Igniting Realism- Where There's Signature, There's Phenomenon

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Abstract

This paper aims to establish and defend a realist position focused on scientific phenomena, particularly in the context of particle physics. Building on insights from scientific practice, the study addresses the limitations of previous realist positions and acknowledges the trend towards local realism. The primary objective is to develop an inferential blueprint that integrates theoretical and ontological layers, with a central focus on the concept of scientific phenomena. The framework is based on bottom-up inferences, specifically identifying robust patterns called 'signatures,' which can be inferred from the data and causally related to the phenomenon, analogous to traces of smoke indicating fire. A phenomenon can be stabilized bottom-up by utilizing multiple partially converging signatures, demonstrating resilience even in the presence of theoretical changes. Theoretical models can serve as a supportive structure atop this stable foundation, encouraging the search for additional signatures.

Keywords: Scientific Realism, Philosophy of Physics, Experimental Data, Phenomenon, Signatures, Inferential Blueprint

Introduction

Consider a scenario where you spend a night in a snow-covered mountain cabin. Upon waking up, you notice an intriguing set of events: your entire house has been meticulously cleaned, with peculiar footprints within the premises and the disappearance of last night's simmering soup. If these events in the cabin reoccur and consistently coincide, it indicates, as traces, the likelihood of a shared origin. According to English folklore, such occurrences are attributed to Hobgoblins, mischievous creatures that engage in household activities, consume food, and leave behind footprints, but elude everyone's gaze.

However, should we accept the reality of Hobgoblins? The hypothesis regarding Hobgoblins may be subject to future revision. Nevertheless, the events, which could be traces caused by the inaccessible Hobgoblin, can persist even when the hypothesis about the cause changes. It remains crucial to demonstrate the robustness of these traces, confirming their non-random nature and indicative relationship to a common cause. By analyzing the traces, one can further aim to uncover potential properties of the cause—an entity or effect responsible for leaving footprints, engaging in cleaning activities, consuming soup, and more.

Ultimately, the investigation may lead us to a phenomenon resembling the theoretical concept of a Hobgoblin. However, we followed only a bottom-up methodology, grounded in empirical evidence, as illustrated in Figure 1.

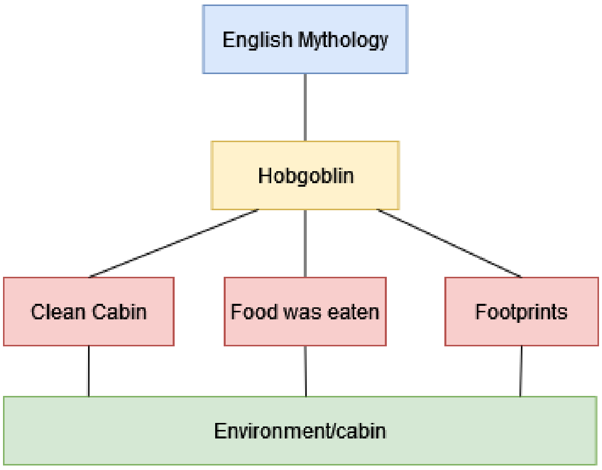

Figure 1: Schematic overview of the different layers of the inquiry. At the investigation's core lies the traces' causal origin, referred to as the 'Hobgoblin.' The key proposition is that this causal origin persists even when the Hobgoblin theory no longer applies. The scheme further accommodates both top-down and bottom-up inferences.

What parallels exist between the Hobgoblin scenario and scientific pursuits? In high-energy physics, particles like the Higgs boson and quarks are often inaccessible and unobservable due to their short lifespan or the requirement of immense energy for isolation. Instead, they are detected indirectly through decay products or traces of interactions with other objects. This raises questions about the reality of these entities. Proponents of scientific realism rely on the truth of the theory in which the entity was proposed, following a top-down, theory-laden approach. However, history has shown the downfall of numerous past theories. Even from an entity realist standpoint, where successful manipulation with an entity serves as evidence for its reality, the attribution of properties to the entity may still require some reliance on a theoretical framework, reintroducing theory-laden assumptions into the analysis. Additionally, what about non-manipulable entities? Alternatively, a bottom-up approach, similar to the Hobgoblin case, can be considered. This approach involves inferring relevant information about the phenomenon from empirical data via robust traces caused by the presumed phenomenon.

This paper aims to establish such a realist position by focusing on stabilizing scientific phenomena bottom-up and introducing their corresponding traces, called signatures. I have three main objectives. First, I define the concepts of data, signatures, and phenomena, building upon existing distinctions [Bogen & Woodward 1988, Maettig & Stoeltzner 2020]. Second, I argue for local realist commitments and causal inferences, highlighting the importance of causal relationships between phenomena and signatures. This draws on insights from [Brading 2010] and [Egg 2012, Egg 2014]. Finally, I develop an inferential blueprint centered around the scientific phenomenon, integrating ontological and theoretical layers as well as different kinds of inferences.

Therefore, in Section 1, I explore scientific realism and entity realism and address fundamental questions regarding the nature of *theory commitment*, the *scope* of the realist position, and the *stabilization* of the respective realist posits. I argue for pursuing local realist commitments instead of global ones and how realism in science can be motivated.

In Section 2, I discuss the reality of observations and extend this to experimental data, especially those produced in large-scale high-energy physics experiments. I introduce the role of models in data analysis and the concept of signatures that go beyond data models. I argue that our realist commitment should be reserved for robust signatures that are repeatedly and reliably inferred, autonomous from high-level theories, and translatable between experiments.

Further, in Section 3, I introduce phenomena as hidden regularities that are causally related to signatures. I demonstrate the importance of multiple signatures for stabilizing a phenomenon and discuss the criteria for causal warrant. To illustrate these concepts, I use examples like the Higgs boson and the diphoton excess signal at 750 GeV.

Finally, I present an inferential blueprint, in Section 4, that integrates data, models, phenomena, and signatures. Overall, this framework emphasizes the central role of the phenomenon while accommodating multiple theoretical models, data sets, and signatures. I further provide examples of its application to other disciplines.

1 The Quest for Reality - Aims & Problems

Before delving into the development of a new realist position, I will examine the *theory commitment*, *scope*, and the *stabilization of realist posits* in scientific realism and entity realism, which will serve as a foundation for motivating the need for a novel realist position.

1.1 Scientific Realism and Entity Realism

Scientific realism and entity realism are potential positions for arguing the reality of scientific objects. Scientific realism asserts that we have justifiable grounds to believe in the (approximate) truth of our best scientific theories. This viewpoint is supported by the No Miracles Argument (NMA) [Putnam 1975a], which states that the empirical success of science would be a miracle if our best and most advanced theories were not (approximately) true and their postulated entities were not real. In the realm of particle physics, adopting scientific realism would lead to the acceptance of the truth of the Standard Model (SM), which is currently considered the most successful and empirically supported theory. Additionally, this position affirms the reality of SM particles, including quarks, gluons, and the Higgs boson. The general theory commitment of scientific realism faces challenges such as the Pessimistic Meta Induction (PMI) [Laudan 1981], which argues that past scientific theories like the phlogiston theory, the electromagnetic ether, and the caloric theory of heat were found to be false or incomplete. These cases raise concerns about the truth status and reliability of our current theories. Additionally, the Underdetermination of Theory by Evidence (UTE) poses a threat to realist commitment. It suggests that different non-inclusive theories can be compatible with the available data, making it difficult to justify a commitment based solely on the evidence. For example, in classical mechanics, conclusions regarding the resting frame are underdetermined, allowing different conclusions about the sun's behavior, such as being at rest or moving with a constant velocity. Furthermore, the Problem of Unconceived Alternatives (PUA) [Stanford 2006] states that future scientific theories may significantly differ from our current ones due to the underdetermination of theoretical descriptions by empirical evidence. This highlights the inherent uncertainty and provisional nature of scientific knowledge. These challenges contribute to the problem of *stabilization*, where realist posits lack sufficient support in the face of potential theory changes.

However, in addressing the *stabilization* problem, the position of scientific realism also encounters a *scope* problem. The claim of truth for **all** mature and successful theories, is a high-level hypothesis, and therefore, especially vulnerable to arguments like the PMI.[Henderson 2017] To address this issue, we can consider realist commitments with the following *scope*: specific components of theories that are responsible for empirical success. By only committing to the reality of these components, which are preserved in more recent theories, we can adopt a more selective approach to realism (cf. [Kitcher 1993], [Psillos 1999], or [Chakravartty 2011]). This can also mean reducing the *scope* of the realist commitment to the indispensable entities of our best theories and becoming entity realists.

Entity realism, also known as experimental realism, was originally proposed by [Hacking 1983] as a realist position that focuses solely on the reality of entities, which refer to (un)observable objects, events, processes, properties, or relations within scientific theories, rather than considering the truth of scientific theories. The existence of an entity is established by being regularly manipulated to produce controllable effects, e.g., they need to be used as tools to create other well-known effects à la the famous *'if you can spray them, they* *are real*[1]' [Hacking 1983, p. 23]

This account is grounded in scientific practice and the premise that successful manipulation of an entity confirms its reality. In other words, an entity that can be effectively manipulated, such as shooting a projectile, undoubtedly exists.

[Cartwright 1983] also offers a version of entity realism, placing special importance on the specific inferences made from observable effects to unobservable causes: *"[...] the peculiar features of the effect depend on the peculiar nature of the cause [...]"* [Cartwright 1983, p. 76]. Her approach aims to uncover the causal mechanisms behind phenomena and relies on a more nuanced understanding of how causes and effects are related. Further:

> When I infer from an effect to a cause, I am asking what made the effect occur, what brought it about [...] An explanation of an effect has an existential component.
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> [Cartwright 1983, p. 91]

To illustrate this, Cartwright presents the example of a lemon tree with yellow leaves. One may infer that the cause of this effect is a lack of water and subsequently dig a hole to search for water. A similar line of reasoning was applied to electrons, positing them as the cause for tracks observed in a cloud chamber, drawing an analogy to vapor trails in the sky generated by airplanes. However, when dealing with claims of existence regarding unobservable entities, it is not a simple matter to ascertain the justification of such claims. Additionally, the question arises as to what extent an entity can exist independently from the theoretical framework in which it was initially formulated. Moreover, as argued by [Psillos 2003], theoretical laws resurface as they are *"the most plausible candidates for explaining why objects have the capacities to do what they can do."* [Psillos 2003, p. 3]. Consequently, counterarguments such as the PMI, UTE, and PUA also reemerge as pertinent challenges within this context.

According to Hacking and Cartwright, it is not necessary to rely on comprehensive theoretical models. Instead, one can adopt a commitment to *"causal principles [and] [...] phenomenological laws"*[Cartwright 1983, p. 8].[2] or focus on *truths [and] [...] well-understood causal properties* [Hacking 1983, p. 265].

However, a challenge persists in distinguishing between phenomenological laws and comprehensive theories, as no clear criterion exists to make this distinction [Clarke 2001]. Moreover, focusing on causal principles or well-understood causal properties only, may give rise to rival entities capable of explaining the same data. The distinction between these entities can only be made by incorporating further theoretical assumptions, but then the challenges posed by the PMI, UTE, and PUA once again threaten the realist

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[1] Referring to electrons and protons sprayed (probed) on superconducting metal spheres to increase charges.

[2] Cartwright distinguishes between 'phenomenological laws' and 'theoretical/fundamental laws,' where the former, such as the Rydberg formula of the hydrogen spectrum, may not offer explanatory power but are approximately true, while the latter, like the Schrödinger equation, explain without necessarily being true. [Cartwright 1983]

commitment.[3]

However, one possible approach is to consider just the existential component of the cause, as suggested by Cartwright, or just focus on the existence of the entity itself, with which one can manipulate as proposed by Hacking. In the context of the Hobgoblin thought experiment, this would mean acknowledging the existence of the Hobgoblin as a cause, while refraining from assigning any specific properties to it beyond its mere existence:

> To believe in an entity, while believing nothing further about that entity, is to believe nothing, I tell you that I believe in hobgoblins (believe that the term 'hobgoblin' is a referring term). So, you reply, you think there are little people who creep into houses at night and do the housework. Oh no, say I, I do not believe that hobgoblins do that. Actually, I have no beliefs at all about what hobgoblins do or what they are like. I just believe in them.
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> [Musgrave 1996, p. 20]

This would entail a very low realist commitment. The world would consist of 'electrons', 'quarks', and 'Hobgoblins', but we would have no additional information.

Moreover, entity realism, particularly in the sense proposed by Hacking, raises the issue of *scope*, as it entails only the manipulable entities. This raises questions about the inclusion or exclusion of non-manipulable entities. Does manipulability serve as a necessary criterion for ascribing reality? [Egg 2014]

This would exclude astrophysical objects as they cannot be actively manipulated in a laboratory setting. [Hacking 1989]

Furthermore, there is the challenge of addressing historical sciences such as geology, cosmology, and evolutionary biology. The objects studied in these fields are not amenable to active manipulation.[Gross 1990, p. 34][4]

The question of *stabilization* also arises in the context of entity realism. Can entity realism effectively stabilize its posits, or does it become too permissive? [Gelfert 2003] addresses this question focusing on entities that have already been refuted but still retain a sense of manipulability, such as unoccupied electron states (holes), and magnons (coherent excitations of electron spins). Gelfert's analysis highlights that even in the absence of certain entities, a form of manipulation can still be attributed, leading to

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[3] A case study conducted by [Massimi 2004] on quarks and partons exemplifies this challenge. Both quarks and partons provided equally plausible explanations for the empirical evidence until a 'choice' was made in favor of quarks. However, it was only through the adoption of the Quantum Chromodynamics (QCD) theory that an experimental result from the CDHS experiment could be properly interpreted by considering quarks instead of partons. However, if the choice had been based solely on experimental data, the determination of the appropriate entity would have been underdetermined at the lower level of phenomenological laws, with quarks and partons remaining equivalent.

[4] [Shapere 1993] proposes a different interpretation of Hacking's notion of 'to use,' suggesting that it encompasses not only active manipulation but also the employment of ontological objects in a weaker sense. However, this weak sense of 'to use' raises concerns about the extent to which we can make realist commitments to entities without knowing the specific properties to which we actually attribute 'the usage'

observable effects. However, this line of reasoning can potentially lead to what Gelfert terms ‘inflationary realism’ [Gelfert 2003, p. 257], which implies a proliferation of entities, due to a commitment to manipulability or cause-effect relations.

1.2 Problems Revisited

To justify a realist commitment, it is crucial to address the critical questions raised in the previous discussion. These questions help identify weaknesses in arguments supporting realism and can guide the development of new positions. In summary, we have:

The *theory commitment* question: Arguments for the (approximate) truth of scientific theories face challenges such as the PMI, the UTE, or the PUA. In the context of entity realism, criticism arises regarding the theoretical basis of the entities. By relying solely on minimal theoretical descriptions, the entities may be experimentally underdetermined. Deciding between competing phenomenological entities necessitates a commitment to a theoretical framework, thereby reintroducing the above-mentioned challenges. On the other hand, not relying on any theoretical description leads to the concept of an ‘empty’ entity, lacking defining properties. Determining the appropriate degree of commitment, whether it involves a few causal principles or a higher-level framework, is crucial in addressing the question of *theory commitment*.

The *scope* question raises concerns about the breadth of a realist commitment, particularly in response to the *theory commitment* question. Entity realism, for example, may be considered too narrow if it only encompasses manipulable entities in laboratory settings, excluding astrophysical and historical entities. Realist positions inherently depend on the extent of their commitment to entities, theories, or structures. Even anti-realist positions like constructive empiricism, as proposed by Van Fraassen, entail a realist commitment to observable aspects of the world. The *scope* needs to be defined in a manner that upholds the epistemological assertion that science unveils aspects of reality while maintaining appropriate boundaries.

The *stabilization* question pertains to the extent to which realist positions can achieve stability. Failed stabilizations, such as overthrown theories (scientific realism) or misguided manipulation (entity realism), exemplify the challenge. This question is closely linked to the problem of *theory commitment* but also raises another concern: how can we establish a robust and stable realist position without excessively narrowing its scope? Even the causal inferences in the extreme notion of an empty entity, as suggested by [Musgrave 1996], may still lack *stabilization* as the ‘observable phenomenon’ could be just an artifact.

1.3 Motivating the Quest for Realism - Going Local?

The intertwined questions discussed earlier present significant challenges to any potential realist position. Is embracing anti-realism regarding unobservable entities or scientific theories an easy way out? However, it should be noted that most anti-realists do not reject all aspects of reality. As [Egg 2014, p. 4] points out, referring to [Boyd 2010], anti-realists often hold beliefs in entities, which are part of common sense realism: *“We* *believe in tropical fish realism; that there are tropical fish, that they behave and look like described in little booklets [...] The fish have properties independent from theories"*. Anti-realist arguments typically target specific aspects of scientific realism that diverge from common sense realism. Hence, realism can be seen as a response to criticisms raised by anti-realists, thereby focusing on shared posits can be our starting point.

What motivates the justification of realist commitments beyond common sense? One motivation is to uphold the credibility of science by asserting its capacity to uncover aspects of reality. This aligns with Michela Massimi's perspective:

> I have always been of the view that a realist stance on science offered a safeguard to a society where trust in science was being eroded before our eyes.
>
> [Massimi 2022, p. 3]

Hasok Chang expresses similar thoughts in *Realism for Realistic People*, as he writes:

> In a world filled with so much misinformation, ignorance, prejudice, deception and mistrust, where can we turn for reliable facts, insightful theories, and guidelines for action? I am old-fashioned enough to believe that science and the scientific attitude constitute our best hope. [...] People will think: if evolution is not completely proven, it is 'just a theory' to be treated equally with creationism.
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> [Chang 2022, p. 1]

Realism serves as a motivation to enhance the credibility of science by distinguishing it from conspiracy theories and unscientific reasoning. The level of realist commitment could determine how science is perceived by the public.

Additionally, it is observed that scientists themselves often disregard the ongoing philosophical debate on scientific realism, and challenges such as the PMI and other counterarguments. For instance, Rutherford's belief in the reality of alpha particles, based on years of experimentation, illustrates this attitude: *"having performed experiments with such particles for some years, it was natural for him to believe in their reality"*[Egg 2014, p. 4].

This encourages a shift towards focusing on actual scientific practice and the progress achieved through experiments, rather than solely relying on overarching theories and absolute Truth. It suggests that a more localized approach to realism, considering the specific circumstances of each scientific inquiry, may be beneficial.

This trend is reflected in the realism debate through the adoption of methodological localism. Rather than making comprehensive realist commitments to entire sets of theoretical statements, case-by-case evaluations can be embraced. The fundamental unit of analysis can be a scientific field, a sub-branch, or even an individual scientific claim.[5]

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[5] Even within a discipline such as physics, there are statements about a great variety of objects, from quarks to galaxies. We could consider the particular empirical evidence regarding each claim and e.g be realists regarding electrons but not quarks.

While the localist approach allows for extensive granularity in considerations, it can potentially lead to hyperlocalism, characterized by a minimal realist commitment: *“ [...] reduc[ing] scientific realism to indefinitely many forms of realism about single, individual theses”* [Asay 2019, p. 602].

This paper still aims to develop a position that applies to science more broadly, but utilizing local inferences and actual scientific practice to create an inferential blueprint. With an awareness of the issues that need to be addressed and a renewed motivation for the pursuit of realism, we can now delve into the core focus of the paper: determining what aspects we should adopt a realist stance towards.

2 Introducing Data, Models & Signatures

2.1 Data & Models of Data

Agreements between anti-realists and scientific realists can exist regarding the reality of observable objects, such as chairs, tables, and trees, reflecting commitments to common sense realism or empiricism. This means further to believe in the reality of observable objects in the Hobgoblin thought experiment, such as items in the cabin, dust, and food. This commitment is necessary to not render discussions about the reality of, e.g neutral currents, the Higgs boson, neural activity or Hobgoblins, meaningless.

Further, the question of what qualifies as ‘observable’ can be raised. The (constructive) empiricist viewpoint is challenged by instruments like microscopes and telescopes, which extend our visual sense. Kitcher proposes the ‘Galilean strategy,’ which argues that when a telescope reliably produces empirically accessible images in one domain, such as the boats on the Venetian shore, it can be deemed reliable in other domains, making those domains observable. This blurs the line between observable and unobservable distinctions and allows for a commitment to conventionally (with the senses) unobservable posits. Consequently, we can become realists about “appearances” (observable phenomena in the sense of [Van Fraassen 1980]), perceivable with both unaided and aided senses.

Quantifying the appearances yields observational data, which can be regarded as *“individual events or their representations, which can be thought of as of the type written-down-in-the-lab-book”* [Teller 2010, p. 816]. For instance, reading different liquid levels from a thermometer provides observational data for temperature measurement, independent of theoretical concepts. While theoretical assumptions can influence data interpretation, they do not affect the acquisition or understanding of the observational tool itself, such as the eye or telescope. Observational data remains the same regardless of theory changes, supporting its ontological existence.

Now, let’s consider extending our commitment to experimental data, specifically data that do not correspond directly to appearances. In high-energy physics (HEP), where a significant amount of data is generated through experimental processes that involve various theoretical and experimental judgments in the design of data acquisition systems and multiple selection steps before the data becomes accessible, theory-ladenness in experimentation (TLE) becomes relevant. [Kuhn 1970, Karaca 2013]

Let's consider the ATLAS experiment at the Large Hadron Collider (LHC) as a concrete example of a HEP experiment [Atlas 1997]. The main detector includes multiple layers, including tracking chambers. These chambers consist of a pixel detector (around 100 million read-out channels), a semiconductor tracker (six million read-out channels), and a Transition Radiation Tracker (TRT) with approximately 350,000 read-out channels.

Additionally, calibration and clustering techniques are applied to correct for various effects caused by misplaced voltages, gas mixtures, and other misalignments. The overall purpose of the multi-layered detection and analysis system is to reduce and analyze the data before reconstructing physics objects such as tracks consisting of interaction points.

Regardless of the system's complexity, we can include experimental data in our realist commitment by treating theory-ladenness in a similar manner as we did for observational data. The crucial aspect lies in determining whether we actively intervene in the system or simply detect its behavior, and how the underlying theory of the target object affects the functioning of the experimental apparatus.

For instance, Shapere argued that we can directly observe the sun's interior through neutrino experiments, despite its hidden nature behind opaque layers. He concluded that the original informational content remains unaltered, allowing us to 'see' the sun's interior [Shapere 1982, p. 492]. This is comparable to human vision, which involves multiple stages such as light entering the retina, transduction by photoreceptive cells, transmission through the optic nerve, and ultimately reaching the visual cortex. Despite these stages, the flow of information remains intact.

Interventions, such as actively tweaking parameters, *"twisting the lion's tail"* [Hacking 1983, p. 246], can disrupt the flow of information. The size, complexity, or number of stages in an experimental setup is not relevant in this context of theory-ladenness.

According to Hacking, a bubble chamber is a detector that relies on theories for its operation and construction. However, the question arises: is "seeing" an electron track, or a curved track, theory-laden in a detrimental way? Using a microscope or relying on human vision does not depend on a theory of electrons for their functioning and operation, as they are based on optical principles independent of the object under investigation (ibid, p.186-209). This implies that if the theory of the experiment is separate from the subject matter, it can be considered an observation [Hacking 1983, Malik 2017].

Similarly, the flow of information can also remain unchanged in high-energy physics (HEP) experiments, as discussed by [Karaca 2013], by distinguishing *senses of theory-ladenness.*[6] In the strong sense, theories guide HEP experiments by setting up the experiment and analyzing the data based on a theoretical target. On the other hand, theory-ladenness in the weak sense refers to the use of theoretical considerations that do not guide the experimental process itself. The construction and operation of HEP

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[6] This distinction is based on work by [Steinle 1997], differentiating between *theory-driven* and *exploratory* experiments, where the first is experimentation with a well-formed theory in mind regarding design and evaluation. The latter concerns various exploratory strategies, such as varying experimental parameters or looking for stable empirical results.

facilities require theories, but they are not always necessary for the specific target of inquiry. [Karaca 2013]

[Suppes 1962] defined the concept of a 'model of experiment,' which includes background information such as the number of trials and experimental parameters, without affecting the flow of information. Therefore, weakly theory-laden experimental data can be included in our realist commitment if we embrace realism about appearances and observational data.

Moving from the data to the explanation of scientific processes raises the question of how to proceed. In HEP experiments like the ATLAS detector, we obtain numerous electronic signals. In order to bridge the gap between data interpretation and theory prediction, researchers can employ data models or models of data. These models, as described by [Frigg & Hartmann 2006], can be corrected, rectified, and idealized versions of the data, serving to reduce data volume by selecting important data points or performing curve fitting. They can also facilitate extrapolation into other domains. [Suppes 1962]

[Teller 2010] further explains that concrete objects can be seen as data models, as the theoretical interpretation applied from the model of experiment provides a more comprehensive representation than the uninterpreted raw data itself.

A data model can incorporate essential information about the data, *"summarizing relative frequencies found in data"*[Van Fraassen 2008, p. 167] and emphasizing qualitative judgments according to [Leonelli 2019]:

> In deciding what counts as useable data, researchers define the evidential scope of their investigation, that is, the range of phenomena that they will be able to consider once they start clustering and ordering data in ways that may help to interpret them as evidence.
>
> [Leonelli 2019, p. 2]

However, *"data models have no ontological fixity"* [Leonelli 2019, p. 20], as they are theoretical constructs. In this article, the focus is on data models that involve data reduction, statistical methods, and filtering of specific frequencies, while also accommodating qualitative preferences, similar to the act of directing a telescope towards specific objects.

Data models can be connected to higher-level models to interpret the data, following the hierarchical framework proposed by [Suppes 1962]. Figure 2 provides a simplified illustration of this hierarchy, distinguishing high-level theoretical models, lower-level data models, and intermediate mediating models [Morrison & Morgan 1999]. These model layers are theoretical constructs that do not directly correspond to ontological objects. However, our ontological commitment and realist stance currently focus on the lower levels of the hierarchy, including "the world" (all there is, but not necessarily accessible), appearances (observations), and data. The previous discussion established that if appearances are ontological, so are data. Now, the question arises whether our realist commitment can be extended to include physics objects. Are they found in the data or do they need to be incorporated into the theory? In order to address this

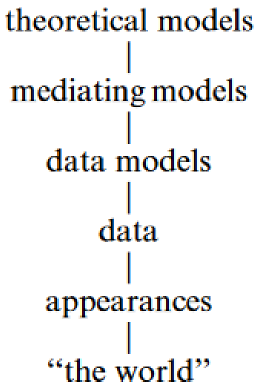

Figure 2: Different layers of scientific inquiry. The models are theoretical and data, appearances, and “the world” ontological. (Picture from [Brading 2010], based on work from [Suppes 1962], [Giere 2010], and [Teller 2010]).

question, an intermediate level between the data and the theory is introduced – the signatures.

2.2 Signatures

Data alone are inadequate for revealing the properties and behaviors of unobservable scientific entities such as quarks or Hobgoblins. The absence of inherent modality in empirical data hinders them from conveying information about potencies and capacities, vital to scientific inquiry. [Massimi 2022]

Consequently, theories seem indispensable in providing insights into the unobservable realm. However, this reliance on theory reintroduces the challenge of *theory commitment.*

According to [Maettig & Stoeltzner 2020] (M&S), “signatures” serve as an intermediary level between data and theory. In most cases, theories do not directly predict data, and data do not directly instantiate theoretical predictions. Signatures bridge this gap by allowing for inferences from data, inferences to models, and serve as the prediction of a model:

$$\text{(Raw) Data} \longrightarrow \text{Signatures} \longleftrightarrow \text{Models}$$

The term ‘signature’ is not new to particle physics and is commonly used in research articles, such as *‘Signature of exotic particles in light by light scattering’* [Tavares-Velasco & Toscano 2000], *‘Novel signatures for long-lived particles at the LHC’* [Banerjee et al. 2018], or *‘Signatures of many-particle interference’*[Walschaers 2020].

However, the term remained previously without a concrete definition. A signature can be understood as both a ‘trace’ of something else, e.g., of an effect or phenomenon (‘contrails in the air are a trail left by an aircraft’)[7], or a special characteristic feature

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[7] The notion of a ‘trace’ is also introduced in [Rheinberger 2023], but as a visually accessible after-effect of an object after going through a physical or chemical transformation, typically a precursor to data. This diverges from my understanding of signatures as traces, as we need data to infer the signatures.

(‘it is the signature ‘trait’ of airplanes to leave contrails’).

In particle physics, according to M&S, the inference process for obtaining signatures involves different detector components. The tracking chamber detects electrically charged particles, measuring their momentum by evaluating track curvatures caused by a magnetic field. The calorimeter measures energy deposits from particles interacting with the detector material. The electronic calorimeter (ECal) is used for particles involved in electromagnetic interactions, while the hadronic calorimeter (HCal) measures energy from particles engaged in strong interactions. Signatures are formed by linking energy deposits with tracking chamber patterns. [Maettig & Stoeltzner 2020] distinguish two types of signatures: *particle signatures*, representing specific particles like electrons or protons (see Figure 3) referring to physics objects, and *event signatures*, which involve combinations of different particle signatures (see Figure 4) referring to generic topologies.

Obtaining signatures enables the ‘black-boxing’ of theory, as described by M&S. The detection of an ‘electron signature’ does not require a high-level theory like quantum electrodynamics. This signature establishes a connection between the behavior in the calorimeter and the activities in the tracking system, allowing for the determination of mass, momentum, or charge based on observed effects in the detector chambers. However, in everyday practice, a detailed understanding of the shower process or the transmission of the electric signal is not a primary concern [Maettig & Stoeltzner 2020, p. 15]. Questions about why an electron signature is formed in a specific manner or the factors contributing to shower generation are typically not addressed during routine operations. Although the construction and operation of a detector require a theoretical framework, the same level of weak theory-ladenness discussed in the previous subsection for data applies here as well. The theoretical description of the experiment does not focus on the target under investigation. The operationally accessible patterns persist independently of the theoretical framework utilized for the detector.

Furthermore, despite differences in reconstruction methods and data structure between high-energy physics experiments such as Atlas and CMS, the signatures are transferable across these experiments. Signatures extend beyond the raw data, which are considered *“material artifacts whose scientific significance changes when the media change”* [Leonelli 2016, p. 88ff]. To illustrate this point, imagine a Hobgoblin footprint leading across a snow-covered yard to a shed. We can identify the same trace visually (by seeing the trace with our eyes) and haptically (by feeling different levels of depth), without knowing its origin or production process. This leads us to the relationship between signatures and models.

Regarding the ‘black-boxing’ concept discussed earlier, signatures are largely independent of high-level theories as they can be inferred operationally from raw data. However, models can still be associated with signatures in two ways: 1) the signature can be used to deduce higher-level theoretical models, which acknowledges signature-based properties but also involves further theorizing and 2) existing models can be compared with the signatures to assess if they align with the model’s predictions. When considering Beyond the Standard Model (BSM) models, which encompass various physics models that extend the Standard Model but have different aims and predictions, it would be difficult to test each model individually if separate experimental setups were required.

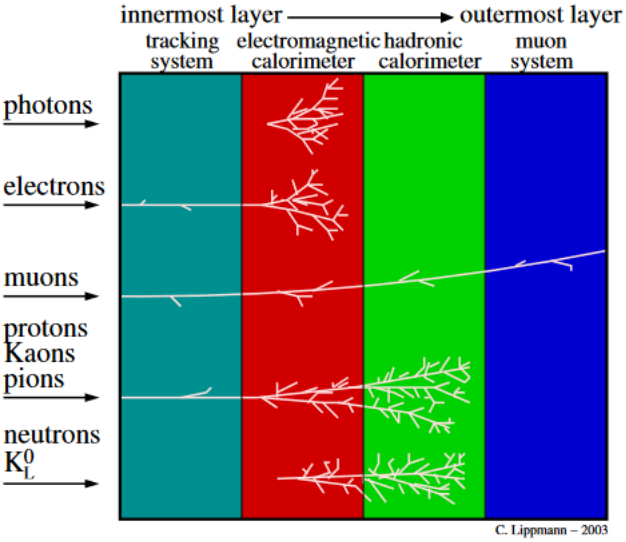

Figure 3: The schematic representation illustrates 'particle signatures' reconstructed from signals originating from different parts of a detector. Even when the detector setup differs or the puzzle pieces are arranged differently, the signatures could still be identified, surpassing the mere data level. (Picture from [Lippmann 2012]

However, with the signature approach, it becomes possible to test multiple theoretical models simultaneously. Signatures can exhibit a 'many-to-many relation' with models [Maettig & Stoeltzner 2020, p. 19], meaning that a single signature can be associated with multiple models, and conversely, multiple signatures can be linked to a single model.

Let's summarize the concept of a signature in particle physics and generalize it to make it applicable to other scientific disciplines:

1. Signatures are more than just signals or the analyzed results of a data set. They encompass patterns that emerge from the combination of different sources of information, such as tracking detectors and calorimeter data. Signatures extend beyond what can be accomplished by data or data models alone. Considering signatures as merely the outcome of statistical methods applied to the data would overlook a crucial aspect of how experimental physicists convert observations into inferences for models [Maettig & Stoeltzner 2020, p. 16-17].

2. Signatures are not restricted to specific experimental contexts and are independent of the local conditions of individual experiments. They can be translated between experiments, whereas raw data cannot.

3. Signatures can be predicted by models, whereas raw data is typically not the object of a model's prediction. Additionally, signatures have an autonomous existence. Even when models associated with signatures change, the signatures themselves

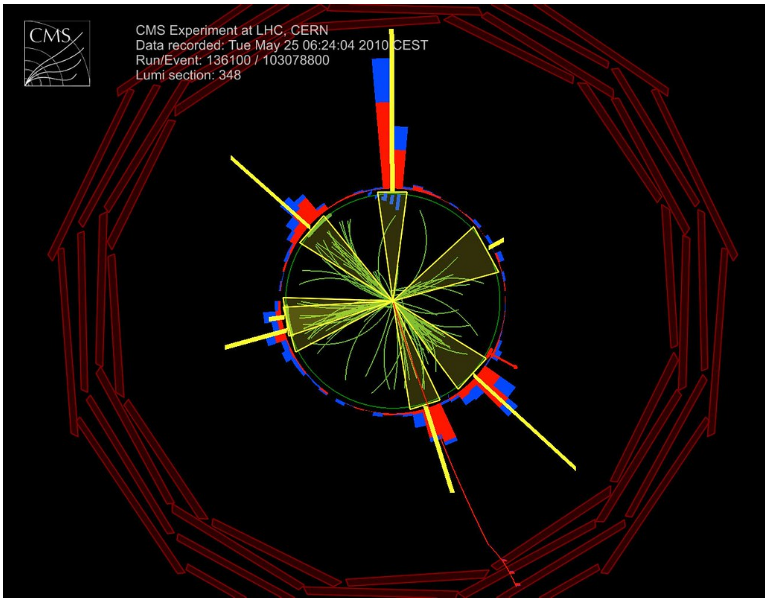

Figure 4: CMS experiment at the LHC: a multi-jet event at 7 TeV, where bundles of particles represent the jets with a narrow transverse momentum distribution per bundle. The triangular shapes in the diagram indicate tracks assigned to each jet event. (Picture from CERN document server, CMS Team, CERN, 2011, `https://cds.cern.ch/record/1369199`)

remain constant due to their ontological status. In contrast, data models lack ontological fixity, as discussed earlier.

Understanding these characteristics of signatures allows us to appreciate their significance in scientific research across various disciplines.

Criticism has been raised against a trifold distinction that extends beyond a simple differentiation between data and theory.[8] [Glymour 2000] argues that intermediate levels, including a signature-like layer, are obsolete because the supposed difference in their epistemic status is considered *‘illusory* [Glymour 2000, p. 33]. According to Glymour, statistical features of data sets, such as the mean value or distribution shape, already serve as the explananda of a scientific theory. As a result, other concepts are deemed redundant.

Statistical inferences contribute to the scientific inquiry, but the process of reconstructing signatures operates on a distinct level. Signature reconstruction incorporates various experiment components and remains consistent across changes in local experimental conditions. Unlike statistical measures, which may not be translatable across different experiments, signatures maintain their translatable nature. [Maettig & Stoeltzner 2020] For example, the mean depth of a Hobgoblin trace in the snow, perceived through touch,

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[8] The criticism does not deal with *signatures* as an intermediate layer, but phenomena in the sense of [Bogen & Woodward 1988], which are going to be discussed later. Still, the criticism also applies to trifold distinctions in general, regardless of the exact nature of the layer between data and theory.

may differ from the difference in brightness observed visually. Nevertheless, both inputs are recognized as representing the same signature [Maettig & Stoeltzner 2020].

If we consider signatures as ontological objects derived from data, we must address the placement of data models. Reconstructing signatures requires them to be inferred from processed and analyzed data using data models to narrow the scope. However, if signatures extend beyond theoretical data models, it introduces a problematic theory-ladenness into the bottom-up inquiry (Figure 5). Is the inference to signatures heavily influenced by theory, leading to the problem of *theory commitment* when including signatures in our realist commitment?

According to [Maettig & Stoeltzner 2020], *"all assumptions involved in the inference from raw data to signatures can be tested if necessary, allowing LHC experiments to validate operational definitions."* These assumptions refer to the background model, assumptions that are not directly related to the target of inquiry. However, a data model represents a theory about the object under investigation. In most cases, we cannot eliminate the need for a data model when inferring signatures because there is always an element of subjectivity in distinguishing patterns from noise. For example, drawing a line through a set of dots, identifying a track among various electronic signals, or combining different signals to form a meaningful pattern all involve interpretation. Consequently, there are multiple options for interpreting the same data, and there is no definitive one-to-one relationship. [McAllister 1997] expressed similar considerations, arguing that patterns are not fundamental ontological objects. While investigators may agree on specific patterns within an acceptable noise level, no single pattern has supremacy over other possible patterns.

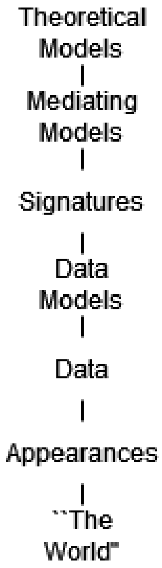

Figure 5: If signatures need theoretical data models to be inferred bottom-up, can they still be ontological and part of our realist commitment?

It appears that establishing a realist commitment to signatures in a bottom-up manner from empirical grounds is becoming increasingly challenging. However, there may be a potential solution that doesn't completely eliminate the challenges but allows us to mitigate them. If we conceptualize signatures as patterns and acknowledge the existence of multiple possible patterns inferred from the data, there are patterns, which are more *robust* than others. Not all signatures need to be considered equally; instead, we can prioritize the more *robust* ones.

While there are various definitions of robustness in the literature, I adopt an adjusted version of the argument initially proposed by [Brading 2010].

Signatures are considered robust if they satisfy the following criteria:

1. They can be repeatedly and reliably produced. For example, the electron signature appears consistently under different experimental conditions with varying parameters.
2. They offer multiple avenues of access, allowing for diverse experimental methods to generate the same signature. Temporal and spatial markers or shared properties can verify that the resulting signatures are the same.
3. They exhibit autonomy by persisting even when higher-level theories undergo changes.

Only a few signatures exhibit high robustness, characterized by their autonomy, translatability, and consistent reproducibility. These robust signatures represent salient patterns with real ontological status. Although the pre-selection of data through data models may lead to the potential exclusion of relevant signatures, those that demonstrate greater robustness than alternative patterns can be included in our realist commitment. Theoretical commitment exists in a many-to-many relationship with theoretical models, but signatures can also exist autonomously, independent of specific models. Thus, the PMI or PUA do not pose a threat to our commitment to signatures.

However, even with this realist commitment, our scope does not encompass Hobgoblins, quarks, or other inaccessible objects as they are not contained in the patterns themselves. Therefore, let us expand our realist commitment to include another layer – the phenomenon.

3 Realism about Phenomena

3.1 The Phenomenon enters the stage

Establishing signatures will now allow us to broaden our realist commitment to encompass the “hidden” entities and effects in science, referred to as phenomena. Drawing partly on the definition by [Bogen & Woodward 1988] (B&W), this subsection aims to characterize phenomena and highlight their distinction from signatures.

B&W also proposed a threefold distinction between data, phenomena, and theory, similar to M&S. Data, as previously discussed, are individual events, measurement points, or signals. According to B&W, phenomena can be defined as:

> [...] stable, repeatable effects or processes that are potential objects of prediction and systematic explanation by general theories and which can serve as evidence for such theories.
>
> [Woodward 2000, p. 163]

A phenomenon is connected to data through a causal process. It can generate different types of data consistently, but it can also be inferred from the data. Examples of phenomena include the decay of a particle over time or the melting point of a material, which cannot be determined by a single time measurement or thermometer assessment alone.[9]

Phenomena can be predicted by theories and also serve as evidence for them. Data, on the other hand, are not part of theory predictions as they are specific to a particular experimental context. Here, the term 'theory' encompasses different layers, ranging from high-level theories like electroweak theory or general relativity to specialized theories such as the kinetic theory of gases or neuronal firing. It also includes principled models that describe how 'in principle' a particle decays or an object moves, as well as representational models that specify concrete objects and boundary conditions[10], further, we have the already discussed models of data and models of experiment.

To further distinguish phenomena from signatures and add another layer to our realist commitment, I will draw on the work of [Feest 2011]. Feest distinguishes two types of phenomena:

1. Surface regularities, which are patterns observed in the data and directly instantiated by individual data points. An example is the track left by an electron as it traverses different detector parts, similar to a skier leaving a trace with their skis.
2. Underlying 'hidden' regularities, which are indicated by the data but not directly instantiated. These phenomena require further theoretical interpretation. Examples include the Higgs boson or quarks, which do not leave traces in the detector but can be indicated by the traces of the decay products.

Our robust signatures align with the first type of Feest's phenomenon, which involves surface regularities instantiated by data. However, our definition of signatures goes beyond mere surface regularities by incorporating the criteria of robustness. While all signatures comprise data, only those that meet the robustness criteria are included in our realist commitment. Therefore, not all surface regularities are considered part of our commitment, only the robust ones.

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[9] Even if the actual melting point of iron seems to be in principle measurable, barely any set of measured data points, acquired from an iron melting experiment in the laboratory, would match the exact value of 1538 °C. [Bogen & Woodward 1988]

[10] An example of a principled model is the behavior of an object with mass m, which follows Newton's laws of motion under the influence of a force. On the other hand, a representational model can be the harmonic oscillator, which provides a more concrete description. More specified models can include additional details such as the properties of the spring material used in the oscillator.

The autonomy of signatures, stemming from their independence from extensive theorizing, is evident in their many-to-many relationship with models. However, can signatures be utilized to circumvent the need for theorizing and thus mitigate the issue of strong theory-ladenness when dealing with phenomena, which then can be seen as the second type in Feest distinction - the hidden regularities?

3.2 The Reality of Phenomena - The Scope Question

Can we adopt a realist stance towards phenomena that are not instantiated by the data and do not align with signatures?

I propose that realism regarding phenomena is feasible if they satisfy the following necessary and sufficient conditions:

- Necessary condition for reality: Phenomena must be inferred from the signature level to ensure bottom-up inferences that transcend the data level, thereby mitigating strong theory-ladenness.
- Sufficient condition for reality: The commitment to the reality of a phenomenon becomes more justified as it is becomes more stabilized by multiple signature-to-phenomenon inferences.

Once a phenomenon attains relative stabilization, a 'theoretical alignment' becomes possible, allowing theories to generate additional signatures pertaining to the phenomenon. However, it is crucial that these top-down motivated signatures can be inferred from the data as real traces in a bottom-up manner.

In the subsequent discussion, I will expound upon these conditions, aiming to establish a hierarchical framework represented in Figure 6.

By conceptualizing phenomena as hidden regularities that are indicated rather than instantiated by the data, we encounter the challenge of underdetermination when attempting to establish their reality through bottom-up inferences from data. Indication implies that there is never a one-to-one correspondence, and when we introduce a theory to alleviate the underdetermination, we are once again confronted with the issue of *theory commitment*. Additionally, we seek to comprehend phenomena such as Hobgoblins, which can persist even when theoretical descriptions change, and to lend credibility to scientific discoveries in the absence of an adequate theoretical framework.

To facilitate successful bottom-up inferences to phenomena, we can embrace an intermediate layer between data and phenomena to mitigate the underdetermination. Fortunately, we have already established such a layer: the signatures. The phenomenon has potentially no direct relation to the data directly but to the signatures. This elucidates the necessity of an intermediate signature layer. However, elucidating the sufficient condition will provide clarity on how to transition from a signature to a phenomenon, how the phenomenon is defined beyond being a 'hidden' regularity, and the extent of theoretical commitment required in the process.

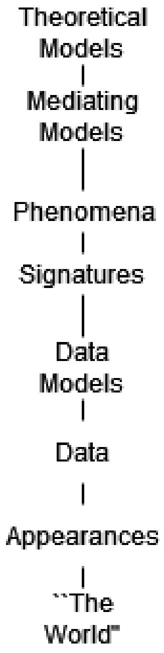

Figure 6: Hierachy of the scientific inquiry including signatures and phenomena.

3.3 The Reality of the Phenomena - The Stabilization Problem

I will demonstrate that bottom-up stabilization is sufficient to establish the reality of a phenomenon. To understand what stabilization means in an experimental context, we can refer to the notion found in the literature on scientific experimentation. Stabilization refers to the processes through which scientists empirically identify a phenomenon or entity and gradually reach a consensus that the phenomenon is a stable and robust feature of the world, rather than being an artifact of any particular experiment or instrument [Feest 2011, p. 59].

However, our focus extends beyond empirical identification alone, as we have already established the need to consider data, signatures, and phenomena. Therefore, Feest's second point becomes more relevant. When we consider only the inferences from signatures to phenomena, what can contribute to the stabilization of the phenomenon? It is important to note that the concept of 'stability' should be distinguished from 'robustness.' While a robust signature is instantiated by different data but does not acquire additional properties with increasing robustness, the phenomenon, in contrast, requires multiple stabilizing signatures that contribute to its definition and introduce new properties (as we will explore further).

Can we interpret a phenomenon as the causal factor behind signatures? This idea resembles the causal relationship between phenomena and data proposed by [Bogen & Woodward 1988], but this time with signatures. If signatures were real, we could attribute their existence to some underlying cause. However, the causal claims made by [Cartwright 1983], who views entity realism as an inference to the most likely cause, have been criticized for relying on Inference to the Best Explanation (IBE) and the associated problems of *theory* *commitment.* [Suárez 2008]

Nevertheless, Suárez argues that it is important to differentiate between causal warrant and theoretical warrant. He suggests that causal warrant provides stronger support for establishing existential commitments without succumbing to problematic theory-ladenness, offering a valid inference scheme.

In his work, [Egg 2012] provides further clarification on the matter. He introduces two specifications regarding the Inference to the Best Explanation (IBE) (ibid., p.261): 1. Every instance of IBE generates theoretical warrant. 2. An instance of IBE generates causal warrant if and only if the corresponding explanation additionally fulfills the criteria of non-redundancy, material inference, and empirical adequacy.

How does this information assist us in stabilizing a phenomenon as the underlying cause of signatures and, consequently, in defining the phenomenon? To address this, let's examine the criteria for causal warrant in more detail:

1. **Non-redundancy:** Egg (2014) defines non-redundancy as the absence of alternative hypotheses that align with the experimental results. However, one could argue that causal inference faces a similar underdetermination issue as theoretical inference, potentially resulting in multiple causal explanations. Causal realists further reject reliance on theoretical commitments and do not employ theoretical virtues to distinguish between alternatives.

   Nonetheless, the signature-phenomenon framework offers an advantage when considering non-redundancy: signatures can be robust ontological entities. Thus, we do not need to rely on volatile data to establish a direct causal relationship with the phenomenon. If our hypothesis posits that the phenomenon generates specific signatures, non-redundancy automatically follows. Let me clarify: If Signature A exhibits Feature x, we could believe that there exists Cause C, which possesses the property of causing A with Feature x. However, relying solely on this single inference from a signature to a phenomenon could lead to empty realism, as [Musgrave 1996] suggests, where belief in the reality of a cause (e.g., Hobgoblins) is upheld without specifying any further properties.

   However, we may discover another signature, B, that shares certain properties with A but remains distinct in others, but the overlapping properties (even temporal and spatial proximity) can indicate the same cause for both signatures, thus increasing the probability of its existence. For instance, Cause C could be responsible for producing Signature A with Feature x and Signature B with Features x and y.[11]

   This approach does not yet define a specific phenomenon and may still encompass a cluster of causes. How can we ascertain that A and B are truly caused by the same C? The strategy involves considering multiple signatures with sufficient overlap to strengthen the causal relationship, thereby stabilizing the phenomenon, and incorporating additional distinct features that can be attributed to the list of properties caused by C. The more detailed our understanding of a suspected cause

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[11] Although exemplified here seemingly easy with Feature x, it is usually difficult to show sufficient overlap between signatures and requires local (case-by-case) evaluations.

or phenomenon, represented by a set of hypotheses, becomes, the more challenging it becomes to argue for alternative causes or the absence of causes, thereby reducing redundancy.

2. **Material inference:** Egg emphasizes that in a causal explanation, the specific features of the effect are determined by the nature of the cause. This allows us, to some extent, to infer the characteristics of the cause based on the characteristics of the effect.[Egg 2012, p. 6]

   In our context, the more signatures we obtain, the better we understand the nature of the presumed common cause. This understanding of the cause's character is crucial because it enables us to ascribe material properties to entities through material inferences [Egg 2012, p. 8].

   When we establish an entity or effect as the responsible agent for generating the signatures, we are essentially explaining why all these signatures exhibit material properties. This requirement further reinforces our commitment to the cause, as it necessitates the existence of a material entity that can produce material outcomes. In other words, we need something material to bring something material about.

3. **Empirical Adequacy:** Empirical adequacy, as a demand for causal warrant, originates from [Van Fraassen 1980] and is typically associated with assuming certain theoretical descriptions and having empirically adequate consequences. However, in the case of causal explanation, the phenomenon itself, as an explanans, may have deductive implications. This raises the question of whether it is possible to deduce anything from a concrete, material entity, or if such deductions would be a category mistake [Egg 2012].

   The causally inferred particulars, the phenomena, are also hypotheses that carry logical consequences, as discussed earlier in relation to non-redundancy. Even if the hypothesis is just about 'causing two specific signatures,' it implies the property that the phenomenon 'causes both A and B.' Since the phenomenon can possess emergent properties beyond those of its individual signatures, there may be additional implications that require empirical adequacy, distinct from the properties exhibited by the individual signatures.

   For instance, consider the behavior of electrons in experiments. In many cases, electrons exhibit classical-like behavior, resembling tiny billiard balls moving along well-defined trajectories and subject to local interactions. However, this classical picture of electrons is not empirically adequate because there are other experiments, like the double-slit experiment, that produce results inconsistent with classical theory [Egg 2012, p. 12]. As a result, we can have two distinct electron signatures with overlapping characteristics. Consequently, the phenomenon C emerges as the cause of these two signatures. Moreover, C can bring about both wave-like and particle-like behavior, leading to the logical consequence of the existence of particle-wave duality, which is empirically adequate.

> In summary, the demand for empirical adequacy in causal explanations acknowledges the logical consequences that can be deduced from a phenomenon, allowing for the emergence of new properties and phenomena that go beyond the characteristics of individual signatures.

The stabilization criterion for phenomena can be refined as follows: A phenomenon C becomes more stabilized as additional signatures B_i are shown to have sufficient overlap and therefore a causal relationship with C. This stabilization is based on the causal properties of C (such as dispositions to produce certain effects, as discussed by [Esfeld 2011]) and their logical consequences. It is important to note that, similar to the robustness of signatures, the stability of phenomena exists on a continuum. While a completely stable phenomenon is unlikely to exist, the increasing degree of stabilization justifies our belief in uncovering a real phenomenon through scientific endeavors.

We can envision the stabilization of phenomena using the analogy of a foundation built upon sturdy pillars of robust signatures. The phenomenon does not easily vanish when numerous supporting pillars already overlap (converge). It can be compared to Neurath's boat, where individual pillars (signatures) may be replaced, yet the boat (phenomenon) persists.

> We are like sailors who on the open sea must reconstruct their ship but are never able to start afresh from the bottom. Where a beam is taken away a new one must at once be put there, and for this the rest of the ship is used as support. In this way, by using the old beams and driftwood the ship can be shaped entirely anew, but only by gradual reconstruction.
>
> [Neurath 1973, p. 199]

The connection to the theoretical layers of our hierarchy is as follows: The more stabilized phenomenon can be seen as a set of hypotheses that could align with existing theoretical descriptions. These models can then inspire the search for further signatures. For instance, let's consider inferring the phenomenon of a 'Hobgoblin' from the signatures of 'food eaten,' 'footprints on the floor,' and 'cabin cleaned,' with properties like 'something that eats food,' 'leaves footprints,' and 'cleans the cabin.' This inference may lead to additional implications that were not part of the initial signatures, such as 'not typical human behavior' or 'specific situations like snowy mountain cabins.'

By comparing the hypotheses about the phenomenon and its implications to a suitable theory like the Hobgoblin theory, we can explore potential alignment. However, we need to be cautious about the *theory commitment* problem that arises from assuming the theory is true. Instead, we can briefly consider the equivalence between the Hobgoblin phenomenon and the theoretically described Hobgoblin. If this equivalence holds, we would expect the Hobgoblin to exhibit additional traces or behaviors beyond what we initially inferred from the data. According to the theory, the Hobgoblin can be mischievous and capable of shapeshifting into different forms like an old man or a horse. Being aware of the presence of unfamiliar creatures in the cabin could help identify robust patterns. If this pattern converges on some properties with our existing signatures, it can further support the stabilization of the phenomenon, provided the criteria of non-redundancy, material inference, and empirical adequacy are satisfied. However, the additional signature needs to be inferrable bottom-up as well. The theoretical alignment just served as an inspiration to find said signature.

In summary, as we discover more signatures with the same causal warrant for the phenomenon, the common cause becomes increasingly stabilized and enriched with information. Theoretical descriptions can guide us in searching for additional signatures, but our commitment lies in the bottom-up inferences and posits associated with the phenomenon itself, rather than the theoretical description.

3.4 Case 1: The Phenomenon of the 'Higgs Boson'

Let's explore a detailed example that incorporates data, signatures, a phenomenon, and models. This case has been partially discussed in previous works [Maettig & Stoeltzner 2020b, Massimi 2022] and centers around a phenomenon, which will be referred to as the 'Higgs boson H.' It's important to note that this phenomenon is not identical to the theoretical Higgs boson described in the Standard Model (SM) of particle physics.

However, let's draw inspiration from the theoretical Higgs boson first. The theoretical Higgs boson is an elementary particle characterized by being electrically neutral, having a spin of 0, and a mass of 125 GeV.

Now, let's focus on four specific decay modes associated with the Higgs boson:[12]

$$H \longrightarrow \gamma\gamma \tag{1}$$

$$H \longrightarrow ZZ \longrightarrow 4l \tag{2}$$

$$H \longrightarrow bb \tag{3}$$

$$H \longrightarrow Z\gamma \tag{4}$$

In order to detect a signal in an experiment, it is necessary to observe a distinct peak in the number of events exhibiting the desired properties compared to other events. As we have previously discussed, the events correspond to what we call event signatures. However, it is important to note that there can be numerous event signatures occurring simultaneously, some of which may have similar characteristics to the one we are specifically interested in. This presence of similar events, known as background, can overwhelm and conceal the detectable signal, rendering it hidden or difficult to distinguish [Maettig & Stoeltzner 2020b, p. 1250].

According to the theory, Decay (1) of the Higgs boson, the decay into two photons, has a relatively low probability of only 0.2% compared to other decay modes. In our previous discussion, we identified photon signatures, and when two photons combine, they

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[12] l refers to a lepton (electron, muon, tau or their respective antiparticles), b to the bottom quark, γ to a photon (mediator of the electromagnetic interaction), and Z to a boson that mediates the weak interaction. Some of the decay products are supposed to further decay into stable particles.

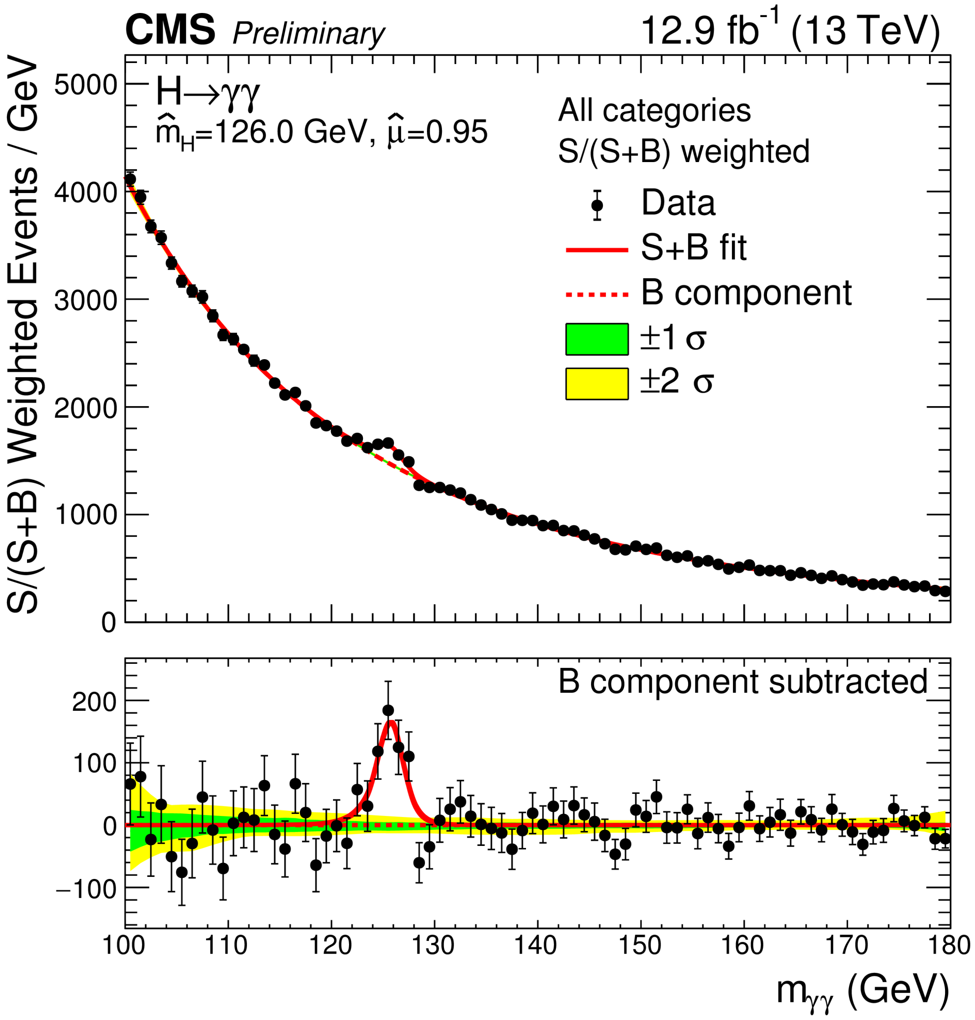

Figure 7: Invariant mass distribution for the Higgs decay into two photons at the CMS experiment, showing a recognizable peak. (Picture from [Cortezon & Enrique 2016])

form a di-photon event signature. Among the various detected di-photon signatures, only some align with a mass of 125 GeV (corresponding to the Higgs boson) as shown in Figure 7. The confirmation of the theoretically predicted decay can be achieved by observing a peak where the signal stands out from the background. However, alternatively, we can infer the signal and its associated event signatures from a bottom-up approach without prior knowledge of the theoretical Higgs, its decay modes, or their probabilities. Even without such knowledge, we would still observe a recognizable peak. By establishing a causal relation, we can then infer the existence of a phenomenon or a cluster of phenomena with a mass of 125 GeV as the underlying cause.

According to the Standard Model (SM), Decay (2) with four leptons as final products is also rare but can be clearly distinguished from the background as well [Massimi & Bhimji 2015]. This signature can be constructed by identifying different tracks in the detector, and it can be inferred bottom-up without relying on the theoretical Higgs boson for guidance. While the two discussed signatures are distinct, they can share certain properties, such as a four-lepton invariant mass of 125 GeV and a total charge of 0. These signatures could be attributed to a common cause, denoted as C, which produces decay products with an invariant mass of 125 GeV and a charge of 0. We can refer to this common cause as the 'Higgs phenomenon.' It is worth noting that these two events could potentially have distinct causes, but for the purpose of analysis, considering them as part of a cluster of causes (represented by C) does not pose any issues, particularly if further stabilization has not occurred yet.

If we are unable to identify additional bottom-up signatures that exhibit clear and distinguishable peaks, it indicates a weak stabilization of the phenomenon. In such cases, the theoretical Higgs can provide guidance for the search of further signatures. Decay modes (3) and (4) are typically challenging to separate from the background noise and can be like finding a needle in a haystack. However, the bb decay mode, for instance, has a probability of 57% according to the Standard Model (SM). If we can use the theoretical prediction to concentrate on a specific regime and discover a persistent signal that is independent of high-level theory, we have successfully found a bottom-up inferable signature. Although we may not have noticed it without the guidance of the theory, it contributes to the stabilization of the phenomenon C. By incorporating these additional signatures, motivated from a top-down perspective but inferred bottom-up, we can enhance the properties and implications of the 'Higgs phenomenon.' It may closely resemble the theoretical Higgs particle. However, it is important to recognize that not all theoretical properties can be inferred as phenomenon properties solely through bottom-up inferences from signatures. To avoid the problem of *theory commitment*, our commitment as realists is limited to the phenomenon itself, which encompasses everything inferred exclusively bottom-up.

3.5 Case 2: The Imposter Signal at 750 GeV

The second case highlights the inability to establish a phenomenon despite obtaining an experimental signal. The case also discussed by [Maettig 2022] involves the rise and subsequent fall of the 'Imposter' signal at an energy of 750 GeV. In 2015, the CERN experiments ATLAS and CMS detected slight indications of a di-photon event enhancement at 750 GeV. However, this signal was not predicted by theory and was later determined to be a statistical fluctuation.

Although the di-photon event could be considered as a standalone signature, given its multi-faceted appearance in two independent experiments, it failed to meet the reliability criteria for establishing a robust signature. Additionally, physicists were unable to identify any other signature with significant overlap, leading to a lack of stabilization regarding a potential cause. Furthermore, there was no existing theory to guide the search for additional signatures.

This example demonstrates a scenario where a realist commitment regarding signatures and an underlying phenomenon does not apply. In cases like these, the potential realist assumptions could not be sufficiently stabilized.

4 The Inferential Blueprint: Many Signatures For a Phenomenon

4.1 Summary

In summary, our realist commitment addresses the questions of *theory commitment*, *scope*, and *stability.* It encompasses appearances, data, robustly inferred signatures, and stabilized phenomena through multiple signature-to-phenomenon bottom-up inferences. The realist posits are independent of a high-level theory, but a theory can build upon these ontological posits and provide additional information, thus inspiring the search for new signatures. The hierarchy presented in Figure 8 represents the core of this ontology, resembling the Hobgoblin hierarchy discussed earlier.

It is worth noting that this hierarchy follows a phenomenon-first ontology [Massimi 2022], where each inferential template focuses on a single phenomenon while accommodating multiple models, datasets, and signatures, and consisting of local realist commitments. The whole structure can serve as an inferential blueprint for discussing realism, not only in particle physics, but in science more generally.

In scientific experiments, we can collect experimental data that surpass mere 'appearances'. While theories may play a role in the experimental setups and the inquiry process may involve multiple stages, their influence can also be limited to the background rather than the target, resulting in weak theory-ladenness. The data that exhibits weak theory-ladenness can be part of our realist commitment.

To filter relevant frequencies from each type of dataset, we employ theoretical data models, which aid in reducing the amount of data. However, signatures go beyond data models. They are independent of local contexts, possess autonomous existence, and can combine diverse types of data. As real patterns inferred from the data, they represent 'surface regularities' and have a many-to-many relationship with models. Our realist commitment encompasses only robust signatures.

Phenomena encompass processes, effects, events, or entities. They align with Feest's concept of hidden regularities that are indicated by the data. While raw data alone cannot account for a phenomenon, the stabilization of a phenomenon occurs through multiple signatures and a causal relation supported by causal warrant, allows us to adopt a realist stance. However, the degree of stabilization varies, and the discovery of additional signatures adds more properties, increasing the likelihood of a secured realist commitment.

Models, as discussed in previous hierarchies, can align with the phenomenon. They have the capability to predict specific signatures that would be caused by the phenomenon when it is considered the theoretical object. This prediction serves as motivation to search for these signatures. However, it is crucial that these signatures can also be inferred bottom-up. I aim for a realist commitment that strikes a balance, neither being overly permissive nor overly restrictive in its *scope.* It navigates the question of *theory commitment* and ensures that its posits are sufficiently *stabilized.*

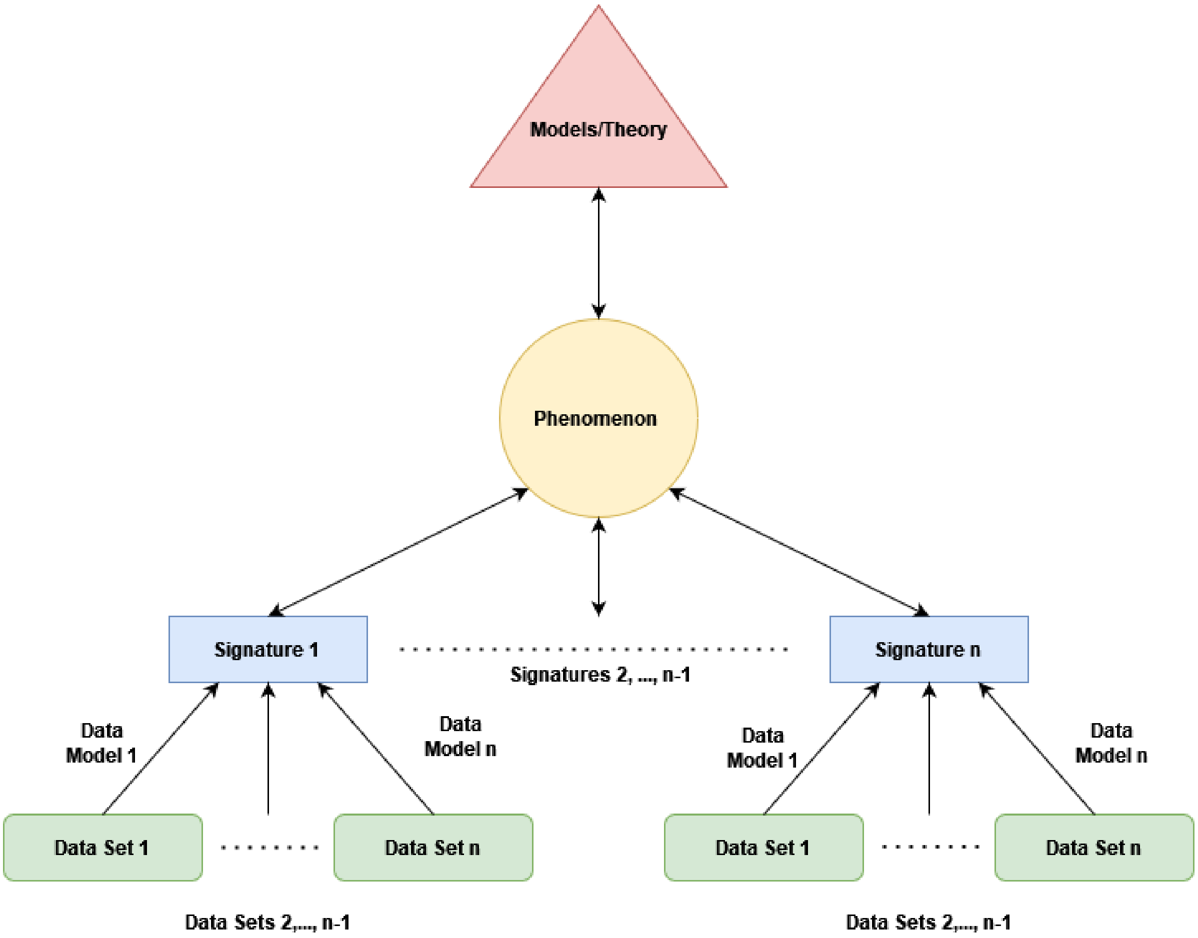

Figure 8: The inferential blueprint with its inferences and layer: At the base we have the data. The models/theory layer comprises various models, including mediating and theoretical models. Inferences from data (rectified with the help of data models) to robust signatures are possible. These signatures, in turn, contribute to the stabilization of a phenomenon. Notably, the phenomenon may also exhibit alignment with a theoretical model.

4.2 Outlook: More Signatures and Phenomena in Science

The concepts of signatures and phenomena have primarily been discussed in the context of particle physics. However, the inferential blueprint can also have applications in other disciplines. Let me briefly outline some potential uses beyond particle physics:

1. **The Phenomenon of Brain Activity** Accessing brain activity directly is not possible; it remains a hidden effect involving structural, functional, and physiological mechanisms. Neuroimaging techniques such as Functional Magnetic Resonance Imaging (fMRI) and Electroencephalography (EEG) provide indirect measures of brain activity. For example, fMRI detects the contrast between oxygenated and deoxygenated blood, assuming that active brain regions receive oxygenated blood.

EEG measures electrical activity in the brain through electrodes placed on the scalp. Despite the indirect nature of these measures, robust signatures can still be identified. Various fMRI experiments, employing different reconstruction methods and statistical measures, yield consistent patterns that persist independent of theoretical explanations of brain activity. Similar signature-based approaches can be applied to other brain imaging methods, such as Positron Emission Tomography (PET) (pattern of cerebral glucose consumption) and functional Near-Infrared Spectroscopy (fNIRS) (changes in the optical properties of brain tissue). While the spatial and temporal resolution could vary across these methods, there is some overlap, which can suggest a common cause: the phenomenon of 'brain activity.' This phenomenon encompasses factors such as increased blood flow, electrical activity, and simultaneous production of other patterns within the same brain region.

2. **The Phenomenon of Living Organisms** While the existence of life currently may not be considered a hidden regularity, it becomes more obscured when we consider non-accessible life forms, such as those deep under the sea, past life on Earth, or even extraterrestrial life. To understand and identify the presence of life, top-down approaches can be employed, focusing on bio-signatures. Bio-signatures are byproducts of living organisms that manifest as specific patterns in biological matter. These patterns can include isotope patterns that occur only at certain times, traces of particular organic products, and specific mineral or biomineral phases, among others. The question is whether it is possible without presuppositions about what 'life' is, to find an overwhelming amount of signatures e.g. at the same place or at the same time, which have overlapping properties, and thus allow a complete bottom-up inference to the cause 'existence of life'.

3. **The Phenomenon of Dark Matter?** Is it possible to establish dark matter (DM) as a stabilized phenomenon? Dark matter is postulated within a cosmological framework that incorporates general relativity to explain gravitational interactions and account for various observations, such as the gravitational effects that differ from expectations based on the amount of visible matter and the distribution of galaxies. However, it could be argued that dark matter, being a predominantly non-interacting form of matter that is abundantly present but was never detected, serves rather as an ad-hoc concept to uphold the predictions of general relativity. In contrast, we have Modified Newtonian Dynamics (MOND), another theory of gravity that operates without the need for dark matter. The question at hand is whether the potential signatures associated with dark matter, such as patterns observed in galaxy rotation curves, Cosmic Microwave Background (CMB) anisotropies, or gravitational lensing effects, can provide robust signatures to stabilize dark matter as a phenomenon. It is possible that the overlap of these signatures is merely a consequence of our choice of general relativity as the theory of gravity, and these patterns may persist without having any fundamental commonality, which is necessary for establishing a stabilized phenomenon, without that theory. A more detailed analysis is required to further investigate and clarify

this issue.

5 Conclusion & Outlook

In conclusion, this paper has aimed to establish a realist commitment that addresses the questions of *theory commitment*, *scope*, and *stabilization*. Through the utilization of local realism, bottom-up inferences, and a focus on experimental practice, I have demonstrated the pathway from appearances and data to robust signatures and stabilized phenomena as essential components of our realist framework.

By considering scientific theories and their accompanying models as a roof to our framework, we allow them to inspire the search for additional signatures. Furthermore, the inferential blueprint developed herein has the potential for broad applicability across various scientific disciplines.

Returning to the Hobgoblin thought experiment, we find that even if the theoretical description of the Hobgoblin undergoes changes, as long as multiple robust traces inferred from the data partially converge and stabilize a common cause, the 'phenomenon of the Hobgoblin', then the Hobgoblins are here to stay.

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Declarations

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used ChatGPT, an AI language model developed by OpenAI, to evaluate the quality of language used. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the manuscript.

Conflicts of interest/Competing interests

Not applicable

References

[Asay 2019] Asay, J. (2016): *Going local: a defense of methodological localism about scientific realism*, Synthese 196, pp. 587–609,

[Banerjee et al. 2018] Banerjee, S. et al. (2018): *Novel signatures for long-lived particles at the LHC*, Phys. Rev. D 98, 115026

[Bogen & Woodward 1988] Bogen, J. & Woodward, J.F. (1998): *Saving the Phenomena*, The Philosophical Review, 97, pp. 303-352

[Boyd 2010] Boyd, R. (2010): *Scientific Realism*, in E. N. Zalta (Ed.), The Stanford Encyclopedia of Philosophy (Summer 2010 ed.), `https://plato.stanford.edu/Archives/spr2009/entries/scientific-realism/` (Access: 01/06/2023)

[Brading 2010] Brading, K. (2010): *Autonomous Patterns and Scientific Realism*, Philosophy of Science, 77(5); pp. 827-839

[Cartwright 1983] Cartwright, N. (1983): *How the Laws of Physics Lie*, Oxford: Oxford University Press

[Atlas 1997] ATLAS (1997): *ATLAS inner detector: Technical Design Report, 1*; CERN, Technical design report. ATLAS, Geneva, p5, `https://cds.cern.ch/record/331063` (Access: 01/06/2023)

[Chakravartty 2011] Chakravartty, A. (2011): *Scientific Realism*, The Stanford Encyclopedia of Philosophy; E. N. Zalta (Ed.), `https://plato.stanford.edu/entries/scientific-realism/` (Access: 01/06/2023)

[Chang 2022] Chang, H. (2022): *Realism for Realistic People - A New Pragmatist Philosophy of Science*; Cambridge University Press

[Clarke 2001] Clarke, S. (2001): *Defensible territory for entity realism*, British Journal for the Philosophy of Science 52, pp. 701–722

[Cortezon & Enrique 2016] Cortezon, P. & Enrique, J. (2016): *Latest results from CMS*, CMS, CERN, Geneva, `https://cds.cern.ch/record/2238304`

[Egg 2012] Egg, M. (2012): *Causal Warrant for Realism about Particle Physics*, Journal for General Philosophy of Science - Zeitschrift für Allgemeine Wissenschaftstheorie, 43(2), pp. 259–280

[Egg 2014] Egg, M. (2014): *Scientific Realism in Particle Physics - A causal approach*, Epistemische Studien / Epistemic Studies (29), De Gruyter

[Esfeld 2011] Esfeld, M. (2011): *Causal properties and conservative reduction*, Philosophia Naturalis, 47, pp. 9-31

[Feest 2011] Feest, U. (2011): *What exactly is stabilized when phenomena are stabilized?*, Synthese, 57, pp.57-71

[Frigg & Hartmann 2006] Frigg, R. & Hartmann, S. (2006): *Models in Science*, The Stanford Encyclopedia of Philosophy (2006, Rev. 2020), Edward N. Zalta (ed.) `https://plato.stanford.edu/entries/models-science/` (Access: 01/06/2023)

[Gelfert 2003] Gelfert, A. (2003): *Manipulative success and the unreal*, International Studies in the Philosophy of Science, 17, pp. 245–263

[Giere 2010] Giere, *An Agent-Based Conception of Models and Scientific Representation*, Synthese 172 (2), pp. 269–281

[Glymour 2000] Glymour, B. (2000): *Data and phenomena: A distinction reconsidered*; Erkenntnis, 52, pp. 29–37

[Gross 1990] Gross, A. G. (1990): *Reinventing certainty: The significance of Ian Hacking's realism.*, Proceedings of the Biennial Meetings of the Philosophy of Science Association (PSA 1990), 1, pp. 421–443

[Hacking 1983] Hacking, I. (1983): *Representing and intervening: introductory topics in the philosophy of natural science*, Cambridge University Press

[Hacking 1989] Hacking, I. (1989): *Extragalactic Reality: The Case of Gravitational Lensing*, Philosophy of Science, 56(4), pp. 555-581

[Hanson 1958] Hanson, N.R. (1958): *Patterns of Discovery: An Inquiry into the Conceptual Foundations of Science*, Cambridge University Press

[Henderson 2017] Henderson, L. (2017): *Global vs. local arguments for realism*, in J. Saatsi (Ed.), *Routledge Handbook for Scientific Realism* (Routledge Handbooks in Philosophy), Routledge

[Karaca 2013] 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(1), pp. 93-136

[Kitcher 1993] Kitcher, P. (1993): *The Advancement of Science*, New York: Oxford University Press

[Kitcher 2001] Kitcher, P. (2001): *Real Realism: The Galilean Strategy*, The Philosophical Review, 110(2), pp. 151-197

[Kuhn 1970] Kuhn, T. (1970): *The Structure of Scientific Revolutions*, 2nd enlarged ed. Chicago: The University of Chicago Press.

[Laudan 1981] Laudan, L. (1981): *A Confutation of Convergent Realism*, Philosophy of Science, 48(1)

[Leonelli 2016] Leonelli, S. (2016): *Data-Centric Biology: A Philosophical Study*, Chicago: University of Chicago Press.

[Leonelli 2019] Leonelli, S. (2019): *What Distinguishes Data from Models*, European Journal for Philosophy of Science, 9(22)

[Lippmann 2012] Lippmann, C. (2012): *Particle identification*; Nucl.Instrum.Meth.A 666, pp. 148-172
Hamburg

[Maettig 2022] Mättig, P. (2022): *Classifying exploratory experimentation – three case studies of exploratory experimentation at the LHC*, European Journal for Philosophy of Science, 12(66)

[Maettig & Stoeltzner 2020] Mättig, P. & Stoeltzner, M. (2020): *Model landscapes and event signatures in elementary particle physics*, Studies In History and Philosophy of Science Part B Studies In History and Philosophy of Modern Physics 69, pp.12-25

[Maettig & Stoeltzner 2020b] Mättig, P. & Stoeltzner, M. (2020): *Searching for Signatures*; Philosophy of Science 87(5); pp. 1246–1256

[Malik 2017] Malik, S. *Observation Versus Experiment: An Adequate Framework for Analysing Scientific Experimentation?*, J Gen Philos Sci 48, pp. 71–95

[Massimi 2004] Massimi, M. (2004): *Non Defensible Middle Ground for Experimental Realism: Why we are justified to believe in coloured quarks*; Philosophy of Science 71(1), pp. 36-60

[Massimi 2022] Massimi, M. (2022): *Perspectival Realism*; Oxford Studies in Philosophy of Science

[Massimi & Bhimji 2015] Massimi, M., and Bhimji, W. (2015): *Computer simulations and experiments: the case of the Higgs boson*; Studies in History and Philosophy of Modern Physics 51, pp. 71–81

[McAllister 1997] McAllister, J. (1997): *Phenomena and Patterns in Data Sets*, Erkenntnis 47. pp. 217–228

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

[Musgrave 1996] Musgrave, A. (1996): *Realism, Truth, and Objectivity*, in R. S. Cohen, R. Hilpinen and Q. Renzong (eds.), *Realism and Anti-realism in the Philosophy of Science*, Dordrecht: Kluwer, pp. 19–44

[Neurath 1973] Neurath, O. (1973) [1921]: *Anti-Spengler*, Empiricism in Sociology, Vienna Circle Collection Vol.1, Dordrecht: D. Reidel, pp. 158–213

[Psillos 1999] Psillos, S. (1999): *Scientific Realism: How Science Tracks Truth*, Routledge

[Psillos 2003] Psillos, S. (2003): *Cartwright's Realist Toil: From Entities to Capacities*, Knowing the Structure of Nature, pp 99–122

[Putnam 1975a] Putnam, H. (1975): *Mathematics, Matter and Method*, Cambridge: Cambridge University Press

[Rheinberger 2023] Rheinberger, H.-J. (2023): *Split and Splice*, Cambridge University Press

[Shapere 1982] Shapere, D. (1982): *The concept of observation in science and philosophy*, Philosophy of Science 49(4), pp. 485-525

[Shapere 1993] Shapere, D. (1993): *Astronomy and antirealism*; Philosophy of Science, 60(1), pp. 134-150

[Stanford 2006] Stanford, K. (2006): *Exceeding Our Grasp: Science, History, and the Problem of Unconceived Alternatives*, New York: Oxford University Press

[Steinle 1997] Steinle, F. (1997): *Entering New Fields: Exploratory Uses of Experimentation*, Philosophy of Science, 64 (Supplement), pp. 65-74

[Suárez 2008] Suárez, M. (2008): *Experimental realism reconsidered: How inference to the most likely cause might be sound*, in Hartmann et al. (2008), pp. 137–163.

[Suppes 1962] Suppes, P. (1962): *Models of data*, Logic, Methodology and Philosophy of Science, Ernest Nagel, Patrick Suppes, & Alfred Tarski (eds.), Stanford: Stanford University Press, pp. 252–261

[Tavares-Velasco & Toscano 2000] Tavares-Velasco, G; Toscano, J.J (1999): *Signature of exotic particles in light by light scattering*, Phys.Lett. B472, pp. 105-112

[Teller 2010] Teller, P. (2010): *Saving the Phenomena" Today*, Philosophy of Science 77(5), pp. 815-826

[Van Fraassen 1980] Van Fraassen, B. (1980): *The scientific image*, Oxford: Clarendon Press.

[Van Fraassen 2008] Van Fraassen, B. (2008): *Scientific representation: Paradoxes of perspective*, Oxford: Oxford University Press

[Woodward 2000] Woodward, J. (2000): *Data, phenomena, and reliability*; Philosophy of Science 67 (3), Supplement. Proceedings of the 1998 Biennial Meetings of the Philosophy of Science Association. Part II: Symposia Papers, pp. 163-179

[Walschaers 2020] Walschaers, M. (2020): *Signatures of many-particle interference*, Journal of Physics B: Atomic, Molecular and Optical Physics, 53(4)