

1 **Model Choice and Crucial Tests. On the Empirical Epistemology** 2 **of the Higgs Discovery**

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7 *Abstract:* Our paper discusses the epistemic attitudes of particle physicists on the
8 discovery of the Higgs boson at the Large Hadron Collider (LHC). It is based on
9 questionnaires and interviews made shortly before and shortly after the
10 discovery in 2012. We show, to begin with, that the discovery of a Standard
11 Model (SM) Higgs boson was less expected than is sometimes assumed. Once the
12 new particle was shown to have properties consistent with SM expectations –
13 albeit with significant experimental uncertainties –, there was a broad
14 agreement that ‘a’ Higgs boson had been found. Physicists adopted a two-
15 pronged strategy. On the one hand, they treated the particle as a SM Higgs boson
16 and tried to establish its properties with higher precision; on the other hand,
17 they searched for any hints of physics beyond the SM. This motivates our first
18 philosophical thesis: the Higgs discovery, being of fundamental importance and
19 establishing a new kind of particle, represented a crucial experiment if one
20 interprets this notion in an appropriate-sense. By embedding the LHC into the
21 tradition of previous precision experiments and the experimental strategies thus
22 established, underdetermination and confirmational holism are kept at bay.
23 Second, our case study suggests that criteria of theory (or model) preference
24 should be understood as epistemic and pragmatic values that have to be weighed
25 in factual research practice. The Higgs discovery led to a shift from pragmatic to
26 epistemic values as regards the mechanisms of electroweak symmetry breaking.
27 Complex criteria, such as naturalness, combine epistemic and pragmatic
28 different values, but are coherently applied by the community.
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31 **1. Introduction**³

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33 The discovery of the Higgs boson at the Large Hadron Collider (LHC) of the European
34 Laboratory CERN, announced in July 2012, is arguably one of the most important
35 scientific achievements of the past few decades. The discovery received world-wide
36 attention; two of the inventors of the Higgs mechanism, François Englert and Peter
37 Higgs, were awarded the 2013 Nobel Prize in physics. The Higgs boson had been the

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³ The study was performed as part of the project ‘Model Dynamics’ supported by the DFG. It is based on questionnaires that were developed by the authors, Arianna Borrelli, Robert Harlander, and Friedrich Steinle, and interviews conducted by Arianna Borrelli. Karsten Egger assisted in the evaluation of the questionnaire. We acknowledge the help of Annette Holtkamp in obtaining the SPIRES email list. We acknowledge discussions within the recently established DFG Research Unit ‘Epistemology of the LHC’ and detailed comments by Robert Harlander, Martin King, and Gregor Schiemann. Some other results from this study can be found in (Borrelli 2016) and her presentation at CERN available under <https://indico.cern.ch/event/232108/>

38 final piece of the so-called Standard Model of particle physics (SM) not observed by
39 previous experiments. The Higgs mechanism in the SM was required to generate masses
40 of the elementary particles in a consistent way. Even though with the discovery of the
41 Higgs boson, the SM – terminology notwithstanding – has now become one of the most
42 successful scientific theories of contemporary physics, all particle physicists agree that it
43 will not be the final word. There are both compelling internal and external reasons to
44 postulate physics beyond the SM (BSM).

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46 Quite a few observers outside the narrower field of elementary particle physics
47 considered the discovery of the Higgs boson in 2012 as largely expected – despite its
48 peculiar conceptual nature within the SM. It appeared to be just the final step in a long
49 series of discoveries and precision tests in which stronger and stronger accelerator
50 experiments had confirmed all particles of the SM and scrutinized their interactions. The
51 present paper argues that as regards the community of elementary particle physics this
52 picture needs qualification. In actual fact, even shortly before the Higgs discovery a
53 significant percentage of physicists raised concerns whether it would at all be found at
54 the LHC and expressed preferences for other explanations of the particle masses.

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56 In this paper, results of questionnaires and interviews with LHC physicists shortly
57 before (autumn 2011) and shortly after (autumn 2012) the discovery are presented and
58 analysed. From these empirical sources, we reconstruct the physicists' beliefs in the
59 adequacy of certain models, in the outcome of the LHC experiments, and concerning the
60 possible impacts of the LHC experiments on those models. This will help us to
61 understand the epistemic attitudes of particle physicists, and the principles and
62 strategies guiding their research. Our empirically informed epistemological
63 investigation also promises new insights for a philosophical analysis of how actual and
64 expected experimental findings, on the one side, and pragmatic quality criteria of
65 models, on the other, influence the research agendas of particle physicists.

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67 We have limited the scope of the present paper to a specific part of the available
68 empirical material: to the Higgs mechanism and competing accounts of mass generation,
69 and to the presently most discussed pragmatic quality criterion, naturalness. It must be
70 said, however, that the LHC was, from the very beginning, designed not only to search
71 for the Higgs boson but also to probe the deep TeV energy range and find signs of BSM
72 physics. Whereas the first objective has now been achieved, no 'new physics' BSM has
73 been observed to date.⁴

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75 The specific descriptive questions addressed in this paper are as such:

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77 1. Did physicists in 2011 expect the Higgs boson to be discovered at the LHC and how
78 did they evaluate the Higgs candidate in 2012, that is, before its properties were
79 known to a sufficient extent? What was their assessment of alternative models for
80 mass generation in 2011 and in 2012?
81 2. How important was the naturalness problem a major guiding principle to develop
82 models of physics beyond the SM (BSM), in shaping physicists' attitudes and
83 preferences?

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85 We will show that, in 2011, physicists were rather undecided whether the SM Higgs
86 boson would eventually be found, that is, even a few months before the first evidence
87 was reported. However, once a candidate had been observed in 2012, they quickly
88 embraced the notion that 'a' Higgs boson had been found. Its discovery immediately

⁴ The attempts at finding physics BSM and their effects on the thinking of LHC physicists will be discussed in a separate paper.

89 affected the research directions in particle physics. There was, on the one hand, less
90 motivation to search for alternatives to the Higgs mechanism. On the other hand, after
91 finding the Higgs boson, the naturalness problem posed by the scalar Higgs particle
92 changed from a virtual into a real problem, especially since in the years since 2012 no
93 BSM effect to cure this problem straight away has been found.⁵ This led some physicists
94 to develop a more critical attitude as to naturalness' significance for elementary particle
95 physics.

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97 The physical developments prompt the following philosophical questions.

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99 3. What do the epistemic attitudes of particle physicists shown in the questionnaire
100 and the interviews mean for the significance and application of criteria of theory (or
101 model)⁶ choice and the principles and epistemic values guiding model development?
102 4. What does the comparison of the situations before and after the discovery of the
103 Higgs boson signify for the relationship between theory (or models) and
104 experiment? In particular, was the Higgs discovery a crucial experiment for the SM?
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106 The paper is organised as follows. After a brief introduction into the theoretical
107 motivation for the Higgs mechanism and the experimental attempts to find evidence for
108 a Higgs boson (Section 2), we provide the background of the philosophical problems
109 raised (Section 3) and discuss the methodology of our study (Section 4). The
110 presentation of the results will be subdivided into the outcomes of the questionnaire
111 and the interviews in 2011 (Section 5) and in 2012 (Section 6) respectively. Finally
112 (Section 7), we outline our answers to the above-mentioned four questions.
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114 115 **2. The physics of electroweak symmetry breaking**

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117 Several articles of both physicists and philosophers discuss the emergence of what is by
118 now called the ‚Higgs‘ mechanism (Cf. Ellis, Gaillard, Nanopoulos, 2015; Nobel laudatio
119 2013; Karaca 2013). Here, only a brief account of the motivation and the concepts
120 behind the Higgs boson can be given. In the early 1960s, various models were developed
121 to unify two interactions governing the subnuclear world, the electromagnetic and the
122 weak ones. These unifications adopted the concept of local gauge symmetry that had
123 previously been applied successfully to quantum electrodynamics (QED). In brief, this
124 symmetry means that the theory is invariant under a specific space-time dependent
125 transformation of the quantum fields. Assuming this symmetry leads to a
126 mathematically consistent interacting field theory.
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128 However, a major problem physicists were facing in applying local gauge symmetry to
129 weak interactions was that observations implied that the corresponding gauge bosons
130 have a non-vanishing mass. As such, gauge boson masses break the symmetry explicitly,
131 thus leading to theoretical inconsistencies, such as the violation of unitarity. To remedy
132 this, in the 1960s, physicists used the concept of spontaneous symmetry breaking (SSB)
133 to generate gauge boson masses in a gauge invariant way at the cost of introducing an
134 additional scalar, i.e. spin-less, particle, which became known as the Higgs boson. This
135 particle was discovered at the LHC some 50 years after its invention. The Higgs sector of
136 the SM is a novel element in physics, in that it describes the mass of elementary particles
137 in terms of their interaction with an elementary scalar field.

⁵ Cf. e.g. the analysis by Friederich, Harlander & Karaca (2014)

⁶ In line with the current philosophical literature, we consider models as autonomous entities in scientific theorizing, not as the logical models of a theory. For how one can apply this conception to elementary particle physics, cf. Borrelli & Stöltzner (2013) and Stöltzner (2014).

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Whereas the weak and the electromagnetic components of the ‘electroweak’ theory have almost the same strength at very high energies, they are substantially different at low energies, since only the weak interaction invokes a massive interacting particle. Therefore the mechanism of mass generation is also referred to as ‘electroweak symmetry breaking’ (EWSB). The Higgs mechanism was originally only devised to give mass to the weak gauge bosons $W^{+/-}$ and Z^0 . (The latter represents the electrically neutral component of the weak interaction, which, however, has an admixture of an electromagnetic component.) It turned out that the Higgs mechanism could also be applied to give masses to fermions, through a Yukawa interaction, albeit without predicting their numerical values.

150 **2.1 The experimental search for the Higgs boson**

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The general conception of the Higgs mechanism just outlined was developed into phenomenological predictions [Ref e.g. J.Ellis, M.K.Gaillard, D.V.Nanopoulos 1976], opening the way for experimental searches of the Higgs boson. Given the masses of the W and Z bosons, the Higgs mechanism introduced just one additional parameter to the SM that had to be determined by experiment, notably by measuring the Higgs mass. Whereas the theory did not provide a prediction for this mass, it did lead to an upper bound of 800 GeV to maintain theoretical consistency. Depending on its mass, it could be unambiguously predicted how the Higgs boson is produced and the way it can be seen by experiments. Since a Higgs boson would only exist for small fractions of a second, it would decay, depending on its mass, mainly into massive fermions and W and Z bosons.

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As a result, a clear strategy for finding the Higgs boson was devised.⁷ However, this did not make Higgs searches easy. Essentially no experiment before the start of CERN’s Large Electron Positron Collider (LEP) in 1989 was sensitive to the Higgs boson. At the end of the LEP data taking no significant signal was observed. However, the sensitivity of LEP was such that a Higgs of 114.4 GeV or less should have been found, allowing physicists to place a lower limit on the SM Higgs mass. Between the end of LEP and the start of LHC, an additional small mass interval around 160 GeV could be excluded at the Tevatron. The outstanding precision of the LEP data and theoretical calculations based on the SM provided an indirect sensitivity to the Higgs mass by quantum fluctuations, e.g. loop corrections to the W and Z bosons, bounding it to be lighter than 157 GeV.

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In 2010, data taking at the LHC started for the final assault. It was clear that the LHC had the sensitivity to observe the Higgs boson in the remaining allowed mass range, using the decay modes that were unambiguously predicted for a SM Higgs. Relatively soon one could exclude a high mass Higgs of 200-600 GeV – in full agreement with LEP’s indirect limits. With the rapid increase in data rate, both the ATLAS and CMS experiments reported, at a CERN colloquium on December 13, 2011, an excess of events that could be taken as initial evidence for a new particle around 126 GeV. On the other hand, the probability that this would be just a background fluctuation was still too high to claim an observation. However, half a year later much more data had been accumulated, such that both detectors presented, at a special CERN seminar, a signal of 5 standard deviations each. This corresponds to a probability of only 10^{-9} for the signature to be a statistical fluctuation of the background of experimentally established physics (SM without Higgs). By convention in particle physics, this was sufficiently small to claim a

⁷ One publication was even titled “The Higgs Hunter’s Guide” (Gunion et al. 1990).

187 discovery, an observation.⁸ A few weeks later, the two experiments published their data.
188 (Aad et al. 2012, Chatrchan et al. 2012).

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190 Still, the data were not sufficient to definitely claim this to be the long-awaited Higgs
191 boson. Some important properties had not yet been confirmed, and the precision of the
192 measurements on production and decay properties was still marginal. On the other
193 hand, those properties that were observed corresponded to what is expected for a SM
194 Higgs boson. For instance, the particle had been found in two decay modes with rates
195 consistent with the expectation, and it had a mass in agreement with the direct and
196 indirect limits known from previous experiments. As of today (2017), more properties
197 of the discovered particle have been studied, the decay modes and the mass have been
198 measured to higher precision, in accordance with the SM. Even though there is still a
199 need for further measurements, there is currently little doubt among physicists that the
200 new particle is indeed a Higgs boson.

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203 ***2.2 Alternatives to the Higgs boson***

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205 Already shortly after the invention of the Higgs mechanism, several authors expressed
206 discontent because this solution of the SSB problem appeared largely ad-hoc. For
207 example, it has limited predictive power in that it cannot determine the quark and
208 lepton masses. Concern was also raised that the Higgs mechanism introduces a new
209 concept into the theory for the one and only purpose of mass generation. Over the years,
210 the list of issues cited by physicists in this respect has expanded. (Cf. Friederich,
211 Harlander, & Karaca 2014, sect. 3).

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213 Several alternative mechanisms of EWSB have emerged over the past decades. They
214 used a scalar particle and a Higgs-like potential to generate mass. However, in many
215 cases, the conceptual framework of the alternative model was very different from, and
216 implied physics beyond the SM. These BSM models will be considered in this article only
217 in relation to mass generation.

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219 A fairly straightforward modification of the original Higgs mechanism was to extend the
220 Higgs sector. Originally, one complex Higgs doublet was assumed, leading to four fields
221 one of which would be the observable Higgs boson, whereas the others would not be
222 directly observable. However, one can also introduce, e.g., a second doublet leading to
223 five physical elementary Higgs bosons with no change in the principal mechanism of
224 mass generation. Such models allow the different Higgs bosons to assume different
225 roles.

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227 The two Higgs doublet model is of special interest in BSM considerations since it is the
228 minimally required Higgs sector in the framework of Supersymmetry, the most often
229 discussed extension of the SM. Supersymmetry assumes a new fundamental symmetry
230 of particles with integer and half-integer spins and offers a rather broad range of
231 features that are able to solve some basic problems of the SM, among them providing a
232 Dark Matter particle and solving the naturalness problem (See below). Moreover,
233 Supersymmetry is the only BSM model that makes a firm prediction on the upper limit
234 of the Higgs mass: it has to be lighter than about 130 GeV, a limit that is much tighter
235 than the range allowed by the SM.

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⁸ On the criteria when particle physicists claim ‚evidence‘, versus ‚observation‘ or ‚exclusion‘ see the ‚Prologue‘ to Franklin (2013).

237 Another class of models assumes the Higgs boson to be a composite, i.e. made up of sub-
238 constituents. The first model of this kind was devised at the end of the 1970s by
239 essentially copying concepts known from the strong interactions that explain hadron
240 masses. This mechanism was dubbed ‘Technicolour’; since it involved strong
241 interactions, it was considered as a type of ‘strong’ or ‘dynamical’ EWSB. The realisation
242 of these models led to inconsistencies with measurements, such that this approach by
243 now has become disfavoured. However, the concept of composite Higgs particles has
244 been implemented within multiple frameworks invoking additional symmetries, new
245 interactions, or additional spatial dimensions (e.g. Csaki and Tanedo 2016).

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247 All these alternative models assume scalar particles like the SM Higgs boson to generate
248 the masses of gauge bosons and fermions. However, the properties of these scalars are
249 different, albeit sometimes by a rather small amount given by tuneable free parameters.
250 All of them also lead to new phenomena, e.g. more scalars and more fermions.

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253 **2.3 The Naturalness problem**

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255 From a theoretical perspective, the existence of an elementary scalar Higgs boson
256 introduces an ‘unnaturalness’ into the SM. The concept ‘naturalness’ was introduced in
257 slightly different forms by ‘t Hooft (1979) and Susskind (1979). During the past decades,
258 naturalness has developed from a merely technical problem into an influential guiding
259 principle for BSM physics; that is, extensions of the SM were developed with the explicit
260 aim to remedy the naturalness problem.

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262 In a nutshell, the naturalness problem is this: since the fundamental equations of the SM
263 can only be solved in a perturbative expansion, at each order a theoretically well-
264 defined correction has to be applied to compensate for quantum fluctuations that would
265 modify a physical quantity like mass or charge. Such ‘renormalisation’ is a standard
266 technical procedure in theoretical particle physics.⁹ For the SM particles of spin $\frac{1}{2}$ or 1
267 these corrections are of a few percent. In the case of the Higgs boson, which is a scalar,
268 however, the correction to the square of the Higgs mass grows quadratically with
269 energy.

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271 Introducing a cut-off mass where the theory would break down, leads to finite
272 corrections. In the case of the SM, this could be at the rather high Planck scale, where
273 gravity becomes important and the SM is known to be insufficient. In case of the Higgs
274 mass, these corrections appear ‘dramatic and even bizarre’ (Peskin and Schroeder 1995,
275 p. 788), i.e. to keep the square of the Higgs mass at its measured value of 125 GeV,
276 corrections have to be invoked that are more than 10^{30} times higher than the Higgs mass
277 itself. Furthermore, these corrections have to be fine-tuned over many decimal places.
278 Although theoretically viable and consistent, the magnitude of these corrections is
279 considered ‘unnatural’. Once this correction is defined the theory is completely
280 consistent and any dependence on the scale is eliminated.

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282 During the past two decades, naturalness has arguably become the most influential
283 guiding principle for constructing and motivating BSM models. Or more specifically,
284 many physicists believed that if a SM Higgs boson existed, it would come with new
285 phenomena to keep the theory ‘natural’. For instance, new symmetries, extra spatial

⁹ The key role of renormalisation for the consistency of modern quantum field theories and the success in giving it a solid mathematical bases have attracted quite a few philosophers to write extensively on the topic. In a philosophical perspective, this indicates that the naturalness problem arises at a systematically critical juncture of particle physics.

286 dimensions, or a composite Higgs boson built from smaller objects would avoid
287 unnaturalness. Allowing for corrections of just a few percent – as for the other sectors of
288 the SM – these new phenomena should be in the mass range of 1 TeV that is well
289 covered by the LHC. One has to be aware that there is no clear definition of when a
290 theory would become unnatural and there is a large freedom how much fine tuning is
291 considered acceptable. Yet once such a bound is set, it determines the mass range at
292 which new phenomena are expected. At any rate, thus far there has neither been a direct
293 observation nor any clear indirect indication from precision studies that such a new
294 effect exists.

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297 ***3. Philosophical Background: Theory Choice and Crucial Experiments***

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299 Our empirical study allows us to address two longstanding problems in philosophy of
300 science from the perspective of the actual practice of scientists. First (in 3.2), we discuss
301 the relationship between epistemic and pragmatic (including aesthetic) criteria of
302 theory acceptance and theory choice in the contexts of models of electroweak symmetry
303 breaking. Presently most discussed among these criteria is naturalness. Second (in 3.3.),
304 we discuss under which conditions complex experiments, such as the Higgs discovery,
305 are considered decisive or even crucial. We begin this section, however, by showing that
306 the present debates about naturalness represent a case in point about the influence of
307 criteria of theory choice. The general aim of the present section is to give a short survey
308 of the current philosophical discussion that provides the basis for Section 7.

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311 ***3.1. The Philosophical Challenge of Naturalness***

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313 Several facets of the naturalness problem have attracted philosophers' attention; among
314 them are its precise content and to what extent it influences current research in particle
315 physics. Porter Williams (2015) has distinguished four (closely related) ways to
316 formulate the naturalness problem: (i) quadratic divergences in renormalisation; (ii) 't
317 Hooft's (1979) suggestion that setting a small parameter to zero must increase the
318 symmetry of the system; (iii) a specific version of the problem of fine-tuning of
319 fundamental constants; (iv) an aesthetic criterion, whose force is derived from various
320 factors prevailing within the scientific community. Williams argues that none of his four
321 reformulations captures the whole naturalness problem and believes that it is rather an
322 expression of the central dogma of effective field theories according to which widely
323 separated scales should eventually decouple.

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325 The physicist James Wells (2015) considers (i) as the root of the problem, but
326 subsequently emphasizes the significant difference between the technical naturalness
327 (ii) and the absolute naturalness involved in fine tuning that eventually goes back to
328 Dirac's classical worries about large dimensionless numbers. He elaborates an example
329 of an exotically augmented quantum electrodynamics (QED) that consistently
330 instantiates absolute naturalness at the expense of "more parameters, more fields, and
331 more complexity in the theory." (2015, 107) He admits that this principle is
332 controversial, but believes, more generally, "that in the era of the Standard Model's
333 ascendancy, the influence of simplicity and Ockham's razor to theory construction has
334 paled in comparison to Naturalness." (2015, 104)¹⁰

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¹⁰ Ockham's razor instructs us not to add basic entities without any need to do so. It has originally been a metaphysical principle, but the term is nowadays used more broadly. Cf. the following section. See also Wells (2017).

336 Grinbaum (2012) instead has argued that – in virtue of its complex nature or even
337 vagueness – naturalness is exclusively an aesthetic criterion. Borrelli (2015), in a similar
338 vein, holds that naturalness represents a useful, albeit vague, narrative that fosters a
339 constructive interaction between different subcultures of particle physics, such as
340 experimentalists and theoreticians advocating starkly different models. Williams (2015)
341 rejects Grinbaum’s interpretation because aesthetic criteria are notoriously vague.
342 Supersymmetry, for instance, is considered most promising by many physicists even
343 though it is aesthetically attractive in the unbroken state, but aesthetically unattractive
344 after its breaking produces a large number of new constants. Borrelli, on the contrary,
345 argues, that it is precisely this vagueness that allows naturalness to function as a
346 common narrative of the different subcultures.

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348 The goal of the present paper is not to analyse all facets of naturalness. Instead we take
349 it as the currently most important example of a guiding principle for a ‘good’ model
350 within contemporary particle physics and provide empirical results about its
351 relationship with other guiding principles. More specifically, we will compare the
352 relatively new and quantitative concept of naturalness with the more familiar
353 pragmatic, aesthetic, and qualitative criteria of elegance and simplicity – Ockham’s razor
354 being one of its manifestations.

355 356 ***3.2 Epistemic and pragmatic criteria of theory choice***

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358 Philosophers have traditionally distinguished epistemic and pragmatic criteria of theory
359 choice (or preference). The former, among them empirical adequacy and theoretical
360 consistency, are held to be rationally compelling. Pragmatic criteria have instead been
361 seen as a way to decide among epistemically equivalent alternatives by appealing to its
362 simplicity or other aesthetic features, or to its fruitfulness for further research. Among
363 the classical examples are the choice between a geocentric and a heliocentric world view
364 at the time of Copernicus and the early philosophical debates about the nature and
365 alleged conventionality of space and time. The philosophical significance of these
366 criteria of theory choice arises from the problem of underdetermination of theory by
367 empirical evidence that Pierre Duhem had exposed at the parallelism between Newton’s
368 corpuscular theory and Huygens’s wave theory of light. For more than a century both
369 theories were equally able to explain a long series of newly discovered optical
370 phenomena. If one accepts the underdetermination argument, pragmatic and aesthetic
371 criteria become inevitable.¹¹

372
373 Traditionally, philosophers of science have set pragmatic criteria firmly apart from the
374 epistemic criterion of empirical adequacy and all other scientific questions that can be
375 resolved within an explicitly formulated theoretical framework (cf. Carnap 1950).
376 Thomas S. Kuhn (1977) rejected this separation and advocated a broader list of
377 characteristics of a good scientific theory. It includes: empirical “accuracy, consistency
378 [internally and with respect to other theories], scope, simplicity, and fruitfulness.”
379 (1977, 357) These five criteria of theory choice are not mutually independent; they are
380 often context-dependent, and may point in opposite directions. For instance, an increase
381 in accuracy can trivially be obtained by adding additional parameters; yet scientists may
382 prefer to make do with a smaller number of fundamental quantities – or with a simpler
383 law – even at the expense of some accuracy. Thus scientists have to assess the relative
384 weight of these criteria when deployed together. Both their form and the relative
385 weight, to Kuhn’s mind, contain idiosyncratic factors. Kuhn was however at pains to
386 argue that such subjectivity does not render theory choice irrational or a mere matter of

¹¹ The underdetermination argument also implies that there are, strictly speaking, no crucial experiments in the sense envisaged by Newton. (See 3.3.)

387 taste, but instead points to its irreducibly factual nature. Historians often find an
388 increasing unanimity of individual choices in a certain field. Such factual unanimity in
389 the decisions of individual scientists does not establish rationally binding criteria for
390 theory choice. Instead of being rules of an algorithm, the criteria of theory choice
391 function “as values, which influence it. ...; they do specify a great deal: what each
392 scientist must consider in reaching a decision.” (1977, 362)

393
394 Heather Douglas has recently proposed a finer-grained account in order to restore the
395 separation between epistemic and pragmatic cognitive values. She distinguishes (i)
396 minimal criteria applied to the theory per se, among them internal consistency; (ii)
397 minimal criteria applied to the relation of theory and evidence, among them empirical
398 adequacy; (iii) desiderata applied to theories per se, among them scope, simplicity, and
399 potential explanatory power of a theory that largely “fall under the rubric of the
400 fruitfulness of the theory”. (2013, p. 800); (iv) desiderata applied to the relation of
401 theory and evidence, among them being supported by a broad range of empirical
402 evidence and not being contrived to match a small domain of facts in an ad hoc fashion.
403 While the values in categories (i) and (ii) are epistemic, category (iii) contains “strategic
404 or pragmatic values” (2013, p. 800) that facilitate scientific activity). Instead, group (iv)
405 “provides assurance that our scientific claims are more likely to be reliable.” (2013, p.
406 800) Moreover: “While simplicity, scope, and explanatory power are often thought to
407 pull against each other when considering theories alone (group 3), they pull together
408 when considering a theory in relation to evidence (group 4).” (2013, 803) Pragmatic
409 criteria mainly come into play “when a scientist is deciding which theory to pursue next”
410 (2013, 804). In these practical situations, on her account, also social and ethical values
411 are considered.

412
413 Perhaps, the most important pragmatic criterion in the history of particle physics is
414 simplicity. Most influential has been the quest for a simple unified theory of all
415 fundamental forces.¹² Simplicity also stands behind particle physicists’ long-time
416 worries about the many parameters that are needed to make the SM empirically
417 adequate. Both employments of simplicity are not necessarily identical. As Baker (2013)
418 rightly observes, it is quite challenging to pin down the notion precisely. We are
419 following here his distinction into “syntactic simplicity (roughly, the number and
420 complexity of hypotheses), and ontological simplicity (roughly, the number and
421 complexity of things postulated)” (2013, 4). Most (but not all) authors call the former
422 elegance, the latter parsimony. Both aspects of simplicity may come into conflict, for
423 instance, if theoretical elegance suggests the introduction of additional entities. Nolan
424 (1997) discusses the postulation and discovery of hitherto unobserved particles in the
425 analysis of cloud chamber pictures. Also model builders in BSM physics are prone to
426 postulating such entities; for instance, the introduction of supersymmetric partners to
427 all fundamental particles adds an additional symmetry at the expense of additional
428 entities – and, it seems, additional parameters.

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430 From the interviews and questionnaires we will attempt to conclude how particle
431 physicists understand and weigh pragmatic and epistemic criteria and how they assess
432 the criterion of naturalness.
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¹² Note that some philosophers – and some physicists, perhaps – would argue that there are metaphysical reasons or some a priori principle of rationality that imply that a simpler theory is more likely to be true. Such questions are, however, outside the scope of the present paper.

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435 **3.3 Making experiments crucial**

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437 The second classical philosophical problem relevant for the present paper concerns the
438 interaction between theory (or models) and experiment. LHC's first task consisted in a
439 definitive and crucial test of the SM, i.e. to find the Higgs boson or exclude its existence.
440 Since the Higgs boson is an essential part of the SM and since LHC would cover the
441 whole energy scale relevant for direct searches, not finding it should have eventually
442 implied that the SM was refuted. Thus, a large majority of elementary particle physicists
443 interviewed expressed the conviction that a Higgs discovery or non-discovery at LHC
444 represented a crucial and decisive test for the SM.

445

446 This widely shared conviction among physicists prompts the question whether the
447 Higgs discovery represented a crucial experiment in a philosophical perspective? Let us
448 take a closer look. The term 'crucial experiment' originated with Francis Bacon and
449 became influential through Newton and his demonstration that sunlight consisted of
450 rays exhibiting different behaviours. A crucial experiment unambiguously and
451 definitively decides the truth of a hypothesis or between rivaling hypotheses. Pierre
452 Duhem objected on the basis of the underdetermination argument: experimental data
453 never uniquely determine a particular hypothesis because setting up and confirming a
454 hypothesis presupposes the correctness of many other hypotheses including the
455 theories governing the measurement devices. Within modern philosophy of science,
456 Duhem's position is often discussed under the rubrics of theory-ladenness of data or –
457 following Neurath and Quine – confirmational holism. This means that any experimental
458 result confirms or refutes both the theory or model investigated and a large set of other
459 assumptions that – typically based on previous experiments – are assumed to be true.¹³

460

461 This tradition has made scholars wary about crucial experiments. While some
462 emphasized that falsifications of a theory were more likely to be crucial experiments
463 than corroborations, Lakatos famously objected to this asymmetry and bluntly stated:
464 "No experiment is crucial at the time it is performed (except perhaps psychologically)."
465 (1974, 320) His main argument was that the assessment of each experiment can only be
466 performed against the backdrop of the entire research program it is embedded into and
467 against its competitors. Thus designating an experiment as crucial is partly a historical
468 assessment. Franklin and Perovic (2015), for one, consider the discovery of parity
469 violation as a crucial experiment, while the discovery of CP-violation left several
470 alternative explanations standing that were only subsequently excluded. These were not
471 all possible alternatives, such that Franklin and Perovic consider CP-violation a
472 'persuasive experiment' that was followed by a "pragmatic solution of the Duhem-Quine
473 problem." (2015, 84) In the case of the Stern-Gerlach experiment the diagnosis of
474 cruciality underwent several changes. By discovering the space quantization predicted
475 by the Bohr-Sommerfeld quantum theory, it became a crucial watershed between
476 classical and quantum physics, but not by confirming the latter theory. For what Stern
477 and Gerlach actually measured was a new quantum phenomenon, electron spin, that
478 was only postulated after the experiment. Thus, the experiment "was regarded as crucial
479 at the time it was performed, but, in fact, wasn't. ... A new theory [quantum mechanics]
480 was proposed and although the Stern-Gerlach result initially also posed problems for
481 the new theory, after a modification of that new theory [the integration of spin], the

¹³ Note that Duhem did not exclude that experiments could actually be crucial. But this could not be inferred from the data as inductivists had believed, but required the *bon sens* of the physicists involved. While *bon sens* might have been a useful notion in Duhem's days, it seems to us too vague for experiments in particle physics. At best one might take it as an umbrella term for the detailed set of experimental strategies given by Franklin (2013).

482 result confirmed it. In a sense, it was crucial after all. It just took some time.” (Franklin &
483 Perovic 2015, 40-41)¹⁴

484

485 It is important to note that the Duhem-Neurath-Quine thesis is an in-principle argument.
486 It has been notoriously difficult (cf. Stanford 2006) to find cases where the
487 underdetermination was not eventually resolved. While this resolution, in the case of
488 optics, took more than a century, in many other cases transient underdetermination has
489 been resolved by experiments explicitly designed to do so or persisted only because the
490 precision needed for a resolution was not yet achievable. Those experiments ending a
491 period of transient underdetermination are then considered as crucial or render the
492 original experiment crucial. Thus it seems, more generally, that the term crucial
493 experiment not only means that an experiment brought a decisive confirmation or
494 refutation of a theory or model, but also that, in historical reconstruction, it actually
495 represented an important milestone – or significant turning point. Moreover, to Kuhn’s
496 mind, crucial experiments “are vehicles for the transmission of criteria of choice.” (1977,
497 360) This also suggests that the question as to whether the Higgs discovery was a crucial
498 experiment for the SM involves a broader claim about the history of the SM and its
499 experimental tests. Such an embedding would also take care of some of Lakatos’s
500 concerns.

501

502 In a modern particle detector, physicists try to keep the intrinsic theory-ladenness (or
503 model-ladenness) at bay and avoid circularity by precision measurements and by
504 applying a variety of rules drawn from previous experiments. To begin with, the very
505 identification of a new particle is based on extremely precise empirical data about the
506 properties of all other particles occurring in the scattering experiments. Embedding
507 these into computer simulations, the background of known physics is modelled in such a
508 way that new particles – predicted or unpredicted ones – can be identified by
509 discriminating them against statistical fluctuations of the background. This statistical
510 discrimination accounts for residual model and detector uncertainties, denoted as
511 systematic uncertainties.¹⁵ Thus, modern elementary particle physics grants Duhem’s
512 in-principle argument, but effectively deals with it by the very method of
513 experimentation.¹⁶ Hence our case study may indicate a possible qualification of
514 Duhem’s objection against crucial experiments.

515

516 There are cautionary tales, though, that show that the strategies applied by particle
517 physicists have not always worked so well as in the case of the Higgs discovery. As
518 Franklin has shown, in the long history of particle physics, there have been experiments
519 where it turned out that experimenters’ presuppositions were wrong or where it was
520 difficult to separate a purported particle from other particles (Cf. 2013, Ch. 14 & 19).
521 This has prompted authors, such as Pickering (1984), to argue that – after a period of
522 tinkering that may involve a single or multiple experiments – the eventual scientific
523 consensus is largely based on a variety of social factors including the agreement with
524 existing commitments of the scientific community. This consensus includes the question
525 as to whether an experiment has been decisive or crucial. But there are also examples

¹⁴ In philosophical discussions about quantum mechanics, spin is considered as the quantum mechanical quantity par excellence and the Stern-Gerlach apparatus as its paradigmatic experiment.

¹⁵ This is also the place where the famous 5σ criterion comes into play; cf. the “Prologue” to Franklin 2013.

¹⁶ Cf. Beauchemin’s (2017) autopsy of measurements with the ATLAS detector. Note that his concept of theory-ladenness is wider than the one typically used in the philosophical literature, where theory-ladenness represents a problem for empirical science, not a feature that can be exploited by clever experimenters.

526 that point in the opposite direction. Challenging confirmational holism and theory-
527 ladenness altogether, Bogen and Woodward (1988) have argued, at the example of weak
528 neutral currents, that one sometimes can distil the phenomena in a significant way from
529 raw data alone. Franklin (2015) understands the discovery of parity non-conservation
530 at the example of beta-decay as close to a crucial experiment in Newton's sense.

531
532 The main lesson of both the successes and cautionary tales for the present investigation
533 is, accordingly, that establishing experimental evidence and whether an experiment is
534 conclusive or even crucial is largely a factual question that involves different time scales.
535 Acquiring precision data represents a long-term process that involves previous
536 experiments and is continued in the experiment itself. The actual discovery of a particle
537 instead represents a precisely dated event; scientists decide after a detailed statistical
538 analysis that the evidence is sufficient – only to embark on further studies of the precise
539 properties of the particle thus discovered. As we shall see, this was also the case for the
540 discovery of the Higgs boson that extends from the initial pronouncement in 2012 to the
541 subsequent acceptance that it was indeed a SM Higgs boson.

542 543 ***4. The methods of this project***

544
545 Against the backdrop of the different experimental situations in 2011 and 2012, and the
546 various solutions of the EWSB (including the Higgs mechanism) proposed by theoretical
547 model builders, our project investigated the general attitudes and preferences of the
548 LHC physicists by quantitative and qualitative empirical methods. In questionnaires and
549 interviews LHC physicists were asked about their views of the status of particle physics,
550 their anticipation of what the LHC will ultimately find, and the ways experimentalists
551 and theorist interact.

552
553 Questionnaires were sent via e-mail to some 15000 physicists related to particle physics
554 in August 2011 and September 2012. Each contained eight groups of questions, which
555 were to be answered by either assigning a subjective probability for the correctness of a
556 certain statement or by choosing an answer among various options. These were (i) the
557 probability to find the SM Higgs particle (respectively confirm a minimal SM Higgs), (ii)
558 the possible explanations of new physics found at LHC, (iii) the preference for certain
559 BSM models independently of the LHC results, (iv) the criteria guiding the researcher's
560 answers to this question, (v) the most critical flaws to the SM, (vi) the signatures in
561 which LHC would most likely find new physics, (vii) general features of particle physics
562 for whose understanding LHC will be most important, (viii) the interaction between
563 experimentalists and theoreticians.

564
565 A large fraction of the questions within the above mentioned groups were identical for
566 the two periods, however, from experience with the first one, modifications were made
567 for the second questionnaire. In the first questionnaire some answers could be ranked
568 up to four times. This was considered less meaningful for the second questionnaire and
569 modified. In 2012, a question was also added to address the Higgs boson candidate. The
570 precise list of the questions can be found in appendix 2.

571
572 The sample of physicists was both in 2011 and 2012 obtained from the INSPIRE data
573 base (Dallmeier-Tiessen, S., Hecker, B., Holtkamp, A; INSPIRE) maintained centrally at
574 CERN. This data base is established by surveying journals, conferences, books, theses
575 etc. in the pertinent fields and listing all authors. For the purpose of the questionnaire,
576 authors in the categories 'hep-ph' (phenomenology), 'hep-th' (theory), 'hep-ex'
577 (experiment) were contacted. In total this amounted to some 15000 authors. About half
578 of the authors are theorists belonging to about the same amount to either the 'th' or 'ph'
579 category, the other half experimentalists. Taking into account that some 8000

580 experimental physicists are directly involved in the LHC experiments, with an additional
581 number of several thousand theorists, our sample included probably almost all
582 physicists actively working on LHC physics. Certainly, some physicists on the list were
583 somewhat remote from LHC experiments or theory, e.g. mathematical theorists or
584 accelerator physicists, but also some retired physicists or those who left the field. It is
585 difficult to assess, how large a fraction this was.

586
587 The anonymous replies were collected and statistically evaluated at Wuppertal. There
588 were 1437, respectively 903 replies to the two questionnaires, which means that around
589 10% of all physicists involved in the LHC have taken part in our survey. From the
590 beginning, the sample reached by the questionnaire was not aimed to be truly
591 representative. The regional distribution is consistent with LHC data, and also the
592 fraction of theorists and experimentalists agrees with the fraction in the total sample.
593 Yet, there are discrepancies as regards seniority: only few PhD students (<5% of the
594 replies) have answered the questionnaires, whereas they amount to about a third in the
595 LHC experiments. In the following, the replies were considered separately for
596 experimentalists and theorists because this promised some interesting insights. In
597 particular, the comparison of the replies before and after the discovery should indicate
598 certain trends in the thinking of the LHC physicists.

599
600 In addition to the questionnaires, 9 (6) LHC physicists were interviewed around April
601 2011 (September 2012). Both groups included experimentalists from different LHC
602 experiments and theorists. Furthermore it was attempted to cover a wide range of
603 interests and responsibilities within the LHC project. There is only a small overlap
604 between the physicists in the two rounds; this was done deliberately in order to obtain a
605 broader picture. The physicists interviewed and their respective roles at the time of the
606 interviews are listed in Appendix 2. In the following discussion, no names will be
607 assigned to the respective citations.

608
609 Each interview took about an hour. A few topics were addressed in every interview, for
610 instance: in 2011, the prospects of a Higgs discovery, the perceived status of super-
611 symmetry, and the chances to find new physics; in 2012, the impact of the Higgs
612 discovery on the interviewee's research. On the other hand, the interviews were kept
613 flexible to better understand the reasoning and preferences of each interviewee. This
614 included, depending on the answers of the counterpart, also questions about the work
615 environment, the methods of research, which outcome is expected at the LHC and why,
616 and which outcome would be preferred on theoretical or pragmatic-aesthetic grounds.

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619 ***5. The physicists' expectations in autumn 2011***

620

621 At the beginning of our empirical study, the physical situation was characterized by an
622 excellent performance of the LHC and its experiments. The year 2011 brought an
623 unexpectedly large amount of data at the energy of 7 TeV. Based on this understanding,
624 the LHC physicists performed simulation studies predicting that the whole range
625 pertinent to the mass of a Higgs boson could be covered at the LHC within two years. On
626 the other hand, although a broad range of searches for new effects had been performed
627 by fall 2011, no sign for any of the many postulated extensions of the SM had been
628 found. In particular, no indication for Supersymmetry was observed. Supersymmetry
629 had been highly favoured by theorists and it was predicted that its particles could be
630 detected shortly after the LHC launch. Supersymmetry is the only BSM model that
631 provides a strict constraint on the highest allowed mass of the Higgs boson (of about
632 130 GeV). The sensitivity of many of these searches for new physics reached the energy

633 scale of about 1 TeV, at which the naturalness problem should have been resolved
 634 before the corrections become too high.

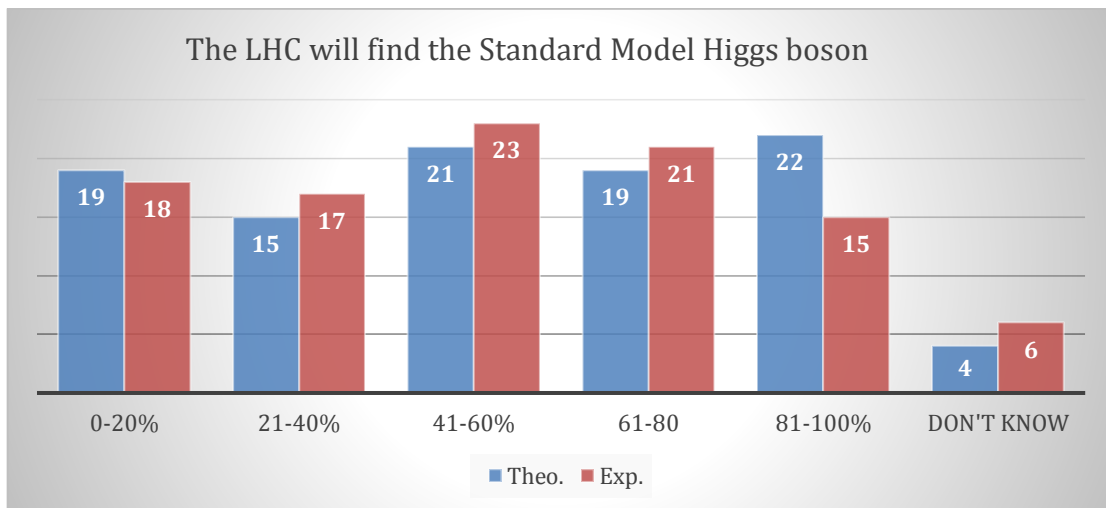
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 636 **5.1 Outcome of questionnaires**
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638 In total 1435 physicists answered the questions, with the number of theorists (769) and
 639 experimentalists (696) being about the same. The number of replies to each of the
 640 questions differed only by a small amount. Assuming multinomial distributions and an
 641 outcome for an answer of 50%, these numbers imply a typical error margin on the
 642 answers of 1.5% for the total sample and 2% for each subgroup. The precise uncertainty
 643 depends on the number of answers given; the fewer there are, the larger is the relative
 644 uncertainty. Where relevant, the exact uncertainties will be provided.

645
 646
 647 **5.1.1 The importance of the origin of mass**
 648

649 The high expectations that physicists had in the LHC to understand the mechanism of
 650 mass generation become most apparent in the replies to a question about the
 651 importance of LHC results for several key problems of current physics. Participants
 652 were asked whether they fully agreed, somewhat agreed, were undecided, somewhat
 653 disagreed, or fully disagreed with the statement: *‘LHC results will be very important to
 654 understand ...’*. Close to 50% (48%/49% of the theorists/experimentalists) chose to
 655 ‘fully agree’, and close to 80% (77%/80%) at least ‘somewhat agreed’ on the importance
 656 of the LHC for the ‘origin of mass’. Comparable results were obtained for two other
 657 topics from the SM, ‘strong interactions’ and ‘flavour physics’, while the outcomes for
 658 BSM physics were much lower. The as of then only undiscovered element of the SM was
 659 accordingly given the highest priority among all the potential features that could be
 660 found at the LHC.

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 662
 663 **5.1.2 Expectation on finding the Higgs Boson at LHC**
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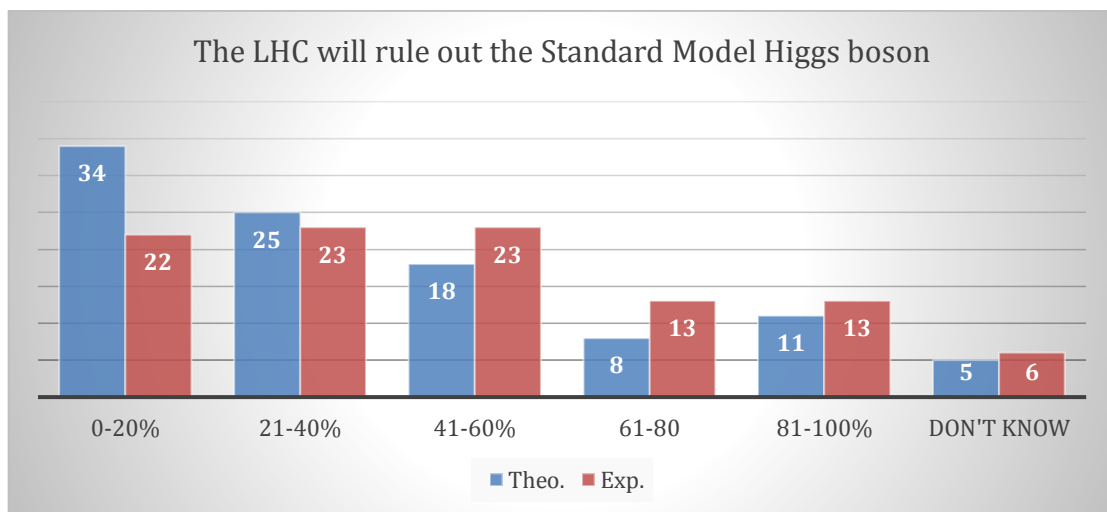


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 667 *Fig.1 Percentage of answers of theorists (blue) and experimentalists (red) assigning probabilities in*
 668 *intervals of 20% on the chance that the LHC will find a Standard Model Higgs Boson (Questionnaire*
 669 *of 2011)*

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672 Given the importance of the origin of mass and the fact that the LHC was expected to
 673 provide the ultimate sensitivity for finding the SM Higgs boson the questionnaire asked
 674 physicists: *‘What is your personal estimate of the probability [that] the LHC will find the*
 675 *Standard Model Higgs boson?’*. This (subjective) probability was to be given in terms of
 676 percentage intervals of 20%, which represented the respondent’s current degree of
 677 belief. The replies did not reveal any strong tendency towards either discovery or non-
 678 discovery, but instead were rather uniformly distributed over all probability values (see
 679 Fig. 1). Some 35% (34% of theorists/35% of experimentalists) assigned a chance of at
 680 most 40% that the SM Higgs boson will be discovered, whereas only a few more
 681 (41%/36%) expected it to be found with 60% probability or more; the values for more
 682 than 80% probability were even lower (22%/15%). Thus, although simulation results
 683 showed that the LHC, in virtue of its foreseeable performance, had the potential to find
 684 the SM Higgs boson if it at all existed, a large fraction of LHC physicists assumed that it
 685 would not be found. These assessments were largely identical for experimentalists and
 686 theorists.

687
 688 A second question addressed the *‘personal estimate of the probability ... that the LHC will*
 689 *rule out the Standard Model Higgs boson’*. In this case 59%/46% of the
 690 theorists/experimentalists considered the probability low (i.e. smaller than 40%). On
 691 the other hand, only 19%/26% (uncertainty about 2.5%) estimated that the SM Higgs
 692 boson could be ruled out with high probability (i.e. larger than 60%). Low probability
 693 here means either that the SM Higgs boson will eventually be found or that a candidate
 694 is found whose properties cannot be measured precisely enough to rule out other
 695 interpretations. High probability instead means that the LHC will be able to definitively
 696 rule out the SM Higgs particle because there is no such particle or it will find one or
 697 more candidates that accomplish mass generation with properties different from the SM
 698 expectations. The responses showed that, in 2011, theorists were more sceptical about
 699 the LHC to rule out the SM Higgs boson than experimentalists.
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 705
 706 Fig.2 Percentage of answers of theorists (blue) and experimentalists (red) assigning probabilities in
 707 intervals of 20% on the chance that the LHC will rule out a Standard Model Higgs Boson
 708 (Questionnaire of 2011)
 709
 710

711 Although the two last questions are closely connected, there are subtle differences that
712 lead to somewhat different replies. Firstly, the fraction of physicists that assigned an at
713 least 60% probability to *find* the SM Higgs boson is smaller than the fraction of
714 physicists who assigned an at least 60% chance that it will *not be ruled out*. Secondly,
715 whereas the answers of theorists and experimentalists were rather consistent with the
716 first question, a significantly larger portion of theorists than experimentalists
717 considered it unlikely that the SM boson will be ruled out.

718
719 The first difference is probably related to the much stricter requirement to confirm not
720 only the existence of a new particle, but to determine all of its properties to a precision
721 that allows one, e.g., to distinguish it from alternative models of EWSB. Especially in the
722 case of a more complicated Higgs group structure (as favoured by many physicists – see
723 below) it will be more difficult to unambiguously identify the particle to be a SM Higgs
724 boson than to rule it out. How-to interpret the differences between experimentalists and
725 theorists is more difficult. In general, the replies – and the interviews below – indicate a
726 greater reluctance of experimentalists to commit themselves to what their data will
727 finally reveal.

728
729 This exemplifies the first lesson from the 2011 questionnaire. In contrast to public
730 perception, interpreting the newly found particle as being the SM Higgs boson was not a
731 simple yes/no alternative to be decided promptly. Physicists were largely prepared for a
732 more complicated outcome that achieved all that the SM Higgs mechanism was designed
733 for. Thus, finding a particle consistent with a SM Higgs would only be the first step in
734 further investigating the properties of the new particle. The second conclusion from
735 these two questions is that there existed a substantial scepticism among physicists as to
736 the existence of a SM Higgs at this stage. This means that, although the LHC was
737 expected to cover the whole allowed mass range for the SM Higgs particle, the LHC
738 community was rather undecided if it exists. Taking both lessons together shows that
739 there was no significant asymmetry in physicists' expectations between refuting and
740 confirming the SM.

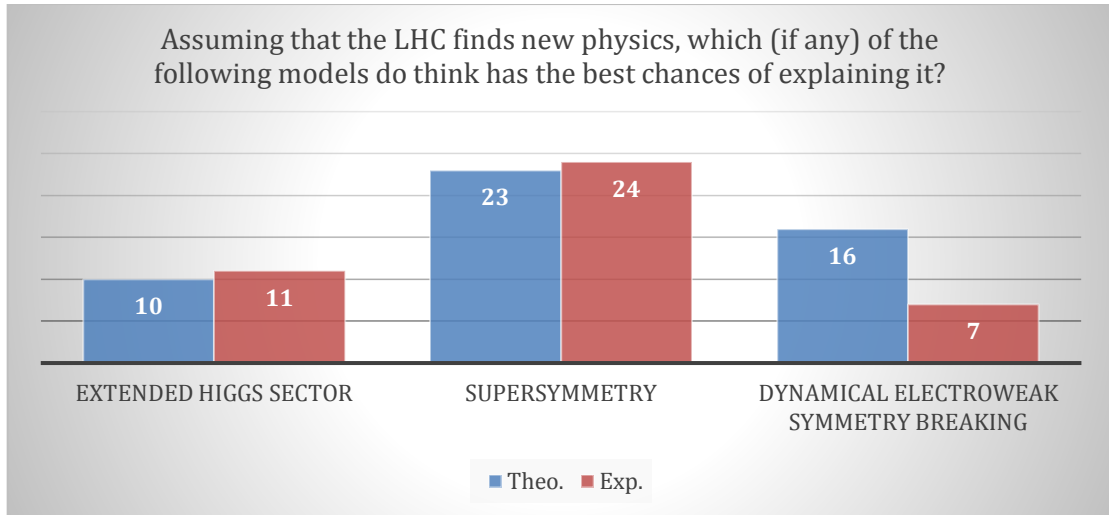
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743 ***5.1.3 Expectations on various EWSB models***

744

745 The questionnaire also addressed potential scenarios for 'new physics', i.e. a process or
746 particle that is not part of the SM. Physicists were asked *Assuming that the LHC finds*
747 *new physics, which (if any) of the following models do you think has the best chance of*
748 *explaining it'*. The physicists had two ranked choices; here we will typically just provide
749 the first choice, the second gives fairly similar results. Several models, including those
750 rather remote from EWSB, like string theory, extra spatial dimensions, or 4th generation
751 models, were also considered. (cf. Appendix 2) In the following, we focus on the three
752 most popular groups that were also those most closely related to EWSB. (Fig.3)

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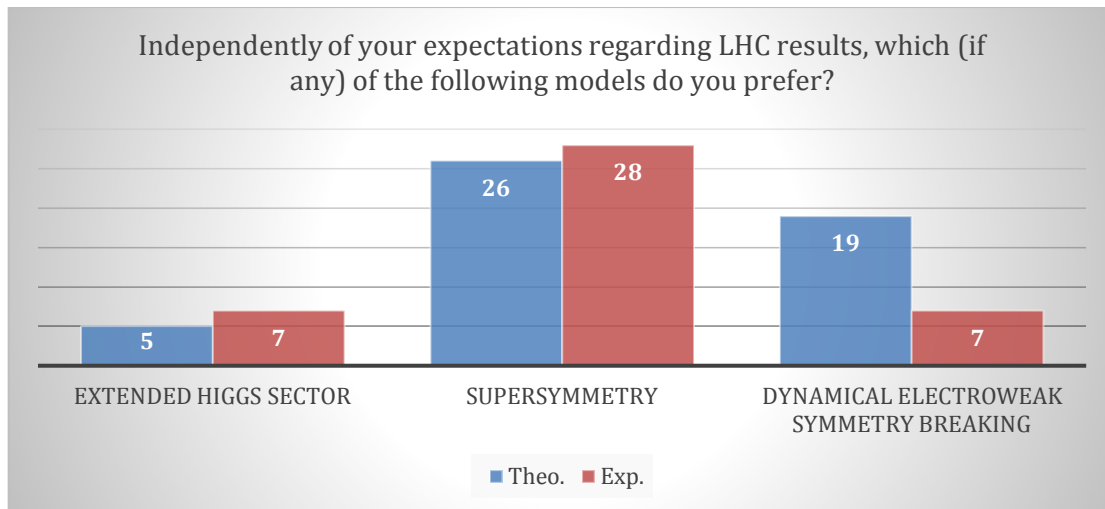
Fig.3 Percentage of answers of theorists (blue) and experimentalists (red) on the most probable model that the LHC might find. Only answers with relation to the electroweak symmetry breaking are given, the remaining 51/58% refer to different models (Questionnaire of 2011)

Fractions of 10/11% of theorists/experimentalists opted for an extended Higgs sector, i.e., more than one Higgs boson. About twice as many (23%/24%) voted for the favourite theory of Supersymmetry, which also requires an extended Higgs sector. Therefore, about one third of physicists were expecting new physics in extended Higgs sectors either without or within the context of an explicit model. Both of these answers assume Higgs bosons and expect them to be elementary as the SM Higgs. As mentioned above, one of the Higgs bosons in the extended sector might have properties very similar to the SM Higgs.

In addition a sizeable fraction of theorists (16±1.3%) expected a dynamically generated electroweak symmetry breaking, leading to a composite scalar particle with several properties that are distinctively different from the SM Higgs boson. As discussed in Sect. 2.3 at least the historically first such model, Technicolour – a model that also contained the least additional assumptions –, had been strongly disfavoured by data. This might be the reason why only 7(±1)% of the experimentalists chose this option.

The follow-up question (Fig. 4) was ‘*which preference*’ [physicists] have ‘*independently of the expectations regarding LHC results*’, i.e., irrespective of experimental constraints from previous experiments and the sensitivity of LHC itself. Whereas the replies alluding to an extended sector remained rather the same as to the previous question, dynamical EWSB was now even more favoured by theorists (19%), while the fraction of experimentalists preferring this was unchanged at 7%.¹⁷

¹⁷ Although the present paper focuses on EWSB, it is worth noting that the largest percentages for new physics are obtained for the option ‘None of those, but something totally unexpected’ (28% for both theoreticians and experimentalists). The perspectives for new physics will be discussed in a separate paper that will also analyse some of the models neglected here.



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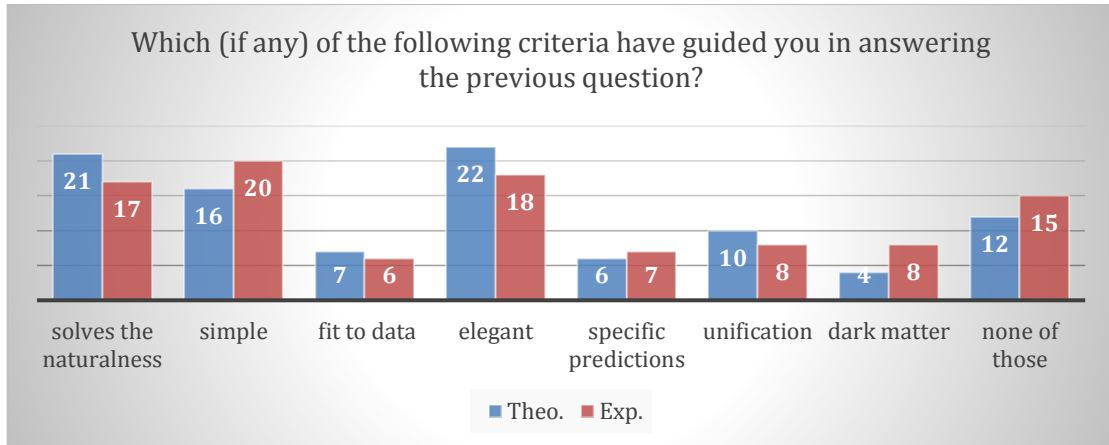
Fig.4 Percentage of answers of theorists (blue) and experimentalists (red) on the preferred model for physics beyond the Standard Model. Only answers with relation to the electroweak symmetry breaking are given, the remaining 50/58% refer to different models (Questionnaire of 2011).

The difference between the answers as to the importance of dynamical EWSB as a vision for the LHC data, on the one hand, and in a general perspective, on the other, shows that physicists' preferences are also guided by nonfactual and non-epistemic aspects. The perceived 'beauty' of a theoretical framework, or other pragmatic values of theory preference, weigh significantly relative to the chances of confirmation or disconfirmation by soon-to-be-available experimental data.

5.1.4 The importance of the naturalness criterion

The question as to the preferred model was followed by the question 'which (if any) of the following criteria have guided you in answering the previous question?'. Four ranked choices were allowed (Fig. 5). Considering only the first choice, the criterion that a model 'solves the naturalness problem' was preferred by 21%/17%. It is thus considered as important as the classical pragmatic, or rather aesthetic, criteria of 'elegance' (22%/18%) and 'simplicity' (16%/20%)¹⁸. More 'factual' criteria like the model 'will provide a better fit to the data', or 'makes specific predictions' or even 'has a candidate for dark matter' are much less considered (each one below 10% for both experimentalists and theorists).

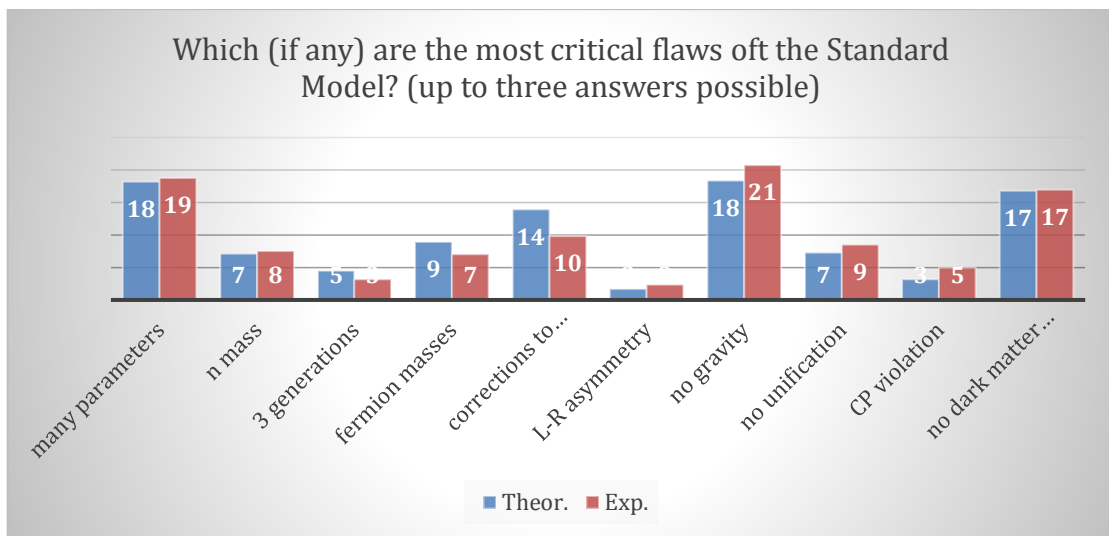
¹⁸ It should be noted that physicists were not given any specific 'definition' of these concepts; hence the replies were based on the intuition of the individual physicist. We do not consider this as too problematic for our purpose, not least because many philosophical authors who provide a definition - cf. Baker 2013 discussed in Section 3.2 - emphasize that the terminology is all over the place.



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Fig.5 Percentage of answers of theorists (blue) and experimentalists (red) on the criteria to choose the preferred model. (Questionnaire of 2011).

Physicists were further asked ‘what (if any) are the most critical flaws of the Standard Model’, and could make up to three unranked choices (Fig. 6). Indeed the problem of ‘quadratic divergences in corrections to the Higgs mass’, causing the naturalness problem, was mentioned often by theorists (14%), while only by 10% of the experimentalists (statistical uncertainty of difference 2.2%). However, quadratic divergences are considered less of a flaw of the SM than its many parameters (18%/19%), the absence of gravity within the Standard Model framework (18%/21%), or that it does not include a Dark Matter candidate (17%/17%).



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Fig.6 Percentage of answers of theorists (blue) and experimentalists (red) on most critical flaw of the Standard Model (Questionnaire of 2011). The three answers were summed up and normalized.

Both of these questions refer to SM properties that point beyond its limits. But they do so from a somewhat different perspective. The first had asked for the motivations of model preferences in view of possible evidence in the near future, the other one was referring to general flaws, irrespective of the chances to soon find solutions. In both questions naturalness, respectively quadratic divergences, scored within the top group of the list and matched their respective counterparts, the pragmatic values of preference simplicity and elegance, and respectively among the flaws, the many parameters, a traditional complaint about the SM’s lack of simplicity. However, the differences in the

841 relative weights for other elements pointing BSM, e.g. for Dark Matter, are significant. To
842 our mind, this has to do with the different perspectives of the questions. There are
843 several proposals of physics BSM, however no universally agreed upon Dark Matter
844 candidate. Hence Dark Matter is not a pivotal aspect for the near-term perspective of
845 LHC; thus its particularly low score among experimentalists. However, it is a significant
846 flaw of the SM, albeit it may be only solved in the longer term. Naturalness, instead, is of
847 immediate relevance to problems of model builders and guides expectations for BSM at
848 the LHC. Experimentalists and theorists largely agree in this attitude.

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851 **5.2 Responses in interviews**

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853 The questionnaires were complemented by interviews with nine theorists and
854 experimentalists¹⁹. Overall, their statements were consistent with the outcomes of the
855 questionnaire. Yet they provide a deeper insight into the reasoning of elementary
856 particle physicists at the time. In particular, they illustrate the rather diverse set of
857 attitudes and the broad variety of expectations among the physicists. The following
858 selected quotes are related to the mechanism of EWSB.

859

860 **5.2.1 Crucial, Long-Awaited, but Uncertain: Does the Higgs boson exist?**

861

862 The interviews were conducted at a time, when the allowed mass range for the SM Higgs
863 boson was rapidly shrinking and the experiments were close to completely covering the
864 remaining parameter space. No wonder that in all interviews the suspense whether the
865 Higgs boson would be discovered or some alternative mechanism of EWSB would
866 become visible, played a pivotal role. Here are two typical examples. One physicist
867 stated that a discovery of the Higgs boson would amount *,to a revolution ... We*
868 *understand the mass, we understand a lot of things'*. Another one assessed the *,Higgs*
869 *problem'* as a *,key question'*. The measurement of its mass should *,be a very important*
870 *clue to what sort of theory maybe goes beyond it'*.

871

872 Although accordingly an experimental verdict, a crucial and long-awaited test for the
873 SM, was in sight, opinions diverged on what its outcome would ultimately be. In this
874 respect, the answers span a large range. At one end of the spectrum, an experimentalist
875 argued that in this situation one should *,press theorists'* to answer the question: *,if there*
876 *is no such thing [the Higgs boson], then what?'*. Being a few femtobarns away from the
877 final call about the Higgs boson, this represented the mood of some physicists that one
878 had to move to a *,provocative question'*. The interviewee even identified a *,change of*
879 *mind-set'* because the - to date unsuccessful - experimental searches led to a general
880 doubt whether the Higgs was a *,done deal''*.

881

882 Other interviewees emphasized the personal and even emotional aspects of this
883 increasingly pressing insecurity. E.g. *'I don't know, I don't know': 'we have been waiting so*
884 *long for this, there is ... no concrete criterion to really judge whether [it] is more or less*
885 *likely and emotionally, needless to say, I would like to see that as soon as possible, so I hope*
886 *it's more likely that it comes out, but it is purely emotional because I do not want to wait*
887 *another five years, but I have no idea.'* Another interviewee diagnosed a change of
888 attitude. Previously colleagues might have argued that it *'is much more exciting to see*
889 *nothing. But it was before LHC started. Now that things work so well, people are sure that*
890 *the Higgs will be found in 2012, 2013, public opinion you know changed dramatically'*. It is
891 *'psychologically very interesting'*. This strong desire to *,find something'* also reflected the
892 increasing gap between the enormous success of the SM predictions during the past 40

¹⁹ For the list of names, see the table in Appendix 1.

893 years and the fact that quite a few still unsolved questions remained.

894

895 Other experimental interviewees were rather optimistic to find the Higgs boson. One
896 stated '*I would be more surprised if they don't find the Standard Model Higgs because I*
897 *think that the Standard Model with the Higgs mechanism at the moment is one of the best*
898 *ways of explaining the masses of the gauge bosons and particle masses, so I would really*
899 *like the Standard Model like Higgs'*, or more pronounced '*I will be surprised if it is not*
900 *found. I think it will be found at 120 GeV.'* (This was in accordance with the indirect and
901 direct limits at that time.)

902

903 The attitude, according to which the Higgs is 'the best way' to explain masses had
904 already been strengthened by indirect measurements disfavouring otherwise preferred
905 alternative models. It also becomes apparent in replies from a theorist, who held that
906 '*there is a lot of circumstantial evidence in favour of that [i.e. the Higgs boson], the case is*
907 *not proved but that might well happen'*. This factual statement, however, is immediately
908 put into perspective, when the interviewee points to his preference '*I would find a lot of*
909 *intellectual attraction in the dynamical symmetry breaking models'*.

910

911 **5.2.2 Is the Higgs mechanism attractive?**

912

913 While the expectation as to the possible discovery of the Higgs boson was an issue of
914 considerable suspense at that time, the motivations to expect or reject the Higgs
915 mechanism, differ among the physicists. Already in the above statements, it became
916 apparent that the mechanism, even if expected, was regarded with some reservations.
917 There were several values of theory preference in play.

918

919 One theorist held that the Higgs mechanism is also disfavoured *,because of its minimal*
920 *predictive power'*. Instead the alternative scenario of strong EWSB is intellectually
921 favoured. '*Whereas the dream would be, in a dynamical theory of electroweak-symmetry*
922 *breaking ..., there is at least a conceivable possibility of making definite predictions,*
923 *however they should turn out."* This requires a '*somewhat bigger theory'*. The scepticism
924 is also shared by experimentalists. One stated drastically. *the Higgs is a totally ad hoc*
925 *thing. If the Higgs is not there, it will not surprise me.'* He argued that *,people had faith*
926 *in it the way people have faith in God'*. Another experimentalist held, that even if the
927 '*Higgs will be found, ... the Higgs mechanism seems not elegant'* and there are '*very*
928 *attractive theories without the Higgs'*.

929

930 In fact, only a few physicists interviewed emphasized the broader virtues of the Higgs
931 boson beyond merely giving a solution for one specific problem. One theorist focussed
932 on its role in the more encompassing theory of Supersymmetry, which as mentioned
933 gives an upper bound of the Higgs mass. It would be '*very disappointing to find Higgs at*
934 *mass compatible with SM at high energies [above 130 GeV]'*. *,If the Higgs boson is light as*
935 *suggested by the data [i.e. indirect measurements and left-over phase space masses], then*
936 *presumably super-symmetry is a prototype of such a weakly interacting extension of the*
937 *standard Higgs mode'*, i.e. the virtue of the Higgs mechanism is its accordance with a
938 larger and generally favoured theory. On the other hand the interviewee points out, that
939 the favoured variant of supersymmetry, has been so tightly tested without finding
940 anything. Therefore, one finds oneself in '*a weird situation'*.

941

942 Moreover, one theorist rejected the statement that the Higgs mechanism is complicated
943 and ad hoc, but emphasised the virtue of introducing spontaneous symmetry breaking
944 into particle physics in general. The Higgs discovery would then be seen as something
945 new '*in the sense of new particles, but it is a break-through since you have the*
946 *experimental test of spontaneous symmetry breaking'*. Moreover this general idea would

947 be ‘not immediately thrown away’, if the Higgs boson would not be found.

948

949 **5.2.3 The problem of naturalness**

950

951 Several interviews stressed the value of naturalness as a pragmatic guideline. Yet as
952 regards its aesthetic aspects, opinions differed. One theorist became a proponent of
953 Supersymmetry once it was shown to solve the naturalness problem *,so for me the big,*
954 *sort of change in my world view came when people pointed out that super-symmetrical*
955 *particles could potentially control the quantum corrections and make the theory more*
956 *manageable.’* Another theorist, who was asked whether the naturalness or the hierarchy
957 problem were serious, answered more cautiously: *,now to assess this, one goes back to*
958 *these convictions somehow that the progress of science is always driven by an aesthetic*
959 *judgement that goes beyond mechanical relations between formulas, equations and the*
960 *need to see beyond. In other words, when you see some recurrence, when you see some*
961 *“accident”, it is natural for a scientist to consider the possibility that it is not an accident*
962 *but there is something beyond and then this accident becomes natural. Now, this is not*
963 *always correct, there are many accidents that we witness around that are not driven by the*
964 *first principles but just accidents. So in that respect one can be wrong, but for the issue of*
965 *naturalness, all of it, so called problems of the standard model, the picture is quite*
966 *compelling.’* Only one experimentalist was explicitly asked about naturalness. Again,
967 there was no strong commitment, but instead it was *‘take[n] easy, it is a matter of taste’*.
968 Note that the interviewees did not distinguish between naturalness, fine tuning of the
969 quantum corrections, and quadratic divergences.

970

971

972 **6. The physicists’ response to the discovery of a Higgs candidate**

973

974 A year after the first questionnaire was sent out and the interviews had been performed,
975 a sufficient amount of data was collected by the LHC experiments to provide the desired
976 sensitivity for a SM Higgs boson in almost the whole remaining mass range. Indeed, in
977 July 2012, the observation of a new boson was announced. Since the signatures were
978 consistent with the expectations, there was a very broad consensus that this particle
979 was a very strong candidate for a SM Higgs. However, the properties known by then
980 were few, and the precision of the measurements was still marginal²⁰. The simultaneous
981 searches for new effects BSM remained inconclusive, although the mass reach and
982 sensitivity was extended.

983

984 Shortly after the announcement, a new questionnaire was sent to the same mailing list
985 and a new round of interviews was performed. One of the main aims was to understand
986 if, respectively how, the views and expectations of physicists had changed.

987

988 **6.1 Outcome of the Questionnaire in 2012**

989

990 The second questionnaire was sent out in September 2012. To a large part, the
991 questions were identical to those of the first questionnaire. Slightly fewer physicists
992 than in 2012 replied, among them 464 theorists and 439 experimentalists. The typical
993 statistical uncertainty in the replies is therefore 1.7% for the whole sample and 2.4% for
994 each of the subsamples. The relative uncertainty of the answers between the two
995 questionnaires depends on whether the same or different physicists replied. In the

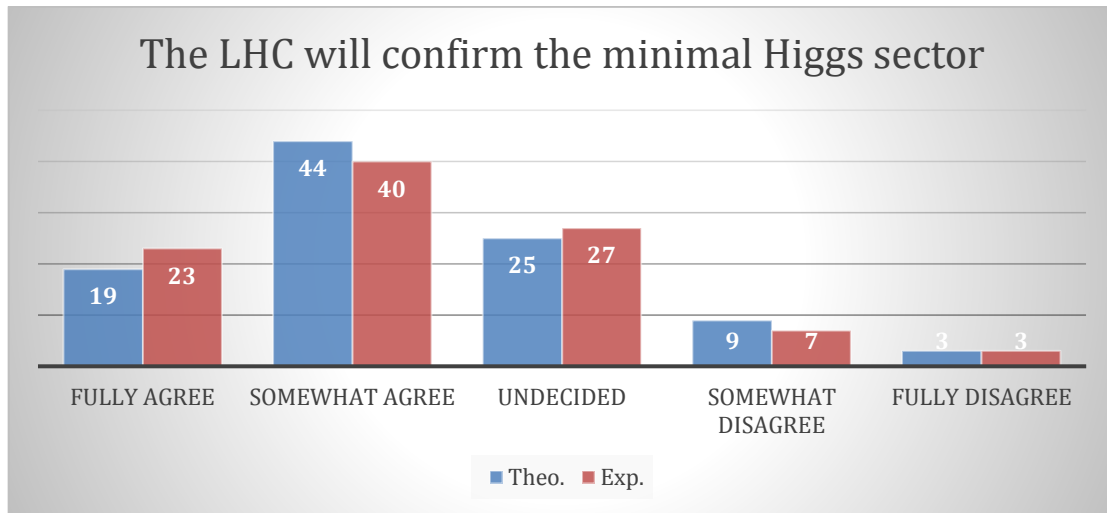
²⁰ It was only half a year later, after more data became available and more studies had been made that the particle lost its status of being a candidate and was indeed considered a Higgs boson. This became apparent in a CERN press release [CERN press office, 2013] in which recent results were summarized.

996 former case the relative uncertainty would be very small, in the latter case some 2.3%
 997 (for the whole sample). Since the answers were given anonymously, there was no way to
 998 tell. Compared to the first round the possibility of ranked answers was restricted to a
 999 single choice only or to unranked options. The subjective degrees of belief in a statement
 1000 (cf. 4.1.1.) were rephrased as ‘fully agree’, ‘somewhat agree’, etc.

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6.1.1 What is the new particle?

Reacting to the discovery of the new particle, a set of questions was directed at its likely
 significance for the SM and beyond. The first statement to be evaluated was *‘After the
 discovery of the new particle at 125 GeV, the LHC will confirm the minimal Higgs sector’*.
 The majority of both experimentalists and theorists (63%/63%) fully or somewhat
 agreed with this statement (see Fig. 7). Compared to the first questionnaire²¹, this is, not
 surprisingly, a significant increase from the 41%/36%. Still, only 19%/23% ,fully
 agreed’ that LHC will confirm the minimal Higgs sector of the SM.



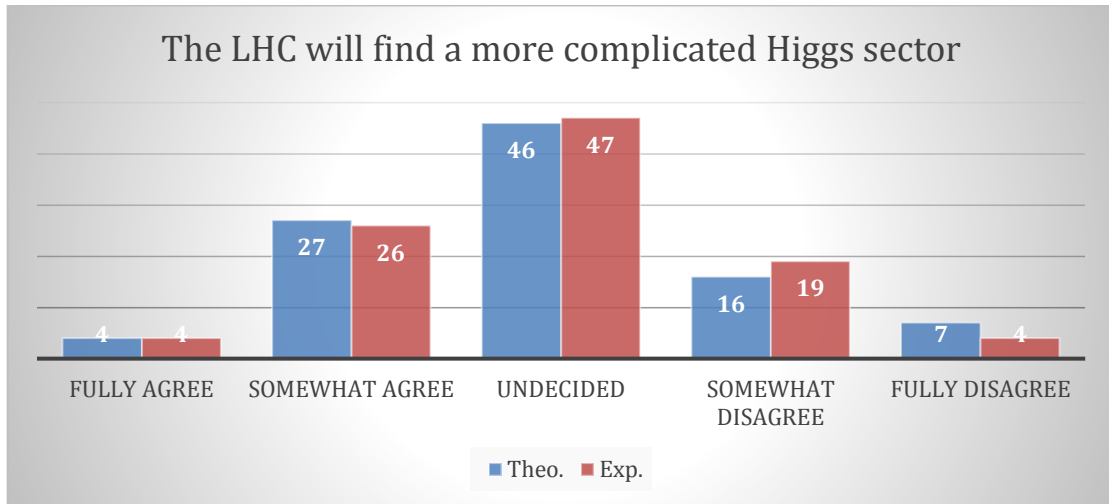
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Fig.7 Percentage of answers of theorists (blue) and experimentalists (red) assigning probabilities in intervals of 20% on the chance that the LHC will confirm a minimal Model Higgs Boson (Questionnaire of 2012)

This question combined two aspects: whether the observed particle was indeed a Higgs boson and whether it would remain the only Higgs boson, i.e. the SM Higgs boson. This ambiguity could be somewhat resolved by asking a second question, to wit, whether the LHC will *find a more complicated sector*; for the new particle could be one of many Higgs bosons (Fig. 8). A sizeable fraction of 30%/31% (theorist/experimentalists) expected this to be the case. This is almost the remainder of those who fully or somewhat agreed with the first statement. However, almost half (46%/47%) of the responses were ,undecided’, consistent for theorists and experimentalists. As in 2011 a more complicated Higgs sector appeared to be a very attractive option for many physicists. One may speculate about the reason for this rather neutral opinion. Certainly the data were too scarce at the time of the questionnaire; moreover the physicists may have been considering the probably limited precision of the LHC measurements.

²¹ As a reminder, the exact wording of the first questionnaire was *‘What is your personal estimate ... that the LHC will find the Standard Model Higgs boson’*.

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Fig.8 Percentage of answers of theorists (blue) and experimentalists (red) assigning probabilities in intervals of 20% on the chance that the LHC will find a more complicated Higgs sector (Questionnaire of 2012)

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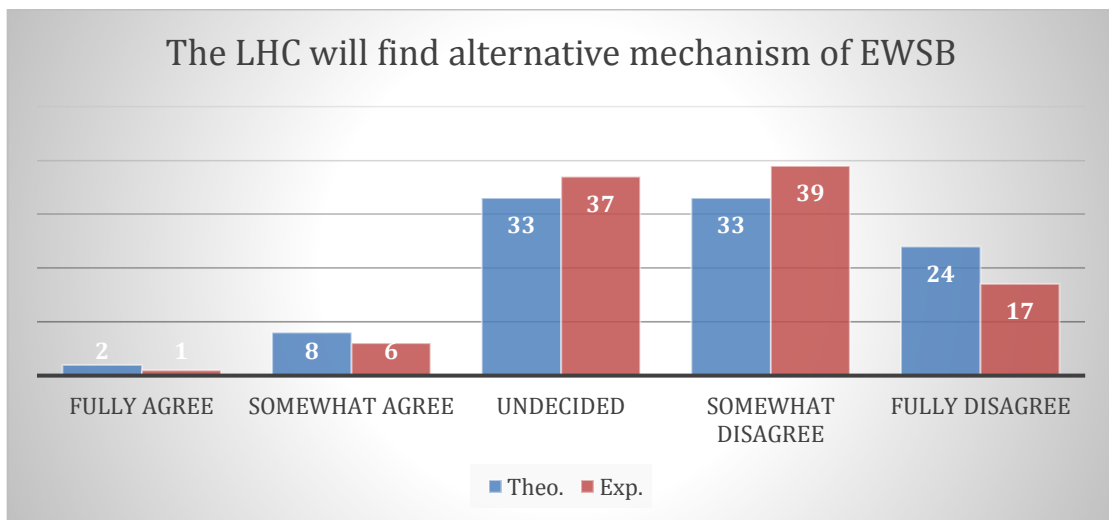
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The third question asked if the LHC will *find an alternative mechanism of EWSB* (Fig. 9). It was only a minority of roughly 10% that agreed at least ,somewhat' with this statement. Full agreement was at the 1% level. Given the discovery of a Higgs candidate shortly before the questionnaire, such a result is not surprising. Even though the LHC data available at that stage were still marginal, the consistency with what is expected for a SM Higgs boson disfavoured a radically different mechanism already then. Although a third of the replies were undecided, the vast majority of physicists no longer expected any radically new physics to emerge in the sector of mass generation.



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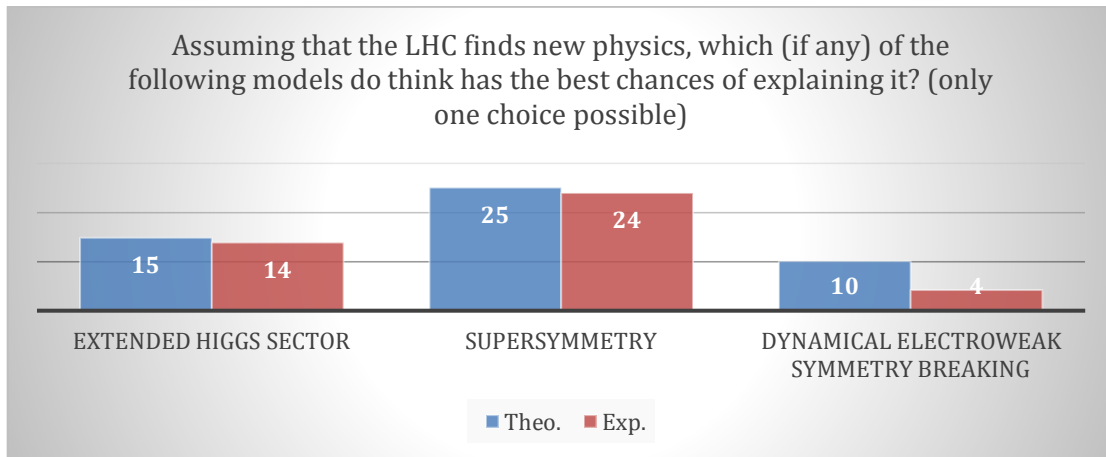
Fig.9 Percentage of answers of theorists (blue) and experimentalists (red) assigning probabilities in intervals of 20% on the chance that the LHC will find an alternative mechanism of EWSB (Questionnaire of 2012)

6.1.2 Which alternatives to the SM Higgs are still considered?

Whereas the new particle was largely considered to be a Higgs boson, its discovery

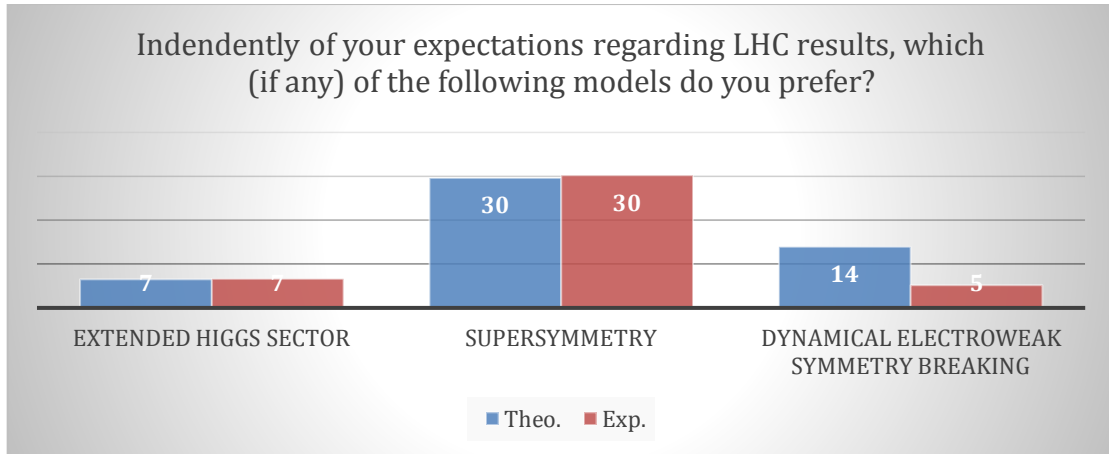
1059 initially did not preclude it to be, or involve, an element of new physics. Hence physicists
 1060 were asked: 'Assuming that the LHC finds new physics, which (if any) of the following
 1061 models do you think has the best chance of explaining it?'. Such a question has been asked
 1062 identically in the first round. However, while in 2011 two ranked choices were possible,
 1063 only one was allowed in 2012 (Fig. 10). To compare the two surveys, only the first
 1064 choice of 2011 is considered here.
 1065

1066 Some 40% favoured extended Higgs sectors either with or without Supersymmetry, an
 1067 increase from the about 34% in 2011. Going into more detail, the fraction of those who
 1068 assumed Supersymmetry to explain new physics did not change with the discovery
 1069 (25%/24% from 23%/24% as the first choice in 2011). Given that Supersymmetry was
 1070 the only theory to predict such a light Higgs boson (cf. Sect. 2), its discovery could be
 1071 seen to have strengthened the case for supersymmetry. On the other hand none of the
 1072 expected direct signals of Supersymmetry had been found, seemingly balancing the
 1073 indirect support from the Higgs mass. General extended Higgs sectors have gained some
 1074 ground in 2012 (increase from 10%/11%, as first choice in 2011, to 15%/14% in 2012).
 1075



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 1079 *Fig.10 Percentage of answers of theorists (blue) and experimentalists (red) on the most likely model*
 1080 *for physics beyond the Standard Model. Only answers with relation to the electroweak symmetry*
 1081 *breaking are given, the remaining 50/58% refer to different models (Questionnaire of 2012).*
 1082
 1083

1084 In contrast, the fraction of physicists considering dynamical EWSB as the best chance
 1085 was reduced to almost half between 2011 and 2012. Just 10%/4% of theorists/
 1086 experimentalists advocated for it after the observation of a Higgs candidate (previously
 1087 16%/7%). Even in spite of the limited parameter space of composite Higgs models, the
 1088 number of proponents was still remarkable among theorists. The replies to the question
 1089 'Independently of your expectations regarding LHC results, which (if any) of the following
 1090 models do you prefer?' (Fig. 11), hardly changed from 2011, 18%/5% chose dynamical
 1091 electroweak symmetry breaking. I.e. this strong minority among theorists prefers a
 1092 solution of EWSB that is different from the Higgs mechanism, even though many do not
 1093 believe this to be realised at LHC energies. This testifies the tenacity of theories that are
 1094 attractive on internal grounds, that have strong pragmatic virtues, notwithstanding
 1095 negative empirical results as long as there remain at least some options to adapt them to
 1096 the data. (cf. 5.1.3.)
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Fig.11 Percentage of answers of theorists (blue) and experimentalists (red) on the preferred model for physics beyond the Standard Model. Only answers with relation to the electroweak symmetry breaking are given, the remaining 50/58% refer to different models (Questionnaire of 2012).

6.1.3 How was the naturalness problem seen after the Higgs candidate?

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With the discovery of the Higgs candidate, i.e. the likely existence of an elementary scalar, it appeared that the naturalness problem had changed from a potential problem to an actual one. It could no longer resolve itself by the absence of a scalar from the set of fundamental particles. Furthermore no BSM signal had been found to alleviate these concerns. We therefore tried to understand whether the physicists' assessment had changed after the Higgs discovery.

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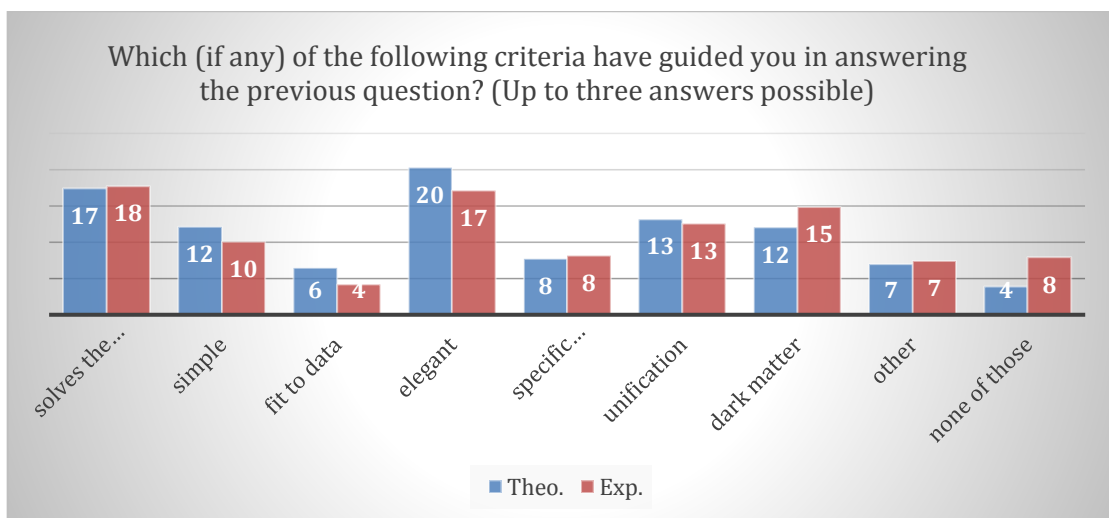
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As in 2011, physicists were asked for the criteria, 'which have guided' their selection of the preferred model, irrespective of the chances of confirming it at LHC. (Fig. 12) The attitude towards naturalness, however had hardly changed after the observation of a Higgs candidate. Naturalness was mentioned in 17%/18% of all answers, only mildly behind the criterion of 'elegance' (20%/17%), but clearly ahead of simplicity (12%/10%).



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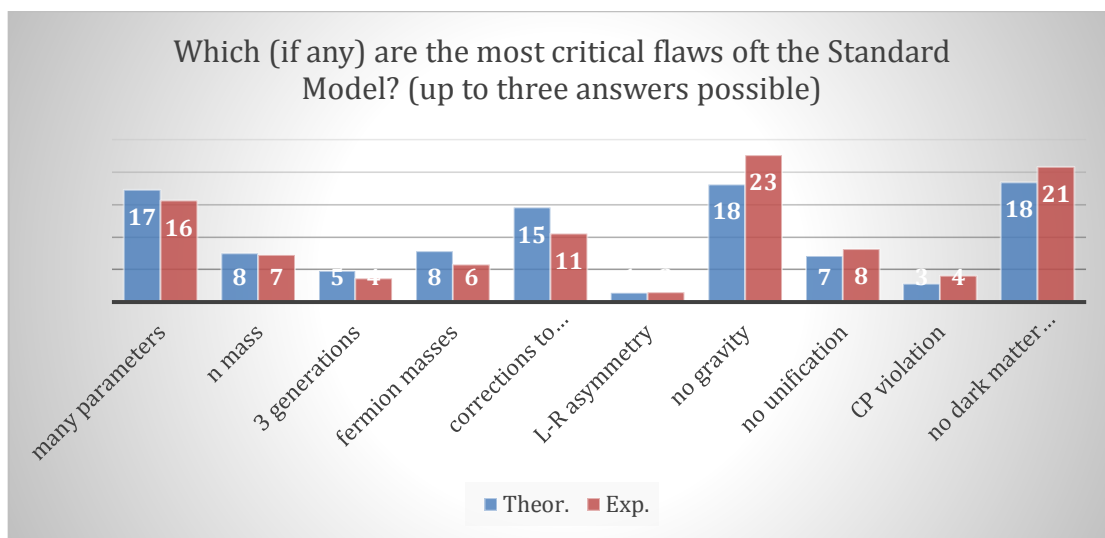
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Fig.12 Percentage of answers of theorists (blue) and experimentalists (red) on the criteria to choose the preferred model (Questionnaire of 2012). The three choices were added up.

1126 The other question pertinent to assessing the physicists' attitude towards naturalness
 1127 was again the 'most critical flaw of the Standard Model'. (Fig 13) As in the 2011 survey
 1128 up to three choices could be given. As before, *quadratic divergences in corrections to*
 1129 *Higgs mass* remained at 15%/11% (compared to 14%/10% in 2011) as one of the three
 1130 major flaws. Also most of the other assessments were fairly similar. A notable exception
 1131 was that experimentalists now tended to consider the absence of a dark matter
 1132 candidate' (21% after 17%) to become more critical. In both cases the replies from
 1133 theorists did not change significantly. After the discovery of the Higgs boson, it seems,
 1134 experimentalists shifted their interest to the next problem, which they thought to be in
 1135 reach of the LHC, dark matter, even though there was no consensus about a suitable
 1136 theoretical model, or whether such a dark matter candidate would be at all in the energy
 1137 range of the LHC.
 1138



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 1141 *Fig.13 Percentage of answers of theorists (blue) and experimentalists (red) on the criteria to choose*
 1142 *the preferred model (Questionnaire of 2012). The three answers were added up and normalized.*
 1143 *Note that the classifications are abbreviated the exact questions are listed in Appendix 2*
 1144

1145 Both questions show that the perceived importance of the naturalness problem has not
 1146 been affected by the change in the problem's specific status. A possible reason for this
 1147 stability is that epistemic and pragmatic criteria, once adopted by the community,
 1148 usually operate on a longer time scale. It takes a certain record of scientific successes to
 1149 support them – as has been the case with the naturalness principle. That said, one may
 1150 expect that after years of unsuccessful searches for BSM physics, naturalness may
 1151 become much less attractive.
 1152

1153 6.2 Outcome from interviews in the light of the discovery

1154 As in 2011 the questionnaire was complemented by interviews, this time with five
 1155 theorists and two experimentalists. Only one of them had already been interviewed in
 1156 2011; this time more emphasis was given to less senior physicists. The interviews took
 1157 place in autumn 2012.
 1158

1159 A large part of the interviewees characterized the Higgs discovery as an 'exciting' event
 1160 that would have decisive implications on future research. Overwhelmingly physicists
 1161 cautioned to jump to immediate conclusions about the details of the SM Higgs boson.
 1162 One interview partner expressed this very clearly, *well, we still do not know what we*
 1163
 1164

1165 *observed*. But: *It would have surprised me more if it would not be it [the Higgs boson].*
1166 *This is in some sense paradoxical, since it is just something one got used to*. Despite all
1167 caution there was agreement about the next steps.

1168

1169 **6.2.1 From the observation to scrutiny**

1170

1171 The focus, both experimentally and theoretically, was now to qualify this boson and look
1172 whether it was the SM Higgs boson or whether it had new physics in its wake. An
1173 experimentalist noted *'At this stage we observe a new particle ... with properties*
1174 *consistent with the Standard Model Higgs. This can change ... if we find something that*
1175 *does not fit into the Standard Model*'. But also theory is required to improve the precision
1176 of the predictions of Higgs properties *,If you don't see new physics directly, then maybe we*
1177 *see it through precision measurements, indirect tests.'*

1178

1179 In this sense, the new particle is seen as a potential harbinger of new physics, not the
1180 closure of a research program. 'Higgs physics' changed from searching for the Higgs
1181 boson towards measuring the properties of the new particle, assuming it to be 'largely'
1182 the Higgs boson, but also searching for deviations from its precisely predictable
1183 properties.

1184

1185

1186 **6.2.2 The implication on other models**

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1188 As discussed above, Supersymmetry predicted the Higgs boson to be lighter than 130
1189 GeV. It would have been in deep troubles, had the Higgs been found at a larger mass.
1190 After unsuccessful searches for direct signs of Supersymmetry, the mere consistency of
1191 the measurements with its prediction, was taken as indirect support. One theorist
1192 says *'if it had been 140 GeV or 150 – that would have changed a lot, because then my SUSY-*
1193 *models would all be dead. And I would stop working on them.'*

1194

1195 Another impact of the Higgs discovery on BSM models is that, within the experimental
1196 uncertainties, it provides additional constraints. Indeed in this perspective *'the discovery*
1197 *of the Higgs' is the main... result that influences our work*, a theorist explained; *'when we*
1198 *[work on] models we have to take... into account ... this particle and this changes... the*
1199 *situation definitely*'. Its existence and even the marginal precision of autumn 2012
1200 constrains the allowed parameter space of BSM models, *'the determination of*
1201 *parameters of models or the testing of models I continue to do, now including the*
1202 *information from the Higgs. And that has changed something in the interpretation*'. E.g. to
1203 determine the allowed parameter space in supersymmetric models. *'What would be a*
1204 *125 GeV Higgs [in super symmetry]? Of course a SUSY Higgs, but what a parameter space*
1205 *would be compatible with this? It would be a very small one.*' In this sense the discovery of
1206 the Higgs candidate has severe implications for many models, at least in limiting
1207 significantly the allowed parameter range. This is of course an effect that becomes
1208 poignant on a larger timescale when it may eventually squeeze out certain models
1209 entirely. Such an effect was not yet visible in the changes of model preference between
1210 the 2011 and 2012 questionnaires. .

1211

1212

1213 **6.2.3 Shedding doubt on the previous guiding principle of naturalness?**

1214

1215 As mentioned in 5.1.3, the naturalness problem in 2012 turned from fiction to reality.
1216 This can also be gathered from the interviews. *'I would say that now that it is certain*
1217 *that there is a Higgs state at this mass, [the naturalness problem] is more alive than ever*'.
1218 And at least some continue to consider it an important question. Naturalness *'is still an*

1219 *important argument. I cannot see any reason, why should happen something like that, such*
1220 *[fine – tuning] just in a natural way. we put this fine-tuning by hand, ... it cannot happen*
1221 *in nature.'*

1222
1223 Naturalness continues to be seen as an important guiding principle for the development
1224 of BSM models. *"We need the guidelines. Because, it's not just the experiment, it's not just*
1225 *mathematics. It's something, which is between induction and deduction. ... And you need ...*
1226 *some guidelines. One guideline could be this naturalness, ... which is a theoretical guideline.*
1227 *Or, 'minimality', one theorist argued, that is, for a model to have the minimal number of*
1228 *free parameters.*

1229
1230 However, this was not the only reaction. The unnaturalness of the SM becomes more
1231 acute since none of the anticipated solutions in terms of New Physics has shown up in
1232 the energy range where it was expected, a fact that was considered highly disturbing.
1233 This dilemma leads to a growing discussion about the status of the naturalness problem:
1234 *'is this problem a real problem or just a fantasy of theoretical physicists? ... I've been*
1235 *trained to look at it as a serious problem'. Yet another theorist raises doubts: 'what we*
1236 *thought was a main motivation to expect Supersymmetry at the LHC, this hierarchy*
1237 *problem or naturalness problem, I'm not so sure anymore whether this is actually*
1238 *something that leads us into the right direction.'* *'People have just [] accepted the fact that*
1239 *there is more and more fine-tuning now, because of the limits that become larger and*
1240 *larger. And it's not so clear to me whether it's still a good idea to consider that'. Similarly*
1241 *another theorist argued, 'We can discuss whether... we have to accept fine-tuning. What*
1242 *could be behind a fine-tuning ... or if one wants a natural theory without fine-tuning. ...*
1243 *This is the main argument which ... I think, drove ... the theoretical community for the last*
1244 *twenty or thirty years. But it's not a solid argument'.*

1245
1246 To sum up, the discovery of the Higgs boson, together with the absence of any sign of
1247 new physics, has turned naturalness from a potential into a real theoretical problem.
1248 While before the discovery of the Higgs boson physicists might have expected that
1249 naturalness could be restored by a different mechanism of EWSB, LHC has now
1250 confirmed the unnatural Higgs mechanism, yet without finding evidence for a potential
1251 solution outside the EWSB sector. It is true, naturalness could still serve as a guideline
1252 for devising new models. But the absence of a cure for the naturalness problem of the
1253 SM has made some physicists wonder whether it is actually a deep problem or whether
1254 one should simply accept fine-tuning as a fact about nature and accept models that
1255 violate naturalness. Therefore, the naturalness problem was still considered to be
1256 important in the questionnaires, but the interviews showed that its previous importance
1257 was put into question. Throughout the interviews, there was no indication that
1258 physicists considered the naturalness problem as multifaceted or vague. Instead they
1259 interchangeably denoted it as hierarchy problem, fine-tuning, or quadratic divergences.
1260 In Section 7.4., we will discuss how this coherence in scientific practice squares with the
1261 differences in philosophical analysis.

1262
1263

1264 **7. Some philosophical lessons**

1265

1266 In this Section we interpret the outcome of interviews and questionnaires in light of the
1267 questions mentioned in the Introduction.

1268

1269 **7.1 Scepticism before and after a crucial test**

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1271 In retrospect, it might appear that the Higgs discovery had been largely expected. Our
1272 studies show that, in actual fact, the expectations of the LHC physicists were fairly

1273 diverse. At least shortly before a Higgs candidate was discovered, the community was
1274 basically split whether to expect the observation of a SM Higgs or not. (cf. 5.1.2) They all
1275 were aware that LHC had sufficient luminosity to accomplish such a crucial test. The
1276 reluctance to embrace the SM Higgs boson is in line with wide-spread criticism of the
1277 conceptual structure of the Higgs mechanism. None of the interviewees emphasised its
1278 theoretical elegance, some even considered it an ad-hoc argument. This reluctance is in
1279 contrast to especially Supersymmetry, which is frequently considered as too beautiful a
1280 theory that nature should not have chosen it – regardless whether it is realised in the
1281 LHC energy range. The proponents of the Higgs mechanism simply regarded it as the
1282 ‘best’ solution for mass generation that had come to the physicists’ mind over the course
1283 of more than four decades. It did not contradict any measurement, was compatible with
1284 a wider theory, and had only relatively few parameters.

1285
1286 On the other hand, after a candidate with the ‘right’ mass and with properties consistent
1287 with the expectations had been observed, most LHC physicists-almost immediately
1288 embraced the notion that ‘a’ Higgs boson had been found – although they left it open
1289 whether it would be the only one. This overwhelming acceptance came, although the
1290 precision of the measurements still left quite some room for alternative solutions of
1291 EWSB. (cf. 6.1.1. & 6.2.1) In fact, one of the main research directions after the
1292 observation of the Higgs candidate, both experimentally and theoretically, became to
1293 scrutinize how large a parameter space for alternative solutions would be left. Whereas
1294 the vast majority did not consider solutions radically different from the SM, such as a
1295 composite scalar, as realistic, there was considerable hope to find deviations from the
1296 SM expectations that would give physicists a hint how to further investigate the complex
1297 landscape of BSM models. (cf. 6.1.2) When doing so, most data analyses after 2012
1298 assumed the existence of a SM Higgs boson at 125 GeV, at least as the best
1299 approximation of the observed boson. This represented a significant discontinuity in the
1300 actual experimental strategy.

1301 1302 **7.2. Was the Higgs Discovery a Crucial Experiment?**

1303
1304 In the interviews, the discovery of a Higgs boson was widely considered as extremely
1305 important for particle physics, This accords with the many statements in the literature
1306 during the last decades [e.g. *Ellis, J., Gaillard, M.K., and Nanopoulos D.V. (2012), Quigg*
1307 *2007*] and the significant material and intellectual resources that went into large
1308 experimental facilities to solve the problem of EWSB. This widely shared conviction
1309 among physicists that the problem of EWSB was at the crossroads of particle physics at
1310 large prompts the question as to whether the Higgs discovery represented a crucial
1311 experiment in a philosophical perspective? In Section 3.3. we have discussed the various
1312 counterarguments against the feasibility of crucial experiments and a few examples
1313 from 20th century physics that came close to being bestowed this honour. In this section,
1314 we argue that the Higgs discovery can indeed be considered as a crucial experiment and
1315 defend this diagnosis against the standard objections. Even though the Higgs discovery –
1316 as shown in Section 7.1 and emphasised in many physics papers – was not a simple
1317 yes/no experiment, its cruciality, to our mind, rests upon the following characteristics:

- 1318
1319 a. The Higgs boson was an essential and indispensable element of the SM.
1320 Moreover, the Higgs discovery was the final confirmation of a theoretical
1321 framework that had been developed over decades. Of course, the SM would also
1322 have broken down if, e.g. no Z^0 boson would have been found. But the Higgs,
1323 belongs to a sector of the SM that had not been seen before and is based on the
1324 additional concept of spontaneous symmetry breaking, for which no evidence
1325 had been observed before.
1326

- 1327 b. The Higgs boson is fundamentally different from all particles found up to date
1328 because it is an elementary scalar. It is not the first scalar found, but e.g. the pion
1329 has been shown to be composed of two quarks and gluons.
1330
1331 c. In view of the importance of the EWSB mechanism, a plethora of alternative
1332 models had been constructed. The discovery of the Higgs boson basically
1333 eliminated several families of these alternative models, and reshaped the
1334 direction of future research in a fundamental way.
1335

1336 Whereas a. and b. emphasise the crucial importance of a Higgs discovery for the SM and
1337 the general concept of elementary particle, characteristic c. widens the traditional
1338 philosophical understanding of crucial experiments that are commonly taken to confirm
1339 or refute a single theoretical hypothesis and, accordingly, are confronted with Duhemian
1340 underdetermination. In the next paragraphs we argue for a broader interpretation of
1341 these two points. In particular we argue that the crucial nature of an experiment as
1342 complex as LHC has to be judged against the backdrop of the historical development of
1343 the respective field
1344

1345 Let us assess the acceptance of the observed particle being a Higgs in more detail.
1346 Immediately after the announcement at CERN in 2012 and the first measurements of its
1347 mass and decay modes, there was a flood of theoretical analyses, significantly reducing
1348 the possible parameter space of the many previously developed BSM models. Some
1349 models, 'higgsless models', 'higgs-gauge unification' etc. were strongly disfavoured and
1350 did not play a role in the subsequent discussions. Others, like 2HDM were more difficult
1351 to reject at this stage. As becomes apparent from the questionnaire, even only a few
1352 months after the discovery was announced, alternative models for EWSB were only
1353 expected by less than 10% of the respondents. (cf. 6.1.1.).
1354

1355 During the following year – with more data being analysed and additional properties
1356 being searched for, especially the spin – the notion of 'having found a Higgs boson' was
1357 adopted by the majority of the LHC physicists. The notion of 'a' Higgs boson leaves open
1358 the option of having a more complicated Higgs sector than the SM Higgs. In principle this
1359 can be resolved by higher experimental precision and additional searches, however, the
1360 precision will never be perfect in the future, such that small deviations from the SM
1361 Higgs cannot be ruled out with 100% certainty.
1362

1363 In this situation physicists are moving forward in their research accepting the SM Higgs
1364 boson to exist. This consensus was not only based on a purely logical inference, in the
1365 sense that physicists waited until all alternative solutions were definitively excluded.²² It
1366 also contained a certain dose of pragmatism in choosing promising research strategies.
1367 Such a 'pragmatic solution' to the Duhem-Neurath-Quine problem, as Franklin and
1368 Perovic (2015, 84) have aptly put it, does not preclude intensive future scrutiny of the
1369 signal both from an experimental and theoretical side. Just the opposite: this scrutiny
1370 leads to the emergence of a very significant new research direction. This persistent
1371 search for potential deviations is not, to our mind, in conflict with the Higgs discovery
1372 being crucial.
1373

1374 Since several theoretical possibilities were not definitively eliminated by the available
1375 data the question arises as to why the Higgs discovery was not just a 'persuasive
1376 experiment' – in the terminology of Franklin and Perovic? (cf. 3.3.) The reason is that in

²² Wüthrich (2016) advocates a notion of diagnostic causal inference that partially dispenses with the explicit assumption of theories without sacrificing talk about causality in particle scattering.

1377 the case of the Higgs boson it is not possible to neatly separate the interpretation of the
1378 experiment as refutation of a hypothesis (SM) from the subsequent rejection of
1379 competing explanations. It is the same experiment that tests the SM, analyses possible
1380 deviations and searches, quite generally, for BSM physics.

1381
1382 Let us now return to the underdetermination problem and argue that the mentioned
1383 pragmatic solution to the problem of alternatives does not thwart the crucial nature of
1384 the Higgs discovery. This is not the only way particle physicists are taming Duhemian
1385 underdetermination. It is openly addressed within the data analysis. There are basically
1386 two strategies to do so. First, the discrimination of two (or several) hypotheses, framed
1387 in an identical theoretical environment, with the same (kind) of experiments is (almost)
1388 completely free of detailed theoretical considerations. For in such cases the well
1389 accepted and identical procedures are applied to either of the hypotheses. In such cases,
1390 underdetermination and theory-ladenness are shielded off by referring in the same way
1391 to an entire experimental set-up – including the proper functioning of cables and
1392 switches. This vastly reduces their sway among scientists.²³

1393
1394 Second, theory ladenness is significantly alleviated by using precision data from LHC
1395 and other experiments and the familiarity with experimental strategies, among them the
1396 rules of data analysis and the knowledge about background processes. The Higgs
1397 discovery, accordingly, was part and parcel of a longer tradition of accelerator
1398 experiments and the associated theoretical research programs. This shows that by
1399 embedding the actual experiment into a broader context and by distinguishing the
1400 different layers of theorizing and experimentation, crucial experiments are possible. In
1401 such cases the philosophical in-principle argument for theory-ladenness remains valid,
1402 but loses its scientific relevance and philosophical clout.

1403

1404 ***7.3. Principles and values of theory choice***

1405

1406 The case of the Higgs discovery has shown that crucial experiments may have a complex
1407 internal structure and be embedded into a broader historical context. This also means
1408 that there remains a significant role for pragmatic values of theory choice; they apply to
1409 those aspects of transient underdetermination that arise from theoretical alternatives
1410 that are not fully excluded by the available data and continue to have some advocates.
1411 Such theoretical alternatives might be simpler, more elegant, or fertile because they
1412 promise a prediction in another field, for instance, they would have a dark matter
1413 candidate.

1414

1415 The approach of many physicists to dynamical EWSB – both in the questionnaires and in
1416 the interviews – revealed a certain split between the assessment of the empirical
1417 evidence and general ideas of what a good theory should look like. Even taking into
1418 account tight experimental constraints, the ‘expectation’ to find dynamical EWSB was
1419 still significant among theorists before the observation of the Higgs candidate. It
1420 decreased after the observation, but remained high. Interestingly, the preference among
1421 theoreticians was, both in 2011 and 2012, always higher when asked ‘independently of
1422 LHC’. (cf. 5.1.3. & 6.1.2.) Even though the chances for experimental evidence in the near
1423 future were low, dynamical EWSB remained a preferred solution for many. Notably, the
1424 preference on dynamical EWSB showed the largest difference in the surveys between
1425 experimentalists and theorists.

²³ This is not to say that such errors do not occur. But once it turned out that a wrongly plugged cable was responsible for the superluminal velocities measured at CERN, there way no interesting debate. As Franklin (2013) shows, interesting failures of experiments are of a different kind.

1426

1427 One may speculate about the reason for this preference. Dynamical EWSB does not
1428 introduce fewer free parameters. But whereas the Higgs mechanism adds the concept of
1429 an elementary scalar particle and SSB, the dynamical EWSB just makes use of the other
1430 concepts of the SM, gauge symmetry and fermionic matter fields. It thus circumvents the
1431 second characteristic (b.) mentioned in Section 7.1. and – by copying concepts from
1432 within the SM – might be considered as simpler. As pointed out in the interviews, there
1433 is an in principle chance to calculate the masses of particles, which are not predicted by
1434 the Higgs mechanism. This would correspond to a second pragmatic virtue: predictive
1435 fertility.

1436

1437 The lesson of the SM and the Higgs discovery for the philosophical assessment of
1438 pragmatic criteria of theory choice seems to be that both pragmatic and epistemic
1439 criteria of theory choice are constantly in play. Their respective weights may change and
1440 they may act differently for experimentalists and theoreticians. In parallel to the general
1441 acceptance of a SM Higgs boson, the favourability of alternative explanations of EWSB
1442 decreased, but given the remaining parameter space, it did not go down to zero. In the
1443 complex landscape of models around the LHC – models that often have several
1444 empirically adjustable parameters – deficits in empirical adequacy can partly be
1445 compensated by theoretical and pragmatic virtues.

1446

1447 The questionnaires and the interviews have shown, more broadly, that in 2011 there
1448 was a large variety of epistemic and pragmatic criteria guiding the physicists'
1449 expectations about the Higgs searches, their concerns about the SM and their
1450 preferences for BSM physics. The discovery of the Higgs boson disfavoured certain
1451 models and strengthened the genuinely epistemic criteria. The example of dynamical
1452 symmetry breaking after the Higgs discovery showed that theoretical simplicity or other
1453 pragmatic criteria, e.g. fertility to calculate further particle masses, can motivate
1454 researchers even if the respective model is experimentally disfavoured. This
1455 corresponds to Kuhn's insight that the balancing of epistemic and pragmatic virtues is
1456 never a perfect logical inference but a fact in the development of science. Even though
1457 physicists are now largely accepting the SM as one of the most successful theories, they
1458 will keep looking for deviations that promise to be interesting.

1459

1460

1461 **7.4 The Guiding Principle 'Naturalness'**

1462

1463 With the Higgs discovery 'naturalness' turned from a potential problem of the SM into a
1464 real one – aggravated by the non-observation of any new particles in the TeV range that
1465 could resolve it in close proximity to the Higgs discovery. One might expect that after
1466 confirming the cause of the naturalness problem, its solution should have been
1467 considered as more urgent. Such a trend was not visible in the questionnaire; its high
1468 ranking as guiding principle or most critical flaw of the SM did not change. The
1469 interviews revealed a more differentiated picture²⁴. Some physicists still regard the
1470 naturalness problem as a nuisance, but contemplated it might be an accidental feature of
1471 particle physics instead of a solid theoretical argument. In a sense physicists are
1472 becoming prepared to live with it.²⁵

1473

1474 The resilience of the naturalness problem may result from the fact that there exists no
1475 clear threshold when a theory becomes 'unnatural'. At least before the first results of the

²⁴ This agrees with several articles by physicists reconsidering the Naturalness problem, e.g. Guidice (2013), Dine (2015).

²⁵ Cf. Friederich, Harlander & Karaca (2014, Sect. 7).

1476 LHC it was folklore that fine-tuning requires new physics at an energy scale of 1 TeV. Yet
1477 there is no prohibitive argument against changing this to 5 or 10 (or more) TeV even if
1478 this increases the amount of fine-tuning. Therefore, with some adjustments, the
1479 naturalness problem may still be applicable to the forthcoming LHC data, moreover also
1480 the parameter space for new physics at the 1 TeV scale has not being completely
1481 covered by previous searches. Thus many physicists defer the final word on the
1482 importance of naturalness to the higher energies and intensities that the LHC is about to
1483 enter. It remains to be seen how far it can be stretched. This relates to a second point.
1484 Naturalness is an operationally easy-to-apply quantitative criterion, at least once it is
1485 specified how much fine-tuning is allowed. This may also be the reason why naturalness
1486 is maintained as an important criterion to devise BSM models.

1487
1488 Our questionnaire has shown that naturalness is indeed on a par with the traditional
1489 pragmatic criteria of theory choice of ‘elegance’ and ‘simplicity’ - as for the guiding
1490 principles of model preference - and on a par with ‘too many independent parameters’,
1491 the ‘missing dark matter candidate’ and the ‘non-inclusion of gravity’ – as for the most
1492 critical flaws of the SM. While the many independent parameters render the SM not
1493 simple – during decades elementary particle physicists have been looking for a simple
1494 unifying theory – the two other flaws concern empirical facts that cannot be
1495 accommodated by the SM.

1496
1497 From the interviews (cf. 6.2.3) we have concluded that naturalness is considered as
1498 sufficiently well entrenched within the community to be considered as a coherent
1499 guiding principle for scientific practice. But it operates both in an epistemic and a
1500 pragmatic mode. Renormalization is the preferred way to guarantee the finiteness of the
1501 theory, that is, its theoretical consistency, which renders naturalness an epistemic value.
1502 (cf. 3.2.) But the as-yet-failed attempts to solve the naturalness problem prompt a
1503 consideration of its pragmatic aspect as to how much fine-tuning one is willing to accept.
1504 Thus the epistemic criteria of consistency and empirical adequacy only provide a
1505 numerical bound for a pragmatic-value judgment, quite in the same sense as the number
1506 of free parameters in the SM one is willing to accept. In a philosophical perspective, the
1507 case of naturalness shows that principles of theory choice can be rather complex. Our
1508 specific findings also match – at least partly – the philosophical differentiations
1509 advocated by Wells and Williams (cf. 3.3). But despite its complexity, naturalness is
1510 coherently applied as guiding principle by the physics community. There is also no
1511 separation of this complex criterion into more elementary epistemic and pragmatic
1512 values, which would then be mutually balanced by researchers in the sense envisaged by
1513 Kuhn.

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1516

1517 **8. Conclusion**

1518
1519 Let us sum up the main results of our paper. First, the discovery of the Higgs boson and
1520 the confirmation of the SM were less expected than is often assumed. With the growing
1521 evidence that the newly discovered particle has properties consistent with the SM
1522 expectations, most physicists accepted it to be a Higgs, and at least tentatively, a SM
1523 Higgs boson. This does not contradict the fact that searches for possible deviations from
1524 the SM will be ongoing for a long time. Second, the Higgs discovery represented a crucial
1525 experiment for the SM if one interprets the notion in a sense that is appropriate for
1526 modern experiments. An experiment as complex as LHC cannot be properly understood
1527 without its embedding into a tradition of previous precision experiment and the
1528 tradition of reliable and established experimental strategies. These are crucial for
1529 keeping confirmational holism at bay. This result is in line with recent debates that have

1530 shown that it is difficult to find interesting examples of non-transient
 1531 underdetermination. Third, our case study suggests that criteria of theory choice be
 1532 understood as epistemic and pragmatic values that have to be weighed in in factual
 1533 practice. The Higgs discovery led to a certain shift from pragmatic to epistemic values as
 1534 regards the mechanisms of EWSB. Complex criteria, such as naturalness, combine
 1535 different values without becoming inconsistent or too vague to be applied by the
 1536 scientific community.

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Appendix 1 List of interview partners

March & April 2011

Prof. V.Sharma	UC San Diego, USA	experimentalist	Convenor of Higgs group in CMS expt.	Male
Prof. F.Gianotti	CERN	experimentalist	Spokeswoman of ATLAS expt.	Female
Prof. G.Tonelli	U of Pisa (Italy)	experimentalist	Spokesman of CMS expt.	Male
Prof. A.Golutvin	IC London (UK)	experimentalist	Spokesman of LHCb expt.	Male
Dr. J.Boyd	CERN	experimentalist	Coordinator data preparation in ATLAS expt.	Male
Prof. J.Ellis	CERN	theorist		Male
Prof. C.Quigg	Fermilab (USA)	theorist		Male
Prof. M.Mangano	CERN	theorist		Male
Dr. M.Mihalla	KIT (Germany)	theorist		Female

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 1544
 1545
 1546

Fall 2012

Prof. M.Krämer	RWTH Aachen	theorist		Male
Prof. L.Feld	RWTH Aachen	experimentalist		Male
Dr. L. Di Luzio	KIT (Germany)	theorist		Male
Dr. F. Domingo	KIT (Germany)	theorist		Male
Prof. C.Issever	U of Oxford (UK)	experimentalist	Convenor exotics ATLAS expt.	Female
Dr. M.Mihalla	KIT (Germany)	theorist		Female

1547
 1548

1549 **Appendix 2: List of questions in questionnaires**

1550

1551 **In 2011**

1552

1553 **1. What is your personal estimate of the probability of the following**
1554 **scenarios? The LHC will...**

1555 a. find the Standard Model Higgs boson

1556 b. rule out the Standard Model Higgs boson

1557 c. find indisputable evidence of new physics

1558 The probabilities to be assigned were in 20% intervals, i.e. 0-20, 20-40%,

1559

1560 **2. Assuming that the LHC finds new physics, which (if any) of the following**
1561 **models do you think has the best chances of explaining it**

1562 a. extended Higgs sector

1563 b. supersymmetry

1564 c. extra-dimensions

1565 d. dynamical electroweak symmetry breaking

1566 e. 4th generation

1567 f. extended gauge symmetry (Z', Little Higgs)

1568 g. string theory

1569 h. other

1570 i. None of those, but something totally unexpected

1571 The questionnaire asked for four ranked choices

1572

1573 **3. Independently of your expectations regarding LHC results, which (if any) of**
1574 **the following models do you prefer?**

1575 a. extended Higgs sector

1576 b. supersymmetry

1577 c. extra-dimensions

1578 d. dynamical electroweak symmetry breaking

1579 e. 4th generation

1580 f. extended gauge symmetry (Z', Little Higgs)

1581 g. string theory

1582 h. other

1583 i. None of those, but something totally unexpected

1584 **Only one choice possible**

1585

1586 **4. Which (if any) of the following criteria have guided you in answering the**
1587 **previous question?(Four ranked answers were possible.)**

1588 a. The model solves naturalness/hierarchy problem

1589 b. The model is simple

1590 c. The model will provide a better fit to the data

1591 d. The model is elegant

1592 e. The model makes very specific predictions

1593 f. The model allows the unification of forces

1594 g. The model has a candidate for dark matter

1595 h. other

1596 i. none of the above

1597

1598 **5. Which (if any) are the most critical flaws of the Standard Model? (up to**
1599 **three answers possible)**

1600 a. too many independent parameters

1601 b. small but nonzero neutrino masses

1602 c. replication of fermion families

- 1603 d. different magnitude of scales of fermion masses
- 1604 e. quadratic divergences in corrections to Higgs mass
- 1605 f. left-right asymmetry
- 1606 g. gravity is not included
- 1607 h. no unification of strong and electroweak forces
- 1608 i. CP violation
- 1609 j. No dark matter candidate

1610

1611 **6. In which of the following signatures (if any) do you think the LHC will most likely find new physics?**

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6. In which of the following signatures (if any) do you think the LHC will most likely find new physics?

- a. signatures with bottom quarks
- b. signatures with top quarks
- c. signatures with tau leptons
- d. signatures with missing energy
- e. signatures with multi – jet topologies
- f. signatures with multi – lepton topologies
- g. soft events
- h. other
- i. I don't know

Two ranked choices were asked for

7. How much do you agree with the following statements? LHC results will be very important to understand...

- a. strong interactions
- b. flavour physics
- c. origin of mass
- d. quantum gravitational effects
- e. dark matter
- f. dark energy
- g. cosmology of the early universe

The answers should be given for each field in terms of

'fully agree', 'somewhat agree', 'undecided', 'somewhat disagree', 'fully disagree'

8. How much do you agree with the following statements?

- a. There is plenty of dialogue between theoretical and experimental physicists on LHC physics
- b. Theorists are fully prepared to tackle future new data from LHC
- c. Theorists are making helpful suggestions on how to collect and analyse LHC data
- d. Experimental physicists are sufficiently taking into account suggestions from theorists
- e. Experimental physicists are presenting their results in the most helpful way for theorists

The answers should be given for each field in terms of 'fully agree', 'somewhat agree', 'undecided', 'somewhat disagree', 'fully disagree'

In 2012

1. How much do you agree with the following statements? After the discovery of the new particle at 125 GeV, the LHC will...

- a. confirm the minimal Higgs sector
- b. find a more complicated Higgs sector
- c. find an alternative mechanism for EWSB
- d. find indisputable evidence of new physics

1657 The answers should be given for each field in terms of ‘fully agree’, ‘somewhat
1658 agree’, ‘undecided’, ‘somewhat disagree’, ‘fully disagree’

1659

1660 **2. Assuming that the LHC finds new physics, which (if any) of the following
1661 models do you think has the best chances of explaining it**

- 1662 a. extended Higgs sector
- 1663 b. supersymmetry
- 1664 c. extra-dimensions
- 1665 d. dynamical electroweak symmetry breaking
- 1666 e. 4th generation
- 1667 f. extended gauge symmetry (Z', Little Higgs)
- 1668 g. string theory
- 1669 h. other
- 1670 i. None of those, but something totally unexpected

1671 Only one choice was possible

1672

1673 **3. Independently of your expectations regarding LHC results, which (if any) of
1674 the following models do you prefer?**

- 1675 a. extended Higgs sector
- 1676 b. supersymmetry
- 1677 c. extra-dimensions
- 1678 d. dynamical electroweak symmetry breaking
- 1679 e. 4th generation
- 1680 f. extended gauge symmetry (Z', Little Higgs)
- 1681 g. string theory
- 1682 h. other
- 1683 i. None of those, but something totally unexpected

1684 Only one choice possible

1685

1686 **4. Which (if any) of the following criteria have guided you in answering the
1687 previous question?**

- 1688 j. The model solves naturalness/hierarchy problem
- 1689 k. The model is simple
- 1690 l. The model will provide a better fit to the data
- 1691 m. The model is elegant
- 1692 n. The model makes very specific predictions
- 1693 o. The model allows the unification of forces
- 1694 p. The model has a candidate for dark matter
- 1695 q. other
- 1696 r. none of the above

1697 Up to three answers were asked for

1698

1699 **5. Which (if any) are the most critical flaws of the Standard Model? (up to
1700 three answers possible)**

- 1701 k. too many independent parameters
- 1702 l. small but nonzero neutrino masses
- 1703 m. replication of fermion families
- 1704 n. different magnitude of scales of fermion masses
- 1705 o. quadratic divergencies in corrections to Higgs mass
- 1706 p. left-right asymmetry
- 1707 q. gravity is not included
- 1708 r. no unification of strong and electroweak forces
- 1709 s. CP violation
- 1710 t. No dark matter candidate

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6. In which of the following signatures (if any) do you think the LHC will most likely find new physics?

- j. signatures with bottom quarks
- k. signatures with top quarks
- l. signatures with tau leptons
- m. signatures with missing energy
- n. signatures with multi – jet topologies
- o. signatures with multi – lepton topologies
- p. soft events
- q. other
- r. I don't know

Two ranked choices were asked for

7. How much do you agree with the following statements? LHC results will be very important to understand...

- h. strong interactions
- i. flavour physics
- j. origin of mass
- k. quantum gravitational effects
- l. dark matter
- m. dark energy
- n. cosmology of the early universe

The answers should be given for each field in terms of 'fully agree', 'somewhat agree', 'undecided', 'somewhat disagree', 'fully disagree'

8. How much do you agree with the following statements?

- f. There is plenty of dialogue between theoretical and experimental physicists on LHC physics
- g. Theorists are fully prepared to tackle future new data from LHC
- h. Theorists are making helpful suggestions on how to collect and analyse LHC data
- i. Experimental physicists are sufficiently taking into account suggestions from theorists
- j. Experimental physicists are presenting their results in the most helpful way for theorists

The answers should be given for each field in terms of 'fully agree', 'somewhat agree', 'undecided', 'somewhat disagree', 'fully disagree'

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