Status and Implications of Beyond-the-Standard-Model Searches at the LHC

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Abstract

The LHC has collided protons on protons at center-of-mass energies of 7 and 8 TeV between 2010 and 2012, referred to as the Run I period. We review the current status of searches for new physics beyond the Standard Model at the end of Run I by the ATLAS and CMS experiments, limited to the 8-TeV search results that have been published or submitted for publication as of the end of February 2014. We discuss some of the implications of these searches on the existence of TeV-scale new physics, with a special focus on two open questions: the hierarchy problem and the nature of dark matter. Finally, we give an outlook for the future.

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1. INTRODUCTION

The LHC is a proton–proton collider designed to operate at a center-of-mass energy of $\sqrt{s} = 14$ TeV and to collect on the order of 100 to 300 fb^{-1} of data. At the end of 2012, the two multipurpose LHC experiments [ATLAS (1) and CMS (2)] concluded what has come to be known as Run I, in which the LHC operated at $\sqrt{s} = 7$ and 8 TeV, collecting integrated luminosities of $\sim$5 fb^{-1} and $\sim$20 fb^{-1}, respectively. Even at these reduced energies, the LHC has well explored the TeV scale (3).

The physics program of ATLAS and CMS rests on two pillars: (*a*) elucidating the mechanism of electroweak symmetry breaking (EWSB) and (*b*) searching for physics beyond the Standard Model (BSM). With the discovery (4, 5) in July 2012 of what appears to be the SM Higgs boson, the first part of the program has passed an important milestone. Although much effort will still be devoted to the important task of precisely measuring the properties of this SM-like Higgs boson, the second major goal of the LHC has attracted renewed attention. The search for BSM physics has already been an active and robust activity at the LHC. It is only expected to intensify during Run II, when the machine is upgraded to its design energy.

To a large extent, searches for new physics have been motivated by two long-standing puzzles:

1. The hierarchy problem. It was recognized long ago that the SM Higgs boson—along with any other elementary scalar particles—suffers from what has come to be known variously as the naturalness, hierarchy, or fine-tuning problem (6–10). Today the problem is typically described in terms of the radiative corrections to the Higgs mass, m_h, which depend quadratically on the high-energy cutoff Λ up to which the SM is valid. For instance, one has

$$\delta m_h^2 \sim \frac{y_t^2}{16\pi^2}\Lambda^2 \qquad 1.$$

at one loop in the SM from the coupling ($y_t \approx 1$) to the top quark. Requiring that this value be of the same order as the Higgs mass itself, one arrives at the conclusion that the cutoff scale, and therefore the appearance of new physics, should be in the 1-TeV range.

Conversely, if the SM is valid all the way up to the Planck scale ($\Lambda \approx 10^{19}$ GeV), then the observed value of the Higgs mass could be explained only by fine-tuning the radiative corrections against the bare mass at the level of one part in 10^{32}.

2. Dark matter (DM). Another major motivation for new physics at the TeV scale comes from DM. The existence of DM has been well established from numerous sources, both astrophysical and cosmological (for recent reviews, see, e.g., References 11 and 12). DM is the dominant component of matter in the universe, yet it interacts only very weakly with ordinary matter. TeV-scale DM is motivated by the so-called WIMP miracle paradigm, which is the observation that a stable TeV-scale particle with weak interactions [i.e., a weakly interacting massive particle (WIMP)] has the right annihilation cross section in the early universe to account for all of the DM present today.

In this article, we review the status of searches for new physics at the end of Run I at the LHC and discuss some of the implications. As is well known by now, no BSM physics has been found so far, and there is a sense in the community that the LHC results are in tension with naturalness (Equation 1). This lack of new physics, and the reintroduction of the fine-tuning problem that accompanies it, is commonly referred to as the little hierarchy problem. By surveying the LHC searches for new physics, together with their weaknesses, gaps, and loopholes, we examine the state of naturalness.

The remainder of this article is organized as follows. In Section 2 we provide an overview of theoretical ideas for BSM physics and review the most prominent models. In Section 3 we describe the current status of searches from the ATLAS and CMS experiments. In Section 4 we assess the implications for specific BSM models and review reinterpretations of LHC results in the literature. We attempt to enumerate the weaknesses in current searches and loopholes in their interpretation. Finally, in Section 5 we conclude with a brief look toward the future of the LHC at close to its design energy of $\sqrt{s} = 14$ TeV.

2. THEORY OVERVIEW

2.1. Solutions to the Hierarchy Problem

As discussed in Section 1, a natural SM Higgs mass implies new physics at the TeV scale. However, this alone is not sufficient to completely solve the hierarchy problem. Generally, the new physics must also have some additional structure, such as new symmetries or strong dynamics, that shields the Higgs mass against quadratic divergences from even higher scales. In this review, we focus on two well-studied frameworks for solving the hierarchy problem: supersymmetry (SUSY) and composite Higgs models.

2.1.1. Supersymmetry. SUSY is the prime example of a solution to the hierarchy problem based purely on symmetries. (Composite Higgs models, reviewed in Section 2.1.2, use a combination of symmetry and strong dynamics.) The basic idea of SUSY is that it groups bosons and fermions into supermultiplets, such that particles in the same supermultiplet have the same properties apart from their spin. In this way, the spin-0 Higgs boson is related to the spin-1/2 Higgsino. Because the Higgsino mass is protected by chiral symmetry in the same way as the SM fermions, the Higgs mass becomes protected as well. In practice, what happens is that the quadratically divergent loop corrections to the Higgs mass in the SM are canceled by corresponding loops of superpartners. For instance, the one-loop top quark diagram that leads to Equation 1 is canceled by a one-loop top squark diagram.

In the minimal supersymmetric Standard Model (MSSM), the particle content of the SM is approximately doubled (for an excellent review of the MSSM and SUSY phenomenology, see

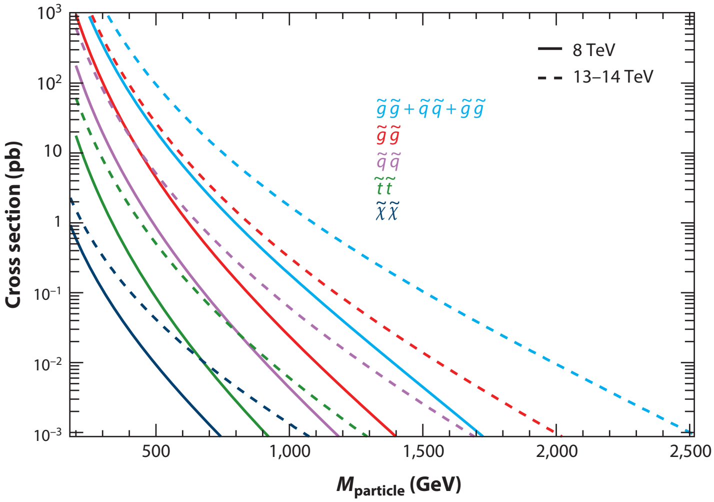

Figure 1

Cross sections for supersymmetric particle production at $\sqrt{s} = 8$ TeV and 13–14 TeV. The colored particle cross sections are from NLL-FAST (14) and were evaluated at $\sqrt{s} = 8$ TeV and 13 TeV; the electroweak pure Higgsino cross sections are from PROSPINO (15) and were evaluated at $\sqrt{s} = 8$ TeV and 14 TeV. The electroweak pair production cross section is sensitive to mixing, and the Higgsino cross sections are approximately a factor of two lower than the pure wino case.

Reference 13). For every SM fermion, there is a spin-0 counterpart; for instance, for a quark q there is a squark $\tilde{q}$, and for a lepton ℓ there is a slepton $\tilde{\ell}$. For every SM gauge boson, there is a spin-1/2 counterpart; for example, for a gluon g there is a gluino $\tilde{g}$, and for each W, Z, and γ there is a wino, a zino, and a photino, respectively. Finally, for the SM Higgs, the MSSM enlarges it to two Higgs doublets H_u and H_d, which have spin-1/2 superpartners called Higgsinos, $\tilde{H}$. Under EWSB, the Higgsinos mix with the winos, zinos, and photinos; these become charginos $\tilde{\chi}^{\pm}$ and neutralinos $\tilde{\chi}^0$. **Figure 1** shows some cross sections for SUSY particle production as a function of mass for $\sqrt{s} = 8$ TeV and 13–14 TeV.

A general problem for the MSSM and SUSY is the proliferation of parameters. The MSSM certainly includes the usual Yukawa couplings $\mathbf{Y}_{\mathbf{u},\mathbf{d},\ell}$ of the SM:

$$W_{\text{Yukawa}} = H_u Q \mathbf{Y}_{\mathbf{u}} U + H_d Q \mathbf{Y}_{\mathbf{d}} D + H_d L \mathbf{Y}_{\ell} E. \qquad 2.$$

Here Q, U, D, L, and E denote superfields containing the SM fermions and their superpartners. However, even in the supersymmetric limit, there are many more possible renormalizable interaction terms:

$$W_{\text{RPV}} = \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \lambda''_{ijk} U_i D_j D_k + \mu'_i L_i H_u. \qquad 3.$$

Here i, j, and k are flavor indices that run over the three generations of the SM. All these new interactions involve at least one superpartner, so they are not present in the SM. They generically violate baryon and lepton number, as well as the approximate flavor and CP symmetries of the SM. Thus, there are stringent constraints on these couplings (see, e.g., Reference 16 for an overview). All these dangerous interactions can be forbidden by imposing an additional discrete $\mathbb{Z}_2$ symmetry on the MSSM called R-parity, which assigns charge 1 to all superpartners and charge 0 to all ordinary SM particles.

A crucial by-product of R-parity is that the lightest superpartner (LSP) is absolutely stable. Cosmological bounds strongly suggest that the LSP must be neutral, in which case it could be a WIMP DM candidate. At the LHC, pair-produced superpartners[1] cascade-decay down to the LSP, producing jets and leptons along the way. The LSP escapes the detector like a heavy neutrino, implying a missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) signature. Therefore, searches for jets and/or leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$ are among the best ways to search for SUSY at the LHC.

Of course, it is possible to reduce or even eliminate the $E_{\mathrm{T}}^{\mathrm{miss}}$ signature by compressing the LSP mass against other particles, elongating the decay chain, or turning on a small amount of R-parity violation (RPV). As the $E_{\mathrm{T}}^{\mathrm{miss}}$-based searches set stringent limits, interest in such scenarios is increasing.

In addition to the RPV supersymmetric operators, there are also many dangerous R-parity-conserving interactions when SUSY breaking is taken into account. If SUSY were unbroken, the superpartners would be degenerate with their SM counterparts. Because the superpartners have not yet been observed, SUSY must be realized as a spontaneously broken symmetry in nature. The superpartner spectrum is parameterized by the soft SUSY-breaking Lagrangian:

$$
\begin{aligned}
L_{\mathrm{soft}} = & \sum_{\tilde{f}=\tilde{q},\tilde{u},\tilde{d},\tilde{l},\tilde{e}} \tilde{f}^{\dagger}\mathbf{m}_{\tilde{\mathbf{f}}}^{2}\tilde{f} + \left(\sum_{r=1}^{3} M_r\lambda_r\lambda_r + \text{c.c.}\right) \\
& + (m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + B\mu H_u H_d + \text{c.c.}) \\
& + (H_u\tilde{q}A_u\tilde{u} + H_d\tilde{q}A_d\tilde{d} + H_d\tilde{\ell}A_\ell\tilde{e} + \text{c.c.}).
\end{aligned}
\qquad 4.
$$

The terms on the first line describe the squark, slepton, and gaugino soft masses; the terms on the second line describe the Higgs soft masses; and the terms on the third line describe the trilinear soft terms (the A-terms). Although the soft masses do preserve baryon and lepton number, they generically violate the approximate flavor and CP symmetries of the SM. Also, unlike the RPV couplings, there is no symmetry that can forbid such terms. This is known as the SUSY flavor and CP problem.

Gauge-mediated SUSY breaking (GMSB) is the most promising solution of the SUSY flavor problem (for a review of GMSB, see Reference 17). It postulates that SUSY breaking is communicated to the MSSM only via the SM gauge interactions. Because these interactions are flavor blind, the resulting soft masses are flavor blind. Minimal GMSB models were first constructed in three seminal works (18–20). The most general parameterization of GMSB was formulated in References 21 and 22.

A distinctive feature of GMSB is that the gravitino is the LSP and is typically quite light: $m_{\mathrm{gravitino}} \lesssim 1\,\mathrm{keV}$. The lightest MSSM superpartner (which in GMSB can be any sparticle) becomes the next-to-lightest superpartner (NLSP), and it decays to the gravitino and its SM counterpart; for example, $\tilde{B} \rightarrow \gamma + \tilde{G}$. Thus, there are spectacular signatures such as $\gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$, $\gamma + \ell + E_{\mathrm{T}}^{\mathrm{miss}}$, and multileptons + $E_{\mathrm{T}}^{\mathrm{miss}}$. The NLSP lifetime is also a free parameter in principle, and the lifetime can range from prompt to displaced to detector stable. In the last case, there are many powerful and inclusive searches for heavy, stable charged particles (CHAMPs) and R hadrons, but for displaced signatures there have been very few so far (see Section 4.3.4).

The complexity of SUSY parameter space is problematic both for theorists and for experimentalists who must design searches and set limits on specific slices of this parameter space. Because it is impossible to cover the entire parameter space by simulation, several complementary approaches are taken when estimating the sensitivity of the searches to SUSY signals. In the first approach, complete SUSY models are simulated; these models typically impose boundary

[1]Single production is forbidden by R-parity.

conditions at a high energy scale, reducing the number of parameters to approximately five and making it feasible to scan the parameter space by brute force. Examples are minimal supergravity (mSUGRA), the constrained MSSM (CMSSM) (23–28), and minimal GMSB and anomaly-mediated SUSY (AMSB) (29, 30) models.

The second approach encompasses what are referred to as simplified models (31–34) and is commonly used in BSM searches in general. As applied to SUSY, the decay cascades are simplified by setting the masses of most SUSY particles to multi-TeV values, putting them out of range of the LHC. The decay cascades of the remaining particles to the LSP, typically with zero or one intermediate step, are characterized only by the masses of the participating particles, enabling studies of the search sensitivity to the SUSY masses and decay kinematics. A typical limitation of this approach is that all events decay through only one chain; even within one decay chain, once the number of states exceeds two, various assumptions are typically imposed on the relationship between the masses, both to save computing time and to simplify the visualization of the final results.

A popular example of a simplified model–type scenario consists of so-called natural or effective SUSY models (for recent reviews on natural SUSY models and original references, see, e.g., References 35 and 36). It was noticed long ago that not all superpartners are equally important for the fine-tuning problem of the electroweak (EW) scale. For instance, in the MSSM, at tree level only Higgsinos contribute to fine-tuning; at one loop stops are most important; and at two loops gluinos are most important. The idea of natural SUSY is to imagine that all but the Higgsino, stop, and gluino are decoupled from the LHC (in practice, these particles are heavier than $\sim$10 TeV). This would be the minimal superpartner spectrum necessary to postpone the hierarchy problem to much higher scales. Aside from having a much simpler parameter space, the main benefit of natural SUSY is significantly weakened LHC constraints, primarily because decoupling the first-generation squarks greatly decreases the SUSY production cross section.

2.1.2. Composite Higgs models. Composite Higgs models attempt to solve the hierarchy problem through a combination of strong dynamics and symmetry (for a recent review of composite Higgs models and many original references, see Reference 37). First, by positing that the Higgs boson is a composite bound state of an additional strongly coupled sector (and not an elementary scalar), these models cut off the quadratic divergence of the Higgs mass at the compositeness scale. Direct searches, precision EW tests, and flavor tests all constrain the compositeness scale to at least the multi-TeV range. Therefore, modern composite Higgs models (especially after the Higgs discovery) generally also equip the composite sector with an approximate global symmetry G to explain why the Higgs boson is a narrow, light state that is apparently well separated from the other resonances of the composite sector. When G is spontaneously broken to a subgroup H at some scale $f \sim 1$ TeV, the SM Higgs boson emerges as a pseudo–Nambu–Goldstone boson (PNGB), much like the pion of QCD. To better satisfy precision EW constraints, one generally assumes that H contains the custodial $SO(4)$ symmetry. G is also explicitly broken by the gauging of $SU(2) \times U(1)$ and by the SM Yukawa couplings. These couplings radiatively generate a potential for the Higgs boson.

A popular and well-studied example is the minimal composite Higgs model (MCHM) (38), in which the strong sector has a global $G = SO(5)$ symmetry that is spontaneously broken down to $H = SO(4)$. Gauging a $SU(2) \times U(1)$ subgroup of $SO(5)$ yields one light PNGB with the correct quantum numbers to be an SM-like Higgs boson.

As in QCD, composite Higgs models predict a tower of resonances starting somewhere around the compositeness scale. Because the composite sector transforms under $SU(2) \times U(1)$, some of these resonances carry EW quantum numbers.[2] The lowest EW spin-1 resonance is usually called the ρ by analogy with QCD. The strongest limits on m_ρ are 2–3 TeV from EW precision constraints (for a pedagogical overview, see Reference 39). These limits would put them out of reach of the LHC. Nevertheless, searches for them (generally phrased as searches for W' particles) are ongoing. These resonances mix with the W and Z bosons, so they can be produced from Drell–Yan and vector boson fusion. They can decay in many ways, including to WW, WZ, Wh, Zh, $t\bar{t}$, and $t\bar{b}$.

In addition to EW vector resonances, there are generally colored fermionic resonances in composite Higgs models. These are necessary to realize the so-called partial compositeness scenario that alleviates the flavor problem of composite Higgs models. Here the SM fermions q are assumed to mix with fermionic resonances $\mathcal{O}_q$ from the composite sector:

$$\mathcal{L} \supset \lambda_q q \mathcal{O}_q + \dots . \quad 5.$$

The third generation is assumed to couple most strongly to the fermionic resonances; thus, the lightest of these are usually referred to as top partners.

For the phenomenology of composite Higgs top partners, see References 40 and 41. The former paper focuses on top partners in the MCHM, whereas the latter takes a more model-independent point of view. Starting from complete multiplets of the global symmetry G of the composite sector, and decomposing them into EW representations, a number of distinct top partners can emerge. They include particles (often denoted by T and B) with the same quantum numbers as the top and bottom quarks, as well as particles with exotic electric charges such as 5/3 (often denoted as $T_{5/3}$). These can be pair-produced via QCD; then their cross sections depend solely on their mass and are essentially those of a heavy vector-like quark. One can also have single production via Wb, Wt, Zb, and Zt fusion from a gluon–quark initial state because these top quark partners mix with the third generation. These production modes are more model dependent because they depend on the unknown mixing parameter; more details are given in References 40 and 41. **Figure 2** shows some typical cross sections for top partners produced singly and in pairs. The top partners decay primarily into Zt, Zb, Wt, and Wb. Decays involving Higgs bosons are also possible. Therefore, events have many b quarks, leptons, jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$.

There is an important correspondence (43–47) between four-dimensional composite Higgs models and extradimensional models such as the Randall–Sundrum (RS) model (48). The holographic principle, especially the AdS/CFT duality (49–51), is believed to relate weakly coupled gravitational theories with strongly coupled field theories living on their boundaries. This principle has given rise to the hope that composite Higgs models could be rendered calculable through holography. In the simplest five-dimensional constructions, there is an IR brane in which the SM fields are localized and a UV brane in which the composite sector is localized. These branes are separated by a compact extra dimension; if the space-time metric in the fifth dimension is exponentially warped as in the RS model, then the warping connects the Planck scale on the UV brane with the TeV scale on the IR brane. Such holographic composite Higgs models can be weakly coupled in five dimensions and can describe many of the properties of a strongly coupled field theory in a calculable way. For instance, the dimensional reduction of a five-dimensional theory down to a four-dimensional theory results in towers of heavier states, the so-called KK states. These are in direct correspondence with the towers of resonances expected in a QCD-like theory in four dimensions.

[2] One can also consider the phenomenology of spin-1 colored resonances. These are not required in composite Higgs models but generically arise as Kaluza–Klein (KK) gluons in extra-dimensional models.

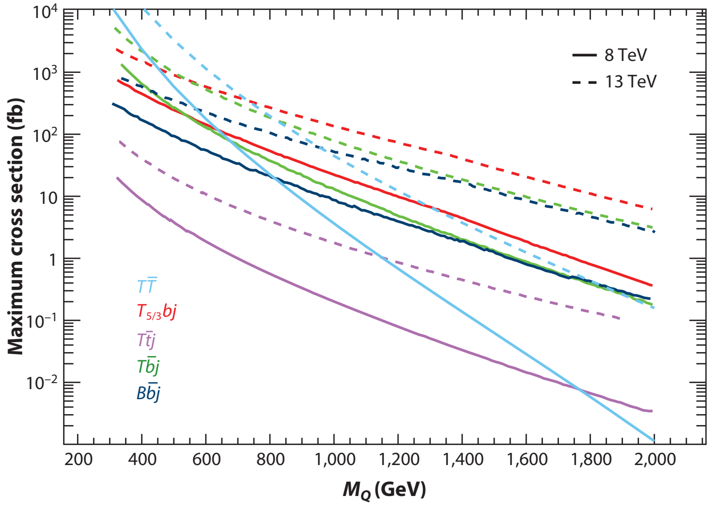

Figure 2

Cross sections for single (41) and pair (42) top partner production at $\sqrt{s} = 8$ TeV and 13 TeV.

In the original RS construction, the Higgs boson is also localized on the IR brane. Therefore, it is naturally the same size as the KK modes, which in practice must be at least ~10 TeV due to flavor and precision EW constraints. Such models therefore suffer from a severe little hierarchy problem. This observation motivated the inclusion of a global symmetry spontaneously broken down to custodial symmetry in which the Higgs boson is a PNGB, which both alleviated the EW precision constraints and explained why the Higgs boson is lighter than the KK modes (38, 52). In the extradimensional context, the global symmetry on the IR brane is gauged, and the Higgs boson propagates in the bulk as the fifth component of the gauge field.

2.2. Dark Matter

As discussed in Section 1, the connection of DM to the TeV scale (and hence the LHC) proceeds through the so-called WIMP miracle. If DM is a cold thermal relic, then its present-day annihilation cross section is $\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm^3 s^{-1}. Meanwhile, if DM interacts with the SM through the weak interactions (including Higgs exchange), then $\sigma \sim (g^4/m_\chi^2)$, which reproduces the desired cross section for $m_\chi \sim 1$ TeV.

Despite the connection to the TeV scale, direct searches for DM at the LHC are inherently challenging. Because DM should be neutral and colorless, it shows up as missing energy at the LHC. Searches for direct production must rely on hard initial-state radiation for triggering (leading to, for example, monojet + E_T^{miss} and monophoton + E_T^{miss} signatures), which reduces the rate. Furthermore, if DM is a WIMP, then its cross section is EW and not strong, further degrading the mass reach.

A popular approach for expressing the results of DM searches in a model-independent way is via effective field theory (EFT; see, e.g., References 53–55). By expressing the DM interactions with the SM (e.g., quarks) via effective operators such as $(1/\Lambda^2)(\bar{\chi}\chi)(\bar{q}q)$, LHC searches can place bounds directly on the mediator scale Λ, and they can map these bounds into the same parameter space as the direct-detection bounds because they proceed through the same effective operators. However, it is important to keep in mind that the EFT approach is valid only for mediator scales $\Lambda \gg m_\chi$, in practice several TeV for $m_\chi \sim \mathcal{O}$ (100 GeV) (56, 57). For lighter mediators (e.g., the SM Higgs boson and the Z boson, relevant to actual standard WIMPs), resonant effects and the general breakdown of the EFT imply that the limits set using the EFT can be wildly different from those in a genuine UV completion.

3. SEARCHES FOR BEYOND-THE-STANDARD-MODEL PHYSICS

The ATLAS and CMS experiments have extensively searched for BSM physics using the 7-TeV and 8-TeV data sets in Run I. So far, these searches have shown no evidence for new physics and have set stringent limits on many BSM models. The searches are based on distinct experimental signatures, and although a particular search may report limits on a particular model, the search is typically sensitive to a wide range of models. Both ATLAS and CMS have attempted to provide enough information in their publications for interested readers to reinterpret (recast) the results in the context of some other model.

In this section, we briefly summarize the current status of such searches, focusing on those models most closely tied to naturalness: SUSY and composite Higgs models [and the related searches for extra dimensions and black holes (BHs)]. In addition, we briefly summarize the searches for DM.

The review is limited to search results at 8 TeV that have been published or submitted for publication as of late February 2014. Both ATLAS and CMS have published an extensive array of search results based on 7-TeV data; most of these results have been superseded by preliminary results from 8-TeV data, which have been presented at conferences but are not reviewed in this article. The full list of results, both preliminary and published, can be found at **http://twiki.cern.ch/twiki/bin/view/AtlasPublic** and **http://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults**.

3.1. Supersymmetry

The following subsections summarize the ATLAS and CMS SUSY searches primarily by sparticle type, mostly following the simplified model approach described in Section 2.

3.1.1. Searches for gluinos and first- and second-generation squarks. For a fixed particle mass, gluinos and first-generation squarks, $\tilde{q} = (\tilde{u}, \tilde{d})$, have the largest SUSY production cross sections at the LHC (**Figure 1**), proceeding through $pp \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$. Thus, they are prime candidates for the most inclusive searches for SUSY. First- and second-generation squarks are often assumed to be mass degenerate in LHC searches (to better comply with flavor constraints).

In simplified models with very heavy squarks, gluinos decay via $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_i^0$ or $qq'\tilde{\chi}_i^{\pm}$. If gluinos are very heavy, squarks decay via $\tilde{q} \rightarrow q\tilde{\chi}_i^0$ or $q'\tilde{\chi}_1^{\pm}$. Ignoring additional jets from initial- or final-state radiation, one therefore expects event topologies with two, three, and four jets for $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, and $\tilde{g}\tilde{g}$ production, respectively. More complicated decay cascades lead to larger numbers of jets in the final state. When gauginos are produced in the decay chain, leptons can be present via the decays $\tilde{\chi}_1^{\pm} \rightarrow W^{(*)\pm}\tilde{\chi}_1^0$ or $\tilde{\chi}_2^0 \rightarrow Z^{(*)}\tilde{\chi}_1^0$. Therefore, the most inclusive searches for SUSY are based on the presence of multiple jets; zero, one, or more leptons; and $E_{\mathrm{T}}^{\mathrm{miss}}$, where the last arises (in part) from the two LSPs in the event. Useful observables include $E_{\mathrm{T}}^{\mathrm{miss}}$ and H_{T}, the latter defined as the scalar sum of the transverse momenta of the jets (and sometimes the leptons[3]) in the event. The sum $H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$, sometimes called the effective mass (m_{eff}), reflects the mass difference

[3]Unless otherwise specified, the term leptons refers to electrons and muons.

Table 1 Summary of the approximate mass reach for a number of simplified supersymmetry production/decay channels, for compressed and noncompressed decay topologies, from the LHC 8-TeV data using up to $\sim$20 fb^{-1}

Mode	min (ΔM)[a] (GeV)	max $\tilde{\chi}_1^0$ mass[b] (GeV)	Mass limit (GeV), massless $\tilde{\chi}_1^0$	Reference
$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0\, q\tilde{\chi}_1^0$	175	300	750	61
$\tilde{g}\tilde{g} \rightarrow qq\tilde{\chi}_1^0\, qq\tilde{\chi}_1^0$	25	530	1,160	58
$\tilde{g}\tilde{g} \rightarrow tt\tilde{\chi}_1^0\, tt\tilde{\chi}_1^0$ $[m(\tilde{t}_1) \gg m(\tilde{g})]$	225	580	1,260	62
$\tilde{g}\tilde{g} \rightarrow bb\tilde{\chi}_1^0\, bb\tilde{\chi}_1^0$ $[m(\tilde{b}_1) \gg m(\tilde{g})]$	50	650	1,170	63
$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0\, t\tilde{\chi}_1^0$	100	230 (165, for off-shell top)	630	65
$\tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0 b\tilde{\chi}_1^0$	15	260	620	66
$\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow W^{(*)}\tilde{\chi}_1^0 Z^{(*)}\tilde{\chi}_1^0$	25	120	345	68

[a]The minimum mass difference is shown, below which mass limits are not evaluated.
[b]Maximum value of $\tilde{\chi}_1^0$ mass for which a limit is quoted.

between the initially produced SUSY particle and the LSP, and it is approximately independent of the details of the intermediate states in the decay cascade.

The most sensitive search as of late February 2014 (58), covering the full 8-TeV data set, uses selection criteria explicitly tuned for jet multiplicities from three up to eight or more; 36 signal regions, binned in H_T, $H_\mathrm{T}^\mathrm{miss}$, and the number of jets, are considered. First- and second-generation squarks below 780 GeV are excluded for LSP masses below 200 GeV in a simplified model of $pp \rightarrow \tilde{q}\tilde{q}$, where $\tilde{q} \rightarrow q\tilde{\chi}_i^0$. The limit reduces to $\sim$450 GeV if only one squark flavor and chirality are accessible. Gluinos below 1.1 TeV are excluded for light LSP masses in a simplified model of $pp \rightarrow \tilde{g}\tilde{g}$, where $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$.

Limits on gluino pair production in simplified models with charginos in the decay cascade are obtained in an ATLAS high-multiplicity jets + $E_\mathrm{T}^\mathrm{miss}$ search (59) with no leptons. In a model in which $pp \rightarrow \tilde{g}\tilde{g}$ and $\tilde{g} \rightarrow qq'\tilde{\chi}_i^\pm \rightarrow qq'W^{(*)\pm}\tilde{\chi}_1^0$, gluinos below $\sim$1 TeV are excluded for LSP masses below 200 GeV, assuming the chargino mass is halfway between the LSP and gluino masses. The CMS search (58) excludes gluinos below 1.2 TeV in a similar scenario but also allows for the decay mode $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0 \rightarrow q\bar{q}Z\tilde{\chi}_1^0$ with equal probability. Searches based on jets + $E_\mathrm{T}^\mathrm{miss}$ and additional leptons reach roughly similar conclusions in such models. A CMS search (60) based on 34 signal regions with same-sign dileptons binned in H_T, $E_\mathrm{T}^\mathrm{miss}$, and the number of ($b$-tagged) jets excludes gluinos below $\sim$900 GeV for light LSPs, approximately independent of assumptions about the chargino mass.

Table 1 summarizes the approximate mass reach for a massless χ_1^0 for selected analyses that are representative of an abbreviated set of probed decay modes. It also shows the maximum value of the χ_1^0 mass above which no exclusion limits exist, as well as the minimum mass difference between the initially produced SUSY particle and the LSP (ΔM) below which no exclusion limits exist. This issue is discussed further in Section 4.3.1.

3.1.2. Searches for gluinos and third-generation squarks. Searches for gluinos and third-generation squarks are particularly well motivated by the natural SUSY scenario and have been carried out in many channels, utilizing various combinations of (b-tagged) jets, leptons, H_T, and $E_\mathrm{T}^\mathrm{miss}$ (59–64). Even before the advent of the natural SUSY paradigm, it had been recognized that third-generation squarks could be considerably lighter than those of the first and second generations due to the possibility of significant left–right mixing and mass splitting, which arises from the large Yukawa coupling.

In the scenario of gluino pair production followed by the three-body decay $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$ via an intermediate off-shell top squark, the best published limit as of late February 2014 (62) excludes gluinos up to a mass of 1,260 GeV for LSP masses ranging up to almost 500 GeV. Additionally, the sensitivity is extended for smaller gluino–neutralino mass splittings in the regions $m(\tilde{g}) - m(\tilde{\chi}_1^0) < 2m(t)$ and $m(\tilde{g}) - m(\tilde{\chi}_1^0) > m(W) + m(t)$, where the decay becomes four body and proceeds through an off-shell top quark.

For gluino decays via on-shell top squarks (followed by $\tilde{t} \to t\tilde{\chi}_1^0$), exclusion limits have been presented that fix the gluino mass to 1,000 GeV and vary the LSP and top squark masses or fix the LSP mass to a value around 50 GeV and vary the top squark and gluino masses (62). In the former model, the 1,000-GeV gluino is excluded for all kinematically accessible top squark and LSP masses, provided that the LSP mass is below ∼520 GeV. In the latter model, the gluino mass limit degrades for smaller top squark masses but still exceeds 1,000 GeV for a top squark mass as low as 200 GeV. For the three-body gluino decay $\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$ via an intermediate virtual bottom squark, gluinos are excluded up to a mass of 1,170 GeV, roughly independent of LSP mass up to 500 GeV (63). Other decay modes that have been considered include $\tilde{g} \to b\tilde{b}_1^* \to b\bar{t}\tilde{\chi}_1^+ \to b\bar{t}W^+\tilde{\chi}_1^0$ and the RPV decay $\tilde{g} \to tbs$ (60).

To cover the possibility in which the gluinos are beyond reach, both CMS and ATLAS have searched for direct production of third-generation squarks. A CMS search (65) for $pp \to \tilde{t}\tilde{t}^*$ excludes top squarks with a mass below 630 GeV for a light LSP in a model where both top squarks decay via $\tilde{t} \to t\tilde{\chi}_1^0$ to unpolarized top quarks, degrading to ∼600 GeV for an LSP mass as high as 200 GeV. Similar limits are obtained in a model in which both top squarks decay via $\tilde{t} \to b\tilde{\chi}_1^\pm \to bW^{(*)}\tilde{\chi}_1^0$, although the limits depend on the mass splitting between the chargino and the LSP, degrading as the chargino and the LSP become mass degenerate. The same CMS search also tackles the three-body decay $\tilde{t} \to bW\tilde{\chi}_1^0$ via a virtual top quark, which can be significant if the mass difference between the top squark and the LSP is sufficiently compressed. An interesting case is the top squark decay $\tilde{t} \to b\tilde{\chi}_1^\pm \to bW^{(*)}\tilde{\chi}_1^0$, in which a small mass splitting between the chargino and the LSP renders the lepton-based searches ineffective; this topology is covered by an ATLAS search (66) for two energetic b-tagged jets + $E_{\mathrm{T}}^{\mathrm{miss}}$ vetoing events with leptons and additional jets. Top squarks with a mass below 580 GeV are excluded for LSP masses up to ∼200 GeV, assuming a mass splitting between the chargino and the LSP of 5 GeV. For larger splittings, the limits weaken due to the increasing likelihood of successful reconstruction of a lepton from the chargino decay.

Allowing for additional jets in the event, ATLAS searches for the process $pp \to \tilde{b}\tilde{b}^*$ with $\tilde{b} \to b\tilde{\chi}_1^0$. The study of a topology in which the two b-tagged jets recoil against a high-p_{T} jet (typically from initial-state radiation) renders the analysis sensitive to compressed scenarios in which the mass difference between the bottom squark and the LSP is relatively small. Bottom squarks with a mass below 620 GeV are excluded for small LSP masses, degrading only slightly up to an LSP mass of ∼200 GeV.

A CMS search (67) considers a natural SUSY model with GMSB in which only the top squarks and Higgsinos are accessible. The model considers top squark pair production, followed by $\tilde{t} \to t\tilde{\chi}_1^0$, $\tilde{t} \to t\tilde{\chi}_2^0 \to tZ^{(*)}\tilde{\chi}_1^0$, or $\tilde{t} \to b\tilde{\chi}_1^\pm \to bW^{(*)}\tilde{\chi}_1^0$, in which the $\tilde{\chi}_1^0$ decays to $h\tilde{G}$. One Higgs boson is required to decay in the diphoton channel, whereas the other is accepted in either the diphoton or the $b\bar{b}$ channel. Top squark masses below 360–410 GeV, depending on the Higgsino mass, are excluded.

3.1.3. Searches for charginos and neutralinos. Direct pair production of gauginos at the LHC is dominated by $\tilde{\chi}_1^+\tilde{\chi}_2^0$ and $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production in most of the MSSM parameter space. One search at 8 TeV, focusing on associated chargino–neutralino production in the trileptons + $E_{\mathrm{T}}^{\mathrm{miss}}$ channel (68), has been published as of late February 2014. Assuming that $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^0$ have equal mass, these gauginos are excluded below 345 GeV in models in which $\tilde{\chi}_1^+ \to W^{(*)+}\tilde{\chi}_1^0$ and with a very light LSP (**Table 1**); the limits are approximately unchanged up to an LSP mass of ~75 GeV. The discovery of a relatively light Higgs boson also introduces the possibility of the decay $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$, and the inclusion of tau leptons in the analysis adds sensitivity via the $h \to \tau\tau$ channel. In models in which the $\tilde{\chi}_2^0$ decays exclusively via $h\tilde{\chi}_1^0$ and the Higgs boson decays according to SM branching ratios (BRs), degenerate $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^0$ below ~140–148 GeV are excluded for LSP masses below ~20 GeV. Results are also interpreted in a phenomenological MSSM (pMSSM) framework (69), in which the strongly interacting SUSY particles, the sleptons, and the *CP*-odd Higgs boson are all assumed to be out of reach; tanβ is set to 10; the gaugino mass parameter M_1 is set to 50 GeV; and limits are explored as a function of M_2 and μ. A pMSSM scenario in which the right-handed sleptons become kinematically accessible is also considered.

3.1.4. Searches for long-lived particles. Searches for long-lived particles are theoretically well motivated. The possibility of a metastable bound state containing a gluino or a squark, the so-called *R* hadron, had been raised in the earliest papers on MSSM phenomenology (70). More generally, a large class of models within SUSY predict the existence of long-lived particles; these models include GMSB, AMSB, RPV, and split SUSY (71, 72). There are many reasons that such particles can have highly suppressed decay rates: Their decays could proceed through very high dimension operators (GMSB and split SUSY), extremely small couplings (RPV), or extreme kinematic suppression (AMSB) (for recent reviews of metastable massive particles, see References 73 and 74). To search for massive particles with long lifetimes, the analyses deal with unconventional signatures including displaced vertices, disappearing tracks, slowly moving particles with a long time of flight, and heavy particles with such long lifetimes that they decay in the calorimeter out of time with the LHC bunch crossing.

The experimental signature for *R* hadrons is complicated by the fact that they may have a significant probability of undergoing hadronic reactions in the detector material (75–77). Several searches are therefore designed utilizing different portions of the ATLAS and CMS detectors. A CMS search (78) based on the full 7- and 8-TeV data sets excludes gluinos with a mass below 1,233 to 1,322 GeV, depending on the interaction model and the fraction of gluinos that form glueballs and, therefore, remain neutral and weakly interacting throughout the transit of the detector. Top squark *R* hadrons are excluded below a mass of 818 GeV. Scalar taus are excluded below 500 GeV when directly and indirectly produced in a minimal GMSB model; directly produced staus are excluded below 339 GeV. Limits are also placed on Drell–Yan production of leptons with nonstandard charge. An ATLAS search (79), also covering the full 7- and 8-TeV data sets, focuses on *R* hadrons that stop in the calorimeter material and decay during periods in the LHC bunch structure without *pp* collisions. The complementarity with respect to the searches described above is model dependent. Limits on the gluino, top squark, and bottom squark masses of 832, 379, and 344 GeV, respectively, are obtained for an LSP mass of 100 GeV.

Although these searches cover a broad range of mechanisms for *R* hadron interactions, there remains the possibility that an *R* hadron stays neutral through the entire detector. This case would be covered by the search for a monojet + $E_{\mathrm{T}}^{\mathrm{miss}}$ signal, discussed in Section 3.3, although explicit limits have not been published. (However, see References 80 and 81 for a recasting of monojet and SUSY searches for compressed gluino–bino and squark–bino simplified models, which would also be relevant to the all-neutral *R* hadron scenario.)

ATLAS (82) has explored chargino production via $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$ + jet or $pp \to \tilde{\chi}_1^+\tilde{\chi}_1^-$ + jet in an AMSB-inspired scenario. In this scenario, the lightest chargino and the LSP are nearly degenerate such that the chargino decay proceeds via $\tilde{\chi}_1^+ \to \pi^+\tilde{\chi}_1^0$, where the pion has a momentum of the order of 100 MeV. The search looks for events in which an isolated, high-p_{T} charged track "disappears" in the ATLAS tracking volume, the low-momentum pion going unobserved. An additional jet from initial-state radiation is required to trigger the event. In the minimal AMSB scenario, charginos with a mass below 270 GeV are excluded. More general limits are derived in the plane of the chargino mass versus the lifetime.

3.1.5. Searches for *R*-parity-violating supersymmetry. ATLAS and CMS have also searched for RPV SUSY. As mentioned in Section 2.1.1, these signatures appear with little to no $E_{\mathrm{T}}^{\mathrm{miss}}$ in the event. As of the end of February 2014, the experiments have published two such searches, both using the full 8-TeV data set. The first, from CMS (83), selects events with at least three isolated leptons and b jets and targets signatures that arise from stop pair production with RPV decays. The search explores several RPV couplings, excluding stop masses for two scenarios below 1,020 GeV and 820 GeV for an LSP mass of 200 GeV. The second analysis, also from CMS (84), searches for the pair production of three-jet hadronic resonances and targets final states with only light-flavor jets and with both light- and heavy-flavor jets. The results are interpreted in the context of pair-produced gluinos decaying via RPV under two different scenarios, with and without heavy flavor. For the light-flavor decay scenario, gluino masses are excluded below 650 GeV; for the heavy-flavor decay scenario, gluino masses are excluded between 200 and 835 GeV for the first time.

3.2. Composite Higgs Models and Extra Dimensions

As discussed in Section 2, composite Higgs models predict the existence of light ($\lesssim$1-TeV) colored, fermionic top partners that couple strongly to third-generation quarks, resulting in signatures with many bottom quarks, leptons, jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$. In addition, composite Higgs models predict the existence of EW spin-1 resonances that mix with the W and Z bosons and thus have phenomenology similar to that of W' and Z' bosons. These are generally constrained to lie above 2–3 TeV by precision EW tests. Finally, colored spin-1 resonances (the so-called KK gluons) are generically present in many concrete (holographic) composite Higgs models and are much less constrained by precision EW. Searches for all of these resonances are ongoing at the LHC. So far, the experiments have performed targeted searches for top partners with charge 5/3 ($T_{5/3}$) decaying to a top quark and a W boson (85); top partners with charge 2/3 (T) decaying to a bottom quark and a W boson, a top quark and a Z boson, or a top quark and a Higgs boson (86); a W' boson decaying to $t\bar{b}$ (87); and excited top quarks decaying to a top quark and a gluon (88), as well as generic searches for anomalous production of $t\bar{t}$ that constrain Z' bosons and KK gluons (89).

In each of these searches, $t\bar{t}$ is a large background, so the searches exploit the kinematic differences between the particles and the top background. Various distinguishing kinematic variables are used in these analyses; examples include invariant mass reconstruction (such as M_{tb} in the $W' \rightarrow t\bar{b}$ search or $M_{t\bar{t}}$ in the anomalous $t\bar{t}$ production search), H_{T}, and more sophisticated multivariate tools (such as a boosted decision tree in the $X_{2/3}$ search).

No evidence for top partners or vector resonances has been found in the LHC data so far, and stringent limits are placed on a variety of scenarios. The exclusion limits on heavy resonances such as W', Z', and RS KK gluons are in the 2-TeV range, whereas limits on vector-like top partners are in the 600–800-GeV range. **Table 2** summarizes the current status of the 8-TeV searches from the LHC experiments.

In models of extra dimensions, access to quantum gravity at the TeV scale can lead to high rates of BH production at the LHC (90, 91). Searches at the LHC have been performed for both small, quantum BHs and large, semiclassical BHs. In the latter case, the experimental signature would present itself as a high multiplicity of high-p_{T} particles, produced as the semiclassical BH evaporates via Hawking radiation. Meanwhile, small quantum BHs would have enough energy to

Table 2 Upper mass limits on top partners and vector resonances from composite Higgs models and limits on extra dimensions[a]

Search	Signature	Limit	Reference
$W' \to tb$ resonances	ℓ + jets	2.05 TeV	87
$T_{5/3} \to tW$	Same-sign dileptons	800 GeV	85
$T \to bW, tZ, th$	ℓ + jets and dileptons	687–782 GeV	86
$t^* \to tg$	ℓ + jets	803 GeV	88
Anomalous $t\bar{t}$ production	ℓ + jets and all-hadronic	Z': 2.1–2.7 TeV	89
		RS KK gluon: 2.5 TeV	
Microscopic BH	Large S_T, jets, ℓ, γ, and E_T^{miss}	4.3–6.2 TeV (12 fb^{-1})	92
Quantum BH	ℓ + jets	5.3 TeV	94
Quantum BH	γ + jets	4.6 TeV	95
ADD BH	Same-sign dimuons	5.1–5.7 TeV	96

[a]These LHC searches use the 8-TeV data up to ~20 fb^{-1}, unless otherwise noted. The limit is on the mass of the heavy particle searched for, unless otherwise indicated. Abbreviations: ADD, refers to the authors of Reference 93; BH, black hole; RS KK, Randall–Sundrum Kaluza–Klein; S_T, scalar sum of the transverse momenta (p_Ts) of all the final-state objects.

decay to only a small multiplicity of particles, yielding a signature that is distinct from that in the semiclassical case.

The ATLAS and CMS experiments have searched for both such signatures for BHs, and **Table 2** summarizes the current status. In the CMS search (92), 12 fb^{-1} of the 8-TeV data are used to explore events with large particle multiplicities. Model-dependent limits are obtained for several scenarios [such as the ADD model (93) and string balls] and assumptions (such as rotating or nonrotating BHs or the number of extra dimensions) and are all in roughly the multi-TeV range. In addition, model-independent limits are provided as a function of the scalar sum of the p_Ts of all the final-state objects (S_T) and the particle multiplicity, which allows straightforward possible reinterpretation of the results. ATLAS has performed three searches for extra dimensions: Two searches targeted quantum BH in either the lepton + jets final state (94) or the photon + jet final state (95), and the third search targeted an ADD model with same-sign dimuons (96). Again, the upper mass limits have been reported for several different scenarios and model assumptions and are in the 5-TeV range (**Table 2**).

3.3. Direct Searches for Dark Matter

In addition to the searches for SUSY described above, which provide a possible candidate for DM (e.g., the LSP), the LHC experiments have searched for direct pair production of WIMP DM particles.[4] Because WIMPs escape the detector without interacting, to be able to trigger on them one assumes that they are produced in association with a particle X, where X can be a jet, a photon, or a vector boson. This assumption gives rise to a mono-$X + E_T^{miss}$ signature. Although searches for DM have been extensively explored with 7-TeV data and in preliminary results from 8-TeV data, currently only one such result has been published. The recent publication from ATLAS (97) used the full 8-TeV data set and searched for a single hadronic large-radius jet whose mass is consistent with that of a W or Z boson, which recoils against large missing transverse momentum. Limits on the DM–nucleon scattering cross section as a function of the mass of the DM particle were set in the context of EFT, as described in Section 2.2, and have been reported for both spin-independent

[4]The pair production is a consequence of the assumed parity symmetry that keeps the WIMPs stable.

(vector-like) and spin-dependent (axial-vector-like) scattering. The results are also presented alongside those from direct DM detection experiments; however, note that direct comparisons using the EFT approach have important caveats, as briefly reviewed above in Section 2.2.

4. IMPLICATIONS

4.1. Implications for Specific Models

Prior to the LHC turn-on, a number of benchmark "complete" SUSY models were studied both in the theoretical literature and by the LHC experiments. In this section, we review the current status of some of these models in the aftermath of Run I.

Perhaps the most-studied benchmark model has been the CMSSM. Here the vast MSSM parameter space is reduced to only five parameters set at the GUT scale: m_0 (common sfermion mass), $m_{1/2}$ (common gaugino mass), A_0 (common trilinear soft term), tanβ, and sign(μ). Fits to existing data in the CMSSM framework hinted at a SUSY mass scale in the hundreds-of-GeV range, although this value was driven primarily by the deviation from SM expectations in the measurement of the anomalous magnetic moment of the muon (see, e.g., the discussion in References 98 and 99). At the end of Run I, the situation of the CMSSM is much different (for the most up-to-date fits and references to earlier work, see References 100 and 101). The Higgs boson at 125 GeV (to a large extent) and the direct LHC searches (to a lesser extent) have pushed the superpartners up much higher in mass; stops $\gtrsim$750–1,000 GeV and gluinos and squarks $\gtrsim$1,500–2,000 GeV are now required.

Another popular complete model with a greatly reduced parameter space is minimal gauge mediation (MGM) (18–20), in which some number of $\mathbf{5} \oplus \bar{\mathbf{5}}$ messengers generate flavor-diagonal soft masses at a messenger scale M. The soft masses are proportional to a common scale Λ. Together with the gravitino mass $m_{3/2}$ and the usual Higgs parameters tanβ and sign(μ), they form the parameter space of MGM. Here the Higgs mass constraint alone is enough to push the soft masses into the multi-TeV range and basically out of reach of even the 14-TeV LHC (102).

The common theme in both of these examples is that for simple, constrained models based on the MSSM, requiring a 125-GeV Higgs mass is generally more powerful than any individual LHC search in constraining the parameter space. In the MSSM, the Higgs mass is bounded at tree level to be less than m_Z. So $m_h = 125$ GeV requires (103–107) large radiative corrections: either stops $\gtrsim$1 TeV with large A-terms [the so-called max-mixing scenario (108–110)] or, in the absence of A-terms, very heavy stops $\gtrsim$8–10 TeV. In constrained models such as CMSSM and MGM, in which all of the superpartner masses are controlled by only a few parameters, requiring such heavy stops generally also pushes the rest of the spectrum out of reach.

Of course, even models based on the MSSM need not be so constrained as the CMSSM and MGM. For example, since the Higgs discovery, much effort has been devoted to extending GMSB models to realize large A-terms (111–121). Such models, although often still out of reach of the 7–8-TeV LHC, could be accessible at 14 TeV. One can also consider going beyond the MSSM; adding more interactions can circumvent the tree-level bound. For instance, the Higgs mass can be raised by couplings to additional singlets [as in the NMSSM (for a review, see, e.g., Reference 122)] or by adding additional gauge interactions (123).

4.2. Broader Implications

Given the vast multitude of LHC searches for new physics that have been performed by ATLAS and CMS in many different channels, each setting a limit on a specific model or simplified model, it can be challenging to draw more general conclusions. Many theorists have endeavored to reinterpret or "recast" LHC analyses to understand broader implications or to understand the constraints on their favorite models and potential loopholes in existing searches (for a comprehensive list of references to such papers, and an interesting proposal for a potentially efficient shortcut to recasting, see Reference 124). In this short review, we cannot do justice to the many recasting papers in the literature. Instead, we attempt to highlight some recent examples that make use of 8-TeV LHC results. In this section, we concentrate on reinterpretations that reach broader conclusions, and Section 4.3 is devoted to a general discussion of loopholes.

Perhaps the largest single theme driving recasting research is natural SUSY. As discussed in Section 2, in the MSSM, the Higgsino, stop, and gluino are crucial for naturalness in SUSY. Much effort has been devoted to recasting LHC analyses for simplified models motivated by natural SUSY, beginning with References 125–129. More recently, for gluinos, an extensive study (130) that reinterpreted nearly all the relevant Run I LHC searches concluded that a gluino with a mass below ~1 TeV is probably excluded for a very broad range of scenarios (RPC, RPV, hidden valleys, top dilution, etc.), provided that the gluino produces either $E_{\mathrm{T}}^{\mathrm{miss}}$ or top quarks in the decay chain. If the top quarks and $E_{\mathrm{T}}^{\mathrm{miss}}$ can be diluted sufficiently such that the final state is all hadronic, then the limit on the gluino can be lowered to $m_{\tilde{g}} \gtrsim 800$ GeV.

A study of natural SUSY production recasted three 8-TeV LHC searches and found that $m_{\tilde{g}} \gtrsim 1.2$ TeV and $m_{\tilde{t}} \gtrsim 700$ TeV for $m_{\tilde{H}} \lesssim 300$ GeV for a few simplified models with tops and $E_{\mathrm{T}}^{\mathrm{miss}}$ in the final state (131; also see References 132 and 133, which obtained similar limits on stop production by using ATLAS and CMS direct stop searches).

Other research has focused on the possibility that the LSP decays via RPV in natural SUSY. In comprehensive studies (134, 135), stop production with RPV was exhaustively classified. All possible decays, either directly via RPV or through an intermediate Higgsino LSP, were classified, and an extensive list of 7- and 8-TeV LHC searches was recasted to derive the current constraints on all of these scenarios. Although in many instances [e.g., those with *LLE* or *LQD* (see Equation 3) decays that give rise to leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$] the limits on stops were near their kinematic limit, ~700 GeV, many scenarios were also identified (for example, $\tilde{t} \to b\tilde{H} \to b\tau qq$ via RPV] in which there is *no current limit* on the stop mass from the LHC!

Meanwhile, for composite Higgs models, the focus of recasting has largely been on fermionic top and bottom partners X (see, however, the recent research in Reference 136, in which some LHC searches were recasted in terms of limits on composite Higgs vector resonances). Existing LHC searches use the same-sign dilepton channel, motivated by decays such as $X \to tW$. A common theme seems to be that the LHC searches assume 100% BRs into specific final states (such as tW or tZ), whereas realistic models have more complicated, mixed BRs. See, for example, References 40, 137, and 138 for recasts of 7-TeV same-sign dilepton searches.

For more recent recasting studies that use the full 8-TeV data set, see, for instance, References 139–142. These papers generalize existing LHC searches to other scenarios. For instance, References 139 considers the constraints when both $T_{5/3}$ and B are light and can be both singly and pair-produced. The authors show that the reach of existing same-sign dilepton searches can be increased somewhat from 770 GeV to ~850 GeV in some corners of parameter space. Reference 140 provides a comprehensive survey of the current status of the littlest Higgs with T-parity model. By recasting a number of LHC SUSY searches and combining the results with other constraints, the authors claim a limit of 640 GeV on the compositeness scale f. Reference 141 is a comprehensive study of bottom partners in composite Higgs models. By combining current LHC limits with precision constraints, the authors determine a best-fit point of $v^2/f^2 \sim 0.07$. Finally, Reference 142 studies the bounds on charge-8/3 top partners, which could be present even in the MCHM if the top partners are embedded in a **14** of $SO(5)$. By recasting same-sign dilepton searches, these authors obtain a limit of $M_{8/3} > 940$ GeV. They also consider the CMS BH search (92), which is not yet competitive.

4.3. Weaknesses and Loopholes in Current Searches

Although the BSM searches for new physics performed by the LHC experiments are broad and comprehensive, some areas remain less well explored. In addition, in some cases, especially in SUSY searches, important assumptions made in the interpretations of the results are worth noting. In this section, we attempt to summarize these weaknesses or loopholes, both by the experiments and in the theoretical literature, and list areas for improvement in future searches.

4.3.1. Compressed spectra. In the context of R-parity-conserving SUSY models, there is a weakness in the case of compressed SUSY in which the mass difference between the initially produced SUSY particle and the LSP is small, leading to lower $E_{\mathrm{T}}^{\mathrm{miss}}$ in the final state and lower signal acceptance. Although compressed spectra may at first seem to require some additional tuning, the literature contains examples in which this is not the case (143, 144).

With a few exceptions, ATLAS and CMS do not generally attempt to set limits in the region of very small mass differences (ranging from 25 to 175 GeV, depending on the channel) because the signal acceptance depends strongly on the modeling of initial-state radiation. **Table 1** shows that mass limits are noticeably weaker for compressed decay spectra. For example, a natural scenario of pair production top squarks with a mass of 500 GeV decaying via $\tilde{t}_1 \to t\tilde{\chi}_1^0$ to an LSP with a mass of 250 GeV is still not ruled out. The production of $\tilde{\chi}_1^+\tilde{\chi}_2^0$ in the natural SUSY scenario, in which the EW partners are mostly Higgsino-like and hence highly mass degenerate, is also unconstrained by the LHC, even when reinterpretations of LHC monojet searches are taken into account (145–148); current limits on Higgsino LSPs are essentially no better than those from LEP! Even with mild compression, all searches for EW partners fail if the LSP has a mass greater than $\sim$100 GeV.

4.3.2. Model assumptions. A second loophole in current BSM search limits arises from the assumptions on decay BRs as in, for example, the SUSY simplified models. Typically the decay is assumed to proceed via a single channel with 100% BR. As of late February 2014, the LHC experiments have not presented SUSY search limits as a function of BR, except in the search for top squarks (65), in which the mass limits are recalculated under the conservative (but pessimistic) assumption that either the search in the $\tilde{t} \to t\tilde{\chi}_1^0$ channel or the search in the $\tilde{t} \to b\tilde{\chi}_1^\pm$ dominates.

As shown in many studies by theorists, mass limits from individual searches that assume 100% BRs can degrade significantly when applied to realistic scenarios with complicated BRs. For example, a study of natural SUSY spectra recasted four different 7-TeV LHC searches in exclusive channels (jets + $E_{\mathrm{T}}^{\mathrm{miss}}$, jets + lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$, opposite-sign dileptons + $E_{\mathrm{T}}^{\mathrm{miss}}$, and same-sign dileptons + $E_{\mathrm{T}}^{\mathrm{miss}}$) (149). This study showed that for a sufficiently complicated spectrum, the limit from any one of these searches was degraded because of BRs but full sensitivity could be recovered by combining channels. Similar studies for direct stop or sbottom production can be found elsewhere (133, 150). These studies have explored the role of the BRs $\tilde{t} \to t\tilde{\chi}_1^0$ or $\tilde{t} \to b\tilde{\chi}_1^+$, as well as $\tilde{b} \to b\tilde{\chi}_1^0$ or $\tilde{b} \to t\tilde{\chi}_1^-$. Finally, the effect of the BRs in chargino–neutralino production on current LHC limits, specifically $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z$ versus $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$, has been investigated (145, 151, 152).

Another example that demonstrates the sensitivity of results on the assumptions of the model is the dependence of SUSY limits on flavor mixing. An illustration can be found in Reference 153, which studied the impact of stop–scharm mixing on the top squark bounds and found that they can be appreciably lower. This study also showed that large stop–scharm mixing can result in interesting and unexplored signatures, such as $t\bar{c}(c\bar{t}) + E_{\mathrm{T}}^{\mathrm{miss}}$, which could be searched for immediately.

A final example of the dependence on model assumptions we discuss here is in the SUSY cross-section calculation. For second-generation squarks, $\tilde{q} = (\tilde{c}, \tilde{s})$, essentially only production via $\tilde{q}\tilde{q}^*$ is available, given that the $\tilde{q}\tilde{q}$ and $\tilde{q}\tilde{g}$ processes are greatly suppressed by parton distribution functions unless q corresponds to a valence quark. Therefore, their rates are generally reduced relative to those for first-generation squarks (154). The squark production cross section would also be lowered if the gluino is a Dirac fermion (155, 156).[5] Other interesting examples with lower production cross sections are the ideas of folded SUSY (157) and twin SUSY (158, 159), in which the partners of the colored SM particles do not carry QCD charges.

4.3.3. Scans for gaps in the coverage. Scans of the pMSSM have been used to search for possible gaps in the coverage of LHC searches for SUSY (160–165). At the time of Reference 160, corresponding to public results available in September 2012, the authors concluded that viable models exist that contain first- and second-generation squarks, gluinos, and third-generation squarks with masses below 600, 700, and 400 GeV, respectively. The authors of these scans identified mechanisms that allow low-mass MSSM phenomenology points to survive the LHC searches. They essentially confirmed loopholes already described above: (*a*) a decrease in the production cross section for first- and second- generation squarks by splitting the mass degeneracy, (*b*) compressed decay chains, and (*c*) branches to multiple final states in the decay cascade.

4.3.4. Displaced decays. As discussed above in Section 3.1.4, searches for heavy, long-lived particles are well motivated by a number of theoretical scenarios in SUSY and beyond. The LHC experiments have searched for such signatures primarily with the 7-TeV data and have obtained only a few results with the 8-TeV data (see Section 3.1.4). These analyses are typically very inclusive and powerful and target a large class of models. However, these searches cover typical lifetimes greater than or equal to a few nanoseconds (10 cm), whereas intermediate lifetimes of 0.01 to 1 ns (corresponding to moderately displaced decays in the tracker volume) are much less constrained. See, for example, References 166 and 167 for a discussion of the weaknesses and discovery prospects of the LHC searches for long-lived particles in the context of GMSB and RPV, respectively.

Several challenges must be met to successfully perform these analyses, including the design of triggers and specialized reconstruction algorithms specific to the search. Nevertheless, the LHC experiments would benefit from designing searches to target this uncovered and more challenging range of longer-lived particles.

4.3.5. Searches for very unusual signatures. It is crucial that searches for very unusual signatures, in particular those that may be missed by other searches, be performed by the LHC experiments. In addition, various unusual signatures have been predicted by many different models that address naturalness; see, for example, Reference 168 for a recent review. Although many of these unexpected new signatures have been searched for at 7 TeV, many of them have not yet been repeated by the LHC experiments with 8-TeV data. We highlight some examples here.

Hidden valley models (169) provide solutions to the hierarchy problem and postulate a new, low-mass hidden sector that is only very weakly coupled to the SM. One way this hidden sector could reveal itself is through the production of many light particles in the final state that could appear as a collimated stream of leptons, which are referred to as lepton jets. [Such signatures were recently motivated by various astrophysical anomalies in the context of indirect DM detection (170, 171).] Searches for lepton jets have been performed at 7 TeV (172, 173) but have not yet been

[5] A Dirac gluino also leads to lower fine-tuning.

repeated or extended at 8 TeV. Dedicated reconstruction tools are required for such searches, and increasing pileup can pose an additional challenge.

Another class of hidden valley models predicts new particles called quirks, which transform under a new strong force called infracolor (174). These quirks are quark-like and fractionally charged. CMS searched for quirks by using the 7-TeV data using the signature of tracks with an associated low rate of energy loss in the silicon tracker (175), but this search has yet to be repeated with the 8-TeV data by either CMS or ATLAS.

Although such searches for very unusual signatures are potentially challenging and require dedicated efforts, they should not be neglected. The LHC experiments should continue to pursue such searches using the 8-TeV data and beyond.

5. OUTLOOK

5.1. Expectations for 14 TeV

The LHC is currently shut down (LS1), and data taking is expected to resume in 2015 at close to the design center-of-mass energy of 14 TeV. In the ensuing data-taking period, an integrated luminosity of $\sim$100 fb^{-1} is expected to be collected by both ATLAS and CMS. This period of data taking will be followed by another shutdown (LS2), during which the injector chain will be modified to approximately double the instantaneous luminosity, after which another 200 fb^{-1} are expected to be collected. Currently under discussion are plans to further increase the luminosity of the LHC by an additional factor of 2.5, leading to a total integrated luminosity of 3,000 fb^{-1} by sometime in the 2030s.

Several large-scale planning exercises for the future of high-energy physics have been held in the past 2 years (176–178). The increase in energy to 14 TeV will extend the kinematic reach to higher mass, while the increase in integrated luminosity will extend the sensitivity for lower mass processes with small cross sections and for difficult kinematic topologies (see **Figure 1** for an example). Both ATLAS and CMS have made projections of the expected physics performance for integrated luminosities of 300 and 3,000 fb^{-1}. The ATLAS projections are derived mostly from fast simulations incorporating parameterizations of detector performance obtained from detailed detector simulations, and reoptimization of the analysis. The detailed detector simulations include the effect of the increased number of additional inelastic *pp* collisions (pileup) accompanying each beam crossing in the LHC. CMS has performed simpler extrapolations on the basis of current physics analyses and has scaled signal and background by the change in cross sections and integrated luminosities from 8 to 14 TeV. **Table 3** shows the projected mass reach for some representative processes.

Several studies have examined the prospects for detecting mass-degenerate Higgsinos in future LHC runs on the basis of the monojet signature (147, 148, 182). An interesting possibility to use the process of vector boson fusion to search for near-degenerate electroweak partners is discussed in Reference 182a. This is a rapidly evolving area of active investigation, and conclusions from these studies vary in quantitative detail. Qualitatively, however, all studies indicate that probing near-degenerate Higgsinos at the LHC will remain challenging in the future. It is worth noting that the more challenging topologies, as highlighted in Section 4.3, have not been studied in these projections, precisely because they are challenging and would require more precise simulations to be reliable.

5.2. Conclusions

The most naïve expectations from naturalness have been dashed by the results from the Run I searches at the LHC, which so far have found no BSM physics. In this review, we have discussed the

Table 3 Projections from CMS and ATLAS for the 5σ discovery reach for selected processes at the 14-TeV LHC, assuming an integrated luminosity of 300 fb^{-1}

Mode	Discovery reach		Reference
	300 fb^{-1}	Comment	
Simplified gluino–squark model	2,700	$m_{\mathrm{LSP}} \approx 0$	179
$\tilde{g}\tilde{g} \to t\bar{t}\tilde{\chi}_1^0\, t\bar{t}\tilde{\chi}_1^0$	1,900	$m_{\mathrm{LSP}} \lesssim 900$ GeV	180
$\tilde{g}\tilde{g} \to b\bar{b}\tilde{\chi}_1^0\, b\bar{b}\tilde{\chi}_1^0$	1,900	$m_{\mathrm{LSP}} \approx 0$	180
$\tilde{t}_1\tilde{t}_1 \to t\tilde{\chi}_1^0\, t\tilde{\chi}_1^0$	1,000	$m_{\mathrm{LSP}} \lesssim 200$ GeV	181
$\tilde{b}_1\tilde{b}_1 \to b\tilde{\chi}_1^0\, b\tilde{\chi}_1^0$	1,050	$m_{\mathrm{LSP}} \approx 0$	181
$\tilde{\chi}_1^+\tilde{\chi}_2^0 \to W\tilde{\chi}_1^0\, Z\tilde{\chi}_1^0$	500–600	$m_{\mathrm{LSP}} \lesssim 100$ GeV	180
$\tilde{\chi}_1^+\tilde{\chi}_2^0 \to W\tilde{\chi}_1^0\, b\tilde{\chi}_1^0$	400–500	$m_{\mathrm{LSP}} \approx 0$ GeV	180
Long-lived $\tilde{\tau}_1$	800	Direct production	180
$TT \to bW/tZ/th(50\% : 25\% : 25\%)$	1,000	Vector-like quarks	180

Abbreviation: LSP, lightest supersymmetric particle.

current status of searches from ATLAS and CMS, with a focus on searches motivated by solutions to the hierarchy problem and searches for DM. **Tables 1** and **2** summarize these searches.

The stringent limits on the existence of new physics at the LHC has led some researchers to question the utility of naturalness as a guiding principle to BSM physics. At one extreme is the camp that is ready to abandon naturalness altogether; this camp is aided by the observation of what is consistent with a nonzero, but small, cosmological constant (see, e.g., Reference 183 for a recent review), which implies a fine-tuning of 120 orders of magnitude (184) that is currently not understood. A less extreme view holds that some level of fine-tuning seems to be implied by the LHC results, but that naturalness is still useful to define the next energy scale milestones; in this view, there is still much room to cover before we are faced with the full fine-tuning of 32 orders of magnitude that would be implied if no BSM physics appears before the Planck scale.

In our view, it is still too early to worry that naturalness is in trouble. As described above, there remain broad categories of topologies without appreciable fine-tuning that have evaded searches so far. Furthermore, it is useful to recall that naturalness itself is not well defined. In addition to the obviously subjective choice of the level of fine-tuning that one calls unnatural, there are difficulties in quantifying fine-tuning in the first place. A recent review of these issues can be found in Reference 35.

At its core, the naturalness principle was only ever meant to be a rule of thumb and, as applied to the EW hierarchy, merely a rough expectation that there should be new physics somewhere around the TeV scale. As discussed above, there are many well-motivated models in which particles below 1 TeV are still allowed by the LHC. Indeed, in one extreme example, the LHC cannot even improve on LEP bounds for a Higgsino LSP, whose mass plays a key role in natural SUSY. Given these considerations, the story of searches for new physics at the energy frontier, still motivated by the hierarchy problem and by the existence of DM, remains compelling as we approach the future running of the LHC.

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