Search for opposite sign muon-tau pair and a b-jet at LHC in the context of flavor anomalies

Debajyoti Choudhury, Nilanjana Kumar, Anirban Kundu

Abstract

Extant anomalies in several semileptonic $B$-meson decays argue for physics beyond the Standard Model. Measurements of both neutral-current decays (such as $R_K$, $R_{K^*}$ and $B_s \to \phi \mu \mu$) as well as charged-current ones—$R(D)$ and $R(D^*)$—provide strong hints for the violation of lepton flavor universality. Recent studies (Refs. [1, 2]) have shown that a class of effective field theory (EFT) models may explain such anomalies in terms of only a few parameters which can be determined phenomenologically. In this literature, we examine such resolutions in the context of the requisite $(\bar{7} b)(\bar{7} \tau)$ operator, and look for its signals at the 13 TeV LHC, with a final state of one $b$-jet, and an oppositely charged $\mu$-$\tau$ pair, with the muon coming from the decay of one of the $\tau$ leptons. We obtain discovery and exclusion limits on the model parameters as a function of luminosity at the 13 TeV LHC.

1 Introduction

Evidence from a multitude of experiments, such as $\text{BaBar}$ [3], Belle [4–9] and, most recently, LHCb [10–15] suggest the presence of effects that violate lepton flavor universality, a cardinal principle within the Standard Model (SM). Related to several mesons containing the bottom (anti-)quark, these “anomalies” appear in both charged- and neutral-current (NC) decays. For example, consider the ratios [16]

$$R(D^{(*)}) \equiv \frac{\text{BR}(B \to D^{(*)}\tau\nu)}{\text{BR}(B \to D^{(*)}\ell\nu)},$$

with $\ell = e$ or $\mu$, and, similarly,

$$R_{J/\psi} \equiv \frac{\text{BR}(B_c \to J/\psi\tau\nu)}{\text{BR}(B_c \to J/\psi\mu\nu)}.$$ (2)

While the SM estimates for the individual decays are already quite robust, the advantage of considering such ratios is that much of the remaining uncertainties, residing in the evaluation of the form factors, cancel out. Thus, any observed anomaly in such areas would be very intriguing, and we begin by recalling the experimental status.

The $\text{BaBar}$ [3] measurements of $R(D)$ and $R(D^*)$, when taken together, exceed SM expectations by more than 3$\sigma$. Though the Belle measurements [4] lie a little below the $\text{BaBar}$ measurements and

\[\text{debajyoti.choudhury@gmail.com, nilanjana.kumar@gmail.com, akphy@caluniv.ac.in}\]
are consistent with both the latter and the SM expectations, their result on $R(D^*)$ [5], with the $\tau$ decaying semileptonically, agrees with the SM expectations only at 1.6$\sigma$ level. Similarly, the LHCb measurement [10] lies 2.1$\sigma$ above the SM predictions. Taking into account all the measurements and their correlations, the disagreement between the data and SM is at nearly 3.8$\sigma$ [17, 18].

The four-fermi effective interaction responsible for $B \to K^{(*)}\ell\nu$, namely $b \to c\ell\nu$ is also responsible for driving $B_c \to J/\psi\ell\nu$ and analyzing 3 fb$^{-1}$ data. The LHCb Collaboration found

$$R_{J/\psi} = \begin{cases} 0.71 \pm 0.17 \pm 0.18 & \text{(exp.)}, \\ 0.283 \pm 0.048 & \text{(SM)}, \end{cases}$$

where the SM prediction [19–21] includes uncertainties accrued from the $B_c \to J/\psi$ form factors and is, thus, quite robust. While the level of the discrepancy is only at the 2$\sigma$ level\(^4\) it is interesting to note that it points in the same direction as the others.

An opposite effect is seen for the neutral current transitions, namely $b \to s\ell^+\ell^-$. Once again, ratios of such decays constitute robust variables leading us to consider

$$R_{K^{(*)}} \equiv \frac{\text{BR}(B \to K^{(*)}\mu^+\mu^-)}{\text{BR}(B \to K^{(*)}\ell^+\ell^-)}.$$  \hfill (4)

While the SM predictions for both $R_K$ and $R_{K^{(*)}}$ are almost indistinguishable from unity [22–26], that for $R_{K^{(*)}}^{\text{low}}$ is $\sim 0.9$ (mainly due to the non-negligible $m_\mu$). The calculations are very precise with only minuscule uncertainties. The earlier result on $R_K$ [13, 14] has recently been superseded by the LHCb Collaboration [15]:

$$R_K = 0.846^{+0.060+0.016}_{-0.051-0.014} \quad q^2 \in [1.1 : 6] \text{ GeV}^2,$$

For $R_{K^{(*)}}$, while the earlier LHCb data [13, 14], viz.

$$R_{K^{(*)}}^{\text{low}} = 0.66^{+0.11+0.03}_{-0.07-0.03} \quad q^2 \in [0.045 : 1.1] \text{ GeV}^2,$$

$$R_{K^{(*)}}^{\text{central}} = 0.69^{+0.07+0.05}_{-0.07-0.05} \quad q^2 \in [1.1 : 6] \text{ GeV}^2,$$

were significantly away from the SM predictions, the recent Belle results [9], taking average over $K^{*0}$ and $K^{*+}$ modes, are more compatible with the SM:

$$R_{K^{(*)}} = 0.94^{+0.17}_{-0.14} \pm 0.08 \quad q^2 \in [0.045, ] \text{ GeV}^2. \hfill (7)$$

While this can be construed as the $R_{K^{(*)}}$ average moving closer to the SM (note, though, the larger errors in the Belle results), an anomaly is still hinted at, with the magnitude of the deviation being somewhat less than that in the $R_K$ data.

A corroborating deviation is seen in $B_s \to \phi\mu\mu$ [27–29], namely,

$$\frac{d}{dq^2} \text{BR}(B_s \to \phi\mu\mu) \bigg|_{q^2 \in [1.6] \text{ GeV}^2} = \begin{cases} (2.58^{+0.33}_{-0.33} \pm 0.08 \pm 0.19) \times 10^{-8} \text{ GeV}^{-2} & \text{(exp.)} \\ (4.81 \pm 0.56) \times 10^{-8} \text{ GeV}^{-2} & \text{(SM)}. \end{cases} \hfill (8)$$

where $q^2 = m_{\mu\mu}^2$. This suggests that the discrepancies in $R_K$ and $R_{K^{(*)}}$ have been caused by a depletion of the $b \to s\mu^+\mu^-$ channel, rather than an enhancement in $b \to s\ell^+\ell^-$. Such a conclusion is lent further

\(^4\)Given the smaller production cross section, the large uncertainty is understandable. This is expected to improve a lot once more data is analyzed.
weight by the long-standing $P_5'$ anomaly [30] in the angular distribution of $B \to K^* \mu \mu$, with a more than 3$\sigma$ mismatch between the data and SM prediction$^5$.

Faced with all these anomalies, two approaches are possible. The first would be to construct an elaborate ultraviolet-complete theory. Examples are offered by $Z'$-models [32] with flavor violating couplings with the quarks and the leptons [33–38] on the one hand, and, on the other, the exchange of leptoquarks [39–41] or, equivalently, sfermions in R-parity violating supersymmetric models [42–44]. The alternative is to take recourse to an effective field theory (EFT) description wherein only a set of Wilson coefficients are altered from their SM values [45–51]. In either case, one would, naively, expect that a sufficiently large set of unknown parameters (and/or fields) would need to invoked so as to enable the simultaneous explanation of all the anomalies while maintaining the rest of the well-tested SM phenomenology. However, if the nature of the UV-theory (operative at a scale higher than the electroweak scale), the integrating out of whose heavy degrees of freedom is supposed to have given us the EFT, is entirely ignored, then a phenomenologically motivated EFT with only a small number of parameters need to be considered. It has been shown [1, 2, 52] that such a minimal set of new physics (NP) operators, accompanied by a single lepton mixing angle, can indeed explain almost all the observables adequately. More interestingly, the natural scale for such an explanation is seen to be a few TeVs, opening the interesting possibility of signatures at the LHC and/or future colliders.

In the present case, instead of attempting a generic study, we consider a particular signature, at the LHC, prompted by the scenarios discussed in Refs. [1, 2]. Some such studies have been attempted in the past, but in entirely different contexts, both at the simulation level [53–60], as well as by the ATLAS and CMS collaborations who have searched for flavor violating signatures with dilepton final states [61–66]. We focus on a model which can explain, simultaneously, both the CC and the NC anomalies in semileptonic $B$ decays, for example, one with an enhanced $\mathcal{O}(s b)(\bar{\tau} \tau)$ operator. We have studied the tell-tale signatures which include an opposite signed $\mu$-$\tau$ pair and a $b$-jet, induced by this operator when one tau decays to a muon. One of the novelties of this channel is that it does not suffer from a very large background unlike opposite sign same flavor lepton-pair signatures. Apart from effecting a full simulation, we also validate our background estimation with Ref. [66]. This, as well as our choice of a robust set of observables renders our methodology applicable to a very wide class of NP scenarios.

The rest of the paper is constituted as follows. In the next section, we briefly discuss the EFT framework. In Section 3, we study the collider signatures of the particular channel with detail analysis of the signal and background at 13 TeV LHC. Then, in Section 4, we discuss the discovery and exclusion perspectives of this particular channel. Lastly, we conclude by predicting some future possibilities in Section 5.

2 Effective Theory Model

Considering all new physics (NP) effects to be parametrized by $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ invariant four-fermi operators, one needs at least two such structures [2] so as to both explain the anomalies and be consistent other low-energy observables. While Refs. [1, 2] did consider several possibilities, they identified certain combinations as favored scenarios. Subsequently, Ref. [52] reexamined the data, taking into account all correlations and, apart from establishing these scenarios (modulo certain alterations in the allowed parameter space), found that even the combinations dismissed in Ref. [1] can

$^5$ Recently, however, it has been argued in Ref [31] that these discrepancies may have their origin, instead, in some new physics in $b \to s e^+ e^-$. 

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be accommodated. Rather than examine each such scenario, we consider a particular representative case, termed “Model IV” in Ref. [1]. Analyses for the other scenarios can also be effected analogously. The Hamiltonian for the new physics can be expressed in terms of two operators involving left handed doublets $Q_{2L}$, $Q_{3L}$ and $L_{3L}$ and right handed singlet $\tau_R$ as,

$$\mathcal{H}_{NP} = \sqrt{3} A_1 \left[ - (\overline{Q}_{2L} \gamma^\mu Q_{3L})_3 (\overline{L}_{3L} \gamma^\mu L_{3L})_3 + \frac{1}{2} (\overline{Q}_{2L} \gamma^\mu L_{3L})_3 (\overline{L}_{3L} \gamma^\mu Q_{3L})_3 \right] + \sqrt{2} A_5 (\overline{Q}_{2L} \gamma^\mu Q_{3L})_1 (\overline{\tau}_R \gamma^\mu \tau_R) + h.c.,$$

where $A_{1,5}$ are unknown coefficients of mass dimension $-2$ and to be determined phenomenologically. For the sake of simplicity, we assume these to be real. The subscripts ‘3’ and ‘1’ represent the triplet and singlet currents respectively. These can be expressed in terms of component fields as

$$\mathcal{H}_{NP} = \frac{3}{4} A_1 (c, b) (\tau, \nu_\tau) + \frac{3}{4} A_1 (s, b) (\tau, \tau) + A_5 (s, b) \{\tau, \tau\} + \frac{3}{4} A_1 (s, t) (\nu_\tau, \tau) + A_5 (c, t) \{\tau, \tau\} + \frac{3}{4} A_1 (c, t) (\nu_\tau, \nu_\tau) + h.c.,$$

where, following the notation introduced in [2], we denote

$$(x, y) = \overline{\tau}_L \gamma^\mu y_L; \quad \{x, y\} = \overline{\tau}_R \gamma^\mu y_R \quad \forall \ x, y.$$  (11)

Note that $\mathcal{H}_{NP}$ is expressed in terms of weak eigenstates involving the second and the third generation quark fields ($Q_{2L}$ and $Q_{3L}$), but only the third generation leptons ($L_{3L}$). While the quark fields would be affected by the usual CKM mixing, in the leptonic sector, the weak eigenstates can be related to the mass eigenstates through a further field rotation [1,2]. This, of course, would induce direct lepton flavor violation. The magnitude of this mixing, as deduced phenomenologically [1,2], is, however small, and, was perfectly consistent with $Br(B^+ \to K^+ \mu^+ \tau^-) < 4.8 \times 10^{-5}$ (at 90% C.L.) [67]. Indeed, it also easily satisfies the recently quoted 95% C.L. upper bound of $Br(B_s \to \tau^\pm \mu^\mp) < 4.2 \times 10^{-5}$ [68]. This very smallness of the mixing allows us to neglect it altogether and concentrate on the operator $(s, b) (\tau, \tau)$ and $(s, b) \{\tau, \tau\}$ alone.\(^6\)

If an ultraviolet-complete origin of Eq.(10) is desired, an individual term could be parametrized as,

$$X(a, b)(c, d) = \frac{\lambda_1 \lambda_2}{2 M^2} (a, b)(c, d),$$

where $M$ is the mass of the integrated-out field, and $\lambda_i$ are some dimensionless couplings, bounded from perturbativity by $\lambda^2/(4\pi)^2 \leq \mathcal{O}(1)$. The mediator, for example, might be a leptoquark, or a $Z'$ with flavor-changing couplings. This inequality, alongwith the requirement of reproducing the requisite $A_i$ would determine the ranges allowed to $\lambda_i$ and $M$. We, however, eschew any assumption as to the UV-completion, resolutely choosing to be agnostic as to the origin of the $A_i$.

While Refs. [2,52] do zero in on “best-fit” points in the parameter space\(^7\), note that the exact location of the same is dependent on the accumulation of more data and, indeed, even the very recent measurements would change it to an extent. Consequently, we investigate the LHC signal for a variety of points, though laying special emphasis to the best fit point of Ref. [52], namely, $A_1 \approx -3.8$ and $A_5 \approx -2.3$ and consider several benchmark regions as listed in Table 1.

\(^6\)It might be argued that, on inclusion of further quantum corrections, this operator can adversely affect the $B_s \to \overline{B_s}$ mixing. This issue has been adequately addressed in Ref. [2].

\(^7\)The best fit values were obtained under the assumption of flavor mixing, but our analysis is independent of the mixing angle. Note, too, that the best fit values of Ref. [2] and Ref. [52] are very similar.
Table 1: Benchmark regions to study \((s,b)(\tau,\tau)\) and \((s,b)\{\tau,\tau\}\) operators in \((\mu^\pm\tau^\mp)\) pair + b-jet final state, based on Ref. [52].

| Observables                        | Set X | Set Y | Set A | Set B | Set C |
|------------------------------------|-------|-------|-------|-------|-------|
| \(\text{Br}(B_s \to \tau\tau) < 6.8 \times 10^{-3}\) | ✓     | ✓     | ✓     | ✓     | ✓     |
| 3σ contour around \(A_1 \approx -3.8, A_5 \approx -2.3\) | ✓     | ✗     | ✗     | ✗     | ✗     |

We consider two factors while defining the regions: one is the 3σ contour around the best fit point as obtained in Ref. [52] and another is the current 95% C.L. limit on \(\text{Br}(B_s \to \tau\tau) < 6.8 \times 10^{-3}\) [69]. All the benchmark points satisfy the latter limit. Set X includes points inside the 3σ contour keeping \(|A_1|\) fixed at 3.8. Set Y represents points just outside the 3σ contour around the best fit. Set A, Set B and Set C constitute regions with smaller values of \(|A_1|\) and \(|A_5|\) and, hence, represent more conservative choices, both in the context of low-energy observables as well as LHC signals. The exact locations of the points are detailed in Table 2 in the next section, where we study the corresponding collider signals originating from \((s,b)(\tau,\tau)\) and \((s,b)\{\tau,\tau\}\).

3 Collider study of \((\mu^\pm\tau^\mp)\) pair and a b-jet at \(\sqrt{s} = 13\) TeV

The signature of our interest, namely, a \(\mu^\pm\tau^\mp\) pair accompanied by a b-jet, originates from the operators \((s,b)(\tau,\tau)\) and \((s,b)\{\tau,\tau\}\) in Eq. (10). The requirement of one additional b-jet with opposite sign lepton pair reduces the SM background significantly. The muon, for the signal events, emanates from the decay of a \(\tau\). While a direct production of a \(\mu^\pm\tau^\mp\) pair is possible if the aforementioned lepton-mixing is nonzero, the very smallness of the corresponding angle renders this channel to a very subdominant role⁸. Consequently, we neglect the mixing altogether, even though it is relevant to explain the anomalies. The final states \(\tau^\pm\tau^\mp b\) and \(\tau^\pm\tau^\mp b\) can be produced from \(g-g\) fusion and \(g-s\) fusion respectively in p-p collision, as shown in Fig. 1, and both the processes are considered in our analysis. In the next section we determine the sensitivity of the LHC in the recently concluded run.

![Figure 1](image-url)  
Figure 1: (L) Feynman diagram for the production of two \(\tau\)'s in association with one b-jet in g-g fusion \([g g \rightarrow \tau^\pm\tau^\mp b(s)]\), (R) and in g-s fusion \([g s \rightarrow \tau^\pm\tau^\mp b]\). In both figures, the solid blob represents the four-point vertex with effective couplings \(A_i\).

⁸If one considers flavor mixing, there can be three signatures: \((\mu^\pm\mu^\mp)\) pair + b-jet, \((\mu^\pm\tau^\mp)\) pair + b-jet and \((\tau^\pm\tau^\mp)\) pair + b-jet, each with effective coupling as a function of flavor mixing angle. The signature \((\mu^\pm\mu^\mp)\) pair + b-jet has been studied in detail recently [53].
as well as in the forthcoming one for the model parameters, \( A_i \). Towards this, we analyze the signal for each of the benchmark regions as listed in Table 1.

Given the preferred size of the four-fermi couplings \( A_i \), the channel \((\tau^\pm \tau^\mp)\) pair + b-jet has a large production cross section, even if we demand that one of the \( \tau \)'s decays into a \( \mu \) (with a branching fraction of 0.174). On the other hand, owing to the smallness of the lepton mixing angle, the cross section for direct production, from \( g-g \) or \( g-s \) fusion, of \( \mu^\pm \tau^{\mp} \) + b-jet is very small. In the four-fermi limit, the production cross-section would depend only on the couplings \( A_i \) with the subprocess cross-section scaling simply as \( s A_i^2 \) where \( \sqrt{s} \) is the subprocess center-of-mass energy. This, of course, is moderated by the \( \sqrt{s} \)-dependent parton flux. However, if an ultraviolet-complete theory is considered instead, the dependence on \( s \) and the mediator mass scale \( M \) is more complicated, and depends on the precise nature of the completion (for example, a \( Z' \)-like theory would admit the possibility of a resonance, while a leptoquark-like theory would only have \( t \)-channel propagators). In addition, the phase space distributions would differ as well. However, for a mass-scale \( M \) that is larger than a few TeVs, these differences quickly subside primarily on account of the relevant parton-fluxes falling quickly with \( \sqrt{s} \). Not only does this result in a suppression of the fraction of events that could potentially be sensitive to a possible resonance, but any such resonance would also be relative wide one, given the preferred values for the \( A_i \).

The new physics here is simple enough to permit an analytic calculation, which, when followed by a simplistic simulation, yields rather robust results. Nonetheless, we also implement the effective theory model in Feynrules [70,71] and generate signal events, at the leading order, uniformly throughout the parameter space with MadGraph5_aMC@NLO (v2.2.1) [72] interfaced with PYTHIA [73]. For this, we use the NNPDF23LO1 [74] parton distributions with the 5-flavor scheme. We kept the factorization scale fixed at \( m_T^2 \) after \( k_T \)-clustering of the event. On varying the factorization scale between \( m_T^2/4 \) and \( 4m_T^2 \) and, similarly, scanning over different parton distribution sets, the uncertainty in the LO signal cross section is found to be less than 16% and 10% respectively, for the entire range of the parameter space. As for the NLO corrections to the SM, the calculation thereof for a scattering process with a multibody final state such as ours, and, especially in an effective theory, is a very arduous task and beyond the scope of the present work. An intelligent estimate can be made nonetheless, by realizing that the effective Hamiltonian of Eq.10 is most easily obtained starting from a theory with a flavour-changing \( Z' \) or one with scalar leptoquarks. The \( K \)-factor for the former is about 1.3 [75,76] while that for the latter is in the range 1.3–1.4 [77]. It should be appreciated, though, that the relevant couplings considered in the said references are not exactly what are needed for the present case. Nevertheless, it stands to reason that the exact \( K \)-factor should not be wildly different from those quoted above. In other words, the higher-order corrections are expected to increase the signal cross sections. We, however, adopt a conservative standpoint in choosing not to include this enhancement.

The signal comprises two processes, namely, \( g s \rightarrow \tau^\pm \tau^{\mp} b \) and \( g g \rightarrow \tau^\pm \tau^{\mp} b s \) and only those events are selected wherein one tau decays leptonically to muon, resulting in a \((\mu^\pm \tau^{\mp})+ b\)-jet final state. The events are passed through DELPHES 3 [78], in order to incorporate detector effects and apply reconstruction algorithms. Jets are reconstructed using the anti-\( k_T \) algorithm in FastJet [79]. For muon isolation, we have required \( \Delta R \geq 0.4 \) and \( p_T > 1 \) GeV. For calorimetric (tracking) isolation, we require the corresponding momentum parameter to be 0.14 (0.15) times the \( p_T \). This ensures that the muons are well isolated from other objects. Tau leptons are reconstructed through their hadronic decays, and we demand that \( \Delta R \geq 0.4 \) and \( p_T > 10 \) GeV for the reconstruction. In DELPHES, the tau-tagging efficiency is considered to be 0.6 and tau misidentification (from gluons and quarks) probability is 0.001. In this analysis, jets are required to have \( p_T \) greater than 30 GeV and \( q(b) < 4.7 \), and must be separated from the selected leptons by \( \Delta R \geq 0.5 \). For tagging the \( b \)-jets, we used a
$b$-tagging module inside DELPHES with 70% working efficiency. The probability of misstaging a charm as $b$-jet is 10% while for the other quarks and gluons, it is 0.1% or less.

The backgrounds for this channel can be classified into two categories. The irreducible backgrounds arise mainly from $t\bar{t}$, single top ($Wt$), and diboson ($W^+W^-$, $WZ$ and $ZZ$) production, whereas the $t\bar{t}W$, $t\bar{t}Z$ contributions are very small. The major contributions to the reducible background arise from $W$+jets, $Z/\gamma$+jets and other QCD multi-jet processes, where jets may be misidentified as leptons. The probability of a jet to be misidentified as a lepton is taken as a module inside DELPHES [80], as a function of $p_T$ and $\eta$ of the jet. All background events are generated using MadGraph and the cross-sections are taken up to NLO and up to NNLO in some cases (see Ref. [81] and references within). Most of the backgrounds will be reduced by the requirement of one $b$-jet and strong isolation selection among the opposite sign leptons.

As we shall see later, the cuts we propose are very effective in suppressing the large background (from a host of SM processes) and, thereby, in increasing the signal-to-noise ratio. To eliminate large errors in background modelling, we effect a comparison with an actual experimental study. In particular, the CMS collaboration has performed a search [66] for a singly produced third-generation scalar leptoquark decaying to a tau lepton and bottom quark in proton-proton collisions at 13 TeV which includes the final state ($\mu^+\tau^\mp$) pair + $b$-jet. The selections we imposed can be summarized as follows: Exactly one each of a $\tau$ and a $\mu$ with these being oppositely charged and with a single $b$-jet, satisfying,

**Selection S0:**

$$p_T(\mu) > 50 \text{ GeV}, \ p_T(\tau) > 50 \text{ GeV}, \ p_T(b) > 50 \text{ GeV},$$

$$\eta(\mu) < 2.4, \ \eta(\tau) < 2.5, \ \eta(b) < 2.4,$$

$$\Delta R(\mu, \tau) > 0.5, \ \Delta R(\mu, b) > 0.5.$$

![Figure 2:](image)

Figure 2: (a) $p_T$ distributions of the signal ($\mu^+\tau^\mp$) pair + $b$-jet. (b) $S_T = p_T(\mu) + p_T(\tau) + p_T(b)$ distribution for the signal and total background. (c) $E_T^{\text{miss}}$ for the signal and total background. All plots are done after after Selection S0. The signals are normalized for Set X1 (|$A_1$| = 3.8 and |$A_5$| = 2.3) C1 (|$A_1$| = 1.0 and |$A_5$| = 0.5), A1 (|$A_1$| = 3.0 and |$A_5$| = 1.5), B1 (|$A_1$| = 2.0 and |$A_5$| = 1.0). Events are weighted at 120 fb$^{-1}$.

Selection S0 constitutes essentially the basic cuts on different variables. The cuts on $\Delta R$ is placed to ensure that the muon is well isolated from the tau and the $b$-jet. We have plotted the respective $p_T$ distributions for the tau, the muon and the $b$-jet for the signal corresponding to a representative point in the parameter space in Fig. 2(a). As already discussed, the hard interaction being a four-fermi one, the production cross sections, typically, grow with the partonic center-of-mass energy (modulo the suppression due to the effective flux). Furthermore, with the cross sections slightly favouring large angle scattering over small-angle, each of the two $\tau$’s as well as the $b$-jet tend to have a sufficiently
large $p_T$. While the $\tau^\pm$ have essentially identical distributions, the $b$ has a softer component, that arises from the $gg$-initiated process. The $\mu$, while having considerable $p_T$, is softer than the $\tau$, being only a descendant of the second $\tau$. Given this, it is profitable to impose stronger cut in terms of the variable $S_T$, which is the scalar sum of the $p_T$ of the final state particles. The distribution is shown in Fig. 2(b) for both signal and the background. The signal is associated with a relatively modest $E_T^{\text{miss}}$, as seen from Fig. 2(c). As in [66], a soft cut on $M_{\mu\tau}$ in S1 is essential to reduce the background coming from the $t\bar{t}$ and single top production. To summarize, the following set of cuts are used, as in Ref. [66].

**Selection S1:**

$$S_T = p_T(\mu) + p_T(\tau) + p_T(b) > 500 \text{ GeV},$$

$$M_{(\mu,\tau)} > 85 \text{ GeV},$$

The distributions at this stage are depicted in Fig. 3. It is worthwhile to point out that our background profile shape agrees very well with the CMS results [66] while we exceed them in total count by about 5%. In other words, our background determination is very robust.

**Figure 3:** The behaviour of the (a) two body and (b) three body invariant mass of distribution of the signal ($\mu^+\tau^-$) pair $+$ $b$-jet for C1, A1 and B1 (defined in Table 2) and the total background is shown after the S1 cut. Events are weighted at 120 fb$^{-1}$.

At this stage, we propose the following additional selections to improve the signal efficiency,

**Selection S2:**

$$E_T^{\text{miss}} < 230 \text{ GeV},$$

$$M_{(b,\mu,\tau)} > 600 \text{ GeV}.$$
cut on this variable is expected to improve the signal-to-noise ratio. Indeed, once this is imposed (as in S2) it turns out that it is an upper restriction on $E^{\text{miss}}_T$ that is more useful rather than a lower cut. Moreover these particular set of cuts in S2 are useful when signal cross section is comparatively small for small $A_i$. The signal cross sections after the cuts are given in Table 2 for different benchmark points of $A_1$ and $A_5$. We have analyzed the signal as a function of $A_1$ and $A_5$, in different regions and show the variation in the signal cross sections.

Table 2: Signal cross section of $(\mu^\pm \tau^\mp)$ pair + b-jet after the selections at 13 TeV p-p collision at some benchmark points.

| Set | $|A_1|$ | $|A_5|$ | $\sigma$(S1)(fb) | $\sigma$(S2)(fb) | Set | $|A_1|$ | $|A_5|$ | $\sigma$(S1)(fb) | $\sigma$(S2)(fb) |
|-----|--------|--------|-----------------|-----------------|-----|--------|--------|-----------------|-----------------|
| Y1  | 4.5    | 3.0    | 44.52           | 34.72           | A1  | 3.0    | 1.5    | 10.69          | 8.34            |
| Y2  | 4.5    | 3.8    | 70.85           | 55.41           | A2  | 2.5    | 1.5    | 6.54           | 5.12            |
| Y3  | 4.0    | 3.0    | 38.95           | 30.17           | A3  | 2.0    | 1.5    | 5.67           | 4.39            |
| Y4  | 4.0    | 4.0    | 80.32           | 62.66           | A4  | 1.5    | 1.5    | 4.24           | 3.31            |
| X1  | 3.8    | 2.3    | 22.78           | 17.77           | B1  | 2.0    | 1.0    | 3.36           | 2.67            |
| X2  | 3.8    | 3.0    | 35.6            | 27.84           | B2  | 1.5    | 1.0    | 2.31           | 1.8             |
| X3  | 3.8    | 4.0    | 72.39           | 55.83           | B3  | 1.0    | 1.0    | 1.23           | 0.98            |
| Y5  | 3.5    | 2.0    | 16.94           | 13.21           | C1  | 1.0    | 0.5    | 0.81           | 0.63            |
| Y6  | 3.5    | 3.0    | 35.65           | 27.8            | C2  | 0.5    | 0.5    | 0.22           | 0.17            |
| Y7  | 3.0    | 2.3    | 18.70           | 14.63           | C3  | 0.1    | 0.5    | 0.03           | 0.05            |
| Y8  | 3.0    | 3.0    | 31.13           | 24.09           | C4  | 0.05   | 0.5    | 0.02           | 0.01            |

The cut-flow of the backgrounds with the selections is demonstrated in Table 3. Even after the selection S2, the majority of the total background comes from $t\bar{t}$ and single top production. Also note that the signal retains reasonable amount of events when passed through S2. The background is notably smaller for the S2 selection as compared to that for S1. Even though the discovery and exclusion limits can be obtained with both S1 and S2, and their behaviour is comparable, in the next section we show the result when events are selected through S2.

Table 3: Background cross sections after several selections at 13 TeV p-p collision.

| Background            | $\sigma$(S1)(fb) | $\sigma$(S2)(fb) |
|-----------------------|------------------|------------------|
| $t\bar{t}$            | 5.715            | 2.78             |
| Wt                    | 1.132            | 0.502            |
| W + jets              | 0.275            | 0.241            |
| Z/$\gamma$ + jets     | 0.076            | 0.038            |
| Di-boson              | 0.014            | 0.0017           |
| QCD + multi-jets      | 0.0624           | 0.016            |
| Total                 | 7.276            | 3.6              |
Figure 4: The discovery significance ($Z_{\text{dis}}$) as a function of the integrated luminosity ($L_{\text{int}}$). Solid, dashed and dotted lines represent 0%, 25% and 50% uncertainty in the background events respectively. Events are selected by $S_2$. The best fit values are $|A_1| = 3.8$, $|A_5| = 2.3$, represented by Set X1 in figure (b).

4 Results

As the analysis of the preceding section shows, it is indeed possible to exclude much of the parameter space favored by the resolution of the $B$-anomalies, and even contemplate discovery. Rather than restrict ourselves to simplistic signal-to-noise estimations, we consider, instead, a slightly more sophisticated statistical test. Towards this end, let us define the null hypothesis as the set of events being composed entirely of the background (irreducible or instrumental). This is to be tested against the alternative hypothesis, which includes both background as well as the sought after signal. To summarize the outcome of such a search, one quantifies the level of agreement of the observed data with a given hypothesis by computing the $p$-value. This $p$-value can be converted into an equivalent significance, $Z_{\text{dis}}$, for a Gaussian distributed variable. The exact formulation is summarized in the Appendix, with the 5$\sigma$ discovery significance ($Z_{\text{dis}} = 5$) and 95% CL exclusion limit ($Z_{\text{exc}} = 1.645$) being given by Eqs. (12) and (15) respectively.

We can now consider the discovery and exclusion prospects of this particular channel under study, and compute the required integrated luminosity ($L_{\text{int}}$) as a function of model parameters $A_{1,5}$. A straightforward computation, using the signal and background cross sections calculated in the last section, leads to very optimistic results though. However, the background is not known with a very good precision. To account for this, we include a variance $\Delta_b$ in the background while calculating the discovery significance and exclusion from Refs. $[82-84]$ (see Refs. $[85, 86]$ for more detail). With the current LHC data and the data that LHC will take in the future, the systematic experimental uncertainties in the estimation of the SM backgrounds are expected to be reduced significantly and the detector response is also expected to be better in future. For example, by comparing Ref. $[87]$ and
we show the variation of the model parameters (middle and right) that even a small as can be envisaged from Fig. 5, which in turn depends on \( L \), a function of the integrated luminosity (section and, hence, the significance is essentially independent of the sign of the Wilson coefficients) as be achieved with \( L \) for each of the two experiments ATLAS and CMS, and 300 fb\(^{-1}\). In Fig. 5, \( \sigma \) can be probed with 5 one has to wait for a larger \( L \) to get \( Z \) and \( \tau \) including the small values of \( A \) current LHC data 95% CL exclusion limits can be set in a large region of the model parameter space from Sets X and Y as the required luminosity is quite small, as discussed before. Overall with the current LHC data 50% or more. For Set C, much higher luminosity is required for 5 is fully analyzed. Fig. 5 shows the corresponding plots. In Fig. 5 we show this variation for Set B (left), Set A (middle), and Set X (right); the values of \( A_1 \) and \( A_5 \) are chosen in such a way as to satisfy all the low-energy constraints, as mentioned before. If the values of \( A_1 \) and \( A_5 \) lie close to their best fit values, it is evident from Fig. 5 (middle and right) that even a small \( L \) is sufficient to either validate or falsify the model, which should be the case once the present dataset is fully analyzed. Fig. 5 (left) shows that with smaller values of \(|A_1|\) and \(|A_5|\) (Set B) it is likely to reach 5\( \sigma \) significance with current LHC data, even if the uncertainty in the background estimation is 50% or more. For Set C, much higher luminosity is required for 5\( \sigma \) discovery, hence we refrain from showing the corresponding plots.

In Fig. 6, we show the exclusion limits on \( A_1 \), keeping \( A_5 \) as a parameter, in terms of \( L \). The plots, from left to right, are for Sets C, B, and A respectively. We do not display the corresponding plots from Sets X and Y as the required luminosity is quite small, as discussed before. Overall with the current LHC data 95% CL exclusion limits can be set in a large region of the model parameter space including the small values of \( A_1 \) and \( A_5 \).
The signal that we focused upon is an unlike-charged $\mu$-$\tau$ pair associated with a $b$-jet, where the muon comes from the leptonic decay of one of the daughter $\tau$’s. With suitable cuts, one may reduce the SM backgrounds for this signal to a very small level, and thus have a very good detection prospect, even with just the currently collected data, for values of $A_{1,5}$ preferred by the analyses of Refs. [1,2,52]. However the values of $A_{1,5}$ are constrained from the non-observation of $\text{Br}(B_s \to \tau\tau)$, and hence cannot be chosen arbitrarily. Even with an uncertainty in the estimation of the background, the situation looks quite optimistic. For example, notwithstanding the agreement of our background estimation, post S2, with the experimental results of Ref. [66], let us consider the ramifications of an uncertainty as large as $\sim 50\%$ in the background estimation. Even for the point $(|A_1|, |A_5|) = (1.8,1.5)$, somewhat smaller than the best fit values of these parameters (and, hence, resulting in a smaller cross section), can be probed with $5\sigma$ significance at $L_{\text{int}} = 20 \text{ fb}^{-1}$. Similarly, with the same $L_{\text{int}}$, and a similar uncertainty in the background, the region of parameter space defined by $(|A_1| \geq 1.0, |A_5| \geq 1.0)$ can be excluded at 95% CL. For even smaller values of $A_i$, one requires a significantly larger luminosity; for example the region $(|A_1| \geq 0.8, |A_5| \geq 0.5)$ can be excluded at 95% CL with $150 \text{ fb}^{-1}$.

5 Outlook

The not-too-insignificant anomalies in semileptonic $B$ meson decays point towards some new physics that violate lepton flavor universality. One interesting option is to consider effective dimension-6 operators of the form $a_{ij}(\bar{\Gamma}_i s)(\overline{\tau} T_j \tau)$ where $\Gamma_i$ are operators in the Dirac space. The charged current counterpart of this operator—arising automatically when $SU(2)_L \otimes U(1)_Y$ symmetry is imposed—may explain the $R(D)$ and $R(D^*)$ anomalies, while this operator itself, aided by lepton flavor mixing, may lead to a possible explanation of the $R_K$ and $R_{K^*}$ results. Without the knowledge of the ultimate ultraviolet-complete theory, the most prudent way to explore the parameter space for new physics is in terms of the Wilson coefficients. Nominally, these would go as $\lambda^2/M^2$, where $\lambda$ is some dimensionless coupling, and $M$ is the mass of the integrated-out mediator, which may be taken as the scale of new physics.

In this paper, we explored direct signals from such class of operators at the LHC. While probing the structure of the most general set of such four-fermi operators would be difficult, the task has been eased by the analyses of Refs. [1,2,52] which have shown that the said anomalies can be very satisfactorily resolved in terms of just two Wilson coefficients, denoted by $A_{1,5}$. We adopt this simplified structure and also examine how well these can be explored in terms of the integrated luminosity. As long as $M$ is much above the scale being probed by the LHC, whether the new operators are generated through an extra $Z'$, or leptoquarks, or some other dynamics, is irrelevant.

The signal that we focused upon is an unlike-charged $\mu$-$\tau$ pair associated with a $b$-jet, where the muon comes from the leptonic decay of one of the daughter $\tau$’s. With suitable cuts, one may reduce the SM backgrounds for this signal to a very small level, and thus have a very good detection prospect, even with just the currently collected data, for values of $A_{1,5}$ preferred by the analyses of Refs. [1,2,52]. However the values of $A_{1,5}$ are constrained from the non-observation of $\text{Br}(B_s \to \tau\tau)$, and hence cannot be chosen arbitrarily. Even with an uncertainty in the estimation of the background, the situation looks quite optimistic. For example, notwithstanding the agreement of our background estimation, post S2, with the experimental results of Ref. [66], let us consider the ramifications of an uncertainty as large as $\sim 50\%$ in the background estimation. Even for the point $(|A_1|, |A_5|) = (1.8,1.5)$, somewhat smaller than the best fit values of these parameters (and, hence, resulting in a smaller cross section), can be probed with $5\sigma$ significance at $L_{\text{int}} = 20 \text{ fb}^{-1}$. Similarly, with the same $L_{\text{int}}$, and a similar uncertainty in the background, the region of parameter space defined by $(|A_1| \geq 1.0, |A_5| \geq 1.0)$ can be excluded at 95% CL. For even smaller values of $A_i$, one requires a significantly larger luminosity; for example the region $(|A_1| \geq 0.8, |A_5| \geq 0.5)$ can be excluded at 95% CL with $150 \text{ fb}^{-1}$. 

Figure 6: 95% CL exclusion limits at 13 TeV LHC in the $(\mu^{\pm}\tau^{\mp})+b$-jet channel as a function of $L_{\text{int}}$ and $A_1$, $A_5$ (in $\text{TeV}^{-2}$). Solid, dashed and dotted lines represent 0%, 25% and 50% uncertainty in the background events respectively. Events are selected by S2.
The case where both the $\tau$’s decay hadronically is not so clean as this channel, but will be taken up in a subsequent study. We have not taken the lepton flavor mixing between $\mu$ and $\tau$ into account. As has been shown in the literature, the mixing angle is bound to be small ($\sim 0.02$). While the mixing can directly produce an unlike-sign $\tau$-$\mu$ pair, the production rate is swamped by the events where one $\tau$ subsequently decays into a muon. Thus, we do not envisage that a study of this nature will shed any light on the mixing angle. This would be better investigated by significantly improving the measurements of lepton flavor violating decays such as $B \to K^{(*)}\mu\tau$ or $B_s \to \tau^\pm\mu^\mp$.

6 Appendix

The significance for discovery in terms of signal events ($s$), background events ($b$) and the uncertainty in the background ($\Delta_b$) is $[82–84],

$$Z_{\text{dis}} = \left[ 2 \left( s + b \right) \ln \left[ \frac{(s + b)(b + \Delta_b^2)}{b^2 + (s + b)\Delta_b^2} \right] - \frac{b^2}{\Delta_b^2} \ln \left[ \frac{\Delta_b^2 s}{b(b + \Delta_b^2)} \right] \right]^{1/2}.$$ (12)

If $\Delta_b = 0$,

$$Z_{\text{dis}} = \sqrt{2(s+b)\ln(1+s/b) - s}.$$ (13)

In the above equation, if $b$ is large, then we obtain the well known expression

$$Z_{\text{dis}} = \frac{s}{\sqrt{b}}.$$ (14)

For discovery reach, $Z_{\text{dis}} \geq 5$ corresponds to $5\sigma$ discovery ($p < 2.86 \times 10^{-7}$). The exclusion limit at a given confidence level (CL) is $[82–84]

$$Z_{\text{exc}} = \left[ 2 \left( s - b \right) \ln \left( \frac{s + x}{2b} \right) - \frac{b^2}{\Delta_b^2} \ln \left( \frac{s + x - b}{2b} \right) \right]^{1/2},$$ (15)

where

$$x = \sqrt{(s + b)^2 - 4sb\Delta_b^2/(b + \Delta_b^2)}.$$ (16)

In the above equation, if $\Delta_b = 0$,

$$Z_{\text{exc}} = \sqrt{2(s-b)\ln(1+s/b)}.$$ (17)

For a median expected 95% CL exclusion ($p = 0.05$), we use $Z_{\text{exc}} \geq 1.645$ for different $\Delta_b$.

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