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A critical assessment of the status of LHC searches for new physics

Mikael Chala[*†]
Institute of Particle Physics Phenomenology, Physics Department, Durham University, Durham DH1 3LE, UK
E-mail: mikael.chala@durham.ac.uk

The hierarchy problem is the main hint of new physics at the TeV scale, supersymmetry and composite Higgs models being two of the big classes of solutions. Several analyses have been performed at the LHC in the search for signals of these models, will null results so far. In this article we argue that *(i)* current searches have only explored small regions of the parameter space of these models, *(ii)* these regions are often less motivated than others not yet explored, *(iii)* in either case, current constraints do not necessarily put naturalness under pressure. We also extend this discussion to searches for models of neutrino masses.

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1. Introduction

The hierarchy problem –and, to a lesser extent, the non-vanishing neutrino masses as well as the observation of Dark Matter (DM) – has driven the most important searches at the LHC. The lack of signals of new particles predicted by models addressing this problem, of course, does not make it disappear. At most, this could be an indication that alternatives to the traditional scenarios, namely SUperSYmmetry (SUSY) and Composite Higgs Models (CHMs), must be considered.

In this article, nevertheless, we will show that the large number of experimental searches for new physics has not been translated to the study of a similar number of new physics models. Instead, the *same* parameter space regions of the *same* realizations of SUSY and CHMs have been explored over and over. We will also argue that such realizations are often oversimplified and poorly justified from the theoretical point of view. Current searches lose a big part of their sensitivity to more realistic setups. In this regard, we will concentrate on SUSY in Section 2. We will consider CHMs in Section 3, and will extend the discussion also to models of neutrino masses in Section 4. We will conclude in Section 5.

2. Searches for supersymmetry

Supersymmetry has been traditionally considered as the best solution to the hierarchy problem, in particular because it can also explain other open question of the Standard Model (SM) —*e.g.* gauge coupling unification or DM– and because it is required by more fundamental UV theories —such as string theory—.

Although SUSY is broken, large corrections to the Higgs mass are still suppressed if its supersymmetric partners, the Higgsinos, are of EW size. Likewise, the supersymmetric partners of the top quark t, namely the stops $\tilde{t}$ —and, to a lesser extent, the gluinos—, are expected to be no much heavier, since they contribute to the Higgs mass at the loop level. The second generation squarks and the sleptons can be however much more massive. Such as spectrum is commonly thought to be the *natural SUSY* [1]. This conclusion relies on an IR analysis which assumes that all soft terms at the EW scale are uncorrelated. In top-down approaches, however, correlations are inherited from the UV; see *e.g.* Refs. [3, 4, 5, 6]. Taking this effect into consideration, the latter studies show that, indeed, all supersymmetric particles can be as heavy as several TeV without implying a large fine-tuning on the Higgs mass. This would perfectly explain the absence of SUSY signals at the LHC.

A different explanation relies on the fact that most LHC searches for SUSY assume that R-parity is conserved. However, R-parity conservation is by no means fundamental. Several other symmetries avoiding proton decay, *e.g.* baryon or lepton parity, are equally plausible in Grand Unified Theories (GUTs) [7]. This opens the door to new stop production and decay mechanisms. The impact on our understanding of the nature of SUSY breaking can then be dramatic. For example, searches for pair-produced stops decaying into pairs of jets via R-parity violating couplings have been discussed in Ref. [10]. The corresponding bounds are as weak as $m_{\tilde{t}} > 410$ GeV.

Moreover, in scenarios with R-parity violation, the lightest neutralino $\tilde{\chi}^0$ is no longer stable and therefore is not a suitable DM candidate. This role can be instead played by a light gravitino or by a right-handed sneutrino [11, 12]. This demonstrates that SUSY spectra completely different

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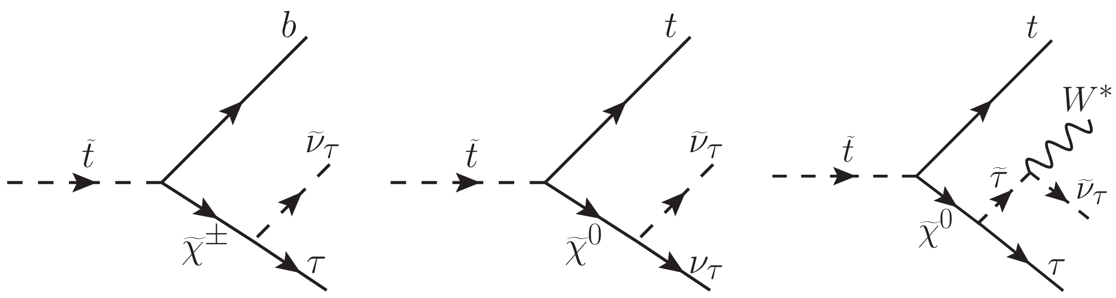

Figure 1: *The dominant stop decays in the analysis of Ref. [13].*

from those most commonly tested in current LHC searches are possible. For concreteness, we assume that the next Lightest Supersymmetric Particle (LSP) is the left-handed tauonic sneutrino $\tilde{\nu}_\tau$ [1], followed by the right-handed stau $\tilde{\tau}$, the right-handed $\tilde{t}$ and all EWinos.

This spectrum arises naturally in Scherk-Schwarz models, in which SUSY is broken by the different boundary conditions taken by bosons and fermions in an extra dimension [8]. It also appears in more common SUSY breakings, such as gauge mediated SUSY breaking [9]. In this latter case, SUSY breaking is transmitted to the visible sector via gauge interactions. Thus, gluinos are heavier than EWinos by a factor of g_s^2/g_α^2; likewise for stops with respect to staus. The (inverse) splitting between $\tilde{\tau}$ and $\tilde{\nu}$ can be explained *e.g.* in theories with an extra $U(1)$ gauge group under which the former is charged while the latter is not. This happens automatically in GUTs based on $E_6 \supset SU(5) \times U(1)$ when the third generation fermions transform in the **27** fundamental representation.

In light of this spectrum, the stop decays mainly in three different ways, depicted in Fig. 1. To the date, no dedicated analysis tailored to this kinematic has been developed. In Ref. [13], though, some of the most constraining searches were recast. Among these we have those for pair-produced stops in fully hadronic final states performed by the ATLAS and CMS Collaborations [14, 15], as well as searches for pair-produced stops in a final state with tau leptons carried out by the ATLAS Collaboration [16]. The bounds obtained in Ref. [13], combining these analyses, as a function of two of the stop branching ratios (the third one is just the rest to the unity) are shown in Fig. 2. It is apparent that masses well below the TeV (as small as 300 GeV) are compatible with current data. The reason for this is basically twofold:

1. The analyses considered, despite being the most sensitive to the signals of interest, are not optimized for them (specially for the tauonic final state).

2. In this respect, it is worth noting that the stop decay is three body, and therefore the amount of missing energy is smaller than in the decay considered traditionally, namely $\tilde{t} \to \tilde{\chi}^0 t$.

As things stand, SUSY is still an absolutely natural solution to the hierarchy problem. Much more experimental work must be carried out in order to refute this possibility.

[1] The strong collider and cosmological constraints on long-lived charged particles force the next LSP —which in this context escapes the detector— to be a neutral particle.

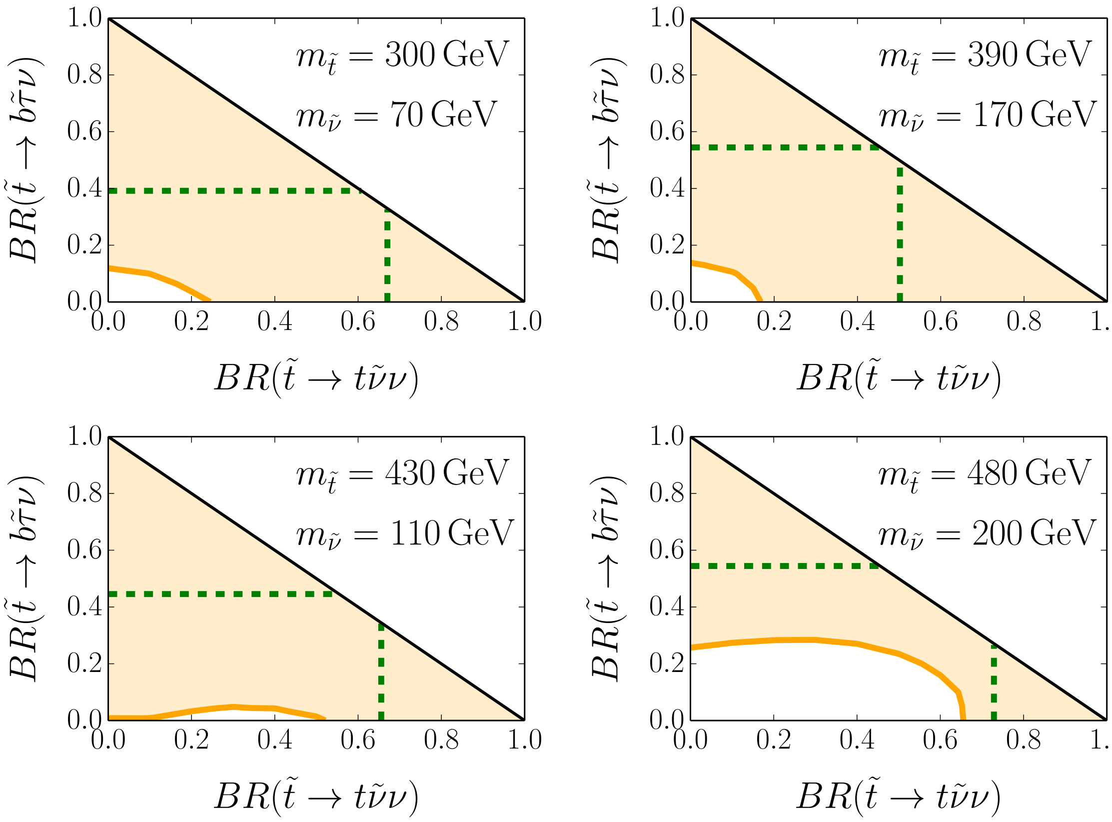

Figure 2: *Excluded regions at 95 % C.L. in the plane of branching ratios for different pairs of values of $m_{\tilde{t}}$ and $m_{\tilde{\nu}}$. The areas below (to the left of) the horizontal (vertical) dashed green lines are allowed if the only decay mode is $\tilde{t} \to b\tilde{\tau}\nu$ ($\tilde{t} \to t\tilde{\nu}\nu$). The areas enclosed by the solid orange lines are excluded when all channels of Fig. 1 are combined.*

3. Searches for composite Higgs models

Composite Higgs models [17, 18, 19] provide a different and appealing solution to the hierarchy problem. In this case, the Higgs is a composite pseudo-Nambu-Goldstone Boson (pNGB), its mass being therefore protected by its finite size and by an approximate shift symmetry. The prime signature of these models is the presence of fermionic vector-like resonances (in particular heavy top-like quarks T), whose mass M is correlated with the level of tuning in the Higgs mass. It is naively expected that $M \lesssim 1$ TeV. In several CHMs in which DM is also a pNGB, M is instead fixed by the actual *measurement* of the relic density, giving $M \gtrsim 2$ TeV [20].

Current ATLAS and CMS searches [21] do not even exclude yet the most conservative (fine-tuning based) values of M. Moreover, *all* these searches assume that the heavy quarks decay only into SM particles, *i.e.* into W, Z and h together with a third generation quark. This assumption is however not always justified. More the contrary: in most CHMs, including the best motivated ones, the Higgs sector contains further scalars S into which the heavy quarks can decay. These scalars, in turn, can either be stable or decay into SM particles. The latter signal can be even elusive to current searches, *e.g.* if $T \to St, S \to jj$, the heavy quark can be easily hidden in the region populated by

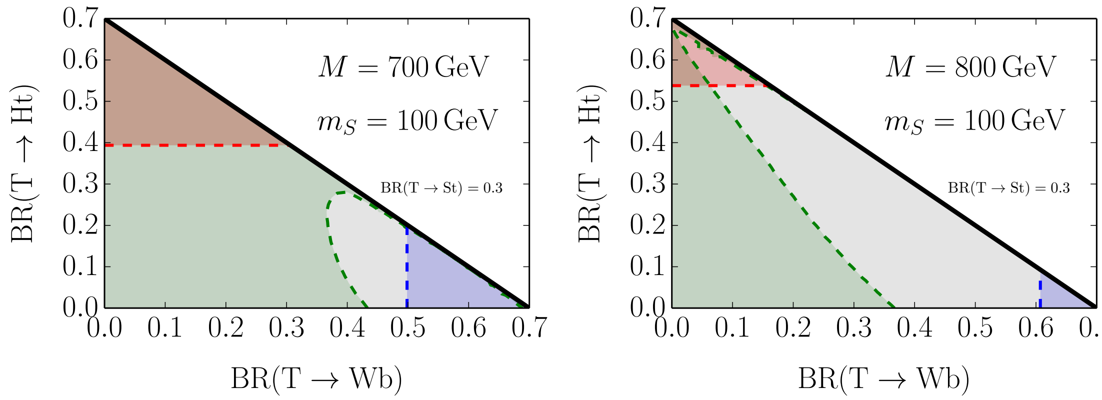

Figure 3: *Excluded branching ratios for a top-like heavy vector-like quark with $M = 700$ GeV (left) and $M = 800$ GeV (right) assuming it decays not only into SM particles, but also into a top quark and a new singlet S with mass $m_S = 100$ GeV. The latter branching ratio has been fixed to 0.3. The red regions are excluded by the search of Ref. [23]. The blue regions are excluded by the search of Ref. [24]. These searches are combined with the analyses of Refs. [25] to bound the gray regions (in which S is assumed to be invisible) and the green ones (in which the final state St is supposed to evade current searches). For such a value of m_S, the branching ratio of $T \to tS, S \to b\bar{b}$, if exists, can be added to the y axis [22].*

the huge SM $t\bar{t} + jets$ background.

As it was shown in Ref. [22], relaxing the assumption that T decays only into SM particles weakens the current bounds on M by a large amount. This is shown in Fig. 3. It is clear from the figure that masses as small as $M \sim 700$ GeV are still allowed by current searches even for small branching ratios into St. As in the case of SUSY, new dedicated analyses, depending on how S (or other possible extra scalars) decay, are required. In this same spirit, it has been recently shown [28] that leptonic composite resonances could be responsible for the recent hints of lepton-flavor universality violation pointed out by the LHCb [26] and Bell [27], while again current experimental analyses can not exclude this hypothesis.

As things stand, CHMs are still an absolutely natural solution to the hierarchy problem. Much more experimental work must be carried out in order to refute this possibility.

4. Searches for new physics behind neutrino masses

Finally, a comment on the impact of theoretical biases on searches for particles arising in models of neutrino masses is also deserved. As it has been pointed out in Ref. [33], current LHC searches are optimized for see-saw models [29, 30, 31, 32], in which new particles decay promptly into SM states. In these models, neutrino masses are generated at tree level, the natural scale of new physics being then $\sim v^2/m_\nu$, with $v \sim 246$ GeV the EW VEV and $m_\nu \lesssim$ eV. This lies orders of magnitude above the TeV. On the other hand, in models in which neutrino masses arise radiatively at n loops, the new physics scale is expected to be a factor of $(4\pi)^{2n}$ smaller, and hence naturally within the LHC reach. However, these models contain particles with exotic decays, to which current searches for see-saws are not sensitive.

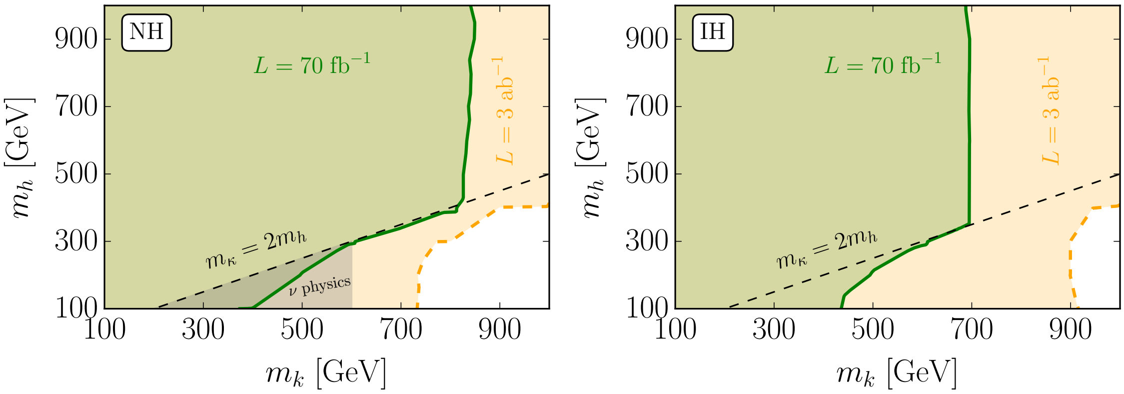

Figure 4: *Regions in the plane m_k–m_h that can be probed at the 95 % C.L. using the analysis of Ref. [33] in the NH (left) and the IH (right) in the Zee-Babu model with 70 fb^{-1} (green solid) and 3 ab^{-1} (dashed orange) at the LHC. The small grey triangle is excluded by neutrino data.*

This situation could be overcome if analyses including several signal regions with different numbers of leptons as well as the interplay between different observables were considered. One such possible broad analysis was presented in Ref. [33]. The LHC reach to different final states motivated by models of radiatively-induced neutrino masses was discussed. Here we summarize the prospects for testing the parameter space region of the Zee-Babu model [34, 35]. This extends the SM Higgs sector with two $SU(2)_L$ singlets, h and k, with hypercharges $Y = 1,2$, respectively. The relevant Lagrangian reads:

$$\mathscr{L} = \mathscr{L}_{SM} + f^{ab}\overline{\tilde{L}_{aL}}L_{Lb}h^+ + g^{ab}\overline{e^c_a}e_b k^{++} - \mu k^{++}h^-h^- + \text{h.c.} + \cdots \tag{4.1}$$

where $\mathscr{L}_{SM}$ stands for the SM Lagrangian, L_{aL} (e_a) with $a = 1,2,3$ are the first, second and third generation SM lepton doublets (singlets) and $\tilde{L}_L = i\sigma_2 L_L^c$ with σ_2 the second Pauli matrix. The ellipsis stand for other terms not relevant for the subsequent discussion. Overall, the model depends only on the antisymmetric (symmetric) dimensionless couplings f^{ab} (g^{ab}), the physical masses of the new scalars, namely m_k and m_h, and the dimensionless parameter κ defined by $\mu = \kappa\, min\{m_h, m_k\}$. All these parameters are constrained by the known values of neutrino masses (which in this model are generated at two loops) and mixing angles, as well as by low-energy experiments.

Thus, in the case of Normal Hierarchy (NH), the following relations must hold: $g^{11} \sim g^{22} \sim 0.1 \gg g^{12}, g^{13}, g^{23}, g^{33}$; as well as $f^{12} \sim f^{13} \sim f^{23}/2$. An overall scale of $f \sim 0.01$ is in agreement with $\mu \to e\gamma$. The region $m_k < 2m_h$ is allowed for $k > 400$ (600) GeV if $\kappa \sim 4\pi$ (5). For concreteness, we fix:

$$g^{11} = g^{22} = 0.1\ , \quad g^{12} = g^{13} = g^{33} = 0.001\ , f^{12} = f^{13} = 0.01\ , f^{23} = 0.02\ , \kappa = 5\ . \tag{4.2}$$

Consequently, for $m_k > 2m_h$, k decays mainly into hh. The pair-production of doubly-charged scalars gives rise to two, three and four lepton events in ~ 35 %, ~ 30 % and ~ 15 % of the cases, respectively. The mass planes that could be tested at the 95 % C.L. by the aforementioned search of Ref. [33] with 70 fb^{-1} and 3 ab^{-1} are displayed in Fig. 4.

It is worth noting that doubly-charged scalar masses as large as 900 GeV could be probed even for k decaying into exotic states. Similar conclusions hold for the Inverse Hierarchy (IH) case. This is however very much constrained by neutrino data, unless the physical Majorana and Dirac phases in the PMNS matrix, ϕ and δ respectively, are very well tuned to $\phi \sim \delta \sim \pi$. Still, for the sake of completeness, we show the prospects for this regime in the right panel of Fig. 4.

5. Conclusions

We have provided exhaustive evidence of the low sensitivity of current LHC searches to less simplified (and more realistic) composite Higgs models and supersymmetric setups. Concerning models of neutrino masses, we have commented on how current analyses could be modified in order to become sensitive to scenarios in which, contrary to the current targets, new particles must be at the TeV scale.

On balance, the traditional solutions to the hierarchy problem, as well as the most interesting models of neutrino masses, are perfectly compatible with current LHC data. Much more (and distinct) experimental work must be carried out in order to refute this possibility.

Acknowledgments

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