Baryons with Charm

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- Project name/ID: Baryons with charm/charmbaryons

- HPC System: JUWELS-Booster (GPU)

Matter interacts through electromagnetic, weak, strong and gravitational forces. The former three form the Standard Model of Elementary Particle Physics. We know that this model, which in fact is a theory, is incomplete. Comparison between ever more precise theoretical predictions and experimental data will eventually enable the discovery of new, Beyond-the-Standard-Model physics. The underlying theory describing the strong force, quantum chromodynamics (QCD), requires to solve nonlinear, strongly interacting, relativistic multi-particle problems. This can only be carried out on supercomputers.

QCD describes the interaction of quarks within subatomic particles, including baryons, to which the proton and neutron also belong. There exist three light quarks in Nature, namely the up, down and strange quarks and three heavy quarks, the charm, the bottom and the top. Protons contain two up and one down quark.

Recently, at the Large Hadron Collider (LHC) at CERN and elsewhere, several new baryons have been discovered that are similar to the proton, replacing one or two of its light quarks by charm quarks. In this project we determined the masses of these new charmed baryons, to understand present data and to guide future experimental searches. This is the first step towards a calculation of the lifetimes or, more accurately, the weak decay rates, of charmed baryons.

The calculations posed several computational challenges. Spacetime is discretized on a four-dimensional grid (Lattice QCD). The computationally dominant part is spent on the inversion of large matrices with up to 2 billion times 2 billion complex entries. Such large sizes are particularly important when simulating the heavy charm quark, which requires very fine lattices since discretization effects depend on the product of the quark mass and the lattice spacing. Keeping the volume constant means that fine lattices contain very large numbers of points.

The problem parallelizes very well and the JUWELS-Booster architecture lend itself to the approach. The mass spectrum of baryons containing one or two charm quarks was computed. In figure 1 preliminary results for different singly charmed baryons are compared to the experimental discoveries (horizontal lines). In figure 2 preliminary predictions are made for the masses of doubly charmed baryons of which only one has been discovered to-date. We find the mass difference between the two lightest such baryons to be about 100 MeV. Therefore, a decay of the so-called Ξ^{*}_{cc} baryon into a Ξ_{cc} and a pion (mass 140 MeV) appears to be ruled out. This explains why the former particle has not been found as yet by the LHCb experiment, when searching for these potential (but impossible) decay products.

The results shown include extrapolations to the quark masses realized in nature and to vanishing lattice spacing, with combined uncertainties of the size needed by experimentalists. At present, these are being finalized, including data obtained at further lattice spacing and quark mass combinations, that were generated using additional computer resources.

Summary

Quantum chromodynamics (QCD) as part of the so-called Standard Model of Elementary Particle Physics addresses strong interactions between quarks in particles such as baryons containing three up, down, and/or strange quarks and recently observed baryons with charm quarks. The research focused on determining charmed baryon masses, where the main computational challenge involved matrix inversions with billions of entries. Predictions for masses of doubly charmed baryons are made, which explain why some of these particles have not been detected by experiment. The research outcomes will guide future experimental searches at the Large Hadron Collider and other facilities.

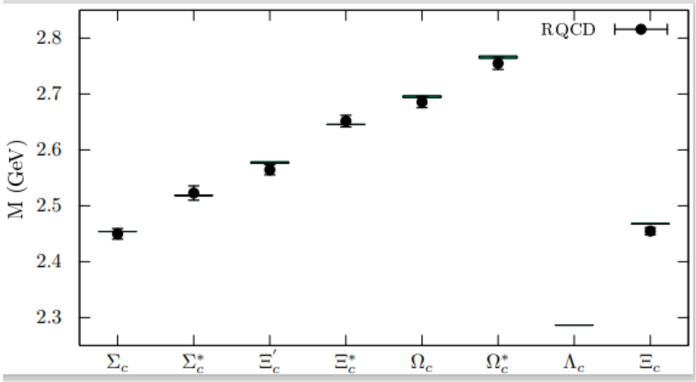

Figure 1: singly
RQCD predictions for the spectrum of singly charmed baryons. Horizontal lines indicate experimental results. The Λ_c was used as an input to adjust the charm quark mass to its physical value and is therefore not predicted.

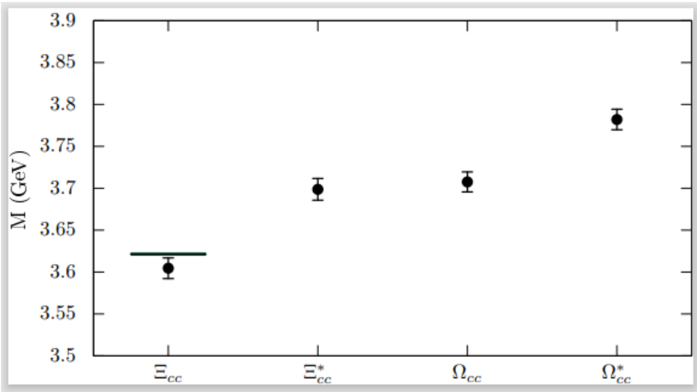

Figure 2: doubly
RQCD predictions for the spectrum of doubly charmed baryons.