Studies in History and Philosophy of Modern Physics 49 (2015) 102–108

Contents lists available at ScienceDirect

Studies in History and Philosophy of Modern Physics

journal homepage: www.elsevier.com/locate/shpsb

The utility of Naturalness, and how its application to Quantum Electrodynamics envisages the Standard Model and Higgs boson

James D. Wells*

University of Michigan Physics, 450 Church Street, Randall Laboratory, Ann Arbor, MI 48109-1040, United States

ARTICLE INFO

Article history:
Received 4 June 2013
Received in revised form
11 December 2014
Accepted 12 January 2015
Available online 14 February 2015

Keywords:
Naturalness
Higgs boson
Quantum Electrodynamics
Standard Model

ABSTRACT

With the Higgs boson discovery and no new physics found at the LHC, confidence in Naturalness as a guiding principle for particle physics is under increased pressure. We wait to see if it proves its mettle in the LHC upgrades ahead, and beyond. In the meantime, I present a justification *a posteriori* of the Naturalness criterion by suggesting that uncompromising application of the principle to Quantum Electrodynamics leads toward the Standard Model and Higgs boson without additional experimental input. Potential lessons for today and future theory building are commented upon.

When citing this paper, please use the full journal title *Studies in History and Philosophy of Modern Physics*

1. Introduction

The discovery of the Higgs boson with mass of 126 GeV (Aad et al., 2012; Chatrchyan et al., 2012) has been an exciting development in physics. At long last dynamics has been found that gives deeper insight into the origin of elementary particle masses. This deeper insight is knowledge of the existence of a Higgs boson, and knowledge of what paths are no longer viable in theory construction that were once thought attractive. For example, the discovery has put to rest many ideas, such as technicolor (Lane, 2002) and "Higgsless theories" (Csaki, Grojean, Pilo, & Terning, 2004), that assumed the Higgs boson did not exist at all. This ultimately misguided effort persisted even up to a few days before the Higgs boson discovery was announced on July 4, 2012 (e.g., Pich, Rosell, & Sanz-Cillero, 2012). The chasm between those who believed in the Higgs boson and those who did not has now been resolved.

A new chasm is coming to the fore. On one side are researchers convinced that the Higgs boson is unnatural all on its own. On the other side researchers are losing faith in the "naturalness ideology" that the Higgs theory is sick and needs new physics. Farina, Pappadopulo, and Strumia (2013) summarize the conflict from the second perspective:

> The naturalness principle strongly influenced high-energy physics in the past decades, leading to the belief that physics beyond the Standard Model must exist at a scale... not much larger than the Higgs mass M_h itself.... However, no new physics has been so far seen at LHC with $\sqrt{s}=8$ TeV.... While this is not conclusive evidence.... it is fair to say that the most straightforward interpretation of present data is that the naturalness ideology is wrong.

The "new physics" referred to by Farina et al. is a supporting cast of particles and interactions needed to protect the Higgs boson from destabilizing quantum corrections. These disquieting contributions suggest themselves when computing quantum corrections to the Higgs boson mass. For example, when considering the top quark loop corrections to the Higgs boson mass ($H\to t\bar{t}\to H$), the top quarks can have an arbitrarily high momentum. The divergent integral over momentum in this computation must be cut off to yield a finite answer, and the quantum correction is $\delta m_H^2 \sim y_t^2\Lambda^2$, where y_t is the top-quark Yukawa coupling to the Higgs boson and Λ is the introduced cutoff scale, which might also correspond to the mass of new particles at this higher scale. These corrections can be cancelled by another term in the Lagrangian, the so-called "bare mass" m_{bare}^2, to yield a small number. In other words, we have

$$m_{bare}^2+\frac{y_t^2}{16\pi^2}\Lambda^2+\mathcal{O}(M_W^2)=m_H^2 \tag{1}$$

* Tel.: +1 734 763 4478.
E-mail address: jwells@umich.edu

http://dx.doi.org/10.1016/j.shpsb.2015.01.002
1355-2198/

where $\mathcal{O}(M_W^2)$ are additional quantum corrections of order the weak scale ($M_W \simeq 80$ GeV), and $m_H^2 = (126\text{ GeV})^2$.

This quadratic sensitivity to the cutoff scale in Eq. (1) gives rise to a Naturalness problem. The cutoff of the theory could be very high. For example, if we assume that the Standard Model is valid up to the Planck scale then we must consider $\Lambda \sim M_{Pl}$. This would require tuning $m_{bare} \sim 10^{18}$ GeV to conspire with $\Lambda \sim 10^{18}$ GeV to give $m_H \sim 10^2$ GeV – an unnatural prospect. Any value of $\Lambda \gg M_W$ can be viewed suspiciously for the same reason.

There are speculative solutions to this Naturalness problem, which include supersymmetry (Dimopoulos & Georgi, 1981; Martin, 2010), warped extra dimensions (Randall & Sundrum, 1999) and composite Higgs theories (Agashe, Contino, & Pomarol, 2005). Each of these ideas has a large community of proponents. The theories anticipate that new particles or new dynamics should set in somewhere near the weak scale (~ 0.1–1 TeV). Thus, "new physics should be below about a TeV" has been the mantra for a few decades, all in service of Naturalness.

On the other side, some argue that there is no Naturalness problem with the Higgs boson mass being 126 GeV, and there is no need to posit any extra symmetries or principles to stabilize it there (Bardeen, 1995; Farina et al., 2013; Lykken, 2013; Lynn & Starkman, 2013). They note that technically one can formulate the renormalizable theory with renormalized couplings and counter terms and order-by-order consistently assign parameter values that keep the Higgs mass light. In dimensional regularization, the most common technique to book-keep the infinities of the quantum field theory, there is no quadratic divergence explicitly manifested in the effective theory. Thus, as the argument goes, Naturalness is only a fuzzy philosophical notion, and should not be taken seriously, and no new particles or dynamics should necessarily be expected.

The side one chooses on this question influences the research direction of the individual and the field. It is thus important to devote considerable reflection on the role of Naturalness in formulating quantum field theories. There is extensive history on Naturalness and related topics in the community, and the issue has become even more urgent in the context of the Higgs boson (Giudice, 2008). The central questions addressed here are whether Naturalness is a useful criterion by which the value of a theory is judged. One approach to justifying Naturalness as a guide to theory model building is to consider how science can progress if researchers firmly devote themselves to the principle. Does it lead us to new more fundamental theories valid at higher energy scales, which can be confirmed by experiment? Although it is conceivable that it could lead us astray at times, I will present here an *a posteriori* analysis of the utility of Naturalness as a criterion for developing new theories.

2. 't Hooft's technical naturalness

Formulating the question of whether Naturalness is a useful concept suffers from imprecision if we do not define the term and its uses precisely. A definition is needed such that it is unambiguous to determine if a theory has the property of Naturalness or not.

The first precise formulation of Naturalness was given by 't Hooft (1980):

> at any energy scale μ, a physical parameter or set of physical parameters $\alpha_i(\mu)$ is allowed to be very small only if the replacement $\alpha_i(\mu) = 0$ would increase the symmetry of the system. In what follows this is what we mean by naturalness. It is clearly a weaker requirement than that of P. Dirac who insists on having no small numbers at all.

This notion of Naturalness first articulated by 't Hooft is widely known and understood in the physics literature and is called 't Hooft Naturalness or Technical Naturalness.

The value of determining if a theory or parameter possesses Technical Naturalness is not controversial, since in quantum field theory the enhanced symmetry protects the small parameter from any large quantum correction. For example, all quantum corrections to m_f must be proportional to m_f and so tend to zero also when m_f tends to zero, thereby making its small value stable and protected.

There are important subtleties to consider when trying to decide whether a theory or parameter possesses Technical Naturalness. In the case that there are no "very small" parameters in the theory, then by definition the theory possesses Technical Naturalness without further analysis. However, how do we decide if a parameter is "very small." First, there can be difference of opinion about the highest number that still qualifies as "very small." This is an important discussion when it comes to quantitative finetuning discussions applied to Naturalness criteria in the literature, but it does not impact our discussion much here. However, when it is helpful to think precisely about a numerical value let us say a "very small number" is less than 10^{-3}, which roughly matches the typically assumed values of unacceptable finetuning in the literature.

There is yet another ambiguity related to "very small" numbers which we must resolve before continuing. For example, in the standard Lagrangian formulation of the Standard Model, the electron Yukawa coupling y_e, which sets the interaction of the left- and right-handed electrons to the Higgs boson, has a very small value of 2.9×10^{-6}. It is widely recognized in the physics literature that this is a "very small" parameter that needs to be analyzed under 't Hooft's Naturalness criterion to decide if the theory has Technical Naturalness. It happens to pass that test, and only because it passes that test do we allow it to be known as a Technically Natural theory. However, if we redefined y_e to be equal to $10^{-5}y_e'$, then the new Yukawa coupling is $y_e' = 0.29$. This is not a "very small" number and so the theory does not have to be subjected to 't Hooft's test and immediately can be declared Technically Natural.

The resolution of this ambiguity is to say that a theory is Technically Natural if the Lagrangian can be rewritten such that there are no very small pre-factor numbers (or very large numbers, which are just the inverse of very small numbers) in the Lagrangian of the theory, and that any other input parameter (Yukawa coupling, mass, etc.) can only be very small if an enhanced symmetry arises when the parameter tends to zero. The above example of y_e being redefined as $y_e{}'$ may seem pedantic, but one experiences more subtle issues when deciding if numerical group theory numbers (Clebsch–Gordon coefficients, traces over representations, etc.) should be absorbed into parameter choices, or if combinatoric factors should be absorbed into parameter choices (e.g., λ or $\lambda/4!$ self-coupling definition when considering quartic scalar interactions). In practice this is not a difficulty in the Standard Model of particle physics because the group theory factors are kept low due to low group ranks of the $SU(3) \times SU(2) \times U(1)$ gauge symmetries, and the combinatoric factors are kept low since we have at most only four fields interacting in the renormalizable interactions that define the theory.

Let us give an example of how a very small parameter can be technically natural. Let us analyze a very light fermion mass in the Standard Model. We can declare a fermion mass to be "very small" by evaluating its Yukawa coupling y_f, which ultimately determines the mass of the fermion after electroweak symmetry breaking. Or we can declare it very small by noting that the ratio of it with another fermion on the theory is very small. The electron mass is very small under both of these criteria, since $y_e \sim 2.92 \times 10^{-6}$ and $m_e/m_t \sim 3 \times 10^{-6}$.