Relaxing LHC bounds on stop mass

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Outline

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Based on collaboration with:
A. Delgado, M. Chala, G. Nardini and M.Q., arXiv:1702.07359

Introduction

- In most SUSY models, R-parity conservation is implemented to avoid rapid proton decay, which implies that the LSP is stable
- As there are strong collider and cosmological constraints on long-lived charged particles, the LSP is preferably electrically neutral
- This fact, together with the appealing cosmological features of neutralinos, has had a strong influence on the experimental choices on the SUSY searches

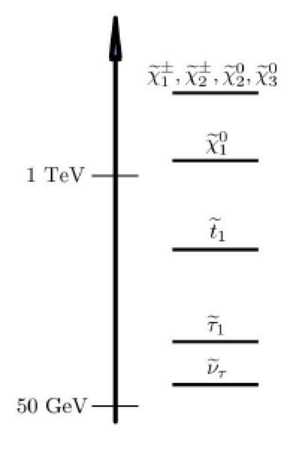
Most of them indeed assume the lightest neutralino to be the LSP or, equivalently for the interpretation of the LHC searches, the long-lived particle towards which all produced SUSY particles decay fast

- Searches under these assumptions are revealing no signal of new physics and putting strong limits on SUSY models
- The interpretation of these findings in simplified models provides lower bounds at around 900 GeV-1 TeV for the stop mass
- The bias for the neutralino as the LSP, as well as the use of simplified-model interpretations, is driving the community to believe that supersymmetry is not a natural solution to the hierarchy problem (modulo focus-point solutions: Graham Ross' talk)

Here we break with this attitude and take an alternative direction:
let's assume that *the LSP is the tau sneutrino* $\tilde{\nu}_\tau$

- Moreover we will avoid peculiar simplified model assumptions (as e.g. compressed scenarios) and deal with realistic, and somewhat non trivial, phenomenological scenarios

- As we assume the lightest neutralino is NOT the LSP we focus on scenarios where all gauginos and Higgsinos are heavier than stops



Models

- These scenarios can arise in some top-down approaches of low scale SUSY breaking
- In particular we can focus on two of them

- Scherk-Schwarz supersymmetry breaking (extra dimensions)
- Gauge mediated supersymmetry breaking (four dimensions)

- In our model analysis we will not consider any detailed top-down approach

SS breaking

- In five-dimensional $S^1/\mathbb{Z}_2$ SUSY theories, supersymmetry can be broken by the SS mechanism
- One can locate the hypermultiplets of the RH stop $\tilde{t}_R$ and the LH third generation lepton doublet $(\tilde{\tau}, \tilde{\nu}_\tau)_L$ at the brane $y = 0$
- All the remaining ones are propagating in the bulk
- Gluinos and electroweakinos feel supersymmetry breaking at tree level and are very massive and almost degenerate
- Localized scalars feel it through one-loop radiative corrections
- The ratio between the gaugino and stop masses is

$$m_{1/2}^2/m_{\tilde{t}}^2 \propto 4\pi/\alpha_s$$

- $\tilde{t}_R$ are light but heavier than the $\tilde{\tau}_L$ and the $\tilde{\nu}_\tau$ by around a factor

$$m_{\tilde{t}}^2/m_{\tilde{\tau}}^2 \propto g_s^2/g^2, \quad m_{\tilde{\nu}_\tau}^2 < m_{\tilde{\tau}}^2$$

Gauge mediation

- In GMSB the ratio of the gaugino ($m_{1/2}$) over the squark (m_0) masses behaves parametrically as

$$m_{1/2}^2/m_0^2 \propto N f(F/M^2)$$

where N is the number of messengers, F the supersymmetry breaking parameter and M the messenger mass.

- The condition

$$F/M^2 \lesssim 1 \Longrightarrow f(F/M^2) \lesssim 3$$

guarantees the absence of tachyons in the messenger spectrum

- For large N and/or F/M^2 close to one, the hierarchy

$$m_{1/2} \gg m_0$$

can be achieved

- Within this hierarchy stops are heavier than staus, parametrically by factors of the order of

$$m^2_{\tilde t}/m^2_{\tilde\tau} \propto g_s^2/g^2, \quad m^2_{\tilde\nu_\tau} = m^2_{\tilde\tau} - m^2_W$$

at the messenger mass scale M

- In practice, we assume that the slepton singlet is very heavy

$$m_{\widetilde\tau_R} \gg m_{(\widetilde\nu,\widetilde\tau)_L}$$

- In GMSB scenarios this hypothesis can be fulfilled only if the messengers transform under a group with e.g. an extra $U(1)$ such that the extra hypercharge $\widetilde Y(\nu_L)=0$, $\widetilde Y(\tau_R)\neq 0$
- For instance one can use a $\widetilde U(1)\in E_6 \to SO(10)\to SU(5)$ with

$$27 = 16+10+1, \quad 16 = 10+\bar 5+\nu^c, \quad 10 = 5_H+\bar 5_H$$
$$4\widetilde Y_{(10,\bar 5,\nu^c,5_H,\bar 5_H,1)} = (-1,0,-2,2,1,-3)$$

Cosmological issues

- In the present study the tau sneutrino is stable at collider scales
- If it also is stable at cosmological scales, its thermal relic density is below the dark matter (DM) abundance
- Moreover, it is also ruled out by direct detection experiments

So the scenario has to be completed somehow, to provide a reliable explanation of the DM relic density and/or avoid the strong bounds from direct detection experiments.

- There are a limited number of possible mechanisms to circumvent the previous problems without altering the stop phenomenology we have investigated

- The simplest possibility is to assume that the sneutrino, even though stable at collider scales, is *unstable at cosmological scales*
- In theories with R-parity conservation this can be realized only if there is a lighter SUSY particle (possibly a DM candidate) which the sneutrino decays to, but such that the sneutrino only decays outside the detector and in cosmological times

GMSB

- In theories with GMSB this role can be played by a light gravitino $\widetilde{G}$
- It is a candidate to warm DM and its cosmological abundance is given by

$$\Omega_{3/2}h^2 \simeq 0.1(m_{3/2}/0.2\ \mathrm{keV})$$

which suggests a rather low scale of supersymmetry breaking

$$F \simeq m_{3/2}M_P$$

- In this case the sneutrino decays as $\widetilde{\nu} \to \nu\widetilde{G}$ and, as far as collider phenomenology is concerned, it looks stable.

SS

- In theories with a heavy gravitino one could always introduce a right-handed sneutrino ν_R, lighter than the left-handed sneutrino

$$\mathcal{L} = -AH_2\tilde{L}\tilde{\nu}_R + \cdots \Rightarrow \tilde{\nu}_L \to h^*\tilde{\nu}_R \to f\bar{f}\tilde{\nu}_R$$

- This can be achieved for instance by localizing the right-handed neutrino multiplet in the brane and thus receiving its mass from higher order radiative corrections
- Moreover the right-handed sneutrino can in principle play the role of DM
- If its fermionic partner is light, also the decay $\widetilde{t} \to b\widetilde{\tau}\nu_R$ appears although this process is suppressed by the small neutrino Yukawa coupling

- Finally the simplest solution to avoid the direct detection bounds is if there is a small amount of R-parity breaking and the sneutrino becomes unstable at cosmological scales
- For instance one can introduce an R-parity violating superpotential as

$$W = \lambda_{ijk} L_i L_j E_k$$

with a small Yukawa coupling λ_{ijk} such that the sneutrino decays as $\widetilde{\nu} \to e_j \bar{e}_k$.

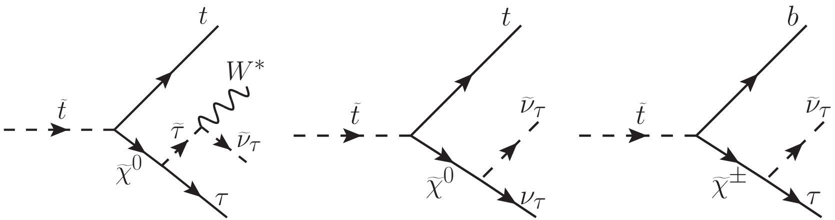
- Depending on the value of the coupling λ the sneutrino can decay at cosmological times. Needless to say, in this case one would need some additional candidate to DM.

Thus, in practice, the stop collider phenomenology would not be different from that considered here

Dominant stop decays

The relevant stop decays are

$$\widetilde{t} \to t\widetilde{\tau}\tau,\ t \to t\widetilde{\nu}\nu,\ \widetilde{t} \to b\widetilde{\nu}\tau,\ \widetilde{t} \to b\widetilde{\tau}\nu$$



The last decay is negligible when the interaction between $\tilde{t}$ and $\widetilde{W}$ is tiny: for scenarios when the lighter stop has a negligible LH component and/or the Wino is close to decoupling

We consider searches of pair-produced stops decaying hadronically at 13 TeV, as well as SUSY searches in final states with τ

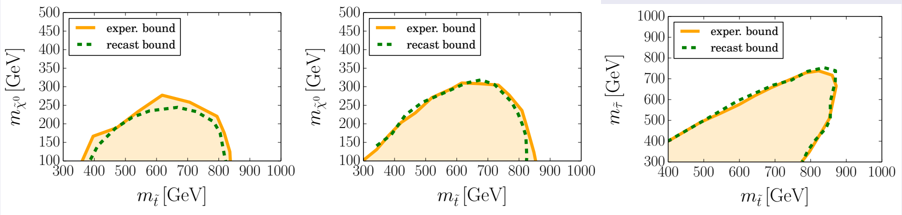
	ATLAS-CONF-2016-077	CMS-PAS-SUS-16-029	ATLAS-CONF-2016-048
$\tilde{t} \to t\tilde{\tau}\tau$		$\surd$	$\surd^*$
$\tilde{t} \to t\tilde{\nu}\nu$	$\surd$	$\surd^*$	
$\tilde{t} \to b\tilde{\nu}\tau$		$\surd$	$\surd^*$
	$\tilde{t} \to t\tilde{\chi}^0$	$\tilde{t} \to t\tilde{\chi}^0$	$\tilde{t} \to b\bar{\nu}\tilde{\tau}$ $(\tilde{\tau} \to \tau\tilde{G})$

Analyses employed for testing the different decay modes. The most sensitive one in each case is tagged with an asterisk.

To validate our implementations of the experimental analyses we apply them to MC events generated using the same benchmark models of those searches

The signal samples are obtained by generating pairs of stop events in the MSSM with `MadGraph v5` at leading order. Such events are subsequently decayed by `Pythia v6`. In the parameter cards produced with `SARAH v4` and `SPheno v3`, the branching ratios are fixed manually to 100%

Validation

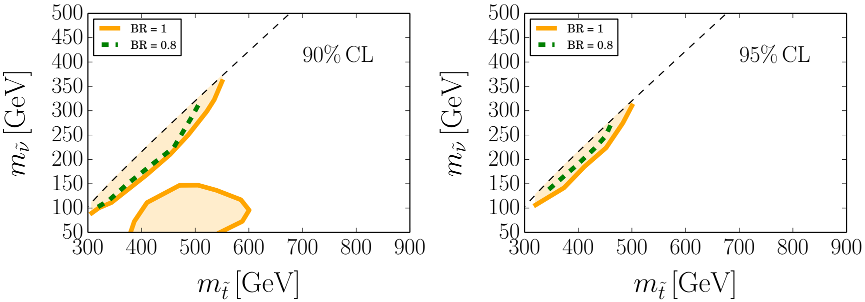


Single channel bounds

We consider here individual decay channels and use LHC data to bound the corresponding BR in the plane $(m_{\tilde{t}}, m_{\tilde{\nu}})$

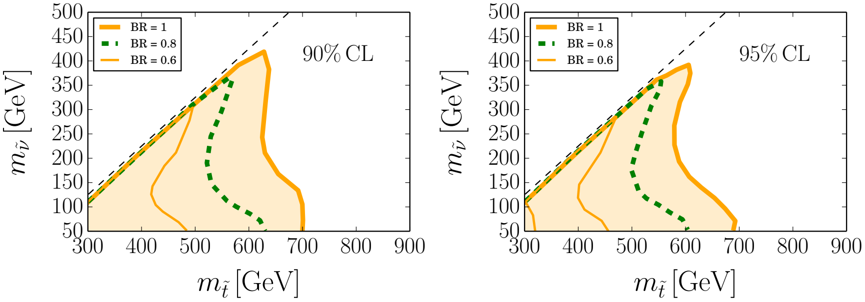
$$\mathcal{B}(\tilde{t} \to t\tilde{\tau}\tau) = 1, 0.8$$

CMS-PAS-SUS-16-029 & ATLAS-CONF-2016-048 are combined into a single statistics: bounds in this channel are weak



$$\mathcal{B}(\tilde{t} \to t\tilde{\nu}\nu) = 1, 0.8, 0.6$$

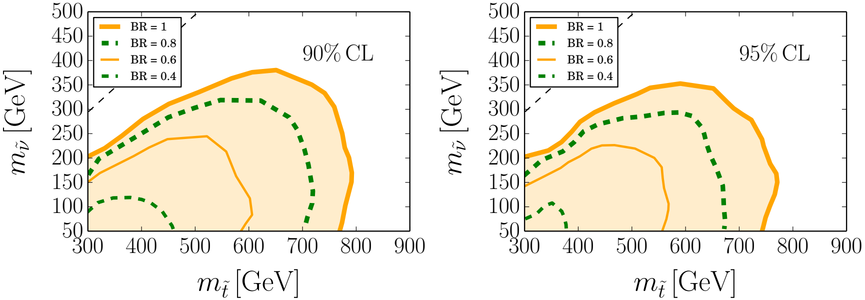
ATLAS-CONF-2016-077 & CMS-PAS-SUS-16-029 are combined into a single statistics



As already pointed out, the stringent cuts optimized for the searches for stops into on-shell LSP neutralinos have rather low efficiency on the "double invisible" three-body decay signal involving an off-shell mediator: Alves-Liu-Weiner, 1312.4965

$$\mathcal{B}(\tilde{t} \to b\tilde{\nu}\tau) = 1, 0.8, 0.6, 0.4$$

CMS-PAS-SUS-16-029 & ATLAS-CONF-2016-048 are combined into a single statistics



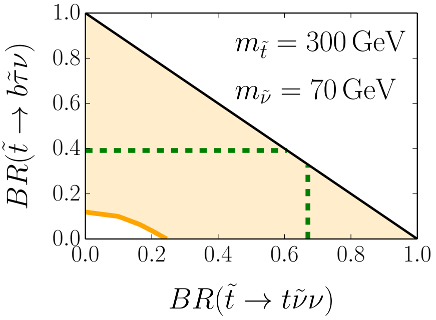
The most sensitive analysis to this channel is the ATLAS counting one: ATLAS-CONF-2016-048

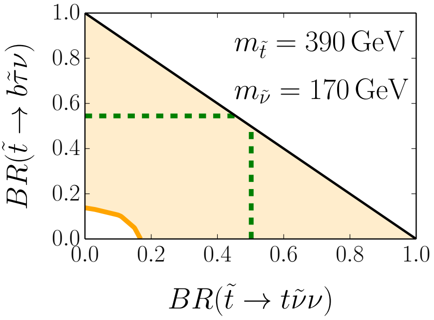
Combined channels

- We consider here the different decay channels and use LHC data to bound the corresponding BR in the plane $(m_{\tilde{t}}, m_{\tilde{\nu}})$
- In concrete models, it is feasible that the branching ratios of the three aforementioned stop decay channels sum up to essentially 100%
- In such a situation, we can consider $\mathcal{B}(\widetilde{t} \to t\widetilde{\nu}\nu)$ and $\mathcal{B}(\widetilde{t} \to b\widetilde{\nu}\tau)$ as two independent variables, and fix $\mathcal{B}(\widetilde{t} \to t\widetilde{\tau}\tau)$ from them
- It is then possible to use the aforementioned ATLAS and CMS searches to constrain the two-dimensional plane for some set of values of $m_{\widetilde{t}}$ and $m_{\widetilde{\nu}}$
- The total number of signal events after cuts is given by

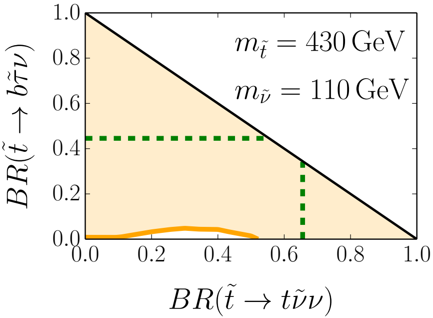
$$N = \sum_{i,j} N_{ij}(m_{\widetilde{t}})\, \epsilon_{ij}(m_{\widetilde{t}}, m_{\widetilde{\nu}}) \;, \quad \epsilon_{ij} = efficiency$$

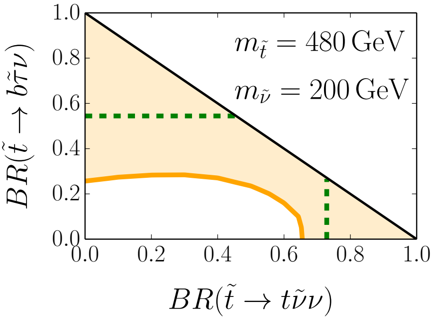
$$N_{ij}(m_{\widetilde{t}}) = \mathcal{L}\, \sigma(pp \to \widetilde{t}\widetilde{t}^*) \times \mathrm{BR}(\widetilde{t} \to i) \times \mathrm{BR}(\widetilde{t}^* \to j) \;,$$





The areas below (to the left of) the horizontal (vertical) green dashed lines would be allowed if only the $\widetilde{t} \to b\widetilde{\tau}\nu$ ($\widetilde{t} \to t\widetilde{\nu}\nu$) mode was considered. The areas enclosed by the orange solid lines are excluded when all channels are combined

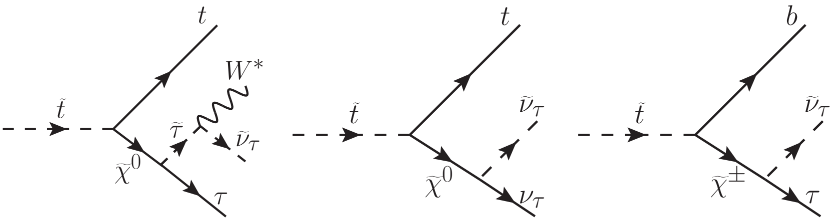




The allowed regions favor large values of $\mathcal{B}(\widetilde{t} \to t\widetilde{\tau}\tau)$. This effect can be easily understood as *there is little sensitivity of the present experimental searches to the channel* $\widetilde{t} \to t\widetilde{\tau}\tau$ when $m_{\widetilde{t}}$ and $m_{\widetilde{\nu}}$ are small.

Benchmark models

- These results can be reinterpreted in concrete SUSY scenarios that exhibit stops decaying as in

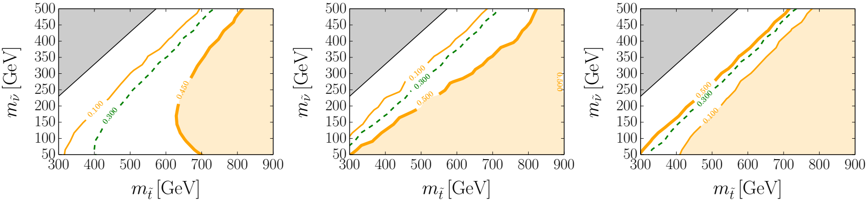


  at least at detector scales
- We impose $\tan\beta = 10$. The slepton and squark soft-breaking trilinear parameters are set to zero. The soft masses of the RH stop, $M^2_{U_R}$, and LH stau doublet, $M^2_{L_L}$, are much lighter than those of their partners with opposite "chirality", $M^2_{Q_L}$ and $M^2_{E_R}$

- The electroweakino soft parameters for scenarios A and B

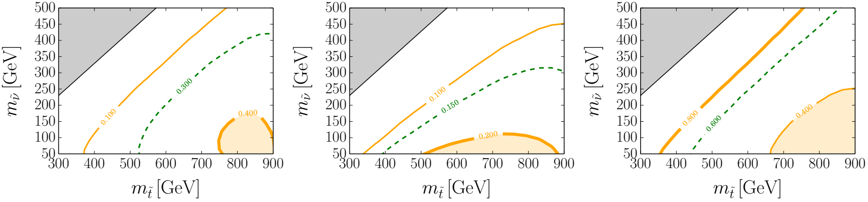
Scenario	M_1	M_2	μ
A	1.1 TeV	5 TeV	5 TeV
B	1.1 TeV	1.1 TeV	1.1 TeV

- The stop, stau, sneutrino and electroweakino mass spectrum and their partial widths are determined by means of `SARAH v4` and `SPheno v3`
- Within each regime, we vary the masses $m_{\tilde{t}}$ and $m_{\tilde{\nu}}$, by scanning over $M^2_{U_R}$ and $M^2_{L_L}$, and consequently $m_{\tilde{\tau}}$ is determined as well
- We discard the parameter points with $m_{\tilde{t}} < m_{\tilde{\nu}} + 70\,\mathrm{GeV}$, which correspond to compressed scenarios that are not investigated



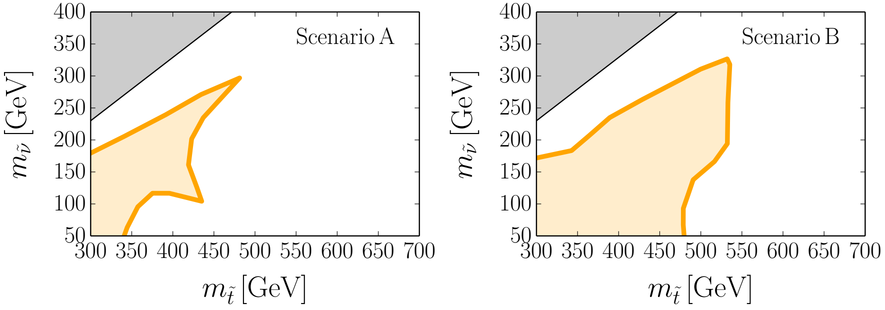
Contour plots of the values of BR($\tilde{t} \to t\tilde{\tau}\tau$) (left panels), BR($\tilde{t} \to t\tilde{\nu}\nu$) (middle panels) and BR($\tilde{t} \to b\tilde{\nu}\tau$) (right panels) in Scenario A

By increasing the value of M_2 and μ (Scenario A)) we increase the branching ratio corresponding to the channel $t\tilde{\tau}\tau$, and we expect to make softer the bounds in the plane $(m_{\tilde{t}}, m_{\tilde{\nu}})$, in agreement with the general behavior found



Contour plots of the values of BR($\widetilde{t} \to t\widetilde{\tau}\tau$) (left panels), BR($\widetilde{t} \to t\widetilde{\nu}\nu$) (middle panels) and BR($\widetilde{t} \to b\widetilde{\nu}\tau$) (right panels) in Scenario B

The sum of these three branching ratios is always above 95% (depending on the range of $m_{\widetilde{t}}$ and $m_{\widetilde{\nu}}$) which is consistent with our general model assumptions. We also checked numerically that the total width of the stau is $\mathcal{O}(10^{-8}\,\text{GeV})$ for $m_{\widetilde{\nu}} \approx 500\,\text{GeV}$, and is much larger at smaller sneutrino masses. Analogously, the mass gap between the stau and sneutrino masses ranges between $5-40$ GeV, the latter value appearing for $m_{\widetilde{\nu}} \approx 60\,\text{GeV}$



- The exclusion bounds (orange areas) are relaxed with respect to their analogous in SUSY scenarios with the neutralino as the LSP.
- As anticipated, bounds are weaker in scenario A than in scenario B, due the larger values of BR($\widetilde{t} \to t\widetilde{\tau}\tau$)
- Remarkably, in the presence of light sneutrinos, a RH stop at around 350 GeV is not ruled out by current LHC data, or at least by the ATLAS and CMS analyses performed till now

Conclusion

- We have explored the phenomenology of the MSSM in the absence of neutralino as DM candidate
- The stop can be light, provided that the EWino sector is heavier and the third lepton family is lighter
- This result relies on:
  - The double-invisible decays
  - The several involved branching ratios
  - The absence of dedicated analyses