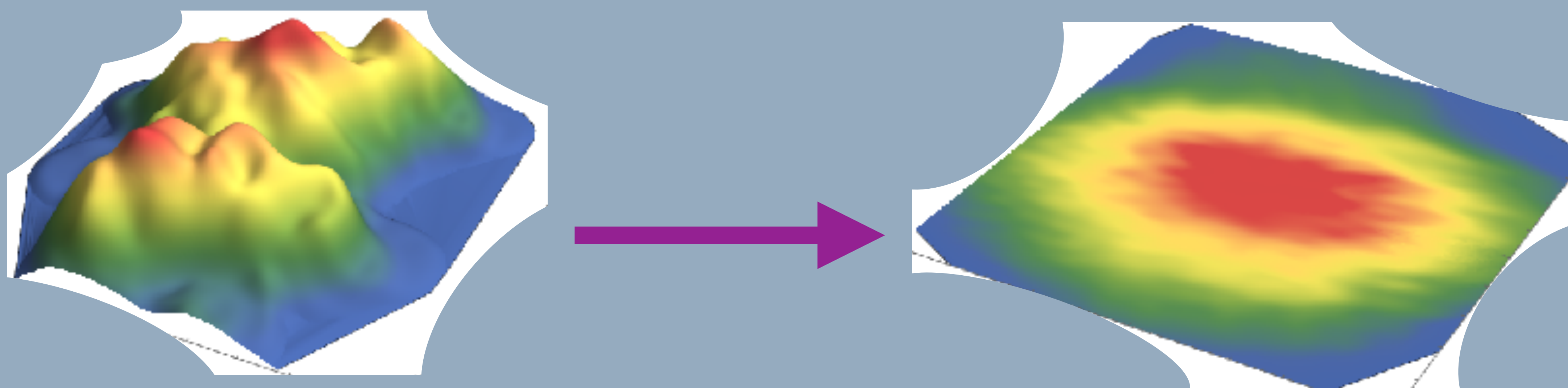
Illinois Center for Advanced Studies of the Universe

Initial shape engineering via final state correlations in (isobar) system scan



Jacquelyn Noronha-Hostler
University of Illinois Urbana-Champaign

RBRC Workshop: Physics Opportunities from the RHIC Isobar Run Jan 2022

Initial conditions: Nuclear structure

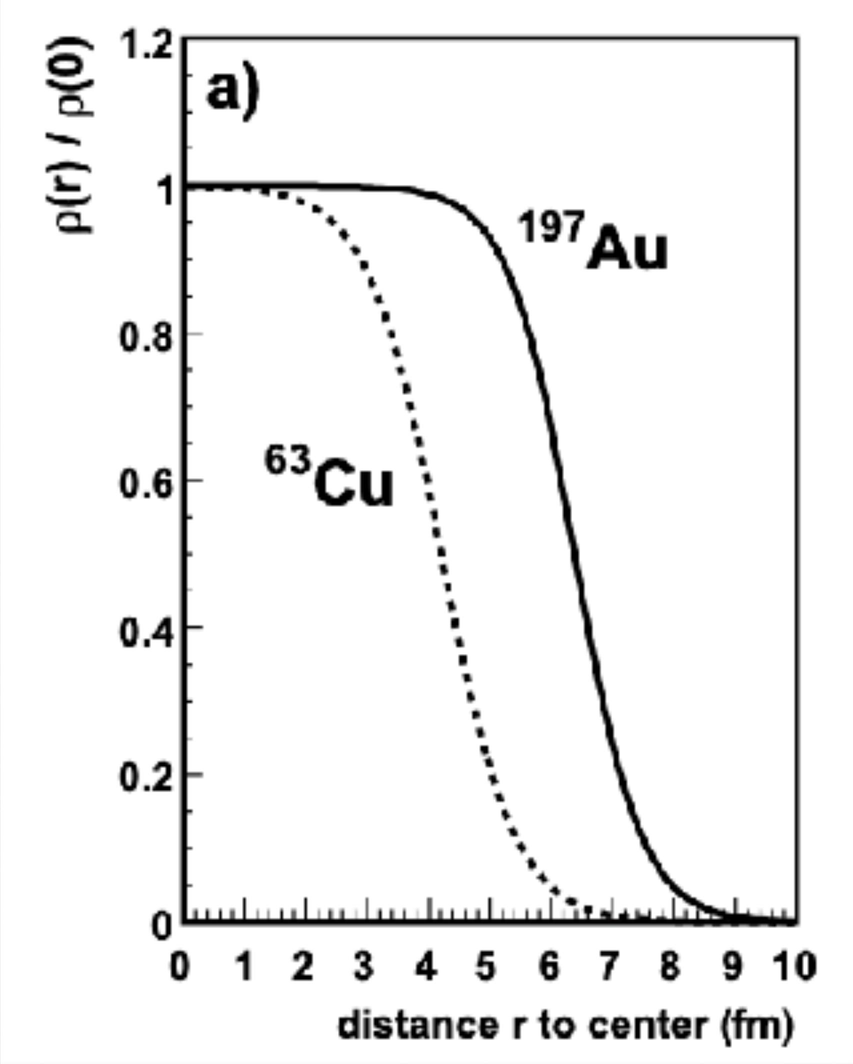
Ann.Rev.Nucl.Part.Sci. 57 (2007) 205-243

Initial conditions typically sample over a density distribution (Wood-Saxon)

$$\rho(r,\theta)/\rho_0 = \left[1 + \exp\left(\frac{r - R(\theta)}{a}\right)\right]^{-1}$$

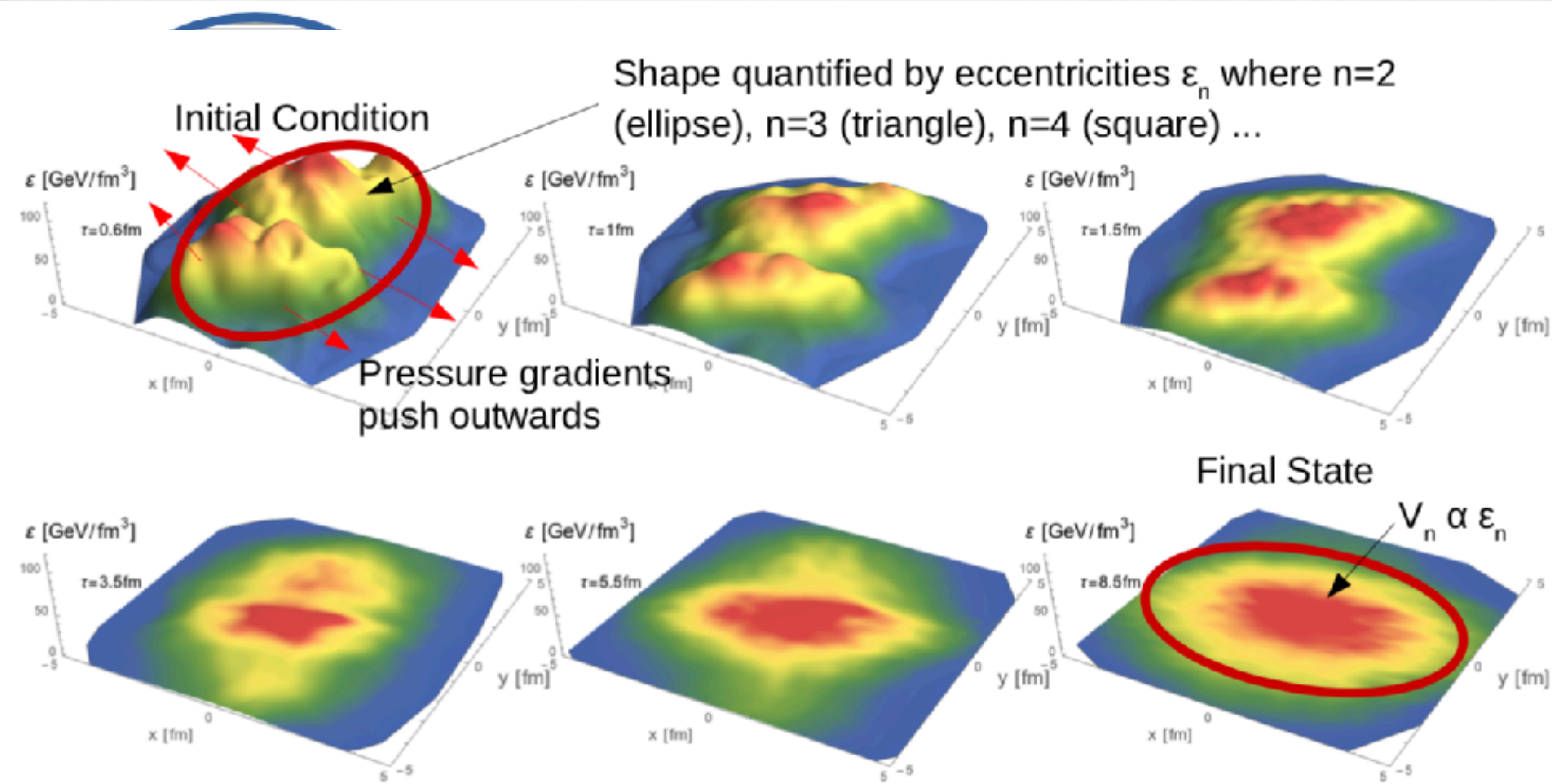
For deformed nuclei, the deformations considered via

$$R(\theta) = R_0\Big(1 + \beta_2 Y_{20}(\theta) + \beta_3 Y_{30}(\theta) + \dots\Big)$$



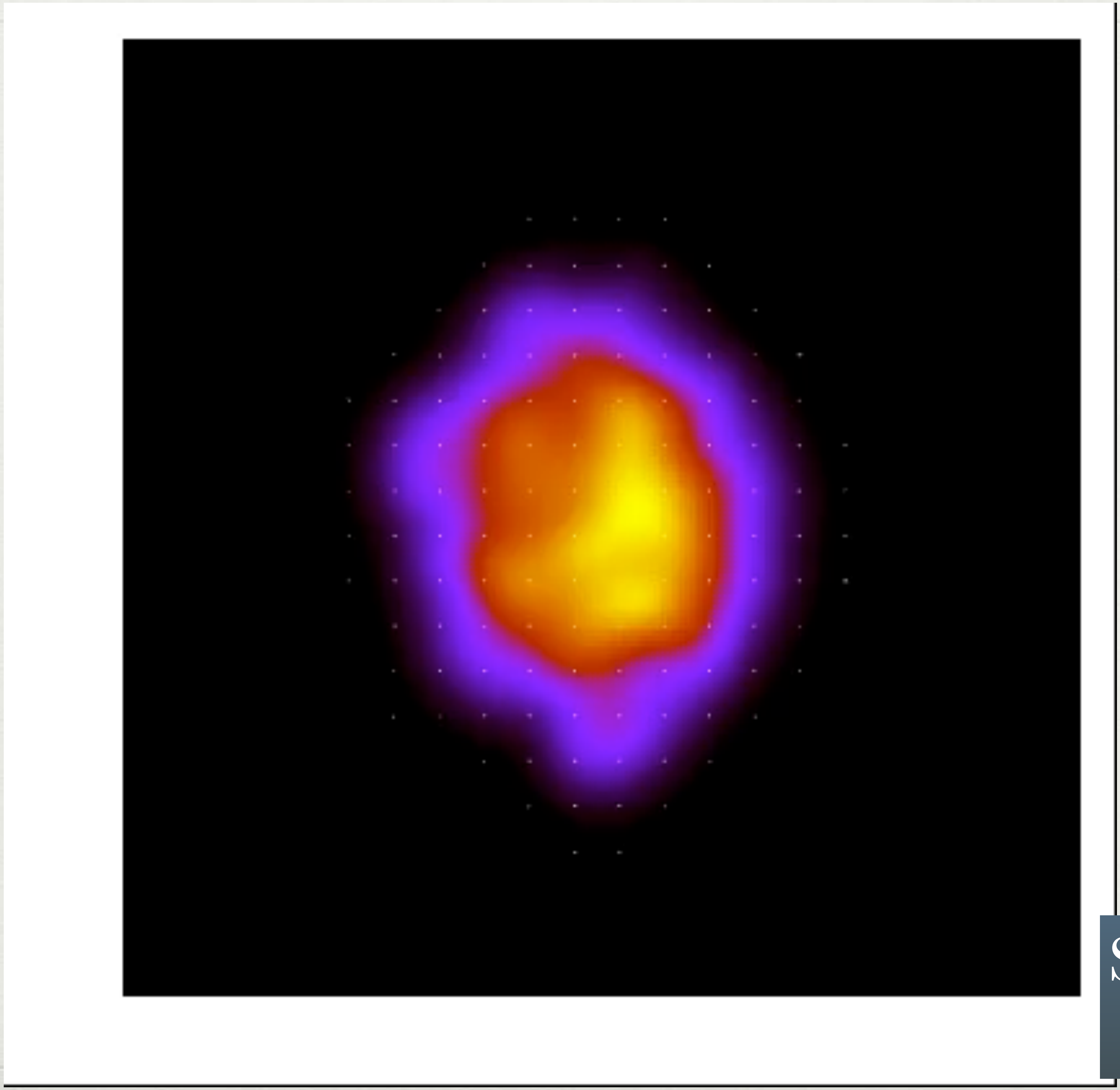
Even Better: Nucleon configurations from lattice effective field theory

Initial conditions: $\varepsilon_{n,m} \equiv \dfrac{\int r^m e^{in\phi}\rho(r,\phi) r dr d\phi}{\int r^m \rho(r,\phi) r dr d\phi}$



Eccentricities ε_2's are directly related to the final measured flow observables v_n's

Transverse plane (2D) right after the collision



Simulation by C. Plumberg

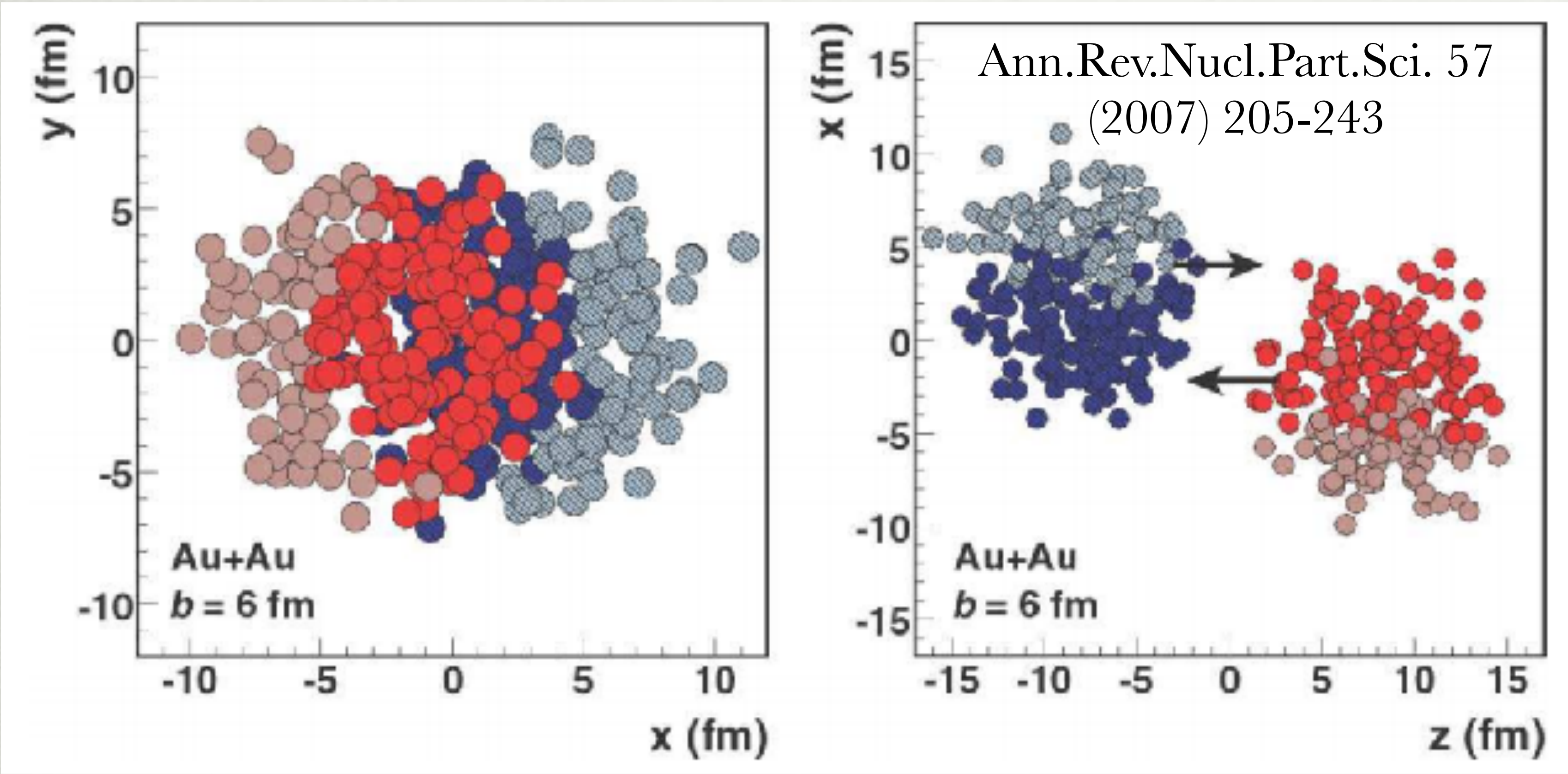
Head on collisions and deformations

Centrality % $\rightarrow 0$

Terminology:

-participants (colliding nucleons)

-spectators (fly off to the detector)

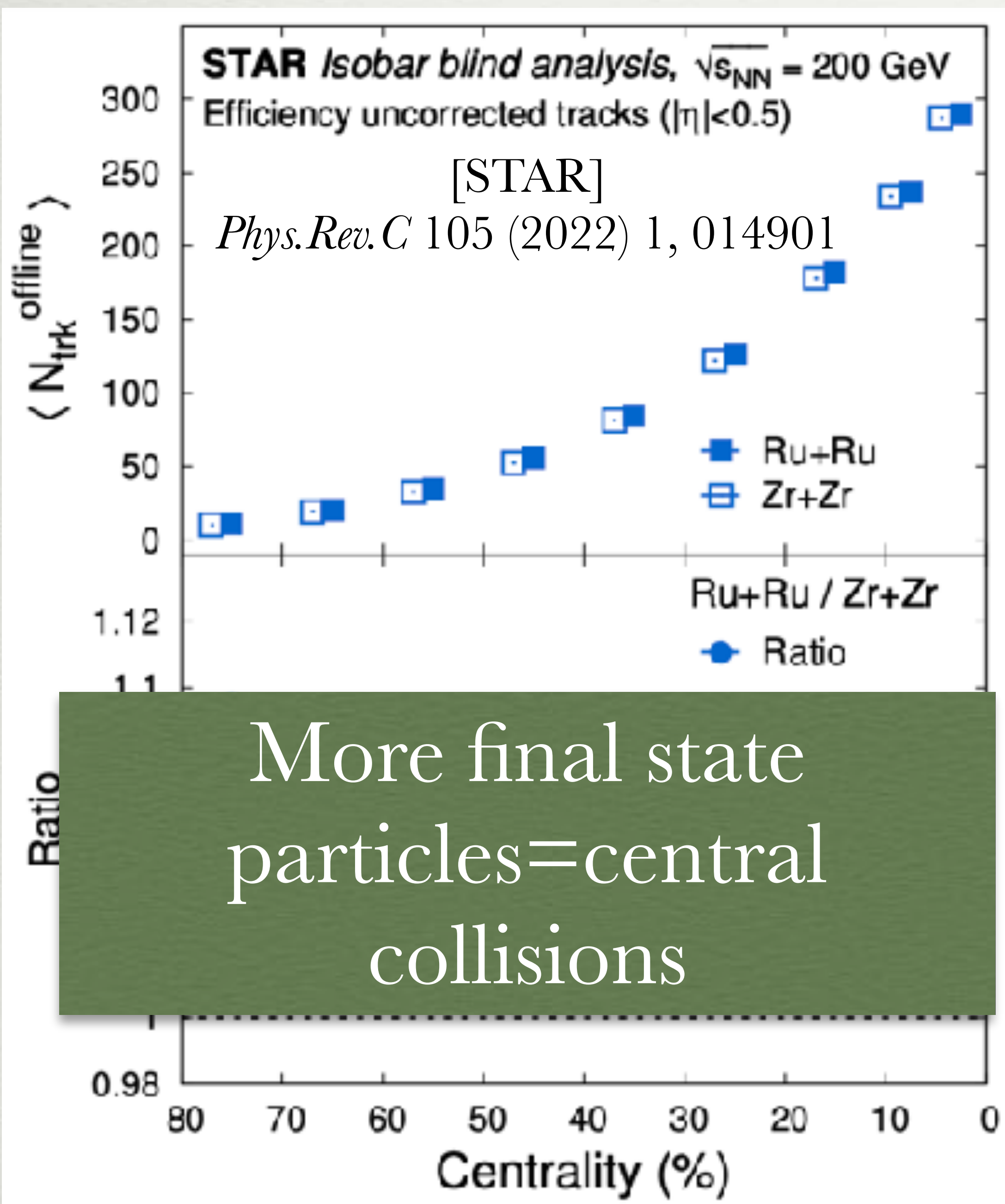


Ann.Rev.Nucl.Part.Sci. 57 (2007) 205-243

Head-on collisions most sensitive to structure, but $b = 0$ doesn't probe everything

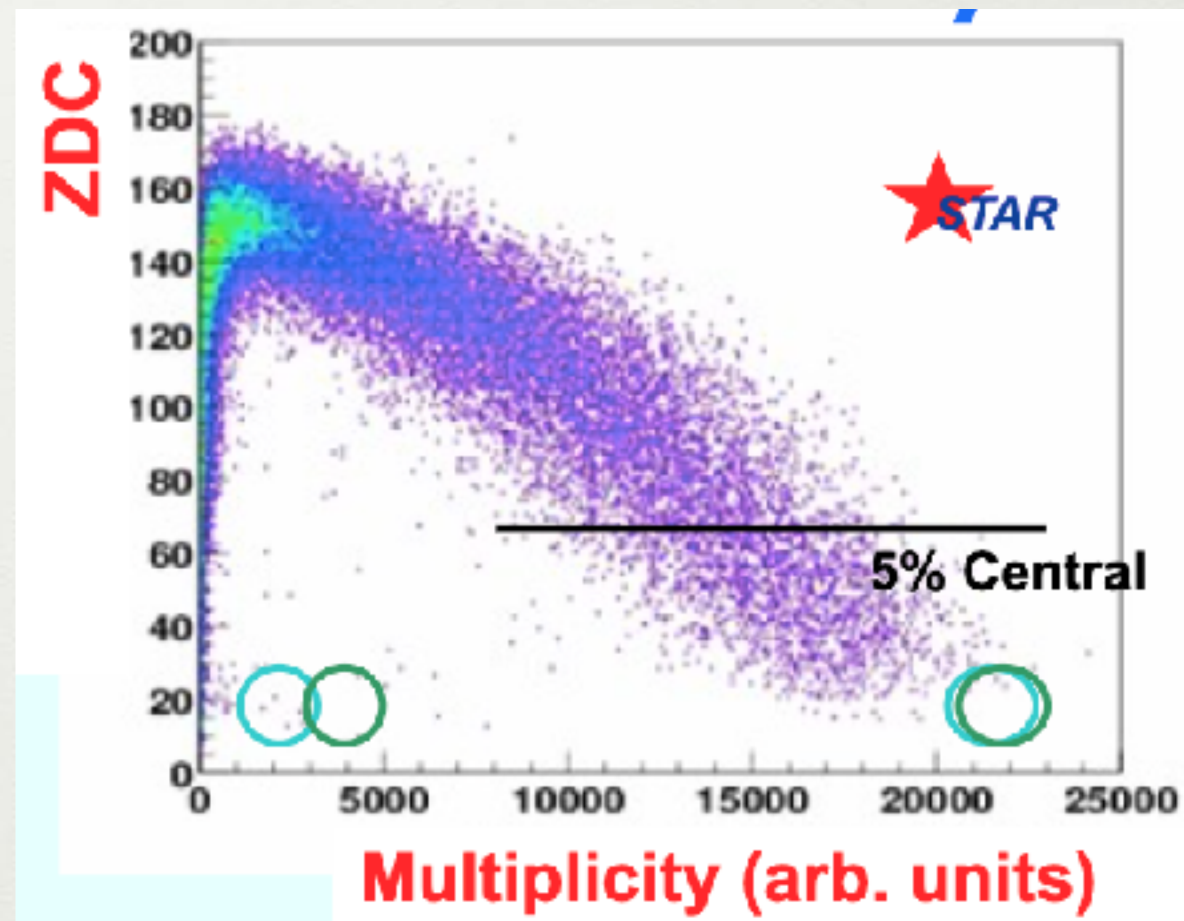
Selecting central events

Multiplicity



More final state particles=central collisions

ZDC (spectators)

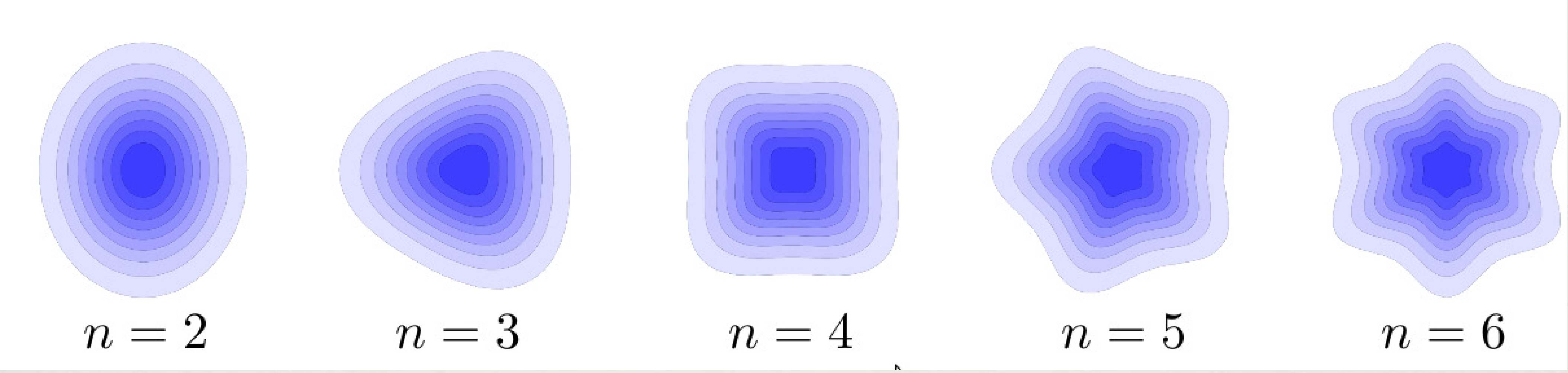


Less spectators = central collisions

Quantifying flow

The distribution of particles can be written as a Fourier series

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + \sum_n 2v_n \cos\left[n\left(\phi - \psi_n\right)\right]\right]$$



Collective flow: Flow harmonics, $v_n\{m\}$, are calculated by correlating m=2 to 8 particles → collective behavior

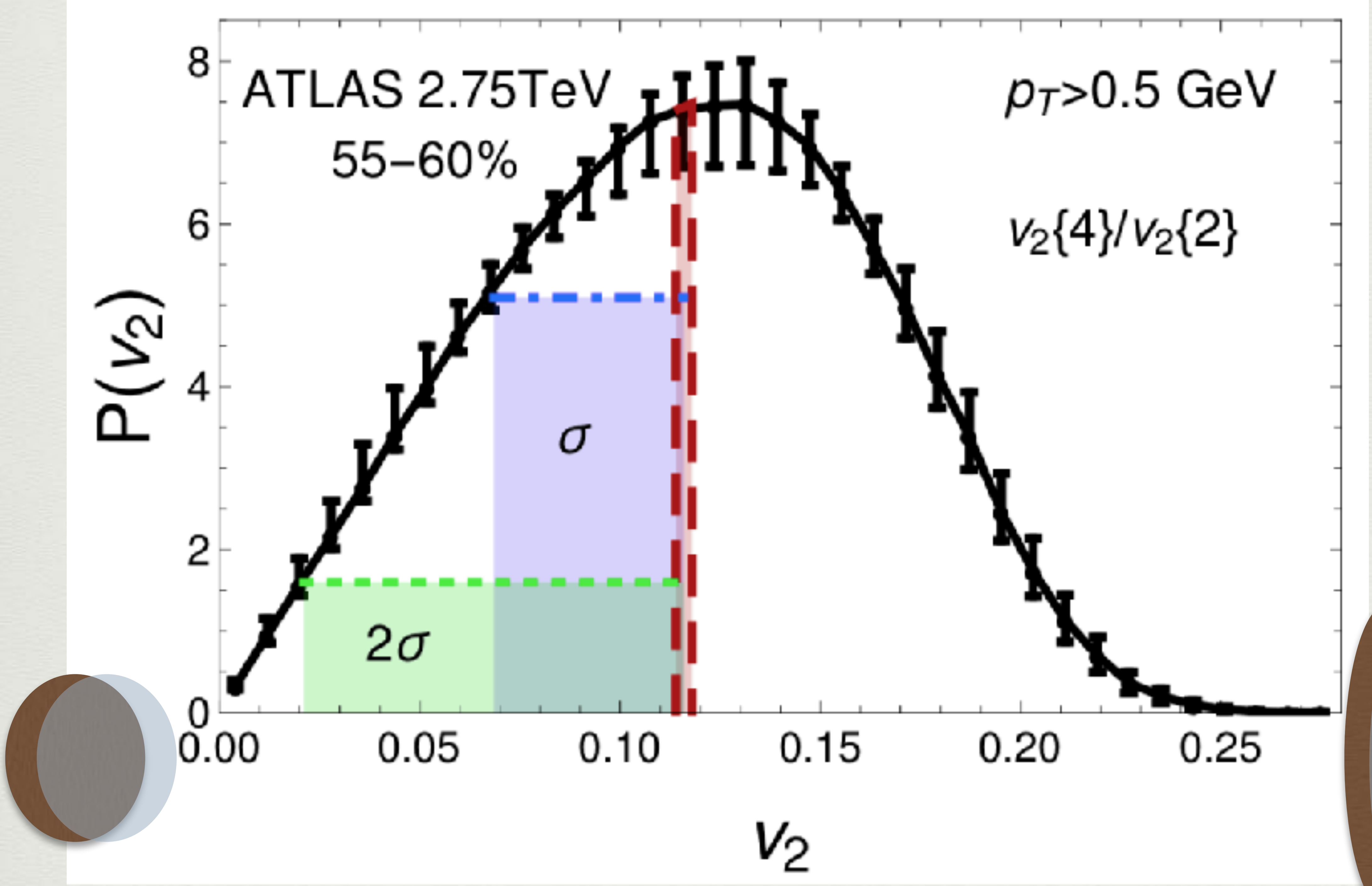
Multi-particle cumulants

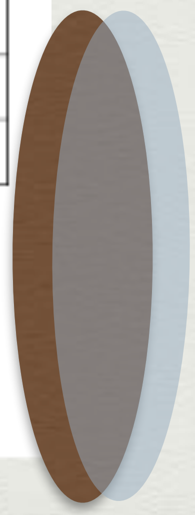
Reconstructing the v_n distribution with cumulants

$$
\begin{aligned}
v_n\{2\}^2 &= \langle v_n^2 \rangle, \\
v_n\{4\}^4 &= 2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle, \\
v_n\{6\}^6 &= \frac{1}{4}\left[\langle v_n^6 \rangle - 9\langle v_n^2 \rangle \langle v_n^4 \rangle + 12 \langle v_n^2 \rangle^3 \right], \\
v_n\{8\}^8 &= \frac{1}{33}\left[144\langle v_n^2 \rangle^4 - 144\langle v_n^2 \rangle^2 \langle v_n^4 \rangle + 18\langle v_n^4 \rangle^2 \right. \\
&\left. + \; 16\langle v_n^2 \rangle \langle v_n^6 \rangle - \langle v_n^8 \rangle \right],
\end{aligned}
$$

where collectivity $\rightarrow v_n\{2\} > v_n\{4\} \sim v_n\{6\} \sim v_n\{8\}$ but there are differences between higher order cumulants!

$v_n\{4\}/v_n\{2\}$: Width of v_n distribution

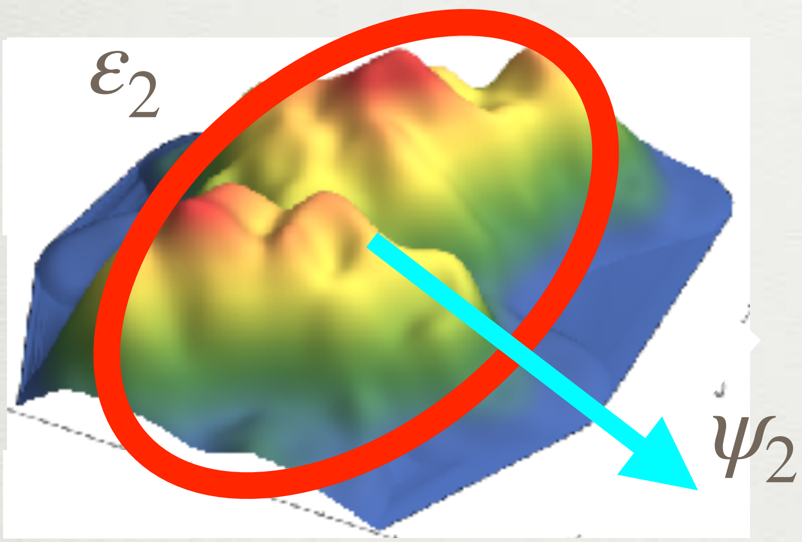




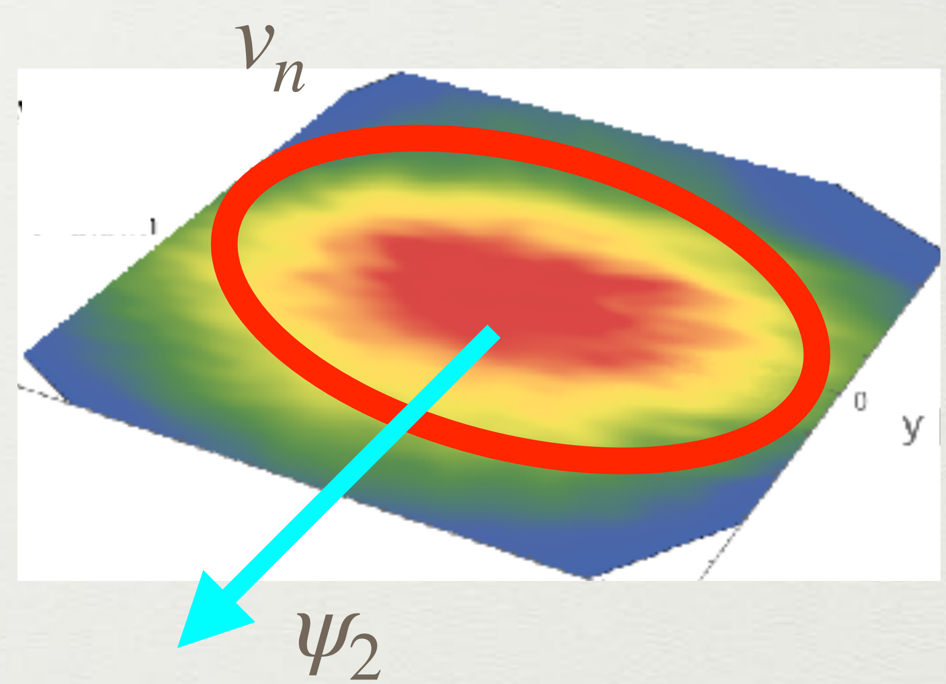
Quantifying initial and final state

$\mathcal{E}_n \equiv \varepsilon_n e^{in\Phi_n}$

$V_n \equiv v_n e^{in\psi_n}$



Calculated in Coordinate space



Measured in Momentum space

Pearson Coefficient $$Q_n = \frac{Re\langle V_n \mathcal{E}_n^* \rangle}{\langle |V_n|^2 \rangle \langle |\mathcal{E}_n|^2 \rangle}$$

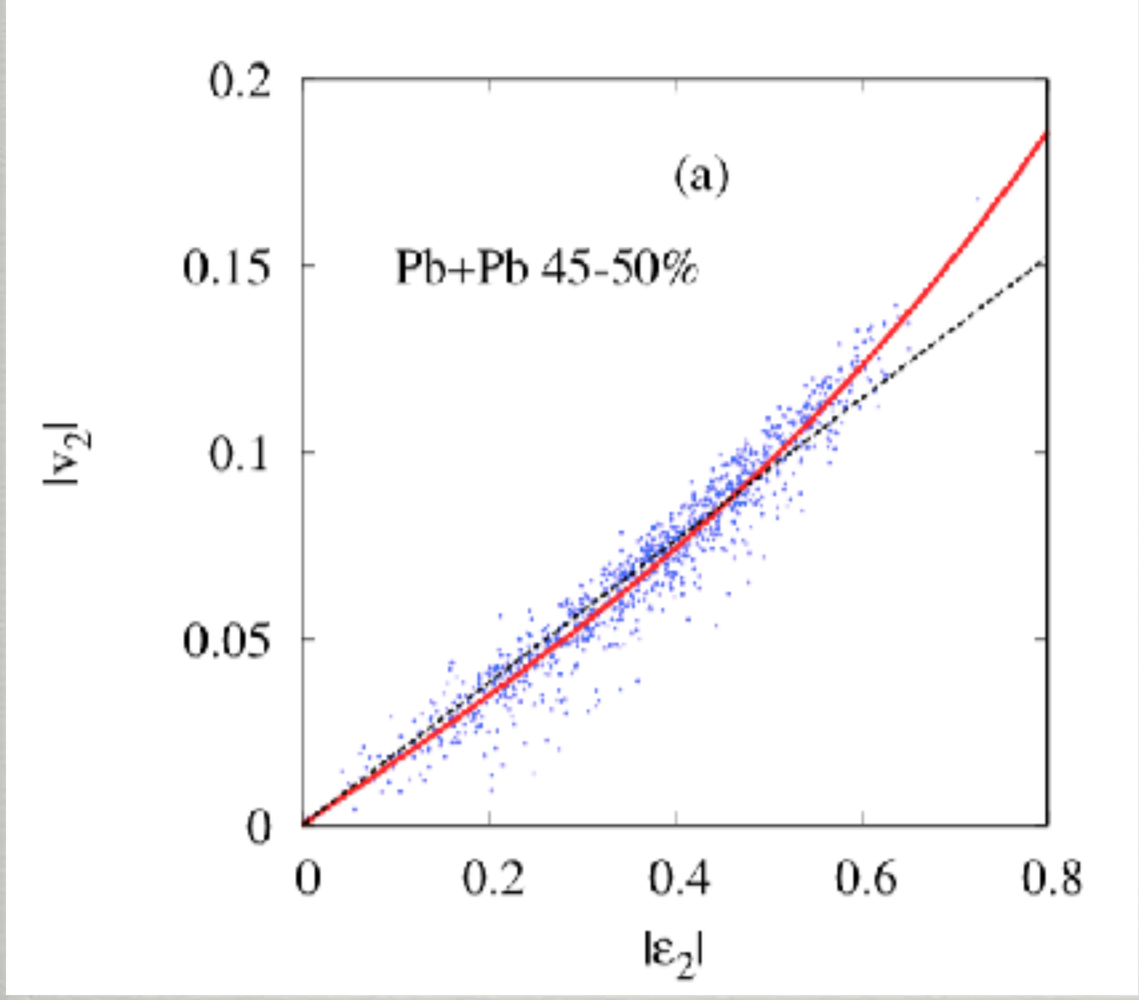
Connecting initial shape $\mathcal{E}_n$ to final flow V_n

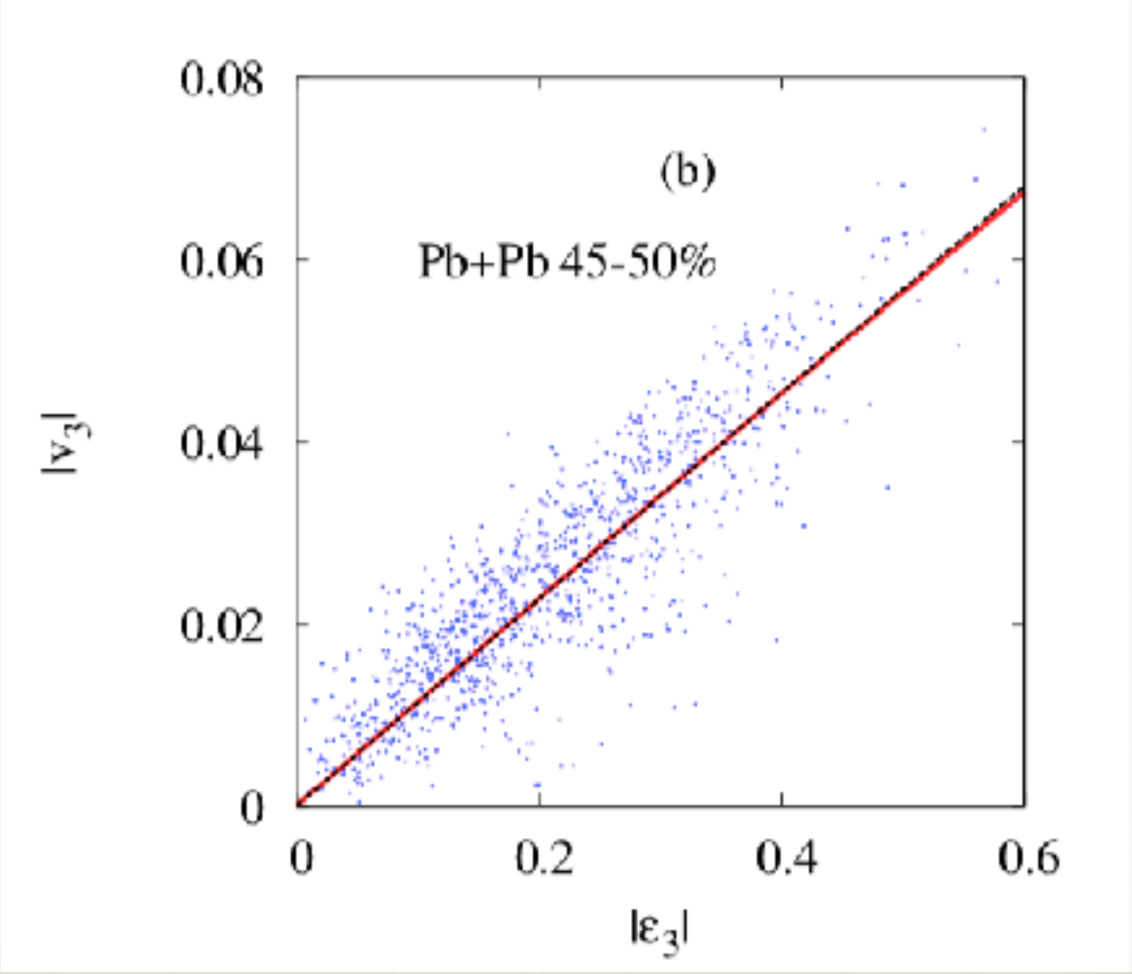
Linear response $$V_n^{pred} = \gamma_n \mathcal{E}_n$$

Teaney,Yan,PRC83(2011)064904;Gardim,et al,PRC85(2012)024908;PRC91(2015)3,034902

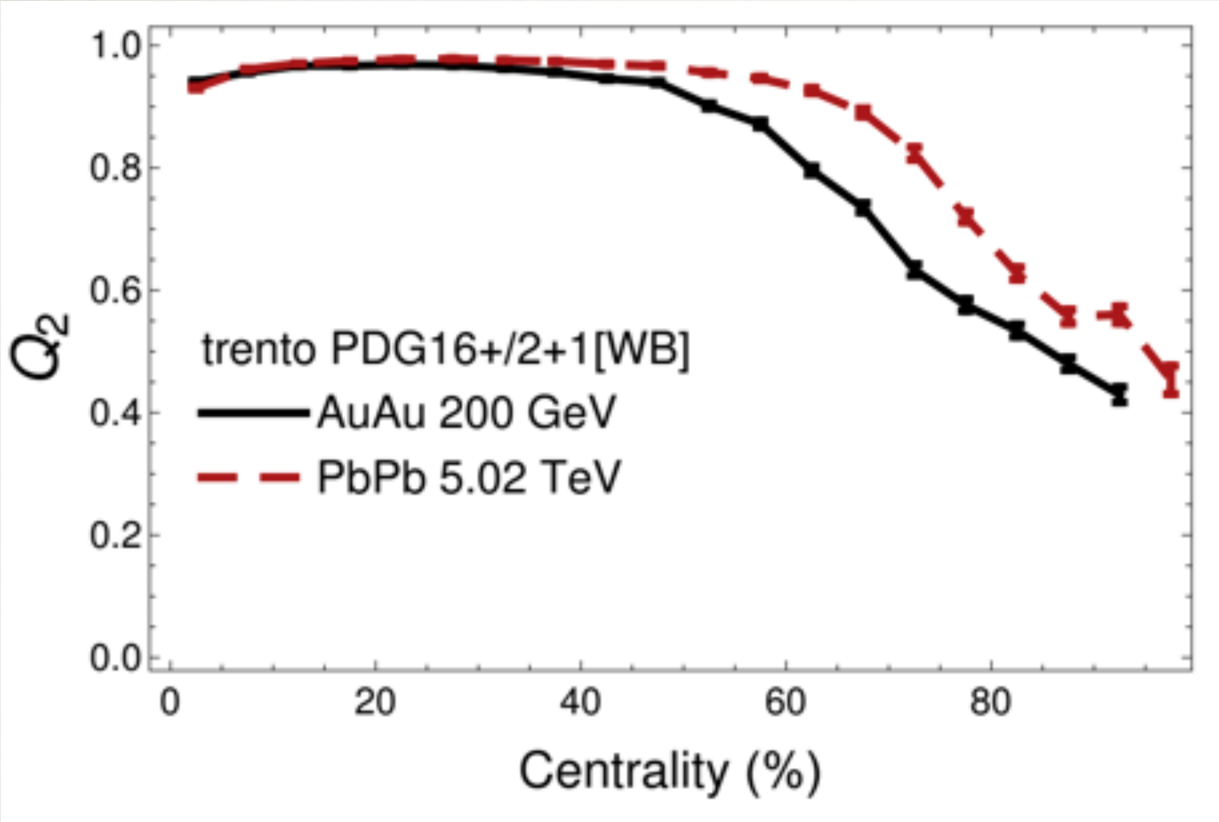
Linear+cubic response $$V_n^{pred} = \kappa_{1,n}\mathcal{E}_n + \kappa_{2,n}|\varepsilon_n|^2\mathcal{E}_n$$

JNH,Yan,Gardim,Ollitrault Phys. Rev. C 93, 014909 (2016)

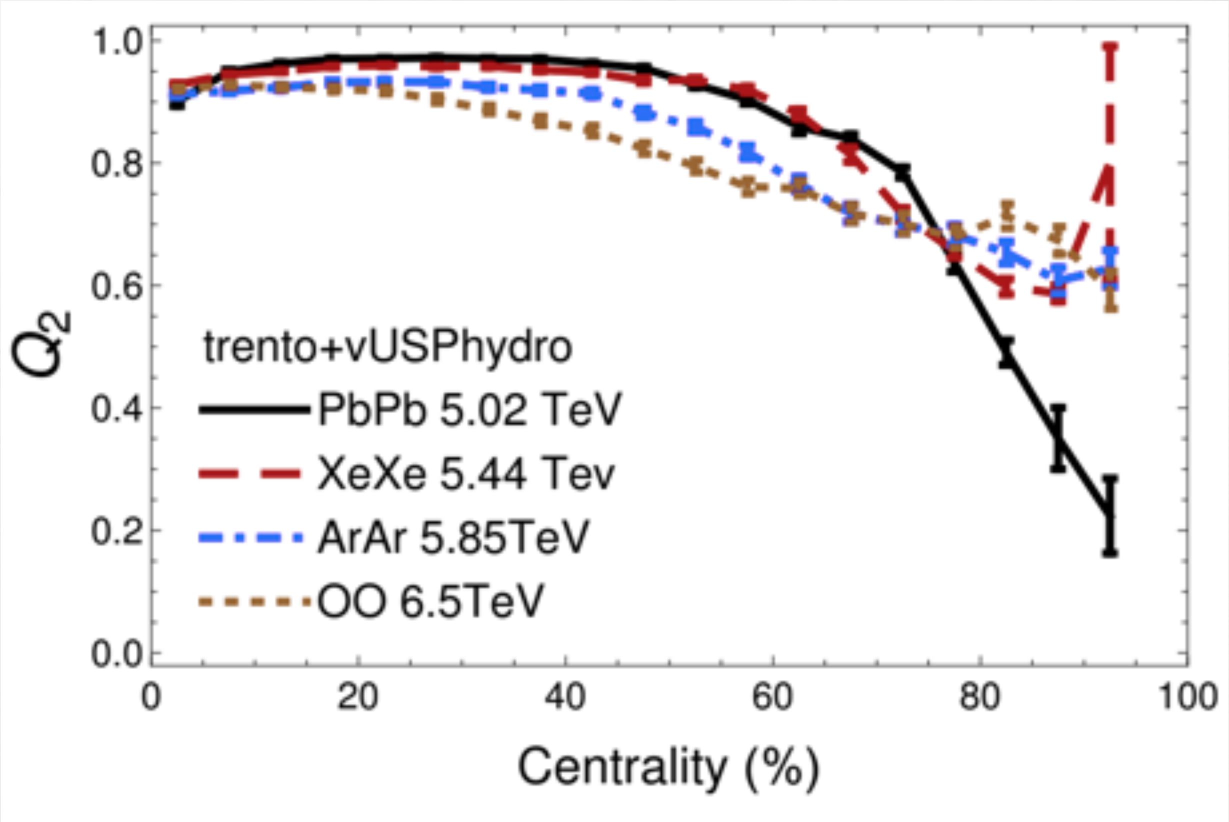




Effectiveness of linear response across $\sqrt{s}$ and system size



Alba, JNH et al, *Phys.Rev.C* 98 (2018) 3, 034909

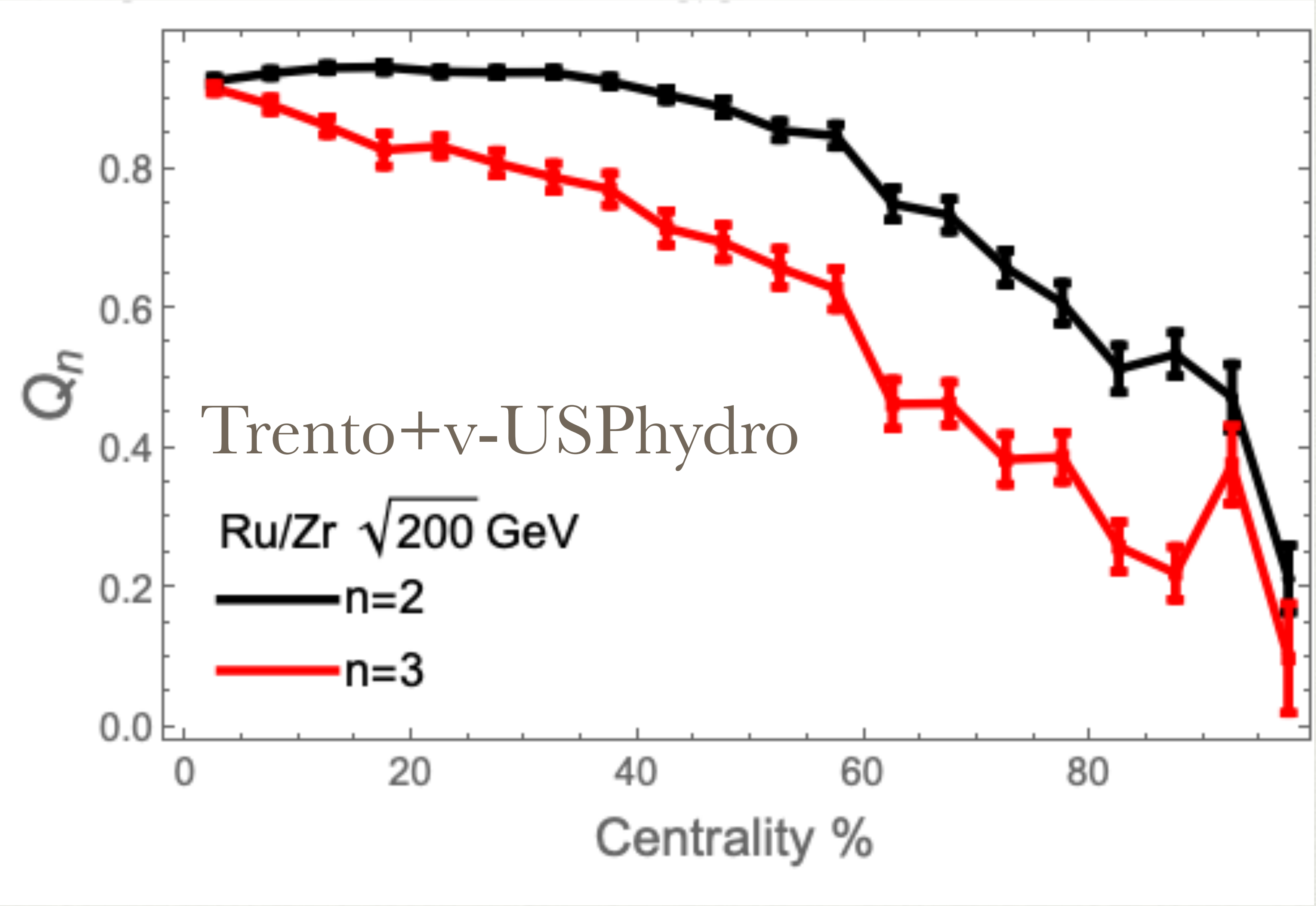


Sievert, JNH *Phys.Rev.C* 100 (2019) 2, 024904

Connection from $\mathcal{E}_n \rightarrow V_n$ strong across beam energy

Connection from $\mathcal{E}_n \rightarrow V_n$ weakens for smaller systems

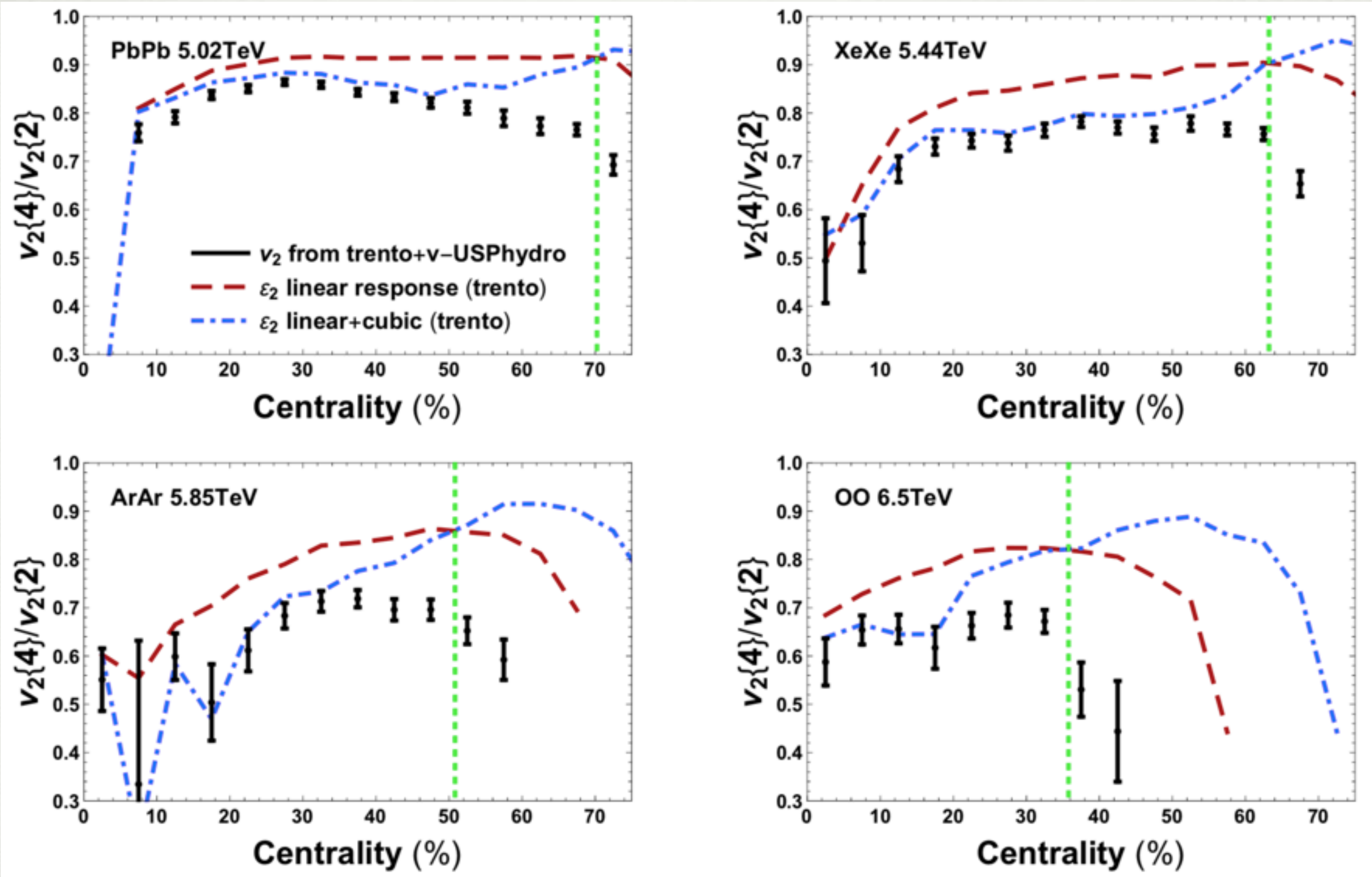
Does this correlation exist for the isobar run?



Mapping is generically the same, regardless of deformation

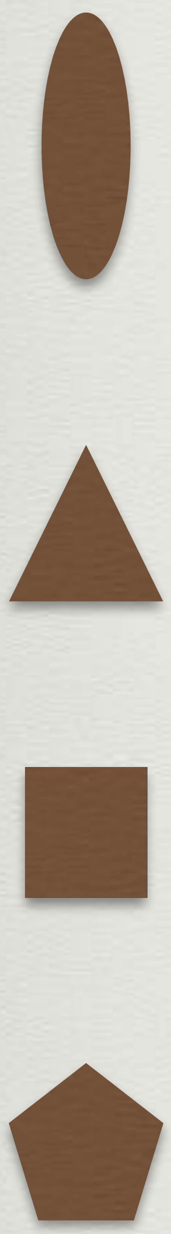
Predictive power of initial state in central collisions (across system size)

Sievert, JNH *Phys.Rev.C* 100 (2019) 2, 024904



Plethora of possible observables

Number of particles correlated



Mixed Harmonics:

Symmetric Cumulants (magnitudes)

Event plane correlations (angles)

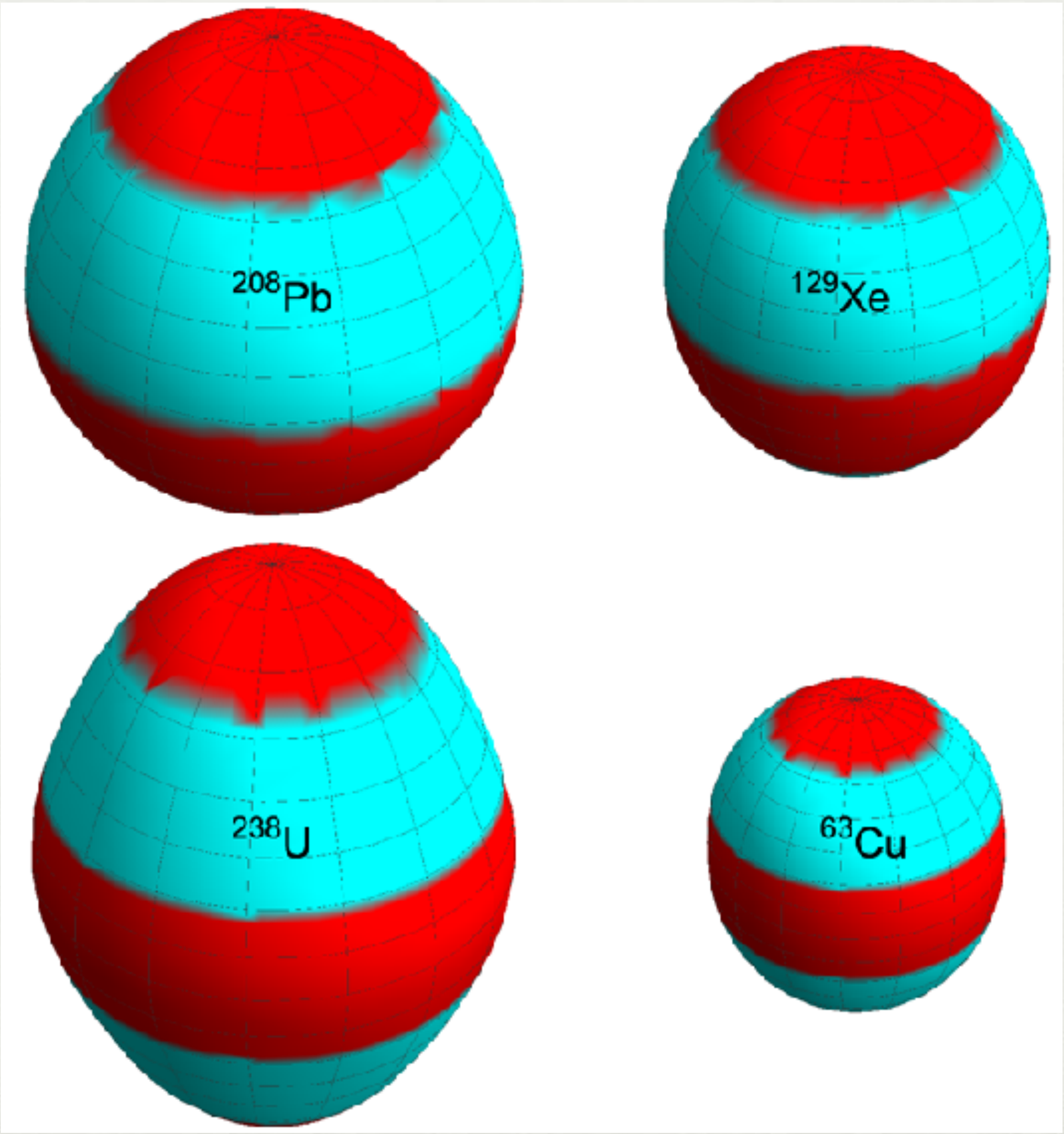
They're actually related: Giacalone et al, *Phys.Rev.C* 94 (2016) 1, 014906

Identified particles, centrality, beam energy etc

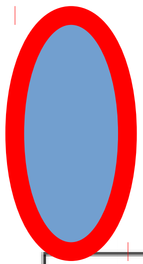
Huge potential phase space!

Harmonics

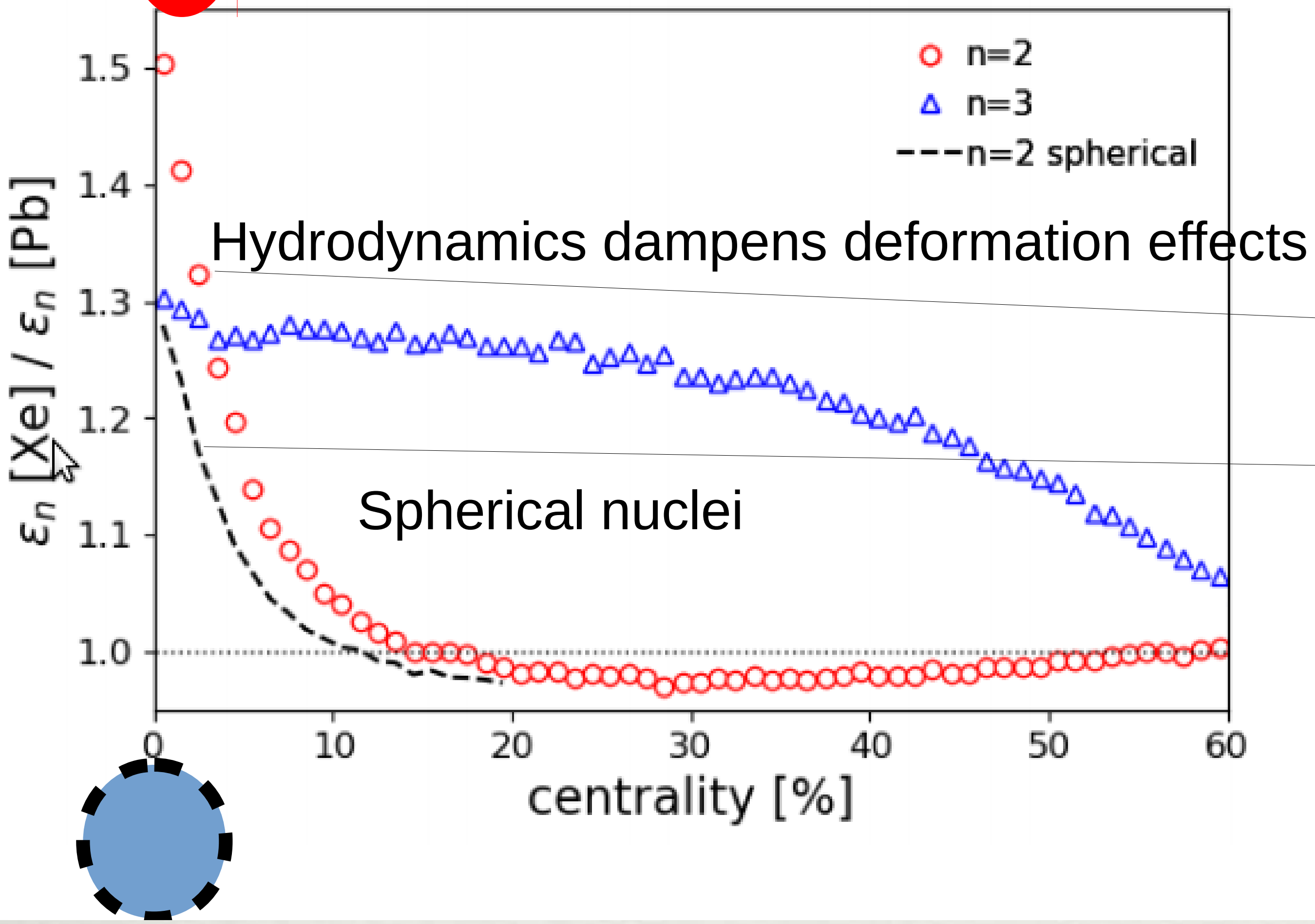
Influence of nuclear structure

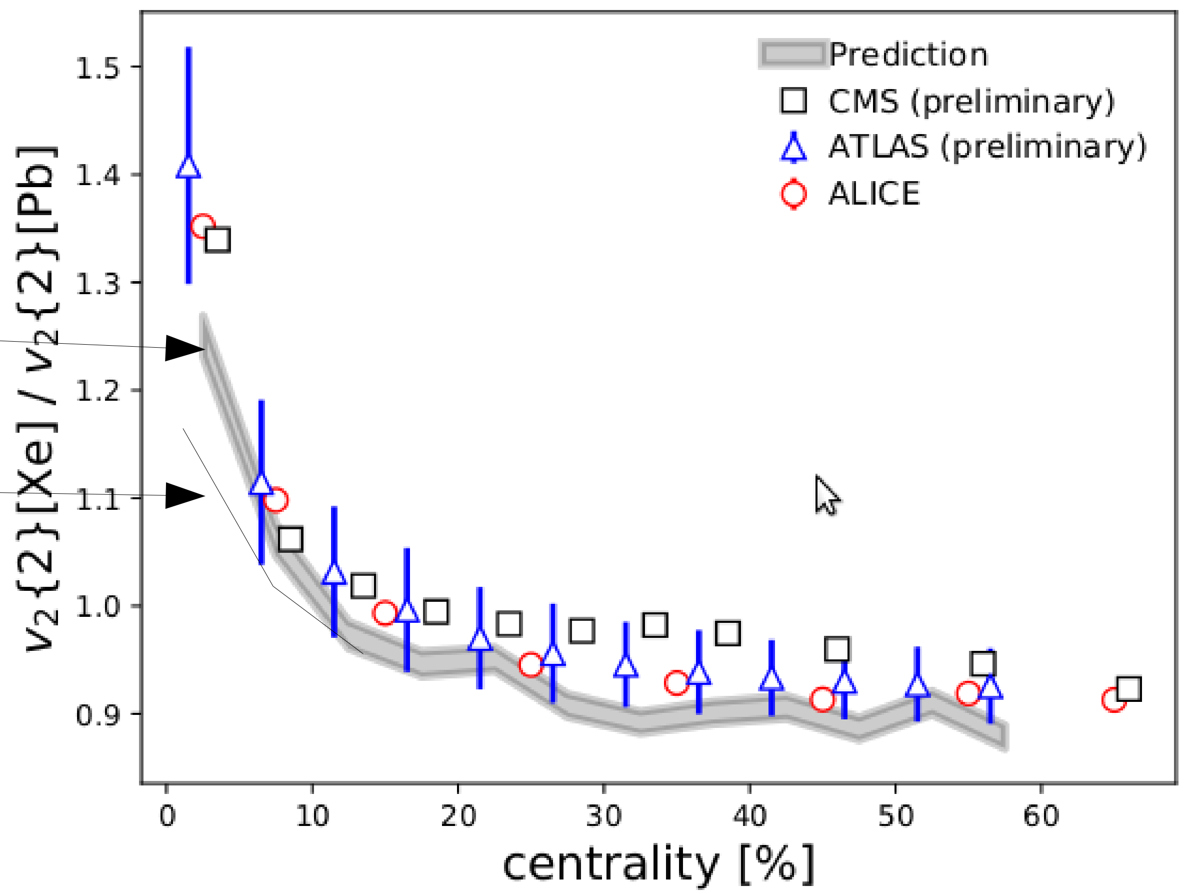


Finding a deformation in ^{129}Xe



v-USPhydro sensitive to deformed nucleus
Giacalone, JNH et al. Phys. Rev. C 97,034904 (2018)





Deviation from experimental data: possible constraints on nuclear structure?

^{16}O: Lattice effective field theory and hydrodynamics

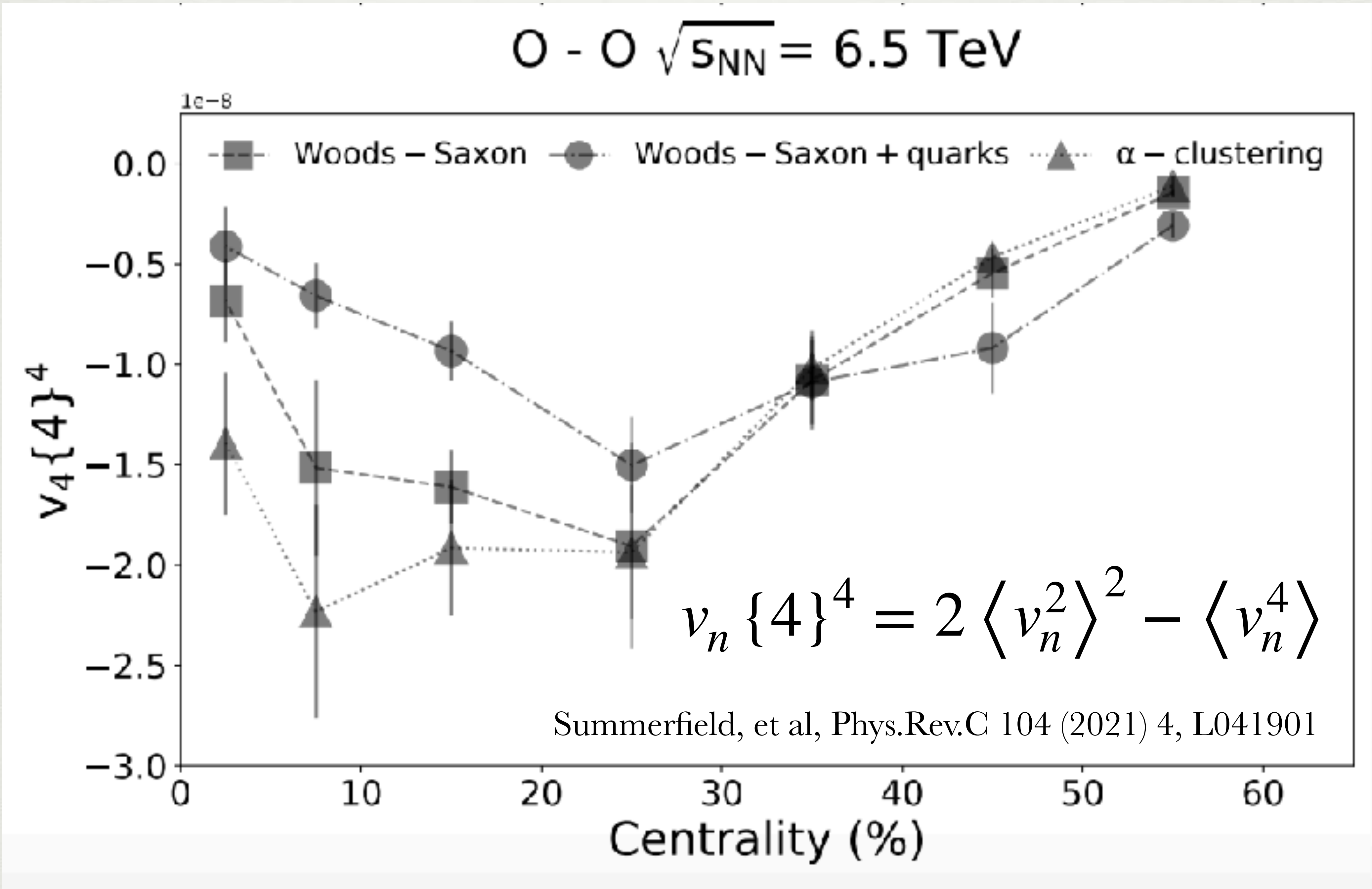
Types of structure

- OO Wood-S
  JNH Phys.Rev. C100 (20
- OO+α clust
  lattice effecti
  Moreland et al, *Phys.Rev.*
- OO+sub-nu
  structure (Tr
  Phys. Lett. B 797, 134863 (2019)

Experimental:
N. Summerfield & A. Timmins
Theory: C. Plumberg & JNH
Lattice EFT: B-N Lu & D. Lee

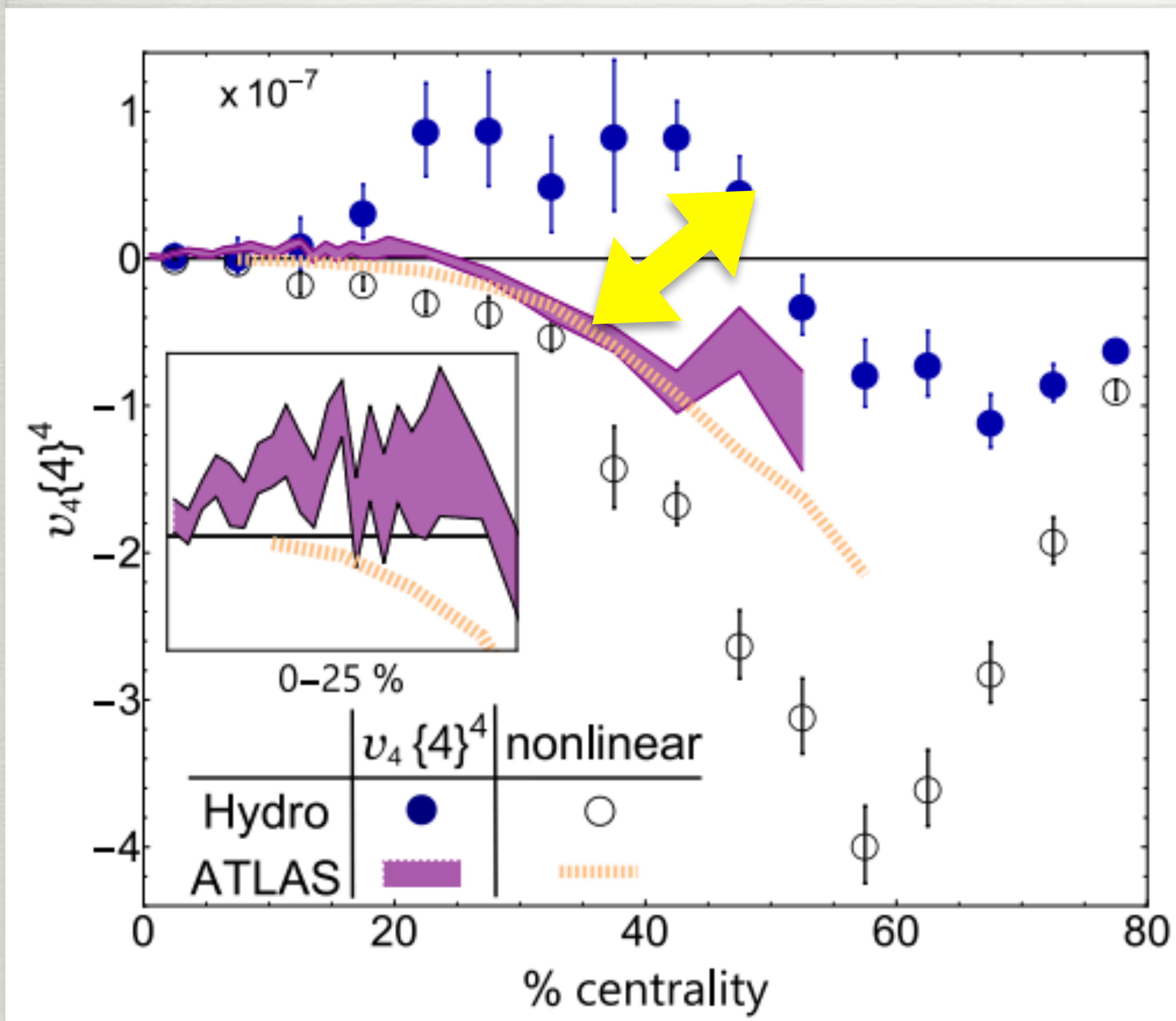
Duke Bayesian analysis set-up
Bernhard et al, Nature Phys. 15 (2019) 11, 1113-1117

Finding α clustering in heavy-ion collisions

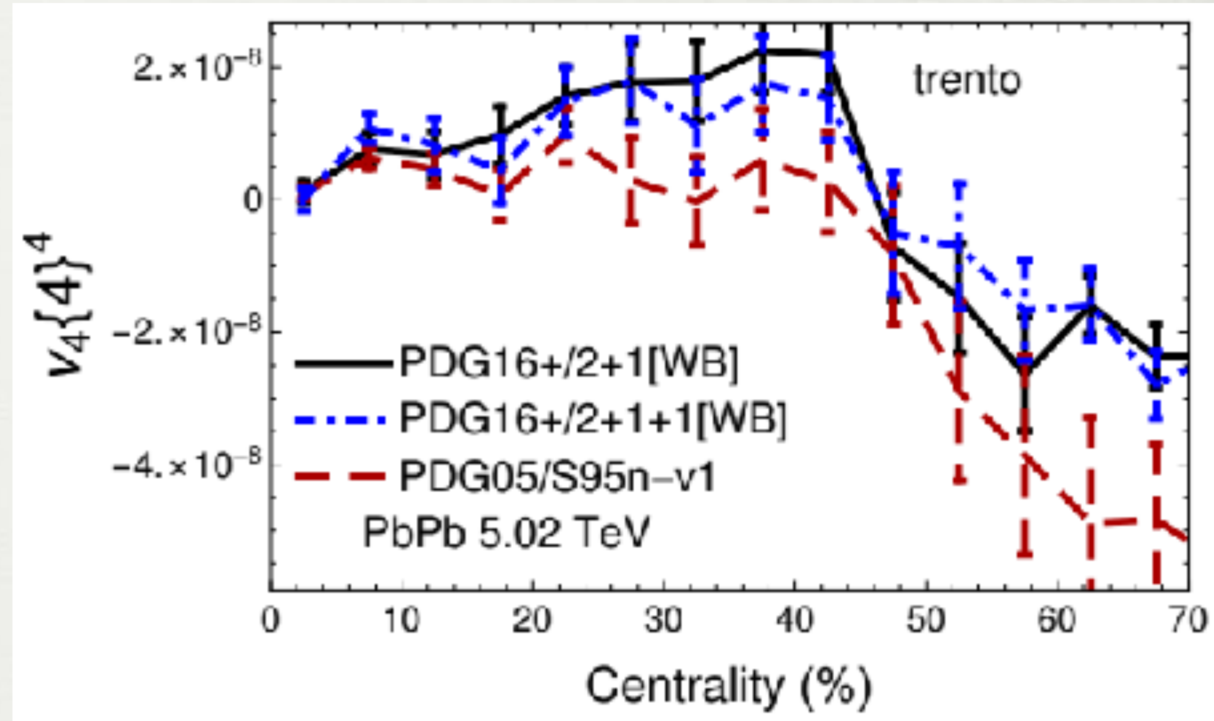


Signal size possible to measure the the LHC, puzzle for ^{208}Pb

Difficulties with ^{208}Pb square/plus shape fluctuations



Giacalone, JNH et al, *J.Phys.Conf.Ser.* 779 (2017) 1, 012064

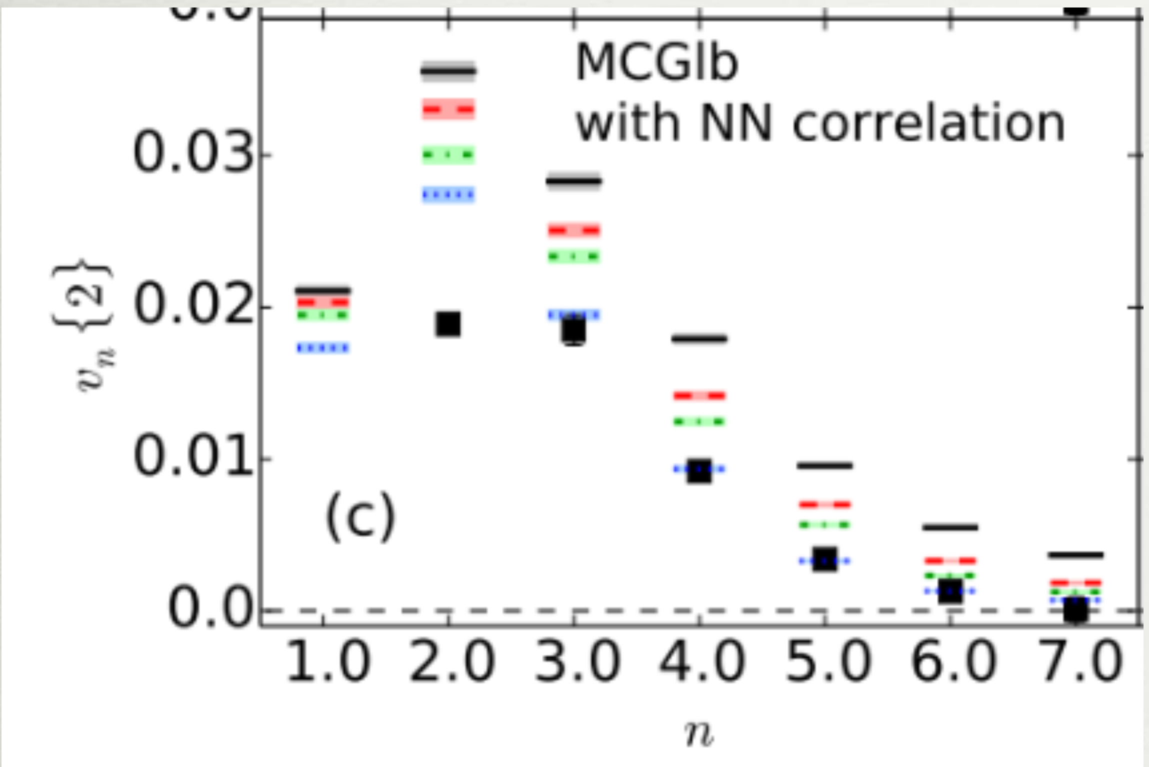


Alba, JNH et al, *Phys.Rev.C* 98 (2018) 3, 034909

Issue still remains, even with hydro improvements

α clustering might push the results towards the data?

Another ^{208}Pb puzzle: v_2 to v_3 in ultracentral collisions

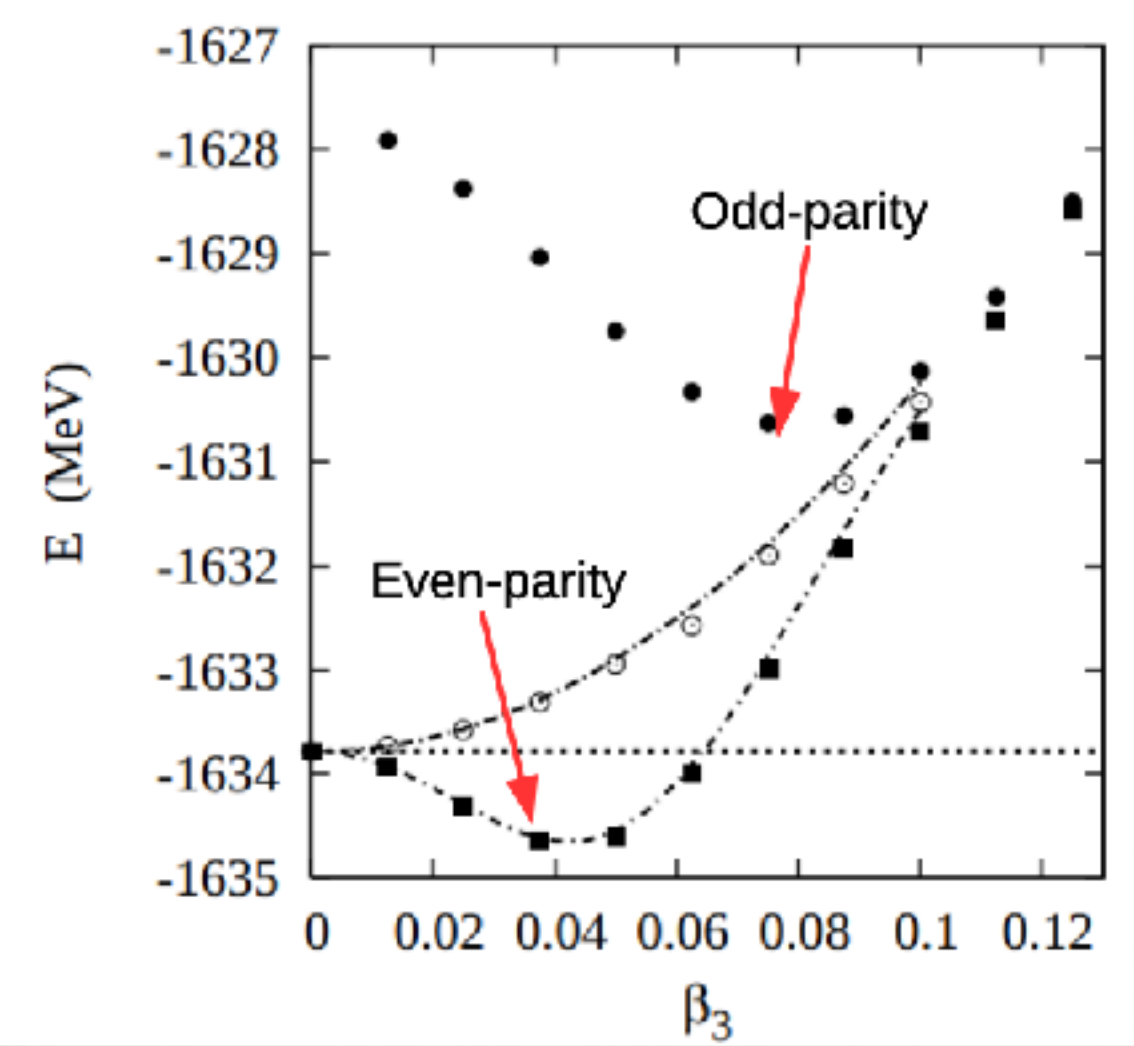


CMS Data: JHEP 02 (2014) 088
Original Idea: Luzum & Ollitrault Nucl.Phys. A904-905 (2013) 377c-380c Retinskaya, et al, Phys.Rev. C89 (2014) no.1, 014902
Many attempts: Shen, et al Phys. Rev. C 92, 014901 (2015); Rose, et al,, Nucl.Phys. A931 (2014) 926-930 + see recent works from Giacalone, Jia, Trajectum, Zakharov

Could an octuple deformation play a role?

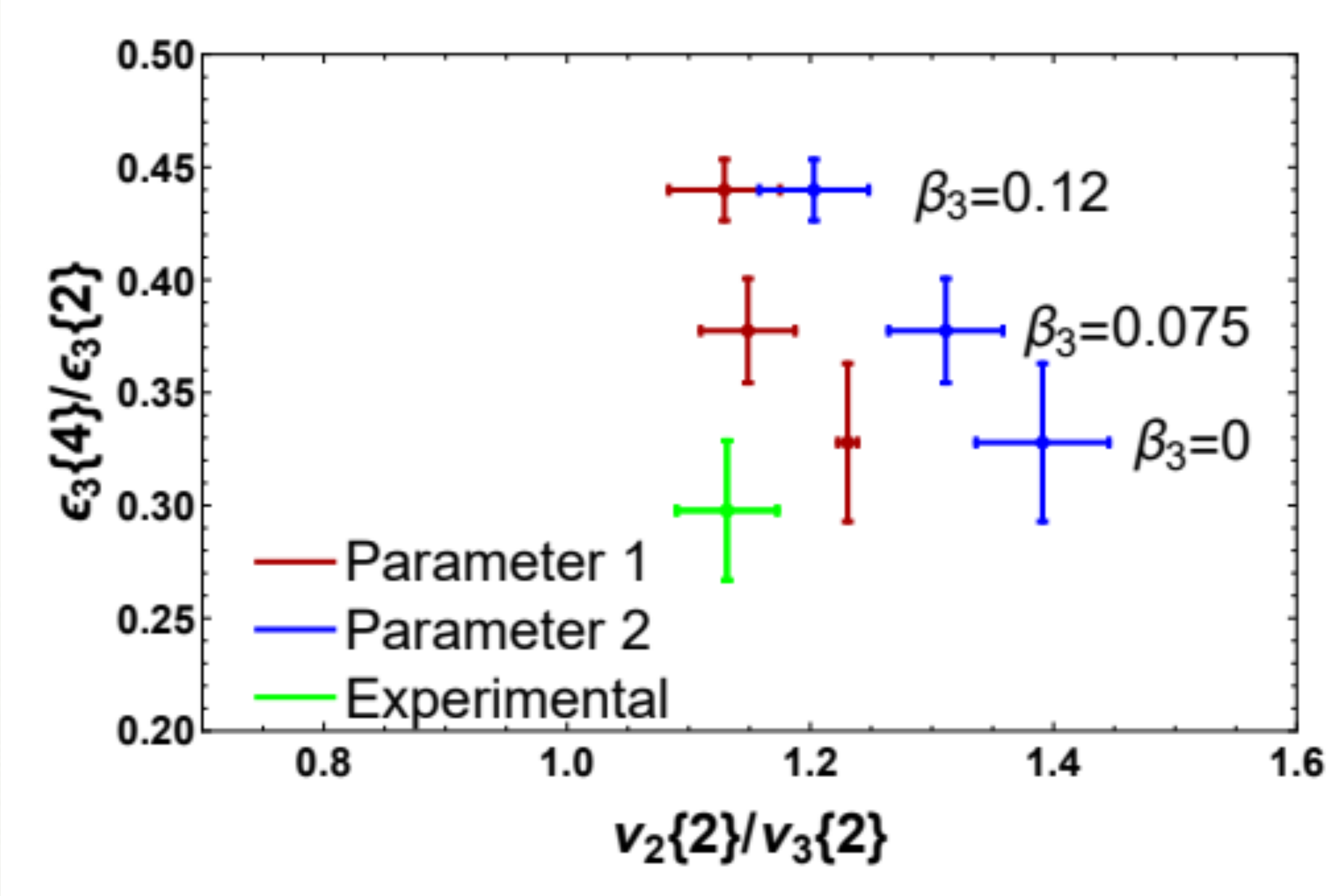
Generally need more v_3 or less v_2

Octupole alone not enough: ideas?



Robledo, Bertsch Phys.Rev. C84 (2011) 054302

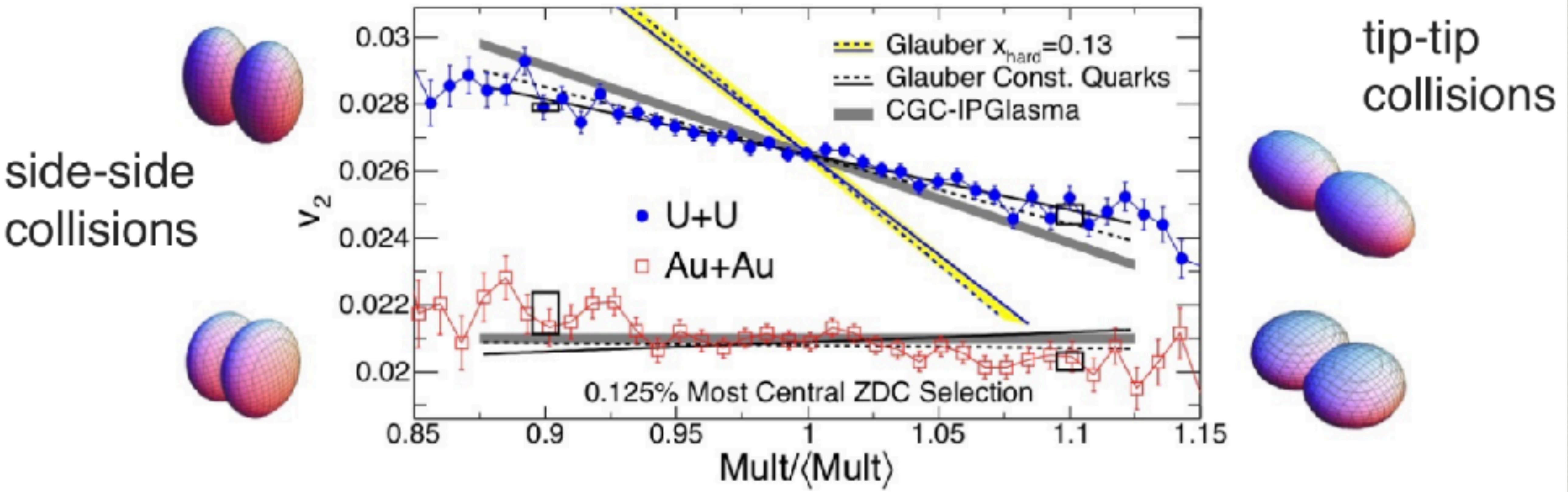
Tried $\beta_3 \geq 0$ in hydrodynamics



Carzon, JNH et al, *Phys.Rev.C* 102 (2020) 5, 054905

Ultracentral collisions should fit the best, but still $\sim 10\,\%$ off

Ultracentral fluctuations

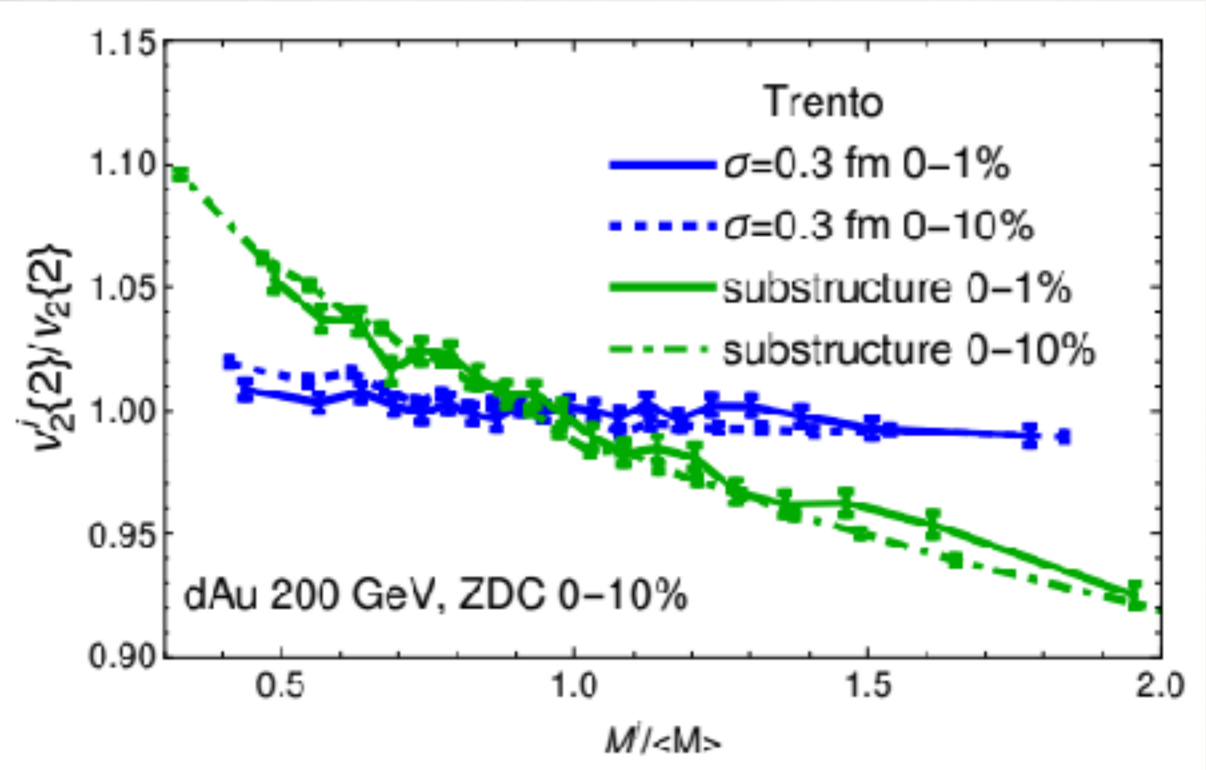


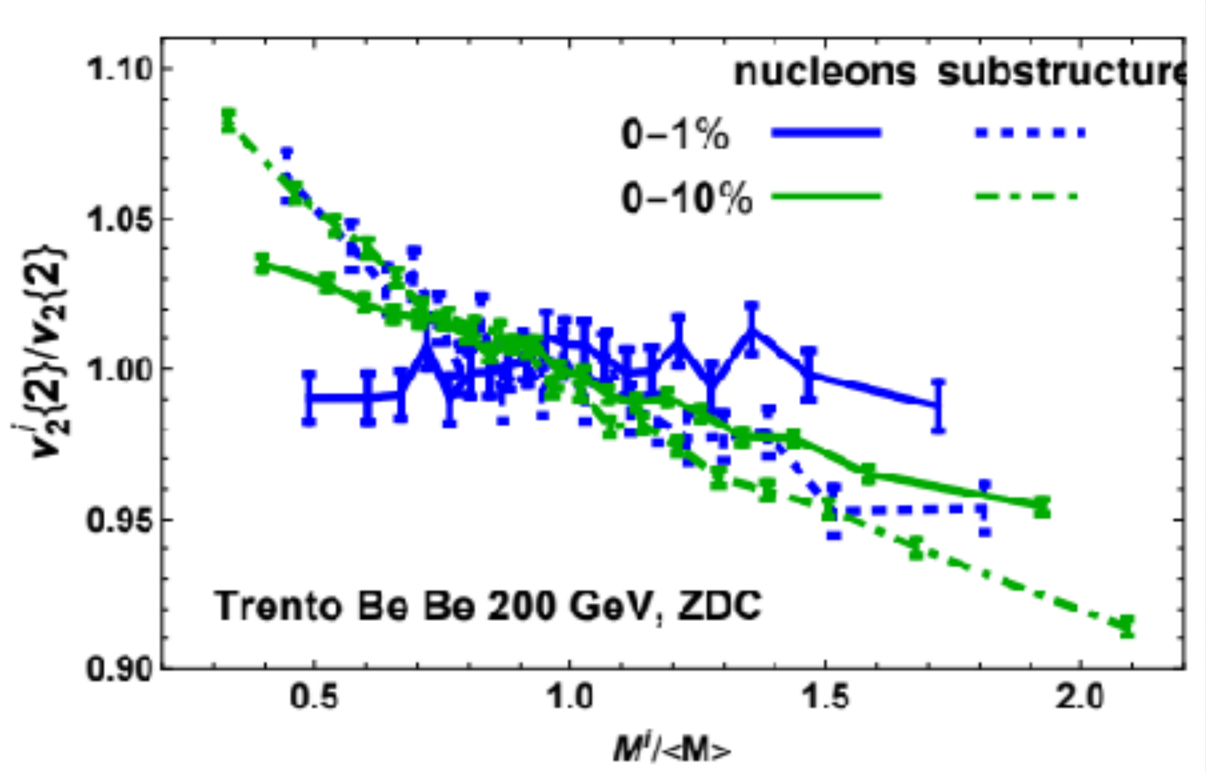
STAR, L. Adamczyk et al., Phys. Rev. Lett. 115 (2015) 222301, 1505.07812, Rybczynski, Broniowski, Stefanek (Phys.Rev. C87 (2013) no.4, 044908 ; Moreland, Bernhard, Bass Phys.Rev. C92 (2015) no.1, 011901 ; Goldschmidt, Qiu, Shen, Heinz arXiv:1502.00603; Schenke, Tribedy, Venugopalan Phys. Rev. C 89 (2014), 064908

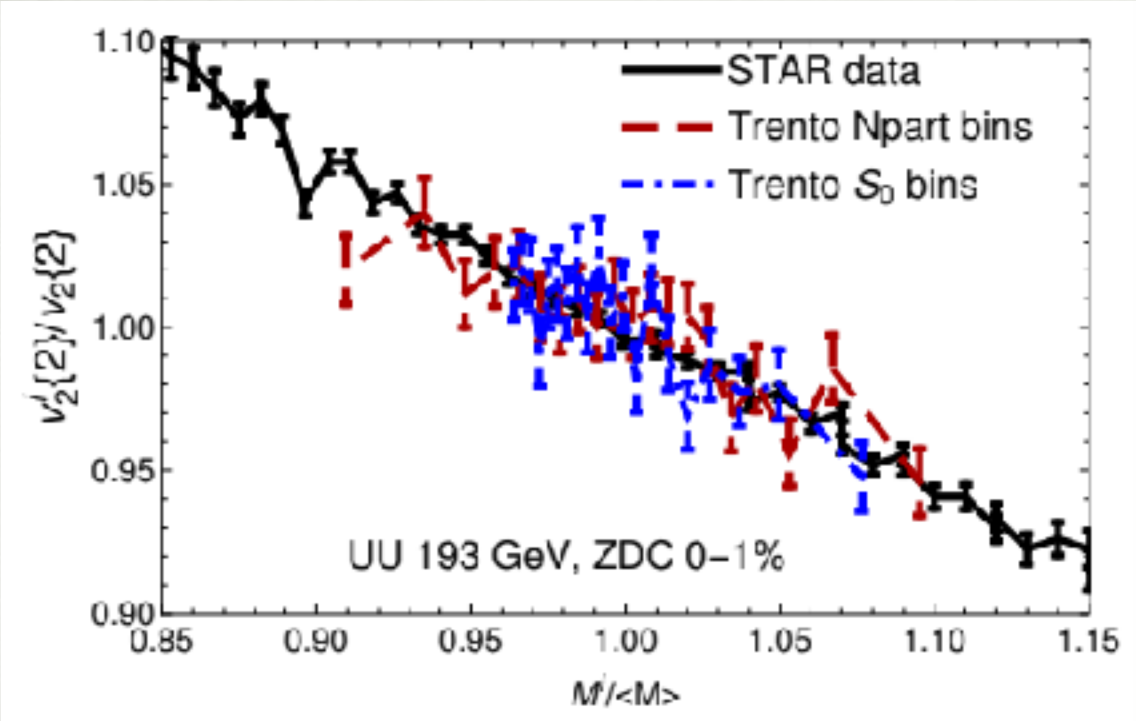
Comparing side to side vs. tip to tip collisions

Future possibilities with ultra central collisions

Wertepny, JNH et al, 1905.13323 [hep-ph]







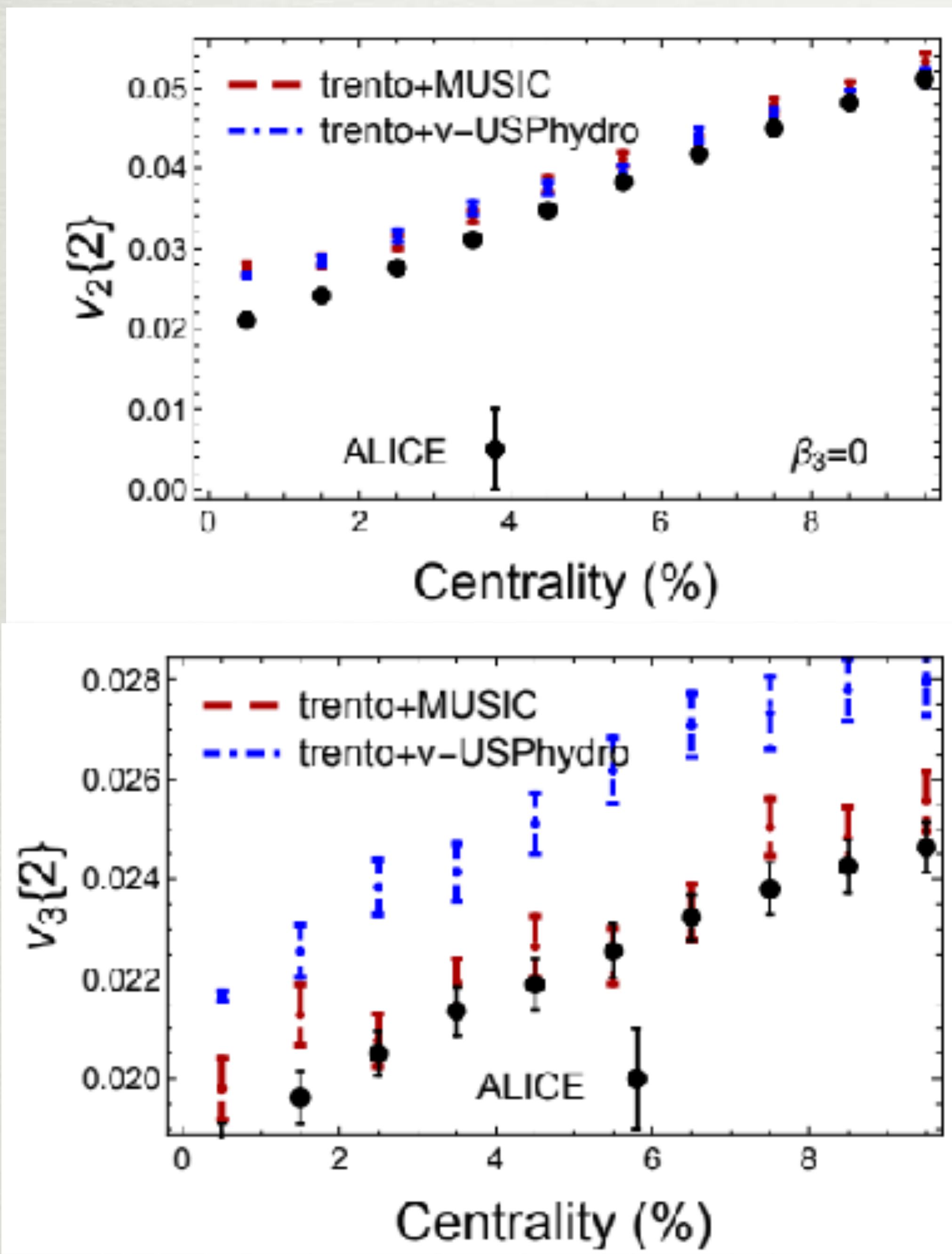
Ultracentral fluctuations sensitive to substructure, nucleon widths

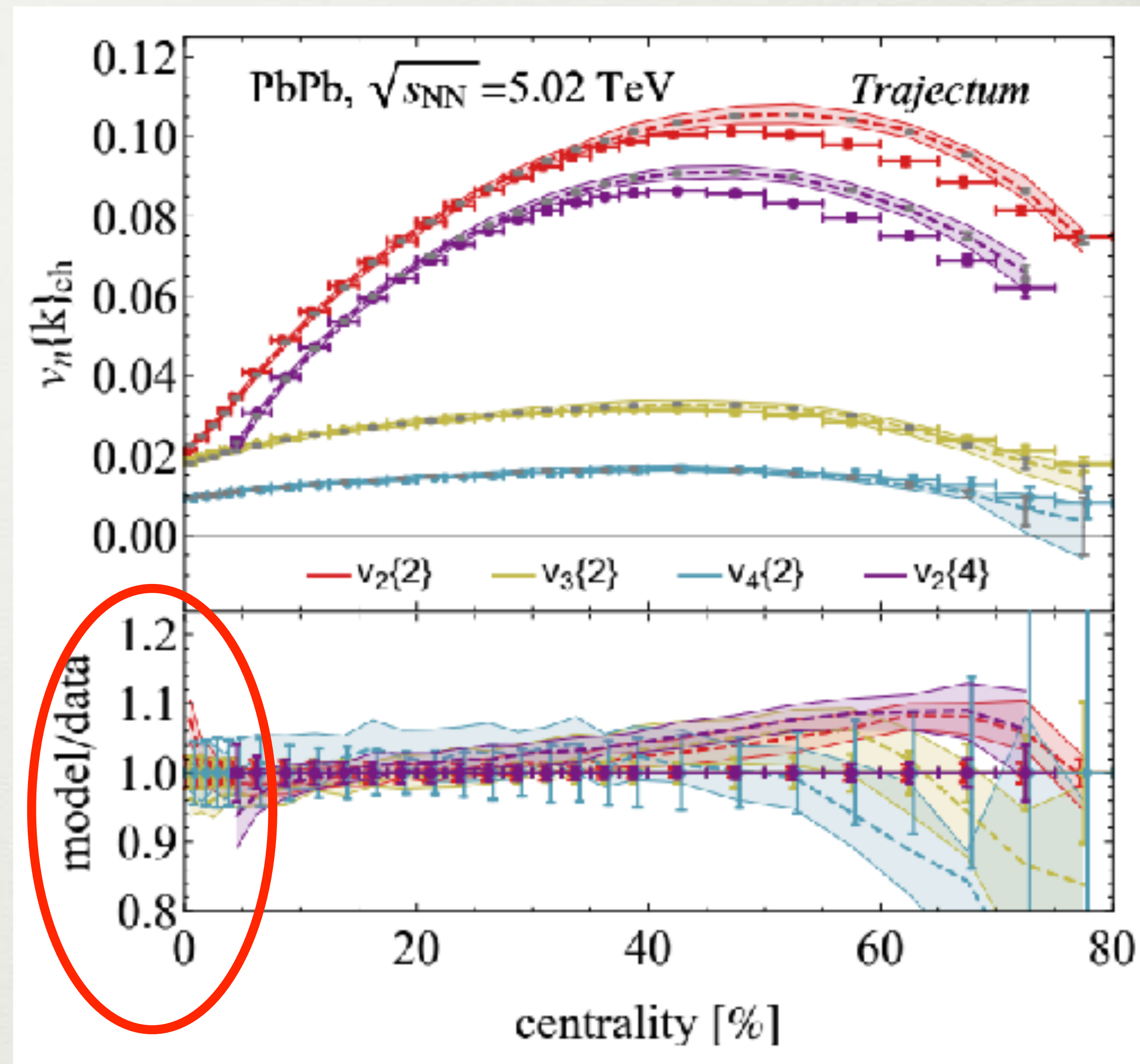
Summary

- Heavy-ion collisions sensitive to nuclear structure even with fluctuations
- Possible to make direct connections between nucleon configurations and heavy-ion collision simulations
- Outstanding puzzles:
  - v_2 to v_3 puzzle in ^{208}Pb
  - $v_4\{4\}^4$ sensitive to α clustering?

INT Workshop
Intersection of nuclear structure and high-energy nuclear collisions
Jan 23rd - Feb 24th 2023

v_2 to v_3 in ultracentral collisions



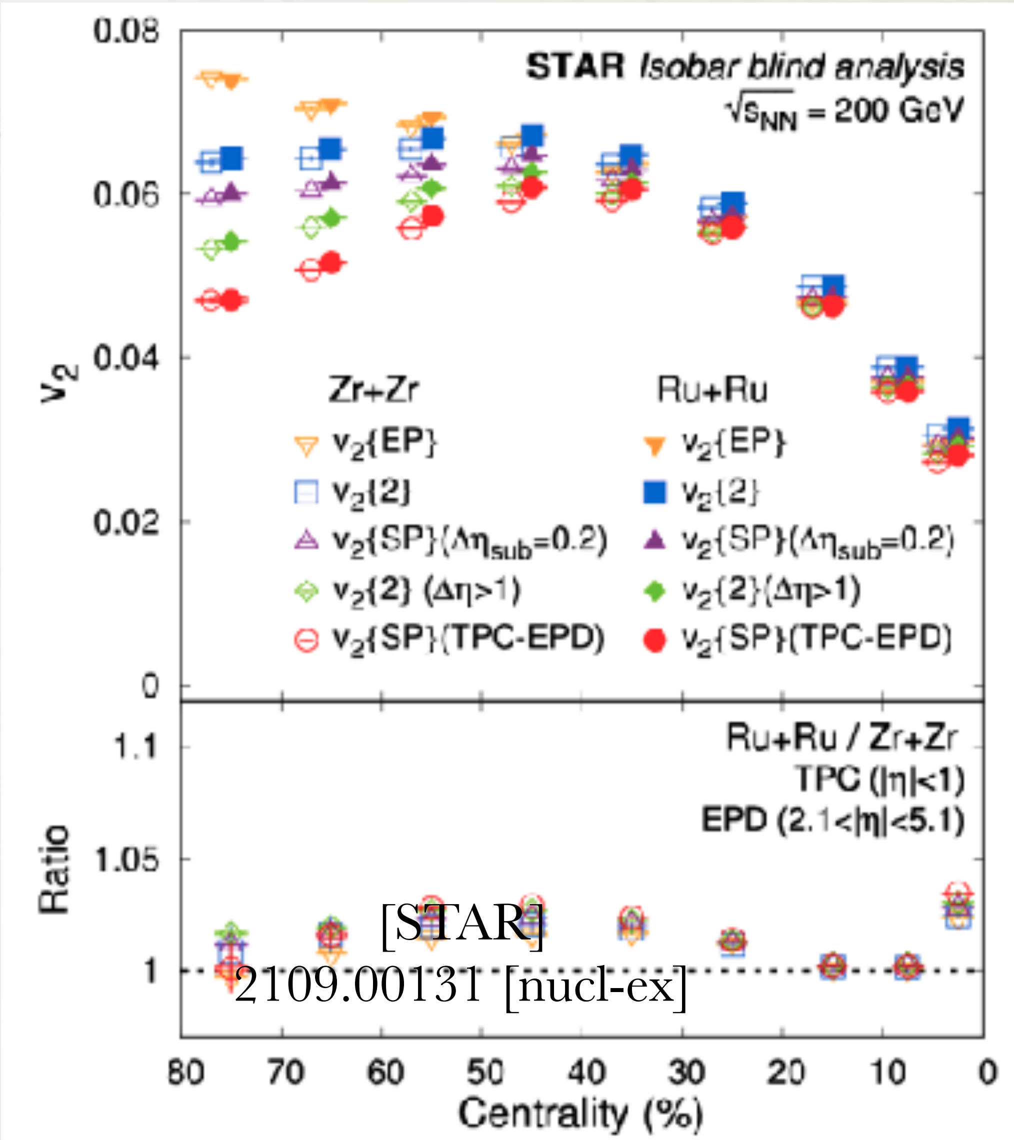


Govert & van der Schee arXiv:2110.13153

Carzon, JNH et al, *Phys.Rev.C* 102 (2020) 5, 054905

Future potential for nuclear structure?

- ^{208}Pb puzzles
  - Elliptical vs. triangular shape
  - Fluctuating "square" shape
- ^{96}Zr and ^{96}Ru
  - Isobar run, high precision data
- ^{238}U: Far from perfect fit…
- Other ions to run??



[STAR] 2109.00131 [nucl-ex]

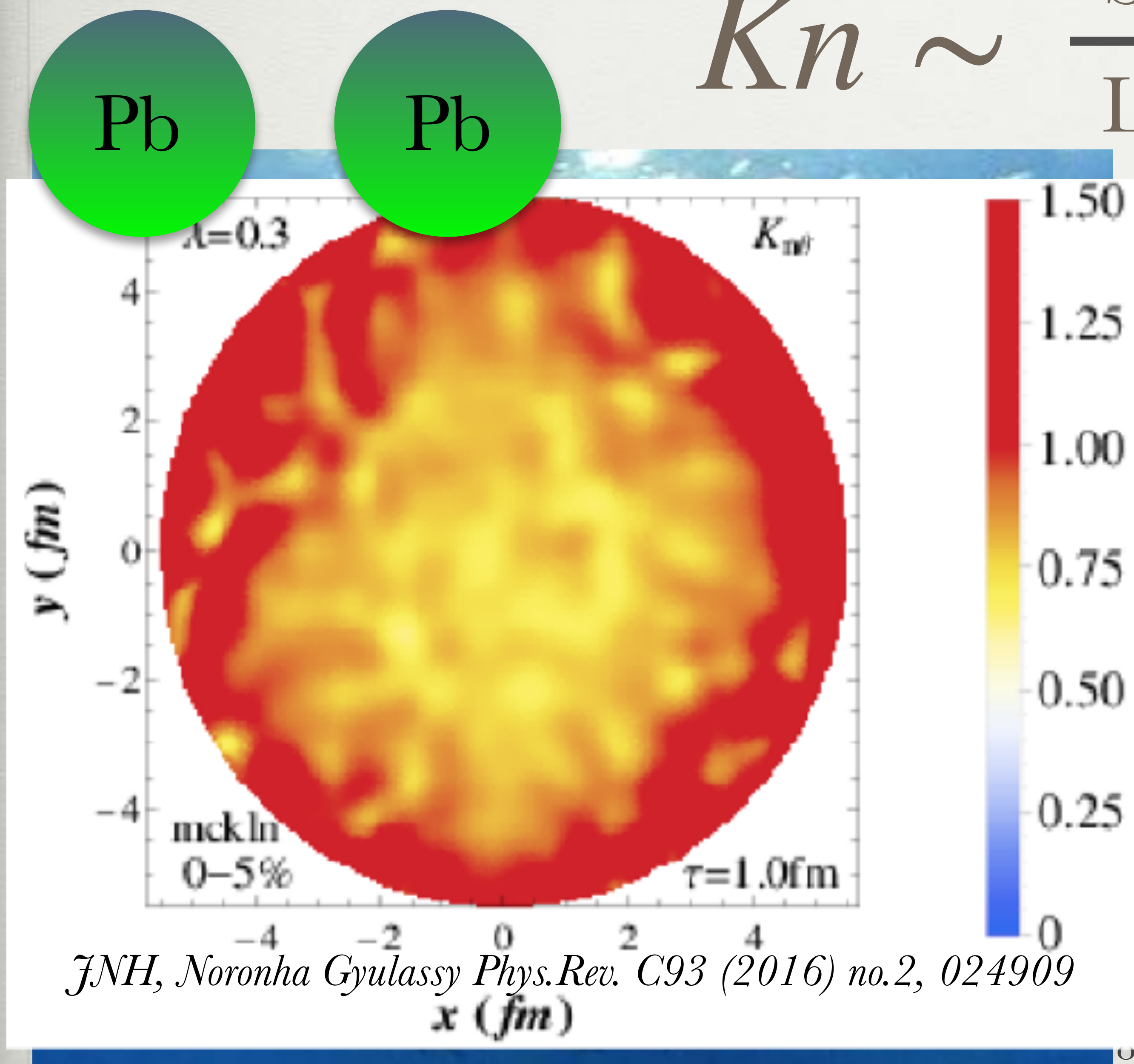
RBRC Workshop
Physics opportunities from the RHIC Isobar run
January 25-28, 2022

- Names: Guiliano Giacalone, Jiangyong Jia, Anthony Timmins, Wojciech Broniowski, Jean-Yves Ollitrault, Bjoern Schenke, Chun Shen, Wei Li

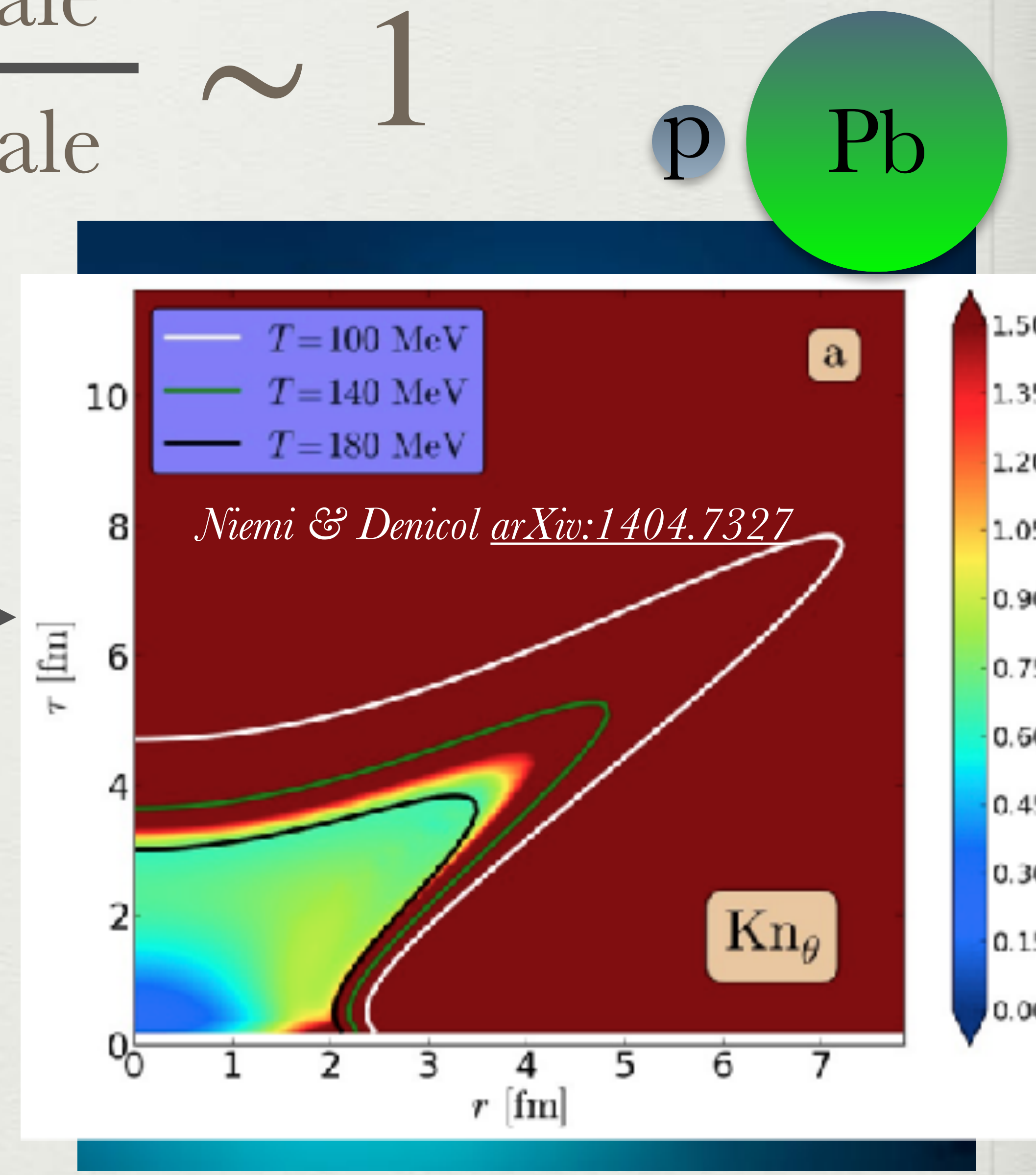
Fluids the size of a nucleus? A proton?

When do you have too few particles to use hydrodynamics?

$$Kn \sim \frac{\text{Small scale}}{\text{Large scale}} \sim 1$$



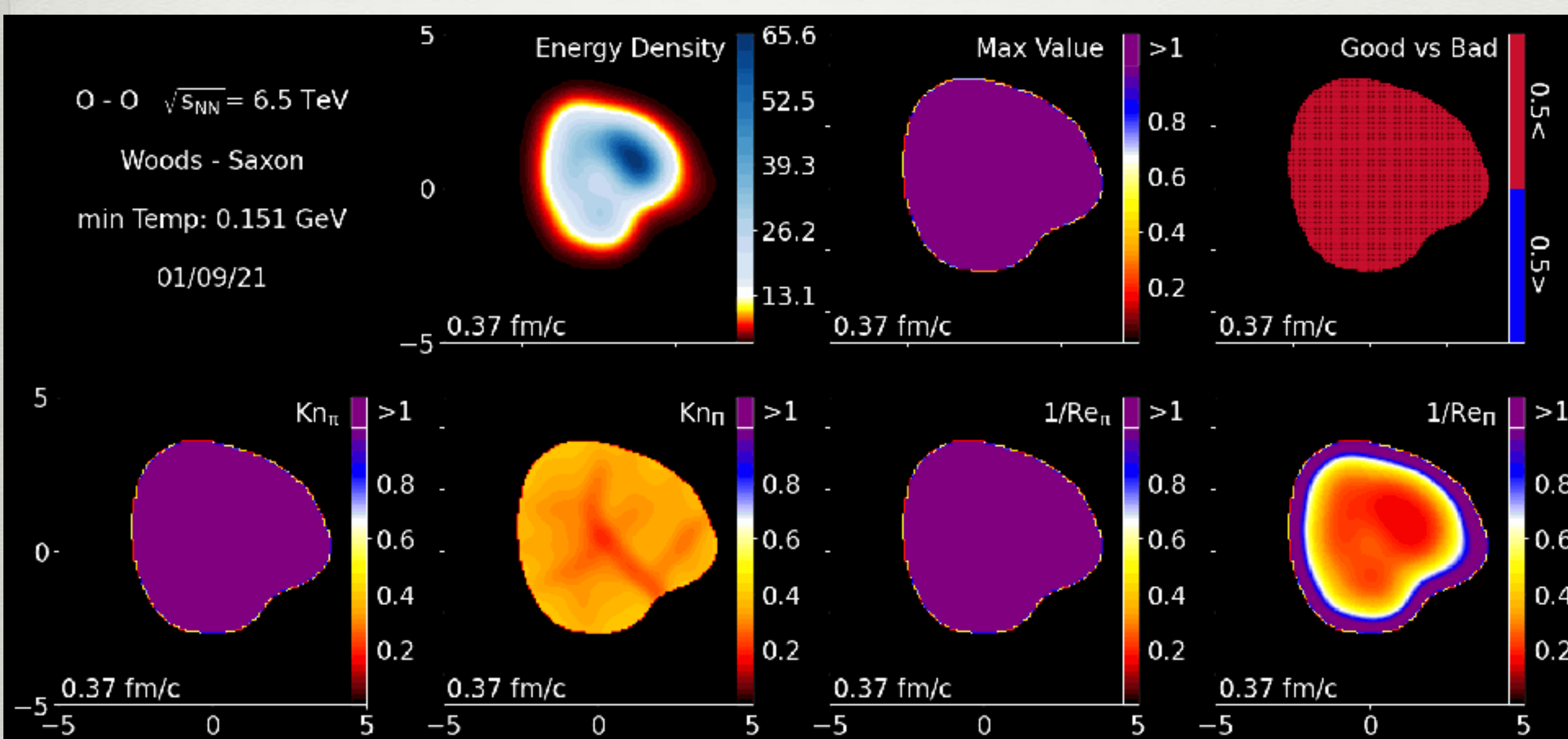
JNH, Noronha Gyulassy Phys.Rev. C93 (2016) no.2, 024909



Niemi & Denicol arXiv:1404.7327

Knudsen/Reynolds numbers in OO from Duke Bayesian setup

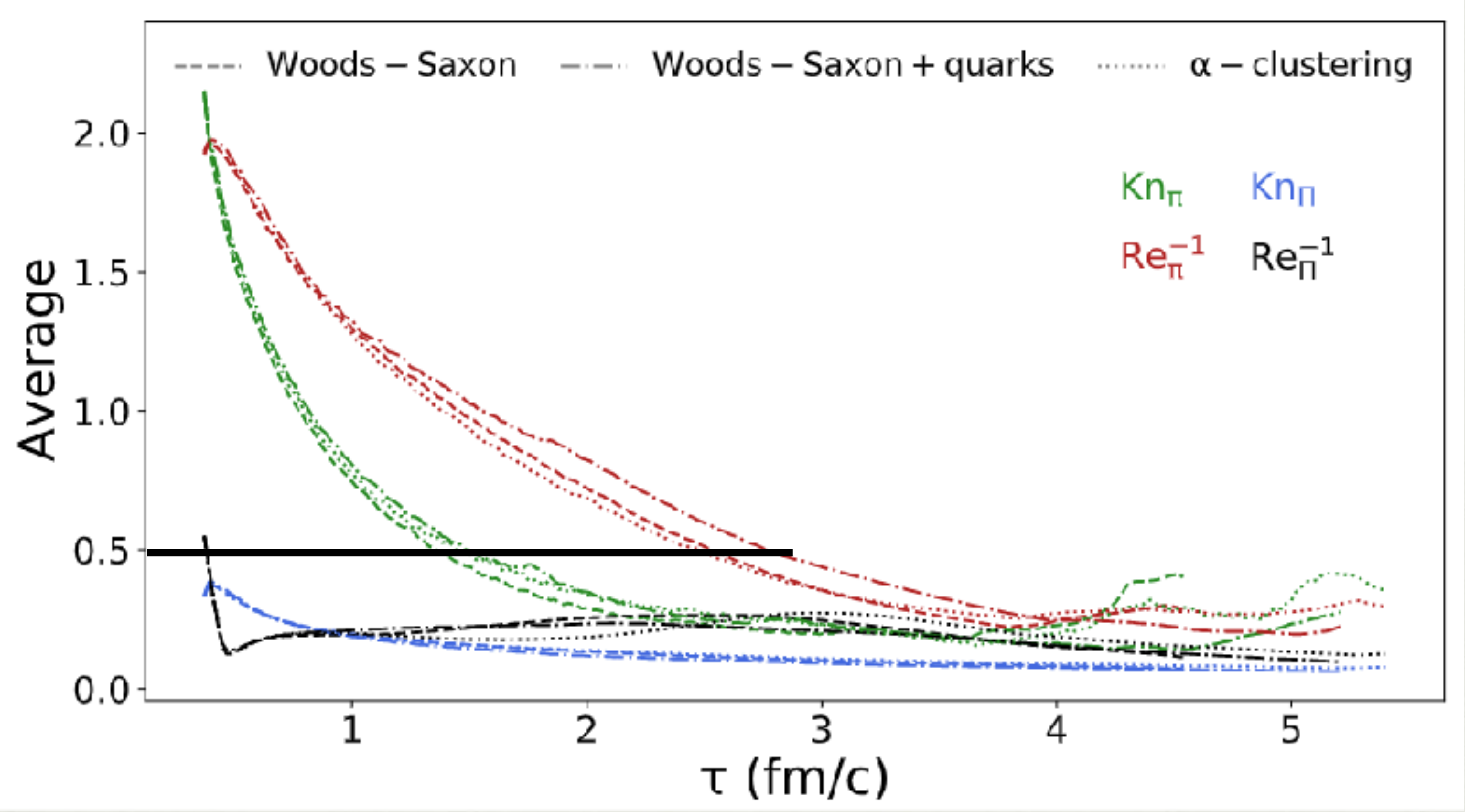
Experimental: N. Summerfield & A. Timmins, Theory: C. Plumberg & JNH, Lattice EFT: B-N Lu & D. Lee



Quite bad throughout almost entire expansion (central event)

Averaged Kn/Re^{-1}

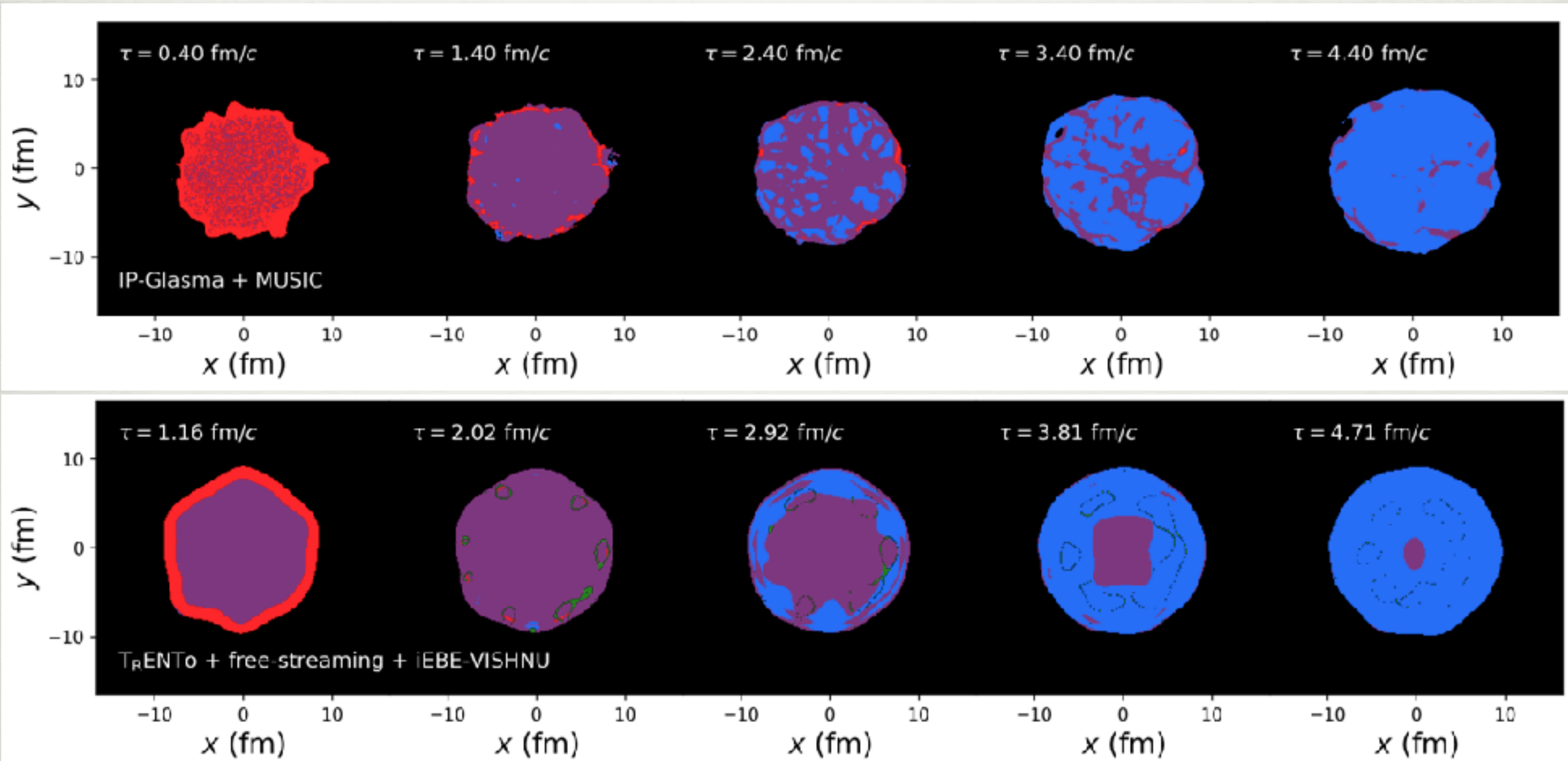
Experimental: N. Summerfield & A. Timmins, Theory: C. Plumberg & JNH, Lattice EFT: B-N Lu & D. Lee



Hydro only applicable after $\tau \sim 3\ fm/c$?

Causality Constraints

Plumberg, Almaalol, Dore, Noronha, JNH rXiv:2103.15889v1 [nucl-th]

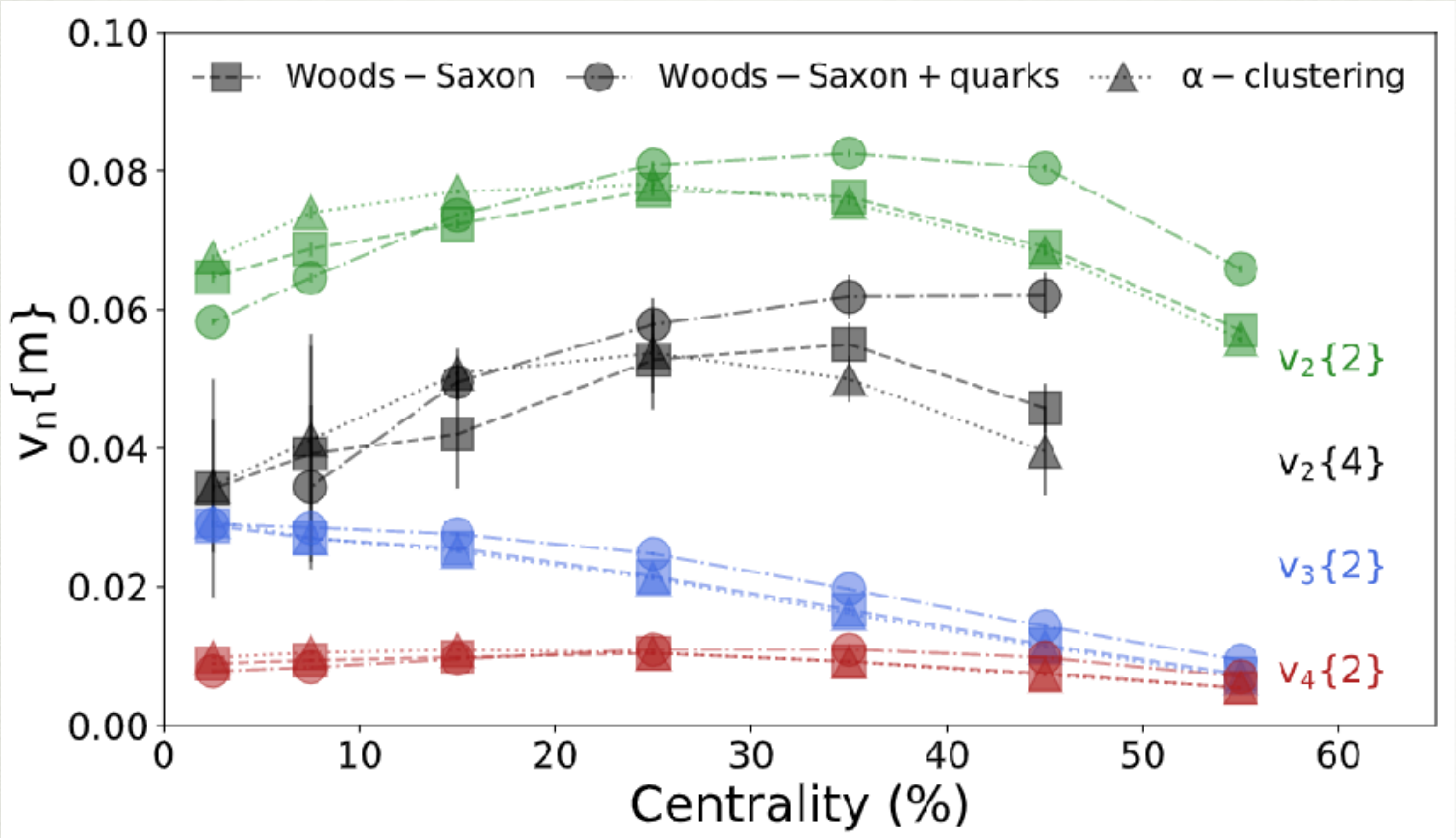


Connection between initial state → hydrodynamics, causality violation

Constrains derived in

Bemfica et al, *Phys.Rev.Lett.* 126 (2021) 22, 222301

^{16}O: Lattice effective field theory and hydrodynamics



Summerfield, et al, Phys.Rev.C 104 (2021) 4, L041901

When is fluid dynamics applicable?

Large separation of scales i.e. small Knudsen (or inverse Reynolds) number

$$Kn \sim \frac{\text{Small scale* } (H_2O \text{ molecule})}{\text{Large scale (size of lake)}}$$

* mean free path i.e. distance before the molecule collides with something else

Question: When can you apply fluid dynamics?
Answer: $Kn \ll 1$

Sufficient conditions

Bemfica et al, *Phys.Rev.Lett.* 126 (2021) 22, 222301

$$(\varepsilon + P + \Pi - |\Lambda_1|) - \frac{1}{2\tau_\pi}(2\eta + \lambda_{\pi\Pi}\Pi) - \frac{\tau_{\pi\pi}}{2\tau_\pi}\Lambda_3 \geq 0,$$

$$(2\eta + \lambda_{\pi\Pi}\Pi) - \tau_{\pi\pi}|\Lambda_1| > 0,$$

$$\tau_{\pi\pi} \leq 6\delta_{\pi\pi},$$

$$\frac{\lambda_{\Pi\pi}}{\tau_\Pi} + c_s^2 - \frac{\tau_{\pi\pi}}{12\tau_\pi} \geq 0,$$

$$\frac{1}{3\tau_\pi}[4\eta + 2\lambda_{\pi\Pi}\Pi + (3\delta_{\pi\pi} + \tau_{\pi\pi})\Lambda_3] + \frac{\zeta + \delta_{\Pi\Pi}\Pi + \lambda_{\Pi\pi}\Lambda_3}{\tau_\Pi} + |\Lambda_1| + \Lambda_3 c_s^2$$
$$+ \frac{\frac{12\delta_{\pi\pi} - \tau_{\pi\pi}}{12\tau_\pi}\left(\frac{\lambda_{\Pi\pi}}{\tau_\Pi} + c_s^2 - \frac{\tau_{\pi\pi}}{12\tau_\pi}\right)(\Lambda_3 + |\Lambda_1|)^2}{\varepsilon + P + \Pi - |\Lambda_1| - \frac{1}{2\tau_\pi}(2\eta + \lambda_{\pi\Pi}\Pi) - \frac{\tau_{\pi\pi}}{2\tau_\pi}\Lambda_3} \leq (\varepsilon + P + \Pi)(1 - c_s^2),$$

$$\frac{1}{6\tau_\pi}[2\eta + \lambda_{\pi\Pi}\Pi + (\tau_{\pi\pi} - 6\delta_{\pi\pi})|\Lambda_1|] + \frac{\zeta + \delta_{\Pi\Pi}\Pi - \lambda_{\Pi\pi}|\Lambda_1|}{\tau_\Pi} + (\varepsilon + P + \Pi - |\Lambda_1|)c_s^2 \geq 0,$$

$$1 \geq \frac{\frac{12\delta_{\pi\pi} - \tau_{\pi\pi}}{12\tau_\pi}\left(\frac{\lambda_{\Pi\pi}}{\tau_\Pi} + c_s^2 - \frac{\tau_{\pi\pi}}{12\tau_\pi}\right)(\Lambda_3 + |\Lambda_1|)^2}{\left[\frac{1}{2\tau_\pi}(2\eta + \lambda_{\pi\Pi}\Pi) - \frac{\tau_{\pi\pi}}{2\tau_\pi}|\Lambda_1|\right]^2}$$

$$\frac{1}{3\tau_\pi}[4\eta + 2\lambda_{\pi\Pi}\Pi - (3\delta_{\pi\pi} + \tau_{\pi\pi})|\Lambda_1|] + \frac{\zeta + \delta_{\Pi\Pi}\Pi - \lambda_{\Pi\pi}|\Lambda_1|}{\tau_\Pi} + (\varepsilon + P + \Pi - |\Lambda_1|)c_s^2$$
$$\geq \frac{(\varepsilon + P + \Pi + \Lambda_2)(\varepsilon + P + \Pi + \Lambda_3)}{3(\varepsilon + P + \Pi - |\Lambda_1|)}\left\{1 + \frac{2\left[\frac{1}{2\tau_\pi}(2\eta + \lambda_{\pi\Pi}\Pi) + \frac{\tau_{\pi\pi}}{2\tau_\pi}\Lambda_3\right]}{\varepsilon + P + \Pi - |\Lambda_1|}\right\},$$