Exploring NSIs in $B^+ \to \pi^+ \nu \bar{\nu}$ and $B \to X_s \nu \bar{\nu}$ with three generations of quarks

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Abstract

We study the rare decays $B^+ \to \pi^+ \nu \bar{\nu}$ and $B \to X_s \nu \bar{\nu}$ for the search of NSIs. We want to constraint the NSIs by using these reactions. We show that there is a strong dependence of these reactions on new physics parameter $\epsilon_{QL_{\tau\tau}}$, where $Q = u, c, t$. We include second and third generation of quarks in the loop for these decays. We further point out that the constraints for $\epsilon_{cL_{\tau\tau}}$ are more precise as compared to $\epsilon_{uL_{\tau\tau}}$ and $\epsilon_{tL_{\tau\tau}}$. We further point out that for $B \to X_s \nu \bar{\nu}$, the $u$ quark induce NSIs are giving very very small contribution

Keywords: NSIs, rare decays, B decays.

PACS numbers: 12.60.-i, 13.15.+g, 13.20.-v

1 Introduction

After the remarkable discovery of Higgs by the ATLAS [1] and CMS [2] collaboration and confirmation in [3] that it is Standard Model (SM) higgs, one important question arises. Is there any room for new physics (NP) beyond SM? No doubt SM predictions have been verified experimentally to the highest level of precision [4][5]. But, along with other limitations, SM lacks any explanation for a possible pattern for particle mass, known as mass hierarchy problem. SM can not predict top quark mass without experimental evidence. The experiments on B meson [6][7][8] are also giving some cracks in standard model. We are yet unable to explain dark matter and matter anti-matter asymmetry. Gravity is not included in the SM. Theoretically SM is thought to be unsatisfactory and there can be some new particles as well as new interactions. It has been believed that standard model is a low energy approximation of more general theory. So, many theoretical extensions of SM has been presented. But, so far, the only concrete evidence against it has been provided by the neutrino oscillations [9] [10][11][12][13][14][15]. To explore NP the study of mesonic rare decays involving neutrinos in final state, can be interesting. These decays proceeds through flavor changing neutral currents (FCNC), highly suppressed [16]
due to GIM mechanism \[17\] and occur at loop level \[18\] \[19\], so their contributions are very small. The discrepancies between experiments and theory (SM) for such reactions provide us an excellent window towards NP. New particles can be added in the loops to improve theory or we can have new interactions. So, FCNC reactions involving neutrinos in the final state can be interesting. Theoretically, $B\to \pi^+\nu\bar{\nu}$ is more clean than $K\to \pi^+\nu\bar{\nu}$ because it has only top quark contribution and no contribution from charm sector. Non standard neutrino interactions (NSIs) of $K\to \pi^+\nu\bar{\nu}$ and $D_s^+\to D^+\nu\bar{\nu}$ are studied in \[20\] and \[21\] respectively and constrained are found for $\epsilon^{uL}_{\tau\tau}$. Loop structure of both processes is same so similar thing should happen to $B\to \pi^+\nu\bar{\nu}$. Another loop level useful reaction for the search of new physics is inclusive $B\to X_s\nu\bar{\nu}$ due to its theoretical cleanliness \[22\].

In this paper we the scheme of study is as: first of all we give experimental status of $B^{+}\to \pi^{+}\nu\bar{\nu}$ and $B\to X_s\nu\bar{\nu}$ then we revise the SM contribution of these reaction. Next, we study these reactions in NSIs with $u$ quark in the loop which is the usual case of NSIs. Then we modify the operator for $c$ and $t$ quarks. We compare these results and then give the conclusion at the end.

2 Experimental Status of $B^+ \to \pi^+ \nu \bar{\nu}$ Decay

$B$ decays are being studied in the detectors like CLEO, CDF, BaBar, Belle, ALEPH collaborations and LHCb but the decays involving neutrinos in the final state will be tested at super $B$ factories in experimentally clean environment. The detection of $B^+ \to \pi^+ \nu \bar{\nu}$ is a hard task and currently we have only experimental bound for this reaction but this will be in the range of super $B$ factories. The experimental bound is given in the Table 1 along with their SM prediction. Our experience with $K^+ \to \pi^+ \nu \bar{\nu}$ guide us that the experimental value should be of the order of $10^{-7}$.

Inclusive process $B \to X_s \nu \bar{\nu}$ are very difficult to observe experimentally because we need to tag all the particles involve in $X_s$ along with missing neutrinos. The limit available till to date is $< 64 \times 10^{-5}$, given in table 1 with reference.

2.1 Standard Model Theory of $B^+ \to \pi^+ \nu \bar{\nu}$ Decay

SM calculation can be divided into two categories, short distance and long distance. This can be found from \[23\] \[24\] \[25\] and \[26\] that the dominant contribution for $B^+ \to \pi^+ \nu \bar{\nu}$ comes from short distance because long distance contribution is $10^{-3}$ less than short distance. The quark level process for our decay is $b \to d \nu \bar{\nu}$ which can be represented by the feynman diagrams shown in figure 1.

In such reactions we can easily separate hadronic interactions from leptonic interaction. For $B$ decays the dominant contribution comes from the short distance just like $K$ decays and we use perturbation theory due to asymptotic freedom. The effective Hamiltonian for such reactions quark level reaction will be
Figure 1: SM b decays to d neutrino antineutrino

\[ H_{eff}^{SM} = \frac{G_F}{\sqrt{2}} \frac{\alpha_{em}}{2\pi \sin^2 \theta_W} \sum_{\alpha,\beta=e,\mu,\tau} V_{tb}^\alpha V_{td} X(x_t) \times (\bar{d}b)_{V-A}(\nu_\alpha \bar{\nu}_\beta)_{V-A} \]

where \( V - A \) in the subscript represents the vector and axial vector current respectively. For such reactions charm quark contribution in the loop is negligible in contrast to \( K \) decay due to smallness of off diagonal \( CKM \) element and \( X(x_t) \) is the loop integral of top-quark exchange [19]. For this reaction we have two penguin and one box diagram [29] and sum of all give the contribution

\[ X(x_t) = \eta_X x_t^2 (x_t + 2) x_t - 1 + \frac{3x_t - 6}{(x_t - 1)^2} \ln x_t \]

Here \( x_t = \frac{m_t^2}{m_w^2} \) and \( \eta_X = 0.985 \) is QCD small distance correction. By using above hamiltonian we can obtain \( Br \) as

\[ Br(B^+ \rightarrow \pi^+ \nu \bar{\nu})_{SM} = r_{iso} \frac{3\alpha_{em}^2}{|V_{ub}|^2 2\pi^2 \sin^4 \theta_W} |V_{tb}^p V_{td} X(x_t)|^2 Br(B^+ \rightarrow \pi^0 \ell^+ \nu_\ell) \]

\( r_{iso} \simeq 0.94 \) is the isospin breaking effect for \( B \). It is discussed for \( K \) mesons in [31] which depends on atleast three things (1) mass effect (2) a suppression of about 4% in neutral form factor comes from \( \eta - \pi \) mixing and (3) about 2% suppression due to absence of log leading correction.

For \( B \rightarrow X_s \nu \bar{\nu} \) the effective Hamiltonian is same except to replace \( d \) with \( s \), but, here we do not have a tree level process like \( B^+ \rightarrow \pi^0 \ell^+ \nu_\ell \). So we have
Figure 2: NSIs b decays to d neutrino antineutrino

to normalize with the process $B \to X_c \nu \bar{\nu}$ and due to different phase spaces for $X_s$ and $X_c$, we have to include other factors. The $Br$ will be

$$Br(B \to X_c \nu \bar{\nu})_{SM} = \frac{3\alpha_{em}^2}{4\pi^2 \sin^2 \theta_W} |V_{ts}V_{tb}X(x_t)|^2 \times \frac{7}{f(z)\kappa(z)} Br(B \to X_c l \nu_l)$$

where $f(z) = 1 - 8z + 8z^3 - z^4 - 12z^2 \ln(z)$ with $z = \frac{m^2}{m_t^2}$ and $\kappa(z) = 0.88, \eta = \kappa(0) = 0.83$.

A useful discussion can about the factors can be found in [26] and [29]. With the latest values of the constants we have the $Br$

$$Br(B \to X_c \nu \bar{\nu})_{SM} = 3.6 \times 10^{-5}$$

2.2 Model Independent Approach

The NSI for the process is shown by the Fig 2 and represented by

$$H^{NSI}_{eff} = \frac{G_F}{\sqrt{2}} (V_{tb}^*V_{tq} \frac{\alpha_{em}}{4\pi \sin^2 \theta_W} \epsilon_{\alpha \beta}^L \ln \frac{\Lambda}{m_w} ) \times (\nu_{\alpha} \bar{\nu}_\beta V_A (\bar{\nu}_b) V_A)$$

We use $V_{ub} = (4.15 \pm 0.49) \times 10^{-3}$ and $BR(B^+ \to \pi^0 l^+ \nu_l) = (7.78 \pm 0.28) \times 10^{-5}$ to find out $Br$
\[ Br(B^+ \rightarrow \pi^+ \nu)_{NSI} = r_{iso} \frac{\alpha^2_{em}}{V_{ub}^2 2 8 \pi^2 \sin^2 \theta_W} \left| V_{ud} \right|^2 |V_{ub}^* V_{ud}| e^{\alpha \beta} \ln \frac{\Lambda}{m_w} |^2 Br(B^+ \rightarrow \pi^{0}\nu_1) \]

Although the current experimental results of \( B \) decays are narrowing the gap between theory and experiments but when we will get more precise experimental data than we will need more accurate theoretical results. With the assumption that experiments will give us the value of \( 10^{-7} \), we can constrain the NSIs from this reaction. As \( \alpha \) and \( \beta \) can be any lepton we take them as \( \tau \), because for other leptons we have already more precise constraints [32]. For \( \Lambda = 10 m_W \) and other values from [34], we get the constraints on NSIs with u-quark in the loop

\[ e^{uL}_{\tau \tau} \leq 4.35 \]

For \( B \rightarrow X_{\nu} \nu \) NSIs Br

\[ Br(B \rightarrow X_{\nu} \nu)_{NSI_s} = \frac{\alpha^2_{em}}{16 \pi^2 \sin^2 \theta_W} \frac{V_{us} V_{ub} X(x_t)}{V_{cb}} e^{uL}_{\alpha \beta} \ln \frac{\Lambda}{m_w} |^2 \frac{\pi}{f(z) \kappa(z)} Br(B \rightarrow X_{\nu} l) \]

and constraints

\[ e^{uL}_{\tau \tau} \leq 50 \]

which is very high value for this constraint and it is not acceptable. So we have to move to other generations of quarks for this particular reaction

2.2.1 c-quark in the Loop

For c-quark we have to modify the operator as

\[ Br(B^+ \rightarrow \pi^+ \nu)_{NSI} = r_{iso} \frac{\alpha^2_{em}}{V_{ub}^2 2 8 \pi^2 \sin^2 \theta_W} \left| V_{ud} \right|^2 |V_{ub}^* V_{ud}| e^{cL} \ln \frac{\Lambda}{m_w} |^2 Br(B^+ \rightarrow \pi^{0}\nu_1) \]

and the constraint is

\[ e^{cL}_{\tau \tau} \leq 1.87 \]

For \( B \rightarrow X_{\nu} \nu \) the Br and constraints are

\[ Br(B \rightarrow X_{\nu} \nu)_{NSI_s} = \frac{\alpha^2_{em}}{16 \pi^2 \sin^2 \theta_W} \frac{V_{cs} V_{cb} X(x_t)}{V_{cb}} e^{cL}_{\alpha \beta} \ln \frac{\Lambda}{m_w} |^2 \frac{\pi}{f(z) \kappa(z)} Br(B \rightarrow X_{\nu} l) \]

\[ e^{cL}_{\tau \tau} \leq 1.15 \]
2.2.2 t-quark in the Loop

With t-quark we have following operator and constraint

\[
Br(B^+ \rightarrow \pi^+ \nu\nu)_{\text{NSI}} = r_{\text{iso}} \frac{\alpha_{\text{em}}^2}{|V_{ub}|^2 8\pi^2 \sin^4 \theta_W} |V_{tb}V_{td}^{\ast}| \epsilon_{\tau\tau}^{L} \ln \frac{\Lambda}{m_w} |^2 BR(B^+ \rightarrow \pi^0 l^+ \nu_l) \\
\epsilon_{\tau\tau}^{L} \leq 2.35
\]

and

\[
Br(B \rightarrow X_s \nu\nu)_{\text{NSIs}} = \frac{\alpha_{\text{em}}^2}{16\pi^2 \sin^4 \theta_W} |\frac{V_{ts}V_{tb}^\ast}{V_{cb}}| \epsilon_{\tau\tau}^{L} \ln \frac{\Lambda}{m_w} |^2 \frac{7}{f(z)\kappa(z)} Br(B \rightarrow X_s \nu_l) \\
\text{from which}\\n\epsilon_{\tau\tau}^{L} \leq 1.24
\]

3 Discussion and results

We study two processes $B^+ \rightarrow \pi^+ \nu\nu$ (exclusive) and $B \rightarrow X_s \nu\nu$ (inclusive), which are theoretically clean processes. So, these are ideal for the search of new physics. Very high Br of $B^+ \rightarrow \pi^+ \nu\nu$ making it very attractive for the experimentalists too. Although, $B \rightarrow X_s \nu\nu$ is very difficult to detect but it is much clean as compared to any other rare decay that's why it is studied for the search of new physics. The results are summarized in table 1 and plots are provided in figures 3, 4 and 5 to make the comparison more clear.

4 Conclusion

We have studied $B^+ \rightarrow \pi^+ \nu\nu$ and $B \rightarrow X_s \nu\nu$ for the search of New Physics in the form of ”Non Standard Neutrino Interactions” (NSIs). We have calculated the Branching ratio (Br) of these reactions and constrained NSIs by using the mismatch between standard Model and the experiments. We found the contrarians for three generations of up type quarks as; $\epsilon_{\tau\tau}^{uL}, \epsilon_{\tau\tau}^{cL}$ and $\epsilon_{\tau\tau}^{tL}$. Charm quark induced constraint is $\epsilon_{\tau\tau}^{cL}$ much more precise as compared to the other two quarks. For $B \rightarrow X_s \nu\nu$ is constraint is very very high and is not acceptable. This shows that NSIs will have affects on the rare decays of $B$ meson both inclusive and exclusive. The comparison indicates that the dominant contribution comes from the c quark in the loop. So, we have to include NSIs while calculating the Br of these reactions.

| Reaction | Theoretical | Experimental | NSIs with u | NSIs with c | NSIs with t |
|----------|-------------|--------------|-------------|-------------|-------------|
| $B^+ \rightarrow \pi^+ \nu\nu$ | $1.5 \times 10^{-7}$ | $< 1.0 \times 10^{-4}$ | $\epsilon_{\tau\tau}^{uL} \leq 4.21$ | $\epsilon_{\tau\tau}^{cL} \leq 1.81$ | $\epsilon_{\tau\tau}^{tL} \leq 2.28$ |
| $B \rightarrow X_s \nu\nu$ | $3.6 \times 10^{-5}$ | $< 64 \times 10^{-5}$ | $\epsilon_{\tau\tau}^{uL} \leq 50$ | $\epsilon_{\tau\tau}^{cL} \leq 1.15$ | $\epsilon_{\tau\tau}^{tL} \leq 1.24$ |

Table 1: Comparison of the constraints
Figure 3: $u$ quark induced NSIs

Figure 4: $c$ quark induced NSIs
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