

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, Duhemian underdetermination is kept at bay. Second, our case study
23 suggests that criteria of theory (or model) preference should be understood as
24 epistemic and pragmatic values that have to be weighed in factual research
25 practice. The Higgs discovery led to a shift from pragmatic to epistemic values as
26 regards the mechanisms of electroweak symmetry breaking. Complex criteria,
27 such as naturalness, combine epistemic and pragmatic values, but are coherently
28 applied by the community.
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31 **1. Introduction**³

32
33 The discovery of a⁴ 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

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³ The study was performed as part of the project ‘Model Dynamics’ supported by the DFG (project no. MA 2793/2-1). 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/>. We thank the anonymous referees for their most helpful criticism and manifold suggestions. We thank Sophie Ritson for having made us aware of Baetu (2017).

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
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).

45
46 In retrospect, the discovery of the Higgs boson might seem to be just the final step in a
47 long series of discoveries and precision tests in which stronger and stronger accelerator
48 experiments confirmed all particles of the SM and scrutinized their interactions. The
49 present paper argues that as regards the community of elementary particle physics this
50 picture needs qualification. In actual fact, even shortly before the Higgs discovery a
51 significant percentage of physicists raised concerns whether it would at all be found at
52 the LHC and expressed preferences for other explanations of the particle masses.

53
54 In this paper, results of questionnaires and interviews with LHC physicists shortly
55 before (autumn 2011) and shortly after (autumn 2012) the discovery are presented and
56 analysed. From these empirical sources, we reconstruct the physicists' beliefs in the
57 adequacy of certain models, in the outcome of the LHC experiments, and concerning the
58 possible impacts of the LHC experiments on those models. This will help us to
59 understand the epistemic attitudes of particle physicists, and the principles and
60 strategies guiding their research. Our empirically informed epistemological
61 investigation also promises new insights for a philosophical analysis of how actual and
62 expected experimental findings, on the one side, and pragmatic quality criteria of
63 models, on the other, influence the research agendas of particle physicists.

64
65 We have limited the scope of the present paper to a specific part of the empirical
66 material available in the questionnaires and interviews: to the Higgs mechanism and
67 competing accounts of mass generation, and to the presently most discussed pragmatic
68 quality criterion, naturalness. It must be said, however, that the LHC was, from the very
69 beginning, designed not only to search for the Higgs boson but also to probe the deep
70 TeV energy range and find signs of BSM physics. Whereas the first objective has now
71 been achieved, no 'new physics' BSM has been observed to date.⁵

72
73 The specific descriptive questions addressed in this paper are as such:

- 74
- 75 1. Did physicists in 2011 expect the Higgs boson to be discovered at the LHC and how
76 did they evaluate the Higgs candidate in 2012, that is, before its properties were
77 known to a sufficient extent? What was their assessment of alternative models for
78 mass generation in 2011 and in 2012?
 - 79 2. How important was the naturalness problem, a major guiding principle to develop
80 models of physics beyond the SM (BSM), in shaping physicists' attitudes and
81 preferences?

82
83 We will show that, in 2011, physicists were rather undecided whether the SM Higgs

⁴ We adopt the usual terminology and address the SM Higgs as 'the' Higgs, whereas those models with a potentially more complicated Higgs sector as containing 'a' Higgs boson.

⁵ The attempts at finding physics BSM and their effects on the thinking of LHC physicists will be discussed in a separate paper.

84 boson would eventually be found, that is, even a few months before the first evidence
85 was reported. However, once a candidate had been observed in 2012, they quickly
86 embraced the notion that ‘a’ Higgs boson had been found. Its discovery immediately
87 affected the research directions in particle physics. The experimental results pulled in
88 different directions as regards the naturalness problem. There was, on the one hand,
89 less motivation to search for alternatives to the Higgs mechanism. On the other hand,
90 after finding the Higgs boson, the naturalness problem posed by the scalar Higgs particle
91 changed from a virtual into a real problem, that is, there existed empirical results
92 directly relevant for it. But since 2012 no BSM effect to cure this problem has been
93 found. This has led some physicists to develop a more critical attitude as to naturalness’
94 significance for elementary particle physics.

95
96 The physical developments prompt the following philosophical questions.

- 97
98 3. What do the epistemic attitudes of particle physicists shown in the questionnaire
99 and the interviews mean for the significance and application of criteria of theory (or
100 model)⁶ choice and the principles and epistemic values guiding model development?
101 4. What does the comparison of the situations before and after the discovery of the
102 Higgs boson signify for the relationship between theory (or models) and
103 experiment? In particular, was the Higgs discovery a crucial experiment for the SM?
104

105 The paper is organised as follows. After a brief introduction into the theoretical
106 motivation for the Higgs mechanism and the experimental attempts to find evidence for
107 a Higgs boson (Section 2), we provide the background of the philosophical problems
108 raised (Section 3) and discuss the methodology of our study (Section 4). The
109 presentation of the results will be subdivided into the outcomes of the questionnaire
110 and the interviews in 2011 (Section 5) and in 2012 (Section 6) respectively. Finally
111 (Section 7), we outline our answers to the above-mentioned four questions.
112
113

114 ***2. The physics of electroweak symmetry breaking***

115
116 Several articles of both physicists and philosophers discuss the emergence of what is by
117 now called the ‘Higgs’ mechanism (Cf. Ellis, Gaillard, Nanopoulos, 2015; Nobel laudatio
118 2013; Karaca 2013b). Here, only a brief account of the motivation and the concepts
119 behind the Higgs boson can be given. In the early 1960s, various models were developed
120 to unify two interactions governing the subnuclear world, the electromagnetic and the
121 weak ones. These unifications adopted the concept of local gauge symmetry that had
122 previously been applied successfully to quantum electrodynamics (QED). In brief, this
123 symmetry means that the theory is invariant under a specific space-time dependent
124 transformation of the quantum fields. Assuming this symmetry in the SM leads to a
125 consistent interacting field theory, which for particle physicists means free of any
126 infinities after renormalization.
127

128 However, a major problem that physicists were facing in applying local gauge symmetry
129 to weak interactions was that observations implied that the corresponding gauge
130 bosons have a non-vanishing mass. As such, gauge boson masses break the symmetry
131 explicitly, thus leading to theoretical inconsistencies, such as the violation of unitarity.
132 To remedy this, in the 1960s, physicists used the concept of spontaneous symmetry
133 breaking (SSB) to generate gauge boson masses in a gauge invariant way at the cost of

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).

134 introducing an additional scalar, i.e. spin-less, particle, which became known as the
135 Higgs boson. This particle was discovered at the LHC some 50 years after its invention.
136 The Higgs sector of the SM is a novel element in physics, in that it describes the mass of
137 elementary particles in terms of their interaction with an elementary scalar field.

138
139 Whereas the weak and the electromagnetic components of the ‘electroweak’ theory have
140 almost the same strength at very high energies, they are substantially different at low
141 energies, since only the weak interaction invokes a massive interacting particle.
142 Therefore, the mechanism of mass generation is also referred to as ‘electroweak
143 symmetry breaking’ (EWSB). The Higgs mechanism was originally only devised to give
144 mass to the weak gauge bosons $W^{+/-}$ and Z^0 . (The latter represents the electrically
145 neutral component of the weak interaction, which, however, has an admixture of an
146 electromagnetic component.) It turned out that the Higgs mechanism could also be
147 applied to give masses to fermions, through a Yukawa interaction, albeit without
148 predicting their numerical values.

149 150 **2.1 The experimental search for the Higgs boson**

151
152 The general conception of the Higgs mechanism just outlined was developed into
153 phenomenological predictions⁷ opening the way for experimental searches of the Higgs
154 boson. Given the masses of the W and Z bosons, the Higgs mechanism introduced just
155 one additional parameter to the SM that had to be determined by experiment, notably by
156 measuring the Higgs mass⁸. Whereas the theory did not provide a prediction for this
157 mass, it did lead to an upper bound of 800 GeV to maintain theoretical consistency.
158 Depending on its mass, it could be unambiguously predicted how the Higgs boson is
159 produced and the way it can be seen by experiments. Since a Higgs boson would only
160 exist for small fractions of a second, it would decay, depending on its mass, mainly into
161 massive fermions and W and Z bosons.

162
163 As a result, a clear strategy for finding the Higgs boson was devised.⁹ However, this did
164 not make Higgs searches easy. Essentially no experiment before the start of CERN’s
165 Large Electron Positron Collider (LEP) in 1989 was sensitive to the Higgs boson. At the
166 end of the LEP data taking no significant signal was observed. However, the sensitivity
167 of LEP was such that a Higgs of 114.4 GeV or less should have been found, allowing
168 physicists to place a lower limit on the SM Higgs mass. Between the end of LEP and the
169 start of LHC, an additional small mass interval around 160 GeV could be excluded at the
170 Tevatron. The outstanding precision of the LEP data and theoretical calculations based
171 on the SM provided an indirect sensitivity to the Higgs mass by quantum fluctuations,
172 e.g. loop corrections to the W and Z bosons, bounding it to be lighter than 157 GeV.

173
174 In 2010, data taking at the LHC started for the final assault. It was clear that the LHC had
175 the sensitivity to observe the Higgs boson in the remaining allowed mass range, using
176 the decay modes that were unambiguously predicted for a SM Higgs. Relatively soon one
177 could exclude a high mass Higgs of 200-600 GeV – in full agreement with LEP’s indirect
178 limits. With the rapid increase in data rate, both the ATLAS and CMS experiments

⁷ Cf. Ellis, Gaillard, Nanopoulos (1976).

⁸ More precisely, the Higgs potential has two parameters, one of which is related to the masses of the W and Z – bosons and connected to the vacuum expectation value v leaving one additional parameter that had not been determined before the Higgs discovery. It should be noted that in the SM the Yukawa couplings g , i.e. the Higgs couplings to the fermions are given by $g = \sqrt{2} * m_f / v$, m_f being the mass of the fermion. Therefore, the Yukawa couplings re-express the fermion masses but are not counted as extra free parameters.

⁹ One publication was even titled “The Higgs Hunter’s Guide” (Gunion et al. 1990).

179 reported, at a CERN colloquium on December 13, 2011, an excess of events that could be
180 taken as initial evidence for a new particle around 126 GeV. On the other hand, the
181 probability that this would be just a background fluctuation was still too high to claim an
182 observation. However, half a year later much more data had been accumulated, such
183 that both detectors presented, at a special CERN seminar, a signal of 5 standard
184 deviations each. The data correspond to a background fluctuation probability of about
185 10^{-9} , where the background is considered as SM without Higgs. By convention in particle
186 physics, this was sufficiently small to claim a discovery, an observation.¹⁰ A few weeks
187 later, the two experiments published their data. (Aad et al. 2012, Chatrchan et al. 2012).

188
189 Still, the data were not sufficient to definitely claim this to be the long-awaited Higgs
190 boson. Some important properties had not yet been confirmed, and the precision of the
191 measurements on production and decay properties was still marginal. On the other
192 hand, those properties that were observed corresponded to what is expected for a SM
193 Higgs boson. For instance, the particle had been found in two decay modes with rates
194 consistent with the expectation, and it had a mass in agreement with the direct and
195 indirect limits known from previous experiments. As of today (2017), more properties
196 of the discovered particle have been studied, the decay modes and the mass have been
197 measured to higher precision, in accordance with the SM. Even though there is still need
198 for further measurements, the majority among physicists now considers the new
199 particle is indeed the Higgs boson.

200
201

202 *2.2 Alternatives to the Higgs boson*

203

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

211

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

217

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

225

226 The two Higgs doublet model is of special interest in BSM considerations since it is the
227 minimally required Higgs sector in the framework of Supersymmetry, the most often
228 discussed extension of the SM. Supersymmetry assumes a new fundamental symmetry
229 of particles with integer and half-integer spins. In the context of LHC physics,

¹⁰ On the criteria when particle physicists claim ,evidence', versus ,observation' or ,exclusion' see the 'Prologue' to Franklin (2013).

230 Supersymmetry typically is studied in several variants of the MSSM ('minimal
231 supersymmetric SM') that contain a rather broad range of features that allow one solve
232 some basic problems of the SM. Among those is providing a Dark Matter candidate and
233 solving the naturalness problem (see below). Moreover, the MSSM is the only BSM
234 model that makes a firm prediction on the upper limit of the Higgs mass: it has to be
235 lighter than about 130 GeV, a limit that is much tighter than the range allowed by the
236 SM. (This limit of 130 GeV is valid for all SUSY models considered at the LHC and for
237 SUSY scales of some 1 TeV.)¹¹

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

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

253

254

255 **2.3 The Naturalness problem**

256

257 From a theoretical perspective, the existence of an elementary scalar Higgs boson
258 introduces an 'unnaturalness' into the SM. The concept 'naturalness' was introduced in
259 slightly different forms by 't Hooft (1979) and Susskind (1979). The problem itself has a
260 longer history (cf. Giudice 2008) and reaches beyond the context of the Higgs problem
261 (cf. Giudice 2013). During the past decades, naturalness has developed from a merely
262 technical problem into an influential guiding principle for BSM physics; that is,
263 extensions of the SM were developed with the explicit aim to remedy the naturalness
264 problem.

265

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

274

275 Introducing a cut-off mass where the theory would break down, leads to finite
276 corrections. In the case of the SM, this could be at the rather high Planck scale, where
277 gravity becomes important and the SM is known to be insufficient. Assuming such a
278 scale within the SM, in case of the Higgs mass, makes these corrections appear 'dramatic
279 and even bizarre' (Peskin and Schroeder 1995, p. 788); for instance, in order to keep the
280 square of the Higgs mass at its measured value of 125 GeV, corrections have to be

¹¹ There exists a small (logarithmic) dependence of this bound on the masses of the SUSY particles. Even if more Higgs multiplets exist, the bound would only rise to 150 GeV.

281 invoked that are more than 10^{30} times higher than the Higgs mass itself. Furthermore,
282 these corrections have to be fine-tuned over many decimal places. Although
283 theoretically viable and consistent, the magnitude of these corrections is considered
284 'unnatural'. Once this correction is defined the theory is completely consistent and any
285 dependence on the scale is eliminated.

286
287 During the past two decades, naturalness has arguably become the most influential
288 guiding principle for constructing and motivating BSM models. Or more specifically,
289 many physicists believed that if a SM Higgs boson existed, it would come with new
290 phenomena to keep the theory 'natural'. For instance, new symmetries, extra spatial
291 dimensions, or a composite Higgs boson built from smaller objects would avoid
292 unnaturalness. Allowing for corrections of just a few percent – as for the other sectors of
293 the SM – these new phenomena should be in the mass range of 1 TeV that is well
294 covered by the LHC. One has to be aware that there is no clear definition of when a
295 theory would become unnatural and there is a large freedom how much fine tuning is
296 considered acceptable. Yet once a bound on the acceptable fine tuning is set, it
297 determines the mass range at which new phenomena are expected. At any rate, thus far
298 there has neither been a direct observation nor any clear indirect indication from
299 precision studies that such a new effect exists.

300
301

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

303

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

314

315

316 ***3.1. The Philosophical Challenge of Naturalness***

317

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

329

330 The physicist James Wells (2015) considers (i) as the root of the problem, but
331 subsequently emphasizes the significant difference between the technical naturalness
332 (ii) and the absolute naturalness involved in fine-tuning that eventually goes back to
333 Dirac's classical worries about large dimensionless numbers. He elaborates an example
334 of an exotically augmented quantum electrodynamics (QED) that consistently

335 instantiates absolute naturalness at the expense of “more parameters, more fields, and
336 more complexity in the theory.” (2015, 107) He admits that this principle is
337 controversial, but believes, more generally, “that in the era of the Standard Model’s
338 ascendancy, the influence of simplicity and Ockham’s razor to theory construction has
339 paled in comparison to Naturalness.” (2015, 104)¹²

340
341 Grinbaum (2012) instead has argued that – in virtue of its complex nature – naturalness
342 is exclusively an aesthetic criterion. Williams (2015) rejects Grinbaum’s interpretation
343 because aesthetic criteria are notoriously ambiguous. Supersymmetry, for instance, is
344 considered most promising by many physicists, even though it is aesthetically attractive
345 in the unbroken state but aesthetically unattractive after its breaking produces a large
346 number of new constants. Borrelli (2015) argues, that it is precisely the vagueness of the
347 concept of naturalness that allows it to function as a useful common narrative of the
348 different subcultures of particle physics, the experimentalists and theoreticians

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

357 358 ***3.2 Epistemic and pragmatic criteria of theory choice***

359
360 Philosophers have traditionally distinguished epistemic and pragmatic criteria of theory
361 choice (or preference). The former, among them empirical adequacy and theoretical
362 consistency, are held to be rationally compelling. Pragmatic criteria have instead been
363 seen as a way to decide among epistemically equivalent alternatives by appealing to a
364 theory’s simplicity or other aesthetic features, or to its fruitfulness for further research.
365 Among the classical examples are the choice between a geocentric and a heliocentric
366 world view at the time of Copernicus and the early philosophical debates about the
367 nature and alleged conventionality of space and time. The philosophical significance of
368 these criteria of theory choice arises from the problem of underdetermination of theory
369 by empirical evidence that Pierre Duhem illustrated at the parallelism between
370 Newton’s corpuscular theory and Huygens’s wave theory of light. Duhem argued that
371 experimental data never uniquely determine a particular hypothesis because setting up
372 and confirming a hypothesis presupposes the correctness of many other hypotheses
373 including the theories governing the measurement devices. If one accepts some version
374 of the underdetermination argument, pragmatic and aesthetic criteria become more
375 relevant or even inevitable.

376
377 Underdetermination is also discussed under the rubrics of theory-ladenness of data or –
378 following Neurath and Quine – confirmational holism. This means that any experimental
379 result confirms or refutes both the theory or model under investigation and a large set
380 of other assumptions that are assumed to be true. Especially in Quine’s hands,
381 underdetermination and holism took a logical and semantic tack that not only ruled out
382 that empirical evidence could deductively entail scientific theories, but that additionally
383 seemed to imply that any theory could be rationally retained in the face of recalcitrant
384 evidence. Laudan has pointed out that, while the latter may be logically possible,

¹² 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).

385 scientists do not act “in an evaluative vacuum.” (1990, 276) To his mind, the non-
386 uniqueness of theory resulting from Duhemian underdetermination can be accepted
387 without adopting an egalitarian approach towards rival theories. Laudan and Leplin,
388 more generally, held “that the epistemic bearing of evidence on theory is ... subject to
389 reinterpretation as science grows and may be indeterminate at a particular point in the
390 process of growth.” (1991, 455) Norton, moreover, has argued that ampliative
391 inferences remain valid if underdetermination focuses locally, “on the confirmation of
392 hypotheses by scientists in actual scientific practice,” (2008, 23) rather than being taken
393 as a global challenge to its rationality. But overall the topic remains controversial (cf.
394 Stanford 2017). Since the present paper is concerned with the analysis of experimental
395 and theoretical practice, we are following Laudan in focusing on the scientific-practical
396 aspects of underdetermination This focus on scientific practice is also a better basis for
397 assessing the role of pragmatic and epistemic criteria of theory choice than debates
398 about the rationality of science globally.
399

400 Speaking of theory choice, philosophers of science have traditionally set pragmatic
401 criteria firmly apart from the epistemic criterion of empirical adequacy and all other
402 scientific questions that can be resolved within an explicitly formulated theoretical
403 framework (cf. Carnap 1950). Thomas S. Kuhn (1977) rejected this separation and
404 advocated a broader list of characteristics of a good scientific theory. It includes:
405 empirical “accuracy, consistency [internally and with respect to other theories], scope,
406 simplicity, and fruitfulness.” (1977, 322) These five criteria of theory choice are not
407 mutually independent; they are often context-dependent and may point in opposite
408 directions. For instance, an increase in accuracy can trivially be obtained by adding
409 additional parameters; yet scientists may prefer to make do with a smaller number of
410 fundamental quantities – or with a simpler law – even at the expense of some accuracy.
411 Thus, scientists have to assess the relative weight of these criteria when deployed
412 together. Both their form and the relative weight, to Kuhn’s mind, contain contextual
413 and idiosyncratic (psychological) factors. Kuhn was however at pains to argue that such
414 subjectivity does not render theory choice irrational or a mere matter of taste. Theory
415 choice, we might add, was not a major battle in the conflict between historical rationality
416 and historical contingency waged during the 1970s. Kuhn’s point was the historical and
417 factual nature of theory choice, not its contingency or arbitrariness. Historians often find
418 an increasing unanimity of individual choices in a certain field. Such factual unanimity
419 does not establish rationally binding criteria for theory choice. Instead of being rules of
420 an algorithm, the criteria of theory choice function “as values, which influence it. ...; they
421 do specify a great deal: what each scientist must consider in reaching a decision.” (1977,
422 331)¹³
423

424 Heather Douglas has proposed a finer-grained account in order to restore the separation
425 between epistemic and pragmatic cognitive values and reduce conflicts between them.
426 She distinguishes (i) minimal criteria applied to the theory per se, among them internal

¹³ Laudan reads Kuhn’s analysis of theory choice against the backdrop of scientific revolutions that represent breaks in rational justification. This rehearses, to Laudan’s (1990) mind, the holistic and egalitarian reading of underdetermination and provides a justification for the sociologizing of epistemology. Without entering into a broader Kuhn debate, it seems to us that once we limit ourselves to an epistemic or local understanding of underdetermination, the Kuhnian analysis of the values of a good scientific theory can still provide important insights into scientific practice. As Kuhn himself has emphasized, these values are only one element of theory choice, alongside sociological factors and inductive reasoning. Moreover, our goal here is not to find all determinants of theory choice, but to focus on the role of the epistemic and pragmatic criteria or values in the preference of models in elementary particle physics.

427 consistency; (ii) minimal criteria applied to the relation of theory and evidence, among
428 them empirical adequacy; (iii) desiderata applied to theories per se, among them scope,
429 simplicity, and potential explanatory power of a theory that largely “fall under the rubric
430 of the fruitfulness of the theory”. (2013, p. 800); (iv) desiderata applied to the relation of
431 theory and evidence, among them being supported by a broad range of empirical
432 evidence and not being contrived to match a small domain of facts in an ad hoc fashion.
433 While the values in categories (i) and (ii) are epistemic, category (iii) contains “strategic
434 or pragmatic values” (2013, p. 800) that help in “deciding which theory to pursue next”
435 (2013, 804)). Instead, group (iv) “provides assurance that our scientific claims are more
436 likely to be reliable.” (2013, p. 800) Moreover: “While simplicity, scope, and explanatory
437 power are often thought to pull against each other when considering theories alone
438 (group iii), they pull together when considering a theory in relation to evidence (group
439 iv).” (2013, 803)

440

441 Perhaps, the most important pragmatic criterion in the history of particle physics is
442 simplicity. Most influential has been the quest for a simple unified theory of all
443 fundamental forces.¹⁴ Simplicity also stands behind particle physicists’ long-time
444 worries about the many parameters that are needed to make the SM empirically
445 adequate. As Baker (2013) rightly observes, it is quite challenging to pin down the
446 notion precisely. Many authors distinguish elegance (typically attributed to a theory)
447 and parsimony (Ockham’s razor that directs us not to introduce unnecessary entities).
448 Both aspects of simplicity may come into conflict. For instance, the introduction of
449 supersymmetric partners to all fundamental particles reduces the basic components
450 into chiral super multiplets, thus reducing the complexity of the theory. The elegance of
451 an exact symmetry between fermions and bosons in the unbroken theory disappears
452 once a breaking mechanism is introduced, which leads to a large number of additional
453 parameters.

454

455 From the interviews and questionnaires, we will analyse in Sect 7.3 and 7.4 how particle
456 physicists understand and weigh epistemic and pragmatic values and how they assess
457 the criterion of naturalness in BSM models. Applying the philosophical debate about
458 those values to model preferences within a variegated model landscape has certain
459 consequences on how to interpret such preferences further. We are following Kuhn and
460 Douglas in speaking about values rather than criteria, and will also speak about
461 preference instead of choice even in cases, such as supersymmetry or not, where the
462 latter terminology could be appropriate.

463

464

465 ***3.3 Making experiments crucial***

466

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

475

¹⁴ 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.

476 This widely shared conviction among physicists prompts the question whether the
477 Higgs discovery represented a crucial experiment in a philosophical perspective? Let us
478 take a closer look. The term ‘crucial experiment’ originated with Francis Bacon and
479 became influential through Newton and his demonstration that sunlight consisted of
480 rays exhibiting different behaviours. A crucial experiment, in this traditional
481 understanding, unambiguously and definitively confirms a hypothesis or decides
482 between rivalling hypotheses. Pierre Duhem objected on the basis of the
483 underdetermination argument.

484
485 This philosophical context has made scholars wary about crucial experiments, especially
486 if they understood underdetermination as a primarily logical and global problem and
487 followed Duhem in allowing only deductive inferences between theories and data.¹⁵
488 While some emphasized that falsifications of a theory were more likely to be crucial
489 experiments than corroborations, Lakatos famously objected to this asymmetry and
490 bluntly stated: “No experiment is crucial at the time it is performed (except perhaps
491 psychologically).” (1974, 320) His main argument was that the assessment of each
492 experiment can only be performed against the backdrop of the entire research program
493 it is embedded into and against its competitors. Thus, designating an experiment as
494 crucial is partly a historical assessment.

495
496 The idea that a crucial experiment is embedded into a broader program is also the core
497 of a recent debate about crucial experiments in biology. Weber (2009) defends the
498 characterization of an experiment as crucial, not within the traditional contexts of
499 deductive reasoning and the refutation of alternative hypotheses, but by developing “an
500 experimentalist version of inference to the best explanation.” (2009, 21) Hypotheses are
501 not refuted, but positively selected as those best supported by the evidence. Weber’s
502 strategy to defend the Meselson-Stahl experiment as crucial is now to show that both
503 parts of Duhem’s problem, the problem of untested auxiliaries and the problem of an
504 exhaustive partition of theoretical alternatives (including the unconceived ones)¹⁶, can
505 be kept at bay. To this end he develops a holistic account of experimental mechanism
506 that includes both a model of the mechanisms producing the phenomena and parts of
507 the experimental system, among them “the characteristic manipulations and
508 measurement devices used.” (2009, 34) Baetu (2017) has criticised Weber’s
509 reconstruction and argued that the Meselson-Stahl experiment was inconclusive for the
510 hypotheses considered. Instead, “it was part of a broader research project aiming to
511 elucidate the mechanisms of DNA replication” (2017, 4.) – which ultimately led to the
512 development of new experimental techniques. “Thus understood, the experiment
513 extended over a decade or more. However, the crucial experiment account attributes all
514 or most of the impact of the whole series of experiments to a single set of experimental
515 results.” (2017) In the same vein as Lakatos put it, an experiment becomes crucial only
516 in historical reconstruction and within the context of a broader research program.

517
518 We believe that the Weber-Baetu debate rightly follows the trend diagnosed in Sect. 3.2.
519 to view underdetermination and crucial experiments as an epistemic and factual
520 problem rather than a logical and semantic one. In this way, the first aspect of Duhem’s
521 problem, the auxiliary hypotheses, becomes embedded into an experimental research

¹⁵ Note that Duhem actually believed that experiments could be crucial. But this could not be inductively inferred from the data, but required the *bon sens* of the physicists. While *bon sens* might have been a useful notion in Duhem’s days, it seems to us too vague for large-scale experiments in particle physics. At best one might take *bon sense* as an umbrella term for the detailed set of experimental strategies given by Franklin (2013).

¹⁶ Cf. Stanford (2006) who shows that it is difficult to find cases where the underdetermination was not eventually resolved.

522 program. The reference to turn to in the present context is of course Franklin's (2013)
523 philosophical reconstruction of the history of modern particle physics. There Franklin
524 distils a list of reliable strategies that in effect allow one to keep Duhem's problem at bay
525 and address the related problem of theory-ladeness of large-scale particle experiments.
526 Beauchemin's (2017) autopsy of measurements with the ATLAS detector¹⁷ can be read
527 as a continuation, into the days of LHC, of Franklin's (2013) history of the reliable
528 experimental strategies and rules of data analysis that characterize contemporary
529 elementary particle physics. We will take up some of these strategies in Section 7.2. and
530 discuss how they permit us to consider the Higgs discovery as a crucial experiment. Let
531 us however first assess Franklin's assessment of crucial experiments.

532
533 Franklin and Perovic (2015) compare two ground-breaking particle physics
534 experiments. While they classify the discovery of parity violation as a crucial
535 experiment, the discovery of CP-violation represented only a 'persuasive experiment'.
536 "The difference lies in the length and complexity of the derivation linking the hypothesis
537 to the experimental result, or to the number of auxiliary hypotheses required for the
538 derivation." (2015, 85) Indeed, physicists had speculated about parity violation before,
539 and the observed effect was maximal. CP-violation was completely unexpected, but most
540 theoreticians quickly settled for it. Franklin and Perovic consider this acceptance as a
541 "pragmatic solution of the Duhem-Quine problem." (2015, 84). In the case of the Stern-
542 Gerlach experiment, as reconstructed by Franklin and Perovic, the diagnosis of cruciality
543 underwent several changes. By discovering the space quantization
544 [*Richtungsquantelung*] predicted by the Bohr-Sommerfeld quantum theory, it became a
545 crucial watershed between classical and quantum physics, but not by confirming the
546 latter theory. For what Stern and Gerlach actually measured was a new quantum
547 phenomenon, electron spin, that was only postulated after the experiment. Thus, the
548 experiment "was regarded as crucial at the time it was performed, but, in fact, wasn't. ...
549 A new theory [quantum mechanics] was proposed and although the Stern-Gerlach result
550 initially also posed problems for the new theory, after a modification of that new theory
551 [the integration of spin], the result confirmed it. In a sense, it was crucial after all. It just
552 took some time." (2015, 40-41)¹⁸

553
554 These examples also indicate that establishing experimental evidence and deciding
555 whether an experiment is conclusive or even crucial, is largely a factual question and
556 involves different time scales. Acquiring precision data sometimes represents a long-
557 term process that involves previous experiments and is continued in the experiment
558 itself. The actual discovery of a particle instead represents a precisely dated event;
559 scientists decide after a detailed statistical analysis that the evidence is sufficient.

560
561 Using the Higgs discovery, in 7.2 we will argue that the diagnosis of Franklin and Perovic
562 seems to us counterintuitive because it makes the characterization of an experiment as
563 crucial or not depend on short-term development of scientific theorizing. In Section 7.2.,
564 we will provide a different characterization according to which all three examples
565 mentioned qualify as crucial experiments.

566
567 **4. The methods of this project**

¹⁷ Note that Beauchemin's concept of theory-ladeness is wider than the one typically used in the philosophical literature, where theory-ladeness represents a problem for empirical science, not a feature that can be exploited by clever experimenters.

¹⁸ 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. Notice that while Stern wanted to test quantum theory, Gerlach himself considered the experiment as part of a broader experimental research program.

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

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

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

The lists of physicists to which the questionnaires were sent both in 2011 and 2012 were obtained from the INSPIRE data base (Dallmeier-Tiessen, S., Hecker, B., Holtkamp, A; 2016) maintained centrally at CERN. This data base is established by surveying journals, conferences, books, theses etc. in the pertinent fields and listing all authors. For the purpose of the questionnaire, authors in the categories 'hep-ph' (phenomenology), 'hep-th' (theory), 'hep-ex' (experiment) were contacted. In total this amounted to some 15000 authors. About half of the authors are theorists belonging to about the same amount to either the 'th' or 'ph' category, the other half experimentalists. Taking into account that some 8000 experimental physicists are directly involved in the LHC experiments, with an additional number of several thousand theorists, the list of physicists included probably almost all those who are actively working on LHC physics. Certainly, some physicists on the list were somewhat remote from LHC experiments or theory, e.g. mathematical theorists or accelerator physicists, but also some retired physicists or those who had left the field. It is difficult to assess, how large a fraction this was.

The anonymous replies were collected and statistically evaluated at Wuppertal. There were 1435, respectively 903 replies to the two questionnaires, which corresponds to a return rate of 10%, respectively 6% which is acceptable for empirical studies that are combined with interviews. Our goal had not been to obtain a truly representative sample in the sense of quantitative sociology. Still, there seems to be no strong bias in our replies: the regional distribution of respondents is consistent with the regional distribution of physicists working in LHC experiments, and also the fraction of theorists and experimentalists agrees with the fraction in the list. Yet, there are discrepancies as regards seniority: only few PhD students (<5% of the replies) have answered the questionnaires, whereas they amount to about a third in the LHC experiments. In the

622 following, the replies were considered separately for experimentalists and theorists
623 because this promised some interesting insights. In addition, the comparison of the
624 replies before and after the discovery should indicate certain trends in the thinking of
625 the LHC physicists.

626
627 In addition to the questionnaires, 9 (6) LHC physicists were interviewed around April
628 2011 (September 2012). Both groups included experimentalists from different LHC
629 experiments and theorists. Furthermore, it was attempted to cover a wide range of
630 interests and responsibilities within the LHC project. There is only a small overlap
631 between the physicists in the two rounds; this was done deliberately in order to obtain a
632 broader picture. The physicists interviewed and their respective roles at the time of the
633 interviews are listed in Appendix 2. In the following discussion, no names will be
634 assigned to the respective citations.

635
636 Each interview took about an hour. A few topics were addressed in every interview, for
637 instance: in 2011, the prospects of a Higgs discovery, the perceived status of super-
638 symmetry, and the chances to find new physics; in 2012, the impact of the Higgs
639 discovery on the interviewee's research. On the other hand, the interviews were kept
640 flexible to better understand the reasoning and preferences of each interviewee. This
641 included, depending on the answers of the counterpart, also questions about the work
642 environment, the methods of research, which outcome is expected at the LHC and why,
643 and which outcome would be preferred on theoretical or pragmatic-aesthetic grounds.

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

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648 At the beginning of our empirical study, the physical situation was characterized by an
649 excellent performance of the LHC and its experiments. The year 2011 brought an
650 unexpectedly large amount of data at the energy of 7 TeV. Based on this understanding,
651 the LHC physicists performed simulation studies predicting that the whole range
652 pertinent to the mass of a Higgs boson could be covered at the LHC within two years. On
653 the other hand, although a broad range of searches for new effects had been performed
654 by fall 2011, no sign for any of the many postulated extensions of the SM had been
655 found. In particular, no indication for Supersymmetry was observed. Supersymmetry
656 had been highly favoured by theorists, and it was predicted that its particles could be
657 detected shortly after the LHC launch. Supersymmetry is the only BSM model that
658 provides a strict constraint on the highest allowed mass of the Higgs boson (of about
659 130 GeV). The sensitivity of many of these searches for new physics reached the energy
660 scale of about 1 TeV, at which the naturalness problem should have been resolved
661 before the corrections become too high.

662

663 ***5.1 Outcome of questionnaires***

664

665 In total 1435 physicists answered the questions, with the number of theorists (769) and
666 experimentalists (696) being about the same. The number of replies to each of the
667 questions differed only by a small amount. Assuming multinomial distributions and an
668 outcome for an answer of 50%, these numbers imply a typical error margin on the
669 answers of 1.5% for the total sample and 2% for each subgroup. The precise uncertainty
670 depends on the number of answers given; the fewer there are, the larger is the relative
671 uncertainty. Where relevant, the exact uncertainties will be provided.

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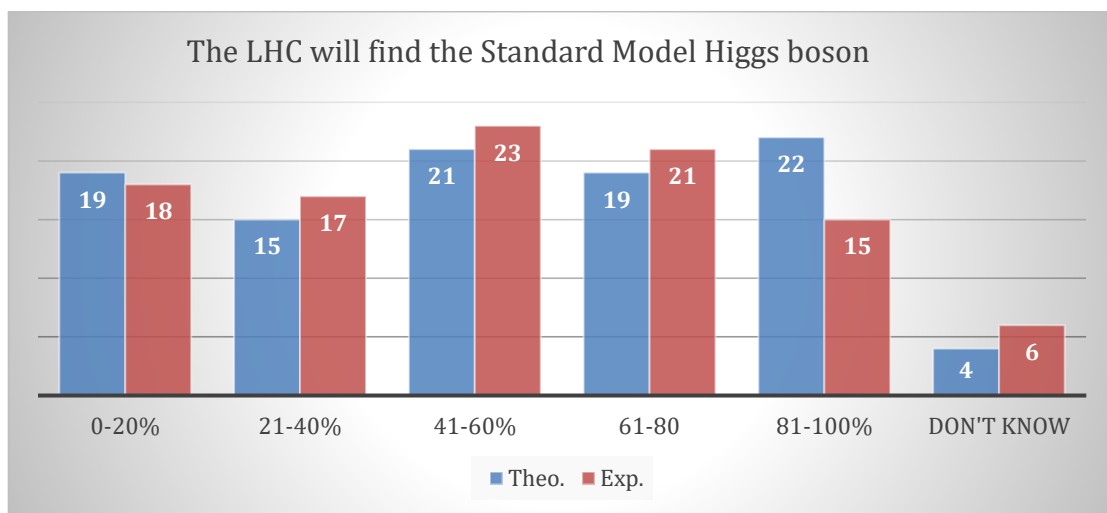
674 ***5.1.1 The importance of the origin of mass***

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676 The high expectations that physicists had in the LHC to understand the mechanism of
 677 mass generation become most apparent in the replies to a question about the
 678 importance of LHC results for several key problems of current physics. Participants
 679 were asked whether they fully agreed, somewhat agreed, were undecided, somewhat
 680 disagreed, or fully disagreed with the statement: 'LHC results will be very important to
 681 understand ...'. Close to 50% (48%/49% of the theorists/experimentalists) chose to
 682 'fully agree', and close to 80% (77%/80%) at least 'somewhat agreed' on the importance
 683 of the LHC for the 'origin of mass'. Comparable results were obtained for two other
 684 topics from the SM, 'strong interactions' and 'flavour physics', while the outcomes for
 685 BSM physics were much lower. The as of then only undiscovered element of the SM was
 686 accordingly given the highest priority among all the potential features that could be
 687 found at the LHC.

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5.1.2 Expectation on finding the Higgs Boson at LHC



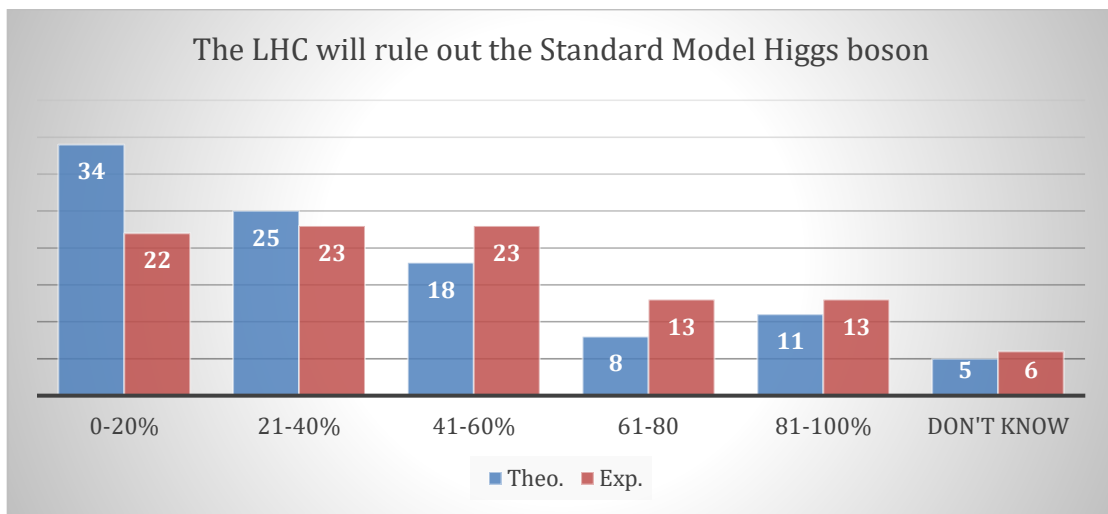
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Fig.1 Percentage of answers of theorists (blue) and experimentalists (red) assigning probabilities in intervals of 20% on the chance that the LHC will find a Standard Model Higgs Boson (Questionnaire of 2011)

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

715 A second question addressed the ‘*personal estimate of the probability ... that the LHC will*
 716 *rule out the Standard Model Higgs boson*’. In this case 59%/46% of the
 717 theorists/experimentalists considered the probability low (i.e. smaller than 40%). On
 718 the other hand, only 19%/26% (uncertainty about 2.5%) estimated that the SM Higgs
 719 boson could be ruled out with high probability (i.e. larger than 60%). Low probability
 720 here means either that the SM Higgs boson will eventually be found or that a candidate
 721 is found whose properties cannot be measured precisely enough to rule out other
 722 interpretations. High probability instead means that the LHC will be able to definitively
 723 rule out the SM Higgs particle because there is no such particle or it will find one or
 724 more candidates that accomplish mass generation with properties different from the SM
 725 expectations. The responses showed that, in 2011, theorists were more sceptical about
 726 the LHC to rule out the SM Higgs boson than experimentalists.
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 733 *Fig.2 Percentage of answers of theorists (blue) and experimentalists (red) assigning probabilities in*
 734 *intervals of 20% on the chance that the LHC will rule out a Standard Model Higgs Boson*
 735 *(Questionnaire of 2011)*
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737
 738 Although the two last questions are closely connected, there are subtle differences that
 739 lead to somewhat different replies. Firstly, the fraction of physicists that assigned an at
 740 least 60% probability to *find* the SM Higgs boson is smaller than the fraction of
 741 physicists who assigned an at least 60% chance that it will *not be ruled out*. Secondly,
 742 whereas the answers of theorists and experimentalists were rather consistent with the
 743 first question, a significantly larger portion of theorists than experimentalists
 744 considered it unlikely that the SM boson will be ruled out.
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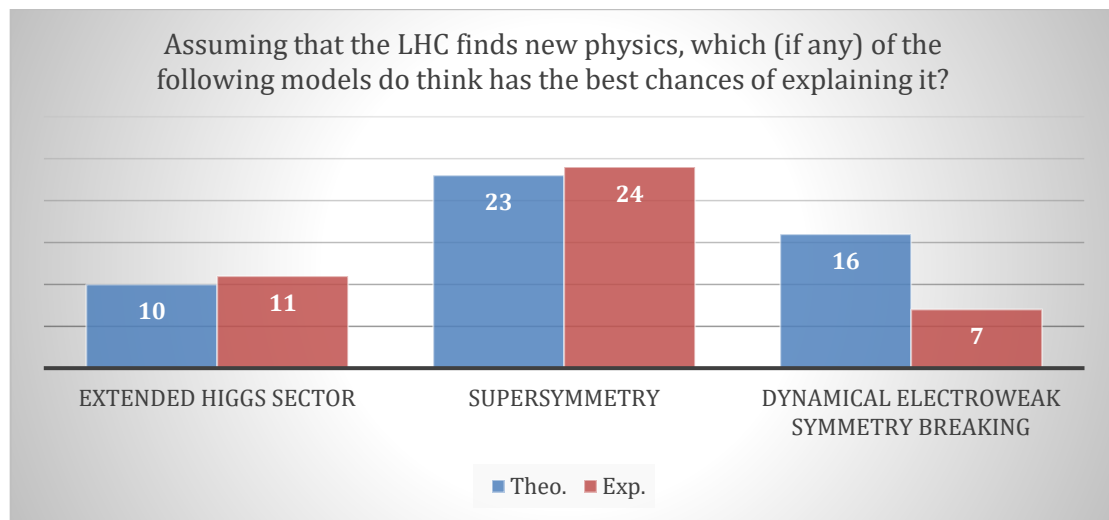
746 The first difference is probably related to the much stricter requirement to confirm not
 747 only the existence of a new particle, but to determine all of its properties to a precision
 748 that allows one, e.g., to distinguish it from alternative models of EWSB. Especially in the
 749 case of a more complicated Higgs group structure (as favoured by many physicists – see
 750 below) it will be more difficult to unambiguously identify the particle to be a SM Higgs
 751 boson than to rule it out. How-to interpret the differences between experimentalists and
 752 theorists is more difficult. In general, the replies – and the interviews below – indicate a
 753 greater reluctance of experimentalists to commit themselves to what their data will
 754 finally reveal.

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

5.1.3 Expectations on various EWSB models

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

795 above, one of the Higgs bosons in the extended sector might have properties very
796 similar to the SM Higgs.

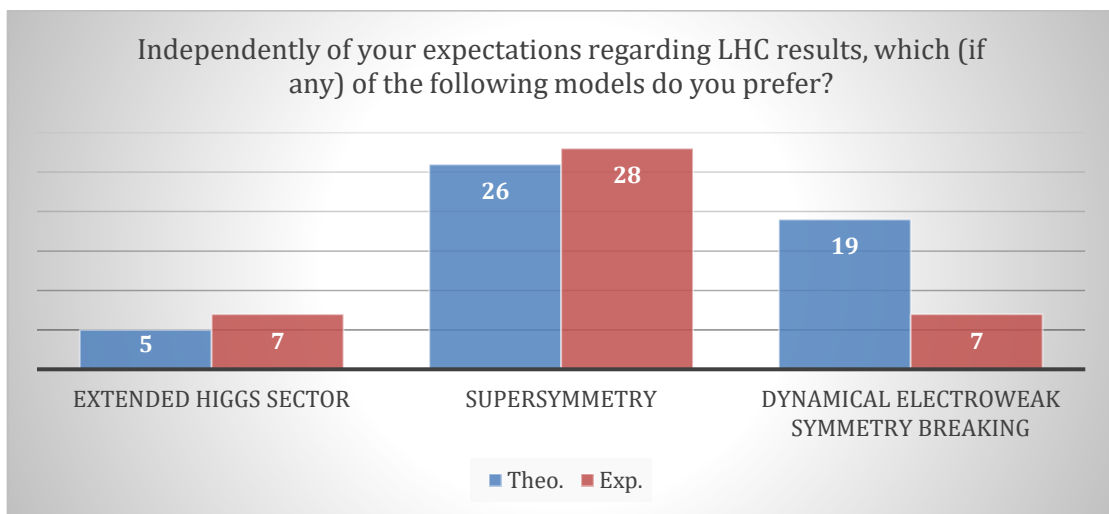
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798 In addition, a sizeable fraction of theorists ($16\pm 1.3\%$) expected a dynamically generated
799 electroweak symmetry breaking, leading to a composite scalar particle with several
800 properties that are distinctively different from the SM Higgs boson. As discussed in Sect.
801 2.3., at least the historically first such model, Technicolour – a model that also contained
802 the least additional assumptions –, had been strongly disfavoured by data. This might be
803 the reason why only $7(\pm 1)\%$ of the experimentalists chose this option.

804

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

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

816

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

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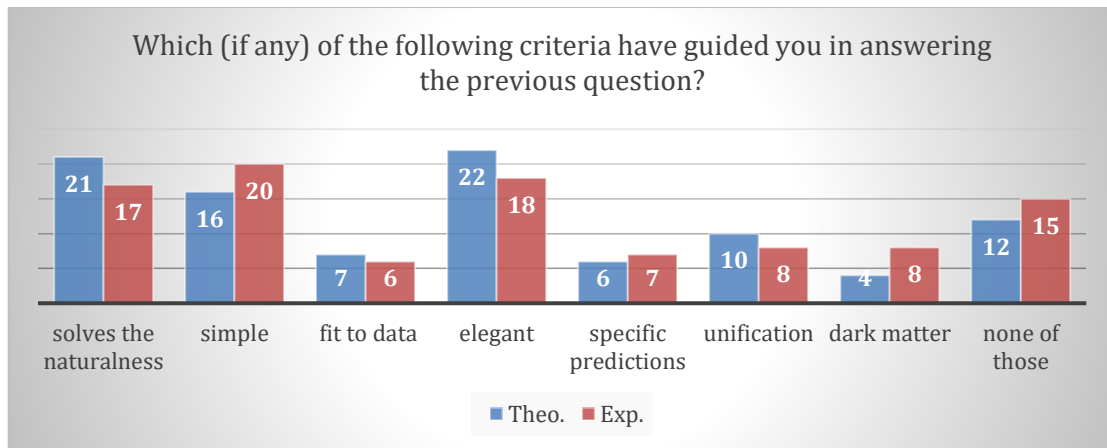
826 5.1.4 The importance of the naturalness criterion

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828 The question as to the preferred model was followed by the question ‘*which (if any) of*
829 *the following criteria have guided you in answering the previous question?*’. Four ranked

¹⁹ 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.

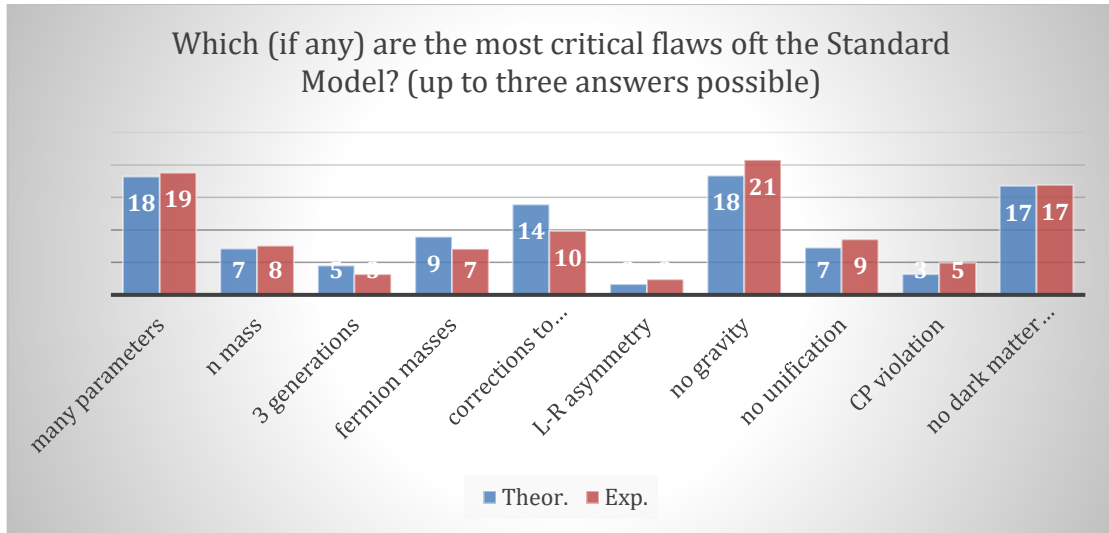
830 choices were allowed (Fig. 5). Considering only the first choice, the criterion that a
 831 model ‘solves the naturalness problem’ was preferred by 21%/17%. It is thus
 832 considered as important as the classical pragmatic, or rather aesthetic, criteria of
 833 ‘elegance’ (22%/18%) and ‘simplicity’ (16%/20%)²⁰. More ‘factual’ criteria like the
 834 model ‘will provide a better fit to the data’, or ‘makes specific predictions’ or even ‘has a
 835 candidate for dark matter’ are much less considered (each one below 10% for both
 836 experimentalists and theorists).
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 842 *Fig.5 Percentage of answers of theorists (blue) and experimentalists (red) on the criteria to choose*
 843 *the preferred model. (Questionnaire of 2011).*
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845 Physicists were further asked ‘*what (if any) are the most critical flaws of the Standard*
 846 *Model*’, and could make up to three unranked choices (Fig. 6). Indeed the problem of
 847 ‘*quadratic divergences in corrections to the Higgs mass*’, causing the naturalness problem,
 848 was mentioned often by theorists (14%), while only by 10% of the experimentalists
 849 (statistical uncertainty of difference 2.2%). However, quadratic divergences are
 850 considered less of a flaw of the SM than its many parameters (18%/19%), the absence of
 851 gravity within the Standard Model framework (18%/21%), or that it does not include a
 852 Dark Matter candidate (17%/17%).
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²⁰ 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 - simultaneously emphasize that the terminology often is all over the place.



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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.

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Both of these questions refer to SM properties that point beyond its limits. But they do so from a somewhat different perspective. The first (Fig. 5) had asked for the motivations of model preferences in Fig. 4, that is irrespective of the chances to soon find solutions at LHC. The second (Fig. 6) asked for flaws of the SM, irrespective of the existence of a credible model or strategy to resolve them. In both questions naturalness, respectively quadratic divergences, scored within the top group of the list and matched their counterparts, the pragmatic values of preference simplicity and elegance, and respectively (among the flaws), the many parameters of the SM.²¹ However, the differences in the relative weights for other elements pointing BSM, e.g. for Dark Matter, are significant. To our mind, this has to do with the different perspectives of the questions. There are several proposals of physics BSM, however no universally agreed upon Dark Matter candidate. Nevertheless, it is a significant flaw of the SM, even though it may be only solved in the longer term. Naturalness, instead, is of immediate relevance to problems of model builders and guides expectations for BSM at the LHC. Experimentalists and theorists largely agree in this attitude.

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5.2 Responses in interviews

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The questionnaires were complemented by interviews with nine theorists and experimentalists²². Overall, their statements were consistent with the outcomes of the questionnaire. Yet they provide a deeper insight into the reasoning of elementary particle physicists at the time. In particular, they illustrate the rather diverse set of attitudes and the broad variety of expectations among the physicists. The following selected quotes are related to the mechanism of EWSB.

²¹ The “many parameters” of the SM (Fig. 6) are traditionally seen as a principal lack of simplicity and motivate physicists to devise other models. In the same vein, the “quadratic corrections to the Higgs mass” (Fig. 6) amount to a peculiar technical feature in the renormalization scheme for the scalar Higgs boson that motivates models “solving the naturalness problem” (Fig. 5). In Section 5.2.3. we will provide some evidence from interviews that notwithstanding the philosophical distinctions discussed in Section 3.1., naturalness is largely treated in the same fashion throughout the community of particle physicists.

²² For the list of names, see the table in Appendix 1.

885 **5.2.1 Crucial, Long-Awaited, but Uncertain: Does the Higgs boson exist?**

886

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

896

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

906

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

919

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

927

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

935

936 **5.2.2 Is the Higgs mechanism attractive?**

937

938 While the expectation as to the possible discovery of the Higgs boson was an issue of

939 considerable suspense at that time, the motivations to expect or reject the Higgs
940 mechanism, differ among the physicists. Already in the above statements, it became
941 apparent that the mechanism, even if expected, was regarded with some reservations.
942

943 There were several values of theory preference in play. One theorist held that the Higgs
944 mechanism is also disfavoured *,because of its minimal predictive power'*. Instead the
945 alternative scenario of strong EWSB is intellectually favoured. *'Whereas the dream would
946 be, in a dynamical theory of electroweak-symmetry breaking ..., there is at least a
947 conceivable possibility of making definite predictions, however they should turn out.'* This
948 requires a *'somewhat bigger theory'*. The scepticism is also shared by experimentalists.
949 One stated drastically, *'the Higgs is a totally ad hoc thing. If the Higgs is not there, it
950 will not surprise me.'* He argued that *'people had faith in it the way people have faith in
951 God'*. Another experimentalist held, that even if the *'Higgs will be found, ... the Higgs
952 mechanism seems not elegant'* and there are *'very attractive theories without the Higgs'*.
953

954 In fact, only a few physicists interviewed emphasized the broader virtues of the Higgs
955 boson beyond merely giving a solution for one specific problem. One theorist focussed
956 on its role in the more encompassing theory of Supersymmetry, which as mentioned
957 gives an upper bound of the Higgs mass. It would be *'very disappointing to find Higgs at a
958 mass compatible with SM at high energies [above 130 GeV]'*. *'If the Higgs boson is light as
959 suggested by the data [i.e. indirect measurements and left-over phase space masses], then
960 presumably super-symmetry is a prototype of such a weakly interacting extension of the
961 standard Higgs mode'*, i.e. the virtue of the Higgs mechanism is its accordance with a
962 larger and generally favoured theory. On the other hand, the interviewee points out, that
963 the favoured variant of supersymmetry, has been so tightly tested without finding
964 anything. Therefore, one finds oneself in *'a weird situation '*.
965

966 Moreover, one theorist rejected the statement that the Higgs mechanism is complicated
967 and ad hoc, but emphasised the virtue of introducing spontaneous symmetry breaking
968 into particle physics in general. The Higgs discovery would then be seen as something
969 new *'in the sense of new particles, but it is a break-through since you have the
970 experimental test of spontaneous symmetry breaking'*. Moreover, this general idea would
971 be *'not immediately thrown away'*, if the Higgs boson would not be found.
972

973 **5.2.3 The problem of naturalness**

974

975 Several interviews stressed the value of naturalness as a pragmatic guideline. Yet as
976 regards its aesthetic aspects, opinions differed. One theorist became a proponent of
977 Supersymmetry once it was shown to solve the naturalness problem; *'so for me the big,
978 sort of change in my world view came when people pointed out that super-symmetrical
979 particles could potentially control the quantum corrections and make the theory more
980 manageable.'* Another theorist, who was asked whether the naturalness or the hierarchy
981 problem were serious, answered more cautiously: *'now to assess this, one goes back to
982 these convictions somehow that the progress of science is always driven by an aesthetic
983 judgement that goes beyond mechanical relations between formulas, equations and the
984 need to see beyond. In other words, when you see some recurrence, when you see some
985 "accident", it is natural for a scientist to consider the possibility that it is not an accident
986 but there is something beyond and then this accident becomes natural. Now, this is not
987 always correct, there are many accidents that we witness around that are not driven by the
988 first principles but just accidents. So in that respect one can be wrong, but for the issue of
989 naturalness, all of it, so called problems of the standard model, the picture is quite
990 compelling.'* Only one experimentalist was explicitly asked about naturalness. Again,
991 there was no strong commitment, but instead it was *'take[n] easy, it is a matter of taste'*.
992 Note that the interviewees did not distinguish between naturalness, fine tuning of the

993 quantum corrections, and quadratic divergences.

994

995

996 **6. The physicists' response to the discovery of a Higgs candidate**

997

998 A year after the first questionnaire was sent out and the interviews had been performed,
999 a sufficient amount of data was collected by the LHC experiments to provide the desired
1000 sensitivity for a SM Higgs boson in almost the whole remaining mass range. Indeed, in
1001 July 2012, the observation of a new boson was announced. Since the signatures were
1002 consistent with the expectations, there was a very broad consensus that this particle
1003 was a very strong candidate for a SM Higgs. However, the properties known by then
1004 were few, and the precision of the measurements was still marginal²³. The simultaneous
1005 searches for new effects BSM remained inconclusive, although the mass reach and
1006 sensitivity was extended.

1007

1008 Shortly after the announcement, a new questionnaire was sent to the same mailing list
1009 and a new round of interviews was performed. One of the main aims was to understand
1010 if, respectively how, the views and expectations of physicists had changed.

1011

1012 **6.1 Outcome of the Questionnaire in 2012**

1013

1014 The second questionnaire was sent out in September 2012. To a large part, the
1015 questions were identical to those of the first questionnaire. In this survey 903 physicists
1016 replied, among them 464 theorists and 439 experimentalists. The typical statistical
1017 uncertainty in the replies is therefore 1.7% for the whole sample and 2.4% for each of
1018 the subsamples. The relative uncertainty of the answers between the two
1019 questionnaires depends on whether the same or different physicists replied. In the
1020 former case the relative uncertainty would be very small, in the latter case some 2.3%
1021 (for the whole sample). Since the answers were given anonymously, there was no way to
1022 tell. Compared to the first round the possibility of ranked answers was restricted to a
1023 single choice only or to unranked options. The subjective degrees of belief in a statement
1024 (cf. 4.1.1.) were rephrased as 'fully agree', 'somewhat agree', etc.

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1027 **6.1.1 What is the new particle?**

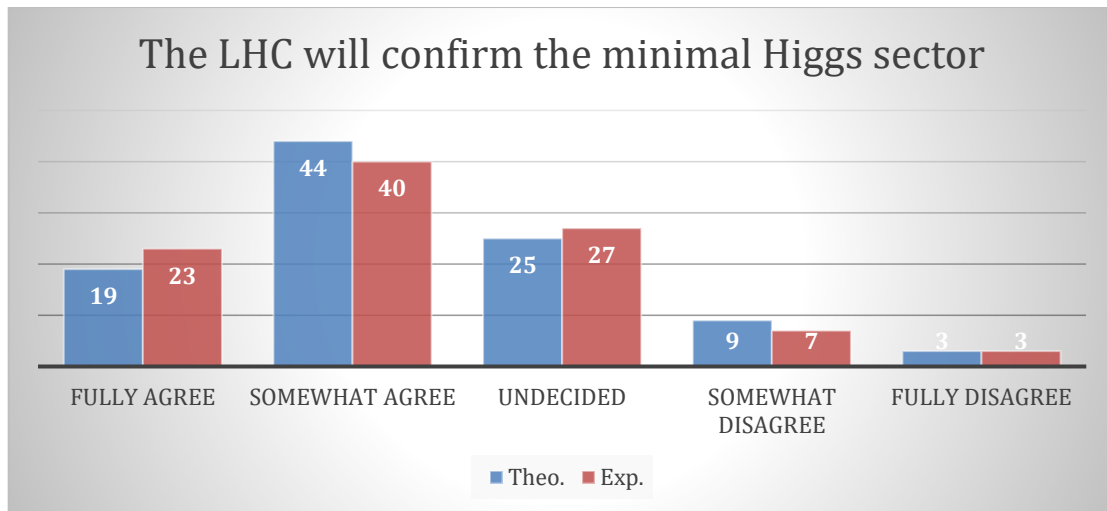
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1029 Reacting to the discovery of the new particle, a set of questions was directed at its likely
1030 significance for the SM and beyond. The first statement to be evaluated was *After the*
1031 *discovery of the new particle at 125 GeV, the LHC will confirm the minimal Higgs sector*.
1032 The majority of both experimentalists and theorists (63%/63%) fully or somewhat
1033 agreed with this statement (see Fig. 7). Compared to the first questionnaire²⁴, this is, not
1034 surprisingly, a significant increase from the 41%/36%. Still, only 19%/23% 'fully
1035 agreed' that LHC will confirm the minimal Higgs sector of the SM.

1036

²³ 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.

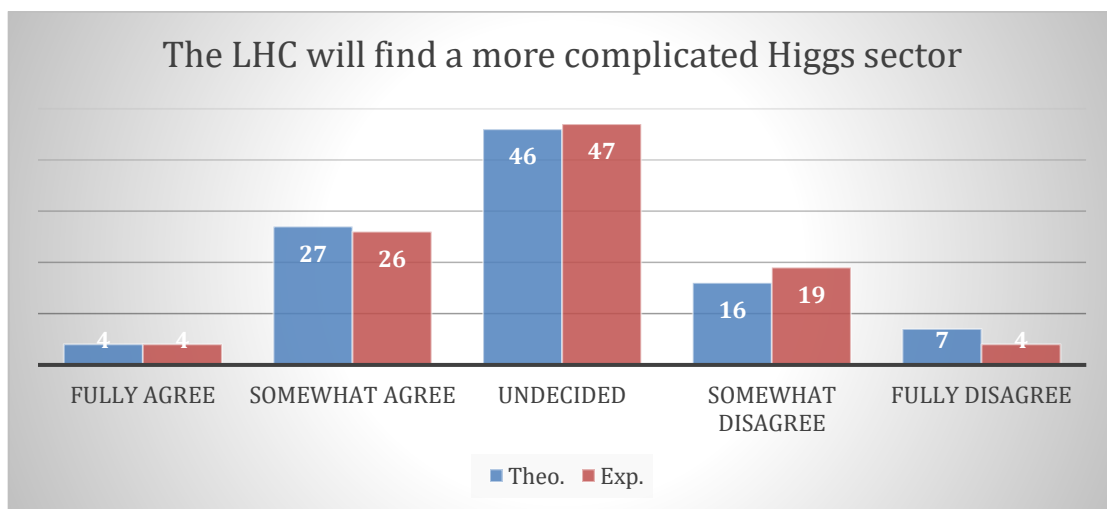
²⁴ As a reminder, the exact wording of the first questionnaire was *'What is your personal estimate ... that the LHC will find the Standard Model Higgs boson'*.



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Fig.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)

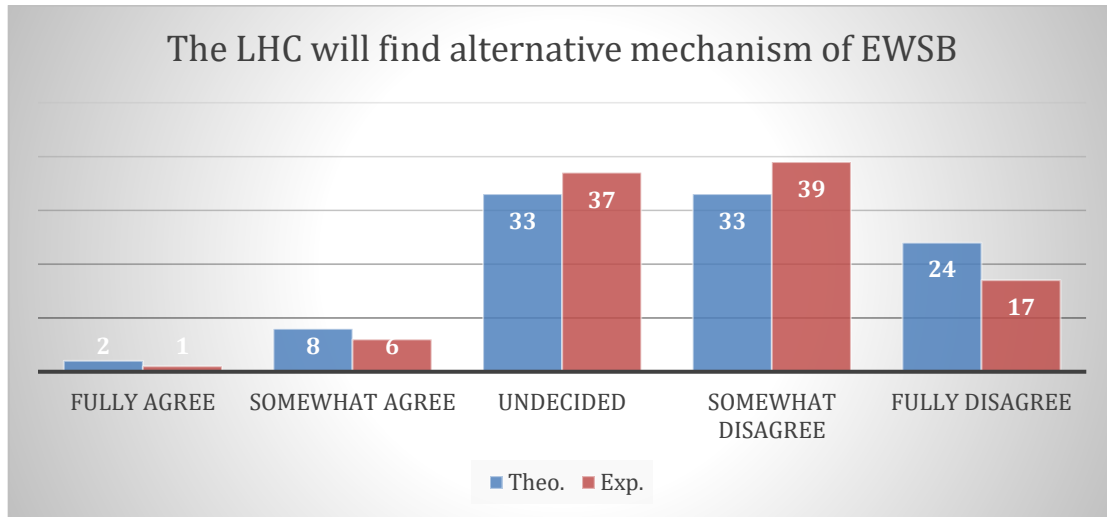
This question combined two aspects: whether the observed particle was indeed a Higgs boson and whether it would remain the only Higgs boson, i.e. the SM Higgs boson. This ambiguity could be somewhat resolved by asking a second question, to wit, whether the LHC will 'find a more complicated Higgs sector'; 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.



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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)

1064 The third question asked if the LHC will *'find an alternative mechanism of EWSB'* (Fig. 9).
 1065 It was only a minority of roughly 10% that agreed at least 'somewhat' with this
 1066 statement. Full agreement was at the 1% level. Given the discovery of a Higgs candidate
 1067 shortly before the questionnaire, such a result is not surprising. Even though the LHC
 1068 data available at that stage were still marginal, the consistency with what is expected for
 1069 a SM Higgs boson disfavoured a radically different mechanism already then. Although a
 1070 third of the replies were undecided, the vast majority of physicists no longer expected
 1071 any radically new physics to emerge in the sector of mass generation.
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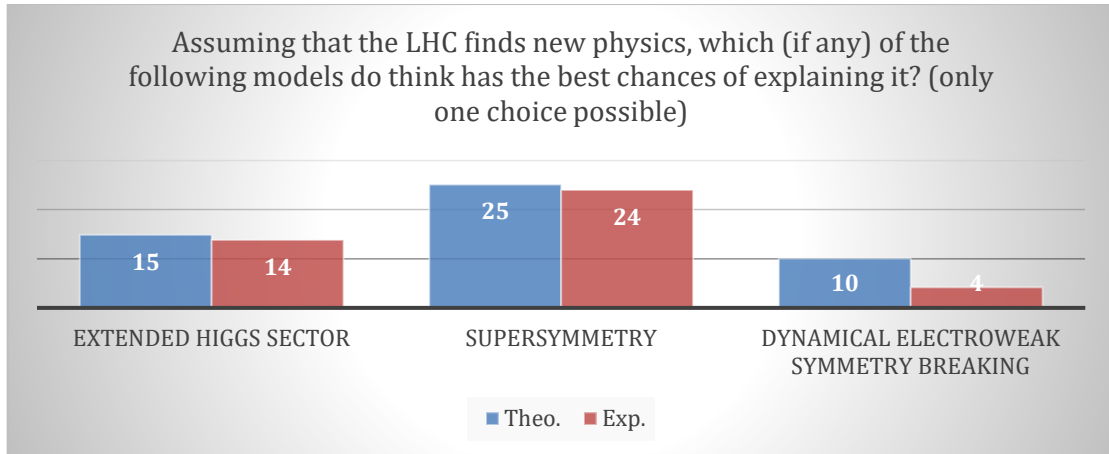


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 1075 *Fig.9 Percentage of answers of theorists (blue) and experimentalists (red) assigning probabilities in*
 1076 *intervals of 20% on the chance that the LHC will find an alternative mechanism of EWSB*
 1077 *(Questionnaire of 2012)*

1080 **6.1.2 Which alternatives to the SM Higgs are still considered?**

1081
 1082 Whereas the new particle was largely considered to be a Higgs boson, its discovery
 1083 initially did not preclude it to be, or involve, an element of new physics. Hence physicists
 1084 were again asked: *'Assuming that the LHC finds new physics, which (if any) of the*
 1085 *following models do you think has the best chance of explaining it?'*. However, while in
 1086 2011 two ranked choices were possible, only one was allowed in 2012 (Fig. 10). To
 1087 compare the two surveys, only the first choice of 2011 is considered here.
 1088

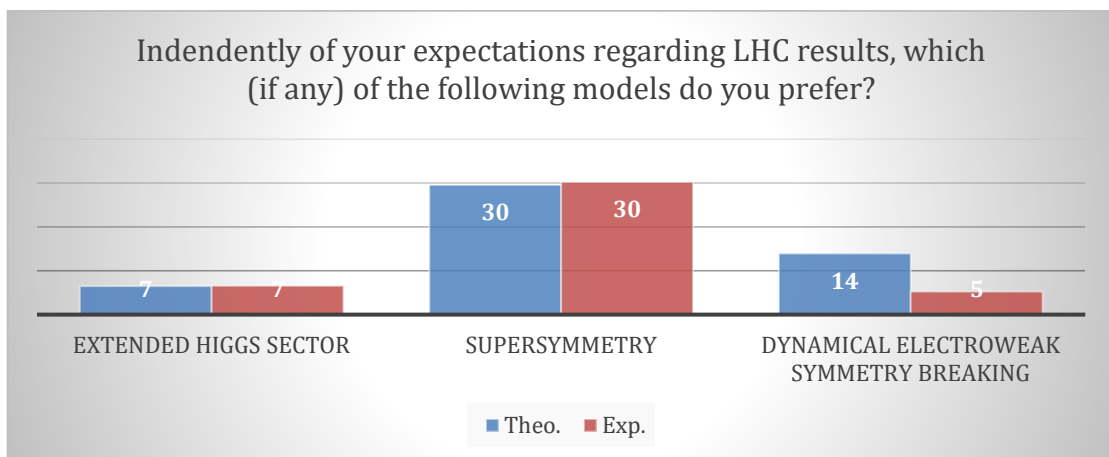
1089 Some 40% favoured extended Higgs sectors either with or without Supersymmetry, an
 1090 increase from the about 34% in 2011. Going into more detail, the fraction of those who
 1091 assumed Supersymmetry to explain new physics did not change with the discovery
 1092 (25%/24% from 23%/24% as the first choice in 2011). Given that Supersymmetry was
 1093 the only theory to predict such a light Higgs boson (cf. Sect. 2), its discovery could be
 1094 seen to have strengthened the case for supersymmetry. On the other hand, none of the
 1095 expected direct signals of Supersymmetry had been found, seemingly balancing the
 1096 indirect support from the Higgs mass. General extended Higgs sectors have gained some
 1097 ground in 2012 (increase from 10%/11%, as first choice in 2011, to 15%/14% in 2012).
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Fig.10 Percentage of answers of theorists (blue) and experimentalists (red) on the most likely 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).

In contrast, the fraction of physicists considering dynamical EWSB as the best chance was reduced to almost half between 2011 and 2012. Just 10%/4% of theorists/experimentalists advocated for it after the observation of a Higgs candidate (previously 16%/7%). Even in spite of the limited parameter space of composite Higgs models, the number of proponents was still remarkable among theorists. The replies to the question *Independently of your expectations regarding LHC results, which (if any) of the following models do you prefer?* (Fig. 11), hardly changed. There was only a small decrease in the responses for dynamical electroweak symmetry breaking (14%/5% after 19%/7% in 2011). Thus, a significant minority among theorists prefers a solution of EWSB that is different from the Higgs mechanism, even though many do not believe this to be realised at LHC energies. This testifies the tenacity of theories that are attractive on internal grounds, that have strong pragmatic virtues, notwithstanding negative empirical results as long as there remain at least some options to adapt them to 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).

1128 **6.1.3 How was the naturalness problem seen after the Higgs candidate?**

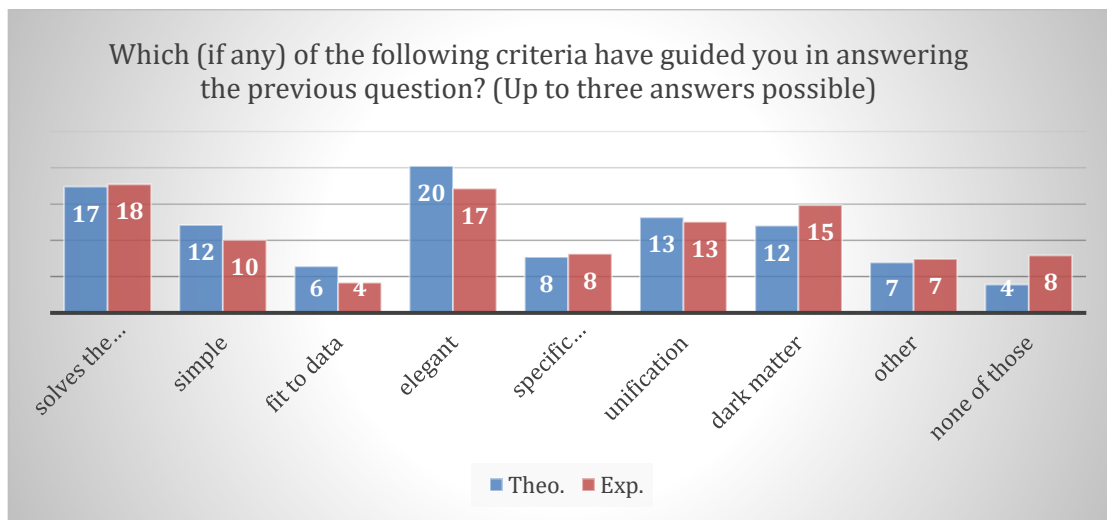
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1130 With the discovery of the Higgs candidate, i.e. the likely existence of an elementary
 1131 scalar, it appeared that the naturalness problem had changed from a potential problem
 1132 to an actual one. It could no longer resolve itself by the absence of a scalar from the set
 1133 of fundamental particles. Furthermore, no BSM signal had been found to alleviate these
 1134 concerns. We therefore tried to understand whether the physicists' assessment had
 1135 changed after the Higgs discovery.

1136

1137 As in 2011, physicists were asked for the criteria, 'which have guided' their selection of
 1138 the preferred model, irrespective of the chances of confirming it at LHC. (Fig. 12) The
 1139 attitude towards naturalness, however had hardly changed after the observation of a
 1140 Higgs candidate. Naturalness was mentioned in 17%/18% of all answers, only mildly
 1141 behind the criterion of 'elegance' (20%/17%), but clearly ahead of simplicity
 1142 (12%/10%).

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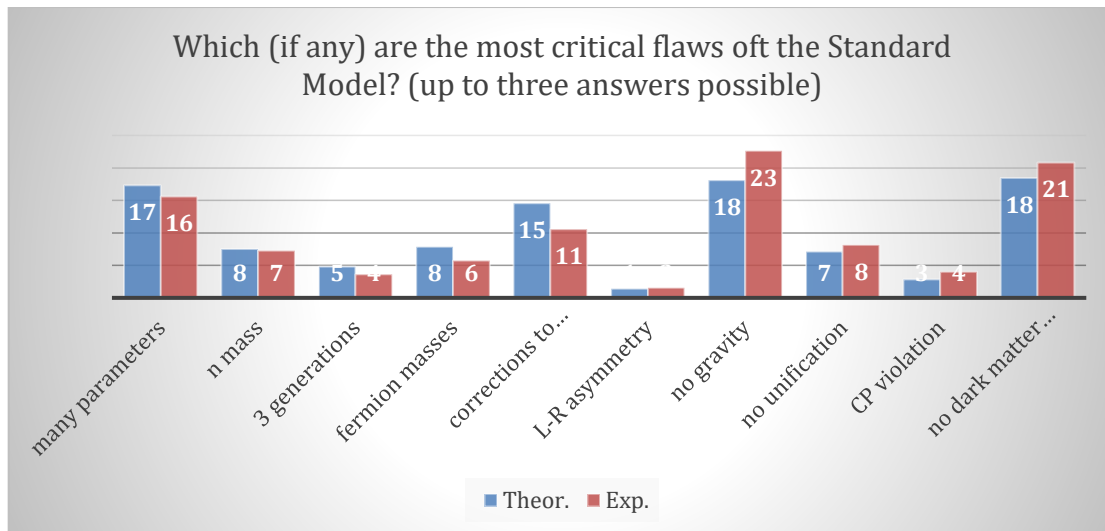
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1146 *Fig.12 Percentage of answers of theorists (blue) and experimentalists (red) on the criteria to choose*
 1147 *the preferred model (Questionnaire of 2012). The three choices were added up.*

1148

1149 The other question pertinent to assessing the physicists' attitude towards naturalness
 1150 was again the 'most critical flaw of the Standard Model'. (Fig 13) As in the 2011 survey
 1151 up to three choices could be given. As before 'quadratic divergences in corrections to
 1152 Higgs mass' remained at 15%/11% (compared to 14%/10% in 2011) as one of the three
 1153 major flaws. Also most of the other assessments were fairly similar. A notable exception
 1154 was that experimentalists now tended to consider the absence of a dark matter
 1155 candidate' (21% after 17%) to become more critical. In both cases the replies from
 1156 theorists did not change significantly. After the discovery of the Higgs boson, it seems,
 1157 experimentalists shifted their interest to the next problem, which they thought to be in
 1158 reach of the LHC, dark matter, even though there was no consensus about a suitable
 1159 theoretical model, or whether such a dark matter candidate would be at all in the energy
 1160 range of the LHC.

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

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Both questions show that the perceived importance of the naturalness problem has not been affected by the change in the problem's specific status. A possible reason for this stability is that epistemic and pragmatic criteria, once adopted by the community, usually operate on a longer time scale. It takes a certain record of scientific successes to support them – as has been the case with the naturalness principle, at least in the eyes of the particle physics community.²⁵ That said, one may expect that after years of unsuccessful searches for BSM physics, naturalness would become much less attractive.

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6.2 Outcome from interviews in the light of the discovery

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

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A large part of the interviewees characterized the Higgs discovery as an '*exciting*' event that would have decisive implications on future research. Overwhelmingly physicists cautioned to jump to immediate conclusions about the details of the SM Higgs boson. One interview partner expressed this very clearly '*well, we still do not know what we observed*'. But: '*It would have surprised me more if it would not be it [the Higgs boson]. This is in some sense paradoxical, since it is just something one got used to*'. Despite all caution there was agreement about the next steps.

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6.2.1 From the observation to scrutiny

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The focus, both experimentally and theoretically, was now to qualify this boson and look whether it was the SM Higgs boson or whether it had new physics in its wake. An experimentalist noted '*At this stage we observe a new particle ... with properties*

²⁵ Guidice (2008) shows that there the record of the naturalness principle becomes mixed if one assumes a broader perspective; and one might even consider the fortunes of fine-tuning arguments more general. However, we are restricting our considerations to the understanding and role of naturalness within the community of elementary particle physicists.

1197 *consistent with the Standard Model Higgs. This can change if we find something that*
1198 *does not fit into the Standard Model'. But also theory is required to improve the precision*
1199 *of the predictions of Higgs properties 'If you don't see new physics directly, then maybe we*
1200 *see it through precision measurements, indirect tests.'*

1201
1202 In this sense, the new particle is seen as a potential harbinger of new physics, not the
1203 closure of a research program. 'Higgs physics' changed from searching for the Higgs
1204 boson towards measuring the properties of the new particle, assuming it to be 'largely'
1205 the Higgs boson, but also searching for deviations from its precisely predictable
1206 properties.

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1209 **6.2.2 The implication on other models**

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1211 As discussed above, Supersymmetry predicted the Higgs boson to be lighter than 130
1212 GeV. It would have been in deep troubles, had the Higgs been found at a larger mass.
1213 After unsuccessful searches for direct signs of Supersymmetry, the mere consistency of
1214 the measurements with its prediction, was taken as indirect support. One theorist says '*if*
1215 *it had been 140 GeV or 150 – that would have changed a lot, because then my SUSY-models*
1216 *would all be dead. And I would stop working on them.'*

1217

1218 Another impact of the Higgs discovery on BSM models is that, within the experimental
1219 uncertainties, it provides additional constraints. Indeed, in this perspective '*the*
1220 *discovery of the Higgs' is the main... result that influences our work', a theorist explained;*
1221 *'when we [work on] models we have to take... into account ... this particle and this*
1222 *changes... the situation definitely'. Its existence and even the marginal precision of*
1223 *autumn 2012 constrains the allowed parameter space of BSM models, 'the determination*
1224 *of parameters of models or the testing of models I continue to do, now including the*
1225 *information from the Higgs. And that has changed something in the interpretation'. E.g. to*
1226 *determine the allowed parameter space in supersymmetric models. 'What would be a*
1227 *125 GeV Higgs [in super symmetry]? Of course, a SUSY Higgs, but what a parameter space*
1228 *would be compatible with this? It would be a very small one.'* In this sense the discovery of
1229 the Higgs candidate has severe implications for many models, at least in limiting
1230 significantly the allowed parameter range. This is of course an effect that becomes
1231 poignant on a larger timescale when it may eventually squeeze out certain models
1232 entirely. Such an effect was not yet visible in the changes of model preference between
1233 the 2011 and 2012 questionnaires.

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1236 **6.2.3 Shedding doubt on the previous guiding principle of naturalness?**

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1238 As mentioned in 5.1.3, the naturalness problem in 2012 turned from fiction to reality.
1239 This can also be gathered from the interviews. '*I would say that now that it is certain*
1240 *that there is a Higgs state at this mass, [the naturalness problem] is more alive than ever'.*
1241 And at least some continue to consider it an important question. Naturalness '*is still an*
1242 *important argument. I cannot see any reason, why should happen something like that, such*
1243 *[fine – tuning] just in a natural way. we put this fine-tuning by hand, ... it cannot happen*
1244 *in nature.'*

1245

1246 Naturalness continues to be seen as an important guiding principle for the development
1247 of BSM models. "*We need the guidelines. Because, it's not just the experiment, it's not just*
1248 *mathematics. It's something, which is between induction and deduction. ... And you need ...*
1249 *some guidelines. One guideline could be this naturalness, ... which is a theoretical guideline.*
1250 *Or, 'minimality', one theorist argued, that is, for a model to have the minimal number of*

1251 free parameters.

1252

1253 However, this was not the only reaction. The unnaturalness of the SM becomes more
1254 acute since none of the anticipated solutions in terms of New Physics has shown up in
1255 the energy range where it was expected, a fact that was considered highly disturbing.
1256 This dilemma leads to a growing discussion about the status of the naturalness problem:
1257 *'is this problem a real problem or just a fantasy of theoretical physicists? I've been*
1258 *trained to look at it as a serious problem'*. Yet another theorist raises doubts: *'what we*
1259 *thought was a main motivation to expect Supersymmetry at the LHC, this hierarchy*
1260 *problem or naturalness problem, I'm not so sure anymore whether this is actually*
1261 *something that leads us into the right direction.'* *'People have just accepted the fact that*
1262 *there is more and more fine-tuning now, because of the limits that become larger and*
1263 *larger. And it's not so clear to me whether it's still a good idea to consider that'*. Similarly
1264 another theorist argued, *'We can discuss whether... we have to accept fine-tuning. What*
1265 *could be behind a fine-tuning ... or if one wants a natural theory without fine-tuning. ...*
1266 *This is the main argument which ... I think, drove ... the theoretical community for the last*
1267 *twenty or thirty years. But it's not a solid argument'*.

1268

1269 To sum up, the discovery of the Higgs boson, together with the absence of any sign of
1270 new physics, has turned naturalness from a potential into a real theoretical problem.
1271 While before the discovery of the Higgs boson physicists might have expected that
1272 naturalness could be restored by a different mechanism of EWSB, LHC has now
1273 confirmed the unnatural Higgs mechanism, yet without finding evidence for a potential
1274 solution outside the EWSB sector. It is true, naturalness could still serve as a guideline
1275 for devising new models. But the absence of a cure for the naturalness problem of the
1276 SM has made some physicists wonder whether it is actually a deep problem or whether
1277 one should simply accept fine-tuning as a fact about nature and accept models that
1278 violate naturalness. Therefore, the naturalness problem was still considered to be
1279 important in the questionnaires, but the interviews showed that its previous importance
1280 was put into question. Throughout the interviews, there was no indication that
1281 physicists considered the naturalness problem as multifaceted or vague. Instead they
1282 interchangeably denoted it as hierarchy problem, fine-tuning, or quadratic divergences.
1283 In Section 7.4., we will discuss how this coherence in scientific practice squares with the
1284 differences in philosophical analysis.

1285

1286

1287 **7. Some philosophical lessons**

1288

1289 In this Section we interpret the outcome of interviews and questionnaires in light of the
1290 questions mentioned in the Introduction.

1291

1292 **7.1 Scepticism before and after a crucial test**

1293

1294 In retrospect, it might appear that the Higgs discovery had been largely expected. Our
1295 studies show that, in actual fact, the expectations of the LHC physicists were fairly
1296 diverse. At least shortly before a Higgs candidate was discovered, the community was
1297 basically split whether to expect the observation of a SM Higgs or not. (cf. 5.1.2) They all
1298 were aware that LHC had sufficient luminosity to accomplish such a crucial test. The
1299 reluctance to embrace the SM Higgs boson is in line with wide-spread criticism of the
1300 conceptual structure of the Higgs mechanism. None of the interviewees emphasised its
1301 theoretical elegance, some even considered it an ad-hoc argument. This reluctance is in
1302 contrast to especially Supersymmetry, which is frequently considered as too beautiful a
1303 theory that nature should not have chosen it – regardless whether it is realised in the
1304 LHC energy range. The proponents of the Higgs mechanism simply regarded it as the

1305 'best' solution for mass generation that had come to the physicists' mind over the course
1306 of more than four decades. It did not contradict any measurement, was compatible with
1307 a wider theory, and had only relatively few parameters.

1308
1309 On the other hand, after a candidate with the 'right' mass and with properties consistent
1310 with the expectations had been observed, most LHC physicists-almost immediately
1311 embraced the notion that 'a' Higgs boson had been found – although they left it open
1312 whether it would be the only one. This overwhelming acceptance came, although the
1313 precision of the measurements still left quite some room for alternative solutions of
1314 EWSB. (cf. 6.1.1. & 6.2.1) In fact, one of the main research directions after the
1315 observation of the Higgs candidate, both experimentally and theoretically, became to
1316 scrutinize how large a parameter space for alternative solutions would be left. Whereas
1317 the vast majority did not consider solutions radically different from the SM, such as a
1318 composite scalar, as realistic, there was considerable hope to find deviations from the
1319 SM expectations that would give physicists a hint how to further investigate the complex
1320 landscape of BSM models. (cf. 6.1.2) When doing so, most data analyses after 2012
1321 assumed the existence of a SM Higgs boson at 125 GeV, at least as the best
1322 approximation of the observed boson. This represented a significant discontinuity in the
1323 actual experimental strategy.

1324 1325 **7.2. Was the Higgs Discovery a Crucial Experiment?**

1326
1327 In the interviews, the discovery of a Higgs boson was widely considered as extremely
1328 important for particle physics. This accords with the many statements in the literature
1329 during the last decades²⁶ and the significant material and intellectual resources that
1330 went into large experimental facilities to solve the problem of EWSB. This widely shared
1331 conviction among physicists that the problem of EWSB was at the crossroads of particle
1332 physics at large prompts the question as to whether the Higgs discovery represented a
1333 crucial experiment in a philosophical perspective? In Section 3.2 and 3.3, we have
1334 discussed underdetermination and its impact on the feasibility of crucial experiments
1335 and other ground-breaking experiments.

1336
1337 In this section, we argue that the underdetermination argument can be contained to
1338 such an extent that it does not play a role in actual scientific practice. On this basis we
1339 also argue that the Higgs discovery can indeed be considered as a crucial experiment.
1340 Even though the Higgs discovery – as shown in Section 7.1 and emphasised in many
1341 physics papers – was not a simple yes/no experiment, its cruciality, to our mind, rests
1342 upon the following characteristics:

- 1343
- 1344 a. The Higgs boson was an essential and indispensable element of the SM.
1345 Moreover, the Higgs discovery was the final confirmation of a theoretical
1346 framework that had been developed over decades. Of course, the SM would also
1347 have broken down if, e.g. no Z^0 boson would have been found. But the Higgs,
1348 belongs to a sector of the SM that had not been seen before and is based on the
1349 additional concept of spontaneous symmetry breaking, for which no evidence
1350 had been observed before.
 - 1351
 - 1352 b. The Higgs boson is fundamentally different from all particles found up to date
1353 because it is an elementary scalar. It is not the first scalar found, but e.g. the pion
1354 has been shown to be composed of two quarks and gluons.
 - 1355

²⁶ See, e.g. Ellis, J., Gaillard, M.K., and Nanopoulos D.V. (2012), Quigg (2007).

1356 c. In view of the importance of the EWSB mechanism, a plethora of alternative
1357 models had been constructed. The discovery of the Higgs boson basically
1358 eliminated several families of these alternative models, and reshaped the
1359 direction of future research in a fundamental way.

1360
1361 Whereas a. and b. emphasise the crucial importance of a Higgs discovery for the SM and
1362 the general concept of elementary particle, characteristic c. widens the traditional
1363 philosophical understanding of crucial experiments which required that only one model
1364 survives. However, even if some alternatives may remain viable, the crucial experiment
1365 drastically reshapes the field. In the next paragraphs we argue that the crucial nature of
1366 an experiment as complex as LHC has to be judged against the backdrop of the historical
1367 development of the respective field.

1368
1369 Let us assess the acceptance of the observed particle being a Higgs in more detail.
1370 Immediately after the announcement at CERN in 2012 and the first measurements of its
1371 mass and decay modes, there was a flood of theoretical analyses, significantly reducing
1372 the possible parameter space of the many previously developed BSM models. Some
1373 models, among them 'higgsless models' and 'higgs-gauge unification', were strongly
1374 disfavoured and did not play a role in the subsequent discussions. Others, like 2HDM
1375 were more difficult to reject at this stage. As becomes apparent from the questionnaire,
1376 even only a few months after the discovery was announced, alternative models for
1377 EWSB were only expected by less than 10% of the respondents. (cf. 6.1.1.).

1378
1379 During the following year – with more data being analysed and additional properties
1380 being searched for, especially the spin – the notion of 'having found a Higgs boson' was
1381 adopted by the majority of the LHC physicists. The notion of 'a' Higgs boson leaves open
1382 the option of having a more complicated Higgs sector than the SM Higgs. In principle this
1383 can be resolved by higher experimental precision and additional searches, however, the
1384 precision will never be perfect in the future, such that small deviations from the SM
1385 Higgs cannot be ruled out with 100% certainty.

1386
1387 In this situation physicists are moving forward in their research accepting the SM Higgs
1388 boson to exist. This consensus was not based on logical inference, in the sense that
1389 physicists waited until all alternative solutions were definitively excluded.²⁷ It contained
1390 a certain dose of pragmatism in choosing promising research strategies. Such a
1391 'pragmatic solution' to the Duhem-Neurath-Quine problem, as Franklin and Perovic
1392 (2015, 84) have aptly put it, does not preclude intensive future scrutiny of the signal
1393 both from an experimental and theoretical side. Just the opposite: this scrutiny leads to
1394 the emergence of a very significant new research direction. This persistent search for
1395 potential deviations is not, to our mind, in conflict with the Higgs discovery being
1396 crucial. To the contrary, such explorative searches that do not test models already
1397 proposed by theorists, can be seen as one way to address the problem of unconceived
1398 alternatives.

1399
1400 Let us discuss now more specifically how Duhemian underdetermination is openly
1401 addressed within the statistical data analysis. First, the discrimination of two (or
1402 several) hypotheses, framed in an identical theoretical environment, as the SM in
1403 particle physics, with the same (kind) of experiments is (almost) completely free of
1404 detailed theoretical considerations. For in such cases the well accepted and identical
1405 procedures are applied to either of the hypotheses. Duhemian underdetermination and

²⁷ 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.

1406 theory-ladenness are shielded off by referring in the same way to an entire experimental
 1407 set-up. This vastly reduces their sway among scientists.²⁸ Second, theory ladenness is
 1408 significantly alleviated by using precision data from LHC and other experiments and the
 1409 familiarity with experimental strategies, among them the rules of data analysis and the
 1410 knowledge about background processes. The Higgs discovery, accordingly, was part and
 1411 parcel of a longer tradition of accelerator experiments and the associated theoretical
 1412 research programs.

1413
 1414 One can formalize the physicists' handling of Duhem's problem as such. We denote the
 1415 observed number of events of a certain signature²⁹ of scattering process by O , T_1 and T_2
 1416 are two theoretical hypotheses and A_i a set of auxiliary hypotheses. The P_i denote the
 1417 predictions to measure a number of events given hypothesis T_i and the auxiliary
 1418 hypotheses. We then have³⁰ in a simplified notation omitting the uncertainties of T_i , A_i ,

1419
 1420 $(T_1 \& A_1 \& A_2 \& A_3 \& \dots A_n) \models P_1, O \models P_1$
 1421

1422 Duhem argues correctly that O can also be inferred from (e.g.)

1423
 1424 $(T_2 \& A_1 \& A_2 \& A_3^* \& \dots A_n) \models P_1, O \models P_1$
 1425

1426 A_3^* being an alternative auxiliary hypothesis. The two-pronged strategy by which
 1427 particle physicists deal with the Duhem problem can be expressed as such. Using the
 1428 identical auxiliary hypotheses for an experimental and theoretical environment allows
 1429 one to test T_1 and T_2 . Most importantly, each of the auxiliary hypotheses has been
 1430 experimentally tested under multiple conditions. Theoretical assumptions are kept
 1431 minimal and, if needed, they also have been tested extensively. Therefore A_3^* can be
 1432 excluded, leading to

1433
 1434 $(T_2 \& A_1 \& A_2 \& A_3 \& \dots A_n) \models P_2, O \not\models P_2,$
 1435

1436 which allows physicists eventually to discriminate between T_1 and T_2 .

1437
 1438 Let us be more specific about the auxiliary hypotheses. They include the known physics,
 1439 rules of data analysis, criteria of statistical significance (cf. Beauchemin 2017). Some of
 1440 these auxiliary hypotheses have been extensively tested before LHC was even built,
 1441 others can be tested in-situ using the redundancy of LHC experiments.

1442
 1443 In the actual practice of particle physics, the T_i and A_i are only known to some statistical
 1444 and systematic uncertainty. This implies that also the predictions P_i have uncertainties,
 1445 i.e. $(P_i \pm \delta_i)$, where the δ_i are convolutions of the uncertainties of the individual A_i and T_i .
 1446 As a result, instead of a strict agreement or disagreement of the predictions with the
 1447 observation O , only a finite likelihood $p_i(O|P_i)$ can be assigned taking into account the
 1448 uncertainty of P_i . Duhem's problem therefore reappears in probabilistic terms. To keep
 1449 underdetermination at bay, to resolve Duhem's problem in scientific practice, two
 1450 additional conditions must be met. The first one is to confirm not only the correctness of
 1451 the A_i , but also all their individual uncertainties. This is done simultaneously with the

²⁸ Assuming the proper functioning of cables and switches is not to say that such errors do not occur. But it seems to us that those are not the kind of victories that advocates of a strong global notion of underdetermination (cf. 3.2.) would want to score. As Franklin (2013) shows, interesting failures of experiments are of a different kind.

²⁹ We will provide a more detailed analysis of the role of signatures in a subsequent paper that draws on the respective material from the questionnaire and the interviews.

³⁰ Note that \models does not amount to deductive entailment in the original Duhemian sense.

1452 extensive tests of the A_i (cf. Mättig 2019). Secondly, this probabilistic reasoning may in a
1453 strict (and naïve) manner be interpreted as impossibility to decide between T_1 and T_2 ,
1454 even if p_2 is ridiculously small, say 10^{-40} . To ‘exclude’ such meaningless hypotheses T_i ,
1455 the actual scientific practice defines conventions on the minimum magnitude of the p_i to
1456 accept a hypothesis.

1457
1458 This shows that by embedding the actual experiment into a broader context and by
1459 distinguishing the different layers of theorizing and experimentation, crucial
1460 experiments are possible. Duhem’s underdetermination can be addressed in scientific
1461 practice. This also agrees with Weber’s intuition discussed in Sect. 3.3. that experiments
1462 are embedded into a broader experimental program and partially takes up Baetu’s point
1463 that such a program may not only contain the purported crucial experiment. LHC has
1464 always tested other models and done exploratory searches alongside testing the SM.
1465

1466 Having dealt with Duhem’s problem, let us discuss more generally what it takes to make
1467 an experiment in particle physics crucial. The Higgs discovery clearly was essential for
1468 the SM, but why was it not simply a ‘persuasive experiment’ in the sense of Franklin and
1469 Perovic? (cf. 3.3) After all, different mechanisms of EWSB are still being discussed even
1470 though – as we have seen in Sect. 6.1. – they are starting to draw less interest. Franklin
1471 and Perovic’s distinction is based on the complexity of the inference \models and the number
1472 of auxiliary hypotheses required. But this seems to be problematic for large experiments
1473 like LHC that use many auxiliary hypotheses that are tested by different research
1474 groups. Taking into account also their analysis of the Stern-Gerlach experiment, it
1475 appears to us that the requirement of an immediate acceptance or refutation of
1476 competing models makes the notion of a crucial experiment subject to matters of short-
1477 term historical developments in the sense that that the status of the P violation
1478 experiment could have changed if some months later some alternative explanation had
1479 emerged that required further experiments to be excluded. Would the discovery of CP
1480 violation turn into a crucial experiment, if those alternatives had been devised before
1481 the experiment? Does the ‘cruciality’ of an experiment depend on the number of models
1482 developed before and afterwards?
1483

1484 On the basis of these classical examples from particle physics, we are thus suggesting a
1485 notion of crucial experiment that is closer to experimental practice and less dependent
1486 on short-term developments in physical theory. This notion seems to us also in the spirit
1487 of Weber’s (2009) discussion. But we are well aware that a substantive discussion of our
1488 proposal would require a broader set of examples, both positive and negative ones.
1489

1490 An experiment with a systematically and statistically significant outcome, is crucial in
1491 some field of science, if it is

- 1492 a) seminal or decisive for the further development of this field,
1493 and at least one of the following criteria are fulfilled.
1494 b) It adds a new concept to the body of physics,
1495 c) it implies a rejection of one or several theoretical solutions of a significant problem,
1496 or refutes an established concept.

1497 The third criterion takes up characteristic b. in the above description of the Higgs
1498 discovery. In the examples discussed, P and CP violation fulfil criteria a) and c), the
1499 Stern-Gerlach experiment fulfilled criteria a), b), c) before the advent of quantum
1500 mechanics, fulfilled a), c) until spin was fully integrated into the theory, after which it
1501 fulfilled a) and b)³¹. The Higgs discovery fulfilled a) and b) by itself, but it also refuted
1502 alternative models, such that it also fulfils c).

³¹ In contrast to Franklin and Perovic, we believe that the experiment’s crucial character was present throughout. Initially, the experiment was proof of the phenomenon of space quantization

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7.3. Principles and values of model choice

The questionnaires and the interviews have shown that in 2011 there was a large variety of epistemic and pragmatic values guiding the physicists' expectations about the Higgs searches, their concerns about the SM and their preferences for BSM physics. The discovery of the Higgs boson disfavoured certain models and strengthened the genuinely epistemic criteria. The example of dynamical symmetry breaking after the Higgs discovery showed that theoretical simplicity or other pragmatic criteria, e.g. fertility to calculate further particle masses, can motivate researchers even if the respective model is experimentally disfavoured. This corresponds to Kuhn's insight that the balancing of epistemic and pragmatic values is neither a perfect logical inference nor a matter of taste, but a fact in the history of scientific practice. Even though physicists are now largely accepting the SM as one of the most successful theories, they will keep looking for deviations that promise to be interesting.

Even taking into account tight experimental constraints, the 'expectation' to find dynamical EWSB was still significant among theorists before the observation of the Higgs candidate. It decreased after the observation, but remained remarkably high. Interestingly, the preference among theoreticians was, both in 2011 and 2012, always higher when asked 'independently of LHC'. (cf. 5.1.3. & 6.1.2.) Even though the chances for experimental evidence in the near future were low, dynamical EWSB remained a preferred solution for many. Notably, the preference of dynamical EWSB showed the largest difference in the surveys between experimentalists and theorists.

Let us evaluate possible consequences of applying the notion of values of preference to models instead of theories. Not all BSM models are as close to the status of a theory as the SM. Some of them are renormalizable and based on a sufficiently elaborated theoretical idea, such as Supersymmetry. But others are not; there is, for instance, considerable freedom in populating an extended Higgs sector. This does not prevent physicists from considering such models as worthy of pursuit, from choosing to investigate them, and indicate their motives for doing so. Finding evidence for such models would certainly have prompted theoretical investigations before physicists would commit themselves to the truth of that model in the same sense as one might commit oneself the existence of supersymmetry in nature. We do not see this as a weakness of our account, but as a consequence of the variegated model landscape.

Let us now look at our findings from the perspective of Douglas's classification of cognitive and pragmatic values. All models are physically consistent and are empirically adequate in the sense that they are not in conflict with the existing data. Thus, they fulfil the minimal criteria (i) and (ii), They also make specific predictions³² and have a high predictive accuracy once basic parameter(s) are fixed. Furthermore, there is a consensus in the importance of the mechanism of EWSB. They are thus fulfilling the

predicted by the Bohr-Sommerfeld theory and a refutation of the classical views developed by Larmor. However, within quantum mechanics the concept of space quantization was replaced by a somewhat different notion of angular momentum, but this did not end the experiments crucial significance against pre-quantum theories (c). When quantum mechanics was fully established, including spin, there was so much spectroscopic evidence against the pre-quantum physics that the Stern-Gerlach experiment became less important in this respect (ending c)), but paradigmatic for the phenomenon of spin (fulfilling b with respect to this concept).

³² The fractions of physicists choosing 'fit to data' and 'specific predictions' seems to be lower than one might expect but has to be seen on the background of these being not special to any model considered.

1546 desiderata (iv). The questionnaire has also revealed a high score for genuinely
1547 pragmatic values that fall in Douglas's category (iii) and we have argued that they we
1548 able to balance the bleak empirical prospects for certain models as long as they were not
1549 ruled out in the sense of the minimal criterion (ii). Douglas admits that such a practice is
1550 legitimate as long as it is done with "the full acknowledgement that the theory is
1551 inadequate as it stands and that it must be corrected to meet the minimum
1552 requirements as quickly as possible." (2013, 802) She also admits that there are
1553 tensions in practice "between a well-supported theory (with group (iv) values
1554 supporting it) and an underdeveloped theory (with lots of group (iii) values and thus
1555 lots of potential)" (2013, 804). But these tensions are only pragmatic ones between
1556 conservatives and risk takers that do not endanger the separation between groups (iii)
1557 and (iv) because they "aim at different purposes" in the sense that "pragmatic criteria
1558 have no bearing on what should be thought of as our best supported scientific
1559 knowledge at the moment." (2013, 804)

1560
1561 It seems to us that when applying the values of preference to a complex model
1562 landscape, matters are a bit more complicated and Douglas' classification has to be
1563 taken with a grain of salt. Let us start with the claim that "groups (i) and (ii) ... trump
1564 groups (iii) and (iv)" (2013, 804) and are clearly distinct as necessary conditions and
1565 desiderata. 'Internal consistency' (group (i)) in particle physics means that the theory is
1566 free of any infinities and can be extrapolated to energies $\Lambda \rightarrow \infty$. Strictly speaking, given
1567 the measurements of the Higgs and top mass this may even not be true for the SM itself,
1568 with the Higgs potential breaking down at high energy, although energies significantly
1569 beyond the Planck scale of 10^{19} GeV. This does not play any role for the 10^3 GeV
1570 reachable at the LHC and the empirical adequacy of the theory within the experimental
1571 uncertainties. However, the same argument applies to the BSM models for EWSB. For all
1572 models, some energy scale Λ is introduced at which some theory should exist - with
1573 properties that are vaguely known - and where it is assumed to be fully renormalizable.
1574 This Λ is, in general, far beyond the reach of the LHC and the models predict just some
1575 'low energy' (i.e. in the LHC range) phenomena, where the details of the full high energy
1576 theory do not play a role. As seen in the questionnaires and the interviews, this is not of
1577 concern for physicists. What is more important to them are solutions of problems like
1578 dark matter, unification, and naturalness (see next section), but also pragmatic criteria
1579 like simplicity and elegance.

1580
1581 In all these models, empirical adequacy is guaranteed by constructing them so as to
1582 encompass the SM that had a very high degree of experimental confirmation, except for
1583 the Higgs sector. While accordingly, empirical adequacy is accepted as a preeminent
1584 value, in the practice of physicists, internal consistency plays only a role if it prevents
1585 clear predictions. This means that group (iv), at least temporarily, can trump group 1. It
1586 is true, physicists are fully aware of this fact, however to reach Λ_{BSM} may take decades, if
1587 not centuries. To evade this, one either has to redefine the meaning of physical
1588 consistency or retrigger the epistemic values. Wells (2012) considers mathematical
1589 consistency (his term for internal consistency) to be as preeminent as empirical
1590 consistency (i.e. adequacy), while not denying that this is not the general attitude among
1591 physicists. To implement this preference, he advocates effective field theories (EFT) that
1592 accomplish internal consistency by adding an infinite series of additional terms made up
1593 of all fields of the model, implying also an infinite set of free parameters. Whereas this is
1594 in principle correct it is hardly a practice followed widely in particle physics. When EFTs
1595 are considered in the actual practice, only a limited set of terms is used destroying the
1596 mathematical consistency but making the theory tractable.

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1600 **7.4 The Guiding Principle ‘Naturalness’**

1601

1602 Our questionnaire has shown that naturalness is indeed on a par with the traditional
1603 pragmatic values of ‘elegance’ and ‘simplicity’ – as for the guiding principles of model
1604 preference – and on a par with ‘too many independent parameters’, the ‘missing dark
1605 matter candidate’ and the ‘non-inclusion of gravity’ – as for the most critical flaws of the
1606 SM. While the many independent parameters render the SM not simple – for decades
1607 elementary particle physicists have been looking for a simple unifying theory – the two
1608 other flaws concern empirical facts that cannot be accommodated by the SM.
1609 From the interviews (cf. 6.2.3) we have concluded that naturalness is considered as
1610 sufficiently well entrenched within the community to be considered as a coherent
1611 guiding principle for scientific practice. But it operates both in an epistemic and a
1612 pragmatic mode.

1613

1614 Renormalization is the way to guarantee the finiteness of the theory, that is, its
1615 theoretical consistency. In principle the huge ‘unnatural’ renormalization corrections for
1616 the elementary Higgs boson do not make the theory inconsistent in a strictly formal
1617 sense. In practice, however, most physicists find this unacceptable - they do not accept
1618 too much fine-tuning of SM parameters – and try to find a remedy by supplementing the
1619 SM. This renders naturalness an epistemic value, in Kuhn’s and Douglas’s terminology.
1620 However, in our understanding, naturalness also acts a pragmatic value. It is an
1621 operationally relatively easy-to-apply quantitative criterion, at least once it is specified
1622 how much fine-tuning is allowed, and it constrains models; e.g. it suggests new particles
1623 with top flavour to compensate the main culprit for ‘unnaturalness’. This may also be the
1624 reason why naturalness is maintained as an important criterion to devise BSM models.
1625 Such a double-track value of preference complicates the grouping of values for model
1626 preference. There is, to our mind, no clear separation of this complex criterion into more
1627 elementary epistemic and pragmatic values. For despite its complexity, naturalness is
1628 coherently applied as guiding principle by the physics community. It seems to us that
1629 this diagnosis does not contradict the philosophical differentiations advocated by Wells
1630 and Williams (cf. 3.3).

1631

1632 With the Higgs discovery ‘naturalness’ turned from a potential problem of the SM into a
1633 real one. The positive empirical finding was not accompanied by an observation of new
1634 particles in the TeV range that could resolve the problem in close temporal proximity to
1635 the Higgs discovery. One might expect that after confirming the cause of the naturalness
1636 problem, its solution should have been considered as more urgent. Such a trend was not
1637 visible in the questionnaire; its high ranking as guiding principle or most critical flaw of
1638 the SM did not change. The interviews revealed a more differentiated picture³³. Some
1639 physicists still regard the naturalness problem as a nuisance, but contemplate that it
1640 might be an accidental feature of particle physics instead of a solid theoretical argument.
1641 In a sense, physicists are becoming prepared to live with it.³⁴

1642

1643 The resilience of the naturalness problem may result from the fact that there exists no
1644 clear threshold when a theory becomes ‘unnatural’. At least before the first results of the
1645 LHC folklore had it that fine-tuning requires new physics at an energy scale of 1 TeV. Yet
1646 there is no prohibitive argument against changing this to 5 or 10 (or more) TeV, even if
1647 this increases the amount of fine-tuning. Therefore, with some adjustments, the
1648 naturalness problem can still be maintained for the forthcoming LHC data; moreover,
1649 also the parameter space for new physics at the 1 TeV scale has not been completely

³³ This agrees with several articles by physicists reconsidering the Naturalness problem, e.g. Guidice (2013), Dine (2015).

³⁴ Cf. Friederich, Harlander & Karaca (2014, Sect. 7).

1650 covered by previous searches. Thus, many physicists defer the final word on the
 1651 importance of naturalness to the higher energies and intensities that the LHC is about to
 1652 enter. It remains to be seen whether BSM physics is found that indeed can cure the
 1653 naturalness problem, If not, one may wonder how far the scale of new physics can be
 1654 stretched or whether naturalness will eventually be abandoned. This again shows that it
 1655 is much more specific than the usual pragmatic values of model preference.
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1661 **8. Conclusion**

1662
 1663 Let us sum up the main results of our paper. First, the discovery of the Higgs boson and
 1664 the confirmation of the SM were less expected than is often assumed. With the growing
 1665 evidence that the newly discovered particle has properties consistent with the SM
 1666 expectations, most physicists accepted it to be a Higgs, and at least tentatively, a SM
 1667 Higgs boson. This does not contradict the fact that searches for possible deviations from
 1668 the SM will be ongoing for a long time. Second, the Higgs discovery represented a crucial
 1669 experiment for the SM if one interprets the notion in a sense that is appropriate for
 1670 modern experiments. An experiment as complex as LHC cannot be properly understood
 1671 without its embedding into a tradition of previous precision experiment and the
 1672 tradition of reliable and established experimental strategies. These are crucial for
 1673 keeping underdetermination at bay. Third, our case study suggests that criteria of
 1674 theory choice be understood as epistemic and pragmatic values that have to be weighed
 1675 in in factual practice. The Higgs discovery led to a certain shift from pragmatic to
 1676 epistemic values as regards the mechanisms of EWSB. Complex criteria, such as
 1677 naturalness, combine different values without becoming inconsistent or inapplicable by
 1678 the scientific community.
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 1680

1681 **Appendix 1 List of interview partners**

1682
 1683 **March & April 2011**

1684

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

1685
 1686
 1687 **Fall 2012**
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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

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1691 **Appendix 2: List of questions in questionnaires**

1692

1693 **In 2011**

1694

1695 **1. What is your personal estimate of the probability of the following**
1696 **scenarios? The LHC will...**

1697 a. find the Standard Model Higgs boson

1698 b. rule out the Standard Model Higgs boson

1699 c. find indisputable evidence of new physics

1700 The probabilities to be assigned were in 20% intervals, i.e. 0-20, 20-40%,

1701

1702 **2. Assuming that the LHC finds new physics, which (if any) of the following**
1703 **models do you think has the best chances of explaining it**

1704 a. extended Higgs sector

1705 b. supersymmetry

1706 c. extra-dimensions

1707 d. dynamical electroweak symmetry breaking

1708 e. 4th generation

1709 f. extended gauge symmetry (Z', Little Higgs)

1710 g. string theory

1711 h. other

1712 i. None of those, but something totally unexpected

1713 j. I don't know

1714 The questionnaire asked for two ranked choices.

1715

1716 **3. Independently of your expectations regarding LHC results, which (if any) of**
1717 **the following models do you prefer?**

1718 a. extended Higgs sector

1719 b. supersymmetry

1720 c. extra-dimensions

1721 d. dynamical electroweak symmetry breaking

1722 e. 4th generation

1723 f. extended gauge symmetry (Z', Little Higgs)

1724 g. string theory

1725 h. other

1726 i. I don't know

1727 The questionnaire asked for two ranked choices.

1728

1729 **4. Which (if any) of the following criteria have guided you in answering the**
1730 **previous question? (Four ranked answers were possible.)**

1731 a. The model solves naturalness/hierarchy problem

1732 b. The model is simple

1733 c. The model will provide a better fit to the data

1734 d. The model is elegant

1735 e. The model makes very specific predictions

1736 f. The model allows the unification of forces

1737 g. The model has a candidate for dark matter

1738 h. other

1739 i. none of the above

1740

1741 **5. Which (if any) are the most critical flaws of the Standard Model? (up to**
1742 **three answers possible)**

1743 a. too many independent parameters

1744 b. small but nonzero neutrino masses

- 1745 c. replication of fermion families
- 1746 d. different magnitude of scales of fermion masses
- 1747 e. quadratic divergences in corrections to Higgs mass
- 1748 f. left-right asymmetry
- 1749 g. gravity is not included
- 1750 h. no unification of strong and electroweak forces
- 1751 i. CP violation
- 1752 j. No dark matter candidate

1753

1754 **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

1799 d. find indisputable evidence of new physics
1800 The answers should be given for each field in terms of 'fully agree', 'somewhat
1801 agree', 'undecided', 'somewhat disagree', 'fully disagree'
1802

1803 **2. Assuming that the LHC finds new physics, which (if any) of the following**
1804 **models do you think has the best chances of explaining it**

- 1805 a. extended Higgs sector
1806 b. supersymmetry
1807 c. extra-dimensions
1808 d. dynamical electroweak symmetry breaking
1809 e. 4th generation
1810 f. extended gauge symmetry (Z', Little Higgs)
1811 g. string theory
1812 h. other
1813 i. None of those, but something totally unexpected
1814 j. I don't know
1815 Only one choice was possible
1816

1817 **3. Independently of your expectations regarding LHC results, which (if any) of**
1818 **the following models do you prefer?**

- 1819 a. extended Higgs sector
1820 b. supersymmetry
1821 c. extra-dimensions
1822 d. dynamical electroweak symmetry breaking
1823 e. 4th generation
1824 f. extended gauge symmetry (Z', Little Higgs)
1825 g. string theory
1826 h. other
1827 i. I don't know
1828 Only one choice possible
1829

1830 **4. Which (if any) of the following criteria have guided you in answering the**
1831 **previous question?**

- 1832 a. The model solves naturalness/hierarchy problem
1833 b. The model is simple
1834 c. The model will provide a better fit to the data
1835 d. The model is elegant
1836 e. The model makes very specific predictions
1837 f. The model allows the unification of forces
1838 g. The model has a candidate for dark matter
1839 h. other
1840 i. none of the above
1841 Up to three answers were asked for
1842

1843 **5. Which (if any) are the most critical flaws of the Standard Model? (up to**
1844 **three answers possible)**

- 1845 a. too many independent parameters
1846 b. small but nonzero neutrino masses
1847 c. replication of fermion families
1848 d. different magnitude of scales of fermion masses
1849 e. quadratic divergencies in corrections to Higgs mass
1850 f. left-right asymmetry
1851 g. gravity is not included
1852 h. no unification of strong and electroweak forces

- 1853 i. CP violation
- 1854 j. No dark matter candidate
- 1855
- 1856 **6. In which of the following signatures (if any) do you think the LHC will most**
- 1857 **likely find new physics?**
- 1858 a. signatures with bottom quarks
- 1859 b. signatures with top quarks
- 1860 c. signatures with tau leptons
- 1861 d. signatures with missing energy
- 1862 e. signatures with multi – jet topologies
- 1863 f. signatures with multi – lepton topologies
- 1864 g. soft events
- 1865 h. other
- 1866 i. I don't know
- 1867 Two ranked choices were asked for
- 1868
- 1869 **7. How much do you agree with the following statements? LHC results will be**
- 1870 **very important to understand...**
- 1871 a. strong interactions
- 1872 b. flavour physics
- 1873 c. origin of mass
- 1874 d. quantum gravitational effects
- 1875 e. dark matter
- 1876 f. dark energy
- 1877 g. cosmology of the early universe
- 1878 The answers should be given for each field in terms of 'fully agree', 'somewhat
- 1879 agree', 'undecided', 'somewhat disagree', 'fully disagree'
- 1880
- 1881 **8. How much do you agree with the following statements?**
- 1882 a. There is plenty of dialogue between theoretical and experimental physicists
- 1883 on LHC physics
- 1884 b. Theorists are fully prepared to tackle future new data from LHC
- 1885 c. Theorists are making helpful suggestions on how to collect and analyse LHC
- 1886 data
- 1887 d. Experimental physicists are sufficiently taking into account suggestions from
- 1888 theorists
- 1889 e. Experimental physicists are presenting their results in the most helpful way
- 1890 for theorists
- 1891 The answers should be given for each field in terms of 'fully agree', 'somewhat
- 1892 agree', 'undecided', 'somewhat disagree', 'fully disagree'
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1927 [results-indicate-particle-discovered-cern-higgs-boson](https://press.web.cern.ch/press-releases/2013/03/new-results-indicate-particle-discovered-cern-higgs-boson)
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