

# Search for $B \rightarrow \nu\bar{\nu}$ decays at the Belle II experiment

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# Abstract

This is a summary.

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# 1

## Theoretical context

The [Standard Model \(SM\)](#) of particle physics is a theoretical framework that describes the electromagnetic, weak and strong nuclear interactions between elementary particles. Based on the principles of [Quantum Field Theory \(QFT\)](#), it has been tested extensively and has been able to describe the observations of particle physics experiments with great accuracy. However, there are several phenomena that the [SM](#) is not able to explain, such as the existence of [Dark Matter \(DM\)](#) or the matter-antimatter asymmetry in the universe. For reasons discussed later on, many tensions with the [SM](#) have been previously observed when quark's flavour transitions occur, such as in the  $b \rightarrow sl^+l^-$ ,  $b \rightarrow c\tau\nu$  or  $b \rightarrow s\nu\bar{\nu}$  transitions. We will study the last one in this thesis, via the prism of the  $B \rightarrow K\nu\bar{\nu}$  decay. In this chapter, we will first introduce the theoretical framework behind the [SM](#) and its limitations ([Section 1.1](#)), which will lead us to the formulation of the [SM](#) as an [Effective Field Theory \(EFT\)](#) ([Section 1.2](#)) and the study of the  $B \rightarrow K\nu\bar{\nu}$  decay ([1.3](#)). We will then mention [New Physics \(NP\)](#) models which could intervene in the  $B \rightarrow K\nu\bar{\nu}$  decay and the experimental constraints on these models ([1.4](#)). Finally, we will present the state of the art in the measurement of the  $B \rightarrow K\nu\bar{\nu}$  decay ([1.5](#)).

## 1.1 The Standard Model of particle physics

The [SM](#) provides mathematical tools to describe the interactions between elementary particles, which can be *fermions*, with half-odd spin, or *bosons*, with integer spin. The elementary bosons, or *gauge bosons*, act as mediators of the fundamental interactions: *electromagnetic*, *weak* and *strong* interactions. The elementary fermions are, in this theory, 12 particles (and 12 anti-particles) forming multiplets of the groups  $SU(3)_C$ ,  $SU(2)_L$  and  $U(1)_Y$ .

The  $SU(2)_L \otimes U(1)_Y$  gauge group describes the electroweak interaction, mediated respectively by the  $(W^i)_{i \in \llbracket 1,3 \rrbracket}$  and  $B$  bosons, acting on the *weak isospin*  $T$  and the *weak hypercharge*  $Y$ . At lower energy, this symmetry is spontaneously broken by the Higgs mechanism, leading to the appearance of the  $W^\pm$  and  $Z$  bosons, and the photon  $\gamma$ , which fields are defined as such:

$$W^\pm = \frac{1}{\sqrt{2}} (W^1 \mp iW^2), \quad Z = W^3 \cos \theta_W - B \sin \theta_W, \quad A = W^3 \sin \theta_W + B \cos \theta_W$$

where  $\theta_W$  is the weak, or Weinberg, angle. One also need to redefine the generator of  $U(1)_Y$  as  $Q = T_3 + \frac{Y}{2}$ , which is the electric charge operator. Additionnaly, this symmetry breaking mechanism leads to the appearance the Higgs boson  $H$ , which is the only scalar elementary particle in the [SM](#).

The  $SU(3)_C$  gauge group describes the strong interaction, and act only on particles with a *colour charge*  $C \in \{R, G, B, \bar{R}, \bar{G}, \bar{B}\}$ . This group being of dimension 8, it has 8 gauge bosons, called *gluons*  $(g_i)_{i \in \llbracket 0,8 \rrbracket}$ . Elementary fermions can then be separated in two categories:

- *Quarks*, with a colour charge, which are grouped in three generations, each containing two quarks with electric charge  $Q = \frac{2}{3}$  and one with  $Q = -\frac{1}{3}$ , as follows:

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

and their anti-particle equivalents. As they interact with the strong nuclear force, quarks are never observed in isolation, but always in bound states called hadrons (except for the top quark because of its mass), since free particles must always have a "null" colour charge. Particles composed of two quarks are called mesons, and those composed of three quarks are called baryons.

- *Leptons*, without a colour charge, which are also grouped in three generations, each containing a charged lepton and a neutrino, as follows:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

and their anti-particle equivalents.

All of the fermions interact weakly, and charged fermions also interact electromagnetically. From the way they act under  $SU(2)_L$ , one can write the fermions as *weak-isospin doublets*

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \quad \begin{pmatrix} u' \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c' \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t' \\ b' \end{pmatrix}_L$$

and *weak-isospin singlets*

$$e_R^-, \mu_R^-, \tau_R^-, u'_R, c'_R, t'_R, d'_R, s'_R, b'_R$$

with the  $L$  and  $R$  subscripts indicating the chirality of the particles, left-handed or right-handed, respectively. The right-handed neutrinos are not included in the [SM](#).

The primes in the expressions above indicate that the quarks' "weak" eigenstates are not the same as their "mass" eigenstates. The two bases are related by the unitary [Cabibbo-Kobayashi-Maskawa \(CKM\)](#) matrix,  $V_{\text{CKM}} \in M_3(\mathbb{C})$ :

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad (1.1)$$

It is to be noted that one can also right this change of basis for the other quarks' states ( $u, c, t$ ) and ( $u', c', t'$ ).

This matrix encodes many information. Firstly, due to physical reasons, we need only three mixing angles  $(\theta_{12}, \theta_{13}, \theta_{23}) \in \mathbb{R}^3$  and one phase  $\delta_{13} \in \mathbb{R}$  in order to fully parametrize this matrix. The phase is interpreted as the *CP-violating* phase and is an important parameter of the [SM](#) to measure because of its implication in phenomena such as the *matter-antimatter asymmetry*. Secondly, the squared modulus of the matrix elements are the probabilities for a quark to change flavour.

The unitary of the [CKM](#) matrix implies that:

$$\sum_{i \in \{u, c, t\}} V_{ij} V_{ik}^* = \delta_{jk}, \quad (j, k) \in \{d, s, b\}^2 \quad (1.2)$$

$$\sum_{i \in \{d, s, b\}} V_{ji} V_{ki}^* = \delta_{jk}, \quad (j, k) \in \{u, c, t\}^2 \quad (1.3)$$

where  $\delta$  is the Kronecker symbol.

As one can see from the unitarity and the transitions represented by the matrix elements, change of flavour between same sign quarks, also called [Flavour Changing Neutral Current \(FCNC\)](#), cannot occur at tree level. It is possible at loop level, but the [SM](#) predicts very low probabilities for these transitions, because of the [Glashow-Iliopoulos-Maiani \(GIM\)](#) mechanism, which makes them very interesting to study in order to search for [NP](#). An explanation of this mechanism will come in the next section.

Let's go back to [Equation \(1.2\)](#) and develop the expression for  $j = b$  and  $k = d$ :

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \quad (1.4)$$

$$\iff 1 + \frac{V_{cd} V_{cb}^*}{V_{ud} V_{ub}^*} + \frac{V_{td} V_{tb}^*}{V_{ud} V_{ub}^*} = 0 \quad (1.5)$$

supposing that  $V_{ud} V_{ub}^* \neq 0$  (which is true for physical reasons). The last relation describe the *unitarity triangle* in the complex plane, with two of its vertices at  $C = (0, 0)$  and  $B = (1, 0)$  respectively. The last vertex is defined to be at  $A = (\bar{\rho}, \bar{\eta}) \in \mathbb{R}^2$ . Consequently, the lengths of the triangle sides are:

$$\bar{A}B = \left| \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} \right| \quad (1.6)$$

$$\bar{A}C = \left| \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right| \quad (1.7)$$

$$\bar{B}C = 1 \quad (1.8)$$

and the angles, also parametrized by the [CKM](#) matrix elements, are:

$$\alpha = \arg \left( \frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right) \quad (1.9)$$

$$\beta = \arg \left( \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} \right) \quad (1.10)$$

$$\gamma = \arg \left( \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right) \quad (1.11)$$



Hence, the measurement of the sides and angles of the unitarity triangle allows to test the SM and search for NP.

## 1.2 An Effective Field Theory approach to the Standard Model

Let's go back to the GIM mechanism. Consider a transition from a  $b$  quark to a  $d$  quark. It is forbidden at tree level, but can occur at loop level, with the exchange of a  $W$  boson. The amplitude of this transition is proportional to the product of the  $b \mapsto j$  and  $j \mapsto d$  amplitudes with the mass of the intermediate quark  $m_j$ , where  $j \in (u, c, t)$ . Moreover because of quantum mechanics, one need to take the sum of the amplitudes for all possible intermediate quarks.

$$\mathcal{M}_{b \rightarrow d} \propto \sum_{j \in (u, c, t)} \frac{V_{bj} V_{jd}^*}{m_j^2} \quad (1.12)$$

Hence, going back to equation Equation (1.4), if  $m_u = m_c = m_t$ , one can factorize by  $\frac{1}{m_j^2}$  for  $j = u$  in Equation (1.12), and get that the amplitude of the  $b \mapsto d$  transition is null. If such a symmetry of masses were to exist, FCNC would be forbidden at the one-loop level by the GIM mechanism. However, this equality is viable at very short distance scales and is not true anymore at low energy, meaning that the GIM mechanism breakdown at the one-loop level.

This is a good example of the limitations of the SM. The breakdown of the model as a function of the energy scale is a hint to believe that the SM is an effective theory, meaning that it is a low-energy approximation of a more fundamental theory. Studying the  $B$  meson physics implies that one need to work at various energy scales: the energy scale for new physics, denoted  $\Lambda_{\text{NP}}$ ; the electroweak scale at  $M_W$ , the mass of the  $W$  boson; the scale of the  $b$  quark  $m_b$ ; and the energy scale of the strong interaction,  $\Lambda_{\text{QCD}}$ .

### 1.3 The $B \rightarrow K\nu\bar{\nu}$ decay in the Standard Model

### 1.4 New Physics models in the $B \rightarrow K\nu\bar{\nu}$ decay

### 1.5 State of the art

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## 2

# Conclusion

This is a conclusion.



# List of acronyms

**CKM** Cabibbo-Kobayashi-Maskawa. [7](#), [8](#)

**DM** Dark Matter. [5](#)

**EFT** Effective Field Theory. [5](#)

**FCNC** Flavour Changing Neutral Current. [8](#), [9](#)

**GIM** Glashow-Iliopoulos-Maiani. [8](#), [9](#)

**NP** New Physics. [5](#), [8](#), [9](#)

**QFT** Quantum Field Theory. [5](#)

**SM** Standard Model. [5](#), [6](#), [7](#), [8](#), [9](#)



# Bibliography

- [1] A N Kolmogorov. *Foundations of the theory of probability*. Chelsea Publishing Company, New York, NY, USA, 1956. (cited on page [10](#))