FIXED-CHARM

FIXED-target exploration of **CHARM**onium and charm mesons production

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1. Research objectives

Scientific context: The LHCb experiment, designed for flavor physics in proton-proton collisions, has broadened its scope to include Quantum Chromodynamics **(**QCD) studies in heavy-ion collisions. Its fixed-target program, enabled by the injection of gas targets into the beam line, provides unique access to proton-nucleus and Pb-nucleus collisions at intermediate center-of-mass energies, typically around $\sqrt{s_{NN}} \sim 72$ GeV, and a large center-of-mass rapidity range $-2.5 < y^* < 0.5$, that are otherwise inaccessible at the LHC. This configuration is particularly well-suited for studying the production and hadronization of charm quarks, which are valuable probes of QCD and especially of the quark-gluon plasma (QGP, the deconfined state of matter). Due to their large mass, charm quarks are produced exclusively in the initial hard scatterings of the collision and cannot be generated thermally within the QGP. As such, they traverse the full evolution of the medium and retain information about its early-time conditions, energy density, and transport properties. Their hadronization into mesons or baryons encodes information about the structure and dynamics of the medium. This makes **charm quarks a robust probe of QCD**.

Charmonium measurements: The $\sqrt{s_{NN}} \sim 72$ GeV energy regime offers a unique opportunity as typically only one $\boldsymbol{c\bar{c}}$ pair is produced per collision, even in the most violent Pb-Pb interactions. This makes it ideal for a decisive test of the long-standing sequential suppression scenario for quarkonium states, originally proposed four decades ago. Sequential suppression refers to the dissociation of charmonium ($\boldsymbol{c\bar{c}}$) bound states in a deconfined medium when the temperature exceeds their respective binding energies. Because excited states are more weakly bound than the ground state, they are expected to dissociate at lower temperatures. Furthermore, the excited states, $\psi(2S)$ and χ_c, decay into J/ψ. Their suppression therefore reduces the observed J/ψ yield, leading to a sequential pattern. Suppression of ψ(2S) at moderate temperatures can lower the J/ψ yield by about 10%, while additional suppression of the χ_c at higher temperatures may cause a further ~30% reduction. Notably, χ_c suppression has never been directly measured, due to the experimental challenges of reconstructing this state. Thanks to the excellent LHCb performances, based on up-to-date detector technologies, χ_c measurement is now accessible. Moreover, in high-energy collisions at RHIC or in the LHC collider mode, multiple $\boldsymbol{c\bar{c}}$ pairs are produced per event and statistical recombination becomes significant, complicating the interpretation of suppression signals. **The LHCb fixed-target program, thanks to its energy regime (only one $c\bar{c}$ pair produced in AA collisions) offers an unique opportunity to unambiguously test the sequential suppression, also providing a baseline for quantifying the recombination mechanism.**

Open charm measurements: The LHCb fixed-target program offers an exceptional opportunity to study open charm hadronization, a process sensitive to the surrounding medium, particularly when comparing the production of excited states (such as D^{*+}) to ground states (like D^0). By exploring charm hadron production across various collision systems, LHCb enables critical insights into hadronization mechanisms such as fragmentation and coalescence. Its configuration allows precise comparisons between proton–nucleus and nucleus–nucleus interactions, supported by excellent particle identification and vertexing. Additionally, the forward rapidity coverage (2 < y < 5), combined with the fixed-target boost, shifts the accessible Bjorken-x range to ~0.01–0.4 probing the valence quark region typically inaccessible in collider mode. This makes **charm production in fixed-target mode a powerful probe of non-perturbative QCD and an ideal testing ground for hadronization models**.

LHCb fixed-target at LHC Run 3 and 4: During Run 2, the LLR team demonstrated the feasibility of fixed-target studies at LHCb, thanks to SMOG system, but faced key limitations: low gas pressure restricted luminosity; SMOG location at the nominal interaction point limited operation to dedicated periods; and only noble gases could be injected, excluding hydrogen references. These issues have been resolved with the upgraded SMOG2 system, deployed for Runs 3 and 4. SMOG2 features a high-density gas target upstream of the nominal collision point, enabling concurrent fixed-target and proton–proton data taking. Crucially, it supports hydrogen injection, allowing for essential proton–proton reference measurements to study nuclear modification effects. These improvements make LHCb uniquely capable of a high-luminosity, multi-species fixed-target program. Notably, the PbAr dataset collected in Run 3 opens the door to **unprecedented studies of charm production and quarkonium behavior in a dense medium.**

__**Expected outcomes:**__ The project, based on the **recruitment of two postdoctoral fellows**, will deliver major scientific results. These include precise measurements of $\psi(2S)$ and J/ψ yields and the first observation of χ_c production in PbAr collisions, both leading to publications in high-impact journals and advancing our understanding of suppression mechanisms and feed-down contributions. The project will also provide the first determination of the D^{*+}/D^0 production ratio in a nuclear environment within this unique kinematic region, offering new insights into charm hadronization and medium-induced effects, and resulting in another high-level publication. On the technical side, the project will contribute to the optimization of trigger strategies for LHCb run 4.

All analysis tools will follow FAIR data principles and be openly shared to ensure full reproducibility and reuse by the broader scientific community. Results will be presented at leading international conferences and specialized workshops, encouraging in-depth discussions. These environments will foster cross-disciplinary exchange between experimentalists and theorists, and promote the broader dissemination of methods and insights developed within the LHCb fixed-target program.

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

The project is connected to the CERN/LHC infrastructures, both for data taking and data access. The LHCb/LLR group has been involved in the LHCb experiment since 2015 and played a key role in the early development of the fixed-target program. It notably contributed to the initial proposal submitted to the LHCb collaboration to enable data collection in ion collisions. Since then, the LLR team has analyzed several datasets, demonstrating both the feasibility and the scientific relevance of the fixed-target program at LHCb. Over the past decade, the group has completed and published five analyses[1], highlighting its sustained and active involvement. Members of the group have also held several responsibilities within the collaboration, including the operation of the SMOG target (gas injection) and the convenorships of the LHCb Ion and Fixed Target (IFT) Analysis working group.

3. Estimated budget request : 458 k€

The proposed research project involves **two complementary postdoctoral positions** aimed to fully exploiting the physics potential of the PbAr data collected during Run 3, while preparing for Run 4.

The first postdoctoral researcher will focus on analyzing the $\psi(2S)$ to J/ψ yield ratio in PbAr collisions, a key observable for studying final-state effects and suppression mechanisms. The researcher will also lead the first measurement of χ_c production in the fixed-target configuration, reconstructing χ_{c1} and χ_{c2} states through their radiative decays into J/ψ and a photon. This work will require advanced photon reconstruction techniques and precise background control, offering new constraints on feed-down contributions to charmonium production.

The second researcher will study excited charmed hadrons, focusing on the D^{*+}/D^0 production ratio in PbAr collisions as a probe of hadronization mechanisms in a nuclear medium. By comparing results with *p*H and *p*Ar collisions, the researcher will explore the interplay between medium effects and hadronization dynamics. They will also contribute to Run 4 preparations by optimizing trigger lines for fixed-target mode, working closely with LHCb software and DAQ teams to ensure readiness for future data-taking.

4. Participating and partner institutions

To support the result interpretation and strengthen ties with theory, the project will host regular virtual workshops with theorists and phenomenologists to discuss ongoing analyses, compare with model predictions, and explore joint publications. Dissemination and training will be enhanced through the co-organization and funding of international workshops that gather experimentalists and theorists from various collaborations.

Finally, the project will include dedicated funding to support short and medium-term research stays abroad, notably at CERN and institutions such as the Universidad de Santiago, to foster collaboration, access key resources, and ensure strong integration within the LHCb and fixed-target physics communities. A dedicated budget of €8,000 will support these activities.

[1] Phys. Rev. Lett. 122 (2019) 132002, Eur. Phys. J. C83 (2023) 541, Eur. Phys. J. C83 (2023) 625, Eur. Phys. J. C83 (2023) 658, JINST **17** P05009 (2022)