Beyond the Standard Model[1]

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1 Overview of BSM physics

"BSM physics" is a phrase used in several ways. It can refer to physical phenomena established experimentally but not accommodated by the Standard Model, in particular dark matter and neutrino oscillations (technically also anything that has to do with gravity, since gravity is not part of the Standard Model). "Beyond the Standard Model" can also refer to possible deeper explanations of phenomena that are accommodated by the Standard Model but only with ad hoc parameterizations, such as Yukawa couplings and the strong CP angle. More generally, BSM can be taken to refer to *any* possible extension of the Standard Model, whether or not the extension solves any particular set of puzzles left unresolved in the SM.

In this general sense one sees reference to the BSM "theory space" of all possible SM extensions, this being a parameter space of coupling constants for new interactions, new charges or other quantum numbers, and parameters describing possible new degrees of freedom or new symmetries [1]. Despite decades of model-building it seems unlikely that we have mapped out most of, or even the most interesting parts of, this theory space. Indeed we do not even know what is the dimensionality of this parameter space, or what fraction of it is already ruled out by experiment.

Since Nature is only implementing at most one point in this BSM theory space (at least in our neighborhood of space and time), it might seem an impossible task to map back from a finite number of experimental discoveries and measurements to a unique BSM explanation. Fortunately for theorists the inevitable limitations of experiments themselves, in terms of resolutions, rates, and energy scales, means that in practice there are only a finite number of BSM model "equivalence classes" competing at any given time to explain any given set of results [1, 2]. BSM phenomenology is a two-way street: not only do experimental results test or constrain BSM models, they also suggest – to those who get close enough to listen – new directions for BSM model building.

Contrary to popular shorthand jargon, supersymmetry (SUSY) is *not* a BSM model: it is a symmetry principle characterizing a BSM framework with an infinite number of models. Indeed we do not even know the full dimensionality of the SUSY parameter space, since this presumably includes as-yet-unexplored SUSY-breaking mechanisms and combinations of SUSY with other BSM principles. The SUSY framework plays an important

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role in BSM physics partly because it includes examples of models that are "complete" in the same sense as the Standard Model, i.e. in principle the model predicts consequences for any observable, from cosmology to b physics to precision electroweak data to LHC collisions. Complete models, in addition to being more explanatory and making connections between diverse phenomena, are also much more experimentally constrained than strawman scenarios that focus more narrowly.

One sometimes hears: "Anything that is discovered at the LHC will be called supersymmetry." There is truth behind this joke in the sense that the SUSY framework incorporates a vast number of possible signatures accessible to TeV colliders. This is not to say that the SUSY framework is not testable, but we are warned that one should pay attention to other promising frameworks, and should be prepared to make experimental distinctions between them.

Since there is no formal classification of BSM frameworks I have invented my own (see also [3]). At the highest level there are six parent frameworks:

- Terascale supersymmetry

- PNGB Higgs

- New strong dynamics

- Warped extra dimensions

- Flat extra dimensions

- Hidden valleys

Here is the briefest possible survey of each framework, with the basic idea, the generic new phenomena, and the energy regime over which the framework purports to make comprehensive predictions.

Terascale supersymmetry

The basic idea (for a review, see [4]) is to invoke a new (possibly unique) extension of Poincaré spacetime symmetry to relate elementary excitations of different spins. Thus the generic prediction is that every SM particle has a superpartner. To explain why superpartners have not yet been observed, SUSY is spontaneously broken, and it turns out that this breaking can naturally trigger electroweak symmetry breaking and stabilize its scale. Supersymmetry models address cosmology because they generically have new very light degrees of freedom (possibly relevant to inflation and baryogenesis) and with the assumption of conserved R-parity the lightest superpartner (LSP) is stable and could be dark matter. The supersymmetry framework can also accommodate ultra-high energy novelties such as grand unification and strings. Thus the SUSY framework in principle covers fundamental physics on all energy scales.

Supersymmetry models can be classified according to the dynamics of supersymmetry breaking, but it is more common to classify them according to the mechanism by which supersymmetry breaking is *mediated* (i.e. coupled) to the SM sector, shifting the masses of the superpartners of SM particles. "Direct" mediation implies that the superfields whose vacuum expectation values break SUSY couple directly to the SM sector, while in "hidden sector" models the coupling is indirect. Following [4] we can divide the hidden sector models into three groups:

- Gravity mediation: Somewhat of a misnomer, since the actual mediation is through Planck scale suppressed couplings to scalar fields that get vevs due to SUSY breaking in the hidden sector. One of these scalar fields is the auxiliary field of the $N{=}1$ supergravity multiplet, but in general one needs a theory of physics at the Planck scale to predict all the couplings. Thus string theory compactifications produce specific gravity-mediated SUSY models, such as "dilaton-dominated" [5] and G_2 models [6]. Alternatively one can assume by fiat the absence of many couplings to achieve a simple breaking pattern; examples of this include "anomaly mediation" [7], minimal supergravity (mSUGRA) [8], gravitino LSP models [9] and "no-scale" models [10]. Gravity mediation provides a natural link between the scale of SM SUSY breaking and the size of the supersymmetric μ parameter, but subsumes flavor issues into the mysteries of Planck scale physics.

- Gauge mediation: SUSY is broken by some new dynamics in a hidden sector, and communicated to some heavy "messenger" fields that also carry charges under the SM gauge group (for a review, see [11]). SUSY breaking in the SM sector comes from integrating out these messengers, and is thus suppressed by loop factors as well as by the heavy messenger mass. Gauge mediation models naturally have a minimal flavor structure but don't have an obvious explanation for the μ parameter. Unlike the other SUSY breaking masses, the gravitino mass is still Planck suppressed, and thus the gravitino is the LSP in gauge mediation models; this perhaps makes them less attractive as explanations of dark matter.

- Bulk mediation: Combines SUSY with one of the extra-dimensional frameworks described below. Some or all of the SM fields are sequestered on a "brane", a kind of slice through the full "bulk" space that includes the extra dimensions. SUSY is broken by dynamics on a different brane. The messengers of SUSY breaking to the SM sector are via fields that propagate in the full bulk space. Examples include gaugino mediation [12] and radion mediation [13].

At the end of the day all of these models reproduce the supersymmetrized version of the Standard Model with some pattern of extra "soft-breaking" masses and trilinear couplings for the superpartners. If the resulting particle content at the TeV scale is just this, we have an effective theory of softly-broken SUSY called the Minimal Supersymmetric Standard Model (MSSM). In particular the Higgs sector is the minimal one consistent with SUSY: two complex Higgs doublets leading to three neutral Higgs bosons and two charged ones.

I know of no reason to assume that the SUSY Higgs sector should be minimal. This nomenclature is also agnostic about the gravitino, which certainly matters if it is the LSP. Often one sees references to the "constrained" MSSM (CMSSM) [14], which is just the low energy SM sector arising from the mSUGRA scenario. From a phenomenological point of view it is more generic to use a less-constrained parametrization, such as the "pMSSM" [15].

PNGB Higgs

The basic idea is that the Higgs boson is a pseudo-Nambu-Goldstone boson of some global symmetry that is both spontaneously broken by some new physics at ~ 10 TeV and explicitly broken because part of the global symmetry is gauged to become the weak interactions. Thus in this framework the Higgs is naturally light compared to the 10 TeV scale for essentially the same reason that the pion in QCD is light compared to the masses of the proton and ρ meson. For reviews see [16].

The explicit breaking of the global symmetry requires extra assumptions to avoid quadratic divergences from loops of W's, Z's, and tops that would destabilize the weak scale. The generic solution is to introduce heavy partners for SM particles and arrange for cancellations of divergences at one loop. In one successful variant, Little Higgs with T-parity, every SM particle has a heavier partner with the same spin and charges, while the top quark has extra partners; the lightest partner particle is stable due to T parity and makes a good dark matter candidate. In another variant, Twin Higgs, the partners have no SM charges but form a mirror copy of the SM under some hidden gauge interactions [17].

The PNGB Higgs framework is designed to explain particle physics comprehensively up to a cutoff energy scale of about 10 TeV. At the cutoff one should replace each PNGB model by some "UV completion", i.e. a high energy model possibly drawn from one of the other frameworks discussed here: supersymmetry, new strong interactions, or warped extra dimensions.

New strong dynamics

In the Landau-Ginzburg theory of superconductivity, the superconducting state is characterized by a charged bosonic order parameter; in BCS theory this picture is only an approximation to a microscopic dynamical condensate of electron pairs. It is possible that the same holds for Higgs theory, with electroweak symmetry broken by fermion condensates bound by some new strong interaction. The simplest version of this idea, called technicolor, assumes a new force similar to QCD but with a much larger characteristic energy scale, and technifermions that carry both electroweak charges and technicharges. In other versions, called top condensation or topcolor, the electroweak breaking condensate involves top quarks. For a review, see [18].

Because strong dynamics is involved, it is difficult to determine directly if there are actually any realistic models in this framework. Furthermore, once the Higgs has been replaced by a condensate, one faces the additional challenge of generating realistic SM quark and lepton masses without benefit of SM Yukawa couplings, i.e. one is forced to construct a realistic dynamical theory of flavor. Models of new strong dynamics typically do not consider physics at scales above 10 to 1000 TeV, unless they are combined with supersymmetry.

Warped extra dimensions

The basic idea is that there is an extra spatial dimension with a strongly warped geometry, such that high energy scales as measured on one slice of the 5th dimension rescale to low energy scales as measured on another slice. In particular the Planck scale (or superstring scale) could be 10^{19} GeV on one slice, but only a few TeV on another [19].

Because of the warped geometry each SM particle has to be described by a wavefunction describing how it is spread out or localized in the 5th dimension. Localizing the Higgs where the ultimate UV cutoff is only a few TeV helps explain the weak scale - Planck scale hierarchy, while localizing the SM fermions to have different overlaps in the 5th dimension gives a natural theory of flavor.

SM particles and/or the graviton have heavy Kaluza-Klein partners that could be produced at the LHC. Realistic warped models typically introduce additional new particles. The Higgs sector is potentially richer, either because of mixing with the scalar "radion" whose mass stabilizes the warped geometry, or because the Higgs is secretly the 5th component of a 5-dimensional gauge field.

Because of AdS-CFT duality in string theory, it is possible that some/most/every warped model can be promoted to a more complete model that in turn has a dual low energy description as a 4-dimensional model of new strong dynamics. There are also Higgsless warped models [20], in which the role of the Higgs is replaced by a combination of new strong dynamics with perturbative effects of the KK partners of the W and Z.

Flat extra dimensions

The basic idea is that there are flat extra spatial dimensions of finite extent with special 4-dimensional slices called branes. If we imagine that all SM particles are confined to a brane, then we are in the ADD scenario [21] and the extra dimensions could have macroscopic size (a few microns). If we imagine that the SM fields extend through all the dimensions (with perhaps some special interactions limited to branes), then we are in the scenario of Universal Extra Dimensions [22].

In realistic 5d and 6d models of UED, all of the SM particles have heavy KK partners. The lightest KK partner is stable, due to a remnant of momentum conservation in an extra dimension, leading to a good dark matter candidate. Note this "KK-parity" is not

ad hoc, unlike its counterparts R-parity and T-parity.

UED and ADD models (and combinations thereof) do not attempt to explain the dynamical origin of their own geometries and energy/length scales. Some models of TeV scale extra dimensions provide novel mechanisms for electroweak symmetry breaking. The most extreme version of ADD is a strawman scenario for black hole production at the LHC.

Hidden valleys

The other frameworks described above sometimes invoke hidden sectors with some essential new dynamics (SUSY breaking, mirror gauge groups, etc.). One can just as well use the assumption of one or more hidden sectors as a framework in its own right [24]. The basic idea is that there are one or many new particles that are relatively light – perhaps as light or lighter than SM particles – but difficult to detect because they interact only weakly with SM particles and may be subject to new conservation laws. This hidden sector would generically have its own gauge interactions; these could be mixed slightly with SM interactions due e.g. to quantum mixing effects from very heavy particles that carry both kinds of charges. The hidden sector gauge theory might also be exotic, e.g. it could respect conformal invariance up to a small breaking due to its coupling to the SM [25].

In recent years the most interesting developments in this framework are related to dark matter. Here the relevant starting point is to ask what are the particles/interactions that *mediate* between dark matter particles (or their relatives in the dark sector) and SM particles [26]. The answer could be only gravitational or other ultra-suppressed interactions, and the answer could be the weak mediators of the SM (Z's and/or Higgs). The third option, currently popular in attempts to reconcile various possible signals in direct or indirect dark matter detection, is exotic mediators such as a new light gauge boson with a mixing-suppressed coupling to SM matter [27].

The hidden valley framework is the most "bottom-up" of the BSM frameworks, meaning that model-building it is driven by phenomenological considerations rather than "top-down" invocations of new principles of fundamental physics.

2   Common problems and features of BSM models

Even from this minimal précis the alert reader may have detected some phenomenological similarities in BSM models arising from very different theoretical frameworks. These similarities may to some extent derive from deep connections between the frameworks, such as AdS/CFT duality, but from a more pedestrian model-builders' perspective they arise from the necessity of evading strong constraints on BSM models coming from existing data.

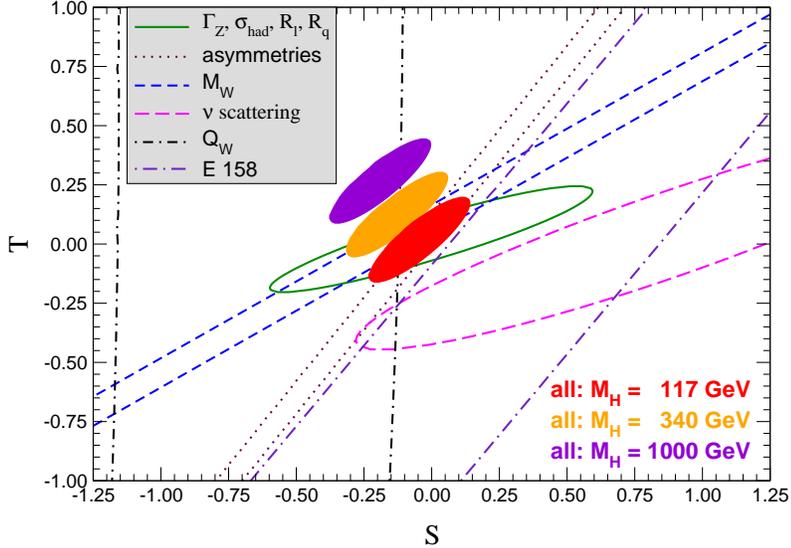Precision measurements from experiments at LEP, the Tevatron, the SLC, the B

Figure 1: The shaded ovals show the 90% CL experimentally allowed regions for the S and T parameters, for three different assumed values of the Higgs boson mass. The dotted and dashed lines are constraints from various particular measurements. Taken from [28].

factories, and with kaons, as well as searches for rare processes such as proton decay or charged lepton number violation, or for CP-violating electric dipole moments, put strong limits on new physics phenomena at multi-TeV energy scales and higher. BSM models from many well-motivated frameworks often get into trouble with these limits, usually for one of two reasons:

- The Standard Model has three accidental global symmetries: $B - L$ is exactly conserved, $B+L$ is conserved up to nonperturbative effects, and custodial symmetry – the diagonal remnant of $SU(2)_L \times SU(2)_R$ – is conserved up to effects from the SM up-versus-down Yukawa splittings. In addition, the SM has no flavor-changing neutral currents at tree level, and a very strong GIM suppression of FCNCs at loop level. BSM models generically violate one or more of these symmetries, sometimes at tree level (operators of dimension four) and sometimes by generating higher dimension operators with insufficient suppression.

- In attempting to make BSM models that explain/stabilize the weak scale, one almost inevitably introduces new particles that carry electroweak charges, or extend the electroweak sector. Generically this creates conflict with, e.g. the Peskin-Takeuchi precision observable S, which roughly speakly counts the number of left versus right-handed fermion weak doublets, the observable T, which is sensitive to large mass splittings between weak isospin partners, and the $Zb\bar{b}$ vertex, which is sensitive to

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new heavy fermions that can contribute to the vertex at one loop. The current $S-T$ constraints are shown in Fig. 1.

In turn there seem to be three general strategies to avoid such problems in BSM model building:

- Make the new particles heavy, where heavy means 2 or 3 TeV in favorable cases, and tens of TeV or more in unfavorable cases.

- Introduce new symmetries to, e.g., forbid tree-level contributions of new particles to SM processes. Thus for example R-parity in SUSY, T-parity in Little Higgs, and KK-parity in UED force new particles to be created in pairs.

- Suppress the couplings between the new particles and SM particles. This of course leads to the hidden valley framework. Note also that the most straightforward mechanisms to motivate such small couplings are to make at least some exotic particles very heavy, or to invoke new symmetries; so this third approach overlaps with the first two.

The net result of all this is that successful BSM models tend to be either "heavy", "hidden", or efficiently decoupling. The "heavy" models are somewhat discouraging in that they put much of the new physics out of reach of even the LHC, and they suffer also from the *little hierarchy problem:* if the new physics is supposed to have the virtue of stabilizing the weak scale, how do the new particles associated with this physics manage to have masses much larger than M_Z and the Higgs mass? The "hidden" models may also put much of the new physics out of reach of the LHC, but this depends on details of the model and the "hiding"; still this raises the piquant question of whether the physics behind dark matter will turn out to be accessible to colliders.

SUSY is the prime example of an efficiently decoupling model, and in fact SUSY models with relatively light superpartners fit the precision data slightly *better* than the Standard Model. However SUSY models also suffer at least somewhat from the little hierarchy problem, since they relate M_Z^2 to a linear combination of superpartner masses-squared with (model-dependent) coefficients of order one; thus the absence of a ~ 100 GeV chargino at LEP and a ~ 200 GeV gluino at the Tevatron creates some tension. In the MSSM this is much worse, because the assumption of a minimal Higgs sector would have made the Higgs boson accessible at LEP, absent large radiative corrections to its mass from heavy (~ 1 TeV) superpartners.

3   How to make new particles at the LHC

Since the LHC is an energy frontier collider, we hope that LHC discoveries at ATLAS and CMS will arise mostly from the production and decay of some new on-shell resonances (as opposed to virtual effects on SM processes). Putting aside the more exotic possibilities of
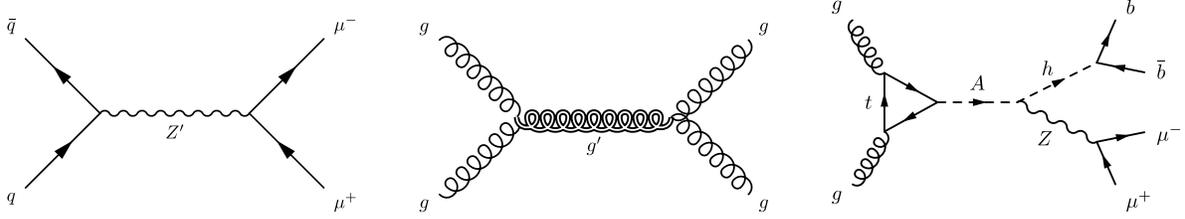
Figure 2: Diagrams for resonant production of an exotic particle: a Z' gauge boson (left), a Kaluza-Klein massive gluon (center), and a heavy pseudoscalar (right)
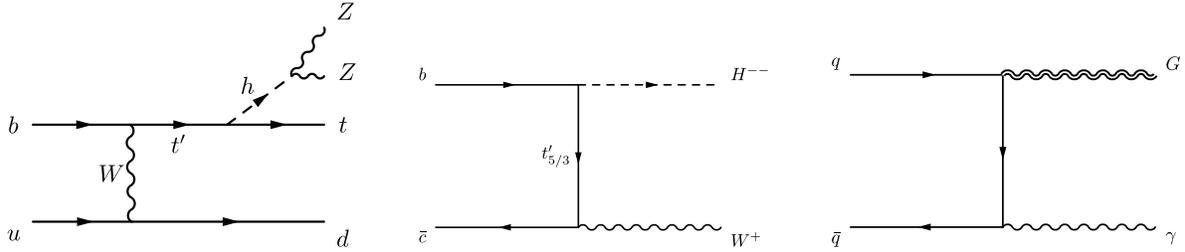

Figure 3: Diagrams for associated production of an exotic particle: a t' heavy quark (left), a doubly charged scalar (center), and a Kaluza-Klein graviton (right).

producing extended objects (e.g. superstrings, quirks) or black holes, the ATLAS/CMS discovery program is to look for new particles. Here is a more-or-less comprehensive model-independent list of all possible discovery modes:

- A new s-channel resonance, with decay to a pair of SM particles, a pair of lighter exotics, to one of each, or more complicated cascades.

- Single production of a new heavy particle in association with an SM particle.

- Pair production of exotics, with decay chains that end in either all SM particles or include one or more stable or quasi-stable exotics.

- BSMsstrahlung, i.e. a high energy SM process with extra radiation of one or more exotic particles.

- Exotics produced in the decays of "Standard Model" particles, probably top or Higgs.

A few examples are illustrated in Figs. 2-5.

An LHC discovery search plan at some level is just making a list of possible final states, performing a large number of careful inclusive searches in different channels, and studying unexplained excesses. Thus to first approximation LHC experimenters do not

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need to know anything about BSM models in order to make discoveries – but they need to know a lot about Standard Model physics!
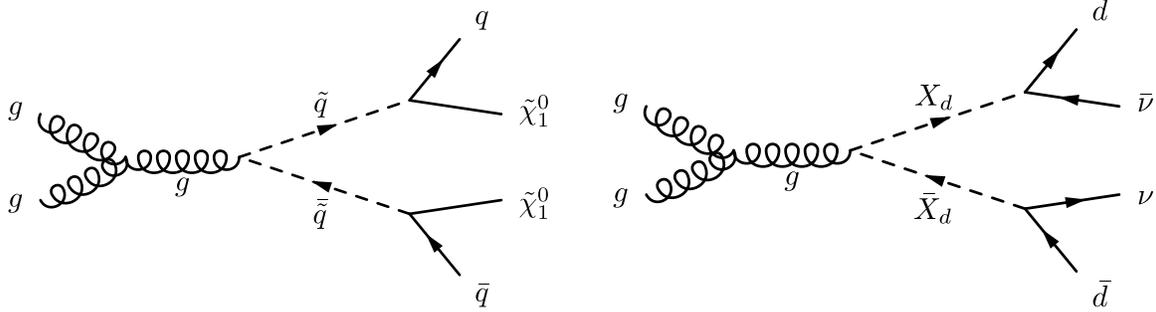

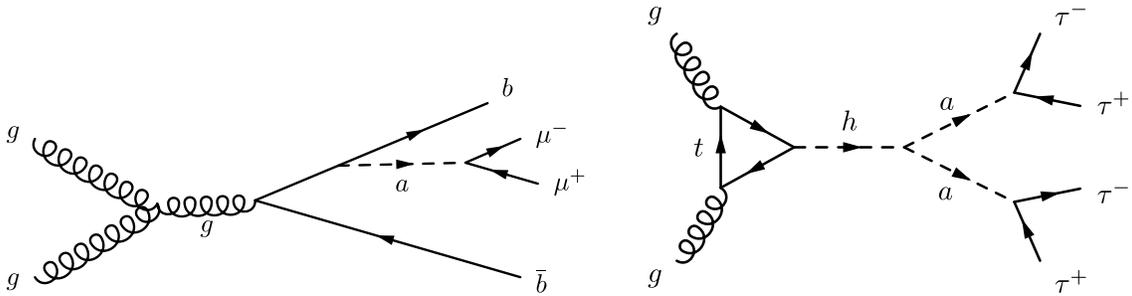Figure 4: Diagrams for pair production of exotic particles: squarks (left) and leptoquarks (right).

Figure 5: Diagrams for BSMsstrahlung production of an exotic pseudoscalar particle (left) and exotic peusdoscalars from the decay of a Higgs boson (right).

4 Look-alikes at the LHC

Suppose you are fortunate enough to see a new resonance in one or more channels at ATLAS or CMS. Now you would like to determine what kind of a beast have you found, and what the existence of this exotic tells us about physics beyond the Standard Model.

This task, I would claim, is best considered as a problem of discriminating between *look-alikes*. At the purely phenomenological level the look-alikes can be particles that differ in their basic quantum numbers but produce the same final state. A good example of this type of look-alike problem is Higgs discovery [29, 30]: just because you found a resonance that decays into, e.g., a pair of Z bosons, doesn't mean that it is the neutral spin 0 CP-even member of a $(2_L, 2_R)$ doublet under $SU(2)_L \times SU(2)_R$. Your new resonance could instead have spin 2, or be a pseudoscalar, or belong to a $(4_L, 4_R)$ of $SU(2)_L \times SU(2)_R$. Before booking a trip to Stockholm you might want to see if your data can discriminate between these hypotheses and the Higgs boson of the Standard Model.

An even greater challenge occurs if you make a "missing energy" discovery, i.e. you establish an excess of unbalanced high energy events with large missing transverse energy. Any such discovery could be related to dark matter, but a long chain of reasoning and additional measurements – not just at colliders – will be required to make this connection. To begin with, one would like to determine how many invisible particles are produced per event (1? 2? 26?) and whether these unseen particles are heavy or light or are just neutrinos. If the invisible particles are produced from decays of other exotics or in association with other exotics, we would like to determine the quantum numbers of these particles as well. With some of this basic information in hand, we then want to map the missing energy signature back to one of the BSM frameworks. This is challenging because, as we saw, several frameworks produce similar signatures of pair-produced new heavy particles cascading to pairs of weakly-interacting stable (or quasi-stable) exotics [1],[31]-[33].

A major advantage of thinking in terms of look-alikes is that, at any given time, you reduce your experimental problem to hypothesis testing: Does the data prefer A or B? More precisely, you can answer a question like "Given that Nature chose hypothesis A, how likely is it that my experimental data would nevertheless favor hypothesis B?" This strategy is very powerful because it allows using all of the information from your data, and because the number of successful hypothesis tests needed to discriminate among N possibilities in BSM theory space scales like $\log N$. The difficulty of this approach is that you need to know a lot about BSM physics, enough to both navigate the BSM theory space effectively and to compute likelihoods for LHC datasets given a particular BSM origin.

5   What is missing?

All existing BSM models that strive for some kind of comprehensive extension of the SM are unsatisfactory in some way. Most resort to some otherwise unmotivated tunings or adjustments of mass scales to avoid conflicts with data, and others are in significant tension with data. As BSM model-builders try to explain more or to be more explicit about the underlying structure and details of their models, the models themselves tend to accumulate more jury-rigged features, ending up somewhere between Baroque and Rococo in appearance. This does not imply that the basic BSM ideas are incorrect, but it may imply that we are all missing some essential ingredients in our model-building.

What is missing? Perhaps our implementation of supersymmetry or the basic idea of "partners" is too naive. Perhaps we need to "deconstruct" [34] our thinking about degrees of freedom in general, not just for extra dimensions. Perhaps everything comes ultimately from strong dynamics and we just don't have the tools to figure out the rules. Perhaps gauge theories and/or quantum field theory is just an emergent approximation for a deeper underlying framework. Perhaps the Standard Model (tweaked to accommodate neutrino masses) is all there is, the parameters of the SM are determined by initial conditions of the

Big Bang, dark matter is all black holes, and the accelerating expansion of the observable universe has a purely macroscopic origin.

What is missing? Enough data from enough experiments to point us in a clear direction, and start to resolve at least some of our long-standing puzzles. We hope that the advent of the LHC, along with exciting results from astrophysics, direct dark matter detection, neutrinos, and searches for rare processes, will do the job.

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