Multilepton signatures of the Higgs boson through its production in association with a top-quark pair

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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 flavor 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 flavor 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 Large Hadron Collider accumulates sufficient luminosity.

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I. 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 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 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. This 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 run II of the LHC (2015–18) would be to establish the existence of the Higgs boson more firmly and really show that it 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 $\tau\tau$ [8–13]. All these major production and decay channels (including rare decays like $H \to \gamma\gamma$ [14,15]) will be observable in run II of the LHC. Some of these channels have already been seen in run I [4]. There have also been several recent studies involving $t\bar{t}H$ production followed by the decay of $H \to WW^*$ and $H \to \tau\tau$ [16,17] focusing on different aspects of the process. Multilepton signatures (three or four leptons) of the same process with $H \to WW^*$ have also been studied [18]. Some composite Higgs models' signatures have also been examined through the associate production of the Higgs boson with a top-quark pair [19] followed by $H \to b\bar{b}$ [20].

In this paper, 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 [21] 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 paper, we look at those signatures which have the most leptons in the final state. Having more leptons in the final state means a smaller background. However, it comes at the cost of fewer signal events. In a subsequent paper [22], we will analyze the signatures which have fewer leptons and more jets. There, we will have more signal events, but a larger background.

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

II. PRODUCTION, DECAY, AND SIGNATURES

We consider the production of the Higgs boson with a top-quark pair. This is the fourth most important

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production mechanism. The process occurs through gluon-gluon or quark-quark annihilation. We will consider semi-leptonic decay of the top quarks and the decay of the Higgs boson into a tau-lepton pair or a W-boson pair. For $M_H =$ 120–130 GeV, the tau-lepton decay mode has a branching ratio of 5%–7%. The tau lepton can further decay into an electron/muon or hadrons and neutrinos. When it decays into hadrons, it manifests itself as a jet—a 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 the 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 mass in the 120–130 GeV range. Here, the 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 electrons/muons and jets, three electrons/muons and jets, and four electrons/muons and jets. Some of these jets can be bottom jets or/and tau jets. Of all these signatures, because of the larger branching ratios, the "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 "four electrons/muons + jets." This signature has the least number of signal events, but also the smallest background. One of the drawbacks 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 "four electrons/muons + jets" and "three electrons/muons + 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 consider four signatures: "four electrons/muons," "three electrons/muons + a jet," "three electrons/muons + a tau jet," and "three electrons/muons + a bottom jet." In this list, "three electrons/muons + a jet" will have the largest signal events, while "four electrons/muons" will have the least number of signal events. We will also consider the signature "three electrons/muons" alone. The numerical results are presented for three of these signatures, as the other two have large backgrounds.

Let us first consider the signature "four electrons/muons." 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 two W bosons. We will see that this makes a 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 the same flavor opposite charge which has mass close to the mass of the Z boson. We have not included these events in the signature. Other signatures, with three electrons/muons, 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 contributions from the decay $H \to WW^*$ after the ttH production. In this case, the tau-lepton decay mode gives a 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.

III. BACKGROUNDS

All the signatures under consideration will receive contributions from the signal events, i.e. the production of the Higgs boson, and other SM processes that do not have a Higgs boson. This raises the following question: 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 backgrounds: (1) direct backgrounds and (2) mimic backgrounds.[1] In the case of the direct background, the background processes produce events similar to the signal events. They have the same particles as in the signal. On the other hand, mimic backgrounds have jets that 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 a large cross section, it becomes smaller when folded with mimic probability. Another issue is an electron/muon from a bottom jet. When a B meson decays into an electron/muon, sometimes it can be away from the jet and can lead to an extra electron/muon appearing in the event. We have explored this possibility in an event sample of 570499 $b\bar{b}jjjj$ events from the $t\bar{t}$ production. The events were generated from ALPGEN [23] with $p_T^{j,b} > 20$ GeV, $|\eta^{j,b}| < 2.5$, $R(jj, bj, bb) > 0.4$, the cuts that we use for the numerical results. These events were then analyzed through PYTHIA [24] to look for an isolated muon. For that, we required $p_T^{\mu} > 20$ GeV, $|\eta^{\mu}| < 2.5$, $R(\mu j, \mu b) > 0.4$, and an additional p_T in this cone to be less than 10 GeV.

[1] In the literature, the direct background is often referred to as the irreducible background, while the mimic background is called the reducible background.

We find that only 11 events have one muon. So the probability of an extra electron/muon appearing in any such event due to a bottom jet can be taken as 1.9×10^{-5}. The fake rate of an electron/muon from the $Wb\bar{b}$ events has also been estimated in [25]. In their estimates of the faking rate of 1 in 200, they have $p_T^\mu > 10$ GeV and $p_T^b > 20$ GeV. We have also generated $Wb\bar{b}$ events using ALPGEN, and we find that a larger cut on the muon, $p_T^\mu > 20$ GeV, can reduce the faking probability by about an order of magnitude. We find that in the $Wb\bar{b}$ events, for $p_T^\mu > 10$, 15, and 20 GeV the faking probability is 2.1×10^{-3}, 6.5×10^{-4}, and 2.3×10^{-4}, respectively. Furthermore, if the p_T^b spectrum is harder, it again reduces the faking probability [25]. This is what is observed in the bottom jets from $t\bar{t}$ events. We are not performing a full detector simulation. If we take a worst-case scenario, in which the probability of an electron/muon appearing from a bottom jet is about an order of magnitude larger, then the above estimate of the faking probability of an electron/muon due to a bottom jet from a top quark suggests that we still do not have a problem from such fake electrons/muons. We also note that our best signatures have at least three electrons/muons and one additional electron/muon or a tau jet. These extra electron/muon/tau jets further help in reducing such fake backgrounds. Therefore, even a worst-case scenario would not lead to significant fake backgrounds to our best signatures that are considered below. Therefore, we are not considering backgrounds with a bottom jet giving an extra electron/muon in an event.

(1) "Four electrons/muons": There are many processes which can be backgrounds. The sources 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 backgrounds occur when a jet mimics an electron/muon. As discussed above, the mimic backgrounds are not significant because of the very small probability of a jet to mimic an electron/muon, about 10^{-4}–10^{-5} [26].

Among the direct backgrounds, the most significant backgrounds are due to the production of $t\bar{t}Z$ and ZZ events and subsequent decay into leptons. Using MADGRAPH V5 [27], we find that the cross section 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 a 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 the subsequent decay of the tau leptons into an electron/muon cannot be reduced in this way. These and the other values of the cross sections from MadGraph are calculated with its default settings, unless stated otherwise. The processes WWZ, $WWWW$, and $t\bar{t}t\bar{t}$ have cross sections of about 100.0, 0.6, and 12.0 fb, respectively. We clearly see that these processes are not an important source of the backgrounds due to small cross sections.

(2) "Three electrons/muons + 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 + 2jets. As above, due to the 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) "Three electrons/muons + 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 + jet, WW + 2jet, WWW + jet, $t\bar{t}W$. As above, the backgrounds that fake a lepton are not important. But the backgrounds WZ + jet and $t\bar{t}W$ can be important where a light/bottom jet mimics a tau jet.

(4) "Three electrons/muons + 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 appears from a top-quark decay. The major mimic backgrounds are $t\bar{t}$, WZ + jet, WW + 2jets, WWZ, WWW + jet, $t\bar{t}W$.

(5) "Three electrons/muons": There are many processes which can be backgrounds. The sources 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 + jet, $t\bar{t}$. These backgrounds occur when a jet mimics an electron/muon.

IV. NUMERICAL RESULTS AND DISCUSSION

In this section, we present numerical results. The signal and the background calculations have been done using

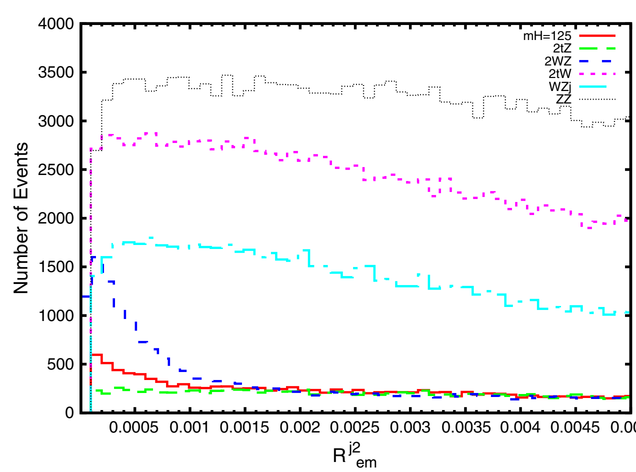

FIG. 1 (color online). The profile of $R_{em}^{j^2}$ for the signal and major SM backgrounds.

TABLE I. Number of events for the signature "three electrons/muons + a tau jet" at the LHC, with an 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)		
τ jets id	120	125	130	$t\bar{t}Z$	WWZ	$t\bar{t}W$	WZj	ZZ	120	125	130
R cut	26	24	23	19	3	16	31	9	2.9	2.7	2.6
LTT	24	22	20	18	3	1	3	8	4.2	3.8	3.5
HTT	44	40	38	31	5	5	13	16	5.1	4.6	4.4
B tag/HTT	36	32	31	24	0	4	0	0	6.8	6.0	5.9

ALPGEN V2.14 [23] and its interface with PYTHIA V6.325 [24]. Using ALPGEN, we generate the parton-level unweighted events. These events are then turned into more realistic events by hadronization, and initial and final state radiation using PYTHIA. We have also applied the following generic kinematic cuts:

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

For an isolated electron/muon, we also require that the transverse momentum within the cone $R(\ell j) < 0.4$ around the electron/muon is less than 10 GeV. We have used CTEQ5L [28] 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 an integrated luminosity of 100 fb^{-1}. We take the mass of the top quark as 174.3 GeV. We use three different values for the mass of the Higgs boson: 120, 125, and 130 GeV.

To take into account the next-to-leading-order corrections, we have multiplied the results obtained from the above procedure by appropriate K factors. The K factor chosen for the $t\bar{t}H$ [29] process is 1.20; the K factors for the $t\bar{t}Z$ [30], $t\bar{t}W$ [31], and ZZ [32] processes are taken to be 1.35. The K factor for the WZ + jet [33] process is taken to be 1.3, while for the WWZ [34] production, it is 1.7. Because of the smaller K factor for the signal, as compared to the backgrounds, the significance increases only marginally, as compared to the leading-order (LO) values.

One of our signatures has a tau jet. Both the CMS and ATLAS collaborations [35] can identify tau jets. A tau jet is a manifestation of the hadronic decays of a tau lepton. A tau lepton has a branching ratio of approximately 65% to decay into hadrons. Two main characteristics of a tau jet are its narrowness and the 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/gluons can also mimic a tau jet with a small probability. Usually there is a trade-off between higher detection efficiency and higher rejection of the mimic jets. We will be considering three different cases. In the first case, we have high tau-tagging (HTT) efficiency [36]; the tau-jet identification rate is 50% and the mimic rate is taken as 1%. In the second case, we have low tau-tagging (LTT) efficiency [37]; the tau-jet identification rate is taken as 27% and the mimic probability is 0.25%. We also present results by identifying a tau jet with an area variable (R cut). We consider the electromagnetic area $R_{em}^{j^2} = \sum_\alpha p_{T,\alpha} R^2(\alpha, j)/\sum_\alpha p_{T,\alpha}$ (adapted from [38]) associated with a jet j. Here the index α runs over the calorimetric cells of the jet, and $R(\alpha, j)$ is the angular distance of the αth cell from the jet. This variable alone would not work well, as our number shows. The number of charged tracks will play a crucial role in discriminating a tau jet. The behavior of this variable for the signal and backgrounds without normalization is displayed in Fig. 1. We clearly see that in the processes where there is a tau jet, the $R_{em}^{j^2}$ 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}) [22]. We have used a cut of $R_{em}^{j^2} < 1 \times 10^{-4}$. We are using only one characteristic of the tau jet, its narrowness, which is not necessarily the best way [39]. We have a tau-identification rate of 30% and a mimic (rejection) rate of about 3%, by this method.

We consider the detection of a bottom jet also. We use the identification probability (ϵ_b) of 55% [40,41]. For other jets to mimic a bottom jet, we use the probability of 1%. As we see in the signature, leptons comes either from the decay of a top quark, 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 the invariant mass of same flavor opposite charge leptons, $|M_{\ell_1\ell_2} - M_Z| < 15$ GeV, to reduce these backgrounds.

We present the results for the three signatures: "three electrons/muons + a tau jet," "three electrons/muons + a bottom jet," and "four electrons/muons."

TABLE II. Number of events for the signature "three electrons/muons + a bottom jet" at the LHC, with an 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
50	41	31	35	421	8	2.3	1.9	1.4

TABLE III. Number of events for the signature "four electrons/muons" at the LHC, with an 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	19	23	26	20	3	4	3.6	4.4	5.0
Extra b	16	19	22	16	0	0	4.0	4.8	5.5

(i) Three electrons/muons + a tau jet: In Table I, we present the results for "three electrons/muons + 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%. We consider four cases. In the case of R-cut tau tagging, the significance of the signature is not very good. It is not surprising, as this cut has low tau-detection efficiency and high mimic probability. In case 2, the LTT case, the signal decreases a bit, and some of the backgrounds, especially WZ + jet and $t\bar{t}W$, reduce significantly. Therefore, the significance of the signature increases. In case 3, the HTT case, we see that the significance of the signature increases again. This is because of the larger number of signal events. In case 4, we have used the fact that some of the backgrounds do not have a "free" bottom jet. So if we observe an extra bottom jet, i.e., the signature "three electrons/muons + 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 use the identification probability of 80%. We note that without the identification of a jet, some of the backgrounds would be higher by 2 orders of magnitude, making the signal harder to observe. So the identification of a jet plays an important role in reducing the backgrounds.

(ii) Three electrons/muons + a bottom jet: In Table II, we present the results for this signature. Here 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 an 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.

(iii) Four electrons/muons: In Table III, we give the results for the "four electrons/muons" 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 of 3–5, depending on the mass of the Higgs boson. This signature is also obtained by the $gg \to H \to ZZ^*$ process [42]. 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 the $t\bar{t}Z$ process. We see that the signature "four electrons/muons + a bottom jet" is a useful signature, with a significance approaching 5 with 100 fb^{-1} of integrated luminosity.

V. CONCLUSION

In this paper, we have considered the "four electrons/muons" and "three electrons/muons + jet" signatures of the process $pp \to t\bar{t}H$. Here the jet can be a light flavor quark-gluon jet, a tau jet, or a bottom jet. We find that, of all these signatures, "three electrons/muons + a tau jet," especially with an extra bottom jet observation, i.e., "three electrons/muons + a tau jet + a bottom jet," appears to be the most promising signature. With 100 fb^{-1} of luminosity, it has a significance of 6.0 for $M_H =$ 125 GeV. This signature may be observable in about a year of running of the LHC in run II. The signature "four electrons/muons + a 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 "three electrons/muons + a bottom jet" and "four electrons/muons" should also be observable in 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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