Conseil Scientifique IN2P3 - Physique Théorique

Physique des Particules[1]

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1 Introduction

Following an intensive experimental programme, the Standard Model (SM) of strong and electroweak interactions has emerged as a very successful description of Nature at the subatomic level, allowing to interpret observation and to predict various phenomena. Nevertheless, several observational problems and numerous theoretical puzzles strongly suggest that the SM cannot constitute the ultimate description of Nature. In particular, the SM – through its interactions and particle content – cannot explain the observed matter-antimatter asymmetry of the Universe, nor massive neutrinos (strictly massless by construction in the SM). Likewise, the SM offers no dark matter (DM) candidate. In recent years, a small number of tensions between observation and the SM predictions have emerged: these include the long-standing tension surrounding the muon anomalous magnetic moment $(g-2)_\mu$, several anomalies in B-meson decay observables and the Xenon1T excess, the interpretation of which is subject to debates. In addition to the pressing experimental and observational problems, the SM is also plagued by numerous theoretical caveats: among them, several are related to the SM description of electroweak symmetry breaking (EWSB) and to the scalar sector (naturalness, hierarchy problem, . . .). Equally important issues 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.

Unveiling the New Physics model (NP) that contains the SM as its low-energy realisation calls for a strong coordinated effort of theorists and experimentalists: precise comparisons between prediction and observation for numerous quantities are required, to readily identify tensions; in order to keep up with the remarkable progress in experimental precision, theory predictions must also aim at an increase in precision and accuracy. Comprehensive theoretical and phenomenological studies (be them model-dependent or relying in the effective field theory approach, EFT) are crucial to constrain viable NP candidates. While the new states will be directly looked for at increasingly high energies, the precision frontier offers a rich testing ground, with observables sensitive to energy scales beyond the reach of any collider.

All these studies, which are part of the future plans of theoretical particle physicists working at the IN2P3, are complementary to and synergetic with the strong experimental effort being carried by numerous experimental collaborations (many of them part of the IN2P3's programme).

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This document aims at a brief description of the activities in particle physics carried by theorists at the IN2P3 Laboratories, offering a panorama of the most active research themes currently pursued. In the Appendix, we offer a tentative listing of the theorists working in the field, as well as their national and international collaborations (research federations, master projects, theory and experimental collaborations); a small summary of activity highlights is also included (publications and dedicated tools).

The Scientific Council on theory activities at the IN2P3 follows a dedicated workshop on the prospects for the evolution of the field ("*Atelier de Physique Théorique des 2 Infinis*"), in which current and future activities were discussed on the dedicated sessions (including "Particle Physics"[2]).

2 Higgs and EWSB

The discovery of the Higgs boson at the LHC was a ground-breaking achievement, and a veritable triumph for the SM description of EWSB. However, the Higgs sector remains far from being theoretically understood, and in fact many theoretical problems of the SM do arise in relation with EWSB and the structure of Higgs interactions to matter fields. Being a scalar field, quantum corrections to the Higgs mass are sensitive to new scales in the theory; explaining why the Higgs mass is comparatively small when $(\Delta m_H)^2 \sim \Lambda^2_{NP}$ is at origin of the naturalness problem. In striking contrast with a simple gauge sector (described by 3 couplings), the SM's description of the Higgs sector requires 15 degrees of freedom, many of these parameters in fact related to the "Flavour and CP problem".

The discovery of the Higgs boson offered a new laboratory and tools for studying the EWSB mechanism. Although the neutral scalar discovered at the LHC remarkably behaves like a SM Higgs boson, one must clarify whether or not it is a part of an extended sector (possibly accompanied by singlets, doublets or even triplets of scalars). Moreover, instead of being an elementary state, the Higgs can be a bound state of a new strongly-interacting confining sector (not unlike QCD, but with a much higher confinement scale) - compositeness.

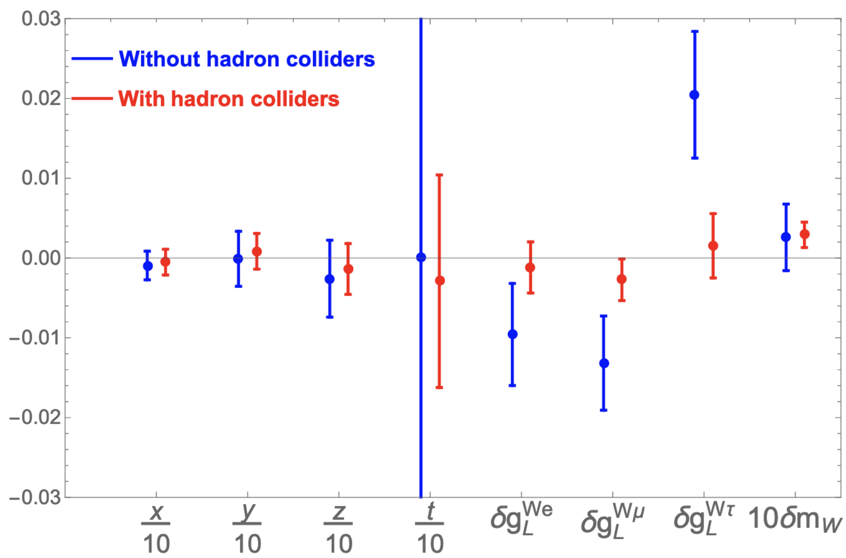

Figure 1: *Impact of the LHC and Tevatron experiments on the EW observables, cf. Ref. [1]. Note that* $(x, y, z, t) = f(g^{Zu}_{L,R}, g^{Zd}_{L,R})$.

[2]See contributions on the dedicated webpage, https://indico.in2p3.fr/e/PhysTh2Infinis

There is a strong activity in the theory community dedicated to probing NP in association with the Higgs sector: from EFT approach, also known as SMEFT, by which one constrains couplings to new operators [1]), to dedicated parameterizations of the Higgs couplings (sensitive to higher order NP contributions) [2], to multi-Higgs doublet models [3].

The assumption of Higgs compositeness is also being scrutinised, in particular in view of its potential studies at future colliders [4] (and in association with promising DM scenarios). Furthermore, scenarios have been put forward in which the Higgs boson emerges in connection with non-thermal mechanisms of dark matter production based on vacuum misalignment (demonstrated for composite models) [5].

LHC experiments improved the knowledge of couplings to the Z-boson, and helped solving several pending issues regarding leptonic W-decays, cf. Fig. 1, which nowadays have become significant constraints when building scenarios of physics beyond the SM (BSM).

3 The flavour and CP problems

After decades of success of the SM of particle physics in describing fundamental interactions at the microscopic level, a series of small deviations from the predictions of this remarkable theory started to emerge. Surprisingly, the deviations were not observed in high-energy collisions, but rather in rare phenomena occurring at relatively low energy, in specific decays of B mesons.

The matter constituents in the SM are organised in three families of quarks and leptons. Quarks and leptons of different families behave exactly in the same way under the three fundamental forces, with the only difference being their masses, which also control their interactions with the Higgs boson. A series of recent precision measurements challenges the universal character of the different families under fundamental interactions, and points towards lepton flavour universality violation (LFUV). The evidence collected so far in B-meson decays can be divided into two classes, according to the underlying quark level transition:

- *Charged-current anomalies* refer to the $b \to U\ell\bar{\nu}$ processes, which occur at tree-level in the SM, $\ell \in \{e, \mu, \tau\}$, $U \in \{u, c\}$. Deviations were observed in the decays to τ with respect to μ and e. The typical examples are

$$R_{D^{(*)}} = \left.\frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}\right|_{\ell\in\{e,\mu\}}, \tag{1}$$

which are measured to be a little over 4σ *larger* than predicted in the SM (R_D and R_{D^*} combined).

- *Neutral-current anomalies*, instead, refer to the $b \to D\ell\bar{\ell}$ processes, with $D \in \{d, s\}$, which are forbidden at tree level in the SM. The most striking deviations were observed while measuring

$$R_{K^{(*)}} = \frac{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \, \frac{d\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{dq^2}}{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \, \frac{d\mathcal{B}(B \to K^{(*)}e^+e^-)}{dq^2}}, \tag{2}$$

in the bin $q^2 \in [1.1, 6]$ GeV^2, indicating that the measured result is over 3σ *lower* than predicted in the SM.

A major benefit in considering the above-mentioned quantities is related to the fact that a large part of hadronic uncertainties cancels in the ratios and that the deviations cannot be attributed to our inability to precisely compute the hadronic matrix elements, for which one would need to solve non-perturbative QCD from the theory's first principles.

A wealth of experimental data regarding the exclusive $b \to s\ell^+\ell^-$ processes allowed for a full reconstruction of the angular distribution of $B \to K\mu^+\mu^-$ and $B \to K^*(\to K\pi)\mu^+\mu^-$ decays, and thus opened a possibility to compare the SM predictions with the measured angular observables and thereby get a clearer picture concerning the structure of BSM. To that end the EFT approach is extended as to include the low energy operators that are allowed in a generic BSM scenario. From the global analyses of all observables it became clear that there was a deficit of events in the decays $b \to s\mu\bar{\mu}$, which results in significant constraints on those couplings to BSM physics that involve the vector and axial-vector leptonic currents. Moreover, it was shown that one of the measured angular observables ($\langle P_5' \rangle$) differs considerably from its predicted value in the bins $[4, 8]$ GeV^2 [7–9], but the precise amount of that deviation is still not fully clear due to underlying hadronic uncertainties. It is expected, however, that $Q_5 = \langle P_5' \rangle_\mu - \langle P_5' \rangle_e$ could be a good probe of LFUV. Using the EFT approach one can focus on the specific operators and, from the global fit with all of the known experimental data involving the exclusive $b \to sl\bar{l}$ decays, one can select the scenarios which are consistent with the data from those which are not [8, 9]. For example, the models in which the SM is extended by two Higgs doublets cannot accommodate $R_{K^{(*)}}$.

A similar EFT approach has been adopted to study the $b \to c\tau\bar{\nu}$ processes, but the angular distribution has not been experimentally elaborated yet and therefore less data is available. From $R_{D^{(*)}}$ alone one can, however, test some of the BSM scenarios offering a coherent description of (at least one type of) B-anomalies [3, 6] (cf. Fig. 2), and several (angular) observables can be predicted [10], the measurement of which will help us disentangling the Lorentz structure of the New Physics operators.

All of the above anomalies can be tested in other exclusive channels, including those involving baryons for which several theory analyses are already available [11]. Furthermore, should there be a new physics CP-violating phase, its presence can be tested once the more accurate experimental data become available, either through the time-dependent analysis of rare B-decays, or through CP-asymmetries in the suitably chosen windows of q^2 [12].

It needs to be emphasised that many experimentally available observables are of limited use because of the hard-to-estimate systematic uncertainties on the theory side. Those uncertainties are related to the hadronisation effects. It is for that reason that a major improvement on the side of numerical simulations of QCD on the lattice (LQCD) is needed. However, the B-physics observables are particularly difficult to compute on the lattice because they involve very heavy (b) quark and a very light (u/d) quark. Lattice grid provides a natural regulator of QCD: the lattice spacing a is the ultraviolet (UV) cutoff, and the physical size of the hypercubic lattice L is the IR one. Seeking precision with heavy-light mesons requires very tiny a and very large L, stretching the computing requirements to the extremes and in such conditions it is virtually impossible to work at various lattice spacings in order to monitor the approach to the continuum limit ($a \to 0$). A way out is to treat the heavy quark as an effective field either in the heavy quark effective theory (HQET) or in the non-relativistic QCD (NRQCD). Matching to full QCD can be, and often is, a source of problematic systematic uncertainties, i.e. those that are difficult to quantify. In such a situation, and for better understanding of the significance of numerical results obtained from LQCD in the case of decays of heavy-light hadrons, it is still useful to employ the constituent quark models in the regimes in which they are fully covariant. For example, that road has been pursued in describing the $\Lambda_b \to \Lambda_c^{(*)}\ell\bar{\nu}$ decays [13], which are currently studied experimentally to establish the amount of LFUV.

Notice also that the hadronic quantities which are relevant to the flavour physics are computed by various LQCD collaborations worldwide and are carefully scrutinized by the Flavour Averaging Lattice Group (FLAG). The world average values of the key quantities are pre-

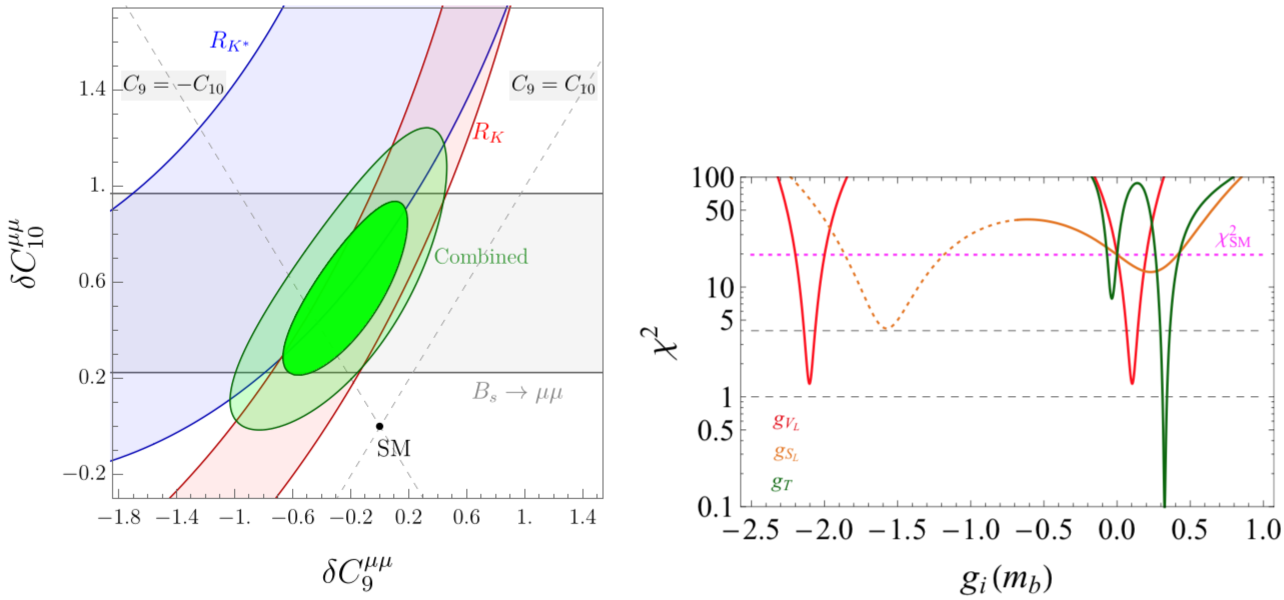

Figure 2: *Left plot shows the constraints on the coupling of NP to the axial ($\delta C_{10}^{\mu\mu}$) and to the vector leptonic current ($\delta C_9^{\mu\mu}$) from the three theoretically cleanest quantities. Right plot shows the improvements in χ^2 in $R_{D^{(*)}}$ with respect to the SM when one of the NP effective couplings is allowed to be non-zero. See Ref. [6] for more details.*

sented in the steadily updated [14], and they are then combined in a global analysis of the Cabibbo-Kobayashi-Maskawa (CKM) unitarity triangle, which is essential for our understanding of flavour in the SM, see Fig. 3. The emerging CKM picture with three families exhibits a pronounced hierarchy among diagonal and off-diagonal entries, and indeed describes very well the flavour phenomena, both in the tree-level as well as in the loop-induced processes. Further improvement in precision can either corroborate this picture or unveil a presence of NP.

Since the naïve scales of two types of B-anomalies differ by an order of magnitude, it is clear that the new interaction has a peculiar flavour structure which is actually very constrained if we aim at simultaneously describing both types of B-anomalies, while using all of the other flavour physics observables as constraints. Exploring such scenarios is a daunting task, and one is instead working with minimal and simplified models of BSM physics, i.e. models which contain a minimal number of parameters relevant for describing the physics phenomena up to the scales $\mathcal{O}(1\ \text{TeV})$.

Among such models, heavy leptoquark (LQ) fields were soon recognised as the most natural mediators behind the semileptonic contact interactions [6]. LQ fields are present in the SM extensions providing a unified description of quark and lepton quantum numbers. They are also present, as composite states, in models featuring new strong dynamics above the electroweak scale. The phenomenological success of the LQ hypothesis, at least at the level of simplified models, in explaining the anomalies is simple: LQs contribute at the tree-level to the semileptonic transitions, which do exhibit anomalies, and they contribute only at the loop level in four-quark or four-lepton contact interactions, which so far do not exhibit deviations from the SM.

When building a model that could offer a combined explanation of both anomalies, it appears that very powerful and important bounds on couplings of SM fermions to a BSM mediator can be deduced from the high-p_T shapes of the $pp \to \ell\ell^{(\prime)}$ cross sections, actually studied by both ATLAS and CMS collaborations at the LHC. In that way it was shown that only one single heavy LQ mediator can survive a combination of all constraints, and that is a vector LQ, known as U_1-field, with SM gauge quantum numbers $(3,1)_{2/3}$ [6, 15]. Other simplified scenarios

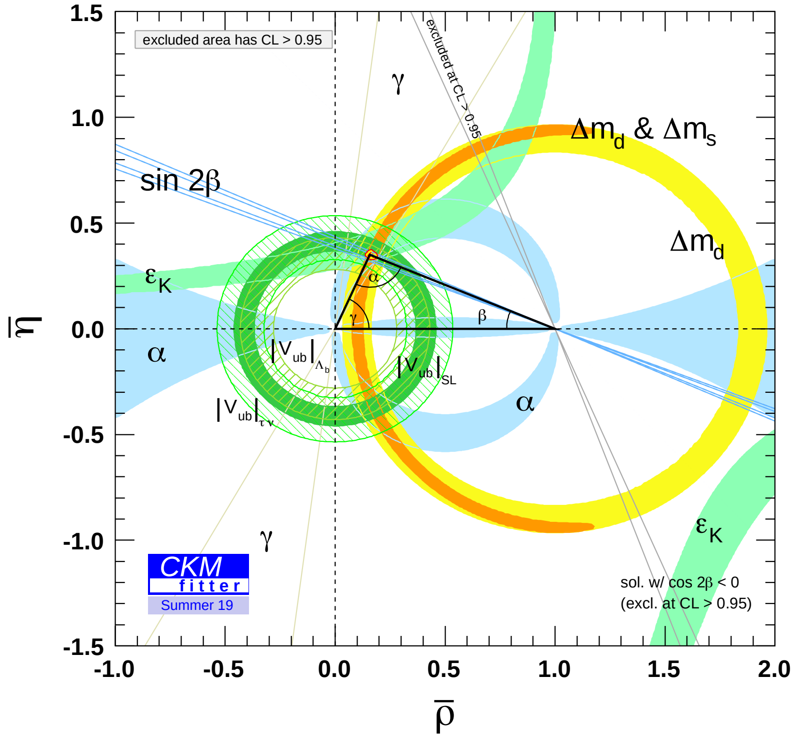

Figure 3: *Unitarity triangle from the global analysis of the CKMfitter collaboration.*

combine two scalar LQ's, namely S_1 with S_3 or R_2 with S_3 [16], with a major advantage that the resulting theory is renormalisable and the UV-completion does not need to be specified when computing the loop-induced quantities, such as the frequency of oscillations in the $B_s - \bar{B}_s$ system, Δm_{B_s}. This is not true for the case of U_1-model for which a UV completion needs to be specified, and that involves new particles and new free parameters. That point might appear as a drawback of the U_1-model, but this can also be viewed as an opportunity to address both the Higgs hierarchy problem and the origin of the SM flavour hierarchies, two fundamental problems which still remain open. One can also go for the non-minimal scenarios and assume the UV-completion to act as deviation of the couplings of U_1 to fermions by making the matrices non-unitary [17].

One of the striking predictions in all of the simplified models is that the branching fractions of the exclusive $b \to s\tau\tau$ processes can be orders of magnitude larger than in the SM [18], and that the lepton flavour violating exclusive modes $b \to s\tau\mu$ can be large and bounded both from above and from below [6].

As mentioned above, it is very difficult to treat the flavour problem in the most generic EFT scenario, but one of the main objectives of research in theoretical flavour physics is to attempt performing a complete analysis of $d = 6$ effective operators written in terms of SM fields (i.e. SMEFT operators). Since the number of such operators becomes prohibitively large, one can at intermediate stages implement specific flavour symmetries and symmetry-breaking patterns in the EFT and thus restrict the analysis to specific classes of operators. This procedure is essential for a wide class of BSM constructions independently from the B anomalies. The task, however, still remains huge and requires a close collaboration among theorists and experimentalists. There are many problems to solve, e.g. how to include next-to-leading order (NLO) SMEFT corrections or how to simultaneously fit PDF's and $d = 6$ operators. Research in this direction has already been reported [1, 19–21]. Note in particular the contribution of Refs. [20, 21] where the method to compute the path integral to one loop more efficiently has been developed, with the key observation being a universal structure of one-loop effective action.

Using tools inspired from Minimal Flavour Violation, the flavour structure of quark and lepton electric dipole moments (EDMs) in the SM and beyond has been investigated, relying on spurion techniques derived from Minimal Flavour Violation. The relevant Jarlskog-like invariants (as well as other non-invariant flavour structures) have been identified for both the quark and lepton sectors, assuming different mechanisms of neutrino mass generation [22]. The formalism has also been used to study the impact of the strong CP-violating interaction and the interplay between the neutrino Majorana phases and possible baryon and/or lepton number violating interactions.

4 Neutrino physics and lepton flavours

The observation of neutrino oscillations marked a first "Laboratory discovery" of physics beyond the SM: in a clear departure from the SM, the lepton sector must be enlarged via new degrees of freedom to describe neutrino masses, leptonic mixing angles and new sources of CP violation. The emerging pattern of masses and mixings is strikingly different from the quark sector, so that the lepton sector has become an integral part of the "flavour and CP" problems.

Understanding neutrino properties is a priority in particle physics (and in its many relations to astroparticle physics and cosmology). This includes intensive studies of standard and non-standard neutrino interactions, propagation in media, as well as the exploration of the role of neutrinos in astrophysical and cosmological environments (for example, the study of neutrino evolution equations in dense media, be it in flat or curved spacetime). For recent highlights, see [23–25].

Ascertaining the final missing details of the neutral sector has become of paramount importance: a word-wide experimental effort is dedicated to establishing the nature and the mass ordering of neutrinos, and to measuring with increasing precision the absolute mass scale and mixing parameters (including the Dirac CP phase).

Irrespective of the BSM at work, massive neutrinos and leptonic mixings open the door to new phenomena, strictly forbidden in the context of the SM: these include the violation of charged lepton flavour (cLFV) and of lepton number (LNV) if neutrinos are of Majorana nature, as well as important new contributions to leptonic EDMs. These observables are among the most powerful indirect probes of NP, with a potential sensitivity to new scales that can reach $\mathcal{O}(10^{5-6}$ TeV) [26].

Due to the relatively clean experimental environment and very promising experimental prospects, muonic cLFV transitions and decays are uniquely sensitive to New Physics in the lepton sector. cLFV muon decays have been intensively studied in the IN2P3 Theory community, both in a model-independent (effective approach) and in the context of specific SM extensions. Complete analysis $\mu \to e\gamma$, $\mu \to 3e$ and $\mu - e$ conversion in nuclei, have been performed for an EFT approach ($M_W \ll \Lambda_{NP}$), leading to severe constraints on the effective couplings. This approach allows to efficiently accompany experimental developments, for instance in what concerns the complementarity of searches planned for the dedicated MEG II and Mu3e experiments [27, 28], as illustrated by the example on the left panel of 4. Likewise, and in view of the expected sensitivity of both COMET and Mu2e experiments, extensive work has also been devoted to studies of $\mu - e$ conversion in nuclei (including spin-dependent studies, $\mu e\gamma\gamma$ interactions, choice of targets, ...) aiming at identifying the underlying NP responsible for a future signal [29, 30].

All data collected so far suggest that neutrinos are extremely light, below the eV scale; in order to explain the striking differences with respect to charged fermions, and supported by the

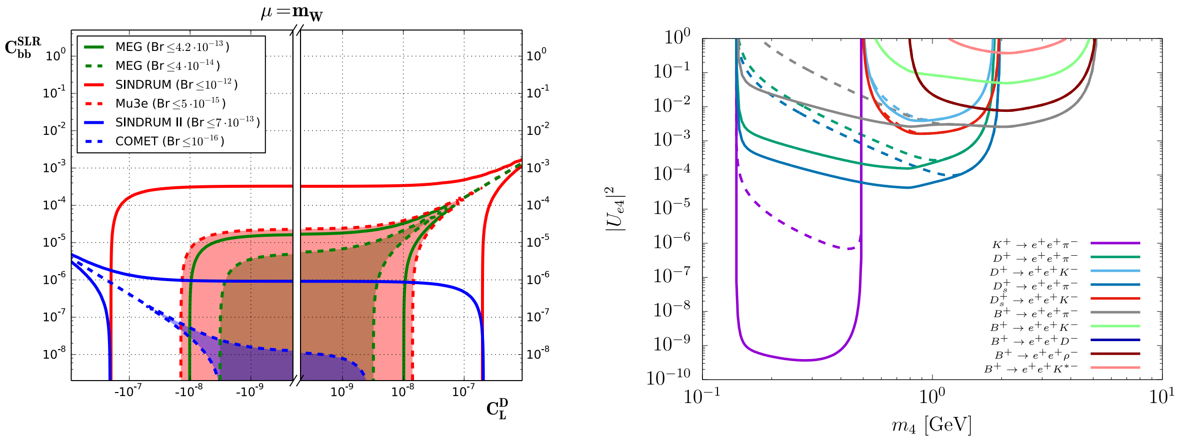

Figure 4: *On the left: allowed regions in the plane spanned by effective couplings (dipole C_L^D and scalar C_{bb}^{SLR}), from $\mu \to e\gamma$ (blue), $\mu \to 3e$ (red) and μe conversion in nuclei, for current (straight) and future (dashed) experimental limits. From [28]. On the right, updated constraints on the relevant combination of leptonic mixing matrix elements $|U_{\ell_\alpha 4} U_{\ell_\beta 4}|$ arising from LNV pseudoscalar meson decays, as a function of the heavy sterile neutrino mass (GeV). From [34], to which we refer for additional details.*

possibility that neutrinos be Majorana particles, new mechanisms of ν mass generation have been put forward. Interestingly, several minimal, well-motivated ν mass models call for the addition of heavy neutral leptons (singlets under the SM gauge group), whose masses could span across many energy scales. This is the case of the type-I seesaw (and its variants) and other minimal constructions, which can also offer an explanation to the BAU (and possibly encompass DM candidates).

The phenomenology of SM extensions via heavy neutral leptons (HNL) has been extensively explored in recent years. At very low-energies, their presence may be detectable by KATRIN (β decays), also possibly giving rise to signals in $0\nu 2\beta$-dedicated experiments (for both orderings of the light neutrino spectrum) [31]. Driven by the modification of the leptonic charged current interaction (due to the new active-sterile mixings and the additional sources of CPV), HNL can lead to signatures both at high intensities and at colliders, especially when their mass is above the EW scale: these include cLFV, LNV and LFUV, invisible and/or cLFV Z-boson as well as cLFV Higgs boson decays, which have been explored in recent years [32]. Moreover, new contributions to the electron EDM - within future ACME reach - can also be expected [33]. Searches for LNV semileptonic meson and tau decays can also offer important information on these extensions, with current data on these decays leading to stringent bounds on active-sterile mixings (an example of such constraints is given on the right panel of Fig. 4). This is a topic of active work, also in connection to re-interpretations of experimental data (e.g. from NA62) by taking into account interference effects in both LFV and LNV decays [34, 35]. It should be mentioned that sterile states can also lead to huge enhancements of $BR(K_L \to \nu\nu)$, otherwise negligibly small in the SM [36].

Models of massive Majorana neutrinos have also been explored in view of the potential to address the BAU - especially constructions which can be realised at low-scales. A successful (and natural) EW leptogenesis has been achieved (through oscillations between two strongly degenerate sterile states), and interesting behaviours were found for the case of 3 HNL, as a consequence of LNV oscillations and decays. Although only efficient for large active-sterile mixing angles, the appeal of such a low-scale leptogenesis lies in its testability by the LHC and other existing experiments [37].

5 New Physics models: from theory to collider searches

As emphasised above, SM extensions must be considered in order to resolve (or soften) its many theoretical and observational problems. All NP models call upon the introduction of new states, whose masses range across many orders of magnitude. While a NP scale around the TeV has long been theoretically preferred, results from the LHC have been having a steady impact in re-shaping both the nature of the candidate SM extension and the strategy of the high-energy search programmes. Current searches have thus shifted the focus from a number of well-motivated models towards a signal-oriented approach, also increasingly considering so-called "difficult-scenarios", in which NP states escape standard searches.

Theoretical particle physics plays a very active role in NP collider searches, and revolves around several axes. On the one hand, thorough phenomenological studies of well-motivated models allow making predictions for high-energy colliders (including associated DM scenarios, as an example, see [38]). This naturally leads to the proposal of promising new signals, or development of strategies to characterise the new states, in general done in close proximity with the experimental collaborations (ATLAS and CMS). On the other hand, the interpretation of experimental data leads to constrains on theoretical models (on different levels, from specific realisations, to broad classes of models).

The IN2P3 theorists have been particularly proactive in what concerns NP physics searches at the high-energy frontier; as a consequence of extensive contributions in recent years, and also relying on the outcome of indirect searches carried at the high-intensity frontier, numerous models of NP have seen their parameter spaces dramatically constrained by these analyses.

It is important to notice that if the discovery of new (heavy) resonances has so far eluded all dedicated direct searches, NP can reveal itself indirectly at high-energies as a deviation from the SM predictions, particularly in the upcoming high-luminosity runs of the LHC. This highlights the role of precision calculations of both the SM background and the NP signals (for instance including NLO QCD corrections, or possible corrections to the production cross sections in the present of new states) [39]. Likewise, deviations from SM-like Higgs couplings are also very sensitive probes to NP heavy states (e.g. $H\gamma\gamma$, Hgg). High-precision calculations of the NP contributions (model-independent, or then for well-motivated candidates as heavy fermions, or scalars) are instrumental to keep the theoretical effort on par with the experimental progress.

5.1 Models of NP at colliders

Members of the community have been very active in proposing and studying numerous new physics scenarios, motivated by the SM hierarchy problem (and the underlying mechanism of EWSB), candidates for dark matter, unification of gauge couplings, among others. The considered BSM frameworks range from minimal extensions of the lepton sector, to enlarged scalar sectors (see, e.g. [3]), extensions of the gauge group, ..., and finally to UV complete constructions.

In recent years, important contributions were made in the context of minimal and non-minimal supersymmetric (SUSY) models[3] (MSSM, pMSSM, ..., NMSSM, RpV SUSY): these studies allowed to better constrain the allowed parameter spaces of the models (see, as illustrative examples [40–43], and contributions to [44]). Scenarios associated with low-energy supergravity constructions have also been revisited [45].

Likewise, models with extra spatial dimensions have equally been the object of numerous studies. These models aim at unifying gravitational and gauge interactions at the EW scale,

[3] Many realisations have been considered: minimal supersymmetric SM (MSSM), 19-parameter phenomenological MSSM (pMSSM), next-to-minimal supersymmetric SM (NMSSM), $R-$parity violating supersymmetric models (RpV SUSY), among many others.

so that the weakness of gravity can be understood from the existence of new compact spatial dimensions (large compared to the weak scale). Recent contributions include addressing conceptual problems in higher-dimensional FT and formal aspects (classification of compact spaces and dual geometries, QFTs in curved spaces [46, 47]), the proposal of new models with new DM candidates arising from geometric symmetries, and finally dedicated phenomenological studies of new heavy particles like Kaluza-Klein excitations of bosons and fermions, arising from specific extra-dimensional (see [48–51]).

The unification of the gauge and Higgs sector has also been investigated, with the possibility of gauge-Yukawa unification being successfully demonstrated [52]; further steps towards unification include asymptotic unification (asymptotically reaching a common fixed point rather than a crossing of gauge couplings at a particular high energy scale) [53].

Dedicated strategies for states with distinctive properties (difficult/stealth scenarios, displaced vertices, long lived particles (LLPs), ...), are also an important part of NP searches at the LHC, and contributions are frequently done in close collaboration with ATLAS and CMS. An interesting example is that of LLPs, which arise in numerous BSM constructions, be it in association with DM candidates, or possibly corresponding to states with small couplings to SM fields, as for instance heavy neutral leptons, present in several models of neutrino mass generation. Developing strategies to unveil the presence of such states (as for instance displaced vertices [54], "kinked tracks" [55], ...) has been the object of several contributions, with promising prospects for the reconstruction of their properties.

5.2 (Re)interpretation of LHC results for NP searches

At the end of the LHC run 2, a large amount of data has been gathered, outperforming all foreseen expectations. The ATLAS, CMS and LHCb collaborations perform precise measurements of Standard Model (SM) processes and direct searches for physics beyond the Standard Model (BSM) in a vast variety of channels. Contributions have been made to Monte Carlo tools such as MadGraph and FeynRules, also allowing for model independent studies.

However, and despite the multitude of BSM scenarios that have been tested, this only represents a small subset of the possible theories and parameter combinations to which the experiments can be sensitive to. What information does current data actually convey about the NP at work? Are particular models being efficiently constrained? Are certain scenarios excluded (as suggested by experimental summary plots) or being merely elusive?

The (re)interpretation of the LHC results in order to fully understand their implications for NP has become a very active field, with close theory–experiment interactions and with new computational tools and related infrastructure being developed. Ensuring that data is analysed in a comprehensive manner is a core task of the IN2P3 theory groups working in this topic; among their goals, to revisit LHC results, in order to evaluate limits and loopholes for realistic new physics models beyond the often simplified (or so-called "vanilla") scenarios considered by the experimental collaborations [56, 57]. The activities naturally lead to the development of dedicated methods and public tools (see Appendix), indispensable to fully explore the theory-experiment interface.

These include a prototype for a novel statistical learning algorithm that is capable of identifying potential dispersed signals in the slew of published LHC analyses; the algorithm is also prepared to build candidate *proto-models* from small excesses in the data, while at the same time remaining consistent with all other constraints [58]. Its ultimate goal is a data-driven bottom-up approach to NP, containing only minimal theoretical bias and which could be used to guide future searches. A fast interpretation of simplified model results from the LHC (within NP extensions respecting a Z2-like symmetry) is offered by *SModelS*, which now includes a wide range of constraints for long-lived particles, now on equal footing as constraints from prompt

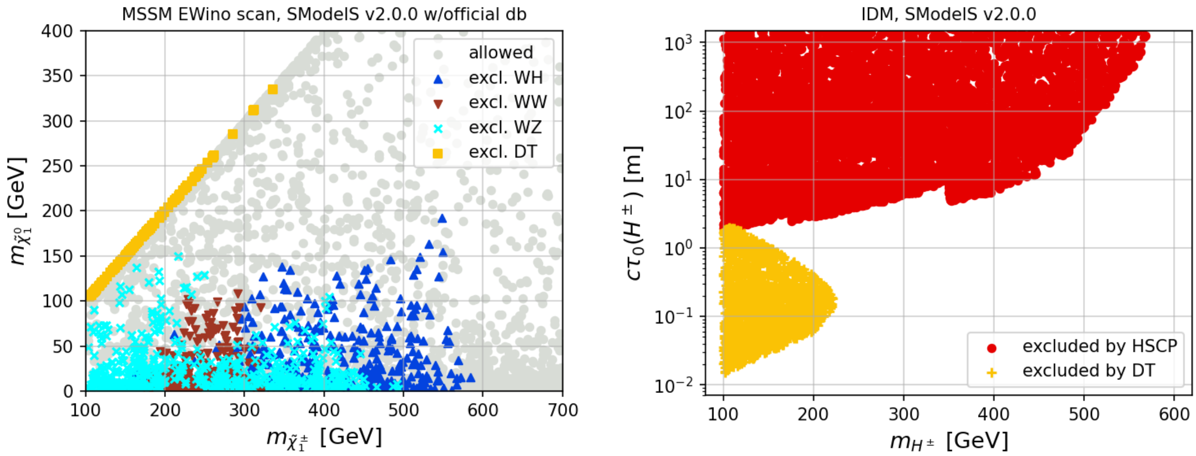

Figure 5: *Examples of model constraints with SModelS 2.0: on the left chargino/neutralino limits in the MSSM, on the right limits on long-lived charged scalars in the Inert Doublet Model [60]. DT stands for disappearing track, HSCP for Heavy Stable Charged Particle searches. WH, WW, WZ are the decay channels considered in the prompt SUSY searches. SModelS is so far the only tool that can treat constraints from prompt and LLP searches simultaneously.*

searches. Full likelihoods (as released by ATLAS) can also be used in SModelS [59]. An example of SUSY model constraints can be found in Fig. 5. Finally, it is important to generically constrain BSM extensions from the signal strength measurements of the 125 GeV Higgs boson (see, e.g. [61]). This is the main goal of *Lilith*, whose latest version successfully uses variable Gaussian and generalised Poisson likelihoods for a better treatment of asymmetric uncertainties (including correlations).

In addition to a thoroughly exploring the data, an important point concerns the **preservation of the results**, in order to ensure that these can be easily accessed and re-used for further analysis. This is particularly relevant should new ideas, or new models be proposed in the (far) future.

6 Quantum field theory

A thorough formulation of any particle physics model necessary begins with (and unavoidably requires) quantum field theory (QFT) studies and methods. Aiming at a correct, precise description of phenomena, and to find alternative ways to address or understand problems of the SM, formal work in QFT remains of paramount importance, and is an integral part of the Particle Physics activities.

This is the case of studies of renormalisation group equations (RGEs) for general renormalisable gauge theories at higher loop order. Revision of available two-loop RGEs, with an impact for the running of several dimensionful parameters (as in the case of quartic couplings in the type III two Higgs doublet model - THDM) [62]. An example of the impact of these corrections can be found in Fig. 6. A dedicated public tool has been developed, *PyR@TE* [63], which allows computing the running of the Lagrangian parameters from high energy scales to the EW scale (and vice versa).

Likewise, new regularisation/renormalisation schemes have been developed; these lead to completely finite elementary amplitudes in physical conditions (no new mass scale nor cut-off, no extension to D-dimensions). The new schemes find a natural application to the naturalness problems of the SM. In particular, the Taylor-Lagrange renormalization/regularization scheme

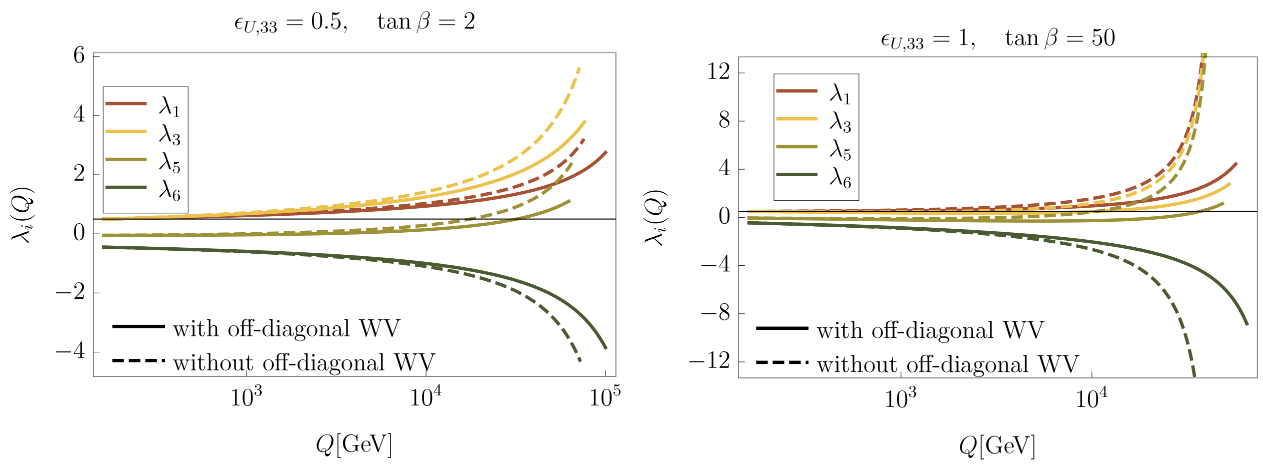

Figure 6: *The running of different quartic couplings in the THDM-III (with and without the contributions of off-diagonal wave-function renormalisation to the β-functions of the quartic couplings). From [62], to which one is referred for details on the setup and input parameters.*

has been successfully applied to the fine-tuning problem of the Higgs mass and how the axial anomaly appears in this scheme [64].

Certain principles are being explored and revisited (such as the Multiple Point Principle, Asymptotic Safety) also in an effort to tackle naturalness problem. These would allow to fix the high-scale boundary conditions of model which then lead to predictions for the parameters at the electroweak scale. Such principles might then explain the value of Higgs mass (and its apparent fine-tuning), and have been applied to two Higgs Doublet Models [65].

7 Summary

Solving some of the fundamental questions of modern physics, such as the hierarchy and/or the flavour problem, requires physics scenario BSM. The most efficient framework for building such a scenario, while relying on numerous data as constraints, is the so called SMEFT, EFT which includes not only the SM but also all the non-renormalisable dimension-5 and dimension-6 interactions. Due to the large parameter space of the SMEFT, the characterisation of the LHC data is a huge and long-term task, requiring a close collaboration between theorists and experimentalists. So far only partial and incomplete results exist; for example, a general likelihood function is available only for small subsets of the SMEFT Wilson coefficients, often involving many simplifying assumptions about the flavour structure of the coefficients. Many technical problems remain to be solved. A complete characterisation of the electroweak precision LHC data in the language of the SMEFT will lead to new stringent constraints on NP, including the one that may be responsible for the observed evidence of LFUV in the B-meson decays.

The IN2P3 Particle Physics theorists are working on numerous fields, many of which are among the Institute's priorities in the domain (Higgs physics, BSM phenomenology, precision observables, neutrino physics, ... among others). In addition to the numerous on-going experiments - and whose results must be thoroughly explored -, the coming decade offers major world-wide experimental opportunities. These include the LHC upgrades (the high-luminosity runs), Belle II and DUNE. An active participation of the theory community - following the effort which is already underway - would offer positive contributions to the physics cases, and naturally to the interpretation of the results.

The long-standing dialogue between theory and experiment in particle physics has proven to be fruitful and clearly positive: new theory ideas emerge in an effort to understand data, and in turn, theoretical proposals can also pave the way to new experimental projects.

Independently of the potential applications to phenomenology, purely theoretical approaches should be preserved, as these are a source of new ideas, and methods.

A TH Particle Physics in IN2P3 Laboratories

A.1 People and Laboratories

Research in Theoretical Particle Physics (theory and phenomenology) is currently carried in several IN2P3 Laboratories, by circa 30 researchers (CNRS and University associates). In addition to the permanent members listed in Table 1, several emeritus researchers as well as numerous postdocs and Ph.D. students compose the different teams.

Laboratory	People
APC Paris (UMR 7164)	D. Semikoz, J. Serreau, M. C. Volpe
IJCLab Orsay (UMR 9012)	A. Abada, D. Bečirević, V. Bernard, B. Blossier, S. Descotes-Genon, A. Falkowski, S. Friot, E. Kou, G. Moreau, O. Sumensari
IP2I Lyon (UMR 5822)	A. Arbey, G. Cacciapaglia, A. Deandrea, F. N. Mahmoudi
IPHC Strasbourg (UMR 7178)	M. Rausch de Traubenberg
LPC Clermont (UMR 6533)	A. Goudelis, J.-F. Mathiot, V. Morénas, J. Orloff, A. M. Teixeira
LPSC Grenoble (UMR 5821)	S. Kraml, M. Mangin-Brinet, J. Quevillon, I. Schienbein, C. Smith
LUPM Montpellier (UMR 5299)	F. Brümmer, S. Davidson, C. Hugonie

Table 1: Summary of IN2P3 Theory Particle Physics teams and members.

A.2 Collaborations

The IN2P3 theorists working in particle physics have extensive collaborations, both within France and at the international level. Certain activities are recognised by the IN2P3 by "Master Projets Théorie".

Particle theorists also belong to (and are active members of) numerous research federations and international platforms, further working in the framework of large international collaborations (theory, phenomenology and experiment).

A.2.1 IN2P3 "Master projects"

- "Speedy Charmonia" (PI: B. Blossier, IJCLab) [2020 - 2022]: B. Blossier (IJCLab), M. Mangin-Brinet (LPSC), Zafeiropoulos (CPT), ...
- "SlowSUGRA" (PI: M. Rausch de Traubenberg, IPHC) [2018 - 2020]: R. Ducrocq, E. Conte, M. Rausch de Traubenberg (IPHC), C. Hugonie, J. Lavalle, G. Facchinetti (LUPM), G. Moultaka (L2C), V. Venin (APC)
- "Lepton flavours: probes of New Physics" (PI: A. M. Teixeira, LPC) [2017-2019]: A. Abada (LPT Orsay), S. Monteil, J. Orloff, A. M. Teixeira (LPC)

- “Flavour probes: lepton sector and beyond” (PI: A. M. Teixeira, LPC) [2020-2022]: A. Abada (IJCLab), A. Goudelis, S. Monteil, V. Morénas, J. Orloff, A. M. Teixeira (LPC)
- “Lattice calculations in hadronic physics” (PI: V. Morénas, LPC [2017-2020]: M. Mangin-Brinet (LPSC), B. Blossier, O. Pène (LPT Orsay), V. Morénas (LPC), S. Zafeiropoulos (CPT)
- “LHCiTools” (PI: S. Kraml, LPSC) [2017 – 2019]: S. Kraml, J. Quevillon, I. Schienbein (LPSC)
- “BSMGA: Global analysis framework for BSM physics” (PI: S. Kraml, LPSC) [2020 - 2022]: S. Kraml, J. Quevillon, I. Schienbein (LPSC)

A.2.2 Research Federations and Platforms

Below, a brief summary of scientific steering and leadership roles in several platforms and groups. Among these, there are numerous CNRS ”Groupements de Recherche” (GdR) and ”International Research Networks” (IRN), several international collaborative platforms, and finally contributions to the US and EU updates for the corresponding Particle Physics 10-year strategies (SNOWMASS and EPPSU).

- **EU ITN “Invisibles”**
  Steering (CNRS node): A. Abada (IJCLab)
- **EU ITN “Elusives”**
  Steering (CNRS node): A. Abada (IJCLab)
- **EU ITN “HIDDeN”**
  Steering (CNRS node): A. Abada (IJCLab)
- **EU Rise “InvisiblesPlus”**
  Steering (CNRS node): A. Abada (IJCLab)
- **GdR “Intensity Frontier”**
  Scientific steering: S. Descotes-Genon (IJCLab), F. N. Mahmoudi (IP2I), C. Smith (LPSC)

  W.G. responsibilities: E. Kou (IJCLab, Heavy flavour production and spectroscopy), C. Smith (LPSC, CP violation), O. Sumensari (IJCLab, “Quark-lepton interplay”), A. M. Teixeira (LPC, “Quark-lepton interplay”)
- **IRN “QCD”**
  W.G. responsibilities: B. Blossier (IJCLab, “Low energy QCD“)
- **IRN “Neutrino”**
  Scientific steering: A. Abada (IJCLab), A. M. Teixeira (LPC)

  W.G. responsibilities: A. M. Teixeira (LPC, “BSM”)
- **IRN “Terascale”**
  Scientific steering: C. Hugonie (LUPM), J. Orloff (LPC)

  W.G. responsibilities: J. Quevillon (LPSC, “BSM”), A. M. Teixeira (LPC, “BSM”)
- “Forum on the **Interpretation of the LHC Results** for BSM studies” - CERN based Platform (Th-Exp)
  Founder and main coordinator: S. Kraml (LPSC); Scientific steering: F. N. Mahmoudi (IP2I)

- **RAMP** “Reinterpretation: Auxiliary Material Presentation” (Th-Exp)
  Organiser: S. Kraml (LPSC)
- **SNOWMASS 2021** (USA)
  Topical steering ”cLFV”: S. Davidson (LUPM); Coordination of ”White Paper on analysis preservation and reuse” S. Kraml (LPSC)
- **European Particle Physics Strategy Update 2020** (EPPSU2020)
  Scientific secretariat (and co-authorship) of “Flavour Physics” group: A. M. Teixeira (LPC); IN2P3’s contribution to EPPSU 2020: A. M. Teixeira (LPC)

A.2.3 International collaborations (theory and experiment)

- **Alpha** Collaboration (Th, LQCD): B. Blossier (IJCLab)
- **ETM** Collaboration (Th, LQCD): B. Blossier (IJCLab), M. Mangin-Brinet (LPSC), V. Morénas (LPC)
- **CKMFitter** Collaboration (Th-Exp, Flavour): S. Descotes-Genon (IJCLab), J. Orloff (LPC)
- **Belle II** Collaboration (Exp, flavours): E. Kou (IJCLab)
- **COMET** Collaboration (Exp, cLFV): A. M. Teixeira (LPC)
- **JUNO** Collaboration (Exp, neutrinos): M. C. Volpe (APC)
- **SModelS** Collaboration (Th, LHC results): S. Kraml (LPSC)

B Public Tool development

An important output of the activities carried consists in the development of dedicated tools (public software).

- **“NMSSMTools”**: tools for the calculation of the Higgs and sparticle properties in the NMSSM
  HTTPS://WWW.LUPM.UNIV-MONTP2.FR/USERS/NMSSM/INDEX.HTML
- **“SuperIso”**: public program for the calculation of flavour physics observables in the SM, general two-Higgs-doublet model, minimal supersymmetric Standard Model (MSSM) and next to minimal supersymmetric Standard Model (NMSSM). Latest release [43]
  HTTP://SUPERISO.IN2P3.FR/
- **“SModelS”**: automated public tool enabling the fast interpretation of simplified model results from the LHC within any model of new physics respecting a Z_2-like symmetry. (For full documentation, see https://smodels.readthedocs.io/en/v2.0.0/) Full likelihoods (as now released by ATLAS) can be used
  HTTPS://SMODELS.GITHUB.IO/
- **“MadAnalysis5 PAD”**: framework for phenomenological investigations at particle colliders. Perform sophisticated physics analyses of event files (as those generated by a large class of Monte Carlo event generators). Public Analysis Database (PAD) for recasting LHC results
  HTTP://MADANALYSIS.IRMP.UCL.AC.BE/WIKI/PUBLICANALYSISDATABASE

- **"Lilith"**: tool for constraining new physics from signal strength measurements of the 125 GeV Higgs boson (see also [61]).
  HTTPS://LPSC.IN2P3.FR/PROJECTS-TH/LILITH/

- **"Proto-model builder"**: public tool to identify potential dispersed signals of new physics in the slew of published LHC results, which might otherwise be missed [58]
  HTTPS://SMODELS.GITHUB.IO/PROTOMODELS/

- Release of **"PBZp"**: provide K factors to ATLAS and CMS collaborations for heavy-resonance searches using top-quark pair observables (available on demand)

- Release of **"PBVp"**: inclusion of NLO QCD corrections to the hadroproduction of top-quark pairs in the presence of new heavy spin-1 resonances (W' and Z'); calculation matched to Parton Shower Monte Carlos using the POWHEG box framework; calculations have also been implemented in the CONTUR/RIVET framework[4]. Based on [39].

- **"PyR@TE 3.0"**: computation of the running of the Lagrangian parameters from high energy scales to the EW scale (or vice versa) [63]; interface to Feynrules and Madgraph is under development and the RGEs at 4-3-2 loop order (for the gauge, Yukawa and quartic couplings, respectively) are now available and will soon be implemented into PyR@TE
  HTTPS://GITHUB.COM/LSARTORE/PYRATE

[4]This allows studying the sensitivity of ATLAS, CMS and LHCb particle-level fiducial cross section measurements, available in RIVET to models predicting W' and Z' resonances.

In addition to general references on given topics, the publications here collected correspond to a variety of highlights identified by the IN2P3 Particle Physics Theorists.

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