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Title of the research project :

Studies of heavy baryons at LHCb

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Code *(ex. UMR xxxx)* : UMR 7585

Doctorate School

Thesis supervisor’s doctorate school (candidate’s futur doctoral school) : STEP'UP

PhD student currently supervised by the thesis supervisor (number, year of the first inscription) :

Currently two students; will be one as of September 2022. Currently:
1) Thomas Grammatico (co-supervised at 50% with Eli Ben-Haim since Sep 2018, soutenance/defense ~ Jan 2022)
2) Renaud Amalric (co-supervised at 50% with Eli Ben-Haim since Sep 2021)

Studies of heavy baryons at LHCb

LHCb is one of the four large particle physics experiments at the Large Hadron Collider at CERN, the European Laboratory for Particle Physics. It was designed to carry out research into the properties of particles containing heavy quarks, known as heavy-flavour hadrons. During the previous decade, LHCb successfully recorded large samples of proton-proton collision data, accumulating $3\,\text{fb}^{-1}$ in 2011–2012 (Run 1) and $6\,\text{fb}^{-1}$ in 2015–2018 (Run 2). The LHCb collaboration, composed of over 1400 members including over 1000 physicists, used these data to make discoveries and produce world-leading publications in several areas of experimental particle physics, including spectroscopy, CP violation, and tests of the Standard Model (SM) with rare and forbidden decays. At the time of writing, LHCb is undergoing a major upgrade, which will enable it to resume data-taking at a higher rate in Run 3, starting in 2022. Thanks to the increased integrated luminosity and improvements in trigger efficiency, the data sample of hadronic decays available at the end of Run 3 will be larger by a factor of approximately 8.

This project concerns research into heavy-flavour baryons. It includes a number of thematically linked sub-projects, spanning both spectroscopy and tests of the SM. These focus on two families of baryons: Ξ_b states (quark content bsu or bsd), and Ξ_{cc} states (quark content ccu or ccd). The planned research includes both searches for new particles whose existence is predicted but not yet observed, and use of recently observed particles to probe the validity of the Standard Model of particle physics. By design, some of these sub-projects are certain to lead to a publication (though not necessarily a discovery/observation) when completed, while others are more speculative and depend on the properties and production rates of currently unobserved states. Each project builds on previous research carried out by the supervisor and by other LHCb members. In a 3-year thesis, it is expected that the student would complete **two** of these analyses, with the choice of topics to be agreed with the supervisor based on the student's research interests and progress. At least one of the topics publishable in the absence of a positive signal (analyses B and D below) should be included.

A. Spectroscopy of Ξ_{cc} states

In 2017, LHCb made the first observation of the ground state of the doubly charmed baryon Ξ_{cc}^{++} [1]; it is expected that the isospin partner state Ξ_{cc}^{+} will also be found at a similar mass, and the data already analysed contain a suggestive (but inconclusive) hint that this is the case [2].

These ground states should be accompanied by a spectrum of excitations. These are, at present, completely unexplored. A simple constituent quark model calculation indicates that the very lowest excitation, a spin-3/2 state, should be roughly 60–70 MeV above the ground state; this is below threshold for strong decay by pion emission, and the state will therefore decay electromagnetically: $\Xi_{cc}^{*} \to \Xi_{cc}\gamma$. While the production cross-section should be comparable to the ground state, this first excitation is more difficult to observe because of the need to reconstruct an additional photon. It is unlikely to be observable with the present Run 1–2, but with more data this will become more viable.

In addition to the first excitation, there should exist a number of higher (orbitally or radially excited) states. These will have lower production cross-sections, but should be above threshold for a strong decay, e.g. $\Xi_{cc}^{*+} \to \Xi_{cc}^{++}\pi^{-}$, which will have a better reconstruction efficiency than the photon mode mentioned above thanks to the presence of the charged track.

There are a number of analyses to be done in this area, in collaboration with institutes in China, the UK, and Italy. The student would contribute to one of these efforts, most likely the search for the electromagnetic decay. If new resonances are observed successfully, this would lead to a publication.

B. Searches for Cabibbo-suppressed Ξ_{cc} decays

Using the existing Run 1–2 data sample, LHCb has observed [1, 3] the Cabbibo-favoured (CF) decay processes $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$. In total, signal yields of approximately 1600 events and 600 events were obtained, with significances above 5σ.

CF decays such as these proceed via a $c \to sW(\bar{d}u)$ weak transition with a tree topology, introducing a factor of $V_{cs}V_{ud}^*$ into the decay amplitude, and therefore a factor of $|V_{cs}V_{ud}|^2 \approx \cos^4\theta_C \sim 0.9$ into the decay rate, where $\theta_C \approx 0.22\,\text{rad}$ is the Cabbibo angle. By contrast, singly Cabibbo-suppressed (SCS) decays such as $\Xi_{cc}^{++} \to \Lambda_c^+ \pi^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \to \Lambda_c^+ K^- K^+ \pi^+$ can proceed via $c \to dW(\bar{d}u)$ or $c \to sW(\bar{s}u)$ processes at tree level, which correspond to a factor of $\cos^2\theta_C \sin^2\theta_C$ in the decay rate, and are therefore suppressed relative to the CF decays by a factor of $\tan^2\theta_C \sim 0.05$ (leaving aside kinematic and phase-space factors). Because of this suppression, such SCS decays of Ξ_{cc} baryons had expected yields of only $\mathcal{O}(\text{few} \times 10^1)$ in the present Run 1–2 dataset and were not observable.

However, by the end of Run 3 with the upgraded LHCb detector, the yield is expected to increase to $\mathcal{O}(\text{few} \times 10^2)$. There is still a significant uncertainty: depending on the true cross-sections and particularly the branching fractions, the yields might still be too low to observe. However, there would be a good chance to observe and measure some of these suppressed decays. This analysis would need most or all of the Run 3 statistics, and would be carried out near the end of the student's Ph.D. It would lead to a publication with either measurements of or upper limits on the suppressed branching fractions.

Beyond simply observing new decay modes, such a measurement would be of interest because it opens the door, in future runs after a further upgrade to the LHCb detector, to measurements of the CP asymmetries in these decays[1]. Measurements of the asymmetries of SCS decays (as opposed to the more copious CF decays) are of particular interest because they can receive contributions not only from the tree topologies noted above (e.g. $c \to dW(\bar{d}u)$ but also penguin topologies (e.g. $c \to ug(d\bar{d})$), which carry different weak phases. The interference between these processes can lead to CP violation, measurable through decay rate asymmetries.

C. Search for $\Xi_b'^0$

The Ξ_b system consists of three quarks, bsq, where b is a heavy beauty quark, s is a strange quark, and q represents a light quark (u or d). Ξ_b states occur in closely linked isospin doublets, Ξ_b^- (bsd) and Ξ_b^0 (bsu). The quark model predicts that there should be three spin configurations of low-lying Ξ_b states, for a total of six distinct states: three Ξ_b^0 and three Ξ_b^-. At present, five of these six states have been observed experimentally, but the sixth, $\Xi_b'^0$, has never been discovered.

Usually, the two members of an isospin doublet of resonances share very similar properties, because they differ in mass only by a few MeV. However, the Ξ_b' doublet sits very close to the energy threshold for decays to the $\Xi_b\pi$ final state, as demonstrated by LHCb in its observation of the decay $\Xi_b'^- \to \Xi_b^0\pi^-$ [4]. Consequently, the small isospin mass differences (between $\Xi_b'^-$ and $\Xi_b'^0$, and between Ξ_b^0 and Ξ_b^-) could nonetheless be significant. This would naturally explain why the isospin partner decay $\Xi_b'^0 \to \Xi_b^-\pi^+$ was *not* been observed in searches by CMS and LHCb (even though the related, heavier state Ξ_b^{*0} was observed by both experiments in the $\Xi_b^-\pi^+$ final state). Under this assumption, the dominant decay mode of the $\Xi_b'^0$ would depend strongly on its mass. If slightly lighter than the $\Xi_b'^-$, it would decay predominantly strongly to $\Xi_b^0\pi^0$; if a little lighter, it would instead only be able to decay electromagnetically to $\Xi_b^0\gamma$.

The student would optimise and carry out searches for $\Xi_b'^0 \to \Xi_b^0\pi^0(\to \gamma\gamma)$ and $\Xi_b'^0 \to \Xi_b^0\gamma$ in the LHCb Run 3 dataset. Due to the presence of one or two soft photons in the final state, these decays are challenging to detect at LHCb and the present dataset (Run 1–2) does not have sufficient sensitivity. However, with the larger Run 3 dataset, there is an improved chance to discover this new particle, measure its mass, and test the hypothesis that the isospin splitting is responsible for the decay $\Xi_b'^0 \to \Xi_b^-\pi^+$ being forbidden. If new resonances are observed successfully, this would lead to a publication.

D. Search for baryon number violation through Ξ_b^0 oscillations

Baryon number violation (BNV) is one of the three Sakharov conditions necessary for formation of a matter-dominated universe. Conservation of baryon number is an accidental low-temperature symmetry of the Standard Model, and is expected to be violated in a more complete theory. Nonetheless, has never been observed experimentally, and stringent limits have been placed on BNV processes such as proton and bound neutron decay. These place strict limits on generic models of physics beyond the SM. However, models of new physics with nongeneric flavour interactions, coupling preferentially or exclusively to the second and third generations (e.g. six-fermion operators with strictly flavour-diagonal couplings), could evade these bounds. This might lead to BNV being observable in heavier baryons but not in light baryons. One particularly promising possibility is oscillations of the Ξ_b^0 (bsu) baryon, which is theoretically appealing because it contains exactly one quark from each generation (so that the six-fermion operator mentioned above could naturally generate $\Xi_b^0 \to \overline{\Xi}_b^0$ oscillations), and experimentally appealing because the resonance decays $\Xi_b^{*-} \to \Xi_b^0\pi^-$ and $\Xi_b'^- \to \Xi_b^0\pi^-$ discussed above cleanly and unambiguously tag the flavour of the Ξ_b^0 at production.

LHCb previously carried out a search for Ξ_b^0 oscillations with the Run 1 data alone, obtaining an upper limit of $0.08\,\text{ps}^{-1}$ on the oscillation angular frequency [5]. This limit can be improved significantly: adding the Run 2 data already available would improve the statistics by a factor of around five, and including part or all of Run 3 would increase this by a further factor. (The limit should improve faster than $1/\sqrt{N}$ and perhaps close to $1/N$, since the $\Xi_b'^-$ tag is essentially background-free.)

The student would update the analysis to include additional data, and would publish a paper with an improved upper limit.

[1]See, e.g., PRD 75:036008 (2007)

Role and background of the supervisor

The supervisor, Dr Matthew Charles, is a Maître de Conférences (HDR) at Sorbonne Université, an academic position roughly equivalent to an Associate Professor. He is based at the LPNHE laboratory in Paris. He has held positions of responsibility in LHCb, most recently as Physics Coordinator from 2018 to 2020, and previously as an Early Career, Gender and Diversity Officer, a member of the Editorial Board, and a physics working group convenor. His research experience includes spectroscopy, charm physics, CP violation and mixing, and heavy baryon oscillations. He has experience in each of the thesis sub-projects A–D listed above, having contributed directly to precursor analyses relevant to each (including [1, 4, 5, 6, 7]), often as a primary analyst[2]. Dr Charles would work directly with the student on the analyses concerned. At the time of writing, it is expected that he would be co-supervising one other student in parallel.

Profile of the student

The student will be attached to the LPNHE laboratory at Sorbonne Université in Paris, and will be a member of the LHCb collaboration. They will undertake a three-year Ph.D. course in experimental particle physics, supervised by Dr Charles and overseen by the STEP'UP doctoral school. This will include research in experimental particle physics, plus graduate lectures arranged through the doctoral school. They may be required to make regular trips to CERN in Geneva to meet with collaborators and participate in data-taking; this may include the possibility of a longer-term stay.

Candidates for this position should have, or be studying for, a Master's-level degree in high-energy/particle physics; successful completion of a Master's-level degree will be required before the Ph.D. begins. They should have an excellent grasp of particle physics and the Standard Model (appropriate to a graduate student), and in particular an understanding of heavy-flavour physics and hadron physics. The research will involve a significant component of data analysis in python and C++, and the candidate should be at ease in one or both of these languages. Previous experience in analysing particle physics data, or working on a particle physics experiment, will be an advantage.

References

[1] R. Aaij *et al.*, LHCb Collaboration, Observation of the doubly charmed baryon Ξ_{cc}^{++}, Phys.Rev.Lett. 119 (2017) 112001

[2] R. Aaij *et al.*, LHCb Collaboration, Search for the doubly charmed baryon Ξ_{cc}^{+}, Sci.China Phys.Mech.Astron. 63 (2020) 2, 221062

[3] R. Aaij *et al.*, LHCb Collaboration, First observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$, Phys.Rev.Lett. 121 (2018) 162002

[4] R. Aaij *et al.*, LHCb Collaboration, Observation of two new Ξ_b^- baryon resonances, Phys.Rev.Lett. 114 (2015) 062004

[5] R. Aaij *et al.*, LHCb Collaboration, Search for baryon-number-violating Ξ_b^0 oscillations, Phys.Rev.Lett. 119 (2017) 181807

[6] R. Aaij *et al.*, LHCb Collaboration, Measurement of the properties of the Ξ_b^{*0} baryon, JHEP 05 (2016) 161

[7] R. Aaij *et al.*, LHCb Collaboration, Search for the doubly charmed baryon Ξ_{cc}^{+}, JHEP 12 (2013) 090

[2]It is conventional in experimental particle physics for the author list to include all members of the collaboration, and at LHCb the authors are always listed in alphabetical order for physics analysis papers. For this reason, the first author is the same in each of the references.