Letter of Intent:
Exploration of heavy hadrons at thresholds (ExHAT)

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1 Research objectives

Hadron spectroscopy, lead by experimental discoveries, has long been a driving force in the exploration of QCD. Recent LHC data, especially from LHCb, has established the leading place of exotic hadrons – states beyond conventional quark models – at the forefront of the research. The many intriguing results involve heavy-quark (c/b) exotics, often with small widths and masses near hadron-hadron thresholds. Prominent examples are $\chi_{c1}(3872)$ and $\mathrm{T}_{\mathrm{cc}}^{+}$ which mass almost coincide with D-meson pair thresholds. This proximity strongly suggests a significant role for molecular-type interactions in meson-meson or meson-baryon systems, analogous to the proton-neutron interaction within a deuteron. Characterizing these interactions across heavy quark systems is paramount for understanding hadron structure and nuclear forces. Our program focuses on this critical phenomenon, aiming to bridge these two neighboring but long separated fields together.

To achieve these goals, we propose to combine expertise from leading experimental collaborations, LHCb and ALICE at CERN, operating in distinct proton-proton and heavy-ion collision environments. Their diverse collision environments and analysis methodologies (exclusive analyses to statistical correlations) offer crucial complementarity. This program leverages existing Run-1/2 data and the ongoing Run-3 campaign, aligning with Run-4 preparations. The experimental effort is paired with leading theory groups (Lattice QCD, advanced quark models). Building on successful past ad-hoc collaborations, this initiative aims to establish a structured framework for joint experiment-theory efforts. Such a framework is designed to foster mutual guidance between experimental and theoretical activities, provide wide access for the theory community to experimental data, and empower their contributions to shaping the future experimental program.

MM: Meson-meson thresholds and charmed exotics

Among the many states known to have mass near meson-meson thresholds, it is the $\chi_{c1}(3872)$ and $\mathrm{T}_{\mathrm{cc}}^{+}$ exotic states which have the smallest natural widths. Therefore their study is pivotal for the program. The $\mathrm{T}_{\mathrm{cc}}^{+}$ is the most promising candidate to establish the interplay between loosely-bound molecular and compact diquark-antidiquark configurations, which is the central question of the field.

Our experimental plan includes a detailed amplitude analysis of $\mathrm{T}_{\mathrm{cc}}^{+} \to D^0 D^0 \pi^+$ by the LHCb to determine its quantum numbers, width, and probe for compact components. Concurrently, the LHCb and ALICE will measure relative $\mathrm{T}_{\mathrm{cc}}^{+}$ and $\chi_{c1}(3872)$ production cross-sections in pp and heavy-ion collisions, studying kinematic and environmental dependencies. The internals of the production mechanisms of exotic hadrons remains a mystery and its study in heavy ion collisions would be particularly insightful.

These experimental efforts will be critically supported by theoretical work deciphering these states' nature and the role of hadron-hadron continuum. A comprehensive range of theoretical tools will be used, prominently Lattice QCD (diverse methods like potential approaches at the physical quark masses, coupled-channel approaches, innovative mixed techniques), complemented by EFTs, quark models, and other computational frameworks. Key theoretical objectives include elucidating fine-tuning phenomena associated with light quark masses and the pion pole, identifying other potential manifestations of strong attraction near meson-meson thresholds, and computing experimentally inaccessible quantities such as $DD^{(*)}$ scattering amplitudes.

BB: Baryon-baryon thresholds and di-baryons

Searches for six-quark (hexaquark/di-baryon) states have a long history, originating with the discovery of the deuteron in 1931. Understanding of such systems is intrinsically linked to understanding of matter structure, long-range hadronic interactions, and the equation of state for neutron stars. While numerous di-baryon candidates near various thresholds are predicted, the $d^*(2380)$ resonance, located near the $\Delta\Delta$ threshold, remains the sole confirmed example. Experimental efforts, notably by ALICE, have provided comprehensive explorations of light di-baryon systems like pΩ, pΞ, and $\Lambda\Lambda$. Supported by Lattice QCD calculations, they indicate a presence of either bound or virtual states below some of the corresponding thresholds, though results are not yet conclusive.

Building upon this foundation, we propose to extend the search for di-baryons to systems with heavy quarks. Inclusion of heavy quarks is expected to simplify both experimental observation, by yielding clearer signatures, and theoretical interpretation, by enabling different class of computational methods. This potentially leads to a breakthrough, as happened with tetraquarks and pentaquarks. Experimentally, LHCb can identify resonances and states both stable against strong decay (e.g., via displaced vertices) and those decaying strongly, while ALICE can leverage heavy-ion collision data to study states above threshold, should their production be enhanced in medium.

Successfully navigating this largely uncharted territory requires a guidance from the theory community. Theory predictions for masses, widths and production mechanisms are the key elements for identifying the most important states for experimental exploration. In turn, continuous dialogue is crucial for benchmarking theoretical assumptions against experimental data. This synergistic interaction between experimentalists and theorists, facilitated by collaborative workshops, is central to the program's success.

MB: Meson-baryon thresholds and excited heavy baryons

Charm and bottom baryons, with their abundant excitation spectrum from numerous baryonic degrees of freedom, are particularly well-suited for studying hadronic threshold effects on quark model states. Meson-baryon dynamics near thresholds can induce molecular characteristics in nearby states, offering a test bench for theoretical approaches applicable to exotic hadrons. Moreover, heavy baryons (a heavy quark and a light diquark) offer an excellent framework for understanding the diquark system, its excitations, and interaction with a heavy core – be it a heavy quark in baryons or the remaining quarks in tetraquarks and pentaquarks.

A complete map of excited charm states is important for the Statistical Hadronization Model, used in the studies of the Quark-Gluon Plasma (QGP). Unaccounted-for states and interactions alter Boltzmann weights for Λ_c/Ξ_c yields, biasing extracted QGP parameters. Reducing this systematic uncertainty is a prerequisite for accurate QGP measurements with heavy-flavour observables. It is crucial to set up a collaboration between hadron spectroscopy and heavy-ion communities for linking charmed baryon studies to QGP physics.

LHCb's Run-1/2 data revealed a numerous new excited b/c-quark baryons, including Ω_c- and Σ_c-like states with anomalously small widths near meson-baryon thresholds. This program will address remaining gaps in their classification and understanding threshold effects. Workshops will unite the consortium to review experimental findings, Lattice QCD computations, and modeling expertise to advance hadronic matter understanding.

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

The LHC accelerator at CERN (ESFRI landmark) produces all the different types of heavy quark hadrons in quantities many times greater than in any other place. The LHCb experiment is the most suited detector for studying these hadrons, dominating the field for over 15 years. The ALICE experiment offers optimal capacity for detecting such hadrons in heavy-ion collisions, important for models predicting enhanced production. Analysis of LHCb and ALICE data is therefore key to accomplishing the proposed tasks.

Setting up a structured collaboration between the experiments and theory community, fostered by a series of topic-focused workshops, will empower the mutual guidance and create the synergy needed to drive the research.

3 Estimated budget request

- €360k to fund a PostDoc position for the duration of the program, shared between University of Manchester and Ruhr-University Bochum (2+2). We have preliminary agreement with the institutions that each of the positions will get supplementary local funds for another 12-18 months.
- €170k for travel: for 14 participants: approx. 2 trips/year (€500/trip) and 15 days/year stay (€135/day);
- €50k for workshops: five topic-focused 2-day workshops over four years;
- €10k for outreach and training.

Total: €590k.

4 Participating and partner institutions

The University of Manchester, United Kingdom – **Ivan Polyakov**; Institute of Experimental Physics I, Ruhr-Universitaet Bochum, Germany – **Mikhail Mikhasenko**; University of Genova, Italy – **Elisabetta Stadaro Norella**; INFN Sezione di Bari, Bari, Italy – **Marco Pappagallo**; Sapienza Universita e INFN, Roma I, Italy – **Ivan Belyaev**; Technical University of Munich, Germany - **Laura Fabbietti, Valentina Mantovani Sarti**; CERN, Switzerland - **Fabrizio Grosa**; University of Ljubljana, Slovenia – **Sasa Prelovsek**; RIKEN iTHEMS, Saitama, Japan – **Takumi Doi, Tetsuo Hatsuda**; University of Cambridge, United Kingdom – **Christopher Thomas, David Wilson**;