LOI ENS@LHCb :
Exploring nuclear structure and nuclear matter with fixed target and collider mode at LHCb

PI: L. Massacrier (IJCLab Orsay, CNRS/IN2P3, Université Paris-Saclay)

Town meeting Hadron Physics in Europe, 1-3rd July 2025, Nantes

Scientific objectives : imaging shapes of atomic nuclei with heavy ion collisions

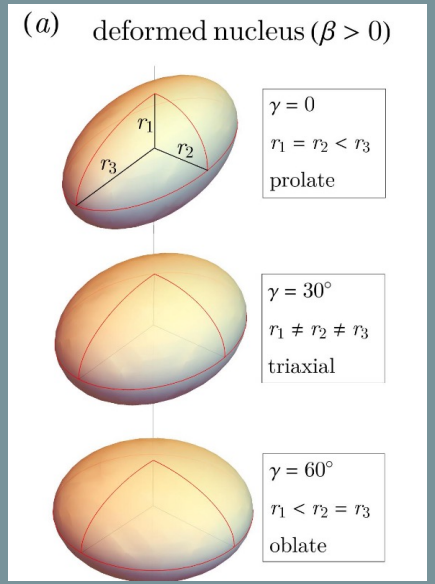
- Nuclei exhibit complex shapes even in their ground states (prolate, oblate, triaxial, **α**-clustering…)

- Heavy ion collisions offer several advantages with respect to coventional low energy nuclear experiments:
  - Access to short timescales and therefore direct access to the *instantaneous* shape of the nucleus
  - Better sensitivity to triaxiality and to **α**-clustering

- ENS@LHCb : perform nuclear imaging via anisotropic flow and photoproduction measurements, over a wide energy range (from fixed target to collider energy)

- Transdisciplinary project with applications to several fields: neutrinoless double beta decay, EDM searches, astrophysics and nucleosynthesis, nuclear fission…

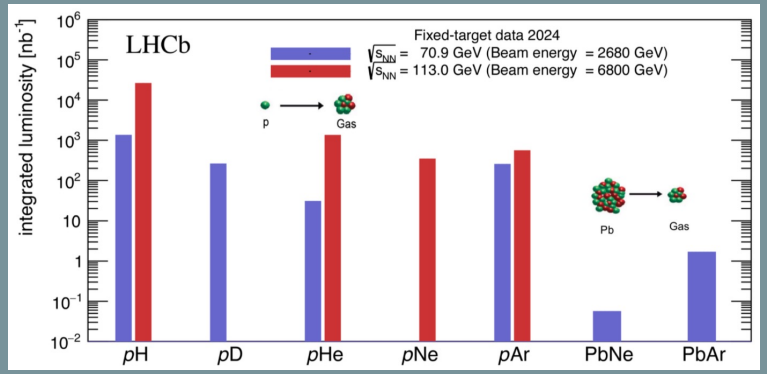
$$R(\theta,\varphi) = R_0\left\{1+\beta\left[\cos\gamma Y_{20}(\theta,\varphi)+\sin\gamma Y_{22}(\theta,\varphi)\right]\right\}$$



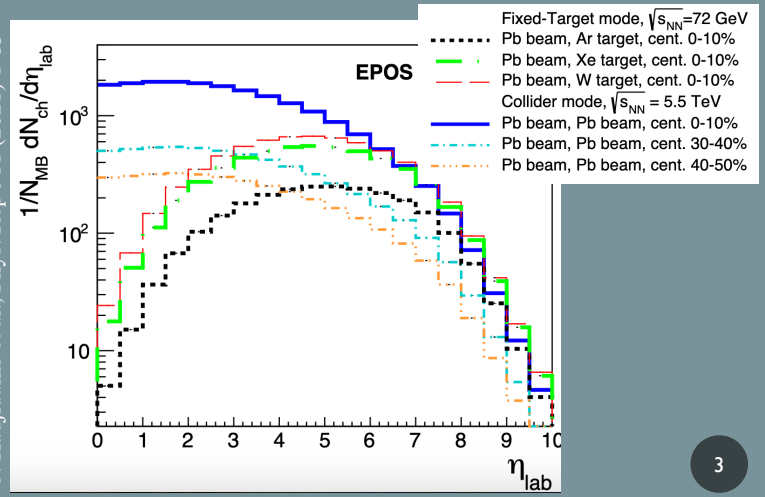
B. Bally et al, Phys. Rev. Lett. 128, 082301 (2022)

LHCb detector strength to conduct the research objectives

- Wide energy range from ~ 70 GeV (fixed target AA) to 5.3 TeV (collider AA) probed with the same apparatus
- Versatility of the probed nuclei thanks to SMOG2 gas injection system already demonstrated (He, Ne, Ar). Other gas types to be explored (O, N, Kr, Xe). Also OO and NeNe collider runs in 2025
- Large integrated luminosity in fixed target thanks to the LHC beams (~ 3 nb^{-1} PbAr in 2024) --> higher order flow coefficients
- Improved centrality reach in Run 3 allows to reach central collisions in heavy nuclei fixed target collisions
- Excellent p_T-resolution for photoproduction measurements
- Brings interest from low energy nuclear community to LHCb/CERN. Develop the SMOG2 potential : study the feasibility for purified gas injection in order to isolate isotopes of interest



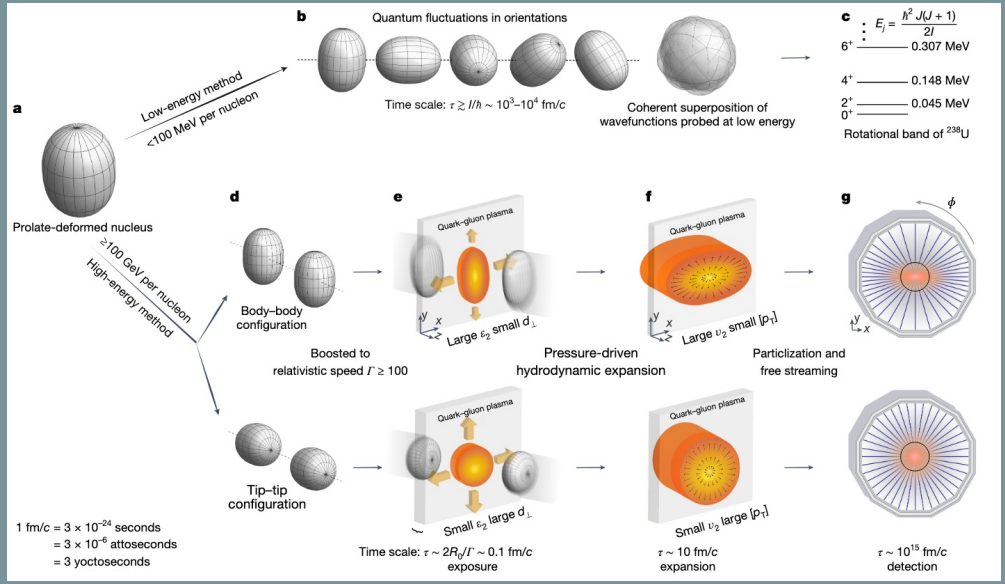
T. Boettcher, Quark Matter 2025



C. Hadjidakis et al., Phys. Rep 911 (2021) 1-83

Nuclear imaging via anisotropic flow measurements in HI collisions

- 2 nuclei collide with non-zero b → spatial anisotropy in the overlap region → pressure gradients
- If QGP is formed → hydrodynamical expansion converts spatial anisotropy in momentum anisotropy. Anisotropic flow measured through Fourier coefficients (v_N)
- Final state anisotropic flow carries memories of the initial shape of the interaction zone



STAR Collaboration, Nature 635 (2024) 67-72

- In central collisions → no initial spatial anisotropy for spheric nuclei, more sensitivity to nuclear deformation
- Small nuclear deformation leads to sizeable v_N thanks to collective hydrodynamics response
- Different harmonics (v_2, v_3…) probe different aspects of deformation (quadrupole, octupole…)
- Triaxiality becomes accessible by studying the interplay between anisotropic and radial flow (v_N-$\langle p_T \rangle$)

Nuclear imaging via vector meson (VM) photoproduction measurements in ultra-peripheral HI collisions

- Coherent vector meson photoproduction:
  - Photon couples to the full nucleus
  - Sensitivity to global nuclear structure
  - |t|-differential VM photoproduction cross section affected by nuclear deformation at large |t|

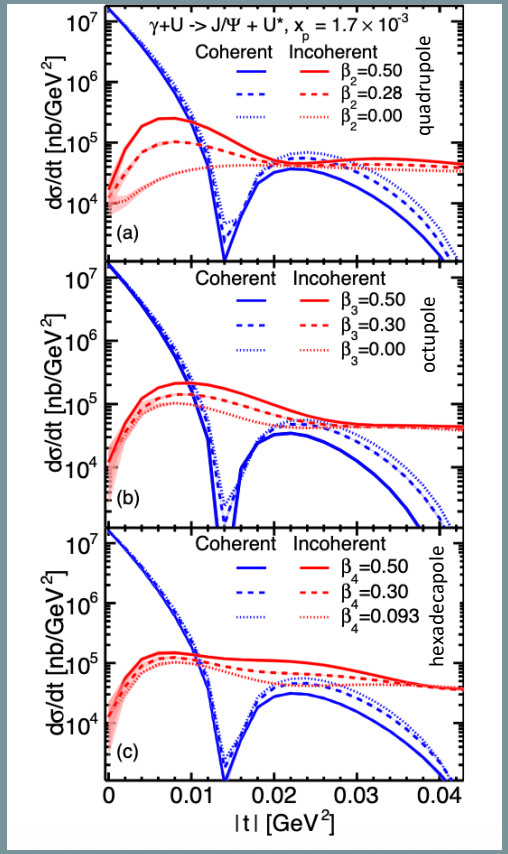
- Incoherent vector meson photoproduction:
  - Photon couples to individual nucleons
  - Sensitivity to nucleon level or sub-nucleonic fluctuations, but can still carry information on nuclear deformation
  - Incoherent cross section increases with increasing degree of deformation
  - Different types of deformation manifest in different |t| regions

- Study feasible for light VM in fixed target mode and light+heavy VM in collider mode

Final state	Pb-Ar
$\rho^0 \to \pi^+\pi^-$	42.50 (24.50) mb
$\omega \to \pi^+\pi^-$	76.32 (46.21) μb
$J/\psi \to \mu^+\mu^-$	88.67 (39.68) nb

V. C. Gonçalves et al., EPJC 78 (2018) 693

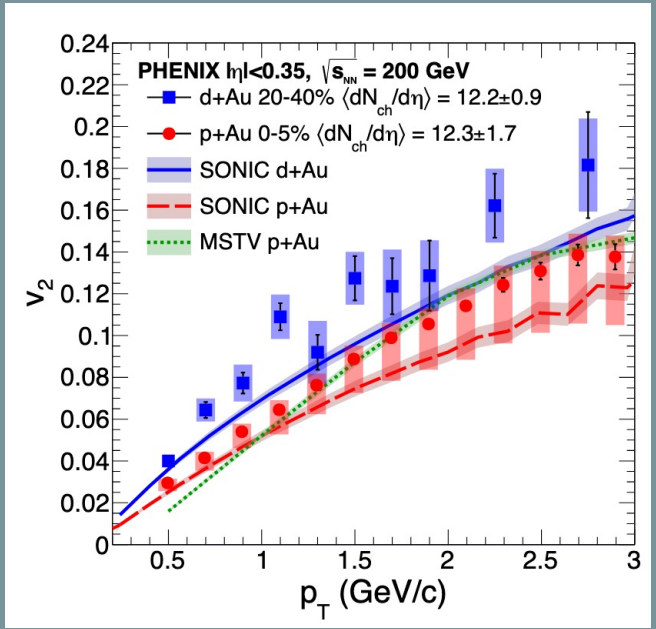
Calculations for EIC



H. Mäntysaari et al., Phys. Rev. Lett. 131 (2023) 062301

Exploring nuclear matter with fixed target and collider mode at LHCb

- Anisotropic flow observable also a well established probes of QGP
- Scan the onset of QGP formation (and initial state effects) with intermediate size nuclei and asymmetric systems (PbNe, PbAr, PbO) at low energy ~ 70 GeV
- Benefit from the large pA SMOG2 datasets (pHe, pD, pNe, pAr) to investigate momentum anisotropies in small systems. Complementarity with RHIC (scan over different nuclear target sizes, access to high order flow coefficients). Also scan as a function of energy with recently collected pO data in collider mode: https://home.cern/news/news/accelerators/first-ever-collisions-oxygen-lhc

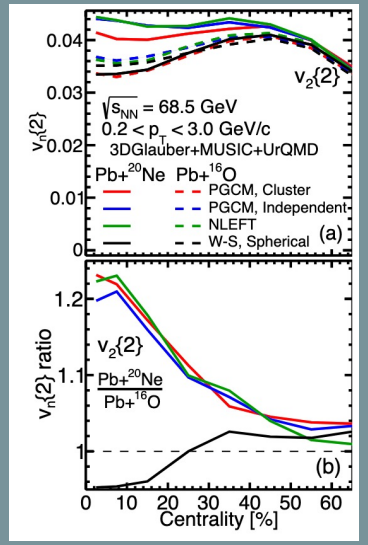


PHENIX Collaboration, Nature Physics 15 (2019) 214-220

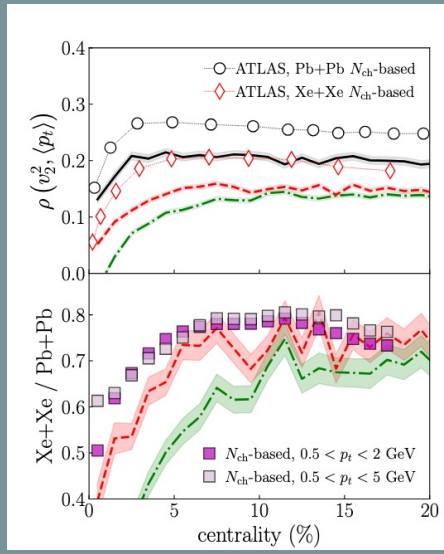
Connection to theory

- Project fostering experimentalists (LHCb, low energy nuclear physics) and theorists from both fields to confront the results with models
- Initial geometry of the collision obtained from nuclear wave function using state-of-the-art ab initio nuclear structure calculations based on microscopic Hamiltonians derived through chiral effective field theory. Coupled with 3D+1 hydrodynamic evolution
- Nuclear densities from ab initio calculations showing clear deformation and clustering patterns
- Predictions for v_n-$\langle p_T \rangle$ correlations to probe triaxial nuclear deformation
- Link with VA NLOACCESS (inclusion of STARLIGHT MC used in photoproduction studies)

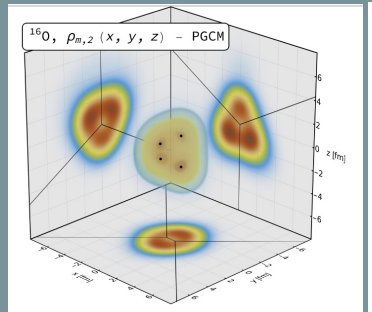
G. Giacalone et al., Phys. Rev. Lett. 134, 082301 (2025)

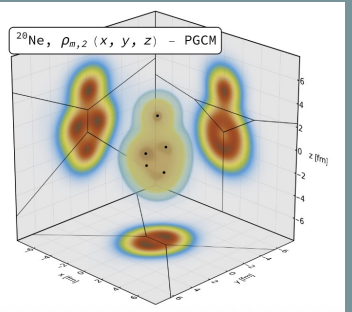


B. Bally et al, Phys. Rev. Lett. 128, 082301 (2022)



G. Giacalone et al., arXiv 2402.05995





Budget request and project members

- 8 participating laboratories
- Hiring of 2 postdocs (IJCLab, INFN Firenze) foreseen to lead the analyses inside LHCb
- Travel money for the members of the project (internal meetings, discussions at CERN with vacuum team for feasibility of gas purification, workshop organization, conference)

Laboratory	Usage	Cost
IJCLab	Postdoctoral researcher (2y)	**134 k€***
INFN Firenze	Postdoctoral researcher (2y)	110 k€
All	Travels	40 k€
		284 k€* (without overhead)

Laboratory	Involved researchers
IJCLab	L. Massacrier, F. Fabiano, D. Verney, F. Ibrahim
INFN Firenze	G. Graziani
IPhT	J-Y Ollitrault
CERN	G. Giacalone, S. Mariani
SUBATECH	G. Martinez
DPhN	T. Duguet, V. Soma
TU Darmstadt	B. Bally
IGFAE Santiago de Compostella	**O. Garcia-Montero***

*** Updates since LOI written proposals (new members, update of costs from DR4 taking into account inflation)**

Conclusions

- ENS@LHCb can make a significant impact on nuclear structure searches with a wide variety of applications outside the hadronic physics field (BSM, nucleosynthesis, fission)
- Transdisciplinary project that fosters low energy nuclear community, LHC collider/fixed target community and theorists. Connexion with existing VA proposal NLOACCESS.
- Collaboration with low-energy nuclear physicists will enable the generation of new, state-of-the-art ab initio calculations which will be directly used to interpret flow data, maximizing the scientific output of the collider and fixed-target runs
- Enlarge the LHCb physics potential, making LHCb a nuclear-physics frontier experiment. Exploit the full potential of the SMOG2 programme, exploring the feasibility of the usage of purified gas with isotopic separation.