Probing cluster structure in ultracentral heavy-ion collisions

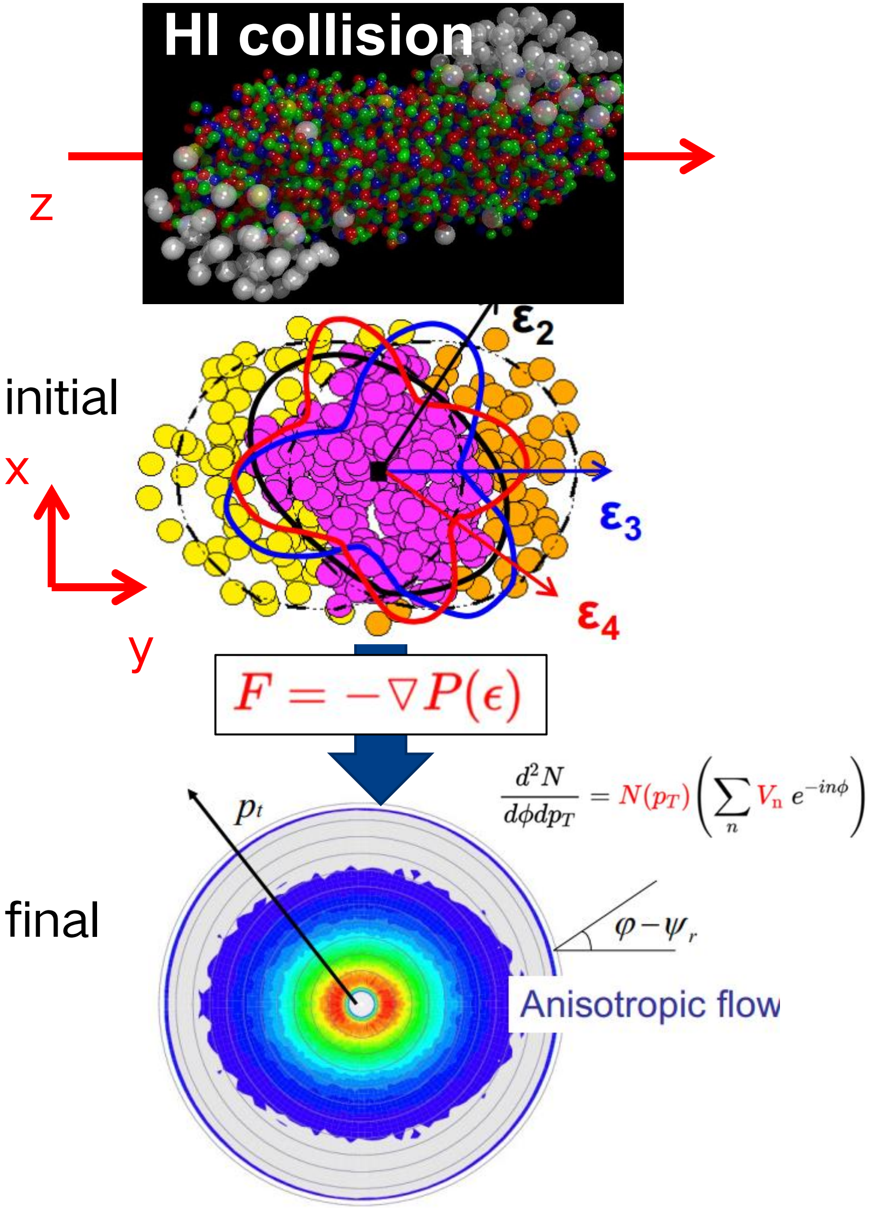
在超中心重离子碰撞中探测团簇结构

speaker: *Pei Li* (李沛)

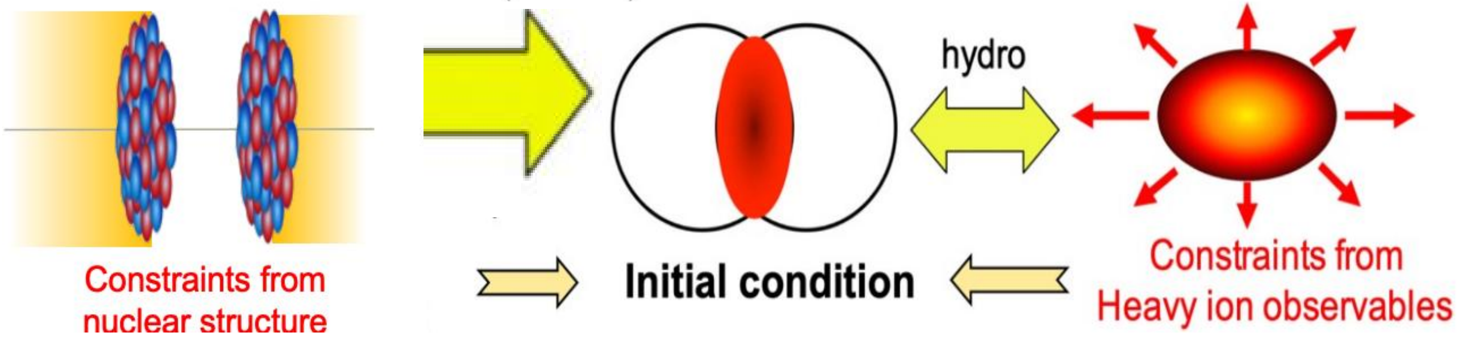
coauthor: *Guo-liang Ma* (马国亮), *Bo Zhou* (周波), *Kai-jia sun* (孙开佳)

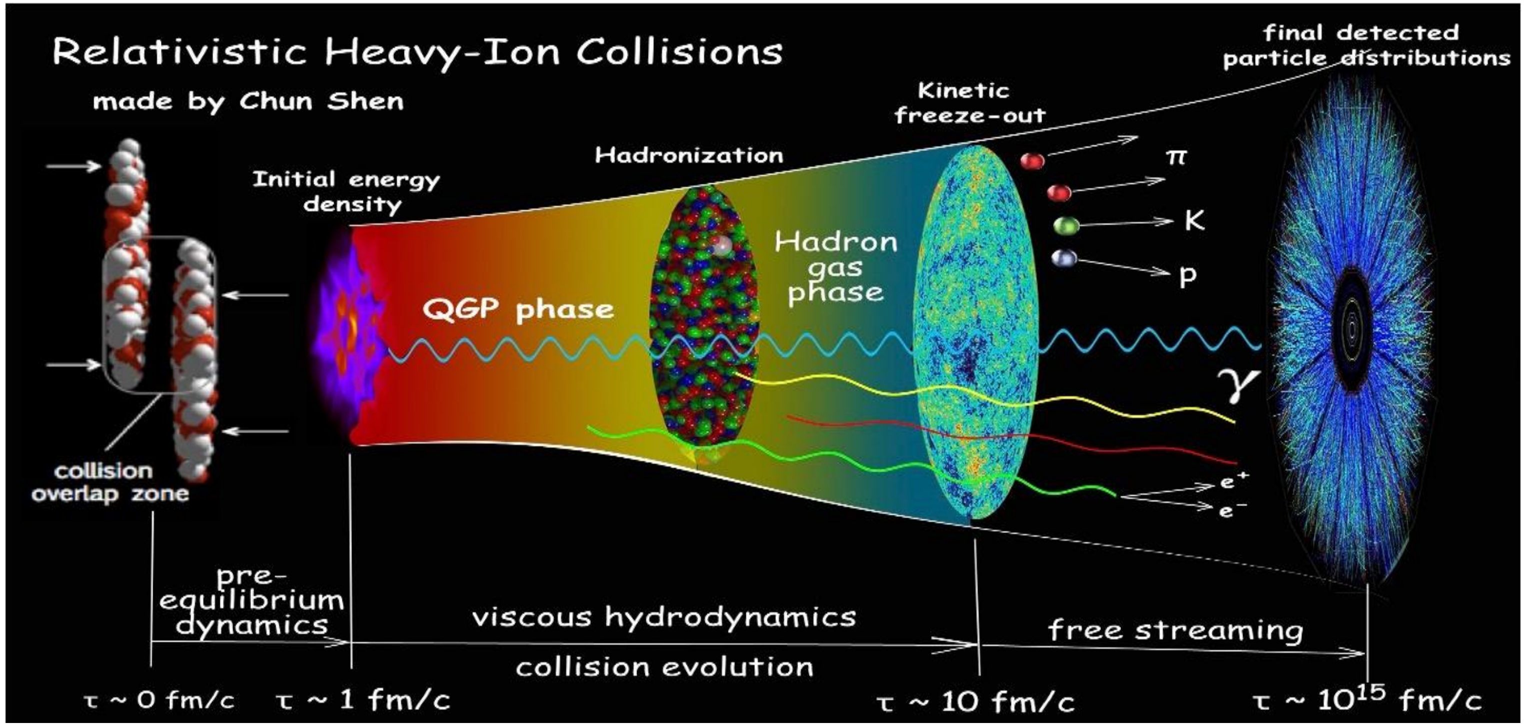
July 16, 2026, 第十二届高能物理全国会议

Heavy-ion collisions



10^{-25} s << rotational time scale 10^{-21} s

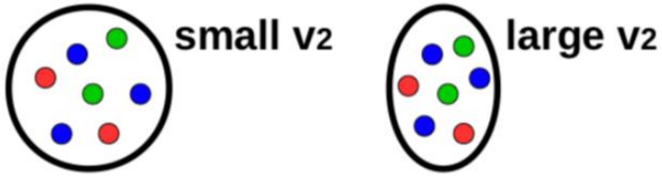


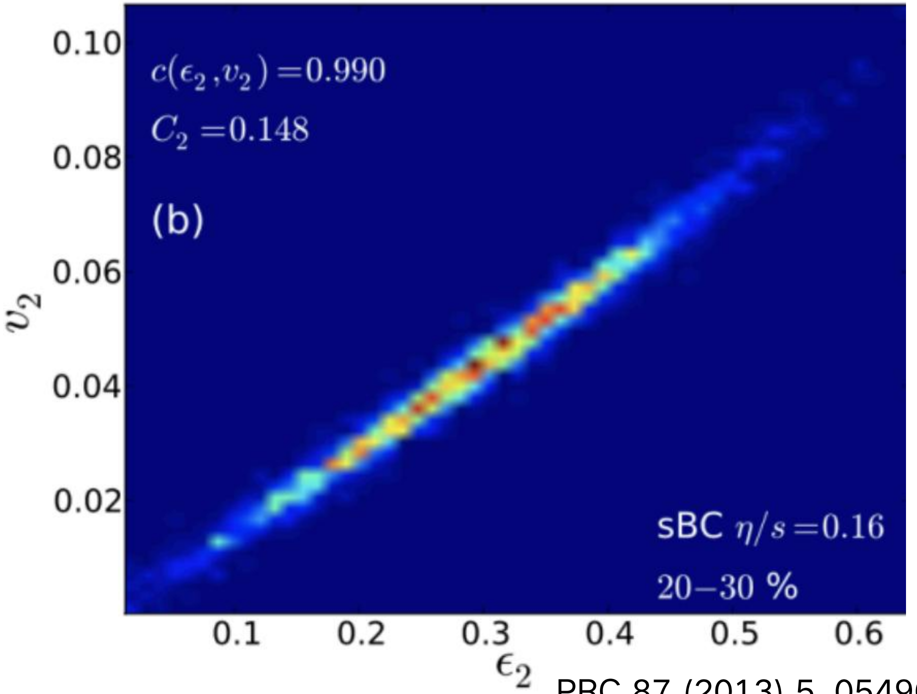


Heavy-ion collisions

Shape ⟺ Anisotropic flow v_n

$$V_n \propto \mathcal{E}_n$$



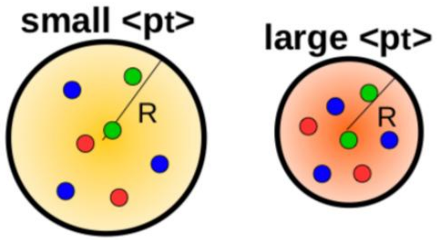


PRC 87 (2013) 5, 054901

Size ⟺ Transvers momentum p_T

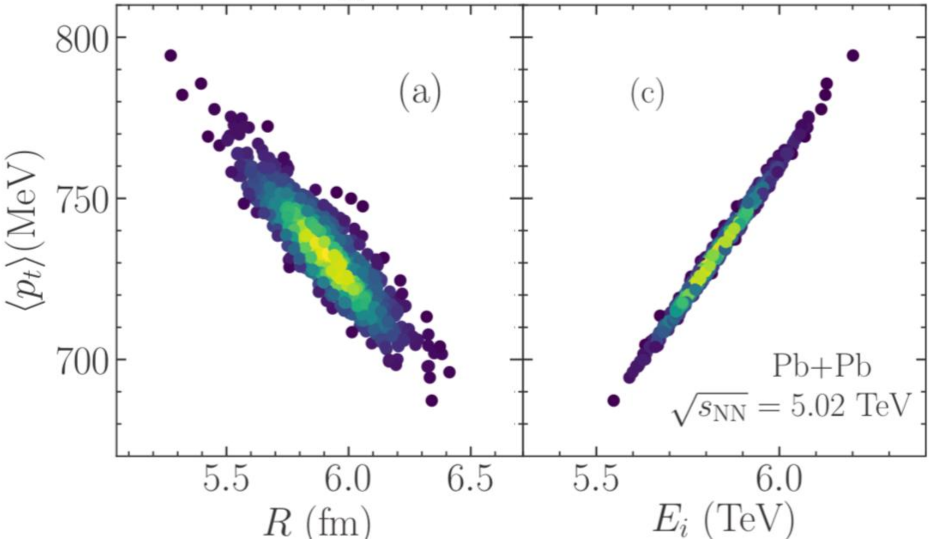
$$\frac{d\langle p_t\rangle}{\langle p_t\rangle} \propto \frac{dE}{E}$$

$$\frac{d\langle p_t\rangle}{\langle p_t\rangle} \propto -\frac{dR}{R}$$



PRC103 (2021) 2, 024909

$[p_\mathrm{T}] \propto \frac{1}{R}$ $[p_\mathrm{T}] \propto E_i$



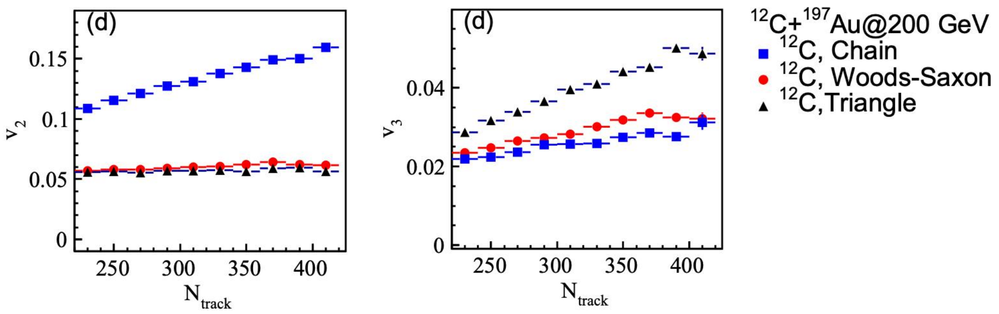
see Chunjian Zhang's talk on July 17

Heavy-ion collisions

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

S. Zhang,[1] Y. G. Ma*,[1,2,3] J. H. Chen,[1] W. B. He,[4] and C. Zhong[1]
[1]Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]ShanghaiTech University, Shanghai 200031, China
[4]Institute of Modern Physics, Fudan University, Shanghai 200433, China

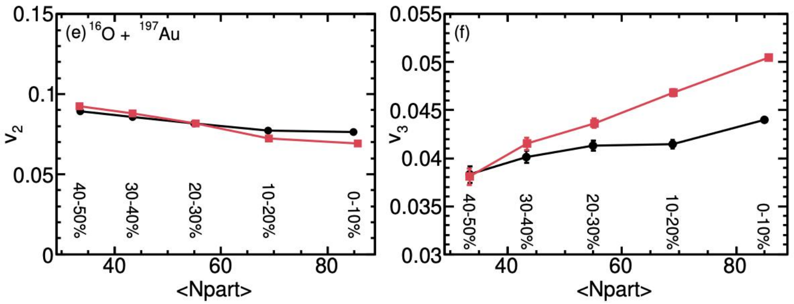
Phys.Rev.C 95 (2017) 6, 064904



Signatures of α clustering in ^{16}O 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,†]
[1]Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
[2]Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China
[3]University of Chinese Academy of Sciences, Beijing 100049, China
(Dated: October 21, 2020)

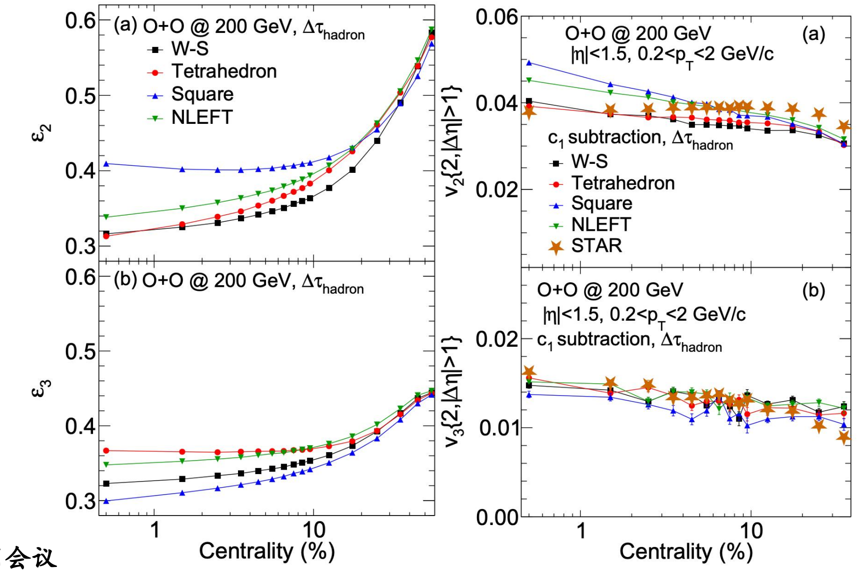
Phys.Rev.C 102 (2020) 5, 054907



Nuclear cluster structure effect in $^{16}O+^{16}O$ collisions at the top RHIC energy

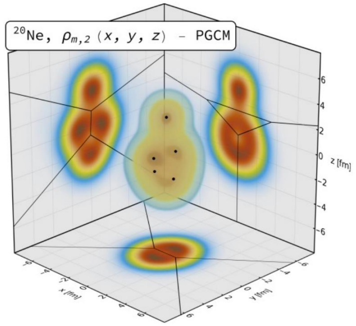
Xin-Li Zhao[1,2,3,*] Zi-Wei Lin[4,†] You Zhou[5,‡] Chao Zhang[6,§] and Guo-Liang Ma[2,3¶]
[1]College of Science, University of Shanghai for Science and Technology, Shanghai 200093, China
[2]Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China
[3]Shanghai Research Center for Theoretical Nuclear Physics, NSFC and Fudan University, Shanghai 200438, China
[4]Department of Physics, East Carolina University, Greenville, NC 27858, USA
[5]Niels Bohr Institute, Jagtvej 155A, 2200 Copenhagen, Denmark and
[6]Department of Physical Science and Technology, Wuhan University of Technology, Wuhan 430070, China

Phys.Lett.B 874 (2026) 140254

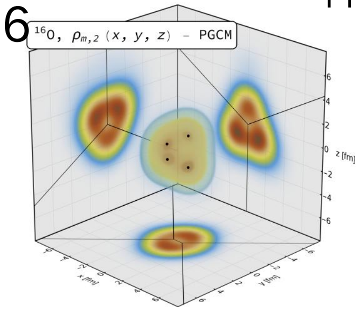


Light-ion collisions

Ne-20



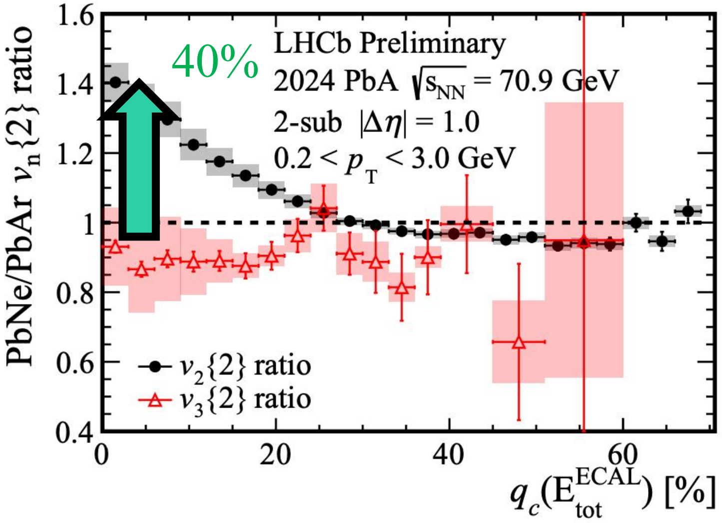
O-16



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

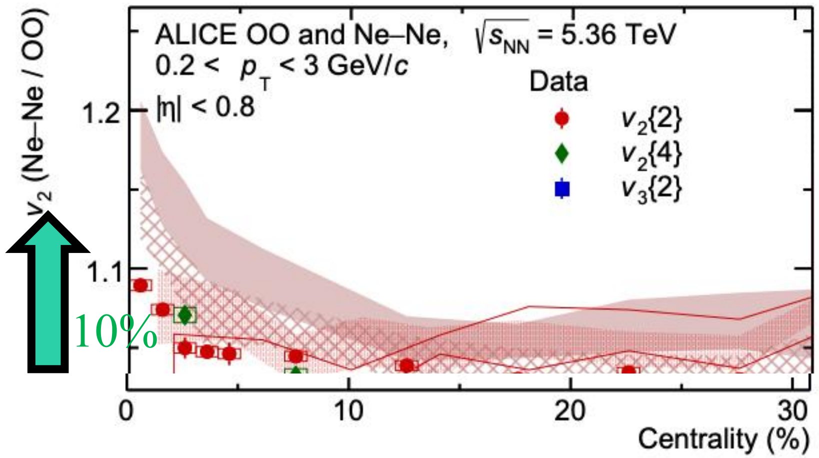
ultracentral: $\frac{v_{2,\mathrm{NeNe}}}{v_{2,\mathrm{OO}}} \sim \frac{v_{2,\mathrm{PbNe}}}{v_{2,\mathrm{PbO}}} > 1$

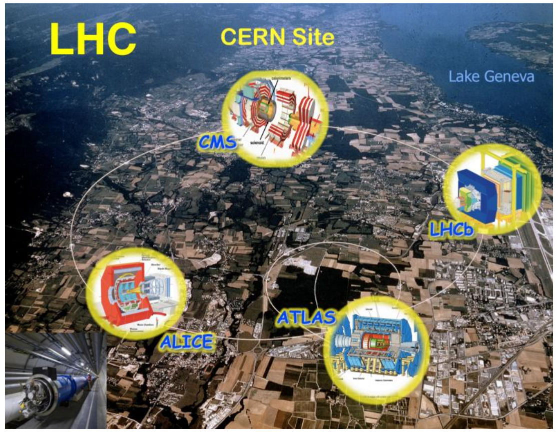
LHCb： Pb+Ne/Pb+Ar arXiv: 2509.12399



ALICE/ATLAS/CMS： Ne+Ne/O+O

2509.06428, 2509.05171, 2510.02580

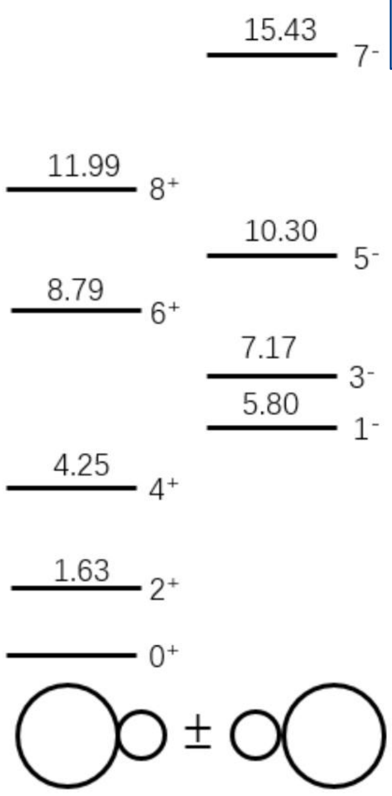




➢ **Evidence for Bowling-Pin structure of the Ne nucleus.**

Just the general shape! More details ?

Clusters in ^{20}Ne

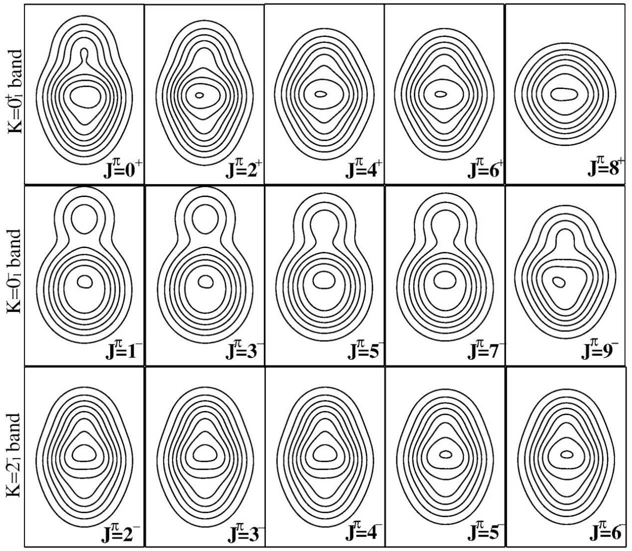


^{20}Ne=α+^{16}O

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

Antisymmetrized Molecular Dynamics Model (AMD)

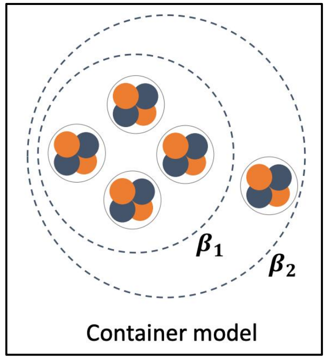
Cluster J ↑ Shell



Nonlocalized THSR model

Front.Phys. 15 (2020) 14401

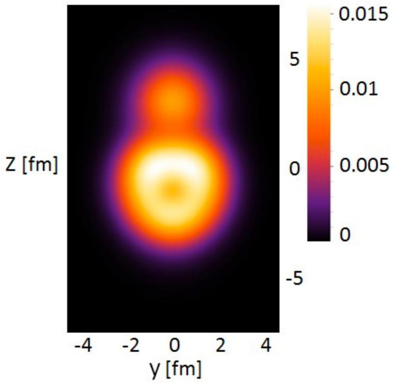
Nature Commun. 14 (2023) 1, 8206

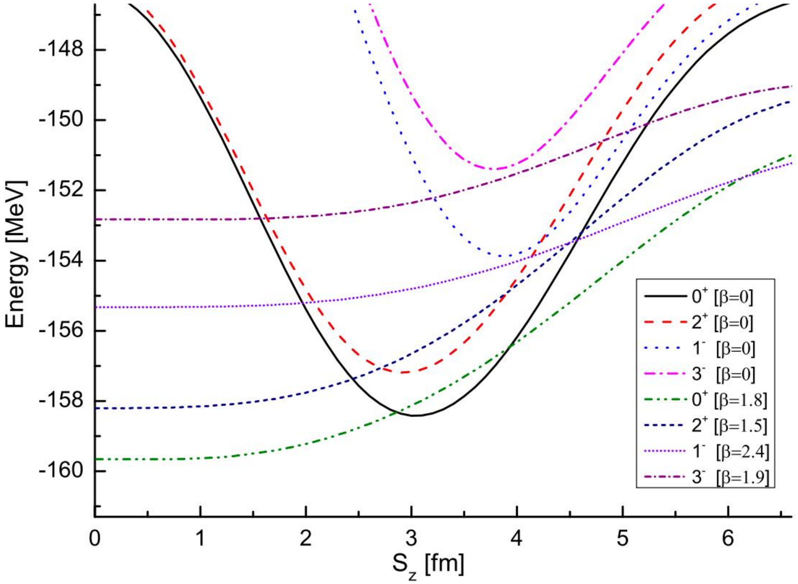


Pauli repulsion

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

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



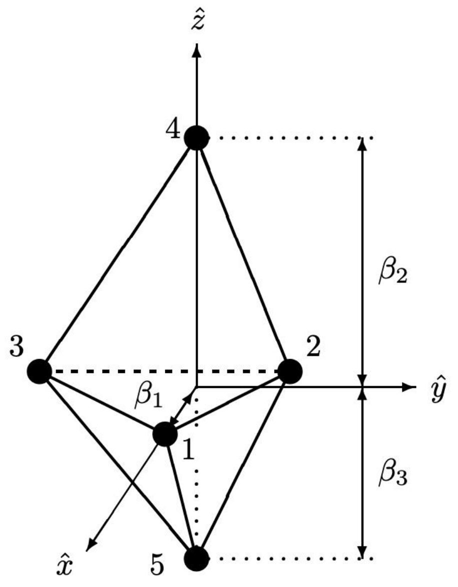


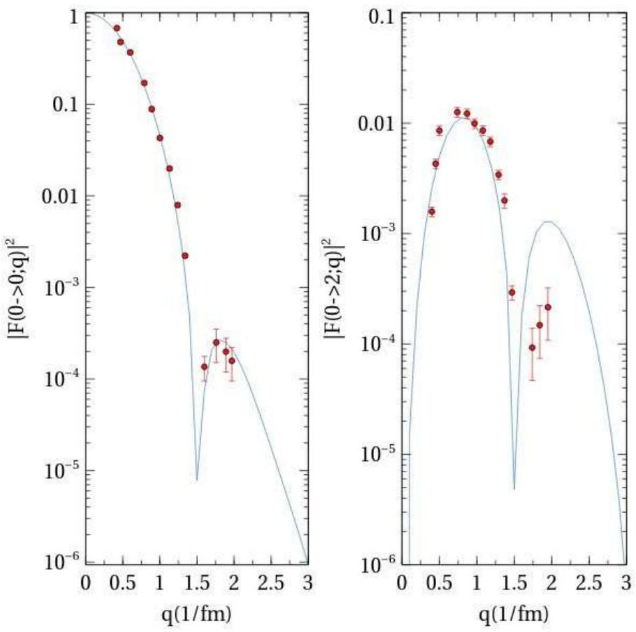
➢ ^{20}Ne with localized cluster with a+^{16}O Or with nonlocalized cluster with 5-alpha

Clusters in ^{20}Ne

Algebraic Collective Model (ACM)

Nucl.Phys.A 1006 (2021) 122077



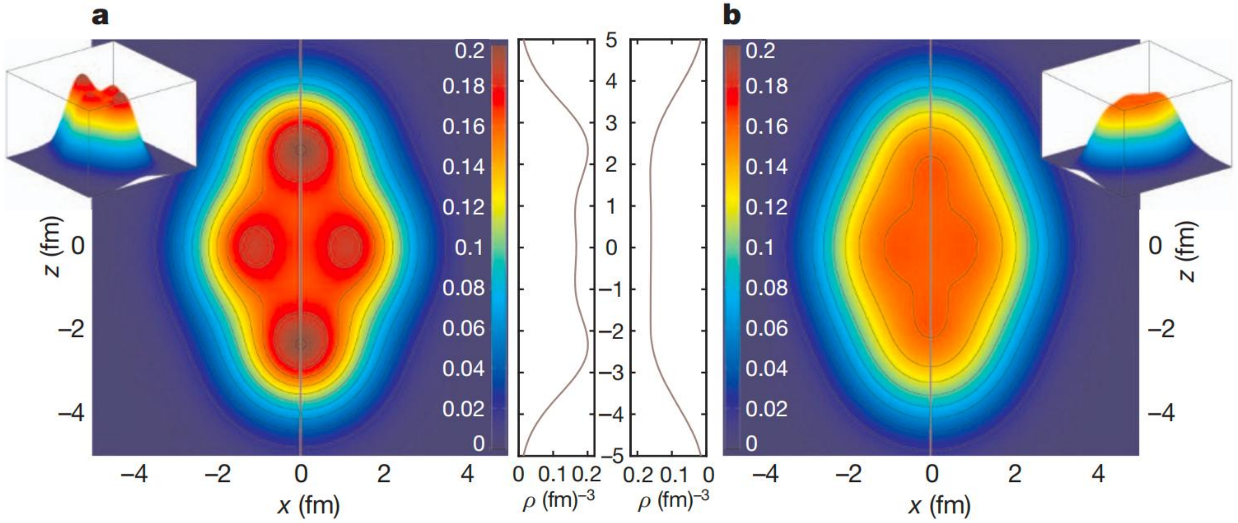


Energy-density functionals

Nature 487 (2012) 341-344

relativistic functional
DD-ME2

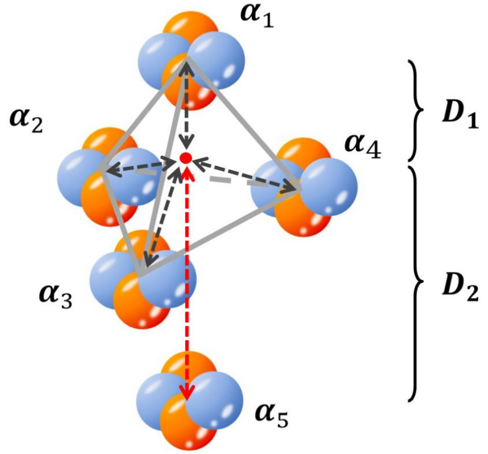
non-relativistic
Skyrme SLy4

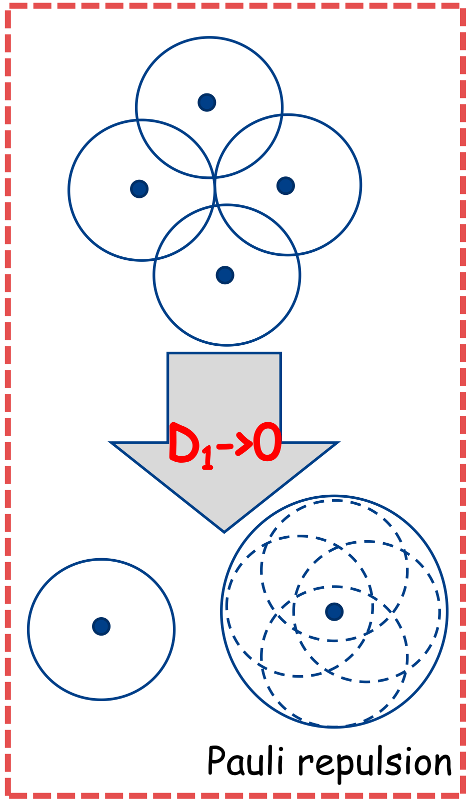


- Evidence of ^{20}Ne with D_{3h} symmtery

Clusters in ^{20}Ne

Two parameters: D_1 and D_2





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

AMD model (localized two-cluster)

D_1->0

D_1->0 D_2->0

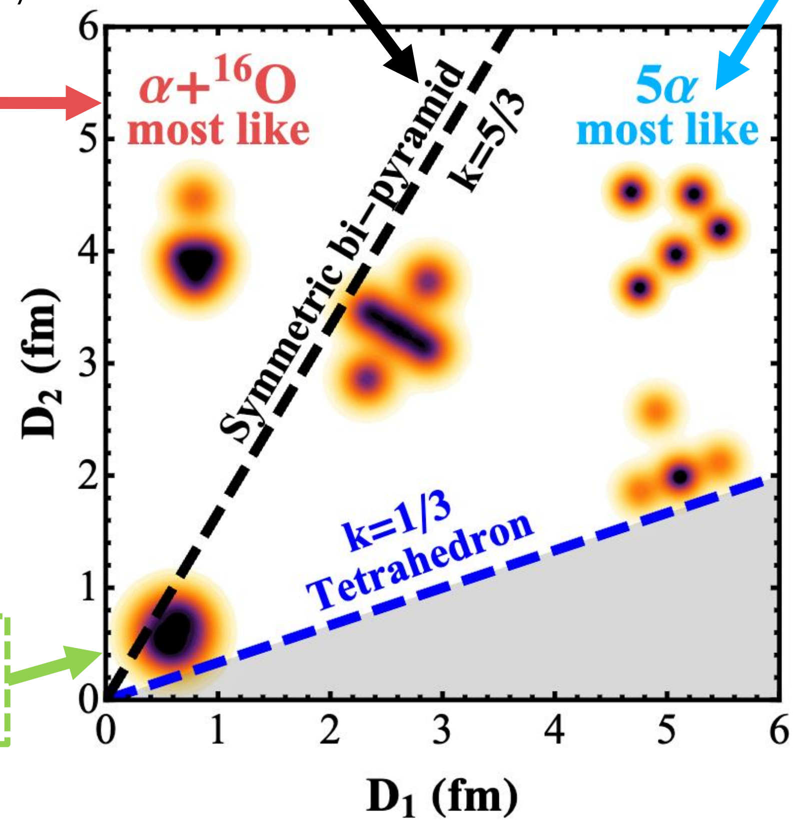
Shell model (Spherical)

Nucl. Phys. A 1006, 122077 (2021)

Clusters with D_{3h} symmtry

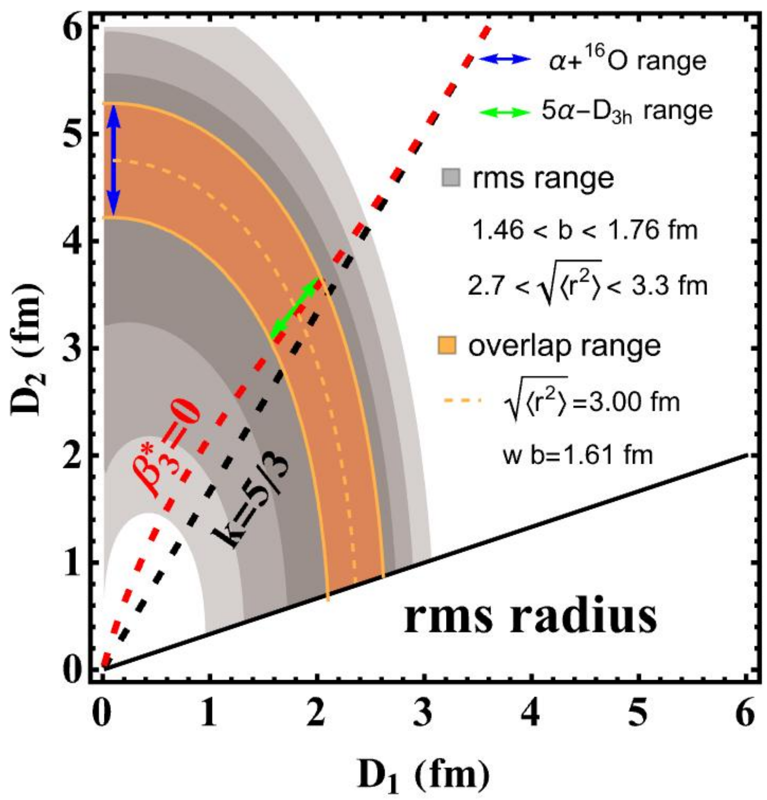
Front.Phys. 15 (2020) 14401

Loose and nonlocalized-like



Clusters in ^{20}Ne

Two parameters: D_1 and D_2



rms radius
$(3.0\pm10\%)$fm
b∈(1.46, 1.76)fm

D_1 D_2 range

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

AMD model
(localized
two-cluster)

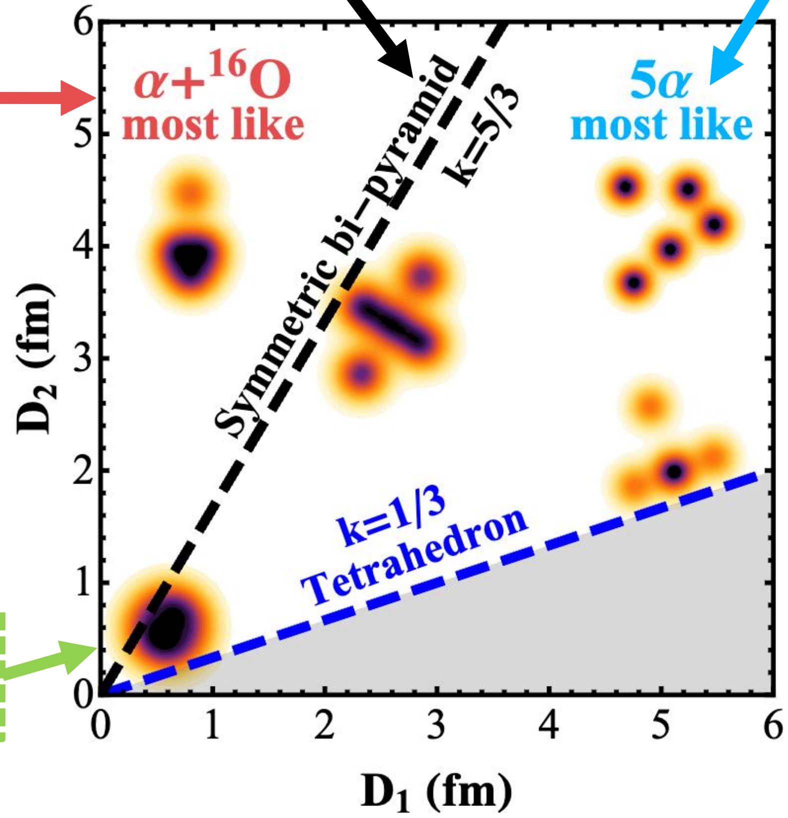
Shell model
(Spherical)

Nucl. Phys. A 1006, 122077 (2021)

Clusters with
D_{3h} symmtry

Front.Phys. 15 (2020) 14401

Loose and
nonlocalized-like

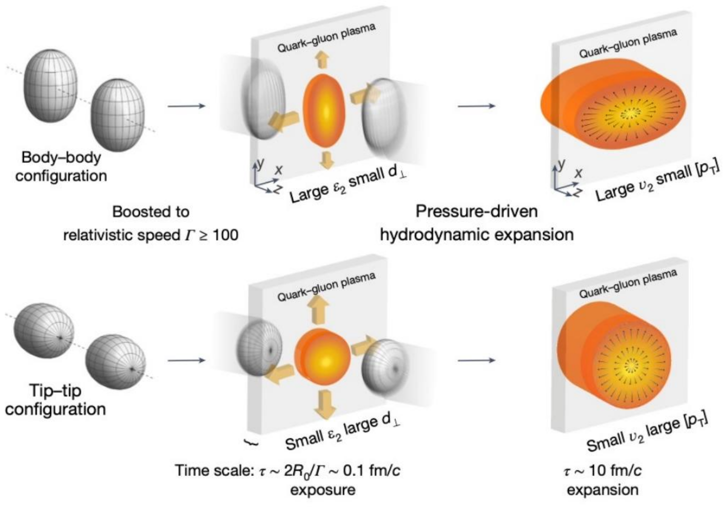


- **How to estimate the systematic error of the theoretical model?**

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

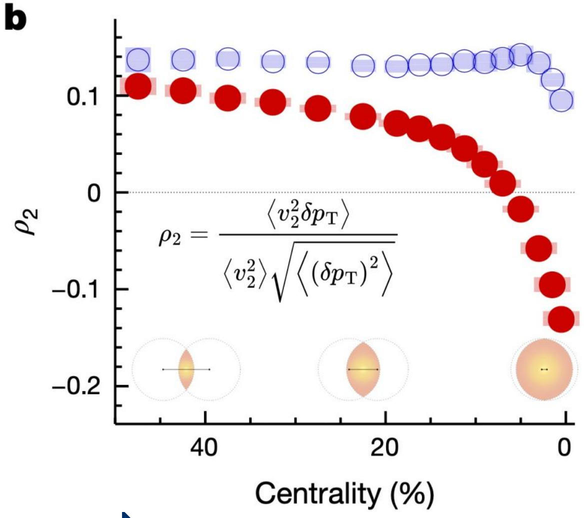
Correlation observables

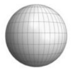
- How to explore more detailed structural effects:



$v_2\nearrow$ $p_T\searrow$

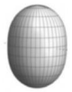
$v_2\searrow$ $p_T\nearrow$





spherical baseline

different sign !



prolate

Correlation between different ε_n

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

Correlation between different v_n

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

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

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

Correlation between v_n and δp_T

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

Symmetric cumulant NSC(n, m)

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

wave function

$$|\Phi^{\mathrm{Brink}}\rangle=\frac{1}{\sqrt{N!}}|\det\{\phi_1(\boldsymbol{r}_1)...\phi_N(\boldsymbol{r}_N)\}\rangle$$

Density

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

Transvers density

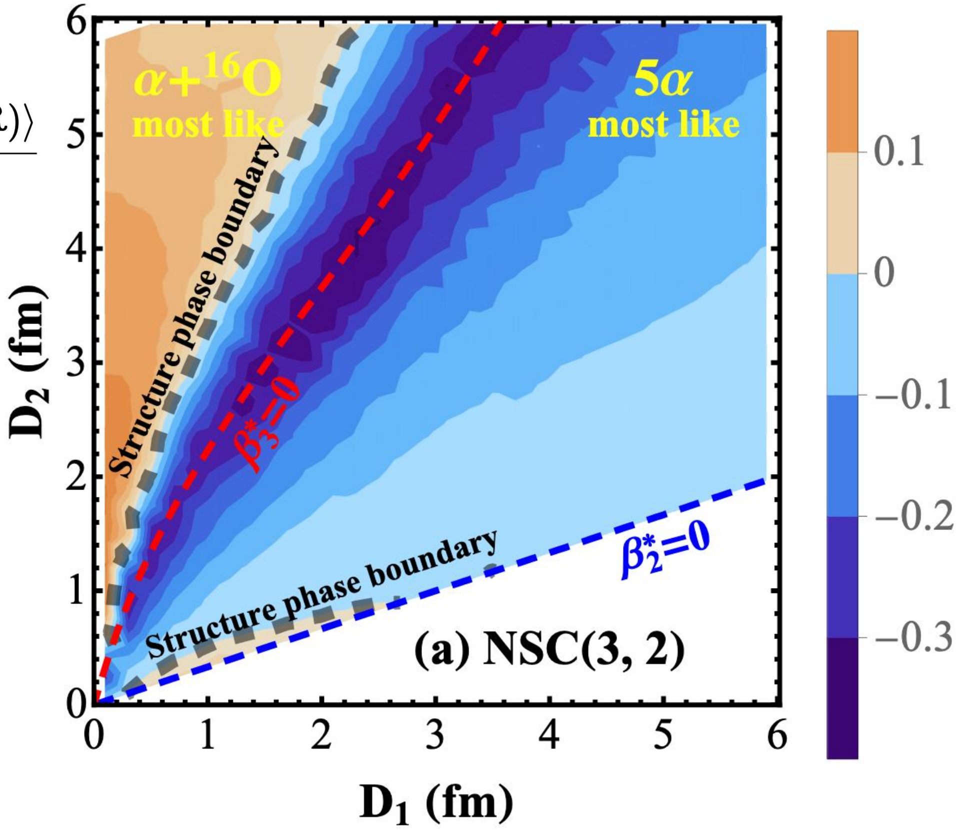
$$\rho(r_\perp,\phi)=\int[\mathcal{R}_p(\phi_{p,1},\theta_p,\phi_{p,2})\rho(x,y,z)+\mathcal{R}_t(\phi_{t,1},\theta_t,\phi_{t,2})\rho(x,y,z)]/2\mathrm{dz}$$

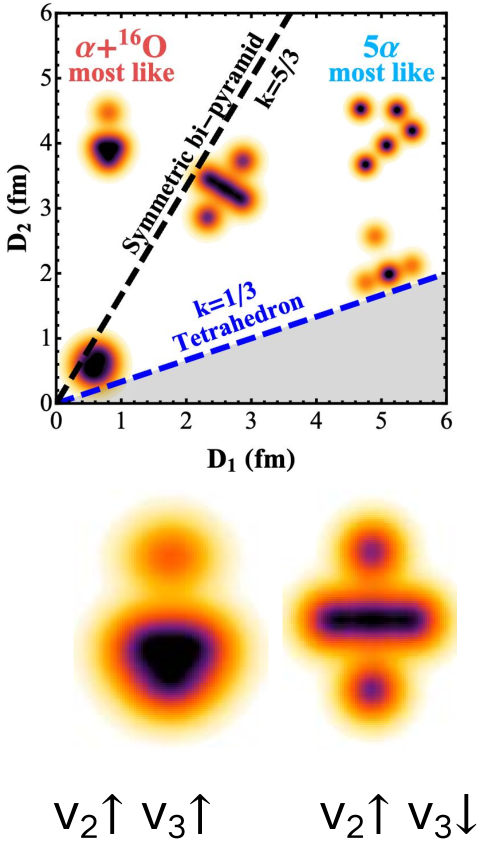
initial-state shape

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

correlation observables

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





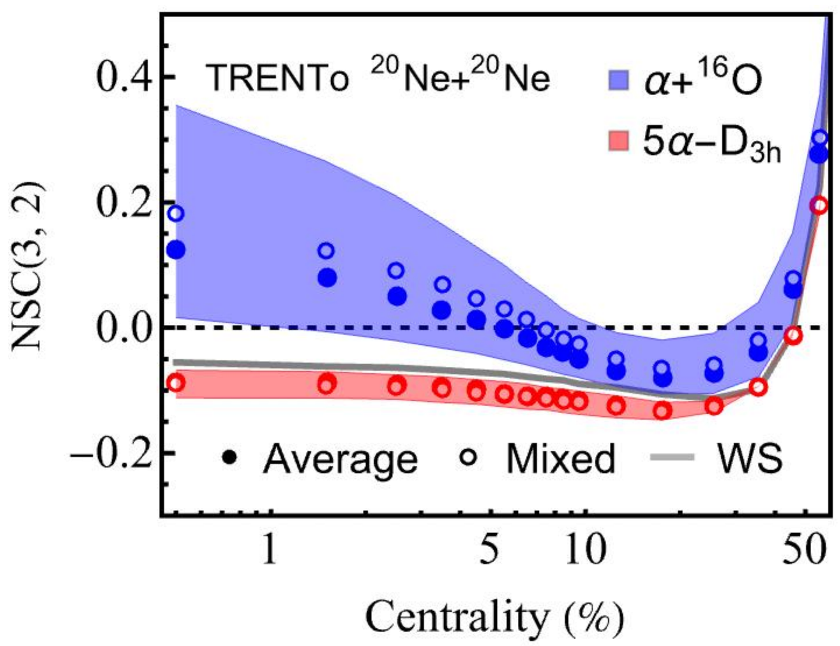
- ✓ The shape of ^{20}Ne can be determined by the positive or negative NSC(2, 3) value.
- ✓ Correlation strength NSC(2, 3) $\propto$ k = D_2/D_1.

Analytical results (b=0) w/o fluctuations | only geometry effect! → Need to add full fluctuations!

Symmetric cumulant NSC(n, m)

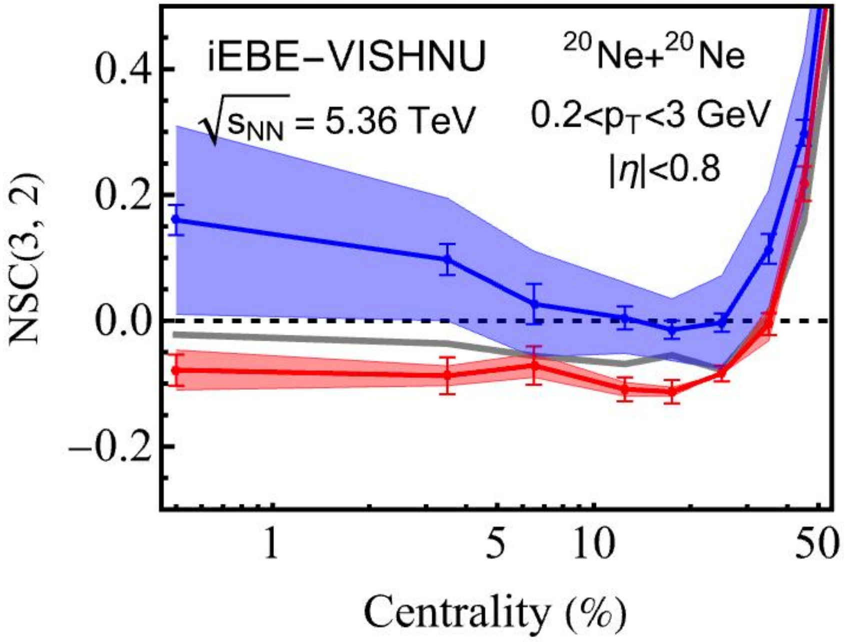
$$\mathrm{NSC}(m,n) = \frac{\langle v_n^2 v_m^2\rangle - \langle v_m^2\rangle\langle v_n^2\rangle}{\langle v_m^2\rangle\langle v_n^2\rangle}$$

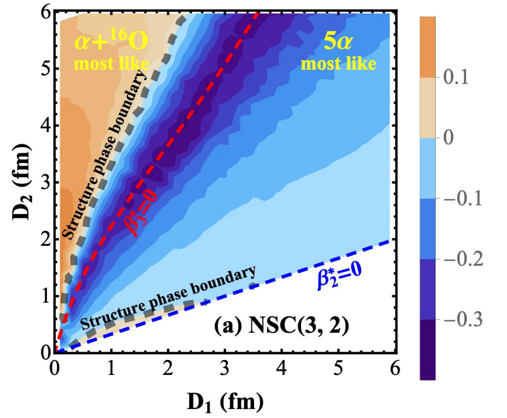
TRENTo results w initial fluctuation

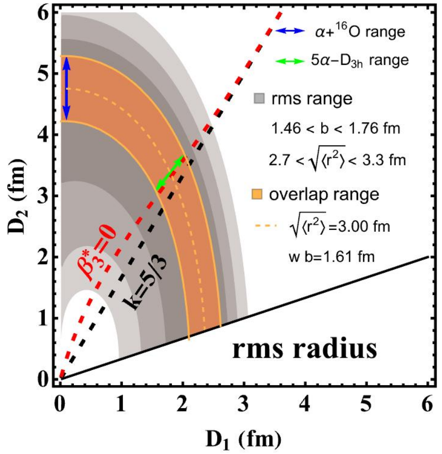


hydro evolution

Hydro results w all fluctuations





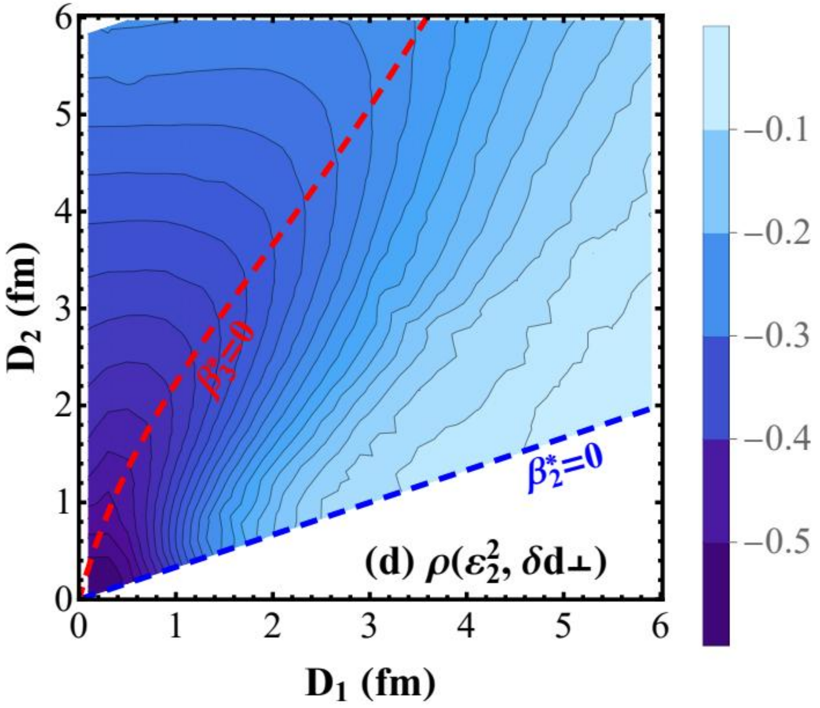


- ✓ The shape of ^{20}Ne can be determined by the positive or negative NSC(2, 3) value.
- ✓ Shape mixing does not affect the sign of NSC(2, 3).
- ✓ The fluctuations of initial and final state do not affect the sign of NSC(2, 3).

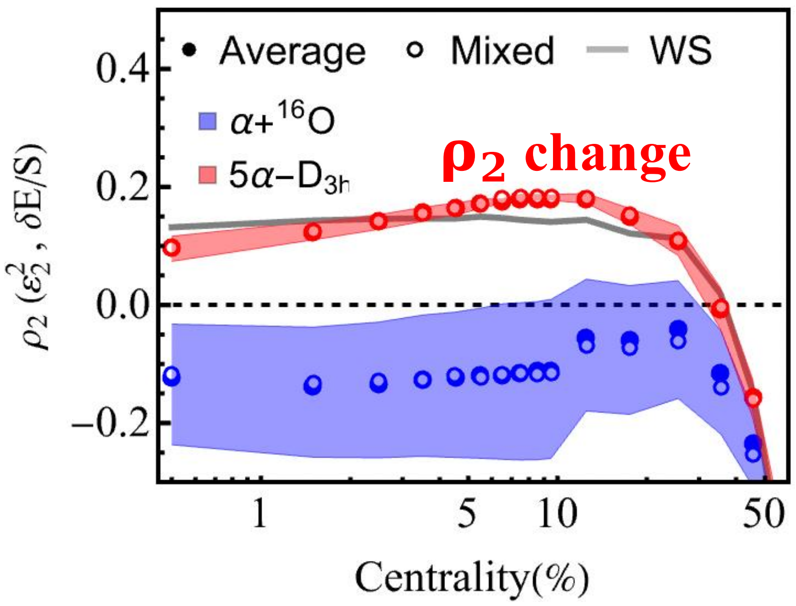
Pearson correlation $v_2 - p_T$

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

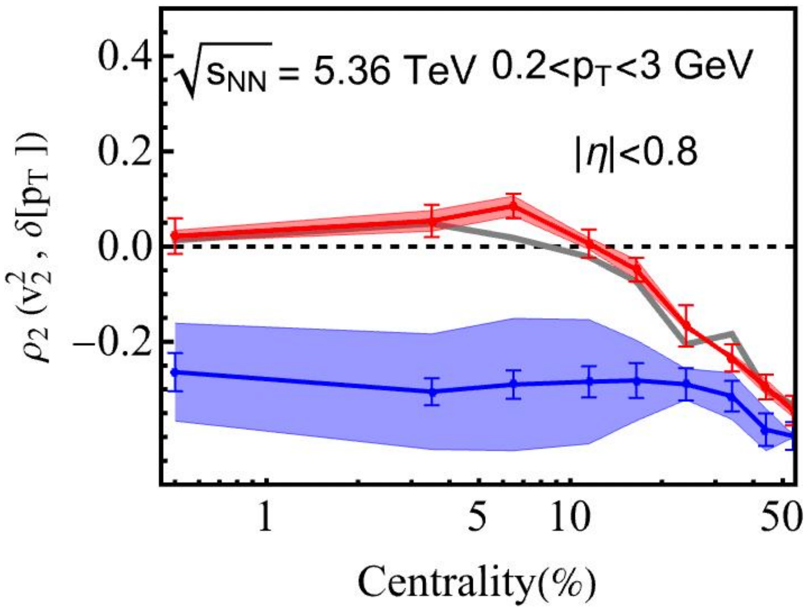
Analytical results w/o fluctuation



TRENTo results
w initial fluctuations



Hydro results
w all fluctuations

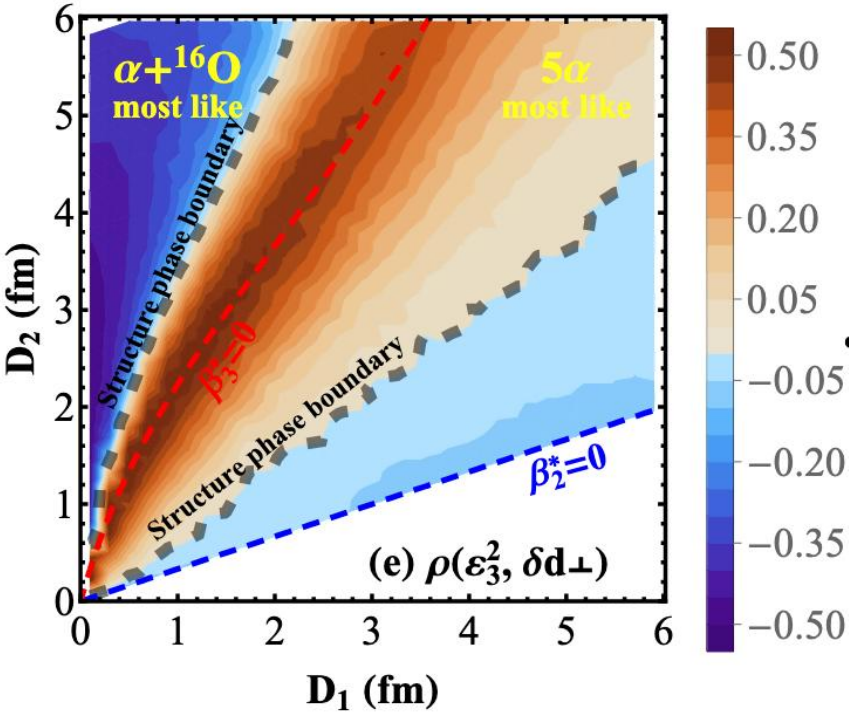


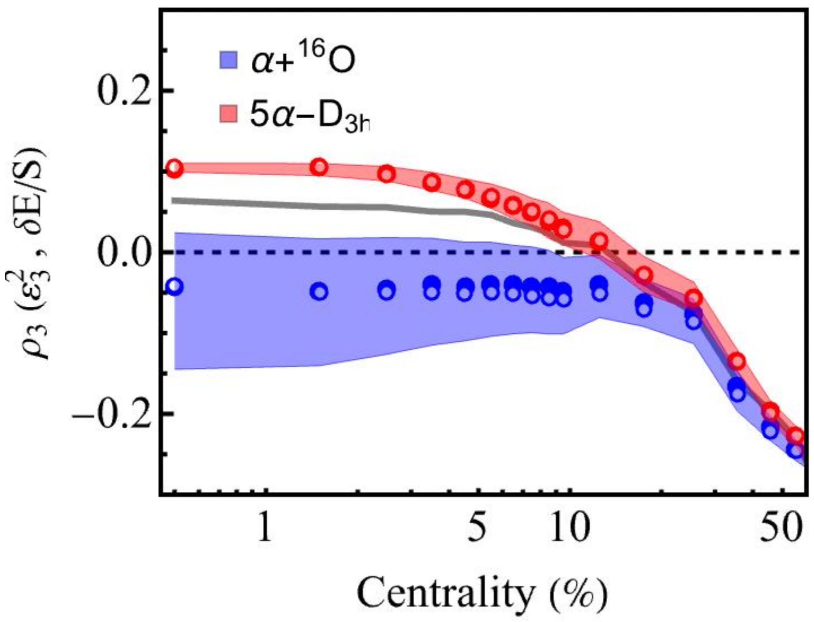
✓ The shape of ^{20}Ne can be determined by the positive or negative ρ_2 value

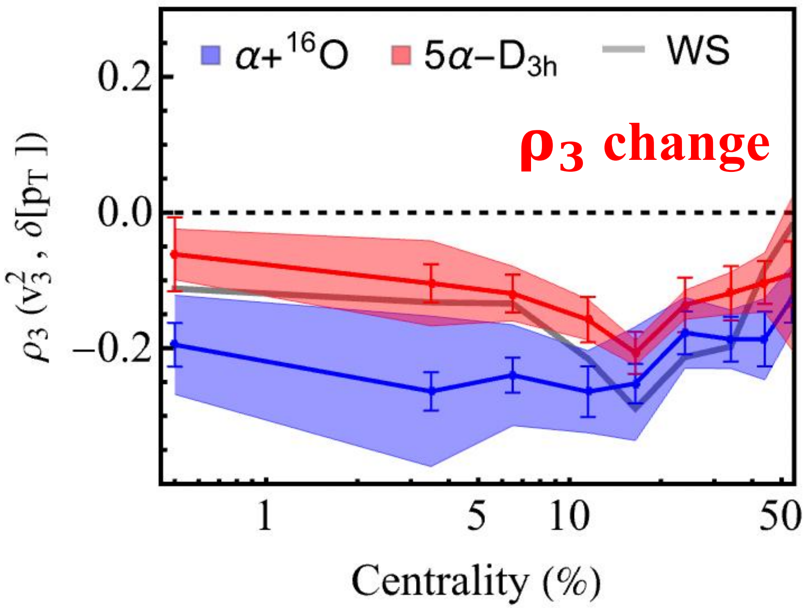
Pearson correlation $v_3 - p_T$

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

Analytical results w/o fluctuation → TRENTo results w initial fluctuations → Hydro results w all fluctuations



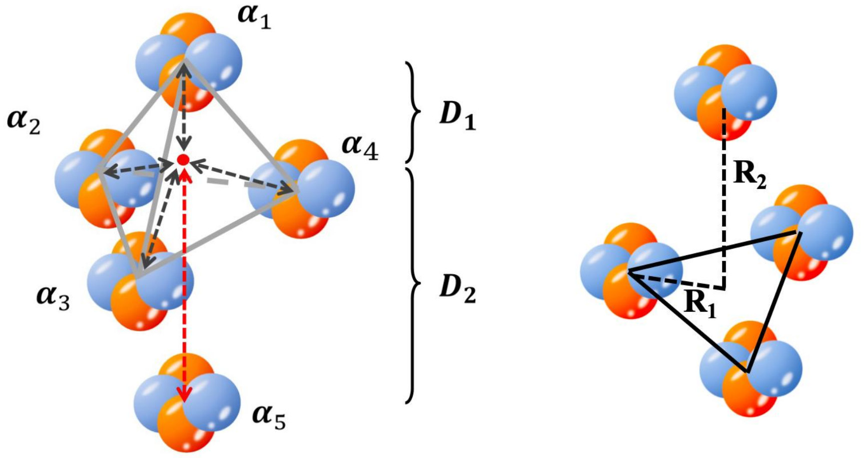


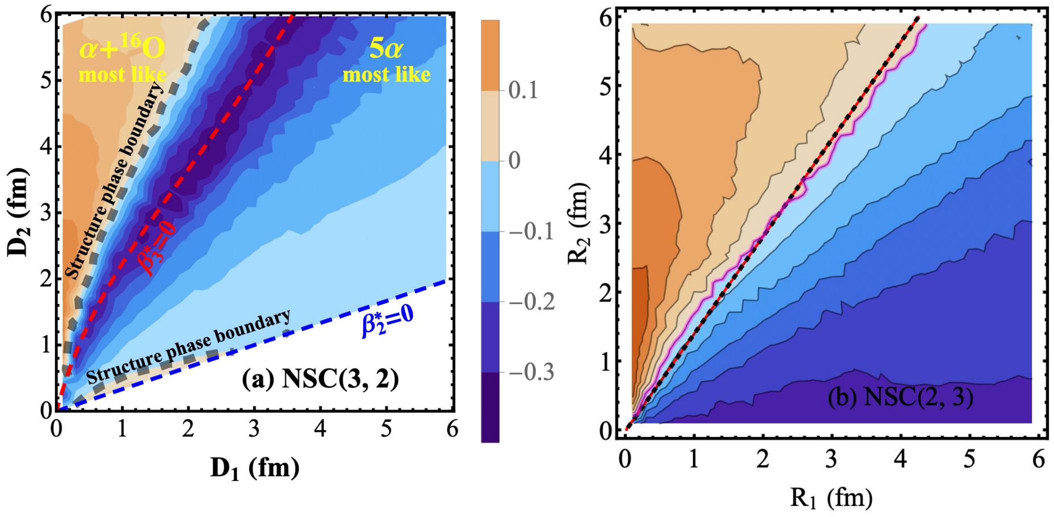


✓ The shape of ^{20}Ne cannot be determined by ρ_3 due to fluctuations.

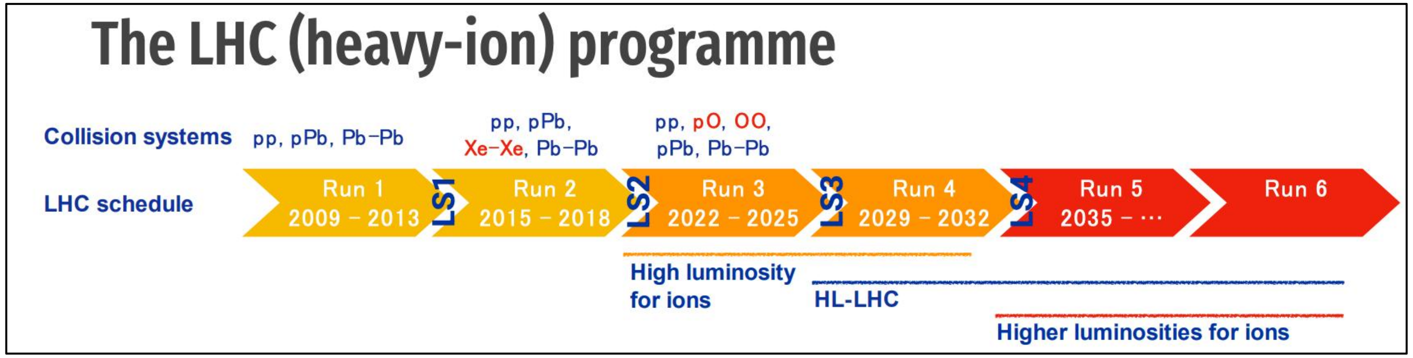
Expantion

^{20}Ne vs. ^{16}O

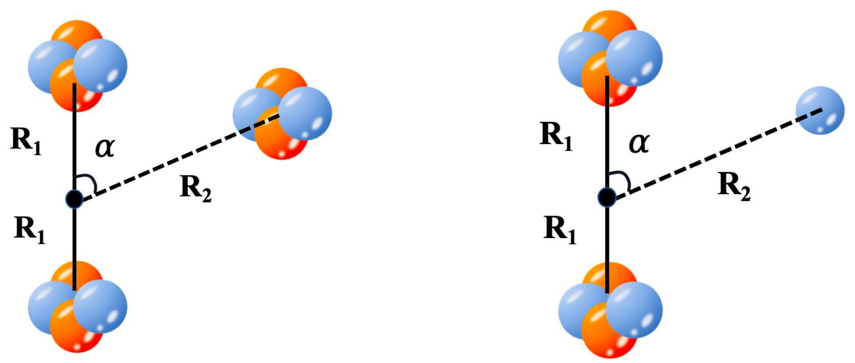




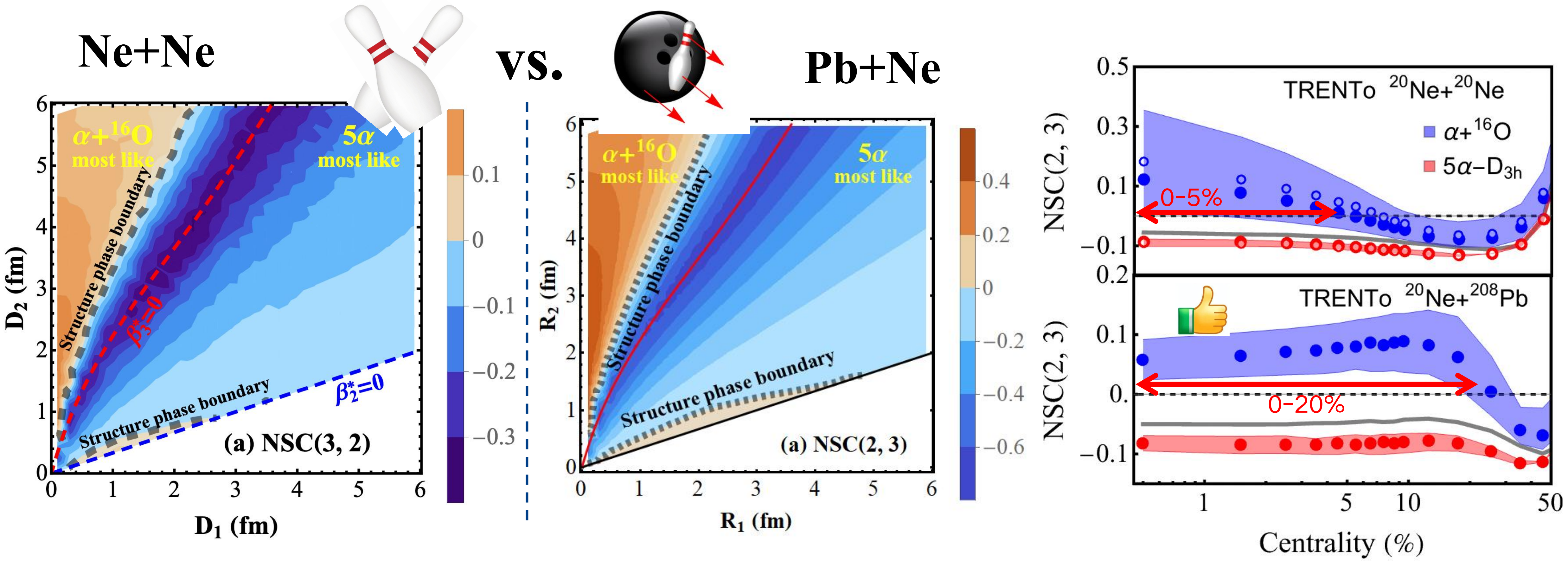
- Candidate species for new ion collisions at LHC Run4.



^{12}C vs. ^{9}Be



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 preparetion.

Summary

PRL 136, 082302 (2026)

1. The Analytical method we developed can isolate the initial-state fluctuations, thus clarifying pure clsuter geometry effect.

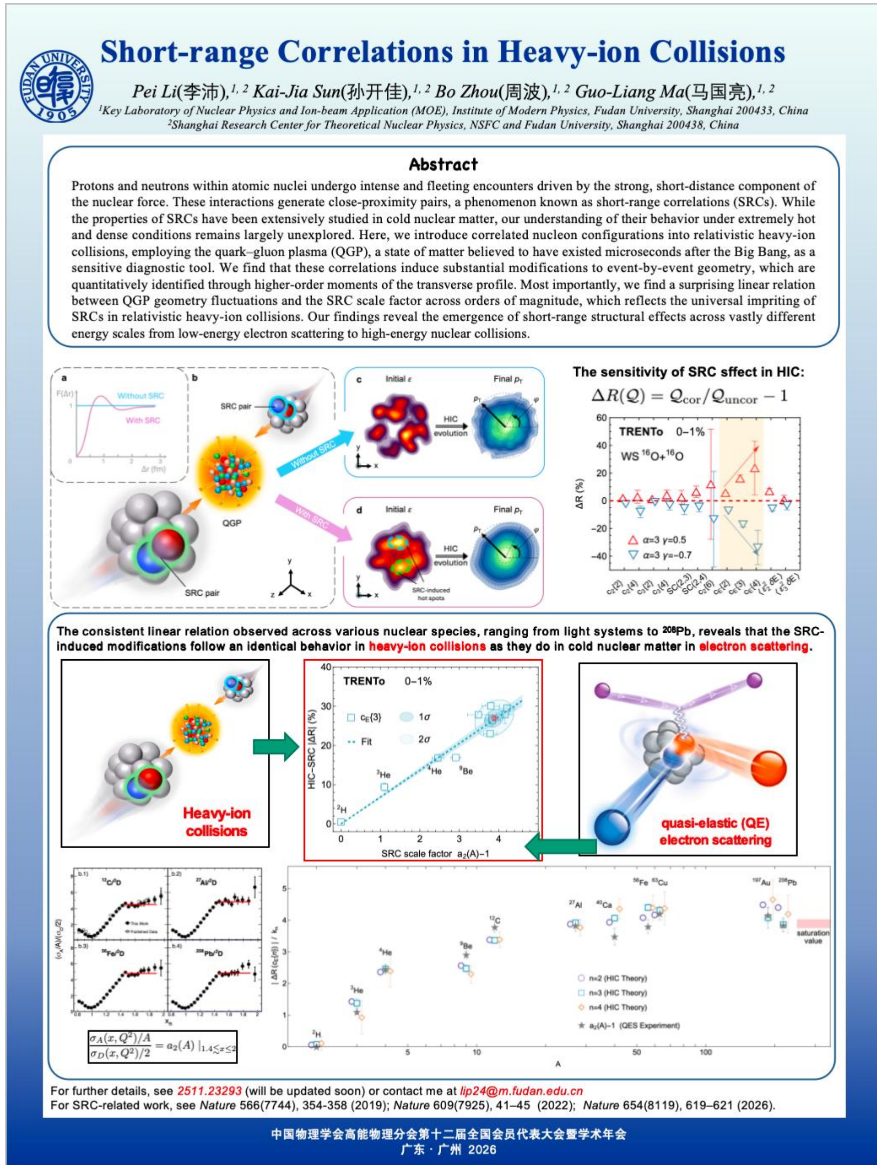
2. NSC(2,3) and $\rho_2(v_2^2, [p_T])$ are very good observables to probe the cluster structure of ^{20}Ne and distinguish a+^{16}O and 5a directly with positive and negative value.

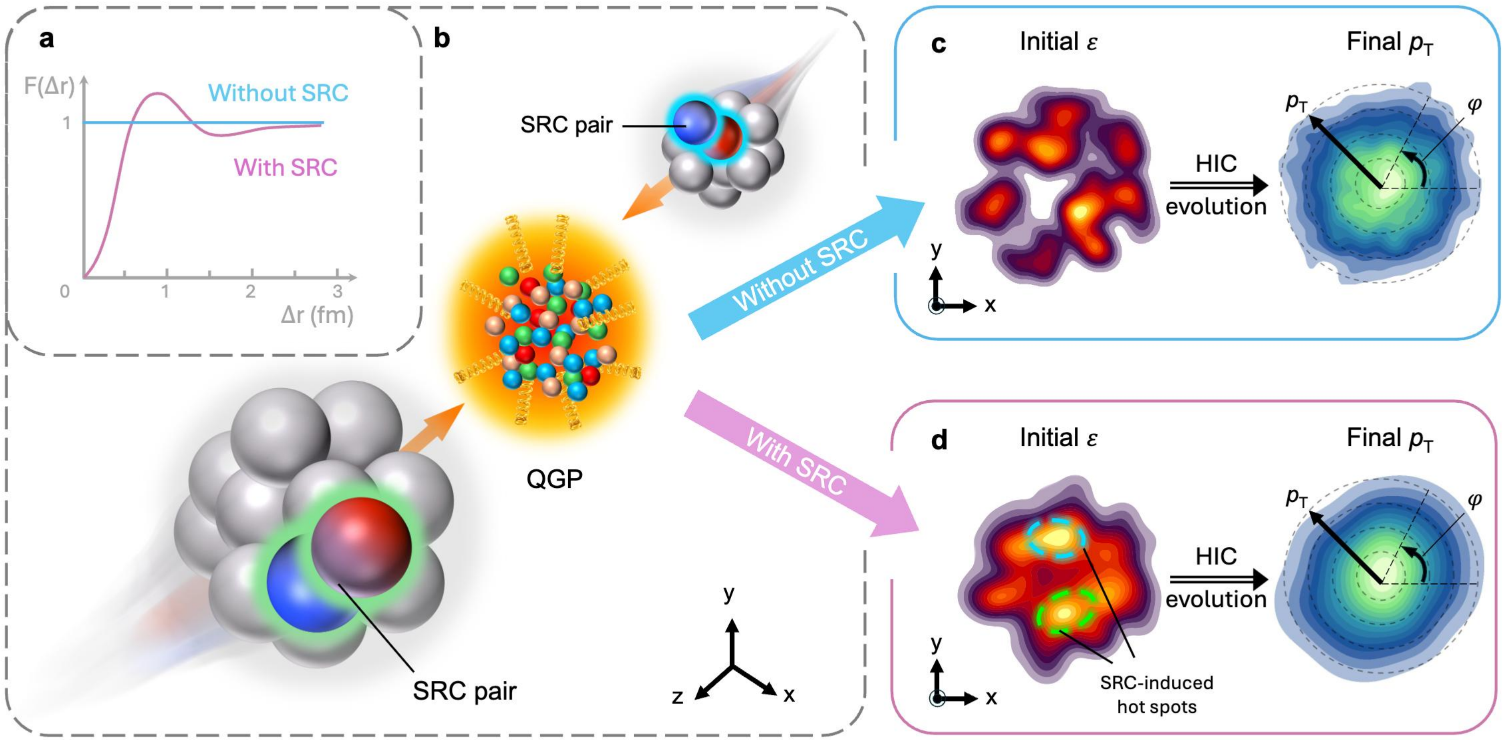
3. The fixed-target experiment Pb+Ne has better theoretical superiority than the collider experiment Ne+Ne ——an opportunity to cross-validate the theory

Thanks for attention!

Short-range correlations

arXiv: 2511.23293





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

Backup

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