Dilepton Signatures of the Higgs Boson with Tau-jet Tagging

Pankaj Agrawal, Somnath Bandyopadhyay and Siba Prasad Das*

Institute of Physics
Sachivalaya Marg, Bhubaneswar, Orissa, India 751 005

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Abstract

We consider the process $pp \rightarrow t\bar{t}H$. This process can give rise to many signatures of the Higgs boson. The signatures can have electrons, muons and jets. We consider the signatures that have two electrons/muons and jets. Tagging of a tau jet and a bottom jet can help reduce the backgrounds significantly. In particular, we examine the usefulness of the signatures “isolated 2 electrons/muons + a bottom jet + a tau jet”, “isolated 2 electrons/muons + 2 tau jets”, “isolated 2 electrons/muons + 2 bottom jets + a tau jet”, and “isolated 2 electrons/muons + a bottom jet + 2 tau jets”. We find that signatures with two tau jets are useful. The signatures with one tau jet are also useful, if we restrict to same-sign electrons/muons. These requirements reduce the backgrounds due the process with Z-bosons + jets and the production of a pair of top quarks. We show that these signatures may be visible in the run II of the Large Hadron Collider.

*email: agrawal@iopb.res.in, somnath@iopb.res.in and spdas@iopb.res.in
1 Introduction

The Higgs mechanism of the Standard Model (SM) now seems to have been validated with the discovery of a Higgs boson-like neutral scalar particle. The strong evidence has been presented by the both ATLAS \cite{1} and CMS \cite{2} Collaborations on the basis of the data taken in run I (2009-12) at the Large Hadron Collider (LHC). Because of the appearance of the signal in multiple channels, as seen by both collaborations, there is little doubt that the Higgs boson of the SM has been found. All channels of the discovery suggest a mass of about 125 GeV for the particle.

The LHC is now on a long shut-down to improve the luminosity and the centre-of-mass energy. When it restarts to take data in 2015, one of its major goals would be to measure the couplings of the newly discovered Higgs boson to all the SM particles. This is specially important because of the prediction of the existence of scalar particles, sometime with properties similar to that of the SM Higgs boson, in various extensions and modifications of the standard model. To do so, one will need to identify the particle through multiple processes and measure the couplings of the scalar particle with various other SM particles. These couplings determine the branching ratios of the decay channels and also the production cross sections. Identification of the scalar particle through multiple processes will allow us to measure the couplings and confirm that the scalar particle is indeed the SM Higgs boson.

In this letter, we consider the production of the Higgs boson in association with a top-quark pair \[ pp \to t\bar{t}H \] \cite{3, 4}, with its subsequent decay into a tau-lepton pair or \[ WW^* \]. As of now the Higgs boson has been primarily looked through its gluon-fusion production mechanism and then decay into channels \[ H \to \gamma\gamma \] \cite{1, 2, 5}, \[ WW^* \] \cite{6, 7}, \[ ZZ^* \] \cite{8}, and \[ \tau\tau \] \cite{9, 12}. Various production mechanisms and the decay channels of the Higgs boson give rise to many signatures. Some of these signatures have already been discussed in the literature \cite{13-30}. In this letter, we focus on those signatures which have two electrons/muons (i.e., two electrons, or 2 muons, or one electron and one muon) and jets in the final state. These jets can be initiated by a light quark/gluons, a bottom quark, or a hadronic decay of a tau lepton (tau jet). It is experimentally possible to tag a jet from a bottom quark or a tau lepton. Such tagging helps in reducing the strong interaction backgrounds. One major source of the backgrounds is the production of a pair of top quarks with or without additional jets. One strategy to reduce this background would be to restrict the signature events to same-sign electrons/muons. We show the usefulness of this strategy, specially when only one jet is
tagged as a tau jet.

In the next section, we will discuss the signatures that we consider. In the section 3, we will discuss the backgrounds to these signatures. In the section 4, we will present numerical results and some discussion. In the last section, we will conclude.

2 Signatures

We are considering a general class of signatures “2 electrons/muons + jets”. As we see from Table 1, without any tagging of the jets, the backgrounds due to $Z$ bosons + jets and $t\bar{t}$ + jets processes would overwhelm the signal. Therefore, to reduce the backgrounds, we are focusing on the signatures with two electrons/muons and at least two tagged jets. Since the top-quark background events always have bottoms jets, so to reduce it we will require at least one jet to be tagged as the tau jet. These signatures occur, when after the production of $t\bar{t}H$, the Higgs boson decays into a tau-lepton pair or $WW^*$. With these considerations, at least one of the top quark accompanying the Higgs boson decays semileptonically. The possibility of a top quark decaying into jets leads to an increase in the signal events, relative to when we have more than 2 electrons/muons in a signature. For the Higgs boson with a mass of $120 - 130$ GeV, the tau-lepton decay mode has a branching ratios of $5 - 7$ percent; the W-boson decay mode has a branching ratio of $14 - 30$%. When a tau lepton decays into hadrons, it can manifest itself as a jet – tau jet. This jet has special characteristics. It is narrow and has very few hadrons. Its narrowness is due to the low mass of the tau lepton; it has few hadrons because a tau lepton decays into mostly 1 or 3 hadrons. These properties of a tau jet help us to distinguish it from a quark/gluon jet. There is usually a $25 - 50\%$ efficiency to tag a tau jet. The probability of a light quark/gluon jet to mimic a tau jet can be taken to be $1 - 0.1\%$ [31,33]. A bottom jet is broader than a light quark/gluon jet and has more particles. It can mimic a tau jet less often. A bottom jet can be identified with a probability of about $50 - 60\%$, while other jets can mimic it with a probability of about one percent [34,36].

To manage the background and at the same time to keep the signal events to a sufficiently high level, we are analyzing the signatures “2 electrons/muons + a tau jet + a bottom jet”, “2 electrons/muons + two tau jets”, “2 electrons/muons + a tau jet + two bottom jet”, and “2 electrons/muons + two tau jet + a bottom jet”. In the signal, the bottom jets
appear due to the decay of the top quarks; a tau jet can occur due to the decay of the Higgs boson, or the decay of the on-shell/off-shell W bosons from the Higgs boson or the top quarks. Electrons/muons can appear due to a decay chain of the Higgs boson, or the decay of the top quarks. Presence of electrons/muons in a signature is important to reduce the background. Recently, we had considered the signatures with three or four electrons/muons [38]. We saw that the presence of a bottom jet with four electrons/muons and the presence of one additional tau jet and a bottom jet with three electrons/muons help in keeping the background low enough to be able to detect the signal.

In the case of two electrons/muons, as we will see, it will be useful to have either at least two tau jets or one tau jet with only same sign electrons/muons in the signatures. Either of these two strategies will reduce the signal events, but will reduce the backgrounds even more. We can have same sign charged leptons in the signature because there are three/four on-shell/off-shell W boson in the production and decay chains under considerations. Two of these W-bosons can produce the same-sign electrons/muons. Sources of off-shell W-bosons can be tau-lepton, which can come from the decays of the Higgs boson, the top quark, the W-boson, or the Z-boson. This strategy of observing same-sign leptons will significantly reduce the large background from the production of a top quark pair with or without jets and Z + jets. Z + jets backgrounds are significantly reduced or eliminated due to the tagging of at least 2 jets as tau and/or bottom jets. This tagging also reduces the top-quark pair production background to the same-sign lepton signatures. This is discussed more in the next section.

3 Backgrounds

All the signatures under consideration will get contribution from the signal events, i.e. the production of the Higgs boson, and other SM processes which do not have a Higgs boson. To establish the viability of the signatures for signal detection, we shall first identify the main background processes and then estimate their contributions. We will consider both types of the backgrounds: direct backgrounds and 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 probabilities. Tagging efficiencies and mimic probabilities were discussed in the last section.

One important type of background occurs when a B-meson in a bottom jet decays into an electron/muon and this lepton is away from the jet. This leads to an extra lepton in the event. Possibility of such backgrounds has been explored in the literature. As we have argued, such backgrounds which can occur due to the top quark production is not significant for the signatures under consideration. This is mainly due to two facts – (1) we have at least one tau jet in the signatures, so backgrounds are to be folded with the tau jet mimic probability; this reduces the backgrounds significantly, (2) the electrons/muons in our signatures are hard and have same minimum transverse momentum as the bottom jet from which they might have separated; the $p_T^{\ell,b} > 20$ GeV. Let us now discuss the backgrounds to the signatures.

1. “2 electrons/muons + a tau jet + a bottom jet”: There are many processes which can be backgrounds. The source of major direct backgrounds is the process $t\bar{t}Z$. The main sources of mimic backgrounds are: $t\bar{t}, WZ + \text{jet}, t\bar{t}W, Z + 2 \text{ jets}, WW + 2 \text{ jets}$. We are not considering backgrounds when a jet mimics an electrons/muons. Such mimic backgrounds are not significant because of the very small probability of a light jet to mimic an electron/muon, about $10^{-4} - 10^{-5}$. Among the direct backgrounds, the most significant backgrounds would be due to the production of $t\bar{t}Z$ and subsequent decay into leptons. Because of similar structure, $t\bar{t}Z$ will always be a significant background to the signal. This background 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 electrons/muons cannot be reduced in this way. The major mimic background is the production of a top-quark pair. Even with the folding of mimic probabilities, it remains large enough to make the signature almost not useful. However, when we consider the subset of events with same-sign electrons/muons, this signature becomes quite viable. This is because now the $t\bar{t}$ process is no longer a significant background.

2. “2 electrons/muons + two tau jets” : In this case, the direct backgrounds are the processes $t\bar{t}Z, WWZ, ZZ$. The main sources of mimic backgrounds are: $t\bar{t}, WZ + \text{Jets}$.
jet, $t\bar{t}W, Z + 2$ jets, $WW + 2$ jets. Presence of two tau jets will be crucial to reduce the mimic backgrounds.

3. “2 electrons/muons + a tau jet + 2 bottom jets”: The source of major direct backgrounds is the processes $t\bar{t}Z$. The main sources of mimic backgrounds are: $t\bar{t} + \text{jet}$, $2WZ + \text{jet}, t\bar{t}W, Z + 3$ jets, $WW + 3$ jets. These backgrounds are similar to that of the first signature, except that some mimic backgrounds have an extra jet.

4. “2 electrons/muons + a bottom jet + 2 tau jets”: The sources of major direct backgrounds are the processes $t\bar{t}Z, WWZ, ZZ$. The main mimic backgrounds are: $t\bar{t} + \text{jet}$, $2WZ + \text{jet}, t\bar{t}W, Z + 3$ jets, $WW + 3$ jets. These backgrounds are similar to that of the second signature, except that some mimic backgrounds have an extra jet.

4 Numerical results and Discussion

In this section, we are presenting numerical results and discussion of the results. The signal and the background events have been calculated using ALPGEN (v2.14) [44] and its interface with PYTHIA (v6.325) [45]. Using ALPGEN, we generate parton-level unweighted events. Using the PYTHIA interface, these events are then turned into more realistic events by hadronization, initial and final state radiation. We have applied following kinematic cuts:

\[ p_{T,\ell,j} > 20 \text{ GeV}, \ |\eta^{e,\mu,j}| < 2.5, \ R(jj, \ell j, \ell \ell) > 0.4. \]

We are presenting results for the three different values of $M_H - 120, 125$ and $130$ GeV. We have used the default values for the parameters including renormalization and factorization scales. For the parton distribution functions, we have used CTEQ5L [46] distribution. We have chosen the center-of-mass energy of 14 TeV and integrated luminosity of $100 \text{ fb}^{-1}$. The mass of the top quark is $174.3$ GeV.

We are presenting the results for four signatures: “2 electrons/muons + a tau jet + a bottom jet”, “2 electrons/muons + two tau jets”, “2 electrons/muons + a tau jet + two bottom jet”, and “2 electrons/muons + two tau jet + a bottom jet”. For the bottom jet, we have used the identification probability of $55\%$ [34, 35]. For other jets to mimic a bottom jet, we use the probability of $1\%$. For a tau jet, we consider two cases. This is because of a trade-off between higher detection efficiency and higher rejection of the mimic-jets. In the
first case of LTT, low tau-tagging, we have taken the low value for the tau-jet identification, 30%, and low mimic rate of 0.25% \cite{31}. The second case of HTT \cite{32}, high tau-tagging, has high identification rate of 50% and higher mimic rate of 1%. To reduce the Z boson related backgrounds, we have required the missing transverse momentum to be more than 25 GeV and applied a cut on the mass of same-flavour and opposite-sign lepton pair by requiring $|M_{\ell_1 \ell_2} - M_Z| > 15$ GeV. We have smeared the jet/lepton energies using the energy resolution function

$$\frac{\Delta E}{E} = \frac{a}{\sqrt{E}} \oplus b,$$

where $\oplus$ means addition in quadrature. For the jets $a = 0.5$ and $b = 0.03$. For the electrons/muons we take $a = 0.1$ and $b = 0.007$. Since we are not using the mass of two or more jets, inclusion of jet energy resolution does not affect the results significantly. Lepton energy resolution is quite good, so the results are also not significantly impacted.

In Table 1, we display results with only basic kinematic cuts with the observation of only two electrons/muons. The table has results for the signal events and various possible backgrounds. There are two cases of same-sign (SS) electrons/muons and opposite-sign (OS) electrons/muons. These events may or may not have a tau or a bottom jet. This table illustrates the importance of jet tagging and observing same-sign electrons/muons. First we note that there is marginal differences in the two-electrons and two-muons events. This is primarily statistical, i.e., due to the finite event sample. We also notice large backgrounds due to Z boson processes and top-quarks only processes. A missing $p_T$ cut and a cut on the mass of the lepton pair will help in reducing these backgrounds. Fig 1 illustrates the importance of the missing $p_T$ cut. We also notice the virtual elimination of the background due to a top-quark pair production for the same-sign electrons/muons. However, it will come at the cost of reducing the signal events by a factor of about 3. In the case of only one tau jet in the signature, one will have to adopt this strategy. For the two tau jets case, the extra rejection factor, due to the observation of the second tau jet, can reduce the backgrounds by about a two orders of magnitude, so the restriction to same-sign electrons/muons is not necessary.

In the Tables 2-5, we present results for various signatures for the integrated luminosity of 300 fb$^{-1}$. This is the expected luminosity for the run II. We have included only the major backgrounds. We have also taken into account Next-to-leading-order (NLO) contributions to the signal and background processes. To do so, we have multiplied the leading-order (LO)
results by appropriate K-factors. The K-factor is taken as 1.20 for the $t\bar{t}H$ process; the K-factors for the $t\bar{t}Z$, $t\bar{t}W$, and $ZZ$ are taken to be 1.35. The K-factor for the $WZ + \text{jet}$ is chosen as 1.3, while for the $WWZ$ production, it is 1.7. For the processes $t\bar{t}$ and $t\bar{t} + \text{jet}$, K-factors are taken to be 1.5 and 1.4 respectively. For the $Z+2\text{ jet}$, the K-factor is 1.3. Because of the smaller K-factor for the signal, as compared to the backgrounds, its inclusion increases the significance only marginally.

| Process | $e\mu$ | $ee$ | $\mu\mu$ | $\ell\ell$ |
|---------|--------|------|-----------|-----------|
| $t\bar{t}H$ (120 GeV) |        |      |           |           |
| $H \to \tau\tau$ | 49.6   | 103.2 | 26.3      | 46.6      |
| $H \to WW^*$ | 81.6   | 173.0 | 40.4      | 86.7      |
| $t\bar{t}H$ (125 GeV) |        |      |           |           |
| $H \to \tau\tau$ | 44.6   | 82.7  | 21.2      | 42.2      |
| $H \to WW^*$ | 116.3  | 245.0 | 57.6      | 121.2     |
| $t\bar{t}H$ (130 GeV) |        |      |           |           |
| $H \to \tau\tau$ | 33.4   | 65.8  | 16.8      | 32.5      |
| $H \to WW^*$ | 150.0  | 315.2 | 72.9      | 153.5     |
| $t\bar{t}Z$ | 125.9  | 158.7 | 62.4      | 845.7     |
| $WWZ$ | 21.5   | 156.0 | 10.4      | 194.8     |
| $ZZ$ | 228.6  | 474.9 | 116.6     | 34488.9   |
| $t\ell$ | 147.5  | 66897.3 | 98.3  | 334339.4 |
| $t\bar{t}j$ | 3.5    | 502156.5 | 0.0  | 245773.5 |
| $t\bar{t}W$ | 471.6  | 920.8 | 223.9     | 450.2     |
| $Z\bar{Z}j$ | 0.0    | 30207.8 | 0.0  | 4900649.0 |
| $Z\bar{Z}j$ | 0.0    | 9668.3 | 0.0  | 1382073.3 |
| $WWZj$ | 23.0   | 159.5 | 10.7      | 204.7     |
| $ZZj$ | 113.1  | 221.6 | 49.2      | 43905.5   |
| $ZZW$ | 7.3    | 8.1   | 3.7       | 92.4      |

Table 1: Number of Dilepton events for 100 fb$^{-1}$ integrated luminosity. The results for different flavor compositions with same-sign (SS) and opposite-sign (OS) electrons/muons are shown.

In Table 2, we present the results for “2 electrons/muons + a tau jet + a bottom-jet”. So we wish to identify a bottom jet and a tau jet. We note that for the different masses of the Higgs boson, the number of signal events are almost identical. This is because as $M_H$ increases, the branching ratio $H \to \tau\tau$ decreases, but it increases for $H \to WW^*$. This together with different kinematics of the electrons/muons from these two decay modes lead to nearly same events for different $M_H$. For example, for the $M_H = 125$ GeV case, the
contribution of the $WW^*$ decay mode is about 32%, but for $M_H = 130$ GeV it is 60%. The signal events for this signature are the largest of all the considered signatures. This happens in part due to the appearance of only one tau jet. With 2 pairs of W boson decaying into only three leptons, it gives rise to an additional combinatorial factor that increases the signal events. This signature has very large background from the $t\bar{t}W$ and $t\bar{t}$ processes. The significance is not good for both the LTT and HTT cases. However, if we restrict to the same-sign electrons/muons in the signature, the signature’s significance becomes more than 6, making it a pretty good signature.

In Table 3, we present the results for the signature “2 electrons/muons + two tau jets”. The major backgrounds are $t\bar{t}Z$, $t\bar{t}$, $ZZ$, and $Z + 2$ jets. Significance for the 125 GeV Higgs boson is 4.0 for the HTT case. Because of the reduction in the signal events, LTT case is not as useful. As we see, restricting to the same-sign electrons/muons is again not useful due to a paucity of events. We can also identify an additional bottom jet. This reduces the number of signal events, but this also leads to a significant reduction in the Z boson backgrounds. As we see from Table 4, this signature of “2 electrons/muons + two tau jets + a bottom jet” has a very good significance.
In the Table 5 we display the results for the signature “2 electrons/muons + a tau jet + two bottom jets”. Here signal events are smaller as compared to that in Table 2. This is due to the identification of an additional bottom jet. As there, here the background due to the production of a top-quark pair is quite large. However, if we observe only the same-sign electrons/muons, the significance may reach the observational value within the run II of LHC.

| $\tau$ jets id | Signal, $M_H$ (GeV) | Backgrounds | $S/\sqrt{B}$, $M_H$ (GeV) |
|----------------|---------------------|-------------|-------------------------|
|                |                     | $t\bar{t}Z$ | $t\bar{t}$ | $t\bar{t}W$ | $Z2j$ | 120 | 125 | 130 |
| LTT            | 333                 | 336         | 8228     | 567         | 30    | 3.4 | 3.4 | 3.4 |
| HTT            | 555                 | 561         | 32889    | 942         | 120   | 2.9 | 2.9 | 2.9 |
| SS/LTT         | 111                 | 111         | 9        | 189         | 0     | 6.3 | 6.3 | 6.3 |
| SS/HTT         | 186                 | 186         | 3        | 315         | 0     | 8.3 | 8.2 | 8.2 |

Table 2: Number of events for the signature “2 electrons/muons + a tau jet + a bottom jet” with the integrated luminosity of 300 fb$^{-1}$ with the cuts and efficiencies specified in the text.

| $\tau$ jets id | Signal, $M_H$ (GeV) | Backgrounds | $S/\sqrt{B}$, $M_H$ (GeV) |
|----------------|---------------------|-------------|-------------------------|
|                |                     | $t\bar{t}Z$ | $WWZ$    | $t\bar{t}W$ | $t\bar{t}$ | $Z2j$ | $ZZ$ | 120 | 125 | 130 |
| LTT            | 42                  | 36          | 6         | 3           | 9         | 9     | 30    | 4.4 | 4.3 | 3.8 |
| HTT            | 117                 | 111         | 15        | 9           | 147       | 276   | 84    | 4.6 | 4.5 | 4.1 |
| SS/LTT         | 14                  | 12          | 3         | 0           | 0         | 0     | 0     | 3.6 | 3.6 | 3.1 |
| SS/HTT         | 39                  | 36          | 6         | 3           | 0         | 0     | 0     | 5.8 | 5.7 | 5.2 |

Table 3: Number of events for the signature “2 electrons/muons + 2 tau jets” with the integrated luminosity of 300 fb$^{-1}$ with the cuts and efficiencies specified in the text.
Let us now comment on the possible uncertainties in the above results. Theoretically, the main sources of uncertainties are choices of parton distribution functions, factorization and renormalization scales. In obtaining our results, we have used the NLO cross sections. These cross sections have the uncertainties of the order 10 – 15%. Furthermore, when these choices increase/decrease the signal cross section, they also correspondingly increase/decrease the background cross sections. Therefore, there is a further reduction in the uncertainties due to the cancellation when we compute the significance – a ratio. Overall, one may expect only a few percent theoretical uncertainty in the significance of the signatures. Similarly, there will be cancellation of uncertainties due to experimental limitations. Therefore, our results about the significance are quite robust.
5 Conclusion

In this letter, we have analyzed the signatures with two electrons/muons for the process $pp \rightarrow t\bar{t}H$. In particular, we have considered the signatures “2 electrons/muons + a tau jet + a bottom jet”, “2 electrons/muons + two tau jets”, “2 electrons/muons + a tau jet + two bottom jets”, and “2 electrons/muons + two tau jet + a bottom jet”. The major backgrounds are from the process $t\bar{t}$ (and jets) and the processes with Z bosons. The signatures with two tau jets have decent significance and may be observed in the run II of the LHC. The signatures with only one tau jet are overwhelmed by the backgrounds due to a top-quark pair production. However, restricting to the same-sign electrons/muons events, these signatures may also be visible. So it appears that to observe the $t\bar{t}H$ process using two electrons/muons, one may need to either tag two tau jets or tag one tau jet but observe same sign electrons/muons. More detailed analysis of various other signatures will be presented elsewhere.

References

[1] G. Aad et al. (ATLAS Collaboration), Phys. Lett. B 716 (2012) 1.

[2] S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 716, 30 (2012) [arXiv:1207.7235 [hep-ex]].

[3] S. Chatrchyan et al. [CMS Collaboration], JHEP 1305, 145 (2013) [arXiv:1303.0763 [hep-ph]].

[4] See for e.g., Pankaj Agrawal, Mod. Phys. Lett. A 16 (2001) 897.

[5] See for e.g., ATLAS Collaboration, ATLAS-CONF-2012-170.

[6] S. Chatrchyan et al. [CMS Collaboration], arXiv:1312.1129 [hep-ex].

[7] C. Kao and J. Sayre, Phys. Lett. B 722, 324 (2013).

[8] The ATLAS collaboration, Phys. Lett. B 710, 383 (2012).

[9] G. Aad et al. [ATLAS Collaboration], JHEP 05, 070 (2012) [arXiv:1206.5971 [hep-ex]].

[10] S. Chatrchyan et al. [CMS Collaboration], Phys. Rev. Lett. 106, 231801 (2011) [arXiv:1104.1619 [hep-ex]].
[11] S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 713, 68 (2012) [arXiv:1202.4083 [hep-ex]].

[12] The ATLAS collaboration, ATLAS-CONF-2012-160, ATLAS-CONF-2011-133.

[13] S. Dittmaier et al. [LHC Higgs Cross Section Working Group Collaboration], arXiv:1101.0593 [hep-ph].

[14] C. Englert, T. S. Roy and M. Spannowsky, Phys. Rev. D 84, 075026 (2011) [arXiv:1106.4545 [hep-ph]].

[15] S. Fleischmann, http://cds.cern.ch/record/1504815/files/CERN-THESIS-2011-291.pdf; F. Scutti, http://cds.cern.ch/record/1495356/files/ATL-PHYS-PROC-2012-251.pdf; R. Prabhu, http://pi.physik.uni-bonn.de/pi_plone/lhc-ilc/theses/Thesis-PI-prabhu.pdf

[16] See for e.g., S. Dutta, Nucl. Phys. B(Proc. Supp.) 169 (2007) 345.

[17] J. Baglio and A. Djouadi, arXiv:1103.6247 [hep-ph].

[18] D. Curtin, J. Galloway and J. G. Wacker, Phys. Rev. D 88, 093006 (2013) [arXiv:1306.5695 [hep-ph]].

[19] N. Craig, M. Park and J. Shelton, arXiv:1308.0845 [hep-ph]; A. Belyaev and L. Reina, JHEP 0208, 041 (2002) [hep-ph/0205270].

[20] P. Onyisi, R. Kehoe, V. Rodriguez and Y. Ilchenko, arXiv:1307.7280 [hep-ex].

[21] E. Contreras-Campana, N. Craig, R. Gray, C. Kilic, M. Park, S. Somalwar and S. Thomas, JHEP 1204, 112 (2012) [arXiv:1112.2298 [hep-ph]]; N. Craig, J. A. Evans, R. Gray, C. Kilic, M. Park, S. Somalwar and S. Thomas, JHEP 1302, 033 (2013) [arXiv:1210.0559 [hep-ph]].

[22] A. Carmona, M. Chala and J. Santiago, JHEP 1207 (2012) 049 [arXiv:1205.2378 [hep-ph]].

[23] A. Azatov and A. Paul, arXiv:1309.5273 [hep-ph].

[24] M. R. Buckley, T. Plehn, T. Schell and M. Takeuchi, arXiv:1310.6034 [hep-ph].
[25] J. Ellis, D. S. Hwang, K. Sakurai and M. Takeuchi, JHEP 1404, 004 (2014) arXiv:1312.5736 [hep-ph].

[26] C. Englert, A. Freitas, M. Muhlleitner, T. Plehn, M. Rauch, M. Spira and K. Walz, arXiv:1403.7191 [hep-ph].

[27] A. Greljo, J. F. Kamenik and J. Kopp, arXiv:1404.1278 [hep-ph].

[28] See for e.g., P. Agrawal, Mod. Phys. Lett. A 14, 1479 (1999) hep-ph/9803203.

[29] P. Agrawal and S. D. Ellis, Phys. Lett. B 229, 145 (1989).

[30] P. Agrawal, D. Bowser-Chao and K. -M. Cheung, Phys. Rev. D 51, 6114 (1995) hep-ph/9410354.

[31] C. Kao, D.A. Dicus, R. Malhotra, Y. Wang, Phys. Rev. D 77 095002 (2008).

[32] See for e.g., CMS Collaboration, JINST 7 (2012) P01001.

[33] G. Bagliesi, arXiv:0707.0928 [hep-ex].

[34] See for e.g., CMS Collaboration, JINST 8 (2012) P04013.

[35] See for e.g., exploiting $b$-tagging in CP-violating MSSM, S. P. Das and M. Drees Phys. Rev. D 83 035003 (2011), arXiv:1010.3701 [hep-ph]; Journal of Physics: Conference Series 259 (2010) 012071, 1010.2129 [hep-ph]; S. P. Das, A. Datta and M. Drees arXiv:0809.2209 [hep-ph].

[36] M. Lehmacher, arXiv:0809.4896 [hep-ex].

[37] Z. Sullivan and E. L. Berger, Phys. Rev. D 82, 014001 (2010) arXiv:1003.4997 [hep-ph].

[38] P. Agrawal, S. Bandyopadhyay and S. P. Das, Phys. Rev. D 88, 093008 (2013) arXiv:1308.3043 [hep-ph].

[39] G. Aad et al. [ATLAS Collaboration], JINST 3, S08003 (2008).

[40] D. Curtin, J. Galloway, J. G. Wacker, Phys. Rev. D 88, 093006 (2013) arXiv:1308.3043 [hep-ph].
[41] J. Alison, https://cds.cern.ch/record/1536507.

[42] G. Aad et al. [ATLAS Collaboration], Phys. Rev. D 87, no. 5, 052002 (2013) arXiv:1211.6312 [hep-ex].

[43] G. Aad et al. [ATLAS Collaboration], Eur. Phys. J. C 71, 1577 (2011) arXiv:1012.1792 [hep-ex].

[44] M.L. Mangano, M. Moretti, F. Piccinini, R. Pittau, A. Polosa, JHEP 0307, 001 (2003).

[45] T. Sjostrand, S. Mrenna and P. Skands, JHEP 0605, 026 (2006).

[46] H.L. Lai, J. Huston, S. Kuhlmann, J. Morfin, F. Olness, J.F. Owens, J. Pumplin and W.K. Tung, Eur. Phys. J. C12 (2000) 375, hep-ph/9903282.

[47] W. Beenakker, S. Dittmaier, M. Kramer, B. Plumper, M. Spira and P. M. Zerwas, Nucl. Phys. B 653, 151 (2003) hep-ph/0211352.

[48] A. Lazopoulos, T. McElmurry, K. Melnikov and F. Petriello, Phys. Lett. B 666, 62 (2008) arXiv:0804.2220 [hep-ph].

[49] J. M. Campbell and R. K. Ellis, JHEP 1207, 052 (2012) arXiv:1204.5678 [hep-ph].

[50] J. M. Campbell and R. K. Ellis, Phys. Rev. D 60, 113006 (1999) hep-ph/9905386.

[51] F. Campanario, C. Englert, S. Kallweit, M. Spannowsky and D. Zeppenfeld, JHEP 1007, 076 (2010) arXiv:1006.0390 [hep-ph].

[52] V. Hankele and D. Zeppenfeld, Phys. Lett. B 661, 103 (2008) arXiv:0712.3544 [hep-ph].

[53] E. Laenen, J. Smith and W.L. van Neerven, Nucl. Phys. B 369, 1992 (543); E.L. Berger and H. Contopanagos, Phys. Rev. D 54, 1996 (3085); S. Catani, M.L. Mangano, P. Nason and L. Trentadue, Nucl. Phys. B 478, 1996 (273).

[54] S. Dittmaier, P. Uwer, and S. Weinzierl, Phys. Rev. Lett. 98, 262002 (2007)

[55] J. M. Campbell and R. K. Ellis, Phys. Rev. D 65, 113007 (2002) hep-ph/0202176.