



MONASH University

School of Physics and Astronomy/Astrophysics

MASTERS THESIS

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

Subrahmanya Saicharan Pemmaraju
ID: 32734719

Supervised by: Prof. Ulrik Egede

Date: November 22, 2022

Abstract

Contents

1	Background and Motivation	3
1.1	Synopsis of the Standard Model	3
1.2	CP Violation	4
1.2.1	The Strong CP Problem	5
1.3	Axions	6
1.4	Axion Like Particles (ALPs)	6
1.5	Experimental Searches for Axions and ALPs	7
1.5.1	Light Shining Through Walls (LSW) Searches	7
1.5.2	Haloscope Searches	8
1.5.3	Helioscope Searches	8
1.5.4	Collider Searches	8
1.6	The $B^0 \rightarrow K^* a_0, a_0 \rightarrow \gamma\gamma$ Decay Process	9
2	The LHCb Detector	11
2.1	Structure of the LHCb Detector	11
2.1.1	Vertex Locator (VELO)	12
2.1.2	Ring Imaging Cherenkov (RICH) Detector	12
2.1.3	Magnet	12
2.1.4	Electromagnetic Calorimeter (ECAL)	12
2.2	Data Analysis at the LHCb	12
2.2.1	The LHCb Data Flow	12
2.2.2	The LHCb Simulation Framework	12
3	Experimental Methods	13
4	Results	14
5	Discussion	15
	Conclusion	16
	References	16

Chapter 1

Background and Motivation

1.1 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 $e^-, \mu^-,$ 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 [1]. A spin-2, massless boson, known as the graviton has also been hypothesised as a mediator of the gravitational force [11]. 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.

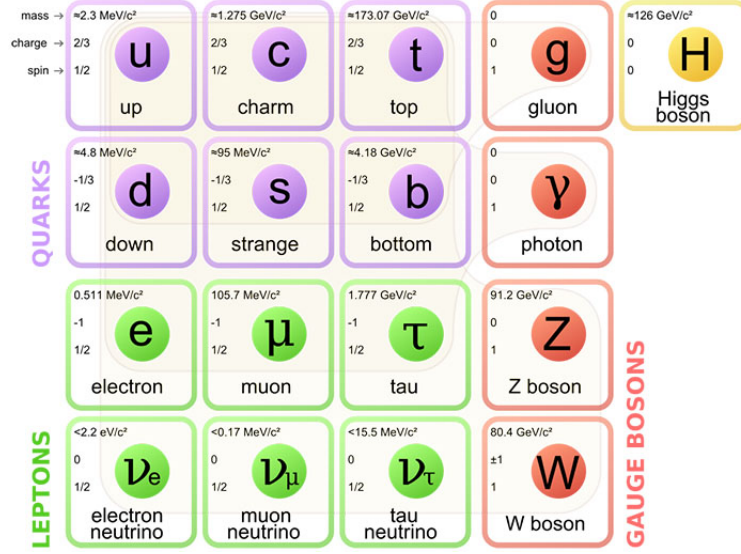


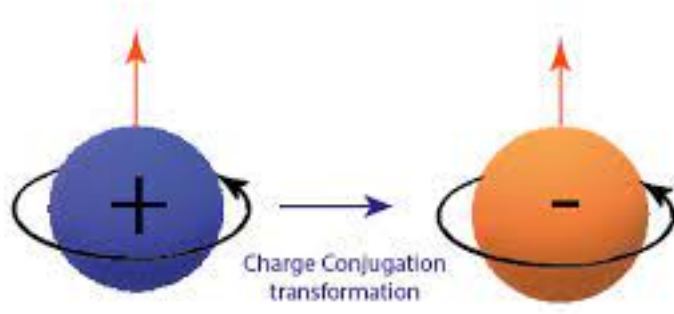
Figure 1.1: The particles of the Standard Model, grouped based on their quantum spin into gauge bosons and fermions (particles that make up all matter). The fermions are further divided into quarks and leptons which are fundamental, and can partake in various interactions that are mediated by the gauge 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. Image sourced from [9]

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 [11]. 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) [12]. 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.

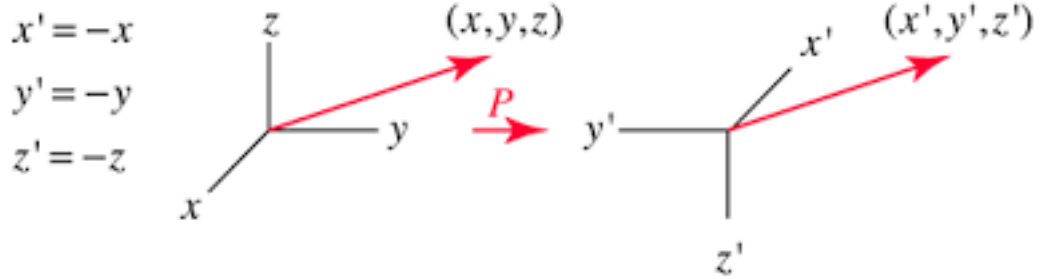
1.2 CP Violation

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 [6]. 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 [25].



(a) The charge conjugation transformation C , which interchanges particles in a physical system with their corresponding antiparticles. Sourced from [8]



(b) An illustration of the parity transformation P , corresponding to the inversion of spatial coordinates in a physical system. Sourced from [18]

1.2.1 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 [20]:

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

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 infinitesimal 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 $|\bar{\theta}| < 10^{-10}$ [2]. 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 in order to maintain consistency with experimental observations [5].

A more elegant solution to the Strong CP problem was proposed by Peccei and Quinn in 1977 [21]. 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, which is elaborated upon in [4].

1.3 Axions

Spontaneous breaking of the PQ symmetry described in Section 1.2.1 mandates the introduction of a light, pseudoscalar (spin-0 and odd parity) particle known as the QCD axion [21]. 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 [20]:

$$f_A m_A = f_{\pi^0} m_{\pi^0} \quad (1.2)$$

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.

Axions are referred to as pseudo Nambu-Goldstone (pNG) bosons, on account of their zero quantum spin and odd parity. There exist various axion models, which differ in their couplings to fermions and the energy scales involved. A detailed description of two of the most prominent axion models, namely the Kim-Shifman-Vainshtein-Zakharov (KSVZ), and the Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) models can be obtained in [12]. Despite the variety of axion models that are proposed, these pseudoscalars are known to mix with mesons, and consequently possess a model-independent coupling to photons. This coupling can be expressed through the presence of the following term in the Lagrangian [12]

$$\mathcal{L}_{a_0\gamma} = -\frac{g_{a_0\gamma}}{4} a_0 F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a_0\gamma} a_0 \mathbf{E} \cdot \mathbf{B} \quad (1.3)$$

where $g_{a_0\gamma}$ is the axion-photon coupling, and $F_{\mu\nu}$ and $\tilde{F}^{\mu\nu}$ represent the electromagnetic field strength tensor and its dual respectively. The term on the far right of Equation 1.3 is an equivalent form of the interaction that is written in terms of the electric and magnetic fields, \mathbf{E} and \mathbf{B} respectively [12]. Other couplings of axions to fermions that are of interest for the purposes of detection include those to nucleons and electrons, the latter of which is model-dependent. The phenomenology of axions described above serves as a motivation for the introduction of other light bosons as a consequence of other spontaneously broken symmetries at a higher energy scale f_a [24]. These are referred to as axion-like particles, or ALPs

1.4 Axion Like Particles (ALPs)

Spontaneous breaking of other symmetries similar to the Peccei-Quinn symmetry described in Section 1.2.1 produces particles similar to the axion, referred to as *axion-like particles* (which will henceforth be referred to as ALPs, or a_0 in decays). Unlike axions, which are expected to be very light (i.e. within the sub-eV regime), the masses of 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 [20].

ALPs are of significant importance to advancements in various fields of physics, particularly cosmology. The feeble nature of the interactions between ALPs and Standard Model particles makes them ideal dark matter candidates. In addition to this, they are believed to be able to offer an explanation of the anomalies in the energy loss of white dwarf stars [13]. Their existence can also offer an explanation of the observational hints on extra dark radiation in the primordial plasma during big bang nucleosynthesis in the form of Cosmic ALP Background (CAB) radiation [23]. Thus, a multitude of experimental methods and strategies have been employed to search for these particles, the most prominent of which include halo-scope searches, Light-Shining-Through Wall (LSW) searches, and helioscope searches. These techniques,

along with the constraints that they have imposed on the masses and couplings of ALPs to Standard Model particles are summarised in the sections that follow. The general search strategy and constraints imposed by collider experiments are also summarised in these sections. This, with an enhanced focus on the Large Hadron Collider beauty (LHCb) experiment, will be the primary emphasis of the remainder of this work.

1.5 Experimental Searches for Axions and ALPs

Since light pseudoscalars are theorised to naturally couple to photons, due to spin-selection rules and mass constraints, the searches for ALPs performed through cosmological and astrophysical observations, as well as those being conducted at low-energy accelerators exploit the (inverse) Primakoff effect, wherein axions are converted to photons (and vice versa) in collisions with photons, or identically with electromagnetic fields [7]. This is the case with the experimental search strategies that are summarised below, namely the Light Shining through Walls (LSW) experiments, helioscope, and haloscope searches. Further details on the nature and structure of the search techniques described below can be obtained in [10]

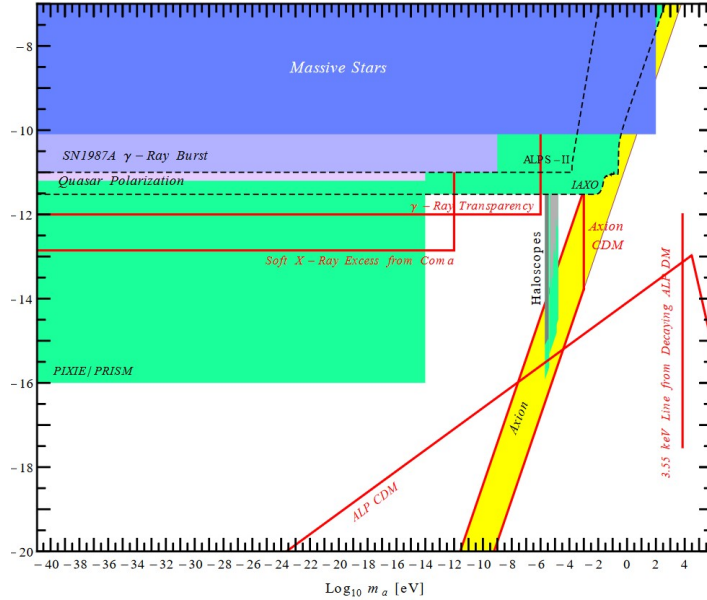


Figure 1.3: Plot displaying the constraints imposed on the masses and coupling strengths of ALPs to photons by a variety of experiments, such as LSW, helioscope, and haloscope searches (such as ALPS-II and ADMX respectively). Of particular interest are the constraints imposed by the LSW experiments ALPS-II, as well as the helioscope limits expected to be set by IAXO. The bright yellow band indicates the prediction for the axion. Figure sourced from [23]

1.5.1 Light Shining Through Walls (LSW) Searches

LSW experiments are intended to produce and detect ALPs in the laboratory by sending laser photons along a strong magnetic field, thereby allowing for their conversion into ALPs towards a blocking wall, behind which these might reconvert into photons, once again in the presence of a strong magnetic field [23]. These photons are susceptible to detection. Currently, the best sensitivity of LSW experiments has been established by the Any Light Particle Search (ALPS I) experiment located at DESY. A successor experiment, known as ALPS II, has also been designed with a high-power laser system, and stronger magnets. The experiment intends to probe the ALP parameter space that is favoured by astrophysical observations. However, the ability of LSW experiments to probe other spectral ranges, particularly in the microwave and X-ray ranges are still in the early stages of development, and are unlikely to yield significant results in the foreseeable future [23].

1.5.2 Haloscope Searches

Haloscopes directly search for galactic halo dark matter axions and ALPs in the laboratory. The most sensitive of these experiments aim to detect the electromagnetic power which is generated from the conversion of dark matter axions and ALPs into detectable photons. The optimal sensitivity is achieved on resonance, at which point the power output is proportional to the quality factor of the cavity. One experiment that has attained a sensitivity to probe axion dark matter is the Axion Dark Matter Experiment (ADMX). The constraints on the masses and couplings of ALPs to photons set by this experiment are indicated by the vertical green band labelled 'Haloscopes' in Figure 1.3 above. The figure also indicates the constraints on the same parameters set by other haloscope experiments such as those performed at the PIXIE and PRISM CMB observatories [23]. Experiments with higher sensitivities than the ADMX, named ADMX (HF) and ADMX-II, which constitutes an upgrade to the existing ADMX experiment, are also proposed in order to further probe the green regions in Figure 1.3 above. Further information on the status of these experiments, including details of their design and structure are detailed in [16] and [19]. There is also scope to probe other mass ranges through the recycling of available microwave cavities and magnets at accelerator laboratories [23]

1.5.3 Helioscope Searches

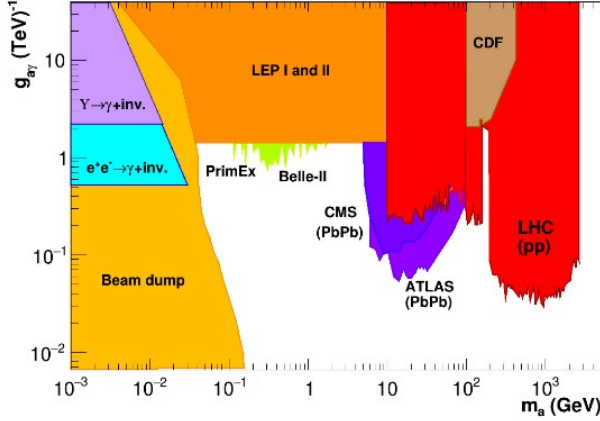
Helioscopes are designed to detect solar ALPs (i.e. the ALPs that are produced in the Sun). The detection occurs through the conversion of the ALPs into photons, which is facilitated by a strong magnet that is directed at the Sun. Presently, an helioscope named the International Axion Observatory (IAXO), which has been modelled largely based on its predecessor, the CERN Axion Solar Telescope (CAST), with enhancements made to the design in the form of a superconducting toroidal magnet and a larger aperture, as well as a detection system consisting of large X-ray telescopes coupled to ultra-low background X-ray detectors, and a large, robust tracking system. These are intended to probe the regions labelled 'IAXO' in Figure 1.3 above. Further details on the design and operation of the IAXO experiment, including details pertaining to a smaller scale experiment known as the BabyIAXO, can be found in [17].

1.5.4 Collider Searches

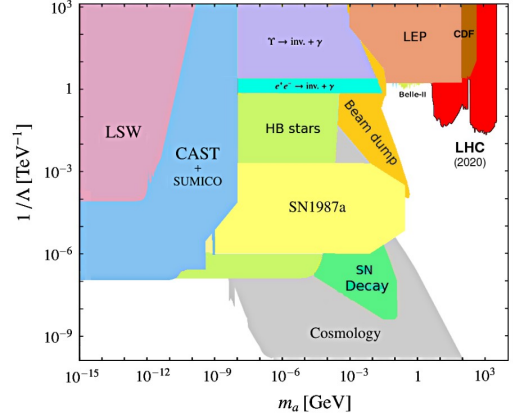
As a consequence of the (inverse) Primakoff effect, described in further detail in [22], the ALP searches conducted at colliders aim to exploit the coupling of these particles to photons by examining decays which contain photons either in their initial or final states [7]. This permits for a link to be established with the various other search strategies described above. Furthermore, the identification of these decays over intrinsically large hadronic backgrounds becomes simpler, thereby suggesting that collider searches provide a strong prospect for probing different regions in the $(m_a, g_{a\gamma})$ parameter space to those containing the limits set by other search methods [7].

Recently, collider experiments have aimed to focus their attention on ALP masses above the MeV scale. The decay rate of $a_0 \rightarrow \gamma\gamma$ is dependent on the third power of the ALP mass, the decay rate diminishes such that the ALP leaves the detector and appears as an invisible particle as its mass increases. There also exist fixed-target proton and electron experiments wherein photons are produced by meson decays or bremsstrahlung respectively. The photons that are present in the final state of each of these processes can convert into ALPs via the Primakoff process off a nuclear target. The inverse Primakoff process is exploited when the decay mode $a_0 \rightarrow \gamma\gamma$ is probed for the presence of ALPs. Various collider experiments have aimed to constrain the masses and couplings of ALPs to photons through a multitude of decay modes, the most prominent of these being CLEO and BaBar, where mono-photon final states with missing energies from long-lived "invisible" ALPs with via radiative decays are investigated, as well as diphoton and triphoton final states, as examined by the LEP-I and LEP-II experiments via, for instance, the decay mode $e^+e^- \rightarrow \gamma a_0$ (where $a_0 \rightarrow \gamma\gamma$). Each of the experiments described above probes a different region in the $(m_a, g_{a\gamma})$ parameter space. The constraints imposed on these parameters is summarised in Figure 1.4a below. Figure 1.4b provides a more holistic perspective on the collider constraints by also including the regions of the parameter space that have been probed by the multitude of experimental techniques described above. The regions probed by the ATLAS and CMS detectors, which are sub-experiments

of the Large Hadron Collider (LHC) are of particular interest, as they investigate the phenomenon in lead-lead (Pb-Pb) collisions, in contrast to the proton-proton (pp) collisions performed at the LHCb [7]



(a) Detailed bounds on the $(m_a, g_{a\gamma})$ parameter space by ALP searches from existing collider and accelerator experiments.



(b) Limits on $(m_a, g_{a\gamma})$ imposed by the techniques described in Section 1.5. The collider constraints in Figure 1.4a are also evident on the far right of this figure.

1.6 The $B^0 \rightarrow K^* a_0, a_0 \rightarrow \gamma\gamma$ Decay Process

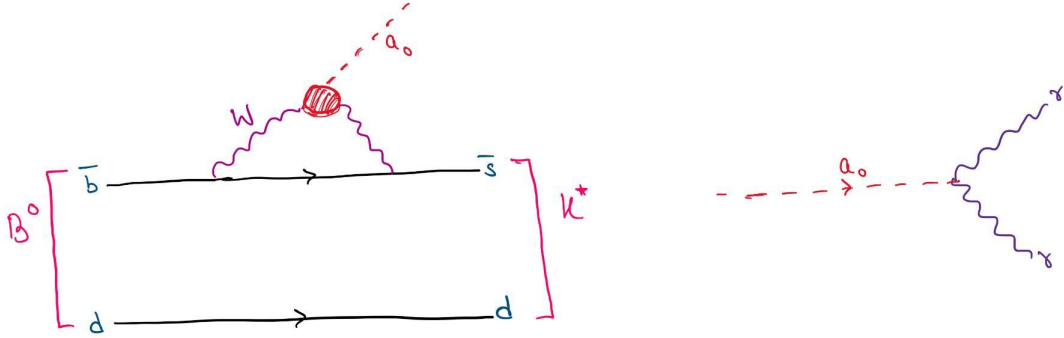


Figure 1.5: Left- One-loop level Feynman diagram of the Flavour Changing Neutral Current (FCNC) process which is responsible for the $b(\bar{b}) \rightarrow s(\bar{s})$ quark transition in the decay process described by the relation (1.5). This interaction takes place through the exchange of a charged W boson, and is forbidden at tree-level in the Standard Model. Figure adapted from [14]. Right- Visual representation of the $a_0 \rightarrow \gamma\gamma$ decay, adapted from [20]

The model considered in the sections that follow is described in detail in [14]. The model describes a coupling to the weak gauge bosons W^\pm , which gives rise to observable signatures within the detector apparatus. This model has a zero coupling with gluons, and its effective Lagrangian is given by

$$\mathcal{L} = (\partial_\mu a)^2 - \frac{1}{2} m_a^2 a^2 - \frac{g_{aW}}{4} W_{\mu\nu} \tilde{W}^{\mu\nu} \quad (1.4)$$

where g_{aW} is the coupling between the ALP field a and the electroweak gauge boson field W . Furthermore, $\tilde{W}^{\mu\nu} = \epsilon^{\mu\nu\alpha\beta} W_{\alpha\beta}/2$ [14]. Promising decay channels which could exhibit this coupling can take place through a Flavour Changing Neutral Current (FCNC) process, further detailed in [3]. One such decay channel is

$$B^0 \rightarrow K^* a_0, a_0 \rightarrow \gamma\gamma \quad (1.5)$$

The above decay channel is of interest, as the decaying particle is a neutral B meson, which has been studied extensively by a multitude of accelerators and colliders that are optimised to generate and detect them. The Large Hadron Collider beauty (LHCb) is one such detector that possesses a substantial amount of data pertaining to the decay of B -mesons. For this reason, the search for ALPs that are produced by the decay channel described in (1.5) appears to be viable and worth pursuing at the LHCb. The design, structure, and computational framework of the experiment are further detailed in the subsequent chapters

Chapter 2

The LHCb Detector

2.1 Structure of the LHCb Detector

The Large Hadron Collider beauty (LHCb) detector is a single-arm spectrometer possessing a forward angular coverage from approximately 10 mrad to 300 (250) mrad in the bending (non-bending) plane [15]. The structure of the detector is motivated by the fact that both the b and the \bar{b} hadrons are predominantly produced in the same forward or backward cone. The components that enable the identification of particles, and aid the deduction of their properties include the vertex locator system (VELO), the tracking system, comprising of a Trigger Tracker (a silicon microstrip detector, TT) located in front of the magnet, three tracking stations behind the magnet made up of silicon microstrips in the inner and outer parts (labelled IT and OT respectively), two Ring Imaging Cherenkov counters (labelled RICH1 and RICH2 respectively), as well as a calorimeter system, comprising of a Scintillating Pad Detector and Preshower (SPD/PS) and electromagnetic and hadronic calorimeters (ECAL and HCAL respectively) [15]. The layout of the LHCb spectrometer including the relative positions of the components described above, is illustrated in Figure 2.1.

Of the abovementioned components, the dipole magnet, VELO, and ECAL play a significant role in the analysis of the decay described in Section 1.6. The structure of these sections of the detector is further elaborated on in the sections that follow.

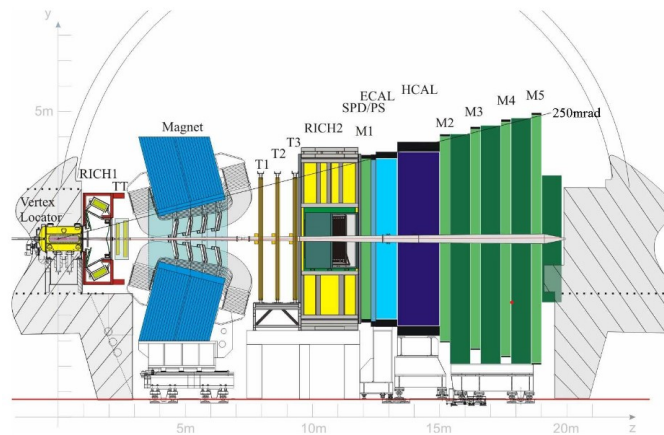


Figure 2.1: Diagram of the LHCb detector illustrating its various components. The coordinate system is oriented such that the beam is directed along the z axis, and the y axis is oriented along the vertical. Figure sourced from ADD REFERENCE

2.1.1 Vertex Locator (VELO)

Angular Coverage

Triggering

Reconstruction Efficiency

Displaced Tracks and Vertices

Decay Time

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

2.2.1 The LHCb Data Flow

2.2.2 The LHCb Simulation Framework

Gauss

EvtGen

Pythia

Geant4

Boole

Chapter 3

Experimental Methods

Chapter 4

Results

Chapter 5

Discussion

Conclusion

Bibliography

- [1] Observation and study of the Higgs boson candidate in the two photon decay channel with the ATLAS detector at the LHC. 12 2012.
- [2] C. Abel, S. Afach, N. J. Ayres, C. A. Baker, G. Ban, G. Bison, K. Bodek, V. Bondar, M. Burghoff, E. Chanel, Z. Chowdhuri, P.-J. Chiu, B. Clement, C. B. Crawford, M. Daum, S. Emmenegger, L. Ferraris-Bouchez, M. Fertl, P. Flaux, B. Franke, A. Fratangelo, P. Geltenbort, K. Green, W. C. Griffith, M. van der Grinten, Z. D. Grujić, P. G. Harris, L. Hayen, W. Heil, R. Henneck, V. Hélaine, N. Hild, Z. Hodge, M. Horras, P. Iaydjiev, S. N. Ivanov, M. Kasprzak, Y. Kermaidic, K. Kirch, A. Knecht, P. Knowles, H.-C. Koch, P. A. Koss, S. Komposch, A. Kozela, A. Kraft, J. Krempel, M. Kuźniak, B. Lauss, T. Lefort, Y. Lemièrre, A. Leredde, P. Mohanmurthy, A. Mtchedlishvili, M. Musgrave, O. Naviliat-Cuncic, D. Pais, F. M. Piegsa, E. Pierre, G. Pignol, C. Plonka-Spehr, P. N. Prashanth, G. Quémener, M. Rawlik, D. Rebreyend, I. Rienäcker, D. Ries, S. Roccia, G. Rogel, D. Rozpedzik, A. Schnabel, P. Schmidt-Wellenburg, N. Severijns, D. Shiers, R. Tavakoli Dinani, J. A. Thorne, R. Virost, J. Voigt, A. Weis, E. Wursten, G. Wyszynski, J. Zejma, J. Zenner, and G. Zsigmond. Measurement of the permanent electric dipole moment of the neutron. *Phys. Rev. Lett.*, 124:081803, Feb 2020.
- [3] F. Archilli, M. O. Bettler, P. Owen, and K. A. Petridis. Flavour-changing neutral currents making and breaking the standard model. *Nature*, 546(7657):221–226, 2017.
- [4] Aron Beekman, Louk Rademaker, and Jasper van Wezel. An introduction to spontaneous symmetry breaking. *SciPost Physics Lecture Notes*, dec 2019.
- [5] Chuan-Tsung Chan. On the symmetry constraints of cp violations in qcd, 1997.
- [6] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay. Evidence for the 2π decay of the k_2^0 meson. *Phys. Rev. Lett.*, 13:138–140, Jul 1964.
- [7] David d’Enterria. Collider constraints on axion-like particles. Technical report, 2021. 11 pages, 8 plots, extended contribution to the ‘Feebly-Interacting Particles (FIPs) 2020 Workshop Report’.
- [8] Universitat di Barcelona. Scientists bring us a step closer to understanding the nature of matter and antimatter, 2022.
- [9] P Gargon. The standard model: a beautiful but flawed theory.
- [10] Peter W. Graham, Igor G. Irastorza, Steven K. Lamoreaux, Axel Lindner, and Karl A. van Bibber. Experimental searches for the axion and axion-like particles. *Annual Review of Nuclear and Particle Science*, 65(1):485–514, 2015.
- [11] Barry R. Holstein. Graviton Physics. *Am. J. Phys.*, 74:1002–1011, 2006.
- [12] Igor Garcia Irastorza. An introduction to axions and their detection. *SciPost Physics Lecture Notes*, mar 2022.
- [13] J. Isern, E. Garcí a-Berro, S. Torres, and S. Catalán. Axions and the cooling of white dwarf stars. *The Astrophysical Journal*, 682(2):L109–L112, jul 2008.
- [14] Eder Izaguirre, Tongyan Lin, and Brian Shuve. A new flavor of searches for axion-like particles. 2016.

- [15] Eddy Jans. The lhcb detector, 2009.
- [16] R. Khatiwada et al. Axion Dark Matter Experiment: Detailed design and operations. *Rev. Sci. Instrum.*, 92(12):124502, 2021.
- [17] Cristina Margalejo Blasco. Status update of the axion helioscope BabyIAXO. *PoS*, ICHEP2022:113, 2022.
- [18] R Nave. Hyperphysics: Parity, 2022.
- [19] Tatsumi Nitta. Operations and Data Taking Status of ADMX. *PoS*, EPS-HEP2021:180, 2022.
- [20] Michael De Nuccio and Francesco Forti. *Search for an Axion-Like Particle in B decays at the BABAR experiment and projections to the Belle II data sample*. PhD thesis, Pisa, University of Pisa, Pisa, 2018. Presented on 19 04 2018.
- [21] R.D. Peccei and Helen Quinn. C_p conservation in the presence of pseudoparticles. *Physical Review Letters - PHYS REV LETT*, 38:1440–1443, 06 1977.
- [22] H. Primakoff. Photoproduction of neutral mesons in nuclear electric fields and the mean life of the neutral meson. *Phys. Rev.*, 81:899, 1951.
- [23] A. Ringwald. Axions and axion-like particles, 2014.
- [24] Andreas Ringwald. Exploring the Role of Axions and Other WISPs in the Dark Universe. *Phys. Dark Univ.*, 1:116–135, 2012.
- [25] Steven Weinberg. A new light boson? *Phys. Rev. Lett.*, 40:223–226, Jan 1978.