Analyzing the effects of some new physics models in *B* to *D* $\tau\bar{\nu}$ decay

Hamza Tajammal
Regn.#00000278422

A thesis submitted in partial fulfillment of the requirements for the degree of **Master of Science**
in
Physics

Supervised by:Dr. Muhammad Ali Paracha

Department of Physics

School of Natural Sciences
National University of Sciences and Technology
H-12, Islamabad, Pakistan

2021

FORM TH-4

National University of Sciences & Technology

MS THESIS WORK

We hereby recommend that the dissertation prepared under our supervision by: Hamza Tajammal, Regn No. 00000278422 Titled: Analyzing the effects of some new physics models in B to D $\tau\nu$ decay be Accepted in partial fulfillment of the requirements for the award of **MS** degree.

Examination Committee Members

1. Name: DR. AEYSHA KHALIQUE Signature: Ayesha Khalique

2. Name: DR. SAADI ISHAQ Signature: Saadi

Supervisor's Name DR. M. ALI PARACHA Signature: Ali

Riaz 20-07-2022

Head of Department

Date

COUNTERSINGED

Date: 22.07.2022

Dean/Principal

Dedication

I'd like to dedicate my work to my family, specifically to my parents, for their unwavering support in my academic endeavors.

Acknowledgements

First and foremost, I would like to praise Allah the Almighty, the Most Gracious, and the Most Merciful for His blessing given to me during my study and in completing this thesis. May Allah's blessing goes to His final Prophet Muhammad (peace be up on him), his family and his companions.

I would like to express my gratitude and sincere thanks to my respected supervisor Dr. Muhammad Ali Paracha for his steadfast guidance throughout my time working with him. I think without his guidance and support it was difficult for me to frame this thesis into final form.

In addition, I would especially like to thanks to the leaders of my Advisory Committee, Dr. Ayesha Khaliqe and Dr. Saadi Ishaq for valuable guidance, advice and encouragement.

Moreover, let me thank to my family, my parents, and my siblings. Also, huge thanks go to my best friends Muhammad Irfan and Tufail Ajmal for every single moment of joy and sorrow we cherished together since the first time we stepped into School of Natural Sciences (SNS) up to this very second. I would wish to express my sincere thanks to all my mates, Zeeshan Rashid, Bilal Jehanzaib, Masood Rehman, for their support and encouragement.

Finally, I have a great expectation that my study will be beneficial and useful for anyone who is interested in reading this thesis.

Abstract

In this thesis, we studied $B \to D\tau\bar{\nu}_\tau$ decay in Standard Model and a few New Physics(NP) models, such as the W'-model, the Vector-leptoquark model, and then the aligned-two-Higgs-doublet model(A2HDM). We calculated the branching fraction $\mathcal{B}(B \to D\tau\bar{\nu})$, Lepton Flavor Universality(LFU) ratio(R_D), Differential branching fraction and LFU ratio $\frac{d\mathcal{B}}{dq^2}$ and $R_D(q^2)$ the Lepton-side forward-backward asymmetry $A_{FB}(q^2)$, the convexity parameter $C_F^\tau(q^2)$ and the τ-polarization fraction $P_L^\tau(q^2)$, using the parameter spaces generated from various flavor restrictions. We found that:

- The branching fraction $\mathcal{B}(B \to D\tau\bar{\nu})$ shows a significant divergence from SM, and the LFU ratio R_D only shows a noticeable divergence from SM in the case of A2HDM.
- The differential branching fraction and LFU ratio both show noticeable divergence from SM in the case of above mentioned NP models.
- The $A_{FB}(q^2)$, $C_F^\tau(q^2)$ and $P_L^\tau(q^2)$ are only sensitive to A2HDM, Due to scalar-type interaction which can be generated in such model.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

The Standard Model[1, 2] for Particle Physics is based on the principle of local gauge invariance, which was established in the second part of the twentieth century, and has been extensively tested over the years and has proven to be exceedingly successful. It represents the elementary particles of matter, the spin–1/2 fermions, and their interactions by the electromagnetic, weak, and strong forces mediated by spin–1 gauge bosons. Unless there is spontaneous electroweak symmetry breaking(SSB), electroweak gauge invariance in the Standard Model requires all fundamental particles to be massless. This difficulty can be solved by adding a complex scalar field coupling to weak gauge bosons and fermions which give them mass. As a result, the new scalar particle is introduced called the Higgs boson[3, 4]

The finding of a new boson with a mass of 125.5 GeV by the ATLAS and CMS teams at CERN's Large Hadron Collider in July 2012 represents a key milestone in the search for the Standard Model Higgs boson. Measurements of its spin, CP, and coupling properties reveal strong agreement with predictions from the Standard Model. More information is needed to determine the nature of the new boson and whether it is a Standard Model Higgs boson or a more complex Higgs sector of a Standard Model extension. It is commonly assumed that the Standard Model is an effective theory that is only valid up to a certain energy scale and that it needs to be expanded to explain physics phenomena at very high energy scales. Semileptonic decays of Rare B mesons[5, 6, 7, 8, 9, 10] provide an excellent window to look for Physics beyond SM.

As shown in Fig. 1, the B-meson decays, $\bar{B} \to \tau\bar{\nu}$ and $\bar{B} \to D^{(*)}\tau\bar{\nu}$, have third generation quarks and leptons in final states and are mediated by a W-boson in Standard Model. As a result, they are more sensitive to the effect of charged Higgs bosons[11, 12]. These decay processes are relatively difficult to identify experimentally due to two or more missing neutrinos in the final states. They are a nonetheless suitable candidate for $e^+e^- B$ factory experiments due to their huge statistics and low background. The $\bar{B} \to \tau\bar{\nu}$ and $\bar{B} \to D^{(*)}\tau\bar{\nu}$ decay processes have observed branching fraction of order $O(10^{-4})$ and $O(10^{-2})$ respectively[13]. When the pure and semi-tauonic B decays are compared, the latter provides a wide range of observables like decay distribution[14, 15, 16, 17, 18] and Polarizations[19, 20, 21, 22]. As a result, the semi-tauonic decay processes allow us to study the relevant charged current interaction, and in this thesis, we focus on $\bar{B} \to D\tau\bar{\nu}$.

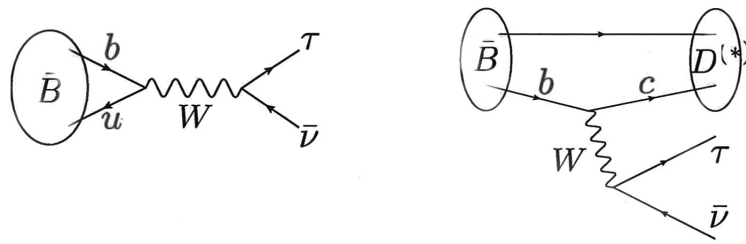

Figure 1.1: W-boson contribution to the $\bar{B} \to \tau\bar{\nu}$ and $\bar{B} \to D^{(*)}\tau\bar{\nu}$ decays.

This thesis is based on Standard Model(SM) and beyond SM study of B-meson flavor-changing-charged-current (FCCC) semileptonic decay specifically,

$$B^+(\bar{b}u) \to \bar{D^0}(\bar{c}u)l^+\nu_l \tag{1.0.1}$$

Here, $l = e, \mu$ and τ leptons. The quark level representation of this decay is: $\bar{b} \to \bar{c}l^+\nu_l$. However, for brevity we will use $B \to D\tau\bar{\nu}$ and $b \to cl\bar{\nu_l}$ throughout this thesis. Both the flavor and charge will change in these decay processes as the b quark is transformed to a c quark by a weak current that produces a factor of CKM matrix element V_{cb} in the amplitude. The semileptonic $\bar{B} \to D^{(*)}l\bar{\nu_l}$ decay can be used to determine $|V_{cb}|$. The $|V_{cb}|$ can be extracted in two ways namely, the exclusive and inclusive final states. As shown in Fig. 2.

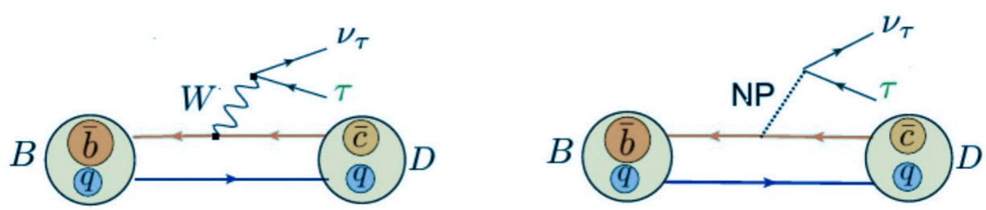

Figure 1.2: $b \to c\tau\bar{\nu_\tau}$ decay processes in the SM (Left) and Possible New Physics (right).

In SM, the semileptonic decays of B mesons induced by $b \to cl\bar{v}l$ are well known. Because of the greater mass of the lepton, these lepton decays may be used to explore the intermediate charged Higgs boson or other non-SM particles in particular. The

Standard parameters $R(D)$ and $R(D*)$[23, 24] are defined as follows.

$$R(D) = \frac{\Gamma(B \to D\tau\bar{\nu})}{\Gamma(B \to Dl\bar{\nu})} \quad , R(D^*) = \frac{\Gamma(B \to D^*\tau\bar{\nu_\mu})}{\Gamma(B \to D^*l\bar{\nu})} \tag{1.0.2}$$

Here, $l = \mu, e$ leptons. The SM predictions[25, 26] and current world averages[27] of R_D and R_{D^*} are given below

$$R(D) = \begin{cases} 0.407 \pm 0.039 \pm 0.024, & \text{Exp.[27]} \\ 0.300 \pm 0.008, & \text{SM[25]} \end{cases} \tag{1.0.3}$$

$$R(D^*) = \begin{cases} 0.304 \pm 0.013 \pm 0.007, & \text{Exp.[27]} \\ 0.257 \pm 0.005, & \text{SM[26]} \end{cases} \tag{1.0.4}$$

Apart from these results the SM predictions and results are shown in the Fig. 1.3[28] These independent measures agree well with one another. Furthermore, the theoretical

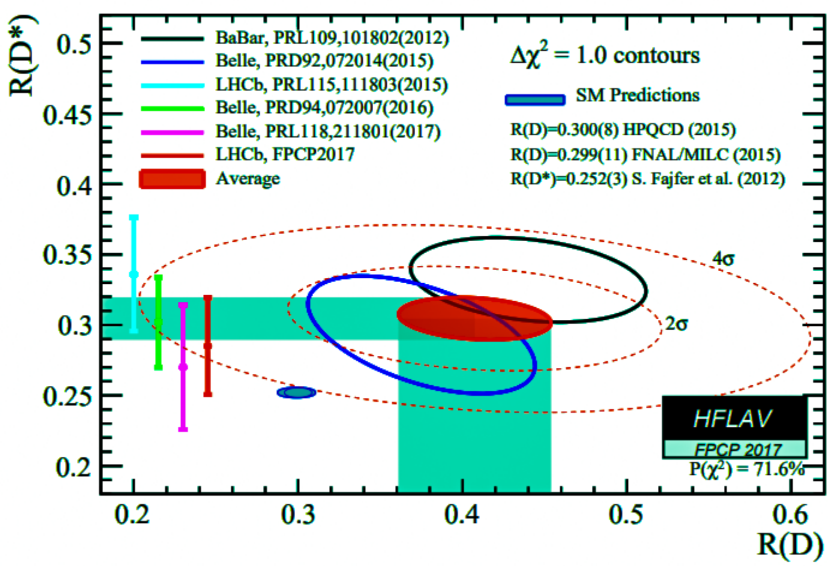

Figure 1.3: $R(D)$ and $R(D^*)$ measurements, their averages and SM predictions

estimates are valid because heavy quark symmetry eliminates the errors from hadronic physics that are required for SM prediction. From the Fig. 1.3 one can clearly see that $R(D)$ and $R(D^*)$ exceed SM prediction by 2.3σ and 3.4σ, respectively.

It is remarkable, from a theoretical viewpoint, to see such substantial deviations from SM in these processes that occur at the tree level. If these data are verified by future studies, it implies that the NP scale may be at or below the TeV scale. Many New Physics models have already been rejected by LHC Run 1 constraints at ATLAS and CMS, and more will be constrained shortly by Run 2 results. Many New Physics models using leptoquarks, W'-bosons, vector quarks, charged scalars, or lepton mixing have been suggested to suit current experimental data. In comparison to scalars, model-independent research reveals that vector-type particles are preferable. Furthermore, leptoquarks that primarily link to the third generation of fermions are preferred to accord with other existing experimental results and circumvent the present limits from direct creation at the LHC experiment. Furthermore, there are few processes in which the $B \to D^{(*)}\tau\bar{\nu}$ are SM like, but $B \to Dl\bar{\nu}$ are suppressed by interference between NP and SM[28]. The anomalies ($R(D)$ and $R(D^*)$) have been thoroughly researched inside the SM and its extensions in recent years, and it has been discovered that the impacts of some NP models are particularly important for the observables of B-meson semi-leptonic decays.

This thesis is organized as follows. Chapter 1 is the introduction to SM. In section 2.1 we briefly discuss the SM gauge principle, in which we write the covariant form of SM lagrangian. In section 2.2 we discussed the SM framework, the SM particles and their interactions with SM fields. The section 2.3 is about Spontaneous Symmetry breaking, we discussed how SM particles gain masses by Higgs Mechanism. Section 2.4 and 2.5 are about Flavor Physics and Quark mixing. In section 2.6 we discussed some problems and limitations of the Standard Model.

In chapter 3 we discuss the theoretical framework, which is needed to study our problem both in SM and NP. In section 3.1 and 3.2 we discuss the Hamiltonian basis and Heavy quark effective theory, we write basic heavy quark effective lagrangian. The section 3.3- 3.6 are NP tools that we will use to study our decay.

In chapter 4 we write Effective Hamiltonian and differential decay rate, including SM and NP effects, for our decay process. In section 4.5 we show plots of some observables in SM and NP for our decay process and compare them. In chapter 5 we concluded the thesis.

Chapter 2

The Standard Model Framework

The Standard model (SM) is a low-energy effective theory that describes Physics at energies lower than the Electro-Weak symmetry breaking scale which is of order $\mathcal{O} \approx 248 Gev$. It is very successful in explaining Physics at low energies. In this chapter, we will discuss a few aspects of the Standard Model.

2.1 Gauge Principle

According to Noether's theorem, for every global symmetry transformation, a conservation law can be derived from the lagrangian and it requires that the fields should be locally transformed rather than globally. To do this we use *gauge principle*.

Gauge principle is a method to obtain an interaction term from a globally invariant lagrangian by turning it into a locally invariant Lagrangian. A global invariant lagrangian can be transformed into a local invariant lagrangian by the addition of some new fields and interaction terms in such a way that the new lagrangian remains invariant with respect to a new group of local gauge transformations.

Lets start with a Lagrangian $\mathcal{L}(\psi(x), \partial_\mu \psi(x))$, which is invarian under following global transformation.

$$\psi(x) = U\psi(x)$$

Where U is unitary transformation representing the SU(N) group Now, we have to construct a lagrangian that is invariant under global as well as following local SU(N) transformation

$$\psi(x) \to U(x)\psi(x), \quad U = e^{(i\tau^a \alpha^a(x))} \tag{2.1.1}$$

τ^a,$a = 1, 2, 3$ are generators of $SU(N)$ group satisfying following algebra

$$[\tau_a, \tau_b] = i\epsilon_{abc}\tau_c$$

Now, to transform the Lagrangian into a local invariant we need to replace the ordinary derivative ∂_μ with covariant derivative D_μ which transforms like the field itself, The covariant derivative for each generator is defined by

$$D_\mu = \partial_\mu - ig\tau^a A^a_\mu \tag{2.1.2}$$

$$(D_\mu\psi(x))' \to \Omega(D_\mu\psi)$$

where,

$$\Omega = e^{(-i\tau^a\alpha^a(x))}$$

As the transformation is invariant w.r.t local gauge symmetry, the field term in equation 2.1.2 transforms as,

$$A'^a_\mu = A^a_\mu - \frac{1}{g}\partial_\mu\alpha^a + \epsilon_{abc}\alpha^b A^c_\mu \tag{2.1.3}$$

In the end, A locally invariant Kinetic part for gauge fields has to be added, which depends on A^a_μ. As field strength tensor reads,

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g\epsilon_{abc}A^b_\mu A^c_\nu \tag{2.1.4}$$

And transforms like,

$$F'^a_{\mu\nu} \to F^a_{\mu\nu} + \epsilon_{abc}\alpha^b F^c_{\mu\nu} \tag{2.1.5}$$

Hence, the term $F^a_{\mu\nu}F^{a,\mu\nu}$ satisfies all the requirements for the Kinetic term, so the final lagrangian can be written as,

$$\mathcal{L} = \mathcal{L}(\psi(x), D_\mu\psi(x)) - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} \tag{2.1.6}$$

Now, this Lagrangian does not have a mass term in it which implies that the interaction is carried out by massless particles and we know that the Weak force carrier fields are massive particles. This problem is solved by *Spontaneous symmetry breaking* which we will discuss further in this chapter.

2.2 Standard Model framework

The Standard model is a Gauge theory based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$. The $SU(3)_C$ is the Quantum Chromodynamics part which is related to the strong interaction, and the $SU(2)_L \times U(1)_Y$ is Electro-Weak interactions. The basic Standard Model Lagrangian can be written as,

$$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{fermions} + \mathcal{L}_{Yukawa} + \mathcal{L}_{Higgs} \tag{2.2.1}$$

Table 2.1: Gauge fields

Interaction	Gauge Fields	Spin	Charge	mass
Weak interaction	$W^{\pm}$	1	$W^{\pm} = \pm 1$	$W^{\pm} \approx$ 80Gev
Weak interaction	Z	Z=0	0	Z≈91Gev
Electromagnetic interaction	Photons	1	0	0
Strong interaction	Gluons	1	0	0

2.2.1 Gauge part

The gauge part consists of gauge fields that mediate interactions between fermions. The strong interaction is mediated by 8 massless gluons and the Electro-Weak interaction is mediated by 3 massive gauge bosons and a massless photon. The gauge fields contribution to SM lagrangian is written as

$$\mathcal{L}_{gauge} = -\frac{1}{4}\left(B_{\mu\nu}B^{\mu\nu} + W^i_{\mu\nu}W^{i,\mu\nu} + G^j_{\mu\nu}G^{j,\mu\nu}\right) \tag{2.2.2}$$

The covariant field strength tensors for the above Lagrangian is written as

$$\begin{aligned} B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu \\ W^i_{\mu\nu} &= \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g_w \epsilon_{ijk} W^j_\mu W^k_\nu \\ G^j_{\mu\nu} &= \partial_\mu G^j_\nu - \partial_\nu G^j_\mu - g_c \varepsilon_{jkl} G^k_\mu G^l_\nu \end{aligned} \tag{2.2.3}$$

The term $G^j_\mu, \quad j = 1, 2, 3, ..., 8$ are Gauge fields called Gluons fields and they mediate strong interaction and belong to $SU(3)_C$ group[36], Whereas the terms $W^i_\mu, \quad i = 1, 2, 3$ and B_μ mediate Weak interaction and electromagnetic interaction respectively, they belong to $SU(2)_L \times U(1)_Y$ group. Where, ϵ_{ijk} and ε_{ijk} are the structure factors and g_w and g_c are gauge couplings. Detail of the above-mentioned gauge, like charge, and fields are given in Table(2.1).

2.2.2 Fermionic Part

There are three generations of fermions. In each generation, there is a charged lepton, a neutrino, and an up and down-type quark. The fermions appear as left-handed, which are doublets w.r.t $SU(2)_L$, or right-handed, which are the singlets w.r.t $SU(2)_L$. The doublet and Singlets are written below.

$$\begin{aligned}
E_L^i &= \begin{pmatrix}\nu_e\\ e^-\end{pmatrix}, \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}, \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}\\
Q_L^i &= \begin{pmatrix}u\\ d'\end{pmatrix}, \begin{pmatrix}c\\ s'\end{pmatrix}, \begin{pmatrix}t\\ b'\end{pmatrix}\\
e_R^i &= (e_R, \mu_R, \tau_R)\\
u_R^i &= (u_R, c_R, t_R)\\
d_R^i &= (d_R, s_R, b_R)
\end{aligned} \tag{2.2.4}$$

The most general lagrangian for the fermions is given as[36]

$$\begin{aligned}
\mathcal{L}_{fermion} = \sum_{m=1}^{F} (\bar{Q}_L^m i\not{D}_Q Q_L^m + \bar{E}_L^m i\not{D}_E E_L^m + \bar{u}_R^m i\not{D}_u u_R^m \\
+ \bar{d}_R^m i\not{D}_d d_R^m + \bar{e}_R^m i\not{D}_e e_R^m)
\end{aligned} \tag{2.2.5}$$

Here, F represents the families of quarks and leptons and $F = 1, 2, 3$.

The covariant derivative of the above Lagrangian is written as

$$\begin{aligned}
D_E^\mu &= \partial_\mu - igY_E B^\mu - ig_l \frac{\tau^a}{2} W^{a,\mu}\\
D_Q^\mu &= \partial_\mu - igY_Q B^\mu - ig_l \frac{\tau^a}{2} W^{a,\mu} - ig_c t^a G^{a,\mu}\\
D_e^\mu &= \partial_\mu - igY_e B^\mu\\
D_{u/d}^\mu &= \partial_\mu - igY_{u/d} B^\mu - ig_c t^a G^{a,\mu}
\end{aligned} \tag{2.2.6}$$

Here, τ are the Pauli matrices, Y is the hypercharge and t are the $SU(3)_c$ generators. The Standard Model fermion content is given in Table 2.2

2.2.3 Yukawa Part

The fermion fields and scalar fields, which are subject to gauge symmetry and lead to Spontaneous Symmetry breaking, make up this part of the Lagrangian. The Yukawa part[29] of Standard Model lagrangian is given as,

$$\mathcal{L}_{\mathcal{Y}} = -[\mathcal{Y}_e \bar{e}_R \Phi^\dagger L_L + \mathcal{Y}_d \bar{d}_R \Phi^\dagger Q_L + \mathcal{Y}_u \bar{u}_R \tilde{\Phi}^\dagger Q_L + \quad h.c] \tag{2.2.7}$$

Where $\mathcal{Y}$ are the 3×3 yukawa matrices of dimensionless couplings and $\tilde{\Phi}^\dagger = i\sigma^2\Phi^\dagger$.

Table 2.2: Standard Model Fields along with gauge quantum numbers

Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$	3	2	1/6
u_R^i	3	1	2/3
d_R^i	3	1	-1/3
$L_L^i = \begin{pmatrix} \nu_L^i \\ l_L^i \end{pmatrix}$	1	2	1/2
l_R^i	1	1	-1
$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$	1	2	1/2

2.2.4 Higgs Part

The Higgs part of the Standard Model describes the Higgs doublet and its interactions with gauge fields and itself. The Higgs lagrangian is written as,

$$\mathcal{L}_H = (D^\mu H)^\dagger (D_\mu H) - V(H) \tag{2.2.8}$$

Where D_μ is a covariant derivative that reads,

$$D_\mu H = (\partial_\mu + iW_\mu + \frac{i}{2} g_h B_\mu) H$$

and $V(H)$ is potential which is invariant under $SU(2)_L \times U(1)_Y$ symmetry. The potential can be written as,

$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \tag{2.2.9}$$

where λ is the dimensionless coupling parameter and μ^2 is the mass term.

2.3 Spontaneous Symmetry breaking(SSB)

Gauge principles are the backbone of theories that explain the interaction of particles. Local gauge invariance demands the existence of massless vector bosons which are responsible for the interactions but there is a problem that only photons and gluons are massless, the bosons which carry weak interactions are massive. In this section, we discuss how to solve this problem.

2.3.1 Goldstone Theorem

Goldstone theorem is the illustration of *spontaneous symmetry breaking* of a continuous symmetry. According to the theorem, there exists a massless particle for every generator of spontaneously broken continuous symmetry which we call Goldstone boson[30].

Let's start with a Lagrangian with κ^i fields

$$\mathcal{L} = Derivatives\ terms - V_{(\kappa)} \tag{2.3.1}$$

Now, Let a field ϕ_0^i that minimizes the potential as,

$$\frac{\partial V}{\partial \phi^i}|_{\phi^i=\phi_0^i} = 0$$

Now, by expanding the field about that minimum field we get,

$$V(\phi) = V(\phi_0) + \frac{1}{2}(\phi - \phi_0)^i(\phi - \phi_0)^j \left(\frac{\partial^2 V}{\partial \phi^i \partial \phi^j}\right)_{\phi_0}$$

Here, the following term is a matrix whose eigenvalues generate mass terms for the fields.

$$\left(\frac{\partial^2}{\partial \kappa^i \partial \kappa^j} V\right)_{\kappa_0} = m_{ij}^2$$

Now we must have to show that every continuous symmetry of the lagrangian 2.3.1 that is not the symmetry of ϕ_0 gives zero eigenvalues of this matrix. By Applying following continuous symmetry transformation

$$\kappa^i \rightarrow (\kappa^i + \alpha\delta^i(\kappa))$$

Where $\delta^i(\kappa)$ is a constant field which is the function of κ^i so the derivatives term in the Lagrangian vanish and only potential transforms and gives us two possibilities.

$$\begin{aligned} &V(\kappa^i) = V(\kappa^i + \alpha\delta^i(\kappa)).........(i) \\ &\delta^i(\kappa)\frac{\partial}{\partial \kappa^i}V(\kappa)........................(ii) \end{aligned} \tag{2.3.2}$$

Now the first condition is trivial, differentiating the second condition w.r.t κ^j and minimizing we get

$$0 = \left(\frac{\partial \delta^i}{\partial \kappa^j}\right)_{\kappa_0}\left(\frac{\partial V}{\partial \kappa^i}\right)_{\kappa_0} + \delta^i(\kappa_0)\left(\frac{\partial^2}{\partial \kappa^i \partial \kappa^j}V\right)_{\kappa_0} \tag{2.3.3}$$

The first term is zero because $\left(\frac{\partial V}{\partial \kappa^i}\right)_{\kappa_0} = 0$ so the second term also must vanish but for Spontaneous Symmetry Breaking $\delta^i(\kappa_0) \neq 0$ so $\delta^i(\kappa)_0(\partial^2/\partial\kappa^i\partial\kappa^j V(\kappa))_{\kappa_0} = 0$, hence $\delta^i(\kappa_0)$ is our desired vector with zero eigen value and this is Goldstone theorem

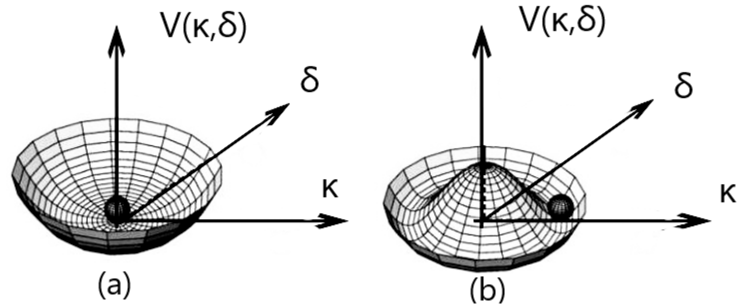

Figure 2.1: Potential when $V(\kappa) = V(\kappa + \delta)$ (a) and when $\delta^i(\kappa)\frac{\partial}{\partial \kappa^i}V(\kappa) = 0$ (b)

2.3.2 The Higgs Mechanism

When a local gauge symmetry is spontaneously broken there will be no Goldstone bosons in the theory but the massless gauge fields will gain mass as a result.

To describe Higgs mechanism[31], Let a theory with SU(2) Symmetry and a scalar doublet with complex scalar fields: ϕ_1 and ϕ_2[32]

$$\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

The Lagrangian reads,

$$\mathcal{L} = \mathcal{L}_{kin} + (D_\mu \phi)^\dagger D_\mu \phi - [m^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2] \tag{2.3.4}$$

Where, the first term is kinetic terms that contain SU(2) field strength tensors and they are equal to zero in the ground state, while the second term contains covariant derivatives and the third term is the Potential of complex scalar fields.

The Potential depends on two parameters m^2 and λ, and the complex scalar-field give non-zero VEV(*vaccum expectation value*) only for $\lambda > 0$ and $m^2 < 0$ which takes the form:

$$\phi^\dagger \phi = \frac{-m^2}{2\lambda} \equiv \frac{\nu^2}{2} \tag{2.3.5}$$

Where, $\nu^2 = -m^2/\lambda$ Selecting one of the minima as the ground state of the system spontaneously breaks the symmetry, How ever Lagrangian is still invariant w.r.t $SU(2)_L \times U(1)_Y$ but the ground state is not symmetric. The VEV reads,

$$< \phi >_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \mu/\sqrt{\lambda} \end{pmatrix} \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu \end{pmatrix} \tag{2.3.6}$$

Where $\mu^2 = -m^2$.

Now, the symmetry $SU(2) \times U(1)$ is spontaneously broken for the selection of the ground state and it gives us an electromagnetic massless gauge field.

$$SU(3)_C \times \boxed{SU(2)_L \times U(1)_Y} \xrightarrow{SSB} SU(3)_c \boxed{U(1)_{QED}}$$

Gauge Bosons massess

For the mass terms of the Gauge boson, we write the kinetic term of the Higgs Lagrangian and evaluate it with VEV, and the contributing terms are[30, 32]

$$\frac{1}{2}\begin{pmatrix} 0 & \nu \end{pmatrix}\left(g_i W_\mu^\alpha \frac{\sigma^\alpha}{2} + \frac{1}{2} g_j B_\mu\right)\left(g_i W_\mu^\beta \frac{\sigma^\beta}{2} + \frac{1}{2} g_j B_\mu\right)\begin{pmatrix} 0 \\ \nu \end{pmatrix}$$

evaluating the above expression we get mass terms for three Gauge bosons:

$$\begin{aligned} W_\mu^\pm &= \frac{1}{\sqrt{2}}(A_\mu^i \mp i A_\mu^j) \quad with \;\; mass \;\; m_{\mathcal{W}} = g\frac{\nu}{2} \\ Z_\mu^0 &= \frac{1}{\sqrt{g_i^2 + g_j^2}}(g^i A_\mu^k - g^j B_\mu) \;\; with \;\; mass \;\; m_{\mathcal{Z}} = \sqrt{g_i^2 + g_j^2}\frac{\nu}{2} \end{aligned} \tag{2.3.7}$$

and a fourth massless field

$$A_\mu = \frac{1}{\sqrt{g^2 i + g_j^2}}(g^i A_\mu^k + g^j B_\mu)$$

Yukawa interactions and Fermion masses

Yukawa interaction terms are added to Standard Model lagrangian in order to generate mass terms for fermions. The Yukawa lagrangian is given by equation 2.2.7

$$\mathcal{L}_{\mathcal{Y}} = -[\mathcal{Y}_e \bar{e}_R \Phi^\dagger L_L + \mathcal{Y}_d \bar{d}_R \Phi^\dagger Q_L + \mathcal{Y}_u \bar{u}_R \tilde{\Phi}^\dagger Q_L + \;\; Hermition \;\; conjugates] \tag{2.3.8}$$

The VEV of the field is given as:

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \nu + h \end{pmatrix}$$

After SSB the simplified Lagrangian is:

$$\begin{aligned} \mathcal{L}_{\mathcal{Y}} = &\left[-\left(\frac{\mathcal{Y}_e \nu}{\sqrt{2}}\right)\bar{e}e - \left(\frac{\mathcal{Y}_e h}{\sqrt{2}}\right)\bar{e}e\right] + \left[-\frac{\mathcal{Y}_d \nu}{\sqrt{2}}\bar{d}d - \frac{\mathcal{Y}_d h}{\sqrt{2}}\bar{d}d\right] \\ &+ \left[-\frac{\mathcal{Y}_u \nu}{\sqrt{2}}\bar{u}u - \frac{\mathcal{Y}_u h}{\sqrt{2}}\bar{u}u\right] \end{aligned} \tag{2.3.9}$$

The above Lagrangian contains the following mass terms:

$$m_e = \frac{\mathcal{Y}_e \nu}{\sqrt{2}} \quad ; m_d = \frac{\mathcal{Y}_d \nu}{\sqrt{2}} \quad ; m_u = \frac{\mathcal{Y}_u \nu}{\sqrt{2}} \tag{2.3.10}$$

2.4 Flavor Physics

The interaction between different flavors of quarks is analyzed in flavor physics there are two types of flavor-changing interactions the charged currents and the neutral currents, FCCC and FCNC respectively.

2.4.1 Charged and Neutral Currents

Flavour Changing Neutral Current(FCNC): The FCNC are the transitions that change the flavor of a fermion without changing its charge. In the Standard Model, FCNC processes are forbidden at the tree level, they only occur at the level of quantum loop correction.

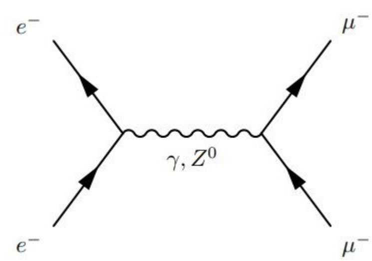

Figure 2.2: Tree level diagram of FCNC processes

/

Flavor changing charged currents: The electroweak interaction of fermions with charged $W_\pm$ bosons in such a way that only left-handed fermions couple to $W_\pm$ bosons and right-handed antifermions couples to $W_\pm$ bosons. In these interactions both the charge and flavor of the fermion are changed. The Lagrangian for the FCCC[38] process is given as,

$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}}[W_\mu^+ \bar{\psi}_L \gamma^\mu (V_{CKM})_{ij} \psi_L + W_\mu^- \bar{l}_L \gamma^\mu \nu_L + h.c] \tag{2.4.1}$$

Where V_{CKM} is the quark mixing matrix called CKM matrix.

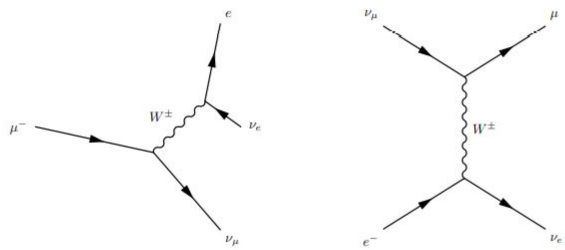

Figure 2.3: Tree level diagram of FCCC processes

2.5 Quark Mixing and Parametrization

Fermion gains mass via Yukawa interaction giving rise to quark mixing which is explained by CKM matrix[35]. The CKM matrix connects mas eigenstates to weak eigenstates. It is a 3×3 unitary matrix that can be parameterized by 3 angles and a phase.

$$\begin{pmatrix} \mathrm{d}' \\ \mathrm{s}' \\ \mathrm{b}' \end{pmatrix} = \begin{pmatrix} \mathrm{V}_{ud} & \mathrm{V}_{us} & \mathrm{V}_{ub} \\ \mathrm{V}_{cd} & \mathrm{V}_{cs} & \mathrm{V}_{cb} \\ \mathrm{V}_{td} & \mathrm{V}_{ts} & \mathrm{V}_{tb} \end{pmatrix} \begin{pmatrix} \mathrm{d} \\ \mathrm{s} \\ \mathrm{b} \end{pmatrix} \tag{2.5.1}$$

This 3×3 matrix is the CKM matrix and it can be parametrized as

The standard parametrization is given as:

$$\begin{pmatrix} c_{12}c_{13} & s_{12}s_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \tag{2.5.2}$$

Where, $s_{ij} = sin\theta_{ij}, c_{ij} = cos\theta_{ij}$ and δ is the phase with range $0 \le \delta \le 2\pi$

The Wolfenstein Parameterization: Experimentally it is known that:

$$s_{13} \gg s_{23} \gg s_{12} \gg 1$$

We use Wolfenstein Parameterization to tackle this[35].

$$\begin{pmatrix} 1 - \lambda^2/2 & \lambda & \mathrm{A}\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & \mathrm{A}\lambda^2 \\ \mathrm{A}\lambda^3(1 - \rho - i\eta) & -\mathrm{A}\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \tag{2.5.3}$$

2.6 SM Limitations

The SM is the most successful model in explaining particles and their interactions, but there are still many questions to which there is no answer in the standard model. Some of the unanswered questions are:

The hierarchy problem: This problem arises from the fact that the Plank scale is meant to be the fundamental scale which is of an order of $10^{19}GeV$ and the masses of the particles are of order $100GeV$, which is 10^{17} blow the plank scale.

The scale for particle masses is governed by spontaneous symmetry breaking in which Higgs acquires a non-zero vacuum expectation value. The problem is why there is so much difference between Higgs mass and plank's scale which SM cannot explain.

Energy of the vacuum: Also known as a cosmological constant has an observed value nearly equal to zero but the value predicted by quantum field theory (assuming the plank scale as fundamental scale) is 120 orders of time bigger than the observed value[40]. This problem is bigger than the Higgs mass problem.

Mass discrepancies between different generations of fermions: As discussed above there is a huge difference between fermions' mass and Plank's scale but there is also a mass difference between different generations of quarks, leptons, and neutrinos. Also, the quark mixing is not very large but the neutrino mixing is very large. This mass and mixing discrepancy is unexplainable by the standard model and points toward a new symmetry.[40]

To study beyond the standard model there is a collection of models and theories called Physics beyond the standard model and some of the New Physics models will be discussed in this thesis.

Chapter 3

Theoretical Frame Work

The Effective field theories are very useful tools in several areas of particle physics, it deals with widely-separated energy scales. The energy scales can be classified on the basis of their transition from basic to an effective level. For example, there are three energy scales in B-mesons decay. The first scale in a mass of W-boson, $M_W \approx 100Gev$, and is a weak energy scale. The second scale is the mass of the B-meson itself, $M_B \approx 5Gev$, because the energy scale of the process is the mass of the decaying meson, and finally the third scale is the strong interaction energy scale, $\Lambda_{QCD} \approx 0.2 - 1Gev$, because mesons is a bound state of quarks.

$$\Lambda_{QCD} << M_B << M_W$$

Now, to construct an effective Hamiltonian we will use the Operator-Product expansion technique.

3.1 Operator Product Expansion (OPE)

OPE for B mesons is very important for the theory of weak decays. Consider, for example, a W-Boson exchange process as shown in the figure 3.1. The process shown in the diagram is the non-leptonic decay of the B meson. This quark level transition is considered to be accompanied by all kinds of QCD interactions, like the binding of quarks in mesons. For simplification, we may use a suitable expansion parameter, like the mass of W-Boson which is larger than other momentum scales in this problem. The amplitude therefore can be expanded as,

$$\mathcal{A} = C\left(\frac{M_W}{\mu}, \alpha\right). < Q_f > + \mathcal{O}\left(\frac{p^2}{M_W^2}\right) \tag{3.1.1}$$

Where, $< Q_f >$ is a local four-quark operator, $< Q_f >= (\bar{d}u)_{V-A}(\bar{u}b)_{V-A}$, and C is the coupling constant. This expansion in terms of $1/M_W$ is called OPE because

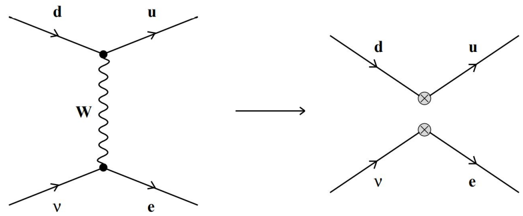

Figure 3.1: Operator Product Expansion for weak decays

the nonlocal product of two quark-current operators $(\bar{d}u)$ and $(\bar{u}b)$ which interacts via W-Boson, is expanded in terms of local operators series.

This expansion shows an approximation of a heavy W-Boson by point like four-quark interaction. Keeping this in mind the OPE can be expressed in more natural language by expressing the local four-quark operator as four-quark interaction vertex[61] and for coupling constant use Wilson coefficient. Together they define an effective Hamiltonian $\mathcal{H}_{eff} = C.Q_f$.

Ignoring QCD(which we will add later in this section) the OPE in momentum space reads,

$$\begin{aligned}\mathcal{A} &= \frac{g_w^2}{8} V_{ud}^* V_{ub} \frac{i}{k^2 - M_W^2} (\bar{d}u)_{V-A} (\bar{u}b)_{V-A} \\ \mathcal{A} &= -i \frac{G_F}{\sqrt{2}} V_{ud}^* V_{ub} C \cdot (\bar{d}u)_{V-A} (\bar{u}b)_{V-A} + \mathcal{O}\left(\frac{k^2}{M_W^2}\right)\end{aligned} \tag{3.1.2}$$

where, $C = 1$ and

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{ud}^* V_{ub} (\bar{d}u)_{V-A} (\bar{u}b)_{V-A} \tag{3.1.3}$$

Without QCD effects there is only one dimension 6 operators in which color indices have been made explicit, $Q_1 (\bar{d}u)_{V-A} (\bar{u}b)_{V-A}$. QCD generates another operator which has the same flavor and Dirac structure but has a different color structure.

$$Q_2 = (\bar{d}_i u_j)_{V-A} (\bar{u}_j b_i)_{V-A}$$

This operator can be defined by the figure 3.1 and a useful identity for SU(N) Gell-Mann matrices[61] which reads.

$$(\bar{d}_i T^a_{ik} u_k)(\bar{u}_j T^a_{jl} b_l) = -\frac{1}{2N} (\bar{d}_i u_i)(\bar{u}_j b_j) + \frac{1}{2} (\bar{d}_i u_j)(\bar{u}_j b_j) \tag{3.1.4}$$

The total effective Hamiltonian is given as,

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{ud}^* V_{ub} (C_+ Q_+ + C_- Q_-) \tag{3.1.5}$$

Where, $Q_\pm = \frac{Q_1 + Q_2}{2}$ and $C_\pm = C_1 \pm C_2$

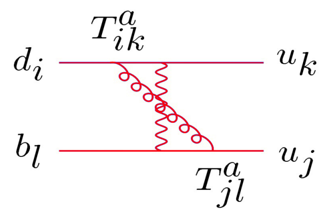

Figure 3.2: QCD corrections with color allocation

3.2 Heavy Quark effective theory

In problems involving heavy quarks, new symmetries appear in Lagrangian which cannot be tackled by QCD. Another approach is being used, which is called Heavy Quark Effective Theory[54]

3.2.1 Heavy quark symmetry

The strong interaction of systems involving heavy quarks is easier to understand than systems involving only light quarks due to several reasons one being asymptotic freedom, which is the variation of QCD coupling constant with length scale. At a short distance scale(large momentum transfer) the QCD coupling constant becomes weak and at a large distance scale(low energy scale) the coupling constant becomes strong which leads to non-perturbative phenomena on a length scale $R_{had} \approx 1/\Lambda_{QCD} \approx 1fm$, which gives the size of hardons.

When the mass of the quark is above $\Lambda_{QCD} \approx 1fm$ it is called a heavy quark according to that scale $t, \ \ b, \ \ and \ \ c$ are heavy quarks and $u, \ \ d, \ \ and \ \ s$ are light quarks.

A system containing heavy and light quarks is like a bound state in which heavy quark serves as a static field source and light quarks interact with that field and this heavy-light quark system resembles hydrogen. The Compton wavelength associated with heavy quark is much less than the size of a hadron which means that heavy quark quantum numbers are resolved at a high energy scale on the other hand the gluon exchange between heavy and light quark is resolved at lower energy than heavy quark due to this reason the light degrees of freedom is suppressed by flavor and spin orientation of heavy quark and therefore the light quark only feels the color field generated by heavy quark.

As we apply the limit $m_Q \rightarrow \infty$ the system of heavy-light quarks has the same configuration of light degrees of freedom regardless of their flavor and spin quantum number that gives the relation between properties of heavy-light quarks particle such as $B^{(*)}$, $D^{(*)}$ or heavy baryons. It is concluded that in a heavy-light quark system if we change the heavy quark with another heavy quark having the same velocity the light degree of freedom will remain the same this gives rise to a new symmetry, To N_h number of heavy quarks there is $SU(2N_h)$ symmetry group this is called heavy quark symmetry.

3.2.2 HQET Lagrangian

At low energy, heavy degrees of freedom in a heavy-light quarks system is repressed by light degrees of freedom. To circumvent the complexity of heavy-light quark interaction via strong color force, we can build a low-energy theory in which heavy degrees of freedom are integrated.

We construct a new energy scale with heavy quark mass as a high energy limit and a low energy scale is Λ_{QCD} and these two scales are separated by a mass scale μ. As we discussed earlier in a heavy-light quarks system(hadron) the heavy quark is massive and serves as a static color source[54] and the velocity of the heavy quark is the velocity of hadron. The momentum of heavy quark reads:

$$p^\mu = m_Q v^\mu + k^\mu$$

Here v is heavy meson 4-velocity in its rest frame and is given as $v = (1, 0, 0, 0)$ and k is residual momentum[55]. The residual momentum changes by a factor $\Delta k \approx \Lambda_{QCD}$ when a heavy quark interacts with a light degree of freedom, but the accompanying changes in the velocity of the heavy quark vanish as $\Lambda_{QCD}/m_Q \to 0$. And at this stage new fields are introduced to the theory termed small and large component fields H_v and h_v respectively and they are given as[49, 50]:

$$\begin{aligned} \mathrm{h}_v(x) &= e^{im_Q v.x}\frac{1+\not{v}}{2}Q(x) \\ \mathrm{H}_v(x) &= e^{im_q v.x}\frac{1-\not{v}}{2}Q(x) \end{aligned} \tag{3.2.1}$$

And these fields follow the following relation[49]:

$$Q(x) = e^{-im_Q v.x}[h_v(x) + H_v(x)] \tag{3.2.2}$$

These large and small fields annihilate a heavy quark and create a heavy antiquark and they satisfy the following relations:$\not{v}h_v = h_v$ and $\not{v}H_v = -H_v$.

The QCD Lagrangian is given as:

$$\mathcal{L}_{QCD} = \bar{Q}(i\not{D} - m_Q)Q \tag{3.2.3}$$

Now this QCD lagrangian in terms of equation 3.2.1 reads:

$$\mathcal{L} = \bar{h}_v iv.\mathrm{D}h_v - \bar{\mathrm{H}}_v(iv.\mathrm{D} + 2m_Q)\mathrm{H}_v + \bar{h}_v i\not{D}_\perp \mathrm{H}_v + \bar{\mathrm{H}}_v i\not{D}_\perp h_v \tag{3.2.4}$$

$$D^\mu_\perp = D^\mu - v^\mu.v.D$$

Now it is clear from the above expression that the large-component field corresponds to the massless degree of freedom and the small-component field corresponds to a heavy degree of freedom with $2m_Q$ that will be removed from ineffective theory construction. The third and fourth term corresponds to the creation pr annihilation of heavy quark and anti-quarks.

The equation of motion gives:

$$H_v = \frac{1}{2m_Q + iv.D} i\not{D}_\perp h_v \tag{3.2.5}$$

Now writing the equation (1.2.4) in terms of h_v by using equation (1.2.5)

$$\mathcal{L}_{eff} = \bar{h}_v iv.Dh_v + \bar{h}_v i\not{D}_\perp \frac{1}{2m_Q + iv.D} i\not{D}_\perp h_v \tag{3.2.6}$$

We can write the above equation in a more elegant way by expanding the second term by Taylor expansion:

$$\mathcal{L}_{eff} = \bar{h}_v iv.Dh_v + \bar{h}\frac{i\not{D}_\perp}{2m_Q}\left(1 + \sum_{n=0}^{\infty}\left(-\frac{iv.D}{2m_Q}\right)^n\right) i\not{D}_\perp h_v \tag{3.2.7}$$

The above Lagrangian is further simplified by using:

$$\not{D}_\perp \not{D}_\perp = g_{\mu\nu} D^\mu_\perp D^\nu_\perp - i\sigma_{\mu\nu} D^\mu_\perp D^\nu_\perp$$

by using this relation we get the Lagrangian in $1/m_Q^n$ expansion which reads:

$$\mathcal{L}_{eff} = \bar{h}_v\left(iv.D - \frac{D^2}{2m_Q} - \frac{g}{4m_Q}\sigma_{\mu\nu}G^{\mu\nu}\right)h_v + \mathcal{O}\left(\frac{1}{m_Q^2}\right) \tag{3.2.8}$$

Here the factor $G^{\mu\nu}$ is the QCD strength tensor and if we apply the limit $m \to \infty$ we are left with:

$$\mathcal{L}_{eff} = \bar{h}_v iv.Dh_v \tag{3.2.9}$$

Now we will write effective Hamiltonian for B-meson semileptonic decays by using these tools.

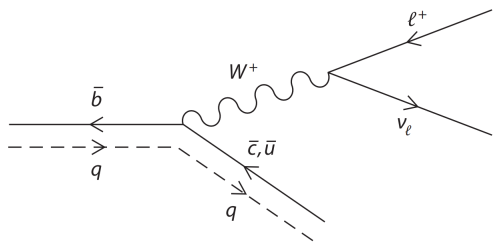

Figure 3.3: FCCC process of B meson decay at quark level
[59]

3.3 B meson decays

The B meson system has shown to be an ideal model for both theoretical and experimental studies of the Standard Model (SM), as well as for examining new physics (NP) events at low energy scales. Semileptonic and leptonic B meson decay, in particular, are ideal for studying NP. Figure 3.3 depicts an FCCC process of B-meson decay.

3.3.1 $\bar{B} \to D^{(*)}\tau\bar{\nu_\tau}(b \to c\tau\bar{\nu_\tau})$

The decay of bottom quark into charm quark including tau-lepton is described in SM by four-fermionic interaction of left-handed charged currents. Other operators may arise in case of new physics effects. The most general effective Hamiltonian describing all possible four fermi operators is written as

$$\mathcal{H}_{eff} = \frac{4G_F V_{cb}}{\sqrt{2}}\left((1 + \mathrm{C}_{V_1})\mathcal{O}_{V_1} + \mathrm{C}_{V_2}\mathcal{O}_{V_2} + \mathrm{C}_{S_1}\mathcal{O}_{S_1} + \mathrm{C}_{S_2}\mathcal{O}_{S_2} + \mathrm{C}_T\mathcal{O}_T\right) \tag{3.3.1}$$

Where the four-fermionic operators are defined as

$$\begin{aligned} \mathcal{O}_{V_1/V_2} &= \bar{c}_{L/R}\gamma^\mu b_{L/R}\bar{\tau}_{L/L}\gamma_\mu\nu_{L/L} \\ \mathcal{O}_{S_1/S_2} &= \bar{c}_{L/R}b_{R/L}\bar{\tau}_{R/R}\nu_{L/L} \\ \mathcal{O}_T &= \bar{c}_R\sigma^{\mu\nu}b_L\bar{\tau}_R\sigma_{\mu\nu}\nu_L \end{aligned} \tag{3.3.2}$$

and $C_{V,S,T}$ are Wilson coefficients and for the tensor operator the following notation is used,

$$\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$$

.

3.3.2 Helicity amplitudes for $\bar{B} \to D^{(*)}\tau\bar{\nu_\tau}$

The $\bar{B} \to D^{(*)}\tau\bar{\nu_\tau}$ helicity amplitude is written as,

$$\mathcal{M}^{\lambda_\tau,\lambda_M} = \mathcal{M}_{SM}^{\lambda_\tau,\lambda_M} + \mathcal{M}_{V_{1,2}}^{\lambda_\tau,\lambda_M} + \mathcal{M}_{S_{1,2}}^{\lambda_\tau,\lambda_M} + \mathcal{M}_{T}^{\lambda_\tau,\lambda_M} \tag{3.3.3}$$

Where the first term is the SM contribution in amplitude and the other terms are NP effects. The amplitude can be written as,

$$\mathcal{M} = \frac{G_F V_{qb}}{2} \sum_{a,a',b,b'} L(a,b)H(a',b') \tag{3.3.4}$$

Where H and L are leptonic and hadronic amplitudes, the hadronic amplitudes for $B \to D\tau\bar{\nu_\tau}$ reads[58]

$$H = \frac{1}{\sqrt{m_B m_D}}[h_+(w)(v+v')^\mu + h_-(w)(v-v')^\mu] \tag{3.3.5}$$

Where $h_\pm$ are the hadronic form factors,v and v' are the velocities of initial and final state particles. In HQET $h+$ normalized to unity and h_- becomes zero at $m \to \infty$ And the leptonic amplitudes are solved conventionally.

3.3.3 $\bar{B} \to D^{(*)}\tau\bar{\nu_\tau}$ decay rate

The $\bar{B} \to D^{(*)}\tau\bar{\nu_\tau}$ differential decay rate is given as,

$$\frac{d\Gamma}{dq^2 dcos\theta} = \frac{1}{2M_B}|\mathcal{M}|^2 dX \tag{3.3.6}$$

Where dX is the 3-body Lorentz invariant phase space,

$$dX = \frac{\sqrt{((M_B+M_D)^2-q^2)((M_B-M_D)^2-q^2)}}{256\pi^3 M_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)dq^2 dcos\theta$$

Now, by putting the value for the amplitude and integrating the above equation on $dcos\theta$ we get,

$$\begin{aligned}\frac{d\Gamma}{dq^2} &= \left[\frac{G_F^2|V_{cb}|^2}{192\pi^3 M_B^3} q^2 \lambda_D^{1/2}(q^2)\left(1-\frac{m_\tau^2}{q^2}\right)^2\right] \\ &\times \left(|1+V_{LL}+V_{RL}|^2+|V_{LR}+V_{RR}|^2\right)\left[(H_{0,V}^s)^2\left(\frac{m_\tau^2}{2q^2}+1\right)+\frac{3m_\tau^2}{2q^2}(H_{t,V}^s)^2\right] \\ &+ \frac{3}{2}(H_S^s)^2\left(|S_{RL}+S_{LL}|^2+|S_{RR}+S_{LR}|^2\right)+8\left(|T_{LL}|^2+|T_{RR}|^2\right)(H_T^s)^2\left(1+\frac{2m_\tau^2}{q^2}\right) \\ &+ 3\mathcal{R}e\left[(1+V_{LL}+V_{RL})(S_{RL}+S_{LL})^*+(V_{LR}+V_{RR})(S_{RR}+S_{LR})^*\right]\frac{m_\tau}{\sqrt{q^2}}H_S^s H_{t,V}^s \\ &- 12\mathcal{R}e\left[(1+V_{LL}+V_{RL})T_{LL}^*+(V_{RR}+V_{LR})T_{RR}^*\frac{m_\tau}{\sqrt{q^2}}H_T^s H_{0,V}^s\right]\end{aligned} \tag{3.3.7}$$

Where, $S_{L/R,L/R}, V_{L/R,L/R}$ and T are Wilson coefficients that are related to NP effects.

3.4 New Physics

3.5 The W' Model

The W' is a spin-1 massive hypothetical particle with an electric charge ±1. It is a color singlet which couples to fermions. The W' bosons appear in many theories which extend the Standard Model gauge group. The Lorentz invariant effective Lagrangian density which describes the coupling of general W' to quarks and leptons reads[41]

$$\mathcal{L}_{eff}^{W'} = \frac{W'_\mu}{\sqrt{2}}\left[\bar{u_i}(\varepsilon_{u_i d_j}^L P_L+\varepsilon_{u_i d_j}^R P_R)\gamma^\mu d_j+\bar{l_i}(\varepsilon_{l_i\nu_j}^L P_L+\varepsilon_{l_i\nu_j}^R P_R)\gamma^\mu \nu_j\right]+H.c., \tag{3.5.1}$$

Where P_l and P_R are left and right-handed projection operators respectively given as $P_{L/R}=(1\pm\gamma_5)/2$ and the terms $\varepsilon_{u_i d_j}^L, \varepsilon_{u_i d_j}^R, \varepsilon_{l_i\nu_j}^L and \varepsilon_{l_i\nu_j}^R$ are dimensionless parameters for new physics flavor effects. In the standard model only left-handed coupling are non-zero .

$b \to c\tau\bar{\nu_\tau}$ process is mediated by W-boson exchange, The Standard Model effective Lagrangian for this process is,

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}}V_{cb}(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau) \tag{3.5.2}$$

According to Eq. (3.4.1), a general W'-boson exchange leads to additional tree-level effective interactions, so the total effective lagrangian can be given as

$$\begin{aligned}\mathcal{L}_{eff} =& -\frac{4G_F}{\sqrt{2}}V_{cb}[(1+C_V^{LL})(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau) + C_V^{RL}(\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu_\tau) \\ &+ C_V^{LR}(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_R \nu_\tau) + C_V^{RR}(\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma^\mu P_R \nu_\tau)]\end{aligned} \tag{3.5.3}$$

Where, C_V^{LL}, C_V^{LR}, C_V^{RL}, and C_V^{RR} are called Wilson coefficients which are related to New Physics effects and defined as

$$C_V^{LL} = \frac{\sqrt{2}}{4G_F V_{cb}} \frac{\varepsilon_{cb}^L \varepsilon_{\tau\nu_\tau}^L}{M_{W'}^2} \quad W' coupling\ to\ LH - quark\ and\ LH - lepton \tag{3.5.4}$$

$$C_V^{LR} = \frac{\sqrt{2}}{4G_F V_{cb}} \frac{\varepsilon_{cb}^L \varepsilon_{\tau\nu_\tau}^R}{M_{W'}^2} \quad W' coupling\ to\ LH - quark\ and\ RH - lepton \tag{3.5.5}$$

$$C_V^{RL} = \frac{\sqrt{2}}{4G_F V_{cb}} \frac{\varepsilon_{cb}^R \varepsilon_{\tau\nu_\tau}^L}{M_{W'}^2} \quad W' coupling\ to\ RH - quark\ and\ LH - lepton \tag{3.5.6}$$

$$C_V^{RR} = \frac{\sqrt{2}}{4G_F V_{cb}} \frac{\varepsilon_{cb}^R \varepsilon_{\tau\nu_\tau}^R}{M_{W'}^2} \quad W' coupling\ to\ RH - quark\ and\ RH - lepton \tag{3.5.7}$$

W' **Model contribution to** $b \to c\tau\bar{\nu_\tau}$**:** The only Wilson's Coefficient contributing to the decay is,

$$C_V^{LL} = \frac{\sqrt{2}}{4G_F V_{cb}} \frac{\varepsilon_{cb}^L \varepsilon_{\tau\nu_\tau}^L}{M_{W'}^2} \tag{3.5.8}$$

Where $M_{w'}$ is W' mass and the factor $\varepsilon_{cb}^L \varepsilon^L$ is given as[53],

$$\varepsilon_{cb}^L \varepsilon^L = (0.12)\left(\frac{M_{W'}}{TeV}\right)^2$$

3.6 Vector Leptoquark Model

Leptoquarks (LQs)[64] are hypothetical particles that appear in extensions of the Standard Model. They have one unique feature that distinguishes them from all other elementary particles. Quarks can be converted into leptons and vice versa using LQs. As a result, they constitute a one-of-a-kind source of New-Physics that can be and has been thoroughly tested. The discovery of LQ could be preliminary evidence of matter unification.

LQs are hypothetical particles that simultaneously couple to a quark and lepton. They can be spin-zero (scalar) or vector (spin-one). It is easy to classify possible LQs due to finite numbers of fermions (quarks and leptons). The Standard Model fermionic multiplets are given as,

$$L_L^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix} \equiv (1,2,-1/2)^i \quad Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} \equiv (3,1,2/3)^i$$
$$e_R^i \equiv (1,1,-1)^1 \quad , u_R^i \equiv (3,1,2/3)^i \quad , d_R^i \equiv (3,1,-1/3)^i \tag{3.6.1}$$

Where the numbers in the parenthesis denote SM gauge group $(SU(3)_c, SU(2)_L)_Y$ and $i = 1,2,3$ are flavor indices and L/R represent Left/Right-handed fields. For example, A Vector Leptoquark triplet U_3 that transforms under gauge group $(3,3,2/3)$ couples to fermions via Lagrangian [65]

$$\mathcal{L}_{LQ} = x_{ij}^{LL} \bar{Q}_i \gamma_\mu \tau . U_3^\mu L_j + H.c \tag{3.6.2}$$

Here τ are the Pauli matrices, L and Q are quarks and leptons left-handed doublets and x_{ij} is the coupling parameter. The lagrangian 1.5.2 can be written on a mass basis by rotating the coupling matrix x_{ij}, where necessary, with Cabibbo-Kobayashi-Maskawa(CKM) matrix U from the left or with Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix V from the right.

$$\begin{aligned} \mathcal{L}_{U_3} = & U_{3\mu}^{(2/3)} \left[(UxV)_{ij} \bar{u}_i \gamma^\mu P_L \nu_j - x_{ij} \bar{d}_i \gamma^\mu P_L l_j \right] \\ & U_{3\mu}^{(5/3)} (\sqrt{2} Ux)_{ij} \bar{u}_i \gamma^\mu P_L l_j \\ & U_{3\mu}^{(-1/3)} (\sqrt{2} xV)_{ij} \bar{d}_i \gamma^\mu P_L \nu_j + h.c \end{aligned} \tag{3.6.3}$$

The decay process $b \to c\tau\bar{\nu_\tau}$ also proceeds via vector Leptoquark $U_{3\mu}^{2/3}$ exchange and vector Leptoquark correction to SM Lagrangian is written as[45]

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cb} (1 + V_L)(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau) \tag{3.6.4}$$

Where the Wilson coefficient is given as

$$V_L = \frac{\sqrt{2}}{4G_F V_{cb}} \frac{x_{b\tau}^* (Ux)_{c\tau}}{M_U^2}. \tag{3.6.5}$$

Vector Leptoquark Model Contribution to $b \to c\tau\bar{\nu_\tau}$: The only contribution of the Vectorleptoquark model that we used in this decay is given as,

$$V_L = \frac{\sqrt{2}}{4G_F V_{cb}} \frac{x_{b\tau}^* (Ux)_{c\tau}}{M_U^2}$$

Where,

$$x_{b\tau}^* (Ux)_{c\tau} = 0.18 \pm 0.04 \left(\frac{M_U}{TeV} \right)^2$$

3.7 The Aligned-Two-Higgs-Doublet Model(THDM)

The THDM is one of the most basic expansions of SM, with several intriguing phenomenological properties. Many New-Physics situations can result in a low-energy spectrum, which extends the SM by one scalar doublet. As a result, THDM is an excellent theory for studying low-energy effects. The scalar doublet extension consists of two charged and three neutral scalar fields, as well as three Goldstone bosons required to provide masses to gauge bosons.

Here, we are going to discuss THDM in its minimum version. The THDM is an $SU(3)_c \times SU(2)_L \times U(1)_Y$ theory with Standard Model fermionic content(with no right-handed neutrinos) with two additional $SU(2)$ scalar doublets $\psi_i (i = 1, 2)$ of $Y = 1/2$ hypercharge. The neutral components of scalar doublets acquire vacuum expectation values $< \psi_i >_0 = 1/\sqrt{2}(0, v_i e^{i\theta_i})$[62]. We can define new basis(Higgs basis) for scalar doublets using $SU(2)$ transformation in scalar space, such that only on doublet has nonzero vacuum expectation value ($tan\alpha \equiv v_2/v_1$)

$$\begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix} = \begin{bmatrix} cos\alpha & sin\alpha \\ sin\alpha & -cos\alpha \end{bmatrix} \begin{pmatrix} \psi_1 \\ e^{i\theta}\psi_2 \end{pmatrix}$$

This has the benefit of isolating the three Goldstone fields $G_{\pm}(x)$ and G_0 as a component of Ψ_1

$$\Psi_1 = \begin{bmatrix} G_+ \\ \frac{1}{\sqrt{2}}(v + C_1 + iG^0) \end{bmatrix}, \quad \Psi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(C_2 + iC_3) \end{bmatrix} \tag{3.7.1}$$

On Higgs basis the Yukawa lagrangian is given as,

$$\begin{aligned} \mathcal{L}_Y = & -\frac{\sqrt{2}}{v}[\bar{Q}_L^{'}(M_d\Phi_1 + Y_d^{'}\Phi_2)d_R^{'} \\ & + \bar{Q}_L^{'}(M_u\tilde{\Phi}_1 + Y_u^{'}\tilde{\Phi}_2)u_R^{'} \\ & + \bar{L}_L^{'}(M_l\Phi_1 + Y_l^{'}\Phi_2)l_R^{'} + H.c.] \end{aligned} \tag{3.7.2}$$

Here, $M_i^{'}$ are fermions mass matrices and $Y^{'}$ are the yukawa couplings, $\bar{Q}_L^{'}$ and $\bar{L}_L^{'}$ are left-handed fermion doublets, $u_R^{'}, d_R^{'}$ and $l_R^{'}$ are right-handed singlets and Φ_i and $\tilde{\Phi}_i$ are scalar doublets. Because there are two alternative couplings of Yukawa matrices to a given right-handed fermion field and they cannot be diagonalized simultaneously, the Yukawa Lagrangian yields FCNC at the tree level. The Yukawa matrices can be diagonalized concurrently if they are aligned in flavor space, which is a simple solution to this problem. [63]

$$Y_{d,l} = \xi_{d,l} M_{d,l}, \quad Y_u = \xi_u^* M_u \tag{3.7.3}$$

Where $\xi_{d,l,u}$ are complex or real parameters. Now, the Lagrangian in terms of fermion mass-eigenstate can be written as

$$\mathcal{L}_{H^{\pm}} = -\frac{\sqrt{2}}{v} H^+ \left[\bar{u}(\xi_d U M_d P_R - \xi_u M_u^{\dagger} U P_L)d + \xi_l \bar{\nu} M_l P_R l\right] + h.c., \tag{3.7.4}$$

Where U is the CKM matrix.
The Contribution of T2HDM to the decay process $b \to c\tau\bar{\nu_\tau}$ can be written as

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + G_S\bar{\tau}(1-\gamma_5)\nu_\tau\bar{c}b - G_P\bar{\tau}(1-\gamma_5)\nu_\tau\bar{c}\gamma_5 b \tag{3.7.5}$$

Where G_S and G_P are Wilson coefficients which are given as

$$\begin{aligned} G_S &= \frac{\xi_d m_b - \xi_c m_c}{M_{h^\pm}^2}(\xi_\tau^* m_\tau) \\ G_P &= -\frac{\xi_d m_b - \xi_c m_c}{M_{h^\pm}^2}(\xi_\tau^* m_\tau) \end{aligned} \tag{3.7.6}$$

A2HDM contribution to $b \to c\tau\bar{\nu_\tau}$: The only Wilson's coefficient which contributes to $B \to D$ decay is given below,

$$G_S = \frac{\xi_d m_b - \xi_c m_c}{M_{h^\pm}^2}(\xi_\tau^* m_\tau)$$

Where, the factors,

$$\begin{aligned} \frac{\xi_\tau^*\xi_d}{M_H^2} &= [-0.036, 0.008] \\ \frac{\xi_\tau^*\xi_c}{M_H^2} &= [-0.006, 0.037] \end{aligned}$$

Chapter 4

Analysing $B \to D\tau\bar{\nu}$ decay in Standard Model and Beyond

4.1 Theoretical Overview

The semi-leptonic $b \to c\tau\bar{\nu}$ decay is explained by charged left-handed currents of four-fermion interaction in Standard Model. As new physics effects begin to appear other operators will be induced. As in previous chapters we built up the theoretical framework for B meson decays, and used that framework to write the effective Hamiltonian for $B \to D\tau\bar{\nu}$ decay with New Physics effects. The most general effective Hamiltonian including NP effects which are related to our work can be written in Eq. 3.3.1,

$$\begin{aligned}\mathcal{H}_{eff} =& \frac{4G_F}{\sqrt{2}} V_{cb}(\bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau \bar{c}\gamma^\mu b + C_L^W \bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau \bar{c}\gamma^\mu b \\ &+ C_R^W \bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau \bar{c}\gamma^\mu b + C_L^{VLQ} \bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau \bar{c}\gamma^\mu b \\ &+ G_S \bar{\tau}\nu_\tau(1-\gamma_5)\bar{c}b) - G_p \bar{\tau}(1-\gamma_5)\nu_\tau \bar{c}\gamma_5 b + h.c..\end{aligned} \tag{4.1.1}$$

where, $C_{l,R}^W, C_L^{VLQ}$ and $G_{S,P}$ are NP effects (Wilson coefficients) for W' model, Vector Leptoquark and A2HDM respectively. Here we neglected all the right-handed neutrinos effects and the effect of tensor-operators. In the next sections, we will explain $b \to c\tau\bar{\nu}$ form factors, decay rate, and observables related to the decay.

4.2 The $B \to D\tau\bar{\nu}$ decay transition form factors

The matrix elements for the above Hamiltonian are given as,

$$\begin{aligned}
&\langle D(k)|\,\bar{c}\gamma^{\mu}b\left|\bar{B}(p)\right\rangle = \sqrt{m_B m_D}[H^{+}(w)(w)(v+v')^{\mu} + H^{-}(w)(\omega)(v-v')^{\mu}]\\
&\langle D(k)|\,\bar{c}\gamma^{\mu}\gamma^{5}b\left|\bar{B}(p)\right\rangle = 0\\
&\langle D(k)|\,\bar{c}b\left|\bar{B}(p)\right\rangle = \sqrt{m_B m_D}(w+1)h_S(w)\\
&\langle D(k)|\,\bar{c}\gamma^{5}b\left|\bar{B}(p)\right\rangle = 0\\
&\langle D(k)|\,\bar{c}\sigma^{\mu\nu}b\left|\bar{B}(p)\right\rangle = -i\sqrt{M_B M_D}H_T(w)(v^{\mu}v'^{\mu} - v^{\nu}v'^{\nu})
\end{aligned} \tag{4.2.1}$$

Where the matrix elements corresponding to $\bar{c}\sigma^{\mu\nu}\gamma_5 b$ can be written by using the following identity,

$$\sigma^{\mu\nu}\gamma_5 = -\frac{i}{2}\epsilon^{\mu\nu\alpha\beta}\sigma_{\alpha\beta}$$

and H^{+}, H^{-} and H_S are the form factors for the above matrix elements which are given as[51],

$$\begin{aligned}
\mathrm{H}^{+}(w) &= \frac{(1-\mathrm{r})^2 S_1(w)(w+1) - (1-\mathrm{r})^2 V_1(w)(w-1)}{2(\mathrm{r}^2 - 2\mathrm{r}w + 1)}\\
\mathrm{H}^{-}(w) &= \frac{(1-\mathrm{r}^2)(w+1)(S_1(w) - V_1(w))}{2(\mathrm{r}^2 - 2\mathrm{r}w + 1)}\\
h_S(w) &= H^{+}(w) - \frac{(1+\mathrm{r})(w-1)}{(1-\mathrm{r})(w+1)}H^{-}(w) = S_1(w)
\end{aligned} \tag{4.2.2}$$

Where $r = m_D/m_B$ and $w = v'.v$ which represent momentum transfer of $\bar{B} \to D\tau\bar{\nu}$ decay

4.3 Observables

We calculated and plotted several observables w.r.t q^2 and compare them in Standard Model and above mentioned New Physics Models and the numerical analysis and data have been discussed in Section 4.4.

4.3.1 $\mathcal{B}(B \to D\tau\bar{\nu}_\tau)$(Branching ratio)

The branching ratio (branching fraction) is the proportion of events detected for a given particle to decay in a particular manner. The total of a particle's branching ratios is one. The branching ratio is calculated by dividing the partial decay width by the overall width. Measurements of particle characteristics and interactions in high-energy physics experiments led to the development of a theoretical model, known as the Standard Model (SM). Estimates for the SM coupling constants are derived from particle production and decay measurements. Cross sections for rare reactions may be predicted using these coupling constants, and the predictions are experimentally validated when possible. The $B \to D$ branching ratio is given as,

$$\frac{d\mathcal{B}}{dq^2} = \tau_B \frac{d\Gamma(B \to D)}{dq^2} \tag{4.3.1}$$

Where, $\frac{d\Gamma}{dq^2}$ is the decay rate which is given by Eq. 3.3.7 and τ_B is the life-time of B meson. By putting numerical values we plotted the Branching ratio against q^2, which is shown in figure[4.3.1].

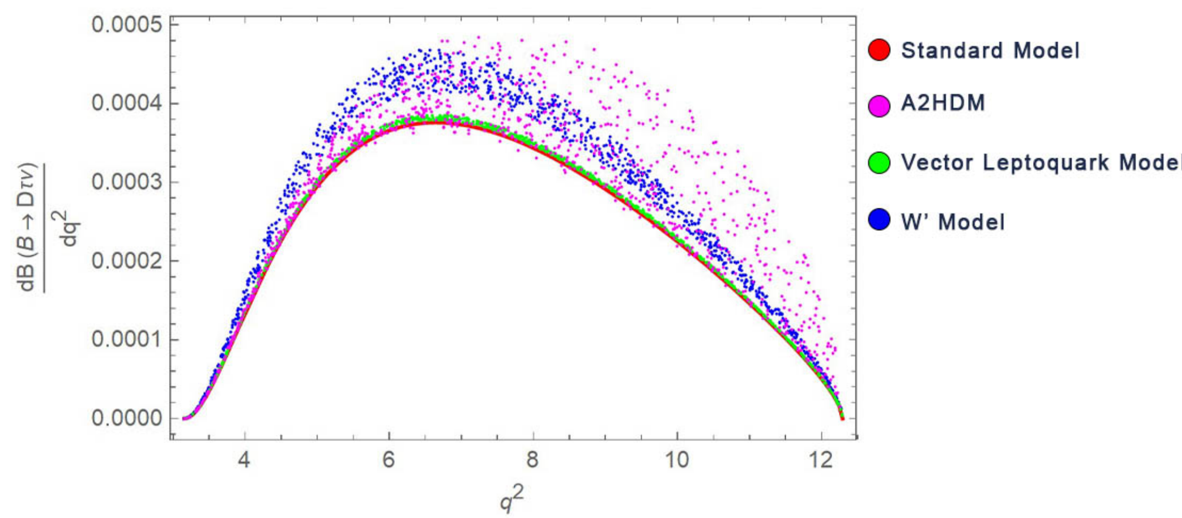

Figure 4.1: Dependence of $\frac{d\mathcal{B}}{dq^2}$ on q^2. The dotted blue, green, and magenta represent

4.3.2 R_D-Lepton Flavor Universality Ratio(LFU)

The leptonic portions of the three families of fermions in the SM are identical, excluding the differing masses of the constituent particles. The photon, W, and Z bosons, in particular, are a couple in the same way as the three generations of leptons. This distinctive property of the SM, known as Lepton Flavor Universality (LFU)[48], may be studied to call its validity into doubt, because any variation from this identity would be a strong indicator that virtual NP particles are contributing to SM decays. As a result, it is reasonable to compare the same observable for processes that differ only in the kind of leptons involved: The branching fraction ratio for two decays, for example. ($b \to c\tau\bar{\nu_\tau}$ *vs* $b \to ce\bar{\nu_e}$ *and/or* $b \to c\mu\bar{\nu_\mu}$).

In this section, we observe the LFU ratio R_D for our decay process in Standard and above-mentioned New Physics models. We plotted the differential ratio against q^2 and discuss its sensitivity to New Physics models. The LFU ratio is defined as,

$$R_D(q^2) = \frac{d\Gamma(B \to D\tau\bar{\nu_\tau})}{d\Gamma(B \to Dl\bar{\nu})} \tag{4.3.2}$$

where, $l = e, \mu$.

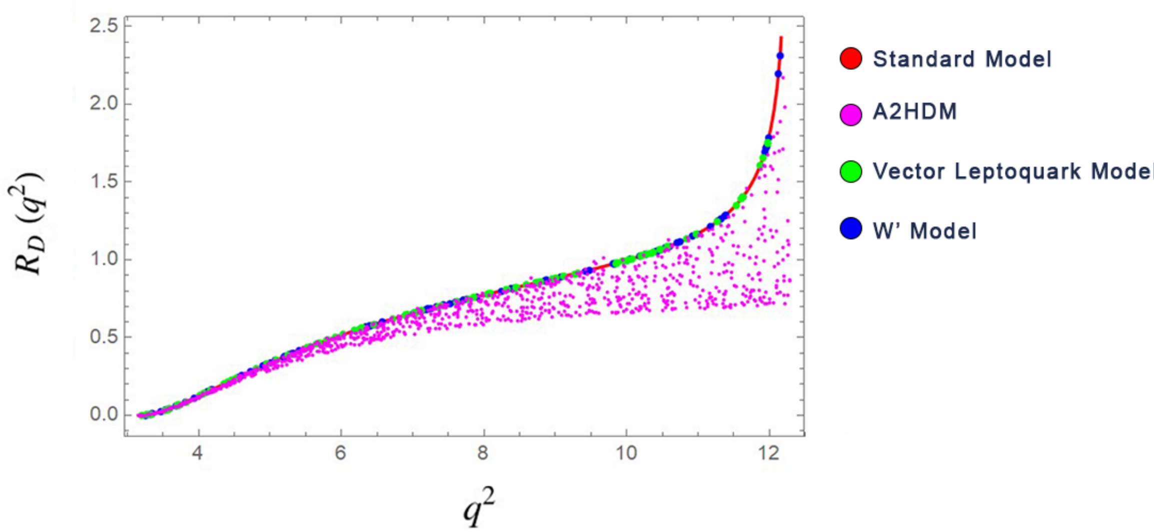

Figure 4.2: Dependence of $R_D(q^2)$ on q^2. The dotted blue, green, and magenta represent SM and NP models

4.3.3 $A_{FB}(q^2)$(Forward-Backward Asymmetry)

Lepton-side forward-backward asymmetry(A_{FB}) has been discussed in this section. This observable is very vital for checking New Physics signals, it is defined as,

$$A_{FB}^{L} = \frac{\int_{-1}^{0}(d^2\Gamma/dq^2dcos\theta)dcos\theta - \int_{0}^{1}(d^2\Gamma/dq^2dcos\theta)dcos\theta}{\int_{0}^{1}(d^2\Gamma/dq^2dcos\theta)dcos\theta + \int_{-1}^{0}(d^2\Gamma/dq^2dcos\theta)dcos\theta} \tag{4.3.3}$$

We plotted Forward-backward asymmetry against q^2 which is shown in figure 4.3.5. One can observe from the figure that A_{FB} does not respond to $W^{'}$ and Vector leptoquark model but, for A2HDM there is some divergence from the Standard Model results which keeps on increasing with the increase of q^2.

4.3.4 $P_L^{\tau}(q^2)$(Tau Polarization)

It is defined as,

$$P_L^{\tau} = \frac{d\Gamma^{1/2}/dq^2 - d\Gamma^{-1/2}/dq^2}{d\Gamma^{1/2}/dq^2 + d\Gamma^{-1/2}/dq^2} \tag{4.3.4}$$

Where tau helicity-dependent decay rates are given as[53]

$$\frac{d\Gamma^{1/2}}{dq^2} = \frac{G_F^2|V_{cb}|^2|\mathbf{P_D}|m_\tau^2}{192\pi^3 m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2[G_V^2H_0^2+3H_s^2]$$

$$\frac{d\Gamma^{-1/2}}{dq^2} = \frac{G_F^2|V_{cb}|^2|\mathbf{P_D}|q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2 G_V^2H_0^2$$

the G_V in the above expressions represent New Physics operators and Standard Model contribution to the decay and $|\mathbf{P_D}|$ is the magnitude of final particle momentum.

The P_L^{τ} is plotted against q^2 and is shown in figure 4.3.5. We can observe that there is no effect of $W^{'}$ and vector leptoquark model on P_L^{τ} but, A2HDM shows significant deviation from Standard Model results which also keeps deviating with an increase in q^2.

4.3.5 $C_F^{\tau}(q^2)$(Convexity Parameter)

In this section we investigate Convexity parameter (C_F^{τ}) w.r.t q^2. The Convexity parameter is defined as,

$$C_F^{\tau}(q^2) = \frac{1}{d\Gamma/dq^2}\frac{d^2}{dcos^2\theta}\left(\frac{d^2\Gamma}{dq^2dcos\theta}\right) \tag{4.3.5}$$

Like Tau polarization and Forward-Backward asymmetry convexity parameter is also insensitive to $W^{'}$ and the Vector leptoquark model but it shows significant sensitivity for A2HDM. The A2HDM reduces the Standard Model, $W^{'}$ and Vector leptoquark model predictions at every q point.

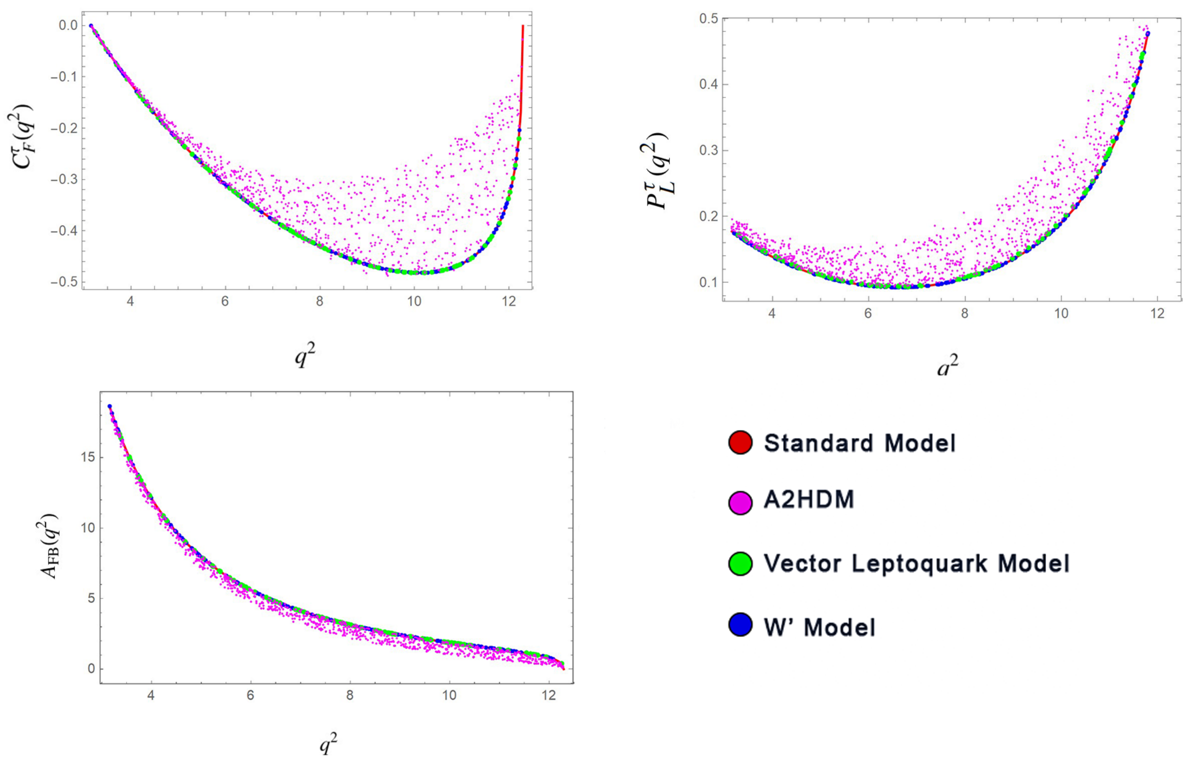

Figure 4.3: Dependence of $C^\tau(q^2)$ on q^2. The dotted blue, green, and magenta represent SM and NP models

4.4 Numerical analysis

In the numerical calculations, all the values like CKM matrix elements, particle masses, and lifetimes are taken from the Particle Data Group(see table 4.1) and The Wilson coefficients for the NP effects are explained in Chapter 3.

We show the dependencies of $\frac{d\mathcal{B}}{dq^2}$ and $R_D(q^2)$ considering the effect of above mentioned three NP models in Fig 4.1 and Fig 4.2.

- From Fig. 1, It is clear that $\frac{d\mathcal{B}}{dq^2}$ is sensitive to all three Np models for whole q^2 region. The contribution of A2HDM much more deviates from SM and also other two Np models, While the vector leptoquark model contribution is the closest to the SM prediction, and the W'-model show moderate deviation.

- From Fig. 2, We can see that the only obvious deviation from SM prediction is due to A2HDM contribution. The vector leptoquark model and W'-model show a close resemblance to SM predictions. The A2HDM model deviation is due to the scalar-type operator which only exists in these types of models.

- Besides $\frac{d\mathcal{B}}{dq^2}$ and $R_D(q^2)$, we also plotted $A_{FB}(q^2)$, $C_F^\tau(q^2)$ and $P_L^\tau(q^2)$. From Fig. 4.3 we can see that for all these observables the only visible deviation is due to A2HDM. This is because NP models(except A2HDM) do not generate new operators so their effects are canceled out in numerators and denominators of these ratios. A2HDM generates a scalar operator which is responsible for the most obvious deviation from SM prediction than the other NP models.

Using above mentioned techniques and NP constraints we also calculated $\mathcal{B}(B \to D\tau\bar{\nu})$ which comes out to be $\mathcal{B}(B \to D\tau\bar{\nu}) = 0.0248$, which is $O \times 10^{-2}$ order of magnitude and is consistent with ref.[66].

Table 4.1: Numerical inputs

	Value	error
m_τ	1776.8 MeV	± 0.12
B^- mass	5279.2 MeV	± 0.26
D^0 mass	1864.8 MeV	± 0.05
τ_B	$1.643 \times 10^{-12} s$	± 0.04
G_F	1.166×10^{-5} GeV	
V_{cb}	40.13×10^{-3} GeV	

Chapter 5

Conclusions

In this thesis we investigate $B \to D\tau\bar{\nu_\tau}$ decay in Standard Model, $W^{'}$ model, Vector leptoquark model and A2HDM. We calculated branching fraction ($\mathcal{B}(\ B \to D\tau\bar{\nu_\tau})$) and LFU ratio ($R_D(q^2)$) in Standard Model and New Physics models. We observed that the branching ratio is sensitive to all three New Physics models that we worked with, but the LFU ratio show less sensitivity to the $W^{'}$ model and Vector leptoquark model and shows a significant deviation from the Standard Model in the case of A2HDM because of scalar operators which are found in such types of models. Besides this we also calculated the$W^{'}$ model, Vector leptoquark model and A2HDM contributions to the following observables, Lepton-side forward-backward asymmetry ($A_{FB}(q^2)$), the tau polarization fraction ($P_L^\tau(q^2)$) and Convexity parameter ($C_F^\tau(q^2)$). We observed that the New Physics effects are only obvious for all three models in the case of Branching faction and LFU ratio. The $A_{FB}(q^2)$, $P_L^\tau(q^2)$ and $C_F^\tau(q^2)$ only show noticeable divergence from SM in case of A2HDM and for $W^{'}$ model and Vector leptoquark model these observables show close resemblance to SM results. In the near future, the analysis of these observables could be a useful tool for exploring and differentiating the clues of these NP models using more precise measurements.

Bibliography

[1] Novaes SF. Standard Model: An Introduction. arXiv:hep-ph/0001283 [Internet]. 2000 Jan 27 [cited 2022 Jan 1]; Available from: http://arxiv.org/abs/hep-ph/0001283

[2] S. L. Glashow, Nucl. Phys. 22, 579 (1961), "Partial-Symmetries of weak interactions."

[3] A. Salam and J. C. Ward, Phys. Lett. 13, 168 (1964), "Electromagnetic and weak interactions."

[4] Rainwater D. Searching for the Higgs boson. arXiv:hep-ph/0702124. 2008 Aug;435–536.

[5] Sahoo S, Bhol A. Efficacy of scalar leptoquark on $B_s \to (K^{(*)}, D_s^{(*)})\tau\bar{\nu}_\tau$ decay modes. arXiv:200512630 [hep-ph] [Internet]. 2020 May 26 [cited 2020 Jul 3]; Available from: http://arxiv.org/abs/2005.12630

[6] Tanaka M, Watanabe R. New physics in the weak interaction of $\bar{B} \to D^{(*)}\tau\bar{\nu}$. Phys Rev D. 2013 Feb 19;87(3):034028.

[7] Heavy Flavor Averaging Group, Amhis Y, Banerjee S, Ben-Haim E, Bernlochner F, Bozek A, et al. Averages of b-hadron, c-hadron, and τ-lepton properties as of summer 2016. arXiv:161207233 [hep-ex, physics:hep-ph] [Internet]. 2018 Jan 3 [cited 2021 Aug 7]; Available from: http://arxiv.org/abs/1612.07233

[8] LHCb collaboration, Aaij R, Adeva B, Adinolfi M, Ajaltouni Z, Akar S, et al. Measurement of the ratio of branching fractions $\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$. Phys Rev Lett. 2018 Mar 23;120(12):121801.

[9] Hagiwara K, Martin AD, Wade MF. Exclusive semileptonic B-meson decays. Nuclear Physics B. 1989 Dec;327(3):569–94.

[10] Gomez JD, Quintero N, Rojas E. Charged current $b \to c\tau\bar{\nu}_\tau$ anomalies in a general W' boson scenario. Phys Rev D. 2019 Nov 20;100(9):093003.

[11] B. Grzadkowski and W. S. Hou, Phys. Lett. B 283, 427 (1992).

[12] W.S. Hou, Phys. Rev. D 48, 2342 (1993).

[13] Tanaka M, Watanabe R. New physics in the weak interaction of $\bar{B} \to D^{(*)}\tau\bar{\nu}$. Phys Rev D. 2013 Feb 19;87(3):034028.

[14] C.-H. Chen and C.-Q. Geng, Phys. Rev. D 71, 077501 (2005). hep-ph/0503123.

[15] C.-H. Chen and C.-Q. Geng, JHEP 0610, 053, 2006. hep-ph/0608166.

[16] U. Nierste, S. Trine and S. Westhoff, Phys. Rev. D 78, 015006 (2008). arXiv: 0801.4938.

[17] S. Trine, Talk given at 34th International Conference on High Energy Physics (ICHEP 2008), Philadelphia, Pennsylvania, 30 Jul - 5 Aug 2008. arXiv:0810.3633 [hep-ph].

[18] J. F. Kamenik and F. Mescia, Phys. Rev. D 78, 014003 (2008). arXiv:0802.3790 [hep-ph].

[19] M. Tanaka, Z. Phys. C 67, 321 (1995). hep-ph/9411405.

[20] M. Tanaka and R. Watanabe, Phys. Rev. D82, 034027 (2010).

[21] S. Fajfer, J. F. Kamenik and I. Niˇsandˇzi´c, Phys. Rev. D 85, 094025 (2012). arXiv:1203.2654 [hep-ph].

[22] A. Datta, M. Duraisamy, and D. Ghosh, Phys. Rev. D86, 034027 (2012). arXiv:1206.3760 [hep-ph].

[23] The BaBar Collaboration. Evidence for an excess of B -> D(*) Tau Nu decays. Phys Rev Lett. 2012 Sep 6;109(10):101802.

[24] Bifani S, Descotes-Genon S, Vidal AR, Schune M-H. Review of Lepton Universality tests in B decays. J Phys G: Nucl Part Phys. 2019 Feb 1;46(2):023001.

[25] Fajfer S, Kamenik JF, Nisandzic I. On the B to D* tau nu Sensitivity to New Physics. Phys Rev D. 2012 May 23;85(9):094025.

[26] Aoki S, Aoki Y, Becirevic D, Bernard C, Blum T, Colangelo G, et al. Review of lattice results concerning low-energy particle physics [Internet]. arXiv; 2016 [cited 2022 May 13]. Available from: http://arxiv.org/abs/1607.00299

[27] Heavy Flavor Averaging Group, Amhis Y, Banerjee S, Ben-Haim E, Bernlochner F, Bozek A, et al. Averages of b-hadron, c-hadron, and τ-lepton properties as of summer 2016. Eur Phys J C. 2017 Dec;77(12):895.

[28] Li Y, Lu CD. Recent Anomalies in B Physics. Science Bulletin. 2018 Mar;63(5):267–9.

[29] Logan HE. TASI 2013 lectures on Higgs physics within and beyond the Standard Model. arXiv:14061786 [hep-ex, physics:hep-ph] [Internet]. 2017 Nov 28 [cited 2021 Jun 23]; Available from: http://arxiv.org/abs/1406.1786

[30] Peskin, M. E., and Schroeder, D. V. (2016). An introduction to quantum field theory. Boulder, CO: Westview, a member of the Perseus Books Group.

[31] Hanno Bertle (May 16, 2018). Goldstone Boson and Higgs Mechanism.

`https://fenix.tecnico.ulisboa.pt/downloadFile/1689468335641966/21_Bertle.pdf`

[32] Valery Rubakov, *Translated by Stephen S Wilson.* Classical Theory of Gauge Field, Princeton University Press.

[33] Michael Kachelriess, Quantum Fields: From the Hubble to the Planck Scale.

[34] Heather E. Logan (june 2014).TASI 2013 lectures on Higgs physics within and beyond the Standard Model. arXiv:1406.1786v2 [hep-ph] 28 Nov 2017

[35] A. Ceccucci (CERN), Z. Ligeti (LBNL) and Y. Sakai (KEK). Revised (january 2018). CKM Quark-Mixing Matrix `https://pdg.lbl.gov/2019/reviews/rpp2019-rev-ckm-matrix.pdf`

[36] Paul Langacker. Department of Physics, University of Pennsylvania, 19 Apr 2003. `http://arxiv.org/abs/hep-ph/0304186v1`

[37] Yosef Nir. June 2017. Weizmann Institute of Science, Rehovot 76100, Israel. Lectures given at the Summer School on Particle Physics, ICTP, Trieste, Italy. The Standard Model and Flavor Physics `http://indico.ictp.it/event/7968/session/73/contribution/278/material/1/0.pdf`

[38] Pich, A. 'The Standard Model of Electroweak Interactions'. ArXiv:Hep-Ph/0502010, Feb. 2005. arXiv.org, http://arxiv.org/abs/hep-ph/0502010.

[39] Mondragon M. Beyond the Standard Model. CERN Yellow Reports: School Proceedings. 2019 Oct 11;101 Pages.

[40] Mondragon M. Beyond the Standard Model. CERN Yellow Rep School Proc. 2018;4:101-24

[41] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018) `https://journals.aps.org/prd/pdf/10.1103/PhysRevD.98.030001`

[42] Bečirević D, Košnik N, Sumensari O, Funchal RZ. Palatable Leptoquark Scenarios for Lepton Flavor Violation in Exclusive $b \to s\ell_1\ell_2$ modes. arXiv:160807583 http://arxiv.org/abs/1608.07583

[43] Pich A, Tuzon P. Yukawa Alignment in the Two-Higgs-Doublet Model. Phys Rev D. 2009 Nov 19;80(9):091702.

[44] Gomez JD, Quintero N, Rojas E. Charged current $b \to c\tau\bar{\nu}_\tau$ anomalies in a general W' boson scenario. Phys Rev D. 2019 Nov 20;100(9):093003.

[45] Fajfer S, Košnik N. Vector leptoquark resolution of R_K and $R_{D^{(*)}}$ puzzles. Physics Letters B. 2016 Apr;755:270–4.

[46] Georgi H, Jenkins EE, Simmons EH. The un-unified standard model. Nuclear Physics B. 1990 Feb 19;331(3):541–55.

[47] Ilisie V. Constraining the two-Higgs doublet models with the LHC data. arXiv:13100931 [hep-ph] [Internet]. 2013 Oct 7 [cited 2021 Sep 8]; Available from: http://arxiv.org/abs/1310.0931

[48] Bifani S, Descotes-Genon S, Vidal AR, Schune MH. Review of Lepton Universality tests in B decays. J Phys G: Nucl Part Phys. 2019 Feb 1;46(2):023001.

[49] Matthias Neubert, Institute for High-Energy Phenomenology Newman Laboratory for Elementary-Particle Physics, Cornell University, December 17, 2005. Effective Field Theory and Heavy Quark Physics. https://arxiv.org/pdf/hep-ph/0512222v1.pdf

[50] Alexy A. Petrov. Andrew E. Blechman, Wayne state University, USA. Effective field theories. World Scientific Publishing Co. Pte. Ltd

[51] Joseph Polchinski, 8 June 1999.Institute for Theoretical Physics University of California Santa Barbara, California 93106-4030.Effective Field Theory and the Fermi Surface https://arxiv.org/pdf/hep-th/9210046.pdf

[52] Andrzej J. Buras 26 Jan 1999, Technische Universitat Munchen Physik Department D-85748 Garching, Germany. Operator Product Expansion, Renormalization Group and Weak Decays https://arxiv.org/pdf/hep-ph/9901409.pdf

[53] Aneesh V.Manohar , Mark B. Wise. University of California, San Diego, California Institute of Technology. Heavy Quark Physics. Cambridge University Press 2000

[54] Fayyazuddin, Riazuddin, Silverman D. A Modern Introduction to Particle Physics. Physics Today. 1994 Jan;47(1):48–48.

[55] Matthias Neubert. October 1996. Theory Division, CERN, CH-1211 Geneva 23, Switzerland. Heavy-Quark Effective Theory arXiv:hep-ph/9610266

[56] Vera G.Luth. Annual Review of Nuclear and Particle Science 2011, SLAC National Accelerator Laboratory, Stanford University. Semileptonic B Meson Decays. https://www.annualreviews.org/doi/pdf/10.1146/annurev.nucl.012809.104421

[57] K.Hagiwara, A.D.Martin and M.F.Wade, Received 22 June 1989. Department of Physics, University of Durham, Durham, DH1 3LE, UK. EXCLUSIVE SEMILEPTONIC B-MESON DECAYS. Nuclear Physics B327 (1989) 569-594

[58] Revised by T.Mannel and P. Urquijo. August 2019. Siegen U., School of Phys. U. of Melbourne. Semileptonic b-Hadron Decays, Determination of Vcb, Vub. https://pdg.lbl.gov/2019/reviews/rpp2018-rev-vcb-vub.pdf

[59] Vera G. Lüth, SLAC National Accelerator Laboratory, Stanford University. May 13, 2011. Semileptonic B Meson Decays. https://www.annualreviews.org/doi/pdf/10.1146/annurev.nucl.012809.104421

[60] Wilson KG, Zimmermann W. Operator product expansions and composite field operators in the general framework of quantum field theory. Communications in Mathematical Physics. 1972 Jun 1;24(2):87–106.

[61] Buchalla G. Heavy Quark Theory. arXiv:hep-ph/0202092 [Internet]. 2002 Feb 9 [cited 2022 Jan 25]; Available from: http://arxiv.org/abs/hep-ph/0202092

[62] Pich A, Tuzon P. Yukawa Alignment in the Two-Higgs-Doublet Model. Phys Rev D. 2009 Nov 19;80(9):091702.

[63] Li X-Q, Lu J, Pich A. $B^0_{s,d} \to l^+l^-$ decays in the aligned two-Higgs-doublet model. J High Energy Phys. 2014 Jun;2014(6):22.

[64] J. C. Pati, A. Salam, Unified Lepton-Hadron Symmetry and a Gauge Theory of the Basic Interactions, Phys. Rev. D8 (1973) 1240–1251. doi: 10.1103/PhysRevD.8.1240.

[65] Fajfer S, Košnik N. Vector leptoquark resolution of R_K and $R_{D^{(*)}}$ puzzles. Physics Letters B. 2016 Apr;755:270–4.

[66] The BABAR Collaboration, Aubert B. Measurement of the Semileptonic Decays $B \to D\tau\bar{\nu_\tau}$ and $B \to D^(*)\tau\bar{\nu_\tau}$. Phys Rev D. 2009 May 13;79(9):092002.