Higgs10: Inventing the future of Higgs research

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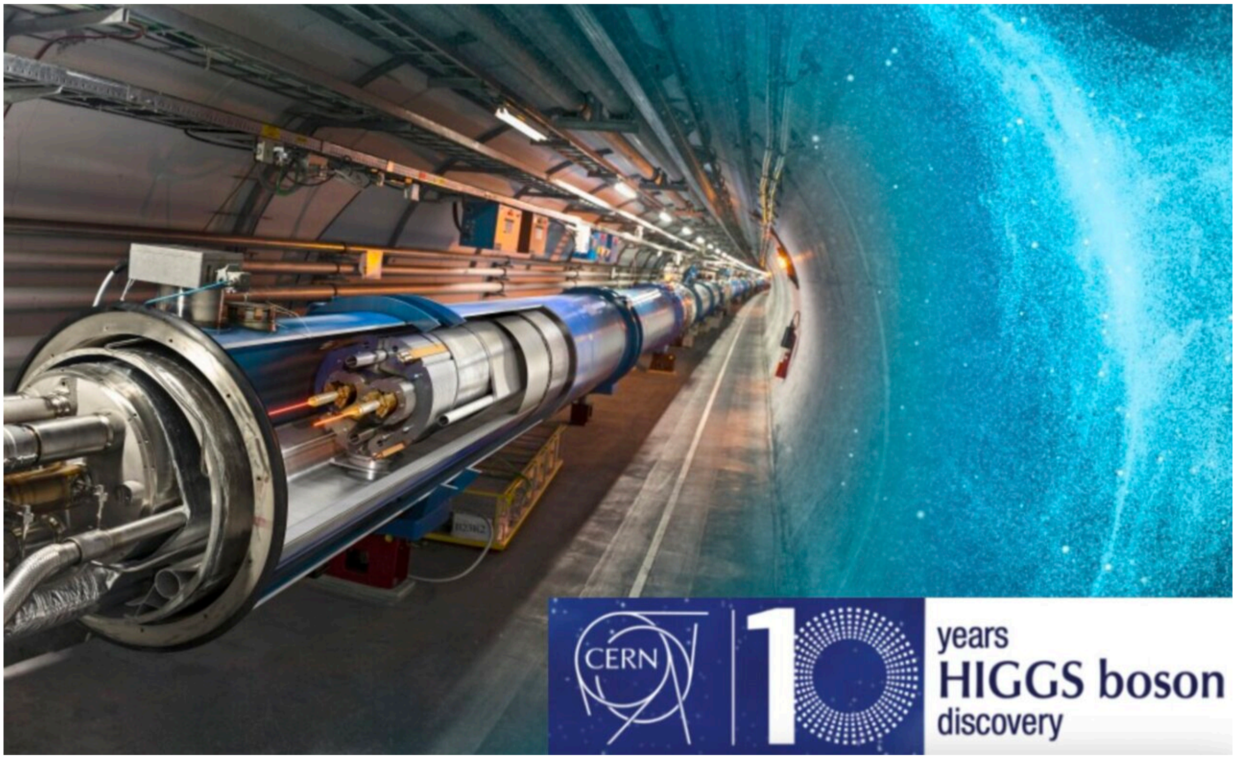

Credit: CERN

In 1975, three CERN theorists, John Ellis, Mary K. Gaillard and Dimitri Nanopoulos, undertook the first comprehensive study of the collider phenomenology of the Higgs boson. Almost 40 years later, it was discovered at the LHC. Now, ten years on, might we have such long-term foresight in anticipating the varied paths that future Higgs research may follow?

On 4 July 2022, enjoying the many beautiful presentations at the Higgs@10 symposium, a phrase kept ringing in my ears: "Compatible with Standard Model (SM) predictions." Alarm bells were ringing. Really? Are we sure? Whether or not the Higgs is SM-like is a question that will shape the experimental future of Higgs research.

We may quantify an answer through the language of effective field theory, which is a mathematical manifestation of the notion that the most effective way to describe an object depends on the length scale you're viewing it from. To astronauts, Earth is very effectively described as a smooth sphere. For summer students hiking to Le Reculet, it is not. So, too, of the quantum world. Far from a neutral atom, it effectively appears as a point-like particle with some leftover multipolar interactions with photons. At shorter distances, getting in amongst the electrons, this description fails entirely.

Ditto the Higgs. Whatever's going on in there, at energies near enough to mh, it is effectively described as a point particle with a handful of additional "operators," which are essentially new particle interactions that aren't contained in the SM (don't feature on that mug or T-shirt) but do involve SM particles. By eye, the astronaut may be able to make out some features on Earth and surmise that there may be mountains, but they couldn't actually estimate the students' elevation gain. Similarly, the non-SM Higgs operators can capture the long-distance leftover effects of the microscopic innards of the Higgs, but not reveal their full glory in detail. If all of these extra operators vanish, the Higgs is SM-like. Let's consider two hand-picked examples and investigate just how SM-like the Higgs is...

How "fuzzy" is it? Is it point-like down to the smallest distance scales or is it, like the pion, made up of other as-yet-unidentified new particles? In the latter case, much as for the pions and their constituent quarks and gluons, directly observing the new stuff would require going to higher energies. Alternatively, it could be point-like but probing it closely may reveal the telltale clues of a cloud of new particles that it interacts with. For your interest, the operator that can capture these properties is written (∂μ|H|2)2. If it vanishes, the Higgs is entirely point-like. If not, it's fuzzier than expected. How fuzzy is it? Present LHC Higgs coupling measurements suggest it is effectively point-like down to a length scale merely a factor three below the electroweak scale. It could still be very fuzzy indeed! As fuzzy as a pion. If so, hardly an SM-like Higgs! We must do better and, through much more precise coupling measurements at the 0.2% level, a future Higgs factory like the FCC-ee could determine if the Higgs is point-like as far down as the 6% level.

Does the Higgs find itself attractive? Yes, according to the SM. New particles means new forces and so it follows that if the Higgs boson interacts with new heavy particles they will generate a new force between the Higgs and itself. The operator effectively capturing this is |H|6 and it literally shapes the way in which the Higgs field gave mass to particles during the very nascence of our universe! So, how SM-like is the Higgs self-attraction? With present experimental constraints, we know the Higgs self-attraction could be 530% stronger than the SM value (not merely self-attraction, more like outright vanity) or even −140% less (self-repulsive, more like). Hardly SM-like in either case! To have any idea of whether the self-attraction is SM-like, we must do a lot better. A future facility, such as the FCC-hh, CLIC or a muon collider, could probe the self-attraction at the much more precise 5% level.

Patience is a virtue; complacency is not. It is far too early to call time at the bar for the Higgs boson. Who knows, we may even be served with something completely unexpected, like a new window into the dark sector of the universe. Truly exploring all facets of the nature of the

Higgs boson, understanding whether or not it is SM-like, will take time (measured in decades) and a lot of hard work. But it can and should be done. This is the experimental future of Higgs research that we look forward to.

All that said, it's no secret that many theorists expected the Higgs to be much less SM-like than it appears to be already. Heads duly scratched, a theoretical coup d'état is now silently under way. There were good reasons to expect something different: chiefly the hierarchy problem. This problem is not simply aesthetic. The SM breaks down at high energies, ultimately making pathological predictions, thus it can only be a long-distance effective field theory description of something else more fundamental. If, as was the case for pions, the Higgs mass is determined by the more fundamental parameters, then for the Higgs there is no mechanism to keep it lighter than the mass scale of the new particles in that theory. Yet colliders tell us there is a gap between the mass of the Higgs and that of those new particles. In the past, this motivated the discovery and development of new mechanisms to explain a light Higgs, such as the venerated low-scale supersymmetry, thus far a no-show at the LHC physics party, with its attendant non-SM-like Higgs.

Rudely awoken by the deluge of exclusion plots, coffee reluctantly smelled, theorists have, in recent years, put forward what could well transpire to be revolutionary theoretical developments. The hierarchy problem hasn't gone away and neither has the data, so the other foundational assumptions covertly injected into the old theories, often linked to symmetry or aesthetic principles such as simplicity or minimality, have been interrogated and found wanting. In response, intrepid new classes of theories have been developed that can address the hierarchy problem whilst being consistent with all those bothersome exclusion plots. They range from relatively modest conceptual tweaks of existing structures, to the abandonment of aesthetic principles, and then all the way out the other side to attempts to link the Higgs mass to the origins of the universe, cosmology, the nature of the Big Bang and, at an extreme, speculations about possible links between the Higgs mass and the existence of life itself. You name it, we're boldly going.

It's no fait accompli. None of these ideas are as intoxicating as supersymmetry or as stupefying as extra dimensions, each leaving those who study them with more of a "watch this space" feeling than the "eureka" that Archimedes enjoyed. Variously, they're not radical enough, too radical or simply not to taste. No Goldilocks moment just yet. However, in my view these issues are cause for hope. In similar moments in the past, we have been essentially on the right track, having to wait a little longer than expected for the confirming experimental data (top quark). At other times, the right ideas have been too radical for most to stomach in one sitting (quantum mechanics). Yet for others the correct approaches languished in relative obscurity far too long, simply for not being à la mode (quantum field theory). Look up the citation records of the original Brout-Englert, Higgs, Guralnik-Hagen-Kibble papers or Weinberg's "A Model of Leptons," all foundational to the physics of the Higgs boson, and you'll see they are important cases in point that we would do well to remember. Nature made no promises that understanding the origins of the Higgs should have been easy, nor should it be in the future, but history teaches that those who explore relentlessly and fearlessly are often the ones rewarded with the greatest prize of all: the truth.

Where will all this go in coming years? Will we be tenacious enough to build the accelerator, the detectors and the village it will take to measure the Higgs self-attraction or discover the fuzziness of the Higgs? Will some plucky theorists unlock the door to the fundamental theory beyond the SM? Will future phenomenologists lay the first foundational stones on the path to discovering it?

As Dennis Gabor, the inventor of holography, put it: "The future cannot be predicted, but futures can be invented." We're working on it.

Provided by CERN

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