An apology for the simple and small

Nick Huggett, University of Illinois Chicago
Mike Schneider, University of Missouri

August 2025

Contact: huggett@uic.edu

Abstract

Recent work on the philosophy of high energy physics experiments has considerably advanced our understanding of their epistemology, for instance concerning measurements by the ATLAS collaboration at the large hadron collider (Beauchemin 2017). In this paper we aim to highlight and analyze complementary low energy 'tabletop' experiments in particle (and other kinds of fundamental) physics. In particular, we contrast ATLAS measurements with high precision measurements of the electron magnetic moment. We find, for instance, that the simplicity of the latter experiment allows for uncertainties to be minimized *materially*, in the very construction of the apparatus. We also sketch how a notion of 'frugality' can be used, in light of considerations of simplicity, to understand the value of low energy experiments with respect to the entrenched field of high energy experiment.

1 Introduction

The next fifty years may well see two major circular colliders constructed over the Eurasian continent. CERN's proposed Future Circular Collider (FCC) and the Chinese Academy of Science IHEP's proposed Circular Electron Positron Collider (CEPC) are designed, respectively, to be more than 3 and 4 times the circumference of CERN's Large Hadron Collider (LHC), at 27km currently the largest collider ever constructed—itself over 4 times Fermilab's Tevatron, the previous largest accelerator, whose circumference was comparable to the length of an arm of LIGO (another current, very large instrument) and nearly twice the length of SLAC, at 3.2km the largest linear collider ever built. These are expensive building projects; they are also paradigmatic of the place of big science at the frontiers of experiment characterizing particle physics. The primary aim of this paper is to contribute to a more complete picture of the vanguard occupying those frontiers. We offer preliminary remarks on a new framework within epistemology of experiment, which is especially well suited to explore and articulate frontier advances in particle physics that come from a smaller kind of science.[1]

Why bother spotlighting the small? We offer three self-standing reasons, then two goals for the remainder of this paper.

First, because the small is easily disregarded. A correlate of the ascendancy of big science is the ease with which comparatively small science gets left out of the limelight, philosophical or otherwise. Yet, as we will argue, there is much of interest for epistemology of experiment concerning the boundaries being pushed in comparatively small science experiments within particle physics today. For instance, certain kinds of precision experiments on particles at low energies advance 'achievements of observability', to name a concept originally developed by Chang (2004): they leave us in a position to observe *better than* before.[2] For reasons we will get a taste of in §2, in high energy collider physics, it is difficult to say whether there is such an achievement (notwithstanding other kinds of achievement in measurement!). By contrast, it is very natural to see an achievement of observability in the case of the precision experiments carried out at low energies: an epistemic virtue of carrying out such experiments. (Additional theory testing virtues of these low energy experiments have already been noted by Koberinski and Smeenk (2020), as we discuss below.) As there are such virtues to get excited about, then all the better: big science often faces big setbacks, for instance, when financial support from governments falls through (Riordan 2016). It makes sense to diversify our epistemological efforts, so that their relevance to the future of experiment in particle physics does not depend too strongly on funding approvals going through for the FCC or CEPC (or even for Fermilab and CERN).

Second, one might worry, as does (Stanford 2019), that big science has a tendency to homogenize research prospects within a discipline.[3] Low energy, small science experiments foster heterogeneity and so push against this tendency. And this is good: pluralism in inquiry is important in science according to more than one conception of scientific process (e.g., Popper (1959); Feyerabend (1993); Lakatos (2014); Longino (1990); Kummerfeld and Zollman (2016)). It is therefore valuable to study more precisely the nature of the pluralism presently realized in particle physics experiment.

[1] We have decided to use 'particle physics' in this paper, since the specific experiments we discuss fall under this description. However, we take our conclusions to apply to 'fundamental physics' more generally construed: the future of fundamental physics may not be quantum field theory or particle accelerators. We also do not consider more general uses of the term 'experiments' in particle physics, e.g., solar neutrino detections, astroparticle physics.

[2] That is, if, following (Chang 2004, p. 86), we understand observation to be any reliable determination that ultimately stems from sensation, we are pushed toward comparative judgments of the form *does this latest accomplishment in experiment make it so that there is some worldly thing we may now observe* better than *before?* If yes, this is an achievement: our ability to carry out the experiment as intended has, in some way, enhanced the observability of that worldly thing.

[3] Stanford does not specifically address the discourse found within high energy particle physics collaborations. Attending to such data may temper the worry in this setting: for instance, one might find that the broad array of specializations found within a single project like ATLAS is a check on this tendency.

Third, in a separate but related vein, the organic growth of science witnessed through history means that philosophers should be wary in their assumptions about the future development of science, particularly concerning which of today's multiple threads will in retrospect prove most fruitful (Shaw 2022). From this perspective, it is inherently valuable to philosophy of science to spotlight how expectations of the future of the field look when one considers precision low energy particle physics experiments in the vanguard, complementing what comes of a more common and implicit centering of high energy collider physics. (For instance, expectations about the integration of machine learning and AI advances within the interpretation of measurement in particle physics, including of new discoveries, differ dramatically between the cases of low energy and high energy experiment (Shanahan et al. 2022).) Not only is such diversity good scientific methodology, it is good philosophical methodology.

Fourth, as we will ultimately argue, an analysis in the epistemology of experiment in particle physics can be meaningfully enhanced by contrasting empirical inferences in low and high energy experiments, in terms relevant to the values in science sub-literature in philosophy of science. In angst about new collider physics, a common sentiment is that building these impressive instruments also makes a daunting footprint—on the environment, on climate, on existing global economic disparities, for instance. Low energy particle physics experiments offer a possible road to new physics that may allay some of these concerns.[4] To the extent that one is interested in studying how such value commitments may become paired with epistemology of science, it is of interest to consider the version of the future of experiment in particle physics that centers searching lower rather than higher.

Of course, some things about the physical world can only be learned from high energy experiments. It is *not* our intention to argue against pursuit of searching higher. Instead, we aim to explicate some of the promise of low energy experiment as a complement to future high energy work, whatever that turns out to be. One helpful framework for communicating the view articulated here is provided by the 'Frugal Science' (and Innovation) literature in development economics (Reardon 2013; Weyrauch and Herstatt 2017; Byagathvalli et al. 2021). Frugal Science is an alternative approach within that discipline, which challenges traditional emphasis on international aid in science and technology sectors (including STEM education) within resource-scarce social systems, in favor of sustainable development planning. The core concept in Frugal Science is *frugality*: a priority or mindset of getting the most out of the least. The basic proposal of Frugal Science is that *figuring out how to* get the most out of the least is not a sad substitute for doing cutting-edge, global research in a scientific domain. To the contrary: figuring out how to be frugal is an independently valuable contribution to that cutting-edge. So too may we consider low energy experiments in particle physics as capable of accomplishing new feats at the frontiers of fundamental physics *through their being (comparatively) frugal.*

[4]Of course, arguments for big science initiatives inevitably include claims about projected economic and social welfare gains. It is interesting to speculate about how to navigate the uncertainties involved in these forecasts, compared to those of small science alternatives.

We will discuss this framing more in §5.[5]

Fifth and finally, while we undertook this work for all these reasons, we hope that the following discussion will demonstrate that there are sufficient interesting philosophical novelties to make studying tabletop particle physics worth the bother of any philosopher of experiment. There is by now, thanks in part to the Epistemology of the LHC research unit funded by the German Research Foundation (DFG) and the Austrian Science Fund (FWF),[6] a sizable literature on philosophy of experiment focused on particle physics 'in the highs'—particle physics in the context of research involving high energy particle collisions. What new appears when we turn the spotlight toward low energy particle experiments—'the lows'? Our aim is to offer some notes towards a philosophical theory of experiment for the lows, primarily in contrast to collider physics in the highs. In §2 we will review some representative work on high energy experiment; while in §3 we sketch an important low energy experiment, the precision measurement of the electron magnetic moment (EMM), drawing attention to some philosophically salient features. In §4 we use the data furnished in the previous sections to draw some important distinctions (not least concerning the different roles that theory and materiality play in the highs versus lows), and to describe how some familiar analytic concepts look different in the unfamiliar context. In §5, we end with some further discussion of framing our analysis in terms of frugality.

We are not the first philosophers to write about EMM experiments: Koberinski and Smeenk (2020) beat us to it, in a paper that gives a very careful account of the precision measurements that have been performed (for details beyond our description below, we recommend their paper). We will discuss some of their work, but it is to a large extent orthogonal to ours. Where we analyze low energy measurements in contrast to high energy experiments, they analyze them within the theory of precision measurements developed by the late, great George Smith (2014) for Newtonian gravity.

2 The highs: physics at the LHC

In a rich, philosophically insightful paper, Beauchemin (2017) analyses the empirical and logical structure of measurements carried out in the LHC's ATLAS detector, on which he is a collaborator. The 'autopsy' that he describes reveals four major features: event (re)construction, measurement construction, error bar determination, and finally comparison with theory. The first two are the most interesting for our purpose of complementing study of the highs with study of the lows; so these are what we will summarize, highlighting some interesting features (but necessarily leaving aside many of the conclusions of this paper).

Protons are sent around the LHC in 30cm long 'bunches', containing 10^{11} particles: accelerated to close to the speed of light, a bunch takes 1ns to pass, and

[5] As we shall explain in §5, although frugality is closely related to the concept of 'pursuitworthiness', it is a distinct notion.

[6] https://www.lhc-epistemologie.uni-wuppertal.de/home.

sequential bunches are spaced 25ns apart. When two proton bunches moving in opposite directions cross, there will be an average of 20 proton-proton collisions, producing a range of quanta that subsequently interact with each other and various detectors (and background fields), or decay, all producing yet more quanta. (As Beauchemin, §2.4, emphasizes, some of the detector physics is thus of the very kind under investigation, and care has to be taken to avoid the experimenter's regress.) All interactions with the detectors cause the latter to produce various electronic outputs, which in turn are recorded. Since the interactions with the detector produce quanta as well as data, the apparatus is not cleanly separable from the measured system—which includes all the quanta produced.

No one of the 20 collisions constitutes an 'event' in the parlance of high energy physics. Nor does the raw data produced by the detectors in response to the 20 collectively, due to uncontrollable uncertainties in the detector responses: "the kinematics of a particle [e.g., its energy] as provided by a reconstructed event constitutes an instance randomly picked from the [instrument] resolution distribution of the energy of the source particle" (286). Thus an event—iconically depicted as a collection of particle trajectories and jets from the collision point—is constructed from the raw data and amounts to "highly imprecise" (286) information about the corresponding occurrences inside the ATLAS detector, due to the various uncertainties inherent in the construction.

As a result, no such event is itself treated as something individually measured, which could be compared with theory. Moreover, because scattering (and detection) are stochastic, the vast majority of events will not involve the physical process relevant to any given theoretical prediction (e.g., the production of specific particles). Therefore, the measurements to which physicists appeal have to be further constructed from multiple (constructed) events. (Beauchemin 2017, §4) describes this process in some detail, but the main steps involve (i) selecting out a set of events relevant to the theoretical process under study, (ii) estimating and taking account of irrelevant events that nevertheless passed the selection criteria, and of relevant events that did not, and (iii) solving a tricky 'inverse problem' arising from the stochastic nature of event construction just discussed—what theoretical scattering process do the statistics of the remaining events encode? All of these inferences are highly theory-laden, including assumptions about the very physics being tested. How the apparent circularity is controlled for is a major topic of Beauchemin (2017). For our purposes, what is more important is that these steps rely on (a) gathering data, any one item of which leaves great uncertainty, (b) in vast quantities so that, (c) through statistical methods, considerable theory can be applied to obtain a clear signal that can be compared with theory. (Of course, crucial to this process is a careful estimation of the remaining error bars in the result, the third step of Beauchemin's 2017, §5 analysis.)

The situation is very different in the case of electron magnetic moment measurement (EMM) and, we suggest, other 'tabletop' experiments. The cause for the difference is that these latter experiments rely on comparatively simple observations of relevant phenomena—smaller, less complex data sets, with less statistical and theoretical heavy lifting—by controlling for uncertainties *materially*: building an apparatus designed to single out some event with great precision and clarity, as we shall illustrate in the next section.

Mention of "relevant phenomena" in the contrast case of the EMM experiment calls attention to a perhaps surprising feature of the preceding analysis. In the latter discussion of high energy *phenomenology* studied by the ATLAS collaboration, we have not mentioned any 'phenomenon'. By 'phenomenon' we mean (crudely) the very physical 'happening' that an experimental apparatus is constructed to probe.[7] In the present case, the best that can be said of the 'happening' is that it involves bunches of protons colliding, decays, interactions with detectors, and so on. As Beauchemin (2017)'s analysis demonstrates, it would miss the point to try to decompose all of that physics into something like proton-proton collision phenomena and detection thereof. Moreover, the data output of all that physics is a far cry from the iconic reconstructed events, or the measurements which are ultimately compared with theory. No wonder that the phenomena themselves faded from the story: the packaging of the data into epistemic objects used to compare to theory (see footnote 7), while capturing salient features of a physical happening, is hardly a literal representation of it.

Recalling a point in §1, to the extent that the phenomena hardly figure in the 'data journey' (Leonelli 2020) relevant at the LHC, it is unclear how to analyze the successful running of the high energy particle collision experiments analyzed by Beauchemin as an achievement of observability.[8] This is different than the case of the electron magnetic moment measurement, where the phenomena naturally occupy center stage, as we shall now see.

3 The lows: the electron magnetic moment

In the mid-noughties, a team at Harvard, led by Gerald Gabrielse (Odom et al. 2006; Hanneke et al. 2008), completed one of the most precise measurements ever carried out, determining the electron magnetic moment, g, to better than one part in one trillion. As we shall see, these experiments—the result of over 20 years' work—were different from those at the LHC in fundamental ways: for one, the equipment used was the size of a small car, not of a small country (and run by a team the size of a carpool, not the size of the population of a UN recognized microstate)![9] The essential idea is to construct an artificial single-electron

[7] Less crudely: consider the relational view of data provided by (Leonelli 2020) (contrasting with Bogen and Woodward's (1988) view), according to which data travels and evolves in the form of theoretically constructed and reconstructed objects put to many uses. Some of those uses are to *represent* something, that which experiments are sometimes performed just to have probed. The 'something' represented, in those uses of the data, is what we mean by 'phenomenon'. Also, we note that Beauchemin (2017) uses the term 'phenomenon' in various senses, including ours, and including the theoretical sense of quantum field theory: a process with non-zero S-matrix element.

[8] We leave it open as to how direct detection experiments at the LHC fare on an analysis of observability.

[9] https://atlas.cern/about.

'atom' and observe transitions between its ground and two lowest excited states (Brown and Gabrielse 1986; Gabrielse 2007; Koberinski and Smeenk 2020).

More specifically, an electron is held in a 'Penning trap': a vertically oriented electric quadrupole field controls the vertical motion, while an axial magnetic field controls its horizontal motion. Because the electron moves *inside* an earth-bound collection of electrodes and electromagnets, and not outside a charged nucleus, the creator of the trap, Hans Georg Dehmelt, dubbed the artificial 'atom' *geonium*.[10] The interior of the trap (the order of 1cm across) needs to be a hard vacuum and close to absolute zero, to avoid entanglement and achieve the ground state, requiring ultra-efficient vacuum pumps and refrigerator. This was done so well that a single electron could be contained in the trap for *months* at a time.

While the LHC is a very high energy, relativistic cyclotron, this set-up is a very low energy mini-cyclotron, with the electron circling as slowly as possible. As such, the motion is non-relativistic to a high approximation: classically, a circular orbit in the horizontal plane, with rapid epicycles and a vertical undulation. This system is simple to quantize, and adding a small relativistic correction (due to a mass effect) yields the lowest energy levels with great precision: crucially, these levels are very sensitive to g. The quantities that need to be measured to determine the magnetic moment are the energies of the lowest two excited states: corresponding to (a) the first excited cyclotron state, with the electron spin aligned with the trap's magnetic field, and (b) the cyclotron ground state with the electron spin flipped.

We emphasize that the theory just described, assumed to perform the measurement, is of the most well confirmed and understood kind in quantum theory (as we shall see further when we discuss uncertainties). Contrast this with the LHC: not only is quantum field theory under less mathematical control, but we also noted above that some of the physics of the detector is the physics under test. (Of course this is a *comparison*: much—enough!—is understood about high energy experiment.) Moreover, this simplicity of the phenomenon allows the apparatus to be (relative to the LHC) simple, and so under exquisite control by experimentalists. Nevertheless, the measurement is in principle (and perhaps already in practice) sensitive to far more speculative and less well controlled physics, of the standard model (SM) and even beyond. While *measuring* the value of the electron magnetic moment relies on (fairly) simple cyclotron physics, what that value should be *in theory* depends on the full SM, and beyond, if one wants it to enough significant figures.

The energy of (a) is determined by measuring the frequency of microwave radiation required to excite the electron from its ground state into (a). *First*, the apparatus can register when the electron jumps to the excited state by sen-

[10]Dehmelt won the 1989 Nobel prize with Wolfgang Paul for developing the trap. Gabrielse joined Dehmelt's University of Washington group as a postdoc in 1978, and subsequently joined the faculty. Note that Dehmelt (and Paul) shared the 1989 Nobel with Norman F. Ramsey for the latter's work developing the atomic clock and hydrogen maser, all work in high precision tabletop physics. This recognition shows that such work has long been recognized; what is perhaps more recent is its realization as a road to new fundamental physics.

sitive measurement of the frequency of the vertical undulations of the electron's motion, which differs according to the state. (It is worth emphasizing the innovation and importance for the precise determination of g of this measurement, which is capable of resolving the frequency to parts per billion.) This measurement requires that the electron stay in the excited state for a few seconds before spontaneously jumping to the ground state. The decay time can be tuned by finely adjusting the strength of the magnetic field in the Penning trap: the energy level depends on the field strength, and thus so does the wavelength of the photon emitted when it decays to the ground state. But the emission rate depends on the ratio of the photon wavelength to the resonant modes of the trap cavity; so, *second*, the spontaneous emission time is tuned with the magnetic field. *Third*, pulses of microwave radiation of precise frequency are produced and shone into the cavity, to observe which frequency produces the greatest rate of excitation into (a).

The energy gap between (a) and (b) is measured using exactly the same technique, to determine what frequency photons will excite the electron from (a) to (b).

The (ratio of the) energy gaps between the ground state and (a) and between (a) and (b) depends on g, according to simple theory, and so conversely g can be inferred from their measurement. In 2006 it was thus determined to 8 parts in 10^{13} (and, with improvements, to 3 parts in 10^{13} in 2008, and in 2023 to 1 part in 10^{13} by Gabrielse's new group at Northwestern University) (Fan et al. 2023). The uncertainties are essentially to do with the apparatus, for instance resonances and fluctuations in the fields are either hard to determine or their exact effects uncertain, and there are effects inherent to a cyclotron; the improvement of course reflects better control and understanding of such behavior. The main statistical uncertainties come from sample size, but these are very small. The ability to observe the electron energy level, along with the slow emission time, mean that selection and background uncertainties are negligible. A great deal of work, perfecting the apparatus, and upgrading it to better control the uncertainties lies behind these incremental advances.

As noted, the experiment measures a fundamental constant of SM because g can be calculated as a perturbative expansion in powers of the fine structure constant α (so in even powers of the electron charge e), plus smaller contributions from other SM sectors. Indeed, the results of the experiments are now so accurate that in principle they are sensitive not only to virtual muon and tauon contributions, but potentially to strong, weak and even beyond SM contributions. However, they currently go beyond the exactly calculated 'pure' QED contributions (which go to $O(e^8)$—there are over 12,000 $O(e^{10})$ Feynman diagrams, of increasing complexity to compute Nio (2023)), and the accuracy of current (i.e., as of 2024) measurements of α. Still: the experiment can meaningfully test SM. Indeed it already does. Insofar as g depends on the size of the electron (is it a point particle, or does it have as yet unknown constituents?) the radius must be less than 10^{-18}m. Thus this frugal physics probes (some of) the same physics as searching the highs, not by ever increasing the energy, but by ever increasing the number of significant figures in the measurement.

The experiment, the calculation of the theoretical predictions, and the application to QED, SM, and beyond SM physics are discussed in greater detail in (Koberinski and Smeenk 2020, §3), to whom we defer. (Their paper appeared before the most recent results, and so its discussion of discrepancies is already slightly dated.) As we noted earlier, we accept their account of these matters, but wish to analyze the experiment from a different perspective.

4 Plenty of room at the bottom

We have described the experiments at the LHC and those to measure g in a way that emphasizes certain brute differences: size by various measures, energy, time, physical theory, and so on. In this section, we will unpack these differences and analyze their philosophical significance, attempting to erect some signposts toward future philosophical investigation. In the background of this section is the notion that experimental frugality provides a vehicle to articulate the *simplicity* of low energy experiments in the vanguard of particle physics as an epistemic complement to the capacities of high energy collider experiments. This notion will be foregrounded in the next section.

Differences in the energy scale, while real, do not in themselves appear to be relevant to the epistemology of experiment (indeed, as noted, that's why we used 'high' and 'low' to distinguish the cases). Differences of material size seem similarly irrelevant. Differences of collaboration size—on the order of 10 versus 10^4 collaborators—are of course relevant, but have been raised elsewhere, as we shall briefly discuss below. Differences in the degree of precision may seem more promising, as (systematic error aside) more precision trivially means more knowledge! However, that fact does not exhaust the interesting epistemic aspects of low energy particle physics, as we shall demonstrate. Indeed, precision is not a good way to contrast high with low: typically high and low experiments are not in direct competition to measure the same quantity, so the comparison cannot actually be made. Moreover, it is not the case that all low energy 'precision' fundamental experiments are more precise than all high energy experiments. While the EMM measurement illustrates the general strategy of using precision to probe new physics in low energy experiments, its extraordinary $1 : 10^{12}$ precision experiment is not typical, and we should not overgeneralize. So, although contrasting *ways* in which precision is achieved will be important to our analysis, mere differences in *degree* will not.

Instead, we organize our investigation of the epistemic differences on the different ways in which the geonium experiment is *simpler* than the LHC: conceptually, materially, theoretically, and phenomenally. (Though perhaps some of the other differences that we will arrive at could themselves equally have been taken as starting points.) In so doing, we also emphasize that Penning traps are merely an illustration, a concrete instance of a (comparatively) 'simple' low energy physics experiment. We do not argue that simpler is epistemically *better*, just epistemically *different*; our point is that the validity of the experimental conclusions does not stand on the same grounds in the two cases.

Simplicity, as we have in mind, is one example of an 'aesthetic' factor in science identified by philosophers of science. That is, following Elgin (2020), aesthetic factors are "formal properties of scientific artifacts such as theories, models, methods, and experiments. A form, let us say, is scientifically significant to the extent that it illuminates something that bears on the scientific acceptability of the item that displays that form" (p. 21). On this view, aesthetic factors in science are "the sorts of things that make [theories, models, methods, and experiments] epistemically attractive in science" (p. 25). (This sense is often in contrast with loose appeals to 'beauty' in the physics literature, which are at best dubiously epistemic.) So other aesthetic factors we might name constitute other possible axes of difference between the particle experiments we have discussed, with epistemic consequence. And there is room for further study.[11]

The experiments differ significantly in (i) the sheer number of components involved in the apparatus, (ii) the complexity of the theory required to understand the apparatus, and (iii) the nature of the phenomenon measured in the experiment; the differences in the theory required to describe the phenomenon are discussed later. After we spell out these differences further, we will discuss their significance: a special focus will be the concrete, how material differences between the very machines built to carry out the experiments affect the empirical conclusions drawn from them.

(i) Of course, there are ambiguities in dividing a piece of equipment into components: in some sense the whole ATLAS detector is only one component of the LHC. But the difference is so huge that the ambiguity is irrelevant. In particular, while the EMM experiment requires only a handful of experimentalists to run, the LHC requires thousands. In the latter, and not the former, confidence in the measurement capabilities of the experiment is essentially distributed over a community. While each in the former group knows how all parts of the apparatus function (though some may specialize in some aspect), no one person knows how each component of the LHC functions: specialists develop the different parts, under a stratified leadership over increasingly large portions of the machine. Some literature discussing such distributed epistemic labor within big science collaborations already exists: see, e.g., (Huebner et al. 2017), and, for instance, Dang (2019); Galison (2020); Galison et al. (2023) regarding questions of consensus negotiation and governance. Murphy et al. (forthcoming)

[11] Some examples of other axes of aesthetic difference that may be fruitful to consider in present context are *elegance*—to what extent the performance of the EMM experiment versus a collider experiment makes immediately manifest the result or upshot of having performed it (Elgin 2020)—and (indeed, recalling our own focus on frugality) *economy*—minimal material involved (Ivanova 2021). We also draw attention to a conceptual point suggested by Murphy et al. (forthcoming): that the 'experimental distance' between individual scientists' aesthetic agency and the experimental phenomenon under study is substantially different in paradigmatic cases of big and small science. While they construe experimental distance to be of epistemological relevance, it needs more articulation to be of immediate assistance here. For instance, as the original authors note, the experimental distance is also substantively different between quick and slow experiments. Yet, while we have already noted that the time scale of performing an EMM experiment is extraordinarily long compared to the time scale of performing a particle collision experiment, this fact strikes us as much the same as the other noted differences of energy scale or material size: not epistemically pertinent in this case.

argue further, from a concept of distributed epistemic labor and such attendant concerns to a concept of distributed aesthetic and epistemic agency relevant in the epistemology of experiments like those at the LHC. We suggest that our notion of simplicity, and an explicit comparison with small, low energy experiment could inform this work, but we will not undertake such a study here.

Moreover, (ii), as we have indicated in our discussions, while the theory of the apparatus itself involves SM (and much more) in the case of ATLAS, the corresponding theory of the geonium 'atom' involves well-established quantum and classical physics, which is better understood and formally simpler to manipulate. In the former case even constructing a single 'event' is laden with theoretical assumptions about the apparatus, whose uncertainty must be carefully managed. In the latter case, the microwave frequency shined onto the electron is under precise control, and the inference to energy levels is a matter of elementary quantum mechanics. Even the further inference to the value of g depends on well-understood quantum physics, under precise physical control (e.g., the magnetic field and cavity geometry). It is only the computation of the theoretical value—the repackaging of the data initially packaged as about the artificial geonium 'atom', to now constitute another epistemic object used to test the SM—that starts to depend on less known physics, especially as improved experiments start to probe beyond known QED.

(iii) These gains in simplicity for the EMM experiment are possible because of the simplicity of the physical phenomenon observed: the energy levels of the geonium atom. This phenomenon involves interactions with the environment inside the Penning trap, but the latter's effects are *mechanically* screened out by creating a hard vacuum, at a very low temperature, and by the cavity geometry, as we have discussed. This control over the experiment allows for the material construction of a single phenomenon—excitation of an (isolated) geonium atom—that dominates all other processes, and which can then be observed with exquisite precision. In contrast, the phenomenon relevant in the ATLAS experiment is the collection of (on average) 20 collisions occurring between two beams of 10^{11} protons passing through each other, and the passage of their products through the detectors. As we saw, even the set of events mathematically constructed from the effects of those collisions on the detectors is mostly a sea of noise: statistical noise from the detectors or processes irrelevant to the quantity of interest (and indeed, even events containing processes of interest also contain irrelevant processes). This noise is then *mathematically* screened out to find the signal of interest (not to mention the treatment of systematic measurement error, relying on theory as well). Instead of looking carefully at one thing, ATLAS singles out a needle from an enormous haystack (or rather, the average of a collection of a few needles). Again, our central point is to contrast the different *means* by which precision—hence, increased knowledge—is achieved in low versus high experiments, not the difference in degree (though of course the means are crucial to the degree). After all, remarkable precision can be achieved in high energy physics, even if not equal to that of EMM.

As we have been emphasizing, a great deal of *uncertainty* is removed materially, by the very construction of the apparatus that constitutes the geonium atom. Of course ATLAS is constructed with similar painstaking care, but its sheer scale and complexity means that such efforts leave uncertainty that must be treated statistically as described earlier, by collecting large amounts of data.[12] For the same reason, the experiments differ considerably in the balance of material versus mathematical *construction*: as sophisticated a machine as ATLAS is, we saw that much formal construction remains to obtain something to be related to theory. Measurements of geonium excitation levels and g follow much more directly from the raw data. We said that the relative material and theoretical simplicity of the EMM apparatus results from the simplicity of the phenomenon observed, but this discussion implies that the relationship is symmetrical: the relative simplicity of the apparatus helps to keep the phenomenon simple, recalling by contrast our tangled discussion of the phenomena within ATLAS.

What is therefore so impressive about the EMM experiment is that, on the basis of simple measurement of a simple phenomenon, one can make an inference about the fundamental (sub)structure of the electron. Recalling the discussion (and footnote) in the introduction section about observation according to Chang (2004): fine-grained study of the electron orbital structure of the artificial geonium atom makes something about electrons *more observable* than before. This is, in effect, the precision testing claim developed by Koberinski and Smeenk (2020), only framed instead in terms of exploration.[13] What we may newly observe about electrons indeed tests the SM electron. But put in this order, theoretical points about improved testing regiments are subsidiary to the point that the machinery itself—the artificial atom—lets us observe *more* of the world.

Notably then, minimizing uncertainty allows the EMM experiment to probe some (though far from all) of the same physics as ATLAS. That may seem puzzling given that they work at radically different energy scales: doesn't that mean that they operate in different physical regimes? In fact the comparison illuminates the fact that energy scales are merely *proxies* for regimes: new regimes are not only found at different energy scales, but also at different degrees of uncertainty—new regimes can be found in new significant places! The role of energy scales is clear in a general effective field theory point of view, since increasing experimental energy can produce greater mass particles, and so new physics. But of course new physics is not simply turned on at a mass scale, it

[12] As a referee pointed out, this is not the end of the story, as both imprecision and systematic error contribute to uncertainty, and we have focused on the former. We wager that the simplicity of small scale experiments helps manage their systematics in much the same way that we have seen it promote precision (see, e.g., Ritson and Staley (2021) for philosophical treatment of the role of managing systematic uncertainties in high energy experiment).

[13] For discussion of exploration on the high energy side, see Beauchemin and Staley (2024), which is engaged in a wider philosophy of science literature on characterizing exploratory experimentation. It is an interesting question the extent to which the exploration of particle physics involved in EMM is ultimately a different kind than that relevant on the high energy side, precisely in virtue of the material versus mathematical handling of uncertainties. It is our sense that this question cross-cuts the existing general debates on the subject of characterizing exploratory experimentation.

is rather, according to theory, heavily suppressed at lower energies; and that of course means that it can, potentially be seen in very fine-grained low energy behavior. That of course is the way in which the geonium experiments have seen some of the same physics as ATLAS: nearly to the weak interaction, and perhaps at some stage to beyond SM. So an important lesson is that one should be careful equating physical regimes with energy scales, since the latter is really just a proxy for the former.

On this note it is interesting to compare the EMM experiment with another we have recently discussed in (Huggett et al. 2023), 'gravitationally induced entanglement' (GIE). It too aims to probe a regime of new physics, in a low energy experiment, where it is often thought that high energy was required (see also Wallace (2022)); it also undermines the false equality of scale and regime. In short, the latter aims to induce quantum entanglement (observable through violations of Bell-type inequalities) between two Planck mass bodies solely by their gravitational interactions, something that can only occur if the mediating field—i.e., gravity—is in a quantum superposition. It therefore functions (in part) as a crucial test between the hypotheses that gravity is classical versus quantum. We would highlight a couple of interrelated points of comparison between these two experiments.

In both cases we have stressed the importance of material aspects of the experiments; however, the relevance is not the same. As our monograph explained, an important achievement of the GIE experiments—if they are successful—will be to achieve the first physical *control* within the regime in which gravity must be described by a superposition. The experiment involves the ability to create such a state at will, and to use it to affect the states of matter. This accomplishment is independent of the interpretational disputes we discuss in the monograph, concerning what is to be learned from successfully completing the experiments. This kind of practical knowledge is material in the sense of being embodied in ability to construct and use the apparatus of the experiment. The EMM experiment is different in that it does not give control over a *new* physical regime, but *better* control over an existing one: that of a charged particle in a cyclotron. The relevant material aspect of the experiment lies in the fine control over that physics, with the goal of knowledge—not control—of new physics, through the sensitivity of the measurement. The experiment measures a quantity, g, from which inferences can be drawn about new physics—does the SM agree or not? But the experiment can be perfectly well understood without any SM theory. On the other hand, the GIE experiment, at least in initial iterations, will provide little if any useful quantitative data: it is not expected to give any empirical tests between string theory and loop quantum gravity, say. Finding entanglement will just indicate that some quantized version of general relativity is needed. So on the one hand we have sensitive material control over known physics (perhaps) allowing inferences about new physics; while on the other, control over new physics but no knowledge of it (besides that it exists). That the upshot of succeeding in performing the GIE experiment is to achieve newfound material control indicates a sense in which the knowledge of new physics produced by the GIE experiment is embodied in the apparatus that experimenters use to exercise that control (see also (Baird 2004)). This contrasts the case of the EMM, where the corresponding knowledge that follows successfully performing the experiment looks more like propositional content: knowledge that is, ultimately, cognitive, in the (collective) mind of physics.

In the foregoing, we have compared a single pair of experiments—LHC and EMM—in part because of the salience of the former in the recent literature, but also to make our points as vividly as possible. We of course realize that there is a continuum of particle physics experiments between these two (for instance, Fermilab's *muon* magnetic moment experiment, https://muon-g-2.fnal.gov). We leave such examples to future work by philosophers of science; all we would say is that our analysis strongly suggests that the experimental epistemology of such work should not be assimilated to that of the LHC.

5 Conclusion: Thinking frugally about particle physics

Our purpose in the preceding was to contrast an epistemology of experiment having to do with the lows of particle physics with an epistemology of collider physics experiments that basically exhausts the highs. Our emphasis with regards to the lows was on the comparative simplicity of both the experimental apparatus (materially and theoretically) and the phenomena thereby observed, yet which materially support inferences about novel particle physics also at work in the highs, to wit tests of the SM electron. In §1, we suggested that the Frugal Science (and Innovation) literature provides an appropriate framework in which to make sense of the view that low energy, small footprint experiments are worth explicit consideration *for their being frugal*. We elaborate on that suggestion here, and relate it to our discussion of simplicity, capping off our analysis.

First, what is Frugal Science, as discussed by, e.g., Reardon (2013); Weyrauch and Herstatt (2017); and Byagathvalli et al. (2021)? A simple example will suffice to demonstrate its general spirit. Consider the extraordinary cost of a Nuclear Magnetic Resonance (NMR) spectrometer to an individual chemistry lab. In light of the cost, what it means to be a trained chemist in impoverished regions can differ substantially, even in ideal cases, from what it means to be a trained chemist in a lab embedded within a G8 state: the former may do their work in a community context that never involves appeals to NMR spectrometry, while in some cases the latter can hardly conceive of their work without it. Attending to this difference in the nature of expertise due to ambient circumstance, one sees that research imperatives on the vanguard of chemistry—its 'cutting edge' projects—inevitably differ, embedded expert community to embedded expert community, in virtue of differences in ambient circumstance. Frugal Science, in part, captures this state of affairs: that the cutting edge is serrated.

That is, differences in ambient circumstance between different communities do not merely differentiate constraints placed on the different researchers' available *paths* toward scientific advance. Instead, Frugal Science reconsiders what *counts* as scientific advance, declaring that it is plural. 'Frugality'—getting the most out of the least—is the underlying concept proposed to articulate the plurality. The cutting edge of science is populated by research imperatives which, given contextually-relative values, maximize gain for minimized cost within that given context.

Frugality takes for granted economic concepts—assessment of costs weighed against benefits of performing the science involved. Hence, moreover, frugality depends on values—assessment of what all enters as a cost and what all enters as a benefit, and how to construct a measure appropriate to balance between them. Values also inform deliberative decisions about what actions scientists are next to do, in a very similar manner. Pursuitworthiness refers, broadly speaking, to the use of values in making such deliberative decisions in science. But frugality and pursuitworthiness are not the same: frugality refers to the use of values in determining what constitutes cutting edge knowledge acquisition in a given scientific domain. It is therefore entirely an epistemic notion, albeit highly contextual. Even in a Peircean tradition of pragmatism (e.g., Beauchemin and Staley (2024)), which largely collapses the distinction between epistemology and economy of science, there is room to distinguish what would constitute a kind of scientific advance from what should be done next. For instance, it may be on such a pragmatism that frugality considerations structure the very decision problems that pursuitworthiness considerations are designated to help solve.

To say that experiment in the lows constitutes a kind of frugality in particle physics, importing in the epistemic pluralism of Frugal Science, is therefore to invoke a values-dependent framework within epistemology. But it is not, therefore, to weigh in on what is pursuitworthy in the field. The latter is difficult (to understate things). Beauchemin has pointed out to us that the sheer number of scientists working on ATLAS may make the cost per person comparable—or even lower!—than the cost of an individual running their own lab. So there is a financial efficiency claim to be entered in along with so many others, in weighing prospects of searching low versus high. Still: frugality helps to make sense of the distinctive promise of research imperatives in particle physics other than those that would (keep) plundering the highs, especially those that consider the lows.

Our schematic proposal is as follows: in particle physics, what enters into quantifying 'getting the most' is an assortment of epistemological considerations concerning its future; meanwhile, (further) value considerations enter into quantifying 'out of the least'. The plurality that results makes room for *both* high and low energy experiments to constitute the cutting edge of particle physics. Note that this suggestion extends the original focus of Frugal Science on regional differences of scarcity, and assumes that relevant differences occur within the physics community independently of geographic variety.[14]

[14]That said, one can expect that regional economy is also an important factor. For instance, small scale, low energy experiments might be especially frugal in countries with small basic science budgets, though large experiments may also prove frugal: for instance, the ATLAS collaboration includes scientists from 40 countries, though the financial costs are almost entirely borne by large European economies, the UK, and the USA.

We have emphasized in the previous section the simplicity of the EMM experiment. We see this discussion as relevant to our proposal in (at least) two possible ways.

(i) Simplicity provides an analytic tool to aid in a thoroughgoing discussion of a pluralism at the vanguard, which invokes any number of values held by the community to interpret the existing landscape of experiments (which includes both improvements in the construction of Geonium atoms and ever more detections in ATLAS). In this case, simplicity is a means involved in assessing all manner of most-least tradeoffs.

Consider: it is crucial in the analysis of the previous section that despite the simplicity of the EMM experiment, it nevertheless is a new probe beyond the SM. Simplicity achieved through much greater epistemic sacrifice would hardly have been worth writing about in the epistemology of experiment in particle physics. This suggests that its simplicity signals that the EMM experiment indeed accomplishes some 'most' out of 'least' (though what values are invoked remains to be fleshed out).

(ii) Simplicity, in our intended (admittedly imprecise) sense, may itself point to a value held by physicists, which experiments like that of the EMM (and that of the GIE) reckon well by. That the EMM experiment is simple thus signals that, likely, it deserves place along the plural vanguard of particle physics for its doing well by that value. And more experiments like it merit explicit consideration in epistemology for their being simple. Conversely, the comparison drawn to the LHC and beyond collider experiments in no way implies that the latter *fail to be* frugal; they just are not all that simple. Vindicating their place at the vanguard requires invoking other shared values, articulating other meaningful ways they succeed at doing the most with the least.

Both of these possibilities strikes us as promising. Frugality has, to our knowledge, not been seriously pursued as a framework within epistemology of experiment. Indeed, it is our impression across many conversations with others that considerations of frugality are (more quickly) captured by pragmatic considerations—considerations of the economy of science, or equally all-things-considered evaluations of pursuitworthiness. Perhaps the present spotlight on the exciting epistemological considerations to do with searching low in particle physics, as complementing existing excitement with searching high, is one way of beginning to pursue it. We hope the above will be read and applied in this light.

References

Davis Baird. *Thing knowledge: A philosophy of scientific instruments.* University of California Press, 2004.

Pierre-Hugues Beauchemin. Autopsy of measurements with the ATLAS detector at the LHC. *Synthese*, 194:275–312, 2017.

Pierre-Hugues Beauchemin and Kent W Staley. The epistemological significance of exploratory experimentation: A pragmatist model of how practices matter philosophically. *European Journal for Philosophy of Science*, 14(4):1–33, 2024.

James Bogen and James Woodward. Saving the phenomena. *The philosophical review*, 97(3):303–352, 1988.

Lowell S Brown and Gerald Gabrielse. Geonium theory: Physics of a single electron or ion in a penning trap. *Reviews of Modern Physics*, 58(1):233, 1986.

Gaurav Byagathvalli, Elio J Challita, and M Saad Bhamla. Frugal science powered by curiosity. *Industrial & engineering chemistry research*, 60(44): 15874–15884, 2021.

Hasok Chang. *Inventing temperature: Measurement and scientific progress*. Oxford University Press, 2004.

Haixin Dang. Do collaborators in science need to agree? *Philosophy of Science*, 86(5):1029–1040, 2019.

Catherine Z Elgin. Epistemic gatekeepers: The role of aesthetic factors in science. In *The Aesthetics of Science*, pages 21–35. Routledge, 2020.

Xing Fan, TG Myers, BAD Sukra, and G Gabrielse. Measurement of the electron magnetic moment. *Physical review letters*, 130(7):071801, 2023.

Paul Feyerabend. *Against method: Outline of an anarchistic theory of knowledge*. Verso Books, 1993.

Gerald Gabrielse. The magnet in the electron. *Physics world*, 20(2):32, 2007.

Peter Galison. Film: Black holes: The edge of all we know, 2020. Sandbox Films.

Peter Galison, Juliusz Doboszewski, Jamee Elder, Niels CM Martens, Abhay Ashtekar, Jonas Enander, Marie Gueguen, Elizabeth A Kessler, Roberto Lalli, Martin Lesourd, et al. The next generation event horizon telescope collaboration: History, philosophy, and culture. *Galaxies*, 11(1):32, 2023.

David Hanneke, S Fogwell, and Gerald Gabrielse. New measurement of the electron magnetic moment and the fine structure constant. *Physical review letters*, 100(12):120801, 2008.

Bryce Huebner, Rebecca Kukla, and Eric Winsberg. Making an author in radically collaborative research. *Scientific collaboration and collective knowledge: New essays*, pages 95–116, 2017.

Nick Huggett, Niels Linnemann, and Mike D Schneider. *Quantum Gravity in a Laboratory?* Cambridge University Press, 2023.

Milena Ivanova. The aesthetics of scientific experiments. *Philosophy Compass*, 16(3):e12730, 2021.

Adam Koberinski and Chris Smeenk. Qed, qed. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics*, 71:1–13, 2020.

Erich Kummerfeld and Kevin JS Zollman. Conservatism and the scientific state of nature. *The British Journal for the Philosophy of Science*, 2016.

Imre Lakatos. Falsification and the methodology of scientific research programmes. In *Philosophy, Science, and History*, pages 89–94. Routledge, 2014.

Sabina Leonelli. Learning from data journeys. *Data journeys in the sciences*, pages 1–24, 2020.

Helen E Longino. *Science as social knowledge: Values and objectivity in scientific inquiry.* Princeton University Press, 1990.

Alice Murphy, Adrian Currie, and Kirsten Walsh. Aesthetics and agency in experiments. *Australasian Journal of Philosophy*, forthcoming.

Makiko Nio. Toichiro kinoshita. *NAS Biographical Memoirs*, 2023. URL `https://www.nasonline.org/wp-content/uploads/2024/06/kinoshita-toichiro.pdf`.

Brian Odom, David Hanneke, Brian D'Urso, and Gerald Gabrielse. New measurement of the electron magnetic moment using a one-electron quantum cyclotron. *Physical review letters*, 97(3):030801, 2006.

Karl Popper. *The logic of scientific discovery.* Basic Books, 1959.

Sara Reardon. Frugal science gets diy diagnostics to world's poorest, 2013.

Michael Riordan. A bridge too far: The demise of the superconducting super collider. *Physics Today*, 69(10):48–54, 2016.

Sophie Ritson and Kent Staley. How uncertainty can save measurement from circularity and holism. *Studies in History and Philosophy of Science Part A*, 85:155–165, 2021.

Phiala Shanahan, Kazuhiro Terao, and Daniel Whiteson. Snowmass 2021 computational frontier compf03 topical group report: Machine learning. *arXiv preprint arXiv:2209.07559*, 2022.

Jamie Shaw. On the very idea of pursuitworthiness. *Studies in History and Philosophy of Science*, 91:103–112, 2022.

George E Smith. Closing the loop. In Zvi Biener and Eric Schliesser, editors, *Newton and empiricism*, pages 262–352. Oxford University Press Oxford, 2014.

P Kyle Stanford. Unconceived alternatives and conservatism in science: the impact of professionalization, peer-review, and big science. *Synthese*, 196: 3915–3932, 2019.

David Wallace. Quantum gravity at low energies. *Studies in History and Philosophy of Science*, 94:31–46, 2022.

Timo Weyrauch and Cornelius Herstatt. What is frugal innovation? three defining criteria. *Journal of frugal innovation*, 2:1–17, 2017.