Swiss roadmap on particle physics – Theory contribution

1 Introduction

Our present understanding of fundamental interactions is based on the Standard Model (SM), the Quantum Field Theory (QFT) that describes in a coherent way the nature and non-gravitational interactions of the fundamental constituents of matter. The SM has been successfully tested over a huge range of energies: from the few eV of atomic bonds up to the few TeV of proton-proton collisions at the LHC. However, compelling arguments from cosmological observations, theoretical considerations related to the difficulties of incorporating gravity in this framework, and the lack of convincing explanations for the peculiar values of the free parameters of this theory, indicate that the SM is not the ultimate theory of fundamental interactions: the SM is an effective a theory valid only over a limited range of energies and interaction strengths. The search for a theory able to overcome the difficulties of the SM, extending its validity range, and possibly predicting some of its free parameters, is the ultimate goal of the forefront research in particle physics, both on the experimental and on the theoretical side.

We can roughly divide the research directions in theoretical particle physics in four main categories:

I. **Precise SM physics.** An essential ingredient to make progress in the field is to develop precise predictions, within the SM, for particle-physics experiments: without precise predictions to compare with, we cannot interpret the experimental results. While the SM is an apparently simple theory in abstract terms, making precise predictions for quantities observed in realistic experiments is often an extremely challenging goal, which requires sophisticated tools, both from the analytical and the numerical side.

II. **Model-building and beyond-the-SM (BSM) phenomenology.** A similarly core ingredient of the theoretical research in particle physics is to develop new models of fundamental interactions, able to address some of the shortcomings of the SM, and to understand how these models could possibly be tested in present and future experiments.

III. **Cosmology, astroparticle, gravitational physics.** A growing aspects of theoretical particle physics concerns cosmology and, more generally, the connections between particle physics, astrophysics and gravitational physics. The challenge here is understanding particle physics and fundamental interactions through predictions and observations of astrophysical phenomena ranging from cosmic messengers to the large-scale structure of the universe.

IV **Formal theory developments.** The last essential ingredient of the theoretical research in fundamental physics deals with more formal aspects. There are still many regimes of QFT that are poorly understood, especially when going beyond a four-dimensional flat geometry, as required by General Relativity. A rich structure of symmetries connecting seemingly different QFT regimes has also emerged in the last few years. A deeper investigation of these aspects, as well as the development of theoretical frameworks able to go beyond QFT, such as String Theory, are the subject of this more formal line of research.

Institution	Main research areas	
EPFL	(II)	High-energy BSM phenomenology, model-building.
	(III)	Cosmology, astroparticle physics, hidden sectors.
	(IV)	Formal aspects of QFT
ETH	(I)	High-precision perturbative QCD, collider phenomenology.
	(IV)	String theory and formal aspects of QFT
PSI	(I)	Precision low-energy physics, collider phenomenology.
	(II)	BSM phenomenology at low- and high-energies, model building.
University of Basel	(II)	Neutrino physics, high-energy BSM phenomenology.
	(III)	Cosmology, astroparticle physics.
University of Bern	(I)	Precision low-energy physics, lattice QCD, collider phenomenology.
	(III)	Cosmology, astroparticle physics.
	(IV)	String theory and formal aspects of QFT.
University of Geneva	(II)	High-energy BSM phenomenology, model-building.
	(III)	Cosmology, astroparticle physics, physics of GW.
	(IV)	String theory and formal aspects of QFT
University of Zurich	(I)	High-precision perturbative QCD, simulation tools for colliders, precision flavour physics.
	(II)	BSM phenomenology at low- and high-energies, model-building.
	(III)	Physics of gravitational waves.

Table 1: Overview of the research activitities in theoretical physics in Switzerland.

Swiss researchers are actively involved in all these four lines of research, with complementary expertise at different universities and research institutes, as qualitatively outlined in Table 1. The Swiss research in theoretical particle physics is of very high quality in all these different directions. Just to mention a representative figure of merit: in the last six years Swiss researchers have been awarded four ERC Advanced Grants and four ERC Consolidator Grants in the area of theoretical particle physics. This is a remarkably high figure given the relatively small community and the highly competitive nature of these grants.

In the following we present a more detailed illustration, with highlights and future prospects, of the main research activities.

2 Highlights of the recent research activity

2.1 Precise SM physics

QCD at colliders. Theoretical predictions based on the SM are a fundamental ingredient for the interpretation of collider data. The vast majority of experimental analyses make use of perturbative predictions at parton level or in combination with parton showers. Such predictions are relevant to test the SM but they are also a crucial ingredient in the experimental measurements, both for the description of acceptance efficiencies and for the modelling of backgrounds in SM measurements and BSM searches. As a result of the continuously growing precision of the experimental data, and in view of the expected improvements that will be achieved with the HL phase of the LHC, an increasing number of analyses is going to be limited by theoretical uncertainties.

Perturbative calculations including NLO corrections in both the QCD and EW couplings are nowadays supported by automated tools, and their systematic application to hadron-collider studies is mandatory in order to reach a precision of $\mathcal{O}(10\%)$. To reach percent-level accuracy NNLO corrections in the QCD coupling are required. For selected benchmark processes, even N^{3}LO accuracy may be required.

Several NNLO QCD calculations have been completed in recent years for relatively simple hadron-collider processes. The range of processes for which NNLO accuracy can be reached is currently limited by the difficulty in computing two-loop amplitudes in process involving more the four external particles. The precise modelling of complex processes requires to go beyond this limitation. The computation of the relevant loop amplitudes is a formidable challenge from both the algebraic and analytic viewpoint, and the relevant integrals often involve genuinely new classes of functions. At present several directions to break this bottleneck are explored, including the clever use of unitarity, new geometric approaches, and fully numerical techniques. In parallel, an effort is ongoing to improve available methods to handle and cancel infrared singularities and to extend them to more complex processes. This step is also essential to ultimately build flexible tools that are able to fully deploy the achieved theoretical precision into experimental analyses.

Members of the particle theory groups at ETH and the University of Zurich work at the forefront of all these activities. Highlights of their recent research activity in this area includes the first ever N^{3}LO calculation for a collider process, namely the Higgs production via gluon fusion at the LHC; the completion of fully differential NNLO calculations for a wide class of processes; the development of parton-level Monte Carlo generator for collider processes incorporating NNLO corrections; the development of new techniques for analytical and numerical calculations of multi-loop amplitudes.

Related activities are carried out also at PSI and at the University of Bern. At Bern, in particular, the issue of all-order re-summations of soft-and collinear parton emissions, which is particularly relevant for an accurate description jet physics, is investigated via the development of an appropriate effective theory approach.

Future efforts in this direction will be targeted towards key processes for the HL-LHC physics program, as well as for future FCC scenarios. The conceptual frontiers to be addressed are high-multiplicity processes where novel approaches to virtual and real radiation corrections are being developed, multi-scale problems combing QCD and electroweak effects or involving top quarks, as well as ultimate precision at N^{3}LO for selected benchmark processes.

Precision low-energy physics. Beside the direct searches for new phenomena performed at high-energy colliders, a complementary way to search for BSM physics is the so-called intensity frontier, namely the search for possible failures in the SM predictions when performing high-precision experiments. Particularly interesting in this respect are high-statistics low-energy experiments testing exact or approximate symmetry properties of SM, such as the absence of flavour-changing processes in the charged-lepton sector, the strong suppression of flavour-changing neutral-current processes in the quark sector, and the approximate matter-antimatter asymmetry in both the quark and the charged-lepton sector.

Also in this case an essential ingredient to make progress in the field is the development of accurate SM predictions, a task which is particularly complicated at low-energies due to the phenomenon of quark confinement. A further complication is also the extreme high accuracy required by these experiments, which often involve very different energy scales (e.g. from the 100 GeV of weak interactions down to the 0.5 MeV of the electron mass). A series of effective theory tools have been developed to deal with these problems, as well as methods based on the combination of analytical calculations and experimental data.

Swiss researchers at PSI, the University of Bern and the University of Zurich are particularly active on this research line. Highlights of their recent research activity in this area includes precise predictions for the anomalous magnetic moment of the muon; detailed estimates of signals and backgrounds for rare muon experiments at PSI; precise predictions for experiments on rare B meson decays performed at the LHCb experiment at CERN. Future efforts in this direction will be addressed to the new generations of experiments in this field, with special emphasis on planned experiments at PSI, as well as the LHCb upgrades.

A special role in this area is played by lattice QCD. The goal here is to overcome the problem of quark confinement through large-scale numerical simulations of strong interactions and determine the properties of hadron physics from first principles. Swiss theoreticians at the University of Bern coordinates the so-called FLAG report, which compiles and critically reviews the results from various lattice collaborations worldwide, and are members of the ETMC (European Twisted Mass Collaboration): one the largest lattice QCD collaborations worldwide.

2.2 Model-building and BSM phenomenology.

The phenomenological attempts to build motivated extensions of the SM, with direct implications for current and near-future experimental efforts in particle physics, can be conveniently organised into two distinct but largely complementary research directions which address different aspects of BSM physics.

The origin of the Fermi scale. The SM Lagrangian contains a single mass parameter, namely the Fermi scale, or the vacuum expectation of the Higgs field. This scale (of the order of 250 GeV) controls the masses of all elementary particles, but is highly unstable with respect to quantum corrections: it would naturally tend to be heavier in presence of heavier degrees of freedom in the theory. Why such scale is much lighter than the fundamental mass scale associated to gravitational interactions (the Plank scale, of the order of 10^{19} GeV) is one of the big open issues in the SM.

In the vast majority of proposed BSM extensions, this problem is solved by introducing new degrees of freedom around the TeV scale, whose main purpose is that of screening the Higgs field from its apparent large sensitivity to high energies. On general grounds, this implies new particles in the TeV range. This is why the direct exploration of the TeV energy domain remains a key priority of particle physics.

Swiss theory groups at EPFL, PSI, the University of Geneva, and the University of Zurich are working on this front developing explicit models of TeV-scale dynamics and, most important, trying to understand how these models could be detected at present and future high-energy colliders. Highlights of their recent research activity in this area include the development of general effective theories describing SM extensions where the Higgs is a composite particle; the development of experimental techniques to access suppressed BSM effects in high-energy collisions; the development of new theoretical methods to deals with QFT theories in the strong-interaction regime. Future efforts in this direction will be addressed to the HL-LHC physics program but, most important, to evaluate the physics reach of future high-energy facilities.

The flavour puzzle. Within the SM, the basic constituents of matter are the three families (or three flavours) of quarks and leptons. Each family contains four fermions (two quarks and two leptons) with different quantum numbers, which determine completely their properties under strong, weak and electromagnetic interactions. Ordinary matter consists essentially of particles of the first family, while the (unstable) quarks and leptons of the second and third family appear to be identical copies of those in the first family except for their different (heavier) masses. Why we have three almost identical replicas of quarks and leptons, and what the origin of their different masses is, are among the key open issues in the SM. The observed excess of baryons (over anti-baryons) in the Universe, unexplained in the SM and requiring additional sources of CP violation besides that present in the quark mass matrices, is likely to be related to these questions.

In many proposed BSM extensions, the flavour puzzle is addressed by a series of new interactions (and new symmetry principles), whose elementary nature manifests itself only at very high energies. The mediators of such new interactions may be too heavy to be directly produced at high-energy colliders. Still, their effect could show up indirectly in deviations from the SM predictions in various rare low-energy processes, such as the decays of the heavy quarks and leptons.

Swiss theory groups at PSI and the University of Zurich are particularly active on this front. In the last few years their research activity has been focused on understanding the interesting phenomenon of the so-called B-physics anomalies: a series of deviations from the SM predictions in various rare B-meson decays. While the statistical significance of these anomalies is not extremely high yet, the overall picture is quite coherent and might represent a first clue of BSM physics. If confirmed, this BSM physics would certainly have a non-trivial flavour structure. Highlights of the recent research activity in this area include the development of consistent models able to describe these anomalies; the detailed investigation of the implications of these models for future experiments, both at low and at high energies. If the anomalies will persist, future efforts in this direction will further intensified with special emphasis on the LHCb upgrades, the LFV experiments at PSI, and ultimately the flavour-physics program at the FCC.

2.3 Cosmology, astroparticle, gravitational physics.

Dark sectors and neutrino masses. The SM could be extended not only by the presence of new heavy states, which have not been identified yet because of the energy limitations of existing colliders, but also by new light states, which have not been identified yet because of their weak coupling to ordinary matter, generically denoted as dark sectors. Dark sectors, which are natural candidates to explain the phenomena of dark matter, have received considerable attention in the last few years. While a large fraction of the parameter space of these modes cannot be probed at accelerators, interesting regions of the parameter space give rise to long-lived particles which can be searched for by the existing experiments at hadron colliders, at dedicated fixed target experiments, and also with high-intensity particle beams also at low energies. A partly related issue is the origin of neutrino masses, whose small values naturally point toward the existence of new fundamental scales in the theory and/or new feebly interacting states (such as light quasi-sterile right-handed neutrinos). Moreover, CP violation in the neutrino sector could well be related to the observed matter anti-matter asymmetry in the universe.

Swiss theory groups at EPFL and the University of Basel work on both these aspects of BSM physics, building consistent models of neutrino masses, including possible new light exotic states, and analysing their implications for collider experiments taking into account astrophysical observations. Highlights of their recent research activity in this area include the development of consistent modes addressing both the origin of neutrino masses and the problem of dark matter; systematic analyses of the phenomenology of feebly interacting particles at existing and future high-intensity experiments; systematic analyses of the impact of the DUNE experiment in constraining unified models predicting neutrino masses. Future efforts in this direction will continue at the interface of particle-physics experiments and astrophysical observations, with a special emphasis on exploiting the physics reach of the forthcoming long-baseline neutrino experiments, and in planning new dedicated experiments targeting unexplored regions of motivated feebly-interacting exotic sectors.

Cosmology and gravitational waves. There is an intimate connection between particle physics and cosmology: the aim is to build a link between the microscopic laws of physics and the macroscopic observations of the universe as a whole. In the last few years this link has been extended to gravitational-wave physics, which represent a powerful new probe of fundamental physics on the cosmological scale. Just to mention an example of such connections, the precise mechanism that implements the electroweak symmetry breaking in the SM, may have been connected to the inflationary phase of the early universe and may also have led to a phase transition which could be observed with the LISA gravitational wave observatory in the near future.

Swiss theory groups at EPFL, and at the universities of Basel, Bern, Geneva, and Zurich are heavily involved in such type of research. Highlights of their recent research activity in this area include important results in the study of CMB anisotropies and large-scale structure (LSS), providing solid theoretical predictions for the LSS observables and actively participating to the current experiments in the field, such as Planck and Euclid. More theoretical results include the possible explanation of the acceleration of the universe and the phenomenon of dark matter as result of primordial black holes, and the corresponding analysis of gravitational waves (GWs) signatures of interest for present and current GW observers. Other interesting theoretical results include the development of the so-called Higgs-inflation scenario, where the SM Higgs boson is the field responsible for inflation, and the detailed analysis of baryogenesis on motivated BSM frameworks. Beside pure theoretical developments, future efforts in this field will be closely connected to the experimental developments both at the particle-physics and at the cosmological/gravitational frontier.

2.4 Formal theory developmens.

Many recent developments in formal theory have been concerned with the AdS/CFT correspondence that relates superstring theory on a d-dimensional Anti-de Sitter background to the large N limit of a conformal gauge theory living on the $(d-1)$-dimensional boundary of AdS. The most promising example is $\mathcal{N}=4$ super Yang-Mills theory in 4 dimensions that is believed to be equivalent to superstring theory on $\mathrm{AdS}_5 \times \mathrm{S}^5$. The AdS/CFT correspondence has powerful consequences since the regime where $\mathcal{N}=4$ SYM is strongly coupled is mapped to the supergravity regime on $\mathrm{AdS}_5 \times \mathrm{S}^5$ which is under good quantitative control, thus providing a promising window into strongly coupled QFTs. At the same time, the duality may also give insights into the quantum behaviour of string theory since the regime in which the AdS space is of string size corresponds to (nearly) free super Yang Mills theory.

Over the years many precision tests of the duality have been performed, and beautiful confirmation has been found. Swiss theory groups at ETH and Geneva have significantly contributed to these developments. In particular, using techniques of integrability, theorists at ETH have used these ideas to make highly non-trivial predictions about the spectrum of $\mathcal{N}=4$ super Yang-Mills theory for arbitrary values of the coupling constant; to the extent that they are accessible by perturbation theory, these predictions have been confirmed by explicit computations. More recently, the focus has moved towards identifying correlation functions between the two theories. An independent development carried out at ETH focused on a low-dimensional version of the duality, relating string theory on $\mathrm{AdS}_3 \times \mathrm{S}^3 \times \mathbf{T}^4$ to the $2d$ conformal field theory that is described by the symmetric orbifold of $\mathbf{T}^4$. In particular, they managed to prove that the complete spectrum agrees between the two descriptions, and their techniques may be strong enough to lead to a complete proof of the duality in this setting. The AdS/CFT correspondence has also been applied to strongly coupled condensed matter systems.

Another important development concerns the so-called modern (or numerical) conformal bootstrap program that was initiated at EPFL. The bootstrap method is based on the insight that one can characterise correlation functions of a (conformal) quantum field theory based on intrinsic consistency conditions, without any direct reference to an underlying action (that may sometimes not even exist). While this general idea had been known for some time, it was only realised recently that, using in particular numerical methods, these constraints are very powerful indeed and allow one to make significant progress for theories that are otherwise out of perturbative control. One highlight has been the high precision determination of various anomalous dimensions for the $3d$ Ising model, but these (and related) techniques have now also been successfully applied to $3+1$ dimensional QFTs. There has also been interesting progress towards understanding sectors of conformal field theories at large global charge developed at the University of Bern, and the application of resurgence techniques to QFTs carried out at the Univerisity of Geneva.