Il Colle di Galileo

"Beyond the Standard Model: where do we go from here?"

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Abstract. The workshop brought together a large number of theorists and experimentalists from a variety of areas of physics, with a majority from high energy particle physics and a significant fraction from low energy, atomic, molecular and optics, as well as accelerator physics. The topics discussed ranged across a wide field of future experimental investigations of physics beyond the Standard Model, both with low and high energy probes, including a focus on future accelerator facilities currently under discussion worldwide. The workshop enjoyed the presence of Simons Fellows, who led broad-scope discussions on the directions of future research in the exploration of physics beyond the Standard Model.

Keywords. Beyond the Standard Model, High Energy Physics, Precision Physics, AMO, Particle Accelerators, Dark Matter, Higgs Boson, New Physics.

Topic and context: After several years of operation, the Large Hadron Collider has discovered and measured several properties of the Higgs boson. Since this discovery, many roads are open to continue the investigation of fundamental interactions. The goal of the workshop was the study of various possibilities for the further exploration of fundamental interactions with accelerators and other types of experiments, as well as astro-particle investigations. The workshop also aimed to critically examine the current understanding of theories of fundamental interactions and their future developments.

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Motivation: The physics of scales above the scale of the weak interactions is starting to be probed in experiments at the LHC with some precision. Yet many aspects of fundamental interactions remain mysterious and pose complex questions on our understanding of Nature. The nature of dark matter, the presence of baryons after the Big Bang, the mechanism for the origin of masses of fundamental particles and the origin of the breaking of the symmetry of weak interactions remain mysterious. Even the validity of the general concepts behind the application of quantum field theory, and especially effective field theories, are the subject of questions originating from the current experimental status and our theoretical understanding of fundamental interactions. These questions are the riddles the community gathered in this workshop aims to solve, taking the next step in our understanding of Nature at the deepest levels.

Results: The workshop was attended by over 100 scientists from America, Asia and Europe. More than 15 arXiv preprints were submitted with contributions from work carried out during the workshop by the participants.

During the final week's conference, around 50 talks from eminent scientists in the fields of high energy particle physics experiments and theory, dark matter, gravity waves, and low energy high precision physics were delivered to an audience of around 100 conference participants.

The workshop was an opportunity to assess the experimental and theoretical considerations that motivate the need to replace the Standard Model of particle physics with a more fundamental theory, capable of addressing all the observational issues and questions left unanswered by the Standard Model. The connections between these questions have been explored in new ways, e.g. linking the origin of the weak scale to the explanation of the cosmological constant, the possibility that weak scale physics may be originated by dynamics at a scale which is a few orders of magnitude away from the scales probed by our current experiments, as well as the possibility that new types of connections between long and short-distance physics rule the experiments sensitive only to long-distance weak-scale degrees of freedom.

Several new ideas on the possible phenomenology for new physics were presented during the workshop. These included non-standard mechanisms for the production of Dark Matter, connections between flavour physics and the weak scale, possible new links between the top and Higgs sector of the Standard Model and their relation to new physics, new models for a dynamical origin of the weak scale both in isolation and in relation to the issue of dark matter, as well as that of the cosmological constant.

A host of new ideas for experiments to search for new physics were presented. These included new dark matter detectors, searches for new long-range forces, and new ultra-light particles, atomic physics precision experiments to search for new interactions, possible gravity waves signatures for new particles.

In dedicated discussion sessions, the workshop participants discussed possible uses of new computational methods, such as machine learning in the analysis of experimental data for the search of new phenomena. Furthermore, the impact of current searches in low and high energy experiments, for foundational ideas aimed at the formulation of new physics models such as supersymmetry and compositeness, was discussed.

During the workshop, there were extensive discussions about the planning of future large experimental facilities to explore the questions that motivate physics beyond the Standard Model, shedding new light on physics beyond colliders and especially on low-energy precision as a tool for discovery, as well as on the complementarity of several high-energy projects currently under evaluation.

The results of the workshop are well summarized by the transparent conclusions in the closing talk by Raman Sundrum shown below. Despite the great expectation for new physics to be discovered in this decade in high-energy experiments, it is becoming increasingly clear that the stick we use to measure the "naturalness of theories" is made of a very plastic material. We can tell what is the most natural outcome to expect from experiments, but is very hard to reliably quantify the *unnaturalness* of the outcome we found running these experiments. Still, it is clear that the Standard Model has a potentially strong sensitivity to ultra-fine and scarcely observable details of the microscopic underlying theory. Whether the Standard Model violates the lore of decoupling of physics from different-length scales is still an open question. There is still plenty of room for an experimental determination of the sensitivity of the Standard Model to microscopic physics in future experiments, but the time also seems to be ripe for theoretical reflections on whether or not such sensitivity should receive only a lower bound to these experiments, hinting at extensive sensitivity to UV physics lying at the heart of the most fundamental theory of Nature we have so far, the Standard Model of particle physics. The time is also ripe for considering an even wider range of experimental investigations aimed at looking at all possible manifestations of new physics. They include for example non-standard signatures from non-prompt processes at colliders and secluded sectors of new particles that are only feebly interacting with us and may show up at colliders or in highly-precise measurements that are best carried out in low-energy experiments.

Simons Fellows

Marie-Hélène Genest (CNRS/Laboratory of Subatomic Physics and Cosmology, Grenoble, France) is an experimental physicist and member of the ATLAS Collaboration, an international team of physicists, engineers and technicians running the ATLAS experiment at CERN's Large Hadron Collider (LHC). Marie-Hélène is a leading expert in Beyond the Standard Model (BSM) physics. After a PhD focused on the search for Dark Matter (DM) as a member of the direct-detection PICASSO experiment (in parallel to prospective work for the ATLAS experiment), she conducted numerous ATLAS searches for supersymmetry (SUSY) during Run-1, quickly taking charge of the ATLAS SUSY subgroup focusing on R-parity conserving searches in 2010-2011, thus supervising the very first publications by ATLAS on this topic. At the end of Run-1, she became active in the ATLAS searches for directly pair-produced DM particles, taking charge of the exotics subgroup focusing on jet resonances and DM searches in 2015-2016, hence supervising the first Run-2 ATLAS publications on the subject. She also contributed to their phenomenological interpretation, collaborating on various white papers from the ATLAS/CMS Dark Matter Forum / LHC DM Working Group. In France, since 2013 she has been BSM convener of the International Research Network (IRN) Terascale, a group dedicated to the experimental and theoretical search for new physics at the TeV scale. In 2016, she received the Bronze Medal of the CNRS, which acknowledges young researchers who have become talented specialists in their field. Since 2017, she has convened the ATLAS exotics work group, a large group of researchers which focuses on a variety of BSM searches, and which published over 45 different results in 2018 alone.

Howard Haber (University of California, Santa Cruz) is a leading expert on the theory of the Higgs boson and on extensions of the Standard Model of particle physics with multiple Higgs fields. As a graduate student with Gordon Kane, he wrote a series of papers in 1978-9 that initiated experimental searches for Higgs bosons at high-energy colliders. In 1985, Haber and Kane wrote an influential Physics Reports article that outlined methods for searching for supersymmetry and its associated Higgs particles. Since then, Haber has been a leader in improving our theoretical understanding of the phenomenology of Higgs bosons and the signatures by which they might appear in data. His important results include the calculation of upper limits to the mass of the Higgs boson in supersymmetric models, the statement of the Decoupling Theorem that controls the size of new physics corrections to the Higgs boson properties, and the explicit calculation of precision corrections to Higgs boson properties generated by new physics interactions. With Sally Dawson, John Gunion, and Kane, he wrote the monograph "The Higgs Hunter's Guide" which is the key reference work in this subject. The authors of this book received the J. J. Sakurai Prize of the American Physical Society in 2017, both for the work itself and for their scientific contributions to this subject.

Jim Olsen (Princeton University, USA) is an experimental physicist and member of the CMS collaboration, an international team of physicists, engineers and technicians running the CMS experiment at CERN's Large Hadron Collider (LHC).

From 1998 to 2008 Olsen's research focus was on the study of CP violation with the BaBar detector at SLAC, where his group was the first to observe large direct CP violation in decays of the B meson. He served as BaBar Physics Coordinator from 2006 to 2007. Olsen joined CMS in 2007 and served as co-leader of the B Physics Group from 2008-2009, publishing the first measurement of exclusive B-hadron production at the LHC. He initiated the first search for the Higgs boson produced in association with vector bosons and decaying to b quarks ("VHbb") at CMS, publishing an upper limit in 2012. He served as the first Co-leader of the Hbb sub-group of the Higgs group (2011-2012) and later as Co-leader of the Higgs Group (2013-2014). In 2012, Olsen served as one of two co-editors of the Higgs discovery paper. Olsen's group was a primary contributor to the final VHbb result from Run 1, which, when combined with the corresponding tt result, produced 3.8σ evidence for fermionic decays of the Higgs boson. He also contributed to a related measurement of boosted VZbb production and the grand combination of LHC Higgs results from Run 1. Olsen was active in the CMS tracking and muon physics object groups during Run 1, where his group's work on muon fake rates was used in the discovery of the rare B_s ® mm decay channel. During 2014-2016, the period corresponding to the start-up of LHC operations at a centre-of-mass-energy of 13 TeV, Olsen served as CMS Physics Co-Coordinator. During his tenure, approximately 200 papers were submitted for publication. These including the rediscovery of the Higgs boson and many searches for physics beyond the standard model using new data. His group has continued the search for the Higgs boson decaying to bottom quarks, recently publishing the first evidence and the first observation of this process by CMS.

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CONCLUSIONS

- There is no security in life, only opportunity – Mark Twain
- Naturalness is not a 0/1 game & even imperfectly realized presents many opportunities
- Dark Sectors are strongly motivated by gauge theory grammar (& dark matter!) & bear on naturalness
- LLPs are a robust landbridge to such sectors & to cosmological punctuated evolution
- Inflation/reheating ⟷ Gauge field Theory
  observability, naturalness