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A case study in experimental exploration: exploratory data selection at the Large Hadron Collider

Koray Karaca[1]

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Abstract In this paper, I propose an account that accommodates the possibility of experimentation being exploratory in cases where the procedures necessary to plan and perform an experiment are dependent on the theoretical accounts of the phenomena under investigation. The present account suggests that *experimental exploration* requires the implementation of an *exploratory procedure* that serves to extend the range of possible outcomes of an experiment, thereby enabling it to pursue its objectives. Furthermore, I argue that the present account subsumes the notion of *exploratory experimentation*, which is often attributed in the relevant literature to the works of Friedrich Steinle and Richard Burian, as a particular type of experimental exploration carried out in the special cases where no well-formed theoretical framework of the phenomena under investigation (yet) exists. I illustrate the present account in the context of the ATLAS experiment at CERN's Large Hadron Collider, where the long-sought Higgs boson has been discovered in 2012. I argue that the data selection procedure carried out in the ATLAS experiment illustrates an exploratory procedure in the sense suggested by the present account. I point out that this particular data selection procedure is *theory-laden* in that its implementation is crucially dependent on the theoretical models of high energy particle physics which the ATLAS experiment is aimed to test. However, I argue that the foregoing procedure is not *driven* by the above-mentioned theoretical models, but rather by a particular data selection strategy. I conclude that the ATLAS experiment illustrates that, contrary to what previous studies have suggested, there are cases of experimentation in which exploration serves to test theoretical predictions and that theory-ladenness plays an essential role in experimentation being exploratory.

✉ Koray Karaca
karacak@gmail.com

[1] Department of Philosophy, University of Twente, P.O. Box 217, 7500 AE Enschede,
The Netherlands

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1 Introduction

Until the advent of *new experimentalism*[1] in the 1980s, it was traditionally maintained in the philosophical literature that the procedures concerning planning, designing and performing an experiment as well as interpreting its results are prescribed by the theoretical accounts of the phenomena under investigation.[2] The scholars[3] of new experimentalism criticized this *theory-dominated* view of scientific experimentation as being overly simplistic and thus failing to account for many of its essential aspects. They showed that there are aspects of experimentation that are not determined by theoretical considerations alone, thus arguing against the subordination of experimentation to scientific theorizing. In the 1990s, a new philosophical literature on scientific experimentation has started to emerge, suggesting that what is called *exploratory experimentation* (EE) has characteristics that have been hitherto neglected and that do not fit in with the aforementioned theory-dominated view of experimentation.

In this paper, first, I will review the philosophical literature on EE and argue that the existing philosophical accounts of EE are unduly restrictive about the possibility of experimentation being exploratory in cases where the procedures necessary to plan, design and perform an experiment are typically dependent on the theoretical accounts of the *target* phenomena, namely phenomena under investigation. I will then offer an account that accommodates the possibility of experimentation being exploratory in the foregoing cases. I will illustrate this account with a case study that examines the procedure of data selection in the ATLAS experiment that has been running since 2008 at CERN's Large Hadron Collider (LHC), where the long-sought Higgs boson has been discovered in 2012 (ATLAS Collaboration 2012c).[4]

2 Philosophical accounts of EE

The notion of EE has been so far discussed through the various case studies concerning the experimental practice in both the physical and biological sciences. Most of these

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[1] For a review, see Ackermann (1989).

[2] This view is rooted in the writings of Pierre Duhem, Karl Popper, Norwood Russell Hanson and Thomas Kuhn. For a short overview, see Karaca (2013).

[3] The most prominent ones include Ian Hacking, Allan Franklin, Peter Galison, David Gooding and Andrew Pickering.

[4] The CMS experiment is the other multi-purpose LHC experiment that has also detected the Higgs boson in 2012 (CMS Collaboration 2012).

case studies have drawn upon Friedrich Steinle's account (1997, 2002),[5] which is the first systematic account of EE. Even though a number of other scholars have later elaborated on the notion of EE, currently Steinle's account is widely acknowledged as the *standard account* of this notion. In this section, I will provide an overview of the philosophical literature on EE. To this end, I will first revisit Steinle's account.

2.1 Steinle on EE

Steinle's account of EE is based on the distinction between two types of experimentation. What he calls " "theory-driven" experimentation bears close similarities to what the [theory-dominated view] regards as being the only type of experimentation" (Steinle 1997, p. 69). Theory-driven experiments are designed and performed in order to investigate well-defined research questions by relying on the well-established theoretical frameworks of the target phenomena. Both the experimental set-up used and procedures carried out in cases of theory-driven experimentation (TDE) are tailored to investigate specific research questions. As a result, new possibilities under which unforeseen experimental outcomes may be obtained are, to a great extent, excluded. It is important to note that in Steinle's account, "[TDE] is not necessarily a *test* of theories or of hypotheses. The determination of a numerical parameter, for example, or the use of theories as a heuristic tool within the search for a new effect would likewise be theory-driven" (ibid., pp. 69–70).

Unlike TDE, what Steinle calls "[EE] typically takes place in those periods of scientific development in which-for whatever reasons-no well-formed theory or even no conceptual framework is available or regarded as reliable. Despite its independence from specific theories, the experimental activity [in EE] may well be highly systematic and driven by typical guidelines" (ibid., p. 70). In Steinle's account, "[r]ather than testing of a theory, the epistemic goal [of EE is] to formulate regularities and create appropriate notions to express them" (Steinle 2002, p. 412). EE achieves this main goal through the use of a particular type of experimental procedure that aims at finding out "which of the various parameters affect the effect in question, and which of them are essential" and that consists in "the systematic variation of experimental parameters" (ibid., p. 417). As a result, in contrast to TDE, the experimental process in EE becomes open to a large variety of outcomes, even to unexpected ones.

Steinle's paradigmatic examples of EE are from the period of early electromagnetism, including experiments performed in the eighteenth and nineteenth centuries by Charles Dufay, André-Marie Ampère and Michael Faraday, where no well-formed theoretical framework of electromagnetic phenomena was yet available. Steinle illustrates the aforementioned experimental procedure in the case of Ampère's "astatic magnetic needle" experiment as follows:

> Ampère varied many experimental conditions: the strength and polarity of the battery; the length and material of the needle; and, most extensively, the position

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[5] The term EE had been previously used by other scholars in the historico-philosophical literature concerning scientific experimentation, see, e.g., Hofmann (1987); Gooding (1989); Sargent (1995).

> of the needle relative to the wire—above, below, right, left, horizontal, vertical, etc. His aim in those variations was to find out which of those factors contributed to the deflection of the needle and to formulate regularities. (ibid., p. 413)

The above quote indicates that, in the case of Ampère's astatic magnetic needle experiment, the systematic variation of the relevant experimental parameters provides a wide range of otherwise unforeseen possibilities to see the effect of each physical parameter, such as the strength and polarity of the battery, the distance between the needle and the wire, etc., on the observed phenomenon, namely the deflection of the needle, thereby enabling Ampère's experiment to be exploratory according to Steinle's account.

In Steinle's account, in order for the relevant experimental parameters to be systematically varied, and thus for experimentation to be exploratory, it is necessary that experimental instruments "allow for a great range of variations, and likewise be open to a large variety of outcomes, even unexpected ones" (ibid., p. 422). This means that in EE the "restrictions posed by the instrumental arrangement must not be too confining" (ibid.). Whereas, in *testing experiments*, which are aimed to test theoretical predictions, "instruments are specifically designed for a single effect" (ibid.) As a result, the "possibilities of variations [of experimental parameters] are much restricted, and so is the openness to outcomes that are not in the range of expectation" (ibid.).

2.2 Burian on EE

Burian (1997) has provided an account of EE in the context of the molecular biology experiments performed by Jean Brachet and his coworkers. Burian's account is less systematic than Steinle's, but he uses similar considerations as those of Steinle to characterize Brachet's experiments as being exploratory. First, Burian points out that "[m]any techniques were employed to cross check the locations, concentrations, and identities of various substances, most especially the nucleic acids, and to determine the differences that arose when they were present in different concentrations or at different times, when a step into which they entered was blocked, or when they were altered in some way" (ibid., p. 42). Second, Burian notes that "the recognition and localization of the distinct classes of nucleic acid was achieved without depending on particular hypotheses about the functions of those distinct substances" (ibid. p. 43). Therefore, in Burian's analysis of Brachet's experiments, no particular theoretical accounts of the target phenomena were relied on to achieve the objective of these experiments. Rather, systematic variation of various experimental parameters, such as locations, times, concentrations and identities of substances, is what enabled Brachet's experiments to achieve their objective, which was "to find correlations between the presence of nucleic acids at particular times and places and the ensuing biochemical, physiological, and morphological changes, with the ultimate aim of understanding the contributions of nucleic acids and related substances to differentiation, growth, morphological change, and the entire ontogenetic process" (ibid. p. 42).

2.3 Elliott's taxonomy of EE

Relatively recently, Kevin Elliott has suggested that EE comes in varieties and proposed a taxonomy to classify different *varieties* of EE along three dimensions, as shown in Table 1. According to Elliott's taxonomy, "one can characterize a particular variety of EE by specifying what its positive aim is, what role theory plays in it, and what methods are employed for varying parameters" (Elliott 2007, p. 323). Elliott also points out that "these dimensions [of EE] appear to be at least partly independent of one another; for example, the positive aim of the experimental activity need not always determine the role that theory plays in it or the methodology used for varying parameters" (ibid.).

With respect to the aim of EE, there seems to exist a clear agreement between Elliott and Steinle. As we have seen earlier, Steinle does not regard theory or hypothesis testing as one of the aims of EE. Likewise, Elliott suggests that "the most fundamental characteristic of EE seems to be that it, in contrast to other types of experimentation, does *not* serve the aim of testing theories or hypotheses" (ibid., p. 322). Similar but less explicit views have been also expressed in the relevant literature regarding the aim of EE. For instance, Burian holds that "[i]n general, EE is limited to situations in which experimental outcomes cannot be accurately predicted by available theories together with general background knowledge plus boundary conditions" (Burian 2007, p. 287). Similarly, Kenneth Waters holds that "the aim of exploratory experiments is to generate significant findings about phenomena without appealing to a theory about these phenomena for the purpose of focusing experimental attention on a limited

Table 1 A taxonomy of various characteristics associated with different kinds of EE organized according to three relatively independent dimensions or categories. (*Source* Elliott 2007, p. 324)

Dimensions of EE	Varying characteristics of EE within the dimensions
Aims of experimental activity	Identifying regularities and developing new concepts
	Isolating or manipulating particular entities or phenomena
	Developing experimental techniques, instrumentation, or simulations
	Resolving anomalies
Role of theory in the activity	Playing a minimal role relative to other forms of experimentation
	Providing background information
	Serving as a starting point or foil
	Being constituted by exploratory projects or strategies
Methods or strategies for varying parameters	Working as an individual investigator to vary elements of an experimental setup
	Using multiple experimental techniques to characterize a phenomenon
	Using "high-throughput" instrumentation to collect large quantities of data
	Working as a community to design a range of experiments that vary key parameters
	Developing models and simulations that can vary parameters

range of possible findings" (Waters 2007, p. 279, entire quote italicized in original). The above quotes from Burian and Waters suggest that they also regard EE as not aiming at theory or hypothesis testing.

With respect to the second dimension in Elliott's taxonomy, which concerns the role of theory in EE, we have seen that there exists a clear agreement between Steinle and Burian, namely that EE is performed without making recourse to any well-formed theory or hypothesis concerning the target phenomena. But, unlike Steinle and Burian, Elliott allows for the *limited* involvement of theory or hypothesis in EE. He illustrates this point with a case study drawn from nanotoxicology and suggests that theory can serve as a "starting point or foil" in EE (Elliott 2007, p. 324). Another account that allows for the involvement of theory in EE is that of Laura Franklin (2005). In her account, experiments in contemporary molecular biology are guided by both *background* and *local* theories. While a background theory provides the general systematic knowledge of molecular biology, a local theory is used to describe the properties of the particular objects under investigation. Franklin thus argues that EE in contemporary biology needs only background theories to be successful and that it does not use local theories and, as a result, does not serve to test particular hypotheses. Even though Franklin's case studies show, unlike those of Steinle and Burian,[6] that EE is possible in cases where there is a background theory guiding the experimental research, her account agrees with those of Steinle and Burian in the sense that EE is performed in cases where well-formed theoretical accounts of the target phenomena do not (yet) exist and that, as a result, it is not directly aimed at theory or hypothesis testing.[7]

In Elliott's taxonomy, the third dimension is the only dimension that is intended to distinguish the procedures of EE from those of other types of experiments. This dimension suggests that EE achieves its various goals listed within the first dimension (see Table 1) through systematic variation of experimental parameters. It is to be noted that experiments performed in the biological and physical sciences typically involve variations of relevant experimental parameters. In experimental practice in these sciences, it is unlikely to find a case in which experimentation is performed without varying relevant experimental parameters. This suggests that the characteristics of EE identified within the third dimension of Elliott's taxonomy (see Table 1) can also well be the characteristics of other types of experiments. For instance, testing experiments also involve variations of experimental parameters that are relevant to test the predictions of theoretical accounts. However, it is to be noted that according to the second dimension of Elliott's taxonomy, testing experiments do not qualify as exploratory. Therefore, in order for Elliott's taxonomy to be successful, it should give us a way

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[6] Note that in a later paper, Burian (2007) acknowledges the involvement of background theories in EE.

[7] Karaca (2013) offers a case study on the *deep-inelastic electron-proton scattering experiments*, which are the HEP experiments performed in the late 1960s at the Stanford Linear Accelerator Center (SLAC) and which led to the discovery of *quarks* as the inner constituents of the nucleon. Karaca characterizes these experiments as illustrating that EE is *laden* with background theories of HEP, including quantum field theory and Maxwell's electrodynamics. Karaca also argues that, as in Steinle's and Burian's case studies, the experimental procedure in the foregoing experiments consists in systematically varying experimental parameters in the absence of a well-established theoretical framework about the inner constituents of the nucleon.

to distinguish the variations of experimental parameters in cases of EE from those in other types of experiments.

Note that the second dimension of Elliott's taxonomy implies that the variations of parameters in cases of EE, unlike those of testing experiments, are not prescribed by the theoretical accounts of the target phenomena. However, this does not help us understand what kinds of variations are essential to the exploratory character of experimentation in those cases. Unlike Elliott's taxonomy, Steinle's case study on Ampère's astatic magnetic needle experiment indicates that systematic variations of experimental parameters relevant to EE are those variations that have the potential to give rise to a variety of outcomes, including possibly the ones that are not expected. This means that in Steinle's account, variations of experimental parameters relevant to EE are characterized in terms of their effects on the range of possible outcomes of an experiment. Therefore, even though Elliott's taxonomy includes a variety of experimental procedures to vary experimental parameters in cases of EE (see Table 1), unlike Steinle's account, it does not provide a criterion to differentiate the variations of experimental parameters that are essential to EE from those that other types of experiments might involve. As a result, it does not help us understand how and what kinds of variations of experimental parameters enable experimentation to be exploratory in cases of EE.

3 Experimental exploration through exploratory procedures

The previous section has presented an overview of the different philosophical accounts of EE. According to the common conception of EE shared by these accounts, both the goal of EE and its underlying experimental procedure(s) are decided and implemented in the absence of the well-formed theoretical accounts of the target phenomena. It is to be noted that this common conception of EE restricts to a great extent, if not precludes, the possibility of experimentation being exploratory in well-established research fields, such as present-day HEP which the present paper is concerned with. This is because, in these fields, experimental goals and procedures are typically heavily dependent on the well-formed theoretical accounts of the target phenomena. However, it is to be noted that the above-mentioned accounts of EE have emerged from the conclusions of the various case studies drawn from the history of the physical and biological sciences. Given that these case studies are concerned with particular cases of experimentation in diverse fields, methodologically speaking, it is not warranted to generalize their conclusions and thereby to dismiss the possibility of experimentation being exploratory in well-established research fields.

Instead of taking for granted the above-mentioned common conception of EE, I shall entertain the possibility that in experimental practice there are cases where experiment involves what I call *exploration* in order to pursue its objective(s). I shall propose that experimental exploration consists in carrying out what I call an *exploratory procedure*. Here, I deliberately use the term *experimental exploration* instead of the term EE for the reasons I shall discuss in what follows. In order to characterize exploratory procedures and thus distinguish them from non-exploratory ones, I draw on the way Steinle characterizes systematic variation of experimental parameters as the underlying type of experimental procedure in his case studies on EE. Accordingly, I characterize an exploratory procedure in terms of its effect on the possible outcomes of an experiment and regard it as an experimental procedure that serves to extend the range of possible outcomes of an experiment and thereby the scope of the experimental inquiry to the investigation of a wider range of phenomena. As defined in this way, exploratory procedures contrast with those experimental procedures (such as the ones in Steinle's case studies on TDE) that restrict the range of possible outcomes of an experiment by narrowing down the scope of the experimental inquiry to the investigation of a small number of *pre-determined* possibilities, such as the ones predicted by a particular theoretical account of some target phenomenon.

According to the above characterization of exploratory procedures, systematic variation of experimental parameters without appealing to any theoretical accounts about the target phenomena can be seen as illustrating a particular type of exploratory procedure as it is used in Steinle's and Burian's case studies. This is because, as these cases studies show, EE is enabled through the implementation of the foregoing type of procedures that serve to open up a diverse range of possibilities to investigate the phenomena under investigation, thereby extending the range of possible outcomes of an experiment in the special cases where there (yet) exist no theoretical accounts of the target phenomena. This also suggests that my account subsumes EE as a particular type of experimental exploration that is enabled through a particular type of exploratory procedure, namely systematic variation of experimental parameters.

It is to be noted that, according to the present account, in order for an experiment to involve exploration, it is *not* necessary that all the individual procedures constituting the experimental process be exploratory in the sense suggested above. Otherwise, the possibility of experimental exploration in well-established research fields would be severely limited, because in these fields the experimental process consists of various procedures. Rather, I propose that a particular experimental procedure by itself can be the source of exploration. Therefore, the present account allows for cases in which an experiment can have both *exploratory* and *non-exploratory* components that, respectively, consist of exploratory and non-exploratory procedures and that contribute to the objectives of the experiment in different and complementary ways. The non-exploratory component of an experiment can involve procedures that are aimed at narrowing down the scope of the experimental research to the investigation of specific research questions. Some of these procedures can be driven, in the sense of Steinle's TDE, by the theoretical accounts concerning the target phenomena. This in turn suggests that the present account also allows for the possibility that an experiment can have both exploratory and theory-driven components. Given that experiments in well-established research fields consist of several stages and various procedures, I take the foregoing aspect of the present account to be an important advantage over the aforementioned accounts that characterize the *entire* experimental process as either of the two mutually exclusive types of experiments, namely EE and TDE, thus dismissing the possibility that an experiment can involve both exploratory and theory-driven components. This and the previous considerations also make it clear why I have called the present account *experimental exploration* rather than EE, which is interchangeably used with the term *exploratory experiment* in the relevant philosophical literature.

While the account of experimental exploration is mainly aimed to bring out the exploratory character of experimentation in well-established research fields, it applies to scientific experimentation in general, as it does not presuppose a particular set of objectives for which experimentation involves exploration, or a particular set of experimental methods, techniques or strategies that scientists use to implement exploratory procedures. Therefore, according to the present account, the answers to the questions of "What specific purposes does exploration serve in experimentation?" and "What kinds of experimental procedures are used to enable exploration in experimentation?" depend on the circumstances of the case under consideration.

In the rest of the present paper, I shall proceed as follows. In the next section, I will characterize the problem of data selection in the ATLAS experiment. In Sect. 5, I will argue that this problem is overcome through a particular data selection strategy. In Sect. 6, I will show that the data selection procedure used in the ATLAS experiment is based on the foregoing strategy and argue that it illustrates an exploratory procedure in the sense previously suggested. Finally, in Sect. 7, I will summarize the main conclusions of the present case study and discuss their implications for the epistemology of scientific experimentation.

4 Data selection problem in the ATLAS experiment

As stated in its Technical Design Report[8] (ATLAS Collaboration 2003) for data acquisition, the ATLAS[9] experiment has been designed as a multi-purpose HEP experiment:

> The ATLAS experiment has been designed to cover the physics in proton–proton collisions with a centre-of-mass energy of 14 TeV at LHC. Amongst the primary goals are the understanding of the origin of electroweak symmetry breaking, which might manifest itself in the observation of one or more Higgs bosons, and the search for new physics beyond the Standard Model. For the latter it will be of utmost importance to retain sensitivity to new processes which may not have been modelled. […] In addition, precision measurements of processes within and beyond the Standard Model are to be made.[10] (ibid., p. 33)

The above passage indicates that the ATLAS experiment is aimed to achieve the following sets of objectives: first, to test the prediction of the Higgs boson by the Standard Model (SM)[11] of elementary particle physics as well as the testable predictions of what are called the models *beyond the SM* (BSM), such as supersymmetric and extra-dimensional models, which have been proposed in the HEP literature as

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[8] This is a technical document (approved by the CERN Research Board in 2004) that contains the design information concerning the ATLAS data acquisition system.

[9] ATLAS (A Toroidal LHC Apparatus) is a detector system consisting of different individual detectors, including the inner detector and the calorimeter and muon detectors.

[10] Currently, the collision energy reached at the LHC is 13 TeV.

[11] The SM consists of two main gauge theories; namely, the electroweak theory of the weak and electromagnetic interactions, and the theory of quantum chromo-dynamics (QCD) that describes strong interactions.

possible extensions of the SM;[12] second, to search for *unforeseen* physics processes, i.e., those that have not been predicted by the present HEP models, including possible deviations from the SM at *low* energies.

In the ATLAS experiment, the collision events[13] that have the potential to serve the objectives of the experiment are often referred to as *interesting events*. It is to be noted that the signatures, i.e., stable decay products, predicted by the SM for the Higgs boson are high transverse-momentum (p_T)[14] photons and leptons,[15] and that the signatures predicted by the BSM models for new particles beyond the SM, such as new heavy gauge bosons W' and Z' and supersymmetric particles, are high p_T photons and leptons, high p_T jets as well as high missing and total transverse energy (E_T). In this context, the term *high* refers to the p_T and E_T values that are approximately of the order of 10 GeV for particles, and 100 GeV for jets. The above considerations indicate that the aforementioned high p_T and E_T types of signatures might be produced at the LHC as a result of the decay processes involving the Higgs boson and the aforementioned particles predicted by the BSM models. The same types of signatures might also be produced at the LHC as a result of some *unforeseen* processes. Therefore, the collision events containing high p_T and E_T types of signatures are primarily relevant to the above-mentioned first set of objectives of the ATLAS experiment, thus making them *interesting* for the process of data selection (for details, see ATLAS Collaboration 2003, Sect. 4).

However, in the ATLAS experiment, there is an important obstacle that needs to be overcome in order to acquire interesting events for evaluation. At the LHC, as shown in Fig. 1, the proton-proton collisions give rise to a large *background* of the events containing the well-known processes of the SM that have much higher production rates than those of novel processes predicted by the SM and the BSM models. Since these background processes have been well studied in the previous HEP experiments, such as the LEP experiments at CERN and the DZero and CDF experiments at Fermilab, the collision events containing background processes at the LHC are not relevant to the aforementioned sets of objectives of the ATLAS experiment. The above considerations indicate that the presence of the aforementioned high p_T and E_T types of signatures is what distinguishes the interesting events relevant to the first set of objectives of the ATLAS experiment from the large background of the well-known events of the SM (for details, see, e.g., Ellis 2010; Spagnolo 2008). Therefore, in the ATLAS experiment, the selection of the interesting events relevant to the first set of objectives of the

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[12] See Ellis (2012) for a review of the BSM models and a discussion of the LHC's prospects for the discovery of new physics. Philosophical discussions of the BSM models can be found in Borrelli (2012) and Stöltzner (2014).

[13] In the terminology of HEP, the term *event* denotes "the record of all the products from a given bunch crossing," (Ellis 2002, p. 6) which occurs when two beams of particles collide with each other inside the collider.

[14] Transverse-momentum is the component of the momentum of a particle that is transverse to the proton-proton collision axis, and transverse-energy is obtained from energy measurements in the calorimeter detector.

[15] A lepton is a spin 1/2 particle that interacts through electromagnetic and weak interactions, but not through strong interaction. In the SM, leptons are electron, muon and tau, and their respective neutrinos.

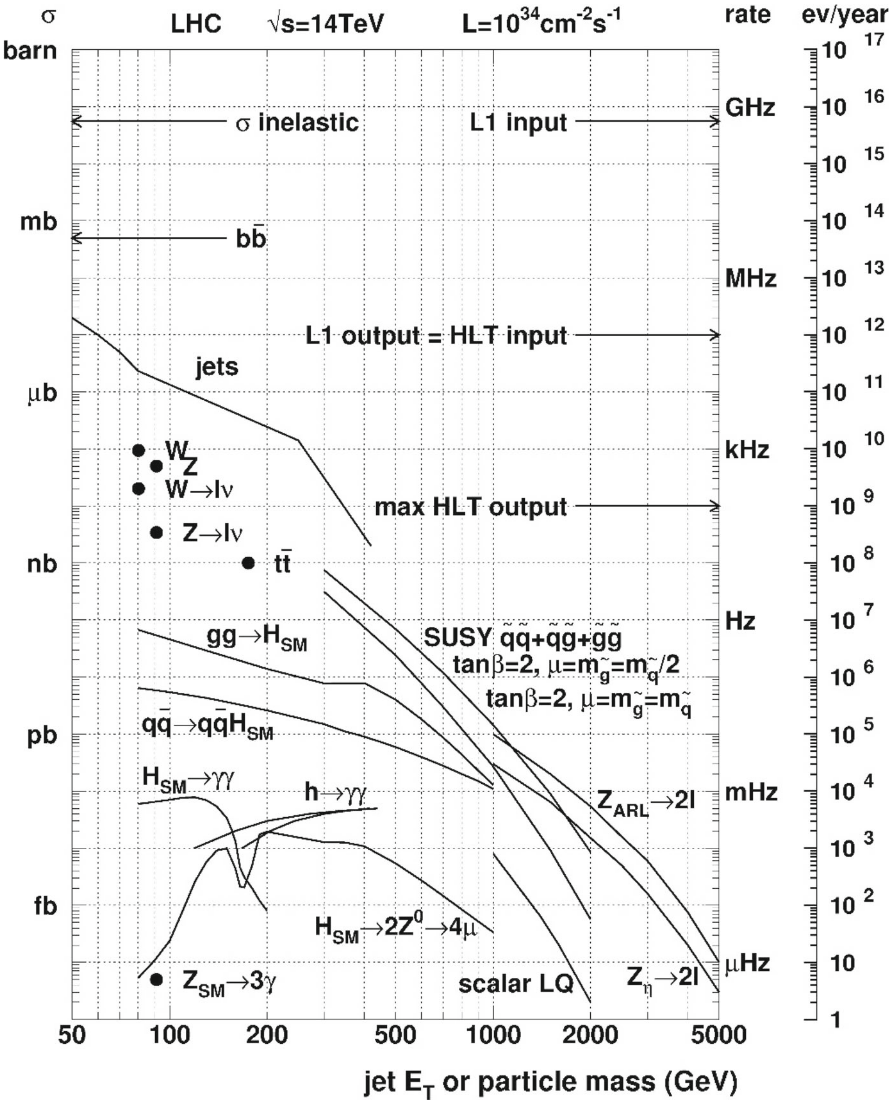

Fig. 1 Expected cross-section and production rates (for a luminosity of 10^{34} cm^{-2}s^{-1}) at the LHC for various processes in proton–proton collisions, as a function of the center-of-mass energy (*Source* Ellis 2002, p. 4)

ATLAS experiment is performed by using selection criteria that consist of *only* the aforementioned high p_T and E_T types of signatures.

In the ATLAS experiment, data selection criteria are applied to collisions events at three different levels through the use of what are called *trigger systems*. These are automated systems designed and used to select the desired events from the collision events.[16] The first stage of the data selection process is carried out by the level-1 trigger system that provides a crude selection of the interesting events in real-time—i.e., during the course of proton-proton collisions at the LHC. In the ATLAS experiment, the initial event rate of the proton-proton collisions is approximately 40 MHz. The first level of the data selection process is performed by the level-1 trigger system, whose technical features allow for an event-acceptance rate of approximately 100 kHz. The second and third levels of the data selection process are respectively carried out by the level-2 and level-3 trigger systems, which are jointly called the *high-level trigger and data acquisition system* (HLT/DAQ). Unlike the level-1 trigger system, which is hardware-based, the HLT/DAQ system is software-based, meaning that the level-2 and level-3 selection processes are performed directly by the specialized software algorithms according to what is called the *trigger menu*, which refers to the set of data selection criteria used in the ATLAS experiment. The level-2 and level-3 trigger systems have much smaller event-accept rates, which are respectively around 2 kHz and 200 Hz, and thereby provide finer selections of the desired events.[17] Therefore, in the ATLAS experiment, the initial event rate is gradually lowered from 40 MHz down to around 200 Hz at the end of the level-3 selection process, meaning that the interesting events are selected from the collision events at a ratio of approximately $200/40{,}000{,}000 = 5 \times 10^{-6}$. The selected collision events are stored for offline data analysis, whereas the collision events that have been rejected by the trigger systems are *irretrievably* thrown away due to the technical limitations in terms of both data-storage capacity and data-process time at the LHC.

It is important to note that the interesting events occurring at the LHC span a wide variety of high p_T and E_T types of signatures across a wide range of p_T and E_T values, i.e., at the energy scale of the order of approximately 10 GeV–1 TeV. However, as the above discussion indicates, due to the aforementioned technical limitations, only a *minute* fraction of the interesting events could be acquired for evaluation. This necessitates, for the fulfillment of the objectives of the ATLAS experiment, that the trigger menu be *sensitive* enough to select the range of types of interesting events that will serve the entire range of objectives of the ATLAS experiment. If the trigger menu were not appropriate to this end, then the data selection procedure would be *biased* against certain types of interesting events. As a result, the ATLAS experiment would fail to achieve some of its objectives, as the fulfillment of a particular objective of the ATLAS experiment requires the acquisition of certain types of interesting events.

5 Data selection strategy in the ATLAS experiment

The discussion in the previous section suggests that a major challenge in the ATLAS experiment is to perform data selection in an unbiased manner with respect to the various objectives of the experiment. This challenge has been addressed through a

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[16] A detailed description of the data selection process in the ATLAS experiment can be found in Karaca (2017).

[17] Note that the aforementioned event-accept rates are valid only for the early data-taking run (Run-1) and have changed significantly during Run-1 and also during Run-2.

particular data selection strategy that aims at increasing the sensitivity of the trigger menu, and thus of the selection procedure, to the extent (allowed by the aforementioned technical limitations) that enables the acquisition of the widest possible range of interesting events that have the potential to serve the entire range of objectives to be pursued in the ATLAS experiment. To this end, the foregoing selection strategy requires the trigger menu to be sufficiently diversified in terms of types of selection signatures that are appropriate for the various objectives of the experiment. Since the ATLAS experiment is largely aimed to test the SM's prediction of the Higgs boson and the predictions of the BSM models, which are considered with guidance from the expectations of the HEP community, the adopted strategy in the first place requires the trigger menu to be sufficiently diversified in terms of selection signatures composed of only high p_T and E_T types of signatures relevant to the aforementioned predictions. For future reference, note that selection signatures composed of only high p_T and E_T types of signatures are often referred to as *inclusive triggers*, in the sense that they constitute the main set of selection criteria in the trigger menu used in the ATLAS experiment. The above discussion suggests that by diversifying the trigger menu in terms of types of inclusive triggers the range of possible outcomes of the ATLAS experiment is extended so as to permit experimental results against which the aforementioned predictions could be tested.

At this point, it is worth noting that inclusive triggers are not appropriate for the search for novel p_T and E_T processes at low energy scale, i.e., below 10 GeV, as they consist of only *high* p_T and E_T types of signatures. In the previous HEP experiments, e.g., the DZero and CDF experiments at the Tevatron Collider at Fermilab, where energies up to 2 TeV have been probed, no deviations from the SM, let alone novel processes at low energy scale, have been detected. However, this does not necessarily mean that at the LHC, where energies up to 13 TeV are currently probed, novel p_T and E_T processes were not to be produced at low energy scale. This is primarily because the current event rate (approximately 40 MHz) at the LHC is considerably higher than the event rate (approximately 2.5 MHz) at the Tevatron Collider. Here, it is to be noted that since novel processes were to occur in rare collision events, event rate, rather than collision energy, is a decisive factor in the production of novel processes at particle colliders and that the higher the event rate, the greater the chance to detect novel processes in HEP experiments.

The selection strategy adopted in the ATLAS experiment also requires the trigger menu to be sufficiently diversified in terms low p_T and E_T types of selection signatures. These selection signatures are referred to as *prescaled triggers* and determined by prescaling inclusive triggers with lower p_T and E_T thresholds (< 10 GeV) (for details, see ATLAS Collaboration 2003, Sect. 4.4.2). In this context, *prescaling* means that the amount of events that a trigger could accept is suppressed by what is called a *prescale factor* in order for the selection process not to be *swamped* by the events containing vastly abundant low p_T and E_T types of signatures, so that the aforementioned first set of objectives of the ATLAS experiment is not endangered. Prescaled triggers are necessary for the trigger menu, and thus of the selection procedure, to be sensitive enough to the search for novel p_T and E_T processes at low energy scale. Since the events containing low p_T and E_T types of signatures have the potential to be of use for some SM studies of strong interactions (see, e.g., ATLAS Collaboration 2015a) as well as to provide support for new physics searches such as providing data for some background estimates, they are primarily relevant to the aforementioned second set of objectives of the ATLAS experiment.[18] Therefore, the above considerations indicate that prescaled triggers permit the acquisition of events that have the potential to serve the detection of novel processes at low energy scale, such as possible deviations from the SM, thereby further extending the range of possible outcomes of the ATLAS experiment.

6 Exploratory data selection procedure in the ATLAS experiment

In this section, I shall discuss how the data selection strategy outlined in the previous section is implemented in the ATLAS experiment in order to establish the trigger menu used for the process of data selection.[19] To this end, I will make use of examples of selection criteria drawn from Table 2 that shows a *sample* trigger menu consisting of some major inclusive triggers used in the ATLAS experiment. Each selection signature given in the left column of Table 2 is represented by the label '$NoXXi$.' Here, 'N' denotes the minimum number of *trigger objects*, namely particles, jets and transverse energy, required for a particular selection, and 'o' denotes the type of signature; e.g., 'e' for electron; 'γ' for photon; 'μ' for muon; 'τ' for tau; 'xE' for missing E_T; 'E' for total E_T; and 'jE' for total E_T associated with jet(s). The label 'XX' above denotes the threshold of E_T (in units of GeV), i.e., the *lowest* E_T at or above which a given selection criterion operates, and 'i' denotes whether the given signature is isolated or not. The right column of Table 2 shows the processes to which the selection signatures in the left column of the same table are relevant (for details, see ATLAS Collaboration 2003, Sect. 4.4).

As the discussion in the previous section suggests, the data selection strategy adopted in the ATLAS experiment requires the trigger menu to be sufficiently diversified in terms of high p_T and E_T types of selection signatures to be used for the testing of the SM's prediction of the Higgs boson (H). This in the first place requires considering the decay processes relevant to the foregoing prediction and thereby identifying the associated high p_T and E_T types of signatures. First, note that in the SM, the Higgs boson could decay into the W and Z bosons, respectively, as follows: $H \rightarrow WW^*$ and $H \rightarrow ZZ^*$, where a '$*$' denotes an *off-shell* boson, i.e., one which does not satisfy classical equations of motions. The W and Z bosons produced in the foregoing decays could subsequently decay into leptons, including electrons and electron neutrinos (ν), as well as into top quarks, as indicated in the first line of the right column in Table 2.[20] In the SM, the top quark could decay into a bottom quark, and a W boson that could subsequently decay into an electron and an electron neutrino. The above considerations indicate that the signatures of the Higgs boson include at least

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[18] Note that these events are also used to determine trigger efficiencies and detector performance.

[19] Note that this discussion is not intended to be comprehensive but rather illustrative of how the adopted strategy is implemented. For a comprehensive discussion, see, e.g., ATLAS Collaboration (2012d).

[20] For a thorough discussion of the decay processes and associated selection signatures relevant to the Higgs boson prediction by the SM, see, e.g., ATLAS Collaboration (2012c).

Table 2 Some major inclusive triggers used at the ATLAS experiment. (*Source* ATLAS Collaboration 2003, p. 38)

Selection signature	Examples of physics coverage
e25i	$W \rightarrow e\nu$, $Z \rightarrow ee$, top production, $H \rightarrow WW(*)/ZZ(*)$, W', Z'
2el5i	$Z \rightarrow ee$, $H \rightarrow WW(*)/ZZ(*)$
μ20i	$W \rightarrow \mu\nu$, $Z \rightarrow \mu\mu$, top production, $H \rightarrow WW(*)/ZZ(*)$, W', Z'
2μ10	$Z \rightarrow \mu\mu$, $H \rightarrow WW(*)/ZZ(*)$
γ60i	Direct photon production, $H \rightarrow \gamma\gamma$
2γ20i	$H \rightarrow \gamma\gamma$
j400	QCD, SUSY, new resonances
2j350	QCD, SUSY, new resonances
3jl65	QCD, SUSY
4j110	QCD, SUSY
τ60i	Charged Higgs
μ10 + e15i	$H \rightarrow WW(*)/ZZ(*)$, SUSY
τ35i + xE45	$qqH(\tau\tau)$, $W \rightarrow \tau\nu$, $Z \rightarrow \tau\tau$, SUSY at large $\tan\beta$
j70 + xE70	SUSY
xE200	New phenomena
E1000	New phenomena
jE1000	New phenomena
2μ6 + $\mu^+\mu^-$+mass cuts	Rare b-hadron decays ($B \rightarrow \mu\mu X$) and $B \rightarrow J/\psi(\psi')X$

one electron with high E_T, meaning that those events that contain at least one electron with high E_T have the potential to contain the aforementioned decay processes of the Higgs boson. Therefore, selection signatures consisting of at least one electron with high E_T are appropriate for the testing of the SM's prediction of the Higgs boson. In Table 2, such a selection signature is illustrated by '$e25i$' that requires at least one isolated electron with an E_T threshold of 25 GeV. It is also to be noted that since the signatures predicted by some BSM models for the new heavy gauge bosons W' and Z' also include leptons, the foregoing type of selection signatures are also appropriate for the selection of the events relevant to the testing of these predictions (see, e.g., ATLAS Collaboration 2015b) as well as to the study of the top quark related processes in the SM, because, as pointed out above, the signatures of the top quark also include electrons.

The trigger menu is further diversified with respect to the SM's prediction of the Higgs boson by considering the following decay in the SM: $H \rightarrow \gamma\gamma$, where the Higgs boson decays into two photons. This decay process indicates that those events that contain at least two photons with high E_T have the potential to contain the foregoing decay of the Higgs boson. Therefore, selection signatures consisting of at least two photons with high E_T are appropriate for the testing of the SM's prediction of the Higgs boson. In Table 2, such a selection signature is illustrated by '$2\gamma 20i$' that requires at least two isolated photons each of which has an E_T threshold of 20 GeV.

Similarly, the adopted selection strategy also requires the trigger menu to be sufficiently diversified in terms of high p_T and E_T types of selection signatures to be used for the testing of the predictions provided by the BSM models which are considered in the ATLAS experiment. To this end, it is necessary that the decay processes relevant to the foregoing predictions be taken into account and that thereby the associated high p_T and E_T types of signatures be identified. In order to illustrate how selection signatures are determined for the testing of the BSM models, in what follows, I shall consider the *minimal supersymmetric* extension of the SM (MSSM), which is currently the most studied BSM model in the HEP literature (see, e.g., Nilles 1984).[21] First, note that the MSSM predicts the existence of *supersymmetric* particles; i.e., for each bosonic (fermionic) particle in the SM, a fermionic (bosonic) *superpartner* with the same internal quantum numbers and mass is predicted.[22] In a publication of the ATLAS Collaboration, the decay processes and associated high p_T and E_T types of signatures predicted by the MSSM are summarized as follows:

> If strongly interacting supersymmetric particles are present at the TeV scale, they may be copiously produced in 7 TeV proton-proton collisions at the [LHC]. In the [MSSM] such particles decay into jets, leptons and the lightest supersymmetric particle (LSP). Jets arise in the decays of squarks and gluinos, [which are respectively the supersymmetric particles predicted by the MSSM to be the superpartners of quarks and gluons,] while leptons can arise in decays involving charginos or neutralinos. A long-lived, weakly interacting LSP will escape detection, leading to missing transverse momentum ($\vec{p}_T^{miss}$ and its magnitude E_T^{miss}) in the final state. Significant E_T^{miss} can also arise in scenarios where neutrinos are created somewhere in the SUSY decay cascade. (ATLAS Collaboration 2012a, p. 1).

The above passage indicates that since the signatures predicted by the MSSM for the squarks or gluinos are jets and missing E_T, selection signatures consisting of various combinations of these signatures are appropriate for the testing of the MSSM. For example, in Table 2, the selection signatures '$j400$', '$2j350$', '$3j165$' and '$4j110$' that consist of different numbers of high E_T jets are appropriate for the testing of the MSSM. As indicated in Table 2, the foregoing selection signatures are also appropriate for the study of the hadronic processes in QCD. Note also that selection signatures consisting of both jets and missing E_T are also relevant for the testing of the MSSM. Such a selection signature, given in Table 2, is '$j70 + xE70$' that denotes the requirement of at least one jet with an E_T threshold of 70 GeV and a missing E_T at or above 70 GeV.

The above passage also indicates that since the signatures predicted by the MSSM for the charginos or neutralinos are leptons and missing E_T, selection signatures

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[21] Note that searches for other types of BSM models are also performed in the ATLAS experiment. A complete set of public results can be found at the URL: https://twiki.cern.ch/twiki/bin/view/AtlasPublic For an overview of the search for supersymmetric particles in the ATLAS experiment; see, e.g., Mitsou (2014).

[22] The previous HEP experiments provided no conclusive evidence for the existence of supersymmetric particles; see Feng et al. (2010).

consisting of various combinations of the foregoing signatures are appropriate for the testing of the MSSM; e.g., in Table 2, the selection signature '$\mu 10 + e15i$' that denotes the requirement of at least one muon with an E_T threshold of 10 GeV and one isolated electron with an E_T threshold of 15 GeV. The same selection signature is also appropriate for the testing of the SM's prediction of the Higgs boson, because, as previously discussed, the signatures predicted by the SM for the Higgs boson also include leptons. The trigger menu is further diversified for the testing of the predictions of the MSSM by incorporating into it other types of relevant selection signatures that consist of various combinations of high p_T and E_T types of selection signatures predicted by the MSSM (for a thorough discussion see, e.g., ibid.; ATLAS Collaboration 2016).

HEP models with extra (spatial) dimensions are another class of BSM models considered for testing in the ATLAS experiment. The adopted selection strategy also requires the trigger menu to be diversified in term of high p_T and E_T types of selection signatures predicted by the extra-dimensional models.[23] Since these models predict signatures consisting of a certain number of high p_T jets, leptons and photons (such as di-lepton, di-jet and di-photon) as well as missing E_T, selection signatures consisting of various combinations of the foregoing signatures are appropriate for the testing of the extra-dimensional models and thus incorporated into the trigger menu of the ATLAS experiment.[24] Such a selection signature, which is not included in Table 2, is '$2\gamma 20$' that denotes the requirement of at least two photons each of which has an E_T threshold of 20 GeV.[25]

Finally, I shall consider the selection criteria '$xE200$', '$E1000$' and '$jE1000$' given in Table 2. Here, '$xE200$' denotes the requirement of a missing E_T at or above 200 GeV, and '$E1000$' and '$jE1000$' respectively denote the requirement of total E_T at or above 1000 GeV and the requirement of total E_T, *only* due to jets, at or above 1000 GeV. The above three selection signatures are not necessarily motivated by the specific theoretical predictions of the current models of HEP. Rather, they illustrate *general-purpose* selection criteria determined according to the adopted data selection strategy, as they are appropriate to select events that have the potential to contain the signatures of unforeseen *high* p_T and E_T processes. Given that the search for the foregoing processes is one of the objectives of the ATLAS experiment, the above three selection criteria illustrate those selection criteria added to the trigger menu in order to potentially increase its sensitivity to the search for novel physics processes that are not predicted by the current models of HEP. It is also important to note that selection criteria appropriate for the testing of the HEP models considered in the ATLAS experiment (namely the SM and BSM models) are also appropriate to select interesting events relevant to the search for unforeseen processes, as the same types of interesting

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[23] Note also that no evidence has been found in the previous experiments regarding the existence of extra dimensions; for a review, see, e.g., Landsberg (2004).

[24] For a detailed discussion of selection signatures that takes into account the differences between the different models with extra dimensions, see, e.g., Kong et al. (2010); ATLAS Collaboration (2012b).

[25] For an analysis based on events selected according to this criterion, see, e.g., ATLAS Collaboration (2012b).

events might also be produced at the LHC as a result of unforeseen processes at high energy scale.

The discussion in this section shows that the data selection strategy implemented in the ATLAS experiment enables the trigger menu to become equipped with selection criteria that are appropriate to carry out a data selection procedure by which to acquire sets of events that have the potential to serve the various objectives of the experiment.[26] Note that if the trigger menu were not established by the aforementioned strategy, it would not be appropriate to carry out such a procedure; as a result, some objectives of the ATLAS experiment would be endangered. Therefore, the data selection procedure based on the trigger menu established by the aforementioned strategy opens up otherwise unavailable possibilities for the ATLAS experiment to fulfill the entire range of its objectives. This in turn suggests that the data selection procedure carried out in the ATLAS experiment illustrates an exploratory procedure—in the sense previously suggested—that serves to extend the range of possible outcomes of the experiment so as to include a wide variety of results concerning the various objectives of the experiment.

7 Conclusions

In this paper, I have provided an account that characterizes experimental exploration in terms of what I call an exploratory procedure whose function is to extend the range of possible outcomes of an experiment. The present account suggests that experimental exploration requires an exploratory procedure to be carried out and that in certain experimental contexts exploration is necessary for an experiment to achieve its objectives. I have illustrated the present account in the case of the ATLAS experiment at CERN's LHC. I have argued that a particular data selection strategy has been implemented in the ATLAS experiment in order to carry out an exploratory data selection procedure that enables the experiment to pursue its various objectives, ranging from the testing of the various predictions by the SM and the BSM models to the search for unforeseen physics processes.

An important conclusion of the present case study concerns the role of the theoretical accounts of the target phenomena in enabling experimental exploration. I have shown that in the case of the ATLAS experiment, in order to implement the above-mentioned data selection strategy, and thus to perform an exploratory data selection procedure, it is necessary to determine data selection criteria in reference to the (experimentally) testable predictions of the theoretical accounts of the target phenomena, namely the SM and the BSM models. This indicates that the exploratory data selection procedure carried out in the ATLAS experiment is *theory-laden* in the sense that its implementation is crucially dependent on the aforementioned theoretical models that the experiment is aimed to test, thus suggesting that theory-ladenness of experimental procedures plays an essential role in experimentation being exploratory. Therefore,

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[26] Note that over the course of the ATLAS experiment, the trigger menu is constantly updated in terms of types of signatures and energy thresholds in order to further increase the sensitivity of the data selection procedure. To this end, the outcomes of the offline sensitivity studies performed by using simulations are also used (see, e.g., Morrison 2015, Chap. 8)

contrary to the widely endorsed conception of EE that suggests that experimentation could only be exploratory in cases where it lacks sufficient theoretical input about the target phenomena, the case of the ATLAS experiment shows that experimentation could also be exploratory in cases where the theoretical input includes a wide variety of theoretical predictions to be tested.

At this point, it is of interest to ask if the theory-ladenness of the data selection procedure carried out in the ATLAS experiment implies that this procedure is also *theory-driven* in the sense of Steinle's account. Note that this is an *epistemological* question that concerns the role of theoretical accounts in the production of experimental knowledge in the context of HEP. In answer to this question, I shall first propose the term *strategy-drivenness* (or *directedness*)[27] of experimentation (SDE) to characterize the kind of guidance provided to an experiment by an experimental strategy that plays the primary role in carrying out an experimental procedure. It is worth noting that SDE, as I propose it, does not entail experimental exploration, as non-exploratory procedures could also be strategy-driven in the aforementioned sense. In the case of theory-driven guidance, the role of theory (or more generally of theoretical considerations) is to prescribe how an experimental procedure is to be carried out, whereas, in the case of strategy-driven guidance, this role is played by an experimental strategy that also prescribes how theoretical accounts about the target phenomena are to be involved in the relevant procedure. It is important to note that the notion of SDE also contrasts with Steinle's notion of TDE, which implies a rather strong sense of theoretical guidance, namely that the different procedures of an experiment—from its design to the interpretation of its results—are prescribed by an overarching theory that accounts for the phenomena under investigation.

Since the ATLAS experiment is a multi-purpose experiment aimed to test the testable predictions by the SM and the BSM models, the involvement of the theoretical accounts of the target phenomena in the procedure of data selection is more complicated than is described by TDE. I have previously argued that this presents a problem of data selection that is overcome by implementing a particular data selection strategy whose primary function is to prescribe to what extent and in what ways the theoretical accounts of the target phenomena are to be involved in the procedure of data selection so as to acquire the range of events that have the potential to serve each of the aforementioned sets of objectives of the ATLAS experiment. This indicates that the involvement of the theoretical accounts of the target phenomena in the procedure of data selection in the ATLAS experiment is through the aforementioned data selection strategy. Furthermore, not only theoretical considerations about the target phenomena, but also experimental considerations regarding the physical circumstances in which the ATLAS experiment is performed are involved in the data selection procedure through the selection strategy. For instance, an important factor that affects the efficiency of the process of data selection in the ATLAS experiment is that the event-acceptance rates of the different levels of the trigger system are constrained by certain technical limitations concerning data-process time and data-storage capacity at the LHC. Note that this factor bears upon the amount of events that a particular trigger could accept and

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[27] Note that this could also read as *method* or *technique-drivenness* in cases where the guidance is provided by a method or technique, respectively.

that it is taken into account by the adopted strategy in specifying the energy thresholds of the triggers. The above considerations suggest that the procedure of data selection carried out in the ATLAS experiment is driven by a particular strategy, rather than by the theoretical accounts of the target phenomena, i.e., the SM and the BSM models, as suggested by TDE.[28]

In conclusion, the present case study shows that the procedure of data selection in the ATLAS experiment is both exploratory and strategy-driven, thereby illustrating that in contemporary HEP, experimenters develop and implement experimental strategies to enable exploration to achieve the objectives of the experiment.

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References

Ackermann, R. (1989). The new experimentalism. *British Journal for the Philosophy of Science*, *40*, 185–190.

ATLAS Collaboration. (2003). ATLAS high-level trigger, data-acquisition and controls: Technical design report. CERN-LHCC-2003-022.

ATLAS Collaboration. (2012a). Further search for supersymmetry at $\sqrt{s} = 7$ TeV in final states with jets, missing transverse momentum, and isolated leptons with the ATLAS detector. *Physical Review D, 86*, 092002.

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[28] Note that Waters speaks of what he calls "investigative strategies." In his account, these strategies are conducive to exploratory research (not just experimentation) in the context of classical genetics, in that they are "aimed towards developing knowledge about phenomena which fall outside the domain, even the potential explanatory domain, of any existing theory" (Waters 2004, p. 786). Elliott refers to these strategies as "exploratory strategies" that "play something like the traditional role of "theory" in a particular domain" and that are conducive to exploratory experimentation (Elliott 2007, p. 327). He also suggests that "the entire discipline of nanotoxicology may be structured more by exploratory strategies than by a single, high-level theory" (ibid., p. 331). In the context of HEP experiments, Allan Franklin (2002, pp. 3–6) argues for a (non-exhaustive) list of what he calls "epistemological strategies that can be used to defend the correctness of an experimental result" (ibid., p. 162). The strategies Franklin illustrates with various case studies are not necessarily dictated by specific theoretical accounts, even though their implementations may be dependent on them to varying extents. The arguments presented in the present paper and the above-mentioned papers by Waters, Elliott and Franklin, notwithstanding the contrasts between them, show that experimental strategies can be more operative in experimental research (in diverse fields such as HEP, classical genetics and nanotoxicology) than theoretical accounts, thus undermining the theory-dominated conception of experimentation.

ATLAS Collaboration. (2012b). Search for extra dimensions using diphoton events in 7 TeV proton-proton collisions with the ATLAS detector. *Physics Letters B, 710*, 538–556.

ATLAS Collaboration. (2012c). Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Physics Letters B, 716*, 1–29.

ATLAS Collaboration. (2012d). Performance of the ATLAS trigger system in 2010. *European Physical Journal C, 72*, 1849.

ATLAS Collaboration. (2015a). Measurement of $D^{*\pm}$, $D^{\pm}$ and $D_s^{\pm}$ meson production cross sections in *pp* collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. *Nuclear Physics B, 907*, 717–763.

ATLAS Collaboration. (2015b). Search for high-mass diboson resonances with boson-tagged jets in proton-proton collisions at $\sqrt{s}$ =8 TeV with the ATLAS detector. *Journal of High Energy Physics*, *12*, 55.

ATLAS Collaboration. (2016). Search for supersymmetry at $\sqrt{s}$ =13 TeV in final states with jets and two same-sign leptons or three leptons with the ATLAS detector. *European Physical Journal C, 76*, 259.

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

Burian, R. M. (1997). Exploratory experimentation and the role of histochemical techniques in the work of Jean Brachet, 1938–1952. *History and Philosophy of the Life Sciences*, *19*, 27–45.

Burian, R. M. (2007). On microRNA and the need for exploratory experimentation in post-genomic molecular biology. *History and Philosophy of the Life Sciences*, *29*, 285–312.

CMS Collaboration. (2012). Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Physics Letters B, 716*, 30–61.

Elliott, K. C. (2007). Varieties of exploratory experimentation in nanotoxicology. *History and Philosophy of the Life Sciences*, *29*, 311–336.

Ellis, N. (2002). The ATLAS years and the future. Talk given at a half-day symposium at the University of Birmingham, July 3^{rd}, 2002. http://www.ep.ph.bham.ac.uk/general/outreach/dowellfest/.

Ellis, N. (2010). Trigger and data acquisition. In *Lecture given at the 5th CERN-Latin-American School of High-Energy Physics, Recinto Quirama, Colombia*, 15–28 Mar 2009. CERN Yellow Report CERN-2010-001, pp. 417–449. http://lanl.arxiv.org/abs/1010.2942.

Ellis, J. (2012). Outstanding questions: Physics beyond the Standard Model. *Philosophical Transactions of the Royal Society A*, *370*, 818–830.

Franklin, A. (2002). *Selectivity and discord*. Pittsburgh: University of Pittsburgh Press.

Franklin, L. R. (2005). Exploratory experiments. *Philosophy of Science*, *72*, 888–899.

Feng, J. L., Grivaz, J. F., & Nachtman, J. (2010). Searches for supersymmetry at high-energy colliders. *Review of Modern Physics*, *82*, 699–727.

Gooding, D. C. (1989). ‘Magnetic curves’ and the magnetic field: Experimentation and representation in the history of a theory. In D. C. Gooding, T. Pinch & S. Schaffer (Eds.), The uses of experiment (pp. 183–223). Cambridge: Cambridge University Press.

Hofmann, J. R. (1987). Ampere, electrodynamics, and experimental evidence. *Osiris*, *3*, 45–76.

Karaca, K. (2013). The strong and weak senses of theory-ladenness of experimentation: Theory driven versus exploratory experiments in the history of high-energy particle physics. *Science in Context*, *26*, 93–136.

Karaca, K. (2017). Representing experimental procedures through diagrams at CERN’s Large Hadron Collider: The communicatory value of diagrammatic representations in collaborative research. *Perspectives on Science*.

Kong, K., Matchev, K., & Servant, G. (2010). Extra dimensions at the LHC. In G. Bertone (Ed.), *Particle dark matter: Observations, models and searches* (pp. 306–324). Cambridge: Cambridge University Press.

Landsberg, G. (2004). Collider searches for extra dimensions. *Electronic Conference Proceedings Archive*, C040802:MOT006. http://arxiv.org/abs/hep-ex/0412028.

Mitsou, V. A. (2014). Highlights from SUSY searches with ATLAS. *European Physical Journal Web of Conferences*, *70*, 00072.

Morrison, M. (2015). *Reconstructing reality: Models, mathematics, and simulations*. Oxford: Oxford University Press.

Nilles, H. P. (1984). Supersymmetry, supergravity and particle physics. *Physics Reports*, *110*, 1–162.

Sargent, R. M. (1995). Exploratory experiments: Scientists at play. Unpublished manuscript delivered at History of Science Society Annual Meeting, Minneapolis, October 27–29, 1995.

Spagnolo, P. (2008). Prospects for discovering new gauge bosons, extra dimensions and contact interaction at the LHC. Talk given at the 34th International Conference on High Energy Physics, Philadelphia. http://arxiv.org/abs/0810.0414.

Steinle, F. (1997). Entering new fields: Exploratory uses of experimentation. *Philosophy of Science*, *64*, 65–74.

Steinle, F. (2002). Experiments in history and philosophy of science. *Perspectives on Science*, *10*, 408–432.

Stöltzner, M. (2014). Higgs models and other stories about mass generation. *Journal for General Philosophy of Science*, *45*, 369–386.

Waters, C. K. (2004). What was classical genetics? *Studies in History and Philosophy of Science*, *35*, 783–809.

Waters, C. K. (2007). The nature and context of exploratory experimentation: An introduction to three case studies of exploratory research. *History and Philosophy of the Life Sciences*, *29*, 275–284.