UNIVERSITÀ DEGLI STUDI DI MILANO

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A STUDY FOR THE MEASUREMENT OF THE Λ BARYON ELECTROMAGNETIC DIPOLE MOMENTS IN LHCb

Relatore: Prof. Nicola NERI
Correlatore: Dott.ssa Elisabetta SPADARO NORELLA

Tesi di Laurea di:
Alessandro DE GENNARO
Matricola 933289
Codice P.A.C.S.: 14.20.-c

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Introduction

Electric and magnetic dipole moments of particles are sensitive to physics within and beyond the Standard Model. In this thesis, sensitivity studies for the measurement of the Lambda baryon electromagnetic dipole moments based on pseudo experiments will be performed. In addition, the possibility of a first measurement using data collected with the LHCb detector will be explored.

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Flavour physics and CP symmetry violation

This chapter explores the theoretical framework for the rest of the thesis. Section 1.1 will provide a basic introduction to the Standard Model of Particle Physics and flavour physics in particular; Section 1.2 will delve into the inner workings of discrete symmetries in quantum physics; Section 1.3 will discuss the relevance of electromagnetic dipole moments of elementary particles as a test for CP violation and CPT symmetry; finally, Section 1.4 will introduce the main topic of the thesis, the study of dipole moments of the Λ baryon.

1.1   The Standard Model of Particle Physics

Ever since Democritus' philosophy of atomism, one of the driving desires behind mankind's advancements in the fields of natural science has been to reduce reality to its basic components. While one can convincingly argue that we may never fully understand what has come to be known as the quantum world, the Standard Model of Particle Physics (Standard Model, or SM, for short) [1] is as close as physics has to offer to a comprehensive theory of the building blocks of matter and energy.

In addition to predicting a number of then-unknown particles discovered in later years, the Standard Model has shown remarkable consistency against high precision tests, especially in the better known electroweak sector [2]. Despite this, it would be a serious mistake to call it *complete*, even if only for the three fundamental forces it covers. Many experimental evidences, some of which will be discussed in the following pages, have already opened cracks in the model, and many more are likely to emerge in the future; one of the recurring topics of this chapter will thus be the need for physics Beyond the Standard Model (BSM).

Standard Model of Elementary Particles
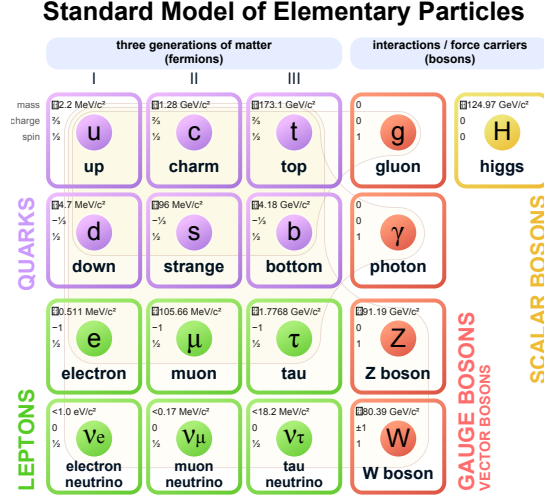
Figure 1.1: The seventeen currently known elementary particles of the Standard Model. Antiparticles are not depicted.

1.1.1 Elementary particles

Intuitively, a particle is said to be *elementary* when no substructure can be probed. A century of efforts in the fields of nuclear, quantum, and high energy physics has whittled down the spectrum of matter to just seventeen unique fundamental particles, colloquially known as the *particle zoo* and depicted in Figure 1.1.

Each particle is joined by an *antimatter particle* (*antiparticle* for short), a companion of opposite charge identified by the prefix *anti-*, e.g. antimuon for the muon; the only exception to this naming convention is the electron, whose antiparticle, for historical reasons, is known as positron. While often omitted for the sake of brevity, antiparticles are elementary particles in every respect, distinct from their partners (bar neutral gauge bosons and the Higgs boson, which are their own antiparticles) and related to them through the transformation of charge conjugation (see Section 1.2.2).

Leptons

Leptons are fermions (half-integer spin particles) not sensitive to the strong nuclear interaction. There are currently six *flavours* of leptons grouped in three generations: each generation comprises a *charged* lepton (electron, muon, tauon) and a *neutral* lepton (electron neutrino, muon neutrino, tauon neutrino).

All charged leptons have a charge of $-e$, where e is defined as the *elemen-*

tary positive charge, and their mass ranges from $\approx 0.5\,\text{MeV}$ for the electron to over $1.7\,\text{GeV}$ for the tauon [3]. By contrast, as the names suggest, all neutrinos are electrically neutral and are assumed massless in the Standard Model[1]; this implies that their only meaningful interactions happen through the weak nuclear force, which grants them their characteristic evasiveness to most particle detectors.

Quarks

Much like leptons, quarks are also fermions existing in three generations. The main difference from the former category is that quarks, besides interacting through weak and electromagnetic forces, are also susceptible to the strong nuclear forces; this allows them to bind together in composite states known as *hadrons*, which are classified as *baryons* (states of three quarks) and *mesons* (states of one quark and one antiquark)[2].

Quarks can be classified as *up-type* (up, charm and top quarks) and *down-type* (down, strange and bottom quarks): up-type quarks have a fractionary charge of $+\frac{2}{3}e$, whereas down-type quarks have a charge of $-\frac{1}{3}e$. All quarks also have one of three *color* charges (red, green or blue), while antiquarks similarly have one of three *anti-color* charges (antired, antigreen or antiblue). A combination of all three colors/anti-colors or a combination of a color and its matching anticolor produces *colorless* particles, a property of all observed quark composite states.

Unlike leptons, quarks are impossible to observe directly: according to the phenomenon of *color confinement*, the energy of the interaction field between two color charges being pulled apart increases with their distance until it becomes high enough to create a quark-antiquark pair. This process of *fragmentation* develops many times over in such a way that the final observable state is entirely composed of colorless particles. For this reason, high energy physics experiments such as LHCb do not detect free quarks, instead observing cone-shaped streams of hadrons known as *hadronic jets*.

Gauge bosons and fundamental interactions

In quantum field theory, the interaction between two fields is implemented through the exchange of an intermediary particle known as *force carrier*. In the Standard Model all force carriers are vector (spin 1) bosons known as *gauge bosons*. The name is owed to the *gauge principle* used to introduce them: the

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[1]The observation of flavour oscillation in solar neutrinos shows that neutrinos do in fact have non-zero, albeit very small, mass [4].

[2]As recently as 2003, evidence has surfaced for the existence of exotic hadrons composed of four (*tetraquarks*) [5] and five quarks (*pentaquarks*) [6].

localization of a global continuous symmetry group provides the free fermion Lagrangians with interaction terms with the proviso that one or more bosonic fields are introduced.

The gauge principle accounts for the implementation of three fundamental interactions along with their gauge bosons: the *strong nuclear force* with its massless gluon, responsible for the binding of both quarks inside baryons and nucleons inside atomic nuclei; the *electromagnetic force* mediated by the massless photon, the importance of which should be known from everyday life; and the *weak nuclear force* with two massive $W^{\pm}$ and Z bosons, the source of many subnuclear processes such as β radioactivity.

The latter two forces share a unified description in the Glashow-Weinberg-Salam theory as a single *electroweak interaction* and are introduced via localization of a $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ symmetry group, the first related to the conservation of weak isospin in left-handed chirality states and the second to the conservation of hypercharge. Quantum chromodynamics (QCD), the theory of the strong nuclear force, is based on a separate $\mathrm{SU}(3)_C$ symmetry acting on the three-dimensional space of color charges.

There are no gauge bosons nor gauge theories associated to the fourth known fundamental force, gravity. Since every attempt to reconcile the general theory of relativity with quantum mechanics has failed so far, gravity is presently excluded from the Standard Model; this doesn't affect SM predictions at the subatomic level on account of the remarkably low intensity of said force, over 30 orders of magnitude lower than the weak interaction.

The Higgs boson

The Higgs boson is one of the latest additions to the Standard Model, being proposed in 1964 [7] and observed in 2012 by the ATLAS [8] and CMS [9] collaborations. Its introduction solved perhaps the most insidious SM shortcoming at the time: gauge theories, which the model was built on, only worked under the assumption that all particles involved were massless, whereas the local invariance would fall apart (*gauge breaking*) when adding a free mass term.

By contrast, the Higgs field accounts for mass generation of the weak bosons $W^{\pm}$ and Z via the Brout-Englert-Higgs mechanism resulting from the spontaneous electroweak symmetry breaking; elementary fermions also gain mass through a distinct, Yukawa-like interaction with the field.

1.1.2 Flavour physics

A reader unfamiliar with SM terminology may find amusing the use of the word *flavour* to refer to what have been so far presented as different kinds of particles altogether. However quirky, the lexical choice highlights a defining feature: flavour, much like the degree of sweetness in a recipe, can change [10].

As often happens in particle physics, the rules are somewhat easier for leptons. For a given generation $\ell = (e, \mu, \tau)$, one can define a *lepton family number* L_ℓ as the difference between the number of particles and antiparticles of said generation, charged leptons and neutrinos alike:

$$L_\ell := n(\ell^-) - n(\ell^+) + n(\nu_\ell) - n(\bar{\nu}_\ell). \tag{1.1}$$

For all three generations, L_ℓ is conserved in every interaction except neutrino oscillations.

Quarks are not as straightforward. A similarly defined quark flavour number, such as the so-called *topness* (or *truth*)

$$T := n(t) - n(\bar{t}), \tag{1.2}$$

is preserved through EM and strong interactions, but can change when the state undergoes a *weak charged interaction*, i.e. a weak interaction mediated by the charged gauge bosons $W^\pm$. In fact, one finds that weak interactions for quarks can be accurately described if we assume that the weak eigenstates (d', s', b') of down-type quarks, i.e. the weak isospin doublet partners to up-type quarks, are related to the free mass eigenstates (d, s, b) through a rotation:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \tag{1.3}$$

In this notation, the probability for a quark of flavour i to change into a quark of flavour j as a result of a weak charged interaction is proportional to $|V_{ij}|^2$.

The unitary rotation matrix is known as the Cabibbo-Kobayashi-Maskawa (CKM) matrix V_{CKM}. The moduli of its components up to the third decimal place, according to the most recent estimates [3], are

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \approx \begin{pmatrix} 0.974 & 0.224 & 0.004 \\ 0.221 & 0.987 & 0.041 \\ 0.008 & 0.039 & 1.013 \end{pmatrix}. \tag{1.4}$$

A full definition of the CKM matrix requires four independent parameters. Particularly useful for the following sections is the standard parameterization with three angles θ_{12}, θ_{23}, θ_{13}, expressing the mixing between different quark

generations, and a complex phase δ_{13}. Defining $s_{ik} := \sin\theta_{ik}$ and $c_{ik} := \cos\theta_{ik}$, V_{CKM} can be written as

$$V_{\mathrm{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \quad (1.5)$$

The phase δ_{13} is known as the CP-violating phase. To fully understand what it means and its role in particle physics, however, a digression into discrete symmetries is needed.

1.2 Discrete symmetries and CP violation

In quantum mechanics, a system described by a Hamiltonian $\hat{\mathcal{H}}$ is *symmetric* under a transformation $\hat{S}$ if the two operators commute, i.e.

$$\left[\hat{\mathcal{H}}, \hat{S}\right] = 0. \quad (1.6)$$

Symmetries are of great relevance in physics on account of Noether's theorem, which establishes a relationship between the *continuous* symmetry of a system and a corresponding conservation law; the emphasis is on the requirement of continuity, meaning the related transformation changes the system «in a smooth way», much like a rotation does. An example of this principle has already been presented earlier in this thesis: the three symmetry groups employed in SM gauge theories all imply the conservation of a specific charge, be it weak isospin, hypercharge, or color.

By contrast, this section will delve into *discrete* symmetries [11], which do not share said «smoothness» property. The absence of a Noether-like theorem for this class of transformations does not detract from their importance in physics: as will be shown, the three symmetries we'll focus on have a remarkable influence on many fields of study.

1.2.1 Parity inversion

By definition, the *parity inversion* (or simply *parity*) transformation $\hat{P}$ flips the sign of the three spatial coordinates:

$$\hat{P} : \begin{pmatrix} x \\ y \\ z \end{pmatrix} \to \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}. \quad (1.7)$$

Its action on a quantum $|\psi(\vec{x}, t)\rangle$ is therefore

$$\hat{P}|\psi(\vec{x}, t)\rangle = |\psi(-\vec{x}, t)\rangle. \quad (1.8)$$

More interestingly, for parity eigenstates (known as *parity-defined* states) a parity quantum number can be introduced; such states may have a *P-parity* eigenvalue $\eta_p = +1$ (parity-even states) or $\eta_p = -1$ (parity-odd states). Since by definition $\hat{P}^2 = \mathbb{1}$, where $\mathbb{1}$ is the identity operator, these are the only two allowed P-parity values.

A similarly dichotomous behaviour is observed on both scalar and vector quantities commonly used in classical physics, such as momenta and electromagnetic fields. Parity-even scalar quantities are called *true scalars* or just *scalars* (e.g. energy), whereas parity-odd ones are called *pseudoscalars* (e.g. helicity). The same distinction is present for vector quantities, which are either *polar vectors* (e.g. angular momentum) or *axial vectors* (e.g. linear momentum).

As far as is currently known, gravity, electromagnetic and strong nuclear interactions conserve parity. The same cannot be said for the weak interaction, the P-violating properties of which were first proven in the 1956 Wu experiment on the ^{60}Co β^- decay [12].

1.2.2 Charge conjugation

The transformation of *charge conjugation* $\hat{C}$ changes the sign of all electric charges:

$$\hat{C} : q \rightarrow -q. \tag{1.9}$$

It should be readily apparent that $\hat{C}$ has close ties with the concept of anti-matter. In fact, the action of charge conjugation turns a quantum state into its antimatter partner, inverting the sign of all flavour quantum numbers in the process:

$$\hat{C} |\psi\rangle = |\bar{\psi}\rangle . \tag{1.10}$$

For single-particle systems, the only possible $\hat{C}$ eigenstates are particles that are their own antiparticle, like the photon, for which a C-parity $\eta_c = \pm 1$ is defined by analogy with the P-parity eigenvalue.

Unlike in the case of parity, there isn't a single breakthrough experiment credited for showing that the weak interaction is not C-symmetric: it was known from theory that parity violation in a weak process, when observed under certain conditions, would also imply a violation of charge conjugation, with such a violation being confirmed shortly after Wu's results [13]. As for the other three fundamental interactions, no evidence of C symmetry violation has surfaced so far.

1.2.3 Time reversal

Perhaps the most intuitively named of the three discrete symmetries discussed here, *time reversal $\hat{T}$* does exactly what it promises:

$$\hat{T} : t \rightarrow -t. \tag{1.11}$$

The action of time reversal on a quantum state is represented by an *antiunitary* (unitary and antilinear) operator, which implies a complex conjugation on top of the time reversal itself:

$$\hat{T} \left| \psi(\vec{x}, t) \right\rangle = \left| \psi^*(\vec{x}, -t) \right\rangle \tag{1.12}$$

There are a number of arguments for the antiunitarity of $\hat{T}$, the most straight-forward being that it prevents final states with negative energy.

Once more, gravity, strong and electromagnetic forces are T-symmetric, whereas the weak nuclear force isn't. However, as will be explained shortly, this knowledge isn't the result of a direct experiment, instead exploiting a side effect of the CPT theorem.

1.2.4 CP symmetry and violation

The sequential combination of C, P and T transformations, commonly designated as CPT symmetry, plays a key role in the foundations of quantum physics. As well as being the only combination of said transformations still observed to be a symmetry of physical laws, the *CPT theorem* states that any Lorentz-invariant local quantum field theory must be CPT-symmetric. Because a violation of the CPT symmetry would imply the collapse of the modern quantum physics framework, it is generally accepted that a T-violating process must also be a CP-violating process. This bears an important consequence on the study of discrete symmetry violations: because of the self-evident hindrances in building a time-reversed experimental setup outside of trivial cases, every test of T violation becomes by necessity a test of CP violation.

Setting this notion aside, CP symmetry is an interesting field of study in and of itself [14]. For one thing, while C and P symmetries are maximally violated by the weak interaction, CP isn't; this is readily seen with the chirally left-handed neutrino, which possesses a CP-partner (the right-handed antineutrino) despite lacking both a P-partner (the right-handed neutrino) and a C-partner (the left-handed antineutrino). The subject of CP violation is also closely tied to another long-standing dilemma in both particle physics and cosmology: the observed asymmetry between matter and antimatter in our Universe. A perfectly CP-symmetric system would produce a roughly equal number of particles and antiparticles, which would annihilate one another and

yield an empty Universe; our very existence implies a primordial imbalance that resulted in baryogenesis and therefore some degree of CP violation.

Since gravity, EM and strong interactions all individually conserve parity and charge conjugation, it stands to reason that they are also CP-symmetric, leaving the weak nuclear interaction as the only possible CP-violating fundamental force. Experiments conducted over the last 50 years have found that, despite CP still being preserved in most weak processes, some select interactions show evidence of CP violation.

The first indirect discovery came in 1964 by Christenson et al. [15], who observed the long-lived neutral kaon two-pion decay $K_L^0 \to \pi^+\pi^-$ with a branching ratio of $\approx 10^{-3}$ over all charged modes. This result could only be explained by assuming that the K_L^0 weak eigenstate is a mixture of both $\eta_{CP} = \pm 1$ eigenstates, with the ability to oscillate between the two. A more direct evidence was found in 1999 by the KTeV collaboration at Fermilab [16] via the observation of differing decay rates in $K_{L/S}^0 \to \pi^+\pi^-$ against $K_{L/S}^0 \to \pi^0\pi^0$ channels, and CP violation in weak processes was definitely established in the early 2000s via studies on B mesons decays conducted in so-called «B-factories» such as BaBar at SLAC [17] and Belle at KEK [18].

Despite the significant number of experimental evidences collected ever since, the extent of known CP-violating processes is several orders of magnitude below what is expected from cosmological estimates. The matter-antimatter imbalance at the time when the Universe cooled below the pair production threshold temperature can be quantified through the *baryon asymmetry parameter* [19], computed as the difference between the densities of baryons and antibaryons divided by their sum:

$$\eta := \frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}}. \tag{1.13}$$

While this parameter cannot be directly measured at the present time, we can approximate it by noting that almost no antimatter currently exists in the Universe ($n_{\bar{B}} \approx 0$) and almost all of the original matter will have annihilated into photons ($n_B + n_{\bar{B}} \approx n_\gamma$):

$$\eta \approx \frac{n_B}{n_\gamma}. \tag{1.14}$$

Both of these quantities can be probed by studying the intergalactic medium and the cosmic microwave background, finding $\eta_{\mathrm{obs}} \approx 10^{-10}$ [20]. As for the Standard Model prediction, all SM sources of CP violation arise from quark mixing, and more specifically from the δ_{13} complex phase mentioned in the parameterization (1.5) of the CKM matrix. Computing the baryon asymmetry parameter with this knowledge leads to a much lower $\eta_{\mathrm{SM}} \approx 10^{-20}$ [19].

New sources of CP violation are therefore required to match the observed value, with a promising field being the search for intrinsic electromagnetic dipole moments [14].

1.3 Electromagnetic dipole moments

1.3.1 EDMs

The electric dipole moment (EDM) $\vec{\delta}$ is the measure of a system's *polarity*, i.e. the spatial separation of positive and negative charges within the system. For the simplest of the relevant charge configurations, a dipole of point charges $\pm q$ separated by a distance r, the EDM is expressed as

$$\vec{\delta} = q\vec{r},\tag{1.15}$$

where the displacement vector $\vec{r}$ points from the negative charge to the positive one.

It's hardly a feat of imagination to theorize that a composite particle like the neutron could acquire an EDM, even if the three quarks inside it cannot be thought of as a system of charges in the classical sense. It may be less intuitive that elementary, point-like particles such as electrons and quarks could also gain one, due to quantum effects resulting in the creation and destruction of virtual particles (so-called *loops* in higher order Feynman diagrams).

For a spin-$\frac{1}{2}$ particle, its EDM is written in Gaussian units as [21]

$$\vec{\delta} = d\frac{\mu_B}{2}\vec{s},\tag{1.16}$$

where d is a dimensionless quantity referred to as *gyroelectric factor*,

$$\mu_B = \frac{e\hbar}{2mc},\tag{1.17}$$

is the particle magneton, c is the speed of light in a vacuum, m is the particle mass and

$$\vec{s} = 2\frac{\langle\vec{S}\rangle}{\hbar}\tag{1.18}$$

is the spin polarization vector, related to the average value of the spin $\vec{S}$ divided by the reduced Planck constant $\hbar$.

When the particle crosses an external electric field $\vec{E}$, its EDM will polarize by changing the direction of the spin. This introduces an energy term in the system's Hamiltonian with the form

$$H_{\text{EDM}} = -\vec{\delta} \cdot \vec{E}.\tag{1.19}$$

One can now check how the term (1.19) behaves when acted upon by some of the discrete transformations outlined in Section 1.2. The behaviour of spin $\vec{S}$, and therefore of the spin-related EDM $\vec{\delta}$, can easily be shown to be that of polar vectors, i.e. parity-even. By contrast, the electric field $\vec{E}$ is an axial vector, i.e. parity-odd, which makes H_{EDM} a parity-odd pseudoscalar:

$$H_{\mathrm{EDM}} \xrightarrow{\hat{P}} -H_{\mathrm{EDM}}. \tag{1.20}$$

When considering time reversal $\hat{T}$, the situation is specular: the EDM $\vec{\delta}$ flips its sign, whereas the electric field $\vec{E}$ remains unchanged, implying

$$H_{\mathrm{EDM}} \xrightarrow{\hat{T}} -H_{\mathrm{EDM}}. \tag{1.21}$$

The above result in particular contains a crucial piece of information: assuming the validity of the CPT theorem, a Hamiltonian containing the EDM's interaction term (1.19) can only be CP-symmetric if the average (or *permanent*) EDM of the particle is zero.

It follows that, for a particle to have a permanent EDM, CP symmetry must be violated in some measure[3]. As explained in Section 1.2.4, the only known source of CP violation within the Standard Model is the complex phase δ_{13} in quark mixing, which may give a small contribution to the EDMs of point-like particles such as electrons ($\delta \approx 10^{-40}\,e\,\mathrm{cm}$ [22]) and quarks ($\delta \approx 10^{-34}\,e\,\mathrm{cm}$ [23]) via beyond-tree-level diagrams. Composite particles such as baryons are accorded some leeway on account of their finite size: the weak interaction between quarks inside the neutron, for instance, contributes to a possible EDM up to $\delta \approx 10^{-31}\,e\,\mathrm{cm}$ [24].

In all cases, the predicted SM contributions are orders of magnitudes below the sensitivity reached by current generation experiments. For all intents and purposes, the observation of a non-zero permanent EDM in a baryon would imply the discovery of a BSM source of CP violation.

1.3.2 MDMs

The magnetic dipole moment (MDM) $\vec{\mu}$ of a system can be interpreted as the measure of how intense a torque the system experiences when crossing a magnetic field $\vec{B}$:

$$\vec{\tau} = \vec{\mu} \times \vec{B}. \tag{1.22}$$

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[3]This line of reasoning only applies to systems that are parity eigenstates. Water molecules are notoriously polar, but their EDMs do not violate any fundamental symmetry because the molecule's ground state is a superposition of parity-even and parity-odd eigenstates.

Unlike the case of EDMs, the extension of MDMs from classical to quantum physics is less extreme, as long as one acknowledges the affinity between angular momentum and a particle's intrinsic spin. A classical rotating body with charge q, mass m and angular momentum $\vec{L}$ gains an MDM in the form

$$\vec{\mu} = \frac{q}{2m}\vec{L}, \tag{1.23}$$

assuming charge and mass are identically distributed. A very similar relation holds for a non-classical, point-like spin-$\frac{1}{2}$ particle [21]:

$$\vec{\mu} = g\frac{\mu_B}{2}\vec{s} \tag{1.24}$$

Here g is the dimensionless *gyromagnetic factor* accounting for the transition from classical to quantum physics, whereas μ_B and $\vec{s}$ are the same particle magneton and spin polarization vector defined in equations (1.17) and (1.18) respectively.

Similary to EDMs, MDMs also induce a spin rotation when subjected to a magnetic field $\vec{B}$, introducing a Hamiltonian term

$$H_{\mathrm{MDM}} = -\vec{\mu} \cdot \vec{B}. \tag{1.25}$$

Under parity and time reversal transformations, the MDM $\vec{\mu}$ behaves in the same way as the EDM $\vec{\delta}$, both being dependent on the particle's spin $\vec{S}$ (odd under $\hat{P}$, even under $\hat{T}$). In contrast with $\vec{E}$, however, the magnetic field $\vec{B}$ behaves in the *same* way as $\vec{\mu}$, effectively cancelling out their signs when the Hamiltonian (1.25) is acted upon:

$$H_{\mathrm{MDM}} \xrightarrow{\hat{P}} H_{\mathrm{MDM}}, \tag{1.26}$$

$$H_{\mathrm{MDM}} \xrightarrow{\hat{T}} H_{\mathrm{MDM}}. \tag{1.27}$$

Factoring in the CPT theorem, this result entails that a non-zero intrinsic MDM for fundamental particles does not imply CP violation. For this reason, measurements of MDMs are instead used as *precision tests* of the CPT theorem, since its value should not change between a particle and its antimatter partner.

1.3.3 Measurement of EDMs and MDMs

For the purposes of this thesis, the measurement of EDMs and MDMs of a particle is performed by exploiting the precession of spin in an electromagnetic field [25]. In the laboratory frame, a neutral particle flying with velocity $\vec{\beta}$

through homogeneous electromagnetic fields $\vec{E}$ and $\vec{B}$ experiences a precession of the non-relativistic spin polarization vector $\vec{s}$ described by the equation

$$\frac{d\vec{s}}{dt} = \vec{s} \times \vec{\Omega}, \qquad \vec{\Omega} := \vec{\Omega}_{\text{EDM}} + \vec{\Omega}_{\text{MDM}}. \tag{1.28}$$

The angular velocity vector $\vec{\Omega}$ is itself the sum of two contributions due to the respective intrinsic dipole moments of the particle:

$$\vec{\Omega}_{\text{EDM}} = \frac{d\mu_B}{\hbar} \left(\vec{E} - \frac{\gamma}{\gamma+1}(\vec{\beta} \cdot \vec{E})\vec{\beta} + \vec{\beta} \times \vec{B}) \right), \tag{1.29}$$

$$\vec{\Omega}_{\text{MDM}} = \frac{g\mu_B}{\hbar} \left(\vec{B} - \frac{\gamma}{\gamma+1}(\vec{\beta} \cdot \vec{B})\vec{\beta} - \vec{\beta} \times \vec{E}) \right). \tag{1.30}$$

Assuming $\vec{E} = 0$, as will be the case in the experimental setup at LHCb, the angular velocity simplifies to

$$\vec{\Omega} = \frac{\mu_B}{\hbar} \left[d\vec{\beta} \times \vec{B} + g \left(\vec{B} - \frac{\gamma}{\gamma+1}(\vec{\beta} \cdot \vec{B})\vec{\beta} \right) \right]. \tag{1.31}$$

An analytical solution of the above system of equations is possible under the approximation that the precession of the particle spin depends only on the integrated value of the magnetic field $\vec{B}$ along the particle's flight path l. In the absence of field gradients, dictated by the homogeneity requirement, such integrated field $\vec{D}$ can be written as

$$\vec{D} := \int_0^l dl' \vec{B}(\vec{r}_0 + \hat{\beta} l') \approx \langle \vec{B} \rangle l, \tag{1.32}$$

where $\hat{\beta}$ is the normalized vector of $\vec{\beta}$. Defining $\hat{\Omega}$ in the same way, the time evolution of the spin polarization vector $\vec{s}$ ($\vec{s}(0) = \vec{s}_0$) is

$$\vec{s}(l) = \left(\vec{s}_0 \cdot \hat{\Omega} \right) \hat{\Omega} + \left[\vec{s}_0 - \left(\vec{s}_0 \cdot \hat{\Omega} \right) \hat{\Omega} \right] \cos \left(\left| \vec{\Omega} \right| t \right) + \left(\vec{s}_0 \times \hat{\Omega} \right) \sin \left(\left| \vec{\Omega} \right| t \right). \tag{1.33}$$

From an experimental point of view, measurement of time isn't trivial; instead, one can efficiently measure the flight length of an unstable particle $l = \beta c t$ during its lifetime. The equation describing the spin precession as a function of l has a very similar form to (1.33):

$$\vec{s}(l) = \left(\vec{s}_0 \cdot \hat{\Phi} \right) \hat{\Phi} + \left[\vec{s}_0 - \left(\vec{s}_0 \cdot \hat{\Phi} \right) \hat{\Phi} \right] \cos \left| \vec{\Phi} \right| + \left(\vec{s}_0 \times \hat{\Phi} \right) \sin \left| \vec{\Phi} \right|, \tag{1.34}$$

with

$$\vec{\Phi} = \frac{\mu_B}{|\vec{\beta}| \hbar c} \left[d\vec{\beta} \times \vec{D} + g \left(\vec{D} - \frac{\gamma}{\gamma+1}(\vec{\beta} \cdot \vec{D})\vec{\beta} \right) \right] \tag{1.35}$$

and $\vec{D}$ defined as in (1.32).

Equation (1.34) therefore provides a way to measure the values of EDMs and MDMs for neutral particles by studying the change in polarization after flying through a magnetic field. For unstable particles, the polarization at the time of decay can be inferred in a fairly straightforward way from the angular distribution of their products. Conversely, theoretical knowledge or measurement of the original spin polarization $\vec{s}_0$ of the particle are both far from easy tasks in a general setting. Thankfully, in selected cases such as the one covered in this thesis, $\vec{s}_0$ can be known by exploiting the same parity violation of weak interactions discovered in 1956 by Wu and her collaborators.

1.4   The Λ baryon

The Λ baryon, also historically known as the Λ hyperon[4] and labeled as Λ^0, is a spin-$\frac{1}{2}$ baryon with (u, d, s) valence quarks. As the first identified baryon beyond the two nucleons, it played a key role in the discovery and christening of the strange quark: its mass of $\approx 1115\,\mathrm{MeV}/c$ [3], the lighest among s-bearing baryons, meant its only viable decay channels were mediated by the flavour-changing weak interaction, giving the Λ a much longer half-life than expected; this property was dubbed *strangeness*, a name later inherited by the new quark that indirectly caused it.

The Λ baryon is a prime candidate to probe CP violation. Unlike in the case of the prospective discovery of a neutron EDM[5], a non-zero Λ baryon EDM could not be explained by any phenomena within the Standard Model and would therefore imply the existence of BSM physics.

[Misure precedenti.]

[Soddisfa tutti i requisiti: neutra, vita media, campo magnetico, polarizzazione.]

[Come si riduce l'equazione della spin polarization nel caso del barione lambda polarizzato.]

It can be shown (see Appendix A) that the expected angular distribution for protons is...

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[4]A *hyperon* is a baryon with one or more strange quarks, but no heavier quarks. The nomenclature emerged in the period following the discovery of the strange quark, when no further quarks besides the first three were known; nowadays, the term is rarely used.

[5]Quantum chromodynamics allows for a CP-violating term proportional to the QCD vacuum angle θ. Current measurements of the neutron EDM constrain $\theta \lesssim 10^{-10}$, a fine-tuning suppression known as the *strong CP problem*; nevertheless, experimental discovery of a non-zero neutron EDM could be traced back to this term and would not necessarily require the introduction of new physics.

Chapter 2

The LHCb experiment

2.1 The Large Hadron Collider

Eeee.

2.2 LHCb

LHCb (the b stands for *beauty*[1]) is one of the four main experiments at the LHC.

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[1]Before settling on the names *top* and *bottom* for the third generation of quarks, the names *truth* and *beauty* were among those proposed. While they never gained enough momentum in the scientific community, echoes of the failed nomenclature are still present in heavy quark vocabulary, for instance in the alternative name *truth* for the *topness* flavour number mentioned in Section 1.1.2, as well as in the official name for the LHCb experiment.

Appendix A

Angular distribution of $\Lambda \to p\pi^-$ decay products

A.1 Helicity formalism

[Il Richman.]

A.2 Computation of the angular distribution

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