



Probing cluster structure in ultracentral heavy-ion collisions

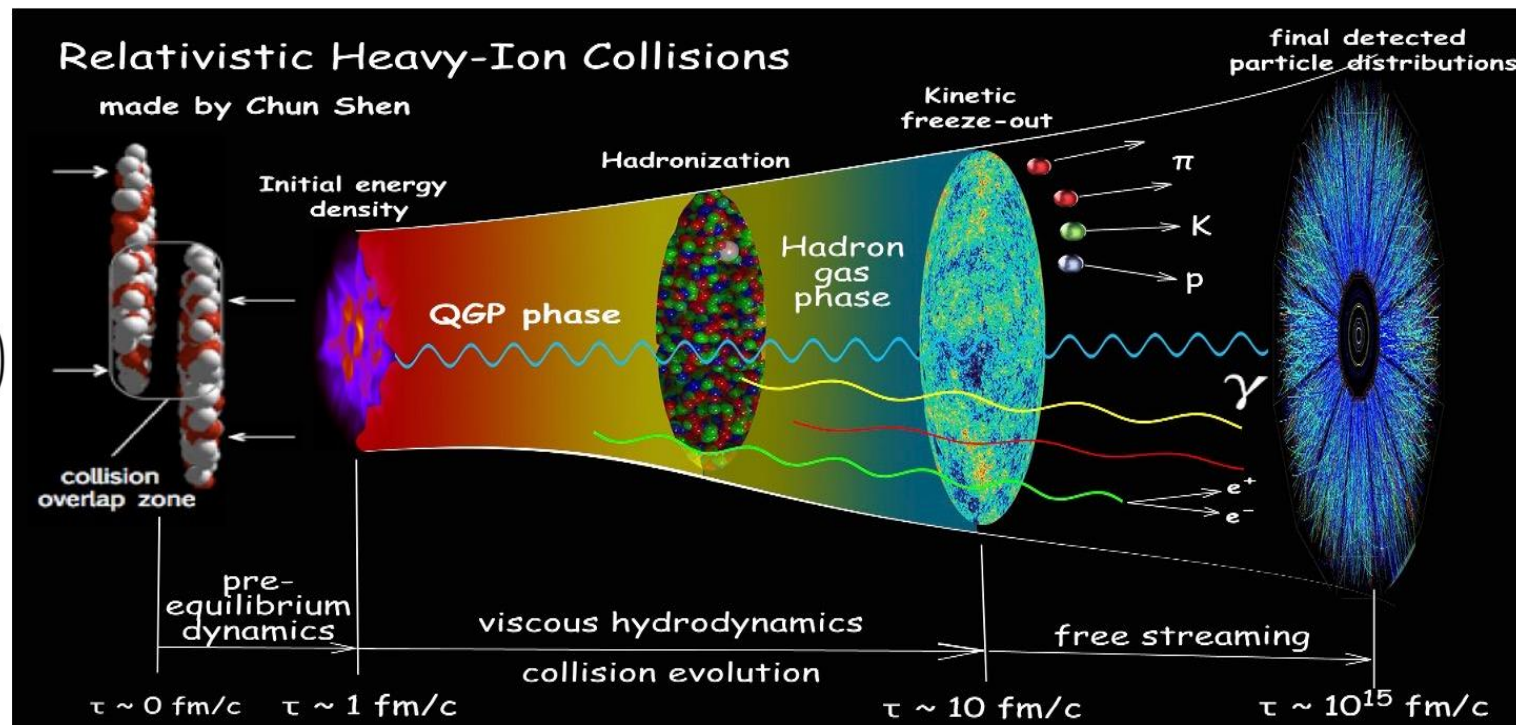
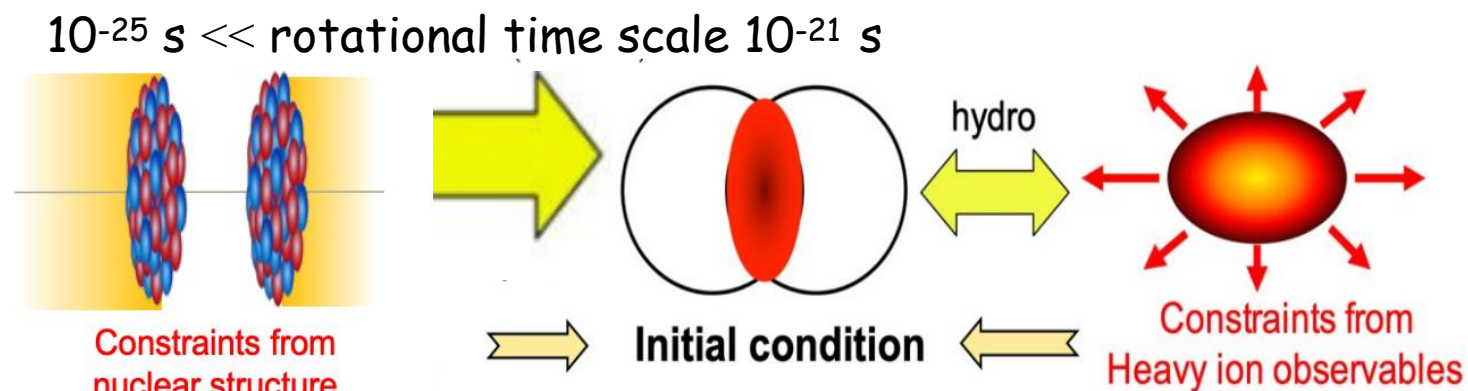
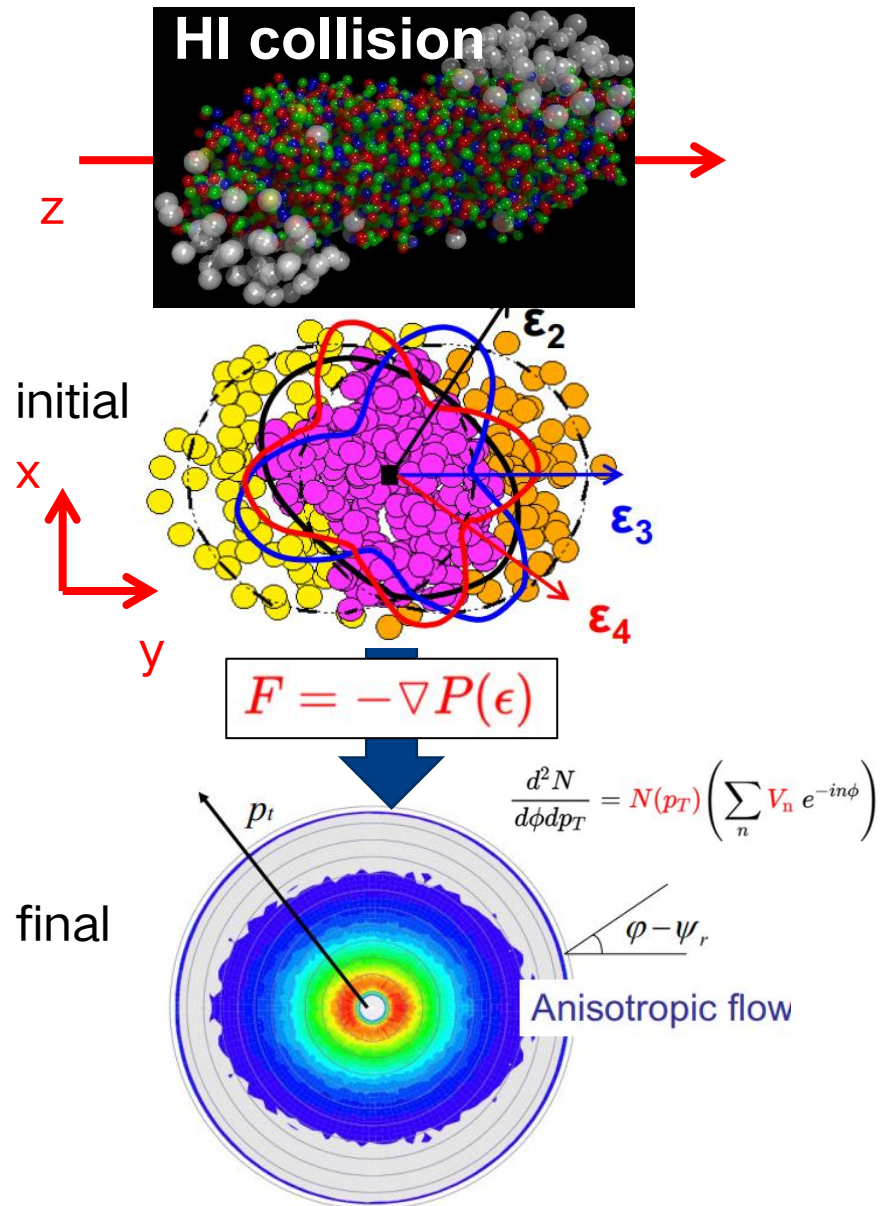
在超中心重离子碰撞中探测团簇结构

speaker: *Pei Li* (李沛)

coauthor: *Guo-liang Ma* (马国亮), *Bo Zhou* (周波), *Kai-jia sun* (孙开佳)

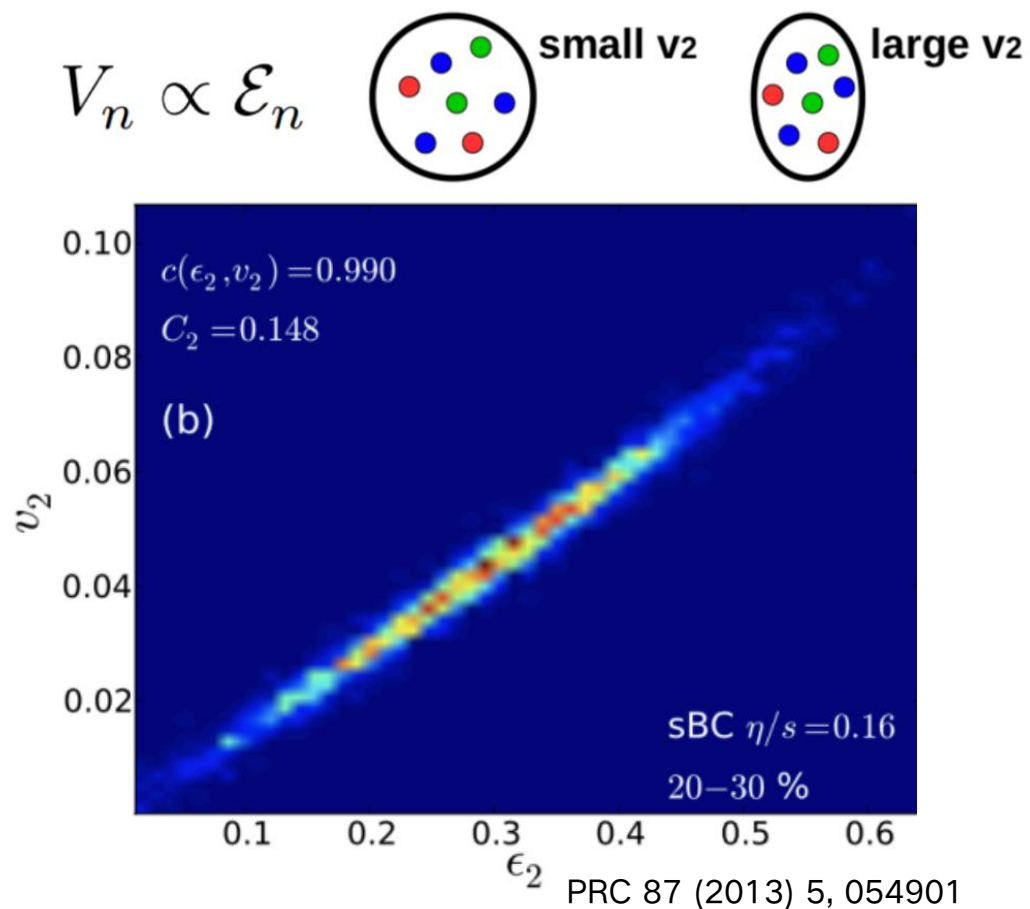
July 16, 2026, 第十二届高能物理全国会议

Heavy-ion collisions

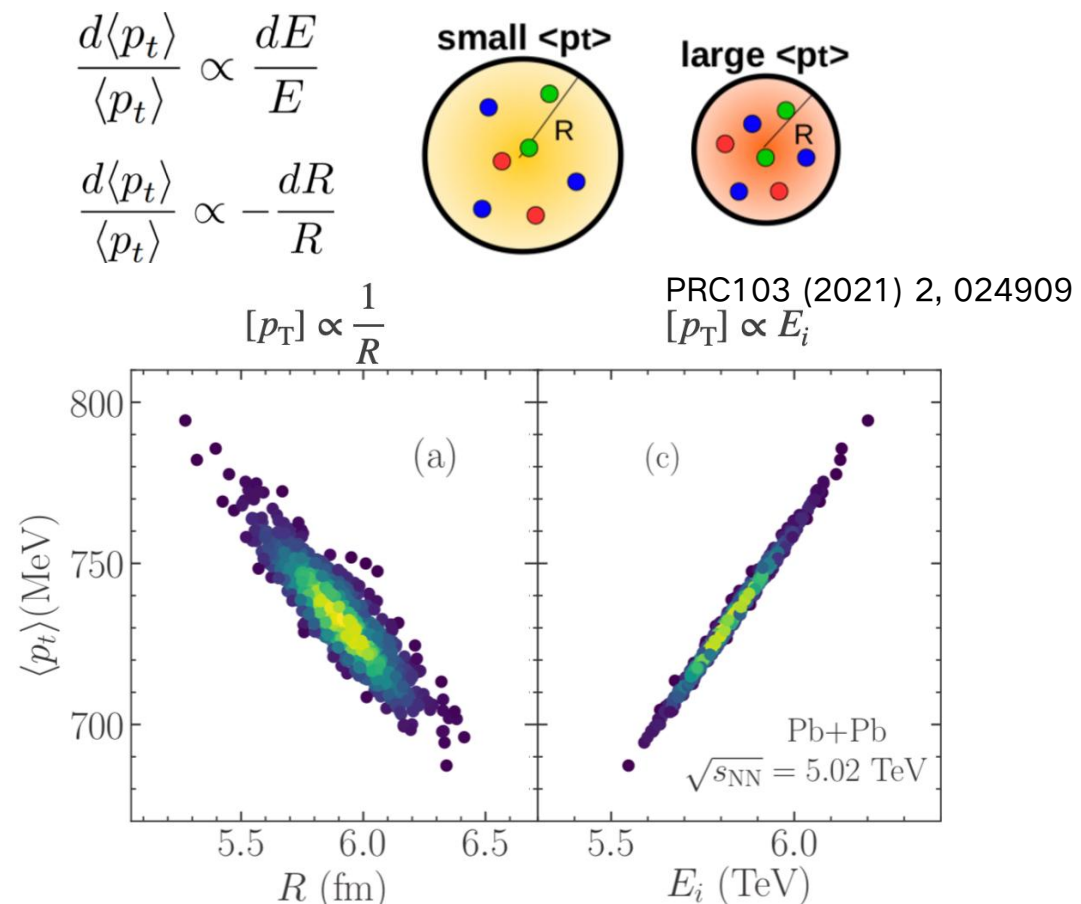


Heavy-ion collisions

Shape ↔ Anisotropic flow v_n



Size ↔ Transvers momentum p_T



see Chunjian Zhang's talk on July 17

Heavy-ion collisions



Nuclear cluster structure effect on elliptic and triangular flows in heavy-ion collisions

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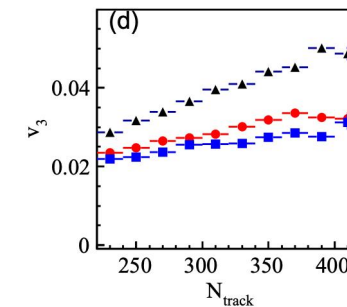
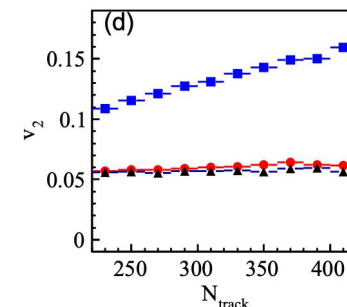
¹Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

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Phys.Rev.C 95 (2017) 6, 064904



¹²C+¹⁹⁷Au@200 GeV
■ ¹²C, Chain
● ¹²C, Woods-Saxon
▲ ¹²C, Triangle

Signatures of α clustering in ¹⁶O by using a multiphase transport model

Yi-An Li(李逸安),^{1,2,3} Song Zhang(张松),^{2,*} and Yu-Gang Ma(马余刚)^{2,1,†}

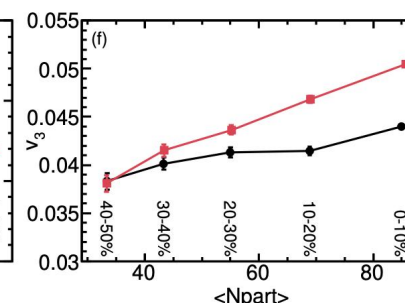
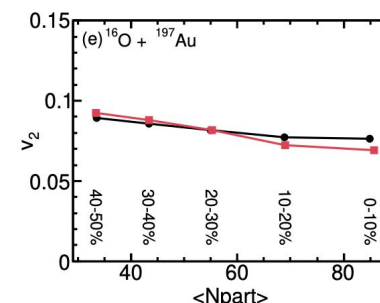
¹Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

²Key Laboratory of Nuclear Physics and Ion-beam Application (MOE),
Institute of Modern Physics, Fudan University, Shanghai 200433, China

³University of Chinese Academy of Sciences, Beijing 100049, China

(Dated: October 21, 2020)

Phys.Rev.C 102 (2020) 5, 054907



Nuclear cluster structure effect in ¹⁶O+¹⁶O collisions at the top RHIC energy

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¹College of Science, University of Shanghai for Science and Technology, Shanghai 200093, China

²Key Laboratory of Nuclear Physics and Ion-beam Application (MOE),
Institute of Modern Physics, Fudan University, Shanghai 200433, China

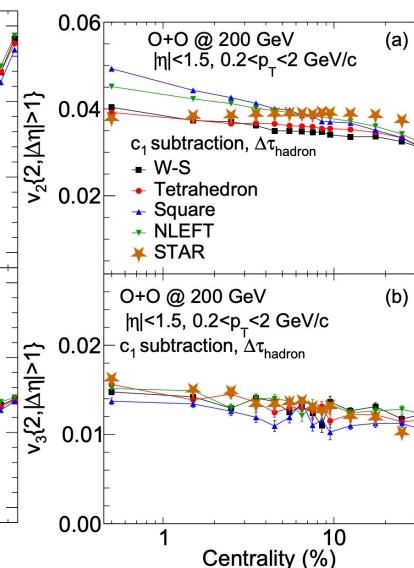
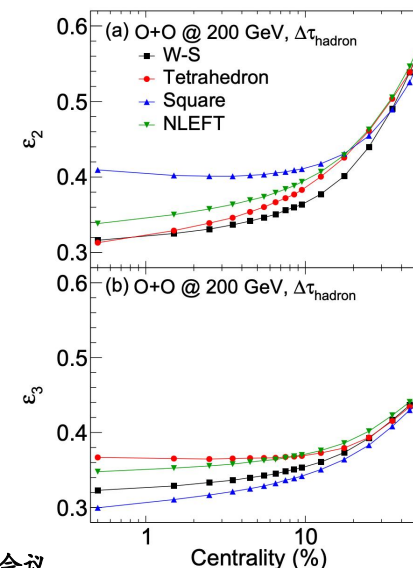
³Shanghai Research Center for Theoretical Nuclear Physics,
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⁴Department of Physics, East Carolina University, Greenville, NC 27858, USA

⁵Niels Bohr Institute, Jagtvej 155A, 2200 Copenhagen, Denmark and

⁶Department of Physical Science and Technology,
Wuhan University of Technology, Wuhan 430070, China

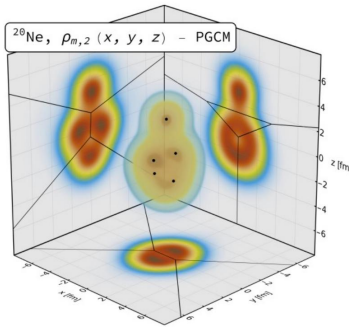
Phys.Lett.B 874 (2026) 140254



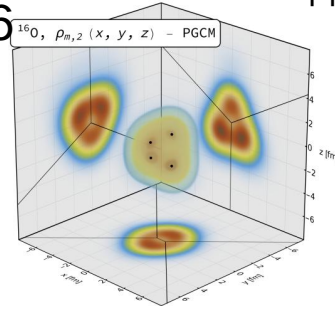
Light-ion collisions



Ne-20



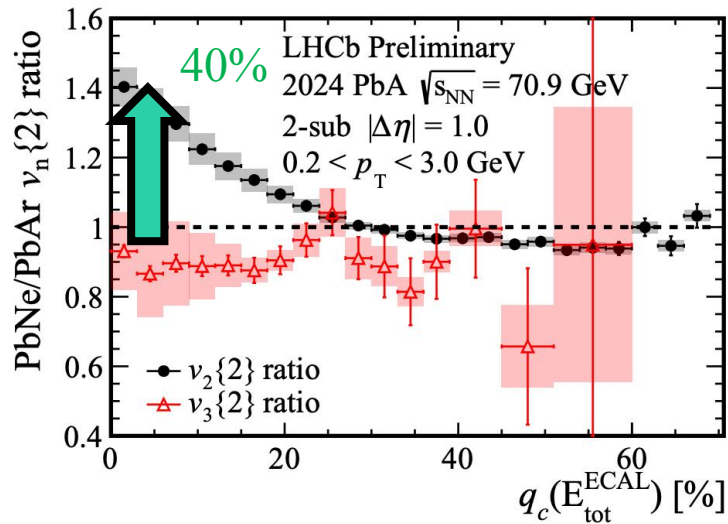
O-16



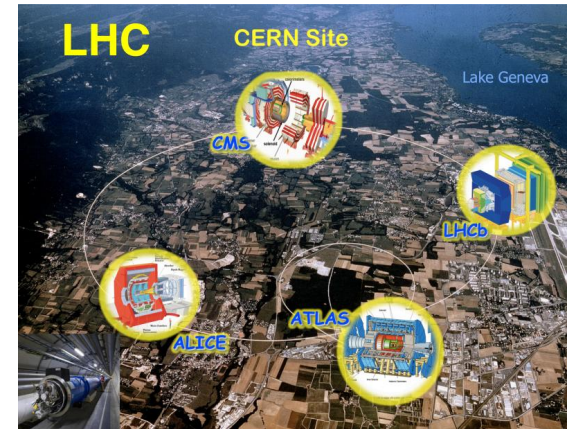
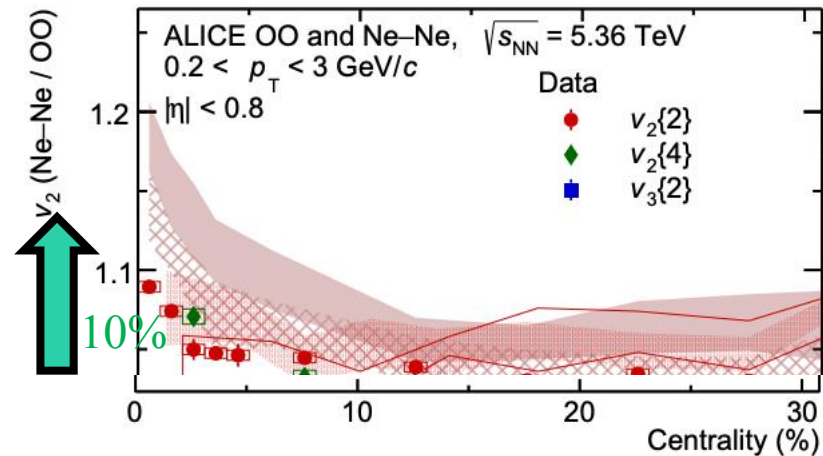
Phys.Rev.Lett. 135 (2025) 1, 012302

$$\text{ultracentral: } \frac{v_{2,\text{NeNe}}}{v_{2,\text{OO}}} \sim \frac{v_{2,\text{PbNe}}}{v_{2,\text{PbO}}} > 1$$

LHCb: Pb+Ne/Pb+Ar arXiv: 2509.12399



ALICE/ATLAS/CMS: Ne+Ne/O+O
2509.06428, 2509.05171, 2510.02580



➤ Evidence for Bowling-Pin structure of the Ne nucleus. Just the general shape! More details?

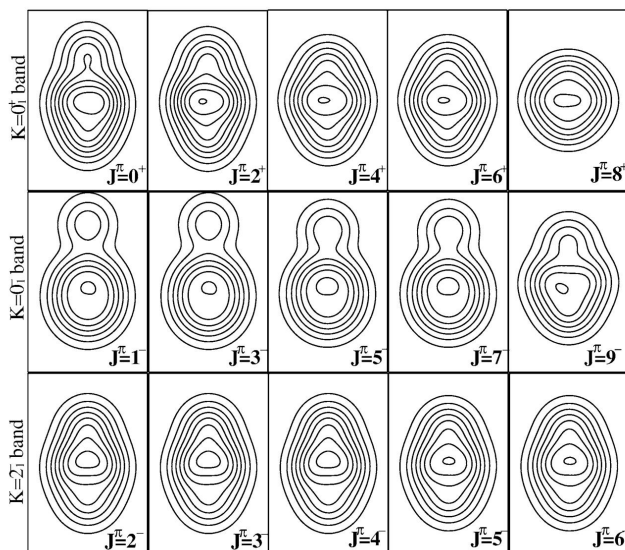
Clusters in ^{20}Ne



Prog. Theor. Phys. 40, 277 (1968)

Antisymmetrized Molecular Dynamics Model (AMD)

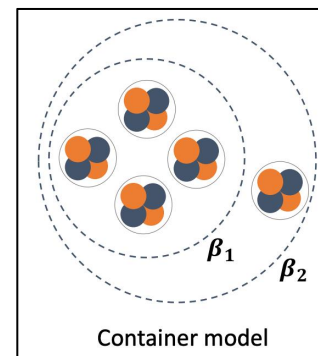
Cluster $J \uparrow$ Shell



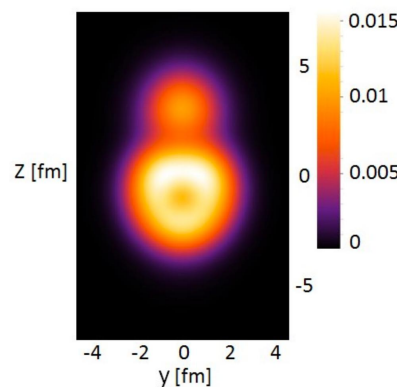
Nonlocalized THSR model

Front.Phys. 15 (2020) 14401

Nature Commun. 14 (2023) 1, 8206

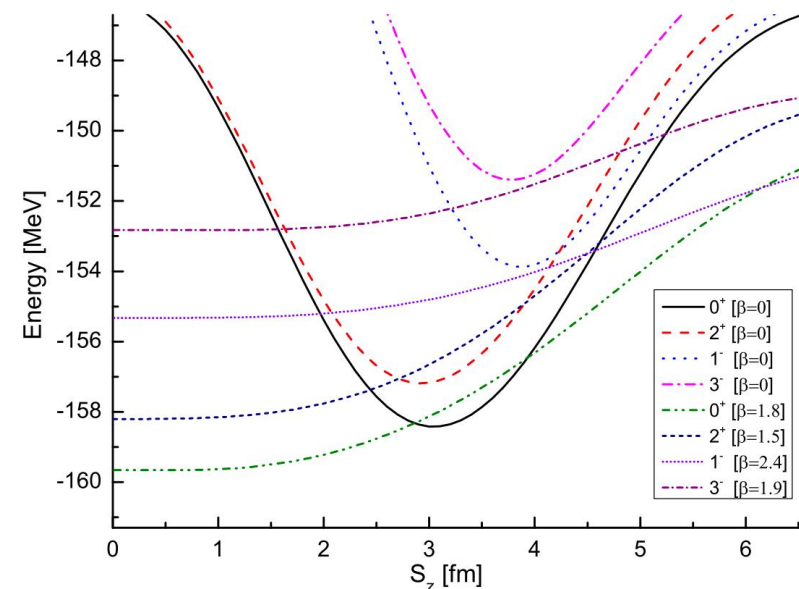


Pauli repulsion



$$\hat{\Phi}_{\text{Ne}}(\beta, S) = \mathcal{A}\left\{\exp\left[-\sum_k \frac{8(\xi - S)_k^2}{5B_k^2}\right]\phi(\alpha)\phi(^{16}\text{O})\right\}$$

$$B_k^2 = b^2 + 2\beta_k^2$$



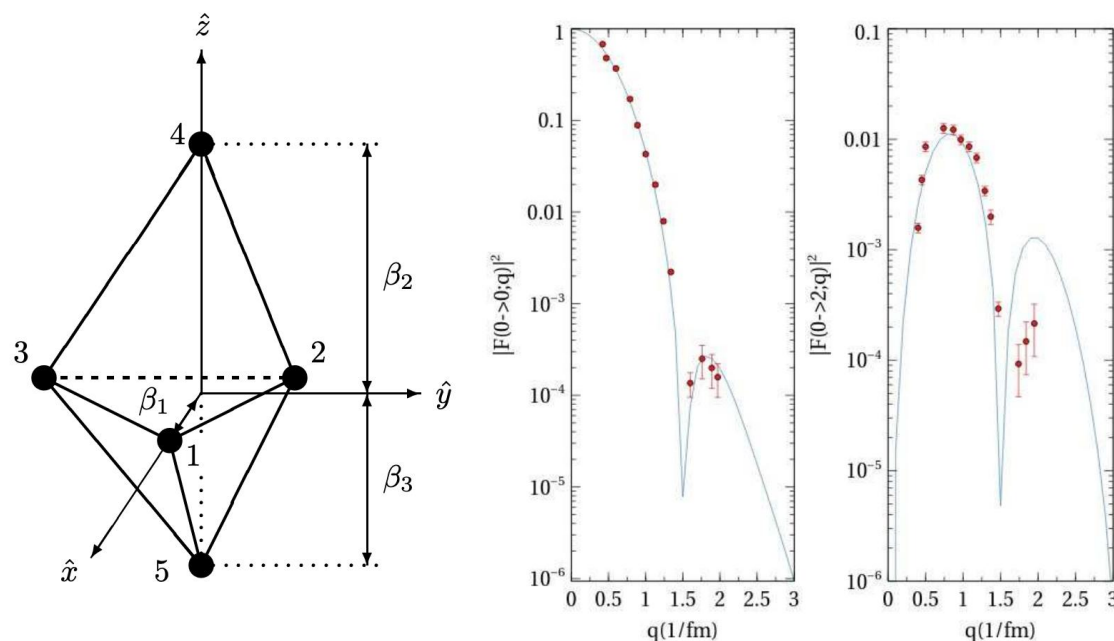
➤ ^{20}Ne with localized cluster with $\alpha + ^{16}\text{O}$

Or

with nonlocalized cluster with 5- α

Algebraic Collective Model (ACM)

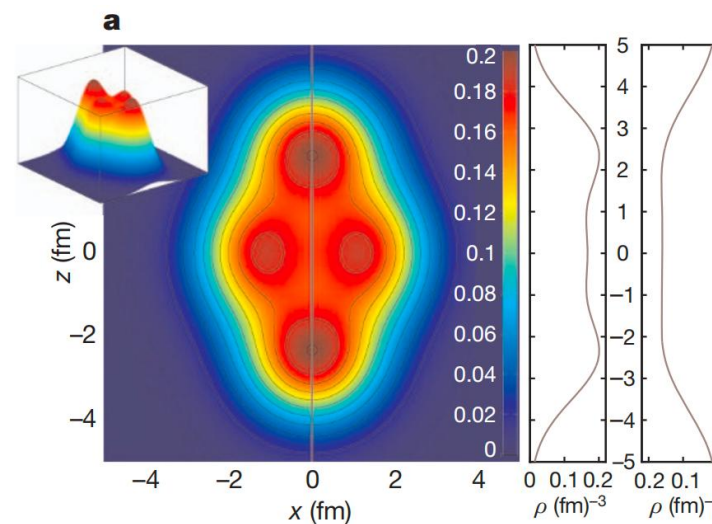
Nucl.Phys.A 1006 (2021) 122077



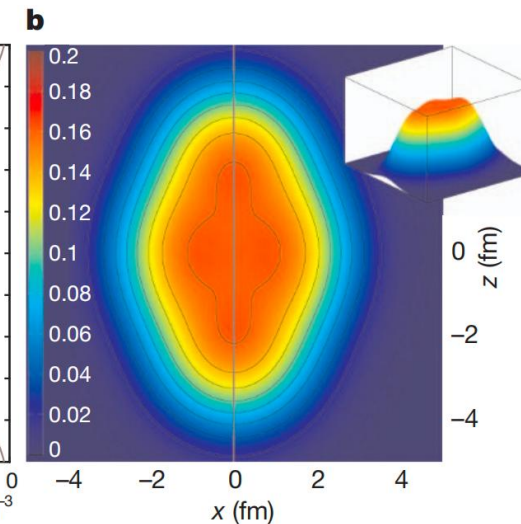
Energy-density functionals

Nature 487 (2012) 341–344

relativistic functional
DD-ME2



non-relativistic
Skymre SLy4



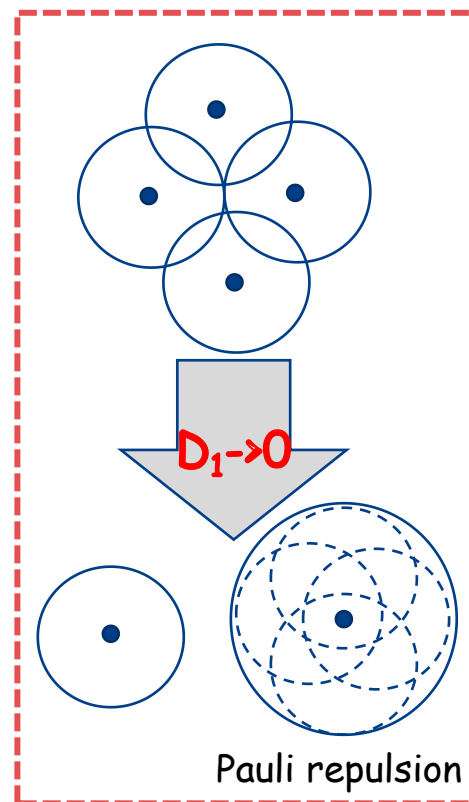
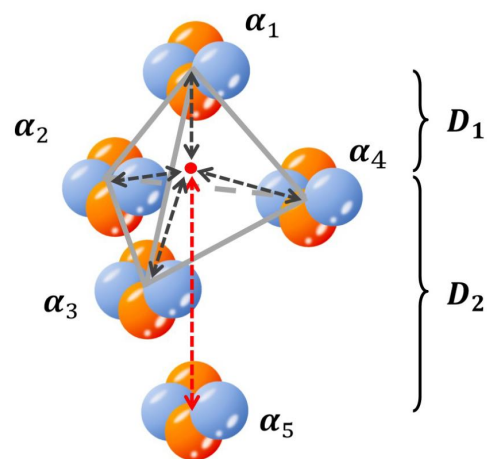
➤ Evidence of ^{20}Ne with D_{3h} symmetry

Clusters in ^{20}Ne

Nucl. Phys. A 1006, 122077 (2021)

Front.Phys. 15 (2020) 14401

Two parameters: D_1 and D_2



Prog. Theor. Phys. 40, 277 (1968)

AMD model
(localized
two-cluster)

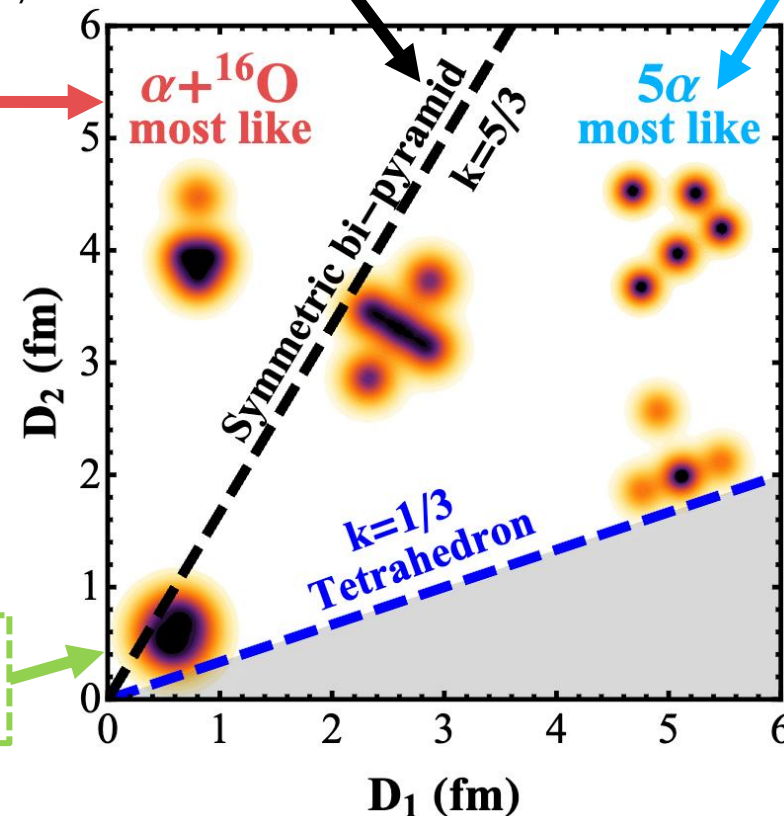
$D_1 \rightarrow 0$

$D_1 \rightarrow 0$ $D_2 \rightarrow 0$

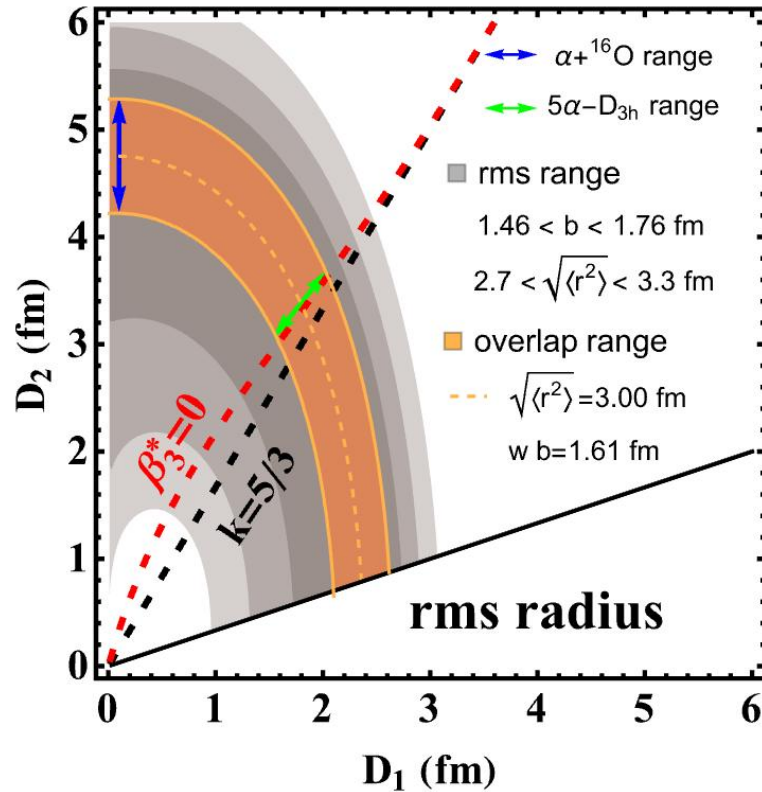
Shell model
(Spherical)

Clusters with
 D_{3h} symmetry

Loose and
nonlocalized-like



Two parameters: D_1 and D_2



Prog. Theor. Phys. 40, 277 (1968)

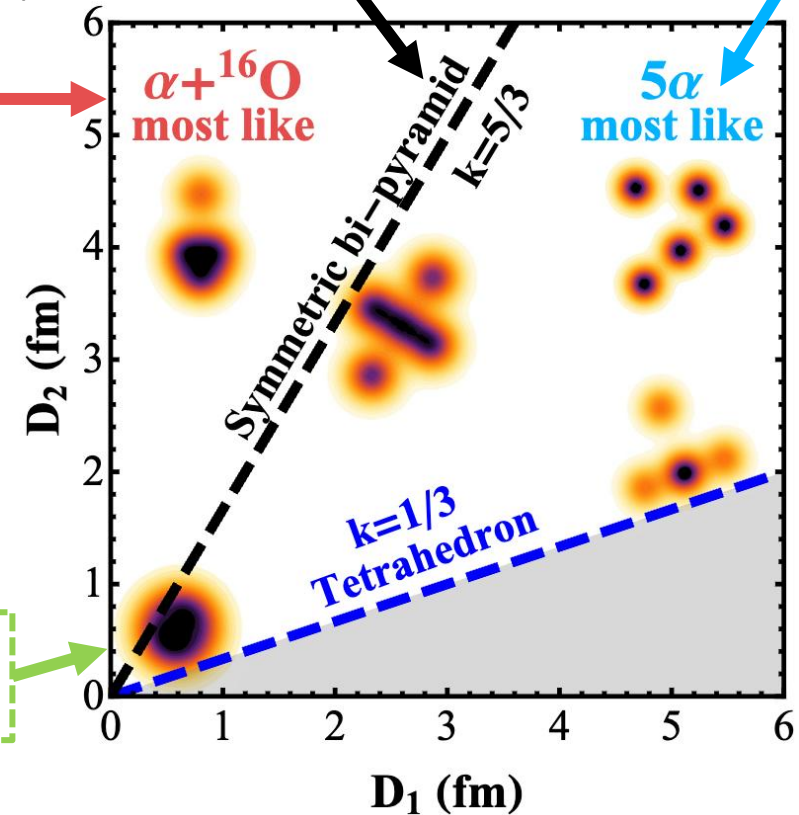
AMD model
(localized
two-cluster)

rms radius
($3.0 \pm 10\%$) fm
 $b \in (1.46, 1.76)$ fm
↓
 D_1 D_2 range

Shell model
(Spherical)

Clusters with
 D_{3h} symmetry

Loose and
nonlocalized-like

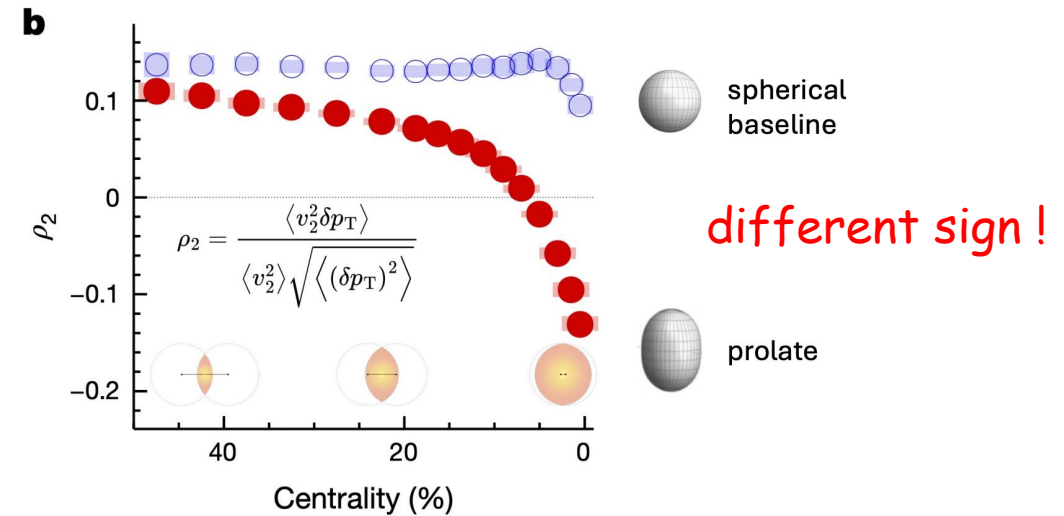
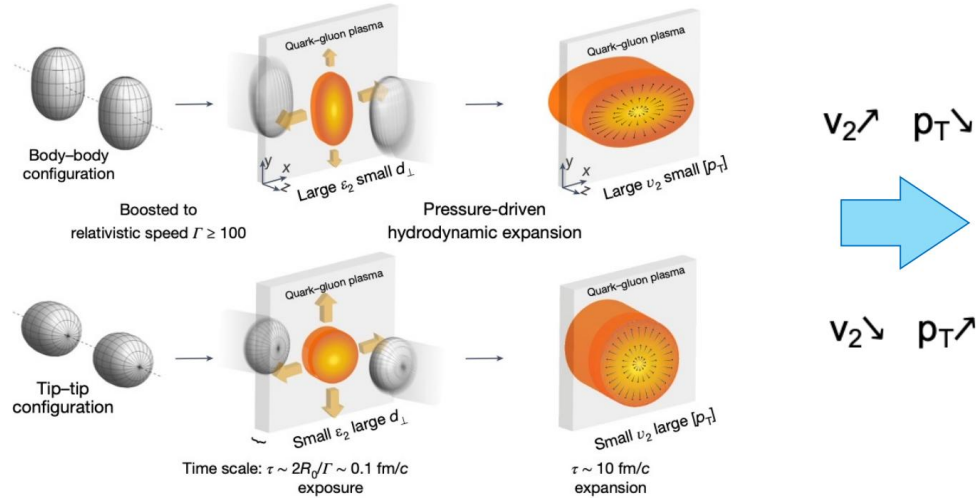


➤ How to estimate the systematic error of the theoretical model?

all parameters : D_1 D_2 (local structural parameters) and b (harmonic oscillator size parameter)

Correlation observables

□ How to explore more detailed structural effects:



Correlation between different ε_n

$$\text{NSC}(m, n) = \frac{\langle \varepsilon_m^2 \varepsilon_n^2 \rangle - \langle \varepsilon_m^2 \rangle \langle \varepsilon_n^2 \rangle}{\langle \varepsilon_m^2 \rangle \langle \varepsilon_n^2 \rangle}$$



Correlation between different v_n

$$\text{NSC}(m, n) = \frac{\langle v_n^2 v_m^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle}{\langle v_m^2 \rangle \langle v_n^2 \rangle}$$

Correlation between ε_n (shape) and $\delta d_\perp$ (size)

$$\rho_n(\varepsilon_n^2, \delta d_\perp) = \frac{\text{cov}(\varepsilon_n^2, \delta d_\perp)}{\sqrt{\text{Var}(\varepsilon_n^2) \text{Var}(\delta d_\perp)}}$$

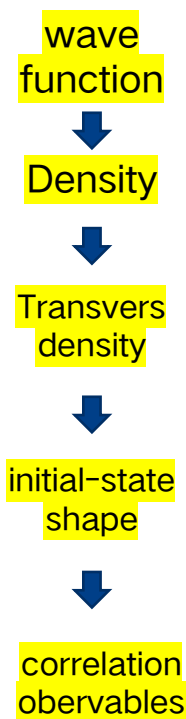


Correlation between v_n and δp_T

$$\rho(v_n^2, \delta p_T) = \frac{\text{cov}(v_n^2, \delta p_T)}{\sqrt{\text{Var}(v_n^2) \text{Var}(\delta p_T)}}$$

Symmetric cumulant NSC(n, m)

$$\text{NSC}(m, n) = \frac{\langle v_n^2 v_m^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle}{\langle v_m^2 \rangle \langle v_n^2 \rangle}$$



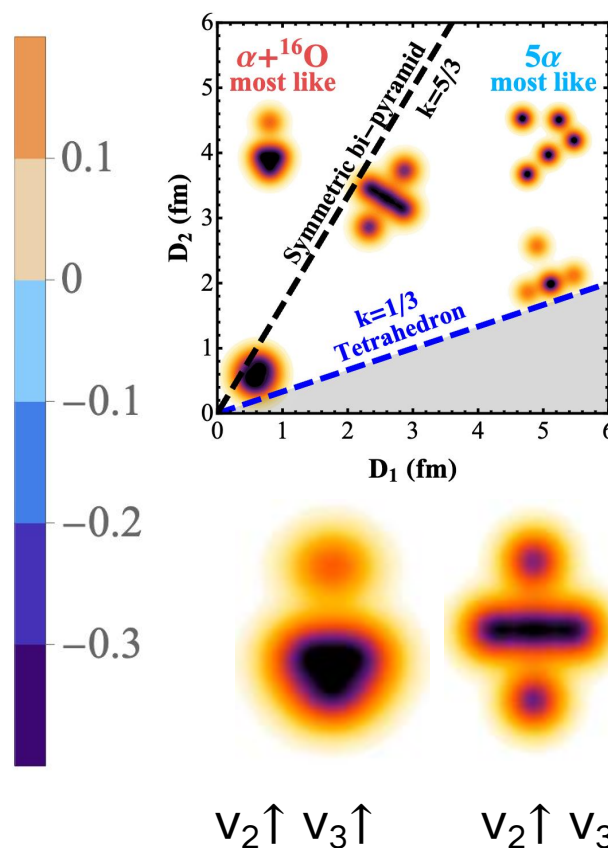
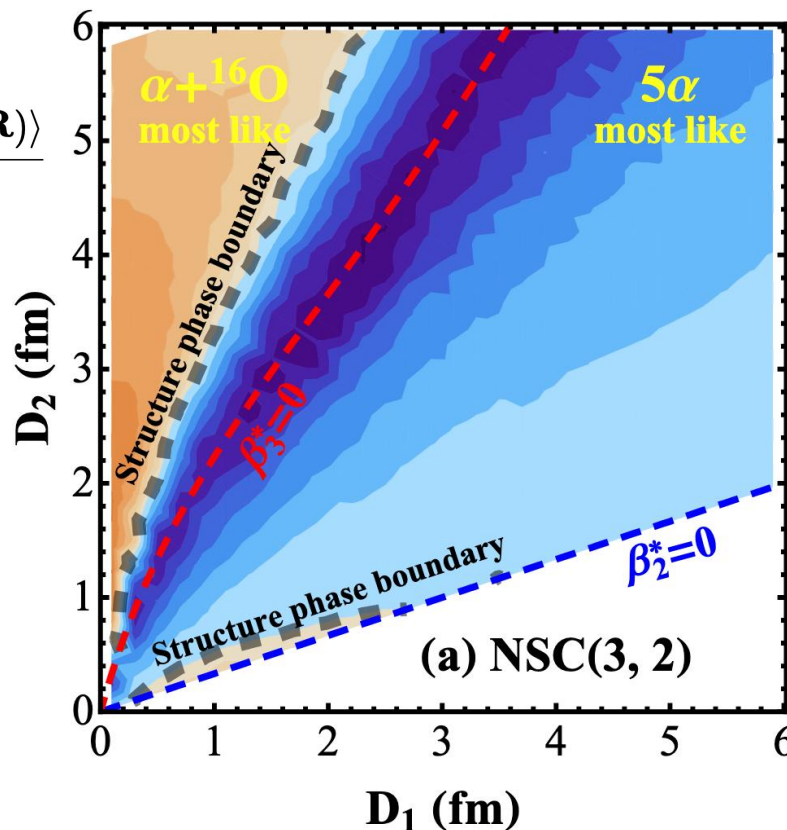
$$|\Phi^{\text{Brink}}\rangle = \frac{1}{\sqrt{N!}} |\det\{\phi_1(\mathbf{r}_1) \dots \phi_N(\mathbf{r}_N)\}\rangle$$

$$\rho(\mathbf{a}) = \frac{\langle \Phi^{\text{B}}(\mathbf{R}) | \frac{1}{A} \sum_{j=1}^A \delta(\mathbf{r}_j - \mathbf{r}_g - \mathbf{a}) | \Phi^{\text{B}}(\mathbf{R}) \rangle}{\langle \Phi^{\text{B}}(\mathbf{R}) | \Phi^{\text{B}}(\mathbf{R}) \rangle}$$

$$\rho(r_{\perp}, \phi) = \int [\mathcal{R}_p(\phi_{p,1}, \theta_p, \phi_{p,2}) \rho(x, y, z) + \mathcal{R}_t(\phi_{t,1}, \theta_t, \phi_{t,2}) \rho(x, y, z)] / 2 dz$$

$$\varepsilon_n e^{in\Phi} = - \frac{\int r_{\perp}^n e^{in\phi} \rho(r_{\perp}, \phi) d^2 r}{\int r_{\perp}^n \rho(r_{\perp}, \phi) d^2 r}$$

$$\text{NSC}(m, n) = \frac{\langle \varepsilon_m^2 \varepsilon_n^2 \rangle - \langle \varepsilon_m^2 \rangle \langle \varepsilon_n^2 \rangle}{\langle \varepsilon_m^2 \rangle \langle \varepsilon_n^2 \rangle}$$



- ✓ The shape of ^{20}Ne can be determined by the **positive** or **negative** NSC(2, 3) value.
- ✓ Correlation strength $\text{NSC}(2, 3) \propto k = D_2/D_1$.

Analytical results (b=0)
w/o fluctuations

only geometry effect!



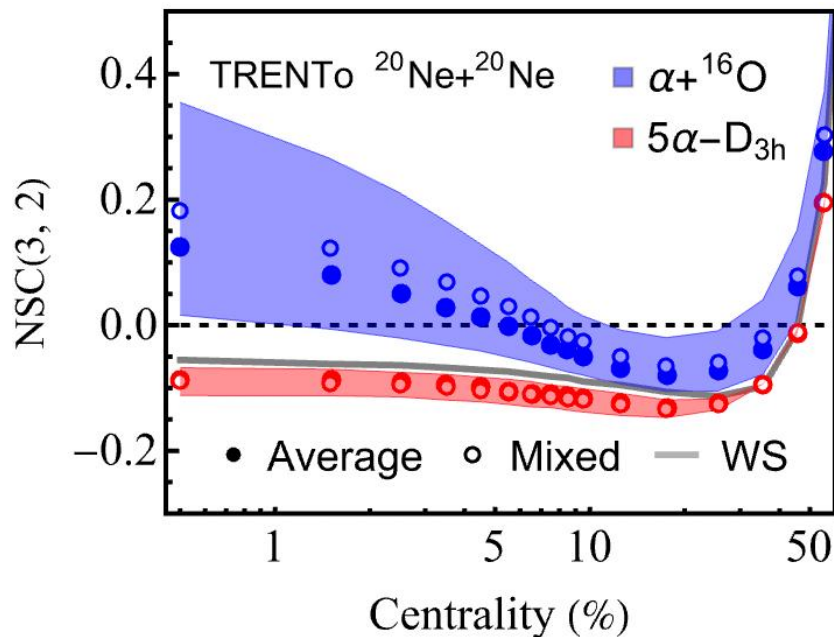
Need to add full fluctuations!

Symmetric cumulant NSC(n, m)

$$\text{NSC}(m, n) = \frac{\langle v_n^2 v_m^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle}{\langle v_m^2 \rangle \langle v_n^2 \rangle}$$

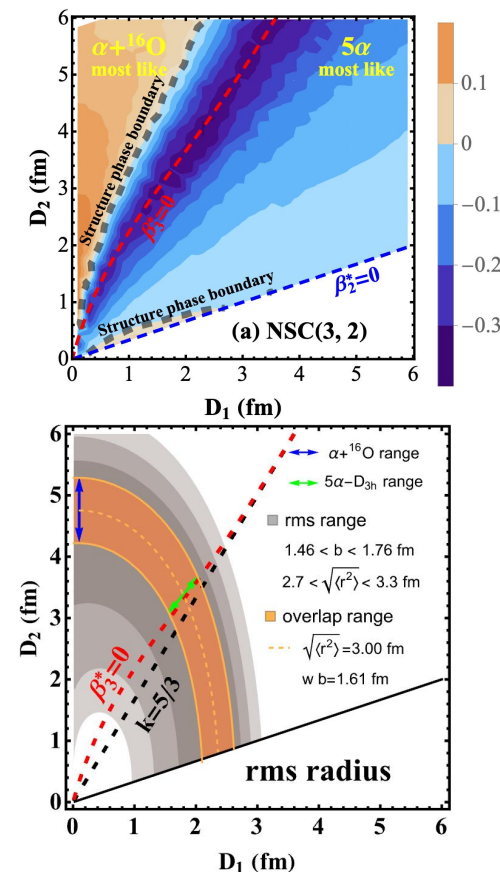
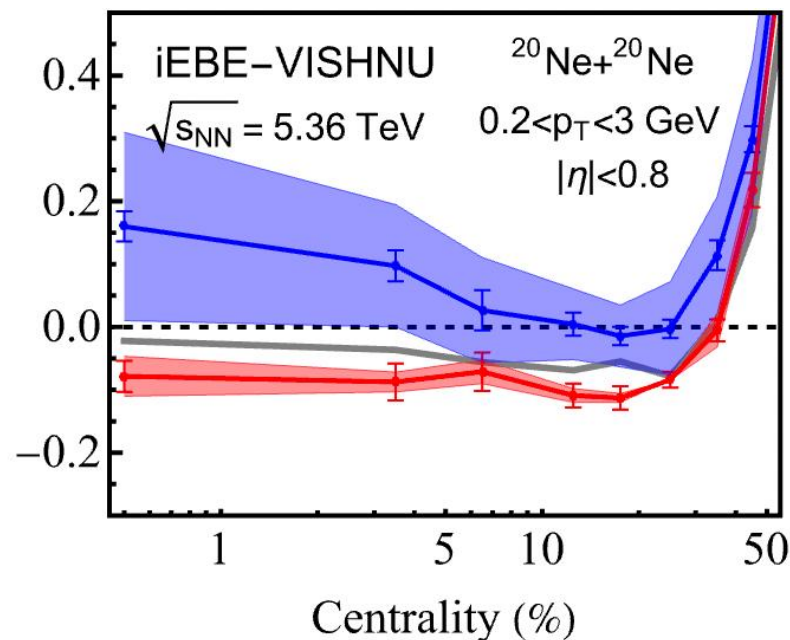


TRENTTo results w initial fluctuation



hydro evolution

Hydro results w all fluctuations



- ✓ The shape of ^{20}Ne can be determined by the **positive** or **negative** NSC(2, 3) value.
- ✓ Shape mixing does not affect the sign of NSC(2, 3).
- ✓ The fluctuations of initial and final state do not affect the sign of NSC(2, 3).

Pearson correlation $v_2 - p_T$

$$\rho(\nu_n^2, \delta p_T) = \frac{\text{cov}(\nu_n^2, \delta p_T)}{\sqrt{\text{Var}(\nu_n^2) \text{Var}(\delta p_T)}}$$



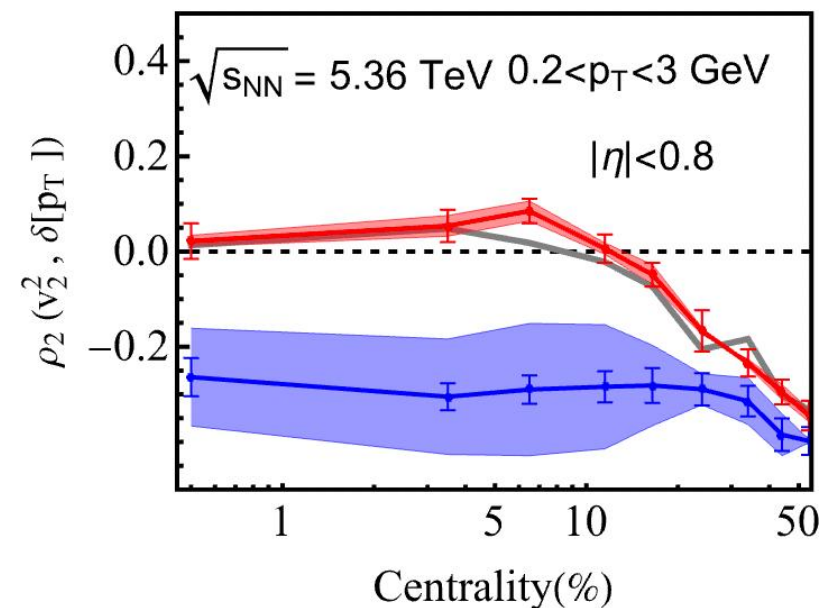
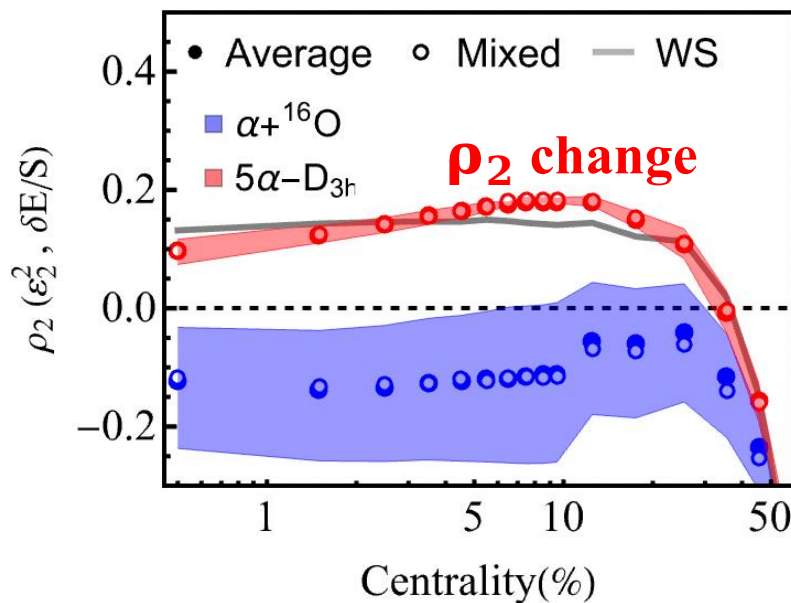
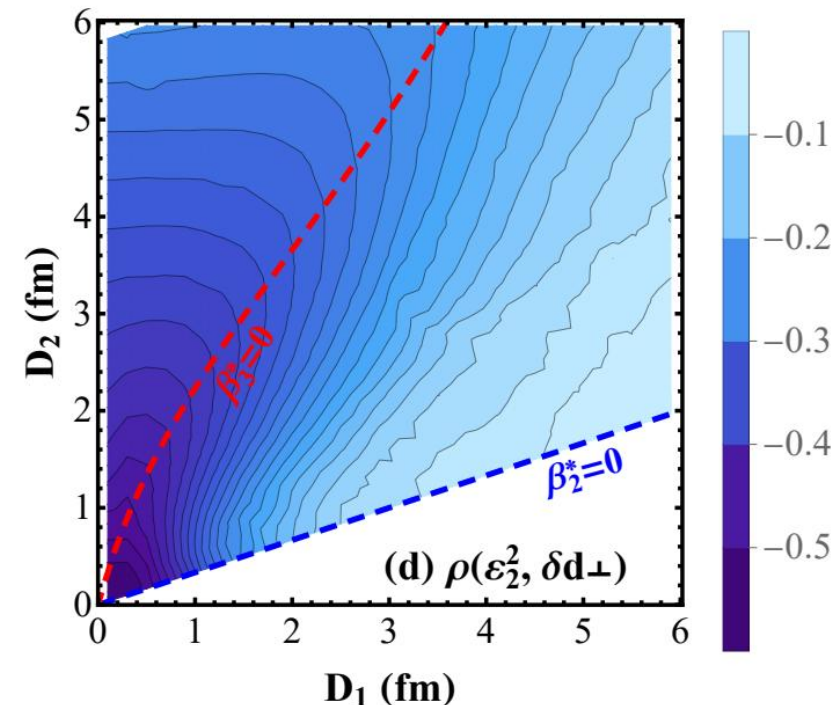
Analytical results w/o fluctuation



TRENTTo results
w initial fluctuations



Hydro results
w all fluctuations



✓ The shape of ^{20}Ne can be determined by the **positive** or **negative** ρ_2 value

Pearson correlation $v_3 - p_T$

$$\rho(\nu_n^2, \delta p_T) = \frac{\text{cov}(\nu_n^2, \delta p_T)}{\sqrt{\text{Var}(\nu_n^2) \text{Var}(\delta p_T)}}$$



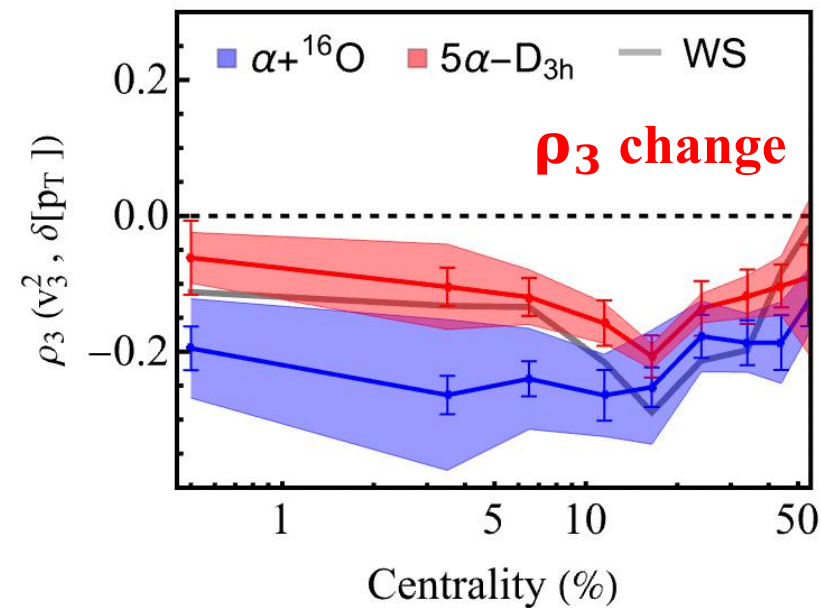
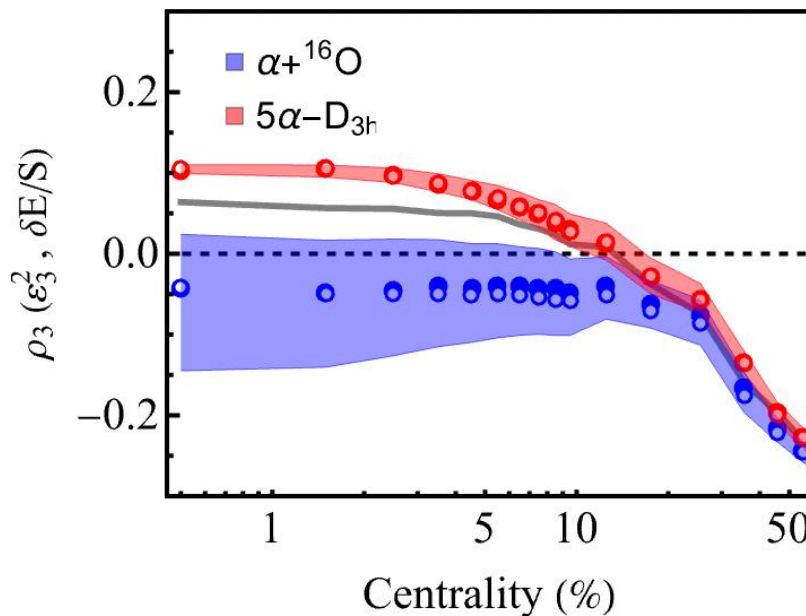
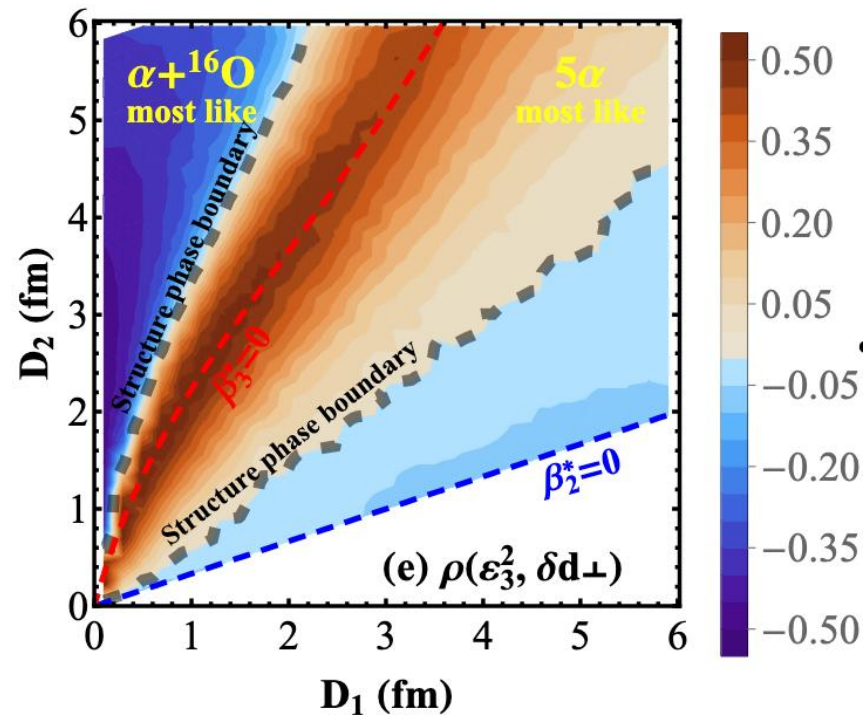
Analytical results w/o fluctuation



TRENTTo results
w initial fluctuations



Hydro results
w all fluctuations



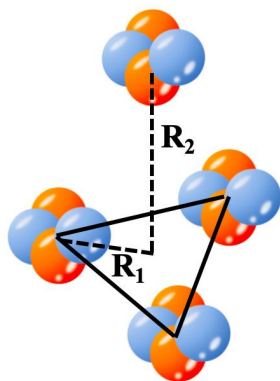
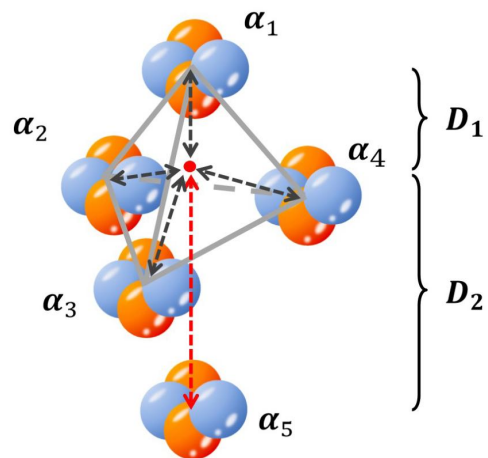
✓ The shape of ^{20}Ne **cannot** be determined by ρ_3 due to fluctuations.

^{20}Ne

vs.

^{16}O

➤ Candidate species for new ion collisions at **LHC Run4**.



The LHC (heavy-ion) programme

Collision systems pp, pPb, Pb-Pb

pp, pPb, Xe-Xe, Pb-Pb

pp, pO, OO, pPb, Pb-Pb

LHC schedule

Run 1
2009 – 2013

Run 2
2015 – 2018

Run 3
2022 – 2025

Run 4
2029 – 2032

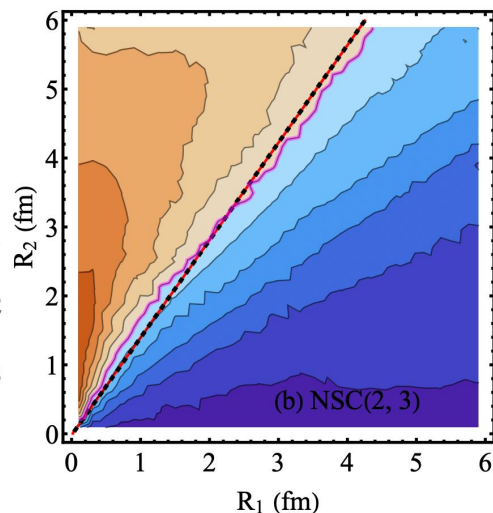
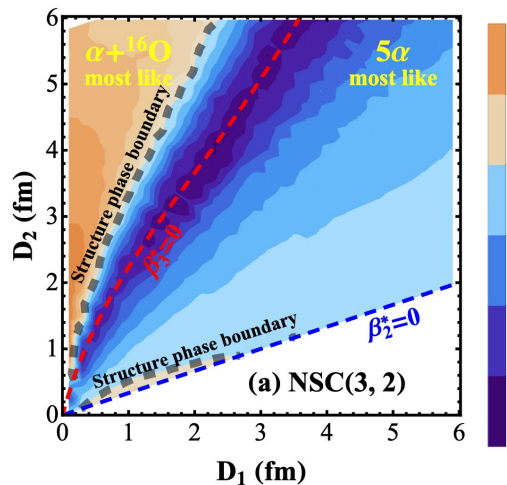
Run 5
2035 – ...

Run 6

High luminosity
for ions

HL-LHC

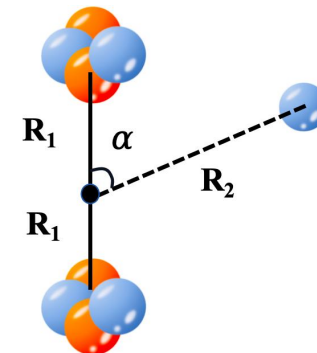
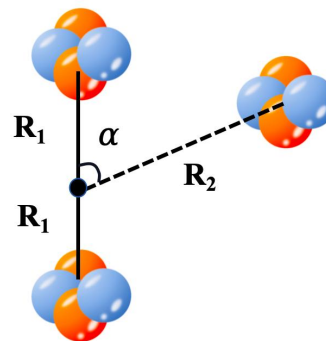
Higher luminosities for ions



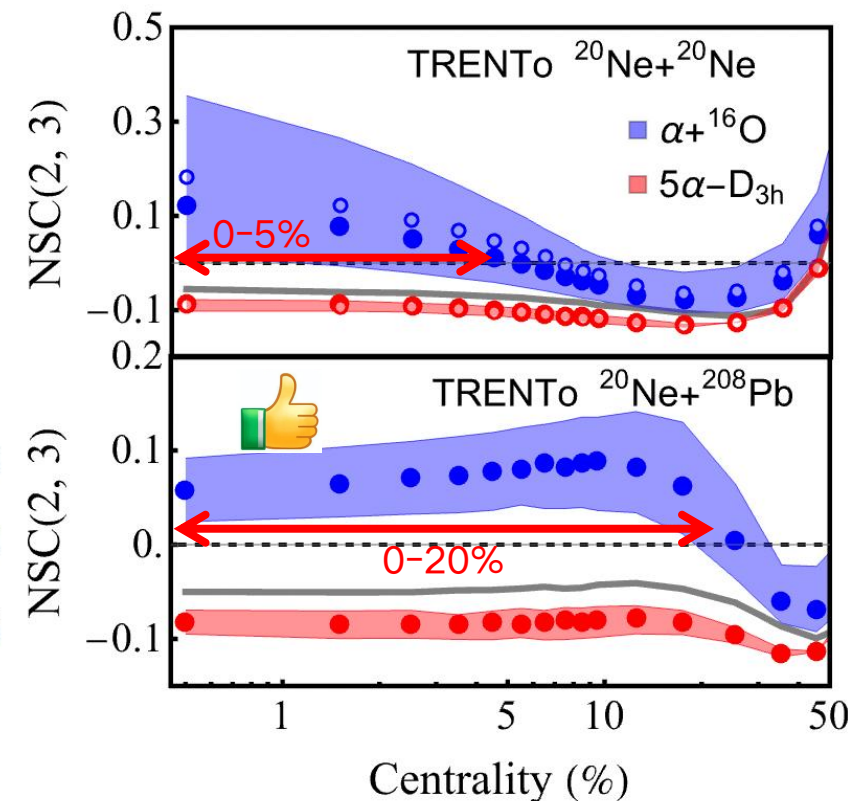
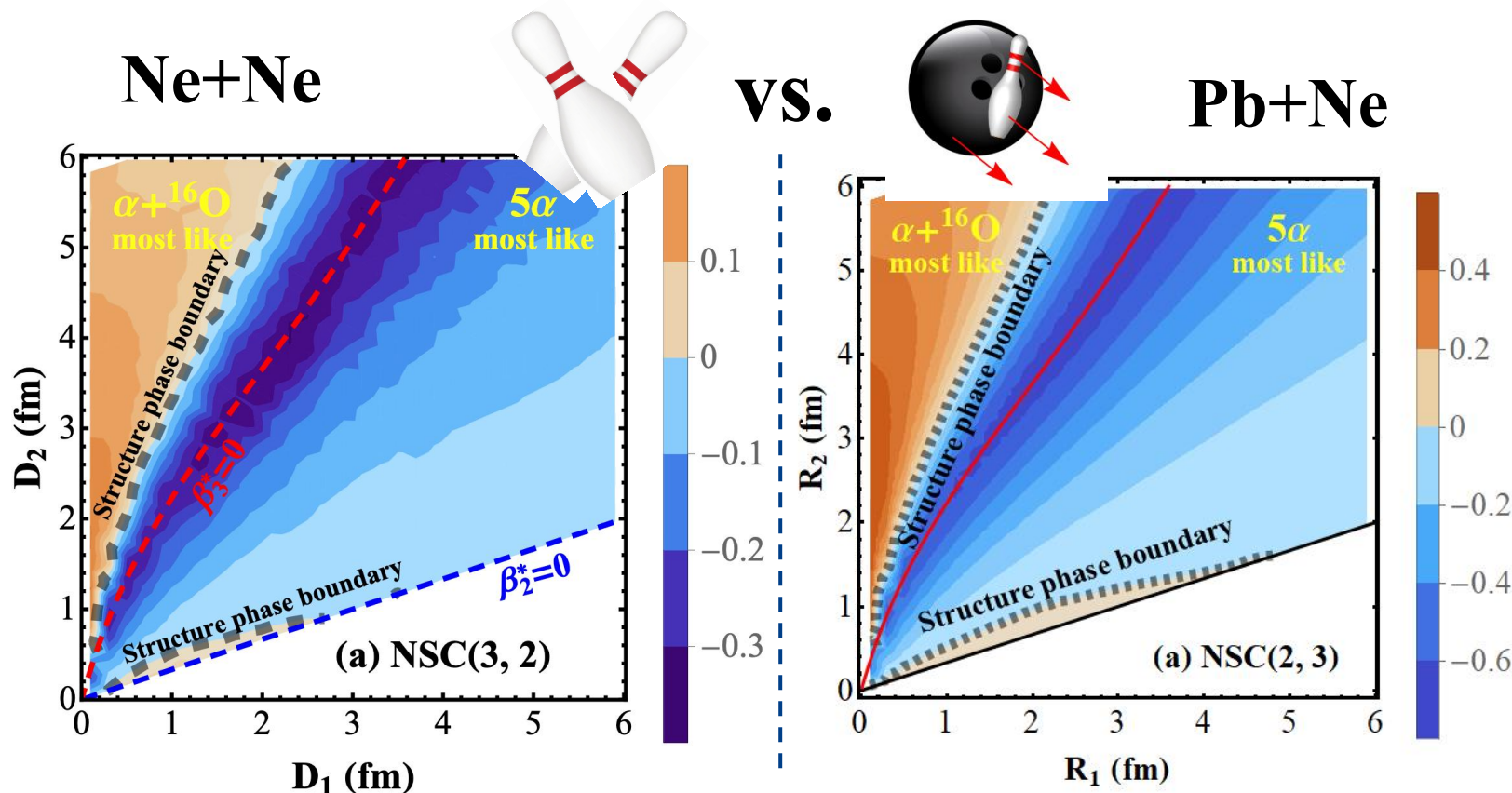
^{12}C

vs.

^9Be



Ne+Ne vs. Ne+Pb



- ✓ The correlation strength of Pb+Ne **increases** compared to Ne+Ne.
 - ✓ The distinguishable range of centrality of Pb+Ne **increases** compared to Ne+Ne.
- (0-20%)  (0-5%)

Pb+Ne paper in preparation.

1. The Analytical method we developed can isolate the initial-state fluctuations, thus clarifying pure cluster geometry effect.
2. $NSC(2,3)$ and $\rho_2(v_2^2, [p_T])$ are very good observables to probe the cluster structure of ^{20}Ne and distinguish $\alpha+^{16}\text{O}$ and 5α directly with **positive** and **negative** value.
3. The fixed-target experiment $\text{Pb}+\text{Ne}$ **has better theoretical superiority** than the collider experiment $\text{Ne}+\text{Ne}$ —an opportunity to cross-validate the theory

Thanks for attention!

Short-range correlations

arXiv: 2511.23293



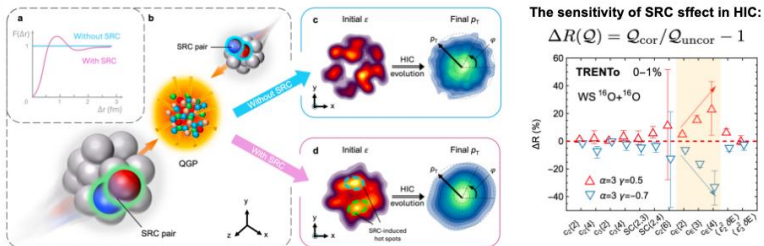
Short-range Correlations in Heavy-ion Collisions

Pei Li(李沛),^{1,2} Kai-Jia Sun(孙开佳),^{1,2} Bo Zhou(周波),^{1,2} Guo-Liang Ma(马国亮),^{1,2}

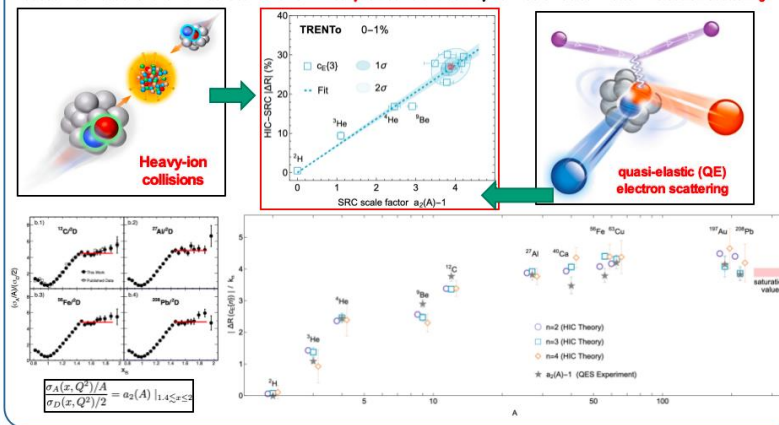
¹Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China
²Shanghai Research Center for Theoretical Nuclear Physics, NSFC and Fudan University, Shanghai 200438, China

Abstract

Protons and neutrons within atomic nuclei undergo intense and fleeting encounters driven by the strong, short-distance component of the nuclear force. These interactions generate close-proximity pairs, a phenomenon known as short-range correlations (SRCs). While the properties of SRCs have been extensively studied in cold nuclear matter, our understanding of their behavior under extremely hot and dense conditions remains largely unexplored. Here, we introduce correlated nucleon configurations into relativistic heavy-ion collisions, employing the quark-gluon plasma (QGP), a state of matter believed to have existed microseconds after the Big Bang, as a sensitive diagnostic tool. We find that these correlations induce substantial modifications to event-by-event geometry, which are quantitatively identified through higher-order moments of the transverse profile. Most importantly, we find a surprising linear relation between QGP geometry fluctuations and the SRC scale factor across orders of magnitude, which reflects the universal imprinting of SRCs in relativistic heavy-ion collisions. Our findings reveal the emergence of short-range structural effects across vastly different energy scales from low-energy electron scattering to high-energy nuclear collisions.

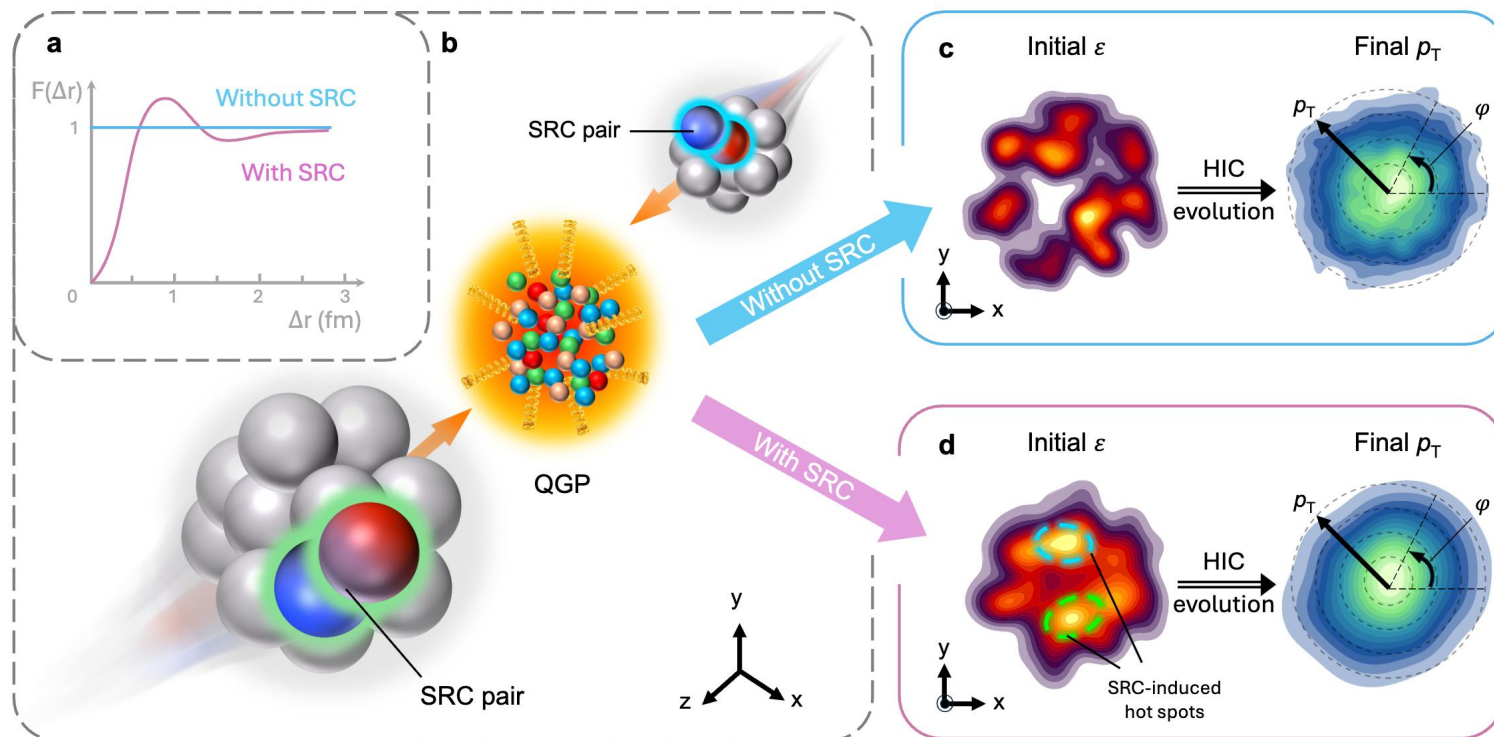


The consistent linear relation observed across various nuclear species, ranging from light systems to ^{208}Pb , reveals that the SRC-induced modifications follow an identical behavior in **heavy-ion collisions** as they do in cold nuclear matter in **electron scattering**.



For further details, see 2511.23293 (will be updated soon) or contact me at lip24@m.fudan.edu.cn
For SRC-related work, see Nature 566(7744), 354-358 (2019); Nature 609(7925), 41-45 (2022); Nature 654(8119), 619-621 (2026).

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see P. Li's poster at 3-21 and look forward to your suggestions

Backup

$v_n\{2\}$ compared to ALICE data

