ENS@LHCb: Exploring nuclear structure and matter with fixed target and collider mode at LHCb - PI: Laure Massacrier (IJCLab)

1. Research objectives

While high energy heavy-ion collisions are well-known tools to explore the phase diagram of strong-interaction matter, they have recently triggered additional interest from the low energy nuclear physics community. In particular, high energy heavy-ion collisions can be used to perform nuclear-shape imaging, via new methods permitting to overcome some limitations of low-energy nuclear physics experiments. Indeed, atomic nuclei are complex systems that manifest, in particular, a variety of shapes, even in their ground states. In low-energy nuclear structure experiments, one does not resolve the *instantaneous* shape of the nucleus, which is typically probed via electromagnetic interactions that are slower than the internal nuclear dynamics. On the other hand, the time scale of a high energy heavy-ion collision is orders of magnitude faster than that. The nuclear shapes are, thus, imprinted onto the geometry of the matter formed in the interaction region, and can be determined by analyzing the collision debris via collective flow measurements (as demonstrated by STAR for Uranium nuclei [1], see also predictions for LHCb [2]). Investigation of nuclear shapes across the Segrè chart has a wide variety of applications in several fields such as nucleosynthesis, nuclear fission and the search for new physics beyond the standard model through precision experiments (e.g., detecting the neutrinoless double beta decay or a permanent atomic electric dipole moment). The LHCb experiment is uniquely suited to perform a scan of the nuclear structure of several nuclei, and across energy scales, in fixed target and collider mode. Thanks to its system for measuring overlap with gas (SMOG2 [3]), anisotropic flow measurements can be conducted in LHCb with the already collected PbNe (L_{int}~$0.055nb^{-1}$) and PbAr (L_{int}~$1.7nb^{-1}$) data. In addition, the versatility of the gas injection system might allow us to investigate other nuclei types such as O, N, Kr, Xe. The usage of purified gas samples in order to isolate isotopes of interest will be investigated, in order to ease the interpretation of the results. In particular, there exists many stable or long-lived xenon isotopes with an expected transition from deformed to spherical ground states with an increasing number of constituent neutrons. Also, high-energy collisions represent an original avenue to identify and study the alpha-clustering phenomenon in light nuclei such as oxygen-16. In collider mode, studies can be conducted for PbPb collisions, but also with the short OO and NeNe runs foreseen by the LHC for 2025. The NeNe run would be of particular interest as Ne can be injected as well in SMOG2 for fixed target physics, permitting to perform two studies with the same setup at two different energies (ranging from ~70 GeV to ~ 5.36 TeV) for the same nuclei.

With this project we will foster experimentalists from LHCb, from the low energy nuclear community, and theorists from both fields, in a joint theory-experiment collaboration with the primary goal of measuring and characterizing the collective flow of this variety of collision systems by means of established multi-particle correlations techniques used in high-energy heavy-ion collisions. As mentioned, measurements of anisotropic flow (v_n coefficients) and of the radial flow (average transverse momentum, $<p_T>$) of the soft particles produced in nuclear collisions have a dramatic sensitivity to the shape of the collided nuclei, most notably on their axial quadrupole, octupole, and hexadecapole deformations, as well as potential nucleon clustering phenomena. In addition, the study of the interplay between radial and anisotropic flow, experimentally accessible via v_n^2-$\langle p_T \rangle$ correlations, sheds light on even more complex features of the nuclear wavefunctions, including especially the so-called triaxiality of the ground states [4], which is difficult to access in low-energy nuclear experiments. In order to facilitate the high-energy simulations and the interpretation of experimental results, the initial geometry of the collisions will be obtained from the nuclear wave functions obtained in state-of-the-art *ab initio* nuclear structure calculations based on microscopic Hamiltonians derived through chiral effective field theory as in Ref. [2].

It is worth mentioning that anisotropic flow measurements are also well-established probes of the Quark Gluon Plasma (QGP), a hot deconfined phase of nuclear matter. Beyond their role in exploring nuclear structure, these measurements in both asymmetric AA and pA collisions offer valuable insights into QGP formation and collective behavior in small systems. Studies at 70 GeV, using intermediate-size systems such as PbNe, PbAr, PbO, permit to scan the onset of QGP formation (energy density, volume, temperature..), while leveraging the unique geometry of asymmetric collisions to enhance sensitivity to initial-state effects and collective phenomena. The large pA datasets (pH, pD, pHe, pAr) collected with SMOG2 at 90 and 113 GeV allow one to investigate momentum anisotropies in small systems, where QGP formation is in principle not expected. Together, these measurements complement results from RHIC and benefit from the higher luminosities available at the LHC (scans over different nuclear target sizes, access to higher order flow coefficients). The interpretation of data from the asymmetric collision configuration probed by SMOG2 requires comparisons with fully-fledged 3+1D hydrodynamic simulations. This offers a unique opportunity to shed light on longitudinal structure of the initial condition of heavy-ion collisions which remains at present largely unexplored.

Another way to probe nuclear structure is via exclusive vector meson photoproduction measurements in ultra-peripheral AA collisions. While such probes are already extensively used due to their interest in the study of cold nuclear matter effects, eg. the modification of the gluon distributions in nuclei, they can also provide a multi-scale imaging of the deformation of the nuclei. Ref. [5] demonstrates that, in particular, the $|t|$-differential[1] cross section of incoherent vector meson photoproduction is sensitive to nuclear deformation at low $|t|$ and to nucleon and subnucleon-size scales at higher $|t|$. The feasibility of vector meson photoproduction measurements with SMOG2 data has been explored in Ref. [6] and shows that light vector meson (rho, omega) measurements should be at reach with PbAr ultra-peripheral fixed target collisions, and possibly the J/psi (~ 250 expected candidates for L_{int} ~3 nb^{-1}).

References:

[1]: STAR Collaboration, Nature 635, 67-72 (2024)

[2]: G. Giacalone et al., Phys. Rev. Lett. 134, 082301

[3]: LHCb Collaboration, Phys. Rev Accel. Beams 27, 111001

[4]: B. Bally et al, Phys. Rev. Lett. 128, 082301 (2022)

[5]: H. Mantysaari et al., PRL 131, 062301

[6]: V. P. Gonçalves et al., Eur. Phys. J. C (2018) 78

Notes:

1. *t* is the mandelstam variable encoding the momentum transfer between the incoming and outcoming nuclei

2. Connection to Transnational Access infrastructures (TAs) and / or Virtual Access projects (VAs)

This project is connected to the successor of "NLOAccess" VA from STRONG2020 (https://nloaccess.in2p3.fr/) which foresees the implementation of the Starlight Monte Carlo generator inside the VA in the context of this call. Such MC generator is of a direct interest for the photoproduction measurements related to this proposal.

3. Estimated budget request

The total request for the project amounts to 263000€, and will be used to hire a 2y postdoc in the LHCb group of IJCLab with experience below 2 years after PhD (113000€), a 2y postdoc in the LHCb group of Florence (110000€), some travel money for exchanges among the WP members and for allowing the postdocs to present their results in international conferences (40000 euros). The postdoc hired at IJCLab will focus on the analysis of anisotropic flow measurements in collider Pb-Pb, O-O, Ne-Ne collisions, and on the analysis of light vector meson photoproduction in ultra-peripheral collisions. The postdoc hired at the INFN Firenze will be dedicated to the analysis of anisotropic flow measurements with SMOG2 data in PbA and pA fixed target collisions.

4. Participating and partner institutions

IJCLab (PHE pole and Nuclear physics pole): D. Verney, F. Ibrahim, L. Massacrier, F. Fabiano
IPhT: J-Y Ollitrault
CERN (Theory and Exp): G. Giacalone, S. Mariani
SUBATECH: G. Martinez
INFN Firenze: G. Graziani
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TU Darmstadt: B. Bally