Supersymmetry with long-lived staus at the LHC

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Abstract

We consider SUSY extensions of the standard model where the gravitino is the dark-matter particle and the stau is long lived. If there is a significant mass gap with squarks and gluinos, the staus produced at hadron colliders tend to be fast ($\beta > 0.8$), and the searches based on their delay in the time of flight or their anomalous ionization become less effective. Such staus would be identified as regular muons with the same linear momentum and a slightly reduced energy. Compared to the usual SUSY models where a neutralino is the LSP, this scenario implies (i) more leptons (the two staus at the end of the decay chains), (ii) a strong $e-\mu$ asymmetry, and (iii) less missing $E_T$ (just from neutrinos, as the lightest neutralino decays into stau). We study the bounds on this SUSY from current LHC analyses (same-sign dileptons and multilepton events) and discuss the best strategy for its observation.
1 Introduction

The determination of the mass and the couplings of the Higgs boson at the LHC will not complete our understanding of the mechanism responsible for the breaking of the electroweak (EW) symmetry. It will be also essential to establish whether or not there is a dynamical principle explaining its nature. Supersymmetry (SUSY) is a possibility that has attracted a lot of work during the past decades. Minimal SUSY extensions with a neutralino as the lightest SUSY particle (LSP) provide a good candidate for dark matter, imply a consistent picture for gauge unification, and can in principle accommodate a 125 GeV light Higgs $^1$. It is apparent that the non-observation of flavor-changing neutral currents or electron and neutron electric dipole moments requires an effort in these frameworks. However, SUSY models have proven flexible enough to adapt, and they have reached the current phase of direct search at the LHC in a (reasonable) good shape.

SUSY searches at hadron colliders have focused on a few generic signals with relatively small backgrounds. The classic one $^2$ is jets with no hard leptons but large $E_T$ from squarks $\tilde{q}$ going into a quark $q$ plus the lightest neutralino $\tilde{\chi}^0_1$. It was then emphasized $^3$ that chain decays of colored SUSY particles through charginos and heavier neutralinos giving two isolated leptons usually have a much larger branching ratio. In particular, gluino pairs provide same-sign (SS) dileptons together with jets and $E_T$, a clean signal of high discovery potential $^4$. Initial searches at the 7 TeV LHC do not show any hints of such signals and set bounds on squark and gluino masses that rise up to 800 GeV and higher, although a complete exclusion of this mass region in the neutralino LSP model would require a careful consideration of some cases with an anomalous signal $^5,^6,^7$.

There are, however, other SUSY scenarios that provide a different generic signal, and one may wonder how constrained they are by current LHC analyses. In particular, a possibility that is well motivated from a model-building point of view is the case with a gravitino LSP. This is natural in all models with a low scale of SUSY breaking, like the ones mediated by gauge interactions $^8,^9$. Even in gravity-mediated models, the LSP gravitino may be an acceptable dark matter candidate with $^10$ or without $^11$ R-parity violation. In all these cases the next-to-LSP could be a long-lived charged particle (e.g., the $\tilde{\tau}$) that, if produced at the LHC, would decay after crossing the detectors.

The search strategy in these scenarios is then different $^12$. A charged particle of mass $m_{\tilde{\tau}}$ and three-momentum $p = \beta \gamma m_{\tilde{\tau}}$ will curve under the magnetic field in the inner detector like a muon of the same momentum. There are, however, two observables that could distinguish such a heavy muon: an anomalous ionization in the silicon tracking detector and a delay in the time
Figure 1: Distributions of $dE/dx$ (left) and speed $\beta$ (right) observed at D0 (from [14]). The scale of $dE/dx$ is adjusted so that the distribution from $Z \to \mu\mu$ peaks at 1.

of flight from the vertex to the muon chambers.

As a stau or a muon propagate in matter, low $q^2$ processes like ionization are insensitive to the mass, and one expects that the effects on the medium will only depend on the velocity (or $\beta\gamma$) of the particle. The Landau most probable energy deposition through ionization is large at low values of $\beta$ (it goes like $(\beta\gamma)^{-2}$), has a minimum at $\beta\gamma \approx 4$ and reaches the so called Fermi plateau at $\beta\gamma > 100$ (see Fig. 30.9 at the PDG [13]). In particular, the ionization along the track of a 100 GeV stau of $\beta\gamma = 2$ (i.e., $\beta = 0.89$ and $p = 200$ GeV) would be very similar to that of a muon of the same momentum, and 25% higher at $\beta\gamma = 1$ (or $\beta = 0.7$). In Fig. 1-left we reproduce a plot from the Tevatron D0 experiment [14] of $dE/dx$ relative to the average value for muons passing certain $p_T$, rapidity and isolation cuts. For an actual stau, given the width of the expected distribution (around 30% of its average value, see Fig. 30.8 at the PDG [13]) and the uncertainty in the response of the detector, one could expect a clear difference with muons only for $\beta \leq 0.7$.

The direct measure of $\beta$ has just a slightly better resolution. At D0 (see Fig. 1-right) 27% of the muons are measured with $\beta > 1.1$, and 3.5% of the subluminal ones have $\beta < 0.8$. A 37 pb$^{-1}$ ATLAS analysis [15] at the 7 TeV LHC shows a more accurate description of the muon velocity, setting the limit $m_{\tilde{\tau}} > 110$ GeV from direct stau production. A recent study [16] by CMS using 5.0 fb$^{-1}$ of data could imply higher bounds. It is difficult, however, to use their results to constrain a particular model, since (i) they do not provide the complete velocity distribution observed for muons, including the region with $\beta > 1$ (necessary to estimate the effect
of the reconstruction on the stau velocity), and (ii) they could be overestimating the anomalous ionization of heavy particles. In particular, their method seems to imply a 10% excess for a stau of $\beta = 0.9$, when such particle is below the Fermi plateau and should ionize like a muon of the same three-momentum (see [17] for a discrimination based on radiative energy deposition).

In addition, in models where the stau is significantly lighter than squarks and gluinos its velocity tends to be high (see [18] for an analysis of the kinematics in these chain decays), and one is left with relatively few events with a $\beta$ small enough to give a clear deviation in the two observables. Let us take, just for illustration, a 150 GeV $\tilde{\tau}_R$ together with 750 GeV Higgsinos, 800 GeV light-flavor squarks and 1 TeV gluinos, with the slepton doublets and the rest of squarks and gauginos in the 800–1000 GeV mass region. We will take the other two $\tilde{\ell}_R$ sleptons with a mass similar to $m_{\tilde{\tau}_R}$ (see next section). The cross section for direct (Drell-Yan) production at the 7 TeV LHC is around 33 fb, which is reduced to 31 fb once we require at least one stau with $p_T > 40$ GeV and $|\eta| < 2.5$. In contrast, indirect production through squarks and gluinos gives $\sigma = 429$ fb, or $\sigma = 428$ fb once we impose the same $p_T$ and rapidity requirements. This accounts for 14 times more stau pairs from indirect than from direct production. We plot their $\beta\gamma$ distribution in Fig. 2. While 28% of the staus from direct production have $\beta < 0.8$, only 5% of the ones from chain decays are in this $\beta$ region. If we restrict to the $\beta < 0.7$ (where a more significant anomaly can be expected) these percentages are reduced to 14% and 1%, respectively.

Figure 2: $\beta\gamma$ distribution (normalized to 1) of 150 GeV staus from direct production and from chain decays of 800 GeV squarks and 1 TeV gluinos (direct production accounts for 1 out of 15 staus produced).
Therefore, in these models most of the events will contain two staus that look like regular muons of momentum $\vec{p}_\mu = \vec{p}_\tilde{\tau}$ and energy $E_\mu = \sqrt{E_\tilde{\tau}^2 - m_\tilde{\tau}^2}$. Although specific analyses have been proposed \cite{19}, one may also ask how the usual SUSY searches constrain these scenarios assuming that the staus are identified as muons, and how to modify the cuts in order to optimize the search. In this paper we study the bounds from recent studies on SS-dilepton \cite{20} and inclusive-multilepton \cite{21} production at the LHC.

2 Same-sign leptons, jets and $p_T^{\not}$

SS dileptons can be an important signature in neutralino LSP models when gluinos are at accessible energies. If the collision produces $\tilde{g}\tilde{g}$ pairs that decay into charginos and neutralinos other than $\chi^0_1$, SS leptons will be very frequent, as each decay chain can give a lepton or an antilepton with equal probability. In addition, gluinos must decay into (real or virtual) squarks producing jets, and there will also be $p_T^{\not}$ from the undetected neutralino LSP. The same type of signal (with a smaller number of jets) may also be obtained from $\tilde{u}\tilde{u}$ pairs produced through gluino exchange in the $t$–channel.

**Gluinos in neutralino LSP models.** In a recent (2.05 fb$^{-1}$ at 7 TeV) study \cite{20} ATLAS selects events in which the two higher-$p_T$ leptons ($\ell = e, \mu$) have the same charge, with at least 4 jets of $p_T > 50$ GeV, and with $p_T^{\not} > 150$ GeV (plus certain isolation and rapidity cuts). They estimate a background of about 1 event from $t\bar{t}X$, fake leptons ($b$ or $c$-hadron decays), charge misidentification and dibosons, while they observe no events in the data.

Then this result is used to constrain the signal from 650 GeV gluinos that decay into $t\bar{t}\chi^0_1$ through a virtual stop of 1.2 TeV. They assume a 150 GeV neutralino and search for the channel where two of the four final top quarks give SS leptons. They predict around 7 events satisfying all the requirements, which allows them to exclude the model. We have reproduced their study in order to understand the differences with the long-lived stau (LLST) scenario. In our analysis we have used MadGraph 5 \cite{22} to obtain the $\tilde{g}\tilde{g}$ and the $\tilde{g}\tilde{g} +$ jet cross sections, Prospino 2.1 \cite{23} to estimate next-to-leading order corrections, PYTHIA 6.4 \cite{24} for hadronization/showering effects and PGS 4 \cite{25} (tuned to ATLAS in this study and to CMS in the multilepton analysis) for detector simulation.

We find that at the given luminosity a 650 GeV gluino mass implies the production of 1047 $\tilde{g}\tilde{g}$ pairs. A factor of $\epsilon = 0.55$ must be included to take into account the detector reconstruction, identification and trigger efficiency, leaving the number of observable pairs in $L\sigma\epsilon = 576$. The detection of two SS leptons (from $t$ decays) is then a very selective requirement, reducing the
signal to just 18 expected events. The successive cuts $N_{\text{jet}} > 3$ and $E_T > 150$ GeV reduce this number further to 12 and 7 events, respectively. Although these two cuts do not affect significantly the signal, they are essential to reduce the background. The total acceptance after cuts is $A = 1.2\%$, implying a visible cross section $\sigma_{\text{vis}} = \sigma \epsilon A = 3.2$ fb that is above the $\sigma_{\text{vis}} < 1.6$ fb limit established by ATLAS.

**Gluinos in long-lived stau models.** Generically, the LLST scenario will imply a signal with some basic differences versus the neutralino LSP case:

- Two extra leptons, as SUSY particles are produced in pairs and each one will chain-decay into a stau.
- A strong $\mu-e$ asymmetry, as these staus taken for leptons look always like muons.
- Less $E_T$, as the lightest neutralino does not escape detection but decays into visible $\ell^+\ell^-$ pairs.

Some comments about the second and third points above, however, are here in order. To be definite we will take $\tilde{\tau}_1 \approx \tilde{\tau}_R$, and $\tilde{e}_R, \tilde{\mu}_R$ of similar mass (as suggested by flavor and other precision observables). This means that, depending on the degree of degeneracy, when a $\tilde{e}$ is produced it may or may not decay into a $\tilde{\tau}$ inside the detector (e.g., $\tilde{e} \to \tilde{\tau}_e\bar{\tau}_e, \tilde{\tau}_\nu\bar{\tau}_e$, \ldots). If $\tilde{e}$ escapes without decaying, it will just look like a long-lived stau. If $\tilde{e}$ decays promptly (we neglect the possibility with displaced vertices) the resulting $\tilde{\tau}$ will take a very large fraction of the selectron energy, and none of the extra particles (charged leptons and/or photons) will have enough $p_T$ to pass the cuts. Moreover, since the $\tilde{e}$ boost is not ultrarelativistic (typically $E_{\tilde{e}}/m_{\tilde{e}} = 2-5$), the extra particles will not be very focused along the stau direction and will not affect substantially its isolation cuts. Therefore, we can consider that the three $\tilde{\ell}_R$ are effectively long-lived staus looking like muons. Regarding the amount of $E_T$ in this scenario, notice that if the last step in the decay is not $\tilde{\chi}^0 \to \ell^+\ell_1^-$ but $\tilde{\chi}^+ \to \ell_1^+\nu_\ell$, then $E_T$ will not be necessarily small. In particular, if $m_{\tilde{\chi}^\pm} \gg m_{\tilde{\tau}}$ then the final neutrino will take close to half of the chargino energy.

Let us then perform the ATLAS analysis assuming the LLST scenario. We will start with the case with a 150 GeV stau (together with $\tilde{e}_R, \tilde{\mu}_R$ of similar mass) instead of the neutralino $\tilde{\chi}_1^0$ (assumed to be mostly a Bino), which is moved to 200 GeV. In our simulation we will just change these three sleptons ($\tilde{\ell}_1^\pm$) to muons of the same three-momentum. The 650 GeV gluinos, like in their study, will be forced to decay through a virtual stop into the neutralino, e.g.,

$$\tilde{g} \to t\bar{t} \to \tilde{\chi}_1^0 t\bar{t} \to \ell_1^+\ell^- t\bar{t}. \quad (1)$$
We find that the 576 gluino pairs yield 209 SS-dilepton events after the geometric and kinematic cuts, with 185 of them including at least 4 jets of \( p_T > 50 \) GeV. The large acceptance reflects the presence of the extra lepton produced in our framework. The requirement \( E_T > 150 \) GeV, however, reduces the 185 events to just 18, defining a signal that is a bit larger than the one obtained in the neutralino LSP scenario. We obtain an acceptable model if the gluino mass is increased to 890 GeV, with only 3.5 events surviving the cuts on 50 initial gluino pairs.

The possibility that most signal events are cut by the \( E_T \) requirement is frequent in these LLST models. For example, if the 650 GeV gluinos are forced to decay through a virtual light-flavor squark \( \tilde{q} \) (instead of the stop), we find 207 SS dileptons, 163 of them with at least four very energetic jets, but only 2.3 events with large \( E_T \). This result is mildly dependent on the neutralino mass. If \( m_{\tilde{\chi}_1^0} \) grows from 200 to 400 GeV the number of SS dileptons does not change, but the \( N_{\text{jet}} > 3 \) cut is significantly stronger (as the total energy that goes into jets is smaller) and reduces the sample to 127 instead of 163 events. A heavier neutralino implies that the charged lepton from its decay tends to carry more energy. If it is a \( \tau \) decaying leptonically, the energy taken by neutrinos will also be larger. The \( E_T \) cut is then weaker in this case: we obtain a total of 13 events, which are enough to exclude the model. Therefore, we find that the analysis would not exclude 650 GeV gluinos for \( m_{\tilde{\chi}_1^0} = 200 \) GeV but would imply \( m_{\tilde{g}} \geq 830 \) GeV if \( m_{\tilde{\chi}_1^0} = 400 \) GeV.

\[
\begin{array}{|c|c|c|c|c|}
\hline
m_{\tilde{g}} & m_{\tilde{\chi}_1^0} & \text{Signal} & \text{SS dilept.} & N_{\text{jet}} > 3 & E_T > 150 \\
\hline
576 & 199 & 159 & 21 \\
\hline
576 & 194 & 89 & 63 \\
\hline
576 & 208 & 158 & 12 \\
\hline
576 & 204 & 114 & 65 \\
\hline
\end{array}
\]

Table 1: Number of events after cuts from gluino production, with Higgsinos decaying into the final staus (all masses in GeV).

As explained above, when charginos appear in the gluino chain decay these models include a larger fraction of events passing the \( E_T \) cuts, e.g.,

\[
\tilde{g} \rightarrow \tilde{t} \tilde{t} \rightarrow \tilde{\chi}_1^+ b \bar{t} \rightarrow \tilde{\ell}^+ \nu_\ell b \bar{t}.
\]

Let us consider the case where they go into relatively light Higgsinos, \( \mu = 200, 400 \) GeV with \( M_{1,2} = 700 \) GeV. The results are summarized in Table 1 where we have assumed the same detector efficiency as in the previous study. We see that the signal is stronger than the one in analogous neutralino LSP scenarios, specially for values of the chargino mass significantly larger
than $m_\tau$. If the Higgsino mass is 400 GeV we obtain that the ATLAS analysis implies $m_\tilde{g} \geq 980$ GeV.

**Squarks in long-lived stau models.** Let us comment on the limits implied by this analysis when gluinos are heavier and the collision only produces squarks. Notice that in the neutralino LSP scenario considered by ATLAS with the squarks decaying into $q\tilde{\chi}^0_1$ the signal would not include charged leptons. In our case, however, each neutralino will go into a muon-like slepton plus a lepton, providing a signal. Actually, these events would look similar to the gluino pairs studied before but with two fewer jets (or top quarks in $t\bar{t}^*$ production). Notice also that in the LLST scenario an event with a pair of light-flavor squarks will not pass the $N_{jet} > 3$ requirement unless the squarks are produced with extra jets (a process that is included in our simulation) and/or the final $\tau$ lepton decays hadronically but is untagged.

$$m_\tilde{t} = 650 \quad m_\tilde{\tau} = 150$$

| $M_1 = 200$ | Signal | SS dilepton | $N_{jet} > 3$ | $E_T > 150$ |
|-------------|--------|-------------|---------------|-------------|
| $\mu = 200$ | 11     | 4           | 2             | 0.29        |
|             | 11     | 3.4         | 1.7           | 0.15        |

Table 2: Number of events after cuts from stop production, with Binos or Higgsinos decaying into the final staus.

For the analysis of stop-pair production (in Table 2), we take $\tilde{t}_1$ (mostly $\tilde{t}_R$) at 650 GeV with the rest of squarks decoupled. The signal will include SS dileptons and 4 jets if, for example, one of the tops decays hadronically and the other one leptonically, which would provide also $E_T$. We find, however, that the requirement $E_T > 150$ GeV is too strong (it reduces the acceptance to just 2.6%) and the model can not be excluded by the current analysis. If the stop can decay both to charginos and neutralinos, e.g., $\tilde{t} \rightarrow b\tilde{\chi}^+ \rightarrow b\tau^+\nu$ and $\tilde{t}^* \rightarrow \tilde{\chi}^0 \rightarrow \bar{b}q\bar{q}'\tau^-\tilde{\tau}^+$, the channel with the two tops going through chargino does not contribute and the signal is even weaker (0.07 events pass the cuts on the initial 11 $t\bar{t}$ pairs). We have included also this case in Table 2.

$$m_q = 650 \quad m_\tau = 150$$

| $M_1 = 200$ | Signal | SS dilepton | $N_{jet} > 3$ | $E_T > 150$ |
|-------------|--------|-------------|---------------|-------------|
| $\mu = 200$ | 672    | 258         | 52            | 1.5         |
|             | 672    | 275         | 48            | 4.6         |

Table 3: Number of events after cuts from squark production, with Binos or Higgsinos decaying into the final staus.

To illustrate the case with light-flavor squark production, we take the first two families of squarks (L and R) with $m_{\tilde{q}} = 650$ GeV together with 1.5 TeV gluinos. We obtain a total of
672 $qar{q}$ events (90% from gluino in the $t$ or the $u$ channels), with 274 of them including an additional jet. In Table 3 we summarize our results when the squarks are forced to decay to neutralinos ($M_1 = 200$ GeV and $M_2, \mu = 700$ GeV) or can also decay into charginos ($\mu = 200$ GeV, $M_{1,2} = 700$ GeV). We observe that the $N_{\text{jet}}>3$ cut is now severe and, again, the $E_T$ requirement puts the first case well below the background. The second case, with one squark giving a chargino ($\tilde{\chi}^+ \rightarrow \bar{\nu} \tilde{\tau}^+$) and the other one a neutralino ($\tilde{\chi}^0 \rightarrow \tau^- h \tilde{\tau}^+$), implies more $E_T$, and squarks masses below 770 GeV would be excluded by these ATLAS results.

### Optimized SS-dilepton search.

The search for LLST SUSY based on SS dileptons could be optimized by slightly adapting the cuts. The same ATLAS cuts used in the neutralino LSP search are optimal only for gluino production with stop and charginos in its chain decay. In the rest of the cases the missing $E_T$ cut must be relaxed. The requirement of 4 very energetic jets is optimal in the search for gluino production, but it must be also relaxed to $N_{\text{jet}} \geq 2$ in squark searches. In that case the background (which tends to be larger) can be reduced requiring for another hard lepton that combined with any of the SS leptons is off the Z mass shell. In all the cases the SS-dilepton excess exhibits a large electron–muon asymmetry, as long-lived sleptons look always like muons. If the $\tilde{\tau}$’s are obtained from Higgsino decays we obtain no $ee$ pairs and just 3–10% of $e\mu$ events, with the rest of them defined by two muon-like particles. For staus from parent gauginos there is 1% of $ee$, 20–30% of $e\mu$, and 70–80% of $\mu\mu$ events.

### 3 Inclusive multilepton search

In a recent work [21] CMS has searched for an anomalous production of multilepton events at the 7 TeV LHC for an integrated luminosity of 4.98 fb$^{-1}$. Their analysis is very complete and model-independent, it applies to any scenario with new particles producing leptons and certainly to our LLST model. They use $H_T$, defined as the scalar sum of the $p_T$ of all reconstructed jets, and the analogous $S_T$ (which includes the leptons and missing $E_T$) to detect the presence of heavy physics. They classify in a systematic way all the possibilities: 4 or 3 leptons; $E_T$ above or below 50 GeV; lepton pairs around the Z mass or not; and low or high values of $H_T$ or $S_T$. Moreover, they separate events with 0, 1 or 2 tau leptons decaying hadronically into a single track (one-prong $\tau_h$ decays). Being heavier, the third lepton family tends to be more sensitive to the new physics. This is also the case in all SUSY models, where the Higgsinos couple to taus but not significantly to muons or electrons. Events with heavy particles decaying into leptons would appear in one or another of the bins that they consider, and the estimated background (which includes double vector-boson, $t\bar{t}$, or $t\bar{t}V$ production) is particularly small in the $4\ell$ channels.
Table 4: Number of observed, SM, and new physics (NP) events. The NP entry corresponds to 650 GeV gluinos decaying through virtual squarks and 200 GeV Higgsinos into 150 GeV staus.

| Selection                  | N(τ̄) = 0 | N(τ̄) = 1 | N(τ̄) = 2 |
|----------------------------|-----------|-----------|-----------|
|                           | obs (SM)  | NP        | obs (SM)  | NP        | obs (SM)  | NP        |
| 4 Lepton results           |           |           |           |           |           |           |
| $E_T > 50, H_T > 200, no\, Z$ | 0 (0.018±0.005) | 6.4 | 0 (0.09±0.06) | 17 | 0 (0.7±0.7) | 5.8 |
| $E_T > 50, H_T < 200, no\, Z$ | 1 (0.20±0.07) | 0.1 | 3 (0.59±0.17) | 0.1 | 1 (1.5±0.6) | 0.1 |
| $E_T < 50, H_T > 200, no\, Z$ | 0 (0.006±0.001) | 8.5 | 0 (0.14±0.08) | 12 | 0 (0.25±0.07) | 4.0 |
| $E_T < 50, H_T < 200, no\, Z$ | 1 (2.6±1.1) | 0.0 | 5 (3.9±1.2) | 0.0 | 17 (10.6±3.2) | 0.1 |
| 3 Lepton results           |           |           |           |           |           |           |
| $E_T > 50, H_T > 200, no\, OSSF$ | 2 (1.5±0.5) | 45 | 33 (30.4±9.7) | 62 | 15 (13.5±2.6) | 2.5 |
| $E_T > 50, H_T < 200, no\, OSSF$ | 7 (6.6±2.3) | 0.0 | 159 (143±37) | 0.4 | 82 (106±16) | 0.0 |
| $E_T < 50, H_T > 200, no\, OSSF$ | 1 (1.2±0.7) | 27 | 16 (16.9±4.5) | 31 | 18 (31.9±4.8) | 0.6 |
| $E_T < 50, H_T < 200, no\, OSSF$ | 14 (11.7±3.6) | 0.1 | 446 (356±55) | 0.0 | 1006 (1026±171) | 0.0 |
| $E_T > 50, H_T > 200, no\, Z$ | 8 (5.0±1.3) | 116 | 16 (31.7±9.6) | 62 | - |
| $E_T > 50, H_T < 200, no\, Z$ | 30 (27.0±7.6) | 0.5 | 114 (107±27) | 0.2 | - |
| $E_T < 50, H_T > 200, no\, Z$ | 11 (4.5±1.5) | 72 | 45 (51.9±6.2) | 30 | - |
| $E_T < 50, H_T < 200, no\, Z$ | 123 (144±36) | 0.0 | 3721 (2907±412) | 0.1 | - |

In LLST SUSY any event has at least two charged leptons (the two staus) at the end of the decay chains. If the staus are produced through neutralino the process will also include extra leptons, whereas the $\tilde{\chi}^±\tilde{\chi}^0$ channel implies a neutrino (i.e., missing $E_T$ instead of $\ell^±$) and an excess of three-lepton events. Notice that if the lighter neutralinos are mostly Higgsinos the muon-like slepton will come with a $\tau$, while gauginos will imply the three lepton flavors with the same frequency.

Under this multilepton analysis the difference between gluino and squark events is not so strong as in the SS-dilepton search, since the number of jets is not a discriminating observable. Instead, the mass difference between the colored particles ($\tilde{g}$ or $\tilde{q}$) produced in the collision and the chargino/neutralino mass becomes critical. It is easy to see that if this mass difference is large the event will have energetic jets and a large value of $H_T$, whereas if it is small most of the energy will go to the leptons.

In Table 4 we show for illustration the implications of a LLST model with 650 GeV gluinos that are forced to decay through virtual squark into 200 GeV (mostly) Higgsinos, which then go to $\tilde{\tau}\tau$ or $\tilde{\tau}\nu$ ($m_{\tilde{\tau}} = 150$ GeV). We have imposed the isolation cuts and the trigger efficiencies described in [21], and have not included events where opposite-sign same-flavor (OSSF) lepton pairs are within the $Z$-mass window ($75$ GeV < $m_{\ell\ell}$ < 105 GeV), as they combine larger
backgrounds with a smaller signal. We obtain close to 2500 $\tilde{g}\tilde{g}$ and $\tilde{g}\tilde{g} + \text{jet}$ events that after cuts translate into 530 $3\ell$ and 74 $4\ell$ events. Relative to the background, the $4\ell$ channels with 0 or 1 $\tau_h$ offer the strongest signal, which is enough to exclude this possibility.

We find that these $4\ell$ channels are very efficient to explore LLST SUSY. In particular, 950 GeV gluino and squark masses seem excluded by this analysis. In the first case we find 97 gluino pairs that after cuts introduce 12 $4\ell$, zero-$\tau_h$ events where the SM expectation is 2.8, with similar figures for the squarks. In both LLST cases around 50% of the $4\ell$, zero-$\tau_h$ events are defined by 3 muon-like leptons plus one electron, 30% are 4 muons, and 20% 2 muons and 2 electrons.

| Selection | $N(\tau_h) = 0$ | $N(\tau_h) = 1$ | $N(\tau_h) = 2$ |
|-----------|----------------|----------------|----------------|
| $E_T > 50$, $H_T > 200$, no Z | 0 (0.018±0.005) 0.5 | 0 (0.09±0.06) 0.9 | 0 (0.7±0.7) 0.5 |
| $E_T > 50$, $H_T < 200$, no Z | 1 (0.20±0.07) 1.6 | 3 (0.59±0.17) 3.0 | 1 (1.5±0.6) 1.4 |
| $E_T < 50$, $H_T > 200$, no Z | 0 (0.006±0.001) 0.0 | 0 (0.14±0.08) 0.0 | 0 (0.25±0.07) 0.0 |
| $E_T < 50$, $H_T < 200$, no Z | 1 (2.6±1.1) 0.1 | 5 (3.9±1.2) 0.1 | 17 (10.6±3.2) 0.0 |

Table 5: Number of observed, SM, and NP events. The NP entry corresponds to 1070 GeV squarks decaying into 200 GeV staus through 1050 GeV Higgsinos.

Finally, we would like to comment on another result described in the CMS study. They find one $4\ell$ event in the zero-$\tau_h$, no-Z, high-$E_T$, low-$H_T$ bin when the expectation is $0.20 \pm 0.07$. This observation comes together with three more $4\ell$ events in the $N(\tau_h) = 1$, no-Z, high-$E_T$, low-$H_T$ bin for a background of $0.59 \pm 0.17$ events (see Table 5). Although these events are not statistically significant, we think it is interesting to find whether LLST SUSY could explain consistently a multilepton anomaly of this type. The low-$H_T$ feature would be obtained if there is a relatively small mass difference between the colored particles (let us say squarks) and the charginos/neutralinos (mostly Higgsinos), which reduces the amount of energy going into jets. The four leptons would result when two neutralinos go into $2\tilde{\tau}\tilde{\tau}$, with both taus decaying.
leptonically $\tau \rightarrow \ell \nu \bar{\nu}$ in the $N(\tau_h) = 0$ event or one leptonically and the other one hadronically in the 3 events with one $\tau_h$.

In Table 5 we have taken 1070 GeV (light-flavor) squarks, 1050 GeV Higgsinos and 200 GeV staus, with the rest of SUSY particles between 1500 GeV and 2 TeV. For the quoted luminosity we obtain $92 \tilde{q}\tilde{q}$ pairs yielding after cuts a total of 8 $4\ell$ and 16 $3\ell$ events in different $E_T$, $H_T$ and $N(\tau_h)$ bins. The model would have also implications in the analysis based on $S_T$ (the total transverse energy from jets, leptons and $E_T$). In particular, the $4\ell$ event in the $N(\tau_h) = 0$ bin and the three events with $N(\tau_h) = 1$ tend to have large values of $S_T$, as the parent particles are very heavy colored particles. Lower values of $S_T$ would require the direct production of the parent neutralino (mostly Higgsino) and masses around $\mu = 400$ GeV.

4 Summary and discussion

SUSY has been during the past decades the favorite candidate to explain the physics above the EW scale. Unfortunately, no signs of SUSY have been observed yet at the LHC. In this paper we have analyzed how model-dependent this SUSY search has been. In particular, we have focused on a scenario where the squarks and gluinos created in $pp$ collisions always produce a long-lived stau at the end of their decay chain. We have argued that if their mass difference is large, most of the staus will be fast ($\beta > 0.8$) and will look indistinguishable from a muon. Instead of the large $E_T$ typical in neutralino LSP scenarios, these LLST models would be characterized by the presence of extra leptons. We have studied how constrained they are by recent SS-dilepton and multilepton searches performed by ATLAS [20] and CMS [21], respectively.

We find that LLST SUSY provides signals with relatively low SM background. The optimal search for SS dileptons would be obtained by relaxing the cuts on $E_T$. In this sense, another very recent CMS analysis [20] of SS dileptons at the LHC provides the results in each region of $E_T$ and $H_T$, which would allow a complete exploration of the scenario presented here (we estimate that it could yield bounds very similar to the ones obtained in Section 3).

Both in SS-dilepton and multilepton searches the larger frequency of muons relative to electrons could be an interesting observation. Notice that any model with long-lived charged particles resulting from the decay of heavier colored ones would imply an excess of muon-like particles, while the usual backgrounds (from top-quark or vector-boson decays) are $\mu-e$ symmetric.

The signature in this LLST scenario is somewhat similar to the one from models with broken $R$-parity and slepton decaying promptly into lepton plus gravitino [21, 28]. Our signal, however,
tends to include less $E_T$, as the whole slepton (and not just half of it) is visible. Given the negative results provided so far by standard SUSY searches at the LHC, in order to complete the search it seems necessary to explore in detail also these other SUSY possibilities.

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