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Physics Beyond the Standard Model Associated with the Top Quark

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Abstract

In this article, I review scenarios of physics beyond the Standard Model in which the top quark plays a special role. Models that aim at the stabilization of the weak scale are presented together with the specific phenomenology of partner states that are characteristic of this type of model. Further, I present models of flavor in which the top quark is singled out as a special flavor in the Standard Model. The flavor and collider phenomenology of these models is broadly presented. Finally, I discuss the possibility that dark matter interacts preferably with the top quark flavor and give an overview of the dark matter phenomenology of these scenarios, as well as collider and flavor signals.

Contents

1. INTRODUCTION

The top quark is a singular object amid the fermions of the Standard Model (SM), as it is the heaviest among them. The top quark entails several peculiar properties: In the domain of QCD, the top quark is the only quark never to be observed forming hadrons, as its decay is much faster than the hadron formation time. After the discovery of the Higgs boson, and for all the time before in which the Higgs mechanism dominated the landscape of model building for the electroweak sector of the SM, the top quark has stood out as the only quark with a normal-sized coupling with the Higgs boson. This latter property has made the top quark very interesting with regard to both the origin of the structure of flavor in the SM and the origin of the electroweak scale itself. The special interest in top flavor concerns the top quark's strong tendency to decay into bottom quarks [i.e., not involving other flavor families, which in the Cabibbo–Kobayashi–Maskawa (CKM) picture results in $V_{tb} = 1$ up to small corrections] and its large mass, which can possibly act as a magnifier of the effects of physics beyond the Higgs boson as the origin of flavor. For electroweak physics, the top quark plays a crucial role in that it affects the properties of the Higgs boson and, via the Higgs mechanism for weak boson mass generation, the physics of weak gauge bosons: Its effect can be seen in their masses and decay rates, which are sensitive to the strength of the top quark gauge and Yukawa couplings and to its mass. Deviations of these properties from the SM predictions can be signs of New Physics related to the top quark. While the importance of the top quark can already be appreciated from these general facts, the detailed role played by the top quark can be better understood by considering explicit New Physics models.

In Sections 2.1 and 2.2 I discuss models in which the top quark plays a special role in the origin of electroweak symmetry. In Section 3 I extend this discussion in a more model-independent direction, using a flavor-conserving effective field theory (EFT) of the top quark sector, which also allows us to consider the prospects for top quark physics at future colliders. In Section 4.1 I examine a different problem, the origin of SM flavors. In Section 4.2 I explore the possibility that SM flavor plays a part in stabilizing dark matter so that it interacts preferably with the top quark flavor, and I discuss the phenomenology of dark matter in these scenarios. Finally, in Section 5, I offer some conclusions.

Since I cover a long list of subjects, I necessarily omit details of specific models. These details can be found in the references provided. This review is conceived so that it can also be useful for younger graduate students seeking a high-level introduction to the subjects discussed. Hopefully, readers can begin their own exploration here on topics that would otherwise require them to go through a large stack of literature. References are kept to a minimum of key works to encourage the reader to actually study these selected works.

2. TOP QUARK AND PHYSICS BEYOND THE STANDARD MODEL RELATED TO THE HIGGS BOSON AND THE ORIGIN OF THE WEAK SCALE

The origin of the weak scale is a mysterious point in the formulation of the SM. The weak scale, which can be identified with the mass of the weak vector bosons, emerges upon the spontaneous breaking of the $SU(2) \times U(1)$ symmetry to the electromagnetism $U(1)$. The order parameter for this symmetry breaking is the vacuum expectation value of the Higgs boson; it controls the masses of weak vector bosons through gauge interactions, the masses of the SM fermions via Yukawa interactions, and the mass of the Higgs boson itself via the Higgs boson self-coupling.

At the Lagrangian level, the size of the vacuum expectation value of the Higgs boson depends on the μ term in

$$\mathcal{L} = \mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 .$$

The value of μ could originate from yet undiscovered physics that plays the role of a microscopic theory for the Higgs boson, as is the case for the theory of Cooper pairs of superconductivity, or μ might be a truly fundamental parameter of Nature. In any event, its value is rather puzzling, as it could take any value in the whole range up to the gravity scale at 10^{19} GeV and still end up at some apparently unmotivated TeV-scale value. Often, the TeV value of μ is compared to the possible maximum value at the gravity scale, and for this reason this puzzle is called the weak/gravity hierarchy problem.

It has been noted (1) that this Lagrangian does not enjoy an enhanced symmetry when $\mu \to 0$. Therefore, although we need a small value for μ, we have no symmetry argument in the SM to enforce it. One suggested solution is to use a new kind of symmetry to enforce the smallness of μ. The proposal of supersymmetry at the weak scale (see, e.g., Reference 2 for a more formal introduction to the topic and Reference 3 for a more phenomenological one) addressed exactly this point. Its phenomenology in the top quark sector is described in Section 2.1. The idea of supersymmetry is that, by relating bosons and fermions, the μ^2 bosonic mass term has to be connected to a fermion mass term. The latter can be seen as a symmetry-breaking effect, as it breaks the chiral symmetry of the action of massless Weyl fermions. Putting this all together, the μ^2 bosonic mass term becomes a parameter controlled by symmetry, thus offering a handle to explain the weak scale through symmetry breaking.

Other routes have been proposed to explain the smallness of μ by obtaining it as a dynamically generated parameter of a confining theory. In those theories some of the SM states are composite objects made of more microscopic states that experience some shorter-distance confining dynamics. Therefore, the composite SM states emerge similarly to how mesons emerge in QCD as composite states made of quarks. The Higgs boson qualifies as a prime candidate to be a composite state, such that its puzzling properties might be explained by the microscopic theory. In Section 2.2 I discuss the model of the Higgs boson as a Nambu–Goldstone boson associated with a global symmetry in the microscopic theory. Because this symmetry is slightly broken, the Higgs boson is not massless; thus, it is said to be a pseudo-Nambu–Goldstone boson (pNGB). A crucial feature stemming from its pNGB nature is that the Higgs boson, for small breaking of the global symmetry of the microscopic theory, will still be rather light compared with the dynamical scale of the theory, thus making μ a term controlled by symmetry breaking.

The precise value of μ that is required to match the experiments can be attained in the models discussed above for suitable symmetry-breaking structures. In all cases the largest breaking is associated with the top quark sector. In models of the Higgs boson as a pNGB, this is so because the top quark mass represents the largest breaking of the global symmetry of the microscopic theory, and hence the largest effect responsible for the mass of the Higgs boson. Assuming some model of supersymmetry breaking and dealing with a phenomenological model such as the minimal supersymmetric SM (for an extensive review, see Reference 3), it is possible to compute the predicted value of the mass of the Higgs boson as a function of SM parameters and supersymmetry-breaking ones. The result is that the most important effect is due to supersymmetry breaking in the top sector, as discussed in more detail in Section 2.1.

On the whole, there are strong indications that the top quark sector plays a crucial role in any microscopic theory of electroweak symmetry breaking, and therefore the review begins with this section.

2.1. Supersymmetry

Supersymmetry has been proposed as a space-time symmetry that involves fermionic generators. Unlike in gauge symmetries, this makes it possible to involve spin and momentum in the definition of the symmetry algebra, which, up to violations of the symmetry itself, would require interactions and masses of bosonic and fermionic particles to be tightly related. One such relation would require the electron to be accompanied by exactly mass-degenerate states of spin 0, very similar to how the Lorentz symmetry of space-time built into the Dirac equation implies the existence of exactly mass-degenerate antiparticles of the electron. The absence of any evidence in experiments for a spin 0 electron-like state motivates one to consider supersymmetry as an approximate symmetry, broken at some unknown scale so that all the supersymmetric partners of the SM states are pushed beyond the mass scale presently probed by experiments.

The mechanism for supersymmetry breaking is a subject for model building, which is outside the scope of this review. For our purpose it is key to recall that the supersymmetry-breaking top quark sector has the rather model-independent tendency to determine the mass and quartic coupling of the Higgs boson, thus leading to the identification of the supersymmetric top scalar quark (usually called the stop squark) as the main player setting the Higgs boson potential. In the concrete example of the minimal supersymmetric SM (for an extensive review, see Reference 3), there are two complex scalar partners for the top quark, so as to match the number of degrees of freedom in fermions and bosons dictated by supersymmetry. In this model there are two Higgs doublets, as required by the necessity to have both up-type and down-type Yukawa interactions in the supersymmetric limit. The top partner states are denoted, on the basis of gauge eigenstates, by $\tilde{t}_L$ and $\tilde{t}_R$, for the $SU(2)$ doublet and singlet partner states, respectively. They can mix in mass eigenstates, for example, due to supersymmetry-breaking trilinear interaction terms A_t with the up-type Higgs boson of this model. The two Higgs bosons are denoted by H_u and H_d depending on which fermion type they interact with. The equations for the constraints on the minimization of the potential of the two Higgs doublets of the model embody the above sensitivity of the Higgs sector to the top sector. These equations are

$$m_Z^2 = \frac{\left| m_{H_d}^2 - m_{H_u}^2 \right|}{\sqrt{1 - \sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2\,|\mu|^2 \qquad 1.$$

and

$$\sin(2\beta) = \frac{2b}{m_{H_u}^2 + m_{H_d}^2 + 2\,|\mu|^2} \qquad 2.$$

and contain an implicit large one-loop effect of the top quark and top squark on the bilinear supersymmetry-breaking terms $m_{H_{u,d}}$ of the two Higgs doublets H_u and H_d. In particular, for the Higgs doublet H_u that interacts with up-type quarks, and hence interacts with the top quark sector, the renormalization group equation is

$$\frac{d}{d\log Q}m^2_{H_u} = 3X_t - 6g_2\,|M_2|^2 - \frac{6}{5}g_1^2\,|M_1|^2 + \frac{3}{5}g_1^2 S, \qquad 3.$$

where $X_t = 2|y_t|^2(m^2_{H_u} + m^2_{Q_3} + m^2_{\bar{u}_3}) + 2|a_t|^2$, $M_{1,2}$ are the $U(1)$ and $SU(2)$ gaugino mass terms, and $S = Tr[Y_j m^2_{\phi_j}]$.

These equations naturally lead to the possibility that the supersymmetry-breaking stop masses $m^2_{Q_3}$ and $m^2_{\bar{u}_3}$ or a large A-term $|a_t|$ might induce a large X_t, which in turn drives $m^2_{H_u} < 0$ as $\log Q$ diminishes from some high scale down to the weak scale. This possibility has given stop squarks a central role in supersymmetric models. In essence, the supersymmetric partner of the top quark is responsible for breaking electroweak symmetry by making $m^2_{H_u} < 0$, hence making the Higgs boson potential unstable at the origin of the H_d, H_u field space and setting the values of the masses that define the weak scale (e.g., m_Z from Equation 1 or the mass of the Higgs boson that receives the abovementioned large radiative corrections from the stop squark).

Once the Higgs boson was discovered and its mass was known, a number of works tried to determine the impact of this measurement on the properties of the stop squark (for the minimal supersymmetric SM and some extensions, see, e.g., Reference 4). In turn, the necessity for peculiar supersymmetry breaking to accommodate the Higgs mass has spurred investigations on the possible supersymmetry-breaking models that can lead to such peculiar stop squarks (for some examples of supersymmetry-breaking models that emerged or reemerged to address the null searches of supersymmetry and the Higgs boson discovery, see, e.g., References 5–10).

2.1.1. Phenomenology. The phenomenology of the supersymmetric partners of the top quark is dictated largely by one feature of the supersymmetric models: the existence of a conserved quantum number that distinguishes SM states from their supersymmetric partners. The standard choice for such a quantity is called R parity, a Z_2 symmetry under which all SM states are even and all partner states are odd. The conservation of this symmetry implies that partner states can appear in interaction vertices only in even numbers; for example, one SM state can interact with two supersymmetric states, but a single supersymmetric state cannot interact with a pair of SM states. For particle colliders this implies that the lowest-order process to produce supersymmetric states in collisions is

$$SM\,SM \to SUSY\;SUSY,$$

and the decay of supersymmetric particles into any number of SM states is forbidden unless there is at least one supersymmetric particle (or an odd number of them), for example,

$$SUSY \to SUSY\;SM.$$

When R parity is exact, a most copious production mechanism for stop squarks at the LHC is

$$gg \to \tilde{t}_i\tilde{t}^*_j, \qquad 4.$$

where $\tilde{t}_k$ denotes $k = 1$ and $k = 2$, the two stop squark mass eigenstates.[1] Other production mechanisms are possible, for example, in decays of supersymmetric partners heavier than the stops or via production of stops in association with other supersymmetric states.

Once produced, the stop squark can decay in a number of possible channels, depending on which supersymmetric states are lighter than the state $\tilde{t}_k$ at hand. The most studied two-body decay modes are

$$\tilde{t} \to t\chi^0 \quad \text{and} \quad \tilde{t} \to b\chi^+, \qquad 5.$$

which feature fermions χ that are mixtures of supersymmetric partners of gauge bosons of the electroweak interactions and of Higgs bosons of the model. The motivation for the prevalence of these decay modes is that, by the rules of unbroken supersymmetry, these decays are mediated by couplings given by gauge and Yukawa couplings of the SM; hence, they are nearly impossible to switch off unless $m_{\tilde{t}} - m_\chi < 0$. Actually, the quantity $m_{\tilde{t}} - m_\chi$ plays a major role in determining the stop phenomenology. When $m_{\tilde{t}} - m_\chi \to 0$, it becomes necessary to consider multibody processes that are also possible and may be phenomenologically relevant, for example,

$$\tilde{t} \to bW^+\chi^0 \quad \text{and} \quad \tilde{t} \to b\bar{f}f'\chi^0, \qquad 6.$$

as well as possible flavor-violating decays that may be induced at the loop level, such as

$$\tilde{t} \to c\chi^0. \qquad 7.$$

In the above discussion, the particle χ^0 is considered the lightest supersymmetric state, such that by the conservation of R parity it is absolutely stable. As χ^0 is not electrically charged and it is color neutral, much like neutrinos, it does not leave directly observable traces in detectors. For this reason the presence of χ^0 can be detected only by a proxy measurement. This is the measurement of momentum missing from the overall momentum conservation in each collision (i.e., the momentum carried away by the sum of all the particles not measured). Because we cannot reliably measure the fractions of the longitudinal momentum of the colliding protons taken by the partons initiating the production of stops (e.g., the gluons entering in Equation 4) and the fraction taken by the rest of the partons, the longitudinal momentum conservation is usually not exploited in hadron colliders; therefore, the presence of χ^0 is usually sought for as missing transverse momentum, most often (mis)named missing transverse energy (MET).

Since it is an electrically neutral, stable particle that is charged only under supersymmetric Yukawa and electroweak gauge interactions, χ^0 qualifies as a perfect candidate for weakly interacting massive particle (WIMP) dark matter (for a recent review and additional references, see, e.g., Reference 12). The possibility of having a dark matter candidate stemming from supersymmetry has provided strong motivation to pursue this scenario—so much so that MET searches have become synonymous with searches for supersymmetry. However, null searches for supersymmetric particles, as well as for WIMP dark matter in the mass range suitable for χ^0 (13), have recently challenged this idea (14, 15).

Given these experimental results, and the vast range of possible models for supersymmetry breaking, recall that in general it is possible to have states other than χ^0 as the lightest supersymmetric particle (LSP). For example, the supersymmetric partner of a neutrino or even a top squark could play this role. The latter scenario leads to peculiar phenomena due to the

[1]The definition of mass eigenstates as stops assumes that the flavor labels we give in the SM are the same for the partner states. It must be stressed that the fate of flavor in the supersymmetric partner sector is largely model dependent, and it is possible to use flavor mixing to change the phenomenology of stop squarks (see, e.g., 11). More details on the gauge and flavor structure of the squark sector are provided in Reference 3.

formation of hadrons containing supersymmetric states (16, 17), but these models typically suffer from quite stringent limits (18–20). Therefore, most searches for supersymmetric states in the top quark sector are carried out in the χ^0 LSP setting.

Wholly alternative phenomenological scenarios for supersymmetric top quark partners are possible and are actively pursued in experimental searches. The main possible alternative involves the nonconservation of R parity (21). With broken R parity, all supersymmetric particles can in principle be produced singly and can decay into just SM states; for example,

$$SM\,SM \to SUSY \text{ and } SUSY \to SM\,SM$$

are now possible processes. In this situation there is no longer an absolutely stable weak-scale particle to fill the role of dark matter as a WIMP.[2] The resulting phenomenology is very different from that just described (23). For instance, R parity–violating couplings, still respecting the full gauge symmetry of the SM, allow, among other possibilities, the following decays:

$$\tilde{t} \to bs \text{ and } \tilde{t} \to \ell d.$$

As the final states of stop decays can now be made entirely of SM particles, it is possible to detect stop squarks as resonances, a very powerful signature that is not present when χ^0 is forced to appear among the decay products. Furthermore, these decays, being mediated by R parity–breaking couplings that need to be small to satisfy several constraints (21), can lead to meta-stable supersymmetric states, which can live for measurable lengths in experiments.

2.1.2. Experimental searches. In a detailed model it is possible to derive very specific signals from top sector supersymmetric partners, including signatures in collider experiments as well as in low-energy precision experiments. However, in low-energy precision experiments, these signatures are usually very much dependent on the model considered (24). A similar issue exists with Early Universe physics, in addition to signals being quite difficult to detect. For this reason, collider experiments are the optimal way to search for top sector supersymmetric partners.

Before listing relevant searches, it is necessary to clarify a point on their scope. The above searches are sensitive in principle to any sign of New Physics related to the top quark sector involving MET or some kind of pair-produced resonances. Although the search is optimized for supersymmetric partners, it can indeed be used to set bounds on other models. The interested reader can refer, for example, to Reference 25 for an interpretation of the supersymmetry searches in the context of fermionic top partners (discussed below in Section 2.2.2).

The searches for top sector supersymmetric partners can be divided into two main categories:

- searches in large momentum transfer signals, which feature detector objects (e.g., jets, leptons, photons) with energy and transverse momentum greater than those of typical SM events
- searches in low momentum transfer signals, in which the detector objects arising from top sector supersymmetric partners production are not very different from those of typical SM events; searches for top partners with mass near the top quark mass belong to this class as they give signatures similar to those in SM top quark pair production

The large momentum transfer searches are classic searches for New Physics and had already been envisaged when the experiments were designed (26, 27). Currently, these searches can probe supersymmetric top partners up to a mass of about 1.2 TeV, although not in full

[2]Alternative dark matter candidates can be found in these models; for a possible gravitino dark matter scenario and issues related to this possibility, see, for example, Reference 22.

generality. Indeed, it is quite hard to probe in full generality even a model as minimal as one having the full freedom to vary the branching ratios of decays (Equations 5–7). For a complete assessment, it is then necessary to test very accurately a large number of searches at once, often relying on a phenomenological incarnation of a sufficiently general supersymmetric model, as studied, for instance, in Reference 28. Interpreting these results is quite difficult because many constraints on the model are imposed at once; for example, the top partner states are required to fix the mass of the SM Higgs boson to its measured value by the dynamics of radiative corrections embodied in Equation 3. This requirement, although sensible in the context of the specific model, can significantly alter the conclusion of the study. Therefore, it remains difficult to answer questions as simple as finding the lightest, nonexcluded mass values of stop-like top partners.[3]

Further difficulties can arise and make it nearly impossible to probe experimentally supersymmetric top partners—for instance, when special kinematic configurations become the typical configuration of top partners' decay products. In these cases the search in low momentum transfer signatures can help. Indeed, these searches have been developed to overcome the difficulty that arise in the limit $m_{\tilde{t}} - m_{\chi} \to 0$. The shortcomings of large momentum transfer searches can be clearly seen in **Figure 1**, as the excluded stop mass for large $m_{\tilde{t}} - m_{\chi}$ differences is much larger than for small differences. In addition, when the stop-LSP mass gap is small and the stop becomes lighter, its production and decay cannot be reliably distinguished from other SM processes (e.g., SM production of top quarks). The figure inset displays how these peculiar cases are covered. The most useful strategies to attack these difficult signatures are through the study of angular observables and fiducial rates of top-like final states (29–33).

Note that there are modest but persistent disagreements between the measured angular distributions in the top quark sample and the theoretical predictions (42). These disagreements are accompanied by other disagreements in the kinematics of the reconstructed top quarks, of small size but persisting from Run 1 through Run 2 of the LHC (45, 46). It will be interesting to see how these anomalies evolve in Run 3 and in the much larger high luminosity (HL)-LHC data set.

The possibility of seeing effects of physics beyond the Standard Model (BSM) related to the top quark and the precision in measurements afforded by the LHC and the HL-LHC have motivated greatly improved predictions for top quark SM observables. Examples include seamless description of fixed next-to-leading-order (NLO) and parton shower (PS) calculations of top quark resonant and nonresonant rates (47), specific next-to-next-to-leading-order (NNLO) and electroweak corrections to the BSM-sensitive rates (48, 49), and increased attention to possibly BSM-sensitive high-energy top quarks (see, e.g., 50) and other production modes that may be of interest for both SM studies and BSM searches (see, e.g., 51, 52).

The searches mentioned above, though motivated and sometimes optimized on supersymmetry searches, are rather general. Thus, it is important to stress that observing an excess in one of these supersymmetry searches would not at all prove the supersymmetric nature of the discovered state. A reliable statement on the supersymmetric nature of the newly discovered object would require several measurements. For a specific proposal at the LHC, the interested reader may consult, for instance, Reference 53. In general, it is believed that a machine cleaner than a hadron collider (e.g., an e^+e^- collider) capable of producing the new particle would be needed to truly confer it the status of being the supersymmetric partner state of some SM state.

At the time of writing there are no statistically significant and convincing signs of New Physics in searches for it, and the searches for supersymmetric top partners are no exception. Despite the absence of signals for top sector supersymmetric partners, these searches are still believed

[3] One possible answer in the context of Reference 28 is offered in the supplementary material of that analysis (see **https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2014-08/figaux_13.pdf**).

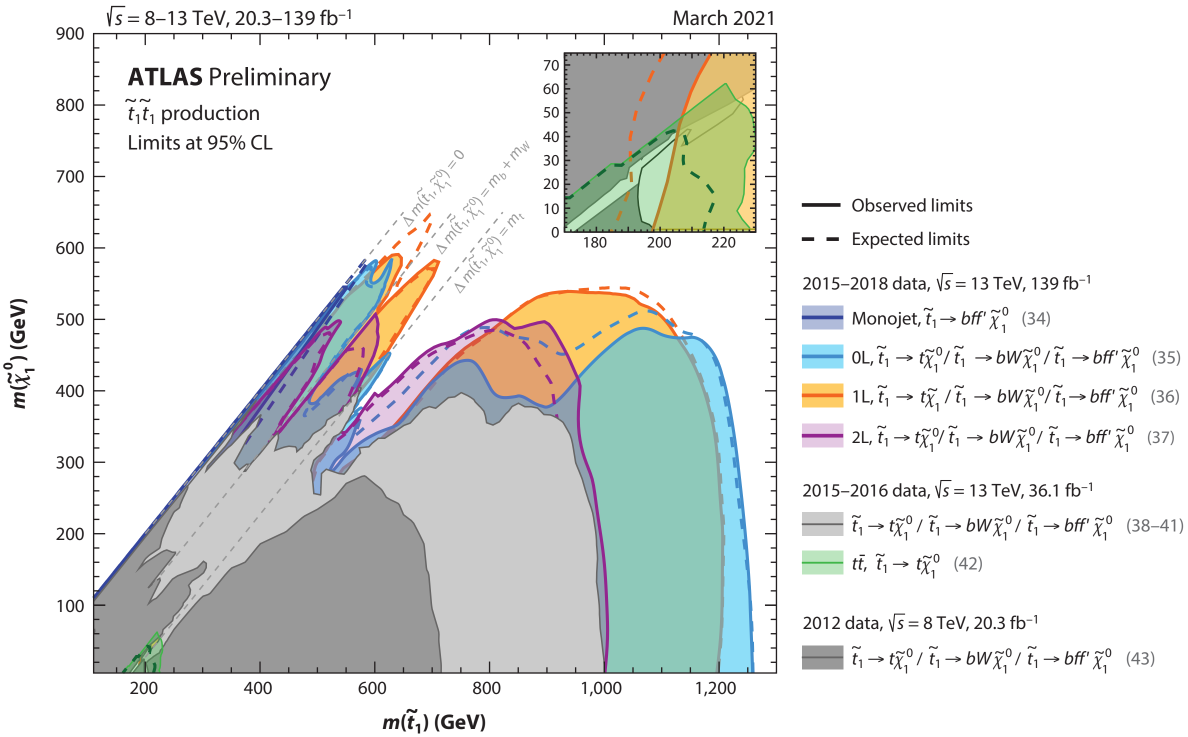

Figure 1

Searches for top sector supersymmetric partners in the stop-LSP (lightest supersymmetric particle) mass plane. Units for the inset are the same as those of the main graph. Data from References 34–43; reference numbers are indicated in parentheses in the key to the right of the graphs. Figure adapted from Reference 44 (CC BY 4.0).

to be one of the best chances to find New Physics. One could even argue that in the minimal model of supersymmetry, the relatively large observed Higgs boson mass requires large loop-level corrections from contributions of the kind in Equation 3. These large loop corrections point toward a mass scale of TeV or larger for stop squarks, which is compatible with present limits and possibly awaits discovery in future updates to searches as more data are collected at the LHC.

As the mass scale of top quark supersymmetric partners is not entirely fixed, these particles may be too heavy to be discovered by the LHC. Therefore, the discovery reach for these particles is often considered in the evaluation of the physics case of future particle accelerators. Projections for a 100 TeV *pp* collider (54, 55) usually cover a mass range that is five to eight times larger than what can be probed at the LHC, whereas a high-energy lepton collider, such as a multi-TeV muon collider (56–60), is expected to probe the existence of top partners up to the kinematic limit at $\sqrt{s}/2$.

2.2. Composite and Pseudo-Nambu–Goldstone Boson/Little Higgs Models

Another approach that motivates New Physics associated with the top quark sector is the idea that the Higgs boson is a composite particle, generated by new interactions at a mass scale much larger than 1 TeV. The large gap between this scale and the TeV scale is explained by interpreting the Higgs doublet as a set of Nambu–Goldstone bosons associated with spontaneous symmetry breaking at the new interaction scale. The mass of the Higgs boson is generated by physics that breaks that symmetry explicitly by a small amount, making the Higgs doublet a set of pNGBs.

2.2.1. Models. Models of the Higgs boson and electroweak symmetry breaking based on these ideas are reviewed in References 61–64. All of these models share a sequential symmetry-breaking pattern, with a large global symmetry group G above the compositeness scale broken spontaneously to a smaller group H but also broken explicitly by small corrections, such that the final gauge symmetry is the weak interaction $SU(2) \times U(1)$. The minimal model of this type (65) assumes an $SO(5)$ symmetry spontaneously broken to $SO(4) \simeq SU(2) \times SU(2)$, generating the four components of the Higgs doublet as pNGBs, with this symmetry broken explicitly to the SM gauge symmetry $SU(2) \times U(1)$. The presence of the second $SU(2)$ as an approximate symmetry allows this model to satisfy constraints from electroweak precision measurements by forbidding the generation of large radiative corrections to m_W/m_Z and the $Zb\bar{b}$ coupling.

The enlargement of the symmetry of the SM motivates the appearance of matter representations in multiplets that are necessarily larger than the usual doublets and singlets of the SM. In particular, to obtain Yukawa interactions, the constructions of pNGB and the little Higgs model converge in the existence of partner states for the top quark, for the bottom quark, and in principle for all the fermions of the SM. The precise phenomenological manifestation of the partner states is highly model dependent, as it depends on the new global symmetry group that one chooses when building this type of model, the representation of this symmetry group that one chooses for the new matter, and the imagined mechanism to originate the SM fermion masses at the most microscopic level.

One possible limitation to the model-building choices may come from the requirement to avoid introducing large deviations into well-known couplings [e.g., the Zbb couplings (66)]; still, a large set of possibilities exists. In this review, I focus on a unifying feature of many models: the presence of partner states directly connected to the SM top quark sector via Yukawa and gauge interactions with relatively universal decay patterns (67–69), although other decay modes and more exotic partners may exist, including possible couplings to scalar states accompanying the Higgs boson in some models (70–72).

2.2.2. Phenomenology. At the core of the experimental tests of the idea of fermion top partners lies the assumption that the main interaction leading to the decay of these top partners into SM states is the Yukawa coupling of the top quark, in which the Higgs boson or longitudinal components of the weak gauge bosons appear. For this reason most of the searches are presented in terms of exclusions for branching fractions of the top partner states into the following pairs of SM states:

$$T \to tZ, th, Wb, \qquad 8.$$

where T is a charge $2/3$ top partner, and

$$B \to bZ, bh, Wt, \qquad 9.$$

where B is a charge $-1/3$ partner of the bottom quark, whose existence is a consequence of the $SU(2)$ weak isospin symmetry that must hold in the theory that supersedes the SM at high energies. In models with a symmetry larger than $SU(2)$ (e.g., 65, 66), it is typical to have additional partner states that appear as needed to furnish full representations of the larger symmetry. A much-studied case is the state of charge $5/3$ that leads to a very characteristic decay,

$$X_{5/3} \to W^+t, \qquad 10.$$

which in turn gives a characteristic same-sign dilepton signal (73). For little Higgs models, the appearance of this type of exotic partner requires the formulation of somewhat more involved models, but it is definitively a possibility (70, 74).

2.2.3. Experimental searches at colliders. Experimental searches for new states are carried out at the LHC, exploiting the color charge of the top partners in processes such as

$$gg \to TT,$$

which are analogous to previous processes for supersymmetric partners and depend only on the QCD charge of *T*. Unlike for supersymmetric partners, for which the conservation of *R* parity plays a crucial role, the single production of top partners,

$$gq \to q'Tb,$$

is possible in the most minimal models and can in principle lead to a deeper understanding of BSM physics, as this process directly involves New Physics couplings for the production of the top partner states (75). For instance, the rate of single production of top partner states can be a discriminant with respect to so-called vector-like quarks, whose couplings are not dictated by the Goldstone property of the Higgs boson (for an in-depth discussion, see Reference 76).

A great difference in the search for the partners discussed in this section is that final state particles in the decays of Equations 8–10 are fully reconstructed, giving rise to observable resonances in the two-particle invariant mass. For example, the first decay of Equation 8 produces a directly observable tZ resonance. The search for this and similar signals is discussed, for example, in Reference 77.

With low-mass partners already excluded, the search for these partners extends to masses above 1 TeV. Here, even the heavy SM particles, such as t, Z, W, and h, are produced with significant boost in the majority of events. This motivates the use of special experimental techniques to identify those detector objects (78), as, for instance, in the search described in Reference 79.

The search strategies mentioned above are combined by the experimental collaborations at the LHC, which present results in a plane with axes spanning the possible values of two decays (e.g., searches for $T \to Ht$ and $T \to Wb$ are shown in **Figure 2**). The underlying assumption of this presentation of the results is that the top partner does not decay into any BSM state; hence, the branching ratio of $T \to Zt$ is determined by the two branching ratios displayed. **Figure 2*b*** shows how the different searches have different sensitivities to each decay mode and how they can be patched together to better exclude top partners of a given mass. More exotic signals from $X_{5/3}$ searches are carried out as well (e.g., 80). The results of searches at the LHC collected in **Figure 2** and newer results (79, 81) on the kinds of top partners described thus far put bounds on the top partners' mass at around 1.2 TeV.

As mentioned above, it is possible to have larger symmetry groups and larger representations in the symmetry-breaking pattern. For example, if the original symmetry pattern is chosen to be $SO(6)$ spontaneously broken to $SO(5)$ (71, 90), the top partner states can be put in a six-dimensional representation of $SO(6)$. Then there is one extra top partner compared with the minimal model with $SO(5)$ symmetry (66). This extra state, denoted by Ψ_1, is an SM singlet fermion, giving decay final states that do not fit into any of the previously considered categories, as well as decays typical of the minimal model. For example, one can have new top partner decays

$$\Psi_1 \to th, tZ, t\eta, Wb,$$

where η is an extra pNGB that arises due to the larger number of broken generators in the breaking $SO(6) \to SO(5) \to SO(4) \simeq SU(2) \times SU(2)$.

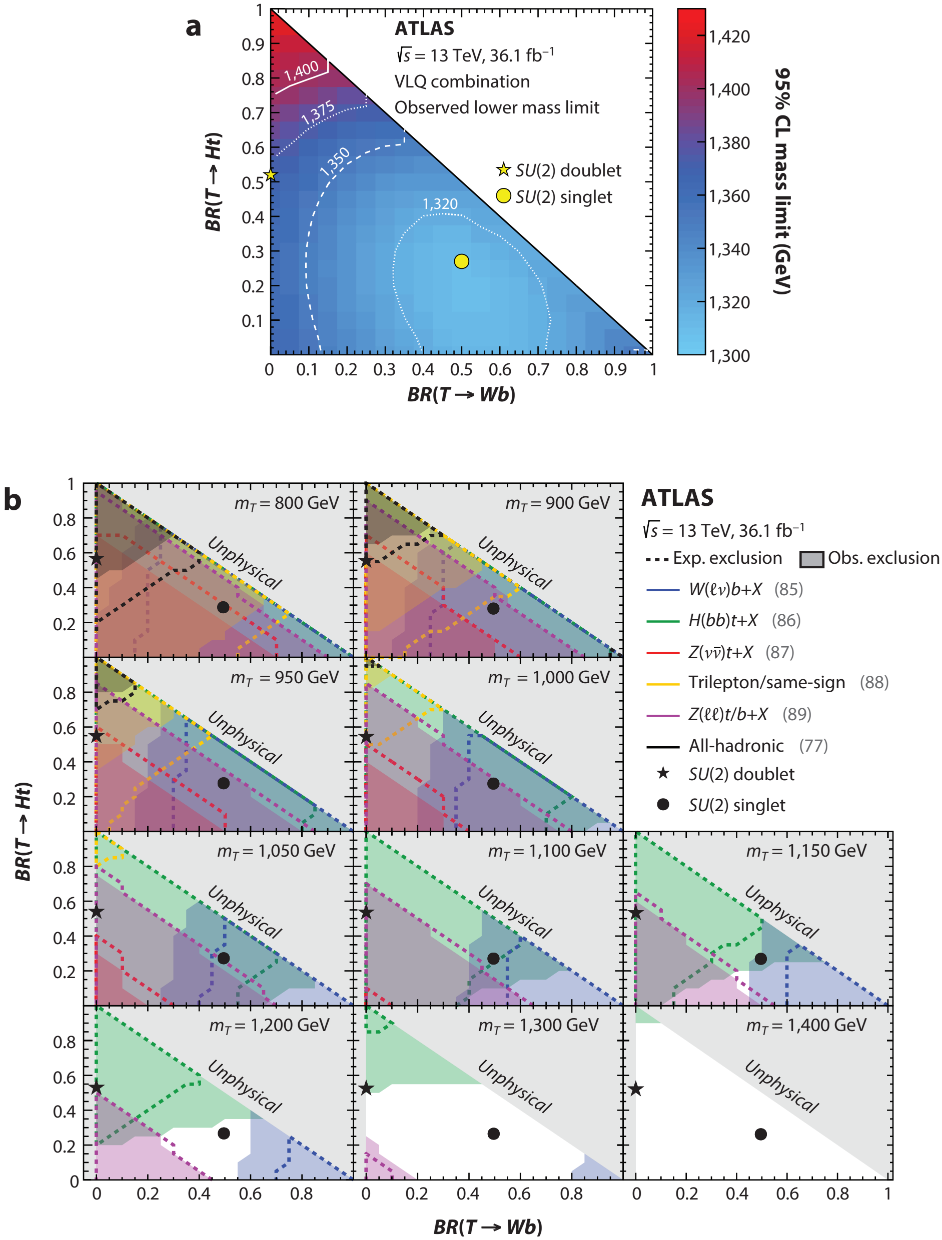

Figure 2

Searches for top fermionic partners (82, 83) in the plane $BR(T \to Ht)$ versus $BR(T \to Wb)$ with the constraint $B(bW) + B(th) + B(tZ) = 1$. For reference, some model-dependent choices of the branching ratios introduced in Reference 84 are shown. Panel *b* data from References 77 and 85–89; reference numbers are indicated in parentheses in the key. Abbreviation: VLQ, vector-like quark. Panel *a* adapted from Reference 82 (CC BY 4.0). Panel *b* adapted from Reference 83 (CC BY 4.0).

In general, the extensions of pNGB models can include possible flavor-changing neutral currents in top quarks with New Physics states; for example, Reference 91 has considered decays of the SM top quark that violate flavor

$$t \to c\eta$$

as a consequence of underlying flavor-changing dynamics in the top partners by a coupling $Tc\eta$, which would also yield a new possible search channel for a top partner $T \to c\eta$. Other exotic possibilities (e.g., $T \to tg, t\gamma, X^{5/3} \to t\phi^{+}$) are covered in the literature (92–94) and can in principle lead to new signals for top quark partners.

3. EFFECTIVE FIELD THEORIES AT CURRENT AND FUTURE COLLIDERS

Section 2 has dealt with explicit models of New Physics giving rise to signals from direct production of particles beyond those of the SM. As these searches have thus far yielded no evidence of New Physics, interest in and motivation for the description of New Physics in EFTs have increased. EFTs are effective because they arise through the removal of heavy states from a theory more microscopic than the SM and lead to a set of BSM interactions that usually overlaps with the set generated by other microscopic theories. Therefore, much work has been done to identify the most general sets of interactions under given assumptions (95, 96), such that New Physics studies can be carried out in a model-independent fashion [e.g., searching for very characteristic interactions involving four top quarks (97–101) or other four-fermion operators involving top quarks or for other kinds of contact interactions independent of their microscopic origin].

A major benefit of the EFT approach is that it is very comprehensive. The trade-off for this comprehensiveness is the possible loss of contact with the microscopic origin of BSM physics, which gives rise to specific patterns and organization principles for the size of each contact interaction. Thus, it is necessary to strike a balance between a fully general EFT and a physically efficacious effective theory. This balance very much depends on the amount of data one can use when constraining the couplings of the effective interactions, as well as the theoretical prejudice on what effects are worth consideration [e.g., pure top sector effects (96, 102–106), effects involving electroweak and Higgs physics (107, 108), flavor-changing effects (109–114)].

Because BSM contact interactions from EFTs affect precision measurements of SM processes, greater attention to BSM signals associated with top quarks has led to improved descriptions of several processes that either are backgrounds or serve as SM references in searches for BSM physics (e.g., for production of four top quarks, see Reference 115; for recent ttV results, see References 116–118; for tth results, see Reference 119 and references therein). For an up-to-date snapshot of the characterization of the top quark electroweak interactions and possible BSM physics in deviations from the SM, readers are referred References 102–106. The upshot of the work is that present measurements, as well as the availability of differential measurements and reliable computations in the same phase-space regions, enable us to set bounds on generic New Physics in the top quark sector in the TeV range.

The possibility to identify indirect signs of New Physics in signatures related to the top quark has become a commonly used benchmark in the evaluation of performances of future colliders, especially clean $e^{+}e^{-}$ machines, whose best chance to observe New Physics in the top sector is through indirect effects. Works such as References 120–123 have studied the outcomes of analyses to be carried out at future colliders and the interplay between present and future collider probes of New Physics in top quark EFTs. The results are summarized in **Figure 3**, which shows the significant improvement that will be attained by the HL-LHC, especially on single-coupling

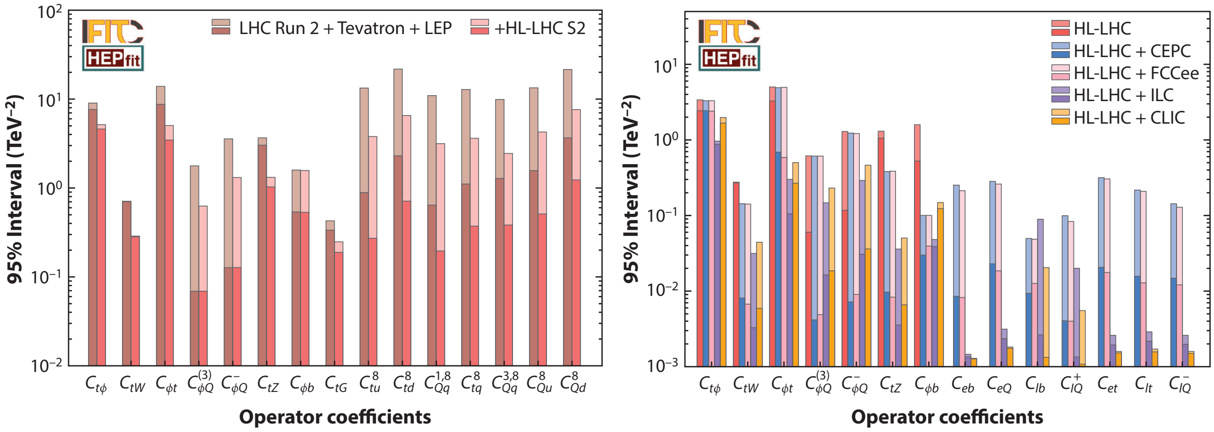

Figure 3

Summary of the constraints on contact interactions involving the top quark. (*a*) The effect of the HL-LHC compared with present constraints. Panel adapted from Reference 121 (CC BY 4.0). (*b*) The effect of future e^+e^- machines. The taller (and lighter-color) bars for each case represent the looser bounds that are obtained when the coupling of interest is bound while the others are allowed to float (see 120, 121, and references therein for details). Panel adapted with permission from Reference 120.

effects. **Figure 3** also shows the strong tightening of the bounds with the addition of future e^+e^- data at the Zh threshold, the $t\bar{t}$ threshold, and above, which will make the global EFT constraints particularly robust by removing possible flat directions in the coupling space and providing new data in channels that can be probed best at clean e^+e^- machines.

4. TOP QUARK AND PHYSICS BEYOND THE STANDARD MODEL RELATED TO FLAVOR DYNAMICS OR DARK MATTER (OR BOTH)

4.1. Top Quark and Physics Beyond the Standard Model Related to Flavor

The top quark flavor remains a special one in the SM. Indeed, the top quark is so heavy that one can easily single out the third generation of quarks as a peculiar source of breaking of the flavor symmetry,

$$G_F = U(3)_{q_L} \times U(3)_{u_R} \times U(3)_{d_R},$$

that the SM would enjoy if all quark masses were zero. A hierarchy of breaking dominated by third-generation quarks can be easily accommodated, owing to numerous possible symmetry-breaking patterns and possible mechanisms for breaking the flavor symmetry of the SM. In addition, this way of organizing flavor symmetry breaking is most compatible with experimental bounds. In fact, bounds on first- and second-generation flavor-changing processes are the most tight, whereas there is a relative lack of constraints on the third generation. If the sole breaking of the symmetry G_F arises from the Yukawa couplings of the SM, or if new sources are aligned with the Yukawa matrices, the breaking is said to comply with minimal flavor violation (MFV) (124–126). In this setting the bounds from flavor observables are most easily accommodated, but this is not the only possibility that complies with observations. The fact that the top quark Yukawa coupling is a possible large source of flavor-symmetry-breaking motivates one to consider BSM physics related to the top flavor, but this conclusion also holds in other settings.

A classification of possible states that can couple to quark bilinears charged under the flavor symmetry (e.g., a new scalar coupled as $\phi_{tu}tu$) has proven useful in the past to assess the possibility of flavorful signs of New Physics. For a recent listing of the possible states, one may consult the tables in Reference 127. From a phenomenological point of view, these models give rise to transitions in four-quark scatterings that do not conserve the flavor charge. For instance, the scattering

$$uu \to tt$$

can arise via a t-channel exchange of a flavored boson. This can alter the kinematics of top quark production and the net charge of the top quark sample at hadron colliders. Indeed, new flavorful bosons of this kind were advocated in response to Tevatron experiments claiming disagreements between the SM predictions and the measured top quark properties, such as the forward-backward asymmetry in the production of top quarks (128–130). In addition, these new flavored states coupled to the top quark can give rise to transitions,

$$f\bar{f} \to t\phi_{tj}u_j,$$

which can be observed quite easily at e^+e^- colliders in multi-jet final states, where the detailed final state depends on the model-dependent decay of the flavored state ϕ.

The possibility that a flavored state connected to the top quark might be among the lightest new states from the New Physics sector has also appeared in models of gauged flavor symmetries. In these models the flavor symmetry G_F is gauged to avoid dealing with unobserved massless Goldstone bosons. For instance, References 131 and 132 have proposed a new set of states that would free the gauged G_F from triangular anomalies by adding vector-like new quarks. In this kind of model the new quarks are charged under the SM flavor symmetry and can be arranged so that top-flavor new states are the lightest ones. Indeed, in these models the masses of the SM quarks would be explained by a seesaw-like mechanism in which the lightest SM fermions are mixed with a very heavy new state, whereas the heaviest SM states are mixed with the lightest of the New Physics states. In this case, the SM top quark would be the state coupled to the lightest of the New Physics states, named t', possibly accompanied by a partner state for the bottom quark, named b'. Remarkably, this type of model gives phenomenological signatures very similar to those of top partner states of composite and little Higgs bosons; for example, the partner states can be produced by strong interactions and decay as

$$b' \to bh, bZ, tW$$

and

$$t' \to th, tZ, bW.$$

These ideas also lend themselves to be paired with supersymmetry. Although supersymmetry is not necessary for the idea of gauged flavor symmetries in general, these models can provide a setup to originate R parity breaking with an underlying structure for the flavor structure of the R parity violation (RPV) couplings (133, 134) that would motivate, for instance,

$$\tilde{t} \to bs$$

as the main channel to search RPV stops (135).

A solution with a hierarchy of flavored New Physics scales inverted with respect to that of the SM quarks has also been proposed for composite Higgs models (136–139). This solution is ideal to better cope with flavor bounds that are otherwise too strong. In fact, despite model building (140–142) aimed at attaining an MFV-like structure, it remains challenging to keep all the New Physics at a common low scale and still survive flavor tests and high-p_T probes (see, e.g., 143–145). As can be appreciated from **Figure 4**, the top quark sector emerges as less constrained and further motivates the consideration of BSM physics related to the top quark and possibly exclusively to the top quark or to third-generation SM fermions.

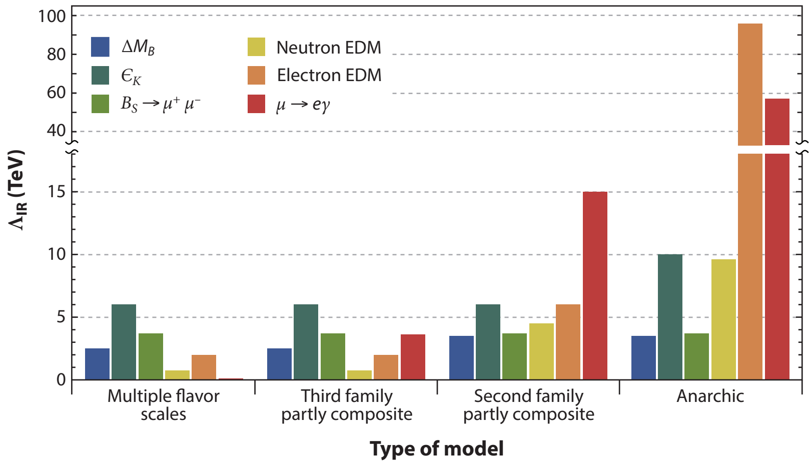

Figure 4

Lower bound on the scale of New Physics related to the SM fermion mass generation in a composite Higgs scenario under different assumptions for the compositeness of SM fermions. Abbreviations: EDM, electric dipole moment; SM, Standard Model. Figure adapted from Reference 136 (CC BY 4.0).

Observables of interest include indirect probes such as electric dipole moments (see, e.g., 146), meson oscillations and decays, and in principle rare Z and Higgs boson flavor-violating decays, which usually receive important contributions from the top quark sector (136). In addition, it is possible to have phenomena more directly related to the top quark, such as

$$t \to cV,$$

where $V = \gamma, Z, g$ (147–150) and deviations from $V_{tb} = 1$ in the CKM matrix (76, 151–153).

4.2. Flavored Dark Matter Models

Given the strength of the bounds from direct searches of dark matter scattering on heavy nuclei, it has become interesting to consider dark matter models in which the flavor of SM quarks and leptons plays a role, as the strongest bounds hinge on effective couplings of the dark matter to first-generation and, to a slightly lesser extent, to second-generation quarks and gluons.

The flavor puzzle of the SM comes equipped with a $U(3)^3$ symmetry, which, though not exact, can be used to stabilize the dark matter if it is broken according to MFV (154, 155) or other suitably chosen, more general patterns of flavor symmetry breaking (156). As a dark matter coupling sensitive to flavor could mediate flavor-changing transitions, the option of the MFV structure, or slight departures from it, has so far been a main route in model building aimed at removing possible tensions with flavor observables.

Among the possible flavor structures in which the dark matter and the SM fields can be cast, I focus here on the top quark flavor. Explicit models have appeared in the context of possible explanations of the CDF A_{FB} anomaly (128–130; e.g., see the model built in Reference 157), but the idea stands on its own even without anomalies in top quark physics. Indeed, if one considers that the complexity of the SM may be replicated in the sector of dark matter, it is natural to consider multiple species of dark matter that are flavors of dark matter (158–160). These flavors can be separated from our own SM flavors or they can be related to our species of fermions. In case some relation exists between flavors of the SM and flavors of the dark sector, the possibility that the top-flavored dark matter is the lightest state is at least as probable as any other flavor assumption. For example, when MFV is advocated, one can explicitly write a mass term for the dark flavor fermion multiplet χ, which in general has the form

$$\bar{\chi}\,(m_0 + \Upsilon(YY))\,\chi,$$

where Υ is a function of combinations of the Yukawa matrices of the SM that form singlets under the flavor group. These combinations are dominated by the piece proportional to $Y_u^\dagger Y_u$; hence, the top quark flavor tends to be special just from the principle of MFV itself. In a concrete case we can have interactions of SM fermions $u_R^{(i)}$ and mass terms for the dark matter flavor multiplet χ

$$\phi\bar{\chi}\left(g_0 + g_1 Y_u^\dagger Y_u\right) u_R^{(i)} + \text{h.c.} + \bar{\chi}\left(m_0 + m_1 Y_u^\dagger Y_u + \ldots\right)\chi, \qquad 11.$$

where ϕ is a suitable representation of $G_{SM} \otimes G_F$. In Reference 157, for instance, $\phi \sim (\mathbf{3},\, \mathbf{1},\, 2/3)_{SM} \otimes (\mathbf{1},\, \mathbf{1},\, \mathbf{1})_F$, $\chi \sim (\mathbf{1},\, \mathbf{1},\, 0)_{SM} \otimes (\mathbf{1},\, \mathbf{3},\, \mathbf{1})_F$, and the Yukawa matrices, as in general in MFV, transform as spurions $Y_u \sim (\mathbf{3}, \bar{\mathbf{3}}, 1)_F$ and $Y_d \sim (\mathbf{3}, 1, \bar{\mathbf{3}})_F$. It is possible to pick m_1 to partly cancel the flavor universal m_0 term, making χ_t the lightest particle of the χ multiplet while retaining full freedom to pick the combinations of g_0 and g_1 that correspond to the couplings of the mass eigenstates χ_i.

In the absence of a field ϕ, one can imagine contact operators to couple the dark matter and the SM flavors *i* and *j*. For example, operators of the type

$$\left(\bar{\chi}\Gamma_S\chi\right)\left(\bar{\psi}^{(i)}\Gamma_S\psi^{(j)}\right) \qquad 12.$$

for some Lorentz structure Γ_S have been considered as low-energy remnants of flavored gauge bosons (158) or other heavy scalar and fermion states charged under an MFV-broken flavor symmetry or in a horizontal symmetry model (159). Operators involving the SM Higgs boson, for example,

$$\left(\bar{Q}\chi\right)(\chi^* H u),$$

have also been considered (154, 161) for a scalar $\chi \sim (\mathbf{1},\, \mathbf{1},\, 0)_{SM} \otimes (\mathbf{3},\, \mathbf{1},\, \mathbf{1})_F$. A variation of the model in Reference 158 could lead to the top quark flavor being singled out; the other referenced works already consider the third generation, hence the top quark and/or the bottom quark, as special either because of the MFV structure or as a result of the horizontal symmetry.

The phenomenology of top-flavored dark matter is very rich because it comprises possible signals both in dark matter searches and in precision flavor observables, as well as in high-energy collider searches. Flavor observables generally set stringent bounds on flavored dark matter models, with top-flavored dark matter significantly less constrained because most of the data belong to *u*, *d*, *s*, *c*, and *b* quark systems. Direct detection of dark matter is also generally suppressed because nucleons involved in dark matter scattering do not contain top flavor. The interactions usually originate at the loop level or via breaking of the flavor alignments; that is, the dark matter interacts almost exclusively with the top quark flavor, but it may have a small, though not completely negligible, coupling to light flavors. The existence of such coupling depends on the model. A specific analysis for a case in which only the top quark flavor interacts with the dark matter in the model (Equation 11) is presented in Reference 162 for both direct detection of dark matter and collider prospects in an MFV scenario. The annihilation rate for the thermal freeze-out is set by the scattering

$$\chi\chi \to tt \qquad 13.$$

mediated by a mediator ϕ (other scatterings are discussed in detail in, for instance, Reference 163). In this specific case the direct detection of scattering on nucleons

$$\chi\mathcal{N} \to \chi\mathcal{N}$$

is mediated by loop-induced coupling of Z, γ to χ from a bubble loop of t and ϕ from Equation 11. Despite the smallness of these couplings, the reach of current and future large-exposure experiments (see, e.g., 164) could probe such a low level of scattering rates for exposures around 1 ton-year. This means the model can be tested with presently available data (13).

A more recent analysis (165) considered flavor, direct detection of dark matter, and collider searches for a model featuring a top-flavored dark matter χ and a new state ϕ. This work considers a dark MFV flavor structure that extends MFV but can recover it as a limit is considered and allows for a more generic structure in flavor space for the vertex

$$\lambda_{ij}\bar{u}_R^{(i)}\phi\chi + \text{h.c.}$$

In this context, it is possible to delay the observation of χ in direct detection experiments, as new contributions to the direct detection rate appear compared with the MFV case, and it is possible to arrange for cancellations among scattering amplitudes. It remains an open question whether it will be possible to claim an observation despite the so-called neutrino fog that future xenon experiments (164) face when probing rates so small that neutrinos from the Sun, supernovae, and other natural sources are expected to contribute an event rate comparable to or larger than that of the dark matter.

In principle, it is possible to have $m_\chi < m_t$ so that the thermal freeze-out is controlled by processes other than the simple tree-level exchange of Equation 13. Reference 165 experimented with this possibility in dark MFV, but it appears to be in tension with the direct detection experiments. This conclusion concurs with what can be extrapolated from the earlier MFV analysis of Reference 157.

The search for models with colored mediators, as for all the models discussed here, can be carried out effectively at hadron colliders searching for signals,

$$pp \to \phi\phi \to t\chi t\chi,$$

that very much resemble the search for supersymmetric top partners. Depending on the model, there can be more general combinations of flavors of quarks:

$$pp \to \phi\phi \to q_j\chi q_i\chi.$$

Therefore, it is generally useful to consider the whole list of squark searches to set bounds on this type of model. References 165 and 166 report bounds in the TeV range that inherit the strengths and weaknesses discussed for the search of supersymmetric quark partners.

Other possible signals at hadron colliders are the single top processes

$$pp \to t\chi\chi,$$

which can arise from interactions such as those in Equation 12 (studied in Reference 159) or associated production of $\phi\chi$, followed by $\phi \to t\chi$ (studied, for example, in Reference 166).

It is also possible to consider models that go beyond what is discussed here, starting from the notable feature that MFV and some extensions may render the dark matter stable. In such a top-philic dark matter model, one can have scalars (167) that couple to $t\chi$ as well as to light quark bilinears (e.g., from RPV supersymmetry) so that they mediate scatterings of the type

$$q_i\bar{q}_j \to S_{ij} \to t\chi.$$

Other potentially interesting signals of flavored gauge bosons with couplings $\rho_{ij}q_iq_j$ can appear by replacing S_{ij} with ρ_{ij} in the above process. Further signals in this type of model arise, such as

$$q_ig \to t\rho_{ti},$$

possibly followed by $\rho \to \chi t$, and similarly for S. A model with a flavored gauge boson has been studied in Reference 168 with the goal of determining the flavor of light quark that interacts with the top quark and the dark matter leveraging charm-tagging and lepton charge asymmetry at the LHC.

Though many general issues follow the same path for scalar and fermionic dark matter, it is worth mentioning that References 169 and 170 contain a full study of the case in which the partner and the dark matter are a fermion and a scalar, respectively. Further studies regarding the top quark sector and dark matter can be found in the context of simplified model building (163, 171, 172).

5. CONCLUSIONS

The connection between New Physics and the top quark sector is well established and has led to a large amount of model building and phenomenological studies. Here, I have presented supersymmetric top partners, motivated by supersymmetry as the symmetry that stabilizes the weak scale, and top partner states motivated by the possible compositeness and pNGB nature of the Higgs boson. The phenomenological relevance of these incarnations of BSM physics in the top quark sector is tightly tied to the motivations of the models to which the top partner states belong. As the models in question are themselves in a critical phase at the moment, so is the situation for this type of New Physics in the top quark sector. On the one hand, we have reached a point where the expectation was to have already discovered signs of New Physics, especially in the top quark sector in the mass range explored by current experiments, and therefore, we should start to dismiss these ideas. On the other hand, we are still largely convinced of the validity of the arguments that led to the formulation of these models. Furthermore, no serious alternatives have appeared in the model-building landscape, and there is still plenty of evidence for the existence of BSM physics. Thus, one might reconsider whether the entire motivational construction for these models was somewhat wrong or at least biased toward solutions close to the energy that could be probed at the time and that give experimentally friendly signals.

The way out of this crisis, in the absence of experimental results changing the situation, is for everyone to decide. A possibility is to conclude that we need to update our beliefs about "where" (173) New Physics can appear in the top quark sector and, more generally, where New Physics can appear in all kinds of experiments. In this sense, top partner searches are a gauge of our progress in testing well-established ideas on New Physics.

The top quark sector also remains central in the formulation of New Physics models that try alternatives to the more well-established ideas (for possible ways in which the top quark can lead the way for constructing New Physics models that are somewhat different from the two mainstream ideas discussed here, see, e.g., References 174 and 175).

Given the absence of clear signs and directions in model building into which we entrust our hopes for New Physics, I have discussed the power of general EFT analyses that can be used to search for New Physics in precise SM measurements. Such analyses have become the tool of choice in a post-LHC epoch for the so-called model-independent search of New Physics. I have presented the power of current LHC and future HL-LHC analyses to show deviations from the SM due to top quark interactions. Overall, the LHC has a chance to observe deviations in some more friendly observables for a New Physics scale in the TeV range. A new particle accelerator is needed in order to secure this result and avoid possible blind spots. A popular option is an e^+e^- collider that can operate at or above the $t\bar{t}$ threshold with the luminosity to produce approximately 10^6 top quark pairs.

Other great mysteries beyond the origin of the electroweak scale remain unsolved in the SM. I have examined possible solutions to the flavor puzzle in which the top quark flavor plays a special role. The phenomenology of models with the lowest-lying New Physics states charged under top flavor has some similarity to that of top quark partners at colliders, but there is also the possibility to generate observable flavor violations as further distinctive experimental signatures.

The top quark may be a key to solve the mystery of dark matter in the Universe. I have presented scenarios in which the dark matter interacts predominantly or exclusively with the top quark flavor, possibly ascribing the stability of the dark matter to the same flavor structure that makes the top quark flavor special among the SM flavors. Such a possibility appears very well motivated as a way to reduce otherwise intolerably large couplings of dark matter with lighter generations and explain the stability of dark matter. The flavor dependence of the couplings has motivated efforts to build models to realize this idea in a coherent, though maybe still effective, theory of flavor, of which I have presented a few examples. In these scenarios, the dark matter phenomenology is quite different from other types of thermal dark matter, and dedicated analyses have been carried out to identify the relevant bounds and constraints. The upshot is that this idea can be broadly tested with current and future direct detection dark matter experiments. At the same time, the new states associated with the dark matter may be observed on-shell at colliders, which can in principle also probe contact interactions that originate from off-shell states associated with the dark matter. Low-energy flavor observables can also help restrict the range of possible models of flavored dark matter, leading to significant constraints on both MFV and non-MFV scenarios when a thermal relic abundance and a significant suppression of spin-dependent and spin-independent direct detection rates are required.

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