“Fundamental” “Constants” and Precision Tests of the Standard Model

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Abstract

In this paper I provide an account of precision testing in particle physics that makes a virtue of theory-ladenness in experiment. Combining recent work on the philosophy of experimentation with a broader view of science as process allows one to understand that the most precise and secure knowledge produced in a mature science cannot be achieved in a theory-independent fashion. I discuss precision tests of the muon’s magnetic moment, and the use of effective field theory to repurpose precision tests for exploratory purposes.

1 Introduction

The Standard Model of particle physics has served as the best theory of the subatomic constituents of the universe since its construction in the 1970s, boasting some of the most precisely confirmed predictions of all time. Yet it is widely considered to be an effective theory, to be replaced by some unknown successor. How do we reconcile the idea that the Standard Model has produced secure knowledge with the fact that it will be replaced? In this paper I explore how the precise knowledge gained predicated on the Standard Model can actually constrain and guide inquiry into theories beyond the Standard Model. In doing so, I will argue that physics is best understood as a collective enterprise of knowledge creation that builds up over time. As part of this perspective, we find that theory-predicated experimentation—to contrast with the often pejorative term “theory-laden”—often provides our most secure knowledge, and that this virtuous circularity should be encouraged rather than avoided.

There currently exist two semi-independent traditions in the philosophy of science that both prioritize scientific practice, the cumulative advancement of knowledge and understanding, and a focus on science as a process through time. They treat empirical knowledge as virtuously theory-laden, and emphasize the epistemic security thereby gained. On the one hand I refer to recent work in the philosophy of measurement and experimentation (Tal 2013; Karaca 2017; Staley 2020), and on the other hand to more theory-focused work in the spirit of Howard Stein (1995; 2004) and George Smith (2014) (Harper 2011; Curiel 2019; Patton 2020; Koberinski and Smeenk 2020). While this work fits together to create a full picture of the process of scientific disciplines, the work has largely occurred in parallel. One of my aims here is to tie these strands together by using concepts and language developed from the side of experiment to analyze frontier theoretical work in particle physics: precision testing of the Standard Model.

Recent work elucidating exploratory experimentation and theory-ladenness of experimental design in particle physics has sought to soften the blow of theory-ladenness (Beauchemin 2017; Karaca 2017; Staley 2020). Coming from the philosophy of experimentation tradition, theory-ladenness is often seen as an epistemic defect needing justification or defense. However, the work of Stein and Smith suggests that theory-laden inquiry is both necessary for the success of science, and provides the most stable, precise claims to knowledge. Those defending experimentation from vicious circularity often reach similar conclusions, though the scope of the argument is made on a case-by-case basis. By merging these lines of argument, I

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hope to make more general claims about the process of establishing knowledge using scientific theory and experiment in tandem. These will be illustrated in the context of particle physics and the Standard Model, though I will emphasize the ways in which this account generalizes to physics more broadly. One can see how theory and experiment virtuously intertwine in the construction/discovery of stable, detailed knowledge regarding causal and functional dependencies in particle physics. This knowledge is predicated upon theory, though the construction of ever more detailed knowledge refines and makes precise the concepts at the heart of theory. I call this 'virtuous circularity' to contrast with 'vicious circularity', though the more appropriate picture is that of an ever tightening spiral moving forward in time, as theory and experiment work together to construct more and more precise agreement. As Stein (1995), Smith (2014) and Koberinski and Smeenk (2020) emphasize, this theory-predicated knowledge is stable through theory change. Precision testing allows us to gain insight into the often overlooked qualifiers of a theory's success. We push the limits of the domain of applicability, and the degree of approximation to which we trust the theory and its functional relationships within that domain.

In particle physics, high-energy exploratory experiments, production experiments, and low-energy precision tests are all predicated upon the Standard Model or its effective field theory (EFT) reformulation. I focus on the structure of precision testing in particle physics, using the EFT framework to guide searches for new physics. The most recent example of tension in the predicted versus measured value of the muon's anomalous magnetic moment (a_μ) provides a good example of the ways that theory and experiment intertwine, and how theory-predicated experimentation produces quantitative knowledge with enough precision to highlight small flaws in the background framework. In doing so, precision testing points the way forward to new physics. These anomalies can serve as crucial tests for new theories that go beyond the Standard Model.

The remainder of this paper is structured as follows. In Section 2 I discuss the structure of precision tests of the Standard Model in particle physics, focusing on the case of a_μ. I highlight how precision testing is only possible when predicated on theory, and how precision tests can point the way toward new physics. In making this case, I highlight the ways in which lessons from the particle physics generalize to other areas of physics. In Section 3 I discuss how the EFT framework provides a method for parameterization and generalization away from the Standard Model to more general EFTs. The method of generalization is used elsewhere in frontier physics; I make connections to quantum foundations and gravity research to note the similarity of method. Precision tests can play the dual role of testing the Standard Model and constraining parameter space beyond the Standard Model. These are generally taken to be very different experimental modes, though here and in some other contexts they come together. The EFT framework further allows for better control of systematic uncertainty in experiment. This serves to underscore the broader claim that theory-ladenness on its own is not a vice to be avoided; the best knowledge produced in the history of physics has been virtuously predicated on theory, and this does not prevent the evidence from serving a wide range of purposes.

2 The structure of precision tests of the Standard Model

Koberinski and Smeenk (2020) have discussed in detail the structure of precision tests in the Standard Model. They focus on quantum electrodynamics (QED), in particular regarding low-energy properties of the electron. Here I will adapt that discussion to a similar property: the anomalous magnetic moment of the muon, a_μ. The muon's magnetic moment is determined by a low-energy expansion of its self-interaction, including effects from QED, the weak sector, and the hadronic sector of the Standard Model. I briefly review how predictions are generated perturbatively in the Standard Model, which involves a systematic expansion in powers of the coupling constants. Causal factors relevant to, e.g., a_μ are ordered by magnitude in this way, and one can determine quantitative error bounds on one's theoretical prediction induced by neglecting high-order terms in this expansion. Koberinski and Smeenk argue that precision testing of the Standard Model is virtuously predicated on the background theoretical structure, with ever-increasing precision in both testing and prediction leading the the discovery of details that make a difference, and the differences those details make. Thus, the theory-ladenness of these tests is a virtue in the same way that the theory-ladenness of Newtonian astronomy was (Smith 2014). Rather than apologizing for this supposed defect, philosophers should recognize the epistemic strength of research programs in physics whose mature practice involves theory-predicated experimental design.

Precision determination of quantities using the Standard Model works as follows, provided one is working in a domain where perturbative methods can be used. In QED, for example, one uses the fact that the coupling $\alpha \sim 1/137 \ll 1$ to write observable quantities Q as a perturbative expansion in powers of α:

$$Q(\alpha) = \sum_{n=0}^{\infty} A_n \left(\frac{\alpha}{\pi}\right)^n , \tag{1}$$

where one uses the Feynman rules to calculate coefficients $\{A_n\}$ up to some given value of n. As n increases, the number of Feynman diagrams one must account for grows factorially, and the corresponding integrals become more and more difficult to evaluate. In practice we are therefore often limited to the first few terms in this expansion.[1] A virtuous circle of increasing precision can start with this expansion as follows. First, one must have a zeroth order estimate for the value of the coupling constant.[2] This is used to determine the $n = 1$ order expression for quantity Q and an error estimate for truncating the series. This first-order prediction is compared to a measured value; if the two agree within the relevant margins of error, the prediction is successful. Further refinements come by designing more and more sophisticated measuring apparatus (whose design often become more theory-predicated) and by calculating the perturbative expansion to higher order. Due to the complexity of integral expressions for the $\{A_n\}$, further approximation techniques must be used as we move to higher n, introducing further errors beyond simple truncation of the expansion. That said, the increased precision both in measured value and theoretical prediction creates an ever stricter mutual constraint on the allowed value of the quantity.

When disagreement persists between theory and experiment, there are several options for how to proceed. First, note that the expression in Eq. (1) is a perturbative expansion including only effects from the QED sector of the Standard Model. In general, one will have to include effects from the other major forces—the weak and strong forces[3]—as these will also contribute to the quantity of interest. Depending on the energy scales at which one is probing, one can use a similar perturbative expansion in powers of the weak and strong couplings to account for the weak and strong effects, respectively. However, these effects are in general much harder to calculate, so further error is introduced in numerical estimation techniques. Low-energy precision measurements preclude the use of perturbative methods for the strong force, whose couplings are too large to be treated perturbatively.

The calculation of a_μ—and other quantities in the Standard Model—is best understood as a process of mutual refinement as described above. To first order in QED, one predicts a departure from $a_\mu = 0$ with precision of 3 significant figures. Similarly approximate measurements find agreement, and encourage the inclusion of more detailed effects from the side of theory. Advances in experimental precision allow a virtuous feedback loop, with higher-precision measurements often steeped in background assumptions from the very theoretical framework being tested. When viewed as a buildup of knowledge over time, this theory-ladenness turns from potential vice into virtue. Without the mutual reinforcement of theory and experiment, we could not claim some of the most precise predictions in the history of science, nor would we discover meaningful tensions allowing us to move beyond the current theoretical framework.

To a first approximation, one can separate the effects on a_μ from different sectors of the Standard Model and predict each component individually:

$$a_\mu(\text{theory}) = a_\mu(\text{QED}) + a_\mu(\text{Hadronic}) + a_\mu(\text{EW}), \tag{2}$$

where a_μ(QED) is the contribution coming from the "pure" QED sector, a_μ(Hadronic) is from the strong sector (with higher-order corrections from QED), and a_μ(EW) is from the weak sector (with higher-order

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[1] Additionally, there exists some $n = N$ beyond which the convergence of the series is spoiled. The radii of convergence of perturbative expansions in quantum field theory are strictly zero; the perturbative expansion is therefore thought to be an asymptotic expansion. For QED this breakdown is thought to occur around $N = \alpha^{-1}$, so this limitation is only a limitation in principle, not practice.

[2] In QED this comes from the relationship $\alpha = e^2/(4\pi\epsilon_0\hbar c)$, where e is the charge of the electron, ϵ_0 is the permitivity of free space, c is the speed of light, and $\hbar$ is the reduced Planck constant. These constants were known to some level of precision prior to the development of QED, and so the coupling α could be input from the start.

[3] In general, gravity would also have to be included as another known force. However, for most practical purposes in particle physics, gravitational contributions are estimated to be so small as to lose all relevance in practice. The hard problem is in domains where particle physics and gravity are both expected to be relevant; there we await a consensus theory of quantum gravity.

contributions from QED and the strong sector). The hadronic effects are further split into two dominant factors: hadronic vacuum polarization (HVP) and hadronic light-by-light scattering (HLbL), each of which is calculated in a different manner.

The current best calculation of a_μ includes a fifth-order calculation of $a_\mu(\mathrm{QED})$, second-order loop contributions from the electroweak and Higgs bosons, and virtual hadronic loop contributions from the strong sector (cf. Aoyama et al. (2020) for a summary of the state of the theoretical work calculating a_μ). The magnitude of these effects depends on having precise values of the relevant coupling constants: the fine-structure constant from QED, weak couplings, and effective hadronic couplings.

Aoyama et al. (2020) report the best-supported value to be

$$a_\mu(\mathrm{theory}) = 116\,591\,810(43) \times 10^{-11}, \tag{3}$$

with the largest source of error coming from the hadronic contributions: $a_\mu(\mathrm{HVP}) = 6845(40) \times 10^{-11}$ and $a_\mu(\mathrm{HLbL}) = 92(18) \times 10^{-11}$. It is important to note that various modelling assumptions, approximation techniques, and phenomenological form factors need to be fixed and improved upon to reach predictions at this level of precision. The hadronic contributions are especially difficult to approximate due to the nature of the strong interaction. First, hadrons are composite particles, whose residual strong interaction is ultimately grounded in the interactions between gluons and quarks. Confinement is a feature of quantum chromodynamics (QCD), which ensures that at low energies quarks and gluons can only exist as composites. The relationship between the quark and gluon fields on the one hand, and the hadronic fields on the other, is complicated. At the state-of-the-art we have numerical models of QCD that predict the emergence of hadronic composites with the correct mass one would expect for the observed hadron spectrum (Brower et al. 2019; Hansen and Sharpe 2019). Virtual hadronic interactions are emergent and effective in the Standard Model, and thus often require advanced approximation techniques to describe. Second, as the name implies, the strong interaction has a large coupling parameter at low energies, and thus the usual perturbative methods employed for QED and low-energy weak interactions no longer work. This means that, even if one could use QCD directly, perturbative methods would not suffice.

Control of these approximation techniques is heavily informed by and dependent upon the Standard Model and the framework of QFT. When one calculates perturbative effects order-by-order, the error introduced by truncation is estimated using renormalization group methods, assuming the validity of the underlying framework. Errors on the hadronic contributions are estimated by testing the data-driven models in situations where comparison with experiment is more direct. Thus we see the impact of experiment and theory on prediction in ways that would be hard to square with a simple deductive-nomological account of prediction, confirmation, or explanation. We also see how error analysis hints at future advances in increasing theoretical precision. In the words of Smith (2014), the Standard Model provides a systematic framework to account for the details that make a difference, and just how much of a difference we should expect those details to make.

Just as experiment plays a large role in the construction of precise prediction, so too does theory play a role in the design of experiment. First, the promise that a_μ will be more informative about new physics than the much more precisely measured electron a_e is informed by theoretical calculations that show that the relative contribution from higher-energy virtual particles scales as $(m_\mu/m_e)^2$. The design of the superconducting magnetic storage ring, the timing of muon beam bunch pulses, the magnetic pulse to direct muons to the storage ring, and the controls to eliminate noise and complicated contributions to the anomalous precession frequency all rely heavily on the background theoretical framework provided by QFT and the Standard Model (cf. Albahri et al. 2021). These state-of-the-art experiments are conducted in a context where the scientific community already expects the Standard Model to include most of the correct dynamically relevant effects. Therefore one can design experiments that rely on principles within the Standard Model: both global principles and more local principles directly related to the muon are needed to control for sources of error to the degree required.

The most recent tests conducted at FermiLab, combined with previous measurements provide an overall experimental value for a_μ:

$$a_\mu(\mathrm{exp}) = 116\,592\,061(41) \times 10^{-11}, \tag{4}$$

which leads to a 4.2σ tension with $a_\mu(\mathrm{theory})$. This increases the previous tension of 3.4σ, hinting that this is a persistent effect. Though standards in the field of particle physics prevent the claim of a discovery until a discrepancy with expectations at or above 5σ, the recent results have caused waves in the community, with the result being heralded as the first hint of new physics in decades.

I want to highlight two major features of this story. First, a note on how to understand uncertainty estimates. On the theoretical side, uncertainty arises in a few different areas. There is uncertainty associated with truncating perturbative expansions in QED and the weak sector. These uncertainties are not related to approximation techniques, and in principle can be estimated directly. They presuppose that the background theoretical framework is correct, but this is unproblematic in the context of predictions. Uncertainties associated with approximation techniques are often harder to quantify. Staley (2020) argues that systematic uncertainty is best understood as an estimate of how much a faulty premise affects the quantitative prediction, and is based on variability across models of the process under consideration. Staley's analysis is in the context of experimental error, but the same can be said for systematic error associated with approximation techniques.[4]

This is relevant to the case of a_μ because the two contributions with the largest error sources are the hadronic effects. These require a great deal of approximation, and hence introduce the most systematic uncertainty. Since comparison across different techniques is only just becoming possible, these estimates could be drastically over- or under-reported. In fact, a paper was published in Nature just before the FermiLab announcement, claiming that refined lattice-QCD techniques allow for a better calculation of the leading-order HVP contribution to a_μ (Borsanyi et al. 2021). These techniques are developed and refined based on experimental results in other domains of hadronic physics. They find a contribution that is 144×10^{-11} larger than the result used to compute a_μ(theory), which would significantly reduce the tension with a_μ(exp). If correct, this result would indicate one way that experiment can lead to improvement in approximation techniques on the side of theory.

The second major feature is that a_μ illustrates the epistemic importance of theory-predicated searches for new physics. Supposing that the current tension is not explained away by the new lattice-QCD methods, such a small discrepancy between theory and experiment ($\Delta a_\mu \sim 2.5 \times 10^{-9}$) would never have been discovered had theory-predicated searches not been conducted. The virtuous feedback loop between ever more precise predictions and measurements has served two important purposes. First, it has shown just how well the Standard Model can account for the dominant functional dependencies behind a_μ. Over the last several decades, we have discovered more details that make a difference, and quantified the exact difference those details make. These details are codified in functional relationships governed by the three major forces. Thus, the fundamental constants play a central role in organizing and unifying precision knowledge in particle physics. Second, this precise tension both constrains any future theory beyond the Standard Model, and provides an empirical window into low-energy effects of exotic physics. The constraint is that future theory must match the Standard Model up to about 9 significant figures; while the window provides evidence that the theory on which searches have been successfully predicated must fail to include *all* physically relevant details. Consider the analogy with Newtonian astronomy as detailed in Smith (2014). Mercury's missing 43 arc seconds of precession per century were just a small component of the overall rate of 575 arc seconds per century. Increased precision within the Newtonian framework was able to account for most of the precession, leaving only a small fraction elusive. When Einstein found that general relativity could account for this additional 43 arc seconds, this was taken to be a striking success for this new theory. But without the precision guidance of Newtonian astronomy, this would have only been a small fraction of the observed precession, and would not have served as conclusive evidence that his theory was on the right track. In the same way, until we learn of a persistent tension between the Standard Model and experiment, a new theory predicting a 10^{-9} effect would similarly not be evidence in favour of the new model. Without theory-predicated measurements, we would therefore have less secure, precise knowledge, as well as little guidance toward new physics.

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[4] Beauchemin (2017) and Tal (2013) have similar model-based accounts of systematic uncertainty, with the latter also arguing that the refinement of measurement standards is virtuously circular.

3 The effective field theory framework as a method of generalization

The knowledge generated via precision testing is encoded in functional relationships describing the magnitude of relevant physical effects, and these relationships constrain the construction of future theories. The fundamental constants at the heart of these knowledge claims, however, may turn out by the lights of future theory to be neither truly fundamental, nor even constant. I turn attention in this section to the effective field theory (EFT) framework, and describe it as a generalization away from the fundamental principles of QFT. Using the renormalization group to explore the space of EFTs at different energies, we see that the couplings in the Standard Model are not constant and should depend on features of a more fundamental successor theory.

The EFT framework started as a phenomenological generalization of the renormalizable quantum field theory (QFT) framework. At a first pass, the EFT framework starts with the QFT framework and drops the requirement that only renormalizable terms are allowed in the Lagrangian (Weinberg 1979). This is only possible due to better understanding of scaling behaviour of QFTs via Wilson's (1975) renormalization group. As long as one deals with energies low relative to the point at which we expect a theory to break down, these terms are small and controllable. At low energies, nonrenormalizable coupling terms are suppressed by powers of a high-energy cutoff Λ. In general, all coupling terms will vary with energy. By dropping the requirement of renormalizability, one has effectively generalized the QFT framework, greatly expanding the space of possible theories under consideration.[5]

One can reconceive of the Standard Model as an EFT by including the infinite number of nonrenormalizable interactions between its fields, consistent with its known symmetries. This Standard Model EFT is enormously complicated, but provides a unifying framework for beyond Standard Model candidates to be directly compared at low energies. In principle, precision tests like the a_μ test described above place constraints on the low-energy values of the nonrenormalizable couplings. These constraints rule out portions of parameter space that may be covered by candidate future theories. We thus have a so-called "model-independent" means for systematizing constraints on new physics.[6]

Using the family of renormalization group methods on the EFT framework, we see that the dominant coupling "constants" at low energies encode the low-energy causal dependencies, but that we should expect new dependencies to grow in importance as we probe systems at higher and higher energy scales. If the successor theory was known—and found to fit within the EFT framework—its couplings would suffice to fix the low-energy values currently treated as empirical inputs. Thus the EFT framework provides reason to think that the "fundamental" constants in the Standard Model are emergent and variable, despite their epistemic security and privileged status for organizing functional dependencies within the Standard Model. Similarly, the gravitational forces contributing to Mercury's orbit were discovered to be approximate and emergent. This does not affect the epistemic stability of the functional relationships between celestial bodies, which remains secure.

This strategy of parameterization and generalization from a known framework has become common elsewhere at the frontiers in physics. One can see this approach in gravitational physics in the parameterized generalizations of weak field and cosmological spacetimes (Patton 2020), and in the new operational frameworks used for reconstructing quantum theory (Koberinski and Müller 2018). Though the exact methods used in each discipline differ, all have in common a relaxing of core assumptions from known theory to produce a theory space delimited by parameterization. The method of generalization here provides a means for operationally converting precision tests of important parameters in the known theory to exploratory experiments ruling out competitors in some specified theory space. Thus, theory-predicated precision tests are repurposed in the generalized framework to serve as explorations constraining the possible parameter values in theory space. Systematic errors in theory-predicated measurements can also be reduced with help

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[5] For more comprehensive overviews of the EFT framework, see Williams (2015), Williams (2018), Wallace (2018), and Rivat (2020). For differing perspectives on the status of EFTs, see Ruetsche (2018), Rosaler and Harlander (2019), Koberinski and Smeenk (2021), and Koberinski and Fraser (2021).

[6] Note that here the independence is from any particular approach to constructing future theories. The EFT framework contains its own assumptions, but as long as these are valid near scales at which the Standard Model has been tested, this method of generalization can still claim some relative independence. See Ruetsche (2018) and Koberinski and Smeenk (2021) for arguments that the EFT framework may be inadequate for capturing all possible successor theories.

from the generalized framework.

In generalizing to a parameterized framework, standard tests become exploratory tests in the parameter space. Early accounts of exploratory experiments claim that exploration is characterized by a minimal dependence on any background theoretical framework (Steinle 1997; Elliott 2007). Steinle (1997) in particular contrasts exploratory experimentation with theory-driven experimentation, which includes precision determination of constants (pp. 69-70). Karaca (2017) argues that exploratory experimentation in high-energy physics is characterized by methods that seek to expand the range of possible outcomes of an experiment. Importantly, he argues that this exploratory methodology is often theory-laden. However, Karaca still emphasizes that precision measurements like that of a_μ are paradigm cases of non-exploratory experimentation.

If we focus strictly on the experimental design and methodology of precision tests, then it seems clear that they are not exploratory in the way Karaca claims. However, by placing precision tests within the theoretical context of the EFT framework, they can be repurposed for the goal of exploration by elimination. The EFT framework itself expands the range of possible outcomes by relaxing constraints from the original QFT framework. Precision tests narrow this range again by placing constraints of possible future models beyond the Standard Model. By switching focus to the interplay between theory and experiment, keeping in mind both methods and goals of both, we can see a new method of exploration using theory-predicated precision tests and a generalized theoretical framework.

The EFT framework provides an additional means to assess and potentially reduce systematic error in theory-predicated measurements like the measurement of a_μ. Staley (2020) argues that one of the major roles of systematic error in particle physics is as a minimal form of robustness analysis. We can think of the quantification of systematic error as a measure of the variation of a measurement result when one changes some subset of assumptions that go into a model of the measurement and its underlying physical processes. This in itself is a theory-laden process: in order to model the effects of varying assumptions, one must have some theoretical understanding of what counts as a reasonable variation, as well as what sorts of quantities are subject to variation. When a measurement is heavily theory-predicated, having more control over variability within the theoretical framework can provide information on the systematic error within the experiment. We can replace modelling assumptions that adhere strictly to the Standard Model with those relaxed to fit the EFT framework. If this new base of assumptions results in greater variability in the possible measurement outcomes, then one must increase the systematic errors accordingly. By better understanding the sources of systematic error, the EFT framework provides a better guide to further reducing those uncertainties.

As a caveat, it is important to note that the method of generalization of theoretical frameworks does not completely avoid problems of unconceived alternatives. Since generalizations start from the principles and formalism of the known theory and relax them, there is a strong sense in which the generalization is still closely tied to the principles of the original theory. Future theoretical developments that radically alter concepts or formalism presently known will not be captured by generalized frameworks such as the EFT framework. Ruetsche (2018) uses the example of a generalized Newtonian gravitational theory missing the crucial insights needed for general relativity. Similarly, Koberinski and Smeenk (2021) argue that the EFT framework is ill-suited to cosmological contexts in quantum gravity. Despite these worries, the method of generalization still does widen the space of possibilities and influence the use of precision tests of current frameworks. The functional dependencies determined from a generalized framework will also continue to hold, regardless of what a successor theory looks like. One must simply be cautious of the fact that these generalizations are not assumption-free or fully model-independent—as sometimes advertised.

4 Conclusions

One cannot gain the type of secure, detailed knowledge that precision tests offer without a virtuous feedback loop connecting theory and experiment. Recent literature in the philosophy of experimentation has recognized the necessity of theory-laden experimentation, but tries to defend against or explain away the potential circularity issues. If we think of science as a process through time, building up more secure knowledge, as in Smith (2014) and Stein (1995; 2004) we can make a broader claim about theory-ladenness in physics. We thus recast potential vicious circles as virtuous; as theories mature and develop, experimentalists can design new tests predicated on that theory to discover new knowledge that would otherwise be inaccessible.

I have briefly outlined how this process works in the precision tests of the Standard Model of particle physics. Beyond securing new knowledge, theory-predicated precision tests can be used to constrain and inform future theory. Though this knowledge is theory-predicated, the stable functional relationships revealed survive theory change and push the framework to its breaking point. The functional relationships are linked together via important fundamental constants relative to that theoretical background. Within the correct domains, and up to a degree of precision determined by these tests, the functional relationships will continue to be stable and meaningful in a new framework. The anomalous magnetic moment of the muon is a great contemporary example of this; discrepancies in the ninth decimal are being heralded as our best hint toward physics beyond the Standard Model. Even if the Standard Model is able to accommodate this discrepancy, we have secured new knowledge about the structure of the muon.

In response to a lack of anomalous evidence, many distinct areas of frontier physics have arrived at methods of generalization. In the context of particle physics, the generalization is from renormalizable QFTs to the EFT framework. This generalized framework then feeds back to inform experimentation. Within the context of the EFT framework, precision measurements of quantities like a_μ can be repurposed to exploration by ruling out values of parameter space. Precise measurements constrain the magnitude of deviation from the renormalizable Standard Model. Following Staley (2020), I treat systematic errors as modelling the impact of changing background assumptions on the measurement outcome. The generalized framework can provide a better understanding of the space of possible background assumptions, allowing scientists to have a better handle on systematic error. As the method of generalization marks a first step beyond the known theoretical framework, it allows us to see important epistemic details in a new light. For the Standard Model, the EFT framework shows us that—despite their epistemic importance—the “fundamental” “constants” are neither fundamental nor constant.

By emphasizing that scientific disciplines evolve and interact through time, the line between theoretical and experimental knowledge is blurred, and concerns of problematic theory-ladenness are replaced by a detailed understanding of how a mature theoretical framework can serve as the background against which we can discover the details that make a dynamical difference. Because of this theory-predication, the resulting knowledge is stable against theory change, and constrains future theory development.

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