PROCEEDINGS OF SCIENCE

Beauty in particle physics

Ivan Melo[*†]
University of Zilina
E-mail: melo@fyzika.uniza.sk

Particle physicists are sometimes described as Platonists, referring to their belief that the ultimate explanation of the Universe must possess beauty. Since scientists in other fields are more sceptical about the role of beauty in science, HEP physicists are in a unique position: we know there is beauty in the fundamental laws that we discovered and this is a great message that we could share. I will give a short sample of ideas of renowned physicists about relation of truth and beauty, discuss beauty criteria and give examples of several elegant physical thories.

European Physical Society Conference on High Energy Physics - EPS-HEP2019 -
10-17 July, 2019
Ghent, Belgium

[*]Speaker.

[†]I would like to thank members of IPPOG for many useful discussions of the topic.

1. Introduction

Philosopher of science Jesus Bonilla finds two different approaches to beauty among scientists and philosophers of science. To one group belong those for whom the pursuit of beauty is a matter of great importance in the process of scientific research (Bonilla calls them Platonists) a to the other group those who deny that scientific research has anything intrinsic to do with beauty (referred to as Sceptics) [1]. Among Platonists, according to Bonilla, we can find mostly quantum physicists and mathematicians, among Sceptics scientists from other fields and also philosophers of science. If Bonilla is right, our own field of particle physics should be the one where aesthetic ideals are routinely used and discussed. I think they are certainly used often but maybe less frequently discussed and this motivated my contribution. Furthemore, we seem to be a minority among scientists in that we see an essential role of beauty in the Universe. This puts us in a unique position: we have a great message worth sharing with the Sceptics and in fact, with the students and the general public.

I will start with a discussion of views on beauty expressed by both the past and the present physicists, next I introduce productivity and symmetry as beauty criteria and show their role in our theories before I conclude.

2. Statements about beauty in physics

Let us investigate what the leading physicists have to say about the role of beauty. For some, beauty is a very useful tool in the search for truth. For example Werner Heisenberg wrote in a letter to Einstein: "If nature leads us to mathematical forms of great simplicity and beauty we cannot help thinking that they are 'true', that they reveal a genuine feature of nature" [2]. His wife recalls that on one occasion he talked about "the miracle of symmetry, about harmony, about the beauty of simplicity, and its inner truth" [3]. Richard Feynman says something similar: "You can recognize truth by its beauty and simplicity. When you get it right, it is obvious that it is right - at least if you have any experience - because usually what happens is that more comes out than goes in" [4]. Feynman gives us here also a practical clue: that a good theory gives more predictions than there were principles which "went in". Murray Gell-Mann also points to the role of beauty as guide to truth: "What is especially striking and remarkable is that in fundamental physics a beautiful or elegant theory is more likely to be right than a theory that is inelegant" [5].

Others even prefer beauty to truth. Henri Poincare suggests that beauty is the motivation for him to study nature: "The Scientist does not study nature because it is useful to do so. He studies it because he takes pleasure in it; and he takes pleasure in it because it is beautiful. If nature were not beautiful, it would not be worth knowing and life would not be worth living" [6]. He does not mention truth. Hermann Weyl states his preference for beauty even more clearly: "In my work, I have always tried to unite the true with the beautiful; but when I had to choose one or the other, I usually chose the beautiful" [6]. He was pointing to his gauge theory of gravitation which turned out to be wrong. And Paul Dirac wrote in 1963, commenting on the fact that the first version of the Schrodinger equation did not agree with experimental data, that "it is more important to have beauty in one's equations than to have them fit experiment. If Schrodinger had been more confident

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of his work, he could have published it some months earlier" [7]. The founders of our field certainly qualify for a membership in the Platonist club.

Is the message from the present-day physicists different? Gian Giudice: "The sense of beauty of a physical theory must be something hardwired in our brain and not a social construct. It is something that touches some internal chord... when you stumble on a beautiful theory you have the same emotional reaction that you feel in front of a piece of art" [3]. Frank Wilczek wrote: "having tasted beauty at the heart of the world, we hunger for more. In this quest, I think, there is no more promising guide than beauty itself" [8] and elsewhere he added: "My work has been guided by trying to make the laws more beautiful" [9]. Brian Greene in The Elegant Universe takes a more cautious approach: "Aesthetic judgements do not arbitrate scientific discourse... But it is certainly the case that some decisions made by theoretical physicists are founded upon an aesthetic sense... So far, this approach has provided a powerful and insightful guide" [10].

We could continue with more statements but this list suffices as illustration.

3. Productivity and symmetry

What kind of beauty are physicists talking about? Is it a real entity that can be uniquely defined? We have seen some clues in the previous section. Beauty is usually recognized by symmetry, simplicity, harmony, power to explain many phenomena, inevitability, conformity with the whole and even strangeness. My preference is for the two criteria, productivity and symmetry, suggested by Frank Wilczek [9]. About the productivity he says: "One is what I call exuberance or productivity, where you get out more than you put in. You find some equation or law by putting together clues and making a guess, and then you can explain seven other things and you know you're on the right track. You get out more than you put in" [9]. Symmetry Wilczek describes as follows: "Symmetry is especially prominent in the fundamental laws of nature. As it's commonly used, symmetry is kind of vague but somehow connotes harmony and beauty. The scientific usage is more precise and has been extremely fruitful. It's change without change. You can make changes in physical objects or changes in the laws that could change them but don't" [9].

Both criteria in my opinion pass as objective. Symmetry is a precise mathematical concept and productivity amounts to counting the number of principles (or equations) of a theory versus the number of phenomena the theory can explain or predict. We will now discuss several theories to demonstrate both their productivity and symmetries.

Greeks believed that the planetary orbits must be circular. The circular symmetry is one of the most simple symmetries and the Greek philosophers and their followers appreciated beauty of this simplicity. Even centuries later people found difficult to accept the Kepler's first law of the planetary motion according to which the planets move around the Sun in elliptical orbits. Has beauty misled us in this case? It appears so but I would like to point out that the original idea of a role of the circular symmetry was not completely wrong. The Newton's law of gravity has the circular symmetry as a special case of its spherical symmetry. Moral to this story is that beauty is not to be found so much in the solutions of a law but in the law itself. The Newton's theory is also productive: the gravitational law describes both planetary motions and falling apples and automatically leads to the Kepler's laws.

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The relativistic theory of gravity, the general theory of relativity, has symmetries which helped to change the role of symmetry in physics. Emma Noether, while studying them, discovered that to each symmetry corresponds a conserved quantity. This insight meant that physicists could construct their theories more easily, demanding symmetries which correspond to observed conserved quantities. The productivity of general relativity includes many predictions (by now observed) such as anomalous precession of the Mercury's perihelion, gravitational bending of light, gravitational time dilation, gravitational redshift of light, gravitational waves or black holes and, of course, the Newton's theory of gravity in its nonrelativistic limit.

Another example is the classical theory of electromagnetism. Maxwell's equations exhibit the Lorentz symmetry which played a crucial role in the development of the special theory of relativity and the fact that these equations alone describe all of classical electricity, magnetism and optics, serves as a proof of their productivity.

The quantum theory of electromagnetism (QED) brings the role of symmetry to yet another level. Symmetry, in this case the so called gauge symmetry, is no longer just an interesting or useful feature of equations, it is the principle from which the equations of the theory are derived. Starting from the free electron term in the Lagrangian, invariance of this term under the gauge symmetry transformation implies all the rest, including the existence of electromagnetic field and its coupling to the electron field. QED equations contain classical Maxwell's equations as a special case and a plethora of quantum effects including the existence of antiparticle (positron) and the annihilation of electron and positron to photons.

In the Standard model of electromagnetic, weak and strong interactions symmetry plays the same central role as in QED. The symmetries of the model are spontaneously broken, meaning that the symmetries of the equations are not the symmetries of the solutions (in particular the solution with the lowest energy, the vacuum). This phenomenon helps us see why symmetry is not appreciated by a wider audience. Solutions with smaller symmetries are simply easier to observe than the equations with the full symmetries and hence the world looks uglier at first sight than it really is. The Standard model describes all currently known physics at the fundamental level except for gravity.

4. Conclusion

There are 19 free parameters in the Standard model which are not predicted by the theory. In order to explain some of these free parameters, theories beyond the Standard model are being developed and symmetries (and their spontaneous breaking) are their cornerstones. The fact that despite expectations we have not seen any sign of these new theories at the Large Hadron Collider, has led some physicists to convert to scepticism (see, e.g., [3]). They remind us that beauty can misguide us and they could be right. However, these beauty principles have worked extremely well so far and we should not forget that. Just as beauty might lead us astray so can our impatience. We are facing the most difficult questions now and we may be in it for the long haul [11].

Let me conclude with a remark that beauty as described here differs from how beauty is perceived in arts. Artists like the tension between symmetry and antisymmetry. Too much symmetry, they say, once you grasp the principle, is boring [12]. Yet there are works of art, like windows of Gothic cathedrals, which fully use the beauty of symmetry. What particle physics is telling us, based on the experience we have accumulated so far, is that the world at the most fundamental level is more like a window of a Gothic cathedral than a painting from an abstract impressionist.

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