Searching for new physics with triple-top signal at the LHC

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A B S T R A C T

We study the triple-top quark production predicted by the effective operators at the Large Hadron Collider (LHC) with 14 TeV center-of-mass energy. We calculate the production cross section and find that the ratio of signal to Standard Model background can be large. Observation of triple-top signal would give evidence of signature of new physics. We also show that top quarks can be reconstructed using on-shell conditions and $M_{T2}$ observable in the case that the anti-top quark decays hadronically and two top quarks decay semileptonically. Using the polarization of top quark, we demonstrate that the effective operators that predict different chirality combinations of top quarks in the final state can be distinguished.

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1. Introduction

One of the important tasks of the Large Hadron Collider (LHC) at CERN is to search for signals of new physics (NP) and, hopefully, to further pin down the underlying theory beyond the Standard Model (SM). The absence of significant deviation from the SM predictions in experimental data up to date at the LHC indicates that the new physics scale should be at least several TeV, which may not be directly accessible at the LHC. The effects of new physics can then be parameterized in terms of effective operators as

$$L = L_{SM} + \sum_{n} \frac{c^{(n)}_i}{A} O^{(n)}_i + \sum_{n} \frac{c^{(n)}_i}{A^2} O^{(n)}_i + \ldots,$$

where $O^{(n)}_i$ are dimension-$n$ operators that consist of SM fields and are invariant under SM gauge symmetry $SU(3)_c \times SU(2)_L \times U(1)_Y$. $c^{(n)}_i$ are coefficients and $A$ denotes the generic new physics scale. Among these effective operators, we are particularly interested in the dimension-6 four-fermion operators [1–3] that involve top quarks. Relevant studies of effective operators in top quark physics have been carried out in the literature, including top quark pair production [2,4,5], single top production and top quark decay [2,4,6–9], Higgs production and decay [10], four-top production [11] and top quark forward–backward asymmetry [12,13].

In this study, we focus on the operators that involve three top quarks, since these operators indicate the production of three top quarks at the LHC, which has very low SM background. The relevant operators are [2]

$$O^{LL \rightarrow \ell \ell} = \frac{1}{2} (\bar{u}_{L,i} \gamma^{\mu} t_L \bar{t}_{L,i})(\ell_L \gamma_{\mu} \ell_L), \quad O^{RR \rightarrow \ell \ell} = \frac{1}{2} (\bar{u}_{R,i} \gamma^{\mu} t_R \bar{t}_{R,i})(\ell_R \gamma_{\mu} \ell_R), \quad O^{LR \rightarrow \ell \ell} = (\bar{u}_{L,i} \gamma^\mu \ell_R)(\ell_R \gamma^\mu \ell_L), \quad O^{LR \rightarrow l \ell} = (\bar{u}_{L,i} \gamma^\mu \ell_R)(\ell_R \gamma^\mu \ell_L),$$

where $i = 1, 2$ is flavor index and the subscript $R(L)$ denotes right-handed (left-handed) chirality. Here, we do not list all the operators with different color contractions, since they can be rewritten in terms of the operators shown above with aid of Fierz identity [2]. For specific models beyond the SM, production of triple-top at the LHC has been studied in the Minimum Supersymmetric Standard Model, a leptophobic $Z'$ model with flavor changing coupling [14] and in the top-color-assisted technicolor model [15].

The rest of paper is organized as follows. We begin in Section 2 with the calculations of production cross sections of triple-top signal and SM background at the LHC with 14 TeV center-of-mass (c.m.) energy. We also estimate the discovery potential. In Section 3, we show that using the on-shell conditions, one is able to reconstruct all of three top quarks and to determine the polarization of top quark that plays an important role to distinguish different effective operators. Our conclusions appear in Section 4.

2. Triple-top at LHC

The existence of operators $O^{\ell \ell \ell}$ in Eq. (2) implies the production of three top quarks at hadron colliders via $ug \rightarrow ttf$. The representative Feynman diagrams are shown in Fig. 1. Since we can always redefine these coefficients $c_i$ to take into account all the operators that involve the same SM fields, we parametrize the effective $\ell \ell \ell$ coupling strength as $c/A$ in the numerical study below. In SM the production of triple-top signal comes from processes

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We are interested in two new cuts, benchmarking the Madgraph 5 [16] with CTEQ 6L1 parton distribution function [17]. The result is shown in Fig. 2. Here, through this paper, we only show and focus on the production cross section of $pp \rightarrow t\bar{t}t$ since the $pp \rightarrow t\bar{t}t$ is much smaller due to the suppressed parton distribution function of $u$ inside the proton. As we can see in Fig. 2, the cross section for SM is about 1 fb, shown with the horizontal dashed line, since it involves weak interactions. We show three benchmark values for $\Lambda = 2.5$ and 10 TeV in black, red and blue curves, respectively. For triple-top in new physics that initiates $O_{\text{urt}}$, assuming an $O(1)$ coefficient $c$, the cross section could be much larger than the SM value when the scale $\Lambda$ is less than 5 TeV. Note that if strong dynamics takes place, the production cross section can be even larger since the $c$ can be as large as $O(10)$. In such case, the triple-top signal can be explored for the new physics scale $\Lambda$ beyond 10 TeV.

For the collider signature at the LHC, we focus on the case that two top quarks decay semileptonically and the anti-top quark decays fully hadronically. Therefore, the signal at the LHC we are interested in is $pp \rightarrow t\bar{t}t \rightarrow b\bar{b}b\ell^+\ell^-v_\ell v_\ell jj$ which leads to a distinguished signature of same-sign dilepton with 3 b-jets, 2 light jets and missing energy. For the event selection, we require the following cuts:

$$p_T > 20 \text{ GeV}, \quad |\eta| < 2.5, \quad p_T^j > 20 \text{ GeV}, \quad |\eta^j| < 2.5, \quad \vec{E}_T > 30 \text{ GeV}, \quad H_T > 800 \text{ GeV},$$

where $p_T$ is transverse momentum, $\eta$ is rapidity, $\vec{E}_T$ denotes the missing transverse energy and $H_T$ is defined as the scalar summation of transverse momentum of leptons and jets. After imposing these cuts, the acceptance for SM background is less than 5% while about 25% of signal remains. It is worth mentioning that the most effective cut to suppress SM background is the cut on $H_T$. In Fig. 3 we show the distributions of $H_T$. Both the SM and signal peak around $H_T \sim 500 \text{ GeV}$, but the distribution of SM drops rapidly while the signal decreases rather slowly when $H_T$ increases. As a result, the signal can be much larger than the SM background as we show the contour of signal to SM background ratio $S/B$ in Fig. 4(a). The green, red and black curves are the contours for $S/B = 10, 30$ and 50, respectively. In Fig. 4(b) we estimate the total number of events after imposing event selection cuts, assuming high luminosity of 300 fb$^{-1}$ at the LHC. The event number of triple-top signal is small due to the small production cross section, especially when $c$ is small or $\Lambda$ is large. Since $S/B$ is large, the event number estimated here is mainly the contribution of new physics. Therefore when the triple-top signal is discovered at the LHC, it would provide strong evidence of the signature of new physics beyond the SM.

3. Reconstruction and model distinction

When the triple-top signature is discovered at the LHC, the next question is how to extract further information from it. As we see previously in Eq. (2), one can write down the effective operator $O_{\text{urt}}$ with different chiralities of top quarks. We can, therefore, classify into three scenarios: right-handed top quarks, left-handed top quarks and unpolarized top quarks produced in the final state. The polarization of top quark obviously plays an important role to distinguish different operators and serves a guide for underlying theory beyond the SM. We describe how we can reconstruct three top quarks and determine the polarization of top quark in the rest of this section. The anti-top quark can be reconstructed by combining one b-jet with two light jets, since it decays hadronically. To choose the b-jet that is associated with anti-top among three tagged ones, we require that the invariant mass of the b-jet and two light jets must be most close to $m_t$ and must be within the mass window $m_t \pm 30 \text{ GeV}$. For two top quarks which decay semileptonically, the reconstruction is more difficult due to the two missing neutrinos in the final state. It is shown that [18], using the measurement
of missing transverse energy, combined with on-shell conditions of two W bosons and two top quarks, one can write down quartic equations for neutrino momentum. After solving the momentum of neutrino, it is straightforward to obtain momentum of top quarks, and many physics about top quark can be studied [19,20]. In order to solve the analytical equations for neutrinos, the correct pairing of b-jet and charged lepton \( \ell^+ \) plays a crucial role. Namely, the b-jet and \( \ell^+ \) we use in top quark on-shell condition should originate from the decay of the same top quark. However, there are two possibilities to pair two \( \ell^+ \) with two b-jets. Following Ref. [20], we use \( M_{T2} \) [21] variable to choose the correct combination of b-jet and \( \ell^+ \).

The \( M_{T2} \) is defined as

\[
M_{T2}^2 = \min \left[ \max \left[ M_T^2 \left( p_T^{(a)}, \not{E}_T^1 \right), M_T^2 \left( p_T^{(b)}, \not{E}_T^2 \right) \right] \right],
\]

where \( \not{E}_T^1 + \not{E}_T^2 \) is equal to total \( \not{E}_T \), \( M_T(p_T^{(a)}, \not{E}_T^1) \) is the transverse mass for the system that has visible particle or cluster \( a(b) \) and missing energy \( \not{E}_T^1 \). In our scenario, the visible cluster is the combination of a b-jet and a charged lepton \( \ell^+ \). The distributions of \( M_{T2} \) for two possible pairings of b-jet and \( \ell^+ \) are shown in Fig. 5. For the correct combination of b-jet and \( \ell^+ \), the black histogram in the left panel, has a sharp drop-off at \( M_{T2} \approx 150 \) GeV, while the distribution of wrong pairing smoothly spreads out, as seen in red histogram. We further show the two dimensional plot of \( M_{T2} \) for correct and wrong pairings of b-jet and \( \ell^+ \) in the right panel of Fig. 5. It is obvious that the correct combination usually has a smaller value of \( M_{T2} \) than the wrong one in the event by event basis. Therefore, we calculate \( M_T \) for two possible combinations of b-jet and \( \ell^+ \) event by event, and then we choose the combination that has a smaller \( M_{T2} \) when we use the on-shell conditions to solve for momentum of neutrino in the quartic equations proposed by Ref. [18]. After the momentum of neutrino is determined, it is straightforward to reconstruct the entire triple-top event and study the polarization of top quark.

It is well known that, among the decay productions of top quark, the charged lepton is the best particle to study polarization of top quark [22]. In the rest frame of top quark, the angular distribution of charge lepton \( \ell^+ \) is given by \( \frac{1}{2} (1 \pm \cos \theta) \), with "+" for right-handed and "−" for left-handed polarized top quarks, where \( \theta \) is the angle between the momentum of \( \ell^+ \) and the spin axis of top quark. Fig. 6 shows the normalized distributions of \( \cos \theta \) of \( \ell^+ \) for different effective operators (i.e. Eq. (2)) that predict different polarizations of top quarks triple-top scenario. The black and red histograms are for \( \mathcal{O}_{unl}^{RR} \) and \( \mathcal{O}_{unl}^{LL} \) that predict right-handed and left-handed top quarks, respectively. The flat green histogram is for \( \mathcal{O}_{unl}^{LR} \) or \( \mathcal{O}_{unl}^{LRL} \) that predict unpolarized top quark in the final state. The distributions are slightly destroyed from the shape of \( \frac{1}{2} (1 \pm \cos \theta) \) due to the kinematic cuts we imposed. However, the difference between different polarizations of top quarks is obvious. If only statistical uncertainty is taken into account, we estimate

![Fig. 4](image-url)

(a) The contour of ratio of signal to SM background (S/B) and (b) the contour of event number of signal at 14 TeV LHC with 300 fb\(^{-1}\) luminosity. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

![Fig. 5](image-url)

Fig. 5. Left: Distributions of \( M_{T2} \) of the pair of a b-jet and a charged lepton. The black histogram is for the b-jet and charge lepton from the same top quark decay (correct pairing); the red histogram is for the b-jet and charge lepton from different top quark decay (wrong pairing). Right: Two dimensional plot of \( M_{T2} \) for correct and wrong pairings event by event. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
that the \( \cos \theta \) distribution of right-handed top quark (black histogram in Fig. 6) can be distinguished from case of left-handed top quark (red histogram in Fig. 6) with about 30 events spread over 10 bins at 3\( \sigma \) level, based on Poisson statistics. To distinguish right-handed top quark from unpolarized case (green histogram in Fig. 6), we need about 100 events.

4. Conclusion

In this paper, we study the triple-top production, \( ug \rightarrow t\bar{t}t \), at the 14 TeV LHC based on the four-fermion operator \( O_{\text{NLO}} \). We focus on the final state in which anti-top quark decays hadronically and two top quarks decay semileptonically. The collider signature is therefore \( \ell^+\ell^- bbjj\bar{\ell} \). Due to the small production cross section of three top quarks in SM, we show that, after imposing event selection criteria, the signal to background ratio could be much larger than 1. Therefore, the triple-top process could be a good place to look for signature of beyond SM.

To reconstruct top quarks, we use a b-jet combined with two light jets for anti-top quark reconstruction. Reconstruction of two top quarks is a challenge due to the two missing neutrinos in the final state. We show that using on-shell conditions for top quarks and \( W \) bosons with the aid of \( M_{T2} \), the momentum of neutrino in top quark decay can be solved. Hence, we are able to boost back to the rest frame of top quark and determine the polarization of top quark using the angular distribution \( \cos \theta \) of the charged lepton. Top quark in the final state from different effective operators can be categorized as right-handed, left-handed and unpolarized. We estimate that about 30 events are needed to distinguish the case of left-handed from the right-handed one. To differentiate unpolarized top quark final state from the right-handed case, we need about 100 events. With the efficient identification of top quark polarization, triple-top signal could shed light on underlying theory beyond the Standard Model.

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