Unexplored Landscape of Top-partner decays

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We propose to study the sensitivity of the HL-LHC and future colliders to top partners (T) decaying into the Standard Model top quark (t) plus either a gluon (g) or a photon (γ). We consider pair-production as well as single-production of a top-partner in association with s SM top quark. The decays $T \to tg$ and $T \to t\gamma$ can be dominant when the mixing between the top partner and top quark are negligible. In this case, the conventional decays $T \to bW$, $T \to tZ$, and $T \to th$ are highly suppressed and can be neglected. A semi-realistic simulation with boosted top quark tagging and an appropriate implementation of a jet-faking-photon rate will provide reasonable estimation for the sensitivity of future colliders. This study will provide a new avenue for top partner searches at future colliders.

Models with top-partners are very well motivated, appearing in many BSM models. The majority of existing analyses focus on the conventional decay modes $T \to Wb$, $T \to tZ$, and and $T \to th$, which arise due to the finite mixing between the top partner and SM top quark. As the top partner-top quark mixing angle vanishes, these decay modes are negligible and new decays become important.

We propose to examine non-standard decays of the top-partners that have often been neglected in LHC searches. In particular, we focus on the top partner decays $T \to tg$ and $T \to t\gamma$. The interactions $T - t - g$ and $T - t - \gamma$ do not appear at tree level due to gauge invariance, and therefore $T \to tg$ and $T \to t\gamma$ are typically suppressed relative to the conventional decays. However, $T \to tg$ and $T \to t\gamma$ can be dominant when the mixing between the top partner and top quark is minimal [1]. We take a model-independent approach using effective operators between the top partner, top quark, and gauge bosons and consider both spin-$\frac{1}{2}$ and spin-$\frac{3}{2}$ top partners. Searches for $T \to t\gamma$ have not been performed. Additionally, while there have been searches for pair produced top partners decaying as $T \to tg$ [2], we update those analyses using boosted techniques and top-

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<table>
<tr><th></th><th>Wb</th><th>tZ</th><th>tH</th><th>tg</th><th>$t\gamma$</th><th>$t(S \to gg)$</th></tr>
<tr><td>Wb</td><td colspan="3" rowspan="3">(1)</td><td rowspan="3">(5)</td><td rowspan="3">(6)</td><td rowspan="3">(7)</td></tr>
<tr><td>tZ</td></tr>
<tr><td>tH</td></tr>
<tr><td>tg</td><td colspan="3">(5)</td><td>(2)</td><td>(3)</td><td>(8)</td></tr>
<tr><td>$t\gamma$</td><td colspan="3">(6)</td><td>(3)</td><td>(4)</td><td>(9)</td></tr>
<tr><td>$t(S \to gg)$</td><td colspan="3">(7)</td><td>(8)</td><td>(9)</td><td>(10)</td></tr>
</table>

TABLE I: Possible final states from the pair-produced top partner.

tagging of fat jets. Although the $T \to t\gamma$ branching ratio is generically smaller than $T \to tg$ due to the gauge couplings, the LHC may be more sensitive to the signal $T\overline{T} \to t\bar{t}\gamma g$ than when both top partner decay into a top quark plus gluon. This is due to the smaller backgrounds associated with requiring a hard isolated photon.

Currently existing analyses on pair-produced top partners involve final states in the entry labeled as (1) in Table I and these final states in (1) assume non-negligible mixing angle between the top partner and the SM top quark, as mentioned before. If the mixing angle is small, other decay modes, such as $T \to tg$ and $T \to t\gamma$, become important and the mixed final states in (5) and (6) are motivated. If the mixing angle becomes negligible, then conventional decays are closed and the only available channels would be those in (2)-(4). The CMS collaboration [2] started looking for spin-$\frac{3}{2}$ top partners ($T_{\frac{3}{2}}$) in the channel (2) and we have advocated the channel (3) [3]. Finally, the top-partner may interact with the SM top quark via a messenger particle S and it may follow a completely different decay mode, $T \to tS$ in (7)-(10), for example see Refs. [1, 4–6]. Depending on the model, S may decay into gg, $\gamma\gamma$, $g\gamma$, WW, ZZ, dark matter particles, etc. Although Table I illustrates possible final states in pair production, a similar classification can be easily done for single production of the top partner. Also instead of a scalar S, one can easily consider a scenario with a vector messenger [7]. We plan to investigate the ability of future colliders to search for and discover many of the unexplored top partner decays in Table I.

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