AMPT simulation with clustering & nuclear structure effects

Guo-Liang Ma
(Fudan University)

[1]Xin-Li Zhao and GLM, Phys.Rev.C 106 (2022) , 034909, arXiv: 2203.15214

[2] Xin-Li Zhao, GLM, You Zhou, Zi-Wei Lin, Chao Zhang, arXiv:2404.09780

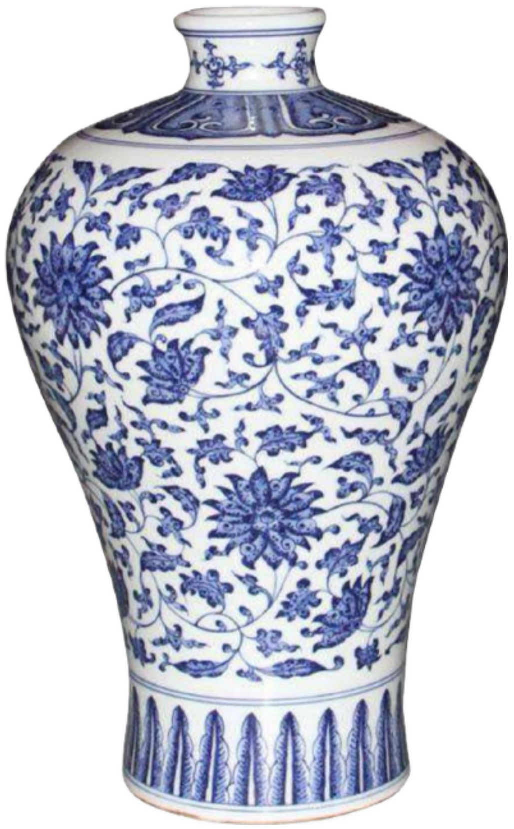
[3] Pei Li, Xin-Li Zhao, GLM, et al., in progress

Outline

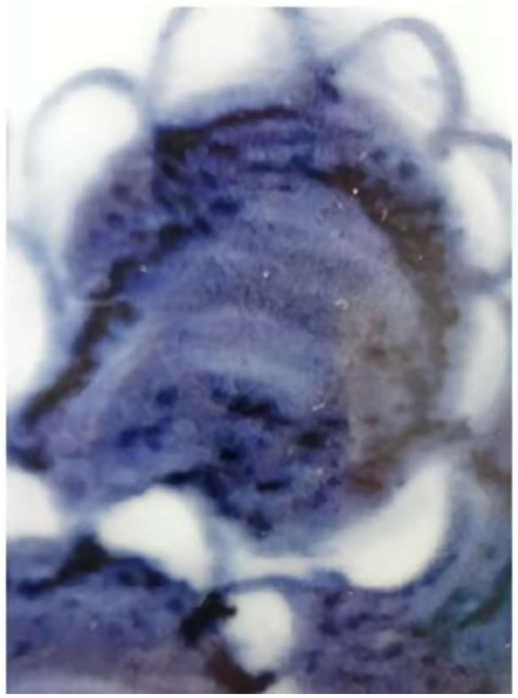
- Introduction
- AMPT simulation on isobar collisions at 200 GeV
- AMPT simulation on O+O collisions at 200 GeV
- Summary and outlook

Nuclear structure vs porcelain design

梅瓶 (Meiping vase)



青花晕散(Aqua Diffusion)



钧窑 (Jun kiln plate)

deformation

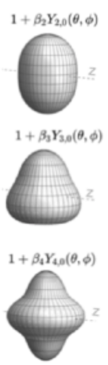
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

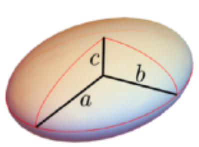
$$R(\theta,\phi) = R_0\left(1+\beta_2[\cos\gamma Y_{2,0}+\sin\gamma Y_{2,2}]+\beta_3\sum_{m=-3}^{3}\alpha_{3,m}Y_{3,m}+\beta_4\sum_{m=-4}^{4}\alpha_{4,m}Y_{4,m}\right)$$

Quadrupole: 四极形变

Octupole: 八极形变

Hexadecapole: 16极形变





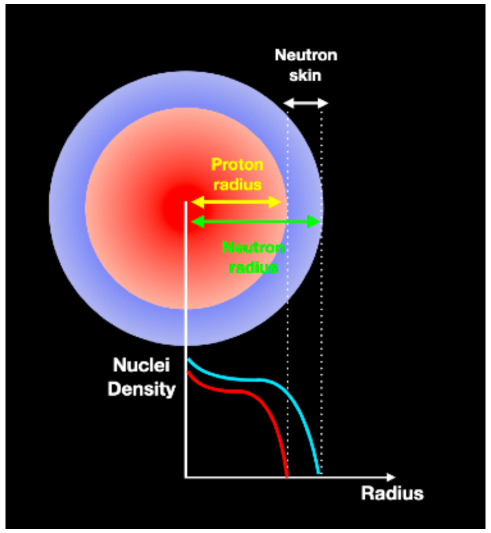
$0 \le \gamma \le \pi/3$

Prolate: a=b<c → β_2, γ=0

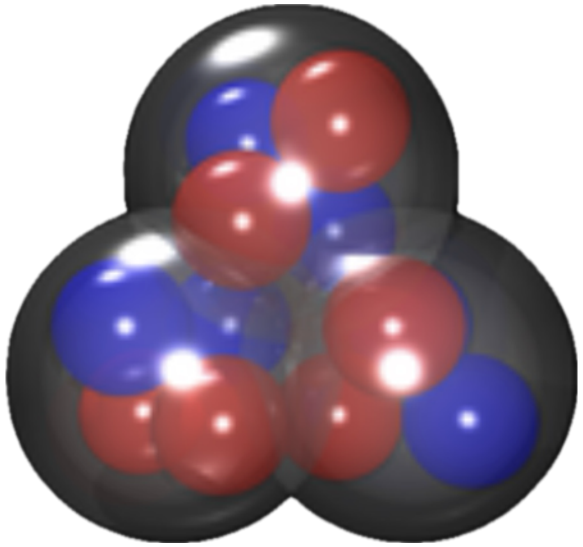
Oblate: a<b=c → β_2, γ=π/3

Triaxial: a<b<c → β_2, γ=π/6

neutron skin/halo



α-cluster



Study nuclear structure using heavy-ion experimental observables

deformation

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

$$R(\theta,\phi) = R_0\left(1+\beta_2[\cos\gamma Y_{2,0}+\sin\gamma Y_{2,2}]+\beta_3\sum_{m=-3}^{3}\alpha_{3,m}Y_{3,m}+\beta_4\sum_{m=-4}^{4}\alpha_{4,m}Y_{4,m}\right)$$

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四极形变

Octupole:
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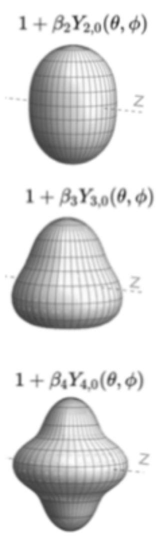
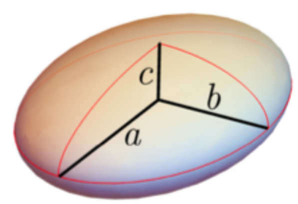
Hexadecapole:
16极形变





$0 \le \gamma \le \pi/3$

Prolate: a=b<c → β_2, γ=0

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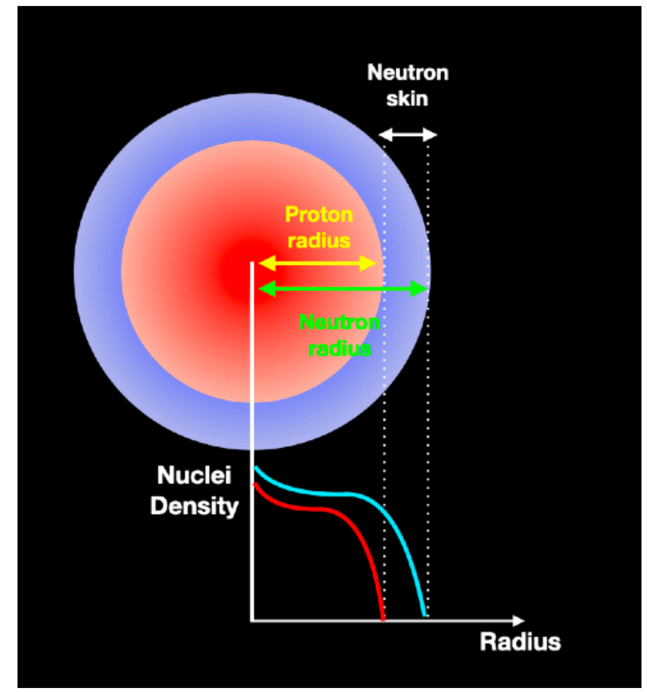
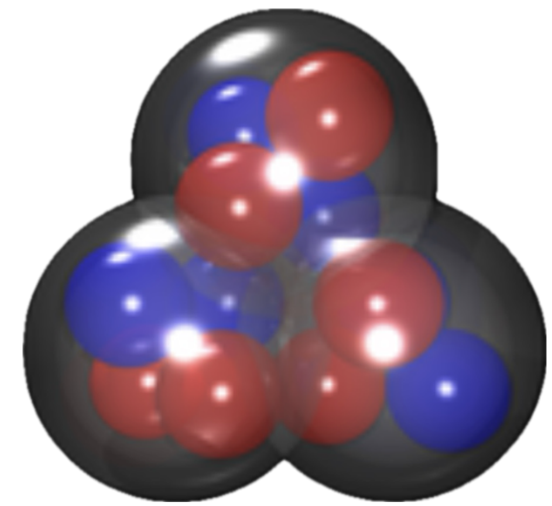
neutron skin

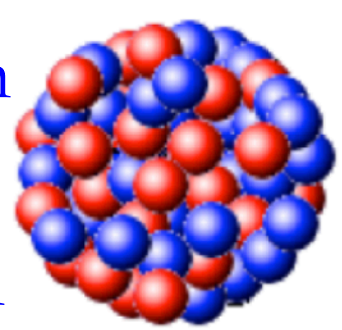


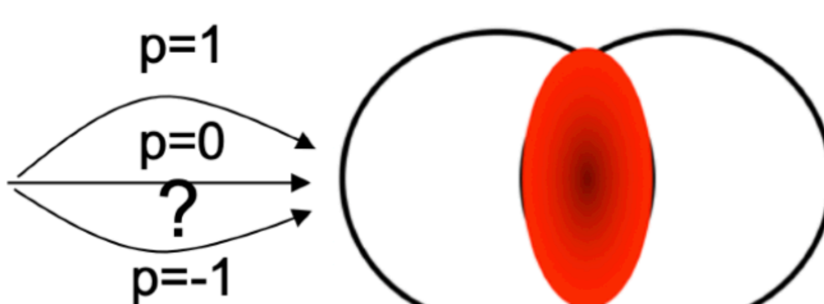
α-cluster



Nucleus

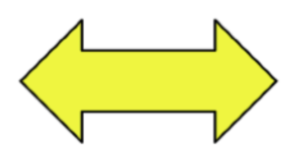
deformation
α-cluster
neutron skin

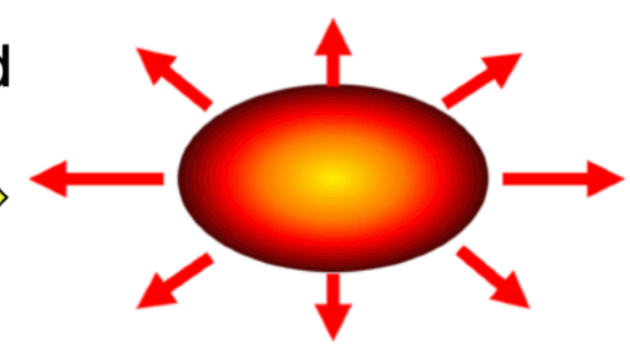




Initial condition $v_n = k_n \varepsilon_n$ Final state

understood



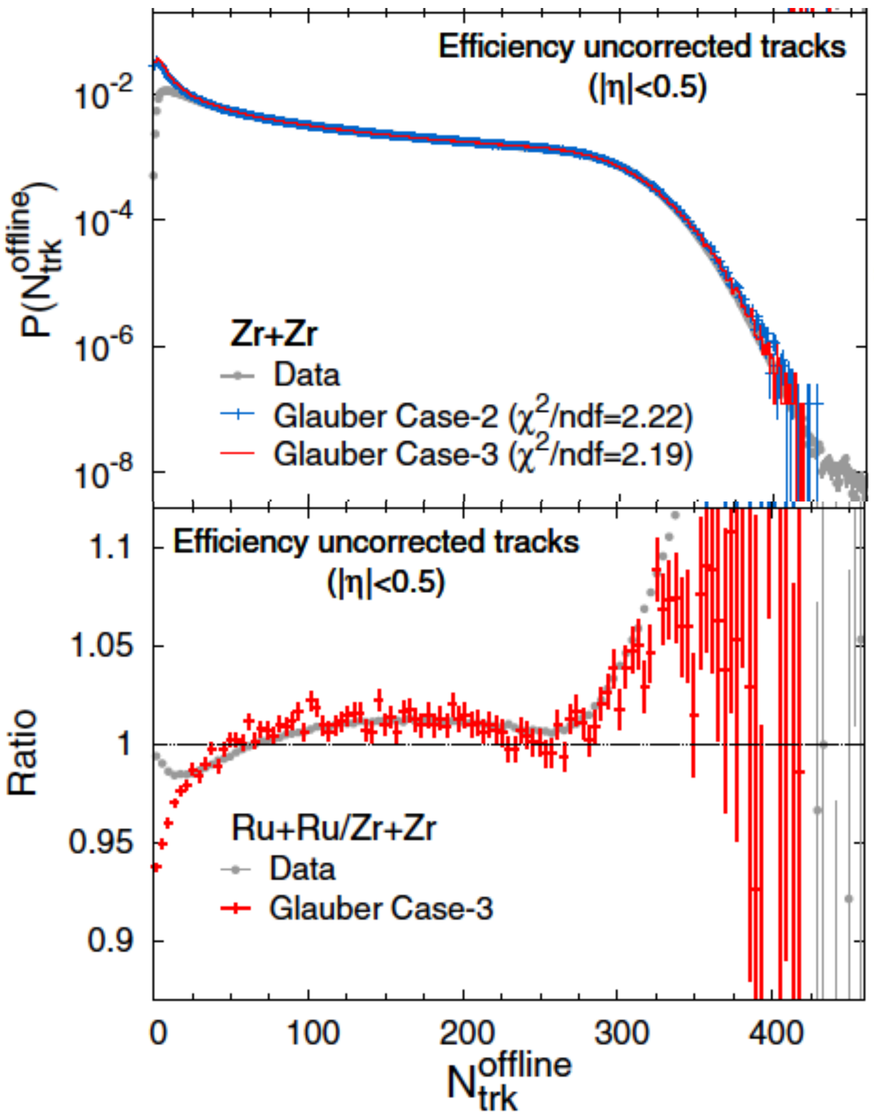


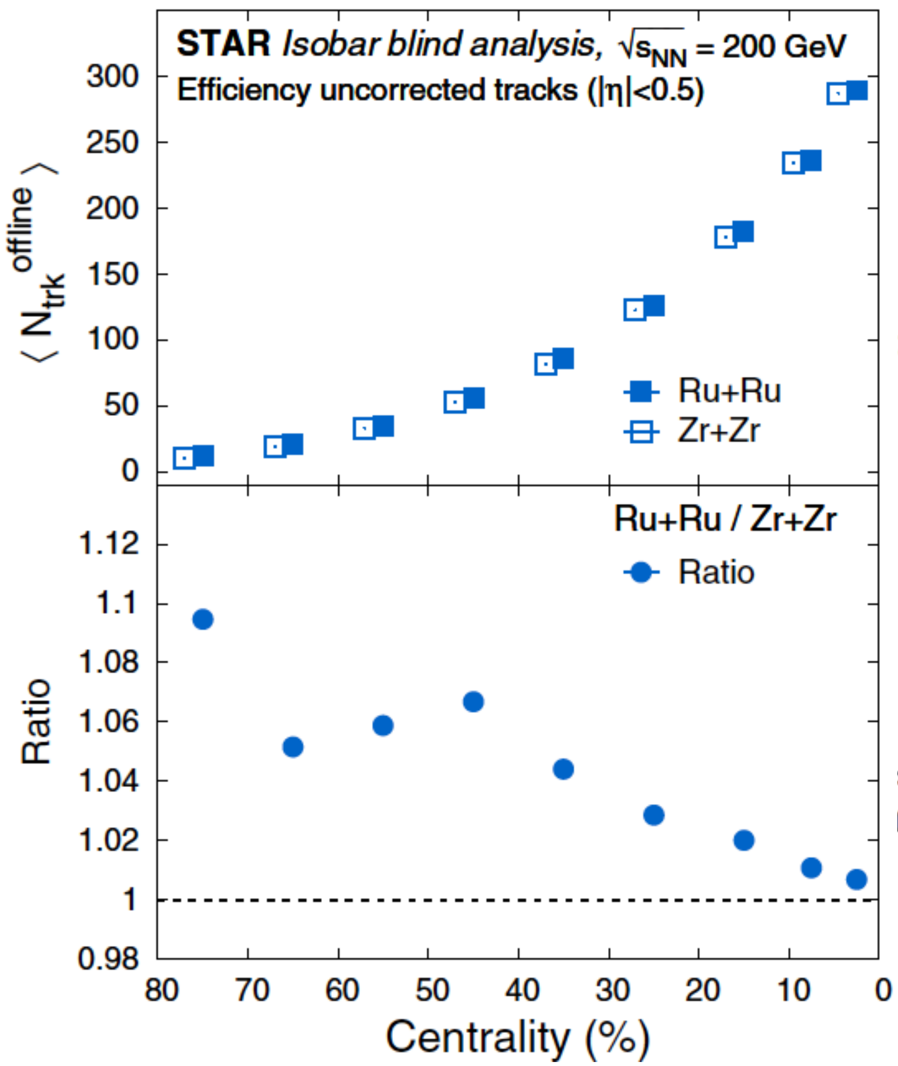
Impact on initial geometry

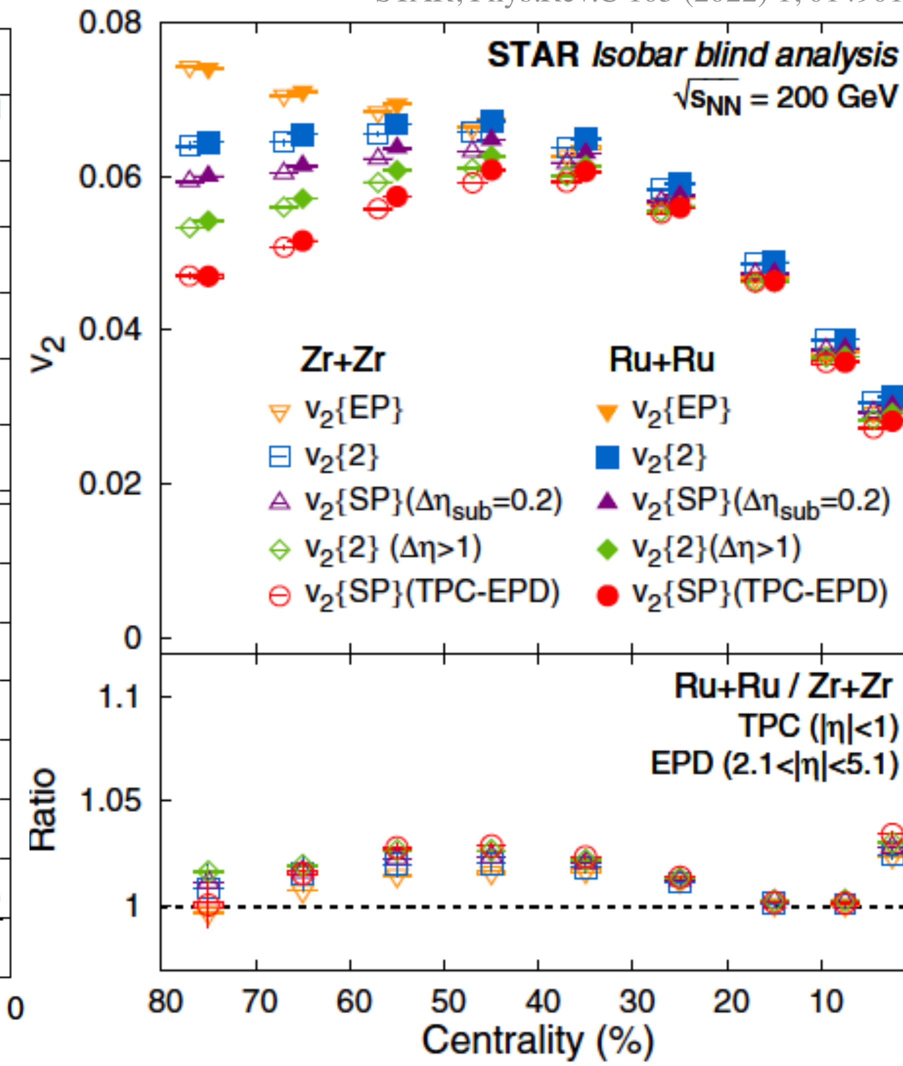
Reflect on collective flow

Different CME backgrounds between isobar collisions

STAR, Phys.Rev.C 105 (2022) 1, 014901

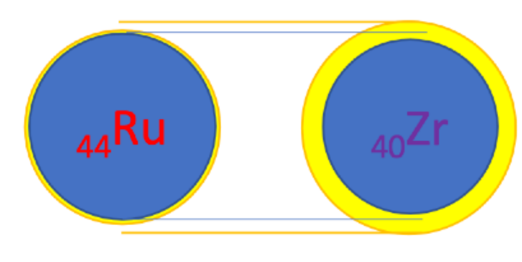






- Differences in multiplicity distribution, <Nch> and v2 between two isobar systems.

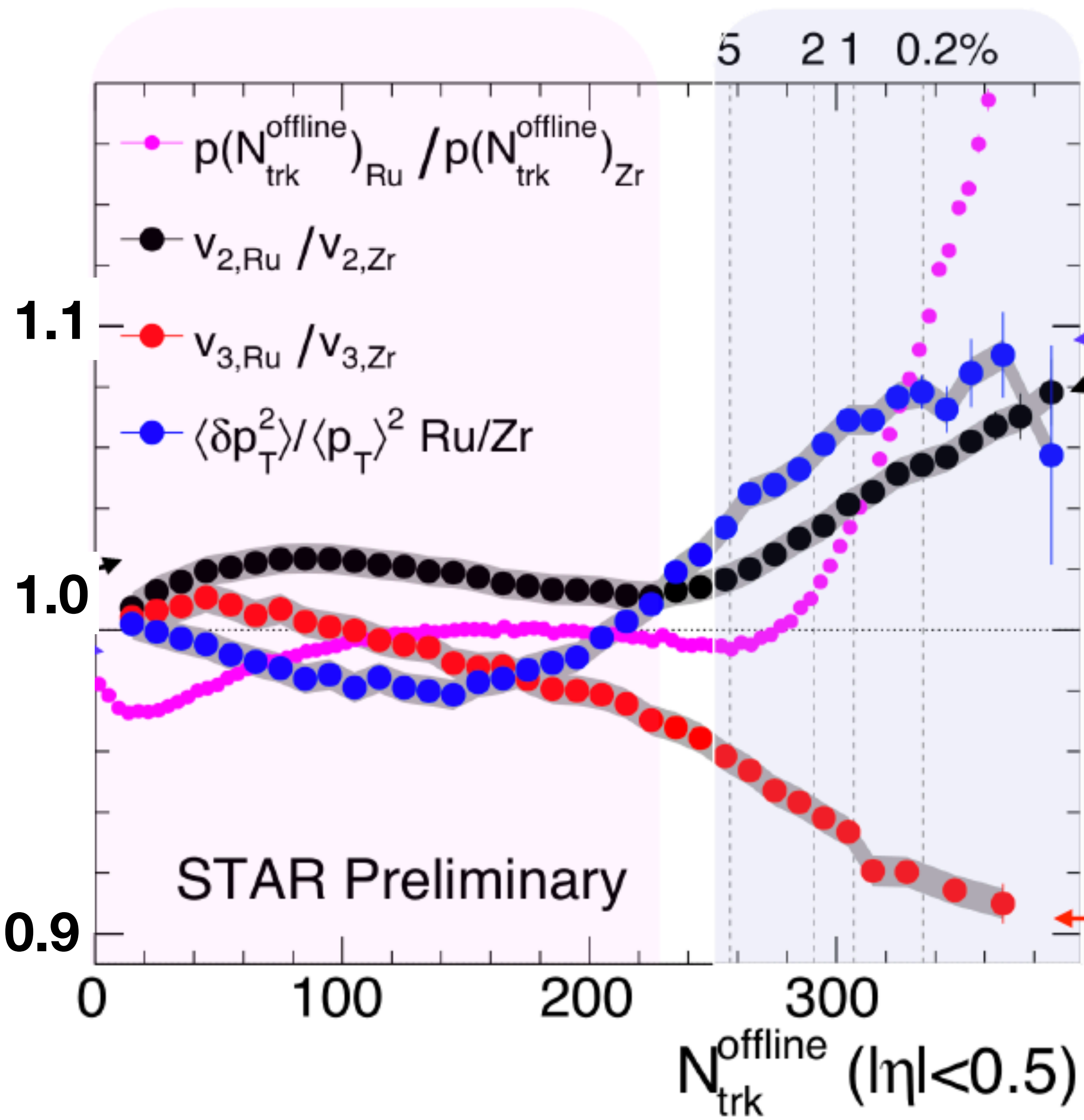
	Case-1 [83]			Case-2 [83]			Case-3 [113]		
Nucleus	R (fm)	a (fm)	β_2	R (fm)	a (fm)	β_2	R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158	5.085	0.46	0.053	5.067	0.500	0
$^{96}_{40}$Zr	5.02	0.46	0.08	5.02	0.46	0.217	4.965	0.556	0

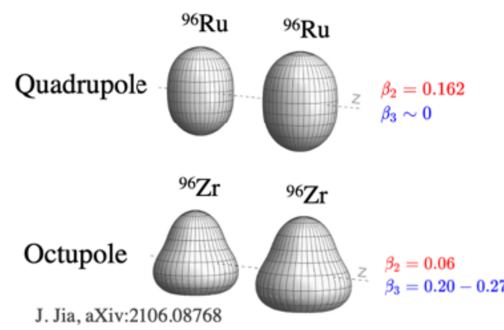


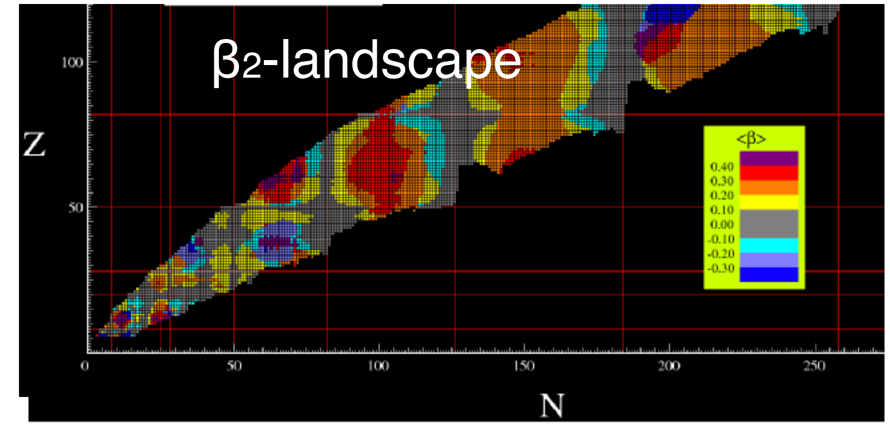
- Related to nuclear deformation/structure.

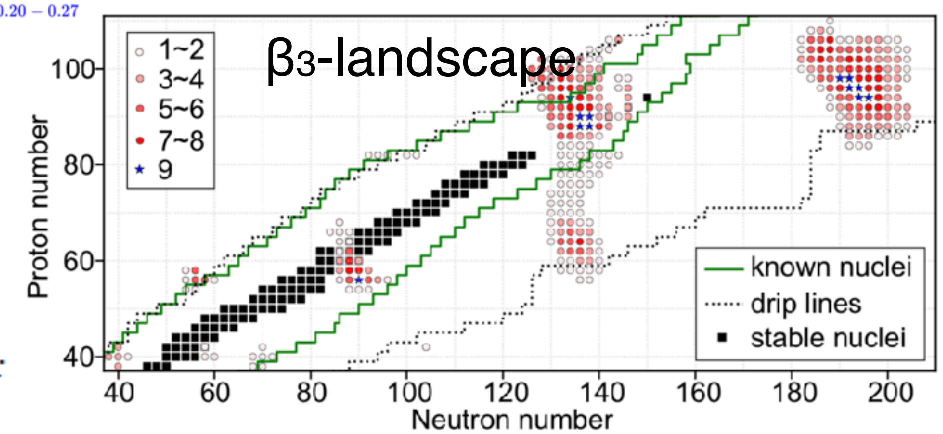
Haojie Xu et al. PRL 121 (2018) 022301
Hanlin Li et al. PRC 98 (2018) 054907

Nuclear structure in relativistic heavy-ion collisions





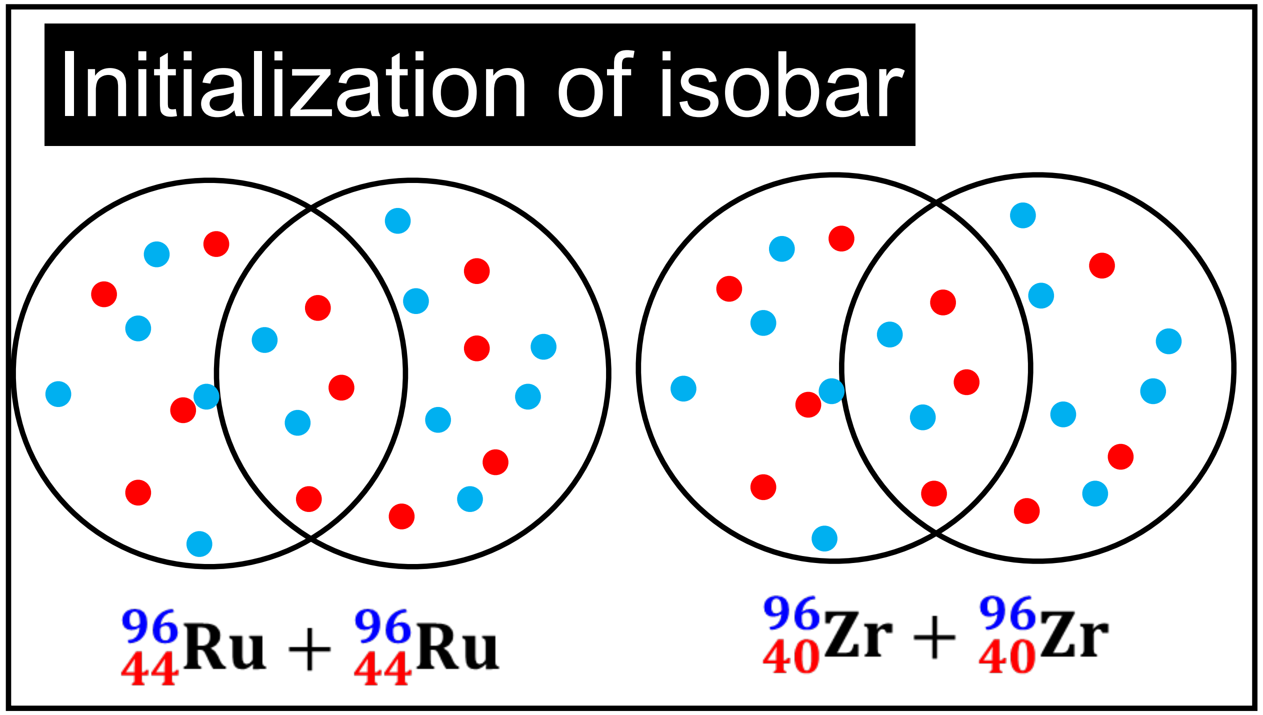




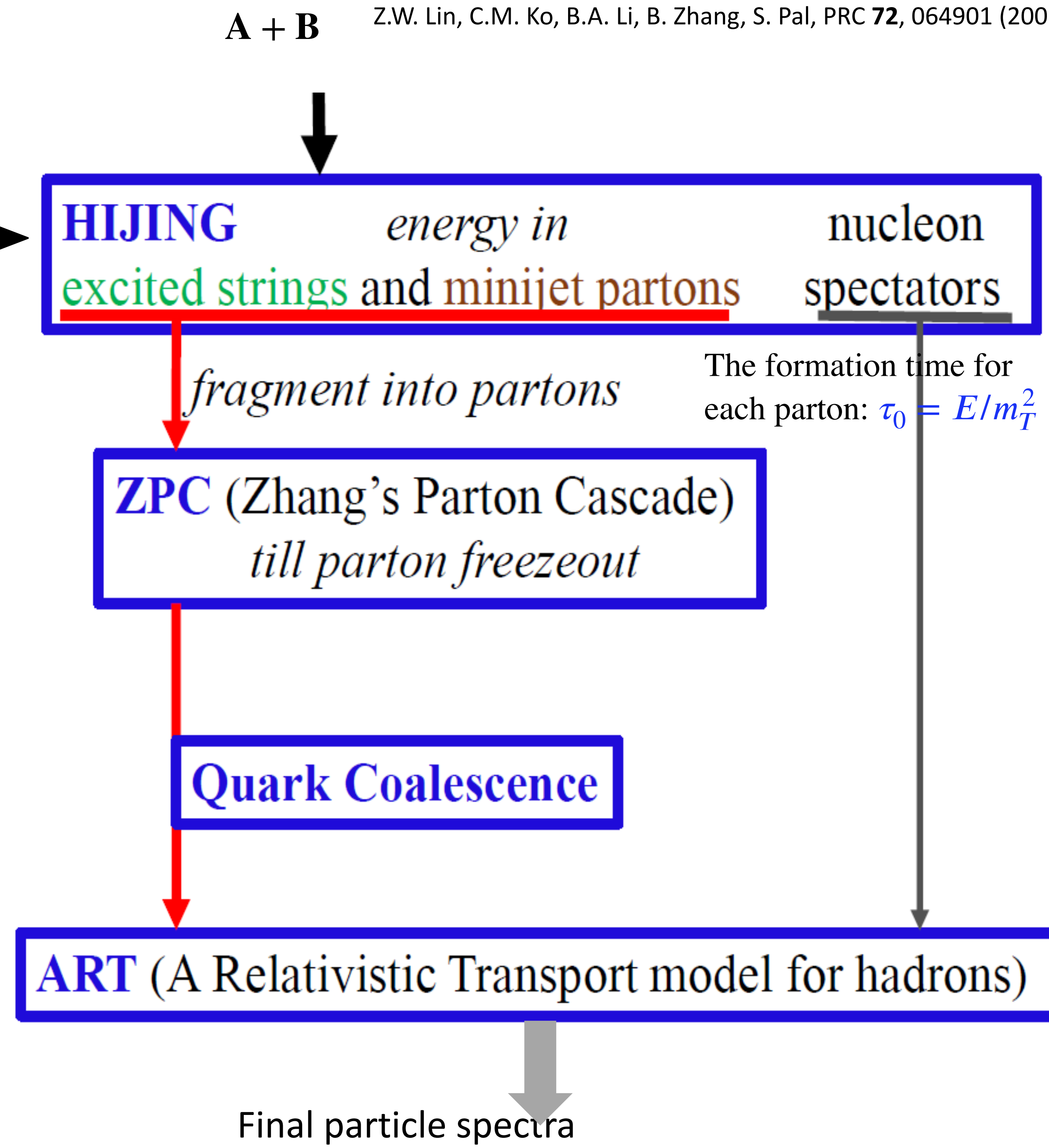
- The ratios of observables between two isobar systems are sensitive to nuclear deformation/structure

STAR, Phys.Rev.C 105 (2022) 1, 014901
H. Li et al., Phys.Rev.C 98 (2018) 5, 054907
H. J. Xu, Phys.Lett.B 819 (2021) 136453
J. Jia, Phys.Rev.C 105 (2022) 4, 044905
J. Jia, Phys.Rev.C 105, 014905 (2022)
C. Zhang and J. Jia, Phys.Rev.Lett. 128 (2022), 022301
G. Giacalone et al., Phys.Rev.Lett. 127 (2021), 242301
J. Jia and C. Zhang, Phys.Rev.C 107 (2023) 2, L021901

Simulating isobar collisions using AMPT

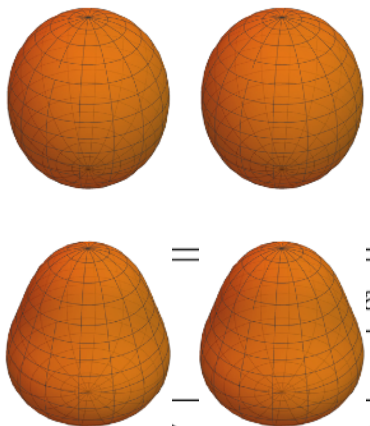


Z.W. Lin, C.M. Ko, B.A. Li, B. Zhang, S. Pal, PRC **72**, 064901 (2005)



Initialization of isobar nuclei with geometry

Woods-Saxon form of spatial distribution of nucleons:

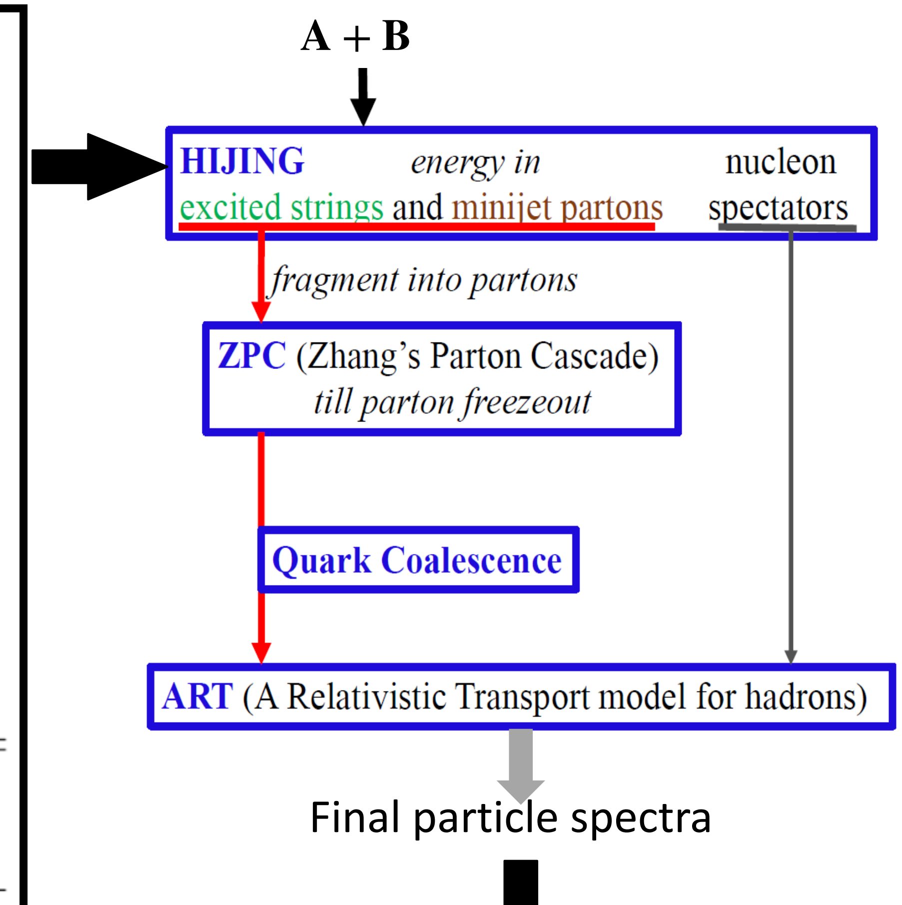


$$\rho(r,\theta,\phi) \propto \frac{1}{1+e^{[r-R_0(1+\beta_2 Y_2^0(\theta,\phi)+\beta_3 Y_3^0(\theta,\phi))]/a}}$$

	ase1			old Case2			Case1			Case2			Case3		
			β_2	R_0	a	β_2	R_0	a	β_2	R_0	a	β_2	R_0	a	β_2
$_{44}$Ru	5.13	0.46	0.13	5.13	0.46	0.03	5.085	0.46	0.158	5.085	0.46	0.053	5.067	0.500	0
$^{96}_{40}$Zr	5.06	0.46	0.06	5.06	0.46	0.18	5.02	0.46	0.080	5.02	0.46	0.217	4.965	0.556	0

	Case4				Case5				Case6				Case7			Case8		
	R_0	a	β_2	β_3	R_0	a	β_2	β_3	R_0	a	β_2	β_3	R_0	a	β_2	R_0	a	β_2
$^{96}_{44}$Ru	5.09	0.46	0.162	0	5.09	0.46	0.162	0	5.09	0.52	0.154	0	5.065	0.485	0.16	5.085	0.523	0
$^{96}_{40}$Zr	5.09	0.52	0.060	0.2	5.02	0.46	0.060	0.2	5.09	0.52	0.060	0.2	4.961	0.544	0.16	5.021	0.523	0

	Case9			Case10			Case11			skin-type			halo-type		
	R_0	a	β_2	R_0	a	β_2	R_0	a	β_2	R_0	a	β_2	R_0	a	β_2
$^{96}_{44}$Ru n	5.075	0.505	0	5.073	0.490	0.16	5.085	0.46	0.158	5.085	0.523	0	5.085	0.523	0
$^{96}_{44}$Ru p	5.060	0.493	0	5.053	0.480	0.16	5.085	0.46	0.158	5.085	0.523	0	5.085	0.523	0
$^{96}_{40}$Zr n	5.015	0.574	0	5.007	0.564	0.16	5.080	0.46	0	5.194	0.523	0	5.021	0.592	0
$^{96}_{40}$Zr p	4.915	0.521	0	4.912	0.508	0.16	5.080	0.34	0	5.021	0.523	0	5.021	0.523	0



- Which is better or worse?
- Three ratios are our judging criteria:

  1) Mult. dist. ratio

  2) <N$_{ch}$> ratio vs centrality

  3) v_2 ratio vs centrality

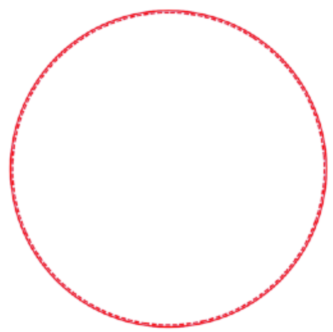
✳ **1 M events for each case are used to test if it can pass the criterion test.**

AMPT performance: Halo-type vs deformation

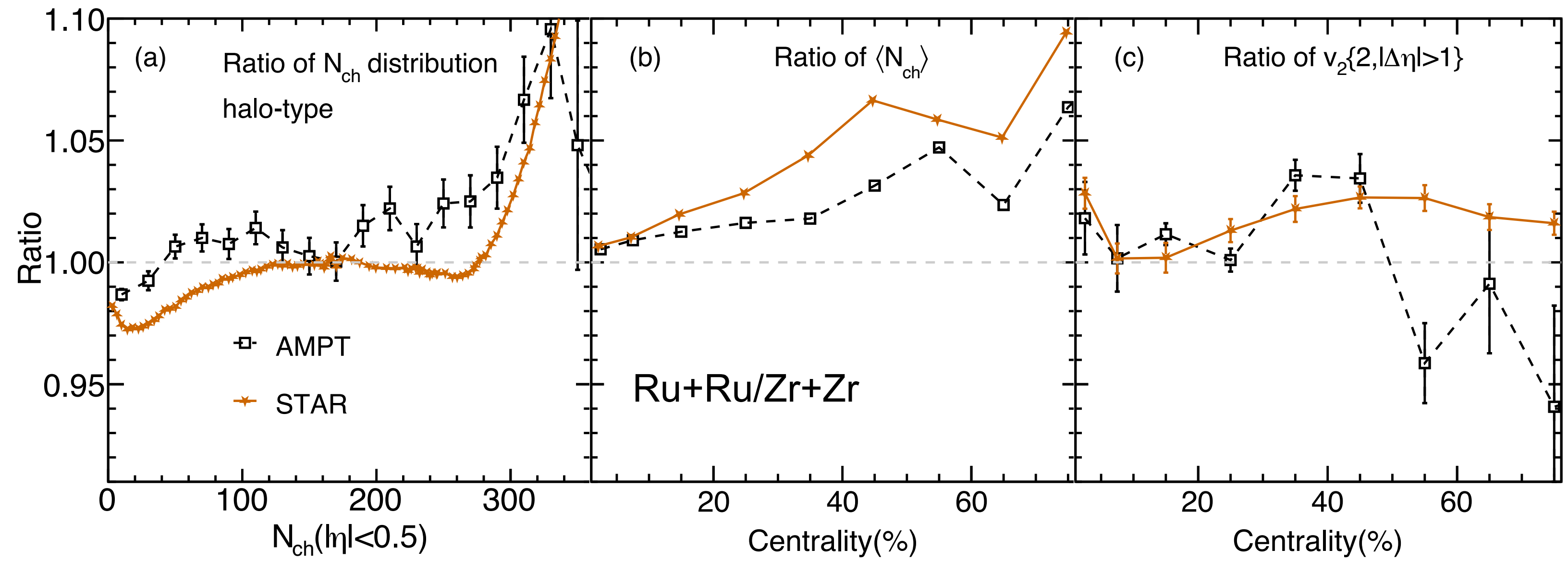
Xin-Li Zhao and GLM, Phys. Rev. C 106, 034909 (2022)

		halo-type		
		R_0	a	β_2
$^{96}_{44}$Ru	n	5.085	0.523	0
$^{96}_{44}$Ru	p	5.085	0.523	0
$^{96}_{40}$Zr	n	5.021	0.592	0
$^{96}_{40}$Zr	p	5.021	0.523	0

Solid: Ru+Ru, Dash: Zr+Zr
Red: neutron, Blue: proton

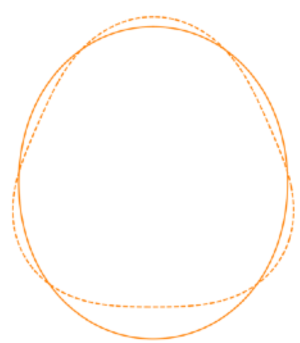


H. j. Xu, H. Li, X. Wang, C. Shen and F. Wang, Phys. Lett. B 819, 136453 (2021)

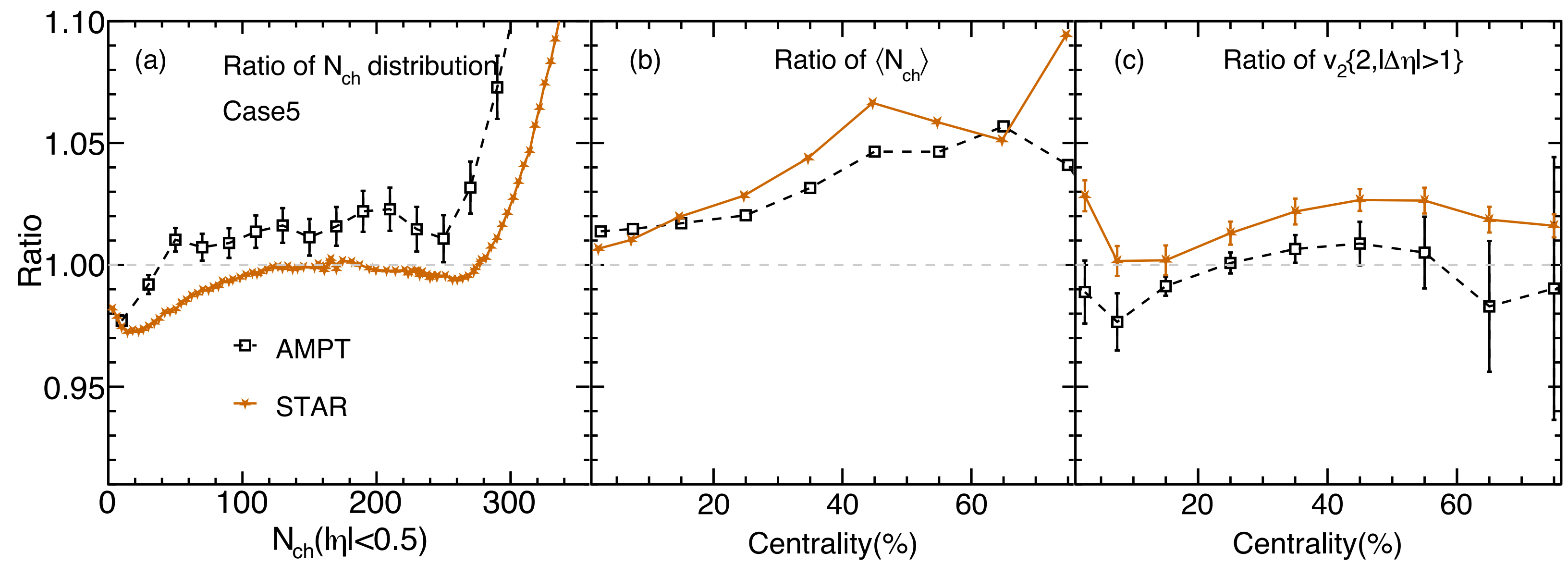


	Case5			
	R_0	a	β_2	β_3
$^{96}_{44}$Ru	5.09	0.46	0.162	0
$^{96}_{40}$Zr	5.02	0.46	0.060	0.2

Solid: Ru+Ru, Dash: Zr+Zr

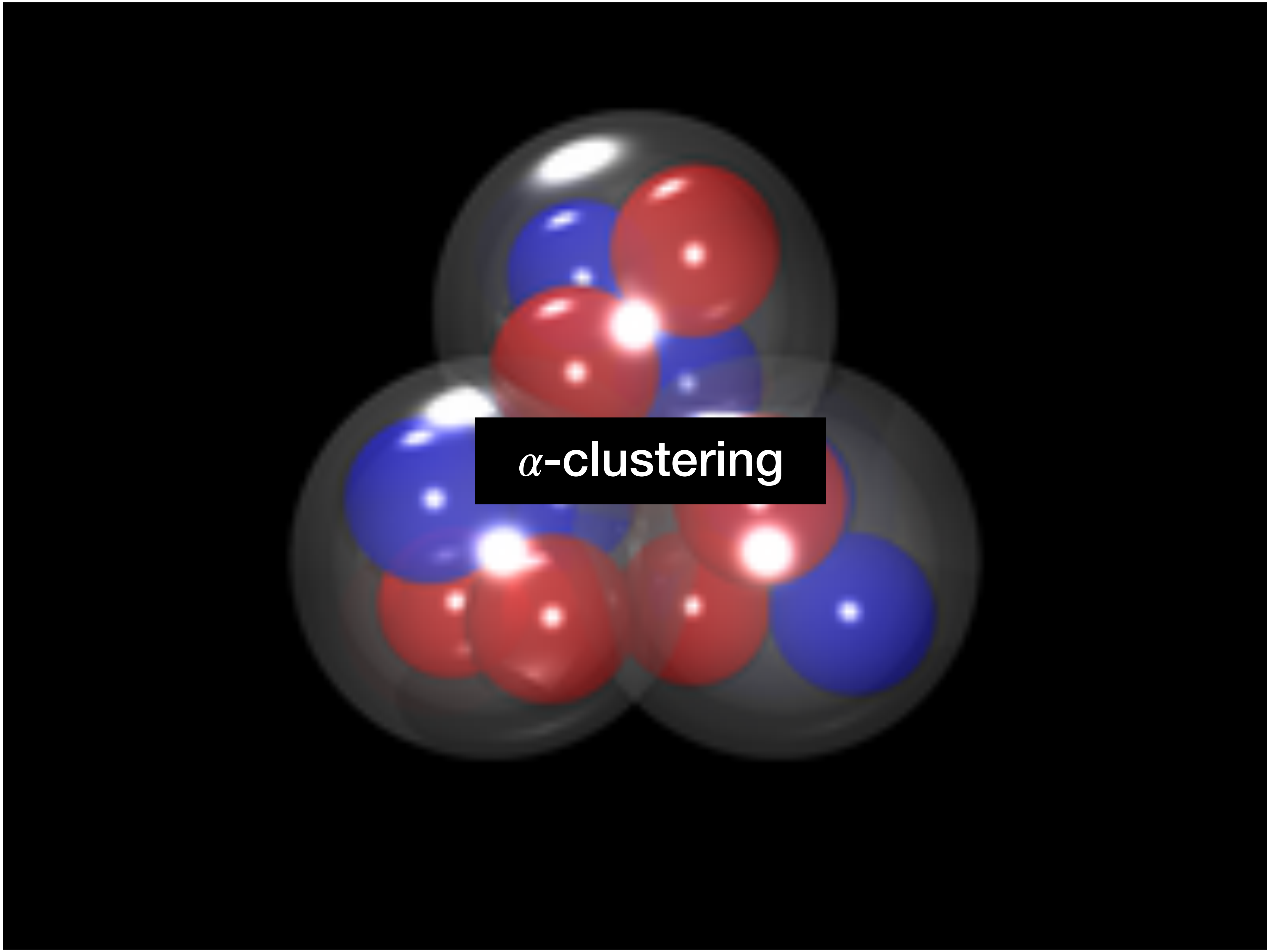


J. Jia and C. J. Zhang, Phys.Rev.C 107 (2023) 2, L021901

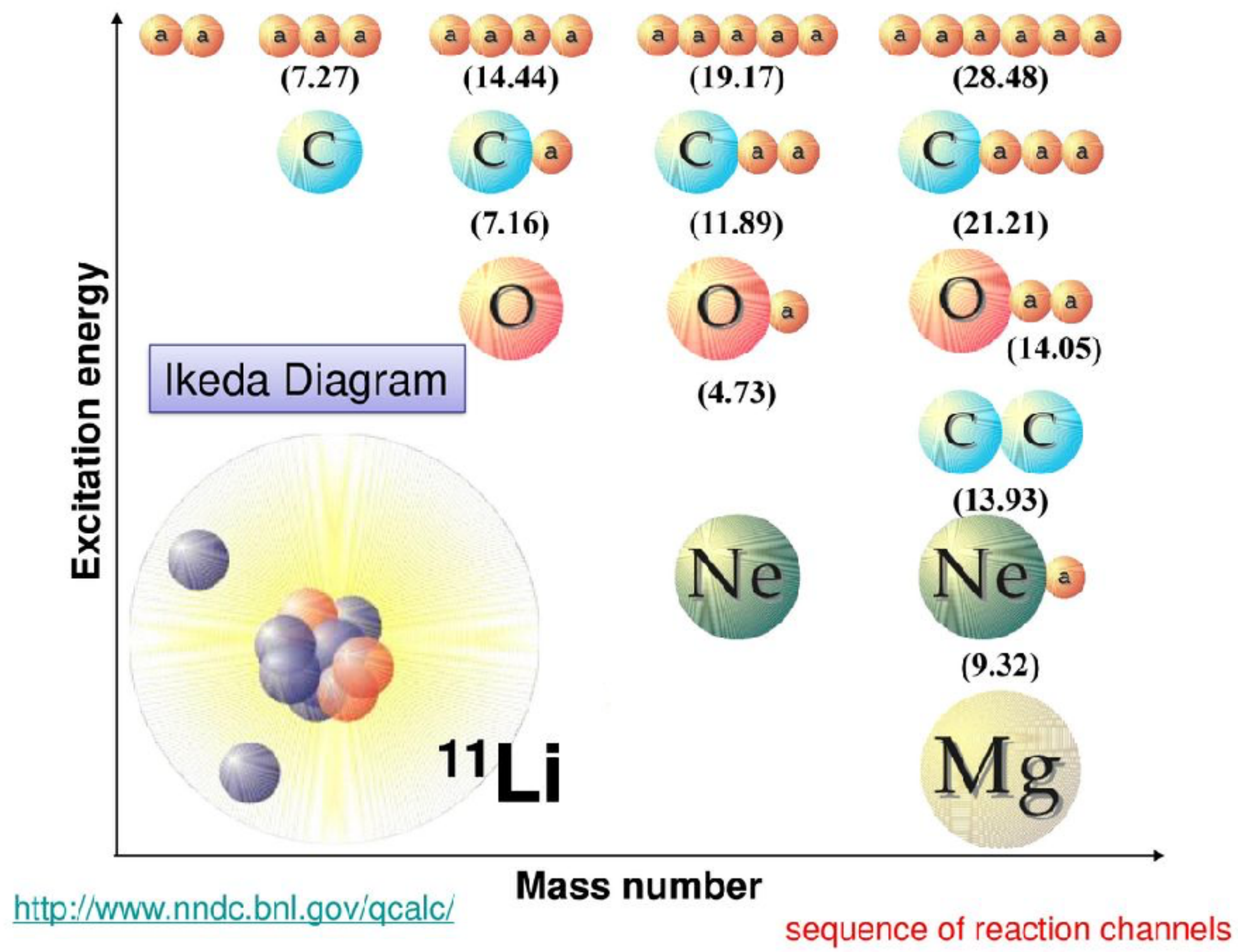


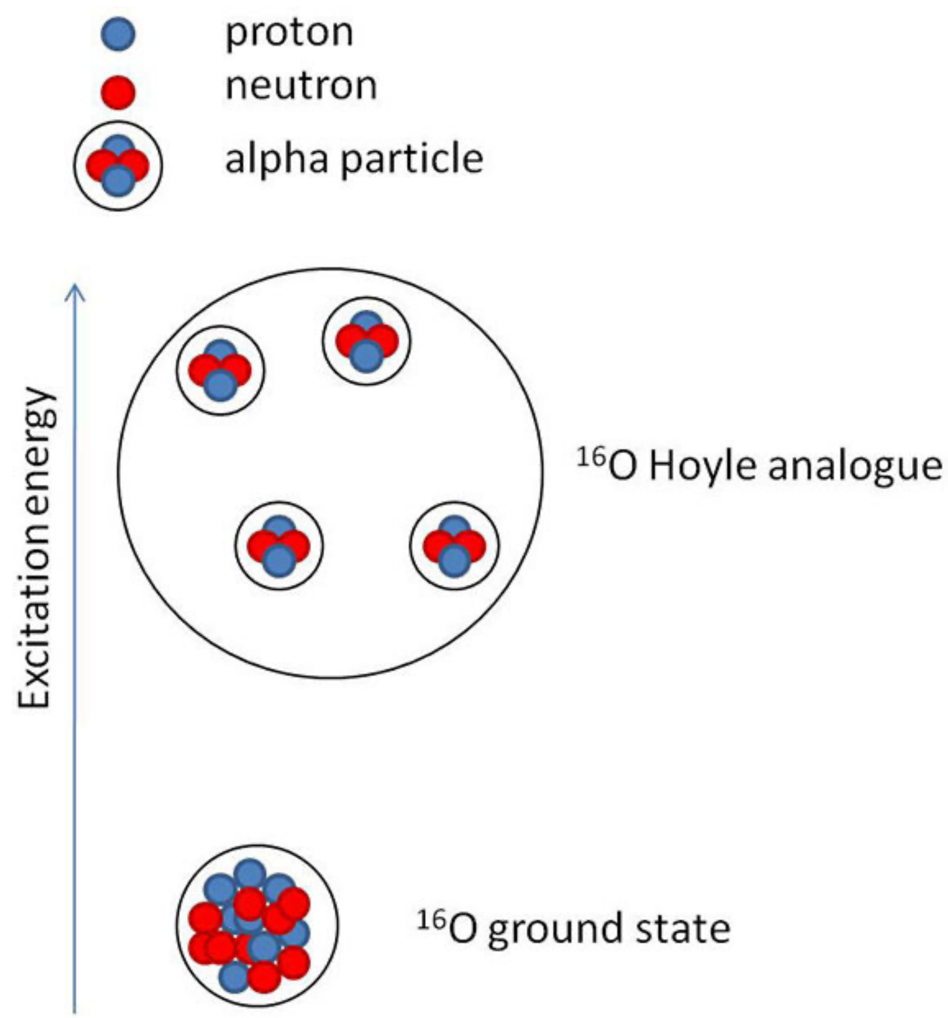
	old Case 1	old Case 2	Case 1	Case 2	Case 3	Case 4
$\langle \chi^2 \rangle$	0.204	0.682	0.255	0.400	0.097	0.053
	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
$\langle \chi^2 \rangle$	0.049	0.224	0.051	0.227	0.057	0.048
	Case 11	skin-type	halo − type	Case 1 w/ β_3	Case 2 w/ β_3	Case 3 w/ β_3
$\langle \chi^2 \rangle$	0.430	0.177	0.047	0.247	0.506	0.166

- Isobar nuclei are with halo-type neutron skin or deformed


α-clustering

Significance of α-clustering structure



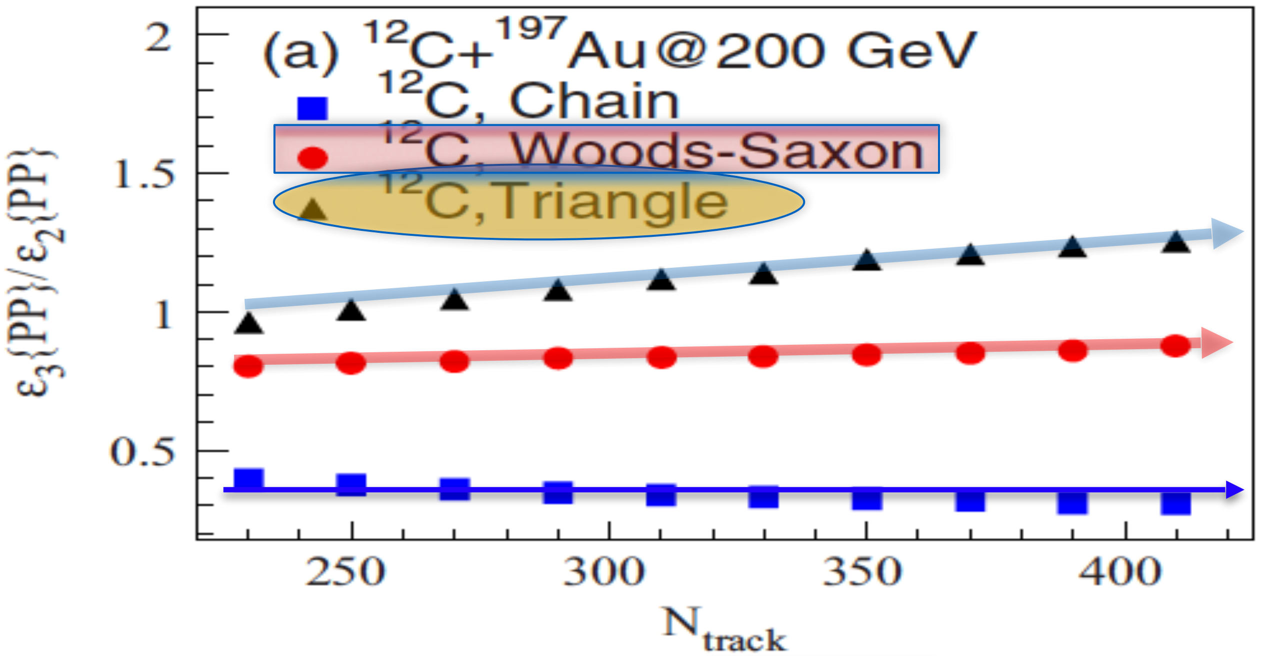


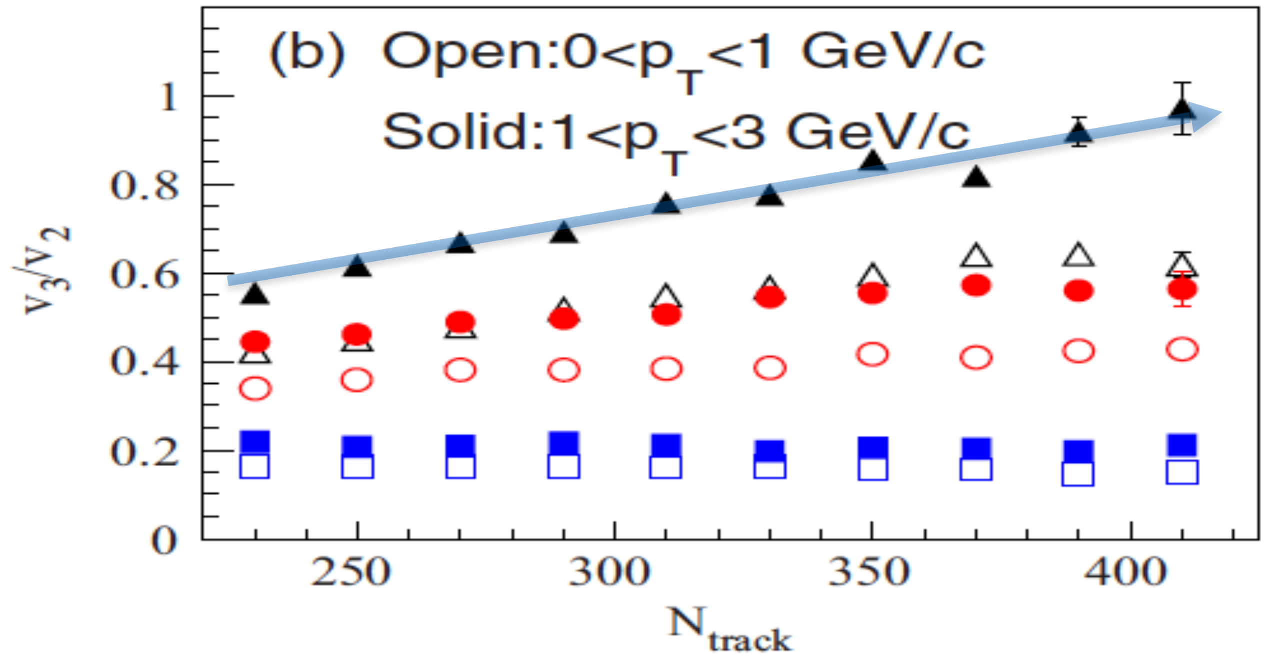
- α-clustering structure inside some nuclei
- The spatial distribution of α-clustering nuclei is diffuse because condensed α-particles are weakly bound
- Heavy-ion collisions are helpful to detect α-clustering structures?

α-cluster effect in C+Au collisions

Song Zhang, Yu-Gang Ma, et al., Phys. Rev. C 95 (2017) 064904.

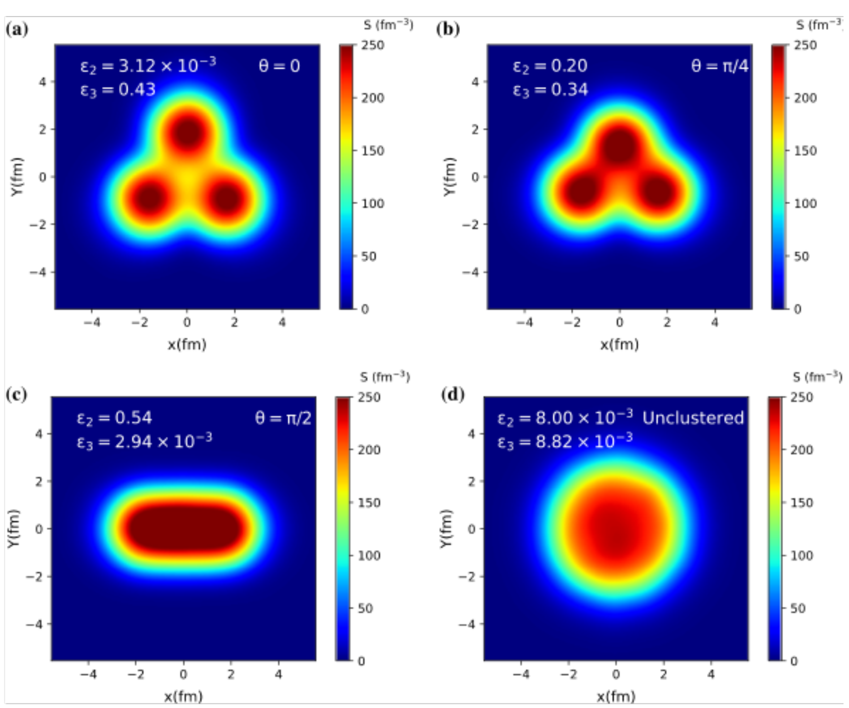
Charged hadron

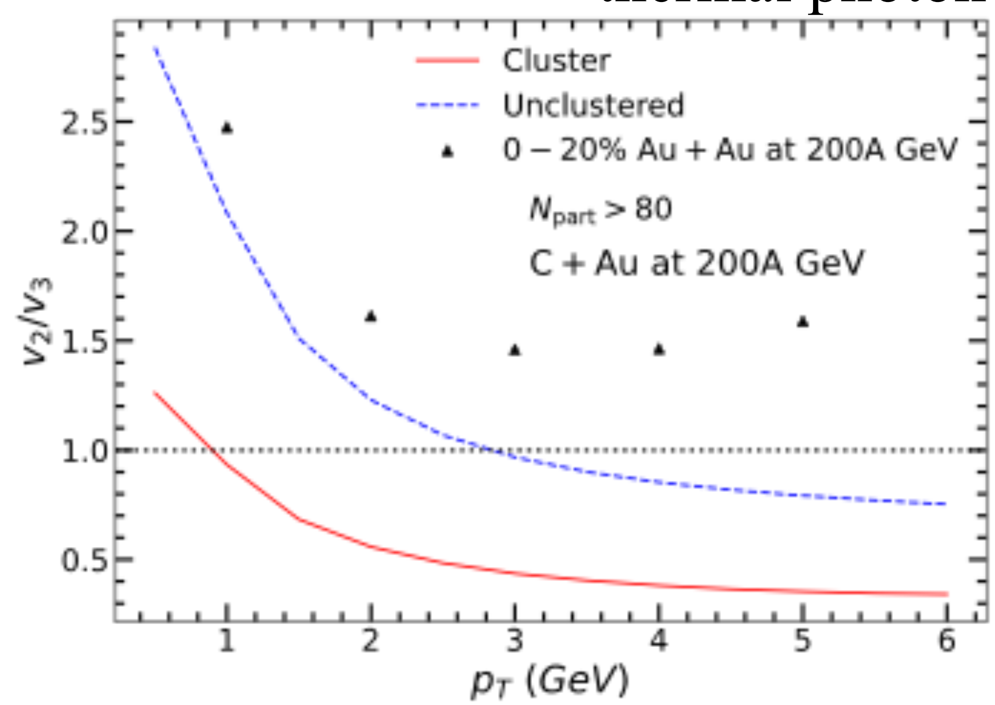




P. Dasgupta, R. Chatterjee, GLM, et al., Phys.Rev.C 107 (2023), 044908

thermal photon

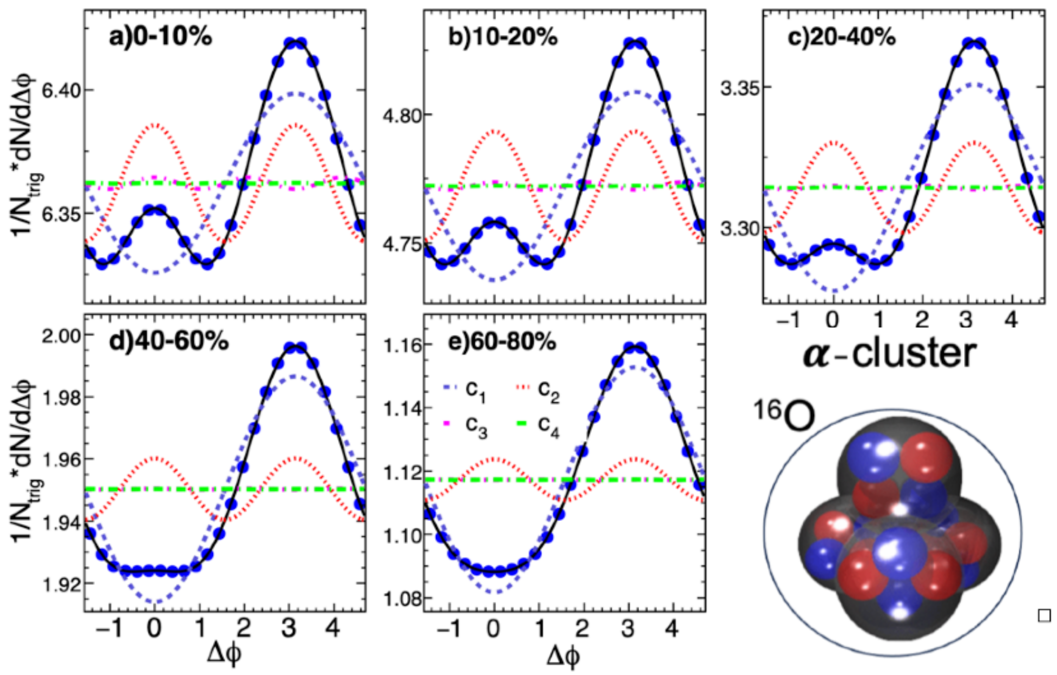




- e3/e2 & v3/v2 is sensitive to α-cluster structure in C+Au collisions at 200GeV

STAR results for O+O collisions

Shengli Huang [for STAR], arXiv:2312.12167

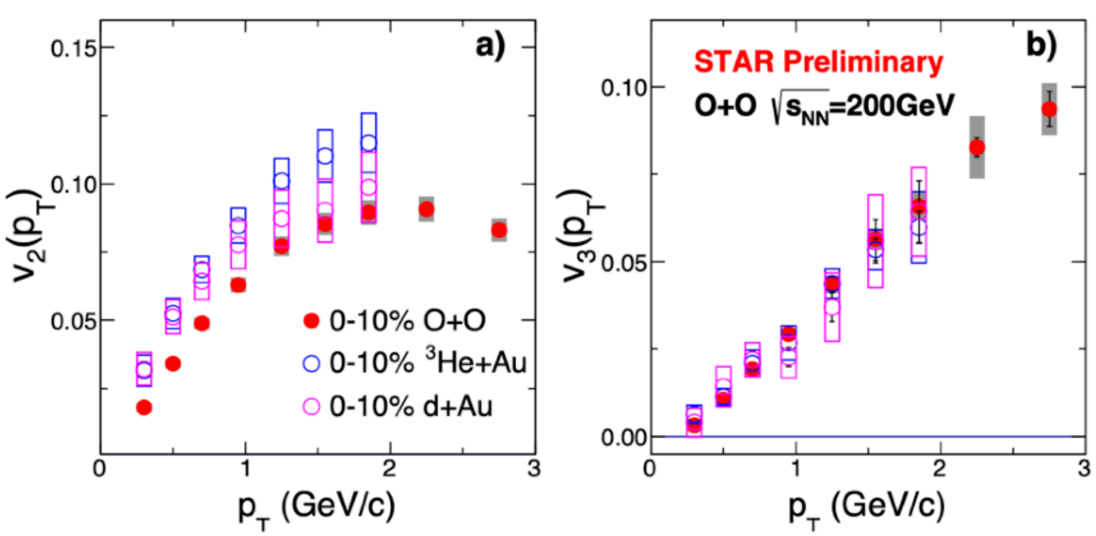


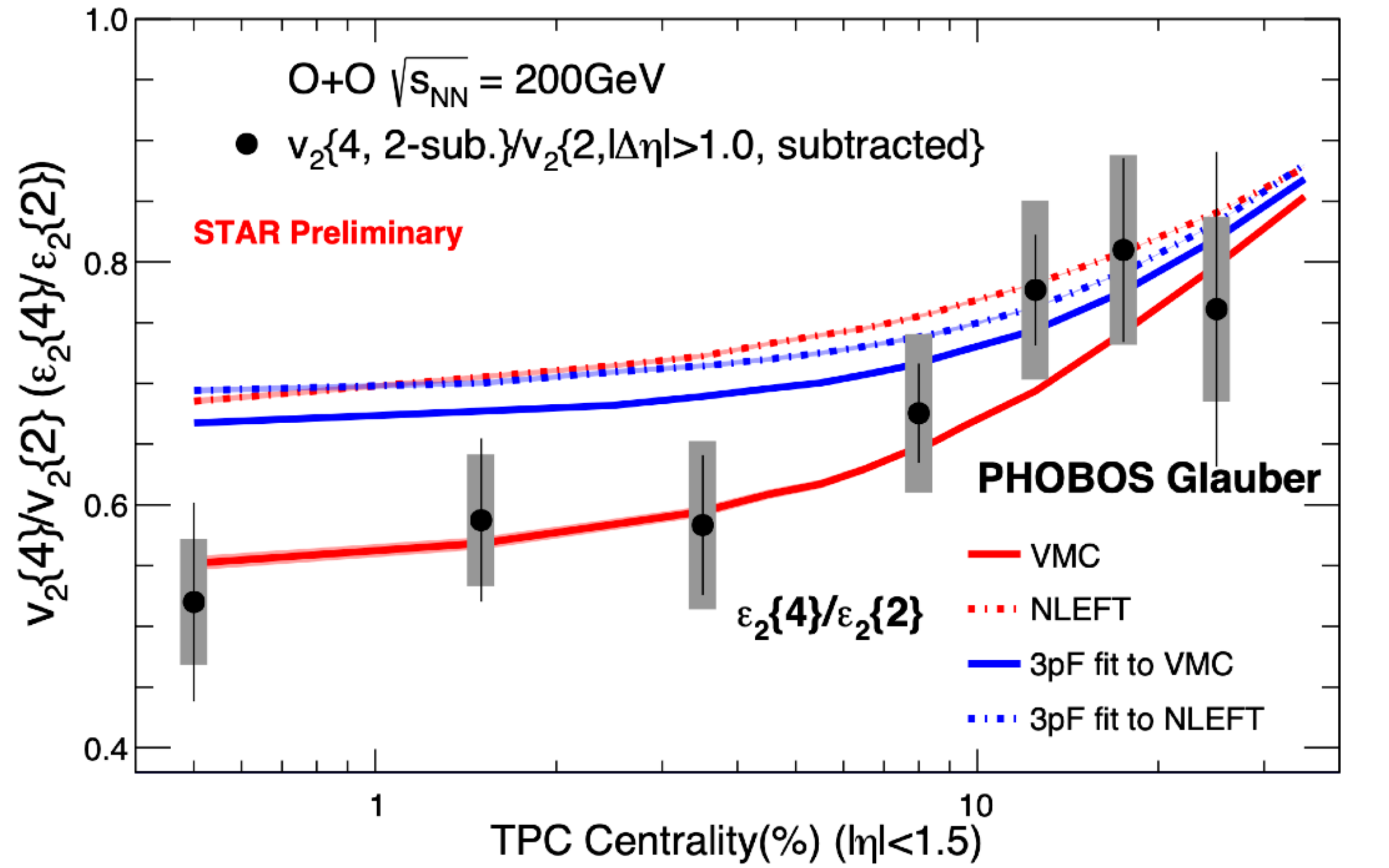
$$Y(\Delta\phi, p_{\mathrm{T}}^{\mathrm{trig}}) = c_0(1 + 2\sum_{n=1}^{n=4} c_n \cos(n\Delta\phi)).$$

$$f = c_1^{\mathrm{cent}} / c_1^{\mathrm{peri}}$$

$$c_n^{\mathrm{sub}} = c_n - c_n^{\mathrm{non-flow}} = c_n^{\mathrm{cent}} - c_n^{\mathrm{peri}} \times f$$

$$c_n = v_n^{\mathrm{trig}} \times v_n^{\mathrm{assoc}}$$

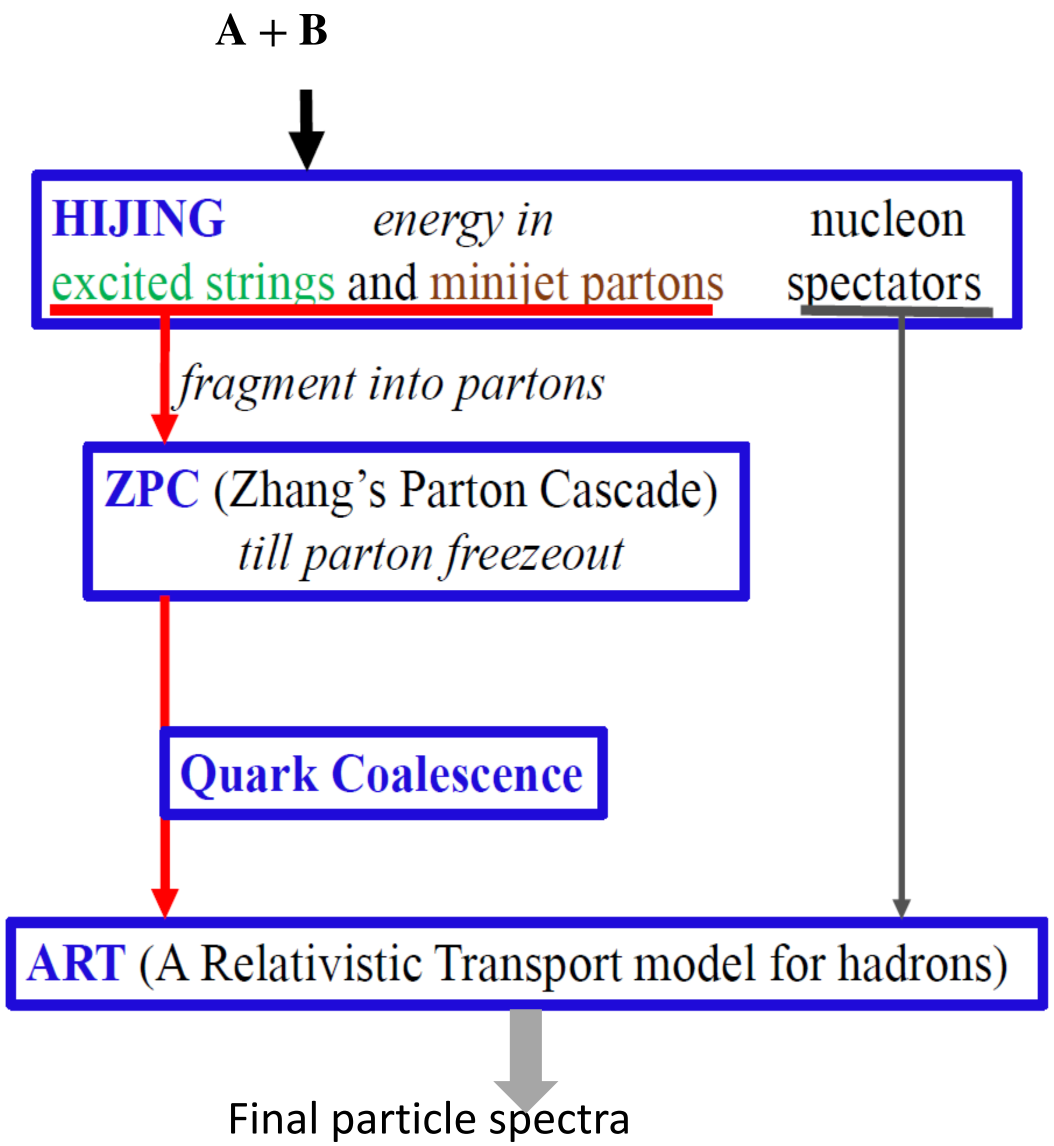




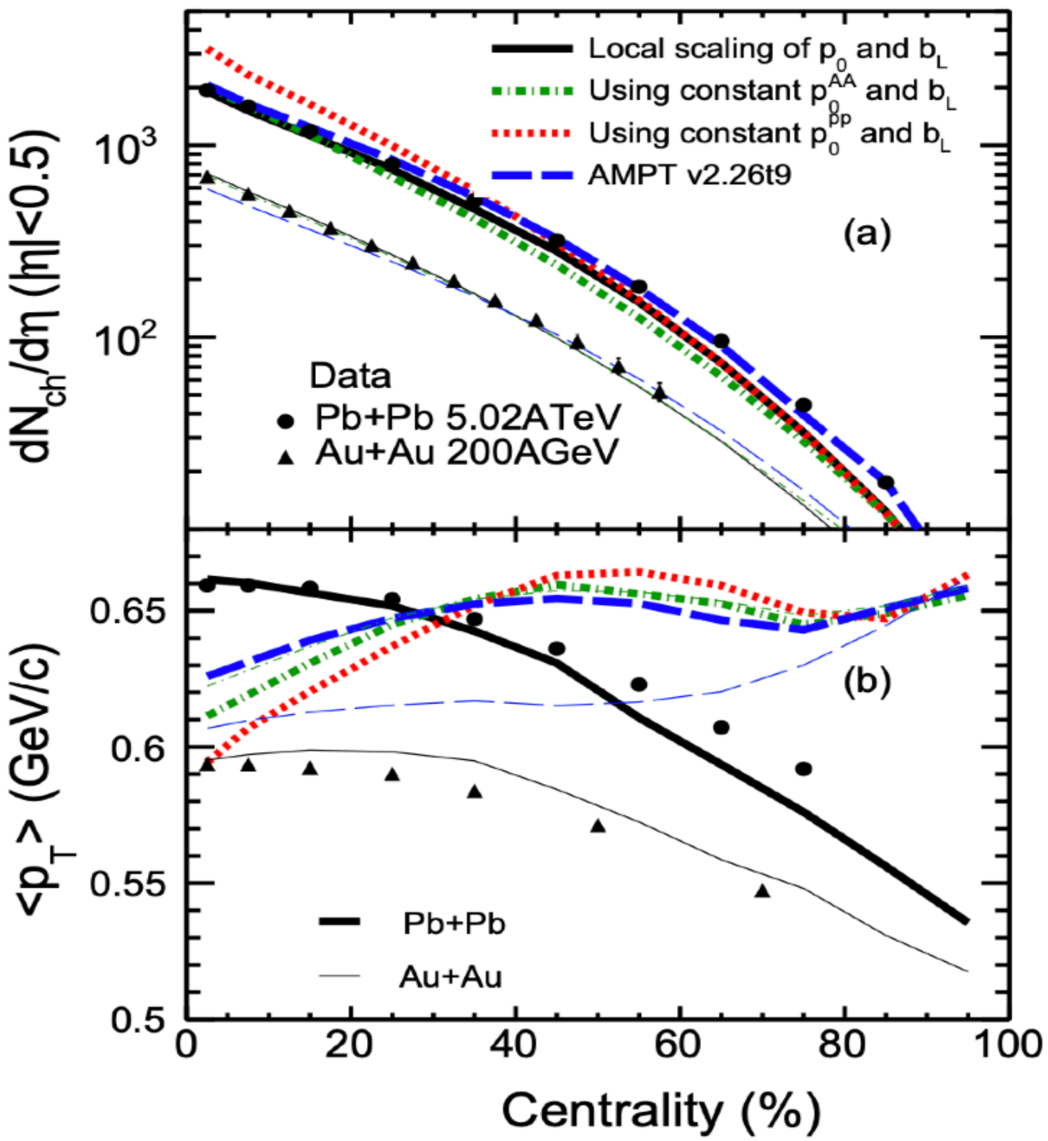
- v2{4}/v2{2} serves as a powerful tool for studying nucleon-nucleon correlations in O+O collisions at 200 GeV.
- A hint on possible α-cluster structure of oxygen nuclei?

Improved Version of String-Melting AMPT model

Z.W. Lin, C.M. Ko, B.A. Li, B. Zhang, S. Pal, PRC **72**, 064901 (2005)



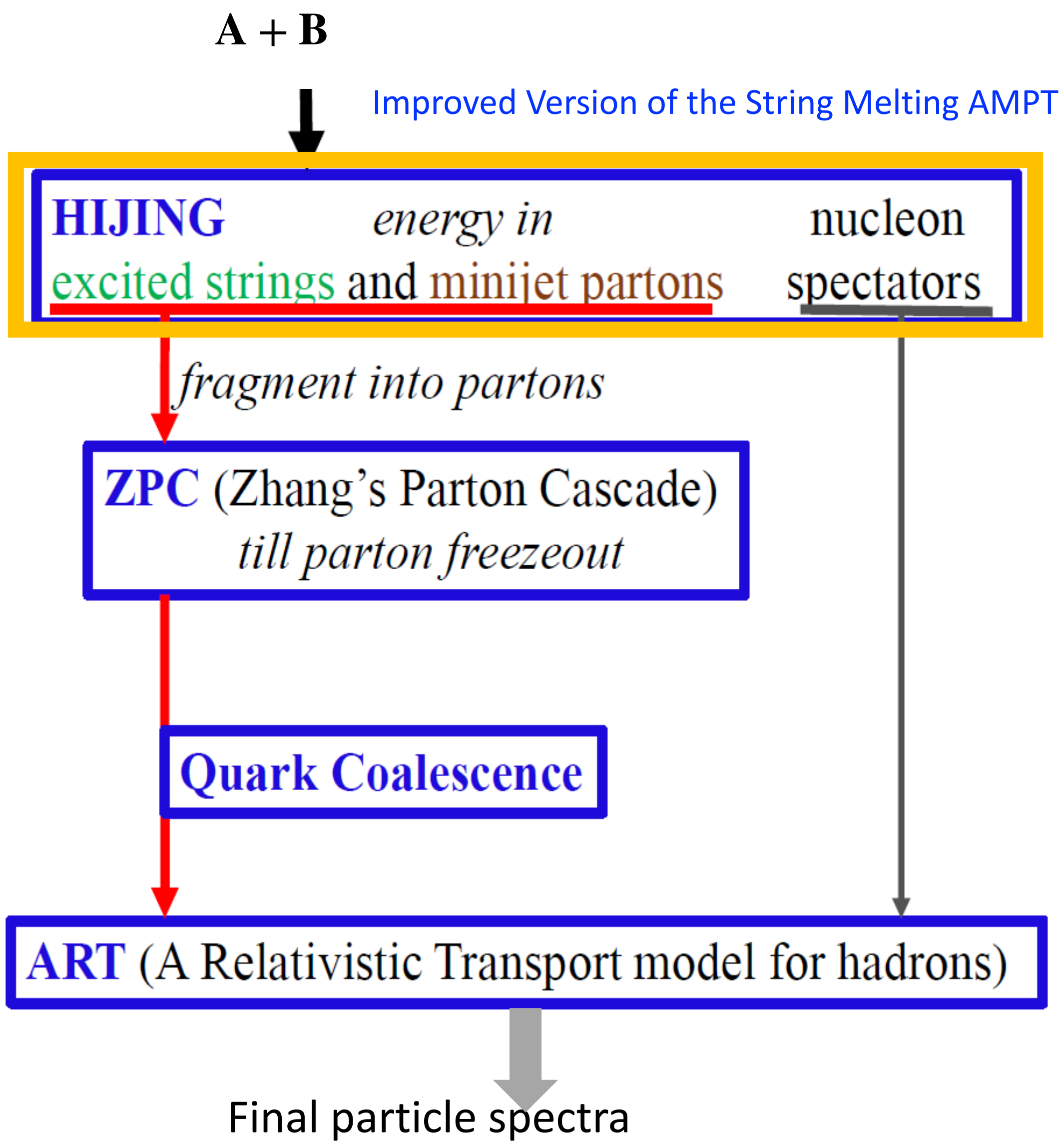
1. New quark coalescence model.
2. Improved heavy quark productions.
3. Modern set of parton distribution functions in proton and impact parameter-dependent nuclear shadowing.

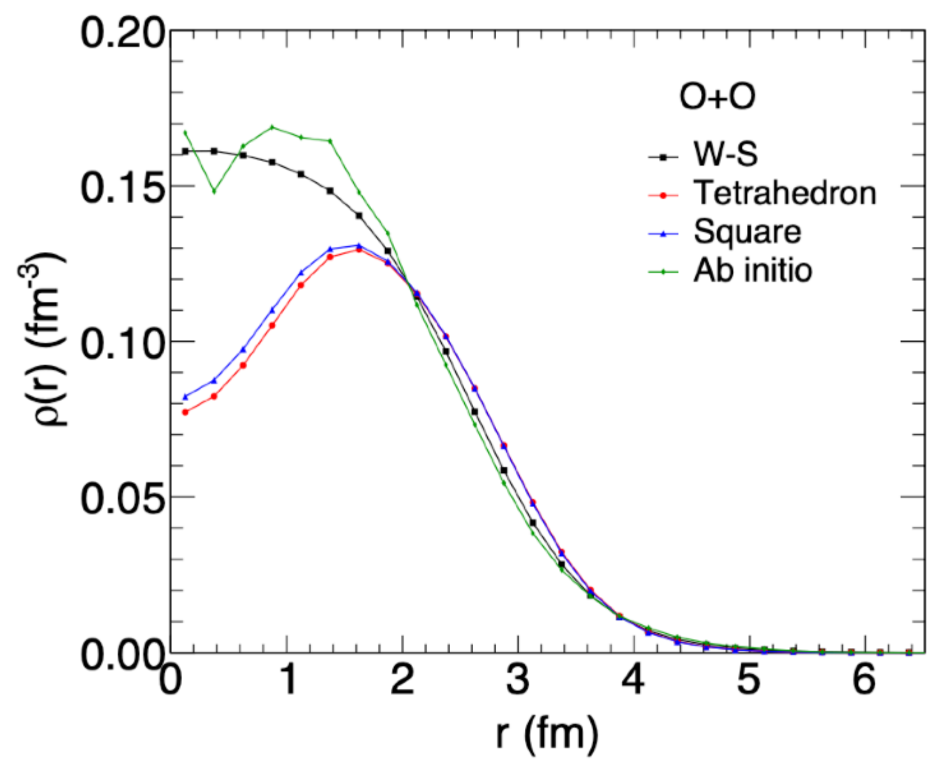


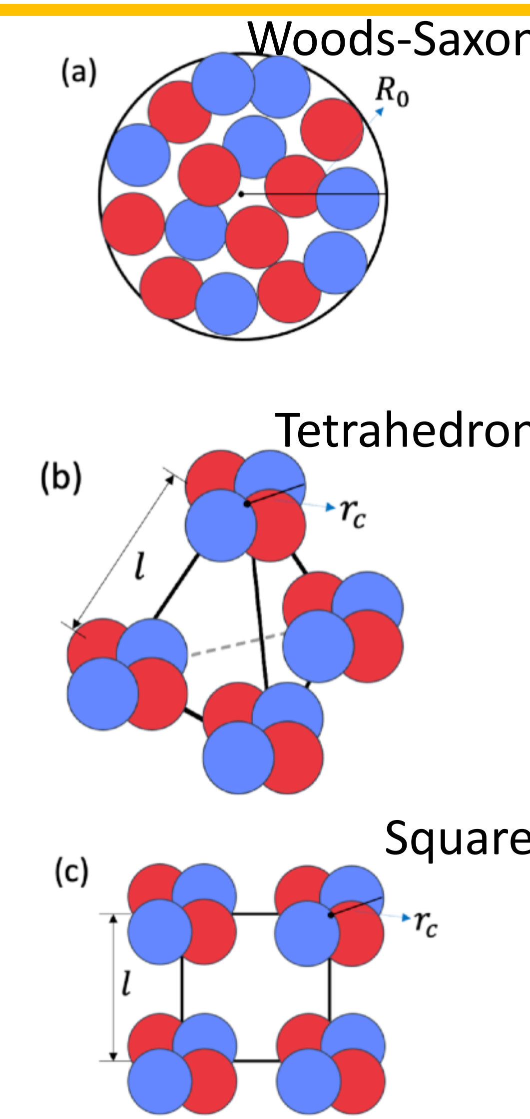
➢ Improved AMPT model correctly describes the centrality dependences of <Nch> and $\langle p_T \rangle$ rather well.

Chao Zhang, Liang Zheng, Shusu Shi, Zi-Wei Lin, PRC 104, 014908 (2021)

Introducing nuclear structures of ^{16}O to improved AMPT





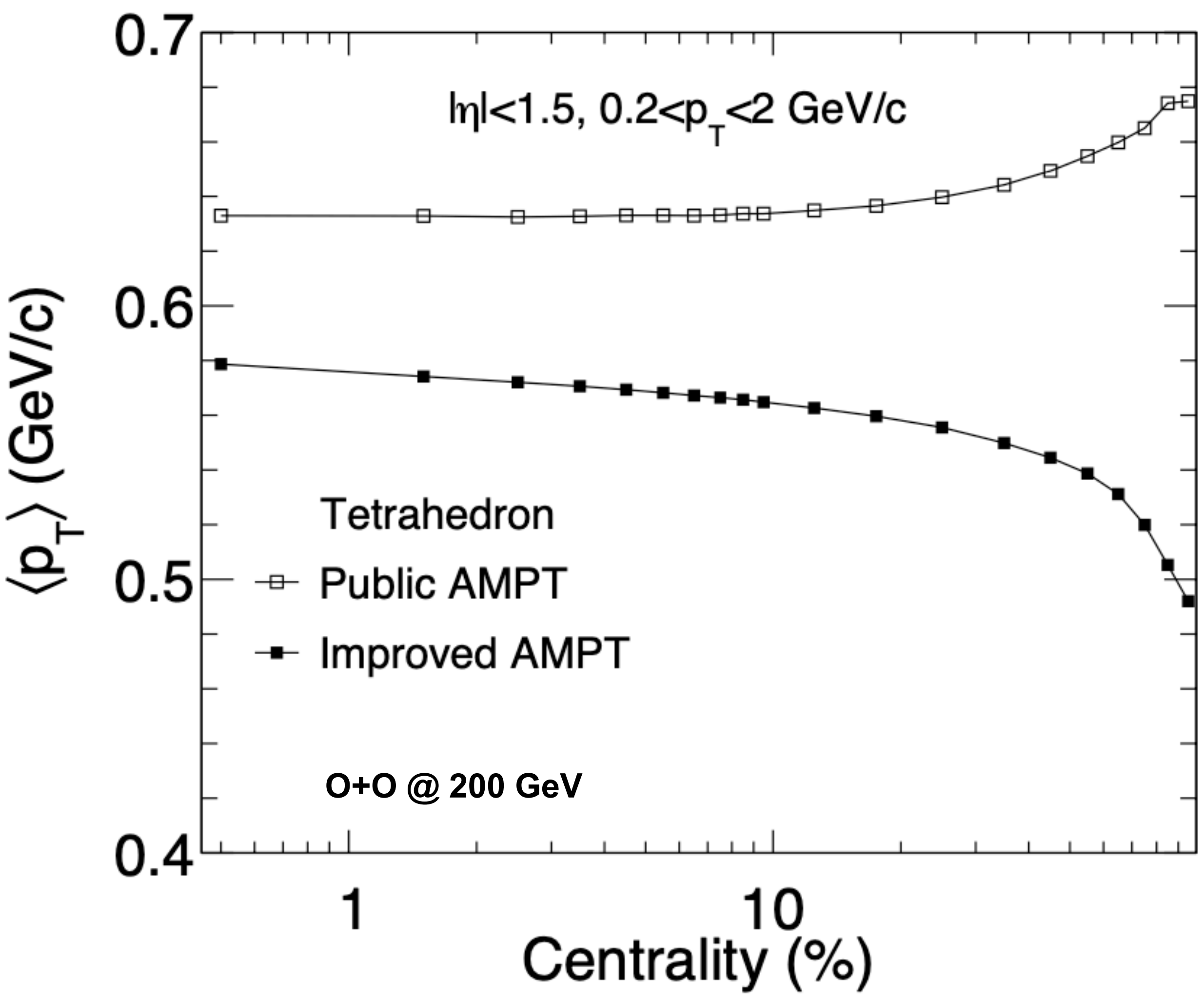


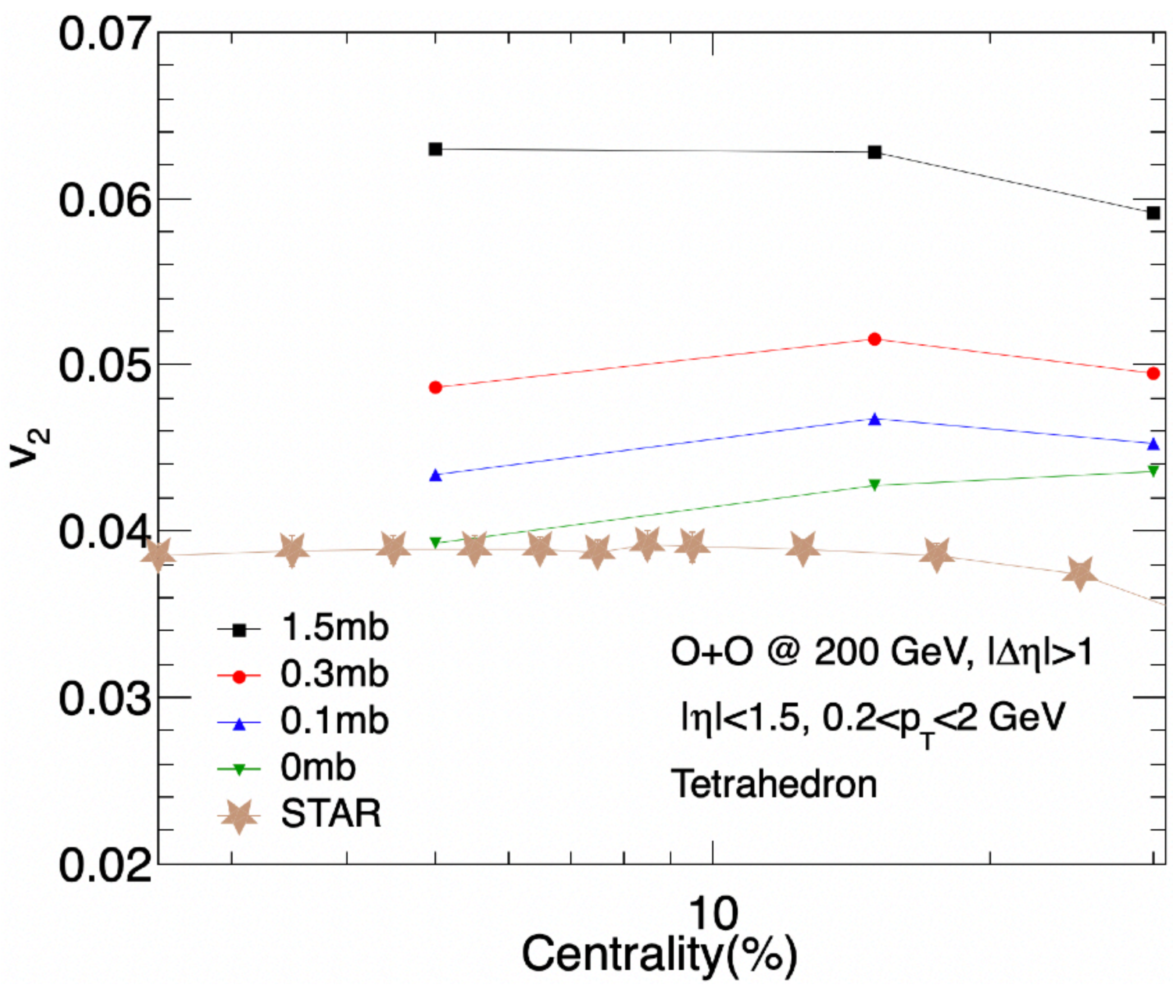
(d) *ab initio* method (NLEFT)

N. Summerfield, B.-N. Lu, C. Plumberg, D. Lee, J. Noronha-Hostler, and A. Timmins, Phys. Rev. C 104, L041901 (2021), 2103.03345.

Nuclear structure effect in O+O collisions at 200 GeV?

Centrality dependence of <p_T>& v_2 in O+O collisions at 200 GeV





➢The centrality dependence of $\langle p_T \rangle$ is reasonable in improved AMPT version.

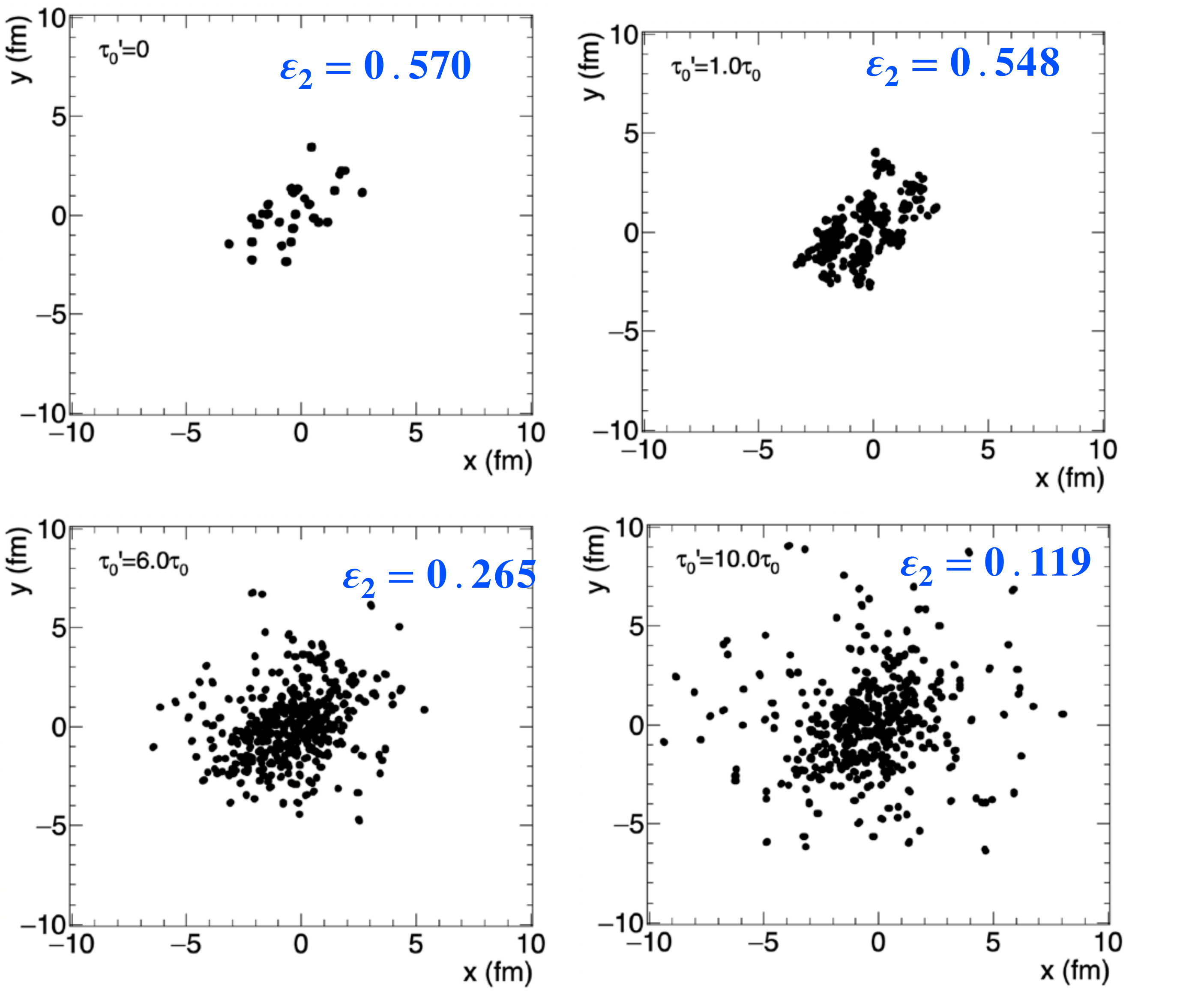
➢Improved AMPT failed to reproduce data even when tuning off parton cascade

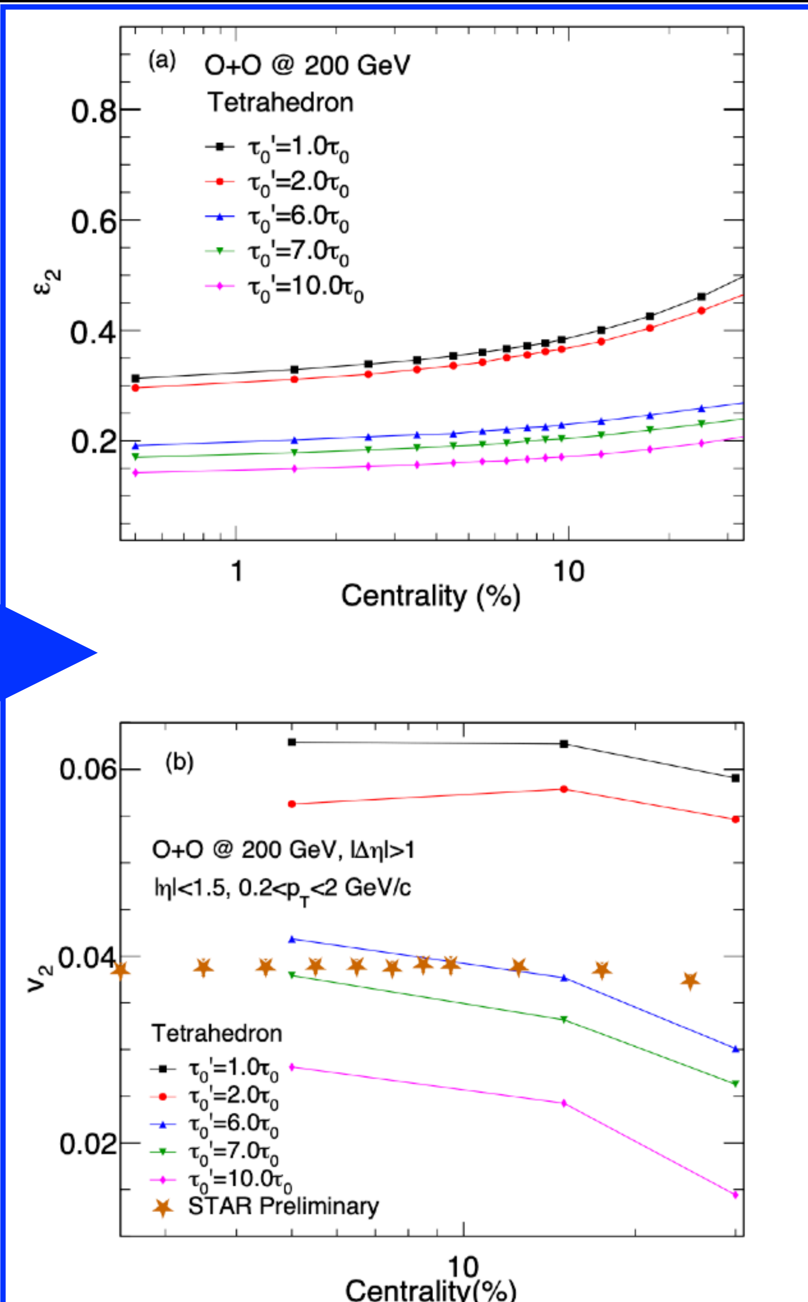
➢Why the v2 problem? How to solve it?

Parton formation time dependence of ε_2 & v_2

The formation time for each parton:

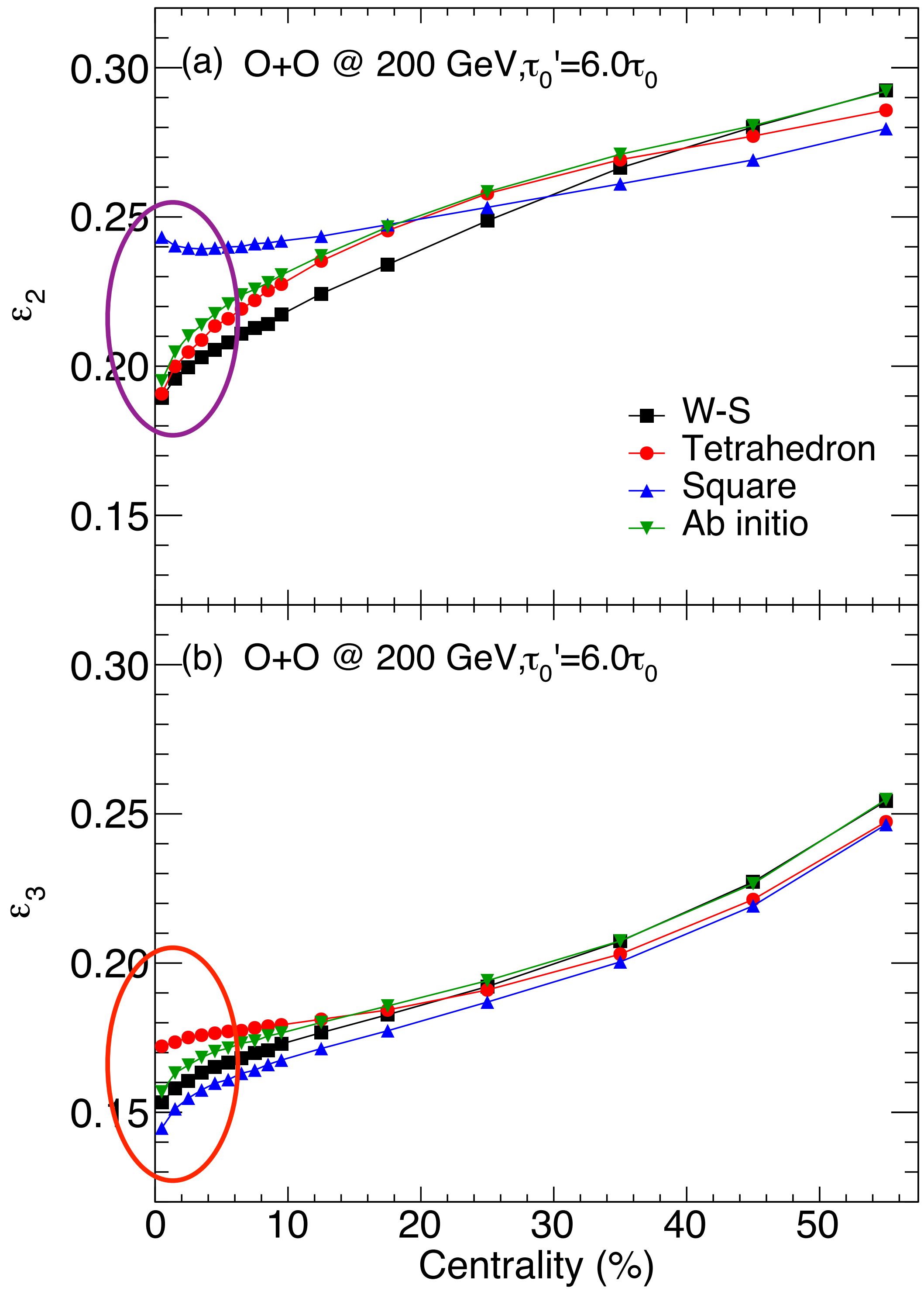
$\tau_0' = const \bullet E/m_T^2,\ \tau_0 = E/m_T^2$





- ➢ ε_2 & v_2 decrease with increasing parton formation time , v_2 at $\tau_0' = 6\tau_0$ is close to data. Why?
- ➢ Is spatial distribution diffuse and gaseous because condensed α-particles are weakly bound?
- ➢ A similar concept/analog as the compactness from Huichao and Haojie et al.'s work (arXiv: 2401.15723).

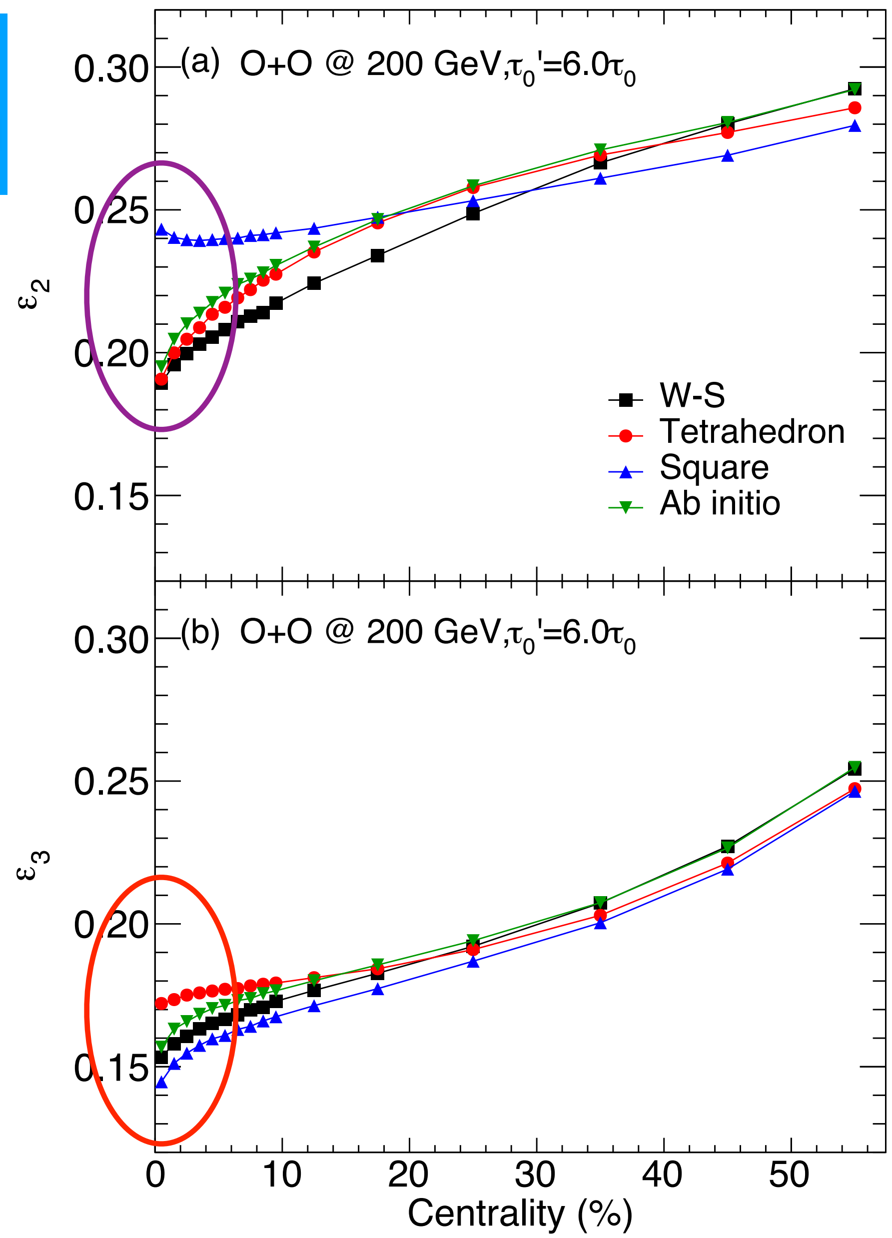
Nuclear structure effect on centrality dependence of $\boldsymbol{\varepsilon}$2 and $\boldsymbol{\varepsilon}$3



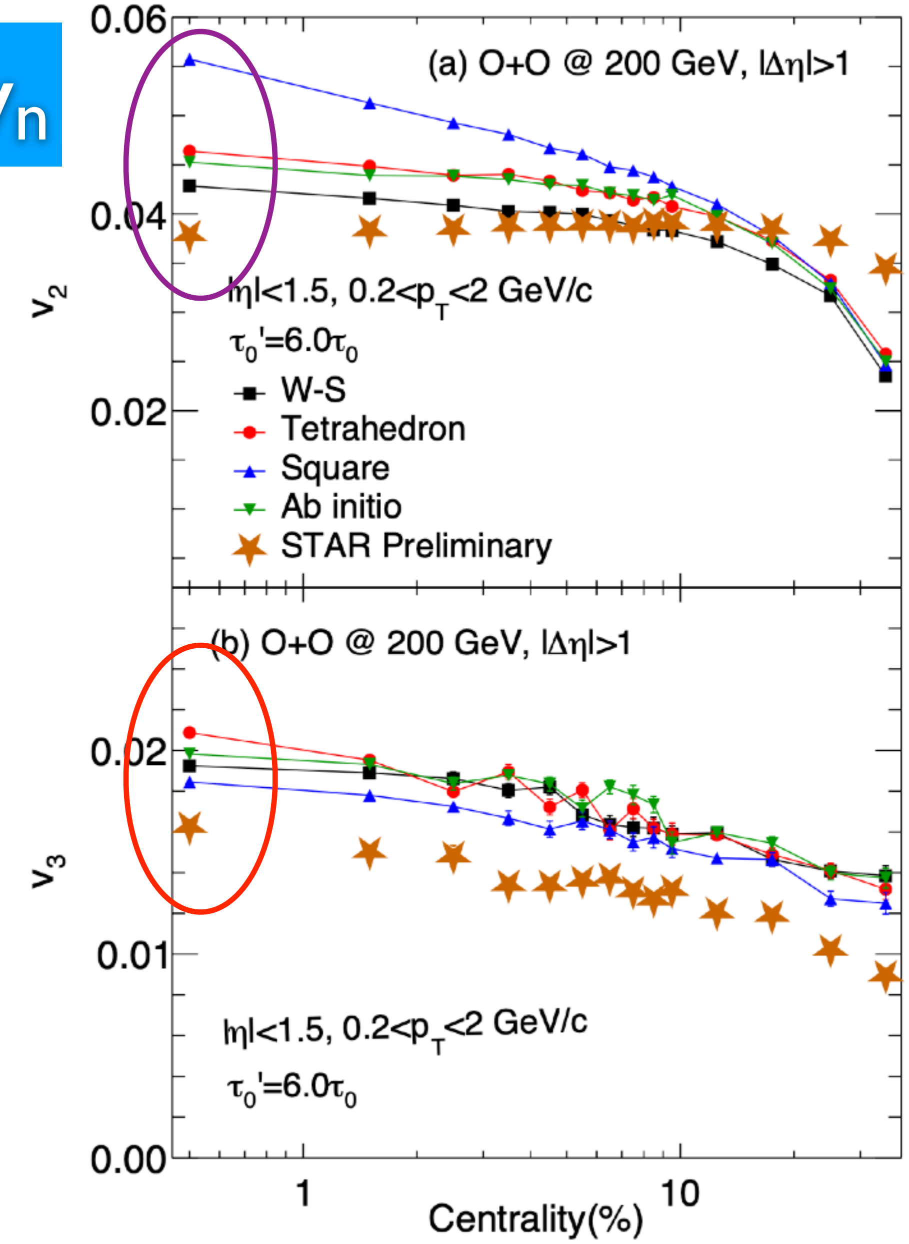
- $\boldsymbol{\varepsilon}$2 and $\boldsymbol{\varepsilon}$3 are more sensitive to nuclear structure for more central collisions
- for central collisions:
  - $\boldsymbol{\varepsilon}$2: Square > Ab initio ≈ Tetrahedron > W-S
  - $\boldsymbol{\varepsilon}$3: Tetrahedron > Ab initio > W-S > Square

Consistence between vn and εn in O+O collisions at 200 GeV

ε_n



v_n

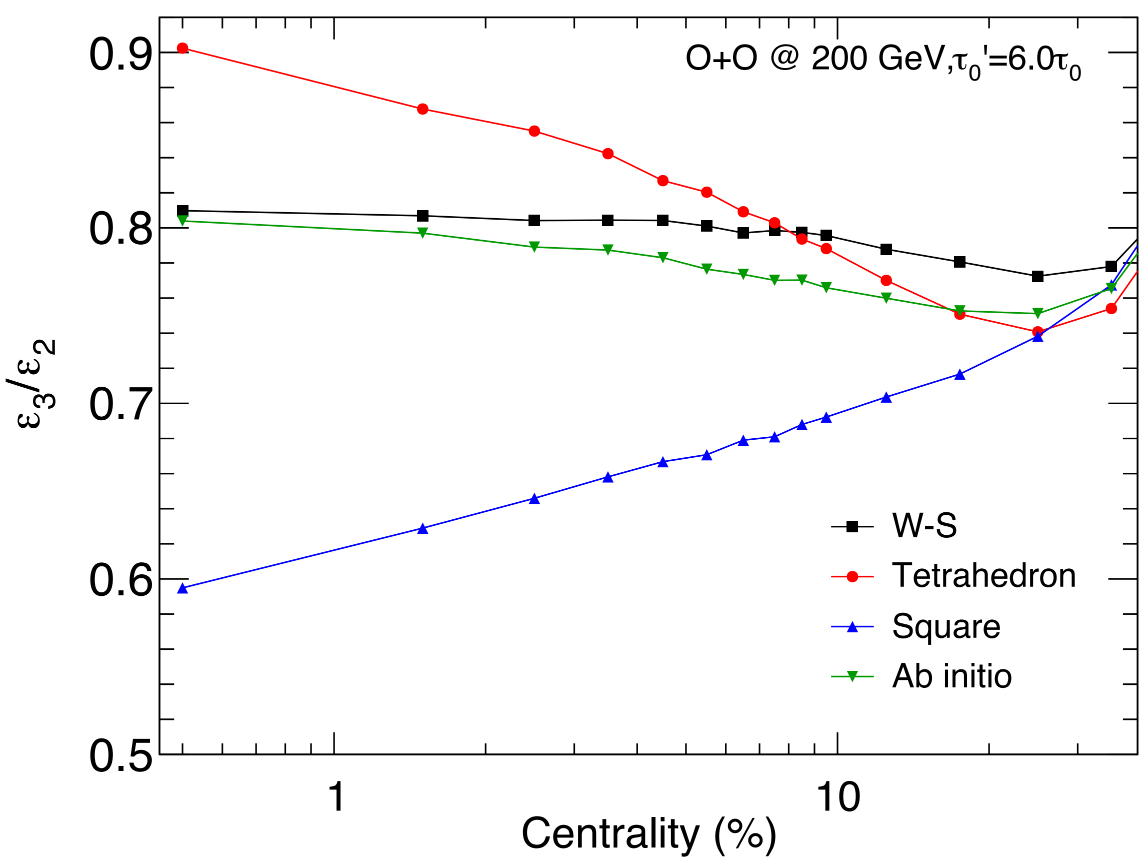


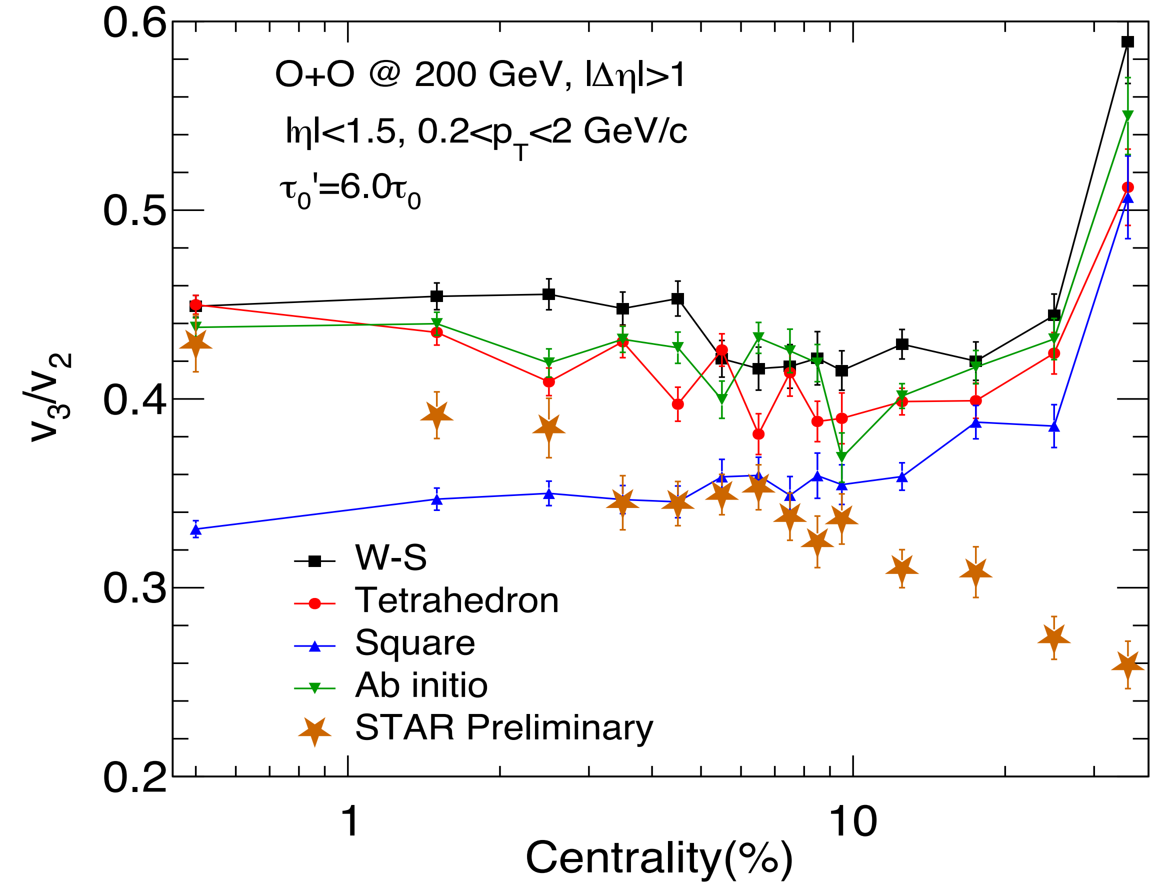
- ε2 and ε3 are more sensitive to nuclear structure for more central collisions
- for central collisions:
  - ε2: Square > Ab initio ≈ Tetrahedron > W-S
  - ε3: Tetrahedron > Ab initio > W-S > Square

Consistent

- v2 and v3 are more sensitive to nuclear structure for more central collisions
- for central collisions:
  - v2: Square > Ab initio ≈ Tetrahedron > W-S
  - v3: Tetrahedron > Ab initio > W-S > Square

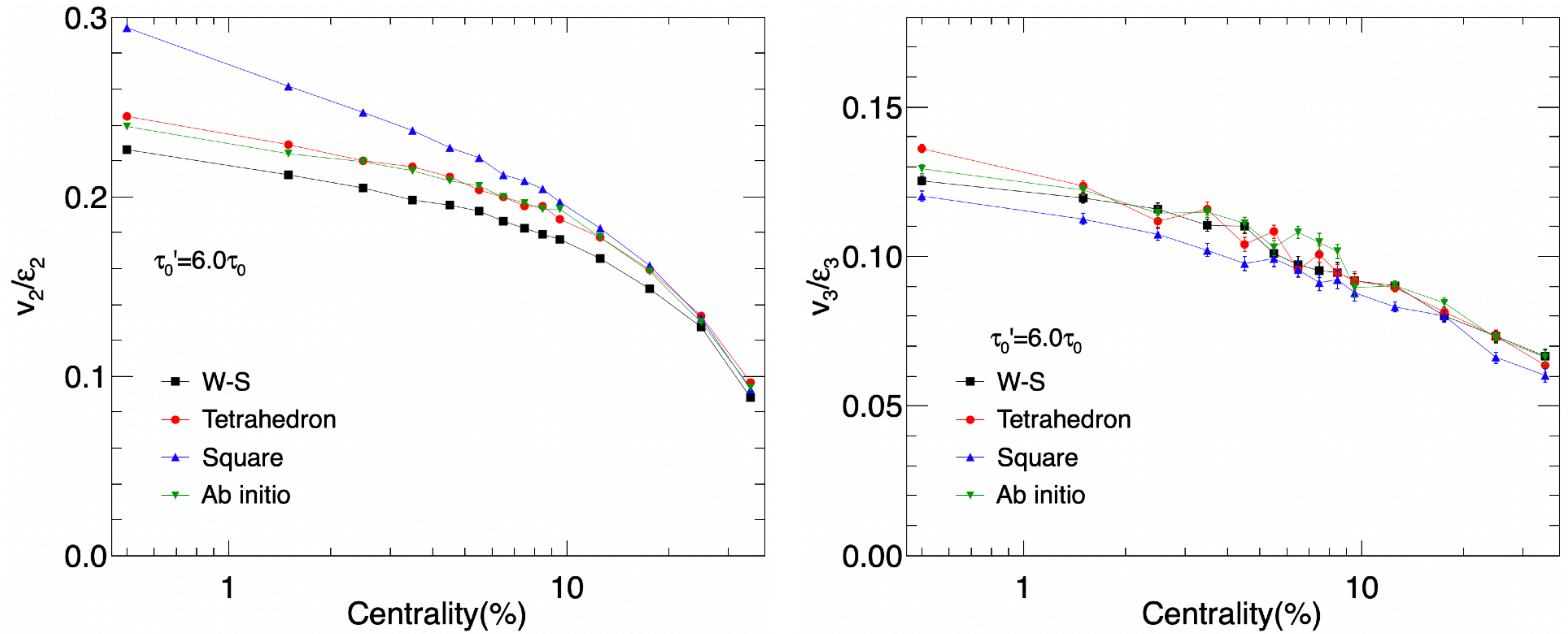
v3/v2 ratio in O+O collisions at 200 GeV





- ➢ **ε**3/**ε**2 are more sensitive to nuclear structure for more central collisions
- ➢ **ε**3/**ε**2 for central collisions: Tetrahedron > W-S ≈ Ab initio > Square
- ➢ v3/v2 for central collisions: Tetrahedron ≈ W-S ≈ A b initio > Square.
- ➢ Why is v3/v2 inconsistent with **ε**3/**ε**2?

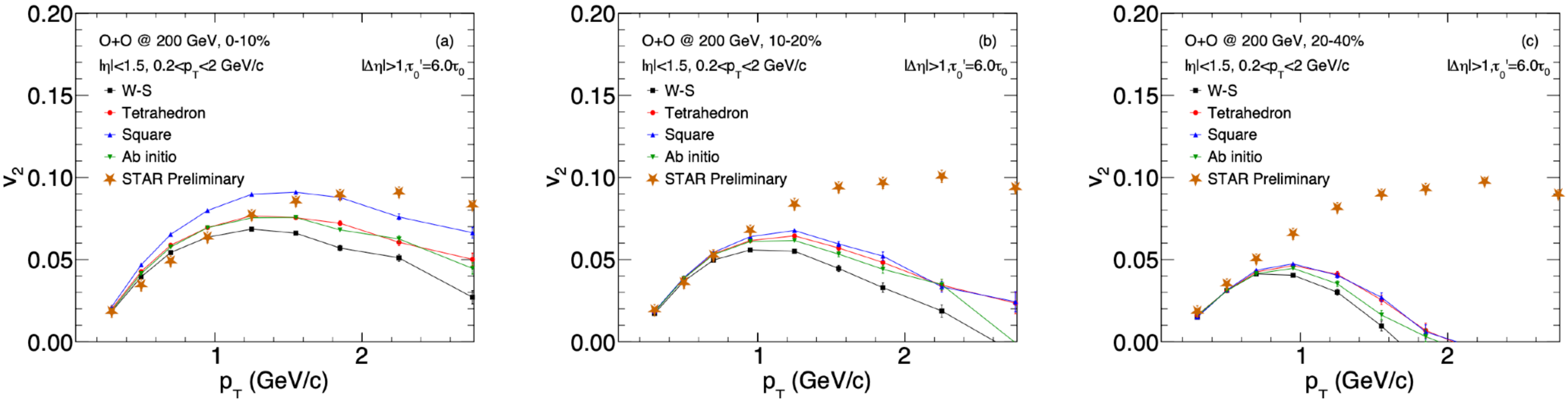
Conversion efficiency (v_n/ε_n) from ε_n to v_n



➢Because $v2/\varepsilon2 > v3/\varepsilon3$

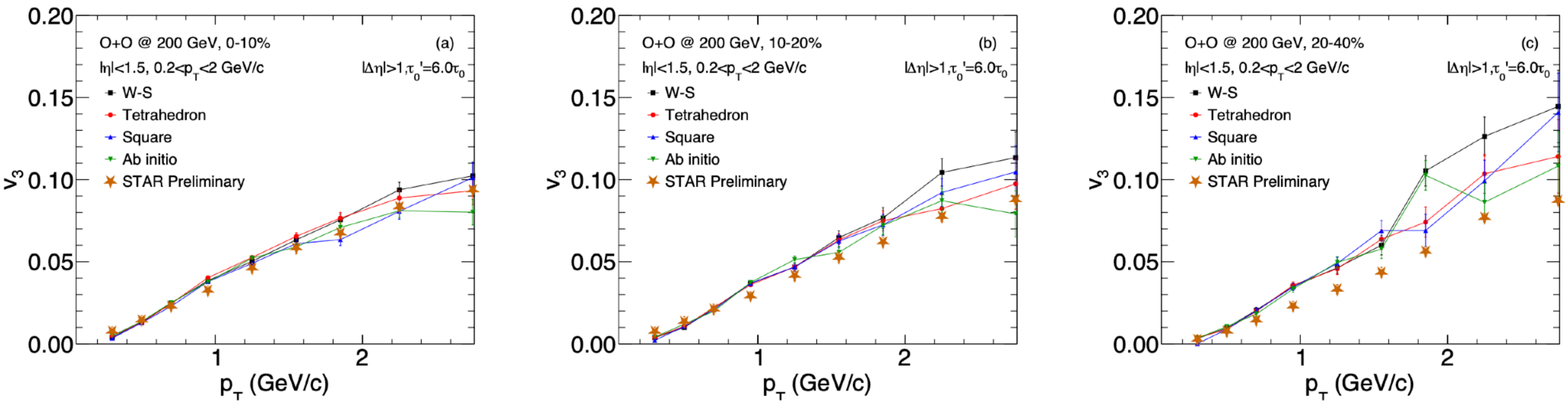
➢The ordering of $vn/\varepsilon n$ in different configurations is consistent with the ordering of vn or εn in central collisions

pT dependences of v2 and v3



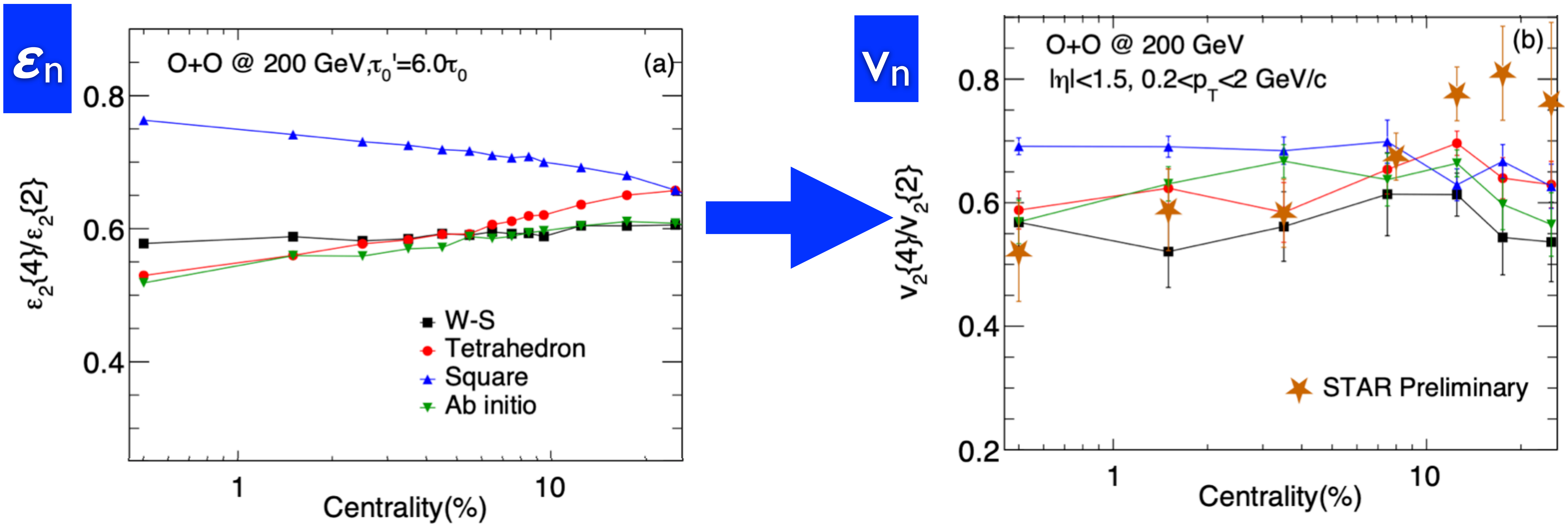
➢ $v_2(p_T)$: The AMPT results are consistent with the data for low pT.

➢ Ours are lower than the data for high pT. Is due to non-flow effect different from the data?



➢ $v_3(p_T)$: The AMPT results are close to data and less sensitive to nuclear structure than $v_2(p_T)$.

ε2 and v2 fluctuations



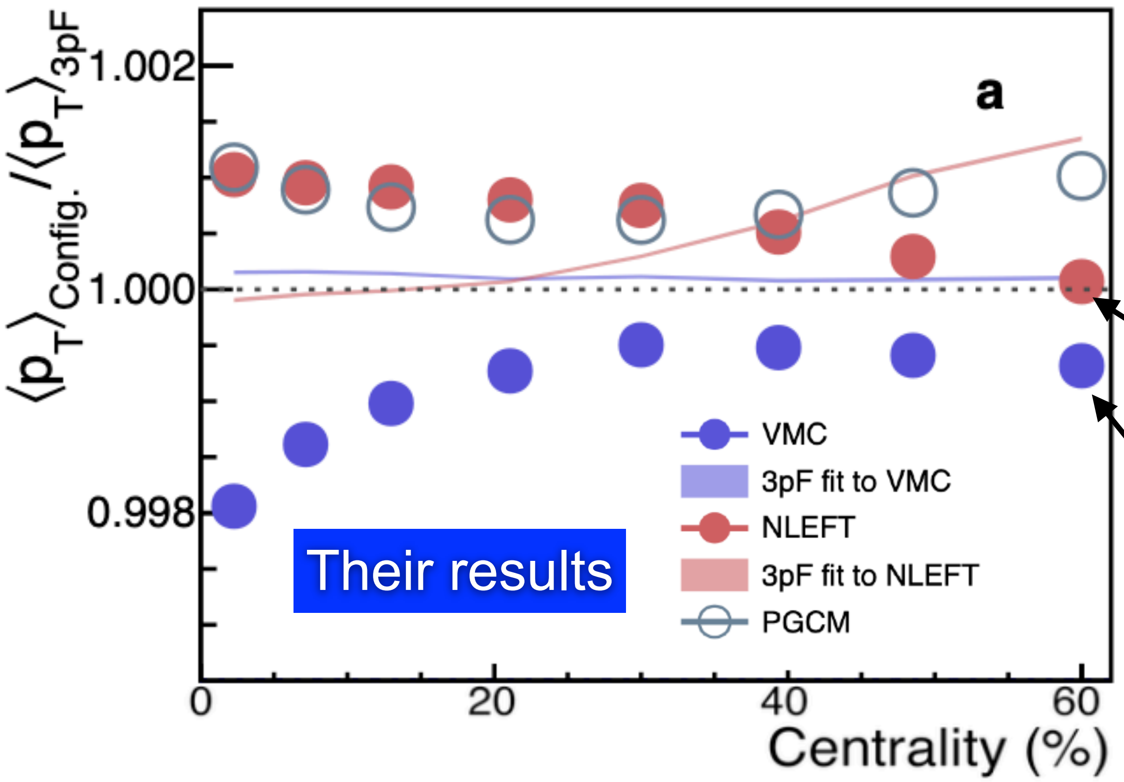
$$\varepsilon_2\{2\}^2 = \langle \varepsilon_2^2 \rangle = \langle \varepsilon_2 \rangle^2 + \sigma_{\varepsilon_2}^2,$$
$$\varepsilon_2\{4\}^2 = \left(-\langle \varepsilon_2^4 \rangle + 2\langle \varepsilon_2^2 \rangle^2\right)^{1/2} \approx \langle \varepsilon_2 \rangle^2 - \sigma_{\varepsilon_2}^2$$

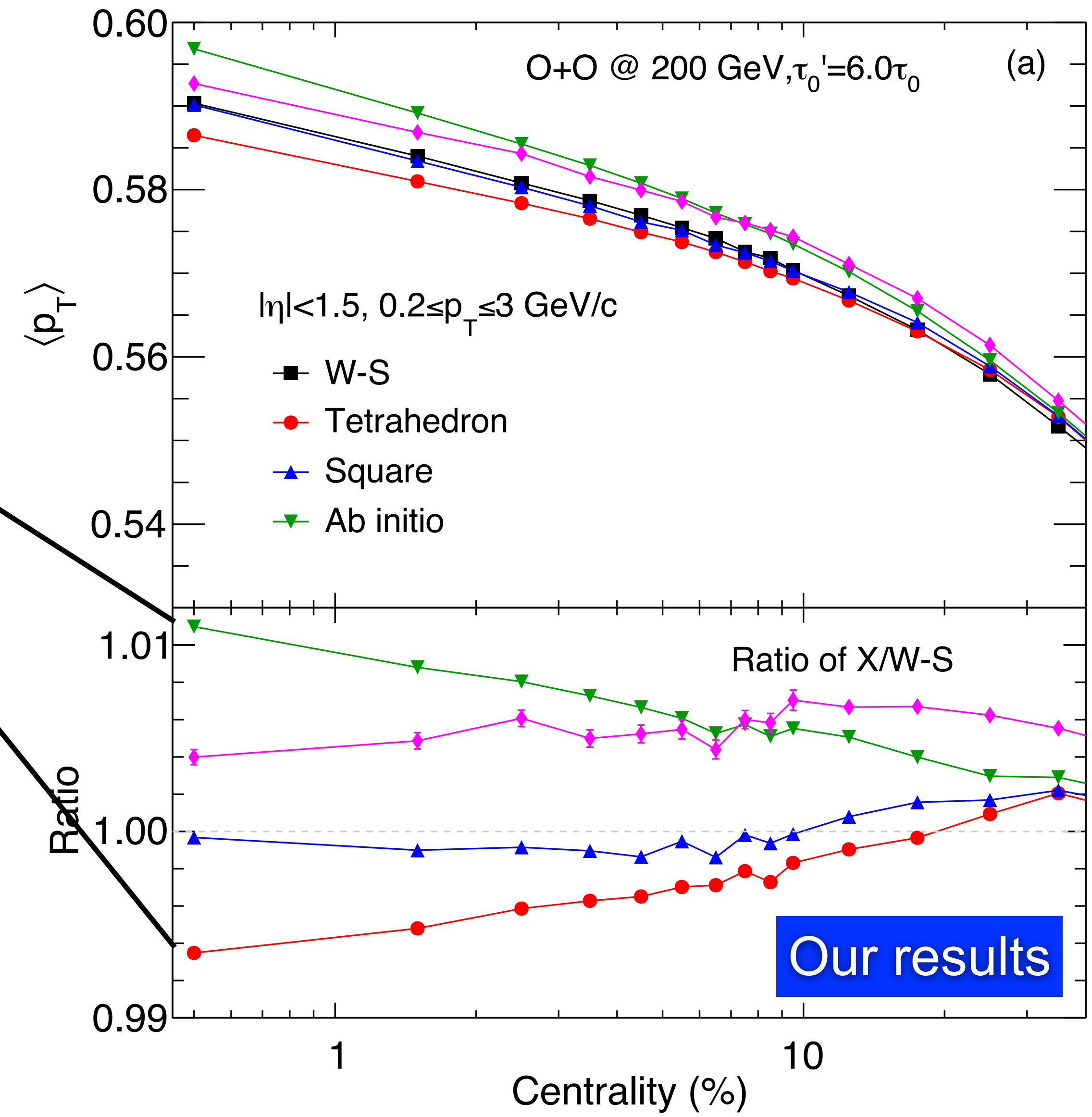
➢ ε_2 and v_2 fluctuations are consistent with each other.

➢ Larger v_2 fluctuations are observed for Tetrahedron and Ab initio cases, which seems more consistent with the STAR data.

<pT> Ratio between with and without nuclear structure

Chunjian Zhang, Jinhui Chen, Giuliano Giacalone, Shengli Huang, Jiangyong Jia and Yu-Gang Ma, arXiv:2404.08385

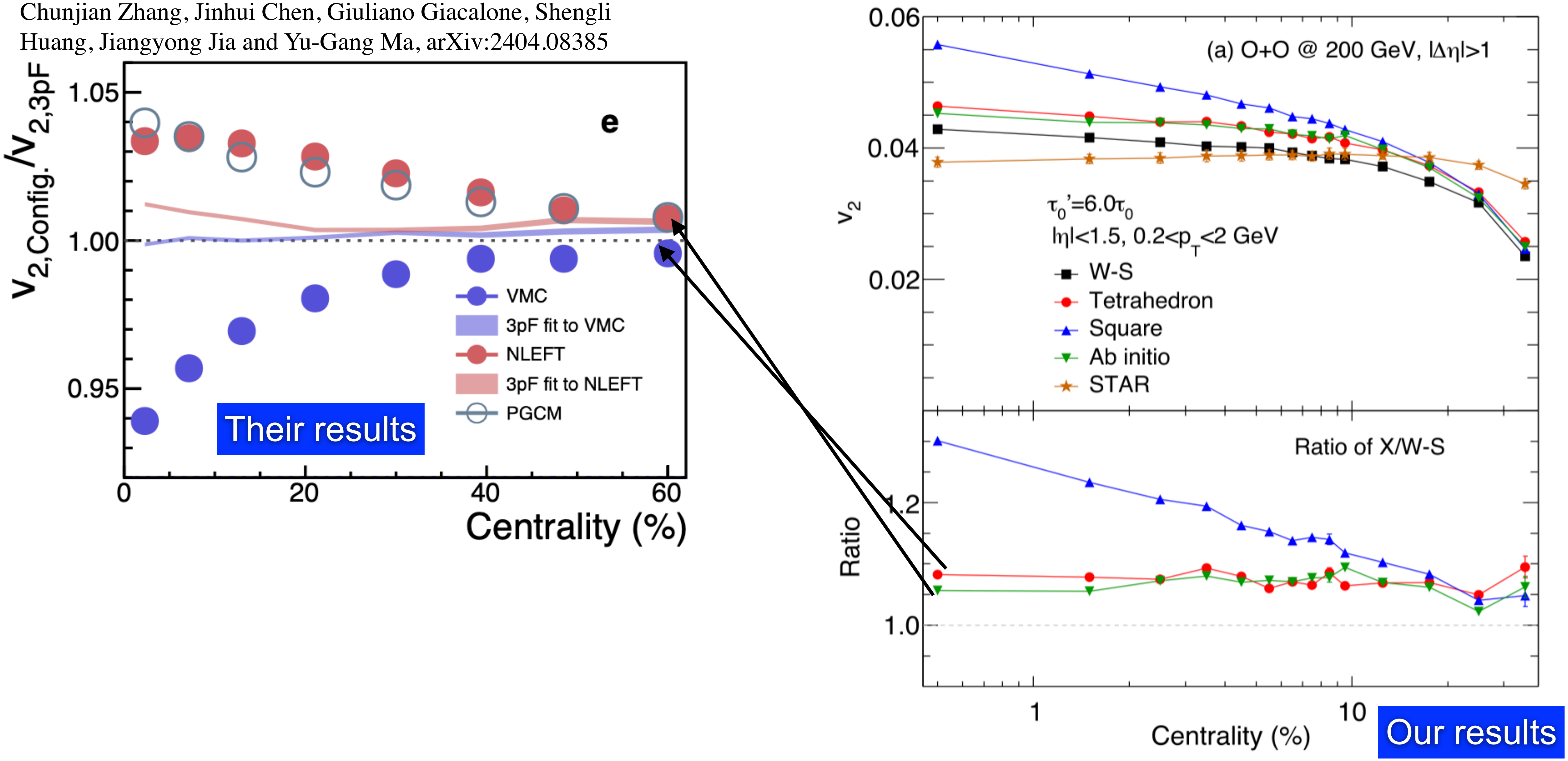




- ➢Our <pT> ratio for Ab initio (NLEFT) is consistent with their NLEFT.
- ➢ Our <pT> ratio for Tetrahedron is consistent with their VMC.

v2 Ratio between with and without nuclear structure

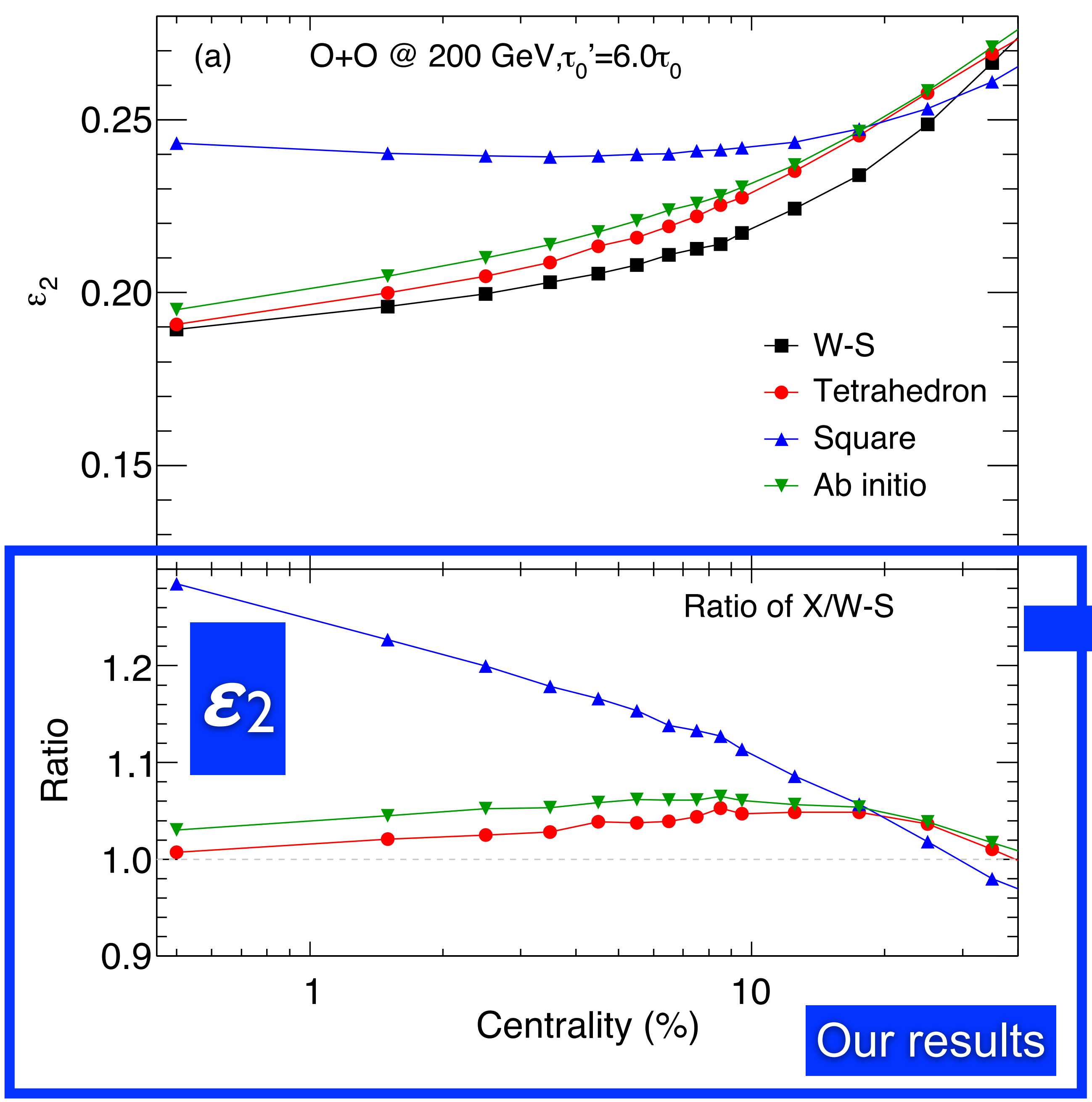
Chunjian Zhang, Jinhui Chen, Giuliano Giacalone, Shengli Huang, Jiangyong Jia and Yu-Gang Ma, arXiv:2404.08385

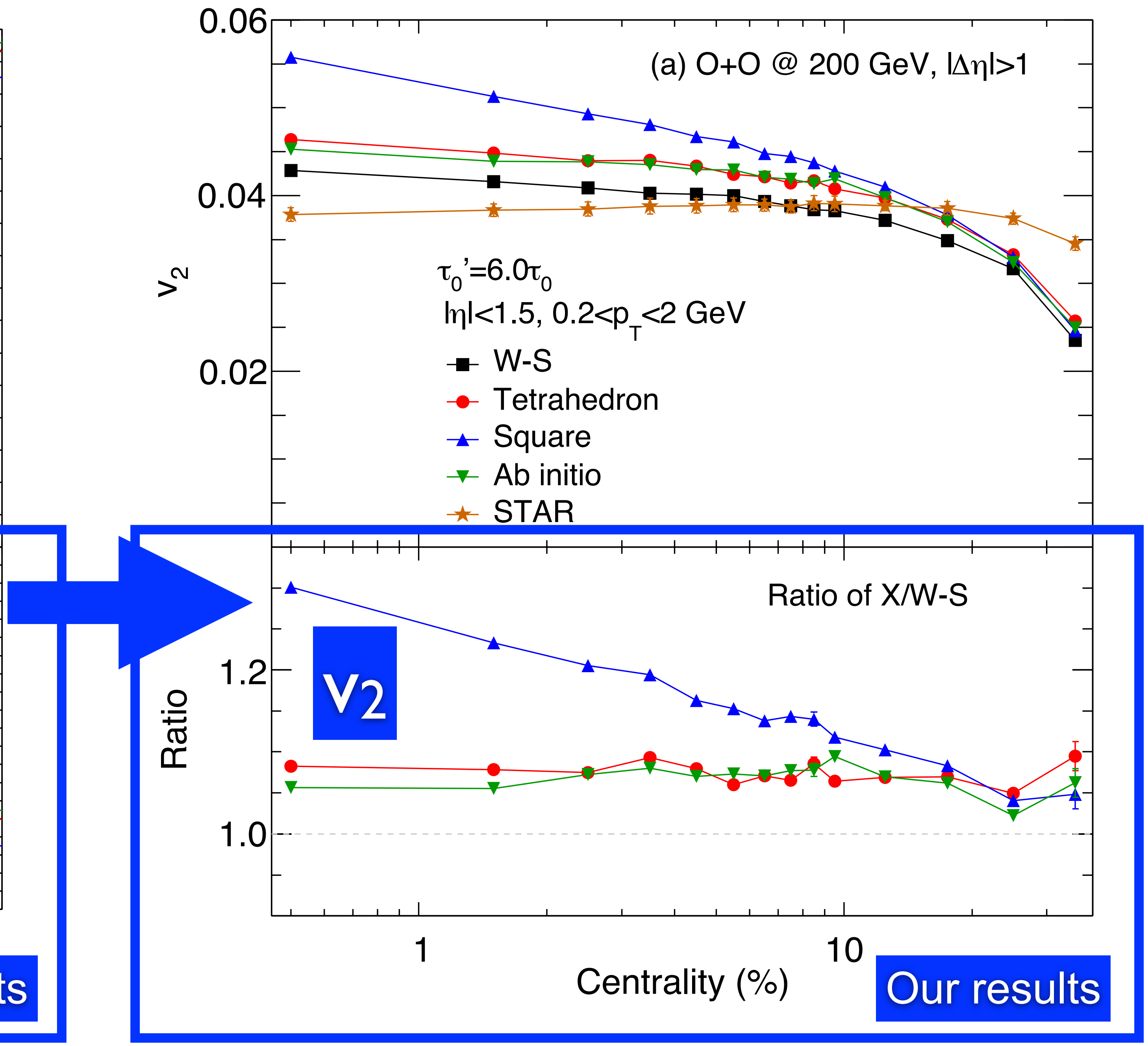


➢Our v2 ratio for Ab initio (NLEFT) is consistent with their NLEFT.

➢ Our <pT> ratio for Tetrahedron is **inconsistent** with their VMC. **Why?**

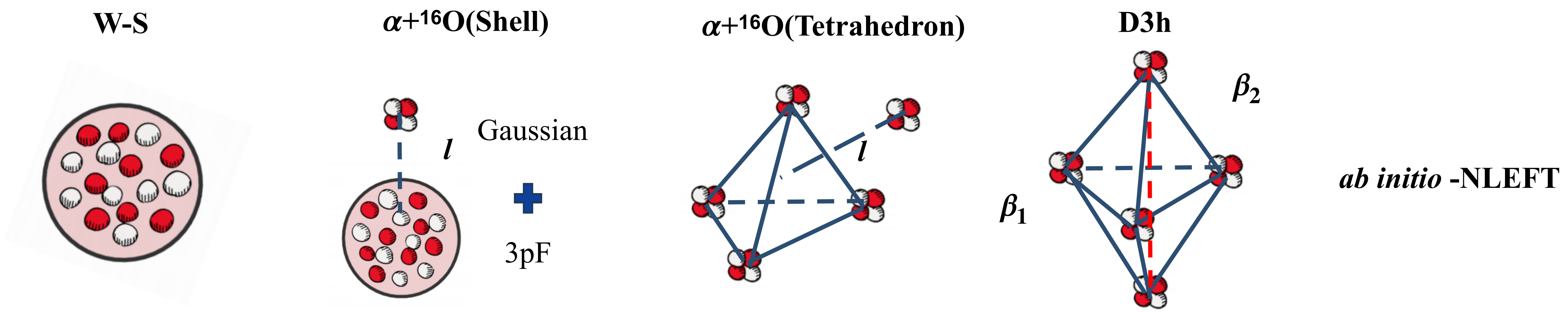
Ratio of v2 and ε2 between with and without nuclear structure

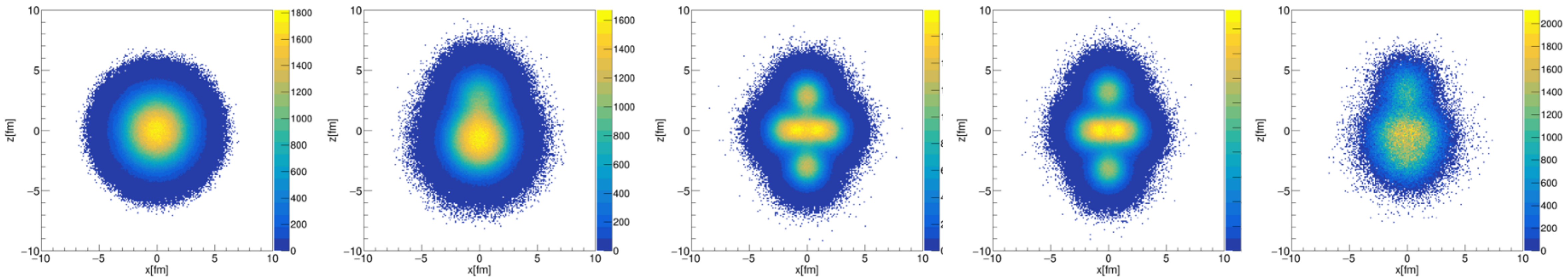


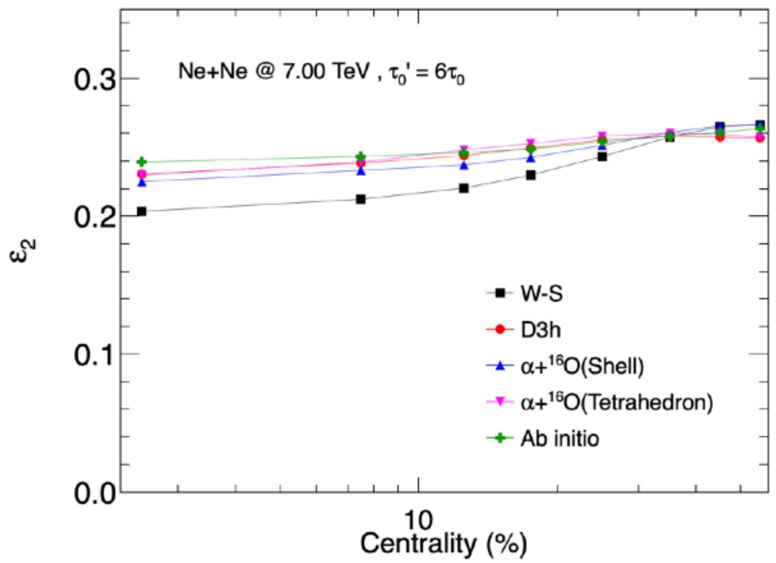


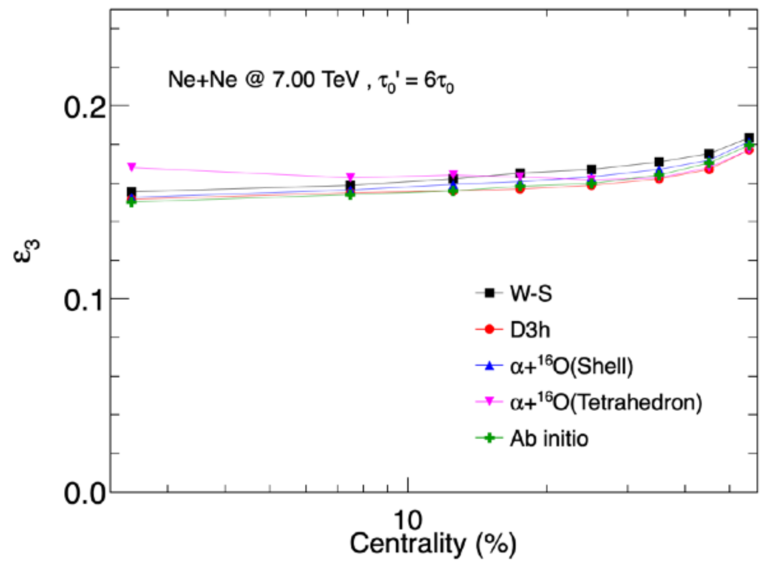
➢Our v2 ratio is consistent with our ε2 ratio. Other reason?

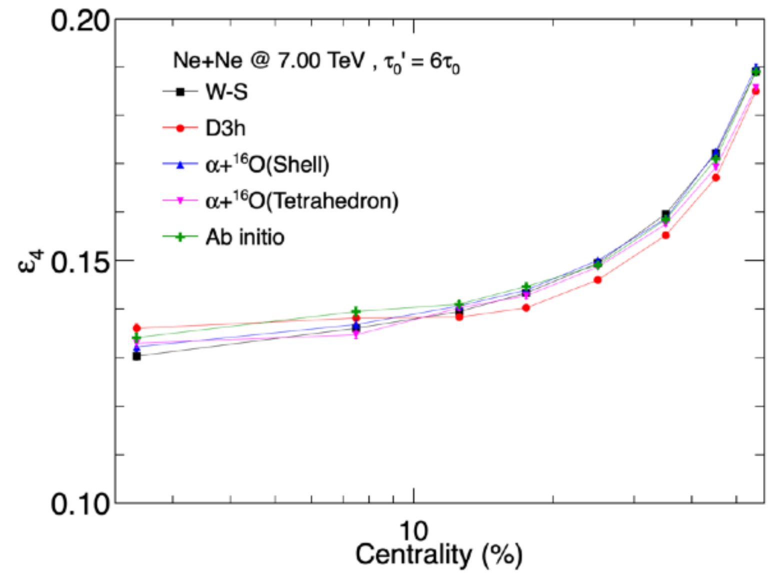
$^{20}Ne + ^{20}Ne$ at 7 TeV



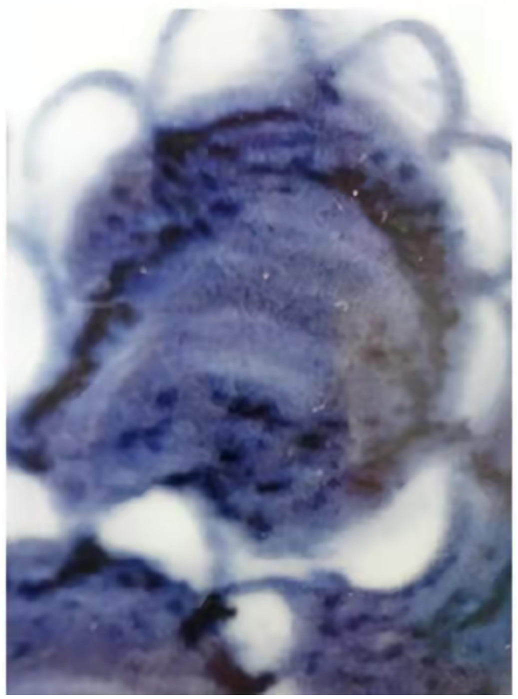








Summary && Outlook

deformation	neutron skin/halo	α-cluster
		

- Different types of nuclear structures as the inputs of the AMPT model
- Isobar collisions at RHIC: Halo-type neutron skin or deformation?
- O+O collisions at RHIC: an extended effective parton formation time indicating a possible α-clustering structure inside oxygen nuclei?
- More studies are in progress for Ne+Ne and O+O collisions at LHC
- Enjoy the beauty of nuclear porcelain!

Thank you!