Impact of deformation on ultra-relativistic nuclear collisions

Benjamin Bally

SSNET24 - Orsay - 04/11/2024

cea irfu

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)

- Nuclear deformation impacts initial conditions and thus final state observables

- Nuclear structure calculations for ^{16}O and ^{20}Ne using EFT-based interactions

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- Nuclear deformation impacts initial conditions and thus final state observables
- Nuclear structure calculations for ^{16}O and ^{20}Ne using EFT-based interactions
- **Predictions for $^{16}\text{O} + ^{16}\text{O}$ and $^{16}\text{O} + ^{208}\text{Pb}$ runs at LHC in 2025**

Preprints: arXiv:2402.05995 and arXiv:2405.20210

CERN-TH-2024-021

The unexpected uses of a bowling pin: 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]

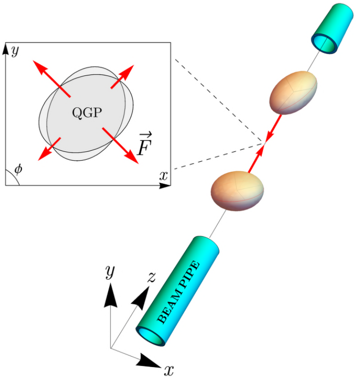
CERN-TH-2024-074

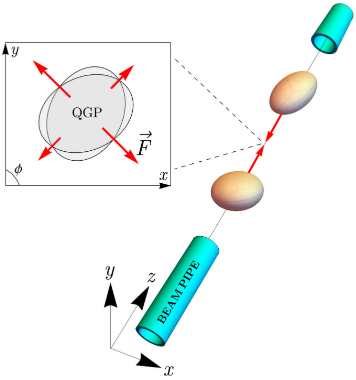
Anisotropic flow in fixed-target ^{208}Pb+^{20}Ne collisions as a probe of quark-gluon plasma

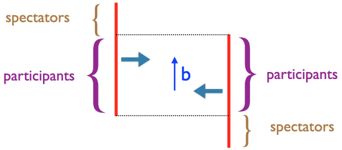
Giuliano Giacalone,[1,*] Wenbin Zhao,[2,3,†] Benjamin Bally,[4] Shihang Shen,[5] Thomas Duguet,[6,7] Jean-Paul Ebran,[8,9] Serdar Elhatisari,[10] Mikael Frosini,[11] Timo A. Lähde,[12,13] Dean Lee,[14] Bing-Nan Lu,[15] Yuan-Zhuo Ma,[14] Ulf-G. Meißner,[16,17,5] Govert Nijs,[18] Jacquelyn Noronha-Hostler,[19] Christopher Plumberg,[20] Tomás R. Rodríguez,[21] Robert Roth,[22,23] Wilke van der Schee,[18,24,25] Björn Schenke,[26,‡] Chun Shen,[27,28,§] and Vittorio Somà[6]

- Collaboration between low- and high-energy nuclear physics communities
  - Heavy-ion collisions
  - Nuclear structure (PGCM)
  - Nuclear structure (NLEFT)

Ultra-relativistic ion-ion collisions







Ollitrault, EPJA 59, 236 (2023)

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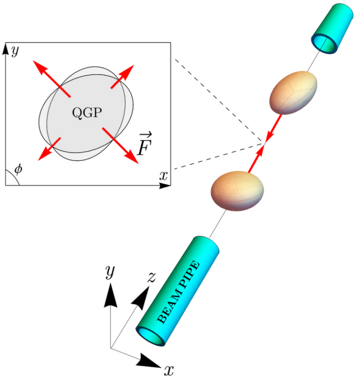

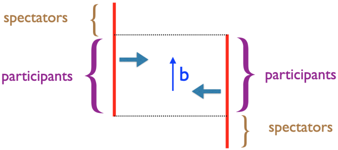

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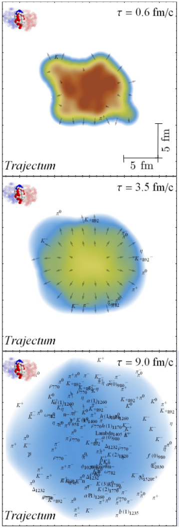
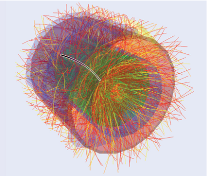
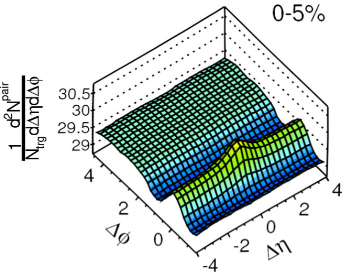




Giacalone *et al.*, PRL 131, 202302 (2023)

ALICE collaboration

Collective flow of particles

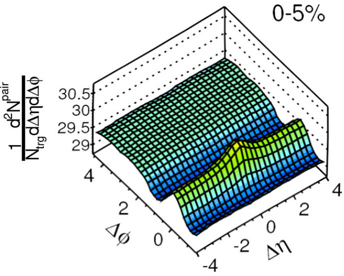


credit: CMS collaboration

- 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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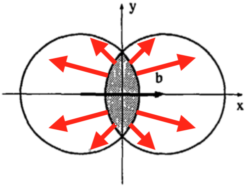
- Average of pair distribution

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

Geometric asymmetry of initial conditions



Ollitrault, PRD 46, 229 (1992)

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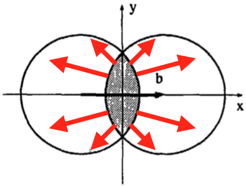

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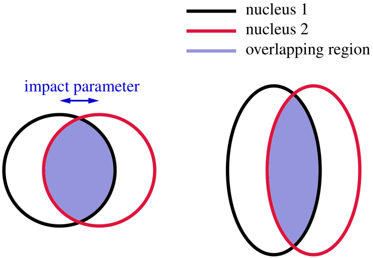

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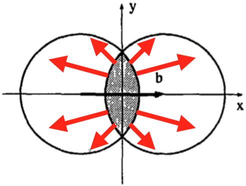

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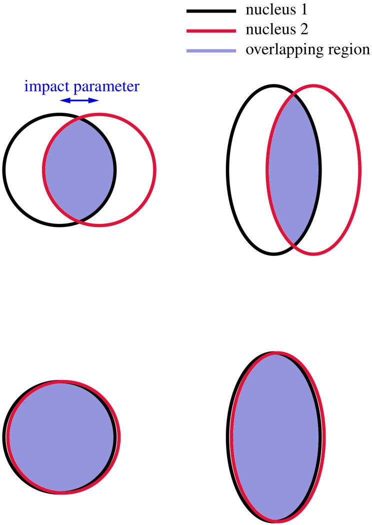
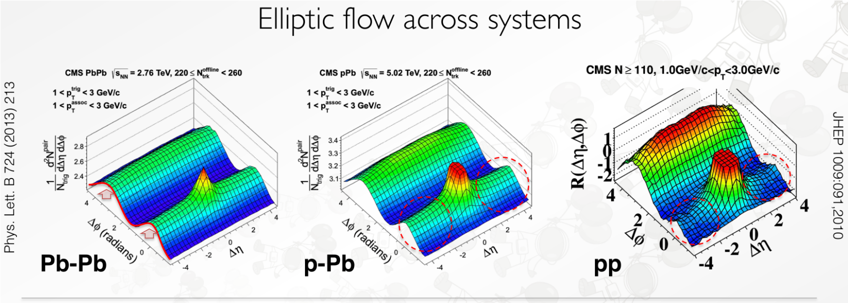




Chinellato, Quark Matter 2023

- Collectivity appears in *small systems* (p+p, p+A, d+A, . . .)
- Is it the same mechanism? Is hydrodynamic the correct description?

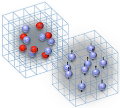
EFT → **Nuclear structure** → **Relativistic hydrodynamic** → **Hadron transport** → **Nucl-th**

χEFT
N3LO

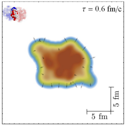
TAURUS

PGCM

$\not\pi$EFT
LO



NLEFT



Trajectum

smash

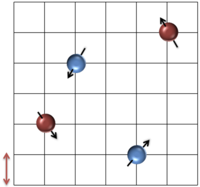
arXiv:2402.05995

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

- 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)

PGCM calculations

- Projected Generator Coordinate Method (PGCM)

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

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- Full method: PGCM + Perturbation Theory

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

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

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→ PGCM enough for relative properties

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

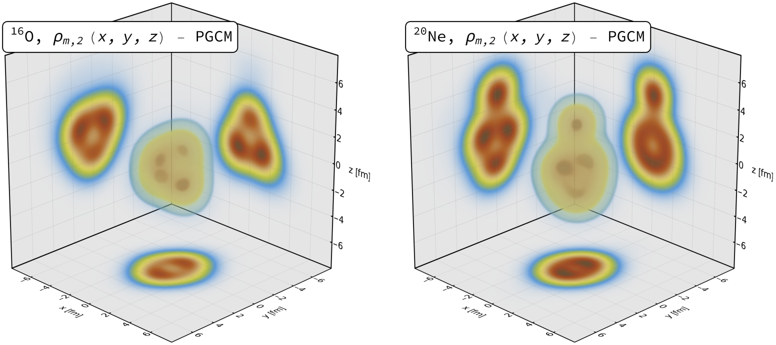
  Hamiltonian: Hüther N3LO

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

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

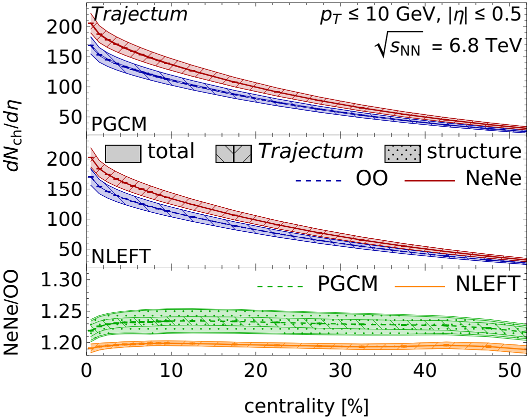
  Collective coordinates q: $\beta_{20}, \beta_{22}, \beta_{30}, \beta_{32}$

PGCM-based densities

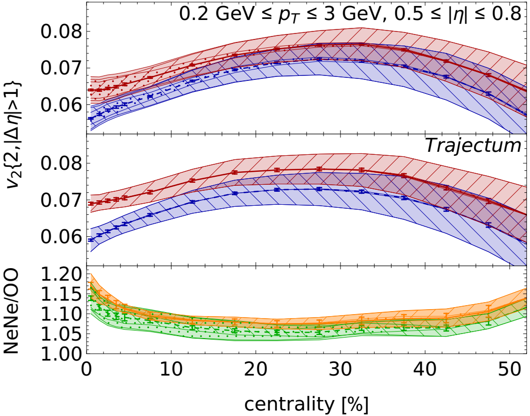


- Determine average deformation of PGCM ground state: $\bar{q}$
- One-body density: $\rho_m(x,y,z) = \sum_{st} \frac{\langle \Phi(\bar{q}) | a^+_{xyzst} a_{xyzst} P^Z P^N | \Phi(\bar{q}) \rangle}{\langle \Phi(\bar{q}) | P^Z P^N | \Phi(\bar{q}) \rangle}$
- Sample directly ρ_m or assuming α clusters

Results: multiplicity



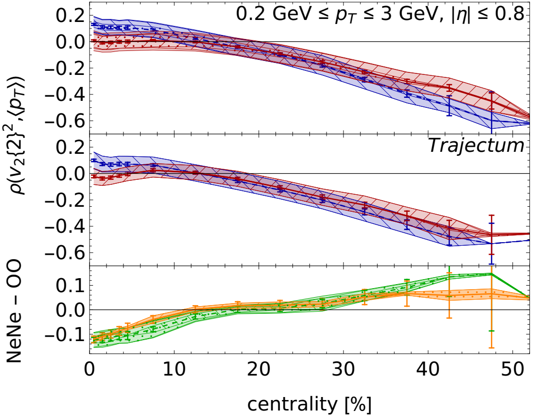
Results: elliptic flow $v_2\{2\}^2$



- In the 0-1% events:

$$\frac{v_2\{2\}_{\text{NeNe}}}{v_2\{2\}_{\text{OO}}} = \begin{cases} 1.170(8)_{\text{stat.}}(30)^{\textit{Traj.}}_{\text{syst.}}(0)^{\text{str.}}_{\text{syst.}} & \text{(NLEFT)} \\ 1.139(6)_{\text{stat.}}(27)^{\textit{Traj.}}_{\text{syst.}}(28)^{\text{str.}}_{\text{syst.}} & \text{(PGCM)} \end{cases}$$

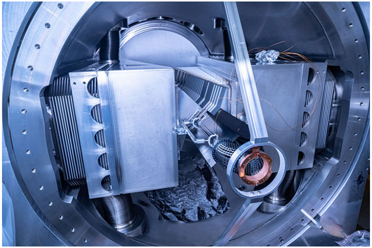
Results: Pearson coefficient $\rho(v_2\{2\}^2, \langle p_T \rangle)$



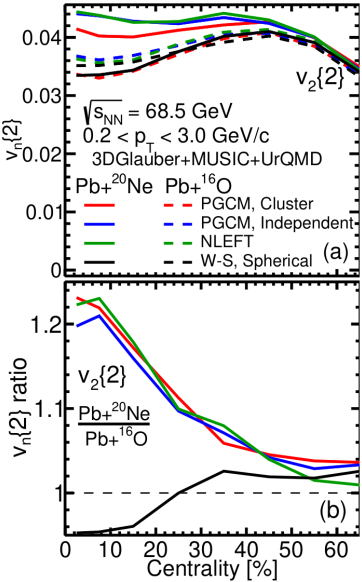
- Negative ρ due to the large deformation of ^{20}Ne

$$\rho_{\mathrm{Ne+Ne}} - \rho_{\mathrm{O+O}} \propto \left(\beta^3_{2,^{16}\mathrm{O}} - \beta^3_{2,^{20}\mathrm{Ne}}\right)$$

Fixed-target program at LHCb/SMOG2



credit: CERN



Conclusion

- Collaborative work at the interface between low- and high-energy physics
  - Make use of the large ground-state deformation of ^{20}Ne
  - Combines several state-of-the-art frameworks and software
  - NLEFT and PGCM give consistent results

- We make **predictions** for
  - $^{16}\mathrm{O} + {}^{16}\mathrm{O}$ and $^{16}\mathrm{O} + {}^{208}\mathrm{Pb}$ runs at the LHC (2025)
  - $^{20}\mathrm{Ne} + {}^{20}\mathrm{Ne}$ and $^{20}\mathrm{Ne} + {}^{208}\mathrm{Pb}$ runs that could be performed in the future