Searching for Signatures

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Since the discovery of the Higgs boson in 2012, particle physicists have not found any statistically significant deviations from the Standard Model. This has led to a shift of emphasis from model testing to exploration and an increasing popularity of 'model-independent' experimental approaches. Our goal is to analyze this shift by focusing on particle and event signatures. A differentiated picture of experimentation emerges between the extremes of theory guidance and theory-free exploration. Using the example of the top quark, we distinguish four types of motivations for the study of physics processes.

Contemporary elementary particle physics is characterized by the tension between a highly predictive theory, the Standard Model (SM), and its explanatory shortcomings, among them the large number of fundamental parameters and the apparent repetitions of its basic structures. For decades, discontent with the SM has driven theoreticians' creativity, yielding a broad spectrum of models of physics beyond the SM (BSM).[1] These models were probed, alongside the searches for the still missing particles of the SM, by a series of particle accelerators of higher and higher energies, using ever more sophisticated experimental methods. After the discovery of the Higgs boson in 2012, the SM's long-sought capstone, this tension has only increased. For,

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1. Our understanding of model follows the approach of Morgan and Morrison (1999). As in the case of the SM, a successful model of broad explanatory scope may eventually be considered a theory. This gradual distinction permits us to apply the philosophical debates about values of theory preference or theoretical virtues to BSM models. We will also continue to speak of theoretical concepts and theory guidance, and distinguish between theory and experiment, even though 'theory' in those cases is represented by a specific model or a class of models.

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experimentalists could not find any features predicted by the available BSM models or any other statistically significant deviations from the SM.

This situation has prompted a change in physicists' attitudes toward models, leading to a shift of emphasis from model testing to experimental exploration and the increasing popularity of so-called model-independent approaches (Chall et al. 2019, sec. 3). In a modern particle detector, such experimentation is based on a large number of reliable experimental strategies and models of data analysis (Franklin 2013; Karaca 2017). Model independence of experiments is understood as searching for new effects without recurrence to any concrete target model. In order to understand model independence properly, one has to distinguish the target model, in this case a model of BSM physics, from the background models comprising the 'known' physics of the SM and the detectors (Karaca 2018). The analyses assume the background model but are largely independent from assuming any target model. Moreover, experimentalists are not searching for models in the first place but for particle and event signatures, which makes experimentation relatively autonomous from models. Model-independent approaches by theorists are mostly formulated as bottom-up effective field theories (Wells 2012). Their main objective is to obtain clues for, and empirical constraints on, BSM physics.

The goal of our article is to characterize this relative autonomy by an analysis of the concept and practice of signatures and to show that it requires a more differentiated picture of experimentation between the extremes of simply testing a target model and model-free exploration. Section 1 introduces the concepts of particle and event signatures that experimentalists use to classify events independently of the details of the individual detectors. We also discuss the relationship between signatures and models and characterize the relative autonomy of signatures. In section 2, we discuss experimental feasibility as a necessary condition for the study of signatures. Section 3 compares model-driven and signature-driven searches for BSM physics. Using the example of the top quark signature, section 4 outlines the variety of motivations to study this signature that range from theoretical ideas to genuinely experimental ones. We argue that the experimentalists' approach is more differentiated than just claiming it to be 'theory-guided'. Section 5 concludes that appraising this variety prevents philosophers from an exclusive focus on theory guidance and permits a more adequate understanding of experimentation in contemporary particle physics.

1. Signatures in Particle Physics Experiments. At the Large Hadron Collider (LHC), as at previous particle physics experiments, the large amount of complex electronic raw data collected by the various components of the detectors are condensed into signatures, which are relatively easy-to-handle

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objects that can then be compared to a background model or to the prediction of a BSM model and allow for relative experimental autonomy. Raw data are detector specific and do not allow experimenters to compare their measurements across different experiments or to any model. To move beyond these limitations, experimenters focus on particle signatures that are inferred from raw data on the basis of suitably chosen operational definitions. The operational definitions of signatures should not be read as reductions to raw data or observations. Doing so would effectively relapse into a dualism between raw data and theories and fail to do justice to the particular role of signatures in particle physics experimentation. Instead, these definitions reflect reliable experimental and theoretical knowledge collected in the past that has been deliberately black-boxed in the definition of the signature.[2] Since raw data are detector specific, the inferences leading to a signature are as well. However, the signatures are independent of these specifics and can be compared between different experiments without further mutual experimental adjustments.

Particle signatures ('physics objects') define particles using the raw data measured in different components of a detector by operational means.[3] For instance, in both ATLAS and CMS, whose detectors are structured fairly similarly, an electron is defined by a large, very localized signal in a calorimeter and an associated track. In ATLAS, "electron candidates are reconstructed by matching tracks in the ID [inner tracking detector, PM&MS] to energy deposits (clusters) in the electromagnetic calorimeter" (ATLAS Collaboration 2018, 487). Similarly, in CMS "the basic principles of offline electron reconstruction . . . rely on a combination of the energy measured in the electromagnetic calorimeter (ECAL) and the momentum measured in the tracking detector" (CMS Collaboration 2015, 2). In the same vein, (almost) all SM particles can be classified and prepared for analysis. As representations of particles, particle signatures are defined independently of the specifics of a detector. If experiment A claims to see an electron with some energy in a process, it can be checked by experiment C, whereas if C would claim to see some electronic signal in a certain detector part, there would be no way for experiment A to check this directly.

The particle signatures of a specific LHC collision event are then combined to define an event signature. An event signature is given by (*a*) how many of these individual particles are observed in the event and (*b*) how these particles are related to each other (e.g., considering ranges of angles, energies, or invariant masses). Event signatures allow experiments to easily

2. This knowledge includes theoretically well-explained properties of particles, precision data, and the reliability of experimental strategies (Franklin 2013).

3. As a matter of fact, physicists are talking about 'particle candidates' indicating that there is always some background due to other particles, which, however, is small in most cases. For simplicity, we will identify the signature with the particle dominantly producing such a signature.

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classify types of events. For example, an event with one electron, a bottom quark, and an apparent momentum imbalance (MET) is taken as a signature for the top quark,[4] or the Higgs boson, which was found through the signature of two photons having a particular invariant mass (125 GeV). As for the particle signatures, event signatures can be compared across different experiments. Event signatures are predicted in (BSM) models, allowing one to relate experiment and model. No paper on BSM models predicts the electronic signals in the detector.

While particle signatures account for recurring patterns in the detectors and are defined operationally, background models are used to fine-tune procedures (e.g., with the aim of improving efficiencies and estimating particle properties); they are not required for the operational definition of a signature. The quality of signatures is constantly validated largely from the data themselves (see Mättig 2019).

Signatures resemble the phenomena of Bogen and Woodward (1988). As we have shown elsewhere (Mättig and Stöltzner 2020, sec. 4.2), the autonomy of phenomena, at least in particle physics, may be better expressed in terms of signatures because this concept allows a much cleaner separation between observation and theoretical concepts. To reach the phenomenon of neutral currents, Bogen and Woodward's main example, several steps are required that involve theoretical concepts, such as weak interaction, but not explicit models.

Signatures mediate between the detector and models that predict which (SM) particles would be produced and which relation should be expected between them. In general, models contain a variety of BSM particles, each of which becomes visible through its decay into different types of SM particles. They can thus be matched to event and particle signatures, and allow models to be tested, and to confirm or exclude predictions. The relation between models and signatures, however, is neither a bijection nor an isomorphism. First of all, models in most cases predict not just one but several particles, each of which can decay in various ways. Thus, a model predicts a broad range of signatures. These signatures, for their part, are not necessarily unique to a specific model, but the same signature may well be predicted by several models. As a result, many-to-many relations exists between models and signatures. Moreover, the variety of experimentally observable signatures is not necessarily exhausted by model predictions, but signatures exist that do not correspond to any known model.

To give an example of this relation—one that is inspired by a specific model—assume the signature of a relatively light supersymmetric top (stop), within the most favored BSM model of supersymmetry. The stop can decay in quite different modes (e.g., into a bottom quark, two light quarks, and a

4. This imbalance could be, e.g., due to a neutrino ν that would leave no trace in the detector.

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neutralino χ^0; or into a charm quark and a χ^0), where the χ^0 would not interact in the detector and is a candidate for a dark matter particle. Let us focus on another stop decay mode stop $\rightarrow$ t + χ^0, where the top quark decays into a bottom quark, an electron and a neutrino ν. The event signature would be defined by MET for the χ^0 and the ν, a bottom quark, and an electron (Alves et al. 2011). SM processes exist with this signature, but since supersymmetry also predicts definite properties, these background processes could be suppressed through additional means. If an excess of events with this signature over the SM processes were observed, it would clearly signal BSM physics but not necessarily a stop quark. LHC has not found such an excess yet, but the measurements of this signature are interpreted in terms of general dark matter models (ATLAS Collaboration 2017c), Leptoquarks (ATLAS Collaboration 2016), vector-like quarks (ATLAS Collaboration 2017b), and several other BSM particles apart from the stop. Specific models like the stop may be a strong motivation to search for a signature, but in the center of experimental practice are the signatures themselves.

2. A Necessary Condition for Signatures: Feasibility. Consider a BSM model predicting a new particle that decays into SM particles and thus leads to a certain event signature. Since, in almost all cases, such a signature can also come from the SM, the signature, as measured in the data, would include the SM background and the BSM signal. To render this signal detectable in an experiment, its mere production is not sufficient; the signal has to stand out against the background. In the worst case, the signal may therefore be swamped by the background and remain hidden. Less likely is that the background has identical features (e.g., the same relation between particles) as the signal sought for.

The need for signals to appear against the background can be exemplified in the process of the Higgs discovery at the LHC. The Higgs has several decay modes, which contributed to the discovery with different weights. The Higgs was first observed in decay modes h $\rightarrow \gamma\gamma$ and h $\rightarrow$ ZZ, leading to different signatures. One obtains a much larger yield of background events containing two photons from well-known SM sources than from a Higgs decay. This would thwart the experimental requirement of a prominent signal-to-background ratio. The Higgs signal, however, becomes visible if special relations are considered: in this case the mass of the two-photon system. The Higgs boson has a definite, although a priori unknown, mass—which turned out to be 125 GeV—and therefore all photon pairs from a Higgs combine to this mass value. In contrast, the two photons in all the background processes have a smooth distribution extending over a large mass range. Therefore, by selecting events with this special event signature, the Higgs signal clearly stands out above the background, given enough statistics. The strength of the enhancement takes advantage of not only the fairly efficient identification

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of photons but also that their energies and directions can be very precisely measured. This, in turn, leads to a very precise mass measurement. Thus, the diphoton signal has a large background and a reasonable event yield.

Similarly, the Higgs decay into ZZ can be measured with very good experimental precision. This, however, is only true if each of the Z's decays into an electron (or a muon). The probability for such decays is, however, only 10^{-3}. As a result, the ZZ channel suffers from low statistics. Otherwise, it is an experimentally excellent channel with very little background and high precision. In contrast, the Higgs decay into two bottom quarks was only seen 6 years after the discovery of the Higgs boson, which is surprising given that it is a factor of 20 times more likely than the ZZ decay and a factor 200 times more likely than a decay into two photons. But the decay into bottom quarks requires rather complicated analyses; it also suffers from an enormous background and has only marginal experimental precision. Hence, there is a significant difference between model expectations for a signature and the experimental feasibility of finding a signal and measuring its properties.

3. Model-Driven and Signature-Driven BSM Searches. The search for stop quarks (sec. 1) is an instance in which predictions are derived from a worked-out model of supersymmetry. Theory guides the analysis, not only by suggesting its relevance ('possibly lightest supersymmetric particle') but also by predicting in which signature the stop can be found and suggesting observables, such as angular distributions, to separate the signal from the much more abundant background. This means that the model provides clear prescriptions for the experimentalist in developing her analysis. There still remains space for her to optimize the analysis, but the general procedure is defined by the model. The stop quark, and supersymmetry in general, is just one of many examples in which explicit models exist whose predictions can be turned into a prescription for experimentalists to search for model effects. In fact, in the decades before the LHC, much effort was spent on theoretically devising such models that could be tested in the years after the launch of the experiment.

But only part of the LHC analyses follows the prescriptions from a model. As discussed in the introduction, the mood among physicists has changed in recent years, and experimental searches have become more independent and receive less lead from concrete model predictions. Key for this model-independent experimental strategy are signatures; they open the prospect for unexpected discoveries and bestow experiments with a relative autonomy from models. Relative autonomy means that a BSM signal can only be identified against the SM background. This autonomy increases with the high precision of the SM prediction, which is essential for signature-driven searches.

In the past, particle physics witnessed several examples in which experimental searches led to discoveries that were largely unexpected by the

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community. Essentially, these are the 'signature without a model' cases discussed above. Among them are the observations of CP violation, that is, a fundamental matter-antimatter asymmetry, in which the signature of a two-particle decay was found in a region where it was supposed to be forbidden. Other examples are the discoveries of the τ lepton by the signature of an apparent flavor violation and of the charm quark in several signatures indicating a resonance of an unexpectedly long lifetime. Common to these examples is the fact that the signatures by which the surprising effects were discovered consisted of particle signatures that had been frequently used before. However, the special conditions of the detection of these particles, long lifetimes of a K^0, high energies of electron-muon events, or the narrow width of the J/ψ, were theoretically unexpected or even forbidden in those regions where they were found.

The potential for finding a new particle at the LHC is underlined by the short episode in 2016, when both ATLAS and CMS found a small excess in the two-photon mass spectrum at 750 GeV (ATLAS Collaboration 2017a; CMS Collaboration 2017). While it eventually turned out to be a statistical fluctuation, in its short lifetime of a few months, it triggered frantic theoretical activity with some 500 papers aiming to make sense of this signature submitted to arXiv.org. In the context of the current article, it is not important that the signal eventually disappeared but that a completely unexpected observation was possible just by looking at the mass of a two-photon signature. Again, models existed that did expect a diphoton resonance but with very peculiar properties and without predicting a specific resonance mass. However, experimentalists took signatures generically and, within experimental sensitivity, extended their search to include diphoton resonances with all possible properties. Indeed, finding the indication at 750 GeV was only possible because of this broad search.

Thus, while a model may contribute to the motivation to search for a signature, the signature as a tool allows experimentalists to discover deviations from theoretical expectations that do not correspond to any existing model. Furthermore, to assess the experimental autonomy, it is not important whether it turns out in retrospect that there actually existed some model predicting the signal in some signature. Models are legion, and the large number of parameters allows them flexibility.

4. The Top Quark Signature: A Case Study. Given the vast number of possible signatures that can be addressed and separated from the background at the LHC, the experimentalist has a choice to make concerning which of them may be epistemically worthy of study. In the absence of any indication from the available models, a broad range of motivations exits. As examples, here are three typical motivations in favor of studying the top signature cited in recent review talks at major conferences: (*a*) "The large statistics provided by the LHC are allowing us to measure processes never observed before and

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to develop new methods to improve the precision for the 'bread-and-butter' measurements" (Owen 2019, 1); (*b*) "Although this particle appears to have no substructure and to be point-like, its mass is of the order of a gold nucleus. . . . Because of its potentially special role, the top quark might be exotic in some way, and could offer a first glimpse of physics beyond the Standard Model" (Schwanenberger 2015, 1); (*c*) "In several extensions of the Standard Model, the large mass of the top quark plays an important role in driving the Electro-Weak symmetry breaking. It is thus natural to expect new physics effects to show up in processes involving the top. . . . It is thus important to explore top physics in great detail, both with regard to searches for New Physics signals, and with regard to precision measurements of its properties, in particular of its mass" (Nason 2016, 2). Notice that, apart from the last sentence, none of these motivations prescribes exactly what and how one should measure something. Physicists are instructed to 'look for the signature of one bottom quark, one muon, and MET' but not which properties of these events should be studied. This is strikingly different from the concrete model of a supersymmetric stop quark discussed above.

While not prescribing a definite procedure, there are different levels of how theoretical ideas affect the motivation of experimenters. On one end of the spectrum, top quarks should be studied because they are there and the new experiment provides new opportunities because of increased statistics, higher measurement precision, and so on. Then there is a general argument to 'search for BSM with the most massive particle of the SM, the top quark'. This latter motivation has a slightly stronger connection to theoretical concepts but also takes up historical precedents. Higher masses or energies were the driving elements to find new effects in the past, as exemplified by the history of particle physics experimentation that is essentially defined by more and more powerful accelerators. The final motivation for measuring the top quark embeds it into the SM and cosmology according to which the mass of the top quark is connected in an unknown way to other parts of these theories: for instance, that its coupling to the Higgs boson has the peculiar value of 'one', or that the values of both the Higgs and the top masses are related to the fate of the universe.

The general motivation for 'measurements on the top quark' has to be translated by the experimentalist into which of the many possible observables she should address. Since, in the first stage, none of the above motivations contains a specific prescription, every aspect of the top quark should be scrutinized, starting from what has generally been measured for other particles (e.g., the mass, the lifetime, the modes of its decay) to more remote properties—among them the production of top quarks in association with other signatures or particles, including the Z^0, jets, or the above-mentioned MET. However, the stronger the relation to a theoretical concept, the more the experimentalist can also refine her choices. For example, if she wants

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to understand how the top quark is embedded in the SM and cosmology, she may emphasize especially the mass and its connection to the Higgs mechanism, look at the coupling of the Higgs to the top, or search for resonances made out of top and antitop quarks.[5] Again, following motivations connected to theory but without specific prescriptions leaves the experimenter with broad latitude to decide on what to measure and how. Theory guidance in such cases, if it is relevant at all, is mostly a matter of general principles and of the historical trajectory of particle physics.

Such differentiated motivations to measure 'something' are not restricted to the top quark but apply to many measurements. To us, they show that a single label like 'theory-guided' does not capture the complexity of the impact of theory on the way experiments are performed. In general, these motivations are a mixture of experimental and theoretical components, extending from purely experimental to strictly model-motivated ones.

Analyzing the above examples, we can distinguish different degrees to which theoretical concepts are entering experimentation. These degrees also correspond to different types of autonomy for signatures. The following list is based on top quark physics, but similar differentiations exist for other particle signatures.

1. Purely experimental motivations, based on the mere fact that a process can be measured more precisely, for example, because of an increase of either available data or experimental precision.
2. Motivations borne out of general theoretical principles or historical precedents, among them looking at the highest masses.
3. Motivations emerging from a detailed and closed model but without providing a prescription of what to measure. The relation of the top quark mass to the Higgs boson is one example.
4. A concrete model, like the stop, providing an exact prescription of what to measure.

5. Conclusion: Beyond Theory Guidance. A more nuanced picture and a better regard for the special role of signatures also paves the way for a more adequate understanding of experimentation in particle physics, in particular the relative autonomy of experiments and their relationship to theory. Inspired by the classical debates about theory-ladenness, philosophers of science have often approached this relationship from the perspective of theory guidance. In discussing explorative experiments, Steinle (2016) has advocated a more nuanced and complex role for theory in finding new phenomena and the concepts describing them. Let us conclude by comparing our

5. In contrast to all lighter quarks, the top quark is supposed to decay before it can build a stable quark-antiquark hadron.

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focus on signatures with two recent papers that approach the issue of guidance in present-day elementary particle physics from opposite sides.

Karaca (2013) distinguishes theory-driven "experimentation that is performed under the *continuous* guidance of some theoretical account" from experimental exploration that allows the "utilization of theoretical considerations that have no *guiding* power" (99). Characterizing the discovery of quarks, he affirms that exploratory experimentation is also possible in large particle physics experiments. Applying the concept to the LHC, Karaca (2017) analyses the use of signatures in the ATLAS trigger, the first stage of data selection. While discussing the selection of signatures along concrete models, he clarifies that these "might also be produced . . . as a result of some unforeseen processes" (342). Thus, he maintains the leading role of models as a heuristic device for such searches. Yet, as we have argued, the role of signatures is far broader, and there exist other motivations to study them.

McCoy and Massimi (2018) analyze the development of 'simplified models' that are largely motivated by well-defined models. But instead of using their full particle content, simplified models just add one or two hypothetical BSM particles to the SM. In this way, they "provide some guidance in what to look for by suggesting theoretically-motivated phenomenology. . . . These models then can be used to optimize searches for these kinds of phenomenology, mitigating the problem from Big Data" (118). They economize LHC analyses since "for every data pattern detected at the CMS or ATLAS experiments, . . . there is a multiplicity of possible BSM particles" (118). While this approach does not commit one to a larger theoretical framework, it provides a clear prescription for experimentalists and is therefore close to the fourth type in the above list.

While McCoy and Massimi globally argue that "experimentalists need theoretical guidance so that they know where to look in the enormous amounts of data for potential new phenomena" (2018, 119), we have provided a more nuanced picture of how theoretical and experimental arguments motivate experimental analyses. We observe a rather differentiated picture leading to different degrees in the relative importance of theoretical and experimental autonomy. They reach from purely data-driven motivations to strict prescription by a model with several nuanced steps in-between. Common to all approaches is the experimental concept of signatures that mediate between the raw data and the eventual physics interpretation. They open the possibility to study physics processes, in terms of both model-independent analyses and concrete model predictions.

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