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Detecting the intermediate-mass Higgs boson through the associate production channel $pp \to t\bar{t}HX$

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We examine the detection of the intermediate-mass Higgs (IMH) boson at the CERN LHC through the associate production channel $pp \to t\bar{t}HX \to l\gamma\gamma X'$. It is shown that by applying kinematic cuts or b tagging on the final state jets, the main backgrounds of $W(\to l\nu)+\gamma+\gamma+(n\text{-jet})$ can be reduced substantially without significant loss of signals. It is possible to detect the IMH boson at the LHC through the $pp \to t\bar{t}HX$ channel using a modest photon detector with mass resolution $\sim 3\%$ of the photon pair invariant mass.

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I. INTRODUCTION

The most mysterious part of the standard model (SM) is the symmetry-breaking sector. The search for the Higgs boson which is responsible for the symmetry breaking has become one of the main tasks in high energy physics. The CERN e^+e^- collider LEP II can search for a Higgs boson of mass up to 80 GeV [1]. For $m_H \geqslant 80$ GeV, the detection of the Higgs boson will be left to the CERN Large Hadron Collider (LHC), Next Linear Collider (NLC) or ep, $e\gamma$ colliders. A Higgs boson in the intermediate-mass range, $80 \leqslant m_H \leqslant 140$ GeV is shown to be particularly difficult for the LHC to detect. Recent studies show that a SM Higgs boson in this region can be detected at LHC [2], LEP $\otimes$LHC ep [3], and TeV $e\gamma$ colliders [4] via WH/ZH production with leptonic or hadronic decays of W/Z and $H \to b\bar{b}$ or $H \to \gamma\gamma$ [5]. There are also proposals of detecting a SM intermediate-mass Higgs (IMH) boson through $t\bar{t}H$ production with inclusive final state signals of $l\gamma\gamma$ [6–10]. However, our recent study [11] shows that there exist difficulties due to the large reducible background processes $pp \to W(\to l\nu)+\gamma+\gamma+(n-\text{jet})+X$ $(n=0,1,2,3,4)$ with which the inclusive $l\gamma\gamma$ detection of the IMH boson in the $t\bar{t}H$ production needs a high level photon detector with photon pair invariant mass ($M_{\gamma\gamma}$) resolution of $\sim 1\%$. In [11], various tree-level contributions have been taken into account. In view of the fact that the infrared divergences (IFD's) in the tree-level collinear- or soft-gluon emission diagrams are canceled by the IFD's in loop diagrams, one may worry about the uncertainty in [11] due to ignoring the probable residual cancellation effect if the jet-p_T cut is not large enough [10]. However, taking the largest one-jet process as an example, our result shows that, with the cut $p_T > 30$ GeV, the main contribution comes from the gluon-quark fusion part which does not contain IFD's, while the gluon emission contribution is only about one-tenth of it. Hence such kind of probable uncertainty does not really affect the main feature of the results in [11]. Therefore the backgrounds $W(\to l\nu)+\gamma+\gamma+(n-\text{jet})+X$ with $n \geqslant 1$ should really be taken seriously. Unfortunately, most of the recent papers concerning the $t\bar{t}H$ production channel, including the most recent realistic Monte Carlo simulations by the CMS and ATLAS Collaborations [12], have not carefully taken such backgrounds into account. Even if an IMH boson can be detected at LHC via WH/ZH production, it is still worthy to observe the $t\bar{t}H$ production to explore the coupling of the Higgs boson to the top quark. It is then our purpose in this paper to investigate the possibility of reducing these backgrounds and obtaining a large signal to background ratio (S/B) at LHC with a modest photon detector of $\sim 3\%$ $M_{\gamma\gamma}$ resolution.

In Sec. II we analyze the backgrounds to the SM $t\bar{t}H$ production with inclusive $l\gamma\gamma$ final states at LHC and propose the methods of reducing them. We then present the number of events of signals and backgrounds without and with b tagging of 100% efficiency. In Sec. III we give our discussions and conclusions.

II. BACKGROUND REDUCTION AND RESULTS

If the Higgs boson is detected via inclusive final states $l\gamma\gamma$ from $pp \to t\bar{t}HX$ production, the final states will contain $0-4$ jets from $t\bar{t}$ decays, e.g., $t\bar{t} \to WbW\bar{b} \to l\nu jjb\bar{b}$. Therefore the processes $pp \to W(\to l\nu)+\gamma+\gamma+(n-\text{jet})+X$ $(n=0,1,2,3,4)$ will be the reducible backgrounds to the Higgs boson signal. After applying isolation cuts it is found that, apart from the above-mentioned backgrounds, the main remained background is from the irreducible $t\bar{t}\gamma\gamma$ process which is not significant [8,10]. Although the $n \geqslant 1$ contributions seem to be of higher order of QCD with respect to the $n=0$ $W\gamma\gamma$ process, our explicit calculations [11] show that they are surprisingly larger than the $W\gamma\gamma$ background, partly due to the appearance of channels of qg and gg in the initial states. Our results are also consistent with the result $\sigma(W+(3-\text{jet})) > \sigma(t\bar{t})$ [13] which implies $\sigma(W+\gamma+\gamma+(3-\text{jet})) > \sigma(t\bar{t}\gamma\gamma)$. Therefore, our main task is to reduce the backgrounds from the $pp \to W(\to l\nu)+\gamma+\gamma+(n-\text{jet})+X$ processes. Inspired by the reduction of $W+(n-\text{jet})$ backgrounds to the $t\bar{t}$ signal [14], we investigate the possibilities of reducing the $W+\gamma+\gamma+(n-\text{jet})$

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TABLE I. Signal and background events after applying $m_{jj}=m_W\pm\delta m$ and $m_{jjj'}=m_t\pm\delta m$ cuts. Number of jets (n_j) $\geqslant 3$, p_T(jet)$\geqslant$30 GeV, $\delta m=10$ GeV. The cut efficiency is $\epsilon_2=0.053$.

Cuts	m_H(GeV)	$t\bar{t}H$	$t\bar{t}\gamma\gamma$	$W\gamma\gamma+3-$jet $+W\gamma\gamma+4-$jet	Total backgrounds	$\frac{S}{\sqrt{S+B}}$
$m_{jj}=m_W\pm\delta m$	70	7.1	0.7	2.0	2.7	2.3
	100	9.5	0.8	2.8	3.6	2.6
	130	6.9	0.7	1.4	2.1	2.3
$m_{jj}=m_W\pm\delta m$	70	5.5	0.5	0.1	0.6	2.2
plus	100	7.3	0.6	0.2	0.8	2.6
$m_{jjj'}=m_t\pm\delta m$	130	5.3	0.6	0.2	0.8	2.1

backgrounds to the $t\bar{t}H$ signal in the $l\gamma\gamma$ mode.

There are some notable features of the $t\bar{t}H$ signal events. First, almost 100% of the events contain at least two jets and 80% contain more than two jets due to the heaviness of the top quark [10]. Second, the final state signal jets contain contribution from $t\to Wb\to jjb$ decay which may allow us to reconstruct W and t from the detected jets. The third feature is that there are b quark jets in the signal from $t\bar{t}\to WbW\bar{b}$ decay which can be tagged.

The first thing we do is to require at least three jets in the final states. As we have mentioned, there are still 80% signals satisfying this requirement, while the largest $n=1,2$ backgrounds are eliminated, i.e., the remaining backgrounds are only $t\bar{t}\gamma\gamma$ and the $n=3,4$ ones. Unfortunately we cannot explicitly calculate the $n=3,4$ backgrounds due to the large number of Feynman diagrams. For example, the number of diagrams is 1758 with the external lines $Wqq'ggg\gamma\gamma$. Our previous estimate shows that they are important [11]. However, we can make an approximate estimate of the $n=3,4$ backgrounds from the calculated $pp\to W+(n-\text{jet})$ cross sections [14]. Our calculations show that $\sigma(W+\gamma+\gamma+(2-\text{jet}))/\sigma(W+\gamma+\gamma+(1-\text{jet}))$ is about 0.7 at LHC. This number is close to the ratio $\sigma(W+(2-\text{jet}))/\sigma(W+(1-\text{jet}))=80/52\approx 0.7$ given in [14]. This implies that the emission of two extra photons does not affect the ratio much. So it is likely that cases containing more jets may have the similar situation. Then we can expect that

$$\frac{\sigma(W+\gamma+\gamma+(3-\text{jet}))}{\sigma(W+\gamma+\gamma+(2-\text{jet}))}$$

and

$$\frac{\sigma(W+\gamma+\gamma+(4-\text{jet}))}{\sigma(W+\gamma+\gamma+(2-\text{jet}))}$$

are close to

$$\frac{\sigma(W+(3-\text{jet}))}{\sigma(W+(2-\text{jet}))}$$

and

$$\frac{\sigma(W+(4-\text{jet}))}{\sigma(W+(2-\text{jet}))},$$

which are $24/52\approx 1/2$ and $8.6/52\approx 1/6$, respectively, according to [14].

What we are going to do next is to impose certain kinematical cuts on the jets to further enhance the signal to backgrounds ratio. As there is large probability that two jets in the signal come from W decays, we impose a cut on the two-jet invariant mass $m_{jj}=m_W\pm\delta m$ with a resolution δm. This will further reduce the $n=3,4$ backgrounds relative to the signal. We define *cut efficiency* as the ratio of the cross-section with the cut to that without the cut. Let ϵ_2 be the cut efficiency of the two-jet invariant mass cut in the $n=2$ process which will be calculated in the way given in [11]. In the $n=3$ process, there are three combinations of two-jet pairs. A simple estimate regarding them as independent events leads to a cut efficiency $\epsilon_3=3\epsilon_2$. In the $n=4$ case, the simple estimate gives the cut efficiency $\epsilon_4=6\epsilon_2$. Therefore, with the above estimated $n=3,4$ background cross sections, the cross section of $n=3,4$ after this cut will be about the same as that of $n=2$. If we can measure the top quark mass more accurately in the future experiments at the Fermilab Tevatron or LHC, we can further require a third jet combined with the two satisfying $m_W-\delta m<m_{jj}<m_W+\delta m$ to form $m_{jjj'}$ and $m_t-\delta m<m_{jjj'}<m_t+\delta m$, reflecting that the three jets come from the t decays which has a large probability in the signal but not in the $n=3,4$ backgrounds. In this case, we get the combined cut efficiencies $\epsilon_3'=3\epsilon_2^2$, $\epsilon_4'=12\epsilon_2^2$. In obtaining this result, we have simply assumed that the cut efficiency of one combination satisfying $m_{jjj'}=m_t\pm\delta m$ cut is ϵ_2. We shall discuss this in the next section. Note that we count the event only once if there is one combination satisfying the cuts regardless of the number of combinations.

In our calculations, we use the following parameters and parton distribution:

$$\sqrt{s}=14\ \text{TeV},\int \mathscr{L}dt=100\ \text{fb}^{-1},\quad M_{\gamma\gamma}\ \text{resolution}=3\%,$$

$$m_t=176\ \text{GeV},$$

$$\text{for}\ \ q\bar{q},gg\to t\bar{t}H\ \ \text{and}\ \ q\bar{q},gg\to t\bar{t}\gamma\gamma:\quad Q^2=\hat{s},$$

$$\text{for}\ \ W\gamma\gamma+2-\text{jet}:\quad Q^2=m_W^2,$$

Martin-Roberts-Stirling (MRS) set A′ [15],

$$\Lambda=231\ \text{MeV}. \quad (1)$$

TABLE II. Signal and background events after applying $m_{jj}=m_W\pm\delta m$ and $m_{jjj'}=m_t\pm\delta m$ cuts. $n_j\geqslant 3$, $p_T(\mathrm{jet})\geqslant 30$ GeV, $\delta m=20$ GeV. The cut efficiency is $\epsilon_2=0.12$.

Cuts	m_H (GeV)	$t\bar{t}H$	$t\bar{t}\gamma\gamma$	$W\gamma\gamma+3-$jet $+W\gamma\gamma+4-$jet	Total backgrounds	$\frac{S}{\sqrt{S+B}}$
$m_{jj}=m_W\pm\delta m$	70	7.8	0.7	4.3	5.0	2.2
	100	10.5	0.9	6.3	7.2	2.5
	130	7.6	0.8	2.9	3.7	2.3
$m_{jj}=m_W\pm\delta m$	70	5.8	0.6	0.8	1.4	2.2
plus	100	7.6	0.7	1.0	1.7	2.5
$m_{jjj'}=m_t\pm\delta m$	130	5.6	0.7	1.2	1.9	2.0

As in [10], the following cuts are used for the final state particles:

$$\begin{gathered} p_T(l,\gamma)>20\ \text{GeV},\quad |\eta(l,\gamma,\text{jet})|<2.5,\\ \Delta R(\text{jet}_1,\text{jet}_2)>0.4,\quad \Delta R(\gamma_1,\gamma_2)>0.4,\\ \Delta R(l,\gamma)>0.4,\quad \Delta R(\gamma,\text{jet})>0.4,\\ \Delta R(l,\text{jet})>0.4,\quad 0<M_{\gamma\gamma}<200\ \text{GeV}, \end{gathered} \tag{2}$$

where $\Delta R\equiv\sqrt{\Delta\phi^2+\Delta\eta^2}$. We allow the transverse momenta p_T of jets to vary as given in the tables.

The results of the $m_{jj}=m_W\pm\delta m$ and $m_{jjj'}=m_t\pm\delta m$ cuts are presented in Tables I and II corresponding to $\delta m=10$ and 20 GeV, respectively. Our results show that the S/B ratios are improved. A good m_{jj} resolution of $\delta m=10$ GeV will give a clear signal even if we use only the $m_{jj}=m_W\pm\delta m$ cut. The S/B ratios are not so good when $\delta m=20$ GeV if only the $m_{jj}=m_W\pm\delta m$ cut is applied. Note that the $S/\sqrt{S+B}$ values with the combined cuts in Tables I and II are all larger than 1.96 which corresponding to a confidence level of 97.5%.

There is another method of reducing the $pp\to W(\to l\nu)+\gamma+\gamma+(n-\text{jet})+X$ $(n=1,2,3,4)$ backgrounds. It is the use of b tagging in the final jets requiring at least one b jet in the final jets which will lead to significant reduction of the reducible backgrounds as in the case considered in [14]. The main backgrounds are then from the irreducible $t\bar{t}\gamma\gamma$ process and the reducible $W+\gamma+\gamma+(1,2,3,4)-$jet processes with jet(s) faking the b-jet(s). We use the approximations of $\sigma(W+\gamma+\gamma+(3-\text{jet}))\sim\sigma(W+\gamma+\gamma+(2-\text{jet}))/2$, $\sigma(W+\gamma+\gamma+(4-\text{jet}))\sim\sigma(W+\gamma+\gamma+(2-\text{jet}))/6$ and a level of 1% jet$\to b$ to estimate this latter background. There are also possible backgrounds coming from $W\gamma\gamma b\bar{b}$ and $W\gamma\gamma c\bar{b}$. The former is a subprocess of $W+\gamma+\gamma+(2-\text{jet})$ in diagrams with four external quark lines such as $q_1\bar{q}_2\to W\gamma\gamma q_3\bar{q}_3$, $q_1\bar{q}_3\to W\gamma\gamma q_2\bar{q}_3$. According to our calculation, these four-quark processes contribute only 1/10 of the total $W+\gamma+\gamma+(2-\text{jet})$, and $W+\gamma+\gamma+b\bar{b}$ contributes at most about 1/10 to the four-quark processes. Therefore, this background will not exceed that of the processes with jet faking b. The $W\gamma\gamma c\bar{b}$ process is a subprocess of $gg\to W\gamma\gamma q_1\bar{q}_2$ which is also about 1/10 of $W+\gamma+\gamma+(2-\text{jet})$ and a subprocess of the four-quark processes. For $q_1=c$, $q_2=b$, there are additional Cabibbo-Kobayashi-Maskawa (CKM) or heavy flavor parton distribution suppressions. These make this background negligible. Although the efficiency ϵ_b of b tagging at present is only ~ 0.4, there may be the possibility of improvement. We present the result in Table III with an extreme case of $\epsilon_b=1$ for reference.

TABLE III. Signal and background events after requiring at least one b jet in the final states in addition to $l\gamma\gamma$. $p_T(\mathrm{jet})\geqslant 20$ GeV. $W\gamma\gamma+(1,2,3,4)-$jet with jet faking b-jet events are estimated with a level of 1% jet$\to b$.

m_H (GeV)	$t\bar{t}H$ signal	$t\bar{t}\gamma\gamma$	$W\gamma\gamma$ $+(1,2,3,4)$ jets	Total backgrounds
70	16.2	1.6	1.1	2.7
100	21.6	1.8	1.5	3.3
130	16.0	1.7	1.5	3.2

III. DISCUSSIONS AND CONCLUSIONS

Our results of applying m_{jj} and $m_{jjj'}$ cuts are obtained with the simple estimate of the relation between the cross sections and the cut efficiencies of $n=3,4$ to those of $n=2$. Therefore there are uncertainties. A factor of 2 uncertainty of the $n=3,4$ backgrounds will not cause any problem if we apply both m_{jj} and $m_{jjj'}$ cuts. Actually, the above estimate gives already an overestimate of the possible backgrounds due to the following fact. As a check, we have calculated the cut efficiency for $m_{jj}\sim m_W$ plus $m_{jjj'}\sim m_t$ cuts of the $W+(3-\text{jet})$ process by using the program PAPAGENO [16]. The result shows that the cut efficiency is actually much smaller than $3\epsilon_2^2$.

Also the above estimate does not include any detection efficiencies of the jets. But this will have no influence on the S/B ratios since both the signal and background are affected in the same way. In the b-tagging case, we see from Table III that a realistic $\epsilon_b\sim 0.4$ still gives 6–8 signal events. These events might be too low for detection if some further detection efficiencies are included. But it can be overcome by increasing the integrated luminosity, say, to about 150 fb^{-1}.

In conclusion, an IMH boson can be detected at LHC in the mode $l+\gamma+\gamma+(n-\text{jet})$ from the $t\bar{t}H$ production with a modest photon detector of photon invariant mass resolution 3% when we use both the $m_{jj}\sim m_W$ and the $m_{jjj'}\sim m_t$ cuts or b tagging on the final state jets if the b-tagging efficiency can be improved. When the jet mass resolution can reach within 10 GeV ($\delta m = 10$ GeV), we can detect an IMH boson by using only $m_{jj}\sim m_W$ cut.

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