# Towards the Reconciliation of Confirmation Assessments

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## 1 Introduction

New scientific models are constantly developed to uncover and explain the unknown and to better explain the known. They are often designed by construction to accommodate existing data and though they may disagree significantly from each other in ontology and concept, they may only disagree about the values of observables by amounts that are currently indistinguishable. Thus, which of these models and hypotheses are supported by results of new empirical evidence and which are unaffected or undermined is more nuanced and complex than ever. A central aim of the paper is to uncover some of the complexities of confirmation in a contemporary setting by taking a detailed look at a scientific discovery and the reasoning behind claims of confirmation. The case study of interest is the discovery of a Higgs boson at the Large Hadron Collider (LHC) in 2012. I examine the effect of the discovery on the predictions of the dominant theory of particle physics, the Standard Model (SM), in comparison to that of a popular model of beyond the Standard Model (BSM) physics, minimal supersymmetry. Prior to the discovery, many models had been proposed that predicted some new particle, called a Higgs boson, would be found that is indicative of a mechanism responsible for generating the masses of the other particles. Even though the allowable mass ranges and predicted properties of these Higgs particles strongly overlap in various models, the discovery is touted as a victory of one model in particular, namely, the Standard Model Higgs. *A* Higgs boson was certainly discovered, but since the discovery, many particle physicists have focused on determining what kind of Higgs it is. Analysing this requires taking a step beyond the confirmation of *a* Higgs, or of the Higgs mechanism (as undertaken in (Dawid, 2017)), and examining the reasoning that distinguishes between different Higgs models.

In the following section, I describe the modern scientific conditions that give rise to the problem the paper is examining, which is at heart an underdetermination of competing models by current and forthcoming empirical data. In Section 3, I provide two differing analyses of the confirmation of the SM Higgs. Using a simple confirmation scheme, I show that in isolation of other hypotheses the SM Higgs is highly confirmed by the data, but curiously when considering it in the context of other hypotheses, at least one of its rivals seems to be even more highly confirmed. Section 4 explores two avenues that may help to reconcile the results of the formal analysis with the informal judgements of physicists, in particular, by modelling two often cited reasons for high confidence in the SM Higgs. The first avenue is to consider what I call the 'indirect confirmation' of the hypothesis, which stems from the degree to which alternative hypotheses are being ruled out by data. The second avenue is to estimate the overall confirmation of a model by taking into account the confirmation of all of its hypotheses. To capture this, I suggest the use of a hierarchical Bayesian model (HBM) that makes use of a structured hypothesis space. I find that these two avenues are not without limitation. Nevertheless, the paper's aim is to make progress

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on understanding how could one account for, and possibly bridge, the gap between such formal and informal assessments of confirmation.

## 2 Confirmation

We have trustworthy and successful empirical generalisations, but justifying knowledge of universal statements is notoriously problematic. Confirmation does not concern justification of certain knowledge, as was the project of many modern philosophers, but rather degrees of confidence. The degrees of confidence can be gauged by comparing the empirical consequences of a scientific model with data. These degrees of confidence can also be conveniently spelled out in terms of probabilities and a theory of confirmation can tell one how a probability changes as new data is taken into account.

Confirmation theory was originally developed in a context where scientific theories were understood as axiomatic systems in a formal language (Hempel, 1965). Here, one treated the confirmation of hypotheses in terms of propositions about observables deduced from the theorems or axioms of a theory. In a more contemporary setting, one can think of theories as collections of models or simply forego talk of theories and focus on the confirmation of models. Scientific models are not linguistically formulated theorems of an axiomatic system and do not deductively entail propositions that can be interpreted as predictions about observations that can be determined by simple hypothesis testing. A better way to picture it is that models 'entail' some observations in the sense that they require with a degree of confidence that certain values of measurable parameters will fall within a specific range given the empirically or theoretically determined values of other parameters. In contemporary confirmation assessments, one also has to deal with the fact that there are many models that can accommodate known data as precisely as it has been determined. These models are empirically adequate and I will often refer to them as 'viable'. This fact also means that one needs new data in order to make preferential distinctions between these models. Because models can have highly-adjustable parameters and allow for broad ranges of parameter values, determining which models we should have increased or decreased confidence in is not straightforward. Making these determinations is an essential aim of science and the complexity involved marks the central problematic of this paper.

In order to see some of the difficulties, let us briefly consider a well-known and often discussed case of confirmation, the Eddington expedition that measured the bending of light around the Sun during an eclipse (for a fuller philosophical discussion of the confirmation, see Earman and Glymour, 1980; Mayo, 1991). This famous experiment is widely regarded as having demonstrated Einstein's victory over Newton. The idea of the experiment was to test whether and to what degree light is deflected when passing close to the Sun. Einstein's theory predicted that the light from distant stars would be deflected by 1.75 seconds of arc when passing directly next to the Sun. On the other hand, Newton could only be vindicated if it was found that the amount of deflection was 0.87 seconds of arc, or if there was none at all. Through the analysis of two distinct measurements, it was determined that there was a deflection that agreed much more strongly with Einstein's prediction than the Newtonian. This of course does not ensure that what Einstein theorised was the cause of this phenomenon was in fact the cause. There were many who suggested alternative (Newtonian) explanations, but these were all eventually found wanting, in particular because they would entail other deviations that would have been observed in other experimental contexts. Scientists had no alternative but to accept Einstein's explanation as the only viable one.

Analogously, in the Higgs case study (Section 3), it is as though there are several theories of gravity, many of which predict the deflection of light, and some by only observationally indistinguishable amounts. Even with new data from the LHC, it is not obvious which models are being confirmed or disconfirmed by the data. This problem comes from the situation where there are models designed by construction to agree with existing data and have ranges for predicted values that overlap with new empirical data points. This paper sheds some light on the fact that the Higgs observation has been taken to confirm one of these hypotheses more than the others. What I will show in Section 3.2 is that this is precisely the case for the SM Higgs and many BSM Higgs models. This case is not contrived or atypical. One finds similar conditions at the forefront of many areas of scientific research where there is any number of viable models that make predictions whose ranges overlap. Even though these model may propose different vastly mechanisms, causes, ontologies, interactions, and so on, there will be a similar difficulty in establishing what has been confirmed. I will examine the confirmation of the SM Higgs boson, but there are other situations where the same issues for confirmation will arise.

# 3 Case of the SM Higgs

Before stepping more deeply in the case study, let me briefly describe the models involved. The Higgs mechanism is a central component of the SM that allows for the generation of the masses of elementary particles within a renormalizable gauge-theoretic framework. The mechanism is crucial for the SM because a gauge theory of the electromagnetic and weak forces features both massless and massive particles. The heaviness or short range of the mediating weak particles was known experimentally, but when mass terms were simply added to the Lagrangian by hand, it ruined the renormalizability that was a major motivation for the gauge theory in the first place. In order to generate the masses, the symmetry of the system must be broken spontaneously, rather than explicitly, and this mechanism of spontaneous symmetry breaking was the key insight of Englert and Brout (1964), Higgs (1964), and Guralnik et al. (1964). The proposal is to introduce a scalar doublet field to the EW Lagrangian in order to spontaneously break the symmetry and give masses to the intermediate vector bosons and the other SM particles. This field breaks the symmetry due to the 'Mexican hat' shape of its potential. The whole potential is symmetrical, but the lowest points (vacuum states) lie in a circle away from the origin. This means that any particular vacuum configuration of the field has a non-zero value called a vacuum expectation value (vev). Because this field always has a value, even in its vacuum state, when particles interact with this field they gain masses proportional to the strength of their interaction with the field.

This one doublet symmetry breaking model is what is called the SM Higgs and it is the simplest implementation of the Higgs mechanism and is sometimes referred to as the minimal Higgs sector. It is of course possible that the symmetry of the system could be broken by a more complicated Higgs sector, such as by two Higgs doublets, a doublet and a singlet, a triplet, and so on. Models of BSM physics, such as Grand Unified Theories and supersymmetry (SUSY) all involve more complicated Higgs sectors. The question of confirmation is to determine to which of these models the particle discovered at the LHC belongs.

This paper is not the first to treat the Higgs discovery in terms of philosophical confirmation. This has been done for instance in (Dawid, 2017), however, his analysis is of the confirmation of the Higgs *mechanism* and involves comparing the Standard Model with a Higgs boson to the Standard Model without one. The analysis would not work if one were considering the two particular models with Higgs bosons, like the SM Higgs and minimal supersymmetry, because it relies in part on a No Alternatives Argument. Physicists' confidence in the Higgs mechanism as responsible for particle masses is supported by the fact that are no other good alternative explanations. This argument cannot be used to assess the confirmation of the SM Higgs, because it has many reasonable alternatives. Dawid's analysis focuses on the time prior to empirical support for the hypothesis, i.e., prior to the discovery of a Higgs boson. However, now that a Higgs boson has been discovered, the question of what kind of Higgs it is is the pressing question for many particle physicists. This paper looks at the confirmation process since 2012, when the focus has been on comparing different realisations of the Higgs mechanism.

In order to make this tractable we can allow grouping of mass predictions into reasonably sized bins of 1 GeV. Second, given that precise predictions of the Higgs mass are non-existent, one could allow that models predict a range of values for the Higgs mass parameter. Thus, instead of a hypothesis $H_1$ predicting that the mass of the Higgs $m_h$ has a particular value $M_1$, it predicts a range of values $m_h = [M_{low}, M_{high}]$ that the parameter may take given other constraints in the model. This should allow us to narrow the focus from the 'Higgs mechanism' vs. 'Higgs mechanism-alternatives' to 'SM Higgs' vs. 'SM Higgs-alternatives'.

### 3.1 Discovery and Direct Confirmation

Following the initial Higgs discovery announcements, physicists turned their attention to examining not whether there was a Higgs, but what kind of Higgs it was. This would involve either continuing to confirm the SM predictions or finding deviations that might count as evidence in favour of some BSM model. Official reports and summary presentations at major conferences all reported that the particle's observed properties were all within margins of error of the predictions of the SM. The discovered particle transitioned from being a "Higgs-like boson" to a "SM-like Higgs boson" as the fact that it was a Higgs become accepted and what remained to be determined was what kind.[1]

There are persuasive reasons for the high confidence that was expressed in the SM Higgs hypothesis. In this section, I review what one may call *direct* confirmation, or confirmation in isolation from other hypotheses. The most important condition for confirmation is that the predictions of the model match empirical data and I will demonstrate this first. For many philosophers, however, this is not enough. It has been argued that, in addition, in order for a hypothesis to be confirmed by data (i) it should entail a novel fact or (ii) the prediction should be risky. I will show that these are also easily satisfied by the SM Higgs hypothesis.

First, as has been summarised by every article and presentation since the discovery, all available data has indicated no significant deviations from SM predictions.[2] As an example, the SM Higgs boson is predicted to decay into specific particles at precisely determined rates. Detectors do not detect the Higgs boson directly but rather can count the number of times the Higgs decays into a particular final state the detector can pick up. One then compares the number of these decays predicted to the number actually observed, which is called the signal strength ($\mu$). The closer the number is to 1, the better is the fit for the SM. In a recent combined analysis, the Particle Data Group has shown that the combined signal strengths across all channels (all final states of Higgs decays) is:

$$\mu = 1.09 \pm 0.04(exp) \pm 0.07(stat) \tag{1}$$

and they conclude that "a coherent picture emerges with an excellent consistency between the observation in each channel and the expectation for a SM Higgs boson" (M. Tanabashi et al (Particle Data Group), 2018). So, in short, SM Higgs has been confirmed by its precisely determined predictions.

[1] For a more encompassing discussion of the physics milestones in the confirmation process see XXXX [self-reference omitted], who have presented a detailed recent history of the Higgs discovery and its effects on BSM models.

[2] For a more comprehensive philosophical look at the various aspects of the direct confirmation of the Higgs see XXXX [self-reference omitted].

If one does not consider the accuracy to be sufficient for confirmation, the prediction can also be shown to be novel. The requirement of novelty for confirmation stems largely from arguments that data cannot confirm a hypothesis, if the hypothesis was constructed to accommodate the data. Exactly how novelty can be distinguished and how it contributes to confirmation has been much debated in the philosophy of science (Hempel, 1965; Popper, 1959; Worrall, 1978; Zahar, 1973). The motivation for the requirement of novelty is that we are much more inclined to think that a hypothesis gets something right if it makes novel predictions because it precludes the use of *ad hoc* auxiliaries and speaks to the ability of a hypothesis to truly predict, rather than accommodate after the fact.

Generally, a novel prediction would be one that involves a phenomenon, behaviour, or property that has not been observed. We can distinguish at least three senses of the word 'novel'. First, there is a weak sense of a novel fact, that we can call *temporal novelty.* Something could be novel in this sense if a prediction has been tested many times in the past and is simply being tested again. E.g. I can make a prediction that tomorrow my pen will drop when I let it go. The particular datum is not yet known and so it should be considered temporally novel. Any time the observation comes later than the prediction, we can say that it is novel in this sense. This is certainly the case with the Higgs as the prediction of the particle was made in 1964 and it was only observed in 2012.

Second, there is a stronger sense of a novel fact, that we can refer to as *novelty in kind.* Dropping my pen tomorrow is not novel in kind, since it may be a new observation, but not a new kind of observable. This kind of novelty requires something much stronger, such as the famous prediction of general relativity that light would be bent by gravity, or in our case that there is a fundamental scalar particle with non-universal couplings that is responsible for breaking the electroweak symmetry.

Third, there is a related and more technical sense of the term 'novel' that originates in the philosophical literature on confirmation. This sense holds that a hypothesis can be confirmed by evidence only if the evidence is not used in the construction of the hypothesis. This is known as *use-novelty* and has been the centre of much discussion over the years (for instance, see Giere, 1991; Howson, 1984; Mayo, 1991, 1996; Nunan, 1993; Schurz, 2014; Worrall, 1978, 1989, 2014). The basic idea is that a successful prediction can confirm a theory, but only if that evidence is not used in the creation of the theory, since that would involve counting the evidence twice and lead to a circularity. Again, since the empirical evidence of the SM Higgs only really came about almost 50 years after the proposal, it is also novel in the use-novelty sense.

Some philosophers have also considered the *riskiness* of a prediction as necessary for its confirmation.[3] There are many ways in which the SM Higgs hypothesis could have been wrong and in this sense it is quite risky.[4]. In fact, there were strong expectations leading up to the launch of the LHC that the Higgs sector would demonstrate evidence for BSM physics. More complicated Higgs sectors were favoured by the many proponents of supersymmetry, which requires at least an additional Higgs doublet. Others favoured composite Higgs models that would turn electroweak symmetry breaking into just another case of dynamical symmetry breaking and avoid the naturalness problem that accompanies fundamental scalars.[5] While there were many risks associated with the prediction of a Higgs boson, the value of the Higgs mass is a free parameter in the SM. As such, the value of the mass itself is not a factor in the riskiness of the hypothesis, as will be elaborated in the following section.

[3]However, for Popper (1959) this is a sign of corroboration rather than confirmation.

[4]Although I claim it is risky, it did not endure much of a *severe test* in Mayo's sense, since there are many ways in which the predictions could be observed while the hypothesis itself is false (Mayo, 1991)

[5]For more on the reasoning behind the SM Higgs and its alternatives, see (Borrelli, 2012; Friederich et al., 2014).

These points make a compelling case that not only is the Higgs mechanism well confirmed, but so is the SM Higgs hypothesis. Physicists are actively looking for BSM physics, but nevertheless are very confident that the particle is a SM-like Higgs boson. In practice, physicists mostly assume that the particle is exactly SM-like and incorporate that into the background signal in searches for new physics. The following section introduces a concern for this high level of confidence, which is that in a comparison, the SM Higgs appears less strongly confirmed by the discovery than a rival hypothesis. This follows primarily from the difficulty in establishing the uniqueness of the SM predictions and from the fact that the value of the Higgs mass in the SM is a free parameter and not a genuine prediction.

## 3.2 Confirmation Comparison

Models that predicted additional low energy particles or large deviations from the SM were increasingly ruled out as LHC data was analysed. BSM models were being 'squeezed out' of their remaining parameter spaces, leaving the SM standing mostly alone. The exceptions to this are models that could accommodate a SM-like Higgs boson, like minimal supersymmetry (MSSM). MSSM is a popular BSM model and was heavily favoured prior to the LHC, because, as a supersymmetric model, it offers solutions to many perceived problems of the SM and it features the simplest Higgs sector beyond the SM, the two Higgs doublet model, or 2HDM. As the name suggests, the basic structure of this Higgs sector is that in addition to the one Higgs doublet of the SM, there is another one. For one doublet, there is a single physical boson remaining after the degrees of freedom are 'eaten' by the $W^{\pm}$ and Z bosons. For two doublets, there are five physical Higgs bosons remaining. There are two charged Higgses $H^{\pm}$, a pseudo-scalar $A$, and two CP-even neutral scalars $h$ and $H$.

Most importantly for our discussion, MSSM necessarily involves an allowable mass range for the Higgs, such that if the particle had been too heavy, the model would have been discounted. Of particular interest is the value of mass of the lightest Higgs boson, $m_h$, which could be identified with the boson discovered at the LHC. At lowest order, the lightest Higgs mass is constrained by other mass values in the following way:

$$m_h^2 = \frac{1}{2}\left((m_A^2 + m_Z^2) \pm \sqrt{(m_A^2 - m_Z^2)^2 + 4m_A^2 m_Z^2 \sin^2 2\beta}\right), \tag{2}$$

as shown in the Higgs Hunter's Guide (Gunion et al., 2000). The tree-level mass is strongly bounded from above by the mass of the Z boson, where $m_h = m_Z|\cos 2\beta|$ and the mass of the Z is about 91 GeV. What this means is that large radiative corrections are needed to increase the bound to reach the observed Higgs mass of 125 GeV. This can be accomplished with minimal supersymmetry, but it cannot be pushed much higher. On all supersymmetric models, there is an upper bound on $m_h$ at around 130 GeV.

On the contrary, the SM predicts that there should be a fundamental scalar particle, but it famously does not predict its mass. Theoretically, the SM has no preference for the value of the Higgs mass—it is a free parameter and its value is not a prediction. From the SM Higgs Lagrangian, we can get the following mass terms for the gauge bosons:

$$m_{W^{\pm}}^2 = \frac{v^2}{4}g^2,\ m_Z^2 = \frac{v^2}{4}\left(g^2 + g'^2\right),\ m_\gamma = 0, \tag{3}$$

and the Higgs mass is given by

$$m_h = \sqrt{\frac{\lambda}{2}}v, \tag{4}$$

where $v$ is the Higgs vacuum expectation value, $\lambda$ is the Higgs self-coupling, and $g$ and $g'$ are coupling constants. Thus, unlike the masses of the the photon, $W^{\pm}$, and $Z^0$, the Higgs mass on the SM is a free parameter that depends only on its coupling to itself and not on any other SM physics. The other properties of the SM Higgs can all be precisely calculated as a function of its mass, but the mass must be experimentally determined.

However, the mass of the Higgs in the SM cannot be just anything; there are some upper and lower bounds whose values depend on the scale of new physics. There are upper bounds from unitarity, lower bounds from triviality, and additionally there are experimental bounds from previous data. If the Higgs mass is too high, perturbation theory breaks down and unitarity is violated. This occurs when $m_h \gtrsim 800$ GeV (Dawson and Willenbrock, 1989; Hasenfratz, 1989). On the other hand, because of the strong dependence on the top mass, if the Higgs mass is too low, where $m_h \lesssim 70$ GeV, then there will be vacuum instability (Casas et al., 1996; Elias-Miro et al., 2012)[6]. Additionally, by the time the LHC started up, ATLAS and CMS could take into account existing exclusions from LEP and Tevatron searches. The Higgs was experimentally excluded at masses less than 114.4 GeV and between about 159 and 180 GeV (De Roeck and Jenni, 2011). Experimentally, there was small window within which one could reasonably expect to find a SM Higgs boson, but these latter constraints on the mass do not follow from theory—it is not a genuine prediction about the value of the mass. If one wants to assess the probability of the Higgs being in a certain mass range given confidence in its existence and the previous searches, then it is quite reasonable to include previous exclusion ranges. However, I do not believe that one should take empirical constraints into account in assessing riskiness of a prediction. The experimental constraints are only the results of not already having found the Higgs at previous experiments and do not reflect the precision of the hypothesis and so should not be a factor in how strongly the $D$ confirms $H$.

Thus, if we are to be generous and admit that the SM makes a prediction for the Higgs mass at all, it should be no narrower than 70–800 GeV. We can then formulate the predictions for the Higgs in terms of its mass range as follows:

SM Higgs hypothesis: $m_h \ \epsilon \ [70, 800]$GeV

2HDM Higgs hypothesis: $m_h \ \epsilon \ [70, 130]$GeV

The Higgs boson was discovered to have the mass of 125 GeV and so the two models have overlapping predictions precisely at the mass where the Higgs boson was found to be. This problem is not unique to these two models, but in fact is common to any viable model in the Higgs sector that can accommodate a SM-like Higgs boson. To state the problem more precisely, any model that remains viable after the discovery also 'predicts' a SM-like Higgs boson. This is a phenomenon known as *SM alignment*. In MSSM, SM alignment can be naturally achieved if the masses of the four heavier Higgses is far greater than the light one discovered. As the mass of the next lightest Higgs increases, the lightest Higgs approaches being SM-like. If the masses are sufficiently decoupled, then the lightest Higgs becomes exactly SM-like, since one can integrate out the heavy fields and recover an effective one-Higgs doublet (Haber, 2013; Heinemeyer et al., 2012). This is known as the Higgs *decoupling limit*.

Given the lack of results in searching for light heavy Higgses, it seems that if there are heavy Higgses, they will be in the decoupling limit. The only way to distinguish models that are SM-aligned would be to confirm predictions elsewhere in the model, such as finding a new particle. However, the decoupling in the Higgs sector could mean that evidence of a non-minimal sector is out of reach. In a recent paper analysing MSSM parameters, Heinemeyer et al. (2018) came to the following conclusion about the prospects of ruling out heavy Higgses:

[6] This assumes that there is no new physics below 1 TeV.

> The SUSY Higgs boson mass scale is found above $\sim 1.3$ TeV, rendering the light MSSM Higgs boson SM-like, in perfect agreement with the experimental data... Consequently, the reduced MSSM is in natural agreement with all LHC measurements and searches. The SUSY and heavy Higgs particles will likely escape the detection at the LHC, as well as at ILC and CLIC.
>
> (Heinemeyer et al., 2018)

Data indicates that if there is an extended Higgs sector, then the heavy Higgses will be too heavy to detect and while physicists are precisely probing the SM for deviations, it may be that conclusive support for a minimal Higgs will not be forthcoming, even at the next generation of detectors.

If the MSSM is SM-aligned, then its achievable predictions are indistinguishable from those of the SM. The only difference is the range of allowed values for the Higgs mass on both models; the precision of their theoretical predictions. Let me present a short formal argument that, counter-intuitively, the Higgs discovery more strongly confirms the MSSM than the SM. This argument was informally presented in XXXX [self-reference omitted], and here I give a more formal reconstruction. I will present this in a Bayesian way, though that interpretation is not necessary for the argument. Bayes' theorem is written as:

$$\underbrace{p(H|D)}_{posterior} = \frac{\overbrace{p(D|H)}^{likelihood}\,\overbrace{p(H)}^{prior}}{p(D)} \tag{5}$$

where $p(H|D)$ is the conditional posterior probability for $H$ given data $D$, $p(D|H)$ is called the likelihood and is the probability of finding the data $D$, given the hypothesis $H$, $p(H)$ is the prior degree of belief in the hypothesis, and $p(D)$ is the expectedness or prior of the data that also serves to normalise the probability. One can also say that the posteriors are proportional to the likelihood times the prior,

$$P(H|D) \propto p(D|H)p(H), \tag{6}$$

and we can focus on these two values to assess the posteriors. We want to assess the ratio of posteriors of the two hypothesis,

$$\frac{p(H_0|D)}{p(H_1|D)}, \tag{7}$$

where $H_0$ is the SM hypothesis and $H_1$ is the MSSM. In order to compare the posteriors we need to establish the likelihoods and the priors for both hypotheses (from 6). Because there is no theoretical preference for the masses within the allowed ranges, I suggest taking a flat likelihood over the allowed range, such that $p(D|H_0) = k_0$, where $k_0$ is constant given by 1 divided by the range of possible mass values. This represents the likelihood of finding the particle in any given 1 GeV bin in the hypothesis' range. Given the earlier stated ranges, we can give the likelihoods as follows:

$$k_0 \approx 1/730 \tag{8}$$

for the SM and

$$k_1 \approx 1/60 \tag{9}$$

for MSSM. We can compare the relative strength of confirmation of $D$ on $H_0$ and $H_1$ by using the following ratio:

$$\frac{p(H_0|D)}{p(H_1|E)} = \frac{k_0 p(H_0)}{k_1 p(H_1)} \tag{10}$$

$$\frac{p(H_0|D)}{p(H_1|D)} = \frac{60p(H_0)}{730p(H_1)} \tag{11}$$

At this point, the argument should be clear on the basis of the likelihood ratio which hypothesis is more strongly confirmed. One can follow through with a Bayesian analysis and take the next step, which is estimating the priors. The prior for the SM should be quite high as the model is the simplest implementation of the Higgs mechanism and many other SM predictions about the W and Z bosons have been precisely confirmed. However, physicists also had very high expectations for new physics and so the MSSM hypothesis, as the simplest and most highly-favoured of the BSM models for EWSB, should perhaps be even higher. Instead of making a single, and rather arbitrary, quantitative estimate, let me say the following instead: given the likelihoods established above, the priors would have to differ substantially in order for them to give a different result. Given the ratios in 11, in order for the SM to have been more strongly confirmed, the SM prior $p(H_0)$ would have to be more than 12x higher than for MSSM to make up for the difference in the ranges. Unless an argument for such a difference can be convincingly made, this gives us the following result: the posterior for the MSSM is greater than that for the SM:

$$p(H_0|D) < p(H_1|D). \tag{12}$$

Because every other distinction between the model is held relatively fixed, the only differentiating factor is the range of the prediction for the mass value. Thus, we have a result that given our minimal assumptions, *ceteris paribus* the riskier (narrower) successful prediction provides a stronger confirmation.[7]

The SM made no prediction about the value of the Higgs mass while MSSM did. But, if one is to be generous, the SM made a much broader prediction than the MSSM and thus was less confirmed by this measurement. Not only did MSSM predict all the same properties of the boson as the SM (and was thus equally confirmed on all those fronts), it predicted that its mass would lie within a much smaller range. The MSSM made a bolder, and riskier, prediction by providing theoretical bounds on the Higgs mass and so the evidence ought to confirm its hypothesis even more strongly.

There should be no doubt that the SM Higgs was highly confirmed by the LHC data, but many other models were as well—any model that could accommodate a SM-like Higgs. What I take from this is the general lesson that what is selected, or favoured, by experiment is a class of models (or theories or hypotheses) that can accommodate the experimental results. Whenever a measurement is made, every hypothesis that can accommodate that measurement is increasingly confirmed, but not all to the same degree. Given some new data, we can distinguish a few different degrees to which some models will be confirmed. Some models will be strongly confirmed if they accurately predict the result when the result is surprising given an accepted theory. Other models will be confirmed if they predict the result when the result was expected from many other models or an accepted theory. Some models will survive by being able to accommodate the result by tweaking or fine-tuning other aspects of the model. Finally, some models will not be able to accommodate a result without radical fine-tuning, severe alterations, or adding in unreasonable auxiliary hypotheses.

[7]If one had insisted on using empirical constraints in this comparison, then at best, the hypothesis would have the same allowed ranges and therefore would have been equally confirmed by the data. In this case, the confirmation gap would still arise.

# 4 Reconciliation

Bayesian statistics is a fertile ground for studying confirmation and I have no doubt that Bayesians may find ways of setting up the confirmation comparison I have made in a way that gives the right result, for instance, by giving arguments for radically different priors. But what I would like to examine in this section is the reasoning that scientists seem to actually be using in making their confirmation judgements. I will model two of the principle reasons actually used and expose some of the limits and prospects of using these reasons to reconcile the formal and informal confirmation assessments. Before this, I should acknowledge that there are some more informal and sociological factors that could contribute to the perceived higher degree of confirmation of the SM Higgs, such as its prior temporal development or its relative simplicity. Here, I will only address simplicity as it is likely one of the most important.

Simplicity is an oft-cited virtue of scientific theories, and though establishing its strict epistemic implications is very difficult, it has great cognitive and pragmatic value for scientists. One might make two arguments with respect to the Higgs' simplicity: it is theoretically the simplest; and it is the simplest with respect to the data. The argument from theoretical simplicity might be that the SM Higgs, with just one doublet, is the simplest way of implementing the Higgs mechanism on paper. One can see that the SM Higgs is simple, because it would have been puzzlingly unnecessary if Brout, Englert, and Higgs had first written symmetry breaking sector with two or three doublets instead of one. One might also argue that the SM Higgs is the simplest with respect to the evidence (a notion one finds articulated in (Douglas, 2013)). Now that a Higgs boson has been discovered with no indications of internal structure, the SM Higgs is the simplest and most minimal model that accommodate all the known data. This could keep the SM Higgs in a kind of default position until something beyond it is observed. Whether they can be formally justified or not, arguments from simplicity are cognitively powerful and could certainly be a contributing factor to the confirmation gap from the informal side.

The two reasons I will attempt to formalise are (i) that alternatives to the SM are being excluded, and (ii) that there is more to these models than predictions for the Higgs mass range. My first suggestion then is that one should look at what I call the *indirect confirmation* of the SM hypothesis. The idea is that, under certain circumstances, a hypothesis could be confirmed by the disconfirmation of its alternatives. The second avenue is to consider the overall confirmation of a model, by looking at the the confirmation contributions of all of its hypotheses. I suggest that this might be done in the framework of a hierarchical Bayesian model. These avenues are promising in bringing to light the reasoning employed in scientific confirmation judgements, but they require further development and have some significant limitations.

## 4.1 Avenue 1: Indirect Confirmation

One of the most commonly cited reasons for confidence in the SM and the SM Higgs is that there has been no significant evidence in favour of BSM physics. Many models of BSM physics have predictions that are well within the energy range and the sensitivity of the LHC and are being pushed to the edges of their parameter spaces. Thus, it is reasonable that confidence in the SM Higgs hypothesis has only increased. This seems intuitive, but is not so easy to formally establish, because this is an unusual case where confirmation is alleged to come by the disconfirmation of alternatives. There are some difficulties in demonstrating that disconfirmation is in fact happening and that confirmation would follow. There are well-known in-principle arguments about never completely ruling out hypotheses, but there are further limitations that follows from the nature of the models involved:

1. BSM models have large parameter spaces and have highly-adjustable parameters.

2. Constraining parameter space does not necessarily decrease confirmation.

3. Decreasing confirmation of one hypothesis does not necessarily increase that of another.

I will examine these in turn.

First, physicists have high expectations for new physics BSM, but the energy range in which the new physics may dwell is enormous: the LHC energy is on the order of $10^4$ GeV, but new physics could be as heavy as $10^{19}$ GeV. Even the FCC, the planned next generation accelerator at CERN, will only reach $10^5$ GeV. The predictions of many BSM models are simply outside the reach of achievable energies and there is no hope of confirming or disconfirming them in the near future. New physics maybe too heavy to be produced or may only couple very weakly to SM particles and have deviations from the SM that are too small to precisely determine.

The models that are actually being probed at the LHC are only the constrained and low-energy versions of BSM models. Even for many of these BSM models, the parameters have very large ranges and can also be adjusted. Some of the unknown parameters of the models depend on other unknown parameters and so excluding even low energy models becomes difficult. One of the most successful cases of LHC data excluding possible alternatives is constrained minimal supersymmetry (cMSSM). Data from runs 1 and 2 have excluded 95% of the parameter space for cMSSM (Bechtle et al., 2016). For less constrained models, the parameter space cannot be so highly excluded. Of course, it must be pointed out that even if there is a tenfold increase in the exclusion of the parameter space for cMSSM, it is in principle still possible that the model obtains.

Second, and related to this last point, there is not a clear link between restricting parameter space and disconfirming a model. If one assumes that the restriction of parameter space is indicative of a decrease in confirmation, then prior to its discovery, the SM Higgs would have been quite highly disconfirmed. As mentioned in Section 3.1, prior to the LHC, the Higgs had been excluded below 114.4 GeV and between 159–180 GeV. After the LHC's preliminary run, the higher exclusion range was increased dramatically to be from around 130 GeV to 450 GeV (ATLAS Collaboration, 2011; CMS Collaboration, 2011). Physicists did not think of this as disconfirming the Higgs, because they were very confident that some particle responsible for symmetry breaking would be found, as shown by Dawid (2017). Confidence that the particle would be found enables the exclusion of part of the parameter space to increase the probability of finding it in the remaining space. Yet in the case of BSM models, this does not occur because the confidence that the sought particle exists in that range at all is not sufficiently high.

To see this, consider a simple Monty Hall-style case where there are 100 doors (bins of 1 GeV) and behind one there is a car (a Higgs boson). When the doors are all closed, the epistemic probability of the car being behind any given door is 0.01. However, if you have opened 95 doors (excluding that part of the parameter space) and still not found a car, then the probability that the car is behind a given remaining door increases to 0.2. But this probability increase only occurs if one is certain that there is a car behind those doors. If you suspected all along that Monty Hall was lying to you, then your rational probability assessment for the remaining doors would not increase and may even decrease. This indicates a kind of paradoxical result that whether constraining parameter space leads to an increase or a decrease of confirmation of a hypothesis depends on independent arguments of whether the sought particle exists in that range at all. So physicists may be constraining parameter space, but it does not indicate that the models are being disconfirmed.

Lastly, even if one can manage to demonstrate disconfirmation of one hypothesis, it is yet another step to show that this leads to confirmation of another. Disconfirmation can straightforwardly lead to the confirmation of another hypothesis if the hypotheses are mutually exclusive and mutually exhaustive (where the hypotheses do not overlap and exhaust the possible hypotheses). MSSM and the SM are not mutually exclusive nor mutually exhaustive hypotheses as there are many other BSM models, and as was also shown, their predictions strongly overlap. This could be circumvented where one makes an idealising assumption that only the two models exist. For instance, one could reformulate the hypotheses in terms of minimal and non-minimal Higgs, such that $H_0$ is minimal Higgs and $H_1$ is non-minimal Higgs, then $p(H_0) + p(H_1) = 1$. But it must then be acknowledged that the results depend on this idealisation and further depends on the initial disconfirmation of a hypothesis, which point 2 above problematized.

### 4.2 Avenue 2: Overall Confirmation

Part of the reason for the confirmation gap is that the confirmation contribution of one of a model's hypothesis presents a potentially misleading picture of the confirmation of the model in general. Just as in the case of Newtonian explanations of the results of the Eddington expedition, it is not the inability to account for some datum, but what the model would predict elsewhere that could make the distinction. A natural remedy for this is to estimate the confirmation of all of a model's hypotheses. We can attempt to account for this by restructuring the hypothesis space and considering a hierarchical Bayesian model (HBM). HBMs have been used in philosophical literature to model the dynamics of theory change in (Henderson et al., 2010), because they reflect the hierarchical structure of theories, models, hypotheses, and data. Presently, I will consider this as a framework for confirmation, since it involves some desirable features, but again it is not without limitations.

Imagine a model $M$ has predictions about certain particle content, which we will call hypotheses $H_1$, $H_2$, up to $H_n$.[8] One hypothesis would be a prediction for the mass of a particle, others for spin, branching ratios, coupling constants, and so on for a number of particles, such that the hypotheses are clearly individuated. The confirmation of each hypothesis would be the conditional probability given the data relevant for each hypothesis, as usual, and the overall confirmation of the model would be the conditional probability of the model given all of its hypotheses. One can calculate the posterior for a given model and compare it to the value of another model to see which is more strongly confirmed overall. Alternatively, and depending on how one individuates the hypotheses, one can have two (or more) models in the diagram, $M_1$ and $M_2$, and have some hypotheses contribute to both models, as in Fig. 4.2. The data are not naturally separated in this way, but represented diagrammatically and indexed here according to which hypotheses they are relevant. Depending on how the data is individuated, they could be relevant for more than one hypothesis and the model could be run with just one 'master' data relevant for all hypotheses. The dependencies and the hypothesis space can be reconstructed in many ways, but the dependencies must be directed between levels, so that, for example, one hypothesis cannot depend directly on another, but could depend on the data upon which another hypothesis is conditional.

The value of interest here is the posterior for the model given the data. We can write this in a form that resembles Bayes' Theorem, where $p(M)$ is now our prior, and our likelihood takes both conditional probabilities.

$$P(M|D) = \frac{\overbrace{p(D|H)p(H|M)}^{likelihood}\overbrace{p(M)}^{prior}}{p(D)} \tag{13}$$

The result that one wants to achieve to bridge the confirmation gap is the following: the SM is actually more highly confirmed than MSSM, because the confirmation of the MSSM predictions

[8]It is important to note that here, unlike in the previous section, the hypotheses do not represent the predictions of different models, but the different predictions of the same model.

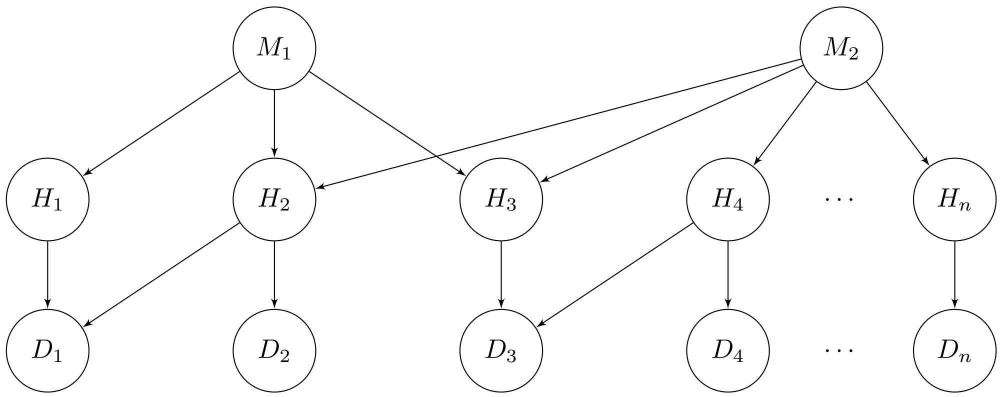


Figure 1: Diagrammatic representation of a hierarchical Bayesian model of confirmation with two competing models $M_1$ and $M_2$ with $n$ hypotheses $H$ and $n$ sets of data $D$, indexed for the hypothesis to which it is relevant.

that match the SM will be high, but that of the BSM predictions will be either very low or zero. Then, because the confirmation of a model is given by the confirmation of all of its hypotheses, every unconfirmed hypothesis the model has, to which physicists have experimental sensitivity, lowers its degree of confirmation.

To see how this emerges in the HBM framework, consider the confirmation of the MSSM ($M_2$). First, assume the SM ($M_1$) has $m$ hypotheses and that $M_2$ has $n$ hypotheses, where $m < n$.

$$M_2 \supset \overbrace{H_1, H_2, H_3, \ldots, H_m}^{SM}, \overbrace{H_{m+1}, H_{m+2}, \ldots, H_n}^{BSM} \tag{14}$$

Then, because the overall confirmation is a sum, we can split $M_2$'s $n$ hypotheses into those that match SM predictions and those that go beyond and are within experimental sensitivity.

$$P(M_2|D_i) = \frac{\sum_{i=1}^{n} p(H_i|M_2)p(D_i|H_i)p(M_2)}{\sum_{i=1}^{n} p(D_i)} \tag{15}$$

$$= \frac{\sum_{i=1}^{m} p(H_i|M_2)p(D_i|H_i)p(M_2) + \sum_{i=m+1}^{n} p(H_i|M_2)p(D_i|H_i)p(M_2)}{\sum_{i=1}^{n} p(D_i)} \tag{16}$$

The first quantity in (Eq. 16) sums the SM confirmation contributions up to $H_m$ and the second sums the remaining contributions from BSM hypotheses from $H_{m+1}$ to $H_n$. Then, because these are normalised by probability for the data up to $D_n$ where there is little to no confirmation, the confirmation for $M_2$ would be strictly lower than that for $M_1$, which would only involve hypotheses and data up to $m$.

This set-up has a few immediate consequences, some more positive than others. One benefit is that its structured hypothesis space more accurately portrays the relations between models, their various hypotheses, and the data and opens up a new toolbox for thinking about and investigating complex cases of confirmation. A specific benefit of the approach is that the confirmation of the SM will remain essentially 1 even when new physics is discovered, because its hypotheses are only assessed by their relevant data. This coincides with a kind of effective field theory view that the SM will not be wrong and replaced when a successor theory that encompasses it is discovered and confirmed. If one limits the data $D$ to a particular domain or energy scale then models like the SM and Newtonian gravity will remain very highly confirmed in that range even compared to General Relativity or a SM successor.

There are few limitations to the approach, however. One potential problem is that there is no simple way to make a necessary prediction, i.e. where one hypothesis' zero confirmation would render the confirmation of the whole model zero. This ought to be the case for some predictions that have been mentioned for both the SM and for MSSM. The spin of the Higgs boson, for example, must be 0. It cannot be that discovering a non-spin 0 Higgs boson (whatever that means) simply does not contribute to the confirmation of the model; it should make its overall confirmation zero as the model could not possibly be correct. It would be a desirable property of a theory of confirmation that it allows for necessary predictions or for predictions have differently weighted impacts on confirmation. Other more practical problems might arise in deciding how to individuate both the hypotheses and the data and it may be that the HBM is too computationally taxing to be a practical theory of confirmation. This framework can only be sketched here and its full merits and shortcomings, both theoretical and in application to cases of confirmation, remain to be seen.

# 5 Conclusions

This paper has taken a detailed look at an interesting result in confirmation, which is that a minimal hypothesis is taken to have been more strongly confirmed by data, even though another hypothesis was also compatible with the data and made a riskier prediction. I examined the factors that give rise to this confirmation gap and attempted to model some of the reasoning that seems to be behind it. I suggested two formal avenues to reconcile these judgements: taking the disconfirmation of alternatives into account; and estimating the overall confirmation of a model. The first of these may be intuitively powerful, but seems to resist a formal treatment. The second presents a more nuanced picture of confirmation dependency relations, but its formal and informal consequences have yet to be fully explored.

I have not attempted to defend or criticise Bayesianism as a general theory of confirmation, but to explore some prospects and reveal limitations in modelling what I see to be the reasoning behind scientific judgements of confirmation in the case of the SM Higgs. The formal avenues are not restricted to the case I examined and should help to understand and perhaps reconcile confirmation judgements in many other areas of contemporary science where there is an abundance of empirically adequate models.

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# References

ATLAS Collaboration (2011). ATLAS experiment presents latest Higgs search status.

Bechtle, P. et al. (2016). Killing the cMSSM softly. *Eur. Phys. J.*, C76(2):96.

Borrelli, A. (2012). The case of the composite higgs: The model as a "rosetta stone" in contemporary high-energy physics. *Studies in History and Philosophy of Modern Physics*, 43(3):195–214.

Casas, J., Espinosa, J., and Quirós, M. (1996). Standard model stability bounds for new physics within lhc reach. *Physics Letters B*, 382(4):374 – 382.

CMS Collaboration (2011). CMS search for the standard model Higgs boson in LHC data from 2010 and 2011.

Dawid, R. (2017). Bayesian perspectives on the discovery of the higgs particle. *Synthese*, 194:377–394.

Dawson, S. and Willenbrock, S. (1989). Unitarity constraints on heavy higgs bosons. *Phys. Rev. Lett.*, 62:1232–1235.

De Roeck, A. and Jenni, P. (2011). Discovery physics from atlas and cms at the lhc. *Proceedings of Science*, pages 1–21.

Douglas, H. (2013). The value of cognitive values. *Philosophy of Science*, 80(5):796–806.

Earman, J. and Glymour, C. (1980). Relativity and eclipses: The british eclipse expeditions of 1919 and their predecessors. *Historical Studies in the Physical Sciences*, 11(1):49 – 85.

Elias-Miro, J., Espinosa, J. R., Giudice, G. F., Isidori, G., Riotto, A., and Strumia, A. (2012). Higgs mass implications on the stability of the electroweak vacuum. *Phys. Lett.*, B709:222–228.

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

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

Giere, R. N. (1991). *Understanding Scientific Reasoning 3rd edition*. Holt, Rinehart, and Winston.

Gunion, J. F., Haber, H. E., Kane, G. L., and Dawson, S. (2000). The Higgs Hunter's Guide. *Front. Phys.*, 80:1–404.

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

Haber, H. E. (2013). The Higgs data and the Decoupling Limit. In *Proceedings, 1st Toyama International Workshop on Higgs as a Probe of New Physics 2013 (HPNP2013): Toyama, Japan, February 13-16, 2013*.

Hasenfratz, P. (1989). Upper bound on the higgs meson mass. *Nuclear Physics B - Proceedings Supplements*, 9:3 – 17.

Heinemeyer, S., Mondragón, M., Tracas, N., and Zoupanos, G. (2018). Reduction of the parameters in mssm. *Journal of High Energy Physics*, 2018(8):150.

Heinemeyer, S., Stal, O., and Weiglein, G. (2012). Interpreting the lhc higgs search results in the mssm. *Physics Letters B*, 710(1):201 – 206.

Hempel, C. G. (1965). *Studies in the Logic of Confirmation*. Free Press, New York.

Henderson, L., Goodman, N. D., Tenenbaum, J. B., and Woodward, J. F. (2010). The structure and dynamics of scientific theories: A hierarchical bayesian perspective. *Philosophy of Science*, 77(2):172–200.

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

Howson, C. (1984). Bayesianism and support by novel facts. *British Journal for the Philosophy of Science*, 35(3):245–51.

M. Tanabashi et al (Particle Data Group) (2018). Review of particle physics. *Phys. Rev. D*, 98:030001.

Mayo, D. G. (1991). Novel evidence and severe tests. *Philosophy of Science*, 58(4):523–552.

Mayo, D. G. (1996). *Error and the Growth of Experimental Knowledge.* Chicago Univiersity Press, Chicago, IL.

Nunan, R. (1993). Heuristic novelty and the asymmetry problem in bayesian confirmation theory. *The British Journal for the Philosophy of Science*, 44(1):17–36.

Popper, K. R. (1959). *The Logic of Scientific Discovery.* Routledge, New York.

Schurz, G. (2014). Bayesian pseudo-confirmation, use-novelty, and genuine confirmation. *Studies in History and Philosophy of Science Part A*, 45(1):87–96.

Worrall, J. (1978). The ways in which the methodology of scientific research programmes improves on popper's methodology. In Radnitzky, G. and Andersson, G., editors, *Progress and Rationality in Science*, pages 45–70. Springer Netherlands, Dordrecht.

Worrall, J. (1989). Structural realism: The best of both worlds? *Dialectica*, 43(1-2).

Worrall, J. (2014). Prediction and accommodation revisited. *Studies in History and Philosophy of Science Part A*, 45:54–61.

Zahar, E. G. (1973). Why did einstein's program supercede lorentzs'? *British Journal for the Philosophy of Science*, 24:95–262.