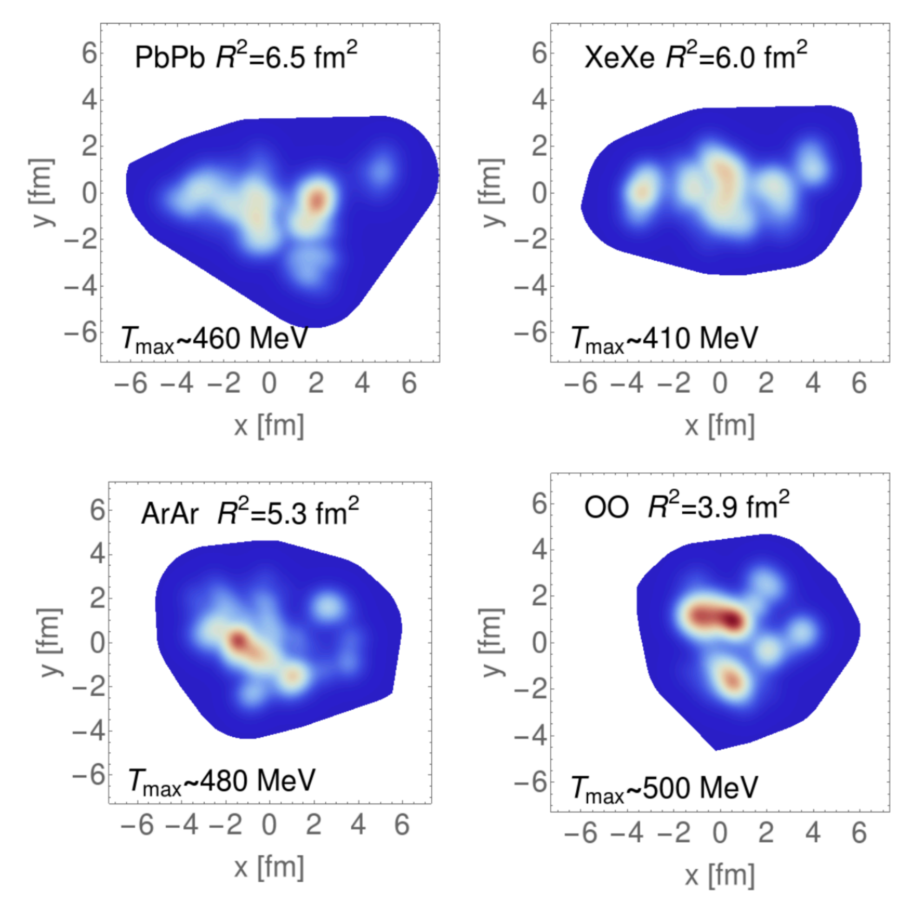
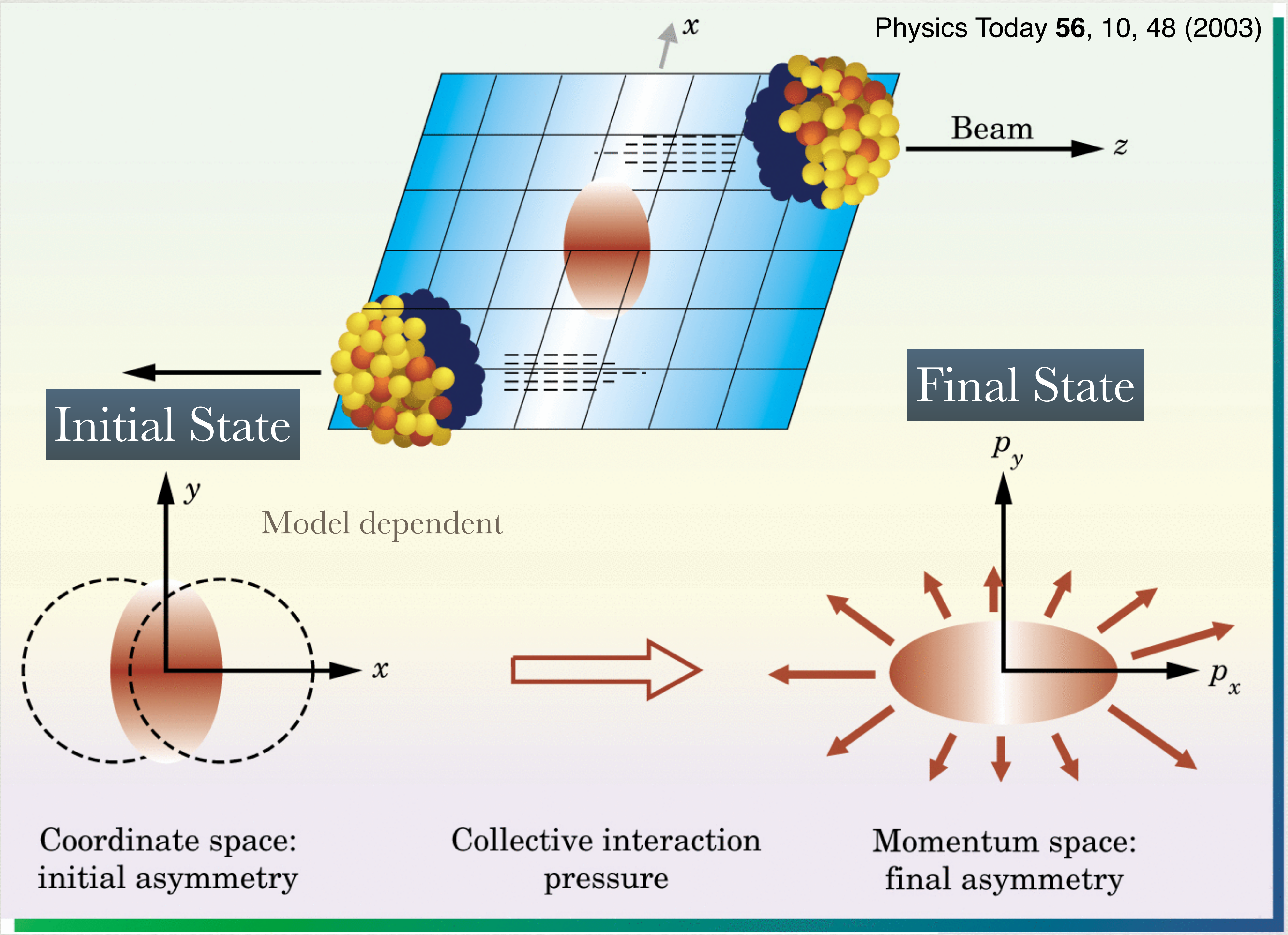
INT Workshop 2023

Initial state from small to large system



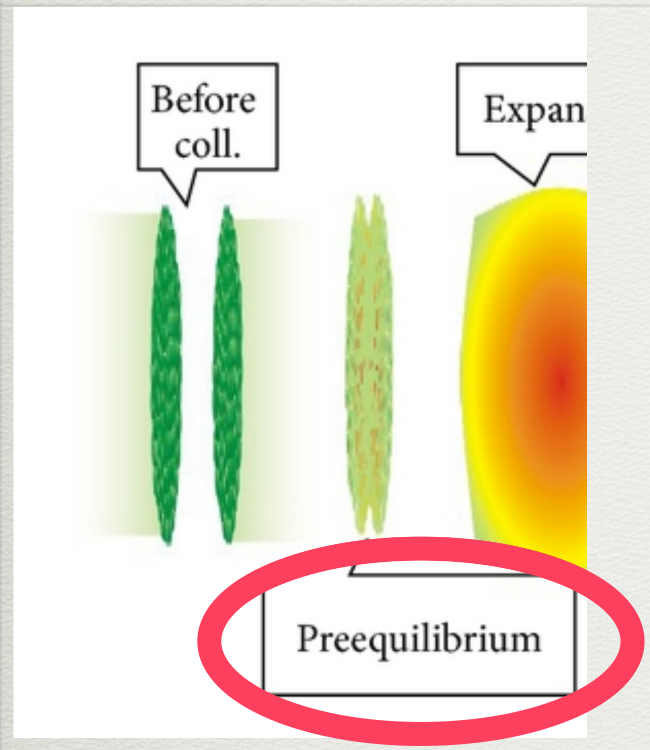
Jacquelyn Noronha-Hostler
University of Illinois at Urbana-Champaign

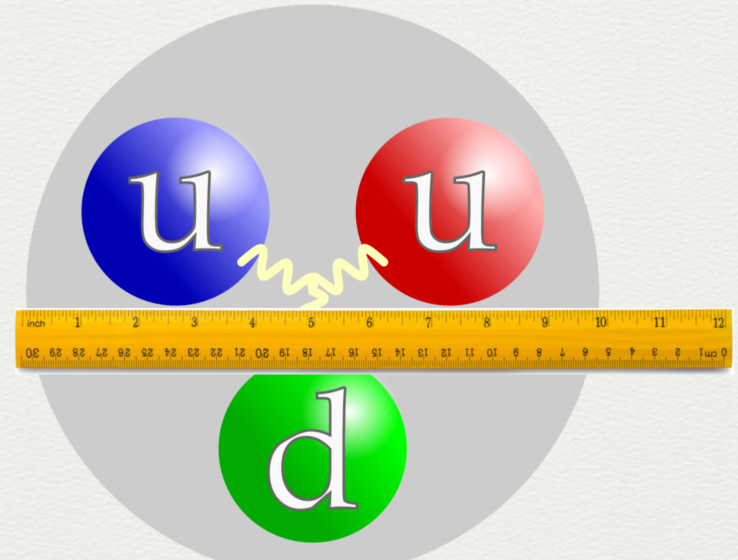
What influence the connection from initial to final state?



Measured experimental through collective flow v_n

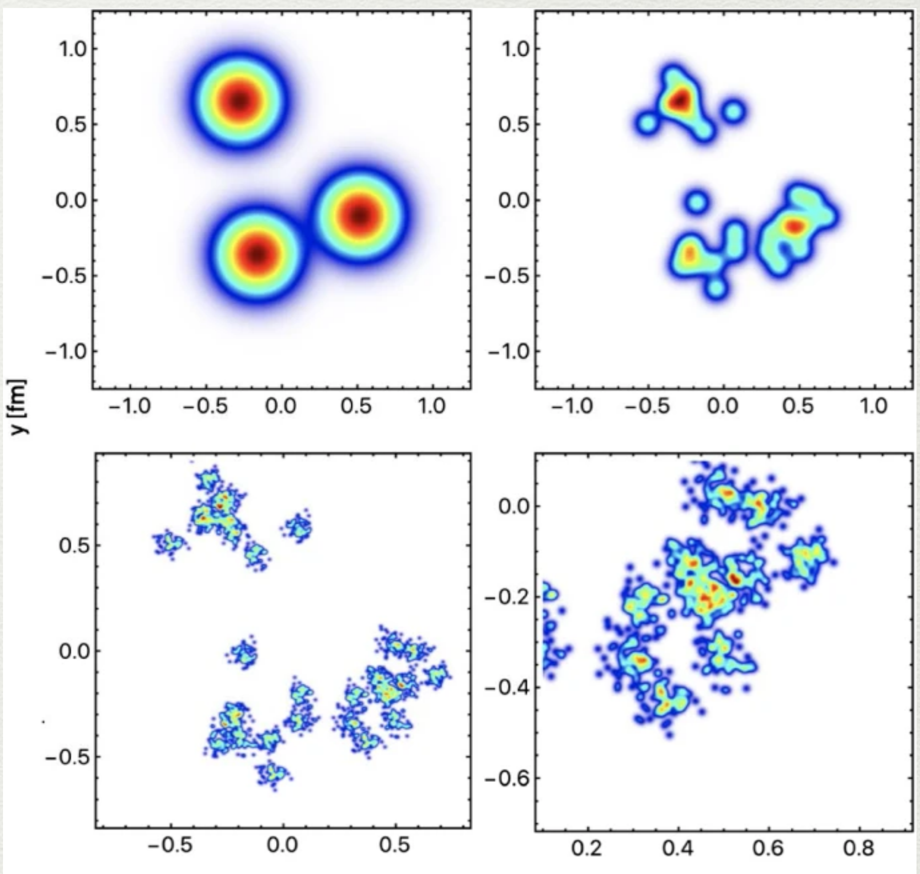
Initial State
What plays a role beyond deformations?

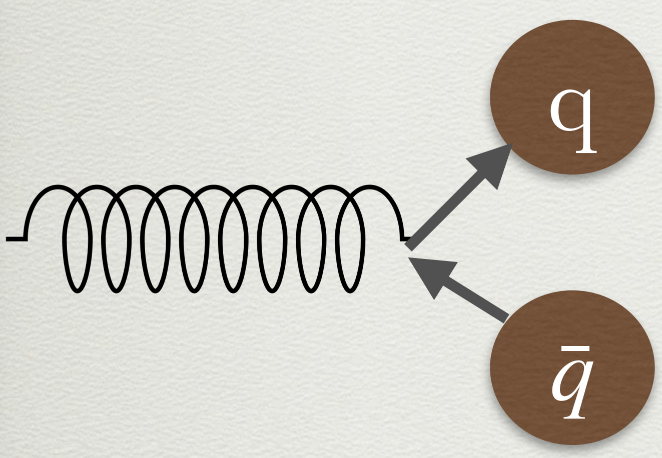




Nucleon width

The European Physical Journal C
volume 82, 837 (2022)





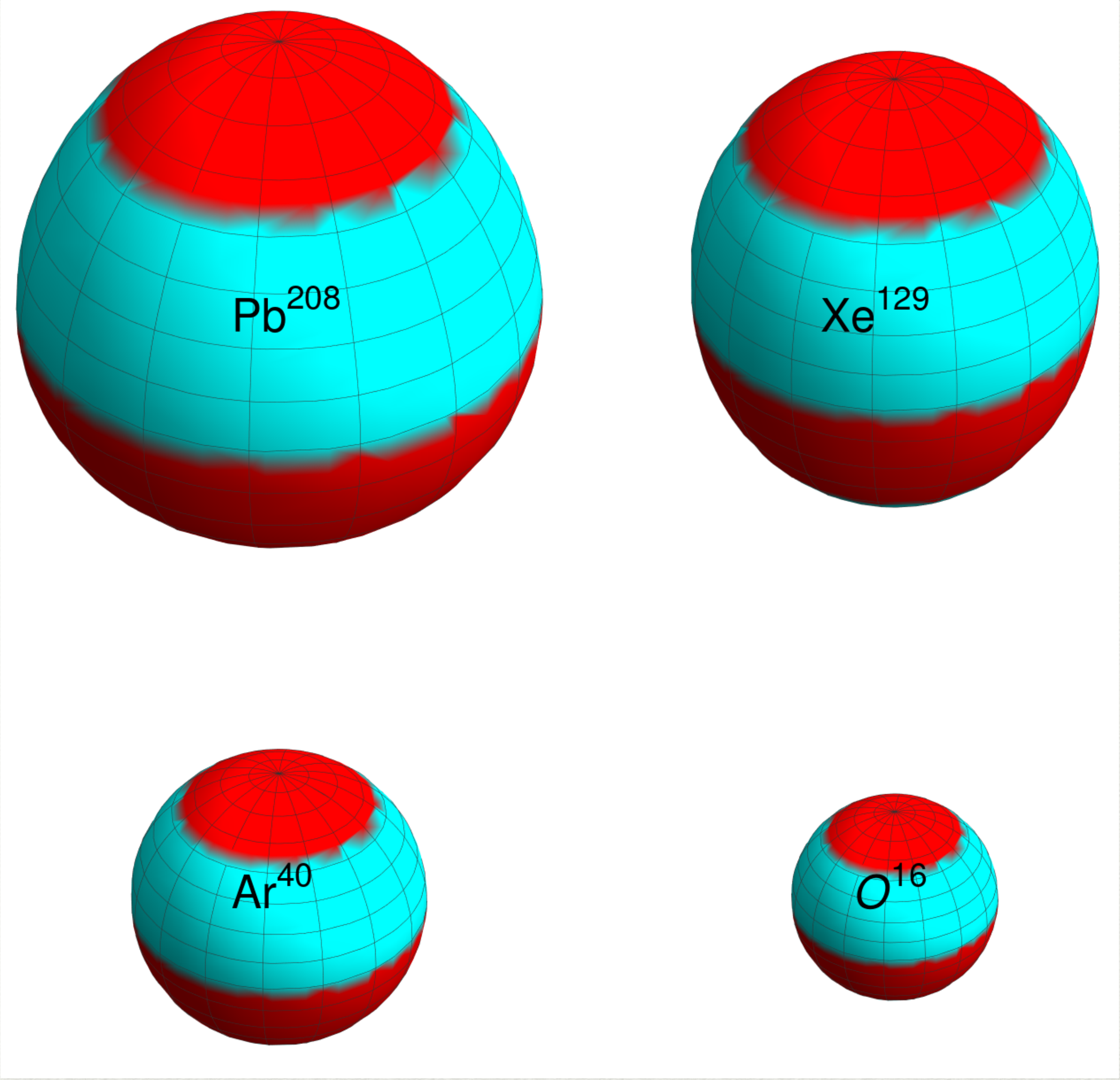
Color, flavor, spin, magnetic fields etc

Proton substructure (quark/gluon fluctuations)

Hydrodynamics
Looking under the hood

What effects from hydrodynamics influence the connection between the initial geometrical shape to the final flow harmonics?

What do we need to consider for light nuclei?



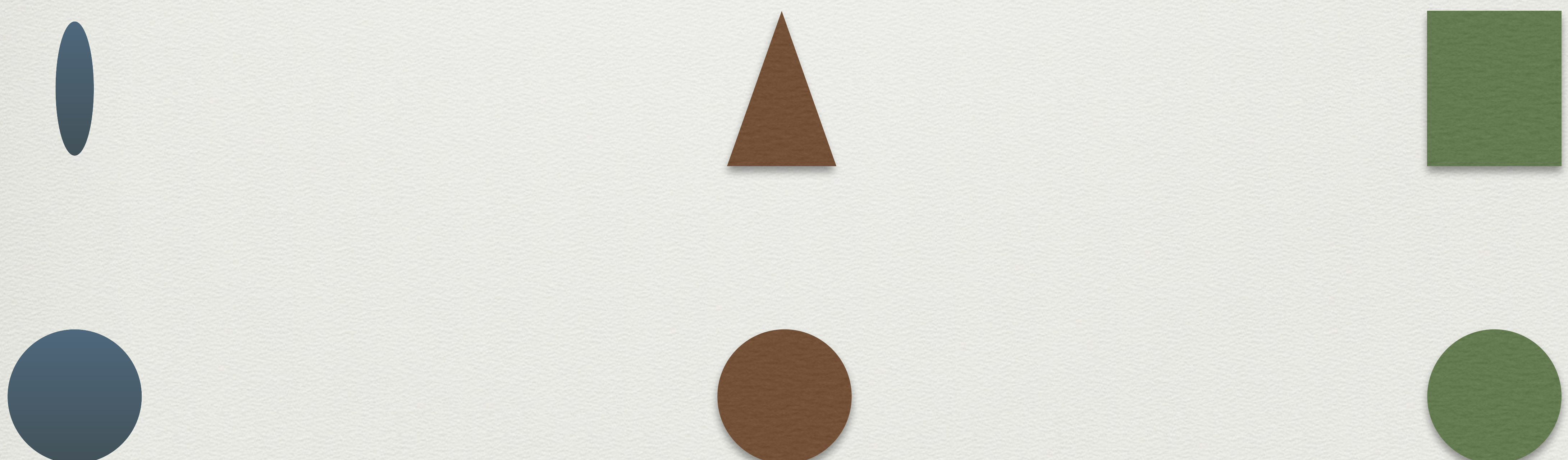
How precise are heavy-ions collisions as a tool for measuring nuclear structure?

- Linear response: Given the same medium, if you vary deformations, do you get the same influence on the final flow?
- What influence does beam energy, system size etc play in extraction nuclear structure?
- What role do medium effects play? How much of an uncertainty does this add?

Quantifying initial state geometry

$$\varepsilon_{n,m} \equiv \frac{\int r^m e^{in\phi}\rho(r,\phi)rdrd\phi}{\int r^m \rho(r,\phi)rdrd\phi}$$

$\varepsilon_{2,2} = 1$ $\varepsilon_{3.3} = 1$ $\varepsilon_{4,4} = 1$



$\varepsilon_{2,2} = 0$ $\varepsilon_{3.3} = 0$ $\varepsilon_{4,4} = 0$

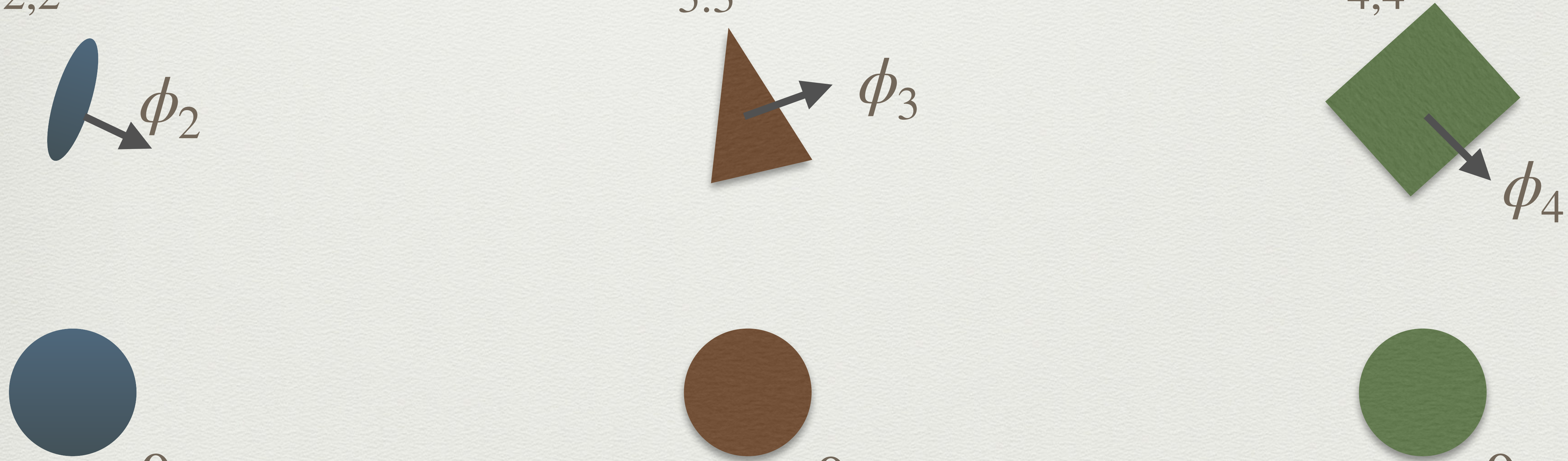
Quantifying initial state geometry

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

Eccentricity Vector

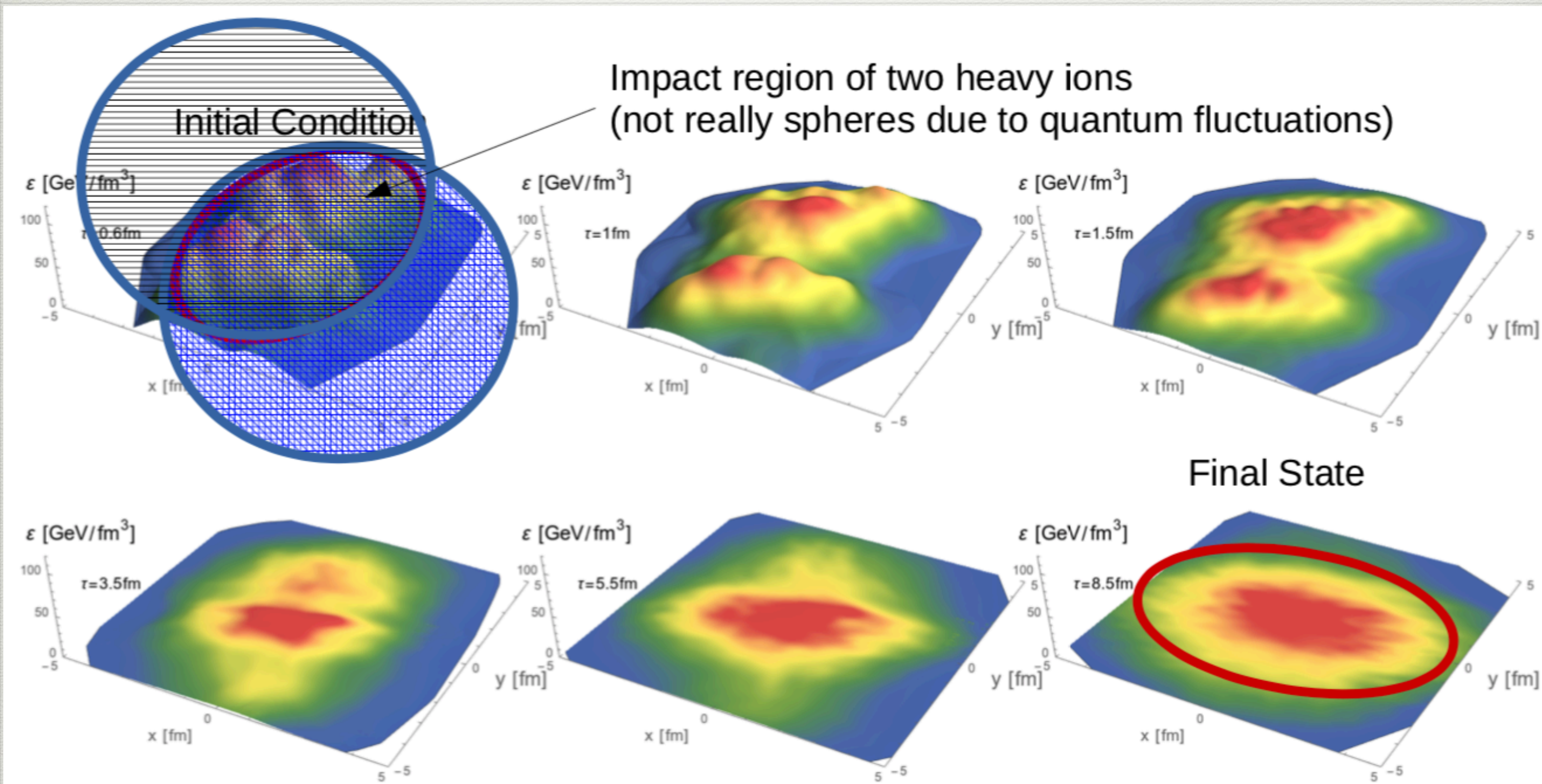
$$\mathcal{E}_n = \varepsilon e^{in\phi_n}$$

$\varepsilon_{2,2} = 1$ $\varepsilon_{3.3} = 1$ $\varepsilon_{4,4} = 1$



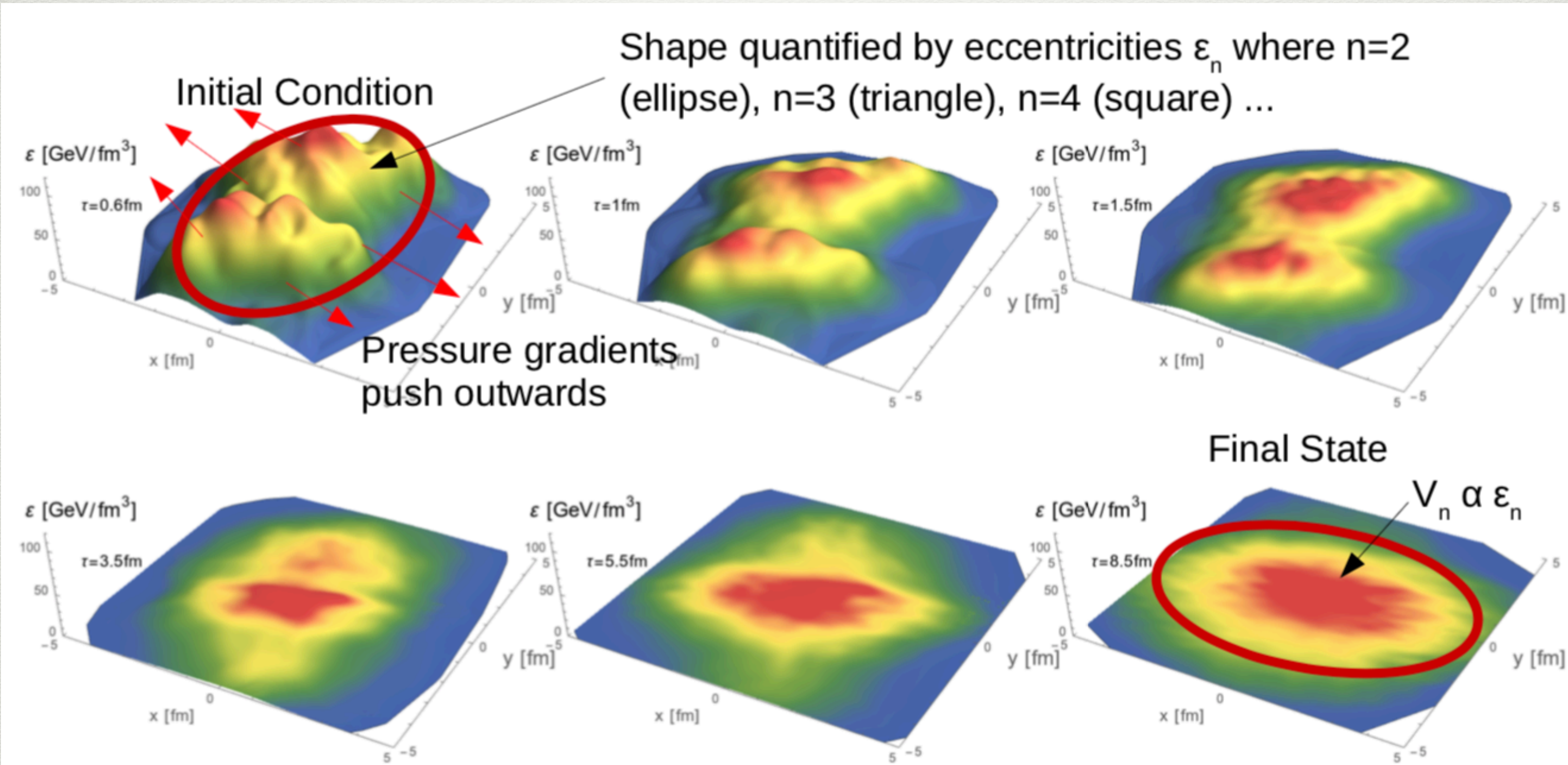
$\varepsilon_{2,2} = 0$ $\varepsilon_{3.3} = 0$ $\varepsilon_{4,4} = 0$

How does $\mathcal{E}_n \rightarrow V_n$



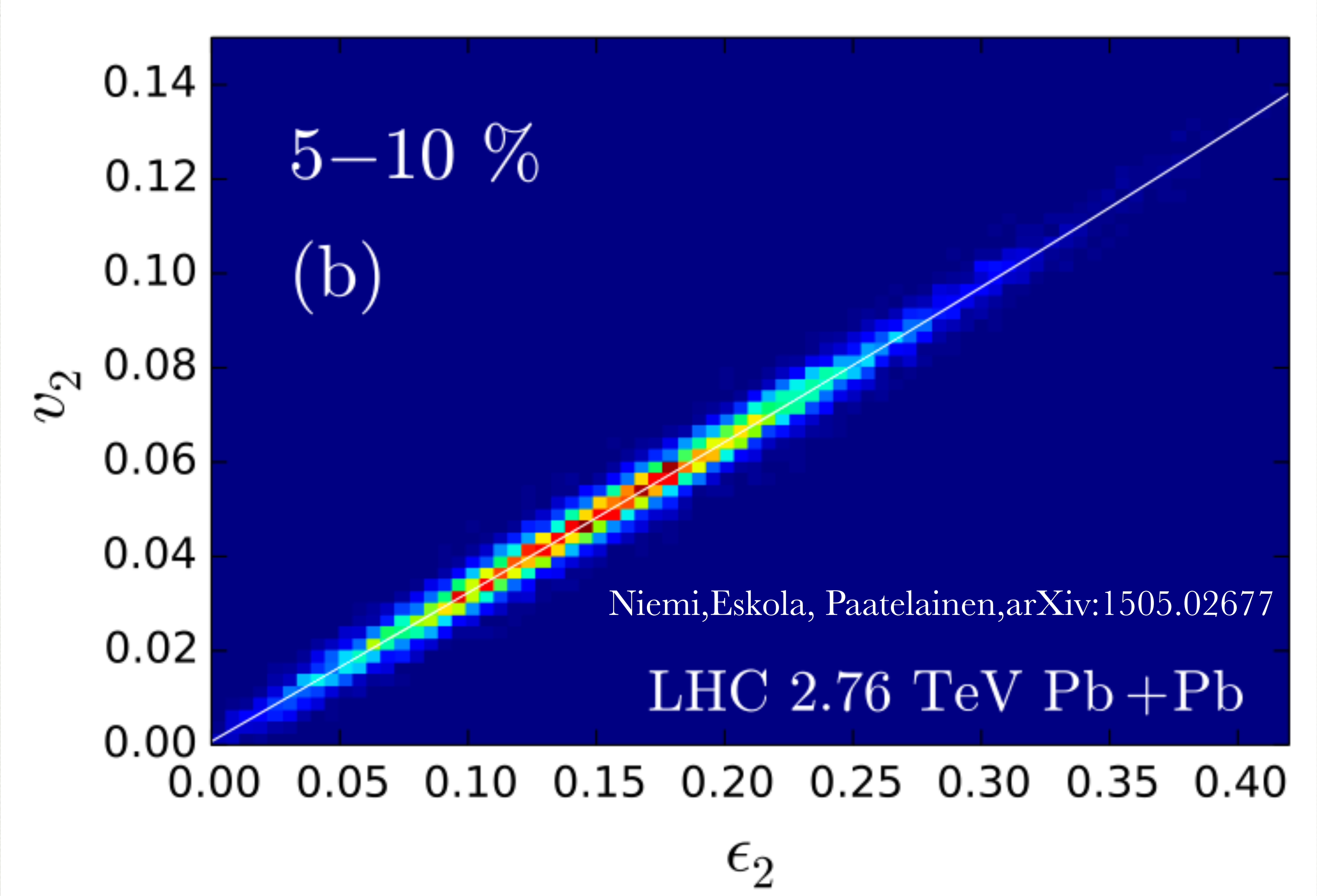
Eccentricities ε_2's are directly related to the final measured flow observables v_n's

How does $\mathscr{E}_n \to V_n$



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

We can visually see that there's a linear-ish scaling



At least for $\varepsilon_2 \rightarrow v_2$, nearly linear scaling in central collisions

Note I'm purposefully using lower cases to indicate magnitudes here

Quantification of Mapping $\mathcal{E}_n \to V_n$

- These are **vectors**: $\mathcal{E}_n = \{\varepsilon_n, \phi_n\}$ $V_n = \{v_n, \psi_n\}$
- Pearson coefficients **quantify linear response**, much better than just plotting one versus the other. Makes comparisons between systems possible.

$$Q_n = \frac{\langle v_n \varepsilon_n \cos n\left(\psi_n - \phi_n\right)\rangle}{\sqrt{\langle v_n^2\rangle\langle \varepsilon_n^2\rangle}}$$

- Only $v_2\{2\}$ $v_3\{2\}$ are mostly from linear response, v_1 v_4+ come from non-linear response AND mode mixing!

Gardim et al, PRC85(2012)024908,;Gardim,JNH,Luzum,Grassi PRC91(2015)3,034902

Central vs. peripheral collisions

Linear response

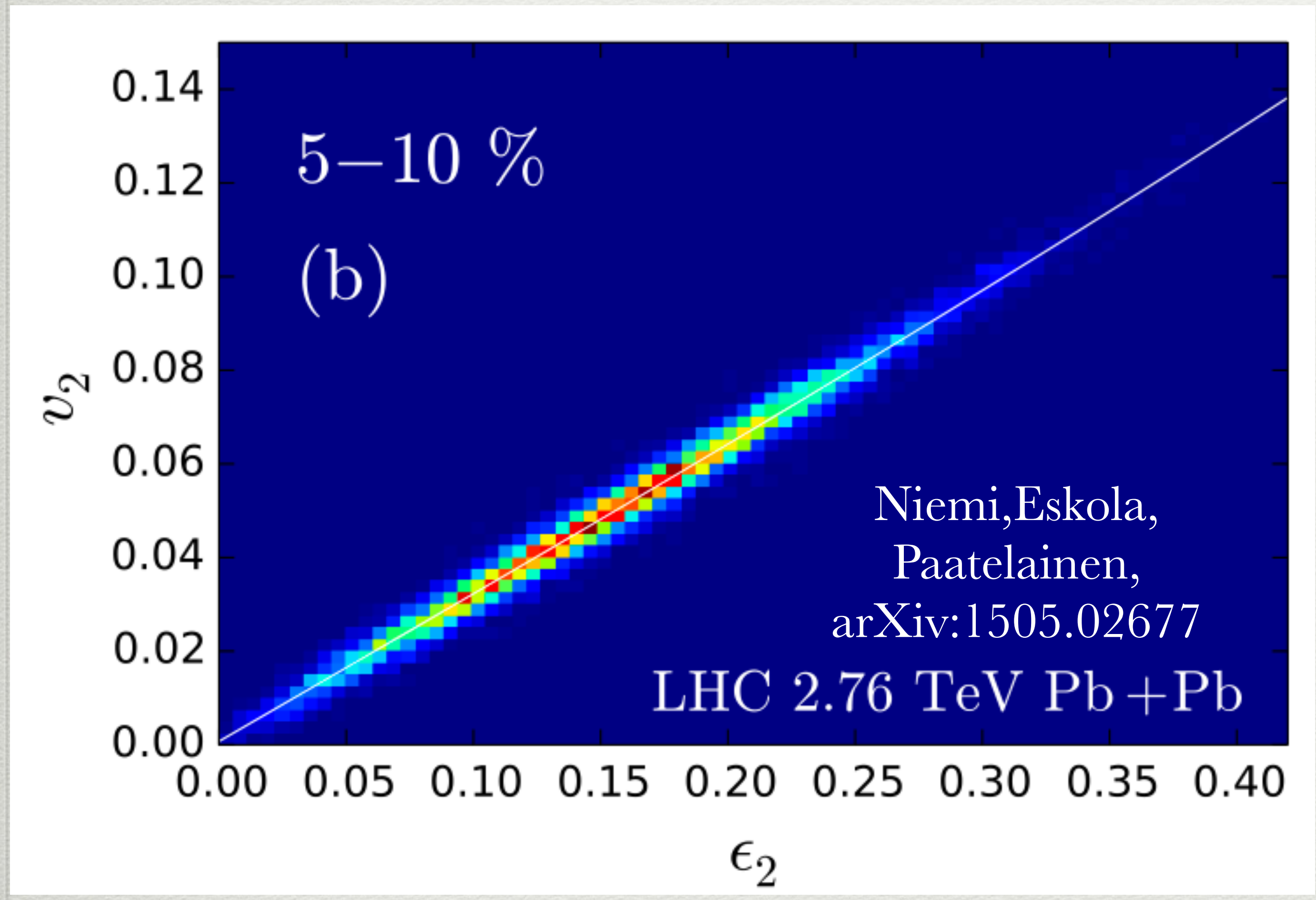
$$V_n^{pred} = \gamma_n \mathcal{E}_n$$

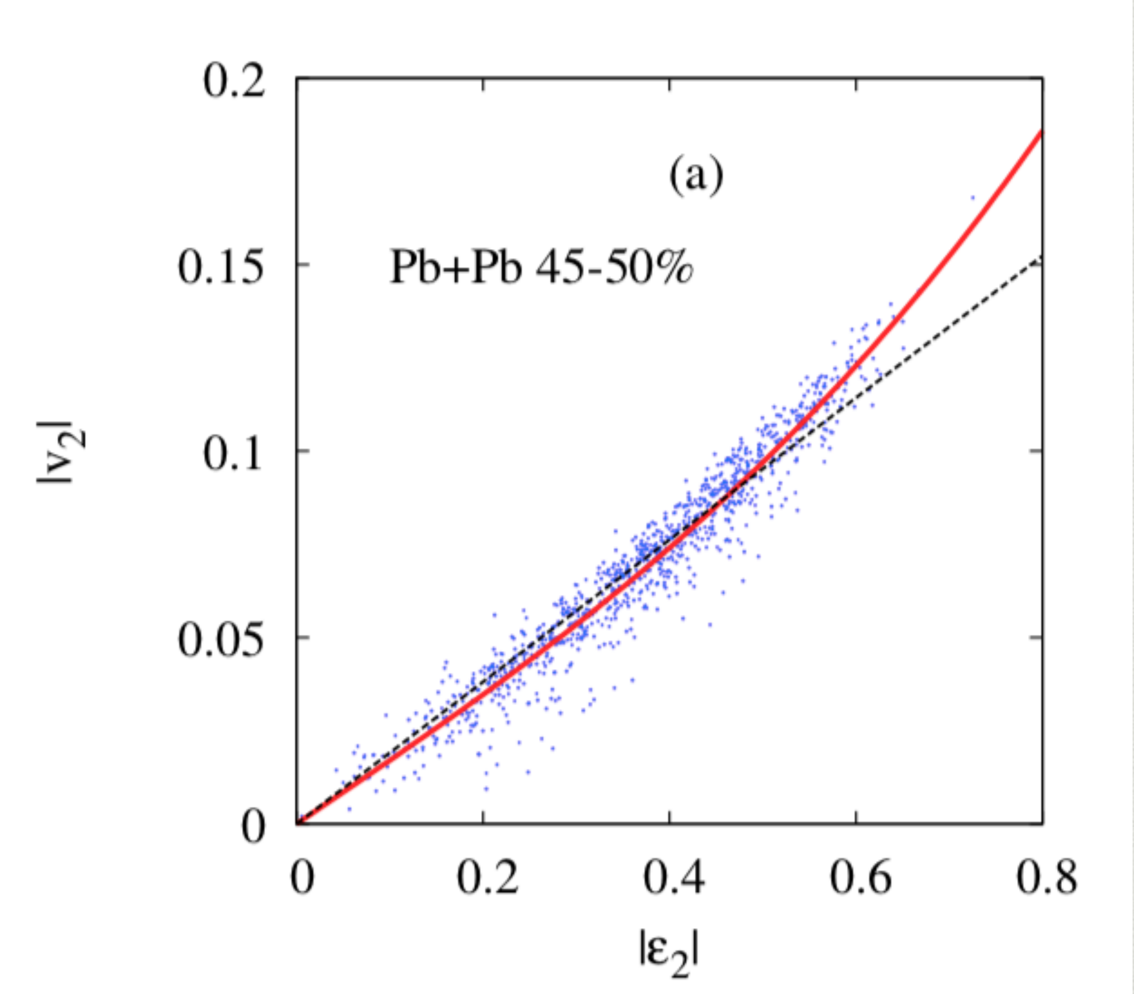
Teaney,Yan,PRC83(2011)064904;Gardim,et al,PRC85(2012)024908;PRC91(2015)3,034902

Linear+cubic response

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

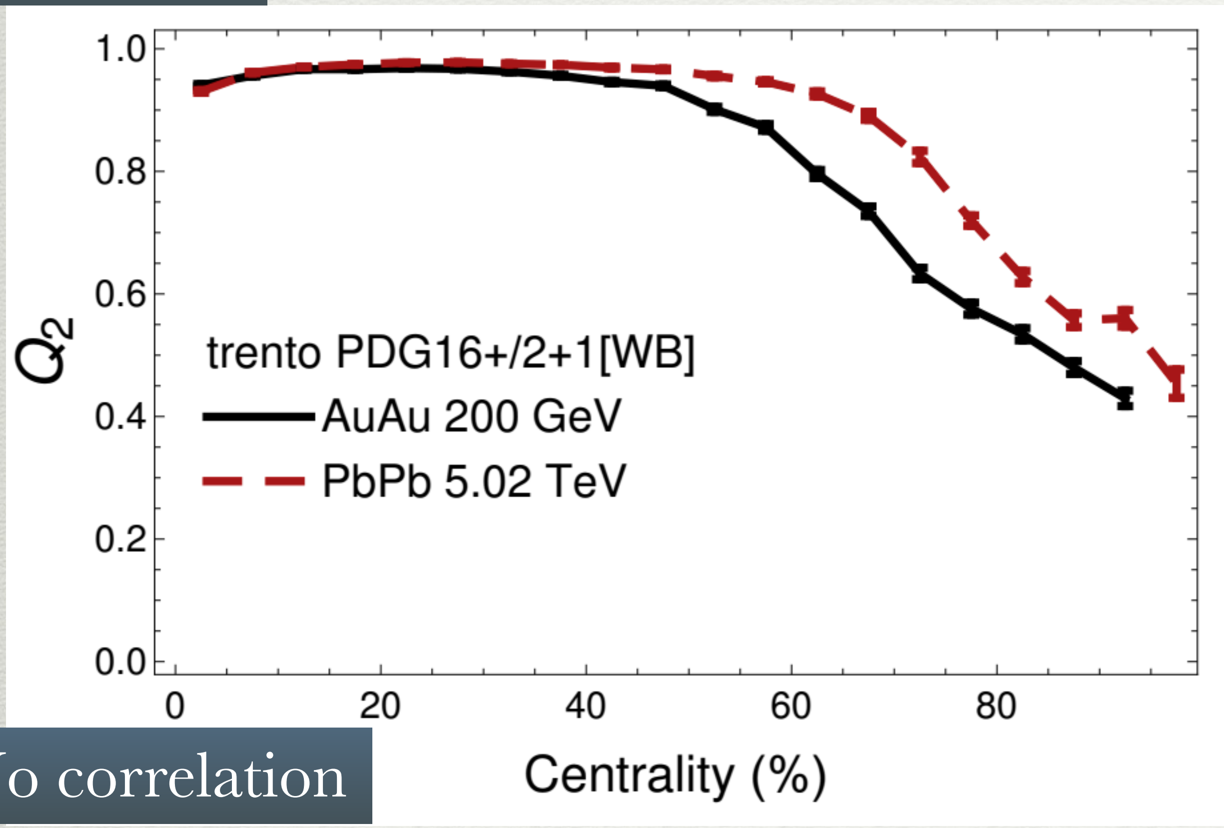
JNH,Yan,Gardim,Ollitrault Phys. Rev. C 93, 014909 (2016)





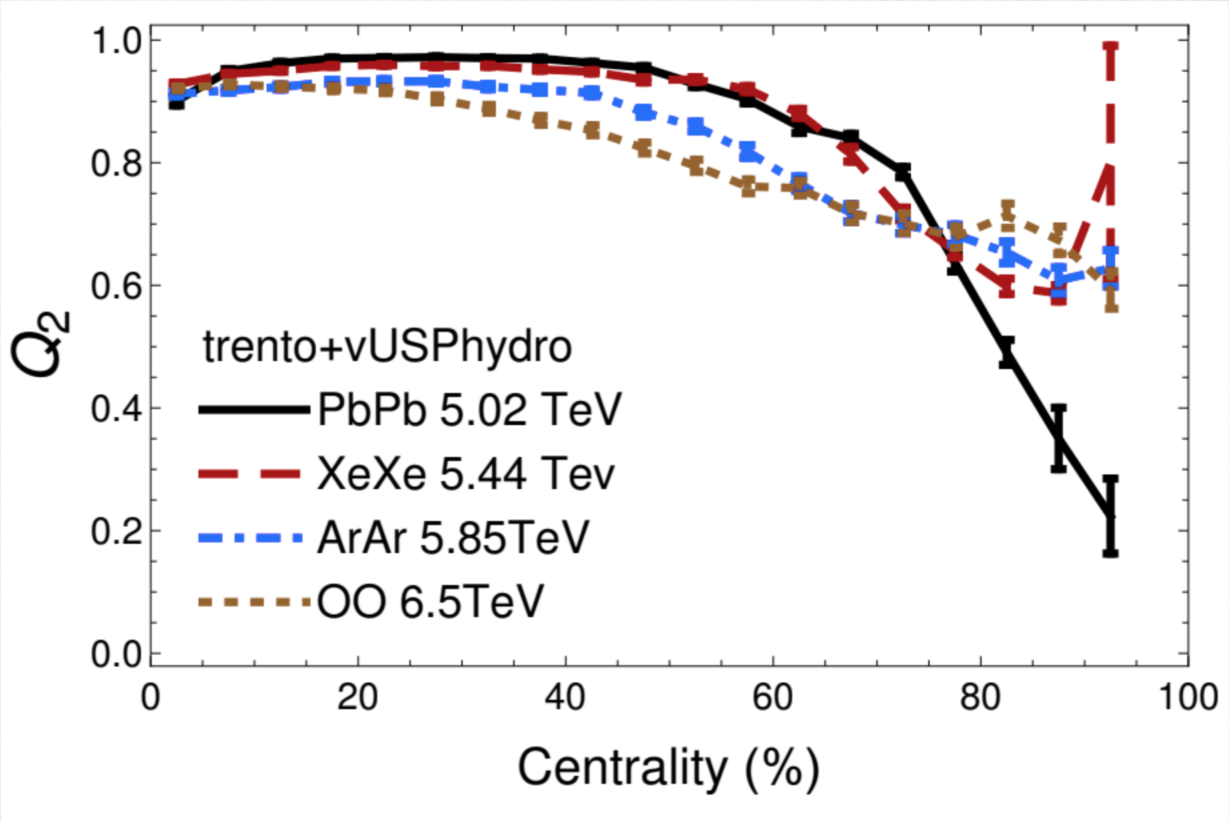
Effectiveness of linear response across $\sqrt{s}$ and system size

Perfect mapping



No correlation

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



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

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

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

Best linear response in central collisions

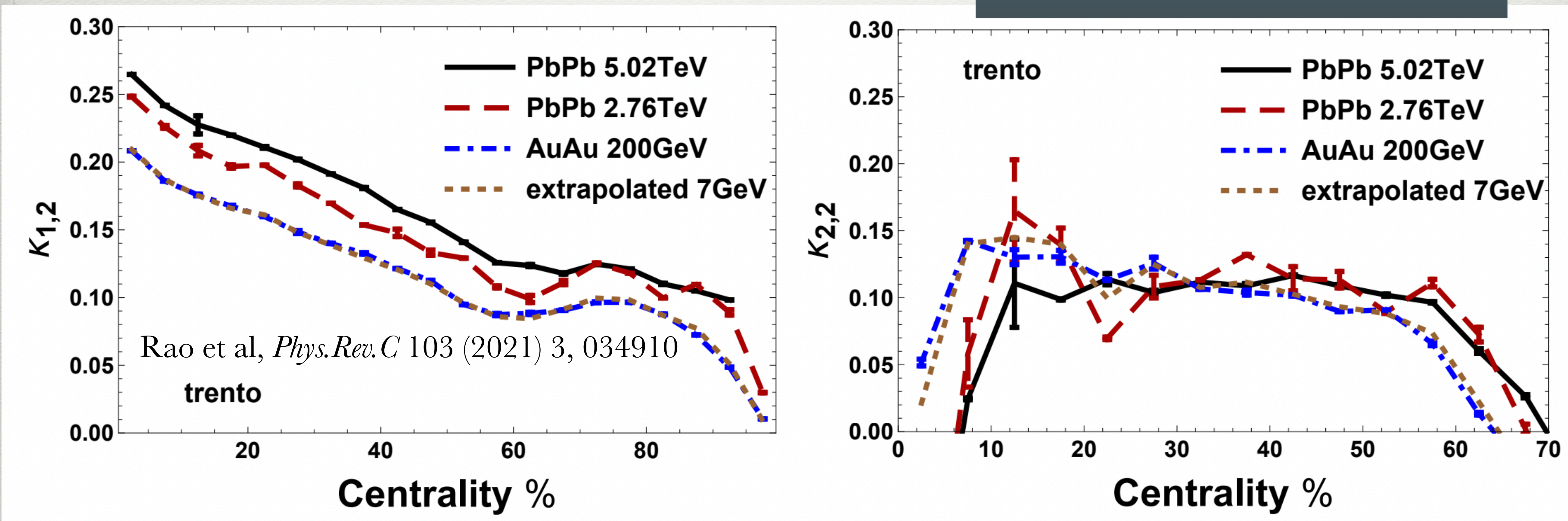
Non-linear response

Non-linear response & beam energy

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

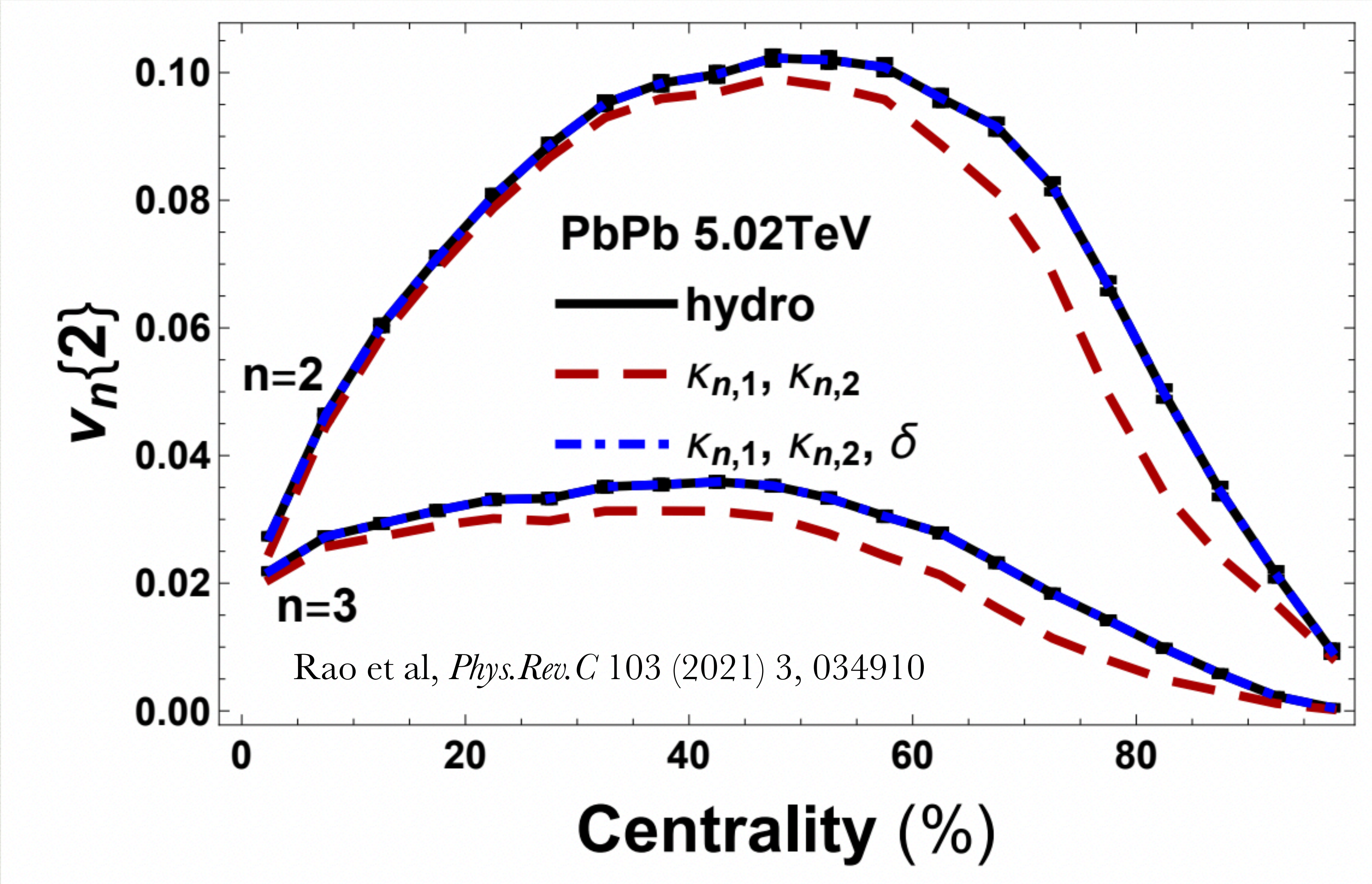
No $\mathcal{E}_n \to V_n$ correlation

Non-linear response coefficient



At lower beam energies, linear response is less dominate

2 particle correlations



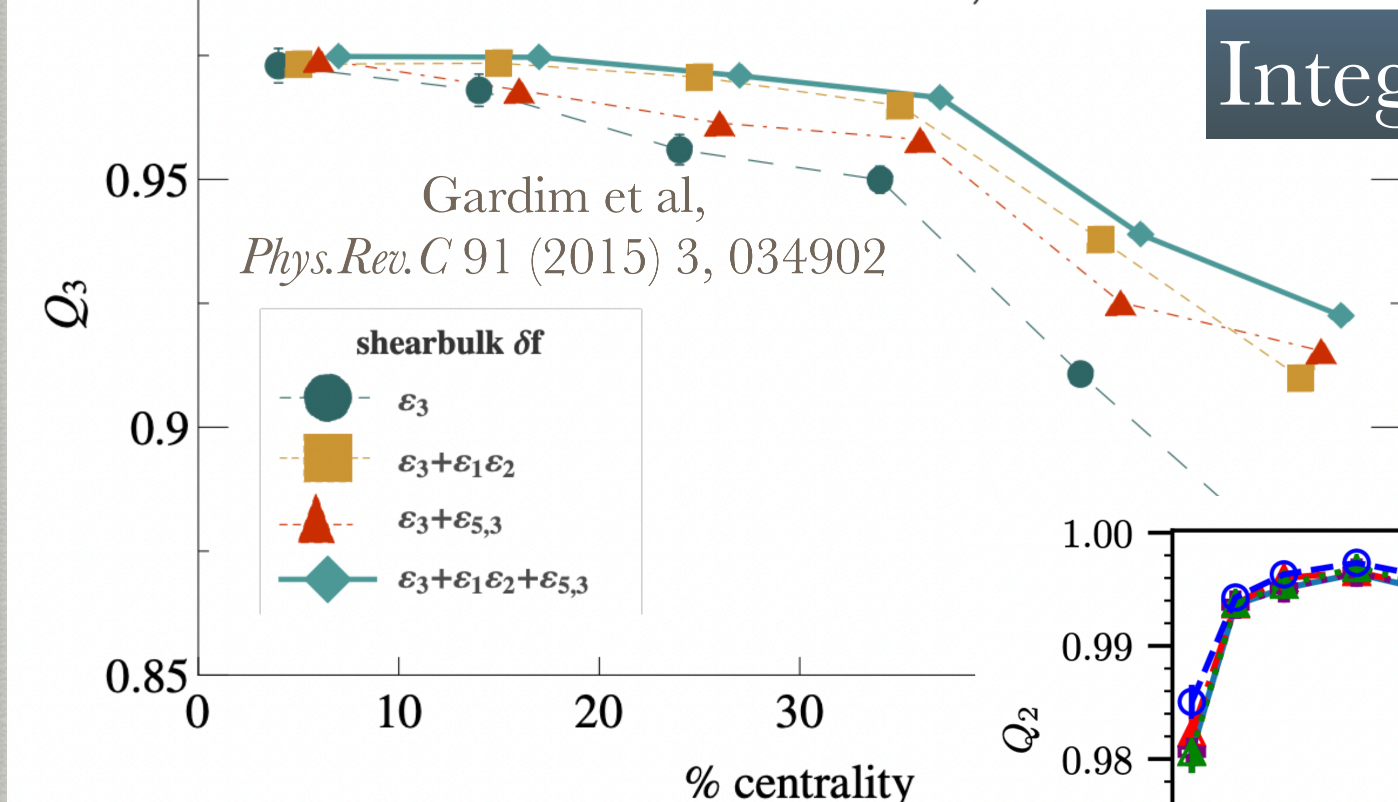
Residual δ is whatever is left in the V_n that we don't get from linear+cubic response. Essentially our unknown influence in V_n

Pearson Coefficient by flow harmonic

Methodology from Gardim et al, *Phys.Rev.C* 85 (2012) 024908; *Phys.Rev.C* 91 (2015) 3, 034902;

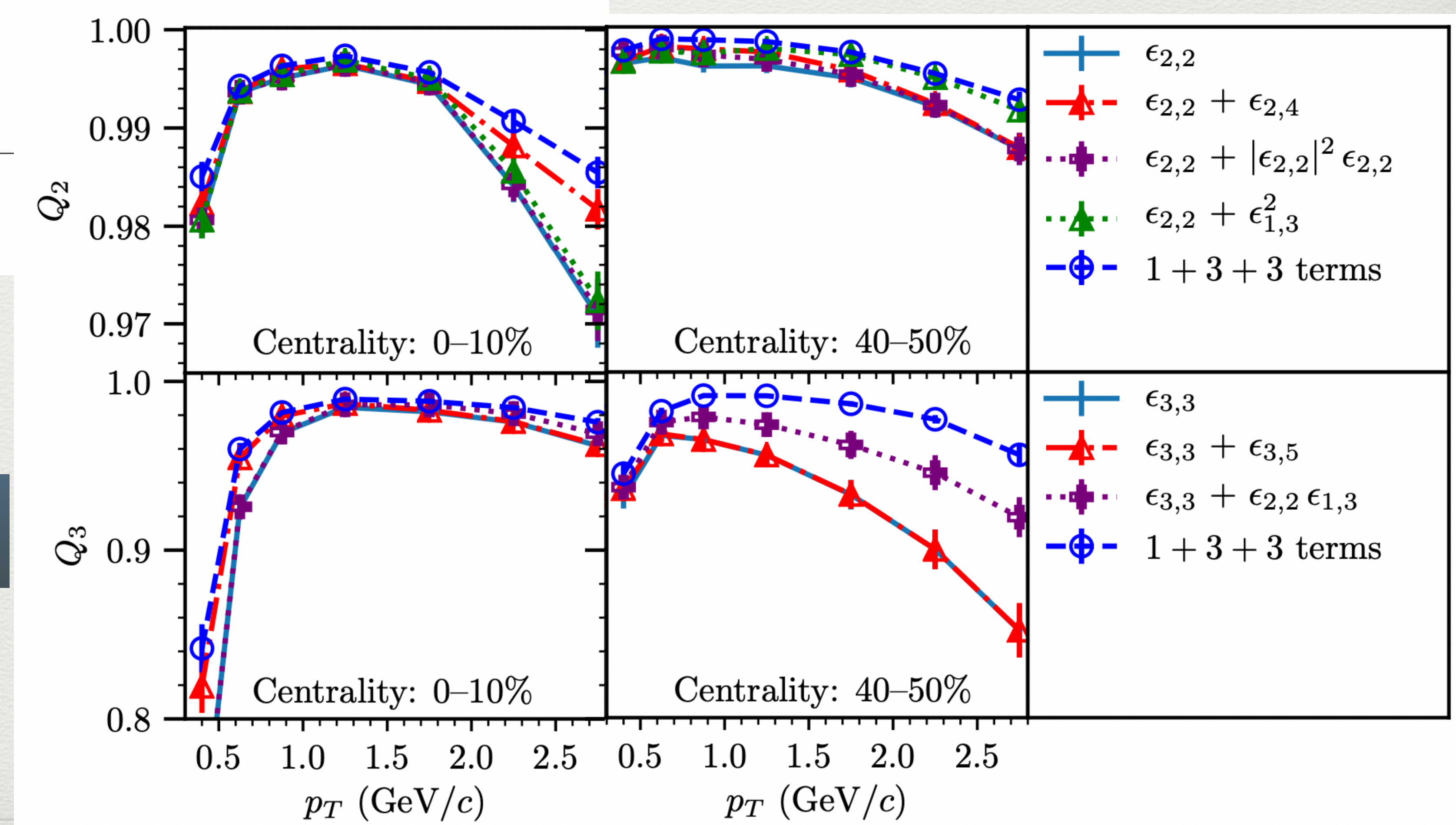
$$V_{est,3} = k\ \varepsilon_3 e^{i3\Phi_3} + k'\ \varepsilon_{3,5} e^{i3\Phi_{3,5}} + k''\ \varepsilon_1\varepsilon_2 e^{i(\Phi_1+2\Phi_2)}$$

Integrated v_n



Higher-order terms play a role for non-central collisions

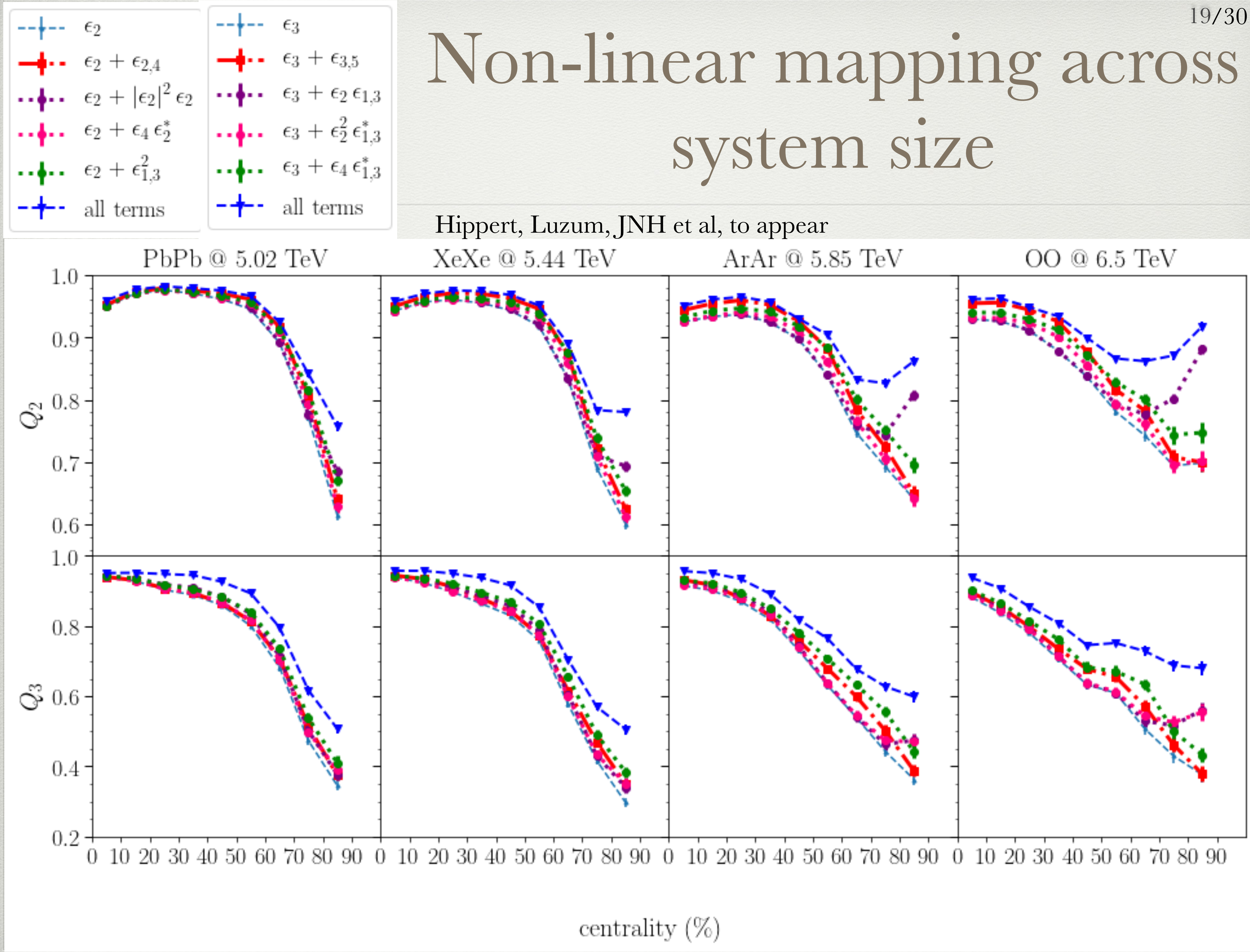
Hippert et al, *Phys.Rev.C* 102 (2020) 6, 064909



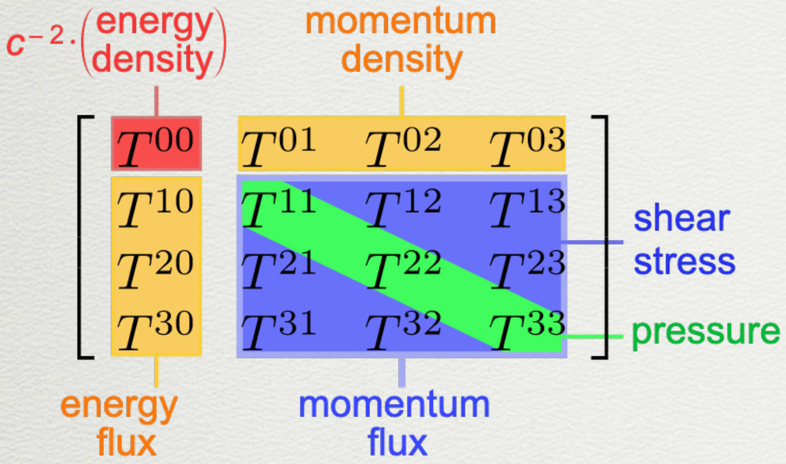
Differential $v_n(p_T)$

Non-linear mapping across system size

Hippert, Luzum, JNH et al, to appear

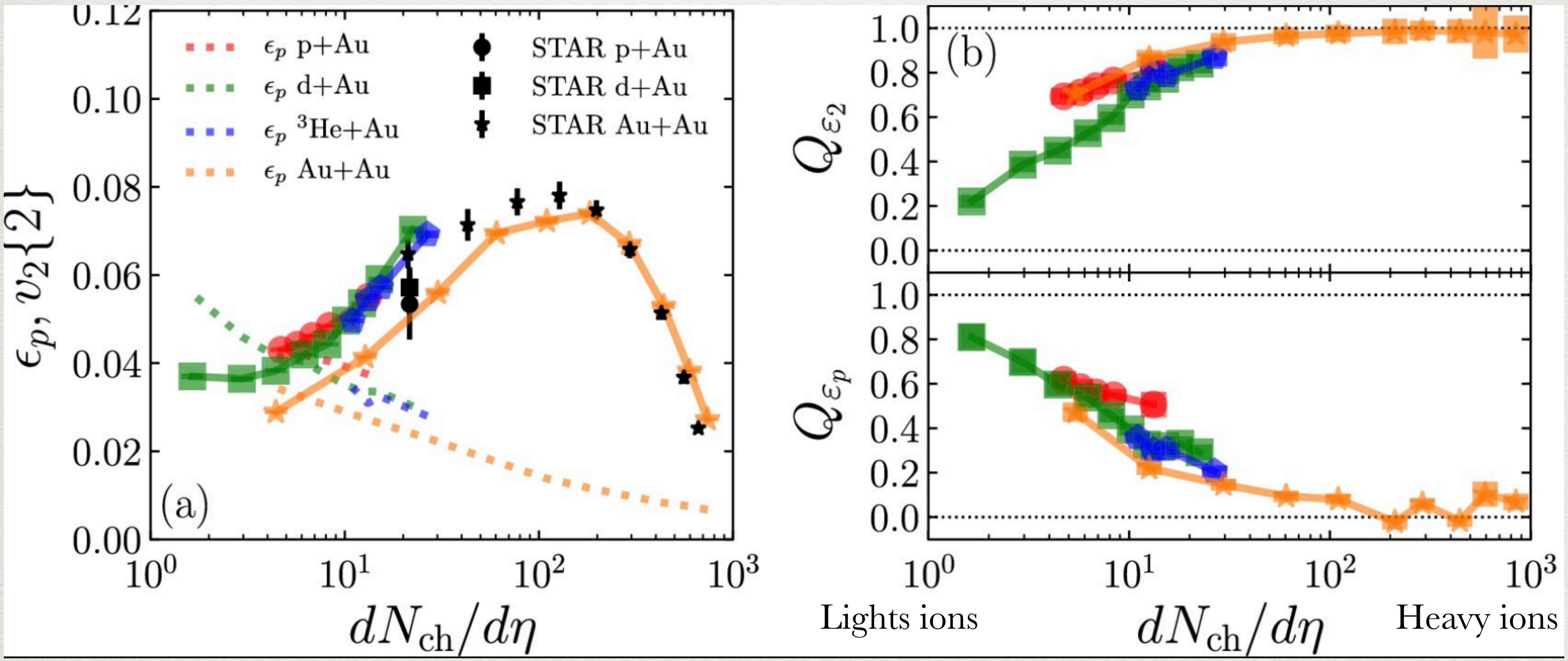


Mapping: Including full $T^{\mu\nu}$ in small systems



Initial flow and out-of-equilibrium effects play a strong role in light ions

Linear response only

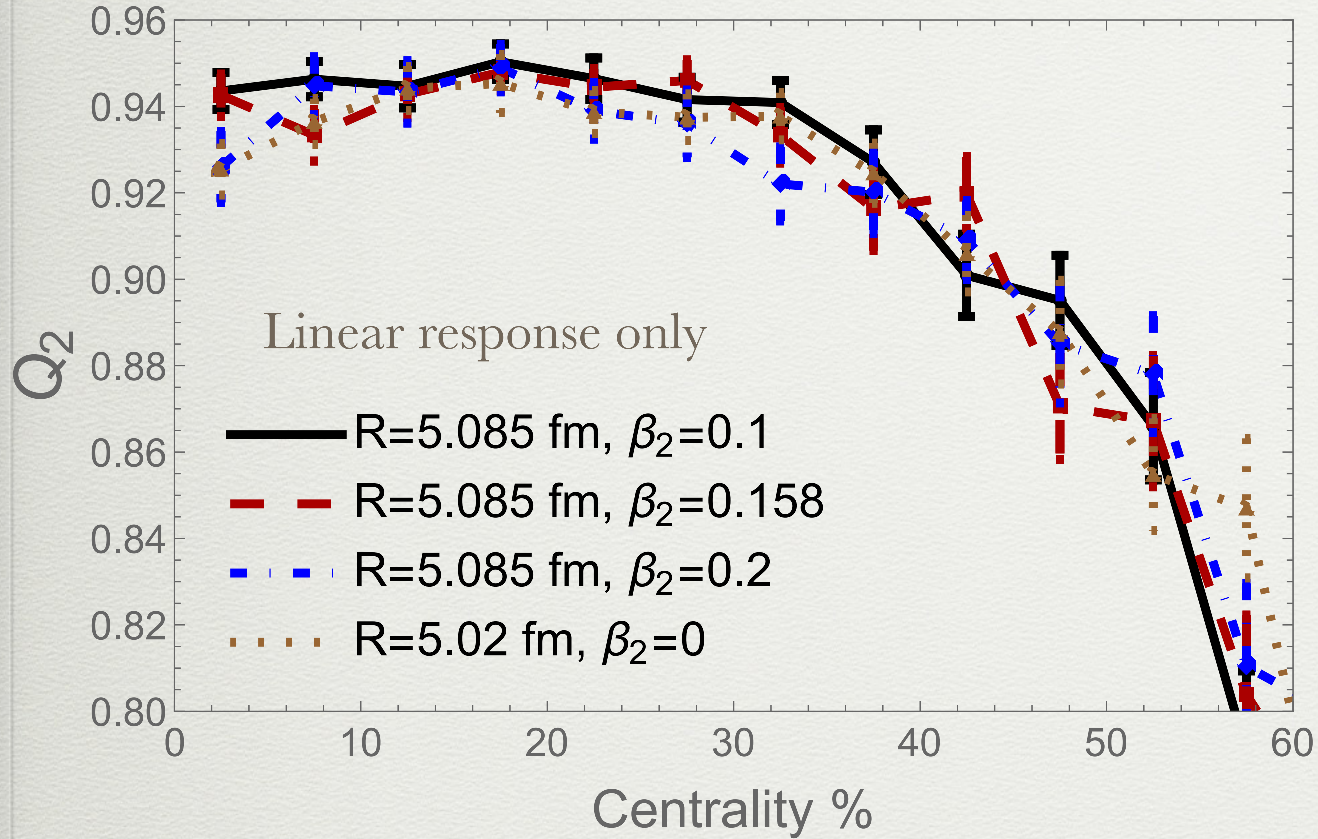


Schenke, Shen, Tribedy *Phys.Lett.B* 803 (2020) 135322

What does this mean for deformed ions?

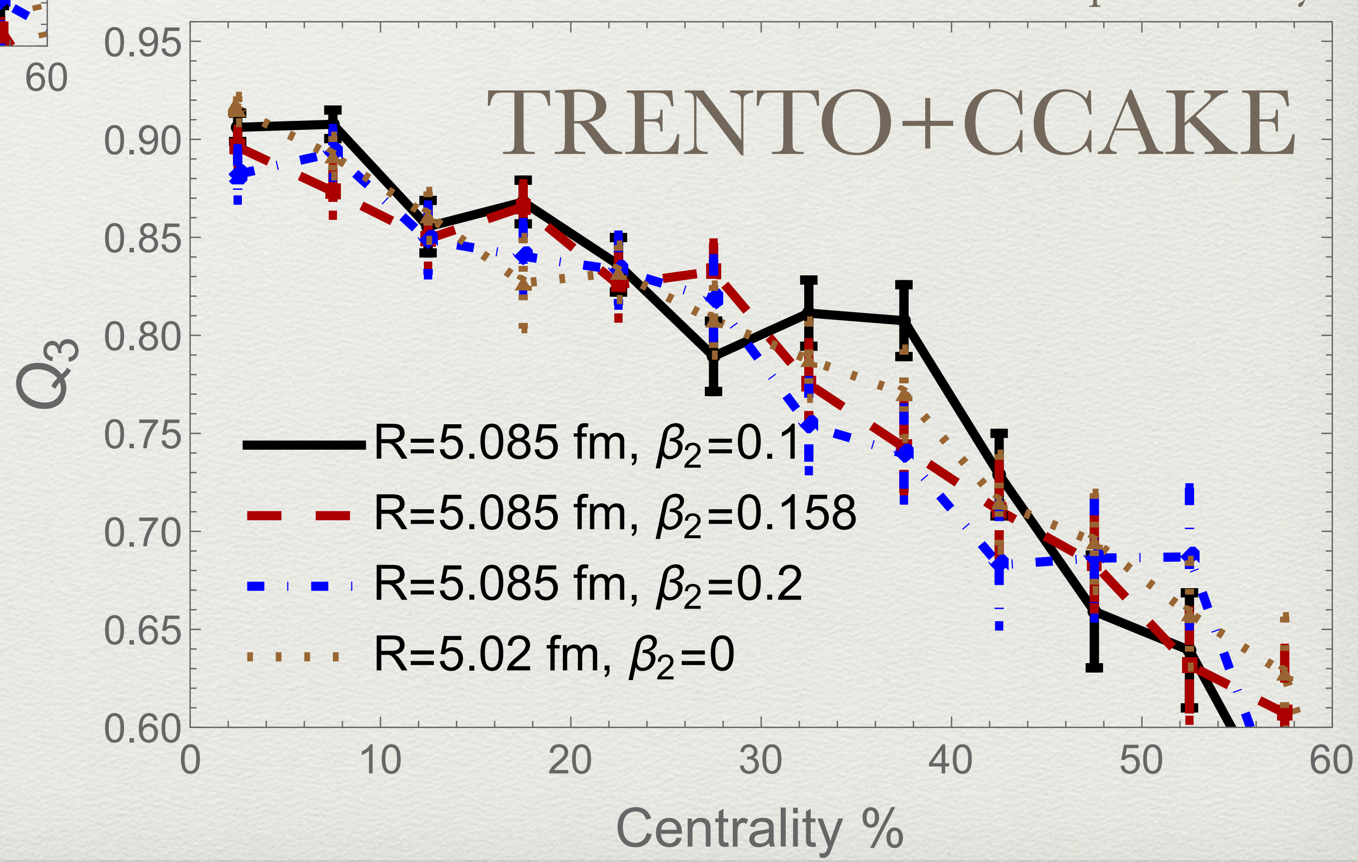
Preliminary!

Carzon, Almaalol, Salinas san Martin, JNH



Mapping works well, not strongly dependent on deformation

Linear response only



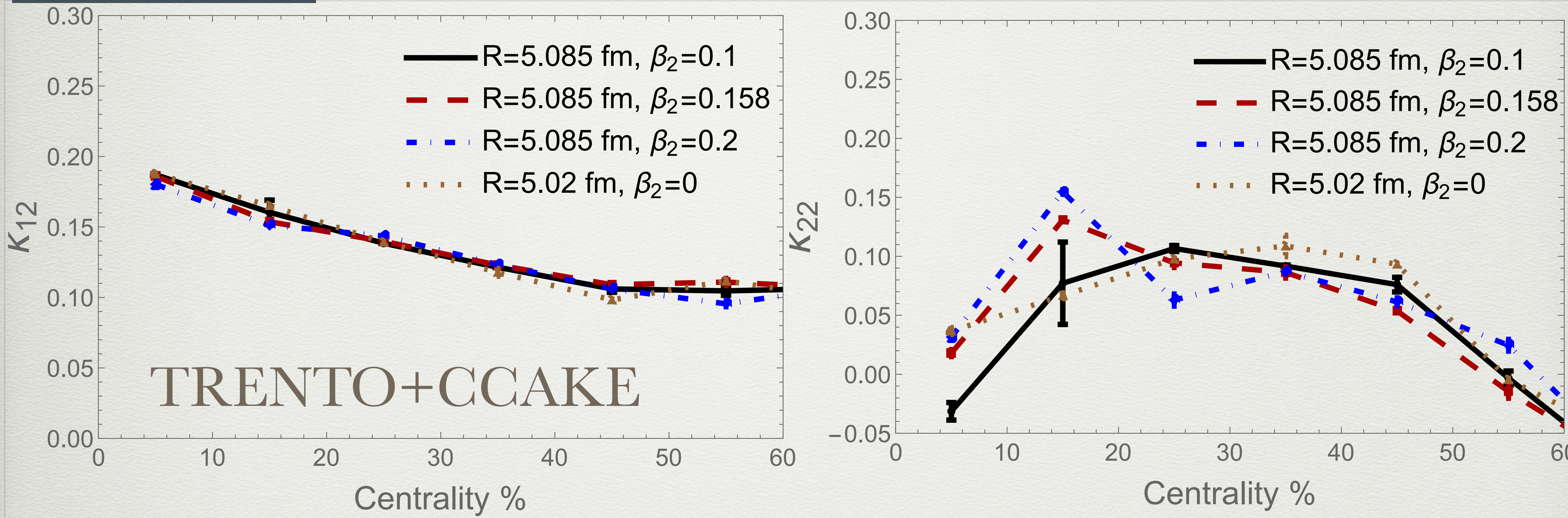
v_3 more strongly dependent on non-linear response

$$V_n^{pred} = \kappa_{1,n}\mathscr{E}_n + \kappa_{2,n}|\varepsilon_n|^2\mathscr{E}_n$$

Non-linear mapping coefficients

Preliminary!

Carzon, Almaalol, Salinas san Martin, JNH



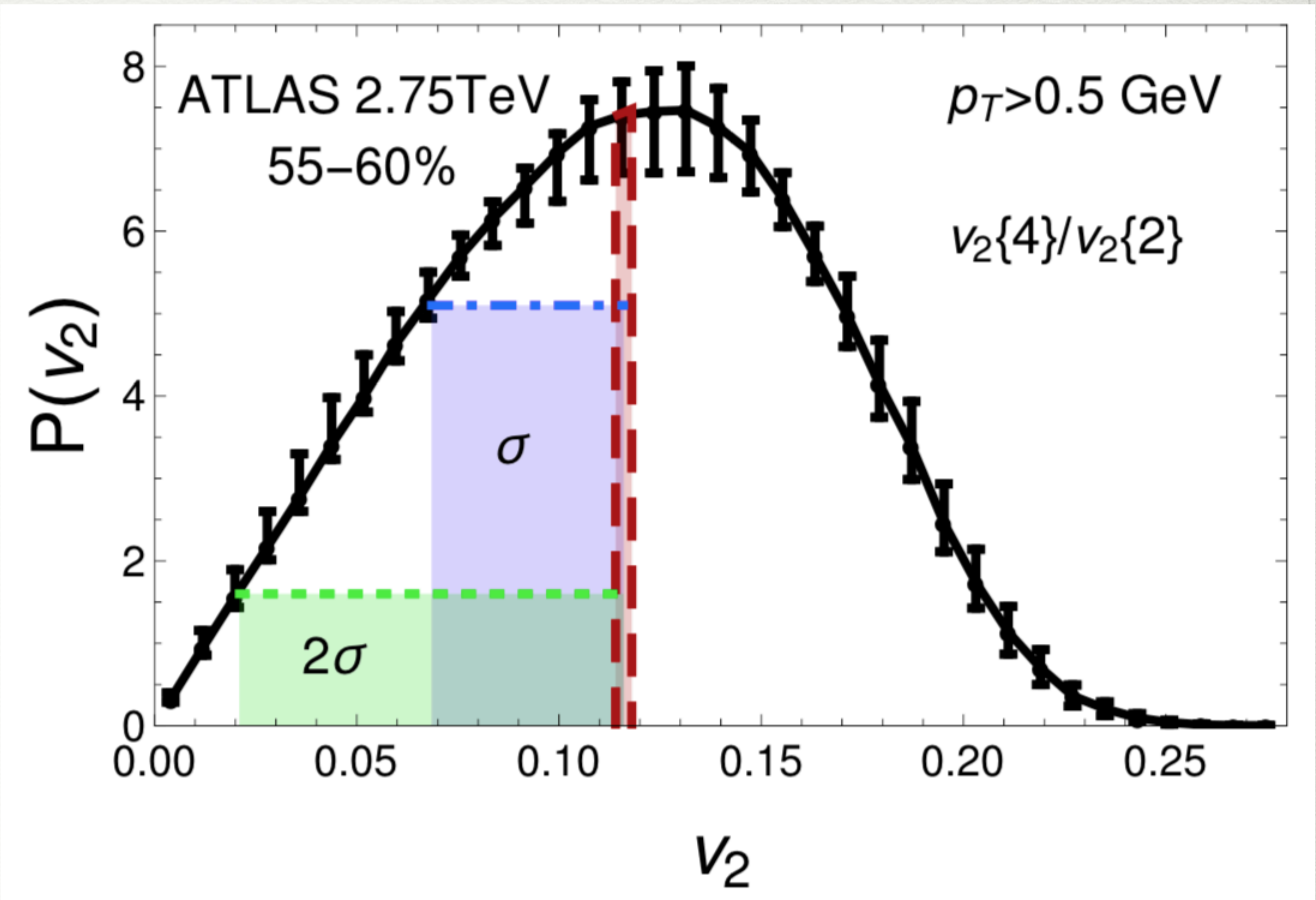
- Deformations change $\mathscr{E}_n$, do deformations also affect the mapping (medium) coefficients?
- Linear term the same, cubic response ↑ by large β_2

Multi-particle cumulants

Measuring 2, 4, 6, … particle correlations

If **only** linear response

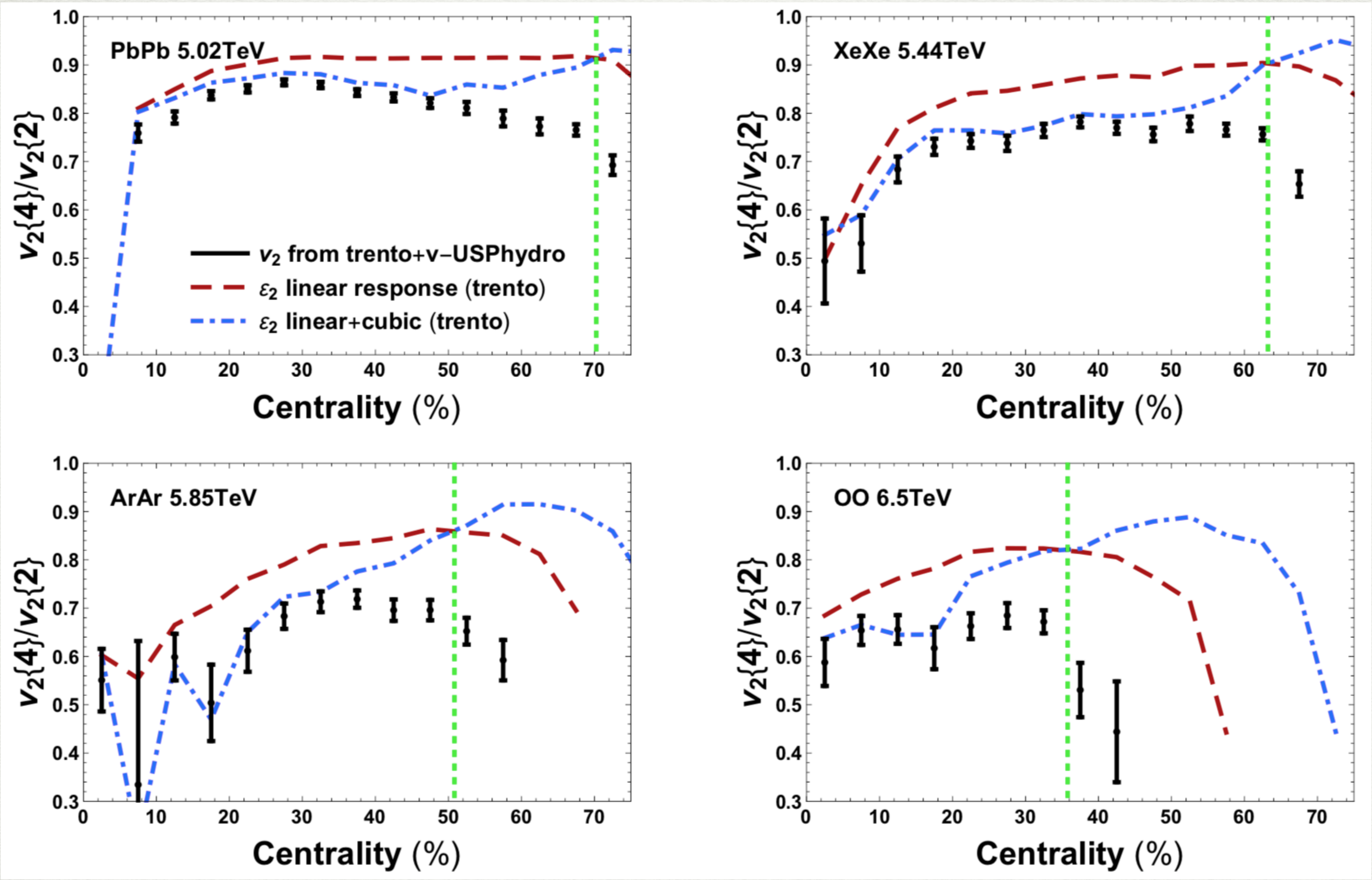
$$\frac{v_n\{4\}}{v_n\{2\}} \sim \frac{\varepsilon_n\{4\}}{\varepsilon_n\{2\}}$$



Accurate within 1% for v_3 in ultra-central collisions

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

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



Quarks vs nucleons vs α clustering

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

Types of structure

- OO Wood-Saxon from Sievert, JNH Phys.Rev. C100 (2019) no.2, 024904
- OO+α clustering from lattice effective field theory Moreland et al, *Phys.Rev.C* 101 (2020) 2, 024911
- OO+sub-nucleonic structure (Trento 2.0) Lu, et al, Phys. Lett. B 797, 134863 (2019)

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

Types of structure

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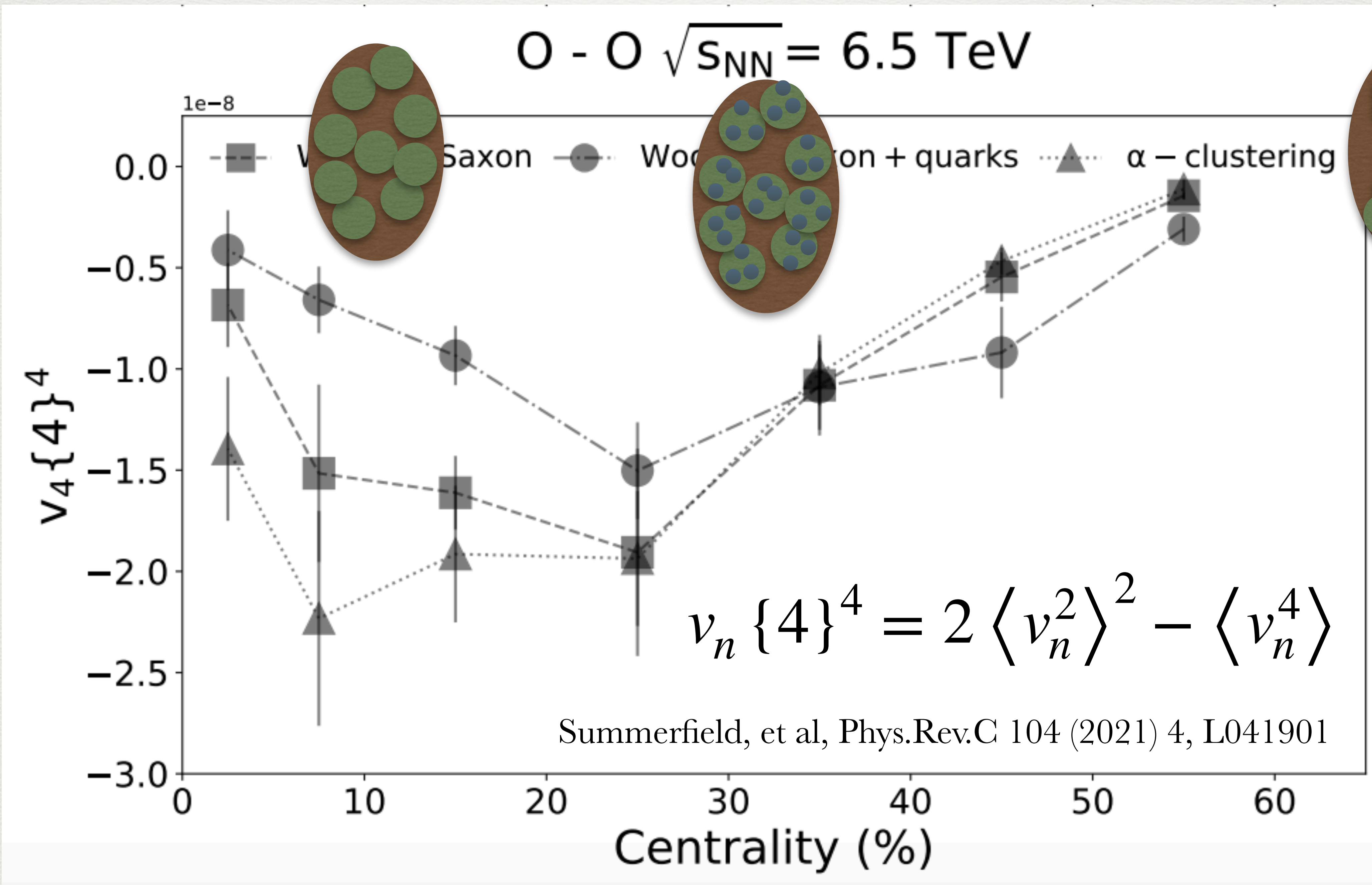
  lattice effecti
  Moreland et al, *Phys.Rev.*
- OO+sub-nu
  structure (Tr
  Phys. Lett. B 797, 134863 (2019)

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

Fluctuations in "square" shape disentangle structure



Observable distinguishes scale of structure in nucleus

Conclusions and Outlook

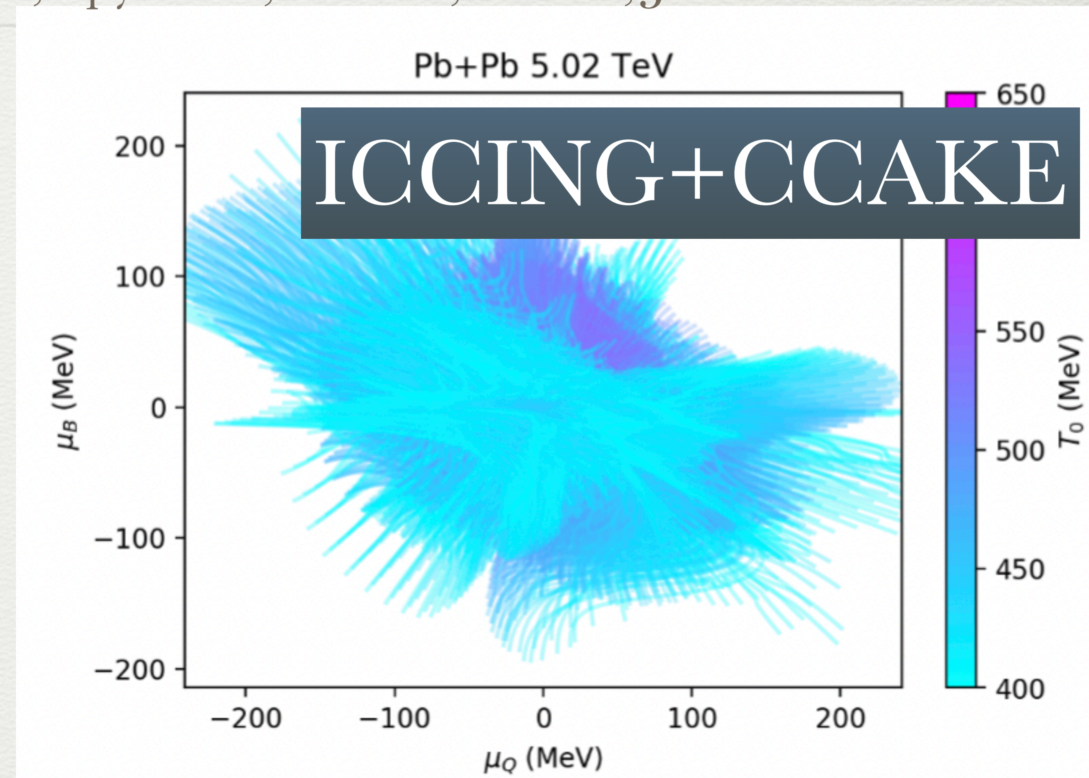
- By studying the mapping of flow harmonics, able to quantify how well we can work back to the initial state
- Central collisions always have a strong mapping, but higher flow harmonics have more non-linear effects
- Non-linear response appears with large deformations
- **Outlook**: run ICCING+CCAKE for isobars (with better fits to data/varying medium) to better understand the mapping from initial to final state

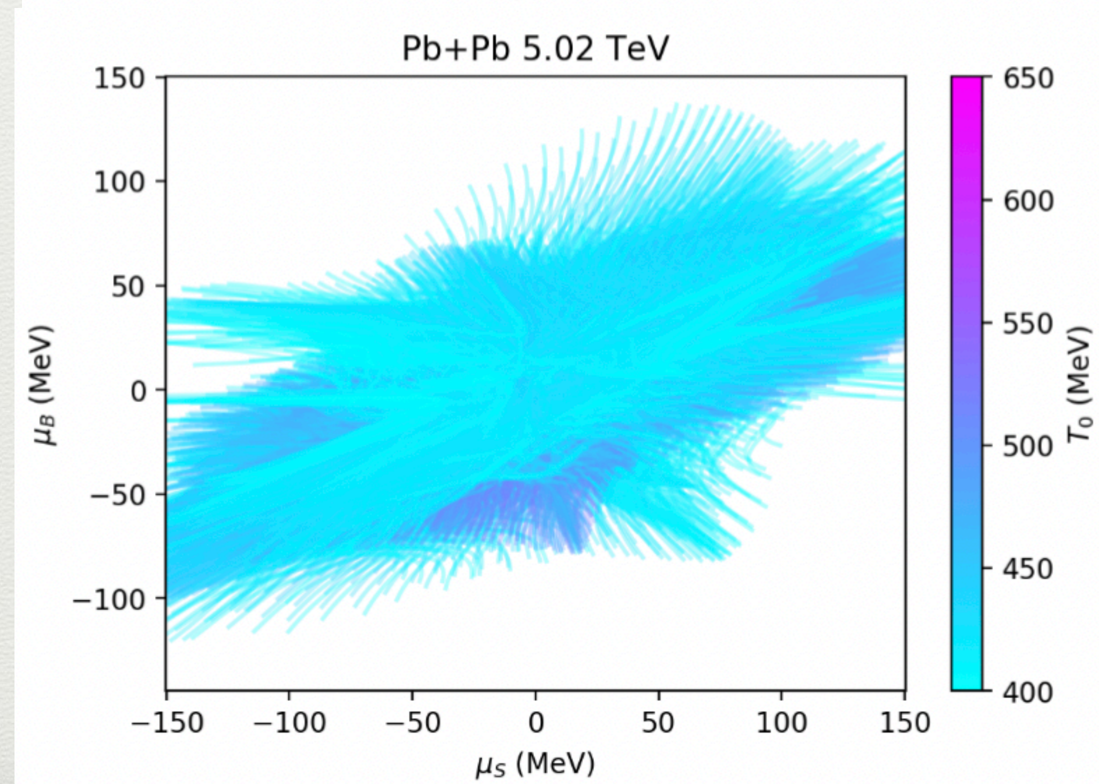
Code upgrades to CCAKE (formerly v-USPhydro)

Plumberg, Almaalol, Dore, Mroczek, Salinas San Martin, Spychalla, Carzon, Sievert, JNH

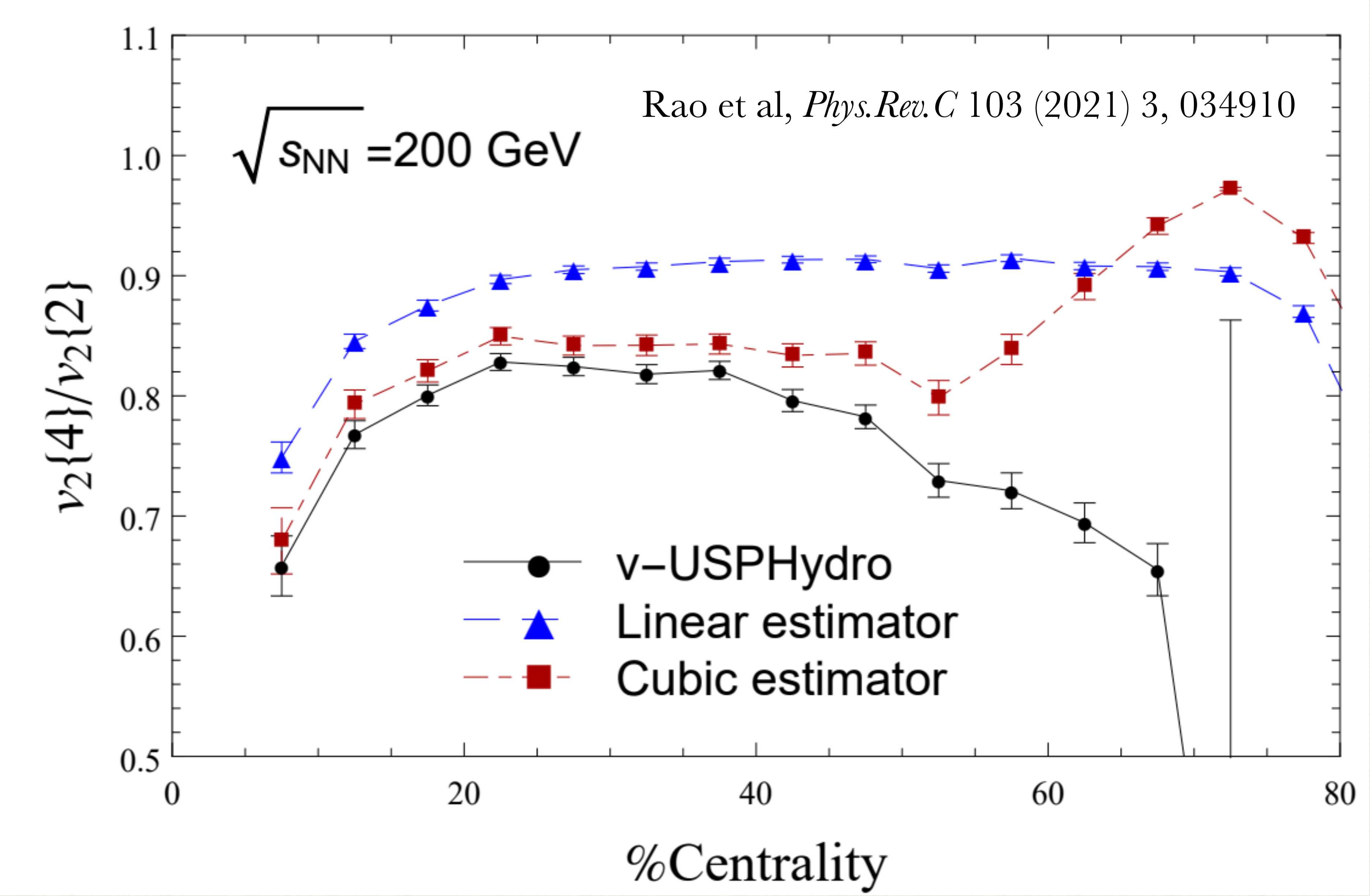
- New upgrades including YAML files, containerization, profiling and optimization
- BSQ conserved charges so 4D EOS (specifically algorithm to handle out-of-bound cells)
- In process: New Israel-Stewart to DNMR terms

Almaalol et al, 2209.11210 [hep-th]

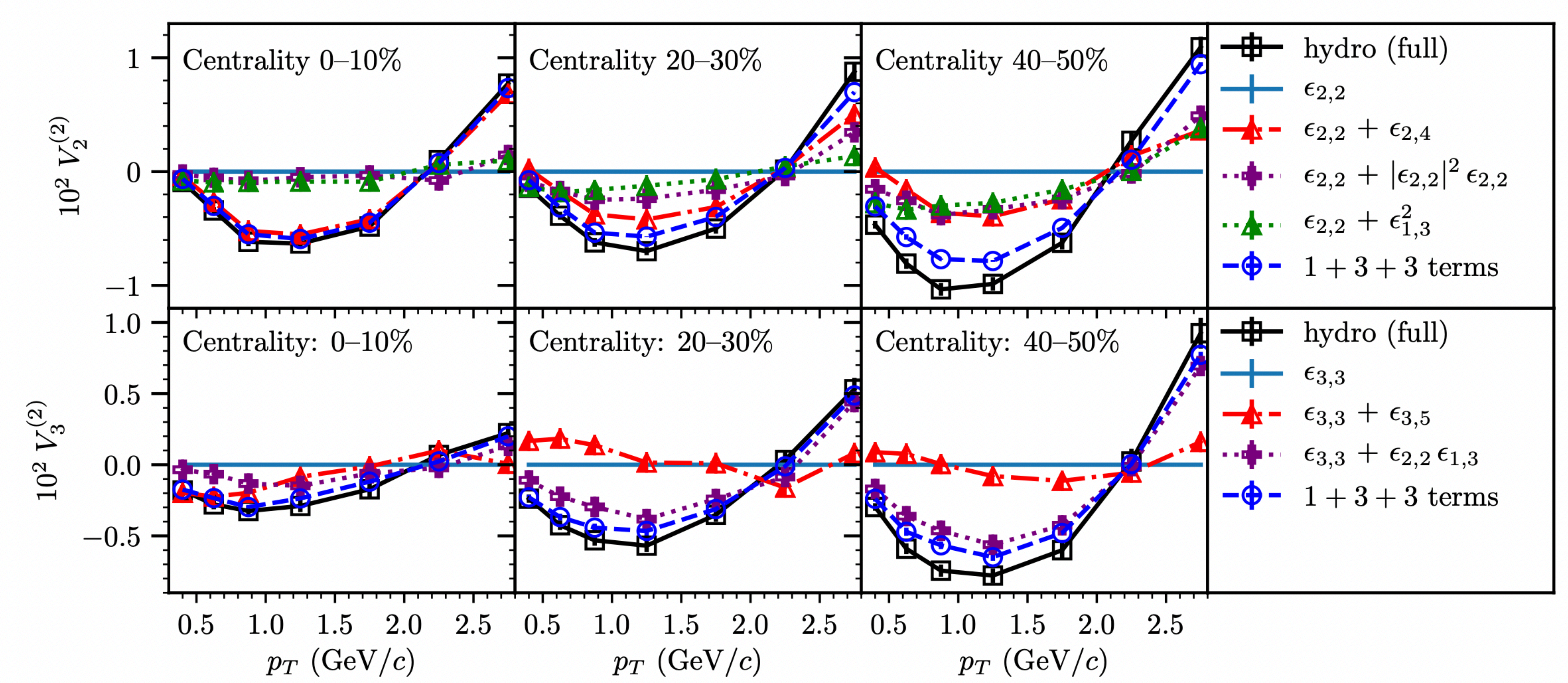




4-particle correlations



$v_n(p_T)$ mapping



Hippert et al, *Phys.Rev.C* 102 (2020) 6, 064909