Lepton flavour violating decay of 125 GeV Higgs boson to $\mu\tau$ channel and excess in $ttH$

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Abstract

A recent search for the lepton flavor violating (LFV) decays of the Higgs boson, performed by CMS collaboration, reports an interesting deviation from the standard model (SM). The search conducted in the channel $H \to \mu\tau e$ and $H \to \mu\tau_{\text{had}}$ shows an excess of $2.4\sigma$ signal events with $19.7\text{ fb}^{-1}$ data at a center-of-mass energy $\sqrt{s} = 8\text{ TeV}$. On the other hand, a search performed by CMS collaboration for the SM Higgs boson produced in association with a top quark pair ($ttH$) also showed an excess in the same-sign di-muon final state. In this work we try to find out if these two seemingly uncorrelated excesses are related or not. Our analysis reveals that a lepton flavour violating Higgs decay ($H \to \mu\tau$) can partially explain the excess in the same-sign di-muon final state in the $ttH$ search, in fact brings down the excess well within $2\sigma$ error of the SM expectation. Probing such non-standard Higgs boson decay is of interest and might contain hints of new physics at the electroweak scale.

1 Introduction

The Higgs boson was hypothesised [1, 2, 3, 4] in the year 1964 and since then experimental searches for this elusive boson have been performed in different collider experiments worldwide. Finally, after around 50 years of its theoretical proposition, a Higgs boson is discovered by both the ATLAS and CMS experiments of LHC at CERN, Geneva; the announcement of which was made on July 4, 2012 [5, 6]. With accumulation of more data throughout the year 2012, the properties of this newly observed boson was measured more accurately. The spin and parity properties and couplings of Higgs boson with fermions and bosons, the so-called $\kappa_f$ and $\kappa_v$, have been measured in different decay channels [7, 8, 9, 10, 11] of Higgs boson. Though most of the measurements are consistent with SM predictions within uncertainties, there is still some room for new physics beyond the SM, given the amount of uncertainties are still quite large in some cases.

2 An excess in lepton flavour violating decay channel of Higgs boson

In the framework of the SM, the interaction between the Higgs boson and the SM fermions, written in the mass eigenstate basis is

$$\mathcal{L}_Y = -Y_{ij} f_L^i f_R^j H + \text{h.c.}$$ (1)

where $f_L$’s are the left handed fermion (lepton or quark) doublet and $f_R$’s denote the right handed fermion singlet. $Y_{ij}$ represent the Yukawa couplings in the mass basis and are diagonal in the

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paradigm of SM. In such a scenario, lepton flavor violating (LFV) Higgs decays are prohibited. However, such LFV decays can be incorporated in many beyond the SM (BSM) scenarios. For example, models with additional Higgs or other scalar fields \([12, 13, 14, 15, 16]\), Higgs portals \([17]\), flavor symmetric models broken at the electroweak scale \([18, 19]\) and horizontal gauge symmetries \([20]\) can explain such exotic decays of the Higgs boson. On the other hand, prototypical supersymmetric models with \([21, 22]\) and without R-parity violation \([23]\) are rather unlikely to explain such signals. However, in the context of this work, we will consider a model independent approach and will remain completely agnostic about different models which can give rise to LFV Higgs decays, more precisely \(H \rightarrow \mu \tau\) channel. From the perspective of effective field theory (EFT), one can write down higher dimensional operators \((d > 4)\) suppressed by a new physics scale \(\Lambda^{d-4}\). These operators would get generated by integrating out the ‘non-standard’ heavy degrees of freedom. All of these operators would certainly leave a fingerprint in the low energy theory. As discussed in ref \([24]\) a dimension 6 operator of the form \(\lambda_{ij}(f^T_L f^T_R)H(H^1 H)/\Lambda^2\) can indeed generate a non-diagonal Yukawa matrix \(Y_{ij}\) in the mass eigenstate basis of the fermions, which leads to LFV decays of the Higgs boson.

On the experimental frontier, the first direct search for lepton flavor violating decays of a Higgs boson to a muon-tau pair has been performed by the CMS collaboration \([24]\). The search has been conducted in two channels \(H \rightarrow \mu \tau_{\nu}\) and \(H \rightarrow \mu \tau_{\nu\bar{\nu}}\), where \(\tau_{\nu}\) and \(\tau_{\bar{\nu}}\) represents hadronic and electronic decays of \(\tau\) respectively. A slight excess of signal events with a significance of 2.4\(\sigma\) is observed, which corresponds to a local p-value of 0.01\(\sigma\). A constraint on \(BR(H \rightarrow \mu \tau) < 1.51\%\) at 95\% confidence level is set and the best fit branching fraction is \(BR(H \rightarrow \mu \tau) = (0.84^{+0.40}_{-0.37})\%\), as obtained by CMS. This limit on the branching ratio can be subsequently translated to constrain the Yukawa coupling \(Y_{\mu\tau}\) \([25]\). Similarly, the ATLAS collaboration also looked into LFV decay modes of the Higgs boson with 8 TeV centre-of-mass energy and with 20.3/fb\(^{-1}\) data. The limit on the branching fraction \(Br(H \rightarrow \mu \tau)\) is set at 1.85\% \([26]\).

### 3 Another excess in \(ttH\) channel

Recently, a search for the SM Higgs boson produced in association with a top-quark pair \((ttH)\) is performed by the CMS collaboration \([27]\). The search has been performed in different final state combinations, such as \(\gamma\gamma, bb,\tau H, 4l, 3l\) and same-sign 2l. The observed values of signal strength modifier \(\mu\) and the corresponding errors have been reported. While the observed \(\mu\) in most of these \(ttH\) channels are more or less consistent with the SM predictions within the error bars, the measurement in the same-sign di-muon channel shows an excess of events. The observed signal strength in same-sign 2l channel is 5.3\(\pm^{+2.1}_{-1.8}\). Within this category, the same-sign di-muon subsample has the largest signal strength, with \(\mu = 8.5^{+3.3}_{-2.7}\) compared with \(\mu = 2.7^{+4.6}_{-4.1}\) for the same-sign di-electron channel and \(\mu = 1.8^{+2.5}_{-2.3}\) for the same-sign electron-muon channel. It is important to note that for this fit, the Higgs boson production rate other than \(ttH\) are considered to be the same to the SM expectations. We shall discuss later the implications when this condition is relaxed.

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4\(\sigma\)-value is defined as the probability, under the background-only hypothesis (b), to obtain a value \(q_0\) which is at least as large as that observed in data, \(q_{0,\text{data}}\): \(p\)-value = \(\text{Prob}\ (q_0 \geq q_{0,\text{data}}|b)\). \(p\)-value measures how likely it is to get a certain experimental result as a matter of chance rather than due to a real effect.

5The signal strength modifier \(\mu\) multiplies the expected SM Higgs boson cross-section in such a way that \(\sigma_{\text{observed}} = \mu \cdot \sigma_{\text{SM}}, \text{ so } \mu = \frac{\sigma_{\text{observed}}}{\sigma_{\text{SM}}}\).
4 Are these two excesses related to each other?

These two excesses, reported by CMS collaboration, may seem uncorrelated but one has to keep in mind that both the observations are related to the newly discovered bosonic state, whose characteristics are yet to be understood completely. If the $H \rightarrow \mu \tau$ decay takes place, then it can show up as excesses in different final states in $t\bar{t}H$ search. The two excesses seen in data can be the two different faces of the same coin and it may contain hints for BSM physics. In this work, we will try to find whether these two excesses are related or not.

5 Scenario at 8 TeV

To check if the excess in $t\bar{t}H$ same-sign di-muon final state comes from the LFV decays of Higgs boson, we have performed a truth-level analysis where we have tried to use a similar event selection criteria as used by CMS $t\bar{t}H$ analysis, whenever possible with an equivalent luminosity of $20 \text{ fb}^{-1}$, which more or less corresponds to the data set recorded by the CMS experiment in 2012. We have generated $t\bar{t}H$ events for center-of-mass energy 8 TeV using PYTHIA 6 event generator [28] for two situations, one is when all SM decays of Higgs boson are allowed and another is when Higgs boson can decay only to a $\mu \tau$ pair. Mass of the Higgs boson and the top quark are taken as 125.6 GeV and 173 GeV respectively. The cross-section of $t\bar{t}H$ process is considered to be 127 fb [29]. Following the CMS analysis, we have selected the events requiring the presence of exactly two muons (and no electron) with same sign of charge and at least four hadronic jets, one of them is required to be a b-quark jet, in the final state. Clustering of jets are done using the built-in Pythia module PYCELL which in turn employs a cone algorithm and incorporates convenient smearing of the momenta. In PYCELL we granted for an angular coverage of $|\eta| < 4.9$ for the hadron calorimeter with a cell segmentation resembling a generic LHC detector, i.e., $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$. In addition, a jet cone of radius $\Delta R(i, j) = 0.5$ has been employed for finding jets. Both the muons should have transverse momentum ($p_T$) greater than 20 GeV. Muons and jets should pass the pseudorapidity requirement of $|\eta| < 2.4$. The scalar sum of the $p_T$ of the two leptons and the missing transverse energy ($E_T^{miss}$) is required to be above 100 GeV. The cuts mentioned above are the event selection cuts from the CMS $t\bar{t}H$ analysis, where they have found the following result after applying these cuts : the number of events expected from SM $t\bar{t}H$ signal is $3.1 \pm 0.4$ and from SM background is $27.7 \pm 4.7$; so the total number of events expected from SM in same-sign dimuon channel is $30.8 \pm 5.1$. In this analysis, CMS has observed 41 events, which is an excess of 10.2 (5.1) events calculated from the central value (upper edge of error bar) of expected number of events. Given that there is an excess of events over the SM expectation, the question is if the LFV decay of Higgs boson can explain this excess of events or not. One has to keep in mind that we have calculated the excess very naively w.r.t the central value and upper edge of the $1\sigma$ error-bar and the data is roughly consistent with $2\sigma$ error-bar. Thus, the exact number of extra events observed in data should not be seen too sacredly. Rather the take-away message from this observation is that there is some upward fluctuation in data, the amount of which is not easy as well as meaningful to quantify without doing a sophisticated multivariate analysis, which have been performed by CMS as the next step after the cut-based event selection. In our analysis we did not apply any multivariate technique, we have used the event selection cuts from the CMS analysis. To validate our analysis method, we have checked that the number of events obtained by us for $H \rightarrow WW, H \rightarrow \tau\tau, H \rightarrow ZZ$ decay channels in $t\bar{t}H$ production mode and for $t\bar{t}W$ background process in the same-sign di-muon
Table 1: Expected number of events after the selection cuts in same-sign dimuon final state at 8 TeV for the $t\bar{t}H$ production mode for different decay channels of Higgs boson.

| Process | BR used in | $N_{\text{event}}$ present | $N_{\text{event}}$ CMS analysis | $N_{\text{event}}$ Analysis |
|---------|------------|----------------------------|---------------------------------|------------------------------|
| $t\bar{t}H$ $H \rightarrow WW$ | 22.4 % | 2.99 | 2.4±0.3 |
| $t\bar{t}H$ $H \rightarrow \tau\tau$ | 6.3 % | 0.8 | 0.7±0.1 |
| $t\bar{t}H$ $H \rightarrow ZZ$ | 2.8 % | 0.05 | 0.1±0.0 |
| $ttW$ | - | 10.2 | 10.4±1.5 |

final state is fairly consistent with the expected number of events reported by CMS after applying the event selection cuts. Our observation and numbers from CMS are presented in Table 1. The branching ratios are taken from [30]. We have generated the $ttW$ process using Madgraph5 event generator [31] at leading order (LO) accuracy and then multiplied the event yield by the $K$-factor, which is the ratio of cross-sections at NLO and LO. The $K$-factor used for $ttW$ process is 1.7. The NLO cross-section of $ttW$ process is 227 fb at 8 TeV [32].

We also find the number of events in the same-sign dimuon final state after applying the event selection cuts in the $t\bar{t}H$ production mode at 8 TeV coming from $H \rightarrow \mu\tau$ and for branching fraction of 1% is roughly 0.75. Now, if $H \rightarrow \mu\tau$ decay is allowed then CMS should also see excess in same sign $e\mu$ channel. Although, there is no such excess observed but the uncertainty on the background is quite large (49.3±5.4 events). We note in passing that the same sign electron-muon pair would also show a similar enhancement. Even 2% and 3% branching fractions in this channel can easily be accommodated given the large uncertainty in the SM background. From this observation, we can conclude that the LFV decay can explain the excess, mostly partially depending on the quantity of the excess and the branching ratio of LFV decay of Higgs boson. We note that although a 2% branching fraction of the Higgs boson in the LFV decay channel is not enough to explain the excess in the same-sign dimuon channel, but it is still a sizeable contribution, nearly 50% of the SM expectation and brings down the excess within 2σ error of the SM value. We point out that for 3% branching ratio of the $H \rightarrow \mu\tau$ channel, one obtains roughly 2.3 number of events in the same-sign dimuon final state. Although higher branching ratios such as these are beyond the constraint given by CMS at 95% confidence level. But we think that it is reasonable to have a look at them because of the following two reasons:

1. In ref [24], the authors showed that the LFV decays of Higgs boson can be sizeable. For example, $H \rightarrow \tau e$ and $H \rightarrow \tau\mu$ branching ratios of $O(10\%)$ are allowed by low energy constraints coming from $\tau \rightarrow 3\mu, \tau \rightarrow \mu\gamma$.

2. In the search for LFV decays, it has been assumed that the cross-sections of various production processes of Higgs boson are SM-like, which may not be the case in presence of any new physics. Further, the best fit value of the cross-section of gluon fusion production mechanism is $\mu_{ggH} = 0.85^{+0.19}_{-0.16}$, as reported by CMS [9]. This is slightly on the lower side than the SM expectation, though within uncertainty it is consistent with SM prediction. If the production cross-section is lower then the same number of observed $H \rightarrow \mu\tau$ events will give rise to a higher value of branching ratio. As a result, the upper bound on the branching ratio as
reported by the CMS collaboration would get relaxed. For example, we have checked that the constraint on $\text{Br}(H \to \mu \tau) < 1.51\%$ can be further relaxed to 2.19\% (2.85\%) if one considers the $1\sigma$($2\sigma$) band on the gluon fusion production as reported by CMS [9]. As stated earlier, even this branching ratio is not enough to explain the excess but is nonetheless sizeable and brings down the excess well within 2\sigma error of the SM expected value. Another possibility to boost the branching fraction of $H \to \mu \tau$ is to reduce the branching ratio of $H \to b \bar{b}$, which reduces the total decay width of the Higgs boson and subsequently increases the branching fraction in this exotic channel. However, one has to respect the experimental bound along with the associated errors on the LFV process, which are much stringent.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{PT_distribution}
\caption{Distribution of $p_T$ of the trailing muon in same-sign dimuon final state at 8 TeV with respect to the number of events normalised to unity.}
\end{figure}

After the event selection, as one can see from the numbers quoted previously, the overall yields are still dominated by background events. Therefore, CMS analysis uses a multivariate technique after applying the mentioned selection cuts. They use Boosted Decision Tree (BDT) which is trained with simulated $t\bar{t}H$ signal and $t\bar{t} + \text{jets}$ background events, using following six input variables: $p_T$ and $|\eta|$ of the of the trailing lepton, the minimal angular separation between the trailing lepton and the closest jet, the transverse mass of the leading lepton and $E_{T}^{\text{miss}}$, transverse energy of all selected jets and leptons ($H_T$) and missing transverse energy of all jets and leptons ($H_{T}^{\text{miss}}$). Among these input variables, CMS has provided the plot of trailing muon $p_T$ in the same-sign di-muon channel and the plot shows that the distribution obtained from data is slightly harder than what is expected from the SM. After using BDT output as the discriminating variable, CMS has seen a clear excess of events in the same-sign di-muon channel which was reported as the observed signal strength as described previously. The CMS paper did not include plots of all six input variables in same-sign di-muon final state, so we are unable to compare our findings with observed distribution for the other variables except $p_T$ of trailing muon. In fig. 1 we have plotted the $p_T$ distribution of the trailing muon as a function of the number of events normalised to unity for four different cases - (a) SM $H \to \tau \tau$ (b) SM $H \to WW$ (c) LFV $H \to \mu \tau$, all of them for the $t\bar{t}H$ production mode and the dominant SM background (d) $t\bar{t}W$. We have found that the $p_T$ distribution of the trailing
muon, obtained from the LFV $H \to \mu\tau$ decay is harder and somewhat similar to the feature that CMS has observed in the 8 TeV data. This is also expected since the muons emerging from the $H \to \mu\tau$ decay are harder compared to the muons coming from $H \to \tau\tau$. As a result, $H \to \mu\tau$ would have a higher efficiency at passing the CMS selections cuts in the $t\bar{t}H$ analysis. We also note in passing that CMS also took into account the contribution from non prompt background coming mostly from $t\bar{t}+\text{jets}$ events, which is also the dominant one.

6 Future Prospects at 13 TeV

The run 1 data of CMS is statistically limited for such an analysis involving low cross-section signal processes, so the errors on the observed data points are huge. However, if both the excesses are genuine then they will be confirmed from the run 2 data. We have performed the analysis in 13 TeV in a similar manner as described before with an integrated luminosity of $100 \text{ fb}^{-1}$.

| Process    | Branching Ratio | $N_{\text{event}}$ |
|------------|-----------------|-------------------|
| $t\bar{t}H \ H \to WW$ | 22.4 % | 24 |
| $t\bar{t}H \ H \to \tau\tau$ | 6.3 % | 6 |
| $t\bar{t}W$ | - | 60 |
| $t\bar{t}H \ H \to \mu\tau$ | 2 % | 16 |

Table 2: Branching ratio of LFV $H \to \mu\tau$ decay and the corresponding number of events obtained in same-sign dimuon final state after applying the event selection cuts in the $t\bar{t}H$ production mode at 8 TeV

At 13 TeV the cross-section of $t\bar{t}H$ production mode is taken to be 503 fb $^{[33]}$. We plot the distribution of $p_T$ of trailing muons in same-sign di-muon final state as shown in figure $2$. The $p_T$ distribution coming from the LFV decay of Higgs boson is harder than other SM processes. So we have applied harder $p_T$ cuts on the muons, compared to the 8 TeV analysis, in order to distinguish between signal and background more efficiently. We require that the leading and trailing muons should pass $p_T > 50$ GeV and $p_T > 30$ cuts respectively. Apart from this change, all other aspects of the analysis are same as before. For 13 TeV, the number of events that we have obtained from the LFV decay of Higgs boson for the branching ratio of 2%, and number of events obtained from $H \to \tau\tau$, $H \to WW$ channels, along with dominant SM background $t\bar{t}W$ are reported in table $2$. Just by applying harder $p_T$ cuts, we are not able to kill the background events substantially. For a better discrimination between signal and background, one should conduct a multivariate analysis which is expected to perform better than a cut-based analysis.

7 Summary and Outlook

CMS has observed an excess of events in $t\bar{t}H$ production mode in same-sign di-muon final state. Another excess of events in $H \to \mu\tau$ LFV decay channel is also reported by CMS. We have shown that it may be possible that these two excesses are correlated and the effect of LFV decay of Higgs boson has shown up in the $t\bar{t}H$ search of CMS. The branching ratio of LFV decays of Higgs boson are not too much constrained from indirect searches performed so far. Keeping that in mind we
have explored a substantially large range of branching ratio to see how much excess can come from this kind of decays of Higgs boson. However, from the direct search of LFV decay, CMS has given an upper bound on the branching ratio $\text{BR}(H \rightarrow \mu\tau)$ which is 1.51% at 95% confidence level. This bound is obtained by assuming the SM-like cross-section for all the production mechanisms of Higgs boson. This assumption when relaxed and if the production cross-sections are lower than the SM cross-sections (which is still allowed from the most recent measurements of CMS collaboration), the upper bound on branching ratio will be pushed further in the upward direction. We have checked that the branching ratio of $H \rightarrow \mu\tau$ can be relaxed up to 3% if one assumes the production cross-section through gluon fusion mode is at its lowest value as reported by CMS. Such a branching is still not enough to explain the excess in the same sign dimuon channel but can notably bring down the excess of events within $2\sigma$ value of the SM expectation. However, the 8 TeV data is not sufficient to clear all the doubts as it is limited by statistics. In the next run of LHC at 13 TeV, we can expect more precise measurements of cross-sections and branching ratios of different processes and will provide a more transparent picture. It is also important to note that if such LFV decays of the Higgs boson are indeed present then in addition to the same sign di-muon channel, an excess of similar size would also show up in the same sign electron-muon final state. Although, the simulation results are well within experimental uncertainties, however, more data is required to shed light in this matter. We also note that the ATLAS collaboration have already searched for lepton flavour violating Higgs decays to $\mu-\tau_{had}$ final state in their 8 TeV analysis and did not found any excess [26]. Nevertheless, it is important to re-examine this issue in the light of 13 TeV run of the LHC.

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