Imprint of α-Clustering

in Relativistic Light Ion Collisions

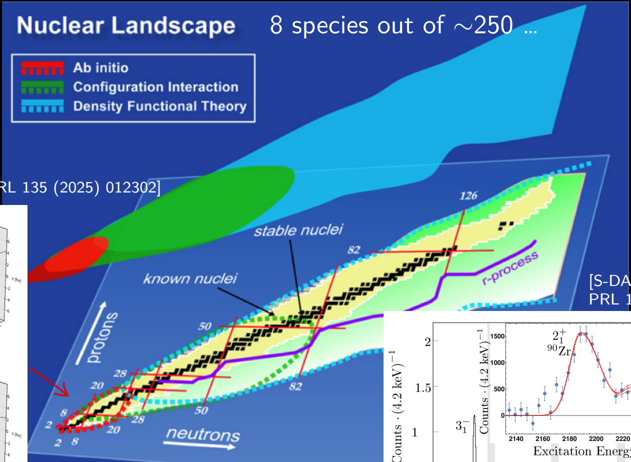
Hadi Mehrabpour

EQHIC 2026

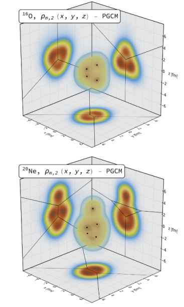
FUDAN UNIVERSITY

PEKING UNIVERSITY
SCHOOL OF PHYSICS

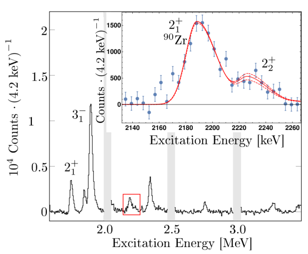
8 species out of ∼250 ...



[G.Giacalone et al., PRL 135 (2025) 012302]



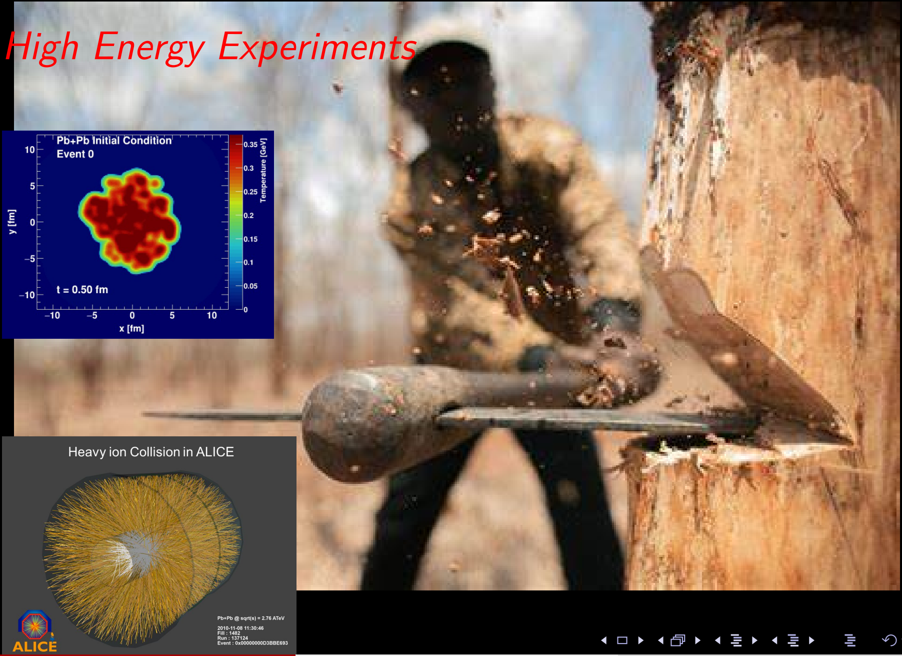
[S-DALINAC, PRL 117 (2017) 172503]



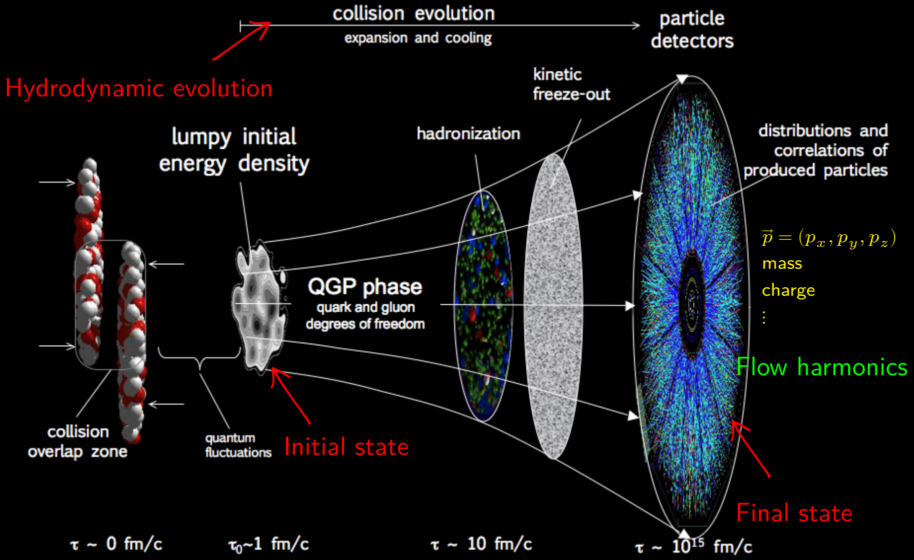
[R.J.Furnstahl and K.Hebeler, Rep. Prog. Phys. 76 126301 (2013)]

Not all forests are beautiful!

High Energy Experiments

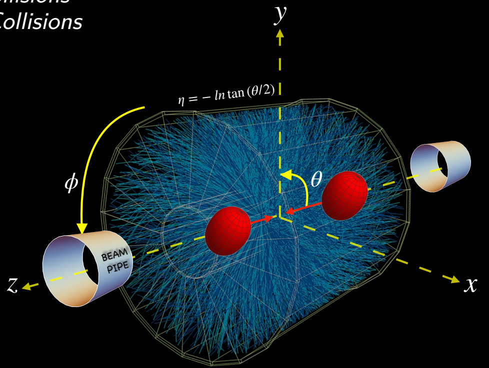


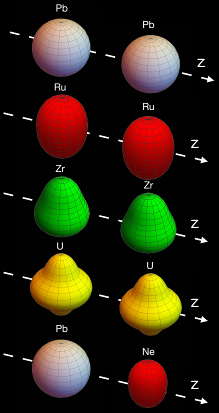
Nuclear collisions and the QGP expansion



Different Collisions:

Symmetric Collisions
Asymmetric Collisions



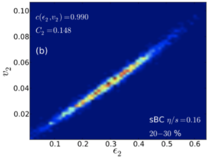


$$\frac{dN}{d^3\boldsymbol{p}} = \frac{dN}{d\phi \, p_T dp_T \, d\eta}$$

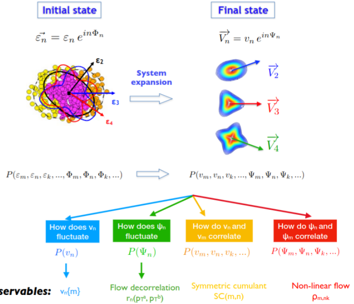
Initial Geometry and Final Distribution

❖ Shape of the fireball: Anisotropic flow

$V_n \propto \mathcal{E}_n$



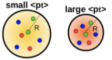
[H. Niemi et al., PRC 87 (2013) 5, 054901]

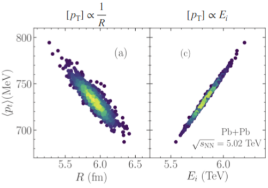


❖ Size of the fireball: radial flow, $[p_T]$

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

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

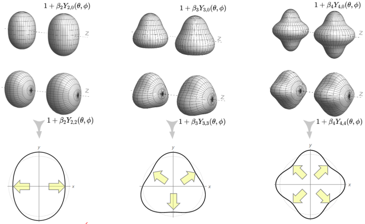




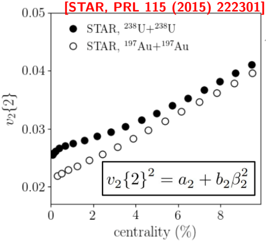
[G. Giacalone et al., PRC103 (2021) 2, 024909]

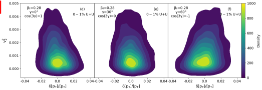
Strong Collective Correlations of Nucleons

[J.Jia, PRC 105 (2021) 014905]

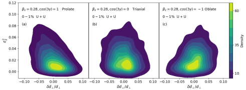


[STAR, PRL 115 (2015) 222301]





[J.Jia,PRC 105 (2022) 4, 044905]

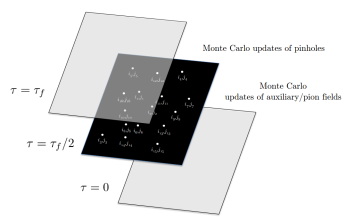


$$R(\theta,\phi) = R_0\left(1 + \beta_2[\cos\gamma Y_{2,0} + \sin\gamma Y_{2,2}] + \beta_3 Y_{3,0} + \beta_4 Y_{4,0}\right)$$

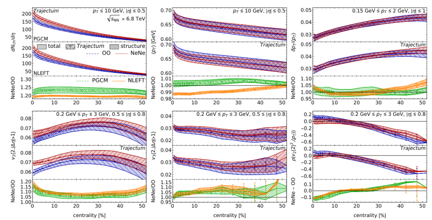
Opportunities of light-heavy Ions Collisions:

– Connecting ab initio inputs of light-nuclei with relativistic nuclear collisions.

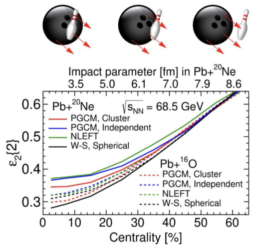
Pinhole Algorithm



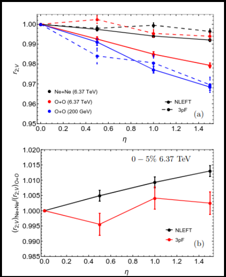
[B.N.Lu et al., PRL 119 (2017) 222505]



[Giacalone et al., PRL 135 (2025) 012302]



[Giacalone et al., PRL 134 (2025) 082301]



[HM, A.Saha, EPJC 85 (2025) 1284]

Light nuclear structures in ultra-relativistic collions:

Evidence of nuclear geometry-driven anisotropic flow in OO and Ne–Ne collisions at $\sqrt{s_{NN}} = 5.36$ TeV

ALICE Collaboration[*]

Abstract

A central question in strong-interaction physics, governed by quantum chromodynamics (QCD), is whether femto-scale droplets of quark–gluon plasma (QGP) form in small collision systems involving projectiles significantly smaller than heavy ions. Collisions of light ions such as ^{16}O and ^{20}Ne offer a unique opportunity to probe the emergence of collective behavior in QCD matter. This Letter presents the first measurements of elliptic (v_2) and triangular (v_3) flow of charged particles in ^{16}O–^{16}O and ^{20}Ne–^{20}Ne collisions at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.36$ TeV with the ALICE detector. The hydrodynamic model predictions, explicitly incorporating the nuclear structures of ^{16}O and ^{20}Ne, exhibit a good agreement with the flow measurements presented. The observed increase of v_2 in central Ne–Ne collisions relative to OO collisions, driven by the nuclear geometries, highlights the importance of utilizing light nuclei with well-defined geometric shapes to constrain the initial conditions. These findings support the presence of nuclear geometry-driven hydrodynamic flow in light-ion collisions at the LHC.

First measurement of pseudorapidity distributions of charged hadrons in oxygen-oxygen collisions at $\sqrt{s_{NN}} = 5.36$ TeV with CMS

The CMS Collaboration

Abstract

We report the first measurement of the charged hadron pseudorapidity (η) distributions in oxygen-oxygen collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 5.36$ TeV. The data were recorded by the CMS experiment at the LHC in 2025. The yields of primary charged hadrons produced in the range $|\eta| < 2.4$ are reported using the CMS silicon pixel detector. The midrapidity particle density as a function of collision centrality is also reported. In the 5% most central collisions, the charged-hadron η density in the range $|\eta| < 0.5$ is found to be 135 ± 3 (syst), with negligible statistical uncertainty. The data are compared to previous measurements of lead-lead and xenon-xenon collisions at similar collision energies and several Monte Carlo event generators. Detailed studies of the dependence of particle production on the collision energy, initial collision geometry, and the size of the colliding nuclei are presented.

Measurement of the azimuthal anisotropy of charged particles in $\sqrt{s_{NN}} = 5.36$ TeV ^{16}O+^{16}O and ^{20}Ne+^{20}Ne collisions with the ATLAS detector

The ATLAS Collaboration

This paper presents the first measurements of the azimuthal anisotropy coefficients v_n, which quantify the n^{th}-order Fourier modulation of charged-particle azimuthal distributions, for $n = 2$–4 in $\sqrt{s_{NN}} = 5.36$ TeV ^{16}O + ^{16}O and ^{20}Ne + ^{20}Ne collisions recorded with the ATLAS detector at the Large Hadron Collider in 2025. The v_n coefficients are measured as a function of transverse momentum (p_T), collision centrality, and event multiplicity. They are extracted using two complementary methods: two-particle correlations with a template-fit subtraction of short-range non-flow contributions, and four-particle subevent cumulants, which intrinsically suppress non-flow effects and provide sensitivity to flow fluctuations. The results show a clear hierarchy $v_2 > v_3 > v_4$ and a non-monotonic dependence on p_T, reaching a maximum around 2 GeV, consistent with trends observed in heavy-ion collisions. Detailed comparisons between the two collision systems reveal an enhanced v_2 in central ^{20}Ne + ^{20}Ne collisions, consistent with theory expectations based on the predicted prolate deformation of neon nuclei, in contrast to the slightly tetrahedral structure predicted for oxygen. The four-particle cumulant results highlight strong event-by-event fluctuations and provide the greatest sensitivity to nuclear shape effects. These measurements can place new constraints on the initial geometry and the hydrodynamic response in light-ion collisions, offering valuable input for models of nuclear structure.

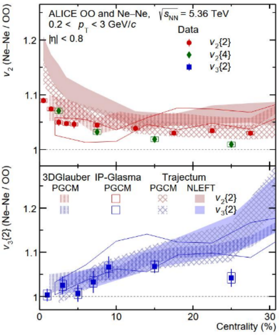
Unveiling the shape of the ^{20}Ne nucleus by measuring the flow coefficients with cumulants in PbNe and PbAr collisions at $\sqrt{s_{NN}} = 70.9$ GeV

LHCb collaboration[†]

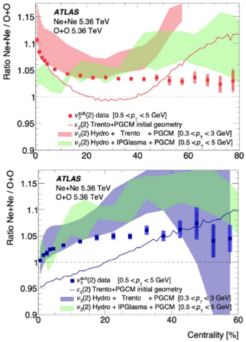
Abstract

The anisotropic flow coefficients v_n quantify the collective medium response to the initial spatial anisotropy of the overlapping region in ion collisions and serve as sensitive probes of both the medium properties and shape of nuclear initial states. In this analysis, the v_2 and v_3 parameters of prompt charged particles are measured using the multiparticle cumulant method in fixed-target PbNe and PbAr collisions at $\sqrt{s_{NN}} = 70.9$ GeV, collected by LHCb using the SMOG2 gas-target system during the 2024 LHC lead-beam run. The cumulant method is first validated using 2018 PbPb collision data, successfully reproducing previous measurements obtained via the two-particle correlation method. Results for the fixed-target collisions are then presented, showing a significantly larger value of the elliptic flow coefficient v_2 in central PbNe with respect to PbAr collisions. This is qualitatively consistent with 3+1D hydrodynamic predictions including *ab-initio* descriptions of the nuclear structure. The results provide the first experimental confirmation of the distinctive bowling-pin shape of the ground-state ^{20}Ne nucleus, validating at the same time the hydrodynamic description of the hot medium formed in high-energy collisions involving light ions.

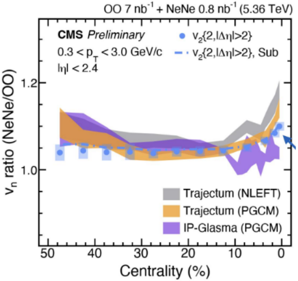
Flow in Ne+Ne/O+O:



ALICE: [arXiv:2509.06428].



ATLAS: [arXiv:2509.05171].



CMS: [arXiv:2510.02580].

Structures of Oxygen-16 and Neon-20

1. Projected Generator Coordinate Method (PGCM)

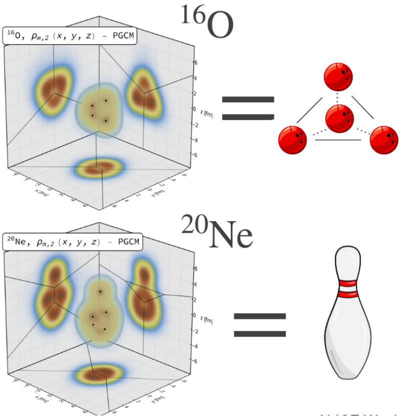
   - *ab initio* formalism
   - N^3LO EFT Hamiltonian
   - Particle-number projected one-body density from intrinsic Hartree-Fock-Bogoliubov state

2. Nuclear Lattice Effective Field Theory (NLEFT)

   - Effective field theory + lattice Monte Carlo
   - Well-suited to probe clustering effects
   - Nuclear many-body correlations to all orders preserved

3. Variational Monte Carlo (VMC)

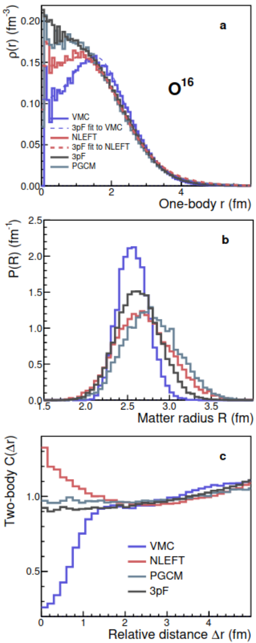
   - N^2LO chiral EFT Hamiltonian
   - Includes short-range repulsive effects



[Light ion collisions at the LHC-2025]

Structures of Oxygen-16 and Neon-20

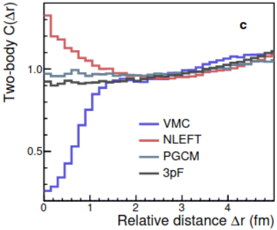
1. Projected Generator Coordinate Method (PGCM)
   - *ab initio* formalism
   - N^3LO EFT Hamiltonian
   - Particle-number projected one-body density from intrinsic Hartree-Fock-Bogoliubov state
2. Nuclear Lattice Effective Field Theory (NLEFT)
   - Effective field theory + lattice Monte Carlo
   - Well-suited to probe clustering effects
   - Nuclear many-body correlations to all orders preserved
3. Variational Monte Carlo (VMC)
   - N^2LO chiral EFT Hamiltonian
   - Includes short-range repulsive effects



[C.Zhang et al., PLB 862 (2025) 139322]

1. Clustering Model

Imprint of isolated NN correlations on O+O: [Q.Liu, HM, B.N.Lu, 2509.00315]



One-body density matrix:

$$\rho(\mathbf{r}) = A \int \prod_{i=2}^{A} d\mathbf{r}_i |\Psi(\mathbf{r}, \mathbf{r}_2, \cdots, \mathbf{r}_A)|^2$$

Nucleon-nucleon correlations:

$$C(\mathbf{r}, \mathbf{r}') = A(A-1) \int \prod_{i=3}^{A} d\mathbf{r}_i |\Psi(\mathbf{r}, \mathbf{r}', \mathbf{r}_3, \cdots, \mathbf{r}_A)|^2$$

Approximated form:

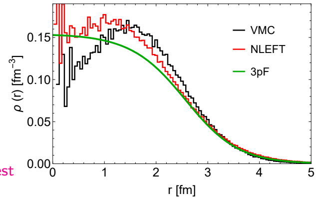
$$C(\Delta r) = 1 - \frac{g(\Delta r)}{g'(\Delta r)}, \quad \Delta r = |\mathbf{r}|$$

*Acceptance-rejection method: [R.Christensen, A.Branscum,and T.E Hanson, (2010) 1st ed.]

- correlated two-body dist.: $g(\Delta r)$ (target dist.)
- uncorrelated two-body dist.: $g'(\Delta r)$
- we accept the nucleons with relative distances $\Delta r'$

  as samples from the the target distribution $g(\Delta r')$ if

  $U \leq \left(g(\Delta r')/M \cdot g'(\Delta r')\right)$, $M = \sup_{\Delta r} \frac{g(\Delta r)}{g'(\Delta r)} = \Delta r_{\text{biggest}}$



Imprint of isolated NN correlations on O+O: [Q.Liu, HM, B.N.Lu, 2509.00315]

*Acceptance-rejection method: [R.Christensen, A.Branscum,and T.E Hanson, (2010) 1st ed.]

One-body density matrix:

$$\rho(\mathbf{r}) = A \int \prod_{i=2}^{A} d\mathbf{r}_i |\Psi(\mathbf{r}, \mathbf{r}_2, \cdots, \mathbf{r}_A)|^2$$

Nucleon-nucleon correlations:

$$C(\mathbf{r}, \mathbf{r}') = A(A-1) \int \prod_{i=3}^{A} d\mathbf{r}_i |\Psi(\mathbf{r}, \mathbf{r}', \mathbf{r}_3, \cdots, \mathbf{r}_A)|^2$$

Approximated form:

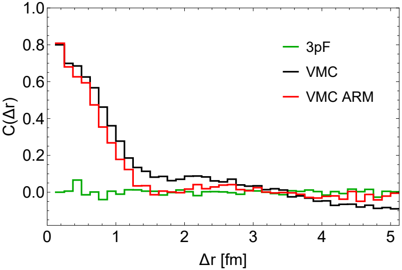
$$C(\Delta r) = 1 - \frac{g(\Delta r)}{g'(\Delta r)}, \quad \Delta r = |\mathbf{r}|$$

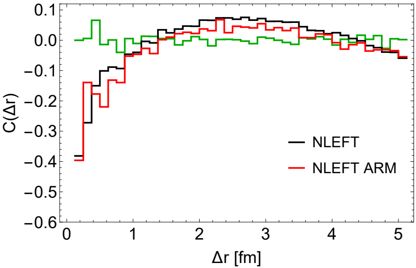
– correlated two-body dist.: $g(\Delta r)$ (target dist.)

– uncorrelated two-body dist.: $g'(\Delta r)$

– we accept the nucleons with relative distances $\Delta r'$ as samples from the the target distribution $g(\Delta r')$ if

$$U \leq \left(g(\Delta r')/M \cdot g'(\Delta r')\right), \; M = \sup_{\Delta r} \frac{g(\Delta r)}{g'(\Delta r)} = \Delta r_{\text{biggest}}$$



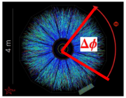


Imprint of isolated NN correlations on O+O: [Q.Liu, HM, B.N.Lu, 2509.00315]

*Acceptance-rejection method: [R.Christensen, A.Branscum,and T.E Hanson, (2010) 1st ed.]

FINAL STATE TWO-PARTICLE CORRELATION

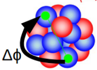
$$\langle v_n^2 \rangle = \left\langle e^{in(\phi_1-\phi_2)} \right\rangle_{\text{events}}$$



TWO-BODY NUCLEAR CORRELATIONS

$$\int_{\mathbf{r}_1,\mathbf{r}_2} \rho^{(2)}(\mathbf{r}_1,\mathbf{r}_2)\; r_{1\perp}^n\; r_{2\perp}^n\; e^{in(\phi_1-\phi_2)} \quad \langle \hat{\mathcal{E}}_n \rangle$$

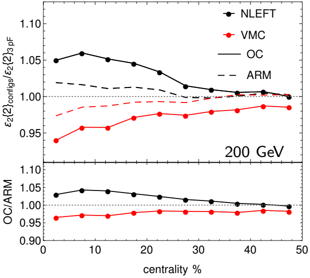
$$\rho^{(n)}(\mathbf{r}_1,\ldots,\mathbf{r}_n) \equiv \int_{\mathbf{r}_{n+1},\ldots,\mathbf{r}_A} |\Psi(\mathbf{r}_1,\ldots,\mathbf{r}_A)|^2$$

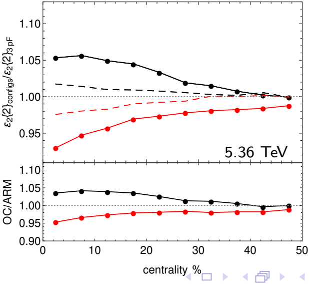


[Duguet, Giacalone, Jeon, Tichai, PRL **135** (2025) 18, 182301]

New many-body operators

$$\left\langle \begin{aligned} \hat{\mathcal{E}}_n(\mathbf{r}_1,\mathbf{r}_2) &= r_{1\perp}^n\; r_{2\perp}^n\; e^{in(\phi_1-\phi_2)} \\ &= r_1^n Y_n^n(\Omega_1)\, r_2^n Y_n^{-n}(\Omega_2) \end{aligned} \right\rangle_\Psi$$





General Picture: [HM, G.Giacalone, M.Luzum, in preparation]

* Can we find an approximation yet realistic analytical model of the collision process?

- the leading dependency of final-state observables on the nuclear strucutre of the two colliding ions
- different symmetric and asymmetric collisions
- small and large systems

* Particel Production: a rotor rigid model

k-body density: $\rho^{(k)}(\vec{r}_1, \cdots, \vec{r}_k) = \frac{1}{8\pi^2} \int d\Omega \, \rho\left(R_{zxz}(\Omega)\vec{r}_1\right) \cdots \rho\left(R_{zxz}(\Omega)\vec{r}_k\right)$

Transverse n-body density of nucleons: $\rho_{\perp}^{(k)}(x_1, y_1; \cdots; x_k, y_k) = \int dz_1 \cdots dz_k \; t_k(\vec{r}_1, \cdots, \vec{r}_k)$

Superposition of A nucleons: $T(x,y) = \sum_{i=1}^{A} \frac{1}{2\pi w^2} \exp\left(-\frac{(x-x_i)^2+(y-y_i)^2}{2w^2}\right) = \sum_{i=1}^{A} g(x-x_i, y-y_i)$

The density of overlapping area: $\epsilon(\mathbf{r}) = T(\mathbf{r})T(\mathbf{r}') = \sum_{i=1}^{A} \sum_{j=1}^{B} g(x-x_i, y-y_i) g(x'-x_j, y'-y_j)$

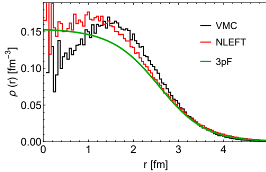
How about α-cluster of ^{16}O and ^{20}Ne? [HM, 2506.12673]

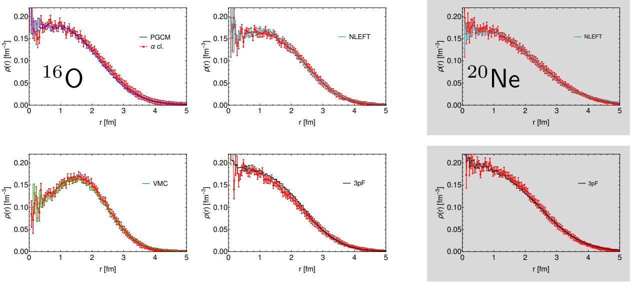
Distribution of nucleons in each cluster: [M.Rybczyński,M.Piotrowska,W.Broniowski, PRC 97 (2018) 034912]

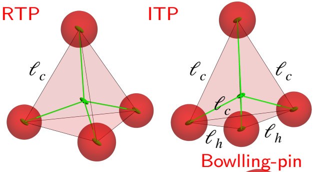
[George Gamow, 1930]

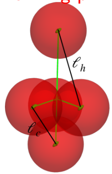
$$\rho_{\alpha_i}(\vec{r}) = \left(\frac{3}{2\pi r_L^2}\right)^{3/2} \exp\left[-\frac{3(\vec{r}-\vec{L}_i)^2}{2r_L^2}\right]$$

Acceptance-rejection method: NN correlations [Q.Liu, HM, B.N.Lu, 2509.00315]

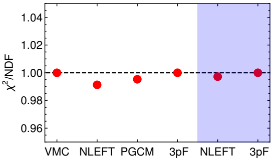








Models	3pF	NLEFT	PGCM	VMC
^{16}O (RTP)	(1.83,3.20)	(1.84,3.17)	(1.88,3.06)	(1.52,3.26)
^{16}O (ITP)	(2.00,3.15)	(1.61,3.88)	(1.57,3.86)	-
^{20}Ne (BP)	(2.00,3.00,3.00)	(2.20,3.00,3.50)	-	-



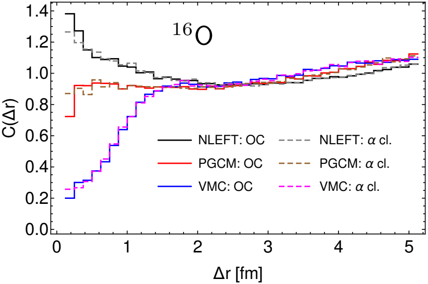
How about α-cluster of ^{16}O and ^{20}Ne? [HM, 2506.12673]

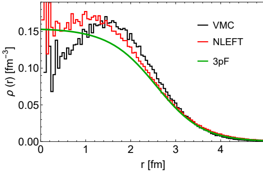
Distribution of nucleons in each cluster: [M.Rybczyński,M.Piotrowska,W.Broniowski, PRC 97 (2018) 034912]

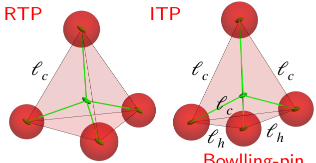
$$\rho_{\alpha_i}(\vec{r}) = \left(\frac{3}{2\pi r_L^2}\right)^{3/2} \exp\left[-\frac{3(\vec{r}-\vec{L}_i)^2}{2r_L^2}\right]$$

[George Gamow, 1930]

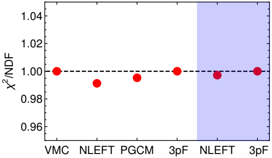
Acceptance-rejection method: NN correlations [Q.Liu, HM, B.N.Lu, 2509.00315]

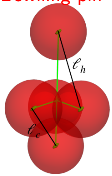






Models	3pF	NLEFT	PGCM	VMC
^{16}O (RTP)	(1.83,3.20)	(1.84,3.17)	(1.88,3.06)	(1.52,3.26)
^{16}O (ITP)	(2.00,3.15)	(1.61,3.88)	(1.57,3.86)	-
^{20}Ne (BP)	(2.00,3.00,3.00)	(2.20,3.00,3.50)	-	-



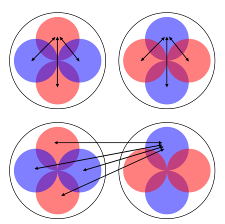


Imprint of α-clustering:

*Symmetric collisions:O+O and Ne+Ne

Intra-Cluster

Inter-Cluster



Transverse density:

one-body function:

$$\rho_\perp^{(1)}(\mathbf{r}) = \sum_{i=1}^{N_\alpha} \int dz \, \langle \rho_{\alpha_i}(\vec{r}, \Omega)\rangle_\Omega$$

$$= \sum_{i=1}^{N_\alpha} \langle \rho_\perp^{(\alpha_i)}(\mathbf{r}, \Omega)\rangle_\Omega = \sum_{i=1}^{N_\alpha} \langle \frac{3}{2\pi r_L^2} \exp\left[-\frac{3(x^2+y^2+f_i-2(xh_{x,i}+yh_{y,i}))}{2r_L^2}\right]\rangle_\Omega$$

two-body function:

$$\rho_\perp^{(2)}(\mathbf{r}, \mathbf{r}') = \sum_{i,j}^{N_\alpha} \langle \rho_\perp^{(\alpha_i)}(\mathbf{r}, \Omega) \rho_\perp^{(\alpha_j)}(\mathbf{r}', \Omega)\rangle_\Omega$$

$$= \frac{9}{4\pi^2 r_L^4} e^{-\frac{3(|\mathbf{r}|^2+|\mathbf{r}'|^2)}{2r_L^2}} \sum_{i,j}^{N_\alpha} \langle e^{\frac{f_i+xh_{x,i}+yh_{y,i}+f_j+x'h_{x',j}+y'h_{y',j}}{r_L^2/3}} \rangle_\Omega .$$

$f_i = |\vec{L}_i|^2 - (L_{z,i}c2 + (-L_{y,i}c1 + L_{x,i}s1)s2)^2$

$h_{x,i} = (L_{y,i}c1c2 - L_{x,i}c2s1 + L_{z,i}s2)s3 + (L_{y,i}s1 + L_{x,i}c1)c3$

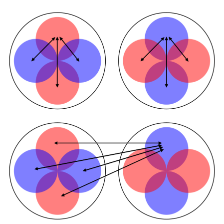
$h_{y,i} = (L_{y,i}c1c2 - L_{x,i}c2s1 + L_{z,i}s2)c3 - (L_{y,i}s1 + L_{x,i}c1)s3$

$\Omega = (a_1, a_2, a_3) \implies ci = \cos a_i$ and $si = \sin a_i$

$\Longrightarrow$

Intra-Cluster: $\rho_{\perp,1}^{(2)}(\mathbf{r}, \mathbf{r}') = \sum_{i=1}^{N_\alpha} \langle \rho_\perp^{(\alpha_i)}(\mathbf{r}, \Omega) \rho_\perp^{(\alpha_i)}(\mathbf{r}', \Omega)\rangle_\Omega$

Inter-Cluster: $\rho_{\perp,2}^{(2)}(\mathbf{r}, \mathbf{r}') = \sum_{i\neq j}^{N_\alpha} \langle \rho_\perp^{(\alpha_i)}(\mathbf{r}, \Omega) \rho_\perp^{(\alpha_j)}(\mathbf{r}', \Omega)\rangle_\Omega$



Two-particle correlations:

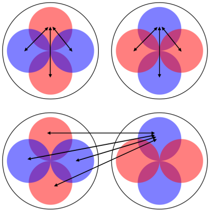
$$\langle \epsilon(\mathbf{r},\Omega,\Omega')\epsilon(\mathbf{r}',\Omega,\Omega')\rangle$$
$$= \langle \sum_{s,t=1}^{A,B} \mathcal{G}(\mathbf{r}-\xi_s)\mathcal{G}(\mathbf{r}-\xi_t) \sum_{n,m=1}^{A,B} \mathcal{G}(\mathbf{r}'-\xi_n)\mathcal{G}(\mathbf{r}'-\xi_m)\rangle$$
$$= \langle \sum_{s,n=1}^{A} \mathcal{G}(\mathbf{r}-\xi_s)\mathcal{G}(\mathbf{r}'-\xi_n) \sum_{t,m=1}^{B} \mathcal{G}(\mathbf{r}-\xi_t)\mathcal{G}(\mathbf{r}'-\xi_m)\rangle$$
$$= F_P F_T,$$

where

$F_P = A\,\mathcal{J}_{1,P}(\mathbf{r},\mathbf{r}',\Omega) + (A^2-A)\,\mathcal{J}^{(1)}_{2,P}(\mathbf{r},\mathbf{r}',\Omega)) + A^2\,\mathcal{J}^{(2)}_{2,P}(\mathbf{r},\mathbf{r}',\Omega)$

Imprint of α-clustering:

*Symmetric collisions:O+O and Ne+Ne



Transverse density:

one-body function:

$$\rho_{\perp}^{(1)}(\mathbf{r}) = \langle \rho_{\alpha_i}(\mathbf{r},\Omega)\rangle_{\Omega} = \langle \frac{3}{2\pi r_L^2} \exp\Big[-\frac{3(x^2+y^2+f_i-2(xh_{x,i}+yh_{y,i}))}{2r_L^2}\Big]\rangle_{\Omega}$$

two-body function:

$$\rho_{\perp}^{(2)}(\mathbf{r},\mathbf{r}') = \frac{9}{4\pi^2 r_L^4} e^{-\frac{3(|\mathbf{r}|^2+|\mathbf{r}'|^2)}{2r_L^2}} \sum_{i,j}^{N_\alpha} \langle e^{\frac{f_i+xh_{x,i}+yh_{y,i}+f_j+x'h_{x',j}+y'h_{y',j}}{r_L^2/3}}\rangle_{\Omega}.$$

$$f_i = |\vec{L}_i|^2 - (L_{z,i}c2 + (-L_{y,i}c1 + L_{x,i}s1)s2)^2$$

$$h_{x,i} = (L_{y,i}c1c2 - L_{x,i}c2s1 + L_{z,i}s2)s3 + (L_{y,i}s1 + L_{x,i}c1)c3$$

$$h_{y,i} = (L_{y,i}c1c2 - L_{x,i}c2s1 + L_{z,i}s2)c3 - (L_{y,i}s1 + L_{x,i}c1)s3$$

$\Omega = (a_1, a_2, a_3)$, $ci = \cos a_i$ and $si = \sin a_i$

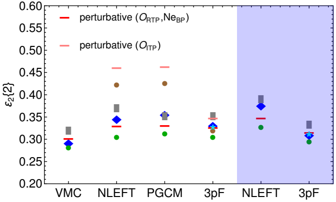
Initial anisotropy:

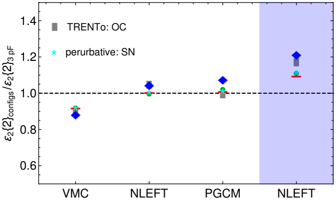
$$\varepsilon_2\{2\}^2 \equiv \langle \mathcal{E}_2\mathcal{E}_2^*\rangle_{ev} = \frac{\int_{\mathbf{r}}\int_{\mathbf{r}'} |\mathbf{r}|^2|\mathbf{r}'|^2 e^{2i(\phi-\phi')}\langle\delta\epsilon(\mathbf{r})\delta\epsilon(\mathbf{r}')\rangle_{ev}}{\left(\int_{\mathbf{r}}|\mathbf{r}|^2\langle\epsilon(\mathbf{r})\rangle_{ev}\right)^2},$$

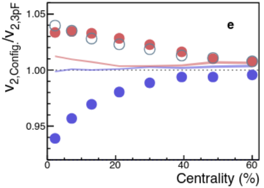
where $\langle\delta\epsilon(\mathbf{r})\delta\epsilon(\mathbf{r}')\rangle = \langle\epsilon(\mathbf{r})\epsilon(\mathbf{r}')\rangle - \langle\epsilon(\mathbf{r})\rangle\langle\epsilon(\mathbf{r}')\rangle$

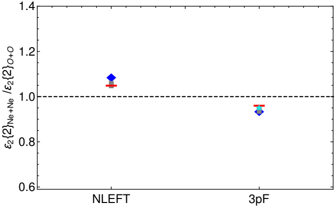
Imprint of α-clustering:

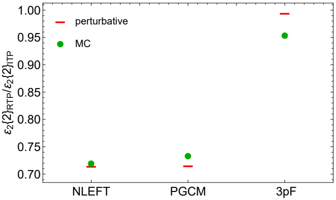
*Symmetric collisions:O+O and Ne+Ne

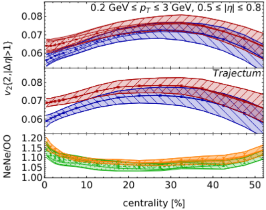










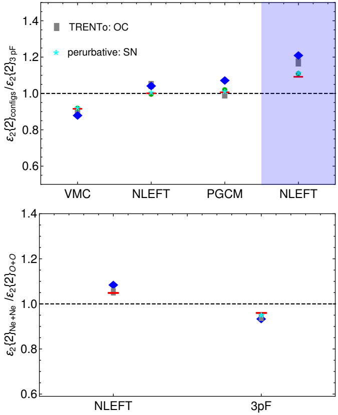


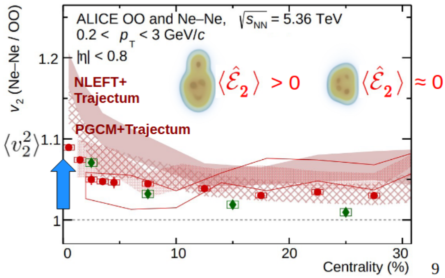
$$N(x,y,z) = \left(\frac{3}{2\pi R_s^2}\right)^{3/2} \exp\left[-\frac{3(x^2+y^2+z^2)}{2R_s^2}\right],\ R_s = r_L\sqrt{\frac{1+3\xi}{\mathcal{P}(\eta,\xi)} - 3\xi},\ \xi = w^2/r_L^2 \text{ and } \eta = \ell_c^2/r_L^2$$

$$N_\perp^{(k)}(\mathbf{r}_1,\cdots,\mathbf{r}_k) = \int dz_1\cdots dz_k \int d\Omega\ N(\vec{r_1})\cdots N(\vec{r_k}) = \left(\frac{3}{2\pi R_s^2}\right)^k \prod_i^k e^{-\frac{|\mathbf{r}_i|^2}{2R_s^2/3}}.$$

Imprint of α-clustering:

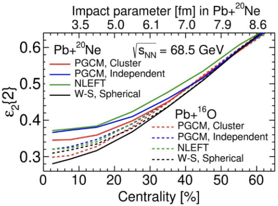
*Symmetric collisions:O+O and Ne+Ne



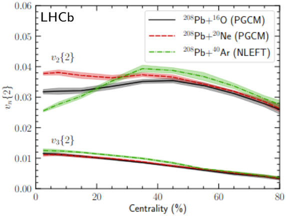


[G.Giacalone,Light ion collisions at the LHC-2025]

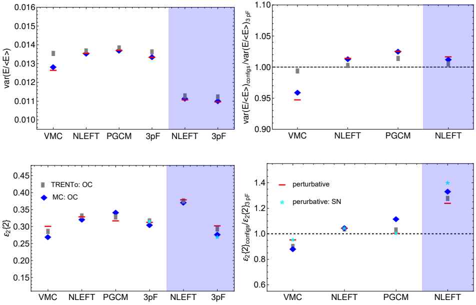
Imprint of α-clustering:

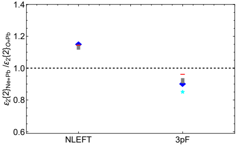


[PRL 134 (2025) 082301]



*Asymmetric collisions:O+Pb and Ne+Pb





TRENTo:

$\bar{B} = \langle N_{part} \rangle$

$\sigma = \langle (N_{part} - \langle N_{part} \rangle)^2 \rangle^{1/2}$

The average of total system's energy:

$$\langle E \rangle_{ev} = \frac{3A\times B}{2\pi(r_L^2+R_s^2+6w^2)} \sum_{i=1}^{N_\alpha} \int d\Omega \; e^{f_i + \frac{(h_{x,i}^2+h_{y,i}^2) r_L^2 (R_s^2+6w^2)}{6(r_L^2+R_s^2+6w^2)}}$$

Weighted observables:

$$\mathcal{O} = \frac{1}{\Delta B} \sum_{B=B_{min}}^{B_{max}} e^{-(B-\bar{B})^2/2\sigma^2} \mathcal{O}(B)$$

2. Heavy Hadrons and Quarkunium

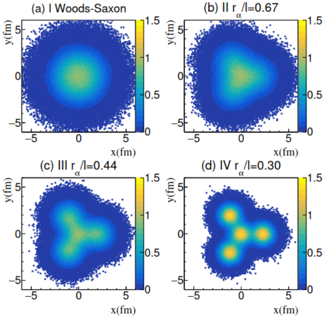


FIG. 1. (Color online) The 2-dimensional density distributions (unit in fm^{-2}) of the different tetrahedral configurations of ^{16}O listed in Tab. II, obtained by integrating their nuclear densities along one of their C3 rotation axes.

[Y.Wang et al., Phys.Rev.C 109 (2024) 5, L051904]

Flow of heavy hadrons as a probe of α-clustering:

Motivation:

– α-clustering in light nuclei modifies the initial transverse geometry.

– Heavy quarks are produced early and propagate through the entire medium.

– Their final-state anisotropy can carry information about the initial geometry.

What is measured:

– Scalar Product Method: $v_n^D\{SP\}(p_T) = \frac{\langle u_n^D(p_T) Q_n^{ch*}(p_T)\rangle}{\sqrt{\langle Q_{n,A}^{ch} Q_{n,B}^{ch*}\rangle}}$

Simulation chain:

– TRENTo+PYTHIA+MUSIC+MATTER+LBT+HybriHadronization+iSS

Analysis cuts:

– $|y| < 0.5$

– reference hadrons: π, K, p

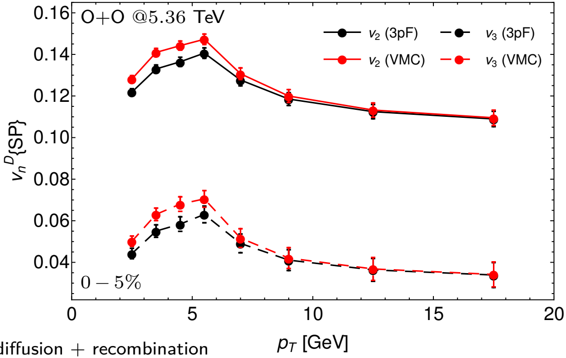
– $|y| < 0.5$ and $p_T > 2$ GeV

– centrality 0-5%

D anisotropic flow in clustered and unclustered O+O collisions:

JETSCAPE: 2M events

D-hadrons: $0.02 - 0.1$ per event



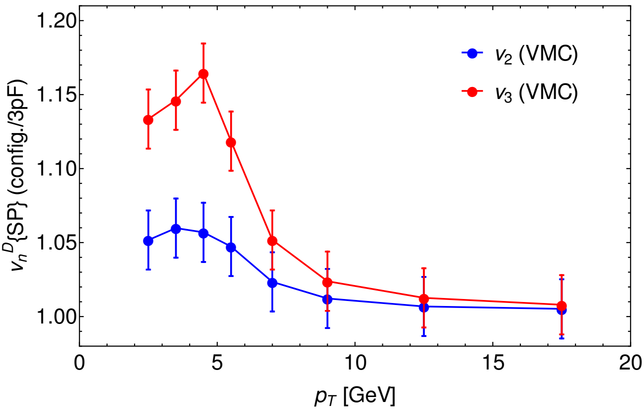
→ Low–intermediate pT ($\sim 2-6$ GeV)

- dominated by medium response + diffusion + recombination
- flow increases with pT

→ Above (~ 6 GeV) production

- production becomes jet-like
- path-length–dependent energy loss dominates
- the azimuthal anisotropy of the parent heavy quark decreases.

Sensitivity of D flow to α-clustering:



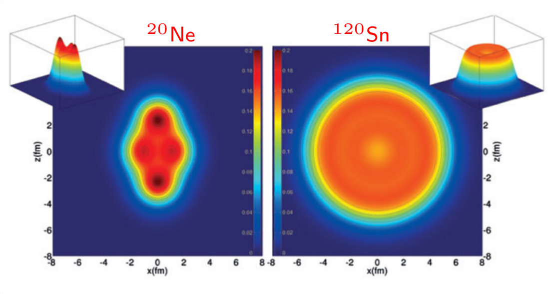
— The enhanced sensitivity of v_3 reflects the stronger response of triangular geometry to the intrinsic clustered structure of the oxygen nucleus.

J/Ψ *sensitivity to α-clustering in light ion collisions?* (in progress)

Motivation:

— Quarkonia are expected to be sensitive to the space-time structure of the medium through dissociation and regeneration.

— α-clustering in the oxygen nucleus modifies the temperature and lifetime profiles of the produced medium.



[J-P Ebran et al., Nature 487 341 (2012)]

Summary:

- A general theoretical picture: *light to heavy nuclei*
- Different between ab-initio models becomes from angular correlations
- Determined cluster parameters
- Symmetric and asymmetric collisions
- ^{20}Ne has a stronger angular (quadrupole) correlations than ^{16}O
- Heavy Hadrons (and Quarkonium) can help to study α-clustering in high energy nuclear collisions.

In progress:

- Deformation and cluster parameters [HM, S.A.Tabatabaee, B.N.Lu]
- Imprint of nuclear structures on identified particles [HM, A.Saha, P.Bozek, L.Yan]
- A neural network framework [A.Saha, HM, J.Jia]
- Shape coexistence [HM, A.Saha, H.Song, J.Jia]

  ⋮


Thank
you

Imprint of isolated NN correlations on O+O: [Q.Liu, HM, B.N.Lu, 2509.00315]

*Acceptance-rejection method: [R.Christensen, A.Branscum,and T.E Hanson, (2010) 1st ed.]

One-body density matrix:

$$\rho(\mathbf{r}) = A \int \prod_{i=2}^{A} d\mathbf{r}_i |\Psi(\mathbf{r}, \mathbf{r}_2, \cdots, \mathbf{r}_A)|^2$$

Nucleon-nucleon correlations:

$$C(\mathbf{r}, \mathbf{r}') = A(A-1) \int \prod_{i=3}^{A} d\mathbf{r}_i |\Psi(\mathbf{r}, \mathbf{r}', \mathbf{r}_3, \cdots, \mathbf{r}_A)|^2$$

Approximated form:

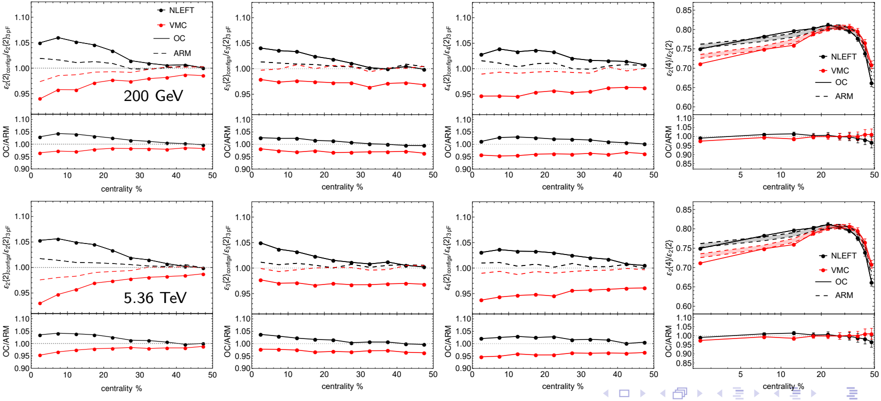
$$C(\Delta r) = 1 - \frac{g(\Delta r)}{g'(\Delta r)}, \quad \Delta r = |\mathbf{r}|$$

— correlated two-body dist.: $g(\Delta r)$ (target dist.)

— nncorrelated two-body dist.: $g'(\Delta r)$

— we accept the nucleons with relative distances $\Delta r'$ as samples from the the target distribution $g(\Delta r')$ if

$$U \leq \left(g(\Delta r')/M \cdot g'(\Delta r')\right), \; M = \sup_{\Delta r} \frac{g(\Delta r)}{g'(\Delta r)} = \Delta r_{\text{biggest}}$$



Charge density

Woods-Saxon distribution:

$$\rho(x,y,z) \propto \frac{1}{1+\exp\left(\frac{r-R(\theta,\phi)}{a_0}\right)}, \quad r=\sqrt{x^2+y^2+z^2}$$

Gaussian distribution

$$N(x,y,z) = \frac{1}{(2\pi)^{3/2}R_0^3}\exp(-r^2/2R(\theta,\phi)^2)$$

$$R(\theta,\phi) = R0\left(1+\sum_{l=2}\sum_{m=-l}^{l}\beta_{lm}Y_l^m(\theta,\phi)\right)$$

$$N(r,\theta,\phi) = \frac{e^{-\frac{r^2}{2R_0^2}}}{2\sqrt{2}\pi^{3/2}R_0^3} + \frac{\mathcal{Y}(\theta,\phi)\beta_2 r^2 e^{-\frac{r^2}{2R_0^2}}}{2\sqrt{2}\pi^{3/2}R_0^5} + \frac{\beta_2^2 e^{-\frac{r^2}{2R_0^2}}\left(-6\pi\mathcal{Y}(\theta,\phi)^2 r^2 R_0^2 + 2\pi\mathcal{Y}(\theta,\phi)^2 r^4 - r^2R_0^2\right)}{8\sqrt{2}\pi^{5/2}R^7},$$

where $\mathcal{Y}(\theta,\phi) = \cos\gamma Y_2^0(\theta,\phi) + \sin\gamma Y_2^2(\theta,\phi)$.

2) Particle production: a rotor rigid model

k-body density:

$$t_k(\vec{r}_1, \cdots, \vec{r}_k) = \frac{1}{8\pi^2} \int d\Omega \, \rho\left(R_{zxz}(\Omega)\vec{r}_1\right) \cdots \rho\left(R_{zxz}(\Omega)\vec{r}_k\right)$$

Transverse n-body density of nucleons:

$$t_{k\perp}(x_1, y_1; \cdots; x_k, y_k) = \int dz_1 \cdots dz_k \, t_k(\vec{r}_1, \cdots, \vec{r}_k)$$

Superposition of A nucleons:

$$T(x, y) = \sum_{i=1}^{A} \frac{1}{2\pi w^2} \exp\left(-\frac{(x-x_i)^2 + (y-y_i)^2}{2w^2}\right) = \sum_{i=1}^{A} g(x - x_i, y - y_i)$$

The density of overlapping area:

$$\epsilon(\mathbf{r}) = T(\mathbf{r})T(\mathbf{r}') = \sum_{i=1}^{A} \sum_{j=1}^{B} g(x - x_i, y - y_i) g(x' - x_j, y' - y_j)$$

Fluctuations: [PLB 738, 166 (2014)]

$$\epsilon(\mathbf{r}) = \langle \epsilon(\mathbf{r}) \rangle + \delta\epsilon$$

k-particle correlation:

$$\langle \delta\epsilon(\mathbf{r}^{(1)})\delta\epsilon(\mathbf{r}^{(2)})...\delta\epsilon(\mathbf{r}^{(k)})\rangle_{ev}$$

1-particle functions:

$$\langle E \rangle_{ev} = \int_{\mathbf{r}} \langle \epsilon(\mathbf{r}) \rangle_{ev} \text{ with } \langle \delta\epsilon \rangle_{ev} = 0$$

$$\vdots$$

2-particle correlators:

$$\text{Var}(E) = \int_{\mathbf{r}} \int_{\mathbf{r}'} \langle \delta\epsilon(\mathbf{r})\delta\epsilon(\mathbf{r}')\rangle_{ev}$$

$$\langle \mathcal{E}_n \mathcal{E}_n^* \rangle = \frac{\int_{x,y}\int_{x',y'}(x+iy)^n(x'-iy')^n \langle \delta\epsilon(\mathbf{r})\delta\epsilon(\mathbf{r}')\rangle_{ev}}{\left(\int_{x,y}(x^2+y^2)^{n/2}\langle \epsilon(\mathbf{r})\rangle_{ev}\right)^2}$$

$$\vdots$$

$\vdots$

k-particle correlation:

One-body function:

$$\langle \epsilon(\mathbf{r}) \rangle_{ev} = \langle \sum_{i=1}^{A} \sum_{j=1}^{A} g(x - x_i, y - y_i) g(x - x_j, y - y_j) \rangle_{ev}$$
$$= A^2 \left(\int_{x_i, y_i} t_{1\perp}(x_i, y_i) g(x - x_i, y - y_i) \right)^2$$

Two-nucleon correlations:

$$\langle \epsilon(\mathbf{r}) \epsilon(\mathbf{r}') \rangle_{ev} = \langle \sum_{i,j=1}^{A} g(x - x_i, y - y_i) g(x' - x_j, y' - y_j) \sum_{i',j'=1}^{A} g(x - x_{i'}, y - y_{i'}) g(x' - x_{j'}, y' - y_{j'}) \rangle_{ev}$$
$$= \Big[A \int_{x_i, y_i} t_{1\perp}(x_i, y_i) g(x - x_i, y - y_i) g(x' - x_i, y' - y_i)$$
$$+ (A^2 - A) \int_{x_i, y_i} \int_{x_j, y_j} t_{2\perp}(x_i, y_i; x_{i'}, y_{i'}) g(x - x_i, y - y_i) g(x' - x_j, y' - y_j) \Big]^2$$
$$= A^2 I_1^2 + 2A(A^2 - A) I_1 I_2 + (A^2 - A)^2 I_2^2 .$$

$\vdots$

1-particle observables:

$$\langle E \rangle_{ev} \approx \frac{A^2}{4\pi R_0^2} - \frac{3A^2\beta_2^2}{16\pi^2 R_0^2} + \alpha^2 \left(\frac{A^2\beta_2^2}{4\pi^2 R_0^2} - \frac{A^2}{4\pi R_0^2} \right)$$

2-particle observables:

$$\mathsf{var}(E\langle E \rangle) \approx \frac{0.667}{A} + 0.040\beta_2^2 + 0.014\beta_2^3 \cos(3\gamma)$$

$$\langle \varepsilon_2^2 \rangle \approx \frac{2.370}{A} + 0.239\beta_2^2 + 0.043\beta_2^3 \cos(3\gamma)$$

$$\langle \varepsilon_3^2 \rangle \approx \frac{2.68}{A} + \frac{1.44\beta_2^2}{A} + \frac{0.55\beta_2^3 \cos(3\gamma)}{A}$$

3-particle observables:

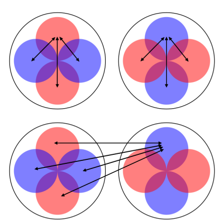
$$\mathsf{skew}(E\langle E \rangle) \approx \frac{2}{A^2} + \frac{0.16\beta_2^2}{A} + 0.0036\beta_2^3 \cos(3\gamma)$$

$$\mathsf{cov}(\mathcal{E}_2\mathcal{E}_2^*, E/\langle E \rangle) \approx \frac{0.89}{A^2} - 0.02\beta_2^3 \cos(3\gamma) + \frac{-0.16\beta_2^2}{A}$$

The liquid drop model ($A \to \infty$):

$$\begin{aligned}
\langle \varepsilon_2^2 \rangle &= 0.239\beta^2 + 0.043\beta^3 \cos(3\gamma), \\
var(E/\langle E \rangle) &= 0.040\beta^2 + 0.014\beta^3 \cos(3\gamma), \\
skew(E/\langle E \rangle) &= 0.003\beta^3 \cos(3\gamma), \\
cov(\varepsilon_2^2, E/\langle E \rangle) &= -0.020\beta^3 \cos(3\gamma).
\end{aligned}$$

Two-particle correlations:



$$
\begin{aligned}
&\langle \epsilon(\mathbf{r}, \Omega, \Omega')\epsilon(\mathbf{r}', \Omega, \Omega')\rangle \\
&= \langle \sum_{s,t=1}^{A,B} \mathcal{G}(\mathbf{r} - \xi_s)\mathcal{G}(\mathbf{r} - \xi_t) \sum_{n,m=1}^{A,B} \mathcal{G}(\mathbf{r}' - \xi_n)\mathcal{G}(\mathbf{r}' - \xi_m)\rangle \\
&= \langle \sum_{s,n=1}^{A} \mathcal{G}(\mathbf{r} - \xi_s)\mathcal{G}(\mathbf{r}' - \xi_n) \sum_{t,m=1}^{B} \mathcal{G}(\mathbf{r} - \xi_t)\mathcal{G}(\mathbf{r}' - \xi_m)\rangle \\
&= F_P F_T,
\end{aligned}
$$

where

$$F_P = A\, \mathcal{J}_{1,P}(\mathbf{r}, \mathbf{r}', \Omega) + (A^2 - A)\, \mathcal{J}^{(1)}_{2,P}(\mathbf{r}, \mathbf{r}', \Omega)) + A^2\, \mathcal{J}^{(2)}_{2,P}(\mathbf{r}, \mathbf{r}', \Omega)$$

$$\langle \epsilon(\mathbf{r},\Omega,\Omega')\epsilon(\mathbf{r}',\Omega,\Omega')\rangle = AB\sum_{i,i'}^{N_\alpha} H_i^{(P)}(\mathbf{r},\mathbf{r}',\Omega)H_{i'}^{(T)}(\mathbf{r},\mathbf{r}',\Omega')$$

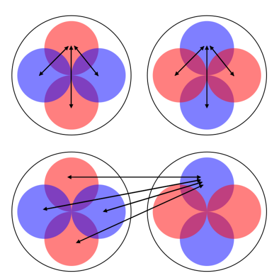
$$+2A(B^2-B)\sum_{i,i'}^{N_\alpha} H_i^{(P)}(\mathbf{r},\mathbf{r}',\Omega)H_{i'i'}^{(T)}(\mathbf{r},\mathbf{r}',\Omega')$$

$$+2AB^2\sum_{i,i'\neq j'}^{N_\alpha} H_i^{(P)}(\mathbf{r},\mathbf{r}',\Omega)H_{i'j'}^{(T)}(\mathbf{r},\mathbf{r}',\Omega')$$

$$+2A^2(B^2-B)\sum_{i\neq j,i'}^{N_\alpha} H_{ij}^{(P)}(\mathbf{r},\mathbf{r}',\Omega)H_{i'i'}^{(T)}(\mathbf{r},\mathbf{r}',\Omega')$$

$$+A^2B^2\sum_{i\neq j,i'\neq j'}^{N_\alpha} H_{ij}^{(P)}(\mathbf{r},\mathbf{r}',\Omega)H_{i'j'}^{(T)}(\mathbf{r},\mathbf{r}',\Omega')$$

$$+(A^2-A)(B^2-B)\sum_{i,i'}^{N_\alpha} H_{ii}^{(P)}(\mathbf{r},\mathbf{r}',\Omega)H_{i'i'}^{(T)}(\mathbf{r},\mathbf{r}',\Omega').$$



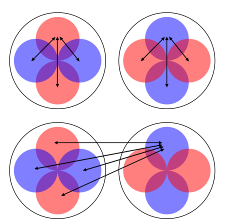
Asymmetric collisions (X+Pb):

$F_P = B\,\mathcal{I}_{1,P}(\mathbf{r},\mathbf{r}') + (B^2-B)\,\mathcal{I}_{2,P}(\mathbf{r},\mathbf{r}'))$ such that we have:

$$\mathcal{I}_{1,P} = \int d^2\xi_s\; N_\perp^{(1)}(\xi_s)\mathcal{G}(\mathbf{r}-\xi_s)\mathcal{G}(\mathbf{r}'-\xi_s) = \frac{3}{4\pi^2 w^2(R_s^2+3w^2)^2}\,e^{-\frac{R_s^2((x-x')^2+(y-y')^2)+3w^2(|\mathbf{r}|^2+|\mathbf{r}'|^2)}{2(2R_s^2w^2+3w^4)}},$$

$$\mathcal{I}_{2,P} = \int d^2\xi_s\; d^2\xi_n\; N_\perp^{(2)}(\xi_s,\xi_n)\mathcal{G}(\mathbf{r}-\xi_s)\mathcal{G}(\mathbf{r}'-\xi_n) = \frac{9}{4\pi^2(R_s^2+3w^2)^2}\exp\left[-\frac{3(|\mathbf{r}|^2+|\mathbf{r}'|^2)}{2(R_s^2w^2+3w^4)}\right].$$

From the perspective of field theory:



Generating function:

$$Z[j] \equiv \langle \exp\left(\int d^2\mathbf{r}\; j(\mathbf{r})\epsilon(\mathbf{r}) \right) \rangle$$

Connected correlation functions: cumulants

$$k_n(\mathbf{r}_1, \cdots, \mathbf{r}_n) = \frac{\delta^n \ln Z[j]}{\delta j(\mathbf{r}_1)\cdots\delta j(\mathbf{r}_n)}\Big|_{j=0}$$

Two-point correlation function of energy field:

$$k_2(\mathbf{r}_1, \mathbf{r}_2) = \langle \epsilon(\mathbf{r}_1)\epsilon(\mathbf{r}_2)\rangle - \langle \epsilon(\mathbf{r}_1)\rangle\langle \epsilon(\mathbf{r}_2)\rangle$$

Decomposition into one- and two-body contributions:

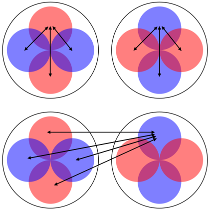
$$\epsilon(\mathbf{r}) = \epsilon_1(\mathbf{r}) + \epsilon_2(\mathbf{r})$$

Alpha-cluster decomposition:

$$k_2(\mathbf{r}_1, \mathbf{r}_2) = k_2^{(1\times 2)} + k_2^{(\text{same}\times\text{same})} + k_2^{(\text{diff}\times\text{diff})} + 2k_2^{(\text{same}\times\text{diff})}$$

Imprint of α-clustering:

*Symmetric collisions:O+O and Ne+Ne



Transverse density:

one-body function:

$$\rho_\perp^{(1)}(\mathbf{r}) = \langle \rho_{\alpha_i}(\mathbf{r},\Omega)\rangle_\Omega = \langle \frac{3}{2\pi r_L^2} \exp\Big[-\frac{3(x^2+y^2+f_i-2(xh_{x,i}+yh_{y,i}))}{2r_L^2}\Big]\rangle_\Omega$$

two-body function:

$$\rho_\perp^{(2)}(\mathbf{r},\mathbf{r}') = \frac{9}{4\pi^2 r_L^4} e^{-\frac{3(|\mathbf{r}|^2+|\mathbf{r}'|^2)}{2r_L^2}} \sum_{i,j}^{N_\alpha} \langle e^{\frac{f_i+xh_{x,i}+yh_{y,i}+f_j+x'h_{x',j}+y'h_{y',j}}{r_L^2/3}} \rangle_\Omega.$$

$f_i = |\vec{L}_i|^2 - (L_{z,i}c2 + (-L_{y,i}c1 + L_{x,i}s1)s2)^2$

$h_{x,i} = (L_{y,i}c1c2 - L_{x,i}c2s1 + L_{z,i}s2)s3 + (L_{y,i}s1 + L_{x,i}c1)c3$

$h_{y,i} = (L_{y,i}c1c2 - L_{x,i}c2s1 + L_{z,i}s2)c3 - (L_{y,i}s1 + L_{x,i}c1)s3$

$\Omega = (a_1, a_2, a_3)$, $ci = \cos a_i$ and $si = \sin a_i$

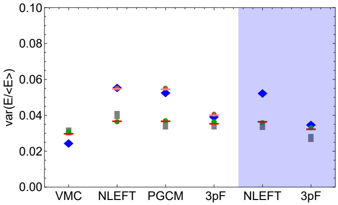
Variance of total energy density:

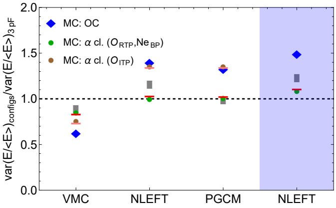
$$\mathrm{var}(E/\langle E\rangle) = \frac{\langle E^2\rangle_{ev} - \langle E\rangle_{ev}^2}{\langle E\rangle_{ev}^2} = \frac{\int d\Omega d\Omega' \int d^2\mathbf{r}\, d^2\mathbf{r}'\, \langle \delta\epsilon(\mathbf{r},\Omega,\Omega')\delta\epsilon(\mathbf{r}',\Omega,\Omega')\rangle}{\Big(\int d\Omega\, d\Omega'\, \langle \epsilon(\mathbf{r},\Omega,\Omega')\rangle\Big)^2},$$

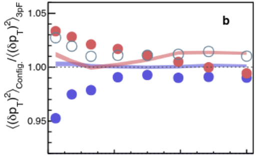
where $\langle \delta\epsilon(\mathbf{r})\delta\epsilon(\mathbf{r}')\rangle = \langle \epsilon(\mathbf{r})\epsilon(\mathbf{r}')\rangle - \langle \epsilon(\mathbf{r})\rangle\langle \epsilon(\mathbf{r}')\rangle$

Imprint of α-clustering:

*Symmetric collisions:O+O and Ne+Ne

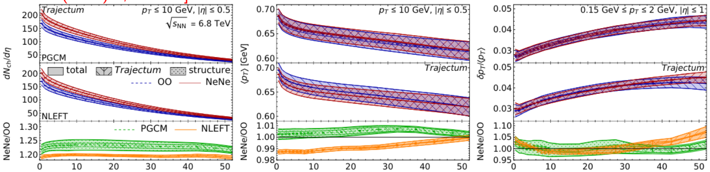






[PLB 862 (2025) 139322]

[PRL 135 (2025) 1, 012302]



MATTER = high-virtuality in-medium parton shower module

- evolves the hard partons coming from PythiaGun
- while they are still high virtuality ($Q > Q_0$)
- including medium-modified splittings.

Physically: vacuum-like + medium-modified shower stage

- early time
- hard partons
- large virtuality

LBT = Linear Boltzmann Transport

- propagates partons after MATTER
- in the medium
- via elastic + inelastic scatterings with thermal partons.

Physically: low-virtuality / on-shell transport stage

- later time
- quasi-on-shell partons
- medium response

```
PythiaGun
   ↓
MATTER   (high virtuality shower)
   ↓   (Q → Q0)
LBT      (in-medium transport)
   ↓
JetHadronization
```