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# “Theory perspective” talk at LHCp 2023

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This article is a summary of the closing theory talk that I gave at the 11th edition of the Large Hadron Collider Physics (LHCp) conference. I briefly discuss the meaning of discovery in particle physics, and I highlight the complementary ways to explore the next New Physics scale, via a combination of precision measurements and direct searches at accelerator-based experiments.

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## 1. Introduction

The Standard Model (SM) of particle physics is perhaps the most successful theory in the history of science. It describes most of the known phenomena to a high level of precision. The classic example is the prediction of the anomalous magnetic moment of the electron that is known to the $10^{-10}$ precision and confirmed experimentally with a similar level of accuracy [1]. The SM is nonetheless not able to answer several open questions in particle physics and cosmology: what is the origin of the electroweak (EW) scale (a.k.a. the hierarchy problem)? What is the nature of Dark Matter (DM)? What is the mechanism responsible of generating neutrino masses? What is the origin of flavor? Why does the Universe have so much more matter than anti-matter? These questions point to what I would call the *"known unknown"*. Beyond these clearly formulated questions, it is the task of particle physics to determine what lies beyond what we have already discovered. Perhaps there are questions that we have not yet formulated that will lead to the next discovery in particle physics. Perhaps there is a *"unknown unknown"* beyond what we have already discovered.

Since its start in 2008, the Large Hadron Collider (LHC) has produced crucial results in broadly testing the EW scale and confirming the predictions of the SM EW sector. Furthermore, the progress in DM direct and indirect detection experiments, together with LHC searches, have put under tension vanilla models for Weakly-Interacting-Massive-particle (WIMP) DM. In this landscape of experimental results, it is no longer certain that New Physics (NP) will show up at around the EW scale. As a result, in the past several years, the field of particle physics has diversified. This diversification has not only sparked new theoretical frameworks but has also prompted experimentalists to design novel searches and initiate new experiments to probe NP at a wide range of energy scales.

Searching for answers to big unanswered questions is vitally important. At the same time, the significance of scrutinizing and refining our understanding of SM particles remains paramount. In fact, we should have clear in mind that the goal of fundamental particle physics is to test the laws of Nature, which include the interactions and properties of the particles that we have already discovered. In this sense, following the LHC pivotal discovery of a fundamental new particle, the Higgs boson, the LHC had several discoveries: one of the last ones being the discovery of the Higgs -bottom quark interaction [2, 3]. This discovery is of fundamental importance since it implies that also the bottom quarks receive (at least part of) their mass through the Higgs mechanism. This conclusion could not be a scientific fact, before the LHC discovery.

In these proceedings, I will give a brief description of this two-fold approach to unravel new fundamental physics: (1) testing the laws of Nature (Sec. 2); (2) discovering either indirectly or directly new particles (Sec. 3). In both contexts, we will highlight recent developments and key results that are expected in the coming years from accelerator-based experiments.

## 2. The study of the laws of Nature

The Standard Model Lagrangian is largely fixed once its particle content and symmetries are specified. It can be written in a concise and illustrative way as

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\psi_i \not{D}\psi_i + |D_\mu\Phi|^2 - V(\Phi) + (Y_{ij}\psi_i\psi_j\Phi + \text{h.c.}), \tag{1}$$

where we show the SM gauge boson interactions, the interactions between the SM fermions and gauge bosons, the Higgs interactions, and the Yukawa fermion-Higgs interactions, respectively. With the Higgs discovery, the LHC successfully completed the exploration of the particle content of the Standard Model. It also discovered several SM interactions, and, in particular, a brand new type of interactions between fundamental particles: the Yukawa interactions.

It will be crucial to experimentally discover every single interaction in (1). By now, after 11 years from its discovery [4], many of the Higgs properties and interactions have been measured at the $5-20\%$ level (e.g., the Higgs interactions with $Z$ and $W$ bosons, and with $\tau$ leptons). We know that the Higgs is "SM-like". At the same time, the experimental exploration of the Higgs sector is only in its youth and the existence of many Higgs interactions predicted by the SM Lagrangian is still a mystery.

It is not known if the Higgs couples to first and second generation fermions. While experimentally testing the interactions between first generation fermions and the Higgs boson poses significant challenges, there are promising prospects for the second generation and in particular the interaction of the Higgs boson with muons, which can be discovered via the $H \to \mu^+\mu^-$ decay. The combination of LHC Run I and Run II data led to the first evidence for the Higgs decaying into muons [5] (see also the ATLAS analysis [6]). The definitive discovery of this decay, if it occurs at a rate that is compatible with the SM prediction, is expected to come within a couple of years with Run III data. The LHC discovery of the Higgs couplings to second generation quarks will be more challenging. To date, Run II LHC sets constraints on the charm Yukawa at the level of a few times the SM prediction ($y_c/y_c^{\rm SM} < 3.4$ [7]). Many novel ideas on how to probe these couplings have been put forward by phenomenologists in the past few years. It will be intriguing to witness the capabilities of the LHC in the coming years and more so in its High-Luminosity (HL) stage in testing these interactions. An $e^+e^-$ collider could easily discover the charm Yukawa interaction and measure it at the 1% level or better [8]. Uncovering the Higgs coupling to lighter fermions holds significant importance, as it has the potential to provide crucial insights into the flavor puzzle and probe NP models with extra sources of flavor universality violation.

Aside from the Yukawa interactions, the other qualitatively new term in (1) is the Higgs potential, $V(\Phi) = -\mu^2|\Phi|^2 + \lambda(|\Phi|^2)^2$, which generates self-interactions of the Higgs boson. Self-interactions of a fundamental scalar have not been observed in Nature as far. Furthermore, the structure of the Higgs potential is fundamentally linked to the stability of the vacuum of the Universe and possibly to the origin of the asymmetry between the matter and anti-matter abundances. For these reasons, the experimental determination of the Higgs potential will be one of the major targets of the LHC. The discovery of di-Higgs production is one of the best ways to test the structure of the Higgs potential and the Higgs self-interaction (single Higgs production channels can be relevant as well, see e.g., [9, 10]). At the same time, this discovery is challenging for the LHC because of the small di-Higgs production rate ($\sim 1000$ smaller than the single Higgs production) and because of the background-limited signatures arising from this production. Based on the present dataset and the combination of all searches, the Higgs boson pair production cross-section is determined to be below 2.4 times the SM expectation by the ATLAS collaboration [11], and 3.4 times by the CMS collaboration [12]. Both experiments have recently reappraised their studies at HL-LHC, to reach individually a sensitivity of approximately $3.5\sigma$ [13, 14], indicating a possible $5\sigma$ discovery after combining analyses. It will be very interesting to see if the HL-LHC will be able to make the groundbreaking discovery of the di-Higgs production process!

These measurements represent just a few of the potential fundamental Higgs discoveries that the LHC may achieve in the years ahead. Numerous other discoveries could also unfold. There are still several rare Higgs channels awaiting for discovery, including the $H \to Z\gamma$ decay (see [15] for the most recent results); the Higgs production in association with two bottom quarks; the Higgs decays to a SM meson and a photon, among others. Having accurate SM predictions for these processes and a "well-working" theory, the SM, does not ensure that these processes are well described by the SM. We do need their measurement. Additional Higgs interactions could also be added to the Lagrangian in (1). For example, the Higgs could have pseudo-scalar interactions with fermions, if it is an admixture of a CP-odd and a CP-even scalar. The Higgs could also have flavor-violating interactions. If realized in Nature, these additional interactions may result in further discoveries at the LHC in the years ahead.

## 3. The new particle discovery

The LHC is both a (direct) discovery and a precision machine. In fact, the LHC has been not only instrumental in the groundbreaking discovery of the Higgs boson but has also exhibited its precision by meticulously measuring the Higgs properties and many other SM processes. The measurement of the Higgs boson productions and decays represent a concrete deliverable for present and future collider projects. The precision extends beyond just the Higgs, with the LHC contributing to precise measurements of the rates and kinematical distributions of various SM processes spanning 13 orders of magnitude in cross-section (from the total $pp$ inelastic cross section, to the four top production [16, 17]). Discovering a deviation from the SM prediction of one of these processes could be an "indirect discovery" for New Physics. At the same time, the LHC covers an unprecedented role in searching for the "direct" production of new particles with a mass at the TeV scale and below.

As we will discuss in this section, direct and indirect searches for NP are highly complementary: direct searches at high-energy colliders can be more effective for new particles that are weakly-coupled to the SM, and indirect searches more effective probing strongly coupled new particles (see e.g., [18]).

### 3.1 Indirect discovery

New Physics particles with a mass well beyond the EW scale can lead to small effects in the rates and kinematical distributions of SM processes.

Higher-dimensional operators in an Effective-Field-Theory (EFT) are the most robust and model-independent way of describing NP virtual effects whenever there is a large separation between the collider energy scale and the scale of NP. EFTs imply NP effects that grow with powers of $s/\Lambda^2$, where $s$ is the center of mass energy of the collider, and $\Lambda$ the NP scale. For this reason, precision measurements benefit not only from the statistics of high luminosity, but also from gains in the collider energy. This makes indirect tests not only a domain of lepton colliders.

Precision measurements at the LHC already provide access to NP scales on the order of 10 TeV, thus extending the reach to NP scales significantly larger than those directly probed (see e.g., [19]). Theorists are at the forefront of designing global fits of Higgs, top, Drell-Yan, and di-boson data to extract bounds on the several SMEFT operators. Several tools have been developed as the

SMEFiT [20], FitMaker [21], HepFit [22], EFTfitter [23], and Sfitter [24] packages, among others. This effort will become more and more important as more data will be collected by the LHC. Future colliders will probe indirectly much larger energies. For example, measurements of di-fermion production at ILC, FCCee, and CEPC will probe scales as high as ~30-40 TeV [25].

We do not know if NP respects the approximate $U(3)^5$ flavor symmetry of the SM, or if this symmetry is further broken at some UV scale. The flavor physics program has been very successful in the past in indirectly discovering new particles, as e.g., the charm quark or the third generation quarks, through $K_L \to \mu^+\mu^-$ and kaon oscillation, respectively. LHCb and Belle II are at the forefront of the precision program for $B$ mesons. Many processes (e.g. CP violation in $B$-mixing) are now known at the percent level. Some of these measurements lead to a bound on the NP scale at the level of $10^3$ TeV or higher, in the case of generic $O(1)$ flavor violating interactions of the NP particles. Even larger scales are probed by experiments searching for charged lepton flavor violation (LFV). The combination of data from the MEG and MEG-2 experiments constrains $\mathrm{BR}(\mu^+ \to e^+\nu) < 3.1 \times 10^{-13}$ at 90% C.L. [26], leading to $\Lambda \gtrsim 2 \times 10^3$ TeV, in the case of a contribution of a dipole operator. Much larger scales will be probed in the future. For example, the Advanced Muon Facility at Fermilab will push this bound to $\Lambda \gtrsim 50 \times 10^3$ TeV in the case of a four-fermion LFV operator, through the search of $\mu \to e$ conversion in nuclei [27, 28].

### 3.2 Direct discovery

During the past 12 years, a broad search program has emerged at the LHC in parallel with precision measurements. The LHC results have challenged the idea of a EW scale symmetry-based solution to the hierarchy problem (supersymmetry, extra dimensions, ...). Also the weakly-interacting-massive-particle (WIMP) DM framework – one of the two leading ideas for DM models in the past several decades – has been put under stringent scrutiny by data from the LHC and from DM direct and indirect detection experiments. This has led to a much more complex situation than it used to be: on the one hand more and more sophisticated searches for EW-TeV scale solutions to the hierarchy problem and for WIMP DM are pursued, on the other hand the field has seen a flourishing of new theoretical ideas, as well as novel search techniques and experiments.

It is clear that most of the WIMP models will be scrutinized in the next decades. Remarkably, even the most hidden ones, such as Higgsino DM, will be fully probed by future hadron, $e^+e^-$ and muon colliders [8]. There is a crucial need to explore DM candidates across a much wider mass range than that of the WIMP. An important development is what goes under the name of FIP, which is an umbrella that includes a large number of phenomena that involve different kinds of Feebly-Interacting Particles (or dark sector particles). FIP models have been proposed to address the DM puzzle, as solutions to the hierarchy problem (e.g., relaxion) or to the strong CP problem (axion-like-particles, ALPs). We need a diversified experimental approach that includes large and small scale projects to broadly test the physics of FIPs.

The LHC, and in particular its HL stage, will have an unprecedented opportunity to test EW scale and below FIPs coupled relatively weekly with the SM, through the combination of a variety of searches, from Higgs exotic decays to FIPs [29], direct production of long-lived FIPs [30], or FIPs produced from $B$ meson decays at the LHCb [31]. In fact, high-energy colliders like the LHC can explore particles with larger and larger masses by increasing $\sqrt{s}$, but also particles with smaller and smaller couplings to the SM by increasing the luminosity. In addition to high-energy colliders, the past several years have seen a large worldwide interest in the pursuit of GeV scale and below FIPs at smaller-scale accelerator-based experiments. Several auxiliary detectors have been proposed for the LHC to search for FIPs [32–37]. The recently created CERN Feebly Interacting Particles Physics Centre aims to developing and further boosting the potential of the Physics Beyond Collider (PBC) experiments for the physics of FIPs [38]. In the US, several proposed fixed-target experiments are poised to investigate phenomena falling within this realm of physics [39]. Over the next decade, there is great potential for discoveries that would transform our understanding of DM if it belongs to a FIP sector.

Beyond direct searches for particles at the TeV scale and below as motivated by the most pressing open problems in particle physics, we need a broad set of searches at accelerator-based experiments to look for the unknown without theoretical priors (what I would call the “*unknown unknown*”). Indeed, LHC data is no longer doubling every year like it did at its very beginning. The places where the LHC could still make quick discoveries is where we have not looked before. For this reason, more and more searches for exotic particles and exotic signatures are coming out of LHC data. Creativity is important! At the same time, data itself can teach us. Over the past few years, modern machine learning (e.g., unsupervised learning for anomaly detection) has been revolutionizing particle physics, since it has enabled the field to conduct searches for new particles or phenomena without relying heavily on predefined theoretical models [40].

## 4. Conclusions

We live in interesting times for fundamental physics, characterized by both groundbreaking discoveries and perplexing mysteries. The LHC stands as a testament to this dichotomy: while it unveiled the long-sought Higgs boson, it has yet to reveal any other particles at the TeV scale, leaving many questions unanswered. Furthermore, null results from DM direct and indirect detection experiments searching for WIMPs have added complexity to the puzzle. Despite these challenges, these circumstances foster a climate of diversification of ideas and creativity within the particle physics community. Historically, new groundbreaking ideas (prime examples are special relativity and quantum mechanics) have always thrived in moments of confusion.

The coming years are indeed poised to be exciting for the field of particle physics. On the one hand, the high-energy frontier will continue to produce innovative results, leveraging its versatility to explore the *unknown*. From uncovering new laws of Nature to achieving precision measurements and directly detecting elusive particles, the high-energy frontier remains a beacon of scientific discovery. Simultaneously, several smaller-scale experiments are primed to complement the efforts at high-energy colliders, probing new particles and interactions connected to smaller energy scales. Finally, the machine learning revolution in particle physics holds tremendous promise for transforming our approach to fundamental questions about particle interactions.

I conclude with a beautiful quote from an article by F. Gianotti and G. F. Giudice that appeared after the completion of the European Strategy for Particle Physics update *“Humanity’s thirst for knowledge, curiosity and spirit of exploration have always been the engines that drive particle physics. Unsurprisingly, the more we dive into uncharted territory the more difficult it becomes to predict what future experimental endeavours could find. This is the very essence of research: if we knew for certain what future experiments will discover, we would not need to build them”* [41].

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