HPQCD predictions for excited Bc states come up trumps!

Particles that are ‘excited’ bound states of a bottom quark and a charm antiquark have been discovered at the Large Hadron Collider and their masses are in agreement with predictions made by the HPQCD collaboration back in 2012. HPQCD used a numerical technique known as lattice QCD to solve the theory of the strong force, Quantum Chromodynamics. This enabled them to calculate the masses of several bound states of bottom and anticharm, each with the quarks in a different configuration, collectively known as the Bc mesons. The CMS and LHCb collaborations have both now reported in 2019 the first clear evidence for two members of this set called the Bc’ and Bc*’ mesons.

The lightest Bc meson, known simply as the Bc, has the bottom and anticharm quarks spinning in opposite directions so that its spin is zero. This is the lowest energy configuration for bottom-anticharm and simplest to calculate in lattice QCD. In 2005 HPQCD (with the Fermilab lattice collaboration) successfully predicted the mass of the Bc meson, ahead of its discovery by the CDF experiment at the Fermilab Tevatron collider. The large mass of this meson, 6.27 GeV/c^2 (where the proton mass is 0.94 GeV/c^2), along with its quark-antiquark content that meant a proton collider was needed to produce it, made it hard to find experimentally.

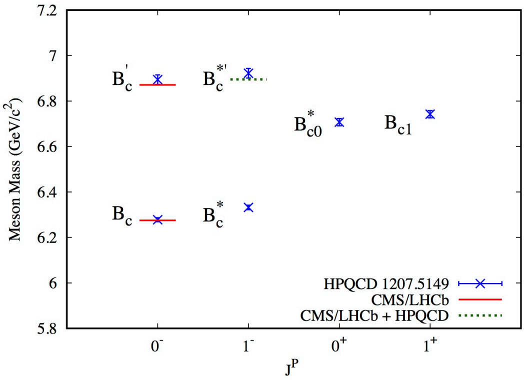

Figure 1. HPQCD’s predictions for the masses of the lightest states in the Bc family (J^P gives their spin and parity quantum numbers) of mesons (blue crosses) calculated on DiRAC. The experimental results for the two states that have been seen are shown as red lines (the experimental uncertainties are around 0.001 GeV/c^2). The green dashed line combines HPQCD results with CMS/LHCb results to reconstruct the mass of the Bc*’. The Bc0* and Bc1 are orbital excitations, not yet seen by experiment.

In 2012, armed with the computing power of the UK STFC’s DiRAC facility and the much-improved QCD calculations that that allowed, HPQCD were able to revisit the topic and calculate the masses of many more states. They predicted the mass of the Bc* meson, a particle with spin because the bottom and anti-charm quarks are spinning in the same direction inside it.

They also predicted the masses of excited states of the Bc and Bc* , known as the Bc’ and Bc*’. These are the analogues of the electronic radial excitations of the hydrogen atom. The mass difference between the Bc’ and the Bc is then a consequence of the way in which the bottom and anti-charm quark are bound together through strong force interactions. To predict this mass difference from QCD requires the numerical techniques of lattice QCD because QCD has such complicated non-linear interactions. In arXiv:1207.5149 HPQCD found the mass difference between Bc’ and Bc to be 0.616(19) GeV/c^2; the CMS result for this mass difference in arXiv:1902.00571 (and LHCb in arXiv:1904.00081) is 0.5961(14) GeV/c^2 , in good agreement. The new experimental results improve substantially on a sighting of an unresolved mixture of Bc’ and Bc*’ states in 2014 by ATLAS and now allow the true picture of these states to be clarified.

LHCb and CMS also see evidence for the Bc*’ but cannot fully reconstruct its mass because there is missing energy in the form of a photon from Bc* to Bc decay. If we add in this mass difference from HPQCD’s calculation we can also obtain a mass for the Bc*’.

The figure shows the HPQCD predictions for Bc meson masses along with the current experimental values, including with dotted line that for the Bc*’ since it requires theory input. Mesons containing b quarks are the Achilles heel of the Standard Model since their rare decay processes are sensitive to the existence of new particles. The Bc meson family provides a new chapter in this search that theory and experiment are now beginning to exploit. The HPQCD collaboration remains at the forefront of this work and is pushing ahead with more precise calculations of Bc masses and differential decay rates on DiRAC 2.5.