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MASTERS THESIS

The Search for Axion Like Particles (ALPs) Through B Meson Decays at the LHCb

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Abstract

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Contents

Chapter 1

Background and Motivation

1.1 Introduction

1.2 Synopsis of the Standard Model

The Standard Model of particle physics is a description of the fundamental constituents of the Universe, as well as the interactions between them. The model is composed of two main groups of particles, namely the fermions, which possess half-integer quantum spin, and make up all of the matter within the Universe, and the gauge bosons, which are of integer quantum spin, and are responsible for mediating forces between the fermions.

The fermions can be further classified into two categories of fundamental particles known as quarks and leptons. There exist six distinct 'flavours' of quarks, which are ascribed the names up, down, charm, strange, top and bottom, denoted, u, d, c, s, t and b respectively. These are grouped into three 'generations' based on their electromagnetic charge and mass. Free quarks are never observed in nature due to a principle known as quark confinement, which mandates that these particles (and their antiparticles) should exist as bound states known as baryons and mesons (which are collectively referred to as hadrons). Quarks can interact via all of the abovementioned forces. The leptons are grouped similarly by flavour, with each generation containing a negatively charged particle and a corresponding neutrino whose electromagnetic charge is zero, and is, to a large extent, massless. The three different flavours of leptons, in ascending order of their masses, are the electron, muon and tau, denoted e^-, μ^-, and τ^- respectively. The charged leptons can only partake in electromagnetic and weak interactions while the neutrinos can only participate in weak processes.

Three of the four fundamental forces of nature (i.e. the strong, electromagnetic and weak forces) are accounted for in the Standard Model, as evident through the presence of vector (spin 1) gauge bosons such as the gluon (g), photon (γ), and charged W and neutral Z bosons, which mediate the aforementioned forces respectively. The model also describes a spin-0 particle, known as the Higgs boson, which, through the mechanism of spontaneous symmetry breaking, is responsible for the Standard Model particles acquiring their mass. A spin-2, massless boson, known as the graviton has also been hypothesised as a mediator of the gravitational force. However, there is no experimental evidence of this to date. Figure 1.1 provides a visual summary of the model that has been described above.
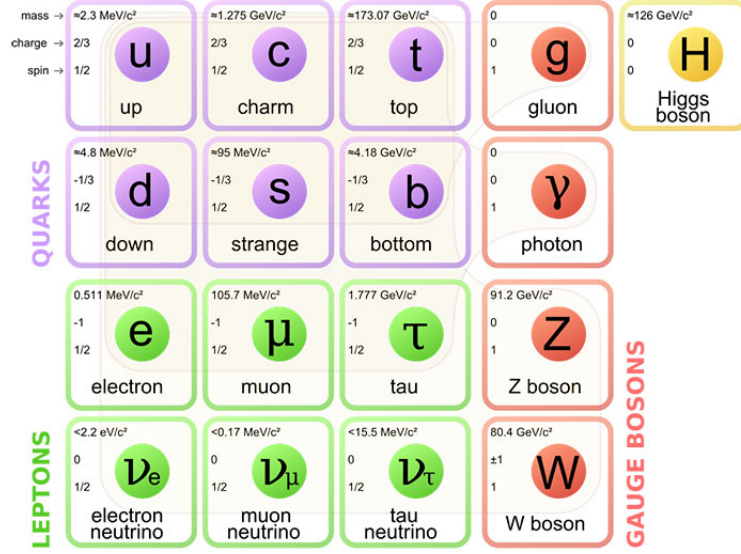
Figure 1.1: The particles of the Standard Model, grouped based on their quantum spin into gauge bosons and fermions (particles that make up all matter).The fermions are further divided into quarks and leptons which are fundamental, and can partake in various interactions that are mediated by the gauge bosons corresponding to each of the three fundamental forces described by the model. The Higgs boson is also included, and is responsible for all of the particles acquiring their mass.

Despite providing a comprehensive description of the fundamental components of nature and the force acting between these, the Standard Model is subject to numerous limitations, the most prominent of which is its inability to account for the gravitational force. Furthermore, the nature of dark matter and dark energy, which account for a large proportion of the matter in the Universe, is not fully understood, and remains an area of ongoing research. A more subtle limitation, however, pertains to a phenomenon known as CP violation and the absence of experimental evidence of this in the strong force, despite being theoretically permissible by the quantum field theory of this force, known as quantum chromodynamics (QCD). This is known as the Strong CP problem and forms the basis for motivating particles such as the axion, as well as Axion-Like Particles (ALPs), both of which are described in further detail in the sections that follow.
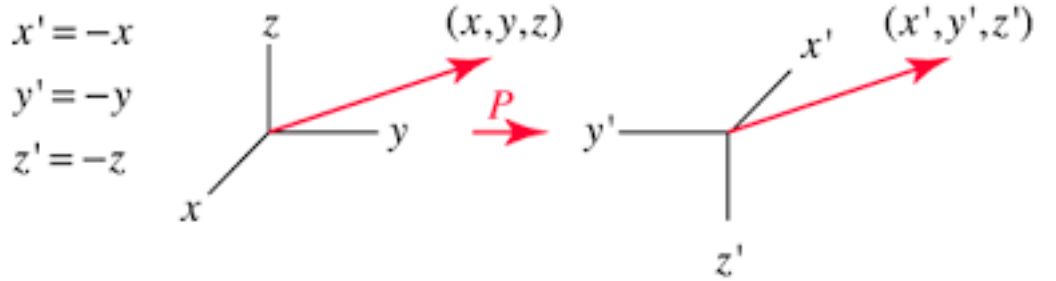
1.3 CP Violation

The principle of symmetry (i.e. the invariance of a physical system under a transformation) is significant in the study of particle physics. Two symmetries that are of particular interest are those of charge conjugation, denoted C, and parity, denoted P. Charge conjugation is a transformation wherein particles within a physical system are interchanged with their antiparticles, as demonstrated in Figure 1.2a, while parity refers to the inversion of spatial coordinates of a physical system, as illustrated in Figure 1.2b below.

The combination of the abovementioned transformations is referred to as CP, and its violation is of particular interest as it provides a possible explanation for the abundance of matter over antimatter in the Universe. CP symmetry has been observed to be preserved in electromagnetic interactions, whilst being violated in weak interactions, as demonstrated by a study of the decay of neutral kaons by Cronin and Fitch in 1964. While the theory of QCD permits the violation of this symmetry in the strong force, there is no experimental evidence of processes that violate this symmetry. This is referred to as the Strong CP problem, and is essential for the theoretical motivation behind axions and ALPs.
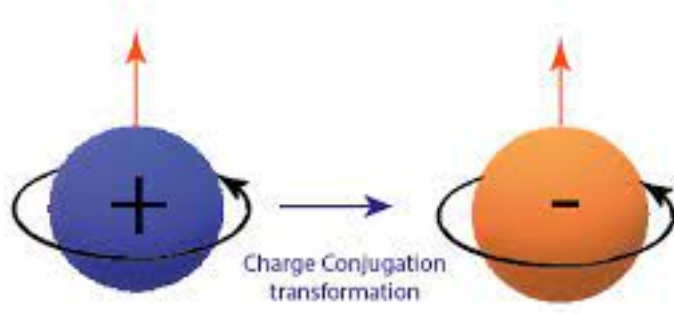
(a) The charge conjugation transformation C, which interchanges particles in a physical system with their corresponding antiparticles.

(b) An illustration of the parity transformation P, corresponding to the inversion of spatial coordinates in a physical system

1.3.1 The Strong CP Problem

The theoretically permissible nature of CP violation in the strong force is evident within the QCD Lagrangian, which can be written in the following form:

$$\mathcal{L}_{QCD} = -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} - \frac{g_s^2\theta}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi \tag{1.1}$$

where $G_{\mu\nu}G^{\mu\nu}$ represents the gluonic field strength tensor, which is the QCD equivalent of the electromagnetic field strength tensor, $F_{\mu\nu}F^{\mu\nu}$, and $\tilde{G}^{\mu\nu}$ is its dual. By inspection, it is evident that the terms θ and θ' in Equation 1.1 are CP-violating, as they both change sign under a parity transformation. The effects of these terms, which can be interpreted as physical angles, are not experimentally observed, thereby suggesting that these angular terms are infinitessimal in magnitude. The angular terms θ and θ' can be combined to form a total effective angle, labelled $\bar{\theta}$. The absence of CP violation in the strong force suggests that $|\bar{\theta}| \approx 0$. This is supported by the experimental measurement of the electric dipole moment (EDM) of the neutron, which impose the constraint $|\bar{\theta}| < 10^{-10}$. This is referred to as a fine-tuning problem, wherein the value of $|\bar{\theta}|$ is constrained to be as small as possible through the tuning of other parameters.

A more elegant solution to the Strong CP problem was proposed by Peccei and Quinn in 1977. This solution involved promoting $\bar{\theta}$ to a dynamic field, thereby introducing a spatial and temporal dependence, along with an associated potential. This field is postulated to have an associated global symmetry, known as the Peccei-Quinn (PQ) symmetry. Spontaneous breaking of this symmetry mandates that $|\bar{\theta}| = 0$, thereby resolving the Strong CP Problem without the need of fine-tuning. This solution results

in the introduction of the axion, which in turn leads to the motivation of Axion-Like Particles (ALPs) through the similar mechanism of spontaneous symmetry breaking.

1.4 Axions

Spontaneous breaking of the PQ symmetry described in Section 1.3.1 mandates the introduction of a light, pseudoscalar (spin-0 and odd parity) particle known as the QCD axion. Axions obey a well-defined relation between their mass and coupling to Standard Model particles. For instance, the coupling constant f_A of the axion-photon coupling in one of the many axion models is inversely proportional to the mass of the axion, m_A, as demonstrated in the relationship represented in Equation 1.2 below

$$f_A m_A = f_{\pi^0} m_{\pi^0} \tag{1.2}$$

where $f_{\pi^0} = 92$ GeV and $m_{\pi^0} = 135$ MeV correspond to the mass and coupling strength to photons of the neutral pion, π^0, respectively.

1.4.1 Experimental Searches for Axions

1.5 Axion Like Particles (ALPs)

Unlike axions, which are expected to be very light (i.e. within the sub-eV regime), the masses of Axion-Like Particles (ALPs) are not as constrained, thereby implying that these can be arbitrarily heavy. Furthermore, Axion-Like Particles are able to couple to pairs of gauge bosons (e.g. $\gamma\gamma, gg, HH$) as well as fermions (i.e. leptons and quarks) depending on the model being considered, and are not solely linked to the strong interaction like their counterparts.

1.5.1 Flavour Changing Neutral Currents

1.5.2 Electroweak Penguin Decays

1.5.3 The $B \to K^* A, A \to \gamma\gamma$ Decay Process

Chapter 2

The LHCb Detector

The LHCb (Large Hadron Collider beauty) experiment is one of the detector experiments that forms a part of the Large Hadron Collider (LHC), located at CERN in Geneva, on the Franco-Swiss border. It is an experiment that is designed to investigate the phenomenon of CP violation in hadrons containing the b (bottom, or beauty) quark. Studies at this detector aim to account for various physical conundra, the most prominent of which is the observed abundance of matter over antimatter in the Universe. The detector is also able to perform measurements pertaining to charm and electroweak processes, and has a $b\bar{b}$ production cross-section of approximately 500 μb at an energy of 13 TeV, making it the most abundant source of B-mesons in the world This chapter is intended to provide the reader with an overview of the structure of the detector, with an emphasis on the components that are relevant for the analysis of the $B \to K^{0*}A, A \to \gamma\gamma$ decay channel, the significance of which has been described in Chapter 1. The section also contains a brief overview of the analysis of the detector data, its flow, the various software modules that are responsible for its processing and analysis, and the framework within which these are implemented.

2.1 Structure of the LHCb Detector

The LHCb is a single-arm spectrometer whose forward angular coverage encompasses the range from approximately 10 mrad to 300 mrad in the bending (non-bending) plane, and whose pseudorapidity, η, lies in the range $2 < \eta < 5$. The detector is designed such that the b and $\bar{b}$ hadrons are produced within the same forward or backward cone at high energies. The detector comprises a high-precision tracking system, which is responsible for the measurement of the properties of the particles that traverse the detector, such as their momenta and electric charge. The tracking system comprises of four main components, namely the vertex locator, (VELO), the two Ring Imaging Cherenkov (RICH) detectors, magnet, and hadronic and electromagnetic calorimeters. Of the aforementioned components (commonly referred to as subdetectors), those that are relevant for the analysis of the decay channel of interest, namely the VELO, magnet, and the Electromagnetic Calorimeter (ECAL), are described in further detail in the sections that follow.

2.1.1 Vertex Locator (VELO)

The Vertex Locator (VELO) is a silicon microstrip detector that surrounds the proton-proton interaction region in the experiment. It is responsible for providing measurements of track coordinates that enable the identification of the primary and secondary interaction vertices, the latter of which is characteristic of beauty and charm hadron decays. The VELO was designed to optimise five major aspects of the LHCb, namely the angular coverage, triggering of events, reconstruction efficiency, displacement of

tracks and vertices, and the decay time of particles that traverse the detector. The significance of each of these aspects is summarised below

Angular Coverage

Triggering

Reconstruction Efficiency

Displaced Tracks and Vertices

Decay Time

The decay time of a particle is obtained from the measurement of its flight distance in the VELO. This is essential for time-dependent measurements in the rapidly oscillating B_s^0-$\bar{B}_s^0$ meson system

2.1.2 Ring Imaging Cherenkov (RICH) Detector

2.1.3 Magnet

2.1.4 Electromagnetic Calorimeter (ECAL)

2.2 Data Analysis at the LHCb

Data collection at the LHCb detector is divided into periods known as fills and runs. A fill is a single period of collisions separated by the announcement of stable beam conditions and the dumping of the beam by the LHCb. Such a phase typically lasts approximately 12 hours. A fill can be subdivided into runs, each of which lasts a maximum of one hour. The high event rate at the LHCb mandates a high-bandwidth data acquisition system, along with a robust, and selective trigger system. The flow of data through this trigger system, along with its various constituent hardware and software-level components are described in further detail in this section

2.2.1 The LHCb Data Flow

The LHCb is provided with approximately 40 million proton-proton collisions by the LHC every second, amounting to approximately 1 TB of storage data each second. In order to optimise the further processing of this data, it must first be filtered so as to retain only the events pertaining to the phenomena of interest. This is first performed through the *trigger*, which is divided into two stages, namely the L0 trigger and the high-level trigger (HLT). The former is implemented in hardware, while the latter operates at the software level, and is implemented in an application known as Moore. This triggered data is then reconstructed to transform the hits of particles incident on the detector into objects such as tracks and clusters, using an application known as Brunel. These objects are stored in an output file in a 'DST' format. Despite being suitable for analysis, such files are often inaccessible to users due to the imposition of computing restrictions. Hence, the data is further filtered through a set of selections known as *stripping*, which is handled by an application known as DaVinci, the output file of this step being produced in a micro-DST (or μ-DST) format

2.2.2 The LHCb Simulation Framework

A large number of Monte Carlo (MC) events are produced in parallel to the detector data. These are processed in a similar manner to the real data, the key difference being the two simulation steps that replace the proton-proton collisions and the detector response, which are controlled by applications known as Gauss and Boole respectively. The analysis of the decay of the resultant particles from the former simulation requires Gauss to call various Monte Carlo generators such as PYTHIA and POWHEG. The decay of these particles is controlled by the EvtGen and Geant4 applications. The architecture of each of these applications is briefly described below

Gauss

The Gauss framework is constructed analogously to the other LHCb software applications (i.e. using the general Gaudi data-processing framework). The Gaudi framework assists in the configuration of algorithms and tools within the application, and also controls the flow of data in the event loop. The Gauss framework has two key purposes, namely to control the generation of collisions (in most cases, proton-proton collisions) with Pythia, where a specific LHCb configuration is implemented, and to propagate generated particles through the experimental apparatus, and to simulate the physics processes within the sub-detectors using the Geant4 toolkit, which mimics the response of sub-detectors when a particle propagates through them.

EvtGen

The EvtGen package is an event generator that is designed for the simulation of the physics of B-meson decays. The package provides a framework to handle complex sequential decays and CP violating decays. The simulation of particle decays takes place through analysis of decay amplitudes, rather than probabilities. The

Pythia

The Pythia progam is a standard tool for the generation of high-energy collisions, comprising a coherent set of physics models for the evolution from few-body hard processes to complex multihadronic final states. hard processes and models for initial and final-state parton showers, multiple parton-parton interaction, beam remnants, string fragmentations and particle decays. One can integrate its usage with other applications due to its various utilities and interfaces to external programs. While its predecessors were written in Fortran, the present version of the software, namely Pythia 8, represents a complete rewrite in C++. Currently, the program only works with pp, e^+e^-, $\bar{p}p$ and $\mu^+\mu^-$ pairs.

Geant4

Boole

Chapter 3

Experimental Methods

Chapter 4

Results

Chapter 5

Discussion

Conclusion