TRACKING THE DYNAMICS OF SYSTEM GEOMETRY USING A HYBRID-HYDRODYNAMIC SIMULATION

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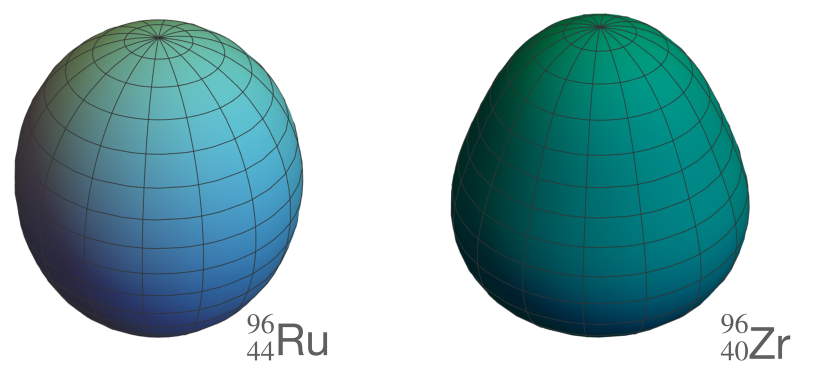
Introduction

- $^{96}_{44}$Ru + $^{96}_{44}$Ru and $^{96}_{44}$Zr + $^{96}_{44}$Zr at $\sqrt{s_{NN}} = 200 \ GeV$ studied by STAR
- Same atomic mass but different nuclear geometry



- STAR results from PRC **105**, 014901 (2022) show small differences in observables from each system
- Differences are attributed to different nuclear structures, bridging high-energy nuclear physics and low-energy nuclear physics

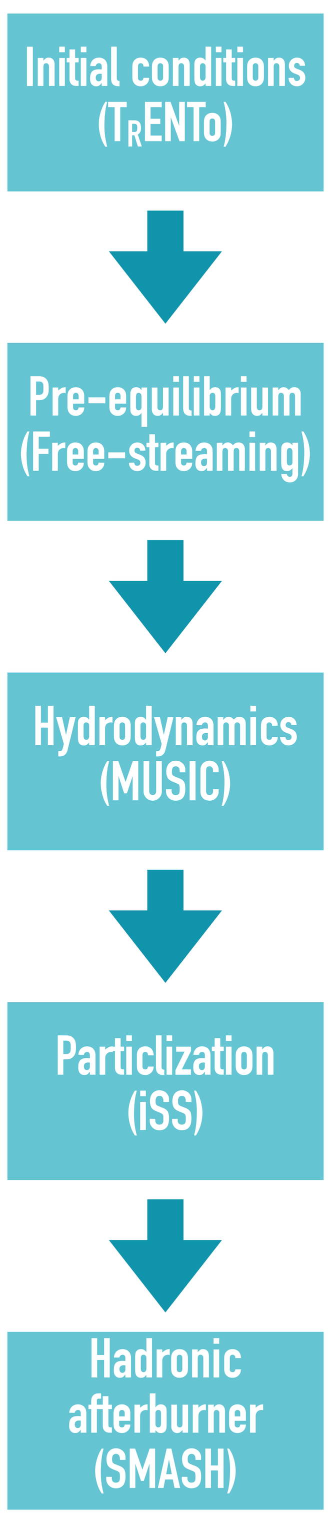
OBJECTIVES

- To perform a systematic analysis (see Table I) of how differences in initial state geometry are carried out to the final state
- To study how observables sensitive to nuclear geometry are dependent on pre-equilibrium, hydrodynamics and hadronic transport

Method

Hybrid-hydrodynamic

- State-of-the-art hybrid hydrodynamics simulates different stages of evolution
- X-SCAPE framework (Putschke et al, arXiv:1903.07706, 2019) is used with parameters from PRC **103**, 054904 (2021)
- 50k nuclear configurations are generated. For each event, two configurations are randomly chosen as input for T$_R$ENTo (Moreland et al, PRC **92**, 011901, 2015)
- Two different free-streaming times are considered:
  - $\tau_{FS} = 1.0$ (fm/c)
  - $\tau_{FS} = 1.46 \left(\dfrac{\{\varepsilon\}}{4 \ Gev/fm^2} \right)^{0.031}$
  - $\{\varepsilon\}$ denotes the average initial energy density of a given event
- Results from different stages of the simulation will be compared to see the effects of those stages, focusing on ratios between Ruthenium-like system and Zirconium-like ones



Nuclear configurations

- Nucleons are sampled from deformed Woods-Saxon distribution to be used as input for T$_R$ENTo

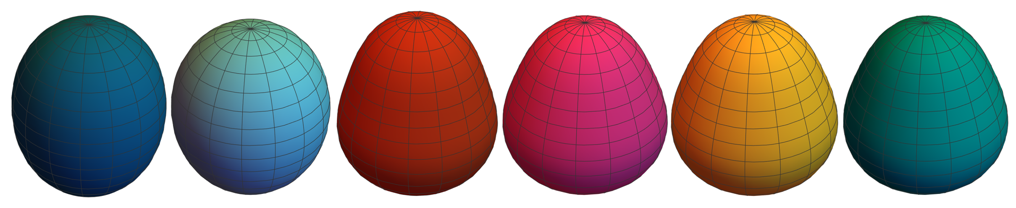
$$P(r,\theta,\varphi) = \frac{\rho_0}{1+\exp\{[r-\mathcal{R}(\theta,\varphi)]/a\}}$$

$$\mathcal{R}(\theta,\varphi) = R_0 \left\{ 1 + \beta_2 \left[Y_2^0(\theta,\varphi)\cos\gamma + \frac{2}{\sqrt{2}} \sin\gamma \, \Re Y_2^2(\theta,\varphi) \right] + \beta_3 Y_3^0(\theta,\phi) \right\}$$

- Parameters are systematically changed from Ru (case 2) to Zr (case 6), with one additional case to study triaxiality effects (case 1)

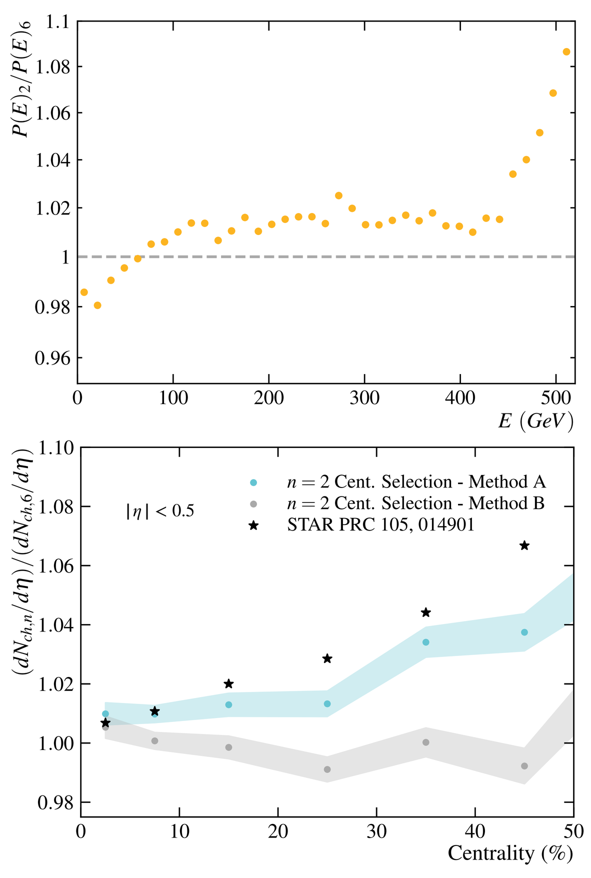
Table I - Nuclear geometry parameters

	R_0 (fm)	a (fm)	β_2	β_3	γ
Case 1	5.09	0.46	0.16	0	$\pi/6$
Case 2	5.09	0.46	0.16	0	0
Case 3	5.09	0.46	0.16	0.20	0
Case 4	5.09	0.46	0.06	0.20	0
Case 5	5.09	0.52	0.06	0.20	0
Case 6	5.02	0.52	0.06	0.20	0



Centrality selection

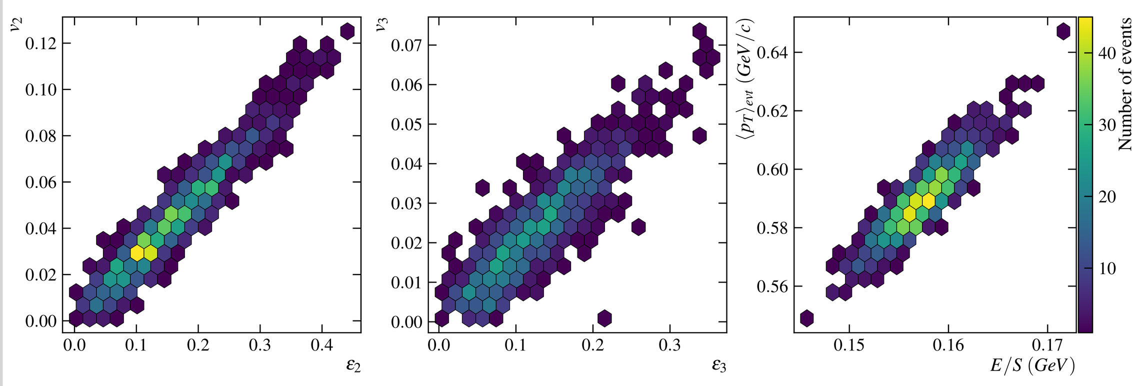
- Differences in probability of an event having total energy E leads to two centrality selection methods
- For Method A, different energy bins for a given centrality are defined for each case of Table I. For Method B, all cases are combined to define common energy bins
- This can affect $dN_{ch}/d\eta$ ratios, but ratios of $\langle p_T \rangle$, $v_2\{2\}$ and $v_3\{2\}$ are not affected



10k full hybrid-hydrodynamic events

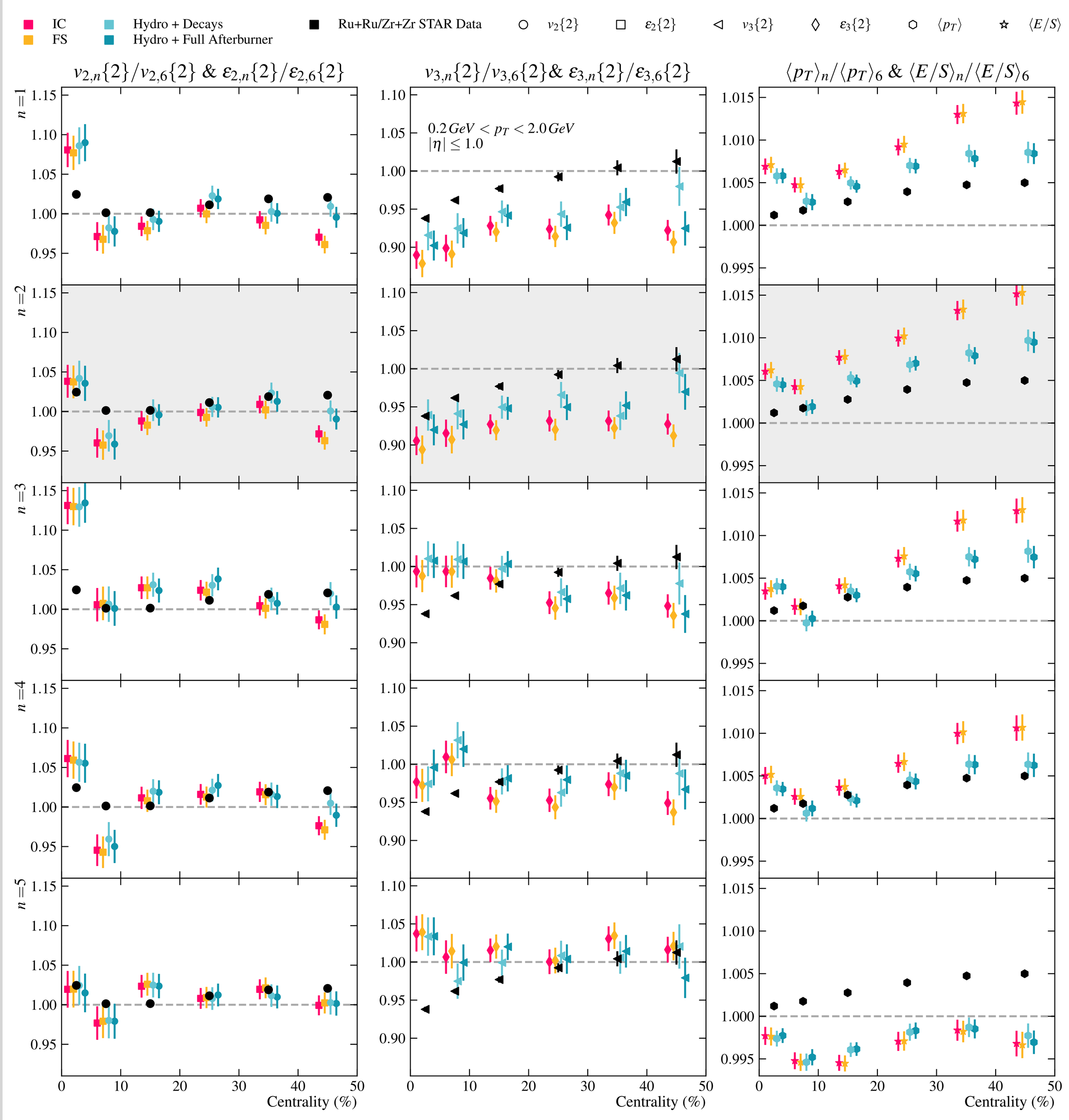
Results

Hydrodynamics results



Relationship between initial state and final state for flow variables (Case 6, 5-10% centrality)

- There are well known relations $v_2 = \kappa_2 \varepsilon_2$ and $v_3 = \kappa_3 \varepsilon_3$ that connect initial conditions to final states. Furthermore, is possible to write a similar relation $\langle p_T \rangle_{evt} = \kappa_{p_T} E/S$ (Giacalone et al, PRC **103**, 024909, 2021)



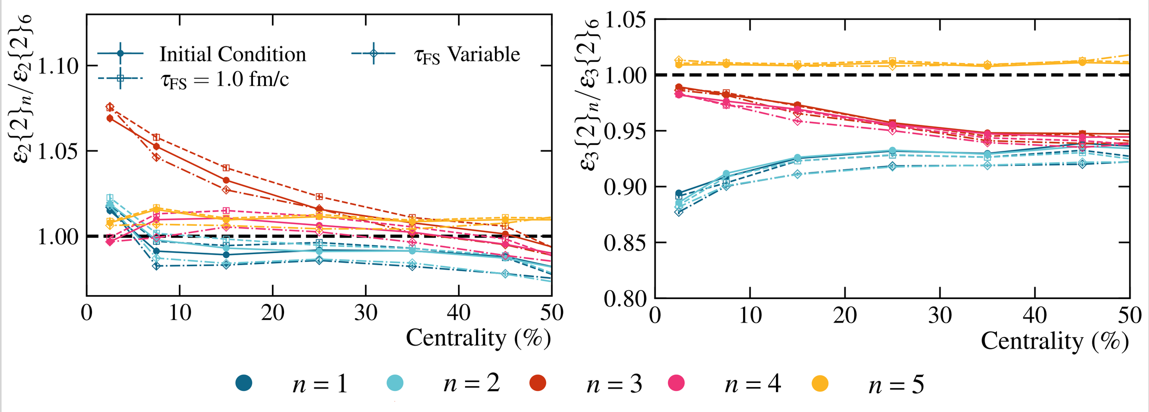
Comparison of ratios computed with initial state estimator (**w** and **w/o** FS) and with flow observables (**w** and **w/o** transport). In the figure we have ~ 20k events for each case and have used Method A for centrality selection. STAR data for $v_2\{2\}$ and $v_3\{2\}$ from PRC **105**, 014901 (2022) and for $\langle p_T \rangle$ from Acta Phys. Polon. Supp., 16(1), 30 (2023)

- From the figure $v_{2,n}\{2\}/v_{2,6}\{2\} \approx \varepsilon_{2,n}\{2\}/\varepsilon_{2,6}\{2\}$ and $v_{3,n}\{2\}/v_{3,6}\{2\} \sim \varepsilon_{3,n}\{2\}/\varepsilon_{3,6}\{2\}$
- Free-streaming and hadronic afterburner have minimal effects for these ratios

- For Cases 1 to 4, $\langle E/S \rangle_n/\langle E/S \rangle_6$ is up to 1% greater than $\langle p_T \rangle_n/\langle p_T \rangle_6$ and this difference decreases for more central collisions
- $\langle p_T \rangle_5/\langle p_T \rangle_6 \approx \langle E/S \rangle_5/\langle E/S \rangle_6$ for all centralities. This indicates that κ_{p_T} is sensitive to nuclear geometry, specially to nuclear diffuseness a

Initial conditions results

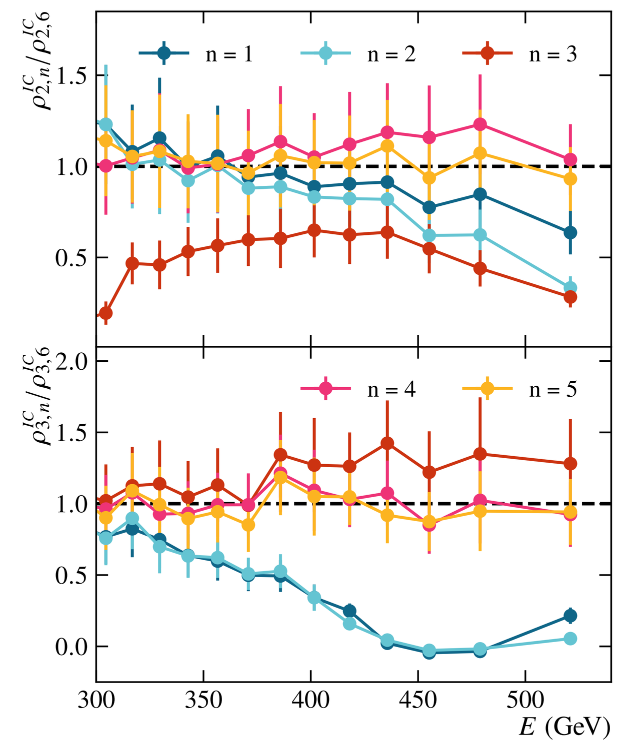
- As just discussed, we can concentrate on initial conditions to study the nuclear geometry



1M ICs +FS using Method B for centrality selection

- Looking at Cases **1** and **2** it is possible to see that neither ε_2 or ε_3 are sensitive to γ
- Comparison between Cases **2** and **3** evidences the non-trivial interplay between β_2 and β_3 in ε_2 and the effect of β_3 in ε_3
- The decrease in ε_2 is explained by the difference in β_2 in Cases **3** and **4**. Those cases show that ε_3 is not sensitive to β_2
- Comparing Cases **4** and **5** it is observed that ε_2 is not sensitive to a, while ε_3 is
- Impact of free-streaming fluctuates by up to 1% in ε_2 and 2% in ε_3 indicating that geometric effects persist throughout pre-equilibrium

Other results available at https://arxiv.org/pdf/2305.03703.pdf



Pearson correlation coefficient between ε_n and E/S. 20M ICs for Cases 1/2 and 10M for the others, using Method B for centrality selection

- ρ_2^{IC} shows sensitivity to γ
- Strong effect of β_3 in ρ_2^{IC} for non-central collisions
- Cases **3** and **4** evidence the effects of β_2 on ρ_2^{IC}
- ρ_3^{IC} is extremely sensitive to β_3 for central collisions
- ρ_2^{IC} and ρ_3^{IC} are not sensitive to a

Conclusions

- For isobars, the results suggest that ratios of ε_2 allow to predict ratios of v_2. Similarly for ε_3 and v_3. Ratios of $\langle E/S \rangle$ do not precisely follow ratios of $\langle p_T \rangle$ unless the diffuseness a is the same
- Results indicate that $\rho_{2,3}^{IC}$ can be used together with $\varepsilon_{2,3}$ to better constraint the nuclear structure parameters at least for central collisions, but more statistics to calculate $\rho_{2,3}$ is necessary (available soon)
- Free-streaming and hadronic transport effects are small or nonexistent when considering ratios between different nuclear configurations

Acknowledgments

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