The heavy charged gauge bosons were proposed in the theories beyond standard model. We explore the discovery potential for $W' \rightarrow t\bar{b}$ with top quark semi-leptonic decay at the LHC. We concentrate on the new physics signal search with the deviation from the standard model prediction if the resonance peak of $W'$ can not be observed directly. The events of signal with two jets plus one charged lepton and missing energy are simulated together with the dominant standard model backgrounds. In this paper, it is found that suitable cuts on the kinematic observables can effectively suppress the standard model backgrounds, so that it is possible to search for $W'$ signal at the LHC with its mass less than 6.6 TeV.

I. INTRODUCTION

Gauge sector extension is one of the promising new physics theories beyond the standard model (SM). Heavy charged gauge bosons($W'^\pm$) are involved in a number of the new physics models, such as Extra Dimension [1–7], Little Higgs [8–10], and GUTs [11–13], etc. A simple but well-motivated scenario is the Left-Right symmetric model [14–18], which is based on the extended $SU(2)_L \times SU(2)_R \times U(1)$ gauge group. Provided the current experimental constraints, a TeV-scaled charged gauge boson is allowed, which provides the opportunity for the new physics searches at the LHC.

The leptonic decay $W' \rightarrow l\nu$ is the golden channel for the search of $W'$ if the couplings to the SM leptons are not specific suppressed. According to a $M_T$-distribution, determined by the transverse momentum of the charged leptons and missing transverse energy, the lower mass limits of 4.1 TeV for the sequential SM $W'$ boson is obtained by the CMS collaboration at $\sqrt{s} = 13$ TeV LHC [19]. Although the leptonic decay modes are experimentally clean and possibly the first observed one, the other decay channels need to be elaborately learned for the understanding
the properties of the heavy bosons, especially in some leptonic branch ratio suppressed scenarios. Although the light quark decay modes of $W' \rightarrow q\bar{q}'$ possess a larger production rate than $W' \rightarrow t\bar{b}$ channel, there is no advantage for the searching of $W'$ boson due to the large QCD backgrounds at the LHC. Furthermore, the $W' \rightarrow t\bar{b}$ mode is featured by the characteristic jet-substructure with the top quark and a large number of events with single top quark production can be accumulated at the LHC.

If the $W'$ is discovered at the LHC, it becomes imperative to investigate the details of its intrinsic properties and the interactions with other particles [20]. The chiral couplings to the standard model fermions are the crucial features which differ from the SM weak interactions in some specific models. It demonstrates that the angular distributions of the top quark and lepton resulting from top decay can be used to disentangle the chiral couplings of the $W'$ to SM fermions with the $W' \rightarrow t\bar{b}$ mode [20]. we also have found that the charged lepton angular distribution can be used to distinguish the chirality of $W'$ in the decay mode of $W' \rightarrow WH \rightarrow b\bar{b}l\nu$ [21]. Moreover, the investigating of $W'$ boson is extended to the associated production or exotic decay modes [20, 22].

Recently, The CMS collaboration has reported the latest results on the search of resonance peak with $W' \rightarrow t\bar{b}$ [23]. The right-handed $W'$ boson is excluded for the mass less than 2.6 TeV with the top quark hadronic and leptonic decaying. Unfortunately, no evidence on the $W'$ resonance peak can be observed directly up to now. Motivated by the reach of $W'$ investigation at the LHC, we provide various strategies to search for the significant excess from the standard model prediction in the kinematics distributions other than the new resonance peak. We propose four schemes based on different cuts to suppress the standard model backgrounds. Cuts on the transverse momentum of jets ($p_T^j$), invariant mass of jets ($M_{jj}$), collision energy scale ($H_T$) and invariant mass of top and bottom quark ($M_{t\bar{b}}$) are adopted to highlight the signal process respectively. One can obtain that the lower mass limit for the sequential $W'$ boson is up to 3.7-6.6 TeV.

This paper is arranged as follows. In Sec. II we briefly depict the theoretical framework and show the difference between $W'_L$ and $W'_R$ boson. The detector simulation and numerical results with various schemes are presented in III. Finally, a short summary is given in Sec. IV.

II. THEORETICAL FRAMEWORK

The heavy charged gauge bosons are predicted in many new physics theories. Provided that the theory of SM is the approximation of the new physics in the low energy scale, it will be the most
directly detection for new physics via the decaying of the heavy particles into the SM particles. The relevant gauge interactions between $W'$ and fermions can be generalized in the formula of

$$\mathcal{L} = g_L \frac{g_2^2}{\sqrt{2}} \bar{\psi}_L \gamma_a \gamma_5 \psi L \frac{1}{2} (1 - \gamma_5) \psi j W'_L + g_R \frac{g_2^2}{\sqrt{2}} \bar{\psi}_R \gamma_a \gamma_5 \psi R \frac{1}{2} (1 + \gamma_5) \psi j W'_R + H.c.,$$

(1)

where $g_2$ is the SM electroweak coupling and $g_L$ ($g_R$) is the left-handed (right-handed) coupling constant, with $g_L = 1$, $g_R = 0$ the pure left-handed gauge interaction (labeled as $W'_L$) and $g_L = 0$, $g_R = 1$ the pure right-handed gauge interaction (labeled as $W'_R$). $V'$ is the flavor mixing matrix as the Cabibbo-Kobayashi-Maskawa matrix in the SM.

Both handed $W'$ bosons can be existed in the left-right symmetric model as well as the right-handed fermion doublets, which lead to a heavy neutrino($N$). As discussed in [24], if the $W'$ is heavier than $N$, the decay mode of $W' \rightarrow lN$ is open, which provides an interesting like-sign dilepton production process to learn the lepton number violating. Otherwise, we can only investigate the $W'$ boson from its couplings to SM particles with the $W' \rightarrow lN$ decay modes forbidden. Thus the dominant three decay modes are $W' \rightarrow t\bar{b}$, $W' \rightarrow q\bar{q}'$, and $W' \rightarrow t\nu$. The right-handed $W'$ has the same decay modes as the left-handed one except for the $W' \rightarrow t\nu$ since the right-handed neutrino is absent in SM. The $W'_L$ has a larger decay width than $W'_R$ which is expressed in the following formulae

$$\Gamma_{W'_L} = \frac{g_2^2 g_R^2 m_{W'}}{16\pi} \left[ 2 + \left( 1 - \frac{m_t^2}{m_{W'}^2} \right) \left( 1 - \frac{m_t^2}{2m_{W'}^2} - \frac{m_t^4}{2m_{W'}^4} \right) \right],$$

$$\Gamma_{W'_R} = \frac{g_2^2 g_R^2 m_{W'}}{16\pi} \left[ 3 + \left( 1 - \frac{m_t^2}{m_{W'}^2} \right) \left( 1 - \frac{m_t^2}{2m_{W'}^2} - \frac{m_t^4}{2m_{W'}^4} \right) \right],$$

(2)

where $m_{W'}$ ($m_t$) is the mass of $W'$ boson (top quark).

In this paper, we focus on the the process of

$$pp \rightarrow W'^+/W^+ \rightarrow b\bar{t} \rightarrow b\bar{b}l^+\nu, \quad l^+ = e^+, \mu^+.$$  

(3)

The corresponding total cross section can be written as

$$\sigma = \int f_q(x_1) f_{\bar{q}}(x_2) \hat{\sigma}(\sqrt{x_1 x_2 S}) d x_1 d x_2,$$

(4)

where $f_q(x_i)$ is the parton distribution function (PDF) with $x_i$ the parton momentum fraction. $\sqrt{S}$ is the proton-proton collision center of mass energy. $\hat{\sigma}$ represents the partonic cross section of process

$$q(p_1) + \bar{q}(p_2) \rightarrow W'^+/W^+ \rightarrow \bar{b}(p_3) + t(p_4) \rightarrow \bar{b}(p_5) + b(p_4) + l^+(p_5) + \nu(p_6),$$

(5)
with \( p_i (i=1,2,3,4,5,6) \) is the momentum of the corresponding particle, and \( p_t \) is the momentum of top quark. The corresponding Feynman diagram is shown in Fig. 1 with the differential cross section

\[
d\hat{\sigma} = \frac{1}{2s} |\mathcal{M}|^2 d\mathcal{L}ips_4,
\]

where \( s = x_1 x_2 S \), and \( \mathcal{L}ips_4 \) denotes the Lorentz invariant phase space of four final particles. \(|\mathcal{M}|^2\) represents the invariant amplitude of the partonic process (5) summed (averaged) over the final (initial) particle colors and spins, and can be written as,

\[
|\mathcal{M}|^2 = \begin{cases} 
|\mathcal{M}_{W'_L}|^2 + |\mathcal{M}_{W'_R}|^2 + 2Re(\mathcal{M}_{W'_L}^* \mathcal{M}_{W'_R}), & \text{for } W'_L; \\
|\mathcal{M}_{W_L}|^2 + |\mathcal{M}_{W_R}|^2, & \text{for } W'_R.
\end{cases}
\]
where $|\mathcal{M}_i|^2$ ($i = W_L, W_R, W$) is the corresponding invariant amplitude and $2Re(\mathcal{M}_{W_L}^{*} \mathcal{M}_w)$ is the interference term between $W_L$ and $W$.

$$|\mathcal{M}_{W_L}|^2 = \frac{32g_L^4g_3^4(p_1 \cdot p_3)(p_4 \cdot p_5)(2(p_2 \cdot p_t)(p_t \cdot p_6) - p_t^2(p_2 \cdot p_6))}{[(p_t^2 - m_t^2)^2 + m_t^2\Gamma_t^2][(p_w^2 - m_w^2)^2 + m_w^2\Gamma_w^2][(s - m_w^2)^2 + m_w^2\Gamma_w^2]},$$

$$|\mathcal{M}_{W_R}|^2 = \frac{32g_R^4m_t^2g_3^4(p_1 \cdot p_3)(p_4 \cdot p_5)(2(p_2 \cdot p_t)(p_t \cdot p_6) - p_t^2(p_2 \cdot p_6))}{[(p_t^2 - m_t^2)^2 + m_t^2\Gamma_t^2][(p_w^2 - m_w^2)^2 + m_w^2\Gamma_w^2][(s - m_w^2)^2 + m_w^2\Gamma_w^2]},$$

$$|\mathcal{M}_W|^2 = \frac{32g_L^4g_3^4(p_1 \cdot p_3)(p_4 \cdot p_5)(2(p_2 \cdot p_t)(p_t \cdot p_6) - p_t^2(p_2 \cdot p_6))}{[(p_t^2 - m_t^2)^2 + m_t^2\Gamma_t^2][(p_w^2 - m_w^2)^2 + m_w^2\Gamma_w^2][(s - m_w^2)^2 + m_w^2\Gamma_w^2]},$$

$$2Re(\mathcal{M}_{W_L}^{*} \mathcal{M}_w) = \left\{ \frac{2[(s - m_w^2)(s - m_{W_L}^2) + m_w\Gamma_wm_{W_L}\Gamma_{W_L}]}{[(s - m_w^2)^2 + m_w^2\Gamma_w^2][(s - m_{W_L}^2)^2 + m_{W_L}^2\Gamma_{W_L}^2]} \right\} \frac{32g_L^4g_3^4(p_1 \cdot p_3)(p_4 \cdot p_5)(2(p_2 \cdot p_t)(p_t \cdot p_6) - p_t^2(p_2 \cdot p_6))}{[(p_t^2 - m_t^2)^2 + m_t^2\Gamma_t^2][(p_w^2 - m_w^2)^2 + m_w^2\Gamma_w^2]]. \tag{8}$$

The couplings of $g_{LL,LR}$ are arbitrary in various models, while it is well known as the Sequential $W'$ model with the $W'$ boson has the same couplings to quarks and leptons as the $W$ boson. We have the numerical results in the framework of Sequential $W'$ model. CTEQ6L1 [25] is set for PDF, with $m_W = 80.4$ GeV and $m_t = 173.1$ GeV [26]. The cross section of process $pp \rightarrow W'^* \rightarrow b\bar{t} \rightarrow b\bar{b}l^+\nu_l (l^+ = e^+, \mu^+)$ with respect to the $W'$ mass at 13 and 14 TeV is shown in Fig. 2. There are even more than ten events produced with a $W'$ mass around 6 TeV with a luminosity of 300 $fb^{-1}$. So in the following work we focus on the investigation of $W'$ at 14 TeV and suppose a luminosity of 300 $fb^{-1}$ if there is no special instruction.

### III. NUMERICAL RESULTS AND DISCUSSION

Once the $W'$ boson is produced at the LHC, the $W' \rightarrow t\bar{b}$ channel will play an important role in the search for $W'$ signal in the large $W'$ mass region. In this work, we provide various strategies to investigate the lower limit on $W'$ mass from the $t\bar{b}$ production with the signal of 2 jets + 1 lepton + $E_T$.

The resonance peak through the invariant mass of $M_{t\bar{b}}$ can be reconstructed as shown in Fig. 3. The differential distributions with the invariant mass of $M_{t\bar{b}}$ between the $W'_L + W$ and $W'_R + W$ differ from the interference term. The valley region due to the negative contribution from the interference term in the mass region of $m_W < M_{t\bar{b}} < m_{W'}$ for $W'_L$, whereas no interference term between $W'_R$ and $W$ boson. This kind of phenomena can be used to distinguish $W'_L$ from $W'_R$ if enough events are accumulated. Moreover, the SM $W$ boson takes over a large number in the $t\bar{b}$
FIG. 3: The invariant mass $M_{tb}$-distribution with $m_{W'} = 2, 3, 4, 5$ TeV at 14 TeV for the process of (3). (a) $W' = W'_L$, (b) $W' = W'_R$. production comparing with $W'$ especially in the small $M_{tb}$ region. Thus it is crucial to suppress the influence from $W$ boson in the search of $W'$ boson.

FIG. 4: The $p_T$-distribution of $b$ and $\bar{b}$ quark related to the process $pp \rightarrow W'^+ \rightarrow \bar{b}t \rightarrow \bar{b}bl'\nu$ ($l^+ = e^+, \mu^+$) with $m_{W'} = 2$ TeV at 14 TeV. Fig.4 shows the transverse momentum ($p_T$) distribution of the $\bar{b}$ and $b$ quark related to the process $pp \rightarrow W'^+ \rightarrow \bar{b}t \rightarrow \bar{b}bl'\nu$ ($l^+ = e^+, \mu^+$) with $m_{W'} = 2$ TeV. The distribution of bottom anti-quark has a peak around one TeV since for a parent particle of mass $M$ decaying to two light particles, there is a Jacobian peak near $M/2$ in the transverse momentum distribution of final state
particle. Such distributions can be used to set cuts to suppress the backgrounds. In addition, the distribution of bottom quark shows difference between $W'_L$ and $W'_R$ because of the top quark spin correlation effects, which provides the opportunity to distinguish the chirality of $W'$ boson [20].

To be as realistic as possible, we simulate the detector performance by smearing the leptons and jets energies according to the assumption the Guassian resolution parametrization

$$\frac{\delta(E)}{E} = \frac{a}{\sqrt{E}} \oplus b$$

where $\delta(E)/E$ is the energy resolution, $a$ is a sample term, $b$ is a constant term, and $\oplus$ denotes a sum in quadrature. We always use $a = 5\%$, $b = 0.55\%$ for leptons and $a = 100\%$, $b = 5\%$ for jets respectively [27]. In order to identify the isolate jet (lepton), we define the angular separation between particle $i$ and particle $j$ as

$$\Delta R_{ij} = \sqrt{\Delta \phi_{ij}^2 + \Delta \eta_{ij}^2},$$

where $\Delta \phi_{ij}$ ($\eta_{ij}$) is the difference of azimuthal angles (rapidity) between the related particles.

For the process of (5), $W'$ decays to two particles which are back to back in the transverse plane. The $W$ boson and bottom quark are collimated due to the top quark is highly boosted, so that the angular separation $\Delta R_{\ell b}$ between the charged lepton and bottom quark is peaked at a low value and the angular separation $\Delta R_{bb}$ between the bottom quark and bottom anti-quark is peaked near $\pi$. Therefore, we impose the basic cuts as

$$\Delta R_{\ell b} > 0.3, \Delta R_{bb} > 0.4, P_T^\ell > 20 \text{ GeV},$$

$$P_T^j > 50 \text{ GeV}, \eta(j) < 3.0, E_T > 25 \text{ GeV}.$$ (11)

Fig.5 shows the invariant mass ($M_{tb}$) distribution for $m_{W'} = 2, 3, 4, 5 \text{ TeV}$ at 14 TeV with the basic cuts. Compared with Fig.3, the discrepancy of the peak between $W'$ and $W$ boson is weakened after the basic cuts due to more events with small transverse momentum are generated in the $W$ boson process.

Besides the $W$ boson intermediate process, the dominant backgrounds include $W^+ jj$, $W^+ b\bar{b}$, $W^+ g \rightarrow t\bar{b}$ and $bq \rightarrow tj$ processes. To suppress these backgrounds, we first require a bottom quark (b-tagging) in the final jets. Then we attempt to use various kinematics variables to highlight the excess out of the standard model prediction in the observation of the final states 2 jets + 1 lepton + $E_T$. In the following we investigate the exclude $W'$ mass region from four strategies, i.e., $P_T^j$-Scheme, $M_{jj}$-Scheme, $H_T$-Scheme and $M_{tb}$-Scheme, respectively.
FIG. 5: The invariant mass $M_{t\bar{b}}$-distribution for $m_{W'} = 2, 3, 4, 5$ TeV at 14 TeV with the basic cuts for the process (3). (a) $W' = W'_L$, (b) $W' = W'_R$.

A. $P_T^j$-Scheme

FIG. 6: The invariant mass $M_{t\bar{b}}$-distribution for $m_{W'} = 2, 3, 4, 5$ TeV at 14 TeV with the basic cuts and $P_T^{j_1} > \frac{1}{2}m_{W'}$, $P_T^{j_2} > 100$ GeV for the process (3). (a) $W' = W'_L$, (b) $W' = W'_R$.

We set cuts on the jet transverse momenta $P_T^{j_i}$ (i = 1,2) with $P_T^{j_1} > P_T^{j_2}$, provided the signal process with a larger number of high $P_T$ than the $W$ boson process. Fig. 6 illustrates the invariant mass $M_{t\bar{b}}$-distribution for various $W'$ masses with the basic cuts and $P_T^{j_i} > \frac{1}{2}m_{W'}$, $P_T^{j_2} > 100$ GeV.
The lower peak in each curve is the remnant contribution from SM \( W \) boson which is about one order of magnitude less than the signal peak. The number of events in each bin is displayed in Fig.7. Taking \( m_{W'} = 3 \text{ TeV} \) as an example, there remain hundreds of events after the cuts. If we set the proper \( P_j^T \) cut, the SM \( W \) boson effects will be suppressed so that it would be possible to observe the excess in the \( M_{t\bar{b}} \)-distribution plots. The other backgrounds are investigated as well.

In Table I we list the remaining cross section after the \( P_j^T \) cuts. The cross section of \( W^+ j j \) is the largest in the backgrounds while it decreases sharply with the increasing of the \( P_j^T \) cuts since most of the jets are soft. The background cross sections decrease with the increasing of the \( P_j^T \) cuts as well as the signal process, thus we adopt a varying cuts as \( P_j^{T1} > \frac{1}{2}m_{W'} \) and \( P_j^{T2} > 100 \text{ GeV} \). The cross sections of the total background cross section and signal are listed in Table II as well as the significance \( S/\sqrt{B} \). We display the significance with respect to the \( W' \) mass in Fig.8 to illustrate the detectable mass region at the LHC with \( \sqrt{s} = 14 \text{ TeV} \). It shows that the upper limit can reach 4 TeV with a \( 3\sigma \) significance for left-handed \( W' \) as well as the right-handed one. Furthermore, the significance for \( W'_L \) is slightly lower than \( W'_R \) because of the negative effects on the cross section from the interference with \( W \) boson.
\[ \sigma(fb) \quad W^+ jj(fb) \quad W^+ b\bar{b}(fb) \quad W^+ g \rightarrow t\bar{b}(fb) \quad bq \rightarrow tj(fb) \quad W(fb) \]

| \( P_T^{j1} > 400 \text{ GeV} \) | 114.0 | 1.159 | 7.726 | 10.85 | 2.947 |
| \( P_T^{j1} > 600 \text{ GeV} \) | 26.44 | 0.2313 | 1.189 | 1.505 | 0.6774 |
| \( P_T^{j1} > 800 \text{ GeV} \) | 9.254 | 0.0608 | 0.1971 | 0.1967 | 0.1961 |
| \( P_T^{j1} > 1000 \text{ GeV} \) | 3.173 | 0.0152 | 0.0435 | 0.0393 | 0.0652 |
| \( P_T^{j1} > 1200 \text{ GeV} \) | 0 | 0.0005 | 0.0108 | 0.0098 | 0.0236 |

TABLE I: The cross section of SM backgrounds at 14 TeV with the basic cuts, \( P_T^{j2} > 100 \text{ GeV} \) and various \( P_T^{j1} \) cuts.

| \( m_{W'} = 2 \text{ TeV} \) | \( m_{W'} = 3 \text{ TeV} \) | \( m_{W'} = 4 \text{ TeV} \) | \( m_{W'} = 5 \text{ TeV} \) |
| \( W'_L \) | \( W'_R \) | \( W'_L \) | \( W'_R \) | \( W'_L \) | \( W'_R \) | \( W'_L \) | \( W'_R \) |
| \( \sigma_S(fb) \) | 29.700 | 33.740 | 3.880 | 4.186 | 0.566 | 0.590 | 0.007 | 0.084 |
| \( \sigma_B(fb) \) | 136.64 | 30.04 | 9.91 | 3.34 |
| \( S/\sqrt{B} \) | 44.0 | 50.0 | 12.3 | 13.2 | 3.1 | 3.3 | 0.7 | 0.8 |

TABLE II: The cross section of signal (\( \sigma_S \)) and that of SM backgrounds (\( \sigma_B \)) at 14 TeV with the basic cut, \( P_T^{j1} > \frac{1}{2} m_{W'} \) and \( P_T^{j2} > 100 \text{ GeV} \).

![FIG. 8: The significance distribution with different \( W' \) mass at 14 TeV with the basic cuts, \( P_T^{j1} > \frac{1}{2} m_{W'} \) and \( P_T^{j2} > 100 \text{ GeV} \).](image-url)
FIG. 9: The number of events in each bin (200 GeV) with respect to the invariant mass $M_{jj}$ at 14 TeV with the basic cuts and $M_{jj} > \frac{1}{2}m_{W'}$ for the process (3). (a) $W' = W'_L$, (b) $W' = W'_R$.

B. $M_{jj}$-Scheme

The distribution of the invariant mass of the two jets $M_{jj}$ for the signal is different from the backgrounds. We show the number of events in each bin with respect to the invariant mass $M_{jj}$ in Fig.9, where the basic cuts are required as well as $M_{jj} > \frac{1}{2}m_{W'}$. The $W$ boson influence can be neglected in the $M_{jj}$ distribution after cuts. Comparing with the $M_{tb}$ distribution in Fig.7, there is no clear peak in the curves, while the excess is obvious. Moreover, the upland is broaden but lower with the $W'$ mass increasing. The cross section of backgrounds with the basic cuts and varying $M_{jj}$ cuts is listed in Table III. After we set $M_{jj} > 3000$ GeV, the main background is $W^+ jj$ with the cross section of 0.26$f b$. As well as the cross section of signal and backgrounds is listed in Table IV with different $W'$ masses. Suppose the $W'$ mass is 4 TeV, after we set a cut of $M_{jj} > 2000$ GeV, there remain 170 (120) events for $W'_L$ ($W'_R$) at 14 TeV LHC with the luminosity of 300$f b^{-1}$. Fig. 10 illustrates the detectable $W'$ mass region at 14 TeV with the basic cuts and $M_{jj} > \frac{1}{2}m_{W'}$ for $S/\sqrt{B} > 3$. The $W'$ mass should be larger than 3.7 (4) TeV with a $3\sigma$ significance for $W'_R$ ($W'_L$) if there is no excess in the $M_{jj}$ distribution.
TABLE III: The cross section of SM backgrounds at 14 TeV with basic cuts and $M_{jj}$ cut.

| $M_{jj}$ (GeV) | $\sigma(fb)$ | $W^+jj$ | $W^+bb$ | $W^+g \rightarrow tb$ | $bq \rightarrow tj$ | $W$ |
|----------------|-------------|---------|---------|-----------------|------------------|----|
| $>1000$        | 104.7       | 0.4459  | 13.19   | 1.495           | 0.8148           |    |
| $>1500$        | 28.56       | 0.0725  | 2.952   | 0.2065          | 0.1366           |    |
| $>2000$        | 7.932       | 0.0018  | 0.7667  | 0.0197          | 0.0306           |    |
| $>2500$        | 3.173       | 0.0039  | 0.2281  | 0.0098          | 0.0797           |    |
| $>3000$        | 0.2644      | 0.0010  | 0.0590  | 0               | 0.0022           |    |

TABLE IV: The cross section of signal ($\sigma_S$) and that of SM backgrounds ($\sigma_B$) at 14 TeV with the basic cuts and $M_{jj} > \frac{1}{2}m_{W'}$.

| $m_{W'}$ (TeV) | $\sigma_S(fb)$ | $\sigma_B(fb)$ | $S/\sqrt{B}$ |
|----------------|----------------|----------------|--------------|
| 2              | 28.720         | 120.64         | 45.3         |
| 3              | 26.840         | 31.93          | 42.3         |
| 4              | 3.724          | 8.75           | 11.4         |
| 5              | 3.028          | 3.44           | 9.3          |

FIG. 10: The significance distribution with different $W'$ mass at 14 TeV with the basic cuts and $M_{jj} > \frac{1}{2}m_{W'}$. 

$M_{jj} > \frac{1}{2}m_{W'}$. 

$5\sigma$ 

$3\sigma$
C. $H_T$-Scheme

Due to the large mass of $W'$ boson, the signal process can happen only if a great energy transferring in the collision. Thus we can use the great energy scale $H_T$ to discrete the signal and backgrounds. $H_T$ is the scalar sum of the transverse momentum for the final state, which is defined as

$$H_T = P_T^{j1} + P_T^{j2} + P_T^j + E_T^j,$$

(12)

Fig. 11 shows the number of events per bin with respect to $H_T$ with the basic cuts and $H_T > \frac{1}{2}m_{W'}$. It has a broaden upland in each curves like in the $M_{jj}$ distribution, while the upper mass limit for $W'$ is up to 5 TeV for two events remaining. The cross section of backgrounds is listed in

![Graphs showing the number of events per bin (200 GeV) with respect to the collision energy scale $H_T$ at 14 TeV with the basic cuts and $H_T > \frac{1}{2}m_{W'}$ for the process (3). (a) $W' = W'_L$, (b) $W' = W'_R$.](image)

Table V with the basic cuts and varying $M_{jj}$ cut. As the results shown in the table, $W'^* jj$ and $bq \rightarrow tj$ processes are cut down to zero after the $H_T > 3000$ GeV, meanwhile other backgrounds have a tiny cross section left. So it is an effective way to suppress the SM backgrounds to set an proper $H_T$ cut. The total cross section for signal and backgrounds is summarized in Table VI. For $m_{W'} = 4$ TeV, there are about 180 events for the signal and 1080 events for backgrounds with a cut of $H_T > \frac{1}{2}m_{W'}$. As shown in Fig. 12, the $W'$ can be detectable with mass below 4.7 TeV in the $H_T$ distribution for $3\sigma$ significance at 14 TeV.
**TABLE V**: The cross section of SM backgrounds at 14 TeV with the basic cuts and $H_T$ cut.

| $H_T > 1000$ GeV | $\sigma(fb)$ | $W^+ jj$ | $W^+ b\bar{b}$ | $W^+ g \to tb$ | $bq \to tj$ | $W$ |
|------------------|-------------|----------|----------------|--------------|-------------|-----|
|                  | 85.4        | 0.9222   | 3.734          | 5.035        | 1.704       |
| $H_T > 1500$ GeV | 14.81       | 0.1490   | 0.3508         | 0.354        | 0.314       |
| $H_T > 2000$ GeV | 3.437       | 0.0294   | 0.0357         | 0.0393       | 0.0771      |
| $H_T > 2500$ GeV | 0.2644      | 0.0074   | 0.0109         | 0.0197       | 0.0222      |
| $H_T > 3000$ GeV | 0           | 0.0020   | 0.0031         | 0            | 0.0070      |
| $H_T > 3500$ GeV | 0           | 0.0010   | 0.0031         | 0            | 0.0022      |

**TABLE VI**: The cross section of signal ($\sigma_S$) and that of SM backgrounds ($\sigma_B$) and the significance at 14 TeV with the basic cuts and $H_T > \frac{1}{2}M_{W'}$.

| $m_{W'}$ | $\sigma_S(fb)$ | $\sigma_B(fb)$ | $S/\sqrt{B}$ |
|----------|----------------|----------------|--------------|
| 2 TeV    | 30.790         | 96.79          | 54.2         |
| 3 TeV    | 36.540         | 15.98          | 64.3         |
| 4 TeV    | 4.000          | 4.248          | 17.3         |
| 5 TeV    | 4.248          | 3.62           | 18.4         |
|          | 0.609          | 0.577          | 5.5          |
|          | 0.577          | 0.32           | 5.2          |
|          | 0.088          | 0.079          | 2.7          |
|          | 0.079          | 2.4            | 2.4          |

**FIG. 12**: The Significance distribution for different $W'$ mass at 14 TeV with the basic cuts and $H_T > \frac{1}{2}M_{W'}$. 

$$H_T > \frac{1}{2}m_{W'}.$$
D. \( M_{tb} \)-Scheme

In the channel of \( W' \rightarrow t\bar{b} \), it will be the most effective way to reconstruct the \( W' \) mass peak by the momentum of top and bottom quark. Provided the semi-leptonic decay of top quarks, all the momenta of the final state can be detected in the detector except neutrino. However, we can obtain the transverse momentum of neutrino with the conservation of transverse momentum in the formula of

\[
P_{\nu T} = -(P_{T\ell} + P_{j1} + P_{j2}),
\]

where \( P_{jT} \) is the transverse momentum of \( j \) particle. While its longitudinal momentum cannot be detected, we can obtain it by solving the equation

\[
m_W^2 = (P_{\nu} + P_{\ell})^2,
\]

which implies the neutrino and charged lepton are generated by the on-shell \( W \) boson. Solving this quadratic equation for the neutrino longitudinal momentum leads to a twofold ambiguity. Furthermore, we can use the solution to reconstruct the top quark invariant mass through

\[
M_{tt} = \sqrt{(P_{\nu} + P_{\ell} + P_{j})^2}.
\]

We adopt the cuts on the top reconstruction,

\[
|M_{tt} - m_t| \leq 20 \text{ GeV}.
\]

Provided that all the final state momentum is confirmed, then we can reconstruct the whole process. The invariant mass of \( M_{tb} \) could obtain from

\[
M_{tb} = \sqrt{(P_{\nu} + P_{\ell} + P_{j1} + P_{j2})^2}.
\]

Fig. 13 displays the number of events per bin with basic cuts and \( M_{tb} > \frac{3}{2}M_{W'} \) for \( W' \) mass varying from 2 to 6 TeV. It is easy to find that the mass peak is clear in the \( M_{tb} \) distribution due to the whole process reconstruction. The cross section of backgrounds is listed in Table VII with the basic cuts and varying \( M_{tb} \) cuts. One can find that if a strict \( M_{tb} \) cut is adopted, all the backgrounds effects can be neglected except for the \( W \) boson process. Table VIII shows the total cross section for signal and backgrounds as well as the significance. The number of the signal events is more than one with \( m_{W'} = 6 \) TeV at 14 TeV with a luminosity of 300\( fb^{-1} \). The corresponding significance
FIG. 13: The number of events in each bin (200 GeV) with respect to the invariant mass $M_{\bar{t}b}$ at 14 TeV with the basic cuts and $M_{\bar{t}b} > 3/4 m_{W'}$ for the process (3). (a) $W' = W'_L$, (b) $W' = W'_R$.

| $m_{W'}$ (TeV) | $W'_{\bar{t}b}$ | $W'_{g\rightarrow tb}$ | $bq\rightarrow tj$ | W |
|----------------|-----------------|------------------------|---------------------|-----|
| 2              | 4.495           | 0.0034                 | 0.4454              | 0.9146 | 0.3978 |
| 3              | 0.2644          | 0                      | 0.0372              | 0.0197 | 0.054  |
| 4              | 0               | 0                      | 0.0016              | 0.0098 | 0.0093 |
| 5              | 0               | 0                      | 0                   | 0.0018 |
| 6              | 0               | 0                      | 0                   | 0.0003 |

TABLE VII: The cross section of SM backgrounds at 14 TeV with reconstruction and $M_{\bar{t}b} > 3/4 m_{W'}$.

| $m_{W'}$ (TeV) | $W'_{L}$ | $W'_{R}$ | $W'_{L}$ | $W'_{R}$ | $W'_{L}$ | $W'_{R}$ | $W'_{L}$ | $W'_{R}$ |
|----------------|----------|----------|----------|----------|----------|----------|----------|----------|
| 2              | 19.060   | 23.440   | 2.230    | 3.600    | 0.288    | 0.490    | 0.037    | 0.066    |
| 3              | 0.2644   | 0.38     | 0.02     | 0.0018   | 0.0003   |
| 4              | 0        | 0.37     | 101.78   | 54.7     |
| 5              | 0.02     | 0.0018   | 0.0003   |
| 6              | 0        | 0        | 0        | 0        |

TABLE VIII: The cross section of signal ($\sigma_S$) and that of SM backgrounds ($\sigma_B$) at 14 TeV with basic cut, reconstruction and $M_{\bar{t}b} > 3/4 m_{W'}$. 

$\frac{S}{\sqrt{B}}$
FIG. 14: The Significance distribution for different $W'$ mass at the LHC with the basic cuts and $M_{t\bar{b}}$ cut. (a) with $M_{t\bar{b}} > \frac{3}{4}m_{W'}$ at 14 TeV for a luminosity of 300 $fb^{-1}$. (b) with $M_{t\bar{b}} > \frac{2}{3}m_{W'}$ at 13 TeV for a luminosity of 72 $fb^{-1}$.

distribution with respect to the $W'$ mass is displayed in Fig.14a. The upper mass limit can be up to 6.2 (6.6) TeV with a 3$\sigma$ significance after we require $M_{t\bar{b}} > \frac{3}{4}m_{W'}$ for $W'_L$ ($W'_R$) if there is no excess to be observed.

Currently, the integrated luminosity is 36.1 $fb^{-1}$ reported by the ATLAS collaboration and 35.9 $fb^{-1}$ [28] by the CMS collaboration with the collision energy of 13 TeV [29], so we investigate the process of (3) at 13 TeV as well. Fig.14b displays the significance distribution with respect to the $W'$ mass with the basic cuts and a loose cut of $M_{t\bar{b}} > \frac{2}{3}m_{W'}$. If there is no excess to be observed, the $W'$ can be excluded with the mass less than 4.9 (5.5) TeV for $W'_L$ ($W'_R$) with 3$\sigma$ significance.

IV. SUMMARY

We investigate the process of $pp \rightarrow W'/W \rightarrow t\bar{b} \rightarrow b\bar{b}l\nu$ for the $W'$ signal via the kinematic distributions. As the signal events are characterized by 2 jets + 1 lepton + $E_T$, the dominant standard model backgrounds are $W^+jj$, $W^+b\bar{b}$, $W^+g \rightarrow t\bar{b}$ and $bq \rightarrow tj$. To reduce the backgrounds and improve the significance, we adopt four schemes, i.e., the transverse momentum of jets, the invariant mass of jets, the scalar sum of the transverse momentum as well as the missing transverse energy and the invariant mass of $t\bar{b}$ with the top quark reconstruction. By applying suitable cuts, it is possible to search for $W'$ signal at the LHC. For example, at 14 TeV with a luminosity of
300 fb$^{-1}$, in $H_T (M_{\tilde{b}})$ scheme the $W'_R$ signal can be observed with the mass below 4.6 (6.6) TeV. These results are the consequence from the process (3), while the significance will be improved if the process $pp \to W'^-/W^- \to \bar{t}b \to b\bar{b}\ell^- \bar{\nu}$ is included. The aim of this paper is to investigate the possibility of search for the $W'$ signal in the single top production, which shows the advantage to scan the kinematic distribution for the excess from the standard model prediction. Once large event numbers of single top quark production have been accumulated, our methods will be helpful to search for the $W'$ signal if the new heavy resonance peak can not be observed directly.

V. ACKNOWLEDGEMENTS

We would like to thank the members of particle groups in University of Jinan and Shandong University for their helpful discussions and comments. HL and WS thank for the hospitality of University of Arizona during the writing of this paper. This work is supported in part by the National Natural Science Foundation of China (NSFC) under grant Nos. 11325525/11635009/11775130/11447009/11305049 and Natural Science Foundation of Shandong Province under grant Nos. ZR2017JL006/ZR2017MA002.

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