

# Unobservability of short-lived particles: ground for skepticism about observational claims in elementary particle physics

Marcoen J.T.F. Cabbolet  
Department of Philosophy, Free University of Brussels  
E-mail: Marcoen.Cabbolet@vub.ac.be

Paper presented at the 7<sup>th</sup> conference of the Dutch-Flemish Association for Analytic Philosophy, held from 1-28-2015 to 1-30-2015 at Erasmus University Rotterdam

**Abstract** — The physics literature contains many claims that elementary particles have been observed: such observational claims are, of course, important for the development of existential knowledge. Regarding claimed observations of short-lived unstable particles in particular, the use of the word ‘observation’ is based on the convention in physics that the observation of a short-lived unstable particle can be claimed when its predicted decay products have been observed with a significance of  $5\sigma$ . This paper, however, shows that this  $5\sigma$  convention is inconsistent with existing concepts of observation by showing that unstable particles with a lifetime of less than 0.01 attosecond are fundamentally unobservable both from the perspective of Fox’s recent concepts of direct and indirect observation, and from the perspective of Van Fraassen’s notion of observability. This cognitive inaccessibility of parts of the subatomic world has far-reaching implications for physics, not the least of which is that the aforementioned convention is untenable: claims that such short-lived unstable particles have been observed will thus have to be retracted. The main implications are two incompleteness theorems for physics, respectively stating (i) that experiments cannot prove completeness of a physical theory predicting short-lived unstable particles, and (ii) that experiments cannot prove correctness of such a theory—one can at most test its empirical adequacy. On a general note, the conclusion is that the importance of philosophical arguments for particle physics is herewith demonstrated: it is, thus, a widespread misconception that philosophical arguments can be completely avoided.

## 1 Introduction

The present situation is that many elementary particles are claimed to have been positively observed. The importance of such observational claims lies therein that existential knowledge—in the sense meant by Cheyne, that is, in the sense of knowledge that this or that exists (1998)—in physics evolves from claimed observations: if one has *seen* something, one *knows* that it exists. This existential knowledge of physics is important for other branches of natural science as well, since these build on the knowledge from physics. Furthermore, this existential knowledge is also important for fundamental research in physics, for any newly developed theory has to correspond to what is known to exist. Thus speaking, observational claims in elementary particle physics are important for the whole spectrum of natural science.

An example of an observational claim is the Higgs claim, i.e. the claim that the Higgs boson has been positively observed. Figure 1 shows a slide that was shown at a press conference at CERN in 2012, where the preliminary results of the hunt on the Higgs boson were presented. Clearly, the claim is made that “we have observed a new boson with a mass of  $125.3 \pm 0.6$  GeV at  $4.9\sigma$  significance”. This claim was repeated in two papers in *Physics Letters B*: in these papers, “observation of a new boson” and “observation of a new particle” was claimed right in the titles (CMS Collaboration, 2012; ATLAS Collaboration, 2012). These claims were followed by the claim that the new boson is indeed the Higgs boson (CERN, 2013). The leading journals *Science* and *Nature* hailed the discovery of the Higgs boson as the “Breakthrough of the Year” (Cho, 2012) and “the biggest particle-physics discovery in a generation” (Chalmers, 2012). In addition, the 2013 Nobel prize for physics was awarded to Peter Higgs and François Englert “for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle” (Nobel Media AB, 2013).



Figure 1: Slide shown at a press conference at CERN in July 2012. Source: CERN Document Server.

The point is now that as far as short-lived unstable particles are concerned, the physicists' use of the term 'observation' is based on a convention. Sometimes the term 'discovery' is used instead, but as far as it concerns particles these two terms can be used interchangeably: if you have *discovered* a new particle then you have *observed* it for the first time, and if you have *observed* a new particle for the first time then you have *discovered* it—ergo, the terms 'discovery' and 'first time observation' are equivalent in this context. That being said, regarding short-lived unstable particles (such as Higgs bosons) the criterion that physicists use for *when* an "observation" can be claimed is laid down in the following convention in elementary particle physics<sup>1</sup>, which henceforth will be called the '5 $\sigma$  convention':<sup>2</sup>

**5 $\sigma$  convention:** the observation of a short-lived unstable particle can be claimed if the predicted decay products with the predicted properties have been observed with a significance of 5 $\sigma$ .

But further research then reveals that this convention is merely voiced orally at particle physics conferences: it has *never* been published in writing in the peer-reviewed literature.<sup>3</sup> So we have the interesting situation that the Higgs claim, the biggest claim in physics in the 21<sup>st</sup> century so far, is based on a convention that has *never* been published and that has *never* been put to scrutiny!

The purpose of the present paper is to show that this 5 $\sigma$  convention is untenable by showing that it is inconsistent with existing concepts of observation: it will be shown that unstable particles with a lifetime of less than 0.01 attosecond are fundamentally unobservable both from the perspective of Fox's recent concepts of direct and indirect observation (2009), and from the perspective of Van Fraassen's notion of observability (1980). It is true that different ideas on observation have been published, most notably by Maxwell (1962) and Shapere (1982), but these have been shown to be not applicable to subatomic physics (Fox, 2009).

The outline of this paper is as follows. The next section shows the inconsistency of the 5 $\sigma$  convention with existing concepts of observation. The last section discusses the main implications and states the conclusions. For the purely philosophically oriented readers, the appendix gives some background information on the term 'significance'.

<sup>1</sup>Dieter Schlatter, editor of Phys. Lett. B, personal communication, 2013.

<sup>2</sup>So we distinguish between this 5 $\sigma$  *convention* and the 5 $\sigma$  *standard*, the agreement that the significance has to be 5 $\sigma$ .

<sup>3</sup>Frank Allen, University of Colorado, personal communication, 2013.



Figure 2: Trace of a positron in a cloud chamber. In a sealed vessel, filled with vapor, highly energetic photons create electron-positron pairs; a strong magnetic field is made present, due to which the positron and the electron each make a curling movement in opposite direction. The interaction with the vapor in the vessel then makes a trace visible: the trace on the upper right is then caused by a positron. Source: public domain.

## 2 Inconsistency of the $5\sigma$ convention with existing concepts of observation

### 2.1 Inconsistency with concepts of observation by Fox

In this section it will be shown that the  $5\sigma$  convention is *inconsistent* with Fox’s concepts of direct and indirect observation, by showing that short-lived unstable particles are fundamentally unobservable, that is, are neither directly nor indirectly observable. To start with, let’s repeat the definitions of direct observation and indirect observation:

**Definition 2.1.** “An object is **directly observed** if it is perceived as an individual within broader acquaintance<sup>4</sup>. The observation does not depend upon any physically-caused phenomenon<sup>5</sup>” (Fox, 2009).

**Definition 2.2.** “An object is **indirectly observed** if the physical phenomenon created by the object is observed directly. The indirectly observed object has to retain its individuality” (*ibid.*).

It is emphasized that definition 2.1 is about an *epistemologically* direct observation. E.g. when we directly observe a tree, then of course from the *physical* point of view the photons emitted from the tree are the input of our senses. But *epistemologically*, there is nothing in between us and the tree—it is *directly* observed (*ibid.*). Furthermore, definition 2.2 implies that indirect observation is theory-laden as it depends on knowledge of the cause of the directly observed phenomenon (*ibid.*). Take the discovery of the positron: a trace as shown in Figure 2 was observed in a cloud chamber, and that trace *could only have been caused* by a particle with the same (inertial) mass as an electron, but opposite electric charge (Anderson, 1933). According to definition 2.2, this is an indirect observation of a positron.

Proceeding, the first point is the following corollary of definition 2.1:

**Corollary 2.3.** *Short-lived unstable particles cannot be directly observed.*

**Proof** Given definition 2.1, an observation of decay products of an unstable particle cannot be called a direct observation of the unstable particle *itself*. Q.e.d.

As it is hard to imagine that anyone will disagree with something so abundantly clear, further elaboration is omitted. The second point is then the following corollary of definition 2.2:

**Corollary 2.4.** *Short-lived unstable particles, which at least includes all unstable particles with a lifetime  $\lesssim 10^{-20}$  s, cannot be indirectly observed.*

<sup>4</sup>Here ‘broader acquaintance’ refers to finding out more about the object. This is to separate *directly observed objects* from *illusions*. E.g. one can distinguish seeing an object on a table from a mere illusion created by a spot on one’s glasses by changing the angle of view.

<sup>5</sup>If an object is directly observed, then it is the object itself that is observed, not some phenomena caused by it. E.g. if we directly see an aeroplane in the sky, then we see the aeroplane *itself* and not merely its vapor trail.

**Proof** The crux is that the decay products are observed *indirectly*, and given definition 2.2 an *indirect* observation of decay products of an unstable particle **cannot** be called an indirect observation of the *unstable particle itself*. The physical phenomenon that is *directly* observed—perceived!—is the output of the measurement equipment (such can be a trace in a cloud chamber, a mass spectrum, or the like). But this phenomenon is created by the *decay products* of the unstable particle, and **not** by the unstable particle *itself*. This applies *at least* for all unstable particles with a lifetime  $\lesssim 10^{-20}$  s: as their speed is bound by the speed of light ( $3 \cdot 10^8$  m/s), they cannot possibly leave a trace of more than  $10^{-10}$  m (the size of an atom) in a cloud chamber, which renders them not indirectly observable. Q.e.d.

The corollaries 2.3 and 2.4 then prove the final corollary:

**Corollary 2.5.** *Short-lived unstable particles are fundamentally unobservable.*

So, on the one hand we have the  $5\sigma$  convention, which—*without reference to any existing concept of observation*—says that the observation of a short-lived unstable particle **can** be claimed whenever the criterion is met. But on the other hand we have derived corollary 2.5 from existing concepts of direct and indirect observation: that means that their observation **cannot ever** be claimed.

**Ergo, the result of this analysis is that the  $5\sigma$  convention is inconsistent with Fox’s concepts of direct and indirect observation, because from the latter perspective one simply cannot ever claim to have “observed” a short-lived unstable particle.**

## 2.2 Inconsistency with Van Fraassen’s notion of observability

We also come to this conclusion when we omit making any distinction between directly and indirectly observable, and instead focus at the border between *observable* and *unobservable* from Van Fraassen’s point of view that ‘observable’ means ‘observable-to-us’, where the ‘us’ refers to the epistemic community (1980): the epistemic community can only observe an output of the measurement device, and can thus at best only observe *properties* of elementary particles—it is then abject nonsense to claim that an unstable particle *itself* has been observed, so that the  $5\sigma$  convention is then nonsensical.

**Ergo, the result of this analysis is that the  $5\sigma$  convention is inconsistent with Van Fraassen’s notion of observability, because from the latter perspective one simply cannot ever claim to have “observed” a short-lived unstable particle.**

## 2.3 Illustration: the case of the Higgs boson

Let’s illustrate this with the case of the Higgs boson (symbol:  $H$ ). This is an unstable particle with a lifetime of  $1.56 \cdot 10^{-22}$  s that has several modes of decay, one of which is the decay into two photons (symbol:  $\gamma$ ):

$$H \rightarrow \gamma\gamma \tag{1}$$

In an experimental set up, the photons interact with the device: the latter registers the energy (mass) of the photon. What the device churns out is a diphoton mass spectrum: on the horizontal axis total masses of photon pairs, on the vertical axis the number of events, i.e. the number of times these masses have been recorded. So if masses of 1, 2 and 3 GeV were recorded each 1 time, the diphoton mass spectrum would show that the sums  $3(=1+2)$ ,  $4(=1+3)$ , and  $5(=2+3)$  GeV were recorded each at 1 event. In the experiment with the Higgs we are talking about millions of events, and the output of the measurement equipment looks like figure 3. At the very best, what is *directly* observed is the peak in the diphoton mass spectrum at 126 GeV<sup>6</sup>. But this peak is caused by pairs of photons with a combined mass of 126 GeV, **not** by a Higgs boson. Thus speaking, the point here is to sharply distinguish between an *observed* excess of photon pairs and the thing *assumed* to have caused that excess. So what they have indirectly observed is an excess of photon pairs at 126 GeV, *not* a Higgs

---

<sup>6</sup>Note that this peak already requires a mechanical processing of data, but alas.

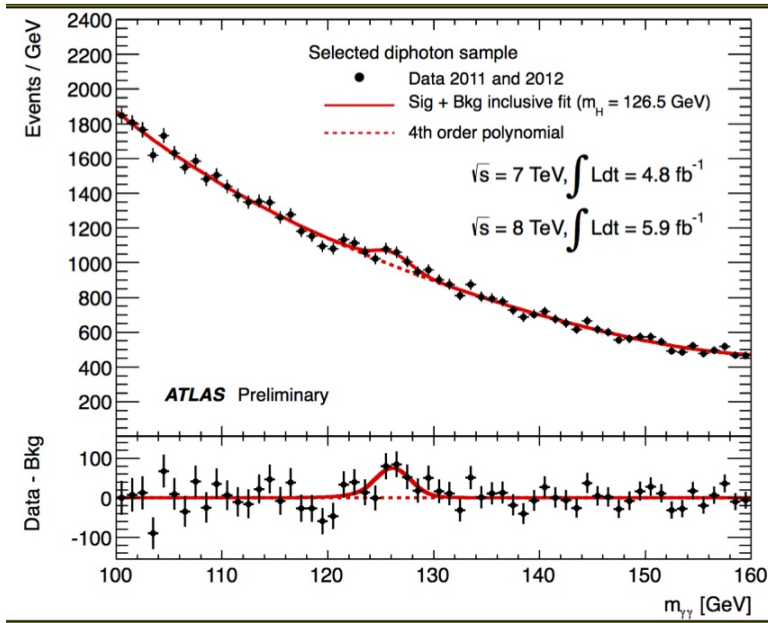


Figure 3: Diphoton mass spectrum obtained in the hunt for the Higgs boson. In the upper curve, the bump around 126 GeV can clearly be seen. The lower curve with the peak at around 126 GeV is obtained from the upper one by subtraction. Source: public domain.

boson! So, regarding hypothesis testing, what one tests with this set up is the hypothesis ‘there is an excess of photon pairs at 126 GeV’ versus the hypothesis ‘no excess of photon pairs at 126 GeV’: this is, thus, **not** a matter of testing ‘a Higgs boson exists’ versus ‘no Higgs boson exists’!

So from Van Fraassen’s perspective, what has been observed is the peak in the diphoton mass spectrum, and nothing else. And from Fox’s perspective, what has been indirectly observed is an excess of 126 GeV photon pairs, and nothing else. (Likewise for the analyses of the other decay channels of the Higgs.)

### 3 Discussion

#### 3.1 Counterarguments

To stick with the example of the Higgs boson, one might counter that, regardless of whether we call it an observation or not, the experimental results still decisively confirm the existence of a Higgs boson. That, however, is a well-known logical fallacy called *affirming the consequence*. The point is namely that the relation between the existence of the Higgs boson and the existence of an excess of photon pairs at 126 GeV has the logical form of an if-then relation  $P \Rightarrow Q$ : if we have  $P \Rightarrow Q$ , and the consequence  $Q$  has been confirmed, then it is an error to conclude that thus the antecedent  $P$  is true. In the case of the Higgs boson, for example, the crux is that the peak at 126 GeV in figure 3 evidences the presence of lots of photon pairs with a combined mass of 126 GeV in the system under observation: **it doesn’t evidence anything else!** And there are no buts about it: although the social structure of post-World-War-II physics has been described as one in which “mandarins” of physics get to decide what is acceptable and what not (Prugovecki, 1993), it is not the case that ‘affirming the consequence’ all of a sudden becomes a correct reasoning when it is being put forwards by any of these “mandarins”.

It is only a slight variation of the foregoing to counter that obviously the decay products of a Higgs boson have been observed, so therefore a Higgs boson exists. But then one assumes what has to be proven, so this is an example of circular reasoning (another well-known fallacy). Of course, in the Higgs case the observed excess of photon pairs with a combined mass of 126 GeV comes from *somewhere*, but the point is that **nothing but** that excess of photon pairs has been observed: it is then circular reasoning to say that these are the decay products of a Higgs boson, so therefore a Higgs boson exists.

Any claim, implicit or explicit, that the experimental results decisively “confirm” the existence of a Higgs boson concerns thus rhetoric outside the framework of scientific discourse! This holds for other short-lived unstable particles as well.

### 3.2 Implications for observational claims

A first implication of the inconsistency of the  $5\sigma$  convention with existing concepts of observation is that the  $5\sigma$  convention is untenable: the physicists’ use of the word ‘observation’ is incompatible with philosophical insights in what it means to have observed an object. Obviously, a direct implication for published observational claims concerning short-lived unstable particles is then that these will have to be *retracted*: if the  $5\sigma$  convention is untenable, then so are *all* thereon based published claims that short-lived unstable particles have been positively observed. This is not to belittle the experimental work, which is of course state-of-the-art: the point is merely that the obtained data do not amount to an observation of an unstable particle. Examples of such particles and corresponding observational claims are given in table 1; the list is not exhaustive but the point is that none of these particles can be said to have been “observed”, neither directly nor indirectly.

particle	lifetime	observational claim
Higgs boson*	$1.56 \cdot 10^{-22}$	(ATLAS Collaboration, 2012) (CMS Collaboration, 2012) (CERN, 2013)
$W^\pm$ bosons*	$3 \cdot 10^{-25}$	(CERN, 1983a)
$Z^0$ boson*	$3 \cdot 10^{-25}$	(CERN, 1983b,c)
Y meson	$1.21 \cdot 10^{-20}$	(E288 Collaboration, 1977)
J/ $\Psi$ meson*	$1.56 \cdot 10^{-22}$	(Aubert <i>et al.</i> , 1974)
$\Omega_b^-$	$1.13 \cdot 10^{-12}$	(DØ Collaboration, 2008)
$Z(4430)^-$	?	(LHCb Collaboration, 2014)

Table 1: examples of unstable particles that are claimed to have been positively observed on the basis of the  $5\sigma$  convention; an asterisk in the first column marks cases where the observational claim led to a Nobel prize award. It is true that the  $\Omega_b^-$  baryon has a lifetime longer than  $10^{-20}$  s and that the tetraquark  $Z(4430)^-$  has an unknown lifetime, but both observational claims are based on the  $5\sigma$  convention.

The question is then: what *can* be claimed? The case of the Higgs boson can be seen as a typical example: at best one can claim that the predictions of the Standard Model, including the Higgs boson, have been confirmed by the CMS and ATLAS experiments at the LHC. This is a substantially different claim: an observational claim implies a claim of true existential knowledge—if one has seen something, one *knows* that it exists—while the latter doesn’t.

### 3.3 Implications for physical theories

The main implications of the untenability of the  $5\sigma$  convention, however, are far more general and can be stated in the form of two incompleteness theorems for physics. These concern the *completeness*<sup>7</sup> and the *correctness*<sup>8</sup> of a physical theory, two notions that were introduced in the EPR-paper as important for the evaluation of the success of a physical theory (Einstein, Podolsky & Rosen, 1935).

**Theorem 3.1.** No experiments can prove *completeness* of a physical theory predicting the existence of short-lived unstable particles.

<sup>7</sup>A theory is *complete* if and only if (i) every element in the physical world has a counterpart in the theory, and (ii) every element in the physical world, predicted with certainty by the theory, indeed exists.

<sup>8</sup>A theory is *correct* if and only if all its predictions are true.

**Theorem 3.2.** No experiments can prove *correctness* of a physical theory predicting the existence of short-lived unstable particles.

**Proof:** To prove completeness, one has to prove the existence of the particles predicted by the theory. But as short-lived unstable particles are fundamentally unobservable, their existence cannot be proven by any experiment—**regardless of the research effort**. Hence a theory predicting such particles cannot be proven to be complete by experimental physical research. Likewise, to prove correctness one has to prove that the predictions of the theory are true. But a prediction that a short-lived unstable particle exists cannot be proven to be true by any experiment. Hence, a theory predicting such particles cannot be proven to be correct by experimental physical research. Q.e.d.

Ergo, even if the Standard Model *is* complete and correct, we cannot ever prove that. This is not to say that the short-lived unstable particles postulated by the Standard Model don't exist: they very well may, but we *cannot ever* know that by testing hypotheses in particle accelerators. That is, of course we can postulate the existence of unstable particles to explain certain phenomena (like the Higgs boson has been postulated to explain 'mass'), but we will *never* get to the point that we can say that we *know* that these particles exist, since they are fundamentally unobservable—and existential knowledge derives from observations. On the other hand, the completeness of the Standard Model can be *disproved*: for example, recently it has been shown explicitly that an observation of gravitational repulsion would refute the postulated existence of virtual particle-antiparticle pairs (Cabbolet, 2014).

Consequently, all we can do with physical theories that predict short-lived unstable particles is testing their *empirical adequacy*. This notion has been defined by Van Fraassen: a theory is *empirically adequate* if and only if all observations—past, present *and future*—in its area of application can be described as predictions of the theory (1980). So this is a somewhat weaker notion than correctness as defined in the EPR-paper: correctness implies empirical adequacy, but the converse is not necessarily true. What is important then is that the fact that the short-lived unstable particles postulated to exist are fundamentally unobservable does not render the empirical adequacy of the Standard Model any less. Of course, the conformation of its predictions is a justification for the belief that the Standard Model is empirically adequate, and thus a ground for its acceptance. Now Sellars remarked that “to have good reasons to hold a theory is *ipso facto* to have good reasons to believe that the entities postulated by the theory exist” (1963), so *mutatis mutandis* there are good reasons to believe in the existence of the short-lived unstable particles postulated by the Standard Model. But the crux here is that *belief on the basis of inference to the best possible explanation* has to be sharply distinguished from *existential knowledge*: one can believe in the existence of a particle that later turns out not to exist, but one cannot have existential knowledge of a particle that doesn't exist. Moreover, at present there might even be *general consensus* that all these unstable particles postulated by the Standard Model exist. But although the post-World War II physics community has gradually replaced the traditional notion of *truth* by *general consensus* (Prugovecki, 1993), one ought to realize that history provides numerous counterexamples to the idea that ‘there is general consensus about X’ implies ‘X is true’. In other words: it should be realized that reaching general consensus about the existence of the Higgs boson, the  $W^\pm$  bosons, and the  $Z^0$  boson is **not** the same as having existential knowledge of these bosons!

### 3.4 Conclusions

The first conclusion is then that the experimental support for the Standard Model is substantially less than suggested by the physics literature, all the more so when the unobservability of quarks shown by Fox (2009) is taken into consideration. It has been shown that what physicists call an “observation” of a short-lived unstable particle is *not an observation at all*: consequently, **all** the celebrated observational claims concerning short-lived unstable particles postulated by the Standard Model have to be dismissed as *gratuitous*, because philosophical insights in what it means that an object has been observed do not resonate in these claims. That means much less is known about the fundamental constituents of the physical world than is currently thought.

But not only that: we also have to conclude that the Standard Model, or any other physical theory predicting short-lived unstable particles, cannot ever be proven to be complete or correct by any future experimental research. The two incompleteness theorems for physics, which follow from this cognitive inaccessibility of part of the subatomic world, effectively destroy the usefulness of the predicates ‘correct’ and ‘complete’ for judging the success of the physical theories: we can only test their empirical adequacy. This raises the question whether the scientific method isn’t bound to leave us on the long run with a *postmodernism in physics*—a scenario where several empirically adequate theories coexist without the possibility to decide between these theories.

On a more general note, the final conclusion is that this paper demonstrates the importance of philosophical concepts for elementary particle physics. In the present case this importance doesn’t lie in advanced calculations, but in understanding that existential knowledge of short-lived unstable particles is *beyond* the epistemic limits of experimental physical research, which has its bearing on what can be claimed by physicists. Decades ago Heisenberg already noted that it is a widely held “misconception” among particle physicists that philosophical arguments can be avoided altogether (1976): hasn’t the time now come for the physics community to finally say goodbye to this “shut-up-and-calculate!” attitude?

**Acknowledgements:** This work has been facilitated by the Foundation Liberalitas.

## A Appendix: about the term ‘significance’

The term ‘significance’ in the  $5\sigma$  convention is a concept from mathematical statistics. For a precise definition the reader is referred to the literature, e.g. (Kreyszig, 1993). What is important here is that one can interpret the significance of  $5\sigma$  as a probability.

Suppose we want to test whether a coin is fair, that is, whether the chance of getting heads is 50%. Suppose we have thrown the coin 10,000 times and have obtained heads 5186 times. The probability of accidentally obtaining more than 5185 times heads with a fair coin is 0.01%, so we can say with a significance level of 0.01% that the coin is not fair.

Although the case of the Higgs boson is more complex, the principle is the same. Looking at figure 3, the point is that the ATLAS/CMS collaboration has observed a *significant* bump above background in the invariant diphoton mass spectrum at 125 GeV. In addition, other spectra have been obtained from investigating other modes of decay of the Higgs boson: they also observed a *significant* excess of events in the  $ZZ$  invariant mass spectrum at the same mass. The adjective ‘significant’ then refers to the significance level, which here is  $5\sigma$  or about 1 in 3.5 million. In the present case, it means that the probability that the peaks in the aforementioned mass spectra at  $125.3 \pm 0.6$  GeV are **not** coincidental is approximately 99.9999997%. It means nothing else, so it is important to notice that the statement “we have observed the predicted properties of the predicted decay products of the Higgs boson with a significance of  $5\sigma$ ” does **not** directly translate to the statement “the probability that the Higgs boson exists is ca. 99.9999997%”!

## References

- C.D. Anderson, The Positive Electron, *Physical Review* **43**(6), 491494 (1933)
- ATLAS Collaboration, *Phys. Lett. B* **716**(1), 1-29 (2012)
- J.J. Aubert *et al.*, *Phys. Rev. Lett.* **33**, 1404-1406 (1974)
- M.J.T.F. Cabbolet, *Astrophys. Space Sci.* **350**(2), 777-780 (2014)
- C. Cheyne, Existence claims and causality, *Australasian Journal of Philosophy* **76**, 34-47 (1998)
- CERN press release, *A major step forward in physics: the discovery of the W vector boson*, CERN-PR-83-03-EN, January 25 (1983)



- CERN press release, *Yet another major discovery at CERN : The Z intermediate Boson*, CERN-PR-83-10-EN, May 31 (1983)
- CERN press release, *Z discovery confirmed*, CERN-PR-83-13-EN, July 22 (1983)
- CERN press release, *New results indicate that particle discovered at CERN is a Higgs boson*, March 14 (2013)
- M. Chalmers, *Nature* 490(7419), S10-S11 (2012)
- A. Cho, *Science* **338**(6114), 1524-1525 (2012)
- CMS Collaboration, *Phys. Lett. B* **716**, 30-61 (2012)
- DØ Collaboration, *Phys.Rev.Lett.* **101**, 232002 (2008)
- E288 Collaboration, *Phys. Rev. Lett.* **39**, 255-255 (1977)
- A. Einstein, B. Podolsky, N. Rosen, *Phys. Rev.* **47**(10), 777-780 (1935)
- T. Fox, Why Quarks are unobservable, *Philosophia Scientiae* **13**(2), 167-189 (2009)
- W. Heisenberg, The nature of elementary particles, *Physics Today* **29**(3), 32-39 (1976)
- E. Kreyszig, *Advanced Engineering Mathematics* (Jon Wiley & Sons, Singapore), pp. 1149-1271 (1993)
- LHCb Collaboration, Observation of the resonant character of the  $Z(4430)^-$  state, arXiv:1404.1903v1 [hep-ex] (2014)
- G. Maxwell, The ontological status of theoretical entities, *Minnesota Studies in Philosophy of Science* **3**, 3-27 (1962)
- Nobel Media AB, “The Nobel Prize in Physics 2013”, Nobelprize.org (2013)
- E. Prugovecki, *Historical and Epistemological Perspectives on Developments in Relativity and Quantum Theory*, in: *Quantum Geometry* (Dordrecht: Kluwer), pp. 433-485 (1993)
- W. Sellars, *Science, Perception and Reality* (Atascadero: Ridgewood Publishing Company), p. 97 (1963)
- D. Shapere, The concept of observation in science and philosophy, *Philosophy of Science* **49**, 485-525 (1982)
- B. Van Fraassen, *The Scientific Image*, Oxford: Clarendon Press (1980)