Stop searches in 2012

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For this year’s 8 TeV run of the LHC we lay out different strategies to search for scalar top pairs. We show results for the hadronic and for the semi-leptonic channels based on hadronic top tagging. For the di-lepton channel we illustrate the impact of transverse mass variables. Each of our signal-to-background ratios ranges around unity for a stop mass around 400 GeV. The combined signal significances show that dedicated stop searches are becoming sensitive over a non-negligible part of parameter space.

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I. INTRODUCTION

The primary goal of the LHC is to unveil the mechanism which breaks electroweak symmetry. The minimal solution, realized in the Standard Model (SM), predicts the existence of a fundamental scalar field, the Higgs boson. The perturbative instability of scalar masses is one of the motivations for the existence of new physics at the electroweak scale \[1\]. One of the proposed solutions to this problem is supersymmetry at the TeV scale \[2\].

The leading contribution to the quadratic divergence of the scalar Higgs mass in the Standard Model arises from the top quark with its large Yukawa coupling. Its supersymmetric partner is the scalar top quark. It can be pair produced at hadron colliders just through its QCD couplings, \textit{i.e.} without any mediation by additional supersymmetric particles. Its production cross section at the LHC therefore only depends on the stop mass \[3\]. The decay channels of the stop depend almost entirely on the supersymmetric mass spectrum \[4, 5\]: if kinematically allowed, it will decay through its strong coupling into a top quark and a gluino. Below this threshold there exist two weak decay channels, a charged current decay to bottom-chargino and a neutral current decay

\[ \tilde{t}_1 \rightarrow t \tilde{\chi}^0_1, \]  

where we assume the lightest neutralino to be the dark matter agent and hence appear as missing transverse momentum at hadron colliders. This neutral current decay we target in this analysis. For even smaller stop masses a loop-induced decay to a charm quark and the lightest neutralino dominates.

At the Tevatron searches for such loop-induced decays as well as the bottom-chargino signature have lead to moderate limits on the stop mass \[6, 7\]. In 2011 the LHC delivered approximately 5 fb\(^{-1}\) of integrated luminosity to ATLAS and CMS. This data set allowed both collaborations to significantly constrain the squark-gluino mass plane through the search for jets plus missing energy \[8, 9\]. \(^1\) Direct stop searches at the LHC are notorious, mostly because of the small signal cross section and the overwhelming background from top pair production \[11\]. Therefore, all limits on top partner searches from 2011 analyses are derived from supersymmetric model assumptions \[12\]: either, the gluino has a sizable branching ratio into 3rd generation squarks \[13\] or sbottom limits get re-interpreted in terms of the stop mass based on the SU(2) symmetry of their left-handed modes. More specifically, assuming gauge mediated supersymmetry breaking with the NLSP decay \(\tilde{\chi}^0_1 \rightarrow Z \tilde{G}\) we can exclude masses below \(m_{\tilde{t}_1} < 330\) GeV for \(m_{\tilde{\chi}^0_1} = 190\) \[14\].

For 14 TeV collider energy we have shown that with the help of top taggers \[15, 16\] we can reconstruct top quarks from stop decays and extract stop pair production from top backgrounds. This holds for purely hadronic decays of the two top quarks from the stop pair \[11, 17\] as well for the semi-leptonic channel \[18\]. The main benefits of the new top reconstruction methods in these analyses is that they automatically resolve any combinatorics of the top decay jets and fully reconstruct the top 4-momenta and angular correlations \[19\]. The associated analysis is not any more complicated than a search for slepton or sbottom pairs, including the application of \(m_{T2}\) for a stop mass measurement \[20\].

In this paper we test a variety of search strategies for light stops (350 \(\leq m_{\tilde{t}_1} \leq 700\) GeV) at 8 TeV. We see that a straightforward adaption of the 14 TeV search strategies is challenging, due to the small signal rate. Instead, we can optimize the signal efficiency by looser requirements on the reconstructed stop decays while benefiting from the also significantly reduced top pair background. This change with respect to the 14 TeV analyses \[11, 17, 18\] reduces the potential of reconstructing masses and model parameters, but it will allow us to probe a significant range of stop masses in 2012 \[21\].

We organize this brief overview in the following way: In Sec. \[II\] we briefly review the properties of the stop signal and of the SM backgrounds at 8 TeV. This includes production cross sections and \(p_T\) distributions. In Sec. \[III\] we discuss our results for hadronic, semi-leptonic and leptonic top decays. In the latter case we find that a simple transverse mass variable removes almost the entire background. For each of these channels we quote signal-to-background ratios and signal significances. A summary follows in Sec. \[IV\].

\(^1\) Note that replacing the squark-gluino mass plane for example by an \(m_0 - m_{1/2}\) plane in the CMSSM implies significant unwanted and unnecessary model assumptions \[10\].
II. STOP PRODUCTION AT 8 TeV

Although the LHC production cross section for stop pairs is much smaller at 8 TeV than at 14 TeV there is a fair chance to disentangle this signal from the also significantly smaller SM backgrounds. For the rest of the paper we omit the index ‘1’ for the lighter of the two stops. Stop pair production always refers to the pair production of the lighter of the two stop mass eigenstates. In Fig. 1 we show the NLO signal cross sections for \( \sqrt{s} = 8 \) TeV and 14 TeV as a function of the stop mass \( m_\tilde{t} \) [22]. It drops by roughly a factor 1/6 from 14 TeV to 8 TeV collider energy. This reduction is partly compensated for by the \( t\bar{t} + \text{jets} \) cross section, which is reduced by a factor 1/4. We consistently normalize our \( t\bar{t} \) cross section to the approximated NNLO result of 234 fb at 8 TeV and 918 pb at 14 TeV [23].

In our 14 TeV analyses we have shown that relying on boosted hadronic tops we can achieve \( S/B \sim 1 \) and \( S/\sqrt{B} > 5 \) in the fully hadronic mode [11] and \( S/B \sim 2 \) and \( S/\sqrt{B} > 5 \) in the semi-leptonic mode [18] for 10 fb\(^{-1}\). For the 2012 run at 8 TeV the envisioned integrated luminosity also ranges around 10 – 20 fb\(^{-1}\). With the small production rates at 8 TeV we need to adapt our search strategies to retain enough signal events to achieve a good signal significance \( S/\sqrt{B} \) for 10 fb\(^{-1}\).

To decide on how to improve the analyses it is instructive to study kinematic correlations between the two tops in the signal process

\[
pp \rightarrow \tilde{t}\tilde{t}^* \rightarrow (t\tilde{\chi}_1^0)(\bar{t}\tilde{\chi}_1^0)
\]

and the \( t\bar{t} \) background. Fig. 2 shows the top versus the anti-top transverse momenta for the signal and background, assuming \( m_\tilde{t} = 400 \) GeV. For the \( t\bar{t} \) background we find a strong correlation between the top and the anti-top, while for tops from stop decays there is almost no correlation. The initially back-to-back configuration of the stops is significantly distorted by the \( \tilde{\chi}_1^0 \) LSP momenta.

A sizable (transverse) top momentum is the key to top tagging. In Tab. I we show the predicted rates for at least one top with \( p_{T,t} > 200 \) GeV. This is the value we need to reliably apply subjet techniques and fully reconstruct hadronic tops [17]. For the top pair background we include up to two hard jets when we simulate the distributions. We see that these additional jets lead to a significant fraction of events where only one of the two tops drops below 200 GeV. The signal with its comparably uncorrelated tops clearly prefers only one strongly boosted top quark.

The last column in Tab. I shows the ratios of rates for 400 GeV stops divided by the \( t\bar{t} \) background rate. Indeed, we gain a factor 2.7 in \( S/B \) by focusing on events with only one top with \( p_{T,t} > 200 \) GeV. This means that focusing on events with asymmetric \( p_{T,t} \) by only requiring one top tag should be the strategy for the 2012 run at 8 TeV. In the following subsections we study four statistically independent samples or analyses:

- two hadronic boosted tops
- one hadronic boosted top and one hadronic un-boosted top
- one hadronic boosted top and one leptonic top
- two leptonic tops

\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
\( m_\tilde{t} \) [GeV] & 300 & 350 & 400 & 450 & 500 & 600 & 700 \\
\hline
\( \sigma_{14\text{TeV}} \) [fb] & 9750 & 4380 & 2150 & 1130 & 623 & 215 & 81.2 \\
\hline
\( \sigma_{8\text{TeV}} \) [fb] & 1870 & 760 & 337 & 160 & 80.5 & 23.0 & 7.19 \\
\hline
\end{tabular}

Figure 1: Production cross section for (s)top pairs as a function of the mass \( m_\tilde{t} \) assuming \( \sqrt{S} = 14 \) and 8 TeV.
The right panel shows the ratio $t\bar{t}^*/t\bar{t}$.

To generate the signal sample we rely on HERWIG++ [24] and assume stop masses of $m_{\tilde{t}} = 350, 400, 450, 500, 600$, and $700$ GeV. We normalize their production cross section to the PROSPINO results at next-to-leading order [3]. They range from $0.8$ pb ($m_{\tilde{t}} = 350$ GeV) to $0.1$ pb ($500$ GeV) as shown in Fig. 1. Resummation slightly increases this rate further [22]. For all stop masses we choose the same lightest neutralino mass $m_{\chi_1^0} = 100$ GeV.

Our Standard Model backgrounds are $t\bar{t}$+jets, QCD jets, $W$+jets, $Z$+jets, and $t\bar{t}Z$. We use ALPGEN+PYTHIA [25, 26] to generate the corresponding samples. For all processes except for $t\bar{t}Z$ production we use MLM matching [27] to simulate additional hard radiation. We match up to $t\bar{t}+2$ jets, $W+3$ jets, $Z+4$ jets, and $3−5$ jets for the QCD sample.

The leading $t\bar{t}$+jets background sample we normalize to the approximate NNLO rate of $234$ pb [23]. For the subleading background channels we use the leading order normalization. The $t\bar{t}Z$ cross section at LO yields $21.5$ fb, based on ALPGEN including the $Z\to\nu\bar{\nu}$ branching ratio. Since the $t\bar{t}Z$ rate only becomes comparable to the stop rate for $m_{\tilde{t}} \gtrsim 600$ GeV we neglect this irreducible $t\bar{t}Z$ background. We have checked that for all processes considered this does not affect the quoted results.

Our analysis is based on a simple calorimeter simulation with granularity of $0.1 \times 0.1$ in $(\eta, \phi)$. We sum the four momentum of all particles in each cell and rescale the resulting three-momentum such as to make the cells massless. The calorimeter cells are later on used as (fat)-jet constituents. Throughout this work we use the Cambridge/Aachen (C/A) algorithm [28] with $R = 1.5$, as implemented in FASTJET [29]. The resulting fat jets are then used as input for the HEPTOPTAGGER. Preliminary ATLAS analysis show that the HEPTOPTAGGER results are only very mildly affected by detector effects, underlying event, or pile-up [30].

For regular QCD jets we use the same C/A algorithm with $R = 0.5$. When analyzing leptonic or semileptonic top decays we require the leptons to be hard and isolated: $p_{T,t} > 20$ GeV and $E_{T,\text{had}} < 0.1 E_{T,t}$ within $R < 0.2$ around the lepton.

| $\sqrt{s} = 8$ TeV | $tt^*$ | $tt$ | $\sigma_{t\bar{t}^*}/\sigma_{t\bar{t}}$ |
|---------------------|-------|------|-------------------------------|
| $m_{\tilde{t}}$[GeV]| 350   | 400  | 500                          |
| at least one top with $p_{T,t} > 200$ GeV | 252.21 | 158.38 | 96.83 | 57.67 | 19.80 | 6.67 | $3.45 \times 10^{-3}$ | $4.6 \times 10^{-3}$ |
| only one top with $p_{T,t} > 200$ GeV | 172.13 | 109.63 | 64.93 | 36.77 | 10.49 | 2.80 | $1.57 \times 10^{-3}$ | $7.0 \times 10^{-3}$ |
| two tops with $p_{T,t} > 200$ GeV | 80.07  | 48.75  | 31.90 | 20.90 | 9.30  | 3.87 | $1.89 \times 10^{-3}$ | $2.6 \times 10^{-3}$ |

Table I: Signal and background cross sections [fb] for different stop masses. We assume $\text{BR}(\tilde{t} \to t\chi_1^0) = 1$. 

For all stop masses we choose the same lightest neutralino mass $m_{\chi_1^0} = 100$ GeV.

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III. STOP RECONSTRUCTION AT 8 TeV

As mentioned in the last section, we present four distinct signatures of stop pairs decaying to a pair of top quarks plus missing energy. The different analyses are chosen such that they are statistically independent and can be combined, if required.

A. Two top tags

As a first attempt to apply the successful 14 TeV strategy to the 2012 run, we analyze fully hadronic stop pairs,

\[ pp \rightarrow \tilde{t}\tilde{t}^* \rightarrow (t\chi^0_1) (\tilde{t}\chi^0_1) \rightarrow (b\bar{b}j\tilde{\chi}^0_1) (\bar{b}jj\tilde{\chi}^0_1) \, . \]

One of the advantages of the fully hadronic mode is that, in principle, the top tagger fully reconstructs both top momenta. This means that the fully hadronic channel is particularly well suited for detailed studies of a top partner signal. For 14 TeV we indeed expect signal-to-background ratios around \( S/B \sim 1 \) \[1\]. In this section we follow the same analysis steps at 8 TeV.

For the fully hadronic double tag mode we veto isolated leptons and require at least two fat jets with

\[ p_{T,j} > 150/150 \text{ GeV} \quad \text{and} \quad \not{p}_T > 100 \text{ GeV} \, , \]

where both numbers are slightly reduced compared to the 14 TeV case \[1\].

In Tab. II we show the numbers of events after each cut. For illustration purposes we compute \( S/\sqrt{B} \) for 10 fb\(^{-1}\) after each step, taking into account only statistical errors.

We first require missing transverse momentum, just like for almost all supersymmetry analyses. To simulate the amount of fake missing energy in the pure QCD jets background we would need a detailed detector simulation. Instead, we adopt a conservative efficiency of 1% for QCD events to pass this cut. With this assumption as a first attempt to apply the successful 14 TeV strategy to the 2012 run, we analyze fully hadronic stop pairs decaying to a pair of top quarks plus missing energy. The different analyses are chosen such that they are statistically independent and can be combined, if required.

As mentioned above, we need an additional tagged \( W \) to simulate the amount of fake missing energy in the pure QCD jets background, which essentially forces us to apply a \( b \)-tag inside the first tagged top later on.

This analysis is based on two top tags, using the HEPTopTagger algorithm. Already at this second stage the \( W + \text{jets} \) and \( Z + \text{jets} \) backgrounds become negligible and we are left with \( tt \) and QCD jets. On the other hand, all rates are already down to a femto-barn level. As mentioned above, we need an additional tagged \( b \)-subjett inside the first tagged top, to reduce the QCD background to a negligible level. It has been shown that \( b \)-tagging is not a problem inside a fat jet, so we apply a \( b \)-tagging efficiency of 50% for \( b \)-quark and a 1% fake rate for light quarks and gluons \[31\]. In the final step the \( tt \) background can be reduced by requiring

\[ m_{T2} > 250 \text{ GeV} \, . \]

This way we achieve \( S/B = 0.79 \) and \( S/\sqrt{B} = 1.5 \) for an integrated luminosity of 10 fb\(^{-1}\). The fact that the significance is reduced by a factor 1/3 as compared to the 14 TeV run is explained by the factor 1/6 in signal cross sections and the softer \( p_{T,t} \) spectrum.

| \( \sqrt{s} = 8 \text{ TeV} \) | \( tt^* \) | \( tt \) | QCD \( W + \text{jets} \) | \( Z + \text{jets} \) | \( S/B \) | \( S/\sqrt{B}_{10\text{fb}^{-1}} \) |
|---|---|---|---|---|---|---|
| \( m_t [\text{GeV}] \) | \( 350 \) | \( 400 \) | \( 450 \) | \( 500 \) | \( 600 \) | \( 700 \) | \( 760 \) | \( 337 \) | \( 160 \) | \( 80.5 \) | \( 23.0 \) | \( 7.19 \) | \( 2.3 \cdot 10^5 \) | \( 6.5 \cdot 10^6 \) | \( 1.6 \cdot 10^6 \) | \( 1.2 \cdot 10^4 \) | \( < 10^{-6} \) | \( 400 \) | \( 0.04 \) |
| \( \not{p}_T \text{ veto} \) | \( 488 \) | \( 215 \) | \( 101 \) | \( 50.5 \) | \( 14.4 \) | \( 4.46 \) | \( 1.6 \cdot 10^7 \) | \( 6.5 \cdot 10^7 \) | \( 1.3 \cdot 10^6 \) | \( 1.2 \cdot 10^5 \) | \( < 10^{-6} \) | \( 0.03 \) |
| \( n_{fat} \geq 2 \) | \( 167 \) | \( 88.3 \) | \( 48.0 \) | \( 26.6 \) | \( 8.71 \) | \( 2.96 \) | \( 3.7 \cdot 10^7 \) | \( 2.0 \cdot 10^7 \) | \( 1.1 \cdot 10^7 \) | \( 1.3 \cdot 10^7 \) | \( < 10^{-2} \) | \( 0.06 \) |
| \( p_{T} > 100 \text{ GeV} \) | \( 104 \) | \( 65.0 \) | \( 38.5 \) | \( 22.5 \) | \( 7.61 \) | \( 2.74 \) | \( 1.6 \cdot 10^8 \) | \( 2.0 \cdot 10^8 \) | \( 1.9 \cdot 10^7 \) | \( 10^3 \) | \( 694 \) | \( 3 \cdot 10^{-4} \) | \( 0.45 \) |
| \( n_{tag} \geq 1 \) | \( 27.5 \) | \( 18.5 \) | \( 11.87 \) | \( 7.60 \) | \( 2.91 \) | \( 1.12 \) | \( 375 \) | \( 2.5 \cdot 10^4 \) | \( 36.7 \) | \( 17.0 \) | \( 6 \cdot 10^{-3} \) | \( 1.1 \) |
| \( n_{tag} \geq 2 \) | \( 3.24 \) | \( 1.65 \) | \( 1.12 \) | \( 0.76 \) | \( 0.34 \) | \( 0.14 \) | \( 6.40 \) | \( 18 \) | \( 0.5 \) | \( – \) | \( 0.07 \) | \( 1.0 \) |
| \( b \)-tag inside top | \( 0.74 \) | \( 0.58 \) | \( 0.35 \) | \( 0.25 \) | \( 0.11 \) | \( 0.05 \) | \( 1.93 \) | \( 0.18 \) | \( – \) | \( – \) | \( 0.27 \) | \( 1.3 \) |
| \( m_{T2} > 250 \text{ GeV} \) | \( 0.24 \) | \( 0.30 \) | \( 0.22 \) | \( 0.18 \) | \( 0.09 \) | \( 0.04 \) | \( 0.34 \) | \( 0.03 \) | \( – \) | \( – \) | \( 0.79 \) | \( 1.5 \) |

Table II: Analysis flow for the two-top analysis. All numbers are given in fb. The symbol “−” denotes less than 0.01 fb.
To study ways out of this rate limitation we can turn to the top tagging efficiencies. After requiring $\hat{p}_T > 100$ GeV we show these efficiencies in Tab. III For the first (mis-)tag it ranges around 30% for the signal, 20% for $t\bar{t}$, and 1% to 2% for QCD jets, $W^{+}\text{jets}$, and $Z^{+}\text{jets}$. For the second tag the efficiencies are around 10% for the signal, 2% for $t\bar{t}$, while QCD jets, $W^{+}\text{jets}$, and $Z^{+}\text{jets}$ remain at 1 to 2%. The reason for this small $t\bar{t}$ efficiency is that in events with large missing momentum one of the tops has to decay leptonically. The second tag then is a fake-top from the remaining $b$ jet combined with hard QCD radiation. Hence the second top tag is very helpful against the leading top pair background. Unfortunately due to the already small signal rate, the second top tag does not increase the sensitivity significantly.

### B. One top tag and one bottom tag

To improve the fully hadronic analysis presented in the last section we propose a search for one boosted top and one $b$-tag in the recoiling softer top decay jets. As a starting point we apply a lepton veto and require exactly one fat jet together with missing transverse momentum,

$$p_{T,j} > 150 \text{ GeV} \quad \text{and} \quad \hat{p}_T > 100 \text{ GeV}.$$  

One subjet inside the tagged top has to be $b$-tagged. In addition, we require a continuum $b$-tag which cannot be a constituent of the tagged top. In Tab. III we see that after these two $b$-tags all backgrounds except for top pair production are negligible.

To reduce the still overwhelming $t\bar{t}$ background we construct a specific transverse mass variable from the general form

$$m_T(p_{\text{vis}}, \hat{p}_T) = \sqrt{m_{\text{vis}}^2 + 2\hat{p}_T(E_{T,\text{vis}} - p_{T,\text{vis}} \cos \phi)},$$

where $\phi$ is the angle between the transverse visible and missing momenta. In events with an isolated lepton and missing momentum this variable is commonly used to reject leptonic $W$ decays because $m_T$ is bounded from above.

The main background in the no-lepton mode with large missing momentum comes from $t\bar{t}$ events where one top decays through a tau lepton. In these events large missing momentum can be induced by the neutrinos from the $W$ and $\tau$ decays. To separate these events from the signal with its two neutralinos we construct the transverse mass with a $b$-jet instead of the lepton, and require

$$m_T^{(b)} \equiv m_T(p_b, \hat{p}_T) > 200 \text{ GeV}. \quad \text{(8)}$$

The left panel of Fig. III shows the normalized $m_T^{(b)}$ distributions for the signal and the $t\bar{t}$ background. As expected, there is an endpoint at $m_T^{(b)}$ for the background. As a cross check the thin dashed line shows the $m_T^{(b)}$ distribution from the missing momentum and the bottom momentum from a leptonic top decay in semi-leptonic $t\bar{t}$ events. This parton level distribution shows good agreement with the background distribution from the hadronic final state. We also tested a similar $m_T^{(b)}$, but the remaining number of signal events turns out to be too small.

| $\sqrt{s} = 8 \text{ TeV}$ | $t\bar{t}^*$ | $t\bar{t}$ | QCD $W^{+}\text{jets}$ | $Z^{+}\text{jets}$ | $S/B$ | $S/\sqrt{B_{\text{full}}}$ |
|-----------------|-------------|-------------|----------------|----------------|-----|-----------------|
| $m_T^{(b)}$ GeV | 350 | 400 | 450 | 500 | 600 | 700 | 400 | 400 |
| $\ell$ veto, $n_{\text{tag}} \geq 1$ | 378 | 186 | 92.3 | 47.8 | 14.0 | 4.4 | 4.0 | 0.1 |
| $\hat{p}_T > 100$ GeV | 264 | 149 | 78.6 | 42.1 | 12.9 | 4.1 | 5.1 | 0.7 |
| $n_{\text{tag}} \geq 1$ | 48.8 | 32.6 | 19.9 | 12.0 | 4.2 | 1.5 | 4.0 | 1.7 |
| $n_{\text{tag}} = 1$, $b$-tag inside | 13.0 | 8.5 | 7.3 | 5.3 4 | 1.1 | 1.4 | 0.024 | 1.4 |
| additional $b$-tag | 4.4 | 2.1 | 1.7 | 1.5 | 0.4 | 0.1 | 0.024 | 0.82 |
| $m_T^{(b)} > 200$ GeV | 0.92 | 0.9 | 0.7 | 0.5 | 0.2 | 0.1 | 0.73 | 2.6 |
| ($\tau$ rejection) | 0.89 | 0.89 | 0.71 | 0.49 | 0.23 | 0.10 | 0.85 | 3.0 |

Table III: Analysis flow for one top tag and one $b$-tag. All numbers are given in fb. The symbol "-" denotes less than 0.01 fb. In the last line we illustrate the potential of a 100% efficient tau veto.
After this final $m_T^{(b)}$ cut all signal and background rates shown in Tab. III are again at the fb level. For a 400 GeV stop we find $S/B = 0.73$ and $S/\sqrt{B} = 2.6$ with 10 fb$^{-1}$ of data. Because we know the origin of the remaining $t\bar{t}$ events we could further improve the results by rejecting tau leptons. Just to illustrate the potential of such a requirement, we assume a 100% efficiency for tau rejection in the last line of Tab. III.

C. One top tag and one lepton

Following the previous section, events with one boosted and one non-boosted top are well suited to extract stop pairs from Standard Model backgrounds. An obvious question then becomes what happens if the softer of the two tops decays leptonically,

$$ pp \to \tilde{t}\tilde{t}^* \to (\ell\nu\chi^0_1) \left( b\ell\bar{\nu}\chi^0_1 \right) + (bjj\chi^0_1) \left( b\ell\bar{\nu}\chi^0_1 \right) + (bjj\chi^0_1) \left( b\ell\bar{\nu}\chi^0_1 \right). $$

This time we require one isolated lepton, a sizable amount of missing energy and one fat jet with a top tag. In Table IV we see that the $t\bar{t}$ background is still overwhelming. The reason is a significant fraction of semi-leptonic $t\bar{t}$ events passing these cuts.

The transverse mass, Eq.(7), has an upper kinematic endpoint for events where the missing energy comes from leptonic $W$ decays. To efficiently reject leptonic top pair events as well as any kind of $W$ events we require

$$ m_T > 150 \text{ GeV}. $$

| $\sqrt{s} = 8 \text{ TeV}$ | $tt^*$ | $ttZ$ $W+$jets | $S/B$  | $S/\sqrt{B}_{10\text{fb}^{-1}}$ |
|-----------------------------|-------|----------------|-------|-----------------------------|
| $m_{\tilde{t}}$ (GeV)       |       |                |       |                             |
| cross section [fb]          | 350   | 400            | 600   | 400                         |
| $n_\ell = 1$               | 241   | 108            | 52.3  |                             |
| $n_{\text{fat}} > 1$       | 145   | 76.5           | 40.6  |                             |
| $p_T > 1$                   | 104   | 61.5           | 34.8  |                             |
| $n_{\text{tag}} = 1$       | 13.1  | 9.02           | 5.80  |                             |
| $m_T > 150$ GeV             | 4.63  | 4.27           | 3.25  |                             |
| $b$-tag inside top          | 1.47  | 1.38           | 1.06  |                             |

Table IV: Analysis flow for one top tag and one lepton. All numbers given in fb. The symbol “–” denotes less than 0.01 fb.
Surprisingly, a non-negligible number of $t\bar{t}$ events survives this cut. Similarly to the last section, purely leptonic top pairs can fake a top tag from the $b$ jets and additional QCD radiation. The right panel of Fig. 3 shows the normalized $m_T$ distributions for the signal, for semi-leptonic $t\bar{t}$ events, and for purely leptonic $t\bar{t}$ events.

After imposing all the above cuts we arrive at a promising signal-to-background ratio of $S/B = 1$ and a significance of $S/\sqrt{B} = 6.5$ for 10 fb$^{-1}$ of 8 TeV running. Unlike the hadronic channels this analysis does not require a $b$ inside or outside the top tag. However, if we are willing to pay the price in available rate we can apply the usual $b$-tag among the top tag constituents.

D. Two leptons

Until now, all our stop pair analyses involve one boosted hadronic top decay which we identify and reconstruct using a top tagger. If we loosen our requirements on event reconstruction we can of course search for top pairs in purely leptonic top pairs,

$$pp \rightarrow \tilde{t}\tilde{t}^* \rightarrow (t\tilde{\chi}_1^0) (\bar{t}\tilde{\chi}_1^0) \rightarrow (b\ell^+\nu\tilde{\chi}_1^0) (\bar{b}\ell^-\nu\tilde{\chi}_1^0).$$

This di-lepton channel turns out to have the largest reach in finding or ruling out anomalies in the top sector. On the other hand, in the absence of any reconstructed mass a deviation from the Standard Model cannot confirm the existence of top partners. Therefore, we consider the di-lepton channel a very powerful tool to confirm and statistically support any anomaly found in one of the hadronic channels.

The previous sections show that the transverse mass $m_T$ with a lepton or a $b$-jet momentum efficiently reduces semi-leptonic $t\bar{t}$ backgrounds. For events with two sources of missing energy a better-suited variable is

$$m_{T2}^{ll} = \min_{\vec{p}_T = \vec{p}_1 + \vec{p}_2} \left[ \max \{ m_T(p_\ell_1, \vec{p}_1), m_T(p_\ell_2, \vec{p}_2) \} \right].$$

$$\sqrt{s} = 8 \text{ TeV}$$

| $m_T$[GeV] | $t\bar{t}$ | $t\bar{t}Z$ | $S/B$ | $S/\sqrt{B}_{10\text{ fb}^{-1}}$ |
|---|---|---|---|---|
| $m_T > 150$ GeV | 0.81 1.21 1.06 0.81 0.34 0.14 | 0.00 (0.03) 0.02 | n.a. | n.a. |
| $m_T > 100$ GeV | 6.05 4.30 2.70 1.65 0.56 0.20 | 0.65 (0.79) 0.09 | 5.8 (4.9) 15.8 (14.5) | |
| $p_T > 10$ GeV | 19.0 9.99 5.40 2.94 0.91 0.30 | 1313 | 0.35 | |
| $p_T > 50$ GeV | 31.0 14.3 7.07 3.58 1.04 0.33 | 7651 | n.a. | |
| $n_T = 2$ | | | | |

Table V: Analysis flow for the di-lepton mode. All numbers are given in fb. The $t\bar{t}Z$ numbers are shown including the decay $Z \rightarrow \nu\bar{\nu}$. The number in parentheses include a smeared transverse momentum measurement.
In this definition the two transverse mass values, Eq. (7), are computed with one of the two observed leptons. The missing momenta in the two transverse mass values are a hypothetical split of the observed missing transverse momentum into two parts. The mass of the unobserved particles we assume to vanish.

To enhance the di-lepton mode we need to identify additional sources of missing energy, as compared to $t\bar{t}$ or $W^+W^-$ events with their $W$ decay neutrinos. The particles contributing to $m_{T2}$ from $t\bar{t}$ events come from the $W^+W^-$ subsystem, so for top quarks close to threshold the upper endpoint is $m_{T2} < m_W$ [33, 34]. In contrast, for the stop signal such an endpoint does not exist. The corresponding $m_{T2}$ distributions we show in Fig. 4. The leading detector effect is the smeared missing momentum according to a Gaussian with $\sigma(p_T) = a \cdot \sqrt{\sum E_T}, a = 0.53 \sim 0.57$ [35]. The thin dotted line in Fig. 4 includes this smearing and shows a slightly enhanced tail.

Our purely leptonic event selection starts with two isolated leptons and $p_T > 100$ GeV. Tab. 4 shows that the $t\bar{t}$ background becomes essentially negligible after we require

$$m_{T2} > 100 \text{ GeV.}$$

(13)

Similarly, the total $t\bar{t}Z$ rate is significantly smaller than the signal. Including a smeared missing energy measurement increased the $t\bar{t}$ background from 0.65 to 0.79 fb. For $m_t = 400$ GeV, we expect more than 40 signal events, giving $S/B = 5.8$ and $S/\sqrt{B} = 15.8$ with 10 fb$^{-1}$. A slightly harder cut $m_{T2} > 150$ GeV removes essentially all the SM backgrounds. What is most impressive is that this analysis completely ignores any jet which might come with the $t^+t^-p_T$ system!

IV. SUMMARY

Reasonably light top partners are necessary to solve the hierarchy problem. Therefore, searches for stops or other top partners are of paramount interest to LHC physics. In 2012 the LHC will gather at least $\mathcal{O}(10)$ fb$^{-1}$ of data at 8 TeV. For four independent search channels we show how 2012 data will start to either find or exclude light top partners, decaying to top quarks and missing energy.

In the fully hadronic mode we study two strategies: tagging either one or two hadronic tops we find $S/B \sim 1$ for a stop mass of 400 GeV. Unfortunately, the statistical significance is rather modest, $S/\sqrt{B} = 1.5$ (two tags) and $S/\sqrt{B} = 3.0$ (one tag).

Searches for semi-leptonic or fully-leptonic top pairs are more promising. In the semi-leptonic mode we tag one top recoiling against an isolated lepton. After cutting on $m_T$ we find $S/B = 2.1$ and $S/\sqrt{B} = 5.4$. In the di-lepton mode a cut on $m_T$ rejects almost all Standard Model backgrounds. This gives us a striking sensitivity of $S/B = 5.8$ and $S/\sqrt{B} = 15.8$.

Obviously, the fully leptonic mode is unlikely to conclusively reconstruct and confirm a top partner. However, the combination with the statistically less significant hadronic modes should allow us to establish a top partner signal in 2012.

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