Flavor violation at LHC in events with two opposite sign leptons and a b-jet

Nilanjana Kumar

1 Department of Physics and Astrophysics, University of Delhi, Delhi 110007, India

nilanjana.kumar@gmail.com

Abstract. Hints of flavor violation at both charged current and neutral current decays have been observed in experiments such as LHCb, Belle, and BABAR. The anomalies in the result can be addressed in the effective field theory (EFT) framework. The effective operators predict different beyond standard model (BSM) signatures and the four point interaction vertices can be probed at Large Hadron Collider (LHC). In this context, the discovery projection of two opposite sign leptons and a b-jet signature is studied in this paper at 13 TeV LHC.

Keywords: Flavor violation, Opposite-sign leptons

1 Motivation

Recent experimental measurements at LHCb, Belle, and BABAR present deviations in the SM prediction of B-meson decays and hints towards Lepton Flavor Violation (LFV). LFV has been observed in charged current decay at tree level, \( b \to c\ell \nu \). Taking into account \( R(D) \) and \( R(D^*) \) measurements by BABAR [1], Belle [2] and LHCb [3] and their correlations, the difference between SM and the data is nearly \( 3.8 \sigma \) [4,5]. The anomaly in \( B_c \to J/\psi \ell \nu \) measurement is at the \( 2\sigma \) level. Whereas, the neutral current transitions, namely \( b \to s\ell^+\ell^- \) shows an opposite effect in the measurements of \( R_K \) and \( R_{K^*} \). The recent results by LHCb collaboration [6] and Belle [7], reflect that the data is more consistent with the SM. A deviation is also seen in \( B_s \to \phi \mu \mu \) [8], that suggests that the discrepancies in \( R_K \) and \( R_{K^*} \) have been caused by a diminution of the \( b \to s\mu^+\mu^- \) channel, rather than an enhancement in \( b \to se^+e^- \).

To address these anomalies one can choose the models with leptoquarks [9] or \( Z' \) [10]. Another way of addressing these anomalies would be to consider an effective field theory (EFT) description with a set of Wilson coefficients. It is possible to construct such a theory with a few unknown parameters, if symmetry relations exist between the Wilson Coefficients. As shown recently in [11,12], with a minimal set of new physics (NP) operators, accompanied by a single lepton mixing angle, it is possible to address the flavor observables. The parameters of these models can be determined phenomenologically and if the scale of the new physics is a few TeVs, this leads to interesting collider signatures at LHC.
Table 1. Operators and their effective couplings. For the notation, see Ref. [11].

| Flavor basis | Mass basis | \( \lambda^* \) |
|--------------|-------------|-----------------|
| \((3A_1/4)(s,b)(\tau\tau)\) | \((3A_1/4)\cos^2\theta(s,b)(\tau\tau)L_\tau\) | \(2M^2(3A_1/4)\cos^2\theta\) |
| \((3A_1/4)\sin^2\theta(s,b)(\mu'\mu')_L\) | \(2M^2(3A_1/4)\sin^2\theta\) | |
| \((3A_1/4)\sin2\theta(s,b)(\mu'\tau')_L\) | \(2M^2(3A_1/4)\sin2\theta\) | |
| \(A_5(s,b)(\tau\tau)\) | \(A_5\cos^2\theta(s,b)(\tau\tau)_R\) | \(2M^2A_5\cos^2\theta\) |
| \(-\) | \(A_5\sin^2\theta(s,b)(\mu'\mu')_R\) | \(2M^2A_5\sin^2\theta\) |
| \(-\) | \(A_5\sin2\theta(s,b)(\mu'\tau')_R\) | \(2M^2A_5\sin2\theta\) |

2 Theoretical Framework

The Hamiltonian for the new physics can be expressed in terms of two operators involving left handed 2nd and 3rd generation quark doublets \(Q_2L\), \(Q_3L\), 3rd generation lepton doublet \(L_3\) and right handed singlet \(\tau_R\) as defined in Ref. [11,12], where the terms that we are interested in are \((\bar{Q}_2L\gamma^\mu Q_3L)\) and \((\bar{Q}_2L\gamma^\mu Q_3L)\), with coefficients \(3A_1/4\) and \(A_5\), following the literature Ref. [11,12]. \(A_i\) are real unknown coefficients with dimension \(\text{TeV}^{-2}\). The flavor eigenstates can be expressed in terms of mass eigenstates by a field rotation,

\[
\tau = \cos\theta(\tau') + \sin\theta(\mu')
\]

\[
\nu_\tau = \cos\theta(\nu_\tau') + \sin\theta(\nu_\mu')
\]

As a result of the mixing, the coupling with the second generation of leptons are induced. The magnitude of this mixing is found to be small \((\sim 0.02)\) [11,12]. Also, for all class of models the best fit values obtained can be approximated as \(A_1 \sim 3.8, A_5 \sim 2.3\).

The flavor violating process, generated by these operators are listed in Table 1. For a process \((a,b) \rightarrow (c,d)\) with coefficient \(X\) in the operator, we can write the four point coupling \((\lambda^2)\) in the mass basis as,

\[
\frac{\lambda^*_a \lambda^*_{c,d}}{2M^2} (a, b)(c, d) = e^{abcd} \frac{4G_F}{\sqrt{2}} (a, b)(c, d),
\]

\[
\lambda^2 \sim \lambda^*_a \lambda_{c,d} \sim 2M^2 X,
\]

where, \(M\) is the mass of the integrated-out field, and \(\lambda's\) are the dimensionless coupling. From perturbativity the bound on \(\lambda\) is \(\lambda^2/(4\pi)^2 \leq 1\).

3 Results

As can be seen from Table 1 there are three possible signatures:

- \((\mu^\pm \mu'^\mp) + b\text{-jet}\),
- \((\mu^\pm \tau'^\mp) + b\text{-jet}\) and
These processes can be generated at 13 TeV LHC via $g-g$ and $g-s$ fusion in $p-p$ collision, with the major contribution coming from $g-s$ fusion. Now as the coupling ($\lambda^2$) is a function of $A_1$ and $A_5$, the cross section also varies with these parameter. We kept the value of $A_1$ fixed at the best fit 3.8 and varied $A_5$. The range of values of the parameters are chosen such that the 95% C.L upper bound of $Br(B_s \to \tau^-\mu^+) < 4.2 \times 10^{-5}$ [14] is satisfied.

The cross section of $(\mu^\pm\tau^\mp)$ and a $b$-jet is very small, because their coupling is suppressed by $(\sin^2\theta)$ and hence we neglect it in this study. The cross section of $(\mu^\pm\tau^\mp)$ and a $b$-jet will be suppressed by $\sin 2\theta$ and hence will be comparatively larger than the previous one, shown in Fig. 1 (left). The cross section of $(\tau^\pm\tau^\mp)$ and a $b$-jet is relatively very high as shown in Fig. 1 (right) with red line. The tau can also decay leptonically to a muon with branching ratio 0.174, enabling the final states with $(\mu^\pm\tau^\mp)$ and a $b$-jet and $(\mu^\pm\mu^\mp)$ and a $b$-jet, as shown in Fig. 1 (right) by green and blue lines respectively.

The major SM backgrounds for these channels are $t\bar{t}$, single top ($Wt$), diboson ($W^+W^-$, $WZ$ and $ZZ$), $W$+jets, $WW$+jets, $Z/\gamma$+jets. We found that the background for the signal with opposite sign same flavor states $(\mu^\pm\mu^\mp)$ or $(\tau^\pm\tau^\mp)$ and a $b$-jet are larger than the opposite sign opposite flavor state $(\mu^\pm\tau^\mp)$. Also, the signal $(\tau^\pm\tau^\mp)$ and a $b$-jet will suffer from tau tagging efficiency at LHC as the both the tau decay hadronically. Hence we study two channels, $(\mu^\pm\tau^\mp)+b$-jet and $(\mu^\pm\mu^\mp)+b$-jet. In Fig. 2 we have shown the discovery projection of these two channels as a function of the integrated luminosity at LHC. We have followed the search strategy as mentioned in [15,16]. Fig. 2 shows that the $(\mu^\pm\mu^\mp)+b$-jet channel requires much larger luminosity than $(\mu^\pm\tau^\mp)+b$-jet channel for 5$\sigma$ discovery significance.
Fig. 2. The $5\sigma$ discovery projection at 13 TeV LHC in $(\mu^\pm \mu^\mp) + b$-jet and $(\mu^\pm \tau^\mp) + b$-jet channel as a function of the integrated luminosity and model parameter $A_5$ with the assumption of 25% uncertainty in the background events.

4 Conclusion

Recently observed anomalies in the decays of B-mesons hints towards new physics interaction which involves a b-quark, a s-quark and a pair of opposite sign leptons. The four point interactions among them can be probed at LHC p-p collision via the direct production of b-quark and two opposite sign leptons. The opposite sign lepton pair have either same or opposite flavor. In this study, $5\sigma$ discovery potential of $(\mu^\pm \mu^\mp) + b$-jet and $(\mu^\pm \tau^\mp) + b$-jet channels are discussed as a function of the effective field theory model parameters. Overall, these channels have a very good detection prospect even with the currently collected data at LHC and a limit on the model parameter space can be set with the 13 TeV LHC data.

References

1. BaBar collaboration, J. P. Lees et al., Phys. Rev. D88 (2013) 072012,
2. Belle collaboration, M. Huschle et al., Phys. Rev. D92 (2015) 072014,
3. LHCb collaboration, R. Aaij et al., Phys. Rev. Lett. 115 (2015) 111803,
4. Heavy Flavor Averaging Group (HFAG) collaboration, Y. Amhis et al., arXiv: 1412.7515 [hep-ph].
5. “https://hflav-eos.web.cern.ch/hflav-eos/semi/summer18/RDRDs.html.”.
6. LHCb Collaboration collaboration, Tech. Rep. CERN-EP-2019-043. LHCB-PAPER-2019-009, CERN, Geneva, Mar, 2019.
7. Belle collaboration, A. Abdesselam et al.,
8. LHCb collaboration, R. Aaij et al., JHEP 09 (2015) 179,
9. D. Bećirević, S. Fajter, N. Košnik and O. Sumensari, Phys. Rev. D94 (2016) 115021,
10. P. Langacker, Rev. Mod. Phys. 81 (2009) 1199–1228
11. D. Choudhury, A. Kundu, R. Mandal and R. Sinha, Phys. Rev. Lett. 119 (2017) 151801,
12. D. Choudhury, A. Kundu, R. Mandal and R. Sinha, *Nucl. Phys.* **B933** (2018) 433–453.

13. S. Bhattacharya, A. Biswas, Z. Calcuttawala and S. K. Patra, arXiv:1902.02796 [hep-ph].

14. LHCb collaboration, R. Aaij et al., *Search for the lepton-flavour-violating decays $B^0_s \to \tau^\pm \mu^\mp$ and $B^0 \to \tau^\pm \mu^\mp$*, arXiv:1905.0661 [hep-ph].

15. D. Choudhury, N. Kumar and A. Kundu, arXiv:1905.07982 [hep-ph].

16. Y. Afik, J. Cohen, E. Gozani, E. Kajomovitz and Y. Rozen, *Establishing a Search for $b \to s \ell^+\ell^-$ Anomalies at the LHC*, *JHEP* **08** (2018) 056.