Study of $t\bar{t}H$ ($H \rightarrow \mu^+\mu^-$) in the three lepton channel at $\sqrt{s} = 14$ TeV; A Snowmass white paper

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Abstract

The $H \rightarrow \mu^+\mu^-$ signature provides excellent mass resolution for Higgs bosons, and is therefore an important Higgs boson decay channel despite the small dimuon branching ratio. We present an optimization of selection criteria in a search for trilepton $t\bar{t}H$ ($H \rightarrow \mu^+\mu^-$) events, in which the top quark pair decays semi-leptonically, at a simulated High Luminosity LHC (HL-LHC) running at 14 TeV. The study is performed with 3000 fb$^{-1}$ of simulated data with an average pileup of $< \mu > \approx 140$. In this ultimate HL-LHC data set, we find that $t\bar{t}H$ ($H \rightarrow \mu^+\mu^-$) will be a very difficult signature to observe due to the very small expected signal.

1 Introduction

The particle with mass around 125 GeV recently observed by both the ATLAS [1] and CMS [2] collaborations is compatible [3, 4, 5] with production of the Standard Model (SM) Higgs boson. The particle nearly completes the SM, and explains both how elementary particles obtain mass as well as electroweak symmetry breaking [6, 7, 8, 9, 10, 11]. Nevertheless, one of the most important questions in particle physics is whether the discovered particle is the Higgs boson predicted by the SM or a similar impostor.

![Figure 1: Representative Feynman diagram of Higgs boson production via gluon fusion.](image1)

The dominant mode for Higgs boson production in proton-proton ($pp$) collisions at the LHC is $gg \rightarrow H$, known as gluon fusion. In gluon fusion, the Higgs boson is produced through a quark (primarily top-quark) loop, as shown in Fig. 1. However, only events with the Higgs boson produced with a top-quark pair ($t\bar{t}$) allow the direct observation and study of the $t\bar{t}H$ vertex, as shown in Fig. 2.

![Figure 2: Feynman diagram of $t\bar{t}H$ production.](image2)

At the observed mass near 125 GeV the Higgs boson will decay most prominently into a pair of bottom quarks as shown in Table 1. The Higgs boson may also decay into a muon pair ($H \rightarrow \mu^+\mu^-$),
table 1: branching ratios for the higgs boson decay modes for \( m_H = 125 \text{ GeV} \).

\[
\begin{array}{cccccccc}
\text{Channels} & \bar{b}b & \tau^+\tau^- & \mu^+\mu^- & c\bar{c} & gg & \gamma\gamma & ZZ \\
\text{BR} & 0.58 & 0.063 & 2.20 \times 10^{-4} & 0.0291 & 0.086 & 2.28 \times 10^{-4} & 0.154 \times 10^{-3} & 0.215 & 0.026 \\
\end{array}
\]

Although with a much smaller branching ratio of \( 2.20 \times 10^{-4} \). The decay benefits from having a very clear \( H \rightarrow \mu^+\mu^- \) mass resolution, similar to the \( H \rightarrow \gamma\gamma \) decay, whose excellent mass resolution made it vital to the Higgs boson discovery despite its small branching ratio. To reduce the background levels, the analysis is performed in trilepton \( t\bar{t}H \) events, where one top-quark decays leptonically to either an electron or muon, which we shall call the electron and muon channel, respectively. An event with the aforementioned production and decay mode in the trilepton channel would be seen in the detector as 4 jets (including the 2 \( b \)-jets), two oppositely charged muons, an additional lepton and a neutrino from the \( W \)-boson decay, inferred by missing transverse momentum \( (E_T^{\text{miss}}) \).

2 Modeling and Object Selection

This study was done in the context of Snowmass with official Snowmass samples using the Delphes fast simulation framework [12] of a generic High Luminosity LHC (HL-LHC) detector with particle flow to mitigate the pileup. The study focuses on a HL-LHC running at 14 TeV, and a combined integrated luminosity of \( 3000 \text{ fb}^{-1} \) with an average pileup of \( \langle \mu \rangle = 140 \).

In the Delphes framework identified leptons (electrons and muons) are required to be isolated [13]. To be accepted as ‘good’, electrons (muons) are required to have \( |\eta| < 2.5 \) (2.4). Jets are required to have \( |\eta| < 2.7 \). After comparing the \( p_T \) spectra of electrons, muons and jets, good leptons are required to have a minimum \( p_T \) of 25 GeV and good jets are required to have a minimum \( p_T \) of 30 GeV [13]. These cuts were chosen to maintain signal efficiency while reducing the background as much as possible.

Further optimization of the \( t\bar{t}H \) event selection have been performed, as described in Section 3.

2.1 Signal Sample

A signal sample of \( t\bar{t}H, H \rightarrow \mu^+\mu^- \) was generated using MadGraph5 v2 beta [14] with showering provided by Pythia6 [15]. The sample was processed through the standard Delphes simulation as all background processes.

2.2 Background Samples

Backgrounds to the trilepton \( t\bar{t}H, H \rightarrow \mu^+\mu^- \) signature are processes with prompt leptons and \( b \)-jets, as well as processes with at least one misidentified (‘fake’) object. For instance, a light-flavor jet can be misidentified as a heavy-flavor jet. A lepton that comes from a non-prompt (non-\( W/Z \)) source or from a misidentified hadron, can also pass the selection criteria. Background processes containing real and misidentified leptons and \( b \)-jets were considered in this analysis.

The background samples and cross sections from the official Snowmass Energy Frontier generation [13, 16] were used for this analysis. Simulation samples of \( V + \text{jets} (V = W, Z^0/\gamma^*) \) production, \( VV \) and \( VVV \) production, single top and top-quark pair production were generated in \( H_T \) bins (where \( H_T \) is defined as the scalar sum of jet and lepton transverse momenta), as described in Ref. [13].

One of the dominant backgrounds is top-quark pair production in association with a boson, i.e. \( t\bar{t}Z \), \( t\bar{t}W \), and \( t\bar{t}W \). These samples were generated using MadGraph5 v2 beta [14] using Pythia6 [15] showering. Cross sections for the signal and \( t\bar{t}+X \) background samples are summarized in Table 2.

\[
\begin{array}{|c|c|}
\hline
\text{Process} & \text{Cross Section, pb} \\
\hline
\text{ttH} & 0.6113 \text{ [17]} \\
\text{ttWW} & 0.0104 \text{ [14]} \\
\text{ttW} & 0.7062 \text{ [14]} \\
\text{ttZ} & 0.0741 \text{ [14]} \\
\text{tt} & 953.6 \text{ [18]} \\
\hline
\end{array}
\]

Table 2: Cross sections for the inclusive \( ttH \) production and for the major backgrounds. The \( ttH \) cross section is the value before the \( H \rightarrow \mu^+\mu^- \) branching ratio is applied.
2.3 Muon Fakes

Inclusive $t\bar{t}$ production (with at least one fake lepton) is one of the dominant backgrounds for this analysis. To mitigate large statistical uncertainties on the prediction of this background in the muon channel, a per-jet $j \rightarrow \mu$ fake rate probability is applied to every $t\bar{t}$ dimuon event.

The fake rate $f_{j \rightarrow \mu}$ was derived by taking the number of events with a fake muon and dividing that by the number of jets that could fake a muon. To estimate the number of fake leptons, we assume that every event in the same-sign (SS) dimuon channel of $t\bar{t}$ has a fake lepton. We further assume that a fake muon is equally likely to have positive or negative charge, so we multiply our count of SS dimuon events by a factor of two to account for the number of fake muons in the opposite sign (OS) dimuon channel. Finally, we divide this number by the total number of jets with minimum $p_T$ of 25 GeV in the semi-leptonic muon channel of the $t\bar{t}$ sample to find the fake rate as follows:

$$f_{j \rightarrow \mu} = \frac{2 \times N_{SS}}{N_{jets \ in \ \mu+jets}} = 6.5 \times 10^{-5}$$

![Figure 3: Distribution and fit of the fake muon $p_T$ derived from same-sign dimuon channel of $t\bar{t}$.](image)

The $p_T$ distribution for fake muons is also taken from the SS dimuon channel of $t\bar{t}$. The sub-leading muon is assumed to be the fake muon. The sub-leading muon $p_T$ distribution is fit to an exponential curve as shown in Fig. 3. The fit is used at random as a probability density for the fake muon $p_T$. The direction ($\eta$ and $\phi$) are taken from the jet which will be the fake muon.

3 Event selection

In this study, we focus on the $t\bar{t}H$ signature where the Higgs boson decays to dimuons and the top-quark pair decays semi-leptonically to either an electron or muon, which we shall call the electron and muon channel, respectively. Each channel was optimized independently, however the two optimizations gave identical cuts.

The $t\bar{t}H, H \rightarrow \mu^+\mu^-$ candidate event is required to have exactly three leptons (with at least 2 OS muons), at least one $b$-tagged jet, and at least four jets in total. The leading lepton is typically a muon from the Higgs boson decay, so to further reject background the leading muon is required to have $p_T > 55$ GeV. This cut maintains nearly full signal efficiency while cutting a respectable fraction of background, as shown in Fig. 4(a) and Fig. 4(b). Similarly, requiring the sum of lepton and jet $p_T$ ($H_T$) $> 350$ GeV is also shown to cut background while maintaining full signal efficiency in both channels and was thus applied as shown in Fig. 4(c) and Fig. 4(d).

In the electron channel, the two OS muons in the event are taken to reconstruct the Higgs boson. For events in the muon channel, there are two OS muon pairs to consider. We select the OS muon pair closest to 125 GeV as the Higgs boson candidate. A major background of $t\bar{t}H$ where Higgs boson decays
leading muon $p_T$ [GeV]

0 50 100 150 200 250 300 350 400 450 500

Events

-1 10

1 10

2 10

3 10

top+ B

top

BB

B

ttH

Snowmass 2013

$\sqrt{s} = 14$ TeVs

Channel

$\mu$

(a) Leading muon $p_T$, muon channel

(b) Leading muon $p_T$, electron channel

(c) $H_T$ distribution, muon channel

(d) $H_T$ distribution, electron channel

Figure 4: Leading muon $p_T$ and the $H_T$ distributions for the muon and electron channels.

to dimuons is $t\bar{t}Z$, which has a similar signature. To suppress the $t\bar{t}Z$ background, which is topologically similar to the signal, we reject an event if any OS dimuon pair falls within the $Z$ window of 91-101 GeV.

The expected number of $t\bar{t}H, H \rightarrow \mu^+\mu^-$ events in the full HL-LHC dataset is about 400. When exactly 3 reconstructed leptons are required in the event, the expected number of $t\bar{t}H, H \rightarrow \mu^+\mu^-$ events is reduced to about 54. The event selection is summarized in Tables 3-4 along with cut efficiencies for signal and background. The resulting signal efficiency with respect to the preselection (‘== 3 Leptons’) is 57% (27% and 30% for the muon and electron channel, respectively).

| Muon Channel                  | $t\bar{t}H$ | $t\bar{t}Z$ | $t\bar{t}W$ | $t\bar{t}$ |
|-------------------------------|-------------|-------------|-------------|-----------|
| == 2 OS Muons + Muon          | 48.8%       | 24.2%       | 9.36%       | 6.83%     |
| Leading Muon Pt > 55 GeV      | 97.8%       | 94.2%       | 79.0%       | 71.1%     |
| $\geq 1$ tag                   | 78.5%       | 78.5%       | 86.7%       | 65.5%     |
| $\geq 4$ jets                  | 83.9%       | 83.4%       | 76.9%       | 49.9%     |
| $H_T > 350$ GeV                | 99.1%       | 98.8%       | 100.0%      | 91.7%     |
| No OS muon pairs in $Z$ window | 87.2%       | 17.6%       | 90.0%       | 53.4%     |

Table 3: Cut efficiencies for $t\bar{t}H$ and selected major backgrounds.

4 Analysis

To compensate for the statistical fluctuations in the background Monte Carlo samples, we fit an exponential curve to each background using a 1 GeV binning and integrate over the mass window of 120-130 GeV. We then count the signal events in the mass window to find $S/\sqrt{B}$. Figures 5-6 show the background fits and the expected SM Higgs boson signal.

The expected numbers of events inside the Higgs boson mass window are shown in Table 5.
Table 4: Cut efficiencies for $t\bar{t}H$ and selected major backgrounds.

| Cut Criteria                                      | $t\bar{t}H$ | $t\bar{t}Z$ | $t\bar{t}W$ | $t\bar{t}$ |
|--------------------------------------------------|-------------|-------------|-------------|-----------|
| $\equiv 3$ Leptons                                | —           | —           | —           | —         |
| $\equiv 2$ OS Muons + Electron                   | 49.8%       | 26.8%       | 32.0%       | 31.8%     |
| Leading Muon Pt > 55 GeV                         | 95.2%       | 88.4%       | 73.9%       | 54.0%     |
| $\geq 1$ tag                                     | 78.1%       | 79.3%       | 83.3%       | 49.3%     |
| $\geq 4$ jets                                    | 83.4%       | 79.9%       | 80.0%       | 25.5%     |
| $H_T > 350$ GeV                                  | 99.3%       | 99.1%       | 100.0%      | 99.6%     |
| No OS muon pairs in $Z$ window                   | 96.4%       | 17.5%       | 59.4%       | 51.8%     |

Figure 5: Dimuon mass plot from the electron channel (a) and muon channel (b) where signal is added to the background fit.

Figure 6: Dimuon mass plot from the combined channel where signal is added to the background fit.

Table 5: Expected number of events for signal and background in each channel.

| Channel   | Background [Events] | Signal [Events] | $S/\sqrt{B}$ |
|-----------|---------------------|-----------------|--------------|
| Electron  | 137.1               | 14.3            | 1.22         |
| Muon      | 107.2               | 13.3            | 1.28         |
| Combined  | 204.4               | 27.6            | 1.93         |
5 Conclusion

A precision measurement of the top Yukawa coupling is a key piece of any further understanding of electroweak symmetry breaking and the origin of mass. Due to the clean event topology, the $ttH$ ($H \rightarrow \mu^+\mu^-$) production and decay would be an excellent signature in which to make such studies. We find that the low branching ratio for Higgs boson decay to muons, combined with the small $ttH$ production cross section, make such analysis in the trilepton signature extremely difficult, even with the ultimate expected luminosity (3000 fb$^{-1}$) at the HL-LHC.

Considering only statistical uncertainties, the expected sensitivity to the Standard Model $ttH$, $H \rightarrow \mu^+\mu^-$ production and decay is at the level of $2\sigma$. To claim the evidence of the $ttH$, $H \rightarrow \mu^+\mu^-$ signal one would need to use multivariate techniques and/or study the signature in the all-hadronic $tt$ decays.

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