MUSINGS ON THE CURRENT STATUS OF HEP
M. SHIFMAN

William I. Fine Theoretical Physics Institute, University of Minnesota, Minneapolis, MN 55455, USA

In 2012 I published an article [1] presenting my personal views on the state of affairs in “our science,” HEP theory.¹ That “old” article opens with a rather optimistic epigraph “Paraphrasing Feynman: Nature is more imaginative than any of us and all of us taken together. Thank god, it keeps sending messages rich on surprises.” Has Feynman’s prophecy come true?

2012 was also the year of the Higgs boson discovery closing the age of the Standard Model (SM) confirmation.

Now, seven years later, I will risk to offer my musings on the same subject. The seven years that have elapsed since [1] brought new perspectives: the tendencies which were rather foggy at that time became pronounced. My humble musings do not pretend to be more than they are: just a personal opinion of a theoretical physicist... For obvious reasons I will focus mostly on HEP, making a few marginal remarks on related areas.

I would say that the most important message we have received is the absence of dramatic or surprising new results. In HEP no significant experimental findings were reported,² old ideas concerning Beyond the Standard Model (BSM) physics hit dead-ends one after another and were not replaced by novel ideas. Hopes for key discoveries at the LHC (such as superpartners) which I mentioned in 2012 are fading away. Some may even say that these hopes are already dead. Low energy-supersymmetry is ruled out, and gone with it is the concept of naturalness, a basic principle³ which theorists cherished and followed for decades. Nothing has replaced it so far.⁴ With the disappearance of this principle the issue of mass hierarchies becomes almost (if not completely) meaningless.⁵ The Standard Model is still unchallenged: today no observed natural phenomena require its expansion. Dark matter composition is still a huge question mark.

¹HEP is the abbreviation for High Energy Physics.
²This statement does not refer to astrophysics and cosmology.
³By the way, this principle has never been substantiated by arguments other than aesthetic.
⁴An alternative – Multiverse in conjunction with anthropic principle – go beyond the conventional paradigm of physics as a natural science. I will discuss it in brief on page 14.
⁵The same refers to fine-tuning of \( \theta \), see below.
With a few exceptions (in quantum field theory at strong coupling), expectations of breakthrough developments in HEP theory and related areas did not materialize.

Of course we could, and should, rejoice with the colleagues working on the mysteries of our Universe – their work was rewarded by the recent discovery of gravitational waves predicted by Einstein 103 years ago.\(^6\) Moreover, the discovery of a nonvanishing cosmological constant (CC) a decade ago or so,

\[ \rho_{\text{vac. density}} \sim 10^{-47}\text{GeV}^4 \sim (2 \times 10^{-3}\text{eV})^4 \]

led to a dramatic change of a paradigm. Previously theorists were aimed at explaining the vanishing of CC by virtue of a symmetry. It is much harder to understand why \( CC \neq 0 \) but is so incredibly small. Fundamental discoveries in astrophysics and cosmology continue, which make physicists working in this area happy.

But this is not the area in which I work. HEP, “my” branch of theoretical physics since the beginning of my career, seems to be shrinking. A change of priorities in HEP in the near future is likely as business as usual is not sustainable. The current time is formative.

Such turn of events is by no means unique. Classical physics which flourished for centuries gave place to quantum physics in the very beginning of the 20th century. The difference is that \( \text{then} \) the experimental data forced theoretical physicists to switch to a new quantum paradigm. What should happen for today’s HEP theory to reincarnate itself? It is not clear to me. It seems that I see a renewed interest in this endeavor among bright young people. Hopefully, it is not wishful thinking.

Meanwhile, more traditional HEP physicists do not hibernate. The routine work goes on unabated, people work hard to polish the ideas that had been put

---

\(^6\) In fact, the situation with the gravitational wave prediction was more complicated. In 1936 Einstein wrote to Max Born: “Together with a young collaborator [Natan Rosen], I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty to the first approximation.” Their paper was submitted to the Physical Review under the title “Do Gravitational Waves Exist?” Einstein and Rosen (ER) rediscovered the so-called Beck vacua [2], a family of gravitational wave solutions with cylindrical symmetry. While analyzing them ER misinterpreted a coordinate singularity in their solutions as instability. ER’s manuscript was retracted from Physical Review shortly after but the debate dragged for decades, till the mid-1950s when the so-called “Sticky bead argument” was anonymously put forward by Richard Feynman at a conference at Chapel Hill. Here is how it was formulated by Feynman in a private letter [3]: “Feynman’s gravitational wave detector: It is simply two beads sliding freely (but with a small amount of friction) on a rigid rod. As the wave passes over the rod, atomic forces hold the length of the rod fixed, but the proper distance between the two beads oscillates. Thus, the beads rub against the rod, dissipating heat.”
forward previously. Theorists revisit corners which were ignored on the previous journeys.

In 2012 I wrote that theorists’ MO\(^7\) could be called (somewhat conditionally) “the giant resonance mode. In this mode each novel idea, once it appears, spreads in an explosive manner in the theoretical community, sucking into itself a majority of active theorists, especially young theorists. Naturally, alternative lines of thought by and large dry out. Then, before this given idea brings fruits in understanding phenomena occurring in nature (both, due to the lack of experimental data and due to the fact that on the theory side crucial difficult problems are left behind, unsolved), a new novel idea arrives, the old one is abandoned, and a new majority jumps onto the new train.” The outstanding mathematician Alain Connes once wrote:

In general mathematicians tend to behave like “fermions” i.e. avoid working in areas which are too trendy whereas physicists behave a lot more like “bosons” which coalesce in large packs and are often “overselling” their doings, an attitude which mathematicians despise [4].

It is quite possible that the lack of new ideas we are currently witnessing will make the HEP community switch to the “fermion-like” MO. If so, this will be the first clear-cut response to today’s challenges.

***

I will start my musings by sketching a huge quantum tree which grew out of the discovery of quantum mechanics in the 1920s. The reason for this digression is two-fold. First, I would like to explain why both HEP and condensed matter theory experienced radical changes in the 1970s and say a few words about their second lives today. Second, I will argue that developing parts of HEP today are in fact the same as developing parts of quantum field theory.

In Fig. 1 I present a simplified picture of the Quantum Tree. The quantum story begins in the early 1920s when quantum mechanics was discovered. Three earliest branches which grew on the tree were condensed matter (CM), quantum field theory (QFT) and nuclear physics (NP). The first branch out of three listed above produced quantum chemistry, material science and modern CM which after 1970 acquired fresh branches, e.g. nanophysics. The third branch gave rise to particle physics (PP) which later transformed itself into HEP and astroparticle physics (AP).

At the third level, at the top of the quantum tree, we see modern disciplines: quantum information/computing, physics of strongly correlated matter, string

\(^7\)Modus Operandi.
theory, string mathematics, supersymmetry and supergravity, strongly coupled QFT, and a few others.

With time some of the old branches died or nearly died out as scientific disciplines. For instance, what was nuclear physics in the 1930s – 1950s in part reincarnated itself as nuclear technology. Its other part fused with HEP and AP. Particle physics and HEP gave birth to string theory. At birth the baby was christened “Veneziano amplitude” [5]. It grew into a powerful branch which made many believe that the “theory of everything” is around the corner. Well... it never happened and – I will risk to say – never will. At the same time people harvested precious fruits from the string/brane branch, for instance, gauge-gravity duality, holography, and many qualitative insights in Yang-Mills dynamics at strong coupling in supersymmetric QFT.
From Fig. 1 you can see that the PP branch is currently withering. HEP and ST were rapidly expanding since the 1970s until approximately 2000 or so, then this growth flattened off and the tendency reversed itself. HEP redefined itself as quantum field theory at strong coupling (including supersymmetric methods and tools), with some islands of phenomenology here and there. The string theory sprout which is still “work in progress” is called rather unconventionally – “Swampland” [6, 7], see the top of the tree in Fig. 1.

Courageous people reaching the very summit of ST probably reason as follows: “OK, string theory is too complicated and too distant from our today’s world knowledge so that currently we cannot fill in all gaps making it a complete theory of everything in our world. Moreover, string Landscape is so vast... However, maybe, we can analyze its most general features and infer which QFT classes might emerge at energies much below the Planck scale and become valid candidates for our world. Those which cannot, lie in the swampland and are not worth consideration.” Similar ideas come from gedanken experiments with black holes.

![Swampland](courtesy of IFT, Madrid).

One relatively simple example of this type is the so called “Weak Gravity” [8]. According to this argument, no particles can exist whose electric charges are so small that their electromagnetic interaction is weaker than gravitational interaction. In other words, gravity is the weakest long-range force.8

---

8In our world this statement was derived long ago from other arguments [9].
The theorists involved went far beyond exploring our world. One can say that today’s theorists mainly investigate imaginary worlds, the worlds which might have existed as an alternative to our world being somewhat similar to ours. The degree of similarity may vary, from very similar to our world (e.g. changing the number of colors and space-time dimensions is quite fruitful, so we are happy) to mildly fantastic (e.g. adding supersymmetry), to those which – I am afraid – could be characterized as “El sueño de la razón produce monstruos.” Whether it is good or bad – time will show.

Figure 3: A mildly fantastic scenario?

A few words are in order concerning a sprout which branched off from ST branch – string mathematics, or SMath as it is labeled in Fig. 1. I think that in the future it will fuse with the Mathematics Tree (not shown in this figure). Mathematical questions emerging from ST are subject to the same logic as mathematics at large. Although historically mathematics developed out of practical needs, at present its philosophy and methodology are drastically different than that of theoretical physics. In math it is customary to start from a set of postulates (axioms) and rigorously derive as many applications (theorems) as possible. *En route* mathematicians establish whether the initial set was complete and selfconsistent. Math is about constructions (quite often, beautiful). Whether or not they may be used for description of nature is secondary.

Two green branches at the top in Fig. 1 labeled “Math. Physics” show that its development is steady.

---

9This characterization was suggested by Andrei Losev.
Small bridges in Fig. 1 indicate interconnections between the branches of the tree. I draw a few of them and anticipate this cartoon to be severely criticized by many readers, and justly so. Indeed, it is hard to imagine drawing some such figure which would be complete and historically faithful since the number of connections between ideas is huge. Moreover, QFT is not a branch like others, a subject of its own. It is a framework that underlies a lot of cosmology, a lot of CM, and all of particle physics. I sinfully draw it as a branch connected to the rest by only three small bridges. In my defense I can only say that this is the best I could do in planar geometry. There are many more interconnections at every stage and in every direction. The reader will have to use his/her imagination to visualize them.

***

In the 1970s (this time roughly corresponds to the middle level of the tree in Fig. 1), CM theory which had been previously based essentially on quasiparticle description and quantum mechanics shifted toward QFT. New key words appeared in CM vocabulary: universality class, topological state of matter, path integrals, etc. They were borrowed from QFT.

In its turn QFT obtained a second life after the discoveries of asymptotic freedom, supersymmetry and supergravity. These fundamental shifts led to a powerful growth of the tree in all directions, as is seen from this figure. Quantum chromodynamics (QCD) was firmly established. Approximately at the same time, after the discovery of the c quark and τ lepton, the Glashow-Weinberg-Salam model of electroweak interactions evolved in the Standard Model. This was the triumph of HEP, a success achieved because theory and experiment went hand in hand with each other being powered by each other. A remarkably thorough understanding of empiric data accumulated by this time was achieved. Theorists worked with joy and enthusiasm, all disconnected pieces suddenly came together and – within a decade – conceptual questions on strong and electroweak interactions were understood and answered. I was lucky that my professional career started in 1973. Till now I vividly remember the stormy days of the “November revolution” in 1974. The few months following the discovery of $J/\psi$ were the star days of QCD and probably the highest emotional peak in my career.

Now, let us discuss the current status of HEP. What was going on in HEP in the last seven years or so? To summarize the answer, on page 9 I present a cartoon made in 2010 on occasion of a conference dedicated to M. Gell-Mann’s 80th anniversary. Please, do not pay attention to geographical background: it was chosen arbitrarily and is unrelated to physics contents.

What is important is that the areas around the dashed pink arrow are becoming depopulated. The reason is that the minimal supersymmetric standard
model (MSSM) no longer seems relevant, as well as the very idea of low-energy supersymmetry which was put forward to solve the hierarchy problem. Basically, experimental data from CERN (or, better to say, their absence) ruled MSSM out. The concept of naturalness seemingly lost its appeal. By the way, if so, there is no need in the celebrated axion (see point 9 in the Map) to guarantee CP conservation in strong interactions. Indeed, without naturalness it could well happen that the $\theta$ angle was set very close to zero by the same mechanism which fine-tuned the Higgs mass. There are no fresh ideas beyond SM either, with the exception of a few contrived, baroque and – most probably – unviable constructions suggested *ad hoc*. Can ongoing research in neutrino physics give us a hint?

On the other hand, explorations at the periphery of the Map continue. This is especially true with regards to the dark matter (DM) mystery. A quick glance at the current HEP theory literature is sufficient to verify this statement. The existence of DM is confirmed beyond any doubt. In fact, DM constitutes about $\frac{1}{4}$ of our Universe. But its composition remains unknown. Ten or 15 years ago the general belief was that DM is built of LSP – the lightest supersymmetric particles. One of the less popular alternatives which was under consideration is the axion cloud around each galaxy. At present, one can find in the literature a spectrum of other hypotheses. Frankly, none of the newcomers seems aesthetically appealing. Nor are they motivated. What is good is that there is still hope that DM could be experimentally detected and studied. One should not forget, however, of a scenario in which DM components interact with us only gravitationally. This scenario is not ruled out, and if it is realized in nature, the DM structure will remain unknown in the near future.

***

The theme of supersymmetry (SUSY) which is so conspicuous in the Map (Fig. 3) redefined itself. To my mind, it is no longer dominated by SUSY phenomenology. The second face of SUSY – supersymmetry as a tool for exploring gauge dynamics at strong coupling – which started emerging in the early 1980s [10] is taking precedence over phenomenology. It is unclear for how long, though.

A *decisive breakthrough* in this direction occurred in 1994, with the discovery of the Seiberg duality and the Seiberg-Witten solution of $\mathcal{N} = 2$ supersymmetric Yang-Mills theory slightly deformed by a mass term of the adjoint chiral superfield [11]. This remarkable achievement to a large extent feeds continuous advances of two branches at the top of the Quantum Tree in Fig. 1: one labeled “SUSY” on the right-hand side and the other labeled “QFT/SC” on the left-hand side (SC stands for strong coupling). In fact, they are interconnected, but I could not visualize this connection in the planar cartoon. QFT/SC is also in-
timately connected with the modern condensed matter theory. To mention just a few findings on the SUSY branch let me mention the exact 2D-4D correspondence (related to the Seiberg-Witten results) and non-Abelian vortex strings revealing a wealth of sigma models on their world sheets with varying degree of supersymmetry, including chiral SUSY. Studies of the above two-dimensional sigma models are of interest on their own.

A few words are in order about non-supersymmetric section of QFT. I am delighted to see that after a long relatively separate existence, HEP and CM theories are moving towards each other, with growing cross-fertilization.

A recent success in non-supersymmetric theories at strong coupling is the discovery of mixed anomalies (say, 1-form vs. chiral anomaly, see Appendix on page 15) for global symmetries [12, 13, 14]. Often they are referred to as ’t Hooft anomalies.11

The basic idea is that in some theories there are two global symmetries,

---

10I write here “relatively separate.” In fact they were always connected, suffice it to mention K. Wilson’s and A. Polyakov’s ideas. Physics is our common edifice, after all!

11Gerard ’t Hooft was the inventor of anomaly matching. This idea played a prominent role in modern QFT. All anomalies are “all-scale” phenomena, they have a UV face and an IR face which must match [15]. ’t Hooft was the first to discuss this aspect in [16]. The ’t Hooft matching became extremely popular after Seiberg’s pioneering exploitation of supersymmetric QCD anomaly matchings (see the first reference in [11]). Shortly after, the ’t Hooft matching became a tool “for everyone.” Everyone calls the mixed anomaly ’t Hooft regardless of its 0-form or higher-form symmetry.
which clash with each other at the quantum level. Only one of them can be maintained. This provides unique information on the infrared (IR) behavior of the theory, in particular, its vacuum structure. In the past anomalies in global symmetries have not been considered in this perspective. Although they could have been uncovered much earlier, the phenomenon was overlooked. The simplest pedagogical example is as follows.

Assume we consider two-dimensional Schwinger model with one massless Dirac fermion of charge 2 [18]. More exactly, in addition to the dynamical charge-2 fermion, there is a heavy probe charge-1 fermion whose mass can be viewed as tending to infinity. Next, assume that in this model we compactify the spatial dimension on a circle of circumference $L$, i.e. impose either periodic or antiperiodic boundary conditions on the fermion fields. Then one can show that this model has two discrete $Z_2$ symmetries – one 0-form and another 1-form. These two global $Z_2$ symmetries have generators which do not commute with each other [18]. Thus, only one of these symmetries can be implemented, the other one must be spontaneously broken. Hence, the ground state is doubly degenerate. In other words, we observe in this example (see Appendix on page 15 and also [17]) the power of the mixed anomalies – the prediction of the projective action of the symmetries and the ground state degeneracy. This is a strong result at strong coupling (i.e. at $eL \gg 1$). Sorry for the pun... After [12, 13, 14] a large number of non-trivial applications has been worked out. Many relevant references can be found in [18, 19].

Other important advances in QFT/SC are connected with the approach which I would call Ünsal’s continuity [20]. Ten years ago Mithat Ünsal and collaborators suggested the following strategy. If you want to analyze a certain Yang-Mills theory with a certain fermion sector, consider first this theory on $R^3 \times S^1$ instead of $R^4$. The compactified direction of circumference $L$ can be viewed as spatial. If for small $L$ you manage to find boundary conditions that would guarantee unbroken center symmetry then there is no phase transition on the way to large (or infinitely large) $L$. The journey from weak to strong coupling confining phase is smooth. Hence all regularities observed at small $L$ remain valid also at strong coupling. This strategy gave rise to intriguing results, see e.g. [21]. In particular, it was found that adjoint QCD exhibits a unique property of unexpected cancellations at large $N$ – not only the leading contribution $\sim N^4$ in the vacuum energy disappears but two subleading terms cancel as well! For one adjoint Weyl fermion this theory is supersymmetric, and cancellations in the vacuum energy are not surprising, of course. However, say, for two or three adjoint Weyl fermions there is no exact supersymmetry, and yet the cancellation persists (although it is not exact in this case).

\footnote{At least, not considered systematically, see, however, [17] for precursors.}
The island of heavy quark physics exists and prosper. Experiments at BE- SIII (Beijing), Belle2 (Japan), and LHCb (CERN) are active and produce lavish fruits. For instance, recently the lifetimes of $b$-containing baryons have been precisely remeasured by LHCb. Disagreements (sometimes drastic) with the QCD-based predictions made in the 1980s and 1990s \[22\] are gone in the LHCb data, the level agreement with theory is quite remarkable. But who cares? Heavy quark containing pentaquarks were found, and so on. If the “old” pentaquarks were buried $\sim 10$ years ago, the new ones are here to stay. A suspicious violation of $\mu$-$e$ universality in semileptonic $B$ decays was reported recently. I believe it will go away with more precise measurements.

***

In the past, experimental data provided guidance for HEP theorists, and I think they will continue to do so. Experiment and observation play the role of Polaris for courageous travelers at high seas far from the shores. In the good old days, theorizing was like sailing between nearby islands of experimental evidence. Now in search of hints of nature the HEP theorists have to travel deep in the ocean. Therefore, the nature of data they fish out may change.

Experimental results were always less numerous (but way more precious) than theoretical production in the form of a stream of papers or conference talks. This was the case even in the glorious days following the November revolution in 1974 as is seen from the cartoon in *CERN Courier*, see Fig. 5.

![Figure 5: Cartoon from the cover of *CERN Courier*, April, 1975.](image-url)
With increasing complexity of experiments and the need for more and more public funding it seems natural that the ratio exp/th would continue to fall in the near future. The peak on the right may well be shrinking for a while, while the peak on the left is growing unconstrained by rigors of nature. This is a new scientific environment to which we, the physicists, will have to adapt, as it usually happens in nature, through self-regulation. In the same way humankind adapts to new political and social conditions. In response to environmental changes populations grow or shrink. Theorists in their community are subject to the same social regularities.

I hope that young people currently entering the area will focus more on the established mysteries of nature (e.g. dark matter) than in the 1990s’ and early 2000s. I expect that on the way they will discover new mysteries (Fig. 3). Perhaps, they will come to a new scientific paradigm. Thinking boldly, why not imagine that quantum mechanics gives place to something else at shorter distances? Or a milder statement: why not replace the concept of naturalness by the following: As we move in the UV all interactions (including gravity) must remain weak? Perhaps, the information loss paradox in evaporating black holes might be solved, perhaps...

I understand that uncovering the fundamental laws of nature became harder due to scarcity of adequate probes for experimentation. Does it mean that we have to give up right now?

***

For never was a story of more woe
Than this of meta-induction show. [23]

In 2013 Richard Dawid, a HEP theorist turned philosopher, published a book entitled “String Theory and the Scientific Method” [24] which caused a significant resonance in the community. This book was a response to the spread of the idea that from now on theories will not need empiric confirmation. It was based on the assumption that physicists’ pursuit for quantum gravity (through string theory) and early cosmology (through Multiverse) cannot be supported by data in principle, and instead, the emerging theory should be subject to the test of “non-empirical confirmation.” According to Dawid, three principles of non-empirical confirmation are to replace experimental data/observations:

(i) The absence of alternatives in the community;

(ii) The degree to which a theory is connected to already confirmed theories (also referred to as meta-induction);

(iii) The amount of unexpected insights that the candidate “non-empirically confirmed” theory gives rise to.
I did not know what meta-induction was. Mathematical induction – yes, but what’s meta? I had to google this term and this is what I found in a philosophy dictionary and a number of articles (brief summary):

Epistemic optimism is a concept in which knowledge is perceived as the true representation of reality and science reveals what the world is. Meta-induction, (or, pessimistic induction) is an argument which seeks to rebut scientific realism, particularly the scientific realist’s notion of epistemic optimism. Meta-inductive methods make predictions based on aggregating the predictions of different available prediction methods according to their success rates. The success rate of a method is defined according to some way of scoring success in making predictions, for instance, through the rate of approval in the community, especially its leading members.

Shortly after, Dawid’s book was criticized by George Ellis and Joe Silk in the article “Scientific method: Defend the integrity of physics” who defended the thesis “a theory must be falsifiable to be scientific.” This triggered an ongoing debate in the community.

On December 7-9, 2015, around 100 physicists and philosophers gathered in Munich at a conference provocatively entitled “Why trust a theory? Reconsidering Scientific Methodology in Light of Modern Physics.” Among distinguished physicists one should note such esteemed theorists as Gia Dvali, David Gross, Dieter Lüst, Slava Mukhanov, Joe Polchinsky and others.

The prevailing theme was that physics entered a new era of the so-called post-empirical science (PES), see a red mushroom at the right bottom in Fig. 1. Starting from Galileo it was believed that the ultimate judge of any theory was observation and experiment. “Not any longer,” was the leitmotiv of many talks.

With all due respect I strongly disagree with Richard Dawid and all supporting speakers at the conference and beyond. David Gross suggested a reconciling compromise. Here is a brief paraphrase of one of his statements: “It is only theories which need experimental confirmation, frameworks do not. The Standard Model is a theory, and it was triumphantly confirmed. But QM, QFT and ST are frameworks, not theories, they need not be confirmed in the usual way. With regards to frameworks, Dawid’s criteria (i), (ii), and (iii) should be applied.”

David Gross is a great theoretical physicist, whose discovery of asymptotic freedom made him immortal, but I respectfully disagree with him. Framework or not both QM and QFT have absolutely solid confirmations in all their

\footnote{What’s in a name? that which we call a rose by any other name would smell as sweet [23].}
aspects in thousands of experiments. I can agree to call them frameworks, alright, but I insist that QM and QFT beyond any doubt describe our world at appropriate distances.

I object against applying the term “non-empirically confirmed” to science (the more so, the term “postempiric science”). Of course, we live in liberal times and everybody is entitled to study and discuss whatever he or she wants. But the word science is already taken. Sorry, colleagues. For “postempiric science,” please, use another word, for instance, iScience, xScience, or something else.

Even in such vague disciplines as, say, sociology scholars search for empiric confirmation of their theories. The only exception is mathematics to some extent, as I argued on page 6.

Figure 6: A friendly discussion with David Gross.

Yes, I accept Multiverse and I even like this concept. After all, the Sun is not unique, our Galaxy is not unique, why our Universe should be unique? Multiverse can be perceived as a poetic symbol or religion, which absolves us,\textsuperscript{14} Earth dwellers, from the need to explain hierarchies, in much the same way as observant Christians do not have to explain immaculate conception. But what is there for modern physicists? The word \textit{physics} came from Ancient Greece. In Greek \textit{τὰ φυσικά} means the natural things. This was the title of Aristotle’s treatise on nature. In HEP this indeed used to be the case until recent years when HEP’s connection to our world started fading away with folding of large accelerator programs. However, neutrino physics is flourishing. Moreover, in

\textsuperscript{14}Through the Anthropic Principle.
physics at very large distances observations are abundant, and in CM which deals with natural phenomena by definition the stream of data will not dry out in the foreseeable future. I believe that pause in accelerator programs we are witnessing now is not necessarily the same as the end of explorations at short distances. They will continue, perhaps in a new form, with novel devices, and at a different pace. Something will come up.

***

I am grateful to Alexey Cherman, Andrey Chubukov, Alexander Gorsky, Alexey Kamenev, Mikhail Katsnelson, Andrey Losev, Eric Poppitz, Mithat Ünsal, and Zohar Komargodski for useful discussions. This work is supported in part by DOE grant de-sc0011842.

Appendix

In two-dimensional Schwinger model with one massless Dirac fermion of charge 2 and non-dynamical probe fermion of charge 1 with compactified spatial dimension (a circle of circumference $L$ with either periodic or antiperiodic boundary conditions on the fermion fields) the Polyakov line along the compactified dimension can take two values

$$P = \left\langle \exp \left( i \int_0^L dx A_1(x, t) \right) \right\rangle_{\text{ground st}} = \pm 1,$$

(2)

This corresponds to a $\mathbb{Z}_2$ center symmetry. Note that the order parameter in (2) is non-local, it is represented by a 1-form.

Another discrete symmetry in this example is the remnant of the U(1) chiral rotations. The U(1) axial symmetry in the Lagrangian is explicitly broken by the axial (diangle in the case at hand) anomaly, but its discrete $\mathbb{Z}_4$ subgroup survives [15]. This is due to the fact that the axial charge is conserved modulo 4, namely, $\Delta Q = -4$. The latter circumstance implies in turn that a four-fermion condensate $\langle \bar{\psi} \psi \rangle$ develops a nonvanishing expectation value. The chiral $\mathbb{Z}_4$ symmetry is, in fact, $Z_2 \times Z_2$, where the first factor is the fermion parity, i.e. $(-1)^F$, and the second factor is related to the sign ambiguity in the bifermion condensate $\langle \bar{\psi} \psi \rangle$ if it develops. A nonvanishing value of $\langle \bar{\psi} \psi \rangle$ would mean that the chiral $\mathbb{Z}_4$ is broken down to $\mathbb{Z}_2$.

A closer look shows that we deal with two global $\mathbb{Z}_2$ symmetries whose generators do not commute with each other [18]. Thus, only one of these symmetries can be implemented, the other one must be spontaneously broken. In both cases the ground state is doubly degenerate.
References

[1] M. Shifman, *Frontiers Beyond the Standard Model: Reflections and Impressionistic Portrait of the Conference*, Mod. Phys. Lett. A **27**, 1230043 (2012) [arXiv:1211.0004 [physics.pop-ph]].

[2] G. Beck, Z. Phys. **33**, 713 (1925).

[3] John Preskill and Kip Thorne, Foreword to *Feynman Lectures On Gravitation*. Feynman et al. (Westview Press; 1st ed. (June 20, 2002) p. xxv-xxvi; see also *An Expanded Version of the Remarks by R.P. Feynman on the Reality of Gravitational Waves*, Cecile M. DeWitt et al. Wright-Patterson Air Force Base (edition-open-access.de).

[4] Alain Connes, *Advice to the beginner, The Princeton Companion to Mathematics*, (Princeton University Press, 2008), pp. 1005-1007 [http://www.alainconnes.org/docs/Companion.pdf] and in the book *Visions in Mathematics*, GAFA 2000 Special Volume, Part II, 2000, p. 884.

[5] Gabriele Veneziano, *Construction of a crossing-symmetric Regge-behaved amplitude for linearly rising trajectories*, Nuovo Cimento, **A57** (1), 190 (1968).

[6] The pioneering papers are: Cumrun Vafa, *The String Landscape and the Swampland*, arXiv:hep-th/0509212 (2005); H. Ooguri and C. Vafa, *On the Geometry of the String Landscape and the Swampland*, Nucl. Phys. B **766**, 21 (2007), [hep-th/0605264]. Many others followed.

[7] A curious April 1 jocular article can be found at D. M. C. Marsh and J. E. D. Marsh, *The Marshland Conjecture*, arXiv:1903.12643 [hep-th].

[8] N. Arkani-Hamed, L. Motl, A. Nicolis and C. Vafa, *The String landscape, black holes and gravity as the weakest force*, JHEP **0706**, 060 (2007).

[9] L.B. Okun, M.B. Voloshin, Valentin I. Zakharov, *Electrical Neutrality Of Atoms And Grand Unification Models*, Phys. Lett. **138B**, 115-120 (1984).

[10] V. A. Novikov, M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, *Exact Gell-Mann-Low Function of Supersymmetric Yang-Mills Theories from Instanton Calculus*, Nucl. Phys. B **229**, 381 (1983); M. A. Shifman and A. I. Vainshtein, *On Gluino Condensation in Supersymmetric Gauge Theories. SU(N) and O(N) Groups*, Nucl. Phys. B **296**, 445 (1988); for the history of the subject see M. Shifman, [arXiv:1804.01191 [hep-th]].

[11] N. Seiberg, *Electric-magnetic duality in supersymmetric non-Abelian gauge theories*, Nucl. Phys. B **435**, 129 (1995), [hep-th/9411149]; N. Seiberg and E. Witten, *Electric-magnetic duality, monopole condensation, and confinement in N = 2...
supersymmetric Yang-Mills theory, Nucl. Phys. B 426, 19 (1994) Erratum: [Nucl. Phys. B 430, 485 (1994)] [hep-th/9407087]; Monopoles, duality and chiral symmetry breaking in $\mathcal{N} = 2$ supersymmetric QCD, Nucl. Phys. B 431, 484 (1994) [hep-th/9408099].

[12] D. Gaiotto, A. Kapustin, N. Seiberg and B. Willett, JHEP 1502, 172 (2015) [arXiv:1412.5148 [hep-th]].

[13] A. Kapustin and N. Seiberg, JHEP 1404, 001 (2014) [arXiv:1401.0740 [hep-th]].

[14] D. Gaiotto, A. Kapustin, Z. Komargodski and N. Seiberg, JHEP 1705, 091 (2017) [arXiv:1703.00501 [hep-th]].

[15] M. A. Shifman, Anomalies in Gauge Theories, Phys. Rept. 209, 341 (1991)

[16] G. ’t Hooft, Naturalness, chiral symmetry, and spontaneous chiral symmetry breaking, in Recent Developments in Gauge Theories. Proceedings, Nato Advanced Study Institute, Cargese, France, August 26-September 8, 1979, vol. 59, pp. 135-157. 1980.

[17] M. A. Shifman and A. V. Smilga, Fractons in twisted multiflavor Schwinger model, Phys. Rev. D 50, 7659 (1994) [hep-th/9407007]; F. Lenz, M. A. Shifman and M. Thies, Quantum mechanics of the vacuum state in two-dimensional QCD with adjoint fermions, Phys. Rev. D 51, 7060 (1995) [hep-th/9412113].

[18] M. Anber and E. Poppitz, Anomaly matching, (axial) Schwinger models, and high-$T$ super Yang-Mills domain walls, JHEP 1809 (2018) 076 [arXiv:1807.00093 [hep-th]].

[19] I. Hason, Z. Komargodski and R. Thorngren, Anomaly Matching in the Symmetry Broken Phase: Domain Walls, CPT, and the Smith Isomorphism, arXiv:1910.14039 [hep-th].

[20] M. Ünsal, Magnetic bion condensation: A New mechanism of confinement and mass gap in four dimensions, Phys. Rev. D 80, 065001 (2009) [arXiv:0709.3269 [hep-th]].

[21] E. Poppitz, T. Schüer and M. Ünsal, Continuity, Deconfinement, and (Super) Yang-Mills Theory, [arXiv:1205.0290 [hep-th]]; G. V. Dunne and M. Ünsal, New Nonperturbative Methods in Quantum Field Theory: From Large-$N$ Orbifold Equivalence to Bions and Resurgence, Ann. Rev. Nucl. Part. Sci. 66, 245 (2016) [arXiv:1601.03414 [hep-th]]; K. Aitken, A. Cherman and M. Ünsal, Vacuum structure of Yang-Mills theory as a function of $\theta$, JHEP 1809, 030 (2018) [arXiv:1804.06848 [hep-th]]; A. Cherman, M. Shifman and M. Ünsal, Bose-Fermi cancellations without supersymmetry, Phys. Rev. D 99, no. 10, 105001 (2019) [arXiv:1812.04642 [hep-th]].
[22] M. A. Shifman and M. B. Voloshin, *Hierarchy of Lifetimes of Charmed and Beautiful Hadrons*, Sov. Phys. JETP **64**, 698 (1986); V. A. Khoze, M. A. Shifman, N. G. Uraltsev and M. B. Voloshin, On Inclusive Hadronic Widths of Beautiful Particles, Sov. J. Nucl. Phys. **46**, 112 (1987); For a review and update see I. I. Y. Bigi, M. A. Shifman and N. Uraltsev, *Aspects of heavy quark theory*, Ann. Rev. Nucl. Part. Sci. **47**, 591 (1997) [hep-ph/9703290].

[23] “Deformed” William Shakespear.

[24] Richard Dawid, *String Theory and the Scientific Method*, (Cambridge University Press, 2013).

[25] George Ellis and Joe Silk “Scientific method: Defend the integrity of physics,” *Nature*, **516**, 321-323 (2014).