Searching High and Low

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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 suggest that a better appreciation of the capacities of such comparatively 'frugal' experiments broadens our conception of 'cutting edge' physics, and ultimately helps to inform value judgments about possible research programs in the field.

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? 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 of the worries about big science is its tendency to homogenize research prospects within a discipline (Stanford 2019). 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.

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

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[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.

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.[3] 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. But low energy experiments may either better probe other aspects of the fundamental physical world or complement collider physics, perhaps replacing the latter wherever possible. One helpful framework for relating the view articulated here to values in science 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.*

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

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[3] 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.

Epistemology of the LHC research unit funded by the German Research Foundation (DFG) and the Austrian Science Fund (FWF),[4] a sizable literature on philosophy of experiment focused on particle physics 'in the highs' — particle physics in the context of research on high-energy particle collisions. What new appears when we turn the spotlight toward low-energy particle physics — '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 below, but it is to a large extent orthogonal to ours. Where we analyze low-energy measurements in contrast to high energy physics, 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 ATLAS detector at the LHC.[5] The 'anatomy' that he describes has four major parts: 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 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

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

[5] N.b. Beauchemin is a member of the ATLAS collaboration.

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 those events of interest, (ii) controlling for those remaining events that are not relevant to the theoretical process under study, 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.[6] 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 6), while capturing salient features of a physical happening, is hardly a literal representation of it.

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.[7] 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)![8] The essential idea is to construct an artificial single-electron '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 earthbound collection of electrodes and electromagnets, and not outside a charged nucleus, the creator of the trap, Hans Georg Dehmelt, dubbed the artificial 'atom' *geonium*.[9] The interior of the trap (the order of 1cm across) needs to be

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[6] 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.

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

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

[9] Dehmelt won the 1989 Nobel prize with Wolfgang Paul for developing the trap. Gabrielse

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.[10] 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 sensitive 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

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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.

[10] Of course this is a *comparison*: much – enough! – is understood about high energy experiment.

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 principal 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 study. 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 energy scale (despite the apparent emphasis given by our title), while real, do not in themselves appear to be relevant to the epistemology of experiment. (Similarly for differences of material size, but perhaps not for size of collaboration — on the order of 10 versus 10^4 collaborators — where questions of consensus negotiation and governance grow prominent for the latter (Dang 2019; Galison 2020; Galison et al. 2023).) The numerical precision (or its inverse, uncertainty) is an important difference, but it is not immediately clear whether this distinction underwrites a qualitative epistemic difference. More precision in measuring the *same* phenomenon allows for more rigorous, better confirming tests, and possible better information about new physics, albeit about a more homely versus more exotic phenomenon. But is better information about the more known better than okay information about the less known? It seems inappropriate to compare tabletop and high energy experiments in so crude a way. 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.

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]

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[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

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.[12]

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) geo-

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it (Elgin 2020) — and (indeed, recalling our own focus on frugality) *economy* — minimal material involved (Ivanova 2021).

[12] There is some literature dedicated to the epistemology of the genuinely distributed epistemic labor that is common within Big Science collaborations. See, e.g., (Huebner et al. 2017).

nium 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. 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). Inevitably, there is greater uncertainty – though by comparison to almost any other experiment still remarkable precision!

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. 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.

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[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.

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 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. 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 phenomenon 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 the introduction, and at several points in discussion thereafter, we have suggested that experiment in the lows constitutes a kind of frugality. Insofar as this is noteworthy at all, it reflects an implicit valuing of economy of experiment — roughly, how inexpensive and straight-forward it is to get the whole thing off the ground. (Of course, this an entirely comparative judgment: there is nothing cheap or easy about any of this work by pedestrian home budgeting standards.) One might value economy as an end in itself (cf. footnote 11). But we think there is something more to say, which helps to clarify our emphasizing the comparative simplicity of the EMM experiment. In the Introduction, we suggested that the frugal science (and innovation) literature provides an appropriate framework to make sense of the view that, within a values-in-science context, low energy, *small* *footprint* experiments are worth explicit consideration *for their being frugal.* We elaborate on that suggestion here, 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)? As a simple example, begin by considering 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 global superpower 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, it is easy to expect that the research imperatives on the vanguard of the field inevitably differ, embedded expert community to embedded expert community, in virtue of differences in ambient circumstance.

The above simple example furnishes what is ultimately a pluralist conception of what counts as the cutting-edge in chemistry: all those research imperatives earnestly and rigorously undertaken by the relevant experts. Each one represents, or at least could represent, a vanguard in the science. The pluralist conception rejects that any one embedded community has unique claim to what amounts to vanguard chemistry research. Yet, plausibly, some research imperatives will feature lower economic barriers for pursuit, researcher training that is more portable or transferrable, lower expected environmental impact, less resource depletion, and so on. Where value commitments favor these (or other related) considerations, one might advocate the importance of pursuing those research imperatives, and relatedly the importance of studying the social and intellectual consequences of dedicating all research toward such ends. Note that in endorsing this position, one need not further commit to (necessarily) penalizing research imperatives that are high-cost, which are taken on in social contexts where such high costs can be borne. To keep to the simple example: latest developments in NMR spectrometry remain instances of good science, where pursuit of such research remains viable. So frugal science is ultimately about promoting frugal research imperatives as good epistemic practice where social context demands it, independent of attitudes about good epistemic practice where social context provides less constraint.

The core concept in frugal science is frugality: getting the most out of the least. In the present context, we might consider that epistemological considerations having to do with the future of particle physics enter in the operationalization of ‘most’, while (further) value considerations enter in the operationalization of ‘least’. Economy, when considered in a frugal mindset, is some combined measure of both. It is crucial in our analysis in the previous section that the simplicity of the EMM experiment makes newly observable *something whose observation is of relevance to probing beyond the SM.* Simplicity achieved through much greater sacrifice would hardly have been worth writing about in the epistemology of experiment in particle physics. Conversely, the very cost of the LHC and beyond collider experiments in no way implies that they *fail to be* frugal in this sense: what is learned may make them cost-effective, a position we summarize many physicists presumably believe (and that we have argued neither for nor against here).

Frugality has, to our knowledge, not been seriously pursued as a framework within epistemology of experiment. 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.

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