Mono-top Signature from Fermionic Top-partner

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We investigate mono-top signatures arising from phenomenological models of fermionic top-partners, which are degenerate in mass and decay into a bosonic dark matter candidate, either spin-0 or spin-1. Such a model provides a mono-top signature as a smoking-gun, while conventional searches with $t\bar{t} +$ missing transverse momentum are limited. Two such scenarios: i) a phenomenological 3rd generation extra dimensional model with excited top and electroweak sectors, and ii) a model where only a top-partner and a dark matter particle are added to the SM, are studied in the degenerate mass regime. We find that in the case of extra dimension a number of different processes give rise to effectively the same mono-top final state, and a great gain can be obtained in the sensitivity for this channel. We show that the mono-top search can explore top-partner masses up to 630 GeV and 300 GeV for the 3rd generation extra dimensional model and the minimal fermionic top-partner model, respectively, at the high luminosity LHC.

I. INTRODUCTION

Mono-top searches have been proposed in a context of supersymmetry (SUSY) [1,3], especially when superpartner (stop, $t$) of the Standard Model (SM) top quark ($t$) is degenerate with (higgsino-like) neutralinos ($\tilde{h}^0$). In such a scenario, $t$ effectively behaves as an invisible particle since its decay products are too soft to be detected, and the sensitivity is therefore deteriorated for the standard $pp \to t\tilde{t}^*$ channel [12, 13]. It has been shown that in this regime the $pp \to th^0$ channel can have a measurable production rate due to the large top Yukawa coupling, leading to a characteristic mono-top + $E_T$ final state, where both $t$ and $h^0$ are effectively invisible. Differently than the usual mono-top signatures exploiting hard QCD initial state radiation and therefore providing very little information on the produced particles, the mono-top signature allows a direct probe of the top and neutralino sectors [1]. This means that the $th^0$ channel is complementary to the mono-jet channel or even essential in exploring the SUSY parameter space. While such a supersymmetric signature is very well motivated theoretically in terms of naturalness [14, 31], it is desirable to phenomenologically expand the scope of current mono-top studies including different spin-scenarios. As supersymmetry provides a spin-0 top partner together with a spin-1/2 dark matter (DM) candidate, we would like to extend the search to the case with a spin-1/2 top-partner, which decays into either spin-0 or spin-1 DM candidate. As in the supersymmetric case, we will assume the degeneracy between the fermionic top-partner and bosonic DM candidates.

For spin-0 top-partner case, ‘natural SUSY’ provides a well-motivated example for the degenerate spectrum. Similarly, for spin-1/2 top partner case, such a compressed spectrum is naturally realized in models with extra dimensions. A good benchmark model for the purpose of our analysis is Universal Extra Dimensions (UED), where all SM particles propagate in the bulk of flat extra dimensions, and the mass spectrum of Kaluza-Klein (KK) particles is degenerate [32]. This degeneracy is broken due to electroweak symmetry breaking, bulk and boundary term corrections from the renormalization group running between the cut-off scale and the electroweak scale [33–37]. Nevertheless, overall mass spectrum is much narrower than that for conventional supersymmetry. This observation strongly encourages revisiting mono-top production in the context of extra dimensions.

UED with a particular mass spectrum derived in [34, 35] is called ‘Minimal Universal Extra Dimensions’ (MUED) and has been extensively studied in the literature [33, 38]. Recently, it has been revisited with the 8 TeV and 13 TeV LHC data with the conventional cascade decays, [39, 40], and the estimated lower bound on the inverse radius is found to be around $R^{-1} \gtrsim 1.4$ TeV with some variation in the cut-off scale (Λ). These searches with jets, leptons and missing transverse momentum are promising in general, but their sensitivity gets poor for smaller mass splitting. On the other hand, the mono-jet channel becomes more sensitive for compressed spectra, which is expected for a low value of AR. This point is examined in Ref. [39], and they find that mono-jet searches result in the current bound $R^{-1} \gtrsim 1.1$ TeV ($\sim 1.2$ TeV and $\sim 1.3$ TeV for the masses of KK quark and KK gluon, respectively) for $AR \lesssim 5$ with 3.2 fb$^{-1}$ of data at the 13 TeV LHC, which is comparable to the mono-jet exclusion limits on the masses of squarks ($\gtrsim 0.8$ TeV) and gluino ($\gtrsim 1$ TeV) in supersymmetry [41, 42]. Since the mono-top signals arise from 3rd generation of KK quarks, we
will study the mono-jet channel with the corresponding particle content in our study. This should be compared to Ref. [38], where entire KK spectrum is included in the analysis.

Although collider phenomenology of extra dimensional models has been examined extensively for many years, its mono-top signature has not been pursued yet. Therefore, our study is worthwhile and will provide useful information concerning SUSY and UED searches. Moreover, in a particular case where only KK tops and KK dark matter candidates are considered without additional KK particles, our analysis is more generally applicable beyond extra dimensional models and our results would be still valid in a generic model with fermionic top partners and a dark matter candidate. Hence, although, in this paper, we refer to the fermionic results would be still valid in a generic model with additional KK particles, our analysis is more generally applicable beyond extra dimensional models and our results can be more general. We consider KK number conserving interactions in our study and therefore all interactions are fixed by the SM ones. Masses of the new particles are treated as free parameters, as in non-minimal UED [36], which we fix following the previous SUSY studies for comparison [1] [2]. We also take SUSY decay chains used in the previous study to guarantee an appropriate comparison against the existing results. All SUSY particles will be replaced with the corresponding ‘KK’ partners with different spins.

This paper is organized as follows. In Sec. II, we define two benchmark scenarios which are addressed in our study and describe the top-partner interactions that are relevant to the mono-top signature. In Sec. III, we present the result of our numerical study based on Monte Carlo simulations and derive the corresponding LHC bounds. Finally, a summary of our main findings is given in Sec. IV.

II. RELEVANT INTERACTIONS FOR FERMIONIC TOP-PARTNER

We consider two different scenarios in our mono-top study:

(i) a phenomenological 3rd generation extra dimensional model, which consists of the top-partner sector $(SU(2)_W$ singlet KK top $t^{(1)}$, and third generation $SU(2)_W$ doublet, $(T^{(1)}, B^{(1)})$) as well as the full KK Higgs and KK electroweak gauge boson spectrum. Such a scenario may be realized in non-minimal UED models [36] [49] [53].

(ii) a minimal scenario with one fermionic top-partner $t^{(1)}$ and bosonic DM candidate $h^{(1)}$ (spin-0) or $\chi^{(1)}_\mu$ (spin-1), as to stop plus neutralino corresponding to the simplified model in SUSY.

Following particle content and interactions as in UED, we assume the lightest KK particle (LKP) to be electrically neutral and colorless, so as to be the dark matter candidate. As long as the LKP is stable and invisible within the detectors, further specification of the LKP is not important since decays of KK particles are not visible due to the mass-degeneracy among them.

The KK photon $\gamma^{(1)}_\mu$ is essentially the KK hypercharge gauge boson, $\gamma^{(1)}_\mu \approx B^{(1)}_\mu$, since the Weinberg angle at KK level is small, $\theta^{(n)}_W \ll 1$. Similarly the KK $Z$ consists of mostly neutral component of $SU(2)_W$ KK gauge boson, $Z^{(1)}_\mu \approx W^{(1)3}_\mu$. This is analogous to the case of pure bino $\tilde{b}$ and zino $\tilde{z}$ in SUSY. $W^{(1)\pm}_\mu$ and $H^{(1)\pm}$ are the charged KK $W$ and KK Higgs bosons. We denote CP even and CP odd Higgs bosons as $h^{(1)}$ and $\chi^{(1)}$, respectively. The SM top quark and KK top quarks form the following Dirac fermions:

$$ t \left( \begin{array}{c} T_L \\ t_R \end{array} \right), \quad \text{SM top quark}, $$

$$ T^{(1)} = \left( \begin{array}{c} T^{(1)}_L \\ T^{(1)}_R \end{array} \right), \quad SU(2)_W \text{ doublet KK top}, \quad (1) $$

$$ t^{(1)} = \left( \begin{array}{c} t^{(1)}_L \\ t^{(1)}_R \end{array} \right), \quad SU(2)_W \text{ singlet KK top}. $$

Often $t^{(1)}$ ($T^{(1)}$) is called the right-handed (left-handed) KK top. However, it is really a vector-like quark. The handedness refers to the chirality of the SM fermion of its origin, i.e., $t^{(1)}$ is KK partner of the right-handed SM top $t_R$ and $T^{(1)}$ is the KK partner of the left-handed SM top $T_L$. The relevant interactions involving the SM top quark and the KK electroweak gauge bosons are

$$ g_1 \frac{Y_R}{2} \bar{t}^{(1)} \gamma^\mu P_R t^{(1)} \gamma^\mu + \text{h.c.}, $$

$$ g_1 \frac{Y_L}{2} \bar{T}^{(1)} \gamma^\mu P_L t^{(1)} \gamma^\mu + \text{h.c.}, $$

$$ g_2 \frac{1}{2} \bar{T}^{(1)} \gamma^\mu P_L t^{(1)} Z^{(1)}_\mu + \text{h.c.}, $$

$$ g_2 \frac{1}{\sqrt{2}} \bar{B}^{(1)} \gamma^\mu P_L t W^{(1)}_\mu + \text{h.c.}, $$

where $Y_{L/R}$ is the corresponding hyper-charge, and $g_1$ and $g_2$ are the gauge coupling strengths of $U(1)_Y$ and $SU(2)_W$ interactions, respectively ($Y_R = 4/3$ and $Y_L = 1/3$).

The $SU(2)_W$ doublet fields are defined as
where \( f_{R/L} = P_{R/L} f \) for a fermion \( f \).

The interactions involving the SM top quarks and KK Higgs are given by

\[
\mathcal{L} \ni \lambda_t \left[ \bar{q}_L t_R i \sigma_2 H^* + \bar{q}_L h_R i \sigma_2 H^*(1) + \bar{q}_L i \sigma_2 H^{(1)*} \right] + \lambda_b \left[ \bar{q}_L b_R H + \bar{q}_L b_R^{(1)} H^{(1)} + \bar{q}_L b_R^{(1)} H^{(1)*} \right] + \text{h.c.}
\]

\[
= \lambda_t \left[ \bar{T}_L t_R \frac{1}{\sqrt{2}} (v + h) + \bar{t}_L t_R \frac{1}{\sqrt{2}} (h^{(1)} - i \chi^{(1)}) - \bar{B}_L t_R \frac{1}{\sqrt{2}} (h^{(1)} - i \chi^{(1)}) - \bar{B}_L t_R H^{(1)} - \bar{B}_L t_R H^{(1)} - \bar{T}_L t_R \frac{1}{\sqrt{2}} (h^{(1)} - i \chi^{(1)}) \right] + \lambda_b \left[ \bar{B}_L b_R \frac{1}{\sqrt{2}} (v + h) + \bar{B}_L b_R \frac{1}{\sqrt{2}} (h^{(1)} + i \chi^{(1)}) + \bar{B}_L b_R \frac{1}{\sqrt{2}} (h^{(1)} + i \chi^{(1)}) \right] + \text{h.c.}
\]

where \( m_{t(b)} = \frac{\lambda_{t(b)} v}{\sqrt{2}} \), and \( v = \frac{2 m_W}{g_2} \approx 246 \text{ GeV} \) are the top (bottom) quark mass and the Higgs vacuum expectation value, respectively.

### III. ANALYSIS

We consider the mono-top signature arising from (i) the 3rd generation extra dimensional model \( pp \to t \bar{K}_T^{(1)} \bar{K}_b^{(1)} \) and (ii) the minimal top-partner scenario \( pp \to t \bar{t} h^{(1)} \), where \( \bar{K}_T^{(1)} \) represents any 3rd generation KK quark \( t^{(1)} \), \( T^{(1)} \) or \( B^{(1)} \), and \( \bar{K}_b^{(1)} \) any KK boson that couples to the top quark, as illustrated in Fig. 1. In scenario (i), as illustrated in the figure, many different processes effectively contribute to the same mono-top + \( E_T \) final state, as all KK particles are quasi-mass-degenerate, being essentially invisible with soft and undetected decay products. Following Refs. [1, 2], we set in our analysis \( m_{\gamma^{(1)}} = m_{Z^{(1)}} = m_{\chi^{(1)}} = m_{h^{(1)}} = m_{H^{(1)+}} = m_{W^{(1)+}} = m_{\eta^{(1)}} + 1 \text{ GeV} \), and assume no particle has a detector scale lifetime (except for the stable lightest KK particles).

In this analysis, we concentrate on the leptonic mono-top signature, see Fig. 2 for a schematic mono-top event display. This channel is characterized by the presence of an isolated lepton \( \ell = e, \mu \), one \( b \)-tagged jet and missing energy \( E_T \). The dominant backgrounds for this signature are \( \bar{t} \bar{t} \)-jets, \( tW \), \( tZ \) and \( WW \) production processes.

In our analysis, we generate the \( \bar{t} \bar{t} \)-jets sample with ALPGEN+PYTHIA6 [54] merged up to one jet, with the MLM multi-jet merging algorithm. The signal and additional background samples are generated with MADGRAPH5_AMC@NLO+PYTHIA8 [55, 56], accounting for hadronization and underlying event effects. Detector effects are simulated with DELPHES3 package [57]. Higher order corrections are accounted for by normalizing the total \( \bar{t} \bar{t} \) rate to the NNLO+NNLL cross-section (831 pb [58]), and the \( tW \) and \( tZ \) to their NLO predictions (71 pb [59]) and (0.88 pb [60]), respectively.\(^3\) We use the K-factor of 1.5 for the signal processes.

We start our analysis requiring one isolated lepton with \( p_T > 10 \text{ GeV} \) and \( |\eta| < 2.4 \). Jets are defined via the anti-\( k_T \) jet algorithm \( R = 0.4 \), \( p_T > 20 \text{ GeV} \) and \( |\eta| < 2.5 \) with the FASTJET package [61]. We require\(^3\)

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\(^2\)The KK gluon is not included here, since it is often the heaviest particle in UED models.

\(^3\)The literature does not provide higher order corrections to the signal under consideration. We indicate the importance of its determination for future studies.
We display the signal results for two benchmark points: (492, 484) and (697, 609), where \(X^{(1)} \equiv \gamma^{(1)}, \ Z^{(1)}, \ W^{(1)}, \ h^{(1)}, \ \chi^{(1)}, \ H^{(1)} \pm\). We show the signal sensitivity in brackets \((S/\sqrt{B}, S/B)\) in the last three columns. We consider all \(t\bar{t}, \ T^{(1)}, \ B^{(1)}\) related modes.

### Table I: Number of signal and background events

| Process | \(\sigma\) | Baseline | \(m_{t\bar{t}} < 150\) | \(m_T > 100\) | \(E_T > 550\) | \(E_T > 600\) | \(E_T > 650\) |
|---------|-----------|----------|------------------|------------------|------------------|------------------|------------------|
| \(t\bar{t}\) | 831 pb | 206 \cdot 10^6 | 165 \cdot 10^6 | 17.7 \cdot 10^6 | 55.2 | 25.0 | 11.2 |
| \(tW\) | 71 pb | 26.2 \cdot 10^6 | 20.7 \cdot 10^6 | 1.68 \cdot 10^6 | 55.5 | 24.3 | 10.4 |
| \(tZ\) | 0.88 pb | 22.8 \cdot 10^3 | 21.6 \cdot 10^3 | 7.3 \cdot 10^3 | 8.0 | 4.9 | 3.5 |
| Wbb | 7.65 pb | 1.82 \cdot 10^6 | 1.51 \cdot 10^6 | 42.3 \cdot 10^6 | 1.4 | 0.7 | 0.3 |
| BG total | 903 pb | 226 \cdot 10^6 | 41.1 \cdot 10^6 | 19.4 \cdot 10^6 | 120.1 | 54.9 | 25.5 |
| BP(317, 309) | 269 fb | 47996 | 45133 | 29750 | 195.1 | 131.2 | 92.0 |
| BP(492, 484) | 32.7 pb | 5502 | 5131 | 3529 | 57.9 | 38.0 | 24.6 |
| BP(617, 609) | 9.56 pb | 1588 | 1471 | 1048 | 22.8 | 15.1 | 11.4 |

We assume the 13 TeV LHC with \(3 \text{ ab}^{-1}\) of integrated luminosity. We further control the background with the transverse mass \(m_T = \sqrt{2 p_T E_T (1 - \cos \phi_{E_T})}\), requiring \(m_T > 100\) GeV that explores the sharp drop above the \(m_T \sim m_W\) for the semi-leptonic \(t\bar{t}\) and Wbb samples.

In Fig. 2, we present the resulting missing energy distributions for signal and background for the 3rd generation extra dimensional model and the corresponding SUSY case. We set the top/bottom partner masses \(m_{t(1)} = m_{T(1)} = m_{B(1)} = 317\) GeV. The signal distribution exhibits a lower suppression with \(E_T\) compared to the backgrounds. We exploit this fact and define three signal regions with different requirements on the missing energy threshold, \(E_T/\mathrm{GeV} > 550, 600\) and 650. The detailed signal and background cut-flow is displayed in table I. For scenario (i), the main contribution comes from \(B^{(1)} W^{(1)}\) sub-channel accounting for 28% of the total rate, followed by \(B^{(1)} H^{(1)}\) with 16%, \(T^{(1)} Z^{(1)}\) with 14%, \(T^{(1)} h^{(1)}\) with 8.8%, \(t^{(1)} \bar{t}\) with 8.7%, \(T^{(1)} \chi^{(1)}\) with 8.2%, \(t^{(1)} h^{(1)}\) with 8.0%, \(t^{(1)} \bar{t}\) with 7.9% and \(T^{(1)} \gamma^{(1)}\) with 0.5%. In
summary, $B^{(1)}, T^{(1)}, t^{(1)}$ involved process, contributes 43%, 32%, 25%, respectively. This fractions are understood straightforwardly from the gauge couplings $g_1, g_2$ and top Yukawa coupling $\lambda_t$ and hypercharges. Here we ignore the processes whose amplitudes proportional to the bottom Yukawa coupling $\lambda_b$, as they present a sub-leading contribution.

In Fig. 4 we show $S/\sqrt{B}$ (solid lines), $S/B$ (dashed lines) $S$ (dotted lines) as functions of the top-partner mass $m_{t^{(1)}}$ for scenario (i), assuming the mass splitting $m_{t^{(1)}} - m_{\chi^{(1)}} = 8$ GeV and the 13 TeV LHC with $\int \mathcal{L} dt = 3$ ab$^{-1}$. For completeness, we show the results for our different signal regions, $E_T/\text{GeV} > 550$ (blue), 600 (green) and 650 (orange). They provide very similar sensitivities in $S/\sqrt{B}$. One can see that the top-partner mass can be probed up to $m_{t^{(1)}} \sim 630$ GeV at 95% CL in scenario (i). A higher $E_T$ cut predicts smaller number of events but $S \gtrsim 10$ can still be achieved with 3 ab$^{-1}$ around $m_{t^{(1)}} \sim 630$ GeV, while keeping $S/B \gtrsim 0.3$.

For the minimal top-partner simplified scenario (ii), the sensitivity can be estimated by rescaling the cross section according to the contribution of the subprocesses quoted above, as we have checked that the missing energy distributions for all relevant processes are practically identical. Since scenario (ii) amounts to a signal that is purely $t^{(1)}h^{(1)}t$, its rate is tantamount to only 8% of the total rate in scenario (i), as mentioned above. We find that the sensitivity reaches only just below 300 GeV in scenario (ii). If we assume the signal strength of 2, corresponding for instance to an inclusion of the $t^{(1)}\chi^{(1)}t$ process, we find the 95% CL expected limit on the top-partner mass $m_{t^{(1)}} \gtrsim 400$ GeV, which should be directly compared with the sensitivity to the stop mass, $m_t \gtrsim 380$ GeV, in the natural SUSY scenario where two different channels corresponding to the two degenerate higgsino-like neutralinos ($\tilde{\chi}_1^0, \tilde{\chi}_2^0$) contribute.

If the DM is selected to the spin-1 KK photon $\gamma_{(1)}^\mu$ instead of the KK Higgs $h^{(1)}$ in the minimal scenario, the strength of interaction is replaced by the $U(1)_Y$ gauge coupling multiplied by the hypercharge $Y_R = 4/3$. As $\gamma_{(1)}^\mu$ has a larger degree of freedom compared to $h^{(1)}$, the cross-section of the $pp \rightarrow t^{(1)}h^{(1)}t$ process appears to be almost identical to that of $pp \rightarrow t^{(1)}h^{(1)}t$. We therefore have very similar conclusion for the $(t^{(1)}, \gamma_{(1)}^\mu)$ minimal simplified scenario.

Finally, as in the SUSY scenario, mono-jet searches can provide important constraints for the degenerate spectrum. We repeat similar analysis performed in Ref. [38] with the KK tops $(t^{(1)}, T^{(1)})$ and KK bottom $(B^{(1)})$ only. Since the work of Ref. [38] includes KK gluon and all three generations of KK quarks in their mono-jet study, their limit does not apply directly to our case, where only $t^{(1)}, T^{(1)}, B^{(1)}$ are considered. We show current bound on the KK top mass in Fig. 5 using the data corresponding to an integrated luminosity of 30.8 fb$^{-1}$ at the 13 TeV LHC. We  used the model-independent 95% C.L. upper limits on signal cross section in the final state with an energetic jet and large missing transverse momentum reported by ATLAS [63]. Our analysis indicates that the current mono-jet study excludes the KK top mass up to $\sim 750$ GeV, which corresponds to $\sim 1.6$ TeV for a higher luminosity of 3 ab$^{-1}$ via a rough rescaling based on [64]. This is more powerful than the sensitivity of
the mono-top channel, which implies that the mono-top channel is not a discovery channel and we should expect excesses both in the mono-jet and mono-top channels if we have a light top partner in the spectrum. Significant improvements in the mono-top sensitivity can be obtained by also exploiting the hadronic mono-top final state [2].

It has been pointed out that the mono-top channel has a complementary role to the mono-jet channel [1]. What is observed in the mono-jet channel is the QCD initial state radiation and the process carries too little information on the details of the top-partner and DM sectors. Conversely, the existence of the top-quark in the mono-top channel is a clear indication that the process is related to the 3rd generation. The helicity of the top-quark can also be measured by looking at the angular distribution between the charged lepton and the $b$-quark in the final state [1], which provides important information on the chirality structure of the top-partner. Moreover, unlike the mono-jet channel, the production rate depends not only on the QCD coupling but also on the couplings of new interactions involving the top-quark and the top-partner. For example, in the simplified scenario (ii), one can introduce the scaling factor $\xi$ as,

$$\mathcal{L} \propto \xi \frac{\lambda}{\sqrt{2}} L^{(1)} L^{(1)} h^{(1)}. \quad (8)$$

With this parametrization, the signal strength scales as $\xi^2$ and one can set the limit on $\xi$ using the mono-top channel. Using the previous analysis, we have estimated the current and projected sensitivities on $\xi$ for $\int \mathcal{L} dt = 36$, 300 and 3000 fb$^{-1}$ presented in Fig. 6. One can see that for e.g. $m_{t(1)} \approx 800$ GeV the high luminosity LHC can prove $\xi$ up to around 6. The $\xi$ can also be effectively increased by introducing additional particles that couple to the top-quark and the top-partner (bottom-partner) in the same way as e.g. $\gamma^{(1)}$ and $h^{(1)} (W^{(1)}_\mu$ and $H^{(1)}_{\pm})$. If those new particles are only electroweakly charged, the enhancement of $\xi$ will be independent of the mono-jet channel. On the other hand, if they are colored, such as the KK gluon, through the mono-top channel is significantly enhanced (due to e.g. $pp \rightarrow t^{(1)}t^{(1)}g^{(1)}$ for the KK gluon case), the rate of mono-jet channel also increases due to the pair production of those colored particles. Even though the sensitivity of the mono-top channel is in general weaker than that of the mono-jet channel, it is important to look for the mono-top channel, since this process provides important information on the top-partner and DM sectors in the fermionic top-partner models.

**IV. CONCLUSION**

The prospects of observing the mono-top signatures at the LHC arising from fermionic top-partner models have been studied. Such a signature was previously studied in the $pp \rightarrow t\bar{t}h^0$ process in the context of Natural Supersymmetry, where the stop and higgsino present a very small mass gap, letting the $t$ decay products soft and undetectable [1][2]. Interestingly, a similar setup arises in the UED framework, where the compressed mass spectra are naturally expected. In extra dimensional models many different channels contribute to the same mono-top final state, resulting in a large gain in the signal rate and the sensitivity. We showed that the mono-top channel can explore the top-partner masses up to 630 GeV (or 300 GeV in the simplified scenario) at the high luminosity LHC. Possible improvements in this bound can be obtained by taking also the hadronic mono-top channel into account. We have compared the mono-jet and mono-top channels and found that the sensitivity of mono-jet channel is in general superior to the mono-top channel. We have also argued that despite of weaker sensitivity of the mono-top channel, it is important to observe and investigate this process since it allows us to access the information on the fermionic top-partners and the new particles that couple to the top-quark and the top-partner. Since this channel has not been investigated experimentally in the contexts of supersymmetry and extra dimensional models, we hope that more detailed studies will be performed by the experimental collaborations at the LHC.

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