Impact of nuclear geometry in symmetry plane correlations in OO and Ne–Ne collisions at the LHC

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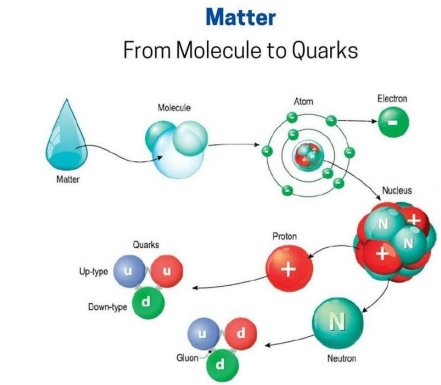
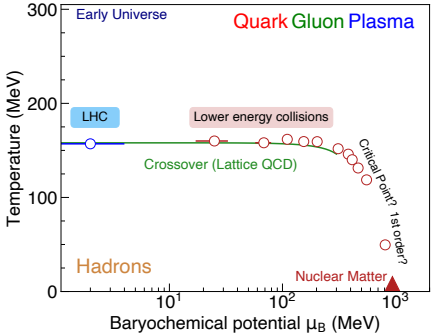
GPU Day 2026

Contents

States of matter and QGP

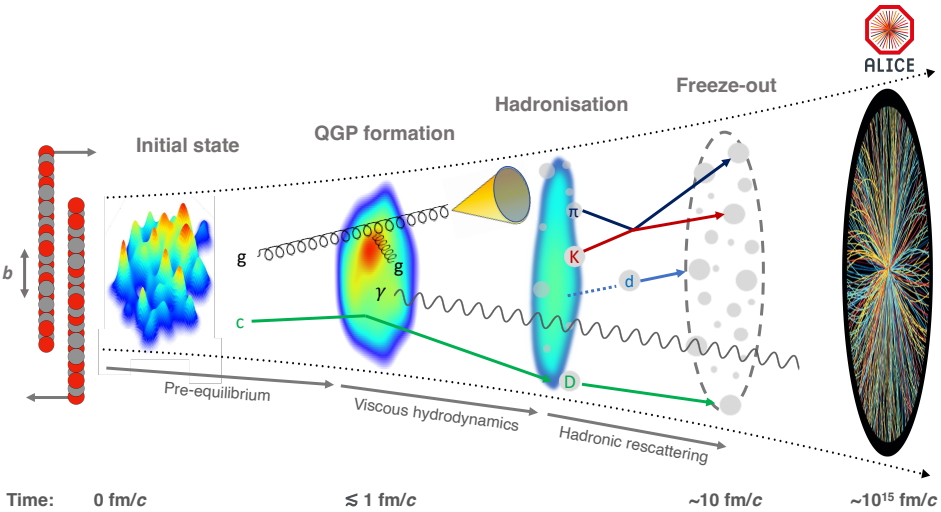




ALICE Collaboration, Eur.Phys.J.C 84 (2024), 813

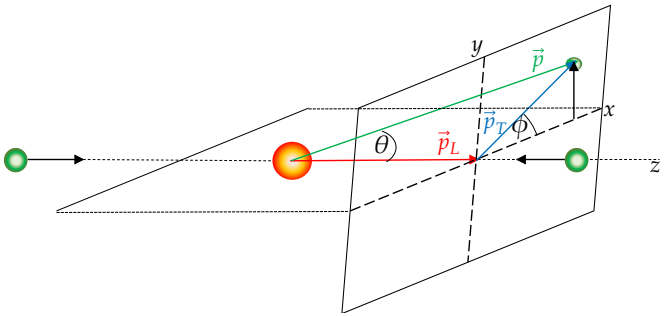
- Quarks/gluons can not exist freely – color confinement
- QGP is a primodial state of matter where the deconfined partons exist freely under thermal equilibrium

Heavy-ion collisions and Quark Gluon Plasma

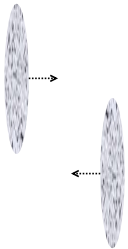


ALICE Collaboration, Eur.Phys.J.C 84 (2024), 813

Some terminologies



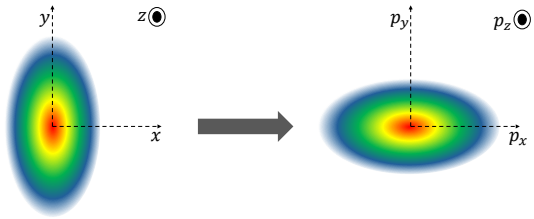
central collisions
(high multiplicity)



peripheral collisions
(low multiplicity)

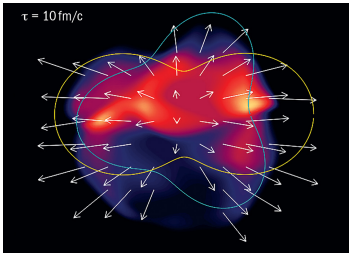
- Transverse momentum (p_{T}), $p_{\mathrm{T}} = \sqrt{p_x^2 + p_y^2}$;
- azimuthal angle (ϕ), $\phi = \tan^{-1}(p_y/p_x)$;
- Polar angle $\theta = \cos^{-1}(p_z/|\vec{p}|)$, where $|\vec{p}| = \sqrt{p_x^2 + p_y^2 + p_z^2}$.
- Pseudorapidity (η), $\eta = -\ln[\tan(\theta/2)]$;
- rapidity (y), $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$.

Anisotropic flow (v_n)



Initial spatial anisotropy

Final momentum space anisotropy

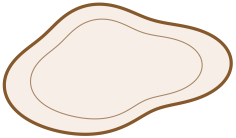


Transformation is driven by collective expansion of QGP leading to observation of final state anisotropic flow coefficients:

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\phi - \Psi_n)\right]$$

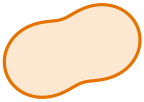
v_n are the flow coefficients and Ψ_n are the symmetry plane angles. Voloshin and Zhang, Z. Phys. C 70 (1996).

Symmetry Plane Angles (Ψ_n)



Collision overlap region

harmonic decomposition

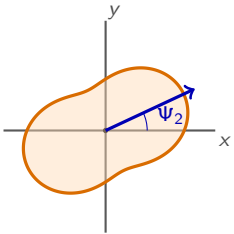


$n = 2$ **elliptic**

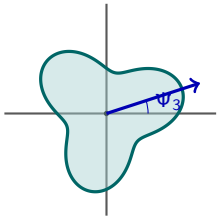
$n = 3$ **triangular**

$n = 4$ **quadrangular**

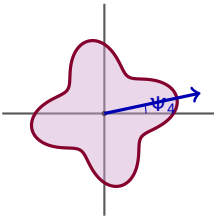
Event-by-event participant fluctuations generate ε_2, ε_3, and ε_4 components mapped to v_2, v_3, and v_4.



$n = 2$
elliptic emission



$n = 3$
triangular emission



$n = 4$
quadrangular emission

Symmetry Plane Angles: Properties and Why SPCs?

- Symmetry-plane angles are harmonic-specific orientations of collective flow:

$$\Psi_n = \frac{1}{n}\arg(Q_n), \qquad Q_n = \sum_{j=1}^{M} w_j e^{in\phi_j}.$$

- For a large event sample, $\langle \Psi_n \rangle \approx 0$.
- **Symmetry Plane Correlations (SPCs)** probe mode coupling beyond single v_n:

$$\mathrm{SPC}\left(c_1 n_1, c_2 n_2, \ldots\right) = \left\langle \cos\left(\sum_i c_i n_i \Psi_{n_i}\right)\right\rangle.$$

- SPCs separate linear response from non-linear hydrodynamic mixing, e.g. $v_4 \leftrightarrow v_2^2$, $v_5 \leftrightarrow v_2 v_3$, etc.
- SPCs are sensitive to initial geometry and transport properties of the QGP, providing stringent tests for theoretical models

Bhalerao, Luzum and Ollitrault, Phys. Rev. C 84 (2011); ATLAS, Phys. Rev. C 90 (2014).

Estimation of SPCs with Gaussian Estimator

The mixed-harmonic correlator can be expressed as Bhalerao, Luzum and Ollitrault, Phys. Rev. C 84 (2011)

$$v_{n_1}^{a_1} v_{n_2}^{a_2} \cdots v_{n_k}^{a_k} e^{i(a_1 n_1 \Psi_{n_1} + \cdots + a_k n_k \Psi_{n_k})} = \left\langle e^{i(n_1\phi_1 + n_2\phi_2 + \cdots + n_l\phi_l)} \right\rangle .$$

Under the factorization assumption, the Gaussian estimator used for SPCs is Bilandzic, Lesch and Taghavi, Phys. Rev. C 102 (2020); ALICE, Eur. Phys. J. C 83 (2023)

$$\left\langle \cos\left(\sum_i a_i n_i \Psi_{n_i} \right) \right\rangle_{\mathrm{GE}} = \sqrt{\frac{\pi}{4}} \frac{\left\langle \prod_i v_{n_i}^{a_i} \cos\left(\sum_i a_i n_i \Psi_{n_i} \right) \right\rangle}{\sqrt{\left\langle \prod_i v_{n_i}^{2a_i} \right\rangle}}.$$

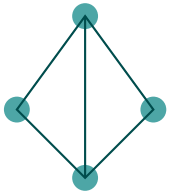
For the two observables discussed here,

$$\langle \cos\left[4(\Psi_2 - \Psi_4)\right] \rangle_{\mathrm{GE}} = \sqrt{\frac{\pi}{4}} \frac{\left\langle v_2^2 v_4 \cos\left[4(\Psi_2 - \Psi_4)\right] \right\rangle}{\sqrt{\left\langle v_2^4 v_4^2 \right\rangle}},$$

$$\langle \cos\left[6(\Psi_3 - \Psi_6)\right] \rangle_{\mathrm{GE}} = \sqrt{\frac{\pi}{4}} \frac{\left\langle v_3^2 v_6 \cos\left[6(\Psi_3 - \Psi_6)\right] \right\rangle}{\sqrt{\left\langle v_3^4 v_6^2 \right\rangle}}.$$

Oxygen and Neon Geometry: Why SPCs Differ

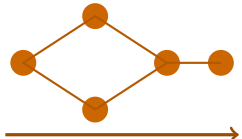
^{16}O: tetrahedral / octupole-rich



projected 4-α tetrahedral motif

- Stronger intrinsic triangular/octupole component.
- Favors larger v_3-driven nonlinear response.
- Hence larger $\langle\cos[6(\Psi_3 - \Psi_6)]\rangle_{\mathrm{GE}}$ in OO.

^{20}Ne: elongated / quadrupole-rich



elongated "pinball" / ^{16}O+α-like motif

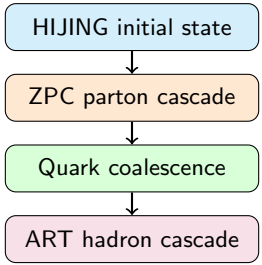
- Stronger intrinsic elliptic/quadrupole deformation.
- Enhances the coupling $v_4 \sim \chi_{4,22}(v_2)^2$.
- Hence larger $\langle\cos[4(\Psi_2 - \Psi_4)]\rangle_{\mathrm{GE}}$ in Ne–Ne.

Prasad and Sahoo, arXiv:2605.00866 (2026); Teaney and Yan, Phys. Rev. C 90 (2014); Gardim et al., Phys. Rev. C 85 (2012).

A multi-phase transport model

AMPT string-melting workflow

1. HIJING initial state: minijets, strings, geometry.
2. ZPC parton cascade: repeated parton scatterings.
3. Hadronization by quark coalescence.
4. ART hadron cascade until freeze-out.



- One event can produce **dozens to thousands** of final hadrons.
- Transport dominates runtime because each parton/hadron may rescatter multiple times.
- Cost rises with multiplicity, density, and the number of tracked scatterings in both cascades.

- The effects of nuclear geometry are prominent in central collisions
- Dense central events are computationally costly because both N_p and rescattering counts increase

Lin et al., Phys. Rev. C 72 (2005); Zhang et al., Phys. Rev. C 61 (2000); Wang and Gyulassy, Phys. Rev. D 44 (1991); Zhang, Comput. Phys. Commun. 109 (1998); Greco, Ko and Levai, Phys. Rev. Lett. 90 (2003); Li et al., Int. J. Mod. Phys. E 10 (2001).

Computing Cost Growth for Higher-Order SPCs

- For event multiplicity M, naive k-particle correlators scale as

$$\mathcal{O}(M^k) \quad \text{per event.}$$

- With N_{evt} events and N_{comb} harmonic combinations:

$$\text{Cost}_{\text{naive}} \sim N_{\text{evt}}\, N_{\text{comb}}\, M^k.$$

- Q-vector / recursive cumulant methods reduce this to approximately

$$\text{Cost}_{Q\text{-vector}} \sim N_{\text{evt}}\, N_{\text{comb}}\, k\, M,$$

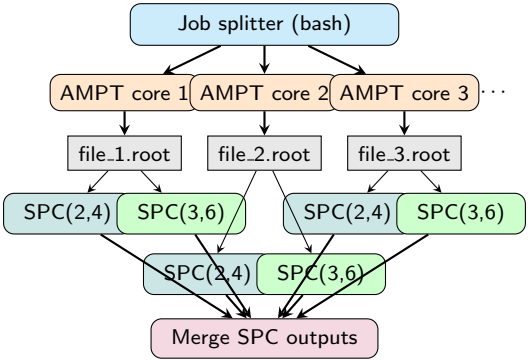
which is why GPUs become critical as k and combination count increase.

Example at $M = 3000$ (single combination, per event, relative units):

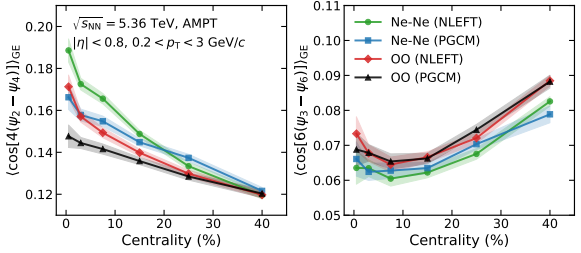
Order k	Naive M^k	vs $k = 2$	Q-vector kM
2	9.0×10^6	$1\times$	6.0×10^3
4	8.1×10^{13}	$9.0 \times 10^6\times$	1.2×10^4
6	7.29×10^{20}	$8.1 \times 10^{13}\times$	1.8×10^4

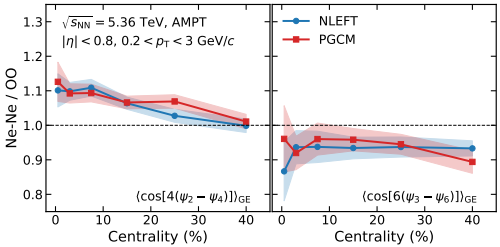
Use of Multiple CPU cores for the analysis

- AMPT is written in Fortran 77 and each executable run uses a single CPU core.
- One long serial run is inefficient for large statistics (millions of events).
- We use a bash workflow to split production into many independent jobs across cores.
- Each output file is then analyzed independently for each SPC observable in parallel.



Results: Two SPCs and Their Ratio

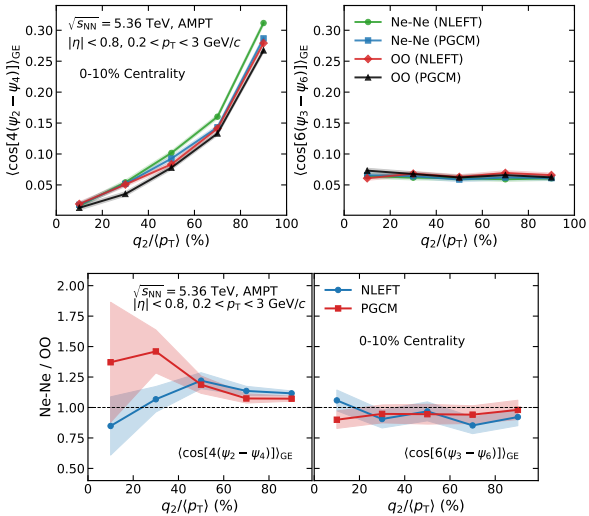




Prasad and Sahoo, arXiv:2605.00866 (2026).

- Centrality dependence of $\langle\cos[4(\Psi_2 - \Psi_4)]\rangle_{\mathrm{GE}}$ and $\langle\cos[6(\Psi_3 - \Psi_6)]\rangle_{\mathrm{GE}}$.
- Ne–Ne gives the larger $\langle\cos[4(\Psi_2 - \Psi_4)]\rangle_{\mathrm{GE}}$, matching stronger quadrupole deformation.
- OO gives the larger $\langle\cos[6(\Psi_3 - \Psi_6)]\rangle_{\mathrm{GE}}$, matching stronger triangular/octupole structure.
- The ratio highlights the clearest system split in central events, where intrinsic geometry survives best.

Results: Tip-Tip and Body-Body Selections



Prasad and Sahoo, arXiv:2605.00866 (2026).

- $q_2/\langle p_T\rangle$ is used to enrich tip-tip and body-body orientations.
- $\langle\cos[4(\Psi_2 - \Psi_4)]\rangle_{GE}$ rises toward body-body selections, reflecting stronger ellipticity-driven coupling.
- $\langle\cos[6(\Psi_3 - \Psi_6)]\rangle_{GE}$ changes much less, consistent with a more fluctuation-driven triangular component.
- The ratio confirms stronger Ne–Ne quadrupole sensitivity, while OO remains competitive for the triangular-sensitive correlator.

Summary

- The two SPC observables show a clear and complementary sensitivity to nuclear geometry in light-ion collisions.
- $\langle\cos[4(\Psi_2 - \Psi_4)]\rangle_{\mathrm{GE}}$ is larger in Ne–Ne, consistent with a stronger quadrupole-deformed initial geometry.
- $\langle\cos[6(\Psi_3 - \Psi_6)]\rangle_{\mathrm{GE}}$ is larger in OO, consistent with a stronger triangular/octupole component.
- The Ne–Ne/OO ratios show that the strongest geometry discrimination appears in central events.
- Tip-tip/body-body selection mainly affects the elliptic-sensitive correlator, while the triangular-sensitive correlator remains much less orientation dependent.
- Together, these results support SPCs as robust probes of intrinsic nuclear structure, not only bulk collectivity.

Prasad and Sahoo, arXiv:2605.00866 (2026).

Outlook

- AMPT provides a microscopic baseline with realistic non-equilibrium transport, rescattering, and finite-particle effects.
- The next step is a **hydrodynamic comparison** and additional higher order SPCs using the same OO and Ne–Ne nuclear configurations as initial conditions
- Hydro can test how much of the observed SPC pattern is controlled by:
  - initial-state geometry versus final-state response,
  - nonlinear mode couplings,
  - transport coefficients such as η/s and freeze-out choices.
- A useful program is: **NLEFT/PGCM geometry** $\rightarrow$ **hydro evolution** $\rightarrow$ **same GE-based SPC analysis**.
- If AMPT and hydro agree on the OO vs Ne–Ne SPC hierarchy, the case for geometry-driven signals becomes much stronger.

Heinz and Snellings, Ann. Rev. Nucl. Part. Sci. 63 (2013); Teaney and Yan, Phys. Rev. C 90 (2014); Gardim et al., Phys. Rev. C 85 (2012).

Thank You

for your attention

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Backup: Tip-Tip, Body-Body and $q_2/\langle p_T \rangle$

- **Tip-tip collisions:** long axes of deformed nuclei align with the beam direction.
  - smaller transverse geometric eccentricity,
  - stronger radial push, typically larger $\langle p_T \rangle$.
- **Body-body collisions:** long axes lie in the transverse plane.
  - larger transverse eccentricity,
  - relatively weaker radial push.

Event-shape observables:

$$q_2 = \frac{1}{M}\left|\sum_{j=1}^{M} e^{2i\phi_j}\right|, \qquad \langle p_T \rangle = \frac{1}{M}\sum_{i=1}^{M} p_{T,i}, \qquad R \equiv \frac{q_2}{\langle p_T \rangle}.$$

- Higher R enriches body-body-like events (eccentricity dominates).
- Lower R enriches tip-tip-like events (radial flow dominates).

STAR, Phys. Rev. C 66 (2002); Prasad and Sahoo, arXiv:2605.00866 (2026).