Nuclear structure theory meets the LHC: the recent ^{20}Ne + ^{20}Ne run

Benjamin Bally

Hirschegg - 23/01/2026

TECHNISCHE UNIVERSITÄT DARMSTADT

DeformedNuclei
[A. Tichai]

Motivations

- Interface between low- and high-energy nuclear physics

- Use of nuclear structure information to better understand heavy-ion collisions
  Giacalone *et al.*, PRL 127, 242301 (2021), Bally *et al.*, PRL 128, 082301 (2022), Jia *et al.*, PRL 131, 022301 (2023), etc.

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- **Predictions for ^{16}O + ^{16}O at LHC in 2025 (already planned)**

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- **Initial proposal that motivated ^{20}Ne + ^{20}Ne at LHC in 2025**

Related publication

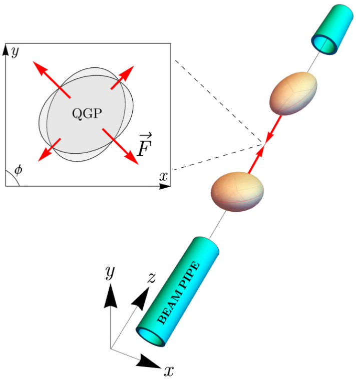
PHYSICAL REVIEW LETTERS **135,** 012302 (2025)

Exploiting ^{20}Ne Isotopes for Precision Characterizations of Collectivity in Small Systems

Giuliano Giacalone,[1,*] Benjamin Bally,[2] Govert Nijs,[3] Shihang Shen,[4] Thomas Duguet,[5,6] Jean-Paul Ebran,[7,8] Serdar Elhatisari,[9,10] Mikael Frosini,[11] Timo A. Lähde,[12,13] Dean Lee,[14] Bing-Nan Lu,[15] Yuan-Zhuo Ma,[14] Ulf-G. Meißner,[10,16,17] Jacquelyn Noronha-Hostler,[18] Christopher Plumberg,[19] Tomás R. Rodríguez,[20] Robert Roth,[21,22] Wilke van der Schee,[3,23,24] and Vittorio Somà[5]

- Collaboration between theorists from:
  - Heavy-ion collisions
  - Nuclear structure: PGCM and NLEFT

Ultra-relativistic ion-ion collisions



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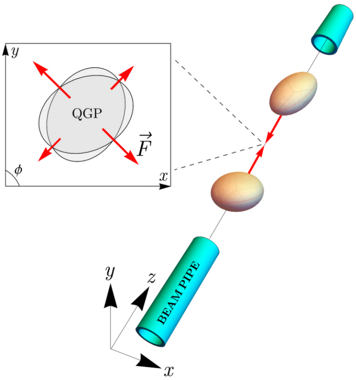

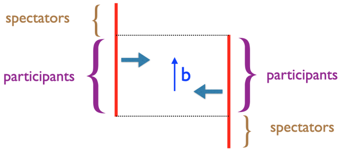

Ollitrault, EPJA 59, 236 (2023)

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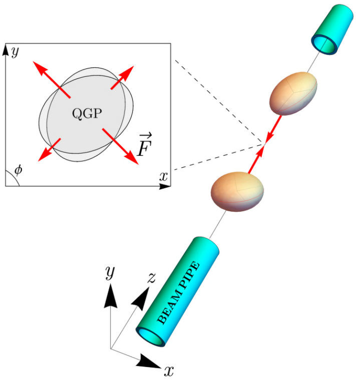

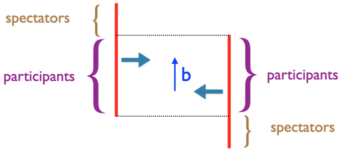

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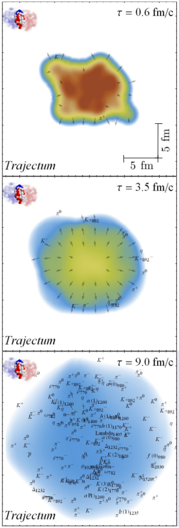
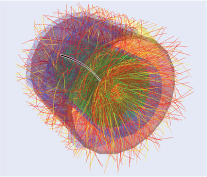
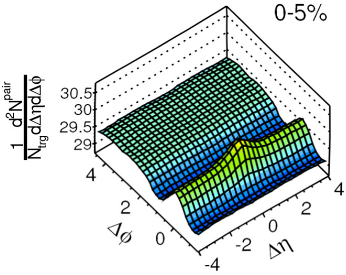




Giacalone *et al.*, PRL 131, 202302 (2023)

ALICE collaboration

Collective flow of particles



credit: CMS collaboration

- Probability distribution of particle emission

$$P(\phi,\eta) = P(\phi) = \frac{1}{2\pi} \sum_{n=-\infty}^{+\infty} V_n e^{-in\phi}$$

$V_2 \equiv$ elliptic flow, $V_3 \equiv$ triangular flow, ...

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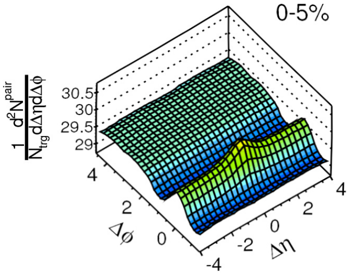

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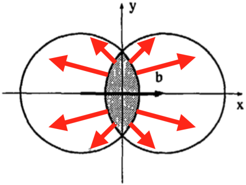
- Average of pair distribution

$$\left\langle \frac{dN_{\text{pair}}}{d\Delta\eta d\Delta\phi} \right\rangle = \langle P(\phi)P(\phi+\Delta\phi)\rangle = \frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{+\infty}\langle |V_n|^2\rangle \cos(n\Delta\phi)\right)$$

Spatial anisotropy of initial conditions



Ollitrault, PRD 46, 229 (1992)

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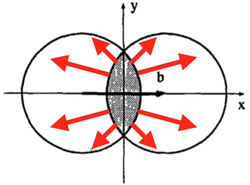

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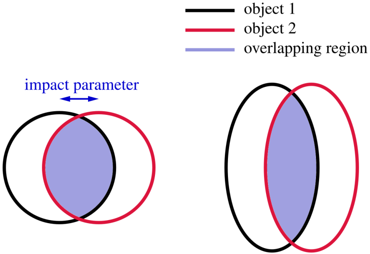

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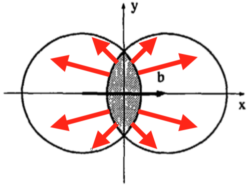

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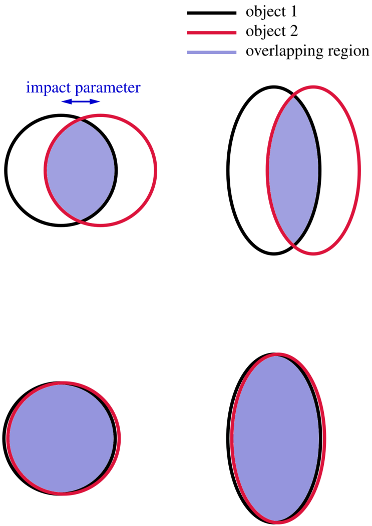

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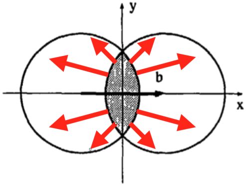

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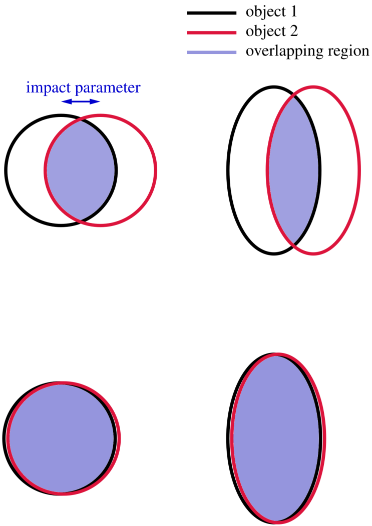
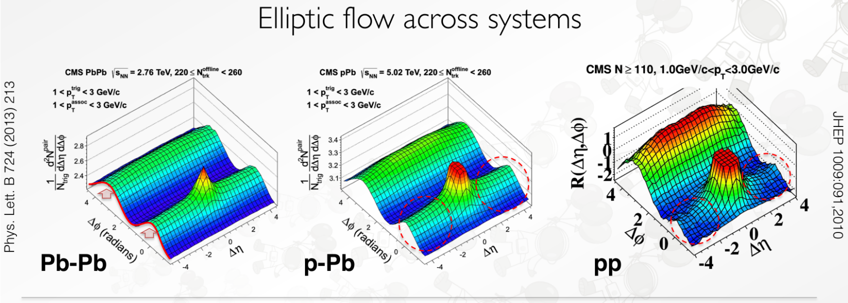


- **Nucleus is a strongly correlated quantum system with symmetries**

Dobaczewski *et al.*, PRR 7, 043159 (2025)



Chinellato, Quark Matter 2023

- Collectivity appears in *small systems* (p+p, p+A, d+A, . . .)
- Minimum size for a droplet of QGP?
- Is hydrodynamic the correct description?

The proposal

- Experimental methods exist but have also limitations
  - $p + {}^{197}\mathrm{Au}$ *versus* $d + {}^{197}\mathrm{Au}$
  - Central ${}^{16}\mathrm{O} + {}^{16}\mathrm{O}$ *versus* peripheral ${}^{208}\mathrm{Pb} + {}^{208}\mathrm{Pb}$

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- **New idea: central ${}^{16}\mathbf{O} + {}^{16}\mathbf{O}$ *versus* central ${}^{20}\mathbf{Ne} + {}^{20}\mathbf{Ne}$**
  - Systems with similar A
  - Same centrality class
  - Overlap region well-defined

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  $\Rightarrow$ **Test hydrodynamic description in small(er) systems**

Tools and workflow

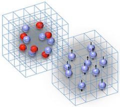
EFT → **Nuclear structure** → **Relativistic hydrodynamic** → **Hadron transport** → **PRL**

χEFT
N3LO

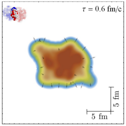
```
(______)
<(0  0)>
 (°°)
```
TAURUS

PGCM

$\not\pi$EFT
LO



NLEFT



Trajectum

smash

135, 012302

- TAURUS: `https://github.com/project-taurus`
- *Trajectum*: `https://sites.google.com/view/govertnijs/trajectum`
- SMASH: `https://github.com/smash-transport/smash`

NLEFT calculations

- Nuclear Lattice Effective field Theory (NLEFT)

  Lee, Front. in Phys. 8, 174 (2020)

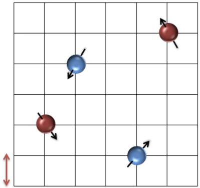
  Lähde and Meißner, Lectures Notes in Phys., Springer (2019)

- Mesh with 8 sites and spacing $a = 1.315$ fm

- Minimal pionless EFT Hamiltonian with SU(4) symmetry

- Pin-hole algorithm → nucleon positions

  Elhatisari *et al.*, PRL 119, 222505 (2017)



$\Rightarrow$ **see Dean's presentation**

PGCM calculations

- Projected Generator Coordinate Method (PGCM)

$$|\Theta_\epsilon^{\sigma M}\rangle = \sum_{qK} f_\epsilon^{\sigma M}(q,K) P^\sigma_{MK} |\Phi(q)\rangle \quad \text{where} \quad \sigma \equiv Z, N, J, \pi$$

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- Full method: PGCM + Perturbation Theory

  Frosini *et al.*, EPJA 58, 62+63+64 (2022)

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- Model space: $e_{\text{max}} = 6$, $e_{3\text{max}} = 18$, $\hbar\omega = 12$

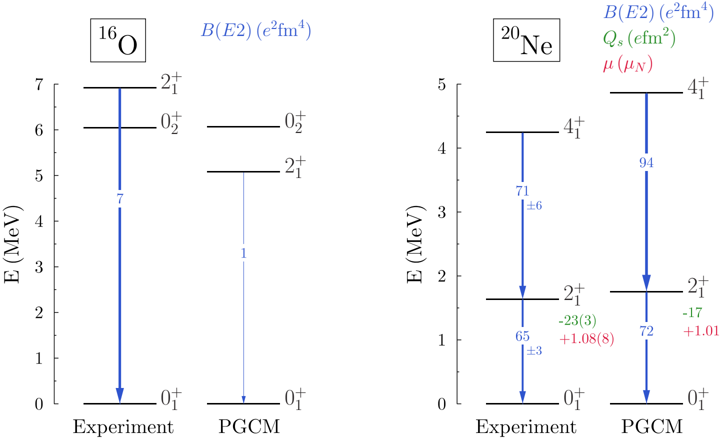
  Hamiltonian: Hüther N3LO

  Hüther *et al.*, PLB 808, 135651 (2019)

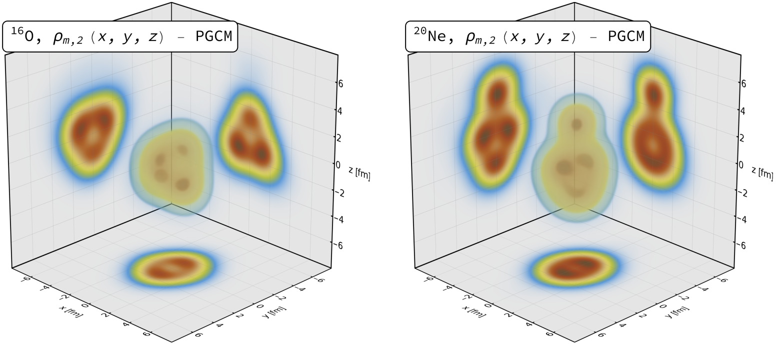
  Reference states $|\Phi\rangle$: real general Bogoliubov (VAPNP mininization)

  Collective coordinates q: $\beta_{20}, \beta_{22}, \beta_{30}, \beta_{32}$

Low-energy spectrum



PGCM-based densities



- Determine average deformation of PGCM ground state: $\bar{q}$
- One-body density: $\rho_m(x,y,z) = \sum_{st} \frac{\langle \Phi(\bar{q}) | a^{+}_{xyzst} a_{xyzst} P^Z P^N | \Phi(\bar{q}) \rangle}{\langle \Phi(\bar{q}) | P^Z P^N | \Phi(\bar{q}) \rangle}$
- Sample directly ρ_m or assuming α clusters

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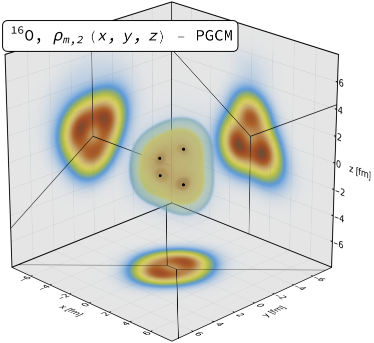

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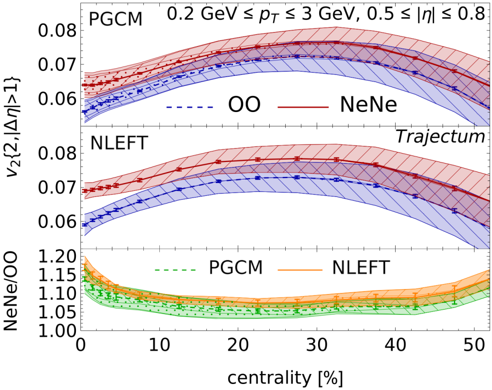
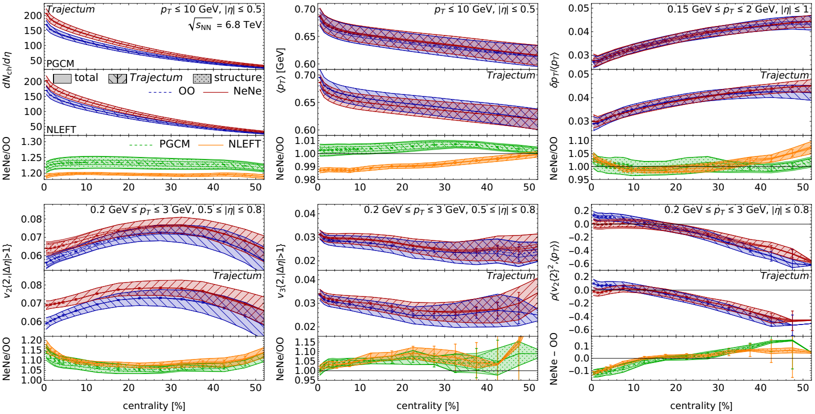
Results: elliptic flow $v_2\{2\}^2$



- In the 0-1% events:

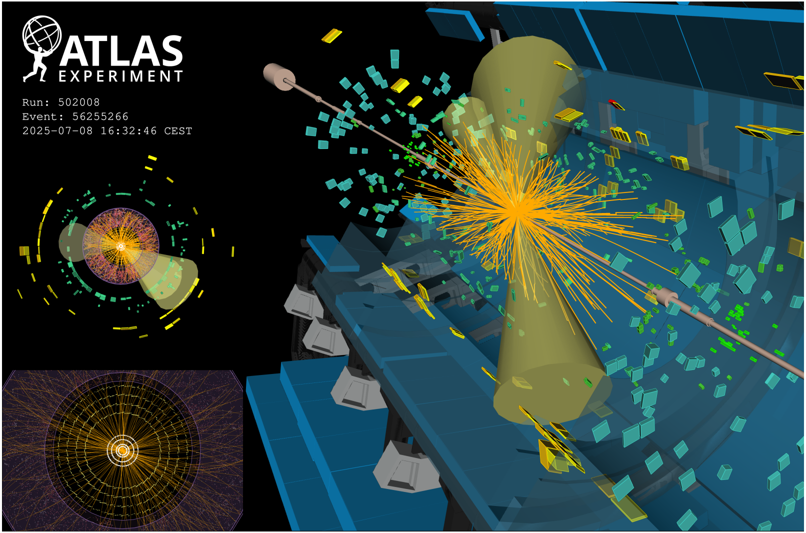
$$\frac{v_2\{2\}_{\mathrm{NeNe}}}{v_2\{2\}_{\mathrm{OO}}} = \begin{cases} 1.174(8)_{\mathrm{stat.}}(31)^{\mathit{Traj.}}_{\mathrm{syst.}}(4)^{\mathrm{str.}}_{\mathrm{syst.}} & \text{(NLEFT)} \\ 1.139(6)_{\mathrm{stat.}}(27)^{\mathit{Traj.}}_{\mathrm{syst.}}(28)^{\mathrm{str.}}_{\mathrm{syst.}} & \text{(PGCM)} \end{cases}$$

Results: general comments



- Ratios/differences between ^{20}Ne + ^{20}Ne and ^{16}O + ^{16}O reduce uncertainties
- NLEFT and PGCM in good agreement

^{20}Ne + ^{20}Ne collisions performed at the LHC on the 8th of July 2025



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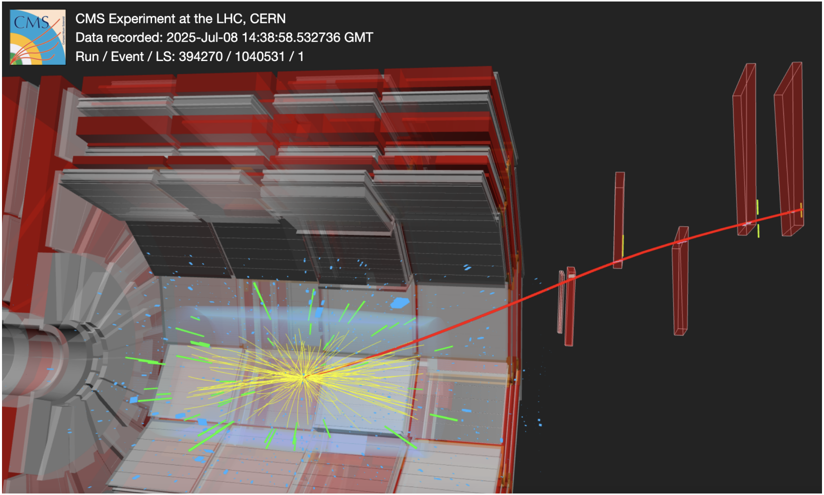
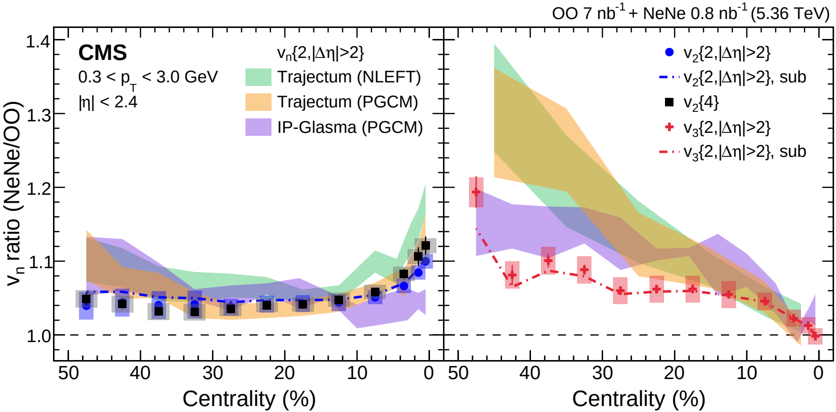
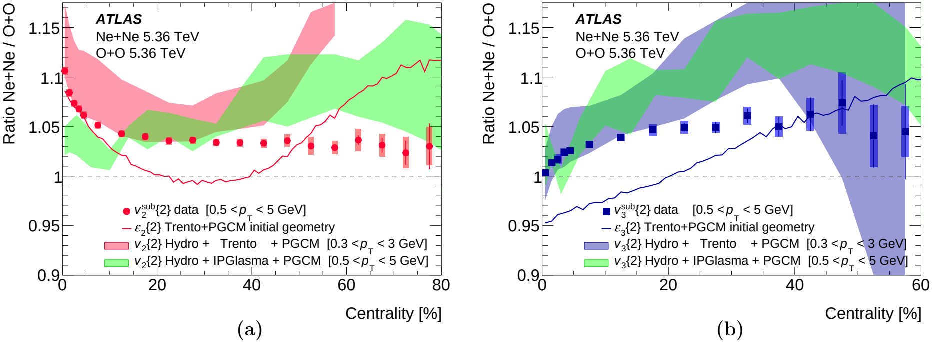


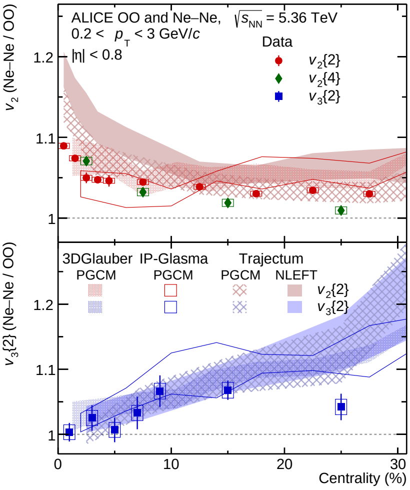


CMS Collaboration, arXiv:2510.02580 (2025)

First results from LHC/ATLAS

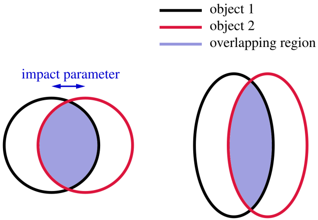


ATLAS Collaboration, arXiv:2509.05171 (2025)



ALICE Collaboration, arXiv:2509.06428 (2025)

Eccentricity operator



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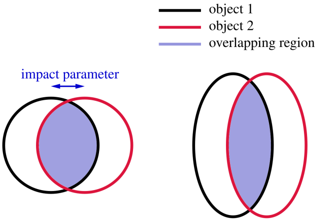
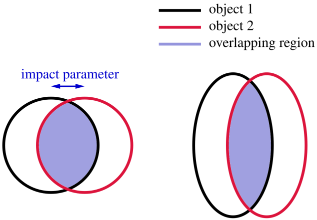


$$\xleftarrow[\textbf{quantum definition}]{\textbf{provide}} \quad O^{(k)}, \rho^{(k)}[J^\pi]$$

Eccentricity operator



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$$\langle \varepsilon_2^2 \rangle = \frac{1}{2A} \frac{1}{\langle \hat{R}_n \rangle^2} \left[\langle \hat{R}_{2n} \rangle + (A-1) \langle \hat{\mathcal{E}}_n \rangle \right]$$

Duguet *et al.*, PRL 135, 182301 (2025)

Blaizot *et al.*, arXiv:2512.18926 (2025)

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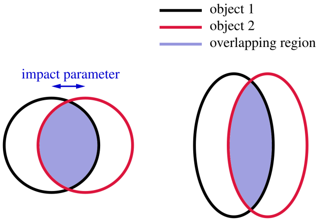

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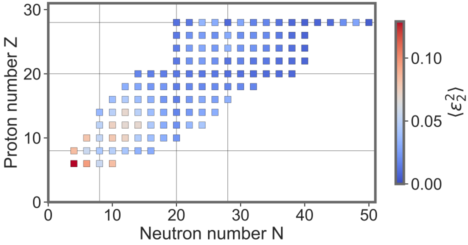
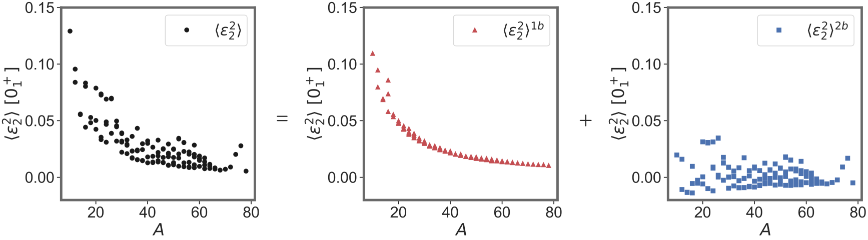
Blaizot *et al.*, arXiv:2512.18926 (2025)



Bofos *et al.*, in preparation (2026)

$\langle \varepsilon_2^2 \rangle$: decomposition and interpretation

$$\left\langle \varepsilon_2^{(2)} \right\rangle = \left\langle \varepsilon_2^{(2)} \right\rangle^{1b} + \left\langle \varepsilon_2^{(2)} \right\rangle^{2b}$$



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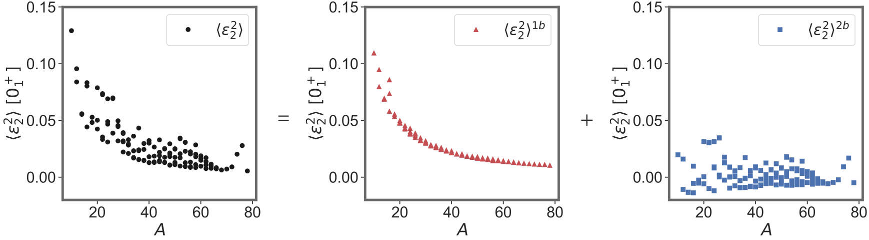
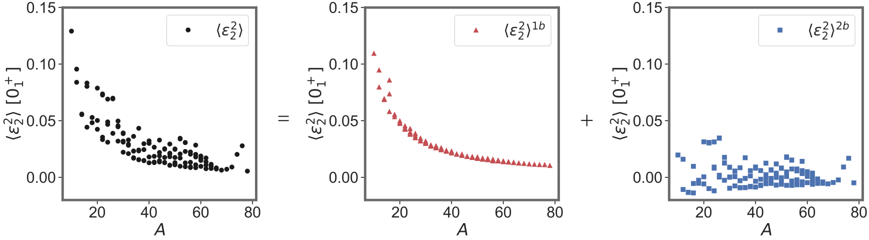
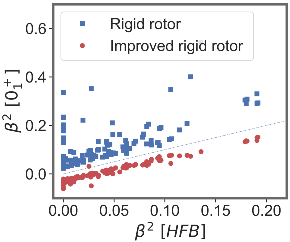


$\langle \varepsilon_2^2 \rangle$: decomposition and interpretation

$$\langle \varepsilon_2^{(2)} \rangle = \langle \varepsilon_2^{(2)} \rangle^{1b} + \langle \varepsilon_2^{(2)} \rangle^{2b} \approx e_1/A + e_2 + e_3\beta^2 \text{ (improved rigid rotor)}$$





Summary

- Interface between low- and high-energy nuclear physics
  - Combines several state-of-the-art frameworks and software
  - NLEFT and PGCM give consistent results
  - First preliminary results for the eccentricity operator

- Many things to understand or improve (nucleon sampling, propagation of uncertainties, . . .)

- **^{20}Ne + ^{20}Ne run performed at the LHC on the 8th of July!**

^{20}Ne + ^{20}Ne collisions performed at the LHC on the 8th of July 2025