Model-Groups as Scientific Research Programmes

Cristin Chall

November 22, 2019

Abstract

Lakatos's methodology of scientific research programmes centres around series of theories, with little regard to the role of models in theory construction. Modifying it to incorporate model-groups, clusters of developmental models that are intended to become new theories, provides a description of the model dynamics within the search for physics beyond the standard model. At the moment, there is no evidence for BSM physics, despite a concerted search effort especially focused around the standard model account of electroweak symmetry breaking (also known as the Higgs mechanism). Using the framework provided by Lakatosian research programmes, we can capture the way the periphery of a model-group changes as the available parameter space shrinks, while its central tenets remain untouched by unfavourable experimental findings. By way of motivation, I provide two case studies of model-groups that offer alternative mechanisms for electroweak symmetry breaking: supersymmetry and composite-Higgs models. Both of these model-groups are under pressure from the discovery of the Higgs boson, yet they have both been active research projects in the years after the Higgs discovery. However, a proper assessment of the progress of an ongoing research programme is impossible through a purely Lakatosian lens, so I propose replacing it with Laudan's problem-solving account, which provides ongoing assessment, while offering normative guidance concerning the pursuit-worthiness of research programmes. My incorporation of model-groups into Lakatosian research programmes captures the developments of two attempts to expand our physical description of the world, and Laudan's problem-solving rationality allows us to assess their pursuit-worthiness.

Keywords

- Model Dynamics
- Particle Physics
- Lakatosian Research Programmes
- Higgs Boson
- Theory Choice
- Scientific Progress

1 Introduction

The standard model (SM) of particle physics is one of our best tested and confirmed theories. However, the SM has well-documented problems (including the hierarchy problem and a lack of explanation for dark matter, gravity, neutrino masses, or matter-antimatter asymmetry) and physicists hope that probing the electroweak symmetry breaking (EWSB) sector at the Large

Hadron Collider (LHC) may provide clues for resolving some of them. Alternative mechanisms of EWSB going beyond the SM (BSM) were introduced long before a particle closely matching the properties of the SM Higgs boson was discovered in July 2012. The SM account of EWSB, the Brout-Englert-Higgs mechanism that describes the spontaneous breaking of the SU(2) gauge symmetry resulting in the masses of weak force bosons and other fundamental particles,[1] was accompanied by worries over naturalness and fine-tuning,[2] and introduced a fundamental scalar field unlike anything else described by particle physics.[3] These worries over the perceived faults of the SM account have driven BSM model-building. Even as the new particle's properties were better determined and a consensus reached that it is indeed a Higgs boson (with a shrinking parameter space for anything besides the SM account), alternative understandings of EWSB are still common, with work from several varieties of BSM models still regularly appearing in publication and the online preprint archive, arXiv.org (see Chall et al., 2019). Though many EWSB models haven't received direct empirical support from data collected at the LHC, they haven't been entirely excluded either. Work on these models continues, despite a lack of evidence. But the question remains: with a well-established competitor and growing reasons to doubt, how are physicists able to continue pursuing these alternative models? I will argue that a suitably modified reading of Lakatosian research programmes provides a description of this persistence, as well as points towards norms for pursuit-worthiness. In order to demonstrate my modifications in action, I will provide case studies composed of the strategies employed by supersymmetry (SUSY) and composite Higgs (CH) models during the Higgs discovery.

First, I will give a brief overview of Lakatos's methodology of scientific research programmes (MSRP). My argument requires two modifications of the MSRP, in order to better suit the current philosophical treatment of scientific models and their use in contemporary particle physics. The first modification, the introduction of the concept of a 'model-group', will allow the BSM alternatives to be given a full Lakatosian analysis. Next, I will provide two in-depth case studies, focusing on the years around the Higgs discovery, where I will show model-groups acting as research programmes, preserving their hard cores. By analysing the conceptual moves made within these model-groups during an episode of unfavourable empirical discovery, I hope to motivate both the need for, and the power of, the framework of research programmes in capturing the model dynamics of particle physics. However, as we will see, Lakatos's views on the rational analysis scientific practice is problematic. In the final part of this article, I will provide my second modification, a solution to the lack of judgement on the progressiveness of ongoing research programmes borrowing from Larry Laudan's (1977) notion of progress through problem-solving. With these two modifications, I believe I can apply the notion of scientific research programmes in analysing the pursuit-worthiness of theorizing that extends beyond our ability to experimentally test.

2 Research Programmes

2.1 The Methodology of Scientific Research Programmes

Lakatos's (1978a) MSRP is meant to rationally reconstruct the history of science and show the growth of knowledge. A research programme consists of a series of overlapping theories, with

---

[1] As originally described by Englert and Brout (1964); Higgs (1964a,b); Guralnik et al. (1964).

[2] The naturalness problem is roughly understood as the large, surprising, and unexplained difference in scale between important parameters in the SM. Fine-tuning in physics is a measure of the precision of adjustments made to various parameters of a model to accommodate experimental observations.

[3] See (Friederich et al., 2014) for an overview of the worries with the SM Higgs mechanism and (Wells, 2018) for an argument that the Higgs boson is an "immoderate speculation."

new theories rising to replace theories discarded due to problematic experimental results and theoretical critiques. The changes in response to challenges occur within the "protective belt" of the research programme, those theories, models, auxiliary hypotheses, and other elements that can be considered disposable. The specific bounds of possible changes are described in the programme's "positive heuristic," which details how the protective belt adjusts to problems. The positive heuristic also describes potential avenues for future development of the programme.

Conversely, the central tenets of the programme form its "hard core" and are insulated from critique. Once it is established, the hard core is protected by the programme's "negative heuristic," which mandates that the hard core cannot be challenged by experimental results: "The negative heuristic of the programme forbids us to direct the *modus tollens* at this 'hard core'. Instead, we must use our ingenuity to articulate or even invent 'auxiliary hypotheses', which form a *protective belt* around this core, and we must redirect the *modus tollens* to *these*" (48). Lakatos did not clearly describe what sorts of elements make up a programme's hard core. His examples ranged from physical laws (the hard core of Newtonian physics, for example, consists of "the three laws of mechanics and the law of gravitation" (4)), to postulates (Lakatos describes the hard core of Bohr's research programme of light emission as consisting of five postulates, some of which encompass laws, but none of which are identical to laws (55–56)), to generalised conjectures (The hard core of the Proutian programme is stated as "the atomic weights of pure chemical elements are whole numbers" (Lakatos, 1978b, 118)). One thing that is apparent, however, is that the hard core makes ontological commitments required of the theories composing it.

A research programme is not determined to be 'true' or 'confirmed' or 'acceptable': rather, it is judged 'progressive' or 'degenerative'. A programme is progressive if "its theoretical growth anticipates its empirical growth, that is as long as it keeps predicting novel facts with some success" (Lakatos, 1978b, 112). A programme is degenerative if empirical progress outpaces its theoretical growth, leading to *post hoc* accommodations rather than predictions. A single negative experimental result is not sufficient to determine that a research programme is degenerative, since Lakatos explicitly rejects the notion of a crucial experiment, except when seen with hindsight. For Lakatos, an experiment can only be seen as crucial once it is clear that there will be no recovery from the disconfirming empirical evidence. This slow process allows a research programme to go through periods where it makes no progress and/or accumulates anomalies. But it is not irrational to continue working on such a programme, since there is always the possibility that it will surpass its rivals in progressiveness in the future. Thus, the proper assessment of research programmes involves rivals operating simultaneously, requiring some form of scorekeeping to track their progressiveness, while demanding humility and patience, since seemingly incontrovertible experimental findings can be overturned. The requirement Lakatos imposes for analysing progressiveness with hindsight will be explored in more detail in Section 4.

As noted above, Lakatos's MSRP emphasised (series of) theories as the unit of analysis, placing models firmly in the protective belt. For Lakatos, a model is a simulation of reality with "a set of initial conditions (possibly together with some of the observational theories) which one knows is *bound* to be replaced during the further development of the programme, and one even knows, more or less, how" (Lakatos, 1978a, 51). However, this view of models is outdated, and doesn't match the practice of model-building in particle physics.[4] I will now address these modelling deficiencies.

---

[4] There are other aspects of the MSRP that might cause one to be 'Lakatos intolerant.' One of these will be explored in more detail later, with mention of additional worries over Lakatos's project.

2.2 Theories vs. Models

Using recent discussions in philosophy, supplemented by the common practices of particle physicists, I will establish a rough distinction between theories and at least some models. This distinction opens the door for my proposed modification of the framework of Lakatosian research programmes, which will admits a better understanding of the model dynamics of EWSB.

A great deal of recent discussion about models has concerned the autonomy they have from both theory and experiment.Morgan and Morrison (1999) argue that both the construction and function of models leads to a degree of independence from theory and data. In addition to this autonomy, Hartmann (1995) provides a taxonomy of models within what he calls the "Diachronic View," which covers dynamic elements of science such as theory construction. These two viewpoints illustrate the dual purposes of this section: establishing some distinction between theory and model; and motivating the function of models within theory construction.[5]

There are cases where models cannot function if they are too dependent on theory, such as when the theory itself is too complex and only a simplified model allows explanations or predictions to be extracted from it. Hartmann calls these "models as substitute for a theory". Some models are constructed solely from a theoretical core and were never intended to match experimental results. They can still teach us valuable things about the phenomenology of the target system or the theoretical ecosystem, however, so Hartmann also emphasises the role of these "toy models" in theory construction. Finally, there are models used in cases where there are no theories at all, like what we see in BSM physics, where some models are frequently treated as preliminary theories (SUSY, for example, is sometimes described as a theory) or extensions of larger theories (BSM models in general extend beyond the more empirically-grounded elements of more general quantum field theories), though this situation occurs wherever there is no overarching theory available. Hartmann refers to these as "developmental models", and argues that they play a critical role in theory construction. This last class of models will be crucial in my first modification of the MSRP, since it is so prominent in BSM searches.

Since I am modifying the MSRP to accept collections of models, in addition to series of theories, something needs to be said about what distinguishes models from theories in the first place. However, distinguishing models from theories is troublesome, since they commonly share many of the same features and functions. Therefore (and because there is such a wide variety of things referred to as models), my distinction will be limited in scope to particle physics and possess a somewhat flexible boundary. I don't find this limitation problematic, since my goal is merely to expand the understanding of research programmes to accommodate additional elements that are already related to theories.

Consider the SM itself, which (as its name implies) started out as a model. The current consensus is that it has become a theory in its own right.[6] The distinction between model and theory that Morgan and Morrison introduce is "rough and ready" and cannot possibly apply to all models, but it approximates what occurred with the SM and aligns nicely with Hartmann's description of developmental models. They distinguish models as "account[s] of a process that is less certain or incomplete in important respects" while a theory "account[s] for more phenomena and has survived extensive testing" (Morgan and Morrison, 1999, 18). On this reading, the SM is a theory, since it accounts for a wide swath of physical phenomena and has survived decades of empirical testing. The various BSM alternatives we will discuss later count as models, since they lack empirical support. But, because they aim to go beyond the bounds of our present theories by describing phenomena that no proper theory does, they are specifically developmental models.

---

[5] For more on incorporating BSM models into the Models as Mediators approach, including Hartmann's (1999) discussion of narratives, see (Stöltzner, 2014).

[6] Iliopoulos (2014) has suggested, for instance, that the SM is now complete and should be referred to as "The Standard Theory."

It is easy to see why this distinction cannot apply to all models. Some models are designed to approximate a specific phenomenon described by a theory, some are meant to simplify a complex theory so that empirical consequences can be derived, some are pedagogical, and so on. There are many roles models play that prevent them from being considered developmental models.However, since developmental models have the potential to become full-fledged theories, the "rough and ready" distinction made by Morgan and Morrison applies to them. For our purposes, this is distinction enough to carve out new space in the Lakatosian MSRP: things that are not (yet) theories, but are still treated like scientific research programmes.

2.3 Model-Groups

Various BSM strategies have been developed, leading to numerous models. Generally, these models introduce additional content to the SM, covering a wider range of phenomena. Under our distinction between developmental models and theory, these BSM strategies are classified as models, since they lack empirical support necessary to reach theory-hood. We can classify many individual models as members of larger groups based on their commonalities, since they are constructed using a small number of common concepts, ontologies, or methodologies.

This natural grouping of models combines the way particle physicists typically organise these models with the framework of Lakatosian research programmes. By seeing the central tenets of these models as the hard cores of research programmes, we can introduce a new concept: the *model-group.*A model-group is composed of developmental models (along with conceptual techniques and mathematical tools) intended to explore and test a pre-theoretic hard core. I claim that model-groups function as research programmes. Only minor adjustments are required to the Lakatosian framework to accommodate them.

Let us flesh out the idea of model-groups as research programmes. The hard core of the model-group guides the construction of its individual members,[7] each demonstrating various strategies for exploring the group's parameter space, making predictions, and describing phenomena. Individual models are created with the conceptual strategies and methodological tools that have been incorporated into the model-building strategies of the group's positive heuristic. These strategies determine how the model-group will adapt to empirical and theoretical challenges. The individual models then form the protective belt of the model-group. It is the individual models that are falsified if they cannot match the data, while the hard core survives to generate new models. Individual models have the potential to increase the programme's empirical content because they make novel predictions that are subject to testing.

The individual models in the protective belt retain the ontological assertions of the hard core (for example, the compositeness of the Higgs particle, or the symmetry between bosons and fermions of SUSY) while differing from one another in other ways. Typically, a model will have parameters in its Lagrangian adjusted differently than others; setting different mass values for a predicted particle, for instance. Different models from the same group may posit different energy ranges for symmetry breaking, or one may include new particles to remain mathematically consistent, while another doesn't need them. The variability between models within a single group have two primary constraints: the hard core and the remaining parameter space available. The hard core constrains individual models exactly as you would expect: certain features must be present in each member of the model-group because they are constructed using the elements of the hard core. The parameter space itself is constrained by both theoretical considerations and experimental findings. Models must operate within the bounds of the parameter space as it is defined by the best experimental evidence available. Thus, if a model describes phenomena

---

[7] Borrelli (2012) offers a precursor to this idea, using the concept of "theoretical core" introduced by Morrison (2007).

within a portion of the parameter space that has been excluded by experiment, then the model must be discarded or reworked, since those parameters are no longer considered viable (though caveats exist: for example, there must be a consensus that the experimental data is trustworthy).

The hard cores themselves can be non-specific, describing general ontological features but leaving the specifics for the individual models to fill in. It is unlikely that the entire parameter space for any of these BSM model-groups will be completely eliminated (they all extend to energy ranges beyond what is currently testable using existing accelerators), there is always the possibility that some new test will vindicate the programme. However, this insulation from experimental exclusion is a double-edged sword. On the one hand, it provides the research programme with stability, preventing the core ideas from being discarded with every unfavourable result. Physicists can continue their attempts to solve the problems with the SM without having to start from scratch with every failed prediction. On the other hand, it can lead to dead ends and charges of artificiality: in other words, to degeneration. Some corners of the parameter space are seen as much more promising than others, or more in keeping with various pragmatic considerations (they are directly testable or are more natural, for instance). When these segments are steadily eliminated by negative experimental results, the creation of models to probe less promising avenues will seem increasingly *ad hoc*. Once the entire energy range open to the LHC has been probed, there will be nowhere else to look until new accelerators are built, a complicated, time-consuming, and increasingly expensive prospect. It may still be rational to pursue research programmes whose parameter spaces have become increasingly marginalised, but we must honestly assess their virtues and label them degenerative when appropriate. More will be said on the possibility for normative guidance in cases such as these in Section 4.

One thing to note is that the diversity of model-groups is encouraged in the MSRP. A variety of rival programmes follows directly from the difficulty in concretely eliminating a programme, leading to long intervals where many programmes compete over the same range of phenomena. Indeed, Lakatos says that "[t]he history of science has been *and should be* a history of competing research programmes" and that "the sooner competition starts, the better for progress" (Lakatos, 1978a, 69, my emphasis).[8] Therefore, the number of competing BSM model-groups meshes quite well with them behaving as research programmes.

There is a certain amount of permeability between model-groups, which is a necessary consequence of the fact that physicists don't work exclusively within the boundaries of a single model-group: cross-pollination is bound to occur as physicists move between BSM projects, collaborate with colleagues, or peruse the preprint arXiv for novel ways to further their work. For instance, you can find composite Higgs models that also contain extra dimensions (and thus blend two quite different strategies to account for EWSB). Supersymmetric variations of every other BSM model-group are common. Cross-pollination can occur even when aspects of the two research programmes are inconsistent, as long as those inconsistencies have at least the appearance that they can be resolved.[9] Lakatos explains this behaviour in the context of two rival programmes: since eliminating a rival is a long process, it becomes rational to pursue both, if possible, allowing scientists to further develop a less-favoured rival programme "in order to show up its weakness" (Lakatos, 1978b, 112). We can also explain this willingness to work in multiple programmes by appealing to physicists' agnosticism towards any model or theory without ade-

---

[8] Lakatos is not explicit about *why* competition is better for progress. From the context, it likely stems from the way programmes are assessed: since programmes are only assessed in hindsight, competition increases the likelihood that some programme will be increasing its "heuristic power" during any particular timespan. Lakatos also remarks that without a rival, a scientist may feel a "hypersensitivity to anomalies and a feeling of a Kuhnian 'crisis'" (68). Of course, one could also see a sort of evolutionary account of competition, like that described by, for example, van Fraassen (1980).

[9] Lakatos describes how whole research programmes can be "*grafted on to older programmes with which they are blatantly inconsistent*" (Lakatos, 1978a, 56), a process he referred to as 'competitive symbiosis.'

quate supporting data. Naturally, physicists who work within multiple model-groups will bring helpful conceptual tools and phenomenological features to each. What is important to note with this cross-pollination, is that elements taken from rival programmes are incorporated into the protective belt, not the hard core, limiting the degree of theoretical overlap.

As I have shown, only a small adjustment is necessary to incorporate model-groups into the MSRP. We need merely to add to Lakatos's framework our expanded account of scientific models. Once the wider features and functions of models are accessible to the MSRP, model-groups can be accommodated as research programmes by focusing on the role they play in theory development. They function analogously to research programmes composed of series of theories. In the next section, we will explore two examples of model-groups as they appear in particle physics.

3 Particle Physics Model-Groups: Two Case Studies

Articles discussing the merits of composite Higgs and supersymmetric models are still very common in the physics literature. However, both model-groups are experiencing pressures, largely due to the discovery of a particle that matches SM predictions for a Higgs boson and the complete absence of new, non-SM particles. This situation raises the question of why these models persist in the face of unfavourable empirical data. The case studies I present will show that our Lakatosian framework offers the best description of this phenomenon.

According to Lakatos, there are three ways to resolve problems that arise for a research programme:

> [B]y solving it within the original programme (the anomaly turns into an example); by neutralizing it, i.e. solving it within an independent, different programme (the anomaly disappears); or, finally, by solving it within a rival programme (the anomaly turns into a counterexample) (Lakatos, 1978a, 72).

An adjustment made to a programme to resolve a problem is known as a problem-shift. In what follows, I will provide a quick overview of the landscape of models for electro-weak symmetry breaking. The CH and SUSY model-groups will receive a more thorough treatment, including a review of the problems that arose with the Higgs discovery and the problem-shifts these research programmes underwent to protect their hard cores.

3.1 The EWSB Landscape

Using recent work examining the landscape of models in the EWSB sector during the Higgs boson discovery (see, e.g., Borrelli and Stöltzner, 2013; Stöltzner, 2014; Chall et al., 2019), we can distinguish the primary model-groups within the EWSB sector: supersymmetry, non-SUSY Extended Higgs models, composite Higgs models, and Extra-Dimensional models.[10]These four model-groups do not exhaust the BSM EWSB alternatives, but they comprise the bulk of current SM alternatives. Only a cursory look at the non-SUSY extended Higgs and extra-dimensional model-groups will be provided here.

---

[10] A technique that has become popular within the physics literature is operator product expansions (OPEs) in the framework of SM effective field theories (SMEFTs). This technique is often referred to as a model-independent search strategy, which raises the question of whether SMEFT/OPEs are a model-group (or otherwise count as a research programme), or if they belong in some other category. There are consistent methods within this approach, and models of some kind are still produced (see, e.g., Dawson, 2017). I don't include SMEFT/OPEs here, since the technique is more of a broad mathematical searching strategy, without an easily discernible hard core, suggesting that the technique is a search strategy to generate new research programmes, rather than a single programme in its own right. Determining whether it can properly be classified as a Lakatosian research programme is beyond the scope of the current discussion.

The standard model itself remains the dominant research programme in particle physics, so a brief understanding of its features is presented here. The hard core of the SM, at least as far as the EWSB sector is concerned, is that there is a universal scalar field (the Higgs field) that causes spontaneous breaking of the symmetry of the electroweak force by condensing below a certain energy scale. Before symmetry breaking, all elementary particles are massless, but below a certain temperature three of the field's degrees of freedom are "eaten" by the particle carriers of the weak force, thus generating the masses of the W and Z bosons. The fourth degree of freedom becomes the Higgs boson, and other elementary fermions gain mass through a different type of interaction with the Higgs field. This process is the simplest method described for electroweak symmetry breaking. The SM could not provide a firm prediction of the mass of the Higgs boson, the particle associated with this field. However, the particle's other properties depend on its mass, so the protective belt consisted of the values of the dependent properties, exactly calculated for each possible mass value of the Higgs. Now that physicists have found a particle matching Higgs predictions at 125 GeV, the protective belt consists of a detailed accounting of its properties and predictions of features that require higher precisions testing. The limits of LHC experimental sensitivity, then, determine the prospects for discovering new physics.

The BSM model-groups incorporate all or most of the experimentally accessible SM into their hard cores. The EWSB sector is where the biggest divergence between the SM and BSM models can be found at lower energy scales, with all BSM model-groups discussed here introducing significant changes to the SM Brout-Englert-Higgs mechanism. Each model-group acts as an extension to the SM, largely adding its own features to the SM Lagrangian or otherwise accounting for non-SM effects. This connection to the SM follows from the need for each BSM model to recover (or otherwise accommodate) the experimental results at lower energies, which accord with the SM. Lakatos states that a fledgling research programme can incorporate pieces of a well-established rival, even if those pieces are later found to be inconsistent with the new research programme.This process is necessary, since the established programme already has access to theoretical and empirical resources, resources the new programme will need in order to attract researchers. Since all the model-groups I consider here share this feature, I will omit mention of SM elements of their hard cores and protective belts, focusing solely on their BSM elements.

The non-SUSY extended Higgs sector adds additional Higgs multiplets (usually in the form of two-Higgs-doublet or triplet models) to the SM's sole doublet (which describes its degrees of freedom). These models handle EWSB similarly to SUSY models, adding more Higgs particles, but are significantly different because they don't double the number of SM particles. The hard core of the extended Higgs sector consists of the extension of the SM to increase the number of Higgs doublets, in order to preserve certain theoretical constraints, like naturalness, and provide an explanation for the asymmetry between matter and antimatter.Its protective belt consists of various models that adjust the parameters of the different multiplets, indicating where to find new physical scalars and deviations in the properties of the boson discovered in 2012.

Extra-dimensional models explain EWSB through boundary conditions that lead to broken symmetries at higher dimensions (see, e.g., Csaki et al., 2004). A consequence of this method of EWSB is that there is generally no Higgs predicted, fundamental or composite. The protective belt thus includes various models accounting for the boson discovered in 2012, with claims that it is not actually a boson associated with EWSB. These individual models also describe how the extra dimensions can be probed and the specifics of how the boundary conditions break electroweak symmetry. The upshot of this model-group is that there is no need to introduce a fundamental scalar particle and there is a solution to the naturalness problem, a hallmark of most BSM models.

This quick overview of the EWSB sector shows the wide variety of research programmes at play in particle physics. What follows is a deeper examination of the CH and SUSY model-groups. The CH model-group is situated roughly in the middle of the complexity of particle physics model-groups. It lacks the widespread appeal that SUSY enjoys, but has a longer history than the groups mentioned above. SUSY is the most prominent programme in BSM physics, and some physicists refer to it as a theory in its own right. Both of these model-groups have long histories that include numerous evolutions, but I will restrict my examination (beyond a brief historical sketch of each) to the timespan of the Higgs boson discovery.

3.2 The Composite Higgs

The composite Higgs model-group is a broad class of models that introduces the existence of a strong interaction at a high energy, which leads to strong EWSB. The group originated from the search for the mass generation of W and Z bosons, much as the SM did, using a framework borrowed from superconductivity. Composite particles arise from a dynamically broken symmetry, as opposed to the spontaneous symmetry breaking appearing in the SM. The first examples of dynamical EWSB were intended to demonstrate alternatives to spontaneous symmetry breaking (Jakciw and Johnson, 1973; Cornwall and Norton, 1973).[11] A composite particle of EWSB is first mentioned by Goldman and Vinciarelli (1974), though it was soon expanded by Susskind and Dimopoulos,[12] who borrowed from the "color" theory of the strong nuclear force, leading to the first Technicolor (TC) models. TC models introduced a local gauge symmetry representing a new interaction at the TeV scale. The gauge bosons acquire mass by coupling to Technihadrons, including a scalar that could serve as a Higgs impostor.[13]

Susskind's popularisation of the idea of dynamic symmetry breaking leading to a composite scalar boson of EWSB sparked many model-building efforts. Mass generation by a composite system attracted lots of attention, since it avoided the 'immoderate speculation' of an elementary scalar boson arising from EWSB. This explanation also provided a potential solution to the naturalness problem, since the addition of a compositeness scale, f, creates some wiggle room to avoid fine-tuning certain parameters. Some variations offered dark matter candidates by predicting new, undiscovered particles.

By the 1980s came the introduction of the notion of dynamical breaking of a global symmetry including a new strong interaction. Models using this notion could accommodate a light (pseudo) Nambu-Goldstone boson (pNGB), generating the Higgs potential through radiative corrections. Since then, multiple variations have emerged, including varying iterations upon the TC theme (Extended TC, Walking TC, Topcolor, etc.) and the 'Little Higgs' (LH) models (which allowed for large, non-derivative interactions, particularly the Higgs quartic interaction (see, e.g., Arkani-Hamed et al., 2002)).This history provide a host of examples of the CH research programme protective belt undergoing problem-shifts in response to empirical and theoretical pressures, but I will restrict my case study to the Higgs discovery. With its long history, its explanation of EWSB without elementary scalars, and its ability to solve perceived problems of the SM, it is easy to see why the CH model-group has interested many physicists.

Turning from the brief historical overview to our Lakatosian analysis, the hard core of the CH model-group can be summarised as 'EWSB is attributable to a strong dynamical process caused by new gauge interactions at high energy scales, so that the particle associated with EWSB (if any) is a composite, rather than a fundamental, scalar.' The positive heuristic provides the

---

[11] Indeed: "It will be evident that this model is not intended as a realistic theory of weak or electromagnetic interactions. Rather,it is only an example of what we feel is probably a large class of theories in which the spontaneous symmetry breaking derives from general features of an apparently symmetric interaction" (Cornwall and Norton, 1973, 3338).

[12] See (Susskind, 1979; Dimopoulos and Susskind, 1979).

[13] It should be noted that some TC models are able to account for EWSB dynamically and without a resulting scalar, and are thus considered 'Higgsless.'

various model-building strategies that create the protective belt, including new strategies and techniques to sustain model-building against anticipated empirical and conceptual challenges. The protective belt is made up of various models describing the properties of the new gauge interactions and any physics associated with them, including the parameters of any composite scalars and other particles associated with new strong interaction scales.

3.2.1 CH Problem-Shifts

The discovery of the Higgs boson created numerous problems for the CH model-group. First, as the search progressed, the upper limit for the possible mass of the new particle became lower than many CH models comfortably predicted. Second, the discovery of any Higgs candidate put immense pressure on Higgsless TC models. Third, its branching ratios, couplings, and flavour measurements very closely conformed (within LHC precision) to SM predictions. Since the SM Higgs is a fundamental scalar, these results were taken as evidence that it was not a composite particle. Finally, no other new particles have been yet been discovered at the LHC. Each of these problems needs to be addressed to prevent the Higgs discovery from becoming a significant counterexample to the CH model-group. Too many counterexamples and no expansion of empirical content would suggest the CH model-group is degenerative, and the SM remains an empirically successful (albeit flawed) rival.

Let's first consider the mass. In TC, the vacuum expectation value, v, approximates the compositeness scale, f, implying the mass of the Technipion is large, and therefore requires significant adjustments to accommodate a Higgs as light as pre-LHC experiments were indicating. Despite the name, Little Higgs models also predicted a mass that was too high without suppressing the quartic coupling, so these models were already disfavoured by the time of the 2012 discovery announcement. After it was announced in December 2011 that there was an excess of 125 GeV in some detector channels, there was an increased urgency in the efforts to accommodate a light Higgs within CH models.[14]

With the discovery of a 125 GeV Higgs candidate announced that following July, a large portion of the CH model-group's parameter space was excluded, since the mass was too low for many CH models to accommodate. There were two obvious ways forward: first, the boson still needed to be checked for signs that it was a Higgs imposter; and second, model-building could focus on the remaining parameter space supporting a low-mass composite Higgs. Naturally, with the discovery of a SM Higgs candidate, proponents of all Higgsless models focused on the first strategy.[15] Attempts were made to explain the existence of the boson using Higgsless TC models by arguing that it arose from a newly posited gauge field (see, e.g., Eichten et al., 2012), though this strategy became unrealistic as more data arrived.

A close examination of the boson's couplings and branching ratios was already underway, with many physicists hoping for an anomaly to indicate the Higgs search wasn't over. One initially promising anomaly was the observed relative signal strength in the di-photon channel of both the ATLAS and CMS detectors, which didn't align with SM predictions for the Higgs (see, e.g., Peskin, 2012). Early talk considered the implications of this excess, whether it would reveal that the boson was not the SM Higgs, or that it wasn't a particle associated with EWSB at all. There were efforts to accommodate it within CH models: Chala (2013), for example, used the excess to create a CH model that introduced new pNGBs that could both explain the excess and provide a dark matter candidate. With further analysis the excess in the di-photon channel's

---

[14] See, e.g., (Redi and Tesi, 2012) for a discussion of possible light composite Higgs particles following the announcement.

[15] In a presentation immediately following the Higgs announcement, Pomarol (2012) displayed a picture of a tombstone labelled 'Technicolor Models' and declared Higgsless models were dead. However, he anticipated the Higgs-imposter strategy, with the next slide showing a zombie emerging from behind the tombstone.

signal strength disappeared. Aside from this anomaly, the data demonstrated a remarkable match with SM predictions: for example, Ellis and You (2012) argued that the new particle did "indeed walk and quack very much like a Higgs boson," and as a consequence some of the CH model-group's parameter space was excluded. Accordance with the SM has only strengthened with time, though the limits of LHC precision ultimately underdetermine the particle's exact nature.

One interesting solution to multiple problems for the CH model-group appears in the form of partial compositeness. Unlike TC or LH, partial compositeness is not a type of model but rather a conceptual and mathematical tool for explaining the origins of fermion masses and flavour structure, while also accounting for the observed mass hierarchy in particle physics. Originally introduced in (Kaplan, 1991) as a response to problems with the top in TC, partial compositeness establishes a new heavy particle for each SM particle, so that each becomes a linear combination of elementary and composite states. The hierarchy of masses is explained by each generation having a different degree of compositeness, with the lightest particles being mostly elementary and the heavier particles being more composite (fermions acquire mass because their composite sector constituents participate in EWSB, so particles that are more composite in nature are heavier). Indeed, this hierarchy also helps explain why no SM deviations have been observed, since the first two (and most precisely measured) generations have lower degrees of compositeness, suppressing BSM effects (see, e.g., Redi and Weiler, 2011). The flavour structure in models with partial compositeness does not preclude a fundamental scalar, so adding a new elementary scalar does not become a fatal empirical problem for the CH model-group, though there is still the theoretical distaste.

As the possible mass range of the EWSB particle lowered, CH models using partial compositeness to explain a light Higgs became more common (see, e.g., Azatov and Galloway, 2012).Since partial compositeness explained the lightness of the Higgs and the lack of SM deviations, it is no surprise that its prevalence in the literature expanded rapidly after 2012. Searching the arXiv for CH entries citing (Kaplan, 1991) reveals that twelve such articles were posted prior to 2012, while more than 120 have appeared since, a ten-fold increase.[16] These entries even follow the Lakatosian tradition of making risky predictions to expand empirical content, as shown in (Harnik et al., 2017), which provides models with predictions testable at the LHC. If the CH model-group is to have any hope of being progressive, such phenomenological predictions need to accompany the theoretical moves made to preserve the programme in the face of problematic experimental evidence.

3.3 Supersymmetry

Supersymmetry represents a major unconfirmed symmetry of the Poincaré Group, that of bosons and fermions. SUSY includes a supersymmetry generator, Q, which mathematically converts half-integer spin particles (fermions) into integer spin particles (bosons), and vice versa. This symmetry requires new particles, at least one corresponding to each SM particle.[17] Since none of these 'superpartners' retain all the properties of their SM counterparts (for instance, their masses must be different, or we would have discovered them alongside their SM twins), we know that SUSY describes a broken symmetry. SUSY has many benefits over the SM: it solves the

---

[16] The search was conducted using the search terms: 'find c Nucl Phys B365 259 and d 1991->2011 and (k "Higgs model: composite" or k "Higgs particle: composite")' and 'find c Nucl Phys B365 259 and d 2012->2017 and (k "Higgs model: composite" or k "Higgs particle: composite")'.

[17] Many CH models also predict heavy partners for SM particles, associated with a new gauge field. The primary difference between the CH partners and SUSY's superpartners is that the latter have spins different from their SM counterparts, while the former have identical spins.

hierarchy problem by naturally removing the massive fine-tuning from the Planck scale,[18] unifies the gauge couplings at high energies, and some of its superpartners act as dark matter candidates (see, e.g., Martin, 1997).

Gol'fand and Likhtman (1971) and Volkov and Akulov (1973) independently discovered the earliest SUSY variations, with a fermionic extension of the Poincaré Group and an analysis of neutrinos in 4-dimensions respectively. These early developments included the introduction of what became known as the superalgebra, which established the commutation relations of SUSY generators. The renormalization features of a quantum field theory linking fermions and bosons together were provided in (Wess and Zumino, 1974a,b,c). SUSY was quickly seen as a serious BSM contender (see, e.g., Fayet and Ferrara, 1977), though it increased the number of unknown parameters in the SM, since it must be broken at relatively low energies (at least in natural versions). The most generic extension, first proposed in (Dimopoulos and Georgi, 1981), is the minimal supersymmetric standard model (MSSM), which includes the minimum number of new parameters necessary to recover SM phenomena. The MSSM has had its own offshoots, including an even more constrained variation (cMSSM) and a more open version, the next-to-minimal supersymmetric standard model, NMSSM. One of the most recent extensions, the phenomenological MSSM (pMSSM), using all the empirical data so far gathered, which act as constraints on a 19 parameter model.

SUSY EWSB occurs much the same as in the SM, though the Higgs couplings and branching ratios differ since the additional higher energy particles affect those values. Since an additional Higgs doublet is needed for consistency, SUSY also predicts additional scalar particles. As previously mentioned, the Higgs doublet provides four degrees of freedom that produce the Higgs boson and weak force boson masses. MSSM is a two-Higgs-doublet model, and so predicts five physical Higgs bosons instead of just one: a light and heavy CP-even (h and H), a CP-odd (A), and two charged scalar bosons ($H^{\pm}$). These extra particles are produced by the extra four degrees of freedom from the additional Higgs doublet. Other SUSY models may introduce additional doublets or singlets.

Therefore, the SUSY model-group's hard core relevant to EWSB can be summarised as follows: "Spontaneous symmetry breaking leads to the mass generation of both the SM particles and their SUSY counterparts. Additional scalar bosons, the fermionic Higgsinos, and differences from the SM Higgs couplings are consequences of the symmetry between fermions and bosons." The positive heuristic provides the techniques and tools for adjusting the parameters of the SUSY particles as experiments rule out certain values. The protective belt is composed of models with various settings for these parameters, such as the MSSM and its various modifications (cMSSM, NMSSM, pMSSM, etc.). These models make predictions of the energy ranges in which to find supersymmetric particles, with the lightest detectable at the LHC, at least in theory.

3.3.1 SUSY Problem-Shifts

Like the CH model-group, proponents of the SUSY model-group understood the problems posed by the Higgs boson discovery. First, the mass of the newly discovered particle, while still within the range predicted by the MSSM, was high enough to impose severe constraints.Second, the boson's branching ratios and couplings were found to fit quite well with SM expectations, but not so well with SM-like SUSY. Finally, no superpartners have been discovered, nor have any

---

[18] The hierarchy problem, previously mentioned in Section 1, arises because the Higgs boson's mass is so much lighter than the Planck mass, which is surprising because it was expected that the Higgs boson mass would receive quantum contributions from every particle it couples with, making its mass comparable to the scale of new physics (either the Planck or grand unification scale) without a fine-tuned correction of the order of $\sim 10^{30}$. Since SUSY provides a symmetry between fermions and bosons, and the quantum contributions to the scalar mass from superpartners have opposite signs, these contributions cancel and a light Higgs mass matching is expected.

additional Higgs bosons been found. Once again, a failure to solve these problems should pose a significant risk to continued trust in SUSY models. As we will see, even if suitable adjustments can be made, they would undermine one of the underlying motivations for favouring SUSY in the first place, namely that it solves the hierarchy problem.

More so than with the problems facing the CH model-group, SUSY's problems are interconnected. For example, the mass of the Higgs proved immediately problematic for the MSSM (see, e.g., Arbey et al., 2012).The MSSM Lagrangian indicates that the (lightest) Higgs mass would be

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \delta_t^2$$

where $\cos^2 2\beta$ is related to the ratio of the two Higgs doublets' vacuum expectation values ($\tan\beta$), M_Z is the mass of the Z boson, and δ_t^2 is the quantum loop correction from the stops, the top quark's superpartners.[19] In order to accommodate a mass of 125 GeV, it is necessary for δ_t^2 to be quite large (just a bit under 90 GeV–near the Z boson's mass), since all other values (besides $\tan\beta$) are experimentally fixed.

There are two ways to achieve sufficient corrections in MSSM.[20] The first is to make the stops much heavier, since their mass depends exponentially on the mass of the Higgs. To properly correct for the observed Higgs, the stop mass would need to be at least a few TeV, though such a high mass reintroduces the sort of hierarchy problem SUSY was meant to solve, since it (along with the lack of superpartners discovered at the LHC) implies that SUSY particles are much heavier than the electroweak scale. Such heavy stop masses would suggest that SUSY particles are out of the accessible range of the LHC. The second way is to have a high degree of stop mixing.[21] Maximal mixing allows the stop masses to be lighter, but requires the quantum loop correction to be very precisely fine-tuned. This much fine-tuning is seen as quite unnatural given the remaining parameter space, so this option also has a significant theoretical (and aesthetic) downside. In either case, the mass of the Higgs boson requires adjustments to the predicted masses of SUSY particles and the SUSY breaking scale, which in turn, mandates a shift in the expected Higgs couplings, shifts that have so far not manifested in the data. The overall effect was to create conceptual problems for the MSSM, since the rationales for adopting it (simplicity, testability, and ability to neatly solve the hierarchy problem) were undermined.

Many of the other theoretically well-explored SUSY models had to make similar adjustments. The NMSSM introduces a new singlet field, λ, that couples with the two Higgs doublets of the MSSM. Since the singlet contributes to the Higgs mass, NMSSM requires fewer adjustments to accommodate a 125 GeV mass. However, it was apparent even before the July 2012 announcement that there would still be fine-tuning involved, of about 5–10% if the mixing isn't maximal (Hall et al., 2012). This fine-tuning requirement severely restricts the NMSSM parameter space. Similarly, Bechtle et al. (2016) use a frequentist analysis to show that the cMSSM should be excluded with a 90% confidence level. They base their analysis on available data from particle accelerators and astrophysics, which they combine with various toy models to obtain a meaningful p value. The reason the remaining parameter space for cMSSM is under so much pressure is the tension between the model's prediction of low mass scales for some SUSY particles and the higher mass scale preferred because of the observed Higgs mass (along with the lack of observation of SUSY particles at the LHC). In both cases, these well-explored models are not completely excluded, as both Hall et al. (2012) and Bechtle et al. (2016) acknowledge. However, efforts seem

---

[19] I've borrowed this formulation from Hall et al. (2012), since their work is used by many commentators contemporaneous with the Higgs discovery. This prediction arises because the Higgs mass is predominantly controlled by the mass of A (the pseudoscalar Higgs), $\tan\beta$, the stop masses, and the stop mixing parameter, X_t.

[20] See (Hall et al., 2012) for more details on the following discussion.

[21] 'Mixing' refers to the linear combination of two or more mass eigenstates. Here, it refers to the way the stop couples to other particles, particularly the Higgs.

to be focusing on more complicated SUSY models because of analyses like these.

4 Progressing on Progressiveness

The brief case studies in the previous section reveal the attempts to solve problems raised by unfavourable experimental results at the LHC. No new particles or other BSM effects have been observed since the Higgs boson, despite the 13 TeV upgrade of the LHC and renewed focus on finding BSM physics. Though the SUSY and CH model-groups have been able to overcome many of these challenges conceptually, neither has truly expanded their empirical contents.[22]However, there is remaining parameter space for both model-groups that is inaccessible to the LHC and necessitates waiting for the next generation of accelerators, which will have greater energy or higher precision. In the meantime, the spectre that these model-groups are degenerating research programmes looms. However, until some historical distance has been achieved, on a strictly Lakatosian analysis, the Higgs discovery cannot yet be declared a counterexample to either the SUSY or CH model-groups.

But, as potent a tool for understanding the process of scientific change and knowledge generation as the MSRP is, even in situations where the empirical data is incomplete, hard to come by, or unfavourable to the lines of research that draw significant interest, because Lakatos provides no real mechanism for assessing the progressiveness of an ongoing research programme, its value in this context is minimal. We are left with a vague feeling that the various BSM model-groups may be degenerative, without being able to justify this feeling within the MSRP, since we lack the ability to perform Lakatosian rational reconstruction with sufficient hindsight. This problem arises from Lakatos's notion of scientific rationality, from his method of assessing the progressiveness of a programme. The inclusion of model-groups into the MSRP offers a potent first step in providing a rational assessment of physics research that requires significant non-empirical consideration for the foreseeable future. But a more comprehensive understanding, one that doesn't rely on waiting to analyse historical cases, requires an account of assessment that addresses the flaws in Lakatos's work. This section offers a brief overview of a more significant adjustment to the MSRP, one that will allow us to make contemporaneous judgements about the amount of progress a research programme is making, and allow the philosopher of science to employ her skills in offering normative guidance to scientists.

4.1 The Limits of Lakatosian Assessment

There remain significant problems for the MSRP and its application to BSM model-groups. Lakatos is insistent that assessments are to be made by philosophers and historians of science working after the fact, analysing the actions taken by scientists in a historical case. As Hacking's (1981) reading of the MSRP emphasises, "one can only tell what is progressive and what degenerative after the event" (132). So Lakatos's framework is of limited use for advising current scientific work because "his philosophy provides no forward-looking assessments of present competing scientific theories" (133).[23]

Laudan (1977), a contemporary of Lakatos and fellow methodologist of science, offers several criticisms. The most relevant for our purposes are that the MSRP has a "conception of progress

---

[22] The steps to adapt to the data are different, but this assessment is true for the non-SUSY extended and extra-dimensions model-groups as well.

[23] Hacking didn't take this to be a defect of Lakatos's methodology, since "[t]here are no significant general laws about what, in a current bit of research, bodes well for the future. . . only truisms" (134). However, such a truism may be better at capturing actual scientific practice, and for providing rational norms for scientific decision making.

that is exclusively empirical," cannot provide "recommendations about cognitive action" through research programme assessments, is unconcerned with the accumulation of anomalies in its assessments, and that research programmes are "rigid in their hard-core structure and admit of no fundamental changes" (77–78). These problems with the MSRP extend far beyond a failure to foresee developments in our understanding of models. However, I believe I can answer these charges by Hacking and Laudan, and in doing so provide a path for a more useful final analysis of the two case studies presented above, though it will require a much more extreme modification to the concept of the Lakatosian research programme than the inclusion of model-groups. Laudan himself will provide a way of assessing progressiveness that can be applied to ongoing research programmes, considers theoretical progress, is more cognizant of anomalies, and can provide recommendations for action.

4.2 Rationality Through Problem-Solving

Like Lakatos before him (whose MSRP acts as a compromise between Popper and Kuhn), Laudan borrows from his predecessors' arguments, but also significantly departs from them. Laudan states that the purpose of scientific theorising is to solve problems. From this perspective, he introduces a new unit of scientific progress, the research tradition. A research tradition is characterised by a shared ontology (the phenomena the tradition is concerned with) and a shared methodology (how the study of those phenomena should be conducted) for its collection of theories.

Research traditions are assessed through an analysis of how many existing problems are solved by its theories, and how pressing those problems were. Problems come in two forms: empirical and conceptual. Empirical problems represent something of the natural world that scientists take to need explaining, and are solved when a theory provides such an explanation that is found to be satisfactory within the bounds of the tradition. Conceptual problems are inconsistencies, either internal to the tradition, or between a theory from the tradition and an external theory that scientists are unwilling to reject. These problems are solved when the inconsistency is resolved. Using his problem-solving sense of rationality, Laudan is able to (in principle) say which traditions should be provisionally accepted: those that have solved the greatest number of problems in their domain of application. But Laudan can also provide an account of pursuit-worthiness based on problem-solving effectiveness. Traditions are pursued because they have offered more, and more significant, recent solutions to problems facing them than competitors, indicating fruitfulness. This notion of pursuit allows newer traditions to survive in the face of well-established ones. In an important sense, Laudan's problem-solving framework flips the usual understanding of the link between progress and rationality, as he claims that his strategy is the "blurring, and perhaps the obliteration, of the classical distinction between scientific *progress* and scientific *rationality*" (Laudan, 1977, 5). Since we have a much clearer model of scientific progress than of rationality, his proposal is that "*rationality consists in making the most progressive theory choices*," rather than defining progress by accepting ever more rational theories (6).

What I suggest is that we incorporate Laudan's problem-solving account of scientific rationality into a modified MSRP, replacing Lakatos's notion of research programme assessment. There are two reasons I suggest for retaining the framework of research programmes over casting aside the MSRP and adopting Laudan's methodology wholesale. First, unlike Lakatosian research programmes, a research tradition's core elements (its shared ontology and methodology) are malleable over time. This malleability raises the question of how a research tradition can retain its identity over time, if these elements central to its identity don't necessarily remain consistent. His solution is that there is a relative similarity over time, preserved by a shared, continuous history that grounds a research tradition's identity over time, along with a claim that "*at any given time* certain elements of a research tradition are more central to, more entrenched within, the research tradition than other elements" and it is these that are "unrejectable" 99. However, the members of the set of unrejectable elements will change over time, and Laudan barely gestures towards a solution to this shifting of the dilemma. Research programmes, on the other hand, retain their hard cores once they are established, providing them with a continuous identity over time that is easier to mark the boundaries of and trace through the available texts outlining the problem-solving activities of a programme. Since the aim of the hybrid framework I am proposing is to assess the problem-solving effectiveness of a particular scientific project, the stability provided by research programmes is virtue rather than a vice.

The second reason is that Laudan characterises research traditions such that they operate at a very high level of scope and generality. In the case of particle physics, for instance, it is unclear whether we would have more than one research tradition, the SM, with the BSM models acting as attempted solutions for its problems. For some purposes, that level of generality is fine for understanding the progress of this particular domain of physics. However, research programmes, based on Lakatos's examples, can operate much more easily on different levels of scope, including at a rather fine-grained level. Therefore, research programmes are the better conceptual framework for capturing the nuance of the model landscape of particle physics, especially since many physicists treat the BSM model-groups as somewhat distinct from the SM (with a hope that someday one of them will eventually supersede it). By retaining research programmes, we avoid washing out the dynamic competition between BSM model-groups and can better capture the details of scientific practice in this ongoing case.

So, my second, more radical modification to the MSRP is to replace the Lakatosian account of progressiveness and degeneracy with Laudan's problem-solving account. Laudan introduced his methodology of problem-solving assessment independently of his research traditions, and ostensibly it should work in any framework that includes theories (or models!) that adapt over time to empirical and theoretical pressures. Because problem-solving effectiveness is (in principle) determinable, even for ongoing research programmes, we avoid Hacking's observation that the MSRP is exclusively backwards-looking. Because Laudan's notion of a problem admits non-empirical solutions,[24] this new hybrid framework is not exclusively empirical, which has the added benefit of allowing a fairer assessment of the proposed solutions that cannot be tested yet. Because a programme can see additional problems arise (as new things require explanations, or inconsistencies are found or introduced), anomalies can be accounted for more easily than in the original MSRP. And because the aim of the problem-solving assessment is to provide advice for acceptance and pursuit-worthiness, the new hybrid account can definitely recommend action: accept the research programme with the most (and most significant) solved problems, and pursue those programmes that have demonstrated a high rate of problem-solving success recently. With this new tool added to the MSRP, we can now apply what we have learned about the recent histories of the CH and SUSY model-groups in Section 3, and take a preliminary look at their progressiveness.[25]

4.3 (Towards) Assessing Our Case Studies

Our new tool in hand, we can see why the SM is the dominant research programme in particle physics. Although it still has several pressing questions (some of which seem to have become increasingly distressing after the Higgs discovery), it is also one of the most well-confirmed theories ever produced. With such high corroboration for the solutions advanced for its empirical problems (up to, and including, EWSB), the SM is by far the most effective problem-solver in

---

[24] This is true for both empirical and conceptual problems.

[25] The arguments in this section are expanded upon in (Chall, 2019).

particle physics overall. As such, it should be (and largely is) accepted as the central particle physics research programme. At the same time, since it is largely considered complete, there is not much effort towards advancing the programme, and so no new solutions to its known problems are being proposed. As a consequence, though it is accepted as *the* theory of particle physics, many physicists are avidly pursuing alternatives.

As we saw in Section 3.2.1, the CH model-group faced several problems after the discovery of a Higgs candidate. Since many existing models in this group posited either no Higgs, or a relatively heavy Higgs, one of the first attempts to solve the problem caused by a light Higgs was to determine if a Higgs imposter had been discovered, mostly by hunting through the data for deviations from the SM predictions. As more data became available, all potential deviations evaporated and physicists are more convinced than ever that we have discovered a Higgs boson. Another possible solution appears in the form of partial compositeness, which explained the light Higgs mass, the lack of SM deviations in the Higgs candidate's properties, and even provided an explanation for the mass hierarchy of the SM.[26] The increased attention towards models with partial compositeness is a sign that this solution has convinced some physicists that the model-group remains pursuit-worthy. However, the lack of evidence for any new particles puts a hard constraint on CH models, since all of the most accessible regions have already been explored at the LHC. Any new models attempting to solve this problem must either provide an explanation for why new particles haven't been discovered by existing experiments, or raise expected energy range for the predicted appearance of the new strong sector beyond the reach of the LHC. In either case, the CH model-group, already winning only modest attention as a SM alternative, has yet to put forth a solution that has convinced many physicists, leaving its problem-solving status fairly stagnant (see Chall et al., 2019).

The SUSY model-group, on the other hand, had proposed solutions to the naturalness problem early on, and represents the addition of a significant, and expected, symmetry to particle physics, and was therefore much more popular before the Higgs discovery. These are problems that physicists take to be very significant, and therefore SUSY's popularity followed from its high degree of problem-solving promise (and therefore pursuit-worthiness). During the last few years, it has also had to deal with a non-ideal Higgs mass and a lack of new particles. However, these problems directly relate to SUSY's ability to solve the naturalness and hierarchy problems, and so the model-group's failure to provide a compelling solution to the problems posed by the Higgs mass has led to a different sort of strategy: considerations of naturalness, one of the features that made simpler SUSY models attractive, are being de-emphasised in the literature. Rather than the guiding principle of model construction it once was, some physicists are beginning to turn away from naturalness (see, e.g., Giudice, 2017). But, for those physicists who still find the naturalness problem a pressing issue (which remains many of them), the fact that SUSY is looking less and less like an acceptable solution has lead to a downturn in the amount of work being done in this research programme (see Chall et al., 2019).

5 Conclusion

Lakatosian research programmes capture the continued construction of BSM models of certain types, even in the absence of convincing empirical evidence for any BSM phenomena, and even in the presence of experimental evidence that is highly problematic for many specific BSM models. Physicists are able to set aside missing and contrary data for a time, until they are either able to explain previously damaging results (using the positive heuristic) or the programme collapses

---

[26] Dawid (2013) argues that making unexpected, unlooked for explanatory connections should raise the credence of a theory.

from lack of interest, starved for new empirical content. Within my modified Lakatosian framework, physicists have warrant to pursue promising research avenues and their own pragmatic interests, without falling prey to charges of scientific irrationality. With the introduction of model-groups, the framework of research programmes can be used to describe the current state of the EWSB sector. This modification requires an acknowledgement that there are clusters of models that are created using a consistent set of core ideas, constructed as potential avenues for finding and describing new theories of physics. By updating the MSRP with modern philosophical understandings of scientific models, incorporating the 'models as mediators' approach from Morgan and Morrison and the classificatory scheme introduced by Hartmann, we increase the utility of the MSRP within the realm of particle physics. With the replacement of Lakatos's assessment criteria with Laudan's, we can provide the further benefit of a normative guide for action considering the acceptance and pursuit of the ongoing BSM research programmes, based on their problem-solving effectiveness.

As we have seen, this new hybrid framework of scientific progress suggests that, in the absence of new corroborative experimental results, two of the BSM research programmes that have been seen as pursuit-worthy in the last few decades seem to be losing their effectiveness. Since Laudan, like Lakatos, suggests that competition amongst research programmes is the natural state, we can expect the rise of research programmes championing new methods of solving the problems of the SM.[27] Of course, we should bear in mind Lakatos's claim that there are no crucial experiments and allow for an unexpected turn of the data (or a new experiment) that indicates one of these older model-groups still has promise. But in the meantime, with a first pass with this hybridisation of the MSRP, we can see reasons for advising physicists to seek new and different avenues of research if they want to make progress in solving the problems of the SM.

Acknowledgements

This paper was written with the support of the Deutsche Forschungsgemeinschaft (DFG) Research Unit "The Epistemology of the Large Hadron Collider" (grant FOR 2063). I would like to thank Martin King, Peter Mättig, Michael Stöltzner, and the rest of the research unit for their helpful comments. This paper benefited from the insightful questions of the participants of the joint philosophy colloquium organized by the Chairs of Theoretical Philosophy at the University of Bonn and University of Cologne, as well as attendees at several conferences (MS8, Foundations 2018, PSA 2019, and GWP 2019). I would also like to thank my anonymous reviewers for their many helpful comments. Finally, I would like to thank my lovely wife, Alicia, who has been endlessly encouraging.

References

Arbey, A., Battaglia, M., Djouadi, A., and Mahmoudi, F. (2012). The Higgs sector of the phenomenological MSSM in the light of the Higgs boson discovery. *Journal of High Energy Physics*, 2012(9):107.

Arkani-Hamed, N., Cohen, A. G., Katz, E., and Nelson, A. E. (2002). The littlest Higgs. *Journal of High Energy Physics*, 034. DOI: 10.1088/1126-6708/2002/07/034. arXiv:hep-ph/0206021.

---

[27] Anecdotally, this appears to be true, as there is a rise in "model-independent" approaches and completely new models. Indeed, one particle physics theorist I've spoken with stated that there is an increasing number of radical, or even ostensibly implausible models appearing as a direct response to the LHC data and its lack of SM deviations.

Azatov, A. and Galloway, J. (2012). Light custodians and Higgs physics in composite models. *Physical Review D*, 85:055013. DOI: 10.1103/PhysRevD.85.055013. arXiv:1110.5646v2 [hep-ph].

Bechtle, P., Eliel Camargo-Molina, J., Desch, K., Dreiner, H. K., Hamer, M., Krämer, M., O'Leary, B., Porod, W., Sarrazin, B., Stefaniak, T., Uhlenbrock, M., and Weinemann, P. (2016). Killing the cMSSM softly. *European Physical Journal C*, 76(2):96. arXiv: 1508.05951 [hep-ph].

Borrelli, A. (2012). The case of the composite Higgs: The model as a "rosetta stone" in contemporary high-energy physics. *Studies in History and Philosophy of Modern Physics*, 43:195–214.

Borrelli, A. and Stöltzner, M. (2013). Model landscapes in the higgs sector. In Karakostas, V. and Dieks, D., editors, *Epsa11 Perspectives and Foundational Problems in Philosophy of Science*, pages 241–252. Springer.

Chala, M. (2013). $h \to \gamma\gamma$ excess and dark matter from composite Higgs models. *Journal of High Energy Physics*, 122. DOI: 10.1007/JHEP01(2013)122. arXiv:1210.6208 [hep-ph].

Chall, C. (2019). *Non-Empirical Modeling and Theorizing: Scientific Progress in Particle Physics*. PhD dissertation, University of South Carolina.

Chall, C., King, M., Mättig, P., and Stöltzner, M. (2019). From a boson to the standard model Higgs: A case study in confirmation and model dynamics. *Synthese*. DOI: 10.1007/s11229-019-02216-7. Forthcoming.

Cornwall, J. and Norton, R. (1973). Spontaneous symmetry breaking without scalar mesons. *Physical Review D*, 8:3338–3346.

Csaki, C., Grojean, C., Pilo, L., and Terning, J. (2004). Towards a realistic model of Higgsless electroweak symmetry breaking. *Physical Review Letters*, 92:101802.

Dawid, R. (2013). *String Theory and the Scientific Method*. Cambridge University Press, New York, NY, reprint 2015 edition.

Dawson, S. (2017). TASI 2016 lectures: Electroweak symmetry breaking and effective field theory. arXiv:1712.07232v2 [hep-ph].

Dimopoulos, S. and Georgi, H. (1981). Softly broken symmetry and su(5). *Nuclear Physics B*, 193:150–162.

Dimopoulos, S. and Susskind, L. (1979). Mass without scalars. *Nuclear Physics B*, 155:237–252.

Eichten, E., Lane, K., and Martin, A. (2012). A Higgs imposter in low-scale technicolor. arXiv:1210.5462 [hep-ph].

Ellis, J. and You, T. (2012). Global analysis of the Higgs candidate with mass 125 GeV. *Journal of High Energy Physics*, 123. DOI: 10.1007/JHEP09(2012)123. arXiv:1207.1693 [hep-ph].

Englert, F. and Brout, R. (1964). Broken symmetry and the mass of gauge vector mesons. *Physical Review Letters*, 13(9):321–323.

Fayet, P. and Ferrara, S. (1977). Supersymmetry. *Physics Reports*, 32:249–334.

Friederich, S., Harlander, R., and Karaca, K. (2014). Philosophical perspectives on ad hoc hypotheses and the higgs mechanism. *Synthese*, 191(16):3897–3917.

Giudice, G. (2017). The dawn of the post-naturalness era. In Forte, S., Levy, A., and Ridolfi, G., editors, *From My Vast Repertoire...:Guido Altarelli's Legacy*, pages 267–292. World Scientific. arXiv:1710.07663 [physics.hist-ph].

Goldman, T. and Vinciarelli, P. (1974). Composite Higg field and finite symmetry breaking in gauge theories. *Physical Review D*, 10:3431–3434.

Gol'fand, Y. A. and Likhtman, E. (1971). Extension of the algebra of Poincaré group generators and violation of P invariance. *JETP Letters*, 13:323–326.

Guralnik, G., Hagen, C. R., and Kibble, T. W. (1964). Global conservation laws and massless particles. *Physical Review Letters*, 13(20):585–587.

Hacking, I. (1981). Lakatos's philosophy of science. In Hacking, I., editor, *Scientific Revolutions*, pages 128–143. Oxford University Press, New York.

Hall, L. J., Pinner, D., and Ruderman, J. T. (2012). A natural SUSY Higgs near 125 GeV. *Journal of High Energy Physics*, 2012(4):131.

Harnik, R., Howe, K., and Kearney, J. (2017). Tadpole-induced electroweak symmetry breaking and pNGB Higgs models. *Journal of High Energy Physics*, 111. doi: 10.1007/JHEP03(2017)111. arXiv:1603.03772 [hep-ph].

Hartmann, S. (1995). Models as a tool for theory construction: Some strategies of preliminary physics. In Herfel, W. E., Krajewski, W., Niiniluoto, I., and Wójcicki, editors, *Theories and Models in Scientific Processes*, pages 49–67. Rodopi, Amsterdam. Poznan Studies in the Philosophy of Science and the Humanities 44.

Hartmann, S. (1999). Models and stories in hadron physics. In Morgan, M. and Morrison, M., editors, *Models as Mediators: Perspectives on Natural and Social Science*, pages 326–346. Cambridge University Press, Cambridge.

Higgs, P. (1964a). Broken symmetries and the masses of gauge bosons. *Physical Review Letters*, 13(16):508–509.

Higgs, P. (1964b). Broken symmetries, massless particles and gauge fields. *Physical Review Letters*, 12(2):132–133.

Iliopoulos, J. (2014). Theory summary talk. Presented at the XLVIXth Rencontres de Moriond for Electroweak Interactions and Unified Theories, La Thuile, Italy, March 15-22, 2014.

Jakciw, R. and Johnson, K. (1973). Dynamical model of spontaneously broken symmetry. *Physical Review D*, 8:2386–2398.

Kaplan, D. B. (1991). Flavor at SSC energies: A new mechanism for dynamically generated fermion masses. *Nuclear Physics B*, 365:259–278.

Lakatos, I. (1978a). Falsification and the methodology of scientific research programmes. In Currie, G. and Worrall, J., editors, *The Methodology of Scientific Research Programmes: Philosophical Papers Volume 1*, pages 8–101. Cambridge University Press, New York.

Lakatos, I. (1978b). History of science and its rational reconstructions. In Currie, G. and Worrall, J., editors, *The Methodology of Scientific Research Programmes: Philosophical Papers Volume 1*, pages 102–138. Cambridge University Press, New York.

Laudan, L. (1977). *Progress and its Problems.* University of California Press, Berkeley and Los Angeles.

Martin, S. P. (1997). A supersymmetry primer. arXiv:9709356v7 [hep-ph].

Morgan, M. and Morrison, M. (1999). *Models as Mediators: Perspectives on Natural and Social Science.* Cambridge University Press, Cambridge.

Morrison, M. (2007). Where have all the theories gone. *Philosophy of Science*, 74:195–228.

Peskin, M. (2012). Theoretical summary lecture for Higgs hunting 2012. Presented at the 3rd Higgs Hunting Workshop: Discussions on Tevatron and LHC Results, Orsay, France, July 18-20, 2012. arXiv:1208.5152v2 [hep-ph].

Pomarol, A. (2012). Electroweak symmetry breaking - status/directions. Presented at the 36th International Conference on High Energy Physics, Melbourne, Australia, July 4-11, 2012.

Redi, M. and Tesi, A. (2012). Implications of a light Higgs in composite models. *Journal of High Energy Physics*, 166. DOI: 10.1007/JHEP10(2012)166. arXiv:1205.0232 [hep-ph].

Redi, M. and Weiler, A. (2011). Flavor and cp invariant composite Higgs models. *Journal of High Energy Physics*, 108. DOI: 10.1007/JHEP11(2011)108. arXiv:1106.6357v4 [hep-ph].

Stöltzner, M. (2014). Higgs models and other stories about mass generation. *Journal for General Philosophy of Science*, 45:396–386.

Susskind, L. (1979). Dynamics of spontaneous symmetry breaking in the Weinberg-Salam theory. *Physical Review D*, 20:2619–2625.

van Fraassen, B. (1980). *The Scientific Image.* Oxford University Press, 2011 edition.

Volkov, D. and Akulov, V. (1973). Is the neutrino a Goldstone particle? *Physics Letters B*, 46:109–110.

Wells, J. D. (2018). Beyond the hypothesis: Theory's role in the genesis, opposition, and pursuit of the Higgs boson. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics*, 62:36–44.

Wess, J. and Zumino, B. (1974a). Supergauge Transformations in Four Dimensions. *Nuclear Physics B*, 70:39–50.

Wess, J. and Zumino, B. (1974b). A Lagrangian Model Invariant Under Supergauge Transformations. *Physics Letters B*, 49:52–54.

Wess, J. and Zumino, B. (1974c). Supergauge Invariant Extension of Quantum Electrodynamics. *Nuclear Physics B*, 78:1–13.