Rare Semileptonic Charmed B meson decay in the Standard Model and Beyond

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Dedicated to my loving parents

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Abstract

Motivated by anomalies in lepton flavor universality ratios for $B \to D^{(*)}\tau\nu$ and $B \to K^{(*)}\mu^+\mu^-$ decays which have found deviations, 2.1-2.3σ and 2.6σ, from standard model(SM) predictions, the deviations between experimental measurements and SM prediction which hint towards new physics(NP) effects.

In this thesis, we study exclusive semileptonic charmed B meson decay, $B_c \to D_s^*\ell^+\ell^-$, with in the SM and beyond which provides a complimentary information regarding NP. We consider the simplest NP models such as, Z' models and model independent/Leptoquark model. We analyze various observables such as the branching ratios, leptons forward backward asymmetry, the longitudinal helicity fractions of the D_s^* meson and lepton flavor Universality(LFU) ratios with in the SM and the above mentioned NP models. We give a combine analysis of model independent NP scenarios and Z' models for above mentioned observables which also deviate from the SM predictions and hints the NP effects in $B_c \to D_s^*\ell^+\ell^-$ decay.

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Chapter 1

Introduction

The standard model (SM) [4] was proposed by Salam, Glashow and Weinberg to unify weak nuclear forces and electromagnetism. Many years have passed since the SM was established. It is a miracle that it still holds the status as the ultimate theory of matter at the most fundamental level. The SM provides a very elegant theoretical framework and it is experimentally well tested theory so far. Despite the successful theory of SM, it has some limitations and some unanswered questions:

- The SM shows the neutrinos are massless, in fact experiment shows that neutrinos have mass.
- Hierarchy problem: Electroweak scale is so small?
- The problem of strong CP violation.
- There is lack of explanation for the quark masses according to their ranges i.e. few MeV to 100 GeV and lepton masses i.e. 0.5 MeV to 1.8 GeV.
- Why gravity is missing from SM?

These limitations and unanswered questions required more fundamental underlying theory. Many extension of SM discussed in literature to understand these limitations and unanswered questions of SM. These problems also hint that new physics (NP) effects may become important beyond the SM. Generally, there are two methods to find NP: First, we can rise the energy of colliders and produce new particles, this is called a direct method. Second, there is the indirect way to determine NP where NP effects can appear itself if we increase the experimental precision on data of SM processes. These processes can be measured precisely because it is rare in SM. So here flavor physics plays its important role. In such a way the flavor changing processes are important to understand the physics beyond the SM. It implies that such processes in the flavor sector are rare B meson decays which are mediated by flavor changing neutral current (FCNC) [5] at loop level based on the Glashow-Iliopoulos-Maiani

(GIM) mechanism [6]. So, rare B meson [7] decays are ideal tool to test NP due to their intrinsic relation to the quark flavor structure of the SM Lagrangian.
B meson are bound state of $(b\bar{q})$. In our dissertation, we focus on rare B_c meson, the initial state B_c meson is the ground state of the bottom-charm bound system. Its first observation was at the Fermilab Tevatron by the CDF Collaboration in 1998 through the cascade decay $B_c \to J/\psi \bar{l}\nu$ and $J/\psi \to \mu\bar{\mu}$ [3].
In this thesis, we analyze exclusive semileptonic B meson decay $B_c \to D_s^* \bar{\ell}\ell$ [3] based on quark level transition $b \to s\ell^+\ell^-$ induced by FCNC at loop level. In the Standard Model, these transitions occur at loop level mediated by W boson and are not allowed at tree level. Furthermore, they are also suppressed in the SM due to their dependence on weak mixing angles of the Cabibo Kobayashi Maskawa (CKM) matrix [8]. It implies that the SM contribution is greatly suppressed and, as the SM contribution is suppressed, the NP effects may become important. This provides the most crucial framework to test the SM. As the quark level $b \to s\ell^+\ell^-$ transition are very sensitive to the physics beyond the SM, so it offers a promising place to search for NP.
We consider only those NP models where the effects of NP can be observed only through the modification of Wilson coefficients. we consider two different NP models such as leptoquark model, heavy and light Z' models, and Model independent(MI) NP scenarios.
Several observables are useful to distinguish between the various extension of SM. We determined various observables such as branching ratio, forward backward asymmetry of leptons, longitudinal helicity fraction of D_s^* meson and lepton flavor universality ratios of leptons which show the deviations form SM predictions.
The purpose of this dissertation is to study the possibility of finding NP in MI scenarios and in Leptoquark and Z' models. When more data will be available at LHC than the study of above mentioned observables will give a precision test of SM and NP .
We organized our dissertation as given below:
In Chapter 2, we give an overview of the SM. We put our focus on the fundamental particles, their parameters and interactions such as masses and coupling constants and we precisely deal with the flavor structure of SM which help us to understand rare B meson decays.
In Chapter 3, we present the theoretical framework for rare B meson decays. Firstly, we write the effective Hamiltonian which is the fundamental of this thesis than we explain how effective field theory is important to compute said process. We compute the amplitude of said decay in helicity basis by using effective Hamiltonian and will be able to write the decay rate of $B_c \to D_s^*\ell^+\ell^-$. In next section, we explore physics beyond SM. We wil do combine analysis of NP models such as, leptoquark and Z' models, and model independent new physics scenarios.
In Chapter 4, we determine several observables for exclusive semileptonic $B_c \to D_s^*\ell^+\ell^-$ decay mode, like branching ratio, longitudinal helicity fraction of D_s^* meson, forward backward asymmetry and Lepton Flavor Universality(LFU) ratios which help us to understand new physics in said process. We analyze the above mentioned physical observables in NP model independent scenarios and in model dependent and will show that above mentioned observables have tension with SM predictions. In last chapter, we summarize all our results and discussions.

Chapter 2

Standard Model

The Standard Model(SM) [4] corresponds to a non-abelian gauge principle [9], it is a quantum field theory based upon local gauge invariance. The SM consists of strong and electroweak interactions which is based on the gauge symmetry $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$. $SU(3)_C$ has the symmetry group of strong interactions and $SU(2)_L \otimes U(1)_Y$ has the symmetry group of electroweak interactions. The SM provides a basic theoretical framework and it is experimentally well tested theory so far. Despite the successful theory of SM, it has some limitations and some unanswered questions which we will discuss later.

2.1 Gauge Theory

Gauge principle give a tool to transform Lagrangian that is invariant with respect to global symmetry transformation of non-abelian symmetric $SU(N)$ group into a Lagrangian that consists of a local symmetry invariance. Suppose a Lagrangian $\mathcal{L}(\Psi(y), \partial_\mu \Psi(y))$ which is invariant under $SU(N)$ *global transformation.*

$$\Psi(y) \to U\Psi(y), \qquad U^{-1} = U^\dagger. \tag{2.1}$$

But our desire to develop a theory i.e. invariant with respect to local $SU(N)$ transformation

$$\Psi(y) \to U(y)\Psi(y), \qquad U = e^{i\alpha^a(y)X^a} \tag{2.2}$$

The Lagrangian is now no more invariant under this local transformation. To preserve the local invariance, we introduce the covariant derivative $\mathcal{D}_\mu$

$$\mathcal{D}_\mu = \partial_\mu - igA^a_\mu X^a \tag{2.3}$$

transform as

$$\mathcal{D}_\mu \Psi(y) \to (\mathcal{D}_\mu \Psi(y))' = U(y)(\mathcal{D}_\mu \Psi(y))$$

Where g is the arbitrary constant defined as coupling constant, A_μ^a defined as a vector fields or it is also called gauge fields and X^a are the corresponding generators that follow the commutation algebra

$$[X^a, X^b] = if^{abc}X^c$$

f^{abc} define as the structure constant. To restore gauge invariance, A_μ vector field transforms as

$$A_\mu^a \to A_\mu^{a'} = U(y)(A_\mu^a + \frac{i}{g}\partial_\mu)U^\dagger(y).$$

Finally, by adding the *kinetic term* for gauge field: Introducing locally invariant term that depends on A_μ and its derivative. The field strength tensor $F^{\mu\nu}$ looks like

$$F^{\mu\nu,a} = \partial^\mu A^{\nu,a} - \partial^\nu A^{\mu,a} + gf^{abc}A^{\mu,b}A^{\nu,c}.$$

The product of $F^{\mu\nu,a}F^a_{\nu\mu}$ satisfies the structure of gauge theory and appears into the Lagrangian.
The new locally invariant Lagrangian takes the following form

$$\mathcal{L} = \mathcal{L}(\Psi(y), \mathcal{D}_\mu\Psi(y)) - \frac{1}{4}F^{\mu\nu}F_{\nu\mu}. \tag{2.4}$$

The Gauge theory principle extended a global to local symmetry and it give an information about gauge field interactions.

2.2 The Standard Model Lagrangian

The SM Lagrangian [10] consists of the following main pieces

$$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{fermions} + \mathcal{L}_{higgs} + \mathcal{L}_{yukawa} \tag{2.5}$$

$\mathcal{L}_{gauge}, \mathcal{L}_{fermions}, \mathcal{L}_{higgs}$ and $\mathcal{L}_{yukawa}$ terms correspond to the gauge group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$, the matter contents of fermions, the Higgs sector and the coupling of Higgs with fermion of SM respectively.

2.2.1 Gauge Symmetry Group

The SM Lagrangian [11,12] is established on symmetry group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$. The $SU(3)_c$ color symmetry group explains the strong interaction between quarks corresponding to quantum chromodynamic (QCD) part. The $SU(2)_L \otimes U(1)_Y$ gauge group explains the Glashow-Weinberg-Salam electroweak interaction theory. The gauge terms Lagrangian is as follows

$$\mathcal{L}_{gauge} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W^{i,\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a,\mu\nu} \tag{2.6}$$

The field strength tensor defined as

$$
\begin{aligned}
B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu \\
W^i_{\mu\nu} &= \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + g_2 \epsilon^{ijk} W^j_\mu W^k_\nu \\
G^a_{\mu\nu} &= \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_3 f^{abc} G^b_\mu G^c_\nu
\end{aligned}
$$

Where $W^i_\mu (i = 1, 2, 3)$ and $G^a_\mu (a = 1, ..., 8)$, and the corresponding covariant derivatives are

$$
\begin{aligned}
D_\mu &= \partial_\mu - i g_1 (Y) B_\mu; \\
D_\mu &= \partial_\mu - i g_2 (\frac{\tau^i}{2} W^i_\mu); \\
D_\mu &= \partial_\mu - i g_3 (\frac{\lambda^a}{2} G^a_\mu);
\end{aligned}
$$

Boson	Tensor	Coupling constant	Physical sate	$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
B_μ	$B_{\mu\nu}$	$g_1 = e$	photon, Z	(1,1,0)
W^i_μ	$W^i_{\mu\nu}$	g_2	γ, W^+, W^-	(1,3,0)
G^a_μ	$G^a_{\mu\nu}$	g_3	gluons	(8,1,0)

Table 2.1: The Standard Model Bosons

2.2.2 Fermionic Field in SM

Fermions have three generations. A charged lepton, neutrino and up and down type quarks belong to each generation. Furthermore, they are split into left and right fermions. Left handed fermions are doublet under $SU(2)_L$ while right handed are singlet under $SU(2)_L$ as shown in Table2.2.
The fermionic field of SM explained by Dirac Lagrangian

$$\mathcal{L} = \bar{\psi} i \gamma_\mu \partial^\mu \psi - m \bar{\psi} \psi$$

as

$$\psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

Where as ψ_L and ψ_R are left and right handed Spinors respectively.
The Gell-Mann-Nishijima formula is defined as

$$Q = I_3 + \frac{Y}{2}$$

The Q, I_3 and Y denotes the charge, isospin and hypercharge respectively
The fermionic field Lagrangian is written as

$$\mathcal{L}_{fermion} = i\bar{l}_L \not{D}_L l_L + i\bar{q}_L \not{D}_Q q_L + i\bar{e}_R \not{D}_e e_R + i\bar{u}_R \not{D}_u u_R + i\bar{d}_R \not{D}_d d_R \tag{2.7}$$

Where $\not{D} = \gamma^\mu D_\mu$

$$\begin{aligned} D_l^\mu &= \partial_\mu - ig_1 Y_l B^\mu - ig_2 \sigma^i W^{i,\mu} \\ D_{q_L}^\mu &= \partial_\mu - ig_1 Y_{q_L} B^\mu - ig_2 \sigma^i W^{i,\mu} - ig_3 t^a G^{a,\mu} \\ D_e^\mu &= \partial_\mu - ig_1 Y_e B^\mu \\ D_{q_R}^\mu &= \partial_\mu - ig_1 Y_q B^\mu - ig_3 t^a G^{a,\mu} \qquad q_R = u_R, d_R \end{aligned}$$

Here $\sigma^i = \frac{\tau^i}{2}$ belongs to pauli matrices are generator of $SU(2)$, $t^a = \frac{\lambda^a}{2}$ belongs to Gell-Mann matrices are generator of $SU(3)$.
So

$$\begin{aligned} \mathcal{L}_{fermion} = \; & i\bar{l}_L \gamma^\mu \big(\partial_\mu + ig_1 B_\mu(-\frac{1}{2}) + ig_2 W_\mu^i \frac{\tau^i}{2}\big) l_L \\ & + i\bar{q}_L \gamma^\mu \big(\partial_\mu + ig_1 B_\mu(\frac{1}{6}) + ig_2 W_\mu^i \frac{\tau^i}{2} + ig_3 G_\mu^a \frac{\lambda^a}{2}\big) q_L \\ & + i\bar{e}_R \gamma^\mu \big(\partial_\mu + ig_1 B_\mu(-\frac{2}{2})\big) e_R \\ & + i\bar{u}_R \gamma^\mu \big(\partial_\mu + ig_1 B_\mu(\frac{2}{3}) + ig_3 G_\mu^a \frac{\lambda^a}{2}\big) u_R \\ & + i\bar{d}_R \gamma^\mu \big(\partial_\mu + ig_1 B_\mu(-\frac{1}{3}) + ig_3 G_\mu^a \frac{\lambda^a}{2}\big) d_R \end{aligned}$$

Notation	I_3	Y	Q	Contents	$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$
l_L	$\binom{1/2}{-1/2}$	-1	$\binom{0}{-1}$	$\binom{\nu_{eL}}{e_L}\binom{\nu_{\mu L}}{\mu_L}\binom{\nu_{\tau L}}{\tau_L}$	$(1, 2, \frac{-1}{2})$
q_L	$\binom{1/2}{-1/2}$	$\frac{1}{3}$	$\binom{2/3}{-1/3}$	$\binom{u_L}{d_L}\binom{c_L}{s_L}\binom{t_L}{b_L}$	$(3, 2, \frac{1}{6})$
e_R	0	-2	-1	$e_R \quad \mu_R \quad \tau_R$	$(1, 1, 1)$
u_R	0	$\frac{4}{3}$	$\frac{2}{3}$	$u_R \quad c_R \quad t_R$	$(\bar{3}, 1, \frac{-2}{3})$
d_R	0	$\frac{-2}{3}$	$\frac{-1}{3}$	$d_R \quad s_R \quad b_R$	$(\bar{3}, 1, \frac{1}{3})$

Table 2.2: Standard Model fermions

Charged Current

According to weak interaction theory the weak interactions only exist on left quark's and lepton's doublet.

$$\begin{aligned} \mathcal{L}_{fermions} &= i(\bar{u}_L, \bar{d}_L)\gamma_\mu(\partial^\mu - \frac{1}{2} igW_i^\mu \tau_i)\begin{pmatrix} u_L \\ d_L \end{pmatrix} \\ &= i\bar{u}_L \gamma_\mu \partial^\mu u_L + i\bar{d}_L \gamma_\mu \partial^\mu d_L - \frac{1}{2} g\bar{u}_L \gamma_\mu W^{-\mu} d_L - \frac{1}{2} g\bar{d}_L \gamma_\mu W^{+\mu} u_L \end{aligned}$$

The pauli matrices ($i = 1, 2$) are used. $W^{\pm}$ gauge boson are responsible for flavor changing from up to down and down to up as well. These kind of interactions are called charge current.

$$\mathcal{L}_{CC} = -\frac{1}{2}g\bar{u}_L\gamma_\mu W^{-\mu}d_L - \frac{1}{2}g\bar{d}_L\gamma_\mu W^{+\mu}u_L \tag{2.8}$$

2.2.3 Higgs Lagrangian

The Higgs sector be explained by introducing a new complex scalar doublet ϕ.

$$\phi = \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix}$$

it transform as

$$\begin{pmatrix} SU(3)_c & SU(2)_L & U(1)_Y \\ 1 & 2 & \frac{1}{2} \end{pmatrix}$$

The scalar doublet embedded in the Lagrangian as

$$\mathcal{L}_{Higgs} = |\big(\partial_\mu + ig_1 B_\mu(\frac{1}{2}) + ig_2 W^i_\mu \frac{\tau^i}{2}\big)\phi|^2 - \frac{m^2}{2}|\phi|^2 - \frac{\lambda}{4}|\phi|^4 \tag{2.9}$$

2.2.4 Higgs Mechanism

Higgs mechanism [13]is an interesting phenomena that explains how to give masses to gauge bosons and fermions in the Standard Model(SM). Higgs mechanism is utilized to get rid of the Goldstone theorem. According to this condition, Lagrangian is invariant under local transformation.

$$\phi(y) \longrightarrow \phi'(y) = e^{ig\alpha(y)}\phi(y), \qquad \phi^*(y) \longrightarrow \phi'^*(y) = e^{-ig\alpha(y)}\phi(y)$$

The Lagrangian is

$$\mathcal{L} = (D_\mu\phi)^\dagger(D^\mu\phi) + m^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \tag{2.10}$$

where A_μ is defined as massless gauge boson field, m and $\lambda > 0$ are real parameters, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, ϕ denote as complex scalar field.
Replacing ∂_μ by $\mathcal{D}_\mu$

$$\partial_\mu\phi \longrightarrow D_\mu\phi, \qquad \partial_\mu\phi^\dagger \longrightarrow (\mathcal{D}_\mu\phi)^\dagger$$

where,

$$\mathcal{D}_\mu = \partial_\mu + igA_\mu$$

and

$$A_\mu \longrightarrow A_\mu - \partial_\mu \alpha.$$

Considering $\alpha(x) = \frac{\eta(x)}{V}$, the gauge transform as

$$\begin{aligned}\phi &\longrightarrow \phi\prime = e^{ig\frac{\eta}{V}}\phi \\ A_\mu &\longrightarrow A_\mu - \partial_\mu \eta\end{aligned}$$

Appling these transformation the $\mathcal{L}$ (2.10) remains same. We use $\phi(x) = \frac{V+h(x)}{\sqrt{2}}$ in Eq(2.10), we obtain the expression

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}[(\partial_\mu - igA_\mu)(V+h)(\partial^\mu + igA^\mu)(V+h)] + \frac{1}{2}m^2(V+h)^2 - \frac{1}{4}\lambda(V+h)^4 \\ &\quad -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \qquad (2.11)\end{aligned}$$

The interaction terms in the Lagrangian(2.11) are h^3, h^4, hAA and h^2AA. The quadratic terms in the Lagrangian correspond to the mass terms i-e $(\frac{g^2V^2}{2}A_\mu A^\mu)$ and $(-\lambda V h^2)$ that refer to the gauge boson and scalar boson mass respectively. The gauge boson A_μ eats up the Goldstone boson and gives it a mass.

2.2.5 Higgs and Yukawa Terms

The dynamic of a spin-0 scalar field can be explained through Higgs part.

$$\mathcal{L}_{higgs} = (D^\mu \phi)^\dagger D_\mu \phi - V(\phi)$$

The potential is

$$V(\phi) = m^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

Where ϕ is a field defined as an isospin doublet

$$\phi = \begin{pmatrix}\phi^+ \\ \phi^0\end{pmatrix} \qquad (2.12)$$

This field ϕ couples the Higgs boson with the fermion fields using Yukawa coupling. We can further expand the lagrangian by the coupling between the fermion doublets and field ϕ to introduce mass terms for the fermions. This rise the new terms, known as Yukawa interactions, preserved by symmetries. The Yukawa terms Lagrangian is given as

$$\begin{aligned}\mathcal{L}_{yukawa} &= \bar{\psi}_L Y \phi \psi_R + h.c \\ \mathcal{L}_{yukawa} &= Y_u \bar{q}_L \phi u_R + Y_d \bar{q}_L \tilde{\phi} d_R + Y_L \bar{l}_L \tilde{\phi} e_R + h.c \qquad (2.13)\end{aligned}$$

Q_L and L_L are defined as left handed quarks and leptons respectively.

$$l_L = P_L \begin{pmatrix}\nu_e \\ e\end{pmatrix}, \qquad q_L = P_L \begin{pmatrix}u \\ d\end{pmatrix}$$

u_R, d_R and e_R are right handed up-type, down-type quarks and lepton respectively.
$u_R = P_R u, \qquad d_R = P_R d, \qquad e_R = P_R e$
where

$$P_L = \frac{(1-\gamma_5)}{2}, \qquad P_R = \frac{(1+\gamma_5)}{2}$$

Y_u, Y_d,and Y_L are Yukawa couplings for up-type, down-type quarks and lepton respectively. The Yukawa coupling Y_q where($q = u, d, l$) are 3×3 matrices. Local symmetry breaking can be achieved by substituting various value for ϕ field in Eq(2.12).

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \longrightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ V + h(x) \end{pmatrix} \tag{2.14}$$

The vacuum expectation value (VEV) is not zero and expected at $\frac{V}{\sqrt{2}}$, where $h(x)$ is a perturbation around new VEV represented as the Higgs boson. The Yukawa terms in $\mathcal{L}$ will be

$$\mathcal{L}_{yukawa} = \frac{V}{\sqrt{2}} \bar{u}_L Y_u u_R + \frac{V}{\sqrt{2}} \bar{d}_L Y_d d_R + \frac{V}{\sqrt{2}} \bar{e}_L Y_L e_R + h.c \tag{2.15}$$

2.3 CKM matrix and Fermion masses

The masses of gauge boson $W^\pm$ and Z gets through the SSB of the gauge group $SU(2)_L \otimes U(1)_Y$. Why flavor changing neutral current is not allow at tree level in SM? How we can generate fermions masses? We desperately required a term that couple the fermions with Higgs doublet. They must be gauge invariant and renormalizable. These terms are called Yukawa terms in the Lagrangian. The Lagrangian for the charge lepton corresponding to first generation is

$$\mathcal{L}^{Leptons}_{Yukawa,1} = -Y_e \bar{e}' \phi^\dagger \begin{pmatrix} e \\ \nu_e \end{pmatrix}'_L + h.c. \tag{2.16}$$

For the three generations, the Lagrangian is written in the generalized form as

$$\mathcal{L}^{Leptons}_{Yukawa} = -(\bar{e}'_R \quad \bar{\mu}'_R \quad \bar{\tau}) Y_l \begin{pmatrix} \phi^\dagger \begin{pmatrix} e \\ \nu_e \end{pmatrix}'_L \\ \phi^\dagger \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}'_L \\ \phi^\dagger \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L \end{pmatrix} + h.c. \tag{2.17}$$

According to Eq.(2.14) after giving VEV the $\mathcal{L}^{Leptons}_{Yukawa}$ splits into two parts. One part explains the interaction of leptons with physical Higgs and other part is explained by

$$\mathcal{L}^{Leptons}_{Mass} = -(\bar{e}'_R \quad \bar{\mu}'_R \quad \bar{\tau})M_l \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}'_L \tag{2.18}$$

where,

$$M_l = \frac{V}{\sqrt{2}} Y_l$$

In principle M_l is an arbitrary 3 complex matrix and cannot be named as mass matrix. However the charge lepton fields are possible to transform in such fashion that M_l is defined as diagonal matrix with positive real or zero number elements. The Lagrangian derived by applying this type of transformation to all of its term will latter be expressed as the mass eigenstate of the leptons. The new Lagrangian of charge current carries flavor mixing term. All lepton fields now taking place are mass eigenstate, for distiction we use without prime notation.
To analyze the quarks masses d ,s and b are the down type quark masses, the Yukawa Lagrangian is same as the one in Eq.(2.17) with Y^d_q Yukawa matrix. The up-type quark is a bit different, we replace ϕ with $i\sigma_2\phi^*$ as the $SU(2)_L$ doublet. Where σ_2 is the pauli matrix

$$\mathcal{L}^{U-quarks}_{Yukawa} = -(\bar{u}'_R \quad \bar{c}'_R \quad \bar{t}'_R)Y^u_q \begin{pmatrix} i\sigma_2\phi^* \begin{pmatrix} u \\ d \end{pmatrix}'_L \\ i\sigma_2\phi^* \begin{pmatrix} c \\ s \end{pmatrix}'_L \\ i\sigma_2\phi^* \begin{pmatrix} t \\ b \end{pmatrix}'_L \end{pmatrix} + h.c. \tag{2.19}$$

The Yukawa matrices are diagonalized by using the unitary transformation of the quark fields explicity it is given as below

$$\begin{pmatrix} u \\ c \\ t \end{pmatrix}'_L = V_u \begin{pmatrix} u \\ c \\ t \end{pmatrix}_L \quad , \quad \begin{pmatrix} u \\ c \\ t \end{pmatrix}'_R = U_u \begin{pmatrix} u \\ c \\ t \end{pmatrix}_R$$
$$\begin{pmatrix} d \\ s \\ b \end{pmatrix}'_L = V_d \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L \quad , \quad \begin{pmatrix} d \\ s \\ b \end{pmatrix}'_R = U_d \begin{pmatrix} d \\ s \\ b \end{pmatrix}_R . \tag{2.20}$$

Where V_u, U_u, V_d, U_d belong to $U(3)$. In the lepton sector only one set exist like these matrices, which diagonalize the yukawa matrices and that is the reason behind the Lagrangian having different mass eigenstates from the weak eigenstate. The quarks mixing in different generation is defined by the CKM matrix known as Cabibbo-Kobayashi-Maskawa matrix which relates weak eigenstates with mass eigenstates.

$$V_{CKM} = V_u^\dagger V_d.$$

We can introduce these quarks coupling terms with $W^\pm$ bosons

$$\mathcal{L}_{CC}^{Quarks} = -\frac{e}{2\sin\theta_W}(W_\mu^+ J^{\mu,-} + W_\mu^- J^{\mu,+}) \tag{2.21}$$

Where,

$$J^{\mu,-} = (\bar{u} \quad \bar{c} \quad \bar{t})_L V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L \tag{2.22}$$

In $\mathcal{L}(2.8)$ for the Charge current will become

$$\begin{aligned} \mathcal{L}_{CC} &= -\frac{1}{2} g \bar{u}_L \gamma_\mu W^{-\mu} d_L - \frac{1}{2} g \bar{d}_L \gamma_\mu W^{+\mu} u_L \\ &= -\frac{1}{2} g \bar{u}_L V_L^{u\dagger} V_L^d \gamma_\mu W^{-\mu} d_L - \frac{1}{2} g \bar{d}_L V_L^{d\dagger} V_L^u \gamma_\mu W^{+\mu} u_L \end{aligned} \tag{2.23}$$

The $V_L^{u\dagger} V_L^d$ mattrix product consisting of off-diagonal terms causes the transition of coupling of quarks from one doublet to the other doublets involving weak transition and charged current. This phenomena is called quark mixing and d'_L defined for down type quarks consists of mixed quark mass states.

$$d'_L = \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_L^{u\dagger} V_L^d d_L = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \tag{2.24}$$

For instance the first element d' is the superposition mass state of d, s and b that depends on V_{ud}, V_{us} and V_{ub}. The $V_L^{u\dagger} V_L^d$ matrix product is called CKM matrix [8]. The components are calculated by experimental analysis [14].

$$\begin{pmatrix} |V_{ud}| \approx 0.974 & |V_{us}| \approx 0.25 & |V_{ub}| \approx 0.003 \\ |V_{cd}| \approx 0.225 & |V_{cs}| \approx 0.973 & |V_{cb}| \approx 0.04 \\ |V_{td}| \approx 0.009 & |V_{ts}| \approx 0.040 & |V_{tb}| \approx 0.999 \end{pmatrix} \tag{2.25}$$

The CKM matrix explain in the following standard parametrization as [14]

$$\mathbf{V}_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \tag{2.26}$$

$$= \begin{pmatrix} C_{12}C_{13} & S_{12}S_{13} & S_{13}e^{-i\Delta} \\ -S_{12}C_{23} - C_{12}S_{23}S_{13}e^{i\Delta} & C_{12}S_{23} - S_{12}S_{23}S_{13}e^{i\Delta} & S_{23}C_{13} \\ S_{12}C_{23} - C_{12}S_{23}S_{13}e^{i\Delta} & -S_{23}C_{12} - S_{12}C_{23}S_{13}e^{i\Delta} & C_{23}C_{13} \end{pmatrix} \tag{2.27}$$

Here $C_{ab} = cos\theta_{ab}$, $S_{ab} = sin\theta_{ab}$ $\quad (a, b = 1, 2, 3)$ and Δ is the phase with the range $0 \leq \Delta \leq 2\pi$. $S_{12} = |V_{us}|$, $S_{13} = |V_{ub}|$, $S_{23} = |V_{cb}|$ and Δ. S_{12}, S_{13} and S_{23} are four independent parameter which is obtained by tree-level decays. Numerical calculations can be done suitably by standard parametrization.

Chapter 3

Theoretical Framework for $\boldsymbol{B}$ Meson Decay

In this chapter we will present the theoretical framework for rare B meson decays which is based on the effective field theory. The formalism of effective field theory can be use to describe the weak decays. Furthermore we also briefly discuss the new physics scenarios such as model independent/ leptoquark model and Z' models. The phenomenology of these models discuss in chapter 4.

3.1 Effective Field Theory

Effective field theory(EFT) [15,16] is one of the ingredient in quantum field theory which will use to analyze the multiscale problems. Consider a field theory whose characterstic energy scale κ, and suppose that we want to discuss physics at some much lower scale $E \ll \kappa$. To build such EFT one chooses a cutoff scale, which is slightly less then the energy scale and integrate out the heavy degree of freedom In general, the effective Lagrangian is written as;

$$\mathcal{L}_{eff} = \sum_{n \geq 0} C_n(\mu) O_n \tag{3.1}$$

The Lagrangian is an infinite sum over the operators O_n, where $C_n(\mu)$ is coupling constant known as wilson coefficients. So one can ask about the predictability of this theory. The answer to above question is by substituting the coupling constant $C_n(\mu)$ with dimensionless constant c_{i_n}. So the new form of Lagrangian is

$$\mathcal{L}_{eff} = \mathcal{L}^0 + \sum_{n>0} \sum_{c_{i_n}} \frac{c_{i_n}}{\kappa^n} O_{i_n} \tag{3.2}$$

The higher dimension of operator are suppressed with the increasing power of κ. The lowest dimensional operators is more important due to which one can cut off the series and only

the finite couplings and number of operator will remain.
The lowest dimensional operator will be more important. However it depends on the precision goal, where one can terminate the series and only the finite number of operators and couplings should preserved

3.1.1 Operator Product Expansion

Operator product expansion (OPE) is one of the important tool to investigate the weak interaction of quarks. To illustrate the phenomenon of OPE, consider a weak decay of hadron $D^0 \to K^-\pi^+$ which at quark level occurs at $c \longrightarrow su\bar{d}$ as shown in the fig.(3.1). The full amplitude of such decay can be written by using Feynman rules for weak interaction process and can be expressed as,

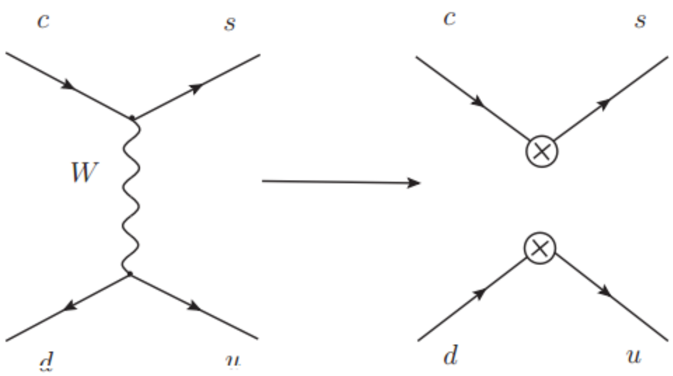


Figure 3.1: Left shows full theory and at Right the effective theory in $c \longrightarrow su\bar{d}$

$$\begin{aligned}\mathcal{M}_{Full} &= \frac{g_2^2}{8}V_{cs}^*V_{ud}[\bar{u}_s(p_s)\gamma_\mu(1-\gamma_5)u_c(p_c)]\frac{g^{\mu\nu}}{k^2-m_w^2}[\bar{u}_u(p_u)\gamma_\nu(1-\gamma_5)u_d(p_d)] \\ \mathcal{M}_{Full} &= \frac{G_F}{\sqrt{2}}V_{cs}^*V_{ud}[\bar{u}_s(p_s)\gamma_\mu(1-\gamma_5)u_c(p_c)]\frac{m_w^2}{k^2-m_w^2}[\bar{u}_u(p_u)\gamma^\mu(1-\gamma_5)u_d(p_d)] \quad (3.3)\end{aligned}$$

G_F is Fermi constant

$$\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8m_w^2} \quad (3.4)$$

Expanding the amplitude to $O(\frac{k^2}{m_w^2})$

$$\mathcal{M}_{Full} = -\frac{G_F}{\sqrt{2}}V_{cs}^*V_{ud}[\bar{u}_s(p_s)\gamma_\mu(1-\gamma_5)u_c(p_c)][\bar{u}_u(p_u)\gamma^\mu(1-\gamma_5)u_d(p_d)] + O(\frac{k^2}{m_w^2}) \quad (3.5)$$

Where k is the momentum transferred due to W propagator and its value is small as compared to m_w. We can neglect the terms $O(\frac{k^2}{m_w^2})$ without any hesitation from Eq(3.5). Now the full amplitude will be approximately equal to

$$\mathcal{M}_{Full} \approx -\frac{G_F}{\sqrt{2}}V_{cs}^*V_{ud}[\bar{u}_s(p_s)\gamma_\mu(1-\gamma_5)u_c(p_c)][\bar{u}_u(p_u)\gamma^\mu(1-\gamma_5)u_d(p_d)] \quad (3.6)$$

The same result is obtained by the effective Hamiltonian

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{cs}^* V_{ud} [\bar{s}\gamma_\mu(1-\gamma_5)c][\bar{u}\gamma^\mu(1-\gamma_5)d] + higher\ Dim\ operator \tag{3.7}$$

where

$$Q = [\bar{s}\gamma_\mu(1-\gamma_5)c][\bar{u}\gamma^\mu(1-\gamma_5)d]$$

In this example the value of Wilson coefficient $C_i(\mu) = 1$. This corresponds to the low energy scale, where the heavier particles momenta is integrated out and the higher dimension operator represented by the terms of order $O(\frac{k^2}{m_w^2})$. The OPE idea is grasped through above example. The significant property of OPE is to separate physics into two regime i-e the low and high energy regime.
In this way the effective Hamiltonian is defined as the linear combination of these operators. From the matching condition $\mathcal{M}_{full} = \mathcal{M}_{eff}$ amplitude we get the Wilson coefficient $C_i(\mu)$

$$\mathcal{M}_{full} = \mathcal{M}_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V_{CKM}^i C_i(\mu) < O_i(\mu) > \tag{3.8}$$

$< O_i(\mu) >$ bracket denoted matrix element to the relevant operator $O_i(\mu)$. This is called the matching condition of the full theory with effective theory. The full theory deals with the particles having dynamical degree of freedom while in effective theory we integrate out the heavy degree of freedom.

3.2 Effective Hamiltonian

The phenomenology of B-decays can be described by effective Hamiltonian. As mentioned in chapter 1, the decay under consideration is $B_c \to D_s^* \ell^+ \ell^-$, at quark level this decay is governed by the transition $b \to s\ell^+\ell^-$ hence the effective Hamiltonian for such decay can be expressed as

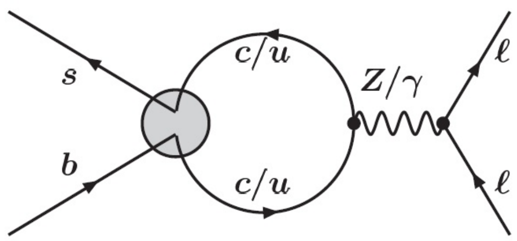


Figure 3.2: Effective diagram of $b \to s\ell^+\ell^-$

$$\mathcal{H}_{eff} = -\frac{G_F V_{ts}^* V_{tb}}{\sqrt{2}} \sum_{i=1} C_i(\mu) Q_i(\mu) \tag{3.9}$$

Now we write amplitude, the initial state of meson B_c goes into D_s^* which is final state meson, can be written as

$$\mathcal{M}(B_c \to D_s^*) = < D_s^*|H_{eff}|B_c > \tag{3.10}$$

$$= -\frac{G_F V_{ts}^* V_{tb}}{\sqrt{2}} \sum_{i=1}^{10} C_i(\mu) < D_s^*|Q_i(\mu)|B_c > \tag{3.11}$$

Where $V_{ts}^* V_{tb}$ are CKM matrix elements, $Q_i(\mu)$ are local quark operators and $C_i(\mu)$ are Wilson coefficients. The high energy physics are encoded in the WC's $C_i(\mu)$ and low energy physics are hidden in the local quark operators. The explicit form of these local quark operators are given as follows [17];

Current-Current Operator

$$\begin{aligned} Q_1 &= (\bar{s}_i c_j)_{V-A}(\bar{c}_j b_i)_{V-A}, \\ Q_2 &= (\bar{s}c)_{V-A}(\bar{c}b)_{V-A}, \end{aligned}$$

Quantum Chromodynamics Penguin Operator

$$\begin{aligned} Q_3 &= (\bar{s}b)_{V-A}\sum_q(\bar{q}q)_{V-A}, \\ Q_4 &= (\bar{s}_i b_j)_{V-A}\sum_q(\bar{q}_j q_i)_{V-A}, \\ Q_5 &= (\bar{s}b)_{V-A}\sum_q(\bar{q}q)_{V+A}, \\ Q_6 &= (\bar{s}_i b_j)_{V-A}\sum_q(\bar{q}_j q_i)_{V+A}, \end{aligned}$$

where q=u,d,b,s,c

Magnetic Dipole Operator

$$\begin{aligned} Q_7 &= \frac{e}{8\pi^2} m_b(\bar{s}\sigma^{\mu\nu}(1+\gamma_5)b)F_{\mu\nu}, \\ Q_8 &= \frac{e}{8\pi^2} m_b(\bar{s}_i\sigma^{\mu\nu}(1+\gamma_5)T_{ij}b_j)G_{\mu\nu}, \end{aligned}$$

Semileptonic electroweak penguin operator

$$
\begin{aligned}
Q_9 &= \frac{e}{8\pi^2}(\bar{s}b)_{V-A}(\bar{l}l)_V, \\
Q_{10} &= \frac{e}{8\pi^2}(\bar{s}b)_{V-A}(\bar{l}l)_A.
\end{aligned}
\tag{3.12}
$$

where (V±A) stands for $\gamma^\mu(1\pm\gamma^5)$. Gluon and photon field are the $G_{\mu\nu}$ and $F_{\mu\nu}$ respectively; T_{ij} represents the generators of the SU(3) color group; i and j are color indices.
In rare B meson decays, several decay modes precisely discussed in literature such as $B \to X_s\ell^+\ell^-$, $B \to (K, K^*)\ell^+\ell^-$ [7, 18, 19] based on quark level transitions $b \to s\ell^+\ell^-$ mediated via FCNC at loop level in SM. Many models are proposed in literature such as Z' models, Leptoquarks, SUSY and Universal extra dimension (UED) model which are powerful tool to search NP in said decays.
In this thesis, we consider only those NP models where the effects of NP can be observed only through the modification of WC's.

New Physics Models

To investigate the NP effects via $B_c \to D_s^*\ell^+\ell^-$ decays, we consider two different NP models such as heavy and light Z' models, Model independent/leptoquark models.

3.3 Model Independent Scenarios

In model independent scenarios all possible contributions in the form of Wilson coefficient and operators are taken into account in effective Hamiltonian. We write effective Hamiltonian for quark level transition $b \to s\mu^+\mu^-$

$$
\mathcal{H}_{eff} = -\frac{G_F V_{ts}^* V_{tb}\alpha}{\sqrt{2}\pi} \sum_{k=9,10} (C_k Q_k + C'_k Q'_k) \tag{3.13}
$$

$$
\begin{aligned}
Q_9 &= [\bar{s}\gamma_\mu P_L b][\bar{\mu}\gamma^\mu \mu] \\
Q_{10} &= [\bar{s}\gamma_\mu P_L b][\bar{\mu}\gamma^\mu \gamma_5 \mu]
\end{aligned}
\tag{3.14}
$$

Where we can get prime operators by replacing $P_L \to P_R$ and primed wilson coefficient have contributions from both SM and NP. There are a number of observables and experimental measurements can be used to constraint on NP for transition $b \to s\mu^+\mu^-$ to get new physics wilson coefficient.
There are three different NP scenarios discussed in literature [20];

- (I) $C_9^{\mu\mu}(NP) < 0$

- (II) $C_9^{\mu\mu}(NP) = -C_{10}^{\mu\mu}(NP) < 0$
- (III) $C_9^{\mu\mu}(NP) = C_9^{\mu\mu'}(NP) < 0$

Scenarios (I) and (II) will be taken to search the effects of NP in MI scenarios [20]. However, scenario (III) is ignored because it disagreed with experimental measurement. Leptoquark model could be only taken for scenario II. However, Z' models could be taken for both scenarios. we add model independent NP wilson coefficient $C_9(NP)$ and $C_{10}(NP)$ in the SM WC's $C_9(SM)$ and $C_{10}(SM)$ to search NP effects in said decay.
Here, we use two types of data fit for this transition $b \to s\mu^+\mu^-$, we analyze only CP conserving observables in fit A and we study R_{K^*} in fit B [1]. Fit-A and fit-B are taken in both the model dependent and MI analysis. The values of these WC's couplings of fit A and fit B taken from ref. [1] are given in table 3.1.

Scenarios	fit-A	fit-B
$(I)C_9^{\mu\mu}(NP)$	-1.20± 0.20	-1.25± 0.19
$(II)C_9^{\mu\mu}(NP) = -C_{10}^{\mu\mu}(NP)$	-0.62± 0.14	-1.68± 0.12
$(III)C_9^{\mu\mu}(NP) = -C_9^{\mu\mu'}(NP)$	-1.10 ± 0.18	-1.11± 0.17

Table 3.1: MI scenarios: WCs values in best fitting are taken from ref. [1]

3.3.1 Leptoquark Model

It is well known that Leptoquarks are spin-0 scalar or spin-1 vector bosonic particles that can couple to a lepton and a quark at the same time. The Leptoquark (LQ) models were explained in Ref. [20,21]. There are only three from the ten, LQ Models which could couple with SM particles having dimension less than or equal to 4 operators, explain $b \to s\mu^+\mu^-$. We consider here scalar isotriplet Leptoquarks(S_3) which potentially contribute to the $b \to s\mu^+\mu^-$ transition. The LQs transform as like SM guage symmetry $SU(3) \otimes SU(2) \otimes U(1)$. After integrating out the heavy scalar LQ boson, effective Hamiltonian of Heavy LQ model can be written as [21]

$$\mathcal{H}_{eff} = -\frac{G_F V_{ts}^* V_{tb}\alpha}{\sqrt{2}\pi}(C_9^{NP} Q_9' + C_{10}^{NP} Q_{10}') \tag{3.15}$$

All LQ models associated with only scenario (II). $C_9^{\mu\mu}(NP) = -C_{10}^{\mu\mu}(NP)$.

$$\mathcal{H}_{eff} = -\frac{G_F V_{ts}^* V_{tb}\alpha}{\sqrt{2}\pi} C_9^{NP}(Q_9' - Q_{10}') \tag{3.16}$$

We will obtain Q_9', Q_{10}' by flipping the projection operator $P_L \to P_R$ in Q_9, Q_{10} from eq.3.12. The WC's of LQ Model is directly proportional to fermions coupling $g_L^{b\mu} g_L^{s\mu}$ is given in ref. [20]

$$C_9^{\mu\mu}(NP) \propto \frac{g_L^{b\mu} g_L^{s\mu}}{M_{LQ}^2} \tag{3.17}$$

couplings of LQ are $g_L^{b\mu} g_L^{s\mu}$ and M_{LQ} is the leptoquark mass. The value of WC's is same as for Model Independent fit, given in table 3.1.

3.3.2 Z' Model

The Z' model [22–27] is the extension of SM, addition of an extra $U(1)'$ guage symmetry to the SM structure. One extra $U(1)'$ guage symmetry associated with a neutral gauge boson Z' gives off-diagonal couplings of non-universal Z' with fermions due to this FCNC transitions could occur at tree level in Z' model [28, 29]. We write the neutral current Lagrangian in the SM with Z' contribution as [30]

$$\mathcal{L}_{NC} = \mathcal{L}_{SM}^{Z} - g_2^{Z'} J'_\mu Z'^\mu \tag{3.18}$$

where $g_2^{Z'}$ is the guage coupling of Z' and $\mathcal{L}_{SM}^{Z} = -eJ_{em}^{\mu} A_\mu - g_Z J_Z^\mu Z_\mu$. The Z' current is given as;

$$J'_\mu = \sum_{i,j} \bar{\Psi}_i \gamma_\mu [(\epsilon_{\Psi L})_{ij} P_L + (\epsilon_{\Psi R})_{ij} P_R] \Psi_j \tag{3.19}$$

where Ψ denotes weak eigenstates of SM fermions, the sum is over the fermion flavors, $P_{L,R} \equiv (1 \mp \gamma_5)/2$, and $\epsilon_{\Psi L,R}$ denote the chiral couplings. Z' must transform as a triplet or singlet of $SU(2)_L$ and couples to left handed quarks. The fermion Yukawa matrices $\mathcal{Y}_\Psi$ in the weak eigenstate basis are diagonalized by the unitary matrices $V_{L,R}^{\Psi}$;

$$\mathcal{Y}_\Psi^{diag} = V_R^\Psi \, \mathcal{Y}_\Psi \, V_L^{\Psi\dagger} \tag{3.20}$$

Here, $V_{CKM} = V_R^\Psi V_L^{\Psi\dagger}$
Now, the chiral Z' couplings in the fermion mass eigenstate basis can be written as;

$$\mathcal{X}^{\Psi L} \equiv V_L^\Psi \epsilon_{\Psi L} V_L^{\Psi\dagger}, \quad \mathcal{X}^{\Psi R} \equiv V_R^\Psi \epsilon_{\Psi R} V_R^{\Psi\dagger} \tag{3.21}$$

Therefore, the chiral Z' couplings are induced by fermion mixing. Hence, FCNC occur at tree level in Z' model due to off diagonal coupling of non universal Z'.

$$\mathcal{X}^{\Psi L,R} = \begin{pmatrix} \mathcal{X}_{11}^{\Psi_{L,R}} & 0 & \mathcal{X}_{13}^{\Psi_{L,R}} \\ 0 & \mathcal{X}_{11}^{\Psi_{L,R}} & \mathcal{X}_{23}^{\Psi_{L,R}} \\ \mathcal{X}_{13}^{\Psi_{L,R}*} & \mathcal{X}_{23}^{\Psi_{L,R}*} & \mathcal{X}_{33}^{\Psi L,R} \end{pmatrix} \tag{3.22}$$

We consider two types of Z' models such as, Heavy and Light Z' models both are consistent with $b \to s\mu^+\mu^-$.

3.3.3 Heavy Z' Model

We have to taken important constraints form other obervables and experimental measurements for transition $b \to s\mu^+\mu^-$ to determine the properties of Z' accordingly, the Lagrangian of Z' model can be written as;

$$\mathcal{L}_{Z'} = J'_\mu Z' \tag{3.23}$$

$$J^\mu = -g_{LL}^{\mu\mu}\bar{X}\gamma^\mu P_L X + g_R^{\mu\mu}\bar{\mu}\gamma^\mu P_R \mu + g_L^{bs}\bar{\psi}_{q2}\gamma^\mu P_L \psi_{q3} \tag{3.24}$$

so, ψ_{qi} denote as the quark doublet, and $X = (\nu_\mu, \mu)^T$. We integrated out the heavy Z' guage boson [1]. Effective lagrangian containing 4-fermion operators written as;

$$\begin{aligned}\mathcal{L}_{Z'}^{eff} = -\frac{1}{2M_{Z'}^2}J_\mu J^\mu = & - \frac{g_L^{bs}}{M_{Z'}^2}(\bar{s}\gamma^\mu(1-\gamma^5)b)(\bar{\mu}\gamma^\mu(g_L^{\mu\mu}P_L + g_R^{\mu\mu}P_R)\mu) \\ & - \frac{(g_L^{bs})^2}{2M_{Z'}^2}(\bar{s}\gamma^\mu P_L b)(\bar{\gamma}^\mu P_L b) \\ & - \frac{g_L^{\mu\mu}}{M_{Z'}^2}(\bar{\mu}\gamma^\mu(g^{\mu\mu}P_L + g^{\mu\mu}P_R)\mu)(\bar{\nu}_\mu\gamma^\mu P_L \nu_\mu)\end{aligned} \tag{3.25}$$

Here, we consider two scenarios for the phenomenology of Z' models are;

- Scenario (I) $\quad g_R^{\mu\mu} = g_L^{\mu\mu}$
- Scenario (II) $\quad g_R^{\mu\mu} = 0$

The modified Wilson coefficient's in TeV Z' are given as;

$$C_9^{\mu\mu}(NP) = \left[\frac{\pi}{\sqrt{2}G_F\alpha V_{tb}V_{ts}^*}\right] \times \frac{g_L^{bs}(g_L^{\mu\mu} + g_R^{\mu\mu})}{M_{Z'}^2} \tag{3.26}$$

$$C_{10}^{\mu\mu}(NP) = -\left[\frac{\pi}{\sqrt{2}G_F\alpha V_{tb}V_{ts}^*}\right] \times \frac{g_L^{bs}(g_L^{\mu\mu} - g_R^{\mu\mu})}{M_{Z'}^2} \tag{3.27}$$

Following are the couplings of NP Wilson coefficients of Heavy Z' model.

$g_L^{\mu\mu}$	$Z'(I)g_L^{bs}$	$Z'(II)\ g_L^{bs}$
0.5	(-1.8± 0.3)× 10^{-3}	(-1.9± 0.4)×10^{-3}

Table 3.2: TeV Heavy Z' model in best fit values of a_L^{bs} in fit A in Ref. [1]

The four fermion operators required with in the scenarios are as follows;

$g_L^{\mu\mu}$	$Z'(I)g_L^{bs}$	$Z'(II)g_L^{bs}$
0.5	$(-1.9 \pm 0.3) \times 10^{-3}$	$(-2.1 \pm 0.4) \times 10^{-3}$

Table 3.3: TeV Heavy Z' model in best fit values of a_L^{bs} in fit B in Ref. [1]

- (I) $[\bar{s}\gamma_\mu P_L b][\bar{\mu}\gamma^\mu \mu]$
- (II) $[\bar{s}\gamma_\mu P_L b][\bar{\mu}\gamma^\mu P_L \mu]$
- (III) $[\bar{s}\gamma_\mu \gamma_5 b][\bar{\mu}\gamma^\mu \mu]$

There are two scenarios for Z' Model. It is natural for Z' guage boson to couple vectorially to $\bar{s}_L b_L$ and $\bar{\mu}\mu$ or $\bar{\mu}_L \mu_L$ as scenario (III) have need that Z' couple axial-vectorially to $\bar{s}b$ which seems not natural. All things considered, we exclude scenario (III) which has disagreement with experiments.

3.3.4 Light Z' Model

In Light Z' Model, we have two different mass ranges $m_{Z'} > m_B$ and $m_{Z'} < 2m_\mu$, first range have implication in dark matter and second range discuss the muon measurement of $g-2$ and have application for neutrino interaction. Here, we consider first range for $m_{Z'} = 10GeV$. The modified Wilson coefficient's for GeV Z' are given as;

$$C_9^{\mu\mu}(NP) = \left[\frac{\pi}{\sqrt{2}G_F \alpha V_{tb} V_{ts}^*}\right] \times \frac{(a_L^{bs} + g_L^{bs}(q^2/m_B^2))(g_L^{\mu\mu} + g_R^{\mu\mu})}{q^2 - M_{Z'}^2} \tag{3.28}$$

$$C_{10}^{\mu\mu}(NP) = -\left[\frac{\pi}{\sqrt{2}G_F \alpha V_{tb} V_{ts}^*}\right] \times \frac{(a_L^{bs} + g_L^{bs}(q^2/m_B^2))(g_L^{\mu\mu} - g_R^{\mu\mu})}{q^2 - M_{Z'}^2} \tag{3.29}$$

Here we have the WC's are q^2 dependent in Light Z' model for $b \to s\mu^+\mu^-$.
In the GeV Light Z' model a_L^{bs} is present, so here we will unconcern g_L^{bs}. Following are the couplings of NP wilson coefficients of Light Z' model.

$g_L^{\mu\mu}$	$Z'(I)\ a_L^{bs}$	$Z'(II)a_L^{bs}$
1.2	$(-5.2 \pm 1.2) \times 10^{-6}$	$(-7.2 \pm 1.8) \times 10^{-6}$

Table 3.4: GeV Light Z' model in best fit values of a_L^{bs} in fit A in Ref. [1]

Chapter 4

Analysis of Decay $B_c \to D_s^*\ell^+\ell^-$ Beyond SM

4.1 Effective Hamiltonian of decay $B_c \to D_s^*\ell^+\ell^-$

We calculate exclusive semileptonic B meson decay $B_c \to D_s^*\ell^+\ell^-$ with in SM and beyond. The decay corresponds to penguin diagram which is also called SD diagram as shown in Fig.4.1.
The Amplitude for $B_c \to D_s^*\ell^+\ell^-$ which is based on quark level transition of $b \to s\ell^+\ell^-$ decay leaded by effective Hamiltonian from eq.3.9 written as follow;

$$\begin{aligned}\mathcal{M}^{PEGN}_{B_c\to D_s^*\bar{\ell}\ell} = & - \frac{G_F\alpha}{\sqrt{2}\pi}V_{tb}V_{ts}^*[\mathcal{C}_9^{tot}(\mu) < D_s^*(k,\epsilon)|\bar{s}\gamma_\mu(1-\gamma_5)b|B_c(p) > (\bar{l}\gamma^\mu l) \\ & + \mathcal{C}_{10}^{tot} < D_s^*(k,\epsilon)|(\bar{s}\gamma_\mu(1-\gamma_5)b)|B_c(p) > (\bar{l}\gamma^\mu\gamma^5 l) \\ & - 2\,\mathcal{C}_7^{eff}(\mu)\frac{m_b}{q^2} < D_s^*(k,\epsilon)|(\bar{s}i\sigma_{\mu\nu}q^\nu(1+\gamma_5)b)|B_c(p) > \bar{l}\gamma^\mu l] \end{aligned} \tag{4.1}$$

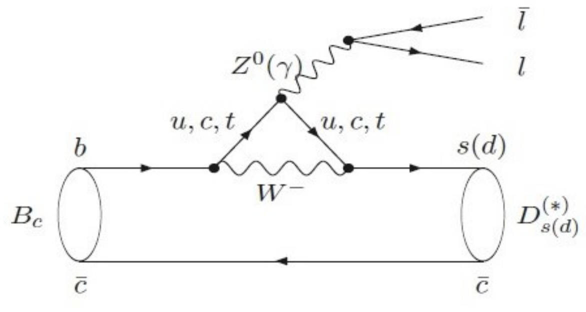


Figure 4.1: Penguin diagram for $B_c \to D_s^*\ell^+\ell^-$ decay [3]

Here, $C_9^{tot} = C_9^{eff}$(SM)+ $C_9^{\mu\mu}$(NP) and $C_{10}^{tot} = C_{10}^{eff}$(SM)+$C_{10}^{\mu\mu}$(NP).
We write wilson coefficient $\mathcal{C}_9^{eff}$ [17] as

$$\mathcal{C}_9^{eff}(\mu) = \mathcal{Y}_{\mathcal{SD}}(r, v') + \mathcal{Y}_{\mathcal{LD}}(r, v') + \mathcal{C}_9(\mu) \tag{4.2}$$

$$\mathcal{C}_9^{eff} = \mathcal{C}_9 + \mathcal{C}_0\{u(r, v') + \frac{3\pi}{\alpha^2}\Delta \sum_{D_i=\Psi(1s),\Psi(2s)} \frac{\Gamma(D_i \to l^+l^-)m_{D_i}}{m^2 D_i} - q^2 - im_{D_i}\Gamma D_i\} \tag{4.3}$$

So here,

$$\mathcal{C}_0 \equiv 3\mathcal{C}_5 + \mathcal{C}_6 + 3\mathcal{C}_1 + \mathcal{C}_2 + 3\mathcal{C}_3 + \mathcal{C}_4$$

.

$$\begin{aligned}
\mathcal{Y}_{\mathcal{SD}}(r, v') &= u(r, v')(3\mathcal{C}_1(\mu) + \mathcal{C}_2(\mu) + 3\mathcal{C}_3(\mu) + \mathcal{C}_4(\mu) + 3\mathcal{C}_5(\mu) + \mathcal{C}_6(\mu)) \\
&\quad -\frac{1}{2}u(1, v')(4\mathcal{C}_3(\mu) + 4\mathcal{C}_4(\mu) + 3\mathcal{C}_5(\mu) + \mathcal{C}_6(\mu)) \\
&\quad -\frac{1}{2}u(0, v')(\mathcal{C}_3(\mu) + 3\mathcal{C}_4(\mu)) + \frac{2}{9}(3\mathcal{C}_3(\mu) \\
&\quad +\mathcal{C}_4(\mu) + 3\mathcal{C}_5(\mu) + \mathcal{C}_6(\mu)).
\end{aligned}$$

$$\begin{aligned}
u(r, v') &= -\frac{8}{9}\ln\frac{m_b}{\mu} - \frac{8}{9}\ln r + \frac{8}{27} + \frac{4}{9}y \\
&\quad -\frac{2}{9}|1-y|^{1/2}(2+y)\left[\ln|\frac{\sqrt{1-y}+1}{\sqrt{1-y}-1}| - i\pi\right] \quad for \quad y \equiv 4r^2/v' < 1,
\end{aligned}$$

$$\begin{aligned}
u(r, v') &= -\frac{8}{9}\ln\frac{m_b}{\mu} - \frac{8}{9}\ln r + \frac{8}{27} + \frac{4}{9}y \\
&\quad -\frac{2}{9}|1-y|^{1/2}(2+y)\left[2\arctan\frac{1}{\sqrt{y-1}}\right] \quad for \quad y \equiv 4r^2/v' > 1, \\
u(0, v') &= \frac{8}{27} - \frac{8}{9}\ln\frac{m_b}{\mu} - \frac{4}{9}\ln v + \frac{4}{9}i\pi.
\end{aligned}$$

where $r = m_c/m_B,\ v' = q^2/m_B^2$ and $\Delta = 1/\mathcal{C}_0$. $\mathcal{Y}_{\mathcal{SD}}$ denotes the SD contributions.

4.2 Matrix Element and Form Factors

The parameterization of matrix elements for decay $B_c \to D_s^*$ are written in terms of form factors [2] which are functions of momentum transfer $[q^2 = (p-k)^2]$.

$$
\begin{aligned}
< D_s^*(k,\epsilon)|\bar{s}\gamma_\mu b|B_c(p) > &= \frac{2i\varepsilon_{\mu\nu\alpha\beta}}{M_{B_c}+M_{D_s^*}}\,\epsilon^{*\nu}p^\alpha k^\beta A_V(q^2) \qquad (4.4)\\
< D_s^*(k,\epsilon)|\bar{s}\gamma_\mu\gamma_5 b|B_c(p) > &= (M_{B_c}+M_{D_s^*})\varepsilon^{*\mu}A_0(q^2)\\
&\quad -\frac{(\varepsilon^*.q)A_+(q^2)}{M_{B_c}+M_{D_s^*}}(p+k)^\mu\\
&\quad -\frac{A_-(q^2)}{M_{B_c}+M_{D_s^*}}(\varepsilon^*.q)q^\mu\\
< D_s^*(k,\epsilon)|\bar{s}i\sigma_{\mu\nu}q^\nu b|B_c(p) > &= 2i\epsilon_{\mu\nu\alpha\beta}\varepsilon^{*\nu}p^\alpha k^\beta T_1(q^2)\\
< D_s^*(k,\epsilon)|\bar{s}i\sigma_{\mu\nu}q^\nu\gamma^5 b|B_c(p) > &= \left[(M_{B_c}^2+M_{D_s^*}^2)\varepsilon_\mu^* - (\varepsilon^*.q)(p+k)_\mu\right]T_2(q^2)\\
&\quad +(\varepsilon^*.q)\left[q_\mu - \frac{q^2}{(M_{B_c}^2+M_{D*_s}^2)}(p+k)_\mu\right]T_3(q^2)
\end{aligned}
$$

where p denotes the momentum of B_c meson and , $\varepsilon(k)$ are the polarization vector D_s^* meson.

The form factors [2] $A_V(q^2), A_0(q^2), A_+(q^2), A_-(q^2), T_1(q^2), T_2(q^2), T_3(q^2)$ are the non-perturbative quantities. Form factors are calculated by using QCD sum rules [2]. We use the parameterization of form factors which depends on momentum transfer (q^2) can be written as; [2]

$$
\mathcal{F}(q^2) = \frac{\mathcal{F}(0)}{1+\alpha\frac{q^2}{M_{B_c}}+\beta\frac{q^4}{M_{B_c}}} \qquad (4.5)
$$

where the values of $\mathcal{F}(0), \alpha$ and β are given in following Table 4.1.

In order to analyze the various observables, such as the branching ratios, the longitudinal helicity fractions, leptons forward backward asymmetry and lepton flavor Universality(LFU) ratios, we can express the amplitude in helicity basis.

4.3 Helicity Amplitude of B meson decay

We write the amplitude of penguin diagram by substituting matrix elements in eq.4.1 and separated out leptonic vector current and leptonic axial current.

$\mathcal{F}(q^2)$	$\mathcal{F}(0)$	α	β
$A_V(q^2)$	0.54	-1.28	-0.23
$A_0(q^2)$	0.30	-0.13	-0.18
$A_+(q^2)$	0.36	-0.67	-0.066
$A_-(q^2)$	-0.57	-1.11	-0.14
$T_1(q^2)$	0.31	-1.28	-0.23
$T_2(q^2)$	0.33	-0.10	-0.097
$T_3(q^2)$	0.29	-0.91	0.007

Table 4.1: Form factors of $B_c \to D_s^*$ decay which are calculated by using QCD Sum rules [2].

$$\mathcal{M}^{PEGN}_{B_c\to D_s^*\ell^+\ell^-} = -\frac{G_F\alpha}{2\sqrt{2}\pi}V_{tb}V_{ts}^*[T^1_\mu(\bar{l}\gamma^\mu l) + T^2_\mu(\bar{l}\gamma^\mu\gamma^5 l)] \tag{4.6}$$

$$T^1_\mu = -i\epsilon_{\mu\nu\alpha\beta}\varepsilon^{*\nu}p^\alpha k^\beta\mathcal{F}_1(q^2) - g_{\mu\nu}\mathcal{F}_2(q^2) + q_\mu q_\nu\mathcal{F}_3(q^2) + P_\mu q_\nu\mathcal{F}_4(q^2)$$
$$T^2_\mu = -i\epsilon_{\mu\nu\alpha\beta}\varepsilon^{*\nu}p^\alpha k^\beta\mathcal{F}_5(q^2) - g_{\mu\nu}\mathcal{F}_6(q^2) + q_\mu q_\nu\mathcal{F}_7(q^2) + P_\mu q_\nu\mathcal{F}_8(q^2)$$

The functions $\mathcal{F}_1$ to $\mathcal{F}_8$ in eq. 4.7 are recognized as auxiliary functions. Auxiliary functions contain both SD (WC's) and LD (Form factors).
We write the auxiliary functions as follow;

$$\mathcal{F}_1 = \frac{2C_9^{eff}A_V(q^2)}{M_{D_s^*}+M_{B_c}} + \frac{4m_b}{q^2}C_7^{eff}T_1(q^2) \tag{4.7}$$

$$\mathcal{F}_2 = C_9^{eff}A_0(q^2)(M_{D_s^*}+M_{B_c}) + \frac{2m_b}{q^2}C_7^{eff}T_2(q^2)(M_{D_s^*}+M_{B_c})$$

$$\mathcal{F}_3 = \frac{A_-(q^2)C_9^{eff}}{M_{D_s^*}+M_{B_c}} + \frac{2m_b}{q^2}C_7^{eff}T_3(q^2)$$

$$\mathcal{F}_4 = \frac{A_+(q^2)C_9^{eff}}{M_{D_s^*}+M_{B_c}} + \frac{2m_b}{q^2}(T_2(q^2) + \frac{q^2T_3(q^2)}{M_{D_s^*}+M_{B_c}})$$

$$\mathcal{F}_5 = \frac{2C_{10}^{eff}A_V(q^2)}{M_{D_s^*}+M_{B_c}}$$

$$\mathcal{F}_6 = C_{10}^{eff}(M_{D_s^*}+M_{B_c})A_0(q^2)$$

$$\mathcal{F}_7 = \frac{C_{10}^{eff}A_-(q^2)}{M_{D_s^*}+M_{B_c}}$$

$$\mathcal{F}_8 = \frac{C_{10}^{eff}A_+(q^2)}{M_{D_s^*}+M_{B_c}}$$

Now square of amplitude modulus is written as;

$$|M|^2 \quad = \quad M^\dagger M$$

$$\begin{aligned} |M|^2 &= \frac{G_f \alpha \lambda_t}{2\sqrt{2}\pi}[T_1^\mu T_1^{|\dagger\nu}(\bar{l}\gamma_\mu l)(\bar{l}\gamma_\nu l)^\dagger + T_1^\mu T_2^{|\dagger\nu}(\bar{l}\gamma_\mu l)(\bar{l}\gamma_\nu\gamma_5 l)^\dagger \\ &+ T_2^\mu T_1^{\dagger\nu}(\bar{l}\gamma_\nu\gamma_5 l)(\bar{l}\gamma_\mu l)^\dagger + T_2^\mu T_2^{\dagger\nu}(\bar{l}\gamma_\mu\gamma_5 l)(\bar{l}\gamma_\nu\gamma_5 l)^\dagger] \end{aligned} \tag{4.8}$$

$$\begin{aligned} |M|^2 &= \frac{G_f \alpha \lambda_t}{2\sqrt{2}\pi}[H_{11}^{\mu\mu}(\bar{l}\gamma_\mu l)(\bar{l}\gamma_\nu l)^\dagger + H_{12}^{\mu\nu}(\bar{l}\gamma_\mu l)(\bar{l}\gamma_\nu\gamma_5 l)^\dagger \\ &+ H_{21}^{\mu\nu}(\bar{l}\gamma_\nu\gamma_5 l)(\bar{l}\gamma_\mu l)^\dagger + H_{22}^{\mu\mu}(\bar{l}\gamma_\mu\gamma_5 l)(\bar{l}\gamma_\nu\gamma_5 l)^\dagger] \end{aligned} \tag{4.9}$$

Where $\lambda_t = V_{tb}V_{ts}^*$ and $H_{ij}^{\mu\nu} = T_i^\mu T_j^{\nu\dagger}$

now as,

$$(\bar{l}\gamma_\mu l)(\bar{l}\gamma_\nu l)^\dagger = tr[\gamma^\mu(p_1^\mu - m_l)\gamma_\nu(p_2^\mu + m_l)] \tag{4.10}$$

$$(\bar{l}\gamma_\mu l)(\bar{l}\gamma_\nu\gamma_5 l)^\dagger = tr[\gamma^\mu\gamma_5(p_1^\mu - m_l)\gamma_\nu\gamma_5(p_2^\mu + m_l)]$$

$$(\bar{l}\gamma_\nu\gamma_5 l)(\bar{l}\gamma_\mu l)^\dagger = -tr[\gamma^\mu(p_1^\mu - m_l)\gamma_\nu\gamma_5(p_2^\mu + m_l)]$$

$$(\bar{l}\gamma_\mu\gamma_5 l)(\bar{l}\gamma_\nu\gamma_5 l)^\dagger = -tr[\gamma^\mu\gamma_5(p_1^\mu - m_l)\gamma_\nu(p_2^\mu + m_l)]$$

so therefore,

$$\begin{aligned} \sum_{pol}|M|^2 &= [H_{11}^{\mu\mu}.tr[\gamma^\mu(\not{p}_1^\mu - m_l)\gamma_\nu(\not{p}_2^\mu + m_l)] \\ &\quad +H_{22}^{\mu\nu}.tr[\gamma^\mu\gamma_5(\not{p}_1^\mu - m_l)\gamma_\nu\gamma_5(\not{p}_2^\mu + m_l)] \\ &\quad -H_{12}^{\mu\nu}tr[\gamma^\mu(\not{p}_1^\mu - m_l)\gamma_\nu\gamma_5(\not{p}_2^\mu + m_l)] \\ &\quad -H_{21}^{\mu\nu}.tr[\gamma^\mu\gamma_5(\not{p}_1^\mu - m_l)\gamma_\nu(\not{p}_2^\mu + m_l)]] \end{aligned} \tag{4.11}$$

$$\begin{aligned} &= [H_{11}^{\mu\nu}.4(-g_{\mu\nu}(m_l^2 + p_1.p_1) + p_1^\mu p_2^\nu + p_2^\mu p_1^\nu) \\ &\quad +H_{22}^{\mu\nu}.4(g_{\mu\nu}(m_l^2 - p_1.p_1) + p_1^\mu p_2^\nu + p_2^\mu p_1^\nu) \\ &\quad +H_{12}^{\mu\nu}.4(i\epsilon_{\mu\nu\alpha\beta}p_1^\alpha p_2^\beta) + H_{21}^{\mu\nu}.4(i\epsilon_{\mu\nu\alpha\beta}p_1^\alpha p_2^\beta)] \end{aligned} \tag{4.12}$$

$$\sum_{pol}|M|^2 = 4[H_{11}^{\mu\nu}(-L_{\mu\nu}^{(2)}(m_l^2+\frac{q^2-2m_l^2}{2})+L_{\mu\nu}^{(1)}) \tag{4.13}$$
$$+H_{22}^{\mu\nu}(L_{\mu\nu}^{(2)}(m_l^2+\frac{q^2-2m_l^2}{2})+L_{\mu\nu}^{(1)})$$
$$+(H_{12}^{\mu\nu}+H_{21}^{\mu\nu})L_{\mu\nu}^{(3)}]$$

$$\sum_{pol}|M|^2 = 4[L_{\mu\nu}^{(1)}(H_{11}^{\mu\nu}+H_{22}^{\mu\nu})-\frac{1}{2}L_{\mu\nu}^{(2)}(q^2H_{11}^{\mu\nu}+(q^2-m_l^2)H_{22}^{\mu\nu}) \tag{4.14}$$
$$+L_{\mu\nu}^{(3)}(H_{12}^{\mu\nu}+H_{21}^{\mu\nu})]$$

We have defined hadron and lepton tensors [17] as

$$\begin{aligned} L_{\mu\nu}^{(1)} &= p_{1\mu}p_{2\nu}+p_{2\mu}p_{1\nu} \\ L_{\mu\nu}^{(2)} &= g_{\mu\nu} \\ L_{\mu\nu}^{(3)} &= i\epsilon_{\mu\nu\alpha\beta}p_1^\alpha p_2^\beta \\ H_{ij}^{\mu\nu} &= T_i^\mu T_j^{\nu\dagger} \end{aligned} \tag{4.15}$$

We will solve these tensors in the following sections.

4.3.1 Hadronic part

The hadronic tensor in terms of helicity basis $\varepsilon^{\dagger\mu}(m)$ as,

$$\begin{aligned} H_m^i &= \varepsilon^{\dagger\mu}(m)T_\mu^{(i)} \\ H_m^i &= \varepsilon^{\dagger\mu}(m)\varepsilon^{\dagger\nu}(n)T_{\mu\nu}^{(i)} \end{aligned} \tag{4.16}$$

Where $T_\mu^{(i)}=\varepsilon^{\dagger\nu}(n)T_{\mu\nu}^{(i)}$, ε^ν is the "vector polarization" of the final state D_s^* meson; $m,n = 0, \pm, t$, are the longitudinal, transverse and time components; and $i = 1, 2$; The helicity components of polarization vector reads as;

$$\begin{aligned} \epsilon^\mu(\pm) &= \frac{1}{\sqrt{2}}(0,\pm1,i,0) \\ \epsilon^\mu(0) &= \frac{1}{m}(|k|,0,0,E) \\ g_{mn} &= diag(+,-,-,-) \end{aligned} \tag{4.17}$$

and in the B-meson rest frame i.e

$$\begin{aligned} p^\mu &= (m_B,0,0,0) \\ k^\mu &= (E_k,0,0,|k|) \\ q^\mu &= (q_0,0,0,|k|) \end{aligned} \tag{4.18}$$

the polarization vectors reads as

$$\begin{aligned}
\varepsilon^{\mu}(t) &= \frac{1}{\sqrt{q^2}}(q_0, 0, 0, |k|) \\
\varepsilon^{\mu}(\pm) &= \frac{1}{\sqrt{2}}(0, \mp 1, i, |k|) \\
\varepsilon^{\mu}(0) &= \frac{1}{\sqrt{q^2}}(|k|, 0, 0, q_0)
\end{aligned} \tag{4.19}$$

where $|k| = \frac{\sqrt{\lambda}}{2m_B}$; $\lambda = m_B^4 + m_{D_s^*}^4 + q^4 - 2(m_B^2 m_{D_s^*}^2 + m_{D_s^*}^2 q^2 + m_B^2 q^2)$ and $E_{D_s^*} = \frac{m_B^2 + m_{D_s^*}^2 - q^2}{2m_B}$, D_s^* is final state meson, so using equation of Hadronic tensor we have,

$$\begin{aligned}
H_0^{(1)} &= \frac{1}{m_{D_s^*}\sqrt{q^2}}[2q_0|k|^2(q_0 - E_{D_s^*})\mathcal{F}_2 + (|k|^2 + q_0 E_{D_s^*})\mathcal{F}_3 \\
&\quad + |k|^2(q_0(m_B + 2E_{D_s^*}) - q_0^2 - E_{D_s^*}(m_B + E_{D_s^*}))\mathcal{F}_4] \\
H_0^{(2)} &= \frac{1}{m_{D_s^*}\sqrt{q^2}}[2q_0|k|^2(q_0 - E_{D_s^*})\mathcal{F}_6 + (|k|^2 + q_0 E_{D_s^*})\mathcal{F}_7 \\
&\quad + |k|^2(q_0(m_B + 2E_{D_s^*}) - q_0^2 - E_{D_s^*}(m_B + E_{D_s^*}))\mathcal{F}_8] \\
H_+^{(1)} &= -i|k|m_B\mathcal{F}_1 + \mathcal{F}_3 \\
H_+^{(2)} &= -i|k|m_B\mathcal{F}_5 + \mathcal{F}_7 \\
H_-^{(1)} &= i|k|m_B\mathcal{F}_1 + \mathcal{F}_3 \\
H_-^{(2)} &= i|k|m_B\mathcal{F}_5 + \mathcal{F}_7
\end{aligned} \tag{4.20}$$

These are the components of hadronic tensor, The subscripts $\pm, 0$ denotes the transverse and longitudinal helicity components, respectively. We have ignored the time component for both leptonic and hadronic tensors.

4.3.2 Leptonic Part

For the leptonic tensors $L_{\mu\nu}^{(k)}$ in $\bar{l}l$-CM frame we can write,

$$\begin{aligned}
q^{\mu} &= (\sqrt{q^2}, \vec{0}) \\
p_1^{\mu} &= (E_l, |p_1|sin\theta, 0, |p_1|cos\theta) \\
p_2^{\mu} &= (E_l, -|p_1|sin\theta, 0, -|p_1|cos\theta)
\end{aligned} \tag{4.21}$$

with $E_l = \sqrt{q^2}/2$ and $|p_1| = \sqrt{q^2 - 4m_l^2}/2$ and the polarization vectors in $\bar{l}l - CM$ frame are;

$$\begin{aligned}
\epsilon^{\mu}(\pm) &= \frac{1}{\sqrt{2}}(0, \pm 1, i, 0) \\
\epsilon^{\mu}(0) &= (0, 0, 0, 1) \\
\epsilon^{\mu}(t) &= (1, 0, 0, 0)
\end{aligned} \tag{4.22}$$

Hence by using this information of polarization of vectors and lepton kinematics, we have calculated the following lepton tensor components;

$$\begin{aligned}
L^1_{00} &= -2|p_1|^2 cos^2\theta \\
L^2_{00} &= -1 \\
L^3_{00} &= 0 \\
L^1_{++} &= E_l - |p_1|^2 sin^2\theta \\
L^2_{++} &= -1 \\
L^3_{++} &= -2E_l|p_1|cos\theta \\
L^1_{--} &= E_l^2 \\
L^2_{--} &= -1 \\
L^3_{--} &= 2E_l|p_1|cos\theta
\end{aligned} \tag{4.23}$$

Now, by using these leptonic tensor components, the hadronic tensor components, we can write amplitude $\mathcal{M}$ of saai decay in terms of helicity basis.

4.4 Differential decay rate

We write branching ratio in terms of helicity amplitude, which is:

$$\frac{d^2\Gamma(B_c \to D_s^* \ell^+ \ell^-)}{dq^2} = \frac{1}{(2\pi)^3} \frac{1}{32M^3_{B_c}} \int_{+(q^2)}^{-(q^2)} dq^2 |\mathcal{M}|^2 \tag{4.24}$$

$$\begin{aligned}
\frac{d^2\Gamma(B_c \to D_s^* \ell^+ \ell^-)}{dq^2 dcos\theta} &= \frac{G_F^2}{(2\pi)^3} \left(\frac{\alpha|\lambda_t|}{2\pi}\right)^2 \frac{|k|\sqrt{1 - 4m_l^2/q^2}}{8m_l^2} \frac{1}{2}[\ L^{(1)}_{\mu\nu}.(H^{\mu\nu}_{11} + H^{\mu\nu}_{22}) \\
&\quad -\frac{1}{2} L^{(2)}_{\mu\nu}(q^2 H^{\mu\nu}_{11} + (q^2 - m_l^2) H^{\mu\nu}_{22}) + L^{(3)}_{\mu\nu}.(H^{\mu\nu}_{12} + H^{\mu\nu}_{21})\ ]
\end{aligned} \tag{4.25}$$

Where $\lambda_t = |V_{ts}^\dagger V_{tb}|$ denotes CKM matrices, |k| denotes as momentum of vector meson given in the rest frame of B meson. After integration over $cos\theta$ and putting the values of the leptonic and hadronic tensor components $L^{(k)}(m,n), H^{ij}(m,n)$ respectively, we get;

$$\begin{aligned}\frac{d\Gamma(B \to D_s^* \ell^+ \ell^-)}{dq^2} &= \frac{G_F^2}{(2\pi)^3}\left(\frac{\alpha|\lambda_t|}{2\pi}\right)^2 \frac{\lambda^{1/2} q^2}{48 M_B^3}\sqrt{1-4m_l^2/q^2}[\ H^1 H^{1\dagger}(1+4m_l^2/q^2) \\ &+ H^2 H^{2\dagger}(1-4m_l^2/q^2)\ ] \end{aligned} \tag{4.26}$$

where m_l denotes as the lepton mass, $\lambda = M_B^4 + M_{D_s^*}^4 + q^4 - 2(M_B^2 M_{D_s^*}^2 + M_{D_s^*}^2 q^2 + M_B^2 q^2)$ and we separated out transverse and longitudinal hadronic components of amplitudes.

$H^i H^{i\dagger} \equiv H_+^i H_+^{i\dagger} + H_-^i H_-^{i\dagger} + H_0^i H_0^{i\dagger}$

Branching ratios precisely used in literature to find NP effects. NP effects can be observe more easily in the branching ratio of $B_c \to D_s^* \ell^+ \ell^-$ than others observables because branching ratios are measured to be consistent with both the SM and NP.

4.5 Forward Backward Asymmetry

We determine leptons forward backward asymmetry(FBA) to analyze our said process. FBA is an importance observables to search NP effects than the other physical observables because its minimize the uncertainties due to form factors and the value of zero crossing of $\mathcal{A}_{FB}$ gives a more clear signal of presence of NP effects.
The FBA of leptons is defined as;

$$\mathcal{A}_{FB} = \frac{\mathcal{N}^F - \mathcal{N}^B}{\mathcal{N}^F + \mathcal{N}^B} \tag{4.27}$$

where $\mathcal{N}^F(\mathcal{N}^B)$ is the number of event in which leptons moving in forward(backward) directions.
We use the double differential decay rate formula from eq. 4.26 to simplify the following expression for forward backward asymmetries;

$$\mathcal{A}_{FB}(q^2) = \frac{\int_0^1 dcos\theta \frac{d^2\Gamma(q^2,cos\theta)}{dq^2 dcos\theta} - \int_{-1}^0 dcos\theta \frac{d^2\Gamma(q^2,cos\theta)}{dq^2 dcos\theta}}{\int_0^1 dcos\theta \frac{d^2\Gamma(q^2,cos\theta)}{dq^2 dcos\theta} + \int_{-1}^0 dcos\theta \frac{d^2\Gamma(q^2,cos\theta)}{dq^2 dcos\theta}} \tag{4.28}$$

We write the analytical expression for forward backward Asymmetry of leptons as follow;

$$A_{FB} = \frac{3}{4}\sqrt{1-\frac{4m_l^2}{q^2}} \frac{Re(H_+^{(1)} H_+^{\dagger(2)}) - Re(H_-^{(1)} H_-^{\dagger(2)})}{H^{(1)} H^{\dagger(1)}(1+\frac{4m_l^2}{q^2}) + H^{(2)} H^{\dagger(2)}(1-\frac{4m_l^2}{q^2})} \tag{4.29}$$

4.6 Helicity Fraction

Longitudinal Helicity fraction of D_s^* meson in said decay which have less dependence on input parameters and uncertainties arising because of form factors. The study of helicity fraction will give a test for NP in said process.
We write an differential expression for longitudinal helicity fraction of D_s^* meson;

$$F_L = \frac{d\Gamma_L(q^2)/dq^2}{d\Gamma(q^2)/dq^2} \tag{4.30}$$

where $d\Gamma_L(q^2)/dq^2$ is the longitudinal component of decay rate. Now we can easily write the following analytical expression for longitudinal helicity fraction by using longitudinal and total component of decay rate in eq.4.30;

$$F_L(q^2) = \frac{H_0^{(1)}H_0^{(1)\dagger}(1+\frac{4m_l^2}{q^2}) + H_0^{(2)}H_0^{(2)\dagger}(1-\frac{4m_l^2}{q^2})}{H^{(1)}H^{(1)\dagger}(1+\frac{4m_l^2}{q^2}) + H^{(2)}H^{(2)\dagger}(1-\frac{4m_l^2}{q^2})} \tag{4.31}$$

The experimentally measured values of $F_L^{K^*}$ for the decay $B \to K^*\ell^+\ell^-$ based on transition of $b \to s\bar{\ell}^+\ell^-$ by Babar collaboration are [31]

$$F_L^{[q^2 \leq 10.24]} = 0.51^{+0.22}_{-0.25} \pm 0.08 \tag{4.32}$$

$$F_L^{[0.1,\,8.14]} = 0.77^{+0.63}_{-0.30} \pm 0.07 \tag{4.33}$$

these values have tension with SM prediction. Longitudinal helicity fraction of D_s^* meson may hint the influence of NP in said decay.

4.7 Lepton Flavor Universality Ratios

Lepton Flavor Universality ratios are the ratio of branching ratios to different lepton generation and this observable an ideal tool to test for NP in said process. We compare cross sections or decay widths which change only in lepton flavor, like electron and muon, So lepton flavor universality ratios can be represented as a function of particle masses where CKM matrix element factors and guage factor void in ratios, although hadronic physics parameters like as form factors and decay constants also suppress in LFU ratios.
Analytical expression for LFU ratio can be written as;

$$R_{D_s^{(*)}} = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B_c \to D_s^{(*)}\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B_c \to D_s^{(*)}e^+e^-)}{dq^2} dq^2} \tag{4.34}$$

Deviation in LFU ratio from the SM predictions is the good sign of the presence of NP. So experimentally measured LFU ratios at LHCb are theoretically very clean observable in the search of NP and the values given by LHCb are [32, 33]

$$R_{K^*}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05, R_{K}^{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036, R_{K^*}^{[0.045,1.1]} = 0.66^{+0.01}_{-0.07} \pm 0.03 \quad (4.35)$$

these values have deviation with the SM values are 2.1-2.3σ, 2.6σ and 2.6σ respectively [34]. The measurements of the ratios R_{K^*} hint towards LFU violation. We test lepton flavor universality ratio in rare B meson decays where interestingly large hadronic uncertainties essentially cancel out. We will consider MI new physics scenarios and Z' models to deduce NP effects by LFU ratios, so we will determine to which pattern new physics effects arises in $R_{D_s^*}$.

Observables	[0.045-1]	[1-2]	[2-3]	[3-4]	[4-5]	[5-6]	[1-6]
$10^{-7} \times \mathcal{B}(B_c \to D_s^* \mu^+\mu^-)$	0.213	0.071	0.078	0.094	0.011	0.012	0.048
$<R_{D_s^*}>$	0.939	0.977	0.981	0.985	0.989	0.991	0.985
$<F^L_{D_s^*}>$	0.177	0.617	0.564	0.469	0.397	0.345	0.458
$< A_{FB}>$	-0.023	-0.055	-0.022	0.003	0.020	0.031	0.001

Table 4.2: In different q^2 bins: averaged values in different observables of $B_c \to D_s^* \mu^+\mu^-$ decay in the SM.

4.8 Phenomenological Analysis

In the numerical calculation, we state all the inputs that are used for our various observables. Renormalization scale is $\mu = 4.8GeV$ in our analysis. Mass of fermions, we use $m_b = 4.18GeV$, $m_\mu = 0.015GeV$, $m_c = 1.28GeV$. Mass of mesons, we use $M_{B_c} = 6.23GeV$, $M_{D_s^*} = 2.112GeV$. Similarly, B_c meson mean life time is $\tau_{B_c} = 0.507 \times 10^{-12}$ and $G_F = 1.15 \times 10^{-5} GeV^{-2}$ is fermi coupling constant which are given in ref. [2]. We take $\alpha_e^{-1} = 137$ for the electromagnetic coupling constant. We use CKM matrix element $|V_{tb}V_{ts}^*| = 38.5 \times 10^{-3}$ [2]. The WC's are taken from ref. [2] given in table4.3. For MI scenarios, we use the wilson coefficient given in table 3.1. We take wilson coefficients of model independent scenario II to deduce new physics effects in LQ model. For Z' models, we use wilson coefficients couplings given in tables 3.2,3.3,3.4.

$\mathcal{C}_1$	$\mathcal{C}_2$	$\mathcal{C}_3$	$\mathcal{C}_4$	$\mathcal{C}_5$	$\mathcal{C}_6$	$\mathcal{C}_7^{eff}$	$\mathcal{C}_8$	$\mathcal{C}_9$	$\mathcal{C}_{10}$
-0.2632	1.0111	0.0055	-0.0806	0.0004	0.0009	-0.313	-0.15	4.0749	-4.3085

Table 4.3: The values of WCs $\mathcal{C}_i(\mu)$ [2] at the scale $\mu = 4.8GeV$ shown in above table.

Like $B \to D^{(*)}\tau\nu$ and $B \to K^{(*)}\mu^+\mu^-$ decays which are precisely studied [32, 33], the $B_c \to D_s^*\mu^+\mu^-$ decay also provide complimentary information regarding NP. From several years, many observables related to the FCNC transitions $b \to s\ell^+\ell^-$ have shown deviation from SM expectations. These transitions are well known to have a high sensitivity to NP contributions due to their suppression within the SM. We show the results achieved in Z' models and model independent/ leptoquark model which have deviation from corresponding SM predictions.

- We plotted branching ratios of our said decay in model independent new physics scenarios and in model dependent, i.e. leptoquark and Z' models. In order to search NP effects in mentioned observables discarded the $\bar{c}c$ resonance region because NP effects are not clear in this region. Branching ratio shows maximum deviation from SM in particular q^2 regions $4<q^2<6$ and $6<q^2<8$. We see in $4<q^2<6$ q^2 region. For MI scenarios I(A), it deviates 21% below the SM. For MI scenarios II(A), it deviates 25% below the SM. For MI scenarios I(B), it deviates 22% below the SM. For MI scenarios II(B), it deviates 28% below the SM. For Heavy Z' I(A), it deviates 35% above the SM. For Heavy Z' II(A), it deviates 40% above the SM. For Heavy Z' I(B), it deviates 37% above the SM. For Heavy Z' II(B), it deviates 45% above the SM. For light Z' I(A), it deviates 23% above the SM. For light Z' II(A), it deviates 34% above the SM, as shown in figs.4.2c4.2d.
  We see in $6<q^2<8$ q^2 region. For MI scenarios I(A), it deviates 22% below the SM. For MI scenarios II(A), it deviates 25% below the SM. For MI scenarios I(B), it deviates 23% below the SM. For MI scenarios II(B), it deviates 28% below the SM. For Heavy Z' I(A), it deviates 35% above the SM. For Heavy Z' II(A), it deviates 40% above the SM. For Heavy Z' I(B), it deviates 37% above the SM. For Heavy Z' II(B), it deviates 44% above the SM. For light Z' I(A), it deviates 24% above the SM. For light Z' II(A), it deviates 35% above the SM, as shown in figs.4.2e4.2f. Deviations from SM could also be seen in high $12<q^2<15$ region as well.
  Consequently, we analyze that, for model independent scenarios and leptoquark model, the branching ratio for the decay is decreased at all q^2 from SM as shown in fig.4.2a. For Z' models, the branching ratio for the decay is increased at all q^2 from the SM as shown in fig.4.2b. Deviations from SM hint the influence of NP in said decay.

- We plotted leptons forward backward asymmetry of our said decay. We analyze that the zero value of forward backward asymmetry $A_{FB}(q^2)$ is shifted to higher values of q^2 than in the standard model for model independent scenarios and leptoquark model as shown in fig.4.3e. For Z' model, the zero value of forward backward asymmetry is shifted to lower values of q^2 than in SM which we can see in region $2.4<q^2<5$ as shown in fig.4.3f. We could not distinguish Z' models NP scenarios in $6<q^2<8$ q^2 region but we can distinguish in MI new physics scenarios. We see all new physics scenarios separately in the $1.2<q^2<2.4$ region as shown in figs.4.3c4.3d. We also analyze that model dependent and model independent new physics scenarios didn't show deviation from SM in high q^2 region $12<q^2<15$ except model independent (I).

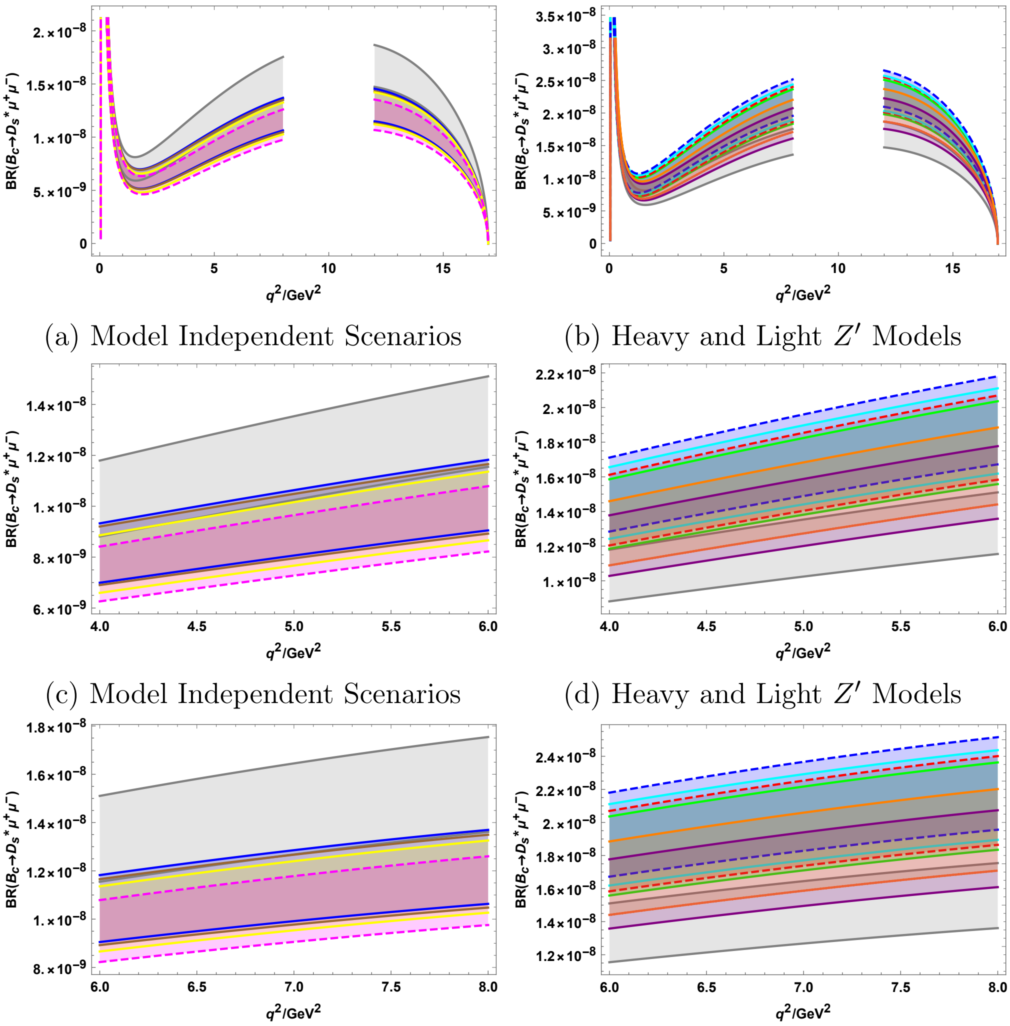
- We plotted longitudinal helicity fraction of the D_s^* meson in model independent scenarios and model dependent for our said decay. Longitudinal helicity fraction have deviation with SM values in low $0.045< q^2 <1.1$ q^2 region. For MI scenarios I(A), it deviates 25% below the SM. For MI scenarios II(A), it deviates 29% below the SM. For MI scenarios I(B), it deviates 26% below the SM. For MI scenarios II(B), it deviates

31% below the SM. For Heavy Z' I(A), it deviates 30% above the SM. For Heavy Z' II(A), it deviates 28% above the SM. For Heavy Z' I(B), it deviates 31% above the SM. For Heavy Z' II(B), it deviates 31% above the SM. For light Z' I(A), it deviates 14% above the SM. For light Z' II(A), it deviates 23% above the SM, as shown in figs.4.4a4.4b. Consequently, for model independent scenarios and leptoquark model, the peak of the distribution is decreased at all q^2 and it is on a small scale shifted nearly higher value of q^2 than in the SM as shown in fig.4.4c, and for Z' Models, the peak of the distribution is increased at all q^2 as shown in fig.4.4d. In longitudinal helicity fraction of D_s^* meson, we also analyze that all new physics scenarios didn't show deviation from SM in central and high q^2 region.

- We calculated the values of polarized and unpolarized LFU ratios of our said decay in the range of low, central and high q^2 region given in tables4.44.54.6. The calculated values of LFU ratios performed in different q^2 bins have tension with SM predictions. Longitudinally polarized LFU ratios deviates from SM values in low $0.045< q^2 <1$ average bin values that observed from experimental data and SM prediction. For MI scenarios I(A), it deviates 7% below the SM. For MI scenarios II(A), it deviates 2% below the SM. For MI scenarios I(B), it deviates 7% below the SM. For MI scenarios II(B), it deviates 2% below the SM. For Heavy Z' I(A), it deviates 6% above the SM. For Heavy Z' II(A), it deviates 7% above the SM. For Heavy Z' I(B), it deviates 2% above the SM. For Heavy Z' II(B), it deviates 2% above the SM. For light Z' I(A), it deviates 4% above the SM. For light Z' I(A), it deviates 6% above the SM. We observed that for MI and leptoquark model, LFU ratios in low q^2 values are smaller than SM value and for Z' models, LFU ratios in low q^2 bin values are greater than SM value. In LFU ratios, we analyze that all new physics scenarios didn't show deviation in central and high q^2 region.

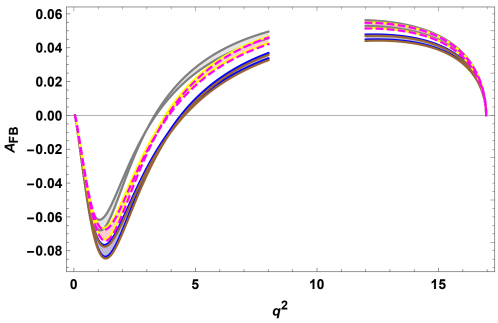
4.8.1 Predictions for $R_{D_s^*}, R_{D_s^*}^{L,T}, F_{D_s^*}^L, A_{FB}$ in Different q^2 Bins

We give a prediction of q^2 average bin values of several observables in SM and in various NP scenarios such as, the MI scenario/ LQ model and the Z' models. We predicts these values in different q^2 bins in the following tables.

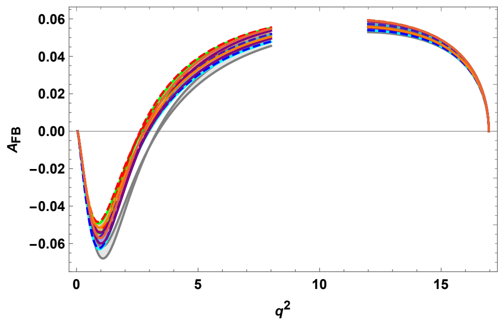


(a) Model Independent Scenarios
(b) Heavy and Light Z' Models
(c) Model Independent Scenarios
(d) Heavy and Light Z' Models
(e) Model Independent Scenarios
(f) Heavy and Light Z' Models

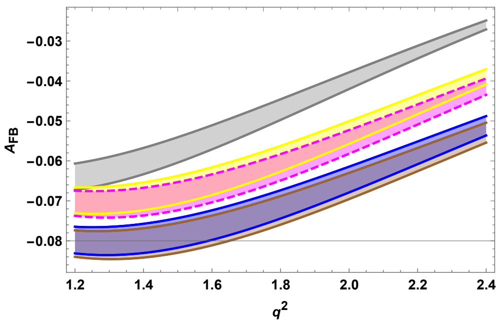
Figure 4.2: Branching ratio in MI Scenarios, Leptoquark Model, Heavy Z' Model and Light Z' Model. The Gray band show the predictions in the SM, Blue, Brown, Yellow and Magenta(dashed) bands show the predictions computed in MI scenario I(A), I(B), II(A) and II(B) respectively. Green, Red(dashed), Blue(dashed) and Cyan bands show the predictions computed in scenario HZ' I(A), HZ' I(B), HZ' II(A) and HZ' II(B) respectively. Purple and Orange bands shows the predictions in scenario LZ' I(A), LZ' II(A) respectively. The results achieved in MI scenarios II(A) and II(B) also represent the results in leptoquark model.



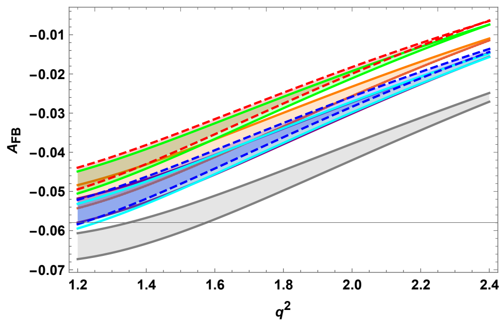
(a) Model Independent Scenarios



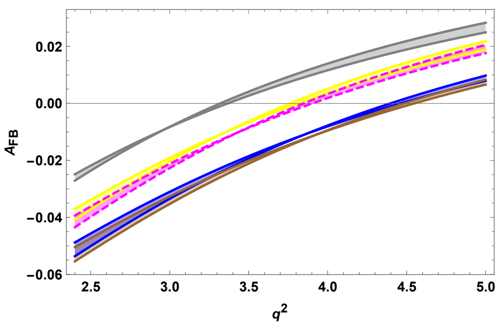
(b) Heavy and Light Z' Models



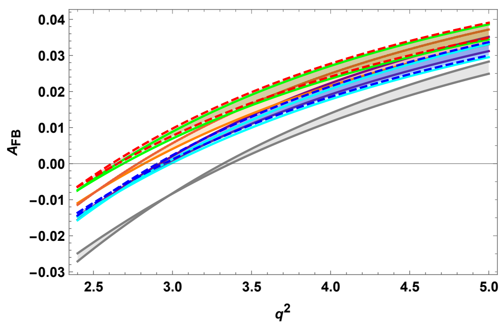
(c) Model Independent Scenarios



(d) Heavy and Light Z' Models

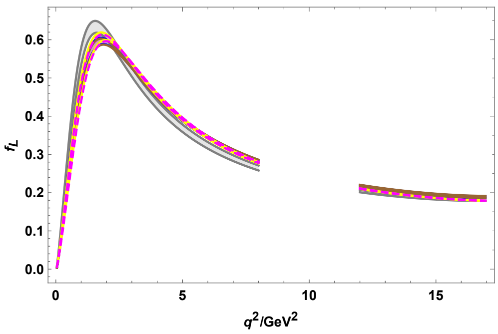


(e) Model Independent Scenarios

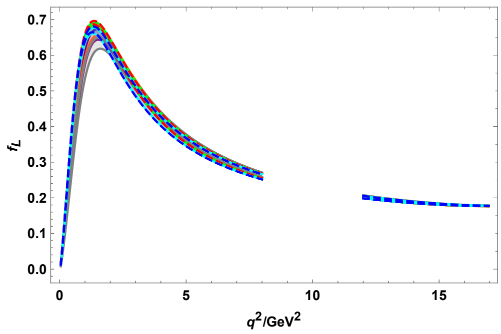


(f) Heavy and Light Z' Models

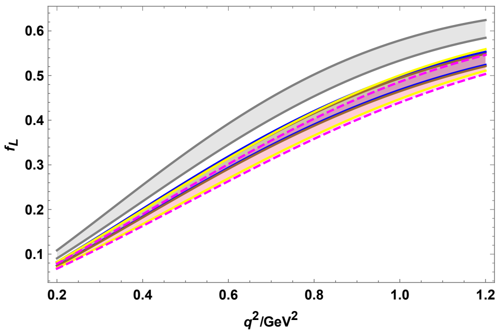
Figure 4.3: Leptons forward backward asymmetry in MI Scenarios, LQ Model, Heavy Z' Model and Light Z' Model. The legends are same as in fig.4.2



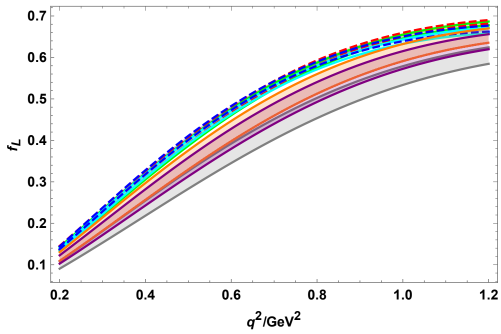
(a) Model Independent Scenarios



(b) Heavy and Light Z' Models



(c) Model Independent Scenarios



(d) Heavy and Light Z' Models

Figure 4.4: Longitudinal helicity fraction of D_s^* in MI Scenarios, LQ Model, Heavy Z' Model and Light Z' Model. The legends are same as in fig.4.2

Table 4.4: Predictions in SM and NP: Lepton flavor universality ratios $R_{D_s^*}$ in different bin values for $B_c \to D_s^* \mu^+ \mu^-$.

Scenarios	low q^2/GeV[0.045,1]	central q^2/GeV[1,6]	high q^2/GeV[14, max]
SM	0.939 $\pm$0.001	0.985 $\pm$ 0.0001	0.996
MI, I(A)	0.941 $\pm$ 0.001	0.984 $\pm$ 0.0001	0.996
MI, LQ, II(A)	0.939 $\pm$ 0.001	0.986 $\pm$ 0.0001	0.996
MI, I(B)	0.941 $\pm$ 0.001	0.984 $\pm$ 0.0001	0.996
MI, LQ, II(A)	0.939 $\pm$ 0.001	0.986 $\pm$ 0.0001	0.996
TeV Z' I(A)	0.939 $\pm$ 0.001	0.987 $\pm$ 0.0001	0.997
TeV Z' II(A)	0.939 $\pm$ 0.001	0.987 $\pm$ 0.0001	0.997
TeV Z' I(B)	0.939 $\pm$ 0.001	0.985 $\pm$ 0.0001	0.997
TeV Z' II(B)	0.939 $\pm$ 0.001	0.985 $\pm$ 0.0001	0.997
GeV Z' I(A)	0.938 $\pm$ 0.002	0.987 $\pm$ 0.0001	0.997
GeV Z' II(A)	0.938 $\pm$ 0.002	0.987 $\pm$ 0.0001	0.997

Table 4.5: Predictions in SM and NP: Lepton flavor universality ratios $R^L_{D_s^*}$ in different bin values for $B_c \to D_s^* \mu^+ \mu^-$.

Scenarios	low q^2/GeV[0.045,1]	central q^2/GeV[1,6]	high q^2/GeV[14, max]
SM	0.752 ± 0.005	0.986 ± 0.001	0.997
MI, I(A)	0.698 ± 0.004	0.982 ± 0.0002	0.996
MI, LQ, II(A)	0.743 ± 0.004	0.986 ± 0.0002	0.997
MI, I(B)	0.696 ± 0.004	0.982 ± 0.0002	0.996
MI, LQ, II(A)	0.742 ± 0.004	0.985 ± 0.0002	0.997
TeV Z' I(A)	0.801 ± 0.004	0.990 ± 0.0001	0.997
TeV Z' II(A)	0.803 ± 0.005	0.990 ± 0.0001	0.997
TeV Z' I(B)	0.762 ± 0.004	0.987 ± 0.0001	0.997
TeV Z' II(B)	0.763 ± 0.005	0.987 ± 0.0001	0.997
GeV Z' I(A)	0.783 ± 0.004	0.989 ± 0.0001	0.997
GeV Z' II(A)	0.794 ± 0.004	0.990 ± 0.0001	0.998

Table 4.6: Predictions in SM and NP: Lepton flavor universality ratios $R^T_{D_s^*}$ in different bin values for $B_c \to D_s^* \mu^+ \mu^-$.

Scenarios	low q^2/GeV[0.045,1]	central q^2/GeV[1,6]	high q^2/GeV [14, max]
SM	0.920 ± 0.002	0.983	0.996
MI, I(A)	0.920 ± 0.001	0.984	0.996
MI, LQ, II(A)	0.920 ± 0.001	0.984	0.996
MI, I(B)	0.920 ± 0.001	0.984	0.996
MI, LQ, II(A)	0.920 ± 0.001	0.984	0.996
TeV Z' I(A)	0.922 ± 0.002	0.983	0.997
TeV Z' II(A)	0.922 ± 0.002	0.983	0.997
TeV Z' I(B)	0.921 ± 0.002	0.982	0.996
TeV Z' II(B)	0.922 ± 0.002	0.982	0.996
GeV Z' I(A)	0.938 ± 0.002	0.983	0.997
GeV Z' II(A)	0.938 ± 0.002	0.983	0.997

Table 4.7: Predictions in SM and NP: Longitudinal helicity fraction $F^L_{D_s^*}$ in different bin values for $B_c \to D_s^* \mu^+ \mu^-$.

Scenarios	low q^2/GeV[0.045,1]	central q^2/GeV[1,6]	high q^2/GeV[14, max]
SM	0.177 ± 0.002	0.458 ± 0.0008	0.183
MI, I(A)	0.133 ± 0.001	0.454 ± 0.001	0.192
MI, LQ, II(A)	0.126 ± 0.001	0.460 ± 0.001	0.184
MI, I(B)	0.131 ± 0.001	0.454 ± 0.001	0.193
MI, LQ, II(A)	0.122 ± 0.001	0.460 ± 0.001	0.184
TeV Z' I(A)	0.229 ± 0.016	0.465 ± 0.011	0.181
TeV Z' II(A)	0.227 ± 0.016	0.453 ± 0.011	0.182
TeV Z' I(B)	0.232 ± 0.016	0.465 ± 0.011	0.181
TeV Z' II(B)	0.232 ± 0.016	0.452 ± 0.011	0.182
GeV Z' I(A)	0.202 ± 0.015	0.465 ± 0.011	0.181
GeV Z' II(A)	0.217 ± 0.015	0.467 ± 0.011	0.181

Table 4.8: Predictions in SM and NP: Forward backward asymmetry A_{FB} in different bins for $B_c \to D_s^* \mu^+ \mu^-$

Scenarios	low q^2/GeV[0.045,1]	central q^2/GeV[1,6]	high q^2/GeV[14, max]
SM	-0.023 ± 0.001	0.001	0.0421 ∓ 0.001
MI, I(A)	-0.024 ± 0.0002	-0.025 ∓ 0.001	0.035 ∓ 0.001
MI, LQ, II(A)	-0.020 ± 0.0002	-0.011 ∓ 0.001	0.041 ∓ 0.001
MI, I(B)	-0.024 ± 0.0002	-0.026 ∓ 0.001	0.034 ∓ 0.001
MI, LQ, II(B)	-0.020 ± 0.0002	-0.012 ∓ 0.001	0.041 ∓ 0.001
TeV Z' I(A)	-0.021 ± 0.0001	0.017 ∓ 0.001	0.043 ∓ 0.001
TeV Z' II(A)	-0.025 ± 0.0001	0.010 ∓ 0.001	0.042 ∓ 0.001
TeV Z' I(B)	-0.021 ± 0.0002	0.018 ∓ 0.001	0.043 ∓ 0.001
TeV Z' II(B)	-0.025 ± 0.0001	0.011 ∓ 0.001	0.042 ∓ 0.001
GeV Z' I(A)	-0.021 ± 0.0003	0.012 ∓ 0.001	0.043 ∓ 0.001
GeV Z' II(A)	-0.021 ± 0.0003	0.016 ∓ 0.001	0.043 ∓ 0.001

Chapter 5

Conclusion

Motivated by the anomalies present in $B \to D^{(*)}\tau\nu$ and $B \to K^{(*)}\mu^+\mu^-$ decays. like mentioned decays which are precisely discussed in literature, the decay $B_c \to D_s^*\ell^+\ell^-$ also provide complimentary information regrading NP. We studied $B_c \to D_s^*\ell^+\ell^-$ decay based on transition $b \to s\ell^+\ell^-$ at quark level. In our study, we performed in SM and beyond. We added NP effects in said decay by the modification of wilson coefficients, used two different approaches to search NP effects including the model independent new physics scenarios (I) and (II), and in model dependent, we search NP effects by two different models leptoquark model and Z' models which involve tree level exchange of new bosonic particle. We analyzed several observables in said decay such as, branching ratios, longitudinal helicity fraction of D_s^* meson, forward backward asymmetry of lepton and lepton flavor universality (LFU) ratio which hint the influence of NP in said process.

We determined that for MI new physics scenarios and leptoquark model, the branching ratio for the decay is decreased at all q^2 and for Z' models, the branching ratio for the said decay is increased at all q^2 from SM prediction as shown in fig.4.2.

The zero value of leptons forward backward asymmetry $A_{FB}(q^2)$ is shifted to higher values of q^2 than in the standard model for model independent NP scenarios and leptoquark model, and for Z' models, it is shifted to lower values of q^2 than in SM as shown in fig.4.3.

We analyze the longitudinal helicity fraction of the D_s^* meson for MI new physics scenarios and leptoquark model, the peak of the distribution is decreased at all q^2 and it is shifted nearly higher value of q^2 than in the SM, and for Z' Model, the peak of the distribution is increased from SM prediction as shown in fig.4.4.

The average q^2 bin values of polarized LFU ratios are performed in low $0.045<q^2<1$ bin values have shown deviation from SM predictions which hint the influence of NP in said process.

Consequently, the deviation in all above mentioned observables from SM predictions is a good sign of the presence of NP in said decay. These predictions can be tested at the LHC and can add information regarding NP in $b \to s\ell^+\ell^-$ decay.

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