Multilepton Signatures of the Higgs Boson through its Production in Association with a Top-quark Pair

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Abstract

We consider the possible production of the Higgs Boson in association with a top-quark pair and its subsequent decay into a tau-lepton pair or a W-boson pair. This process can give rise to many signatures of the Higgs boson. These signatures can have electrons, muons, tau jets, bottom jets and/or light flavour jets. We analyze the viability of some of these signatures. We will look at those signatures where the background is minimal. In particular, we explore the viability of the signatures "isolated 4 electron/muon" and "isolated 3 electron/muon + a jet" The jet can be due to a light flavour quark/gluon, a bottom quark, or a tau lepton. Of all these signatures, we find that "isolated 3 electron/muon + a tau jet", with an extra bottom jet, can be an excellent signature of this mode of the Higgs boson production. We show that this signature may be visible within a year, once the Large Hadron Collider (LHC) restarts. Some of the other signatures would also be observable after the LHC accumulates sufficient luminosity.

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1 Introduction

The Standard Model (SM) has been enormously successful [1, 2]. Until recently, one important ingredient of the model, the Higgs mechanism, had no direct experimental support. The implementation of the Higgs mechanism through a set of scalar fields has been a standard paradigm, which is also used in a variety of the extensions of the Standard Model (SM) to break the gauge symmetries and bring it to the level of the SM. One consequence of the Higgs mechanism is the existence of the scalar particles. The number and nature of the particles depend on the symmetry that has been broken.

In the SM, the mechanism gives rise to a neutral scalar particle – the Higgs boson. In the run I (2009-12) of the Large Hadron Collider (LHC), strong evidence for a Higgs-boson like particle has been found [1]. Some of its properties like spin and mass have also been measured by the CMS [2] and ATLAS collaborations [3]. Combining the signal of the Higgs boson from its various decay modes, more than 5σ enhancement above the background is seen by both collaborations. It has all but confirmed the existence of the Higgs boson. Its mass is expected to be around 125 GeV.

One of the main goals of the run II of the LHC (2015-18) would be to establish the existence of the Higgs boson more firmly and really show that its is a SM Higgs boson scalar. To show that this particle is indeed a SM particle, and does not belong to its extensions or modifications, it would be important to identify the Higgs boson through multiple production mechanisms and decay channels. There are many important production mechanisms, like gluon fusion, W-fusion, associated production with a vector boson and the production in association with a bottom-quark pair or top-quark pair [4]. For a 125 GeV Higgs boson, there are a number of important decay channels – $H \to b\bar{b}$[5], WW^* [6, 7], ZZ^* and $\tau\tau$ [8, 9, 10, 11, 12, 13]. All these major production and decay channels (including rare decays like $H \to \gamma\gamma$ [14, 15]) will be observable in the run II of the LHC. Some of these channels have already been seen in the run I [4].

In this letter, we focus on the production mechanism $pp \to t\bar{t}H$, at $\sqrt{s}$= 14 TeV, with the subsequent decay of the Higgs boson into a tau-lepton pair [16], or a W-boson pair. There are enormous possibilities for a variety of signatures because there are many heavy particles in the final state which then decay into many more particles. In this letter, we will look at those signatures which have most leptons in the final state. More leptons in the final state means smaller background. However, it comes at the cost of fewer signal events. In a subsequent paper [17], we will analyze the signatures which have fewer leptons and more jets. There we will have more signal events, but larger background.

In the next section, we will discuss production, decay and signatures in a bit more detail. In the section 3, we would discuss the backgrounds. In the section 4, we would present numerical results. In the last section, we would conclude.

2 Production, Decay and Signatures

We are considering the production of the Higgs boson with a top-quark pair. This is fourth most important production mechanism. The process occurs through gluon-gluon or quark-quark annihilation. We will consider semileptonic decay of both the top quarks and the decay of the Higgs boson into a tau-lepton pair, or a W-boson pair. For the $M_H = 120 - 130$ GeV, the tau-lepton decay mode has a branching ratios of a $5 - 7$ percent. The tau-lepton can further decay into an electron/muon or hadrons and neutrinos. When it decays into hadrons, it manifest itself as a jet – tau jet. This jet has special characteristics compared to a quark/gluon jet. It is narrow and has very few hadrons. It is narrow because of the low mass of the tau lepton; it has few hadrons because tau lepton mostly has one-prong or three-prong decays. These properties of a tau jet can be used to distinguish it from a quark/gluon jet. The W-boson decay mode of the Higgs boson has a branching ratio of $14 - 30\%$ for the Higgs boson with the mass in the $120 - 130$ GeV range. Here both W-boson cannot be on-shell. The W-boson decays into leptons/quarks and neutrinos.

This production and decay chain can give rise to a multitude of signatures. The final state can have only jets, one electron/muon and jets, two electron/muon and jets, three electron/muon and jets and four electron/muon and jets. Some of these jets can be bottom jets or/and tau jets. Of all these signatures, because of the larger branching ratios, "only jets" signature will give rise to most signal events; but it will also have the largest background due to the production of the jets through the strong interaction processes. On the other hand, we have a signature of "4 electron/muon + jets". This signature has least number of signal events, but also the smallest background. One of the drawback of all these signatures is that one cannot reconstruct the Higgs boson mass through its decay products. This is because of the presence of many neutrinos in its decay products. However, as we will see, due to the manageable background, we can still identify the Higgs boson through these production and decay chains.

We shall consider the signature of “ 4 electron/muon + jets” and “3 electron/muon + jets”. Because of the small cross section for such events, due to small semileptonic branching ratios, we would minimize the number of jets to be observed. This will help us in increasing the number of signal events marginally, without increasing the background. So in the end, we shall be considering four signatures: “4 electron/muon”, “3 electron/muon + a jet”, “3 electron/muon + a tau jet”, and “3 electron/muon + a bottom-jet”. In this list, “3 electron/muon + a jet” will have largest signal events, while “4 electron/muon” will have the least number of signal events. We will also consider the signature “3 electron/muon” alone. The numerical results would be presented for three of these signatures, as the other two have large backgrounds.

Let us first consider the signature: “4 electron/muon”. Such events occur when both the top quarks and tau leptons decay semileptonically. Such events also receive contributions when the Higgs boson (in $t\bar{t}H$ production) decays into 2 W-bosons. We will see that it makes larger contribution. Another contribution comes from the process $gg \to H$ and $H \to ZZ^*$. Such a contribution will be reduced if we veto events with a lepton pair of same flavor opposite charge (SFOC) which has mass close to the mass of the Z-boson. We have not included these events in the signature. Other signatures, with 3 electron/muon, occur when out of the top-quark pair and the tau-lepton pair, only three particles decay semileptonically; the remaining particle decays into hadrons/tau jet. These events also receive contribution from the decay $H \to WW^*$ after the ttH production. In this case, tau-lepton decay mode makes larger contribution. Because of the decay of the top quarks, these events naturally have bottom jets, irrespective of whether we observe them or not. We will find that observation of an extra bottom jet can increase the significance of a signature. We can also have a real tau jet in the signal events through the Higgs boson or a top-quark decay.

3 Backgrounds

All the signatures under consideration will receive contribution from the signal events, i.e. the production of the Higgs boson, and other SM processes which does not have a Higgs boson. Question is – is the background small enough to be sure that signal events have been produced ? To establish the viability of the signatures, we shall first identify the major background processes and then estimate their contributions. There are two classes of the backgrounds: (1) direct backgrounds, (2) mimic backgrounds. In the case of the direct background, the background processes produce events similar to the signal events. They have same particles as in the signal. On the other hand, mimic backgrounds have jets, which can mimic (fake) a tau jet, a bottom jet, or even an electron/muon. These mimic probabilities are usually quite small – less than a percent. So even if a background has large cross section, it becomes smaller when folded with mimic probability.

1. "4 electron/muon": There are many processes which can be backgrounds. The source of direct backgrounds are the processes $t\bar{t}Z, WWZ, WWWW, ZZ, t\bar{t}t\bar{t}$. The main sources of mimic backgrounds are: $WZ+$jet, $t\bar{t}W$, $WWW+$jet. These background occur when a jet mimics an electron/muon. As discussed below, the mimic backgrounds are not significant because of the very small probability of a jet to mimic an electron/muon, about 10^{-5} [18].

   Among the direct backgrounds, the most significant backgrounds would be due to the production of $t\bar{t}Z$ and ZZ events and subsequent decay into leptons. Using `MadGraph v5` [19], we find that the cross sections for the signal $t\bar{t}H$ is about 0.44 pb for $m_H = 125$ GeV, while the cross sections for $t\bar{t}Z$ and ZZ are 0.66 pb and 10.8 pb respectively. Because of very similar structure, $t\bar{t}Z$ will always be a significant background to the signal. These two backgrounds can be reduced by requiring appropriate $M_{\ell_1\ell_2}$ to be away from the mass of the Z-boson. But the background when a Z-boson decays into a tau-lepton pair and subsequent decay of the tau-leptons into electron/muon cannot be reduced in this way. These and the other values of the cross sections from MadGraph are with its default settings, unless stated otherwise. The processes $WWZ, WWWW,$ and $t\bar{t}t\bar{t}$ have the cross sections of about 100.0, 0.6 and 12.0 fb respectively. We clearly see that these processes are not important source of the backgrounds due to small cross sections.

2. "3 electron/muon + a jet": In this case, the direct backgrounds are $t\bar{t}Z, t\bar{t}W, ZZ, WZ+$ jet, $WWW+$jet, WWZ; the major mimic backgrounds are $t\bar{t}$ and $WW+$2jet. As above, due to small probability of a jet faking an electron/muon, the mimic backgrounds can be ignored. Most of the direct backgrounds are self-explanatory. ZZ production is a background, when a Z-boson decays into a tau-lepton pair, and one of the tau leptons appears as a tau jet.

3. "3 electron/muon + a tau jet": In this case, the direct backgrounds are $t\bar{t}Z, t\bar{t}t\bar{t}, WWZ$; the major mimic backgrounds are $t\bar{t}, WZ + \text{jet}, WW + 2\ \ \text{jet}, WWW + \text{jet}, t\bar{t}W$. As above, the backgrounds that fake an lepton are not important. But that backgrounds $WZ + \text{jet}$ and $t\bar{t}W$ can be important where a light/bottom jet mimics a tau jet.

4. "3 electron/muon + a bottom jet": In this case, the direct backgrounds are $t\bar{t}Z, t\bar{t}W, t\bar{t}t\bar{t}$. In these processes the bottom jet would appear from a top-quark decay. The major mimic backgrounds are $t\bar{t}, WZ + \text{jet}, WW + 2\ \ \text{jet}, WWZ, WWW + \text{jet}, t\bar{t}W$.

5. "3 electron/muon": There are many processes which can be backgrounds. The source of direct backgrounds are the processes $t\bar{t}Z, t\bar{t}W, WWZ, WWW, WZ, t\bar{t}t\bar{t}$. The main sources of mimic backgrounds are: $WW + \text{jet}, t\bar{t}$. These background occur when a jet mimics an electron/muon.

4 Numerical results and Discussion

In this section, we are presenting numerical results. The signal and the background calculations have been done using `ALPGEN v2.14` [20] and its interface with `PYTHIA v6.325`[21]. Using `ALPGEN`, we generate the parton-level unweighted events. These events are then turned into more realistic events by hadronization, initial and final state radiation using `PYTHIA`. We have also applied following generic kinematic cuts:

$$p_T^{e,\mu,j} > 20 \text{ GeV},\ |\eta^{\mathrm{e},\mu,\mathrm{j}}| < 2.5,\ \mathrm{R}(\mathrm{jj}, \ell\mathrm{j}, \ell\ell) > 0.4.$$

We have used CTEQ5L [22] parton distribution functions and other default parameters including renormalization and factorization scales. For the results, we have chosen the center-of-mass energy of 14 TeV and integrated luminosity is 100 fb^{-1}. We take mass of the top quark is 174.3 GeV. We are taking three different values for the mass of the Higgs boson – 120, 125 and 130 GeV.

One of our signatures has a tau jet. Both CMS and ATLAS collaborations [23] can identify tau jets. A tau jet is a manifestation of the hadronic decays of a tau lepton. A tau lepton has a branching ratios of approximately 65% to decay into hadrons. Two main characteristics of a tau jet are its narrowness and presence of only a few hadrons. These two features have been used to identify a tau jet. However, like the identification of a bottom jet, the identification of tau jet can only be done with some probability. The other jets due to quarks/gluon can also mimic a tau jet with small probability. Usually there is a trade-off between higher detection efficiency and higher rejection of the mimic-jets. We are taking two cases - one with high tau jet detection efficiency, other with low tau-detection efficiency. We are also presenting results by identifying a tau jet with an area-variable. This variable alone would not work well, as our number shows. The number of charge tracks will play a crucial role in discriminating a tau jet.

We are considering the detection of a bottom-jet also. We have used the identification probability (ϵ_b) of 55%[25, 26]. For other jets to mimic a bottom jet, we use the probability of 1%. For a jet faking a lepton, the probability is quite low. A light flavour jet can mimic a lepton with a probability of about 10^{-5}. For a bottom jet such a number is 5×10^{-5}. As we see in the signature, leptons comes either from the decay of a top-quark, or the decay of a tau-lepton, or a W-boson. So a pair of leptons would not have mass near the mass of a Z-boson. But a number of backgrounds have a Z-boson, so we use a cut of invariant mass of SFOC leptons: $|M_{\ell_1 \ell_2} - M_Z| < 15 \text{ GeV}$ to reduce these backgrounds.

We are presenting the results for the three signatures: "3 electron/muon + a tau jet", "3 electron/muon + a bottom jet", and "4 electron/muon". In Table 1, we present the results for "3 electron/muon + a tau jet". For the signal events, the largest contribution comes from the tau-lepton decay channel of the Higgs boson. The Contribution of this channel is about 75%. The contribution of the W-boson decay channel is about 25%. Here we have considered four cases. In the first case, R-cut, we have used an area-variable of the tau jet cone, $R_{em}^{j^2}$ (adapted from [27]) to identify a tau jet. The behavior of the variable for the signal and backgrounds without normalization are displayed in Fig. 1. We clearly see that in the processes where there is a tau jet the variable is peaked towards a low value. We have checked that the area-variable gives better tau-jet efficiencies than the radius (R_{em}^{j}) [17]. We have used a cut of $R_{em}^{j^2} < 1 \times 10^{-4}$. As we are using only one characteristic of the tau jet, its narrowness, so it is not necessarily the best way [28]. We have tau-identification rate of 30% and mimic (rejection) rate of about 3%. In the second case of LTT, low tau-tagging, we have taken the low value for the tau-jet identification, 27%, and low mimic rate of 0.25%. Compared to the case 1, the signal decreases a bit and some of the backgrounds, specially $WZ+jet$ and $t\bar{t}W$ reduce significantly. Therefore, the significance of the signature increases. The case 3 of HTT[24], high tau-tagging, has high identification rate of 50% and the mimic rate of 1%. We see that the significance of the signature increases again. This is because of the larger number of signal events. In the case 4, we have used the fact that some of the backgrounds do not have a bottom jet for “free”. So if we observe an extra bottom jet, i. e., the signature “ 3 electron/muon + a tau jet + a bottom jet”, then the background will reduce further, thus enhancing the significance of the signature. Since there are two bottom jets and only one is to be identified, we have used the identification probability of 80%. We will note that without identification of a jet some of the backgrounds would be higher by two-orders of magnitude, making the signal harder to observe. So identification of a jet play important role in reducing the backgrounds.

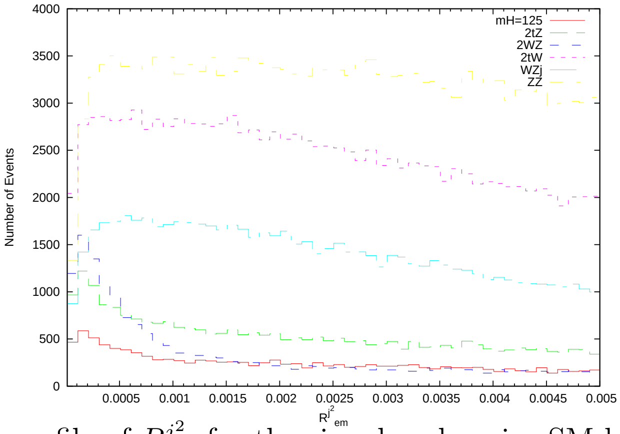

Figure 1: The profile of $R^{j^2}_{em}$ for the signal and major SM backgrounds.

In Table 2, we present the results for “3 electron/muon + a bottom-jet”. So we wish to identify a bottom jet instead of a tau jet. We now have fewer major backgrounds. But the $t\bar{t}W$ background increases by more than a order of magnitude. This is because this process has a bottom jet, and there is no need for this jet to mimic a tau jet. Therefore this is not an attractive signature, but with enough integrated luminosity, this signature can be observed.

In Table 3, there are results for the “4 electron/muon” signature. In this case, 75% of the events are through the W-boson decay channel of the Higgs boson; the rest are from the tau-lepton decay channel. We notice that this is an observable signature with a significance 3 – 5, depending on the mass of the Higgs boson. This signature is also obtained by the $gg \to H \to ZZ^*$ process [29]. So we also look for an extra bottom jet to make the signature exclusive for the $t\bar{t}H$ process. The major background is $t\bar{t}Z$ process. We see that the signature “ 4 electron/muon + a bottom-jet” is a useful signature with significance approaching 5 with 100 fb^{-1} of integrated luminosity.

	Signal, M_H (GeV)			Backgrounds					$S/\sqrt{B}$, M_H (GeV)		
τ jets id	120	125	130	$t\bar{t}Z$	WWZ	$t\bar{t}W$	WZj	ZZ	120	125	130
R-cut	22	20	19	14	2	12	24	7	2.9	2.6	2.5
LTT	20	18	17	13	2	1	2	6	4.1	3.7	3.5
HTT	37	33	32	23	3	4	10	12	5.1	4.6	4.4
B-tag/HTT	30	27	26	18	0	3	0	0	6.6	5.9	5.7

Table 1: Number of events for the signature "3 electron/muon + tau jet" at the LHC with the integrated luminosity of 100 fb^{-1} with the cuts and efficiencies specified in the text.

Signal, M_H (GeV)			Backgrounds			$S/\sqrt{B}$, M_H (GeV)		
120	125	130	$t\bar{t}Z$	$t\bar{t}W$	WZj	120	125	130
42	34	26	26	312	6	2.3	1.8	1.4

Table 2: Number of events for the signature "3 electron/muon + bottom jet" at the LHC with the integrated luminosity of 100 fb^{-1} with the cuts and efficiencies specified in the text.

	Signal, M_H (GeV)			Backgrounds			$S/\sqrt{B}$, M_H (GeV)		
bottom jet id	120	125	130	$t\bar{t}Z$	WWZ	ZZ	120	125	130
no extra b	16	19	22	15	2	3	3.1	4.3	4.9
extra b	13	16	18	12	0	0	3.8	4.6	5.2

Table 3: Number of events for the signature "4 electron/muon" at the LHC with the integrated luminosity of 100 fb^{-1} with the cuts and efficiencies specified in the text.

5 Conclusion

In this letter, we have considered "4 electron/muon" and "3 electron/muon + jet" signatures of the process $pp \to t\bar{t}H$. Here jet can be a light flavour quark/gluon jet, a tau jet, or a bottom jet. We find that, of all these signatures, "3 electron/muon + a tau jet", specially with an extra bottom jet observation, i.e., “3 electron/muon + a tau jet + a bottom jet”, appears to be the most promising signature. With 100 fb^{-1} of luminosity, it has the significance of 5.9 for $M_H = 125$ GeV. This signature may be observable in about a year of running of the LHC in run II. The signature “4 electron/muon + bottom jet” is a distinctive signature of the $pp \to t\bar{t}H$ process and it should also be observable within a year of run II. The signatures “3 electron/muon + a bottom jet” and “4 electron/muon” should also be observable in the run II. A more detailed analysis of these and other signatures of the Higgs boson, when it is produced in association with a pair of top-quarks, will be presented elsewhere.

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