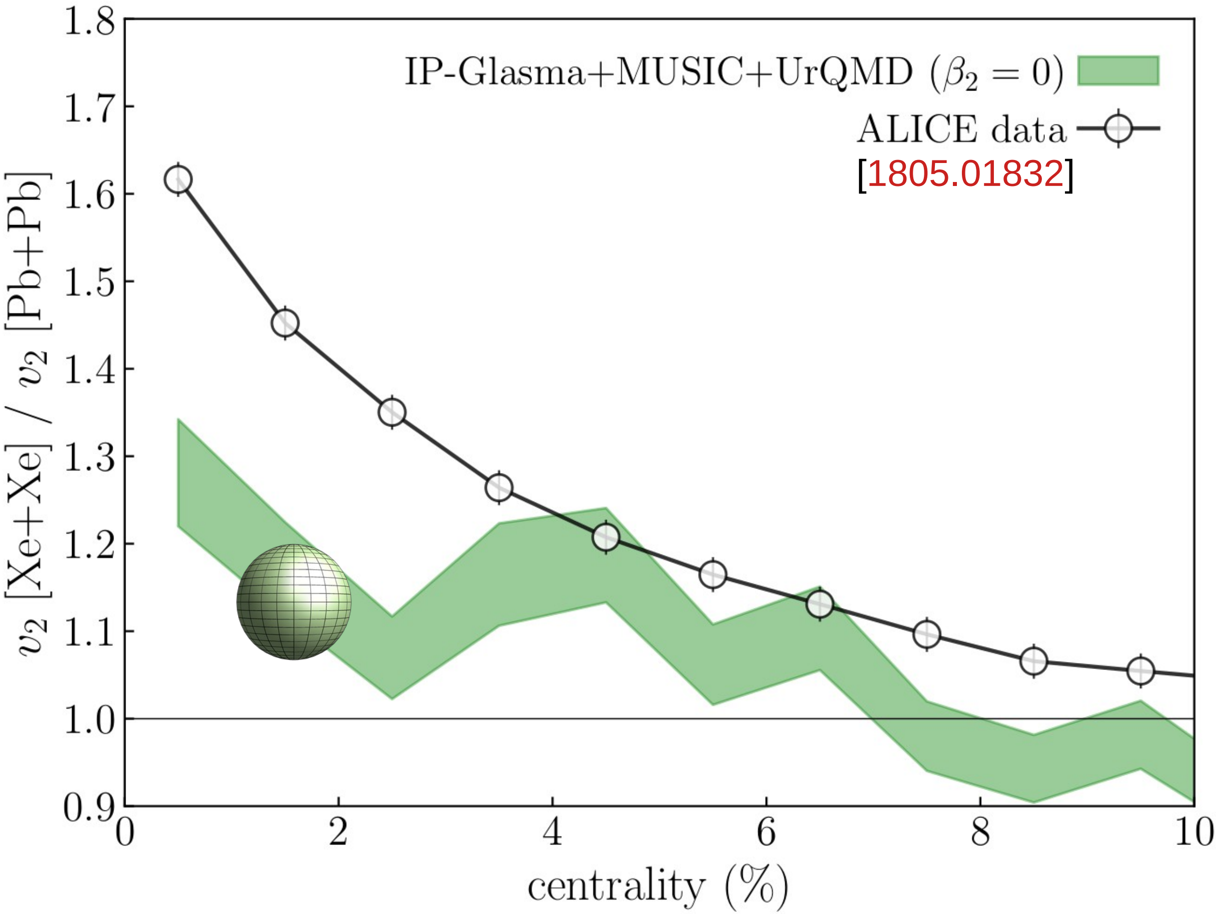
Mean transverse momentum discerns body-body and tip-tip geometries.
A **new tool for nuclear deformation**.

Effect of the deformation across the full range of multiplicities.

Result confirmed in AMPT and IP-Glasma+MUSIC+UrQMD.

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

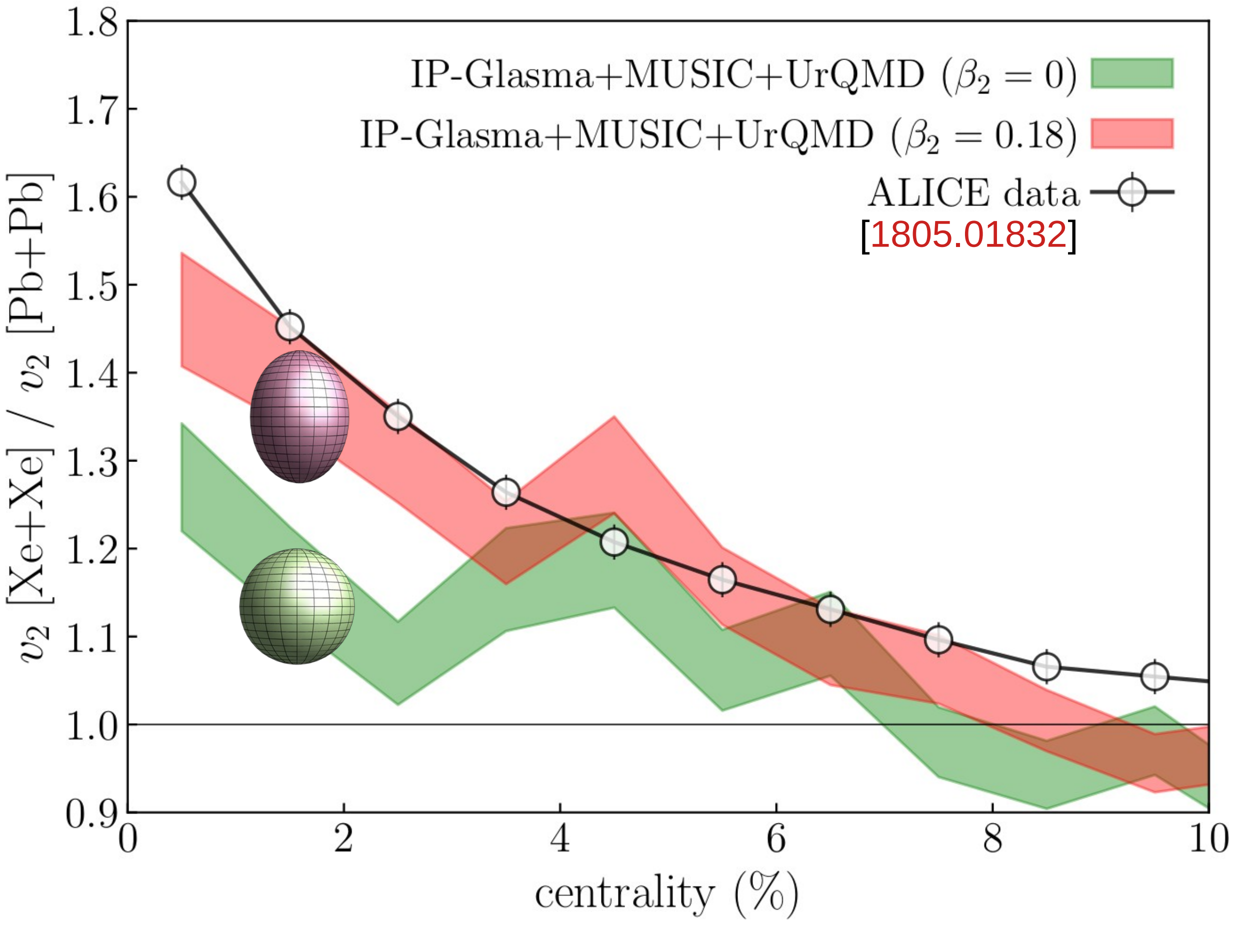
talk by You Zhou



Model fails with spherical 129Xe.

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

talk by You Zhou



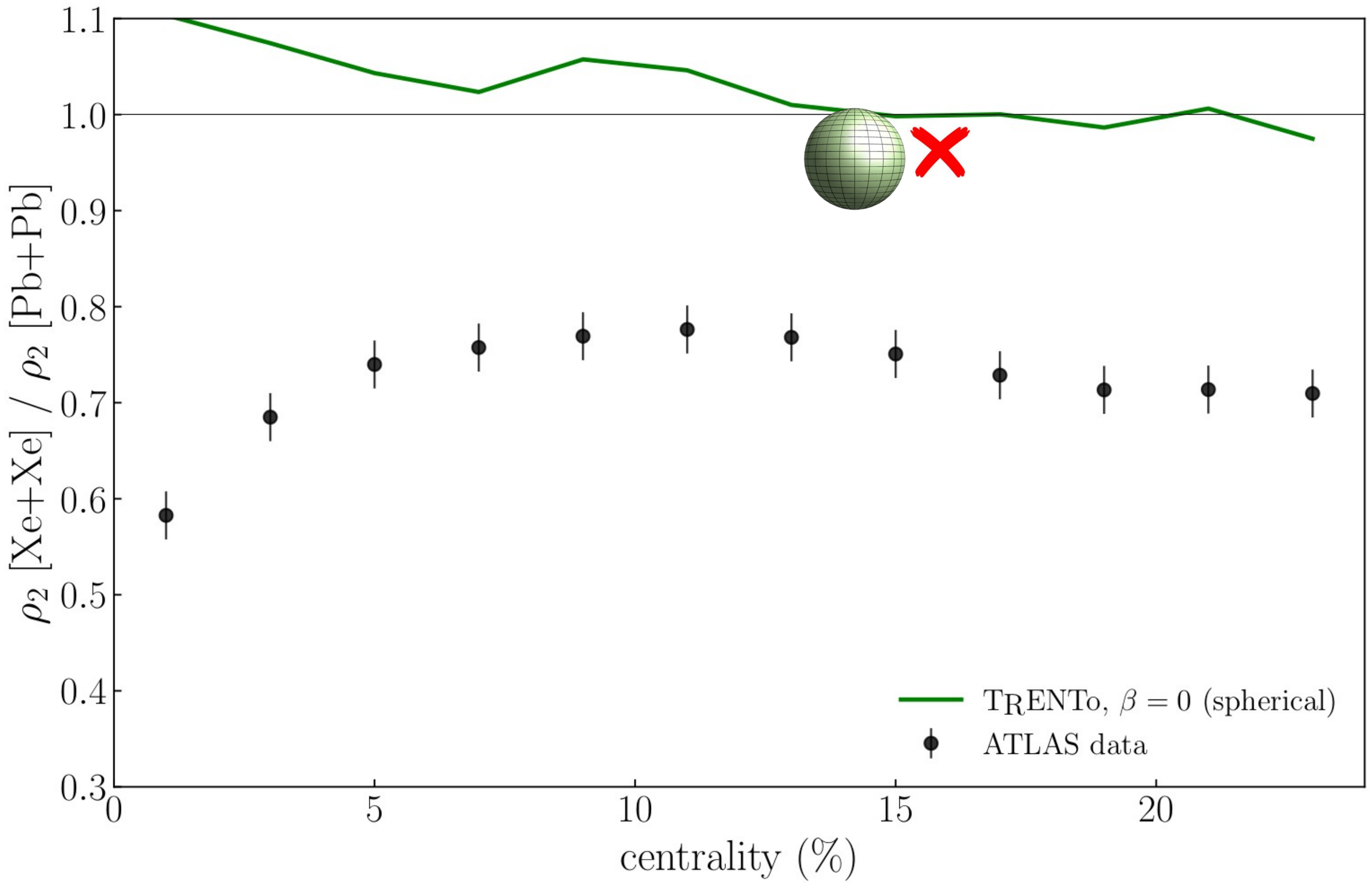
See also [Giacalone, Luzum, Noronha-Hostler, Ollitrault, 1711.08499]

Dramatic improvement with deformed 129Xe.

NB: value of β_2 of 129Xe recently evaluated and is ≈0.21.

Elliptic flow–mean transverse momentum correlation from TRENTo estimator.

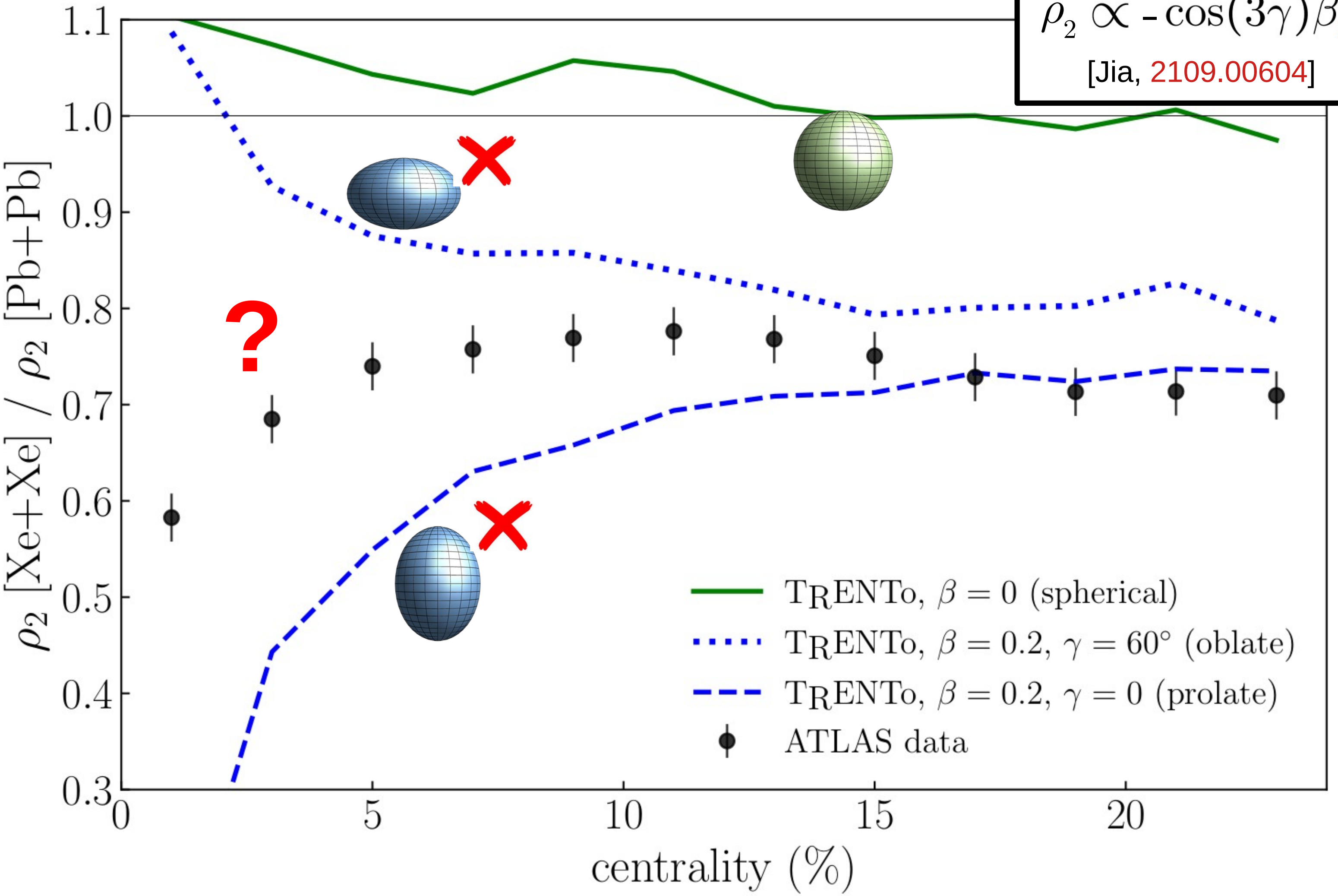
[Gardim, Giacalone, Noronha-Hostler, Ollitrault 2004.01765]



Add deformation **β₂=0.2**. Sensitive to prolate and oblate shapes to leading order.

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

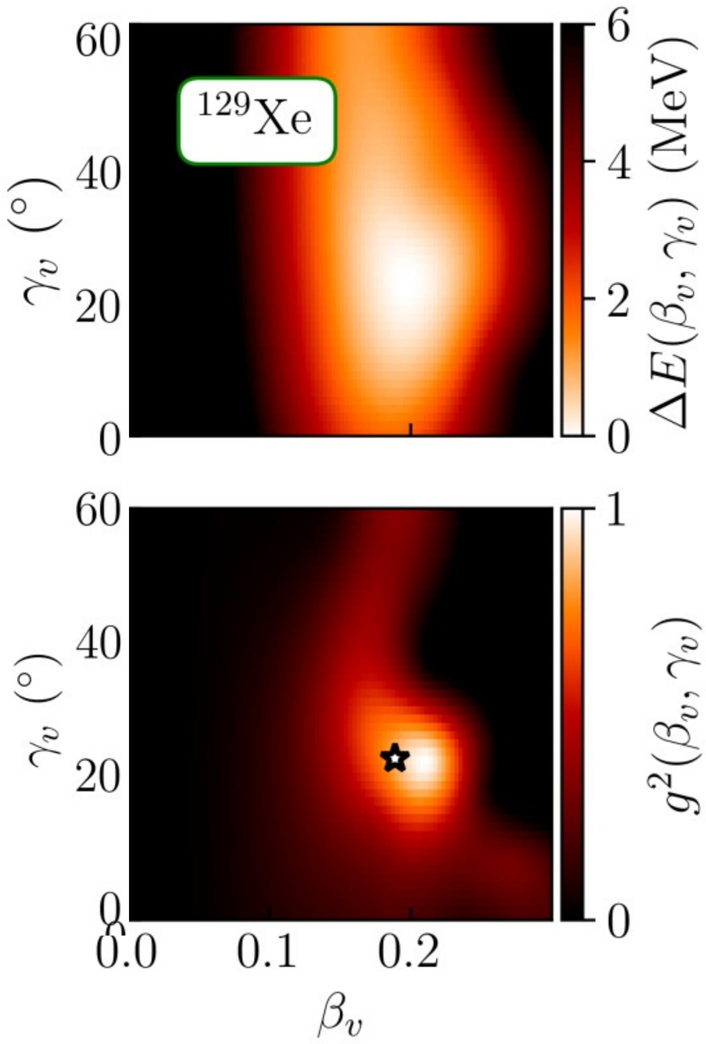
[Jia, 2109.00604]



Back to nuclear structure theory.

[Bally, Bender, Giacalone, Somà, 2108.09578]

First calculation of 129Xe ground state within energy density functional framework.



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

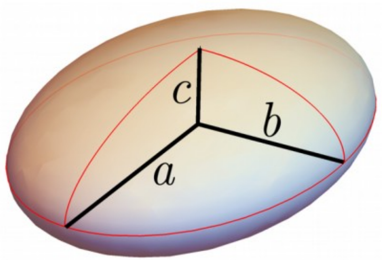
wave function

weights depend on (β, γ)

projection operators

Symmetry-breaking Hartree-Fock-Bogoliubov intrinsic states

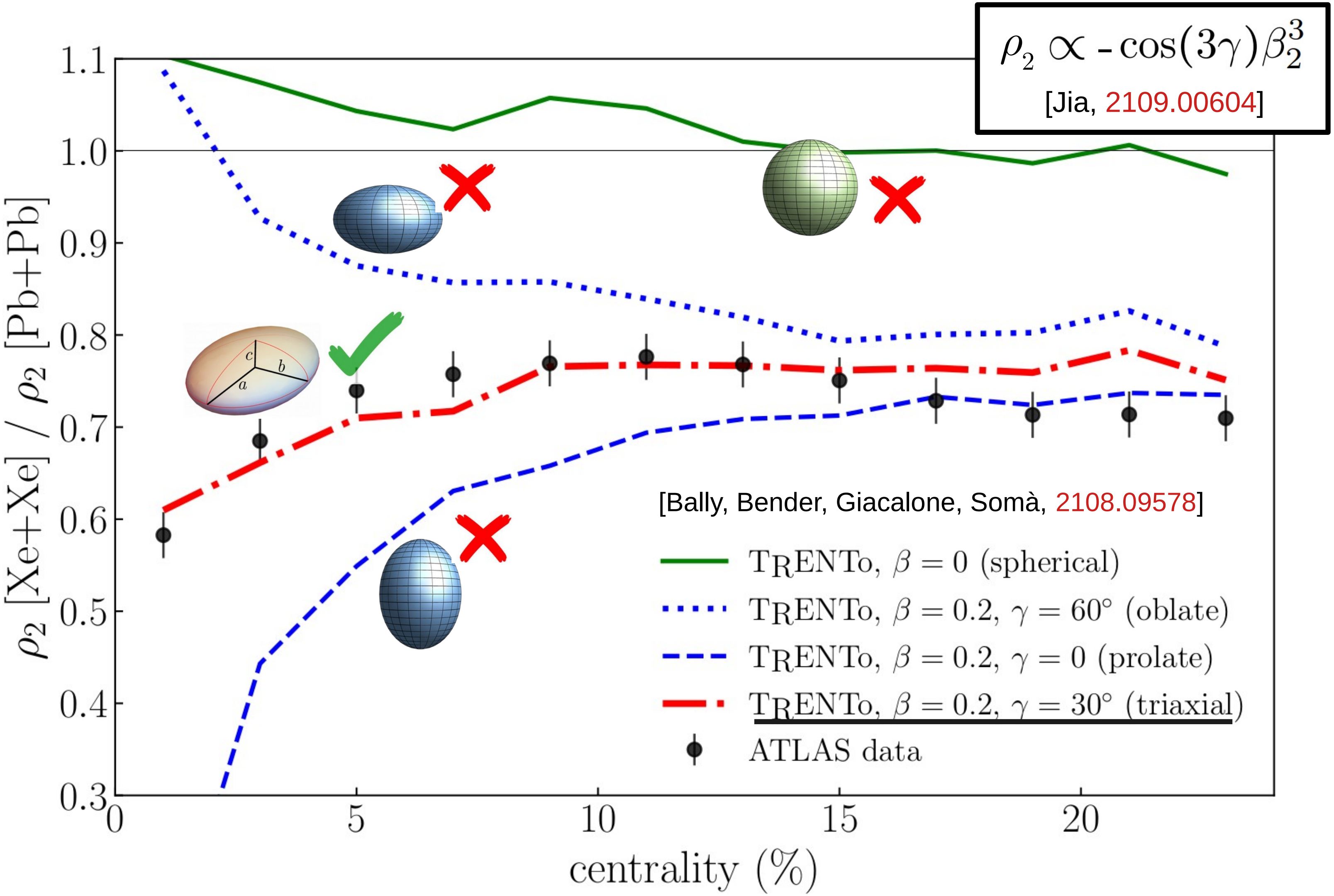
Xenon-129 looks like this (triaxial):



NB: evidence of triaxial 130Xe in low-energy experiments.

[Morrison et al., PRC 102 054304]

Evidence of fully-triaxial 129Xe at LHC, as predicted by low-energy nuclear structure.

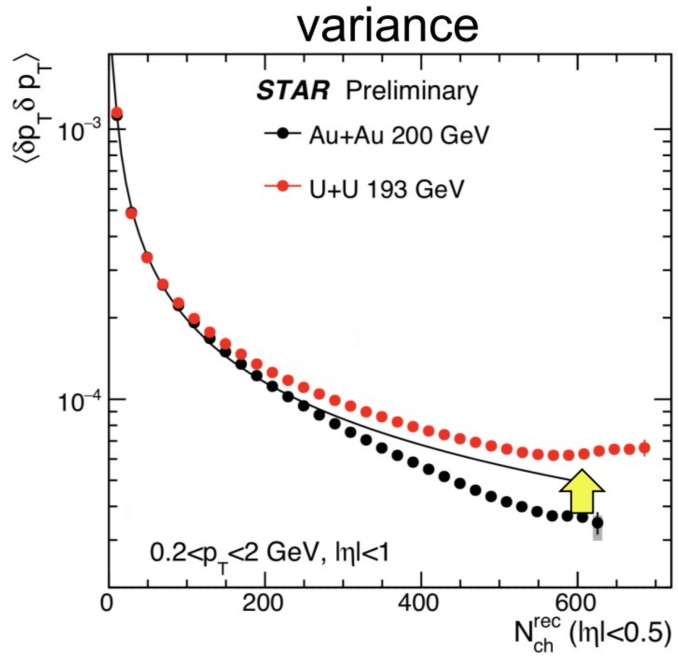


New probe of deformation: non-Gaussianity of [pt] fluctuations. [Gardim, Giacalone, Noronha-Hostler, Ollitrault, 2004.09799]

The skewness probes the triaxiality. [Jia, 2109.00604]

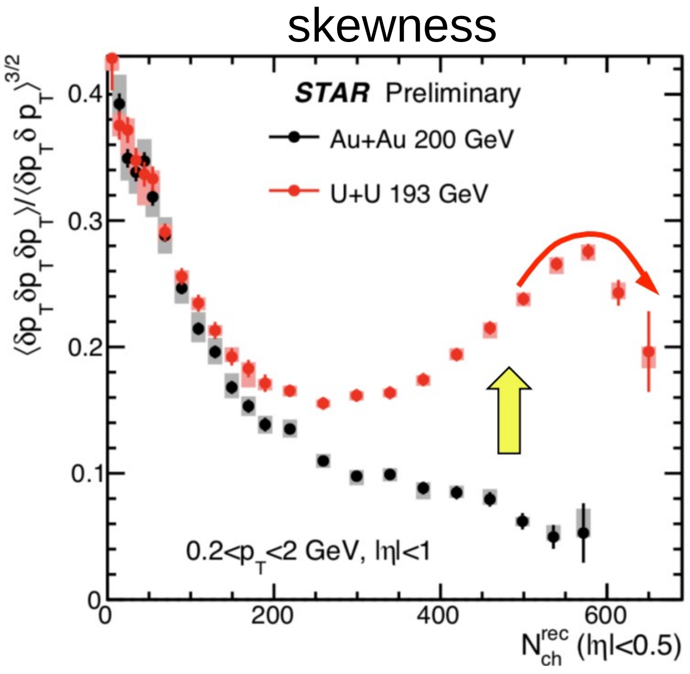
Data is out at RHIC, high-stat hydro not available yet.

variance



$$\boxed{\langle \delta p_T \ \delta p_T \rangle = a + b\beta_2^2}$$

skewness



$$\boxed{\langle \delta p_T \ \delta p_T \ \delta p_T \rangle \propto \beta_2^3 \cos(3\gamma)}$$

3.

Isobars: the ultimate tool

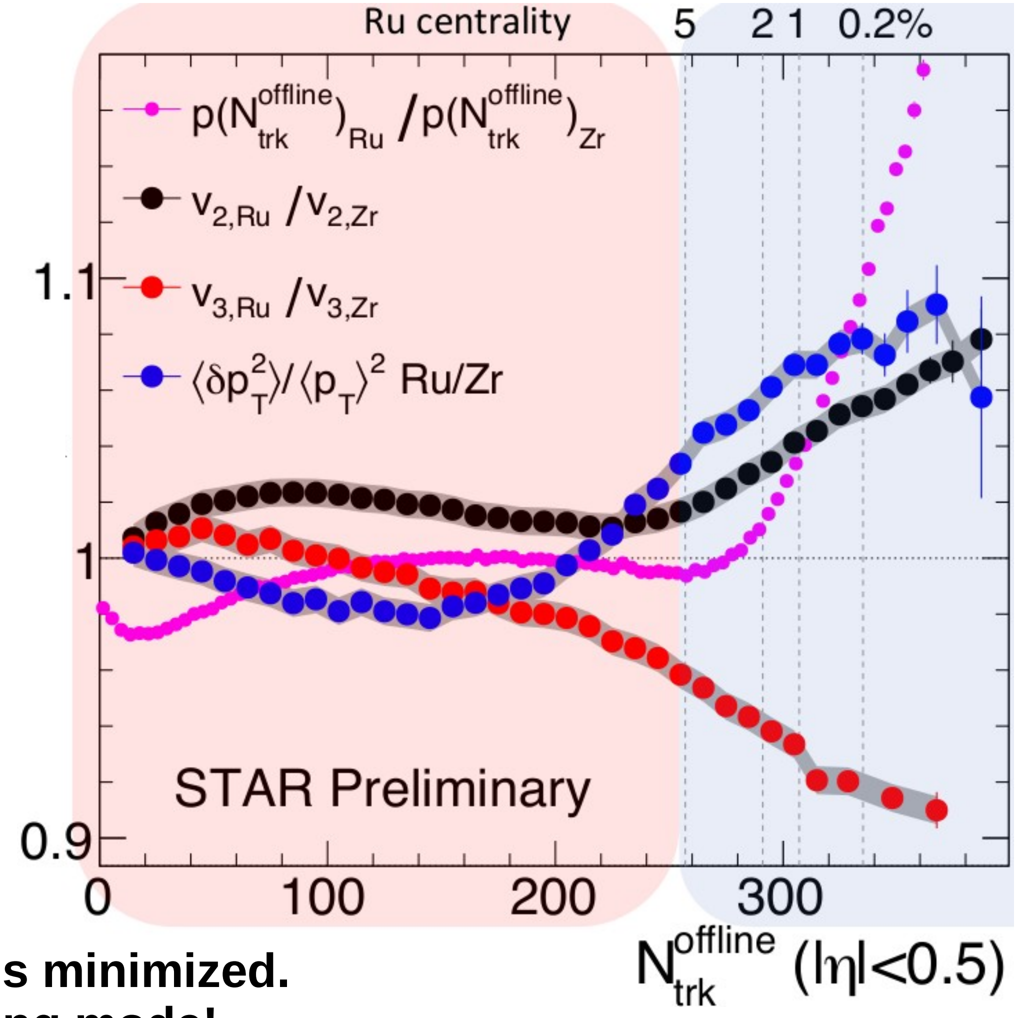
[STAR collaboration, 2109.00131]
[see e.g. Zhang, APS DNP fall meeting 2021]

Unique possibilities with collisions of isobars?

[Giacalone, Jia, Somà, 2102.08158]

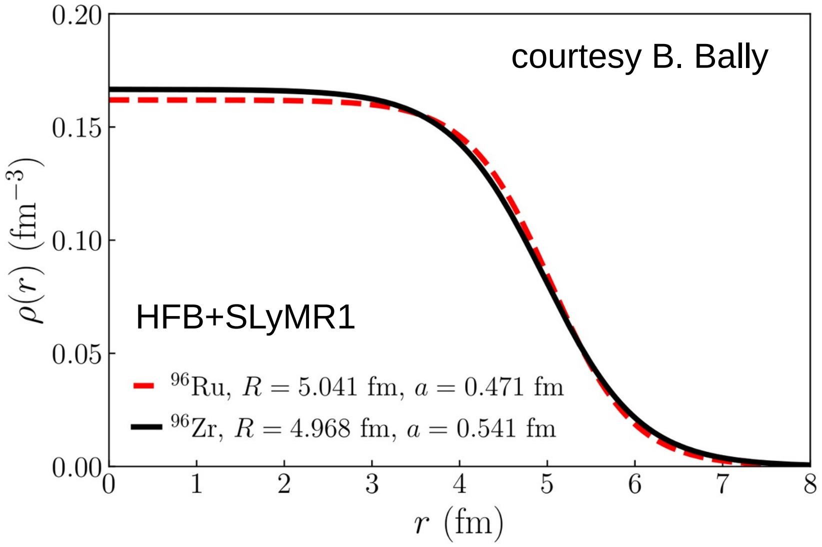
If X and Y are isobars:

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



Departure from unity from nuclear structure.

1) Theory uncertainty from high-energy side is minimized.
2) Expt error is only statistical in isobar running mode!



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.

New features: accessing the neutron skin difference.

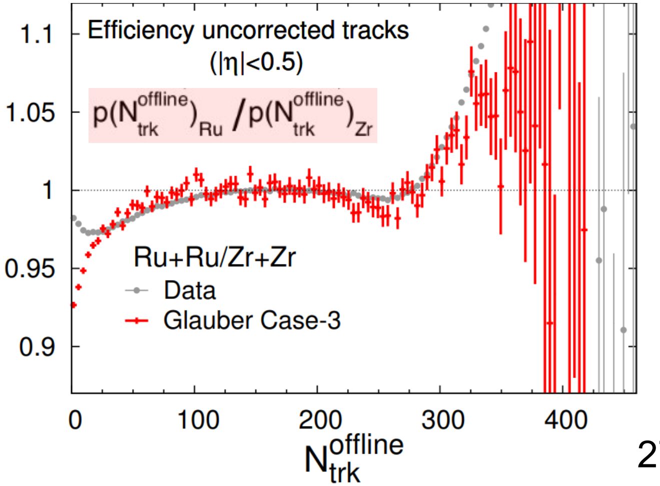
See also [Shou, Ma, Sorensen, Tang, Videbaek, Wang, 1409.8375]

Same multiplicity corresponds to different impact parameters.
Shows up in probabilities of multiplicities. **talk by Haojie Xu**

[Li, Xu, Zhao, Lin, Zhang, Wang, Shen, Wang, 1808.06711]

[Li, Xu, Zhou, Wang, Zhao, Chen, Wang, 1910.06170]

[Xu, Li, Wang, Chen, Wang, 2103.05595]



Neutron skin is a topic of great relevance.

talk by Pawel Danielewicz

New features: accessing the neutron skin via the ratio of [pt].

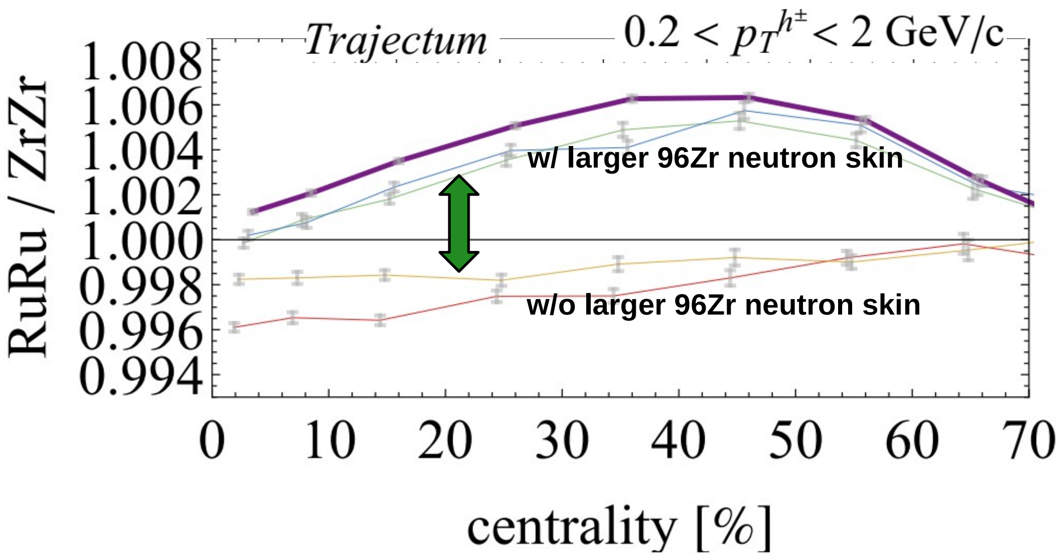
talk by Haojie Xu

talk by Wilke van der Schee

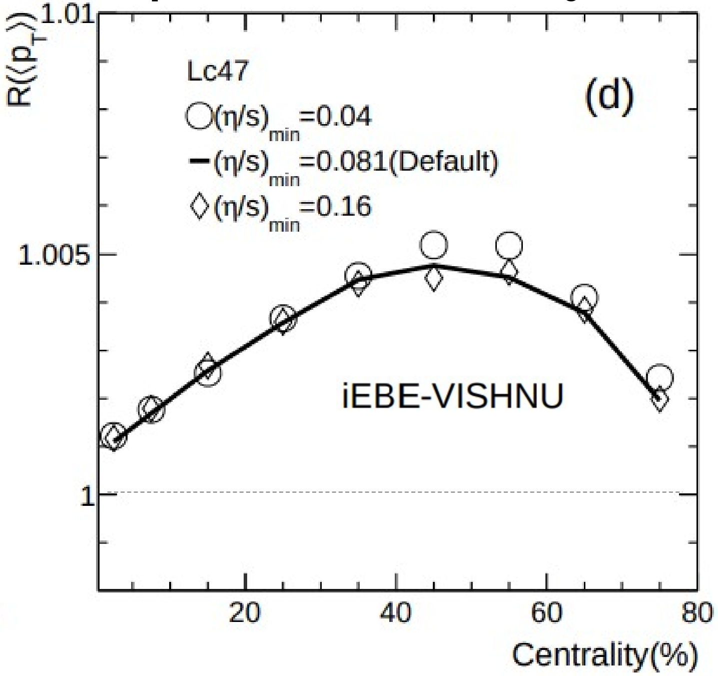
Due to the smaller neutron skin, Ru+Ru systems are more compact. [pt] is enhanced.

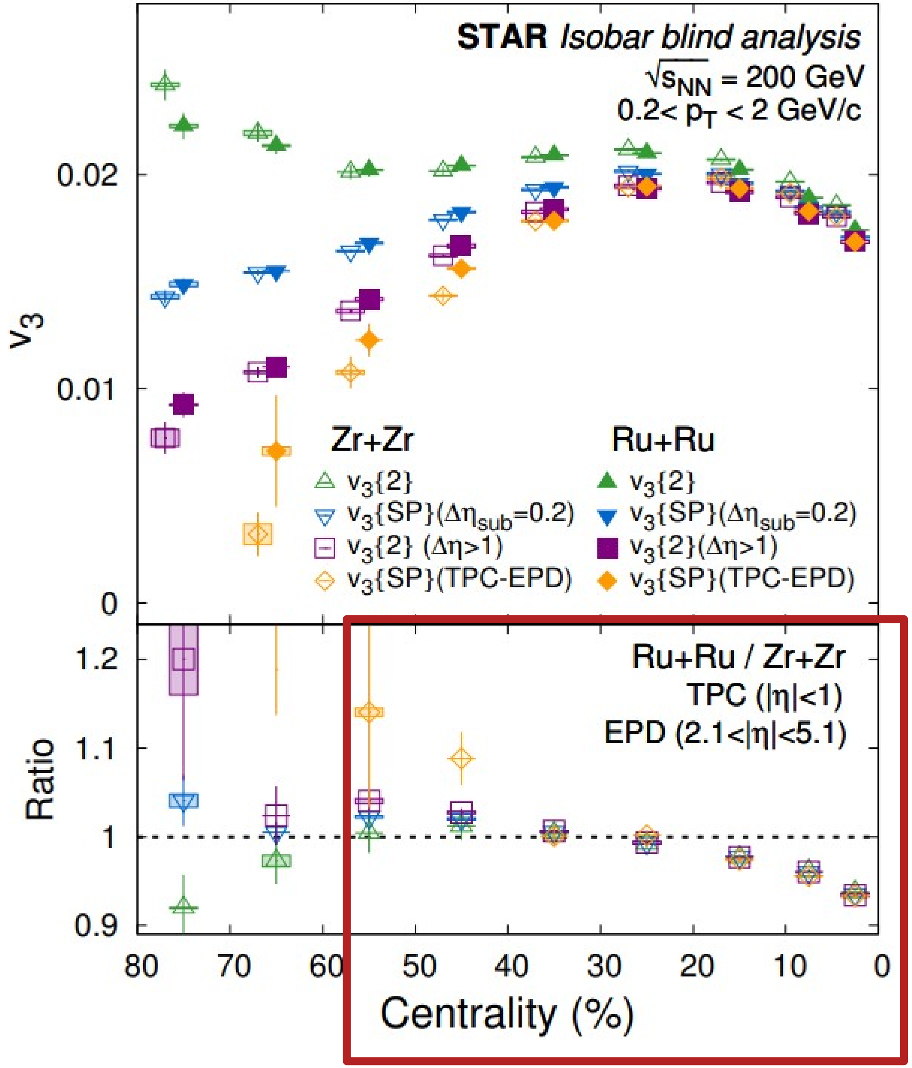
Minor impact from deformations and viscous corrections during hydro.

[Nijs, van der Schee, 2112.13771]



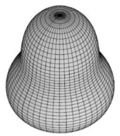
[Xu, Zhao, Li, Zhou, Chen, Wang, 2112.13771]





New features: octupole deformation in 96Zr.

talk by Luis Robledo



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]

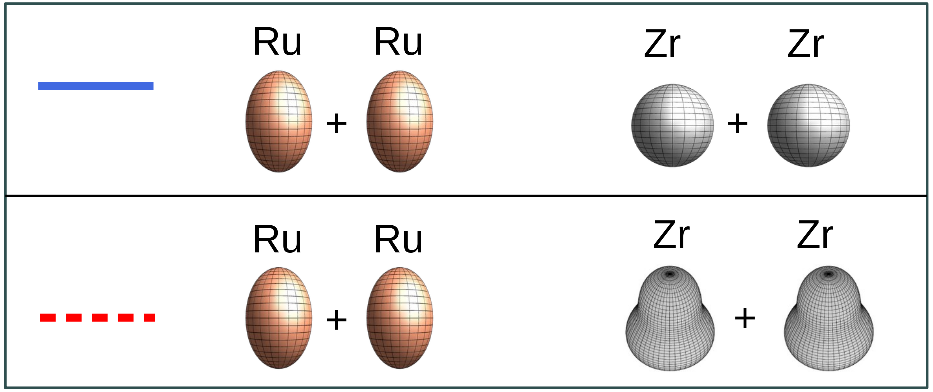
Nuclear physics does not have a clear explanation for this observation.

Now assume a static octupole deformation.

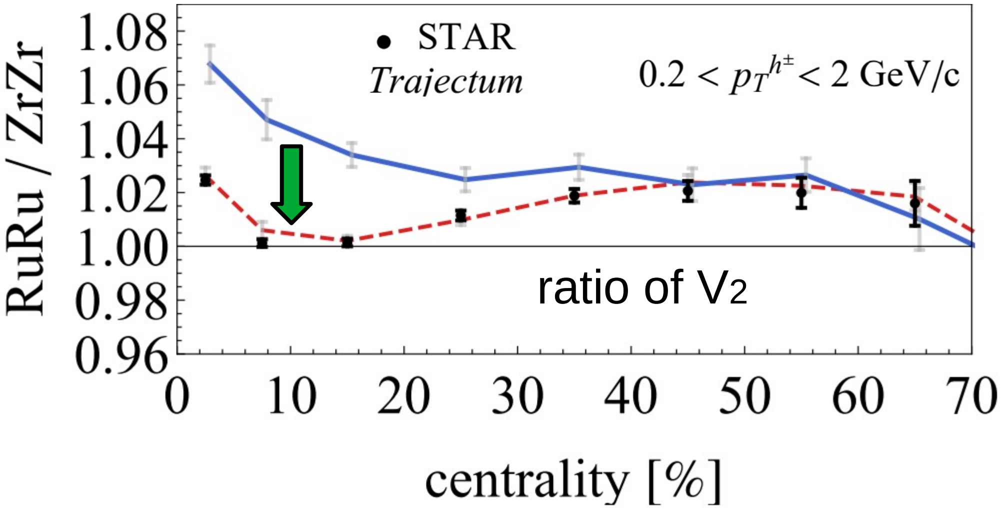
Unambiguous signatures at high energy.

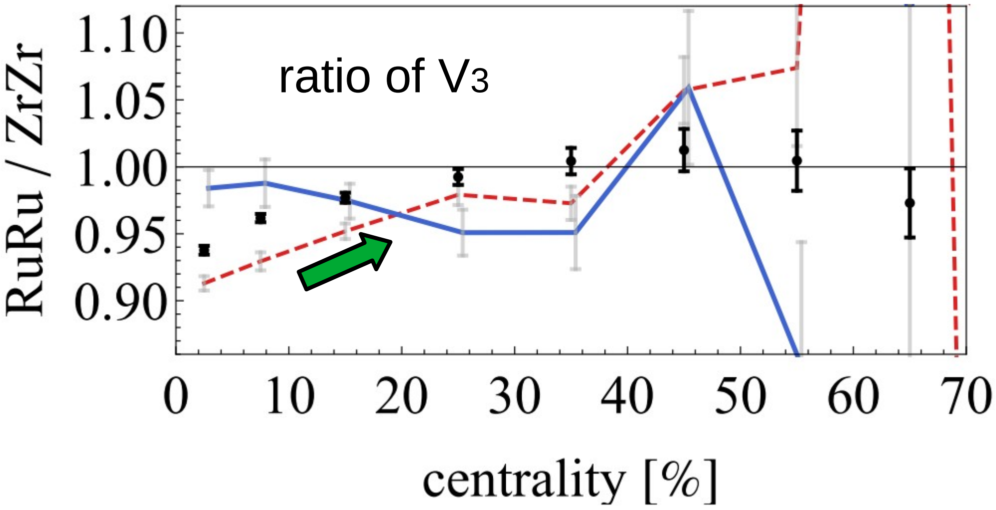
Suggests β3 ≈ 0.15.

LEGEND:



[Nijs, van der Schee, 2112.13771]





talk by Wilke van der Schee

[see also Zhang, Jia, 2109.01631, 2111.15559]

QUESTIONS

Unreasonable effectiveness of nuclear shapes?

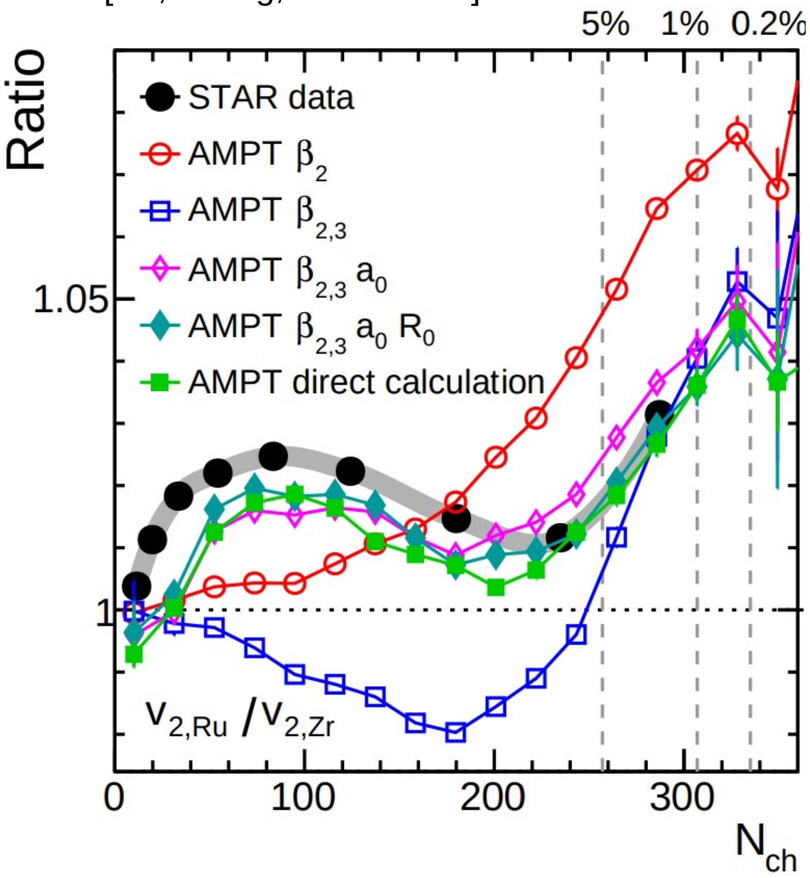
Why does it work so well?

Are the approximations justified for 96Ru and 96Zr?

How much physics do we learn from more isobars?

talk by Chunjian Zhang

[Jia, Zhang, 2111.15559]



4.

Recap and future prospects

RECAP

- We can use heavy-ion collisions to image the shape of nuclei.

- Evidence of **axial and triaxial quadrupole**, **axial octupole**, and **neutron skin** effects.

- Colliding isobars offers the cleanest access to nuclear shapes.

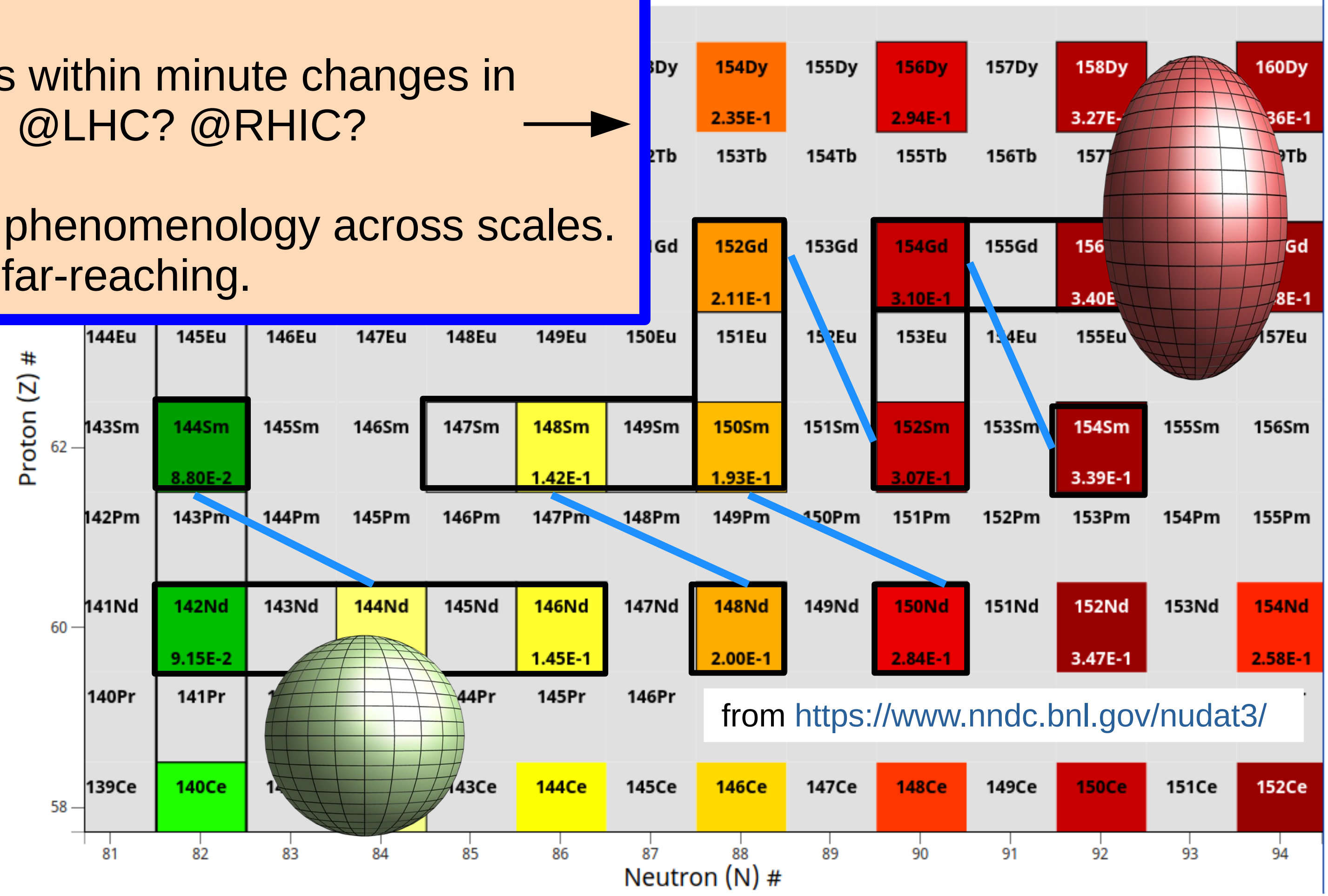
- What next? Implications?

Challenging the whole picture? My suggestion.

Wild structure variations within minute changes in proton/neutron number. @LHC? @RHIC?

Consistency of nuclear phenomenology across scales. Physics outcome likely far-reaching.

red=well-deformed
green=quasi-spherical



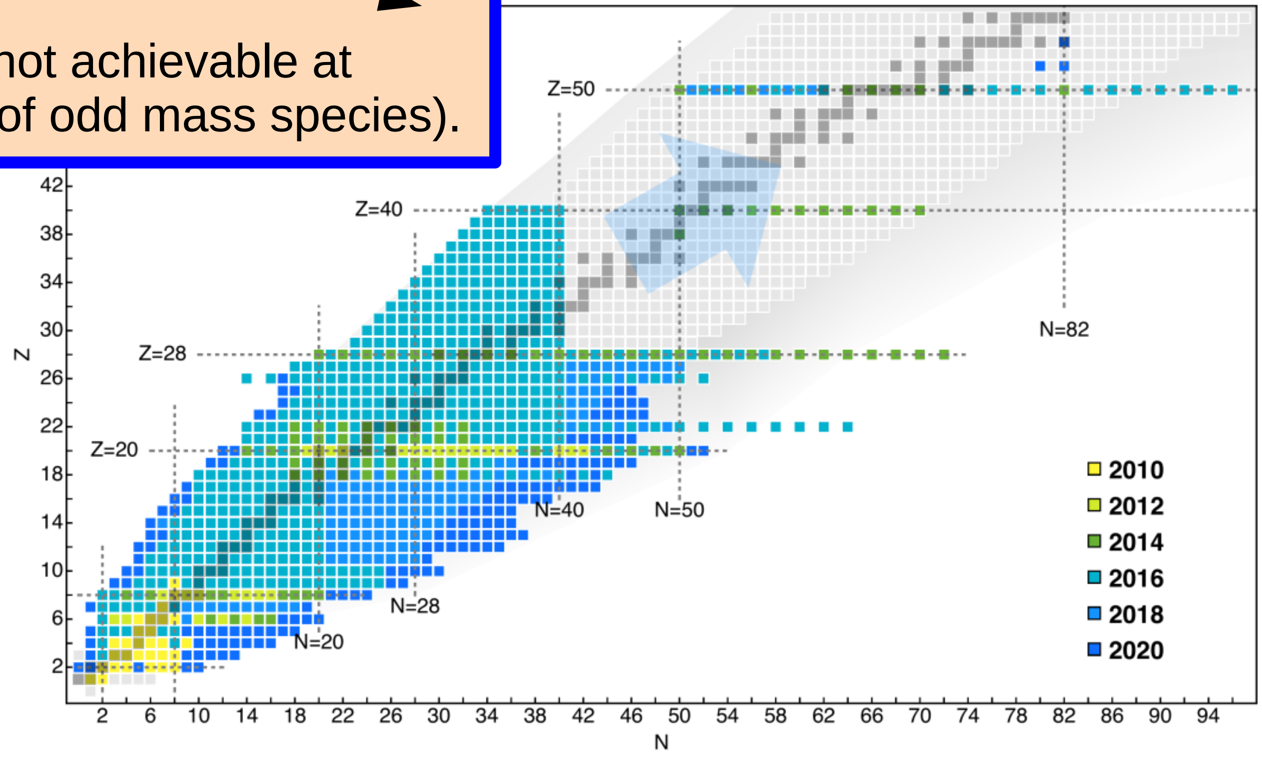
Most of these nuclei have a <u>measured</u> β_4.

Can high-energy collisions help develop new ab-initio nuclear theories?

Reach of ab-initio theories over the years.

Features probed at high energy not achievable at lower energy (e.g. deformations of odd mass species).

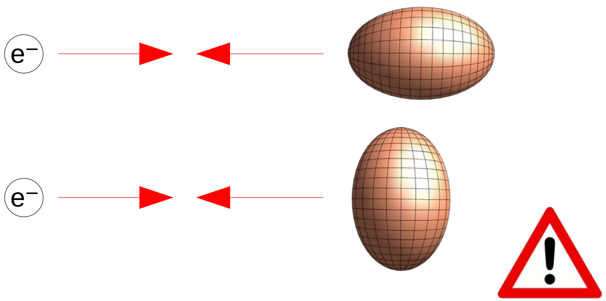
talk by Dean Lee



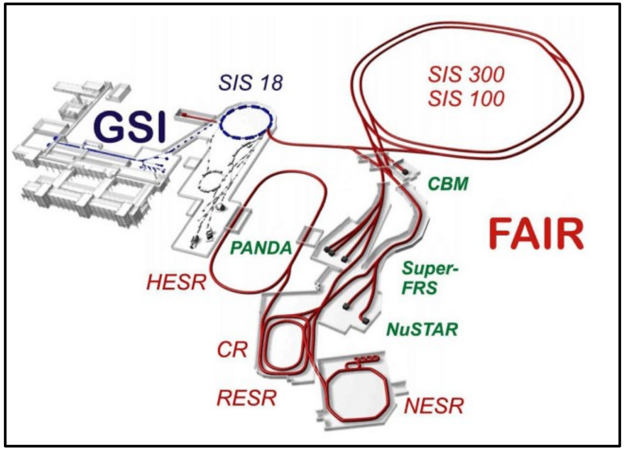
Electron-ion collider?

Nuclear collisions at lower energy?

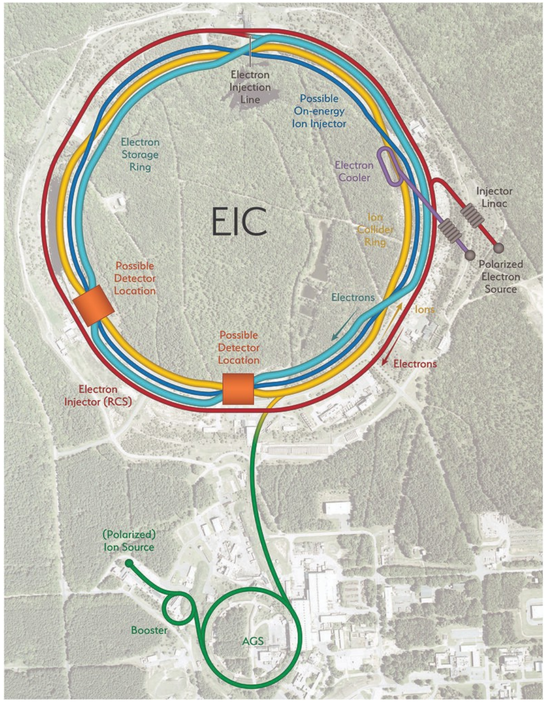
Nuclear structure should not be overlooked.



talk by Hannah Elfner



talk by Grigory Nigmatkulov



Intersection of nuclear structure and high-energy nuclear collisions

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Fuqiang Wang (Purdue)

Jan 23rd - Feb 24th 2023

Deciphering nuclear phenomenology across energy scales

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

Sep 20th - Sep 23rd 2022

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