Research Proposal

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Introduction

Particle Physics has always been one of the areas of physics that excites me the most. The science of exotic matter is at the cutting edge of theoretical physics – which is exactly where I want to be. This research project would give me a real insight into what my career may look like and give me the experience and confidence I need to pursue my goal of making a real impact with my future research.

Background

The Standard Model (SM) of particle physics is a framework which unites three of the four fundamental forces in Nature: the strong nuclear force, the weak nuclear force, and electromagnetism. It describes the properties and interactions of visible matter, and experimental results have agreed with SM predictions to date.

Although the SM is not complete - for example it does not describe gravity and it does not accommodate the physics of dark matter - it has nevertheless withstood experimental tests. To find new physics beyond the SM we must focus on constraining the model predictions which requires very precise theoretical, as well as experimental, input.

Theorists must, therefore, fully understand the properties of the forces and their interactions that make up the SM. Quantum Chromodynamics (QCD) is the theory of the strong nuclear force in terms of the elementary particles - quarks and gluons. The Higgs boson, discovered at CERN, is often said to give mass to everything in the universe but, in fact, it accounts for only a small contribution while the strong force described by QCD is responsible for more than 90% of the mass of visible matter. The theory provides a theoretical framework in which quarks and gluons are not observed in nature, but form observable composite particles called hadrons, such as protons and neutrons. QCD calculations are also crucial inputs in tests of the Standard Model and in searches for new physics.

In successful early approaches, such as the quark model qualification system, hadrons are thought of as bound states dominated by a quark-antiquark pair forming a meson like a pion, or three-quark combinations forming baryons like the proton and neutron. However, the strongly-coupled dynamics also permits exotic states, that is states of matter not commonly encountered in nature, e.g. tetraquark states, hybrid states which have non-trivial gluonic components and even ‘glueballs’ made purely from interacting gluons.

Methodology

A central question is: are exotic states of matter realised in nature and can we understand their properties?

The first part of that question was unexpectedly answered in the early 2000s. In 2003, the BELLE experiment in Japan found an unexpected, narrow, charmonium-like resonance called the X(3872)~(Choi:2003ue). This was quickly followed by the discovery and verification of a plethora of similarly unexpected charmonium-like states, christened the XYZs at a range of experiments.

This project will explore some of these exotic states and seek to understand their properties under the strong interaction.

The XYZs have been predominantly found in the charm system i.e. as combinations of charm and anticharm quark. Much less is known from experiments about the same states made with bottom quarks.

The project will begin with an overview of the current status - what states are discovered, what is known about their structure and properties, and then focus on a small number of test cases in the charm system. Using heavy quark effective theory, which promises symmetries and known mass-dependence rules between charm and bottom quark regimes, predictions of states made from bottom quarks will be derived from charm. These predictions will be tested against the small number of states found at experiments and also against recent results using a numerical simulation approach known as lattice QCD. The aim will be to uncover properties of these mysterious XYZs and to shed light on complicated interactions that are allowed by QCD, improving our understanding of visible matter.

Research supervisor: I will be working alongside Prof. Sinéad Ryan. This project topic coincides with her own research. Her role in the project will be to guide me and to help me to understand the high level concepts needed to undertake the research. However I will ultimately be carrying out the testing of the predictions using lattice QCD as illustrated above.

Outcomes: I aim to present the findings of this project in a clear, concise manner using appropriate visual aids. My goal for the research project is to further my knowledge of the physics behind this topic as well as to develop skills in the following areas:

- Organisation: I will need to be self-disciplined, stick to a strict time frame, and plan my days efficiently.
- Problem Solving: As with any project, it is likely that I will encounter obstacles during my research. I will need to overcome these obstacles by coming up with creative, well-thought-out solutions, and by learning from my supervisor.
- Communication: Communicating the concepts behind my project by presenting my findings on a poster will be a key part of the project. I want to do this in an interesting and visually appealing way, without compromising the content of the poster.

Covid-19: If necessary, I will be able to complete this project entirely online without too much difficulty, since it is computational in nature.