IRN Terascale extension: 2022-2026

Marie-Hélène GENEST (LPSC, Grenoble)
genest@lpsc.in2p3.fr

Ana M. TEIXEIRA (LPC, Clermont)
ana.teixeira@clermont.in2p3.fr

Tilman PLEHN (Heidelberg, Germany)
plehn@uni-heidelberg.de

1 Introduction and presentation of the IRN Terascale

The results of an intensive experimental research programme, spanning decades, have firmly established the success of the Standard Model (SM) of strong and electroweak interactions in describing Nature at the subatomic level. The SM relies on a product of three gauge symmetry groups (each associated with a given force of Nature), $SU(3)_c \times SU(2)_L \times U(1)_Y$. While Nature preserves strong interactions (associated with $SU(3)_c$ and mediated by a massless spin 1 boson, the gluon), the electroweak (EW) symmetry is broken, leaving as its remnant electromagnetism $U(1)_{em}$ (mediated by another massless vector boson, the photon). The discovery of a scalar (spin 0) boson at the LHC firmly established the existence of the Higgs boson, the key ingredient of the SM mechanism of spontaneous EW symmetry breaking, $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$, which is responsible for the mass of the W and Z bosons, mediators of the weak interaction, as well as that of all matter constituents (spin ½ fermions, present in the form of three families of quarks and leptons).

Despite its undisputed array of successes, both in interpreting observation and in predicting phenomena, many observational problems and theoretical puzzles strongly suggest that the SM cannot constitute the ultimate description of Nature. In particular, and as of today, strong evidence for new (particle) physics - beyond the scope of the SM - stems from the observed matter-antimatter asymmetry of the Universe (for which the SM offers no explanation) and the existence of massive neutrinos (strictly massless by construction in the SM). Likewise, compelling evidence from cosmological observations suggests that the most abundant form of matter in the Universe is non-luminous or “dark” (i.e. without electromagnetic interactions, only weak and gravitational), and that there is an even more abundant energy component, called “dark energy”, which is responsible for the accelerated expansion of the universe. The SM offers no dark matter (DM) candidate nor an explanation to the dark energy.

In recent years, a small number of tensions between observation and the SM’s predictions have emerged: these include the long-standing tension surrounding the muon anomalous magnetic moment $(g\text{-}2)_\mu$, and more recently, also in that of the electron. Other tensions stem from charged and neutral current B-meson decays, some of them interestingly pointing towards a violation of the universality of gauge interactions in the lepton sector ($R_{K(*)}$ and $R_{D(*)}$). The situation should be clarified over the next decade, possibly starting to reveal the underlying physics beyond the SM (BSM).

The SM is also plagued by numerous theoretical caveats: despite being seemingly verified by the discovery of the Higgs, the SM EW symmetry breaking (EWSB) mechanism remains to be fully understood; the scalar sector is also at the origin of the well-known Higgs hierarchy and naturalness issues. Other theoretical puzzles stem from unexplained aspects of the SM (including the choice of gauge group, the possibility of gauge coupling unification, the flavour and CP problems, the strong CP problem, or even the fact that the SM does not include gravity - to mention only a few), and further fuel the search for models of new physics.

Many well-motivated, appealing BSM scenarios have been proposed; these range from minimal extensions of the SM field content (additional neutral fermions, extended scalar sectors, exotic states…) to enlarging its symmetry (either enlarging the gauge sector, or considering new flavour symmetries, for example), also including new complete theories which contain the SM as a low energy effective realisation. The latter includes supersymmetric models, grand unified theories, extra dimensional models - just to mention a few. Many of the constructions are realised at scales ranging from the electroweak scale, to a few tens of TeV, the *“Terascale”*.

On the experimental side, searches for the new phenomena can take place at colliders, by searching directly for the new states or by looking for deviations from the SM (in precision measurements, flavour observables, ...), but also with other experimental approaches such as direct and indirect DM search experiments. Not only are the analysis of the current data and development of new analyses using existing facilities important, but so are also the studies related to proposed/planned upgrades and/or new facilities, such as future colliders.

All these searches and measurements can only be performed and optimally exploited when fruitful exchanges between theorists and experimentalists take place. From the theory side, model building, precise computations or phenomenological predictions can help motivate further analyses, while more precise experimental measurements or access to novel signatures through experimental advances can help motivate particular computations or studies of less explored models. Furthermore, tools often need to be developed in order to make precise computations, phenomenological predictions, reinterpretations of experimental results, etc. The IRN Terascale provides such an environment, where experimentalists and theorists can discuss in a convivial and effective way, fostering new collaborations across several “Terascale” research domains.

2 Scientific programme and activities

The IRN Terascale scientific programme thus focuses on three core research topics, “Higgs and electroweak symmetry breaking (Higgs)”, “Beyond the Standard Model (BSM)”, and “Dark Universe”, as well as on “Methods and Tools (Tools)” which are a common need to all of them. These four working groups (WGs) have been an integral part of the GdR/IRN Terascale since 2013, and the current proposal will continue developing its scientific activities relying on the same structure. All WGs include both theoretical and experimental approaches. One of the goals of the IRN lies in bridging gaps between the two communities, offering common grounds for exchange, discussion and collaboration.

A successful exploration of both the SM and its possible extensions at the Terascale and beyond further requires a synergy across the different WGs, with collaborations emerging from shared interests. As subsequently argued, these are goals of the IRN Terascale.

2.1 Working groups

Higgs and electroweak symmetry breaking (Higgs)

Although the experimental measurements of the Higgs boson properties performed at the LHC experiments seemingly agree with the SM paradigm of EWSB (within current uncertainties), many questions remain: is the observed Higgs a minimal SM Higgs or part of an enlarged scalar sector? Does it arise in the framework of new physics models including a light neutral scalar? Is it a fundamental or a composite state? Could it couple to dark matter (dark matter portal)? Could there be further sources of CP violation?

Multiple measurements also remain to be done, either by differentially measuring already observed channels, or by measuring new channels such as the Higgs couplings to second-generation fermions, rare Higgs decays (e.g. $H \rightarrow Z\gamma$) and the Higgs self-coupling. Measuring the latter directly is fundamental, as it is the only model-independent way to experimentally reconstruct the Higgs potential. The di-Higgs production is the most sensitive probe for this coupling, but the production rate, which can be modified by BSM physics, is three orders of magnitude smaller than the single-Higgs production. This is thus a challenging analysis for the years to come and will be an important target for the HL-LHC. The level of Higgs measurement precision that can be reached at possible future colliders is also a topic of interest.

Due to its very large mass, and sizeable couplings to the Higgs boson, the top quark can also offer a unique window into the mechanism of EWSB: an improved precision in the knowledge of its mass and width is also of paramount importance to test the stability of the SM EW vacuum - determined by both the top and the Higgs masses. Several BSM constructions can lead to an (effective) modification of the top couplings to SM bosons (W, Z, γ); likewise, top-Higgs couplings can also be enhanced or modified (e.g. allowing for new qtH interactions). This renders the study of rare top processes, such as single-top production, pair-production, or four tops, a powerful test of new physics, also allowing testing the SM consistency.

The electroweak sector of the SM can also be explored through scattering of vector bosons. These measurements on the one hand test the non-abelian structure of the SM through the studies of the three and four boson couplings and, on the other hand, probe the coherence of the SM through direct exploration of the symmetry breaking mechanism.

Beyond the Standard Model (BSM)

Motivated by the various open questions left by the SM, multiple BSM models exist or are being developed, from extra dimensions to supersymmetry (SUSY), axion/axion-like particles to heavy neutral leptons, leptoquarks to new vector-like fermions, or even other light/weakly coupled new states, to name but a few. The new models often rely on enlarged gauge symmetry groups (e.g. U(1), Left-Right, Heavy Vector Triplets, ...), or discrete symmetries (usually to address the flavour and CP puzzles). The BSM constructions may have a diverse phenomenological impact, possibly opening the door to phenomena forbidden or strongly suppressed in the SM, leading to deviations from the latter. The new heavy states may manifest themselves through virtual effects, as for EW precision observables, flavour observables (including $(g-2)_\mu$, lepton flavour violation, or anomalies in the B-meson sector), or be directly produced at high-energies, leading to exotic resonances, new cascade decays, missing energy signatures, and so on.

Complementary to the study of the different BSM constructions, the effective (field theory) approach makes it possible to study the effect of the new states by parameterising all possible deviations from the SM via a minimal complete set of gauge-invariant local operators with dimensions greater than four. This approach also allows for a convenient “model-independent” recast of the available experimental constraints on new physics models.

While the direct BSM searches have so far pushed many limits on new states to the TeV scale, these limits are usually set on benchmark configurations (representative of a given regime) or simplified models (for instance focusing on given production and decay chains): strengthening the latter approach while understanding the coverage of more complete or complex models is thus of great interest, as well as combining search results. The direct searches will continue to be performed in existing facilities to probe higher masses and/or lower couplings, with an increased focus on production modes needing more statistics to be effectively probed and on more challenging experimental final states, such as the search for long-lived particles.

Model building, phenomenological studies of well-motivated models for existing or future facilities, and constraints from experimental data, including the re-interpretation of existing direct searches and/or measurements, are all pertinent topics for this WG.

Dark Universe

Other than the knowledge that the SM offers no viable candidate, the nature of dark matter (DM) remains unknown: not only the candidates have masses ranging from sub-eV to hundreds of TeV, but the strength and actual nature of its interaction with SM particles also remains elusive. Several well-motivated BSM models, such as some SUSY or extra-dimension models, encompass weakly interacting massive particles whose masses can range from tens of GeV to tens of TeV. In recent years, a lively interest has also surrounded much lighter DM candidates, including axions and axion-like particles, as well as models in which the DM is a constituent of a larger set of “hidden” particles (Dark Sector), some of which could interact with SM fields via portal operators. The DM production mechanism in the early Universe is also unknown: thermal production in general leads to heavier DM candidates (keV - 100 TeV range), while ultralight candidates (sub-eV range) are produced non-thermally; it is also plausible that DM possesses a particle-antiparticle asymmetry that is linked to the baryon asymmetry of the universe.

Searches for DM can be carried out in three different ways: indirectly, by looking for the annihilation products of DM particles, directly, by looking for interactions of DM particles with SM particles in detectors, or in collisions of SM particles, by looking for signatures often based on the presence of large missing transverse momentum coming from the escaping, weakly interacting DM candidate. These three methods are complementary in the information they can bring regarding the DM nature and interactions.

This information can also be combined with information coming from astrophysical and cosmological measurements.

Clearly, there will often be common topics amongst the Higgs, BSM and Dark Universe groups.

Methods and Tools (Tools)

The interplay between theory and experiment is primordial. On the one hand, new models should respect current constraints, the precision of predictions should be in line with what the experimental measurements can achieve and phenomenological studies should be made to nurture further experimental analyses and motivate new experimental facilities. On the other hand, new experimental results can motivate further theoretical developments and should be presented in as clear and complete a way as possible in order to allow their use.

To achieve this, the development of multiple tools is of paramount importance, often addressing physics issues which can span one or more of the three other WGs. This WG is thus interested in updates and new developments of tools which include, but are not limited to, the ones making it possible:

- to generate accurate predictions: e.g. production cross sections and kinematic distributions for various SM or BSM processes, possibly including higher order corrections, dependency on the energy scales, DM relic density in various models
- to produce and analyse Monte Carlo events: e.g. event generation for new BSM scenarios, simulation of their interactions with current or future detectors, analysis framework
- to perform global fits linking different analyses (e.g. various Higgs measurements or various direct BSM searches) or different experimental methods (e.g. comparing direct/indirect/collider DM searches)
- to reinterpret the experimental results (e.g. in terms of complete or simplified models, or effective field theories)
- to improve experimental analyses and optimise the extraction of theoretical information from experimental data (e.g. jet reconstruction algorithms or use of machine learning techniques)

2.2 GPS

In addition to the 4 WGs, the Scientific Management Committee (see Section 3) envisages the creation of (extraordinary) “Groupements de Priorité Scientifique”, or GPS. These GPSs focus on more narrow, dedicated topics, and have a limited duration. In general motivated by the need to address a given issue or question (fuelled by a scientific breakthrough, or the need to bring together certain expertises), the GPSs can span across scientific topics of several WGs. More goal-oriented, a GPS can organise dedicated meetings, either in association to the biannual IRN general workshops (see Section 2.3), or independently (usually for a reduced number of participants). Examples of past GPSs include one on next-to-minimal supersymmetric models and one on dark matter (which led to a joint publication by theorists and experimentalists).

2.3 Activities

During the period 2017-2020, the IRN Terascale (http://terascale.in2p3.fr/) has organised seven general workshops (see https://indico.in2p3.fr/category/202/), in Montpellier (July 2017), Marseille (December 2017), Strasbourg (May 2018), Durham (September 2018), Annecy (May 2019), Bruxelles (October 2019), and one fully online in November 2020 due to restrictions linked to the pandemic. Several topical meetings were also organised by different groups, for example on supersymmetric extensions of the SM or on the recent results from the Xenon experiment.

These general IRN workshops, with an average of around 65 participants, typically last three days, with approximately half a day devoted to each group and with all talks given as plenaries. Half a day can also be allocated to free discussions on selected topics in separate rooms at the end of the workshop. These general meetings aim at maintaining the contact between the various theoretical and experimental communities involved, and fostering possible collaborations. Moreover, they offer an interesting opportunity for Ph.D. students and postdoctoral researchers to present their work and exchange with the community, which is an important part of their scientific education. An especially important aspect of these workshops is the convivial atmosphere which allows for free discussions.

In addition to topical meetings and general workshops, a moderated mailing list (open to subscription) is also used by the members of the IRN Terascale to share topics pertinent to the whole group, such as raising awareness to particular results, advertising upcoming IRN events or other workshops/schools, and even circulating job openings.

3. Organisation

The organisation of the IRN Terascale relies on several platforms bringing together French and International representatives: a directorate, the scientific management committee (SMC), and the scientific working groups (WG). In all cases, the composition of these groups aims at preserving a balance between theorists and experimental physicists, and at ensuring a good representation of the distinct scientific domains to which the IRN Terascale is dedicated. Likewise, the steering groups also comprises members of the European institutes.

The IRN Terascale directorate is composed of three members: two French co-directors, Marie-Hélène Genest (LPSC Grenoble, ATLAS experiment) and Ana M. Teixeira (LPC Clermont, Theory) - replacing Dirk Zerwas (IJCLab) and Gilbert Moultaka (L2C Montpellier) who directed the IRN Terascale during the previous approval period - and one European, Tilman Plehn (Heidelberg, Theory).

The SMC ensures the scientific steering of the IRN Terascale, and plays a role in the organisation of the different activities. Composed by representatives of all the participating institutes (17 French partners and 14 European partners, see Sections 3.1 and 3.2), as well as by the directors and convenors of the WGs (ex-officio), the SMC meets at every workshop of the IRN Terascale, and holds extraordinary meetings, at the initiative of the directors when required by the dynamics of the network or by scientific evolutions.

The core of the scientific activities pertains to the coordinators (convenors) of the different WGs, responsible for identifying key topics, putting together the scientific programme of the meetings, and ensuring lively discussions. Each WG is coordinated by (at least) one experimental physicist and one theorist, and their composition is given in Section 3.3.

3.1 French partners

Partner	**Representative in the SMC**
CPPM Marseille	Steve Muanza
CPT Palaiseau	Emilian Dudas
IRFU Saclay	Emmanuel Moulin
IJCLab Orsay	Nikola Makovec, Ulrich Ellwanger
IP2I Lyon	Suzanne Gascon-Shotkin
IPHC Strasbourg	Ulrich Goerlach
IPhT Saclay	Stéphane Lavignac
L2C Montpellier	Jean-Loïc Kneur
LAPP Annecy	Tetiana Berger-Hryn'ova
LAPTh Annecy	Björn Herrmann
LLR Palaiseau	Christophe Ochando
LPC Clermont-Ferrand	Jean Orloff
LPNHE Paris	José Ocariz
LPSC Grenoble	Marie-Hélène Genest
LPTHE Paris	Pietro Slavich
LUPM Montpellier	Cyril Hugonie
Subatech Nantes	Julien Masbou

3.2 International partners

Partner	**Representative in the SMC**
Belgium	
ULB Bruxelles	Michel H.G. Tytgat
VUB Bruxelles	Alberto Mariotti
Germany	
University of Bonn	Herbert K. Dreiner
DESY Hamburg	Christophe Grojean
ITP Heidelberg	Tilman Plehn
KIT	Margarete Mühlleitner
Italy	
University of Milano	Stefano Forte
Sapienza University of Rome	Marumi Kado
University Roma Tre	Roberto Franceschini
INFN Torino	Marco Taoso
University of Torino	Nicolao Fornengo
Spain	
University of Valencia	Veronica Sanz
United Kingdom	
IPPP Durham	Steven Abel
University of Oxford	Gavin Salam

3.3 Working groups and convenors

Working Group	**Convenors**
Higgs	Nicolas Morange (IJCLab Orsay, Experiment)
	Christophe Ochando (LLR Palaiseau, Experiment)
	Pietro Slavich (LPTHE Paris, Theory)
BSM	Éric Chabert (IPHC Strasbourg, Experiment)
	Björn Herrmann (LAPTh Annecy, Theory)
	Romain Madar (LPC Clermont, Experiment)
	Jérémie Quevillon (LPSC Grenoble, Theory)
Dark Universe	Julien Masbou (Subatech Nantes, Experiment)
	Emmanuel Moulin (CEA Saclay, Experiment)
	Kallia Petraki (LPTHE Paris, Theory)
Tools	Anja Butter (ITP Heidelberg, Theory)
	Samuel Calvet (LPC Clermont, Experiment)
	Éric Conte (IPHC Strasbourg, Experiment)