Nuclear Modification Factor of light charged hadrons and quarkonia in p-O, O-O, Ne-Ne and Pb-Pb collisions at LHCb (R$_{AA}$LHCb)

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The activities of the LHCb collaboration have significantly expanded beyond its original core objectives. Initially designed for precision heavy-flavor physics, the exceptional performance of the detector has enabled the experiment to contribute meaningfully to a wide range of research areas, effectively transforming it into a general-purpose detector in the forward region. In fact, some characteristics of the experiment, as its coverage forward region, the precise vertexing and tracking and the particle identification with full reconstruction of hadronic decays of charm or beauty, have permitted the use of the LHCb detector for the study of collisions with heavy ions (HI), either proton-lead (p-Pb) collisions, SMOG fixed target proton ion (He, Ne and Ar) collisions and, lately, lead-lead (Pb-Pb) collisions.

Beam configurations for ion-ion collisions began in 2015 at LHCb, both Pb-fixed target and peripheral Pb-Pb collisions. However, it is only recently, following the completion of the upgraded LHCb spectrometer in 2022, that the physics program has been expanded to include more central Pb-Pb collisions. Data collection with other beam configurations, such as p-O, O-O and Ne-Ne is also planned. A document compiling this program can be found in [4].

Three institutions are participating in this project: Instituto Galego de Física de Altas Enerxías at the Universidade de Santiago de Compostela (IGFAE-USC), Università degli Studi di Cagliari (UC) and the Quark Gluon Plasma Laboratory of the Commissariat à l'Énergie Atomique et aux Énergies Paris-Saclay (CEA). For some years the proponents, affiliated with these institutes, have closely collaborated within the Ion and Fixed Target (IFT) Working Group at the LHCb experiment.

1 Research objectives

LHCb has a large potential to probe and characterize the initial state of heavy-ion collisions, both in the low-x frontier of QCD, accessible in the forward-rapidity region for the collider mode, and in the high-x region accessible in the fixed-target mode. In ion-ion collisions the Quark Gluon Plasma (QGP) is supposed to be formed and the produced particles are affected by the hot medium in different ways. The hydrodynamic expansion of the QGP influences light particles the most, while the high temperature prevents heavy quarks from hadronizing into quarkonia. A quantity used to evaluate these effects is the nuclear modification factor, R_{AA}, defined as the ratio of the production cross section of a certain particle measured in heavy-ion collisions to the one measured in proton-proton collisions, scaled by the number of protons in the colliding nuclei. Deviations from unity in R_{AA} may indicate the presence of QGP.

However, different Cold Nuclear Matter effects (CNM), such as gluon saturation, initial-state energy loss and Cronin effect, could be the source of correlations among the nucleons producing competing effects with QGP signatures. A way to evaluate CNM contributions is to study collisions where QGP is not expected to form, like proton-nucleus collisions, and measure the relative nuclear modification factor R_{pA}. Thus, determining R_{pA} and R_{AA} across different nuclei is crucial for disentangling CNM effects from genuine QGP signatures in heavy-ion collisions.

The LHCb collaboration has produced results that study the relevant quantities to understand CNM effects. For instance, the determination of the nuclear modification factor R_{pPb} in proton-Lead collisions with quarkonia and charged particles and flow measurements at several center-of-mass energies [3, 1, 2]. The members of the Research Team were the proponents of these analyses. A new result reporting the measurement of R_{pPb} for protons and charged pions and kaons at $\sqrt{s_{NN}} = 5$ TeV is to be published soon.

Experience shows that the data analyses for determining R_{pA} and R_{AA}, particularly if particle identification is needed, are complex and in average take more than five years for completion. Despite the IFT Working Group at LHCb having increased its human-power, these analyses are carried by small groups. **The proponents of this project are persuaded that resources are essential to accelerate the availability of experimental results. This will have a remarkable impact in the possibilities to contrast theory predictions with very precise measurements**.

The goal of this project is to determine the nuclear modification factor for charged particles, identified light hadrons and quarkonia in p-Pb, p-O, O-O, Ne-Ne and Pb-Pb collisions studying the data taken by the LHCb experiment. The O-O, Ne-Ne and p-O datasets to be studied have been requested by the theory and experimental heavy-ion community to the CERN committees, that has approved these special runs. Thus, it is crucial to have available human-power to analyze them.

The study of the p-O system will complete the ongoing analysis of p-Pb events permitting to distinguish CNM effects from genuine QGP signatures. In fact, depending on which value of the ratio is found, this could clearly indicate the very nature of the hot medium, or of the dominant cold matter mechanisms. For instance, R_{pA} values less than unity may establish the presence of gluon saturation (CGC). Comparing R_{AA} across different nuclei (O-O, Ne-Ne and Pb-Pb) will probe QGP effects vs. the size of the medium by measuring suppression of high-p_T particles from Energy Loss. The larger nuclei (Pb-Pb) imply a longer path length and a stronger suppression, which would result in $R_{AA} \ll 1$. On the contrary, in the smaller nuclei (Ne-Ne, O-O), the weaker suppression will help isolate size effects. The ion-ion analyses will also allow to understand centrality and system size dependence. The Ne-Ne (bowling pin), O-O (tetrahedral) and Pb-Pb shapes would test geometric scaling of the physical processes.

2 Connection to Transnational Access infrastructures (TAs)

This project is structured around the LHCb collaboration, which is one of the four LHC main experiments at CERN, the European Laboratory of Particle Physics. CERN and its LHC collaborations are a pillar of the European hadron physics landscape. The LHCb experiment supports a broad user community by enabling access to cutting-edge experimental data, fostering scientific excellence and innovation. This project will build upon CERN strategy ensuring sustained and enhanced availability of key infrastructure capabilities to the European research community in full alignment with Horizon Europe's strategic objectives.

3 Estimated budget request

The project requires funds for two years of three postdoctoral Research Associate (RA) and four years of PhD student salaries for two PhD students, one to be based at IGFAE-USC, the other at UC. A co-supervision of the PhD students with the CEA researchers is planned. The total funds requested are 568 thousand euros, as detailed in Table 1.

Year of contract	1^{st}	2^{nd}	3^{rd}	4^{th}	Total
Postdoc salary IGFAE-USC	55	55	-	-	110
Postdoc salary UC	53	53	-	-	106
Postdoc salary CEA	75	75	-	-	150
PhD student salary IGFAE-USC	26	26	27	33	112
PhD student salary UC	30	30	30	-	90
Total	568 k€.				

Table 1: Funds requested in k€.

4 Participating and partner institutions

The team will be composed of:

- IGFAE-USC: Prof. Cibrán Santamarina Ríos, Prof. Abraham Gallas Torreira, Prof. Juan José Saborido Silva, Dr. Samuel Belin.
- UC: Prof. Giulia Manca, Prof. Rudolf G.C. Oldeman, Dr. Camilla De Angelis.
- CEA: Dr. Benjamin Audurier, Dr. Imanol Corredoira.

Partnerships will be established with other LHCb institutes participating in the IFT Working Group. Particularly with the Laboratoire Leprince-Ringuet (LLR) and CERN groups.

References

[1] R. Aaij et al. "Rapidity and multiplicity dependence of charged-particle flow in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV". In: (May 2025). arXiv: 2505.09273 [nucl-ex].

[2] Roel Aaij et al. "Measurement of the Nuclear Modification Factor and Prompt Charged Particle Production in $p - Pb$ and pp Collisions at $\sqrt{s_{NN}}$=5 TeV". In: *Phys. Rev. Lett.* 128.14 (2022), p. 142004. arXiv: 2108.13115 [hep-ex].

[3] Roel Aaij et al. "Study of Υ production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV". In: *JHEP* 11 (2018). [Erratum: JHEP 02, 093 (2020)], p. 194. DOI: 10.1007/JHEP11(2018)194. arXiv: 1810.07655 [hep-ex].

[4] Vincenzo Vagnoni. "Heavy ion physics at LHCb Upgrade II". In: (Mar. 2025). arXiv: 2503.23093 [hep-ex].