Chapter 2

Finding the underlying symmetries behind the fundamental components of matter

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Unraveling the structure behind the components of matter and the fundamental laws governing their interactions is the ultimate goal of particle physics. One of the central questions in the Standard Model is the origin of the fermion family replication, which may point towards a hidden flavour symmetry. Many experiments will be soon addressing this issue by exploring the flavour sector with impressive sensitivities. Understanding other symmetries, such as CPT and lepton or baryon numbers, is also crucial, since their violation would have dramatic consequences for the shape of the underlying physics. Other open questions, such as the origin of the chiral character of the weak interactions, the stability of the particle that may constitute the dark matter of the Universe and the possible unification of the fundamental interactions at high energies, may also be associated to the existence of new symmetries and dynamics, possibly better described with a new mathematical language.

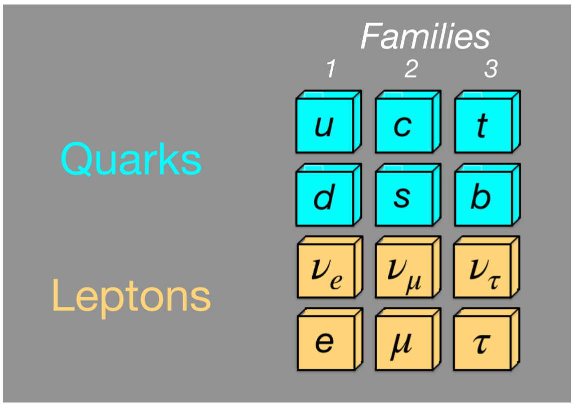


Figure 2.1: The three fermion generations in the Standard Model.

2.1 Introduction

The flavor puzzle

The fermionic components of matter display an intriguing family structure that is not yet understood. With just one family of fermions, the up and down quarks, the electron and its corresponding neutrino, the Standard Model (SM) would be a beautiful and very economical explanation of the world. These four particles are enough to describe the rich structure of ordinary matter (atoms, nuclei and radioactivity) with the SM interactions. Besides the values of their masses and electric charges, the SM would only need five inputs to describe the world: three gauge couplings and the two parameters of the Higgs potential. However, two more fermionic families with increasing masses do exist in Nature and we are totally ignorant about the reasons of this replication.

The three fermion generations only differ by their masses. Thus, we have now a new “periodic table” of elementary particles with four columns and three rows, where the three elements of any given column have almost identical interactions. Furthermore, the four fermion masses of the one-family model get converted into four 3-dimensional complex matrices in flavour space, giving rise to a rich pattern of fermion masses and mixings that are empirically determined. There should be some fundamental dynamical explanation of this “flavour” structure, in the same way that the (at the time unknown) atomic structure was behind the periodic table of the XIX century. Finding out such explanation, which must be beyond the SM, and understanding how the pattern of fermion masses and mixings emerges from some underlying flavour dynamics, is a primary goal of fundamental physics.

Symmetries are usually the key to uncover hidden dynamics. In the absence of Yukawa couplings to the Higgs (and thus of masses), the SM Lagrangian has a huge $\mathrm{U}(3)^6$ flavour symmetry (including right-handed neutrinos) that is explicitly broken by the Yukawa matrices, which point into specific directions in the flavour space. Flavour experiments indicate a quite distinctive pattern of symmetry breaking that is different in the quark and lepton sectors. Improving our knowledge of these parameters is a challenging task of great importance, since they give us precious hints on the underlying flavour dynamics.

The Standard Model predicts a strong suppression for certain *rare* processes, which would only take place at very low rates. This is the case for many flavour violating transitions, such as the $K \to \pi\nu\bar{\nu}$ and $B \to K\mu^+\mu^-$ decays, to mention a couple of representative examples. Several reasons are behind the SM suppression, including accidental symmetries and small mass ratios. However, these suppression mechanisms are "fragile", and any tiny variation of the theoretical framework may drastically alter the predictions. Similarly, there are also flavour processes which are *forbidden* in the SM but may take place in other scenarios, like $\mu \to e\gamma$ and $H \to \mu\tau$. In summary, large deviations from the SM predictions may be found in rare and forbidden processes, which makes their study one of the most powerful probes of new physics. In fact, the search for these processes will allow us to probe energy scales about a thousand times higher than those directly accessible at the CERN LHC.

Several experiments are already (or will be very soon) actively exploring the flavour sector with unprecedented sensitivities. The LHCb detector at the LHC is the most prominent example at present, but the list also includes experiments looking for the violation of individual lepton flavours, such as MEG-II and Mu3e (in Europe) or Mu2e (in USA), experiments specialized in processes involving quark flavour transitions, such as NA62 (in Europe) or KOTO (in Japan), and experiments with a broader coverage of flavour observables, like the aforementioned LHCb (in Europe) or Belle II (in Japan). The two multi-purpose LHC detectors, ATLAS and CMS, also play a complementary role in the study of flavour observables. This worldwide effort makes the question of the fermion replication in the SM more timely than ever.

Symmetries and the fundamental structure of matter

Other symmetries are behind other fundamental, and not yet understood, facts.

This is the case of the CP symmetry. Owing to the chiral structure of the SM gauge group, the fermionic couplings to the weak gauge bosons break parity (P) and charge-conjugation (C) in a maximal way, but the product of these two discrete transformations (CP) remains an exact symmetry with one or two families of fermions. Therefore, the violation of CP in hadrons seems to be directly related with the three-fold fermion replication. On the other hand, these symmetries are related to a fundamental cosmological problem. As it is well known, C and CP violation is a key ingredient to explain the observed and intriguing matter-antimatter asymmetry of the universe. Therefore the investigation of these issues directly connects and can give valuable insights to the research in other challenges, particularly "Origin and fate of the Universe" (section 4).

On the other hand, the apparent conservation of CP in the strong interactions is another problem in the SM. In order to solve this open question a new symmetry is often postulated, a Peccei-Quinn symmetry, naturally predicting the existence of the axion, a hypothetical particle that may constitute the dark matter (DM) of the Universe. Furthermore, due to the CPT theorem, violations of CP imply corresponding violations of time reversal (T). Understanding the realization and violation of these symmetries in nature is another fundamental challenge to be faced.

The mixings among fermion families break the conservation of the individual lepton and quark flavour quantum numbers, but the total lepton and baryon numbers remain as conserved quantities, because of accidental global symmetries of the dimension-4 SM Lagrangian. The breaking of these symmetries (even if it is tiny) has dramatic consequences. Namely, some violation of the baryon number is also a necessary ingredient to generate the above-mentioned matter-antimatter asymmetry of the Universe. Likewise, lepton number violation might be at the origin of neutrino masses (as well as at the root of the baryon asymmetry of the Universe). In fact, the unification of fundamental interactions might imply the breaking of baryon and lepton numbers at some high-energy scale. Hence, precise tests of these symmetries have the potential to be sensitive to new physics interactions at higher scales and contribute to the understanding of other challenges ("Origin of mass of elementary particles" and "Origin and fate of the Universe").

Finally, the physics associated to the mysterious dark matter of the universe, in particular the symmetry that could be behind its stability, is another crucial basic question which also connects to the just-mentioned challenges.

All these questions are going to be probed at different levels in the forthcoming years. Namely, CP violation is going to be explored in Higgs interactions at the LHC and in hadron physics in the above-mentioned experiments, e.g. LHCb and Belle II. Likewise, the peculiar flavour pattern in the neutrino sector, including potential CP violation, will be explored in DUNE. In addition different candidates to dark matter are going to be probed in a plethora of space-based and ground-based experiments, using different techniques, e.g. XENON, CDMS, PANDA, CTA, ADMX, etc.

Other open questions

The chirality of the SM gauge group (why left is different from right?) is another open question that is lacking a convincing dynamical answer. Can the SM be embedded at higher energies in a larger symmetry group with corresponding left and right fermionic sectors? Does this group allow for unification of the different interactions? How does the larger symmetry get broken at low energies? Does it stabilize the particle that constitutes the dark matter of the Universe? Can gravity be merged with the other interactions in a consistent theoretical framework? Does supersymmetry play any role? What are the mathematics describing such super-unification?

2.2 Impact

The issues described in the previous section are among the most prominent indications of physics beyond the Standard Model (BSM). Therefore, any progress in their theoretical or experimental status, even if it is small, will be of crucial relevance for fundamental physics. Let us mention here that, in the past, flavour-related physics has already been

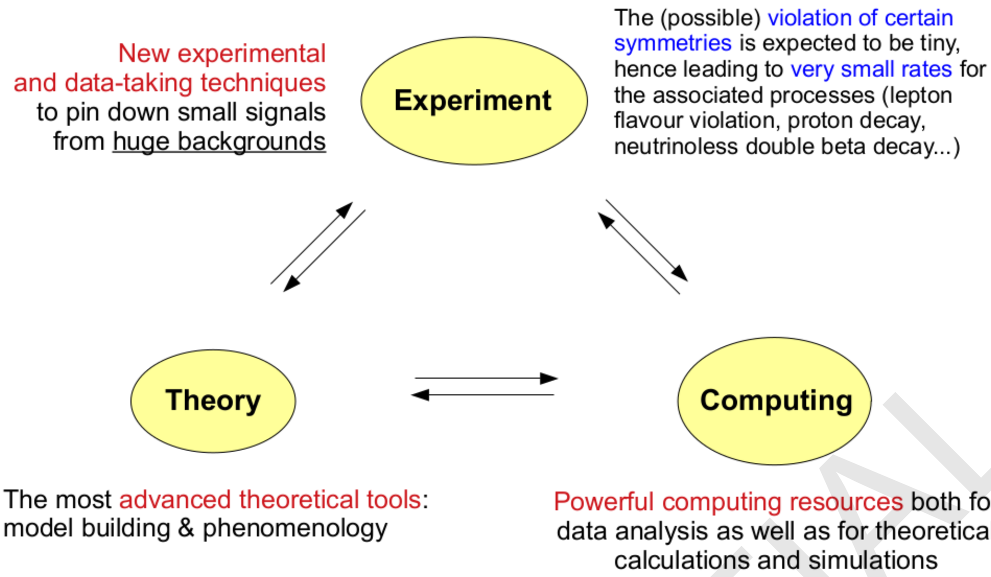


Figure 2.2: This challenge requires a multidisciplinary approach, combining theoretical, experimental and computing developments.

instrumental to show the existence of new physics before its direct observation. For instance, the study of the $K - \bar{K}$ system was the key to predict the existence of the charm quark and its mass, the measurement of ϵ_K, (a parameter that quantifies the CP violation in kaon mixing), indicated the existence of a third generation, neutrino flavour oscillations showed that neutrinos are massive, etc.

Part of the previous achievements and the potential success of the research in this area is due to the fact that the measurement of rare (or forbidden) processes is extremely sensitive to the existence of new BSM physics. In this sense, any real progress must involve experimental results as the main ingredient, but theory is also key to refine the SM predictions and to interpret the results in a theoretically consistent way that may lead to new and relevant predictions. At present, the most promising areas where this progress may take place involve searches for flavour and CP anomalies at the LHC and other accelerators, anomalous decays of heavy mesons, forbidden lepton decays, electric dipole moments and anomalous Higgs Yukawa-couplings. These can all be found among the main goals of this challenge. In addition, other promising areas include direct and indirect detection of dark matter, production of new particles at the LHC and future colliders, experiments of $\nu-$less double $\beta-$decay and neutrino beams and QCD-corrections to flavour and DM processes. A signal of new physics emerging from any of these research fronts would have an importance comparable to the discovery of the Higgs boson at the LHC.

On the other hand, although this challenge mainly deals with basic science questions, it also comes with a variety of applied science consequences. Developments in computing, by the experimental collaborations or by the theoretical groups performing new physics fits, and in data analysis, both with traditional (supercomputing, parallelization) and artificial intelligence (machine learning) techniques, are expected. The experimental groups also face very specific technological challenges, due to the high precision (and intensity) they are aiming at. In fact, this challenge requires a multidisciplinary approach, combining new data-taking techniques to pin down small signals from huge backgrounds, powerful computing resources and the most advanced theoretical tools. Fig. 2.2 illustrates this multidisciplinarity and highlights the relevance of high-luminosity experiments in the search for rare processes, a promising gate to new physics due to their high sensitivity to BSM contributions.

2.3 Key challenges

In short, the basic challenges in this area of fundamental research are

(i) Identify new theories and symmetries that can improve our understanding of some very fundamental problems, namely

- The origin of flavour structure (family pattern, masses and mixing angles of elementary particles)
- Sources of CP violation (necessary to understand the matter-antimatter asymmetry)
- Nature and origin of the dark matter
- Other symmetries that might play a crucial role to solve other fundamental puzzles: Supersymmetry, Peccei-Quinn symmetry, left-right symmetry, etc.

(ii) Derive novel strategies to explore (and hopefully discover or discriminate among) these theories/symmetries in the experimental/observational front, namely:

- LHC (including the forthcoming high-luminosity LHC, HL-LHC)
- Other accelerator experiments, such as Belle II, ...; as well as future projects, such as e^+e^- colliders.
- Neutrino oscillation experiments, including the forthcoming DUNE. Also $0\nu2\beta$ decay experiments.
- DM direct-detection experiments including axion detectors; also DM indirect-detection experiments
- Study of the large scale structure of the Universe

(iii) Establish fruitful connections between the experimental and the theoretical fronts, such as

- Perform theoretical calculations for SM backgrounds or precise BSM predictions, in order to improve the discovery power of the experiments.

Experiment	Location	Begins data-taking in
LHCb	Europe	Ongoing
Belle II	Japan	Ongoing
MEG-II	Europe	2020-2022
Mu3e	Europe	2022
DeeMe	Japan	2020-2022
COMET	Japan	2020-2022
Mu2e	USA	2022
NA62	Europe	Ongoing
KOTO	Japan	Ongoing
Muon g-2	USA	Ongoing
ATLAS & CMS	Europe	Ongoing

Table 2.1: Current and near future flavour experiments.

- Use novel statistical and machine-learning techniques to extract signals from background in complex experimental data, like those from the LHC or indirect-detection experiments.
- Study the performance of future experiments, like new accelerators, neutrino facilities and DM experiments.

More precisely, some key challenges which should combine the effort and expertise of different groups and researchers are the following:

1. Flavour experiments

A most natural arena to explore the physics behind the flavour structure of the SM is the physics of mesons. For instance, the exploration of lepton flavour universality (LFU) and flavour violating decays of K and B mesons can lead to a major discovery, giving a first signal of BSM physics. This is at present a hot issue, where flavour factories, especially LHCb and Belle II, are involved.

The experimental aspect of this challenge is to strengthen the presence of CSIC in these crucial experiments by bolstering the existing experimental groups.

On the theoretical side, one of the main technical difficulties to explore flavour is the dominant role of the strong interactions in the quark and hadron dynamics. The challenge here is to use novel techniques to evaluate those contributions, which leads to a natural synergy between the experimental and theoretical sides of this enterprise. A particularly appropriate scheme to cope with this problem is Lattice QCD, which connects this challenge to the “Solving Quantum Chromodynamics” challenge (section 3).

Let us mention that the search for charged lepton flavour violating processes is also going to be central in the next years, with an intense experimental activity led by flavour factories and other new low-energy experiments, such as Mu3e and Mu2e, as shown in Table 2.1. In this case, the challenge on the theoretical side will be the interpretation of the experimental results, which may require the development of global fits and specific models that accommodate them.

Finally, we notice that neutrino physics is a line (also represented in challenge 9.1, section 1), which is intimately connected to flavour physics. In this sense, the (CSIC) NEXT project or the CSIC participation in DUNE will be instrumental in the forthcoming years to explore fundamental symmetries in the leptonic sector, namely lepton number and leptonic CP violation. The latter is particularly relevant at the moment, after the first hints of a non-vanishing Dirac CP violating phase have been found and can have dramatic consequences to understand the matter-antimatter asymmetry of the universe, which connects to the “Origin and fate of the Universe” challenge (section 4).

2. Higgs, top and flavour

The physics of flavour is intimately related to that of the Higgs. In this sense, there are fundamental measurements which are still pending and will shed light on basic questions.

In particular, while the Higgs Yukawa couplings to third-generation SM fermions are rather well measured, the values of the Yukawas for the first and second generation SM fermions remain very weakly constrained, yet their measurement is key to confirm that the SM Higgs gives mass to the first two generations of matter. This goal is central to challenge 9.1, “Origin of mass" (section 1), but it also constitutes a fundamental input for this challenge, since it concerns the flavour structure of the matter fermions and the Higgs properties, both related to the Yukawa couplings.

The aim here is to develop novel approaches to probe the SM Higgs mass generation mechanism for light quarks and leptons, which are complementary to existing methods and can help improve the precision of the LHC in measuring these couplings. This requires identifying LHC processes which are particularly sensitive to a departure of the light quark/lepton Yukawas from their SM values. This is the case of Higgs production processes which are directly proportional to such Yukawas. A known and studied case is Higgs production in association with a charm-tagged jet; but there are other yet unexplored possibilities, like Higgs production in association with a photon.

Central to our challenge is the search for Higgs couplings to pairs of fermions of different families and/or containing non-vanishing complex phases. In particular, flavour anomalies in Higgs (and also Z) decays, such as $h \to \mu\tau$, and other flavour violating processes involving the Higgs boson, e.g. the top quark decay $t \to h\, c/u$, would represent a major discovery, with profound implications for particle physics. Similarly, finding CP violation in the Higgs sector, and its potential interplay with flavour, would constitute a major breakthrough. These experimental challenges involve the existing ATLAS and CMS groups at CSIC.

Finally, one should keep in mind that the ultimate goal of this challenge is to fully understand the origin of flavour. It is therefore necessary to combine the experimental information with theoretical developments. In particular, an important effort in model building and phenomenological study of novel setups involving flavour symmetries is required. This theoretical challenge takes advantage of the expertise of the theory groups at IFT and IFIC.

3. Higgs, top and CP

CP violation in the Higgs sector remains a possible source of the baryon asymmetry of the Universe. Measuring the the amount of CP violation in the Higgs sector is one of the key tasks of the LHC and a crucial ingredient for precision studies, for example through effective field theory coefficients. Differential measurements of signed angular distributions in Higgs boson production provide a general experimental probe of the CP structure of Higgs boson interactions.

However, new LHC search strategies to probe CP violation in the Higgs sector, complementary to existing ones, would be of major relevance for this fundamental issue. A possible new avenue to search for CP violation would be to identify and target Higgs decay modes forbidden by CP.

Similar studies could be realized in connection to CP violation in top physics.

This challenge would involve both experimental and theoretical research groups.

4. Search for new symmetries

There are other symmetries, such as supersymmetry, left-right symmetry or Peccei-Quinn symmetry, that have been postulated to solve some of the most intriguing aspects of the SM. An important issue in particle physics, and one of the main goals of the LHC, is to search for signals of this new physics.

For supersymmetry, the theoretical goal is the identification of viable models, provide calculations to test these models and perform those tests, in particular global fits that could lead to a cornering of the actual supersymmetric scenario (if it is really there). This connects with the experimental searches in ATLAS and CMS, where several CSIC groups are involved. These groups will be deeply involved in the HL-LHC, expected to begin in 2026. This new phase will provide a huge amount of data, hence being sensitive to rare signatures with lower number of events. In the precision frontier it is clear that a new machine will be required in the future, i.e. an e^+e^- collider. The studies for the performance of such machine require also the collaboration between theoreticians and experimentalists.

Concerning the left-right symmetry, the goal is to determine whether such symmetry does exist. This can be explored in the front of high-energy experiments (ATLAS and CMS, with the help of theoretical work to perform simulations) and in the front of flavour physics, e.g. studying the angular distribution in an eventual observation of $\mu \to e\gamma$, which will give information about the muon polarization and thus the left-right structure of the theory behind flavour physics.

In the context of dark matter research, a key experimental goal that spans over many of the challenges in this chapter is to discover the particle(s) that constitutes the dark matter of the Universe. This will be a clear window to physics beyond the standard model, shedding light on the properties of the unknown dark sector and hopefully finding out the symmetries behind its dynamics, e.g. the possible presence of a new symmetry that protects the stability of the DM particle. This connection goes also in the opposite direction: the theoretical construction of plausible models of DM gives hints and suggests experimental techniques to detect DM. An example of this is supersymmetry with R-parity conservation, which has stable candidates for dark matter such as the neutralino or the sneutrino; whereas without R-parity the axino or the gravitino, having a lifetime longer than the age of the Universe, are also interesting candidates. Actually, in the latter case, the direct connection with gravity allows to explore a framework where all interactions of nature are unified. Other decaying candidates such as the axion (or the axino) are related to the Peccei-Quinn symmetry and the solution of the strong CP problem. Hence, our goal here is connected to other challenges, in particular 9.4 “Origin and fate of the universe", 9.1 “Origin of mass" and 9.7 “Gravity" (sections 4, 1, and 7), and also to our key-challenge 7 below.

5. Axion physics

The existence of axion particles is a classical prediction of theories with a Peccei-Quinn symmetry able to solve the strong CP problem. In addition, these particles are very well motivated candidates for DM. In recent times, axion-like particles emerging from a more generic Peccei-Quinn symmetry with free parameters have been also intensively considered.

Study of axions and axion-like particles require the collaboration of experiment (high-energy colliders and other kinds of experiments) and theory (particle and astroparticle physics as well as cosmology). Thus, it is a highly interdisciplinar area.

One interesting challenge that illustrates these synergies is the following.

An open question in axion physics nowadays consists in quantifying precisely the axion strings contribution to dark matter (if the Peccei-Quinn symmetry is broken after inflation). Current estimates indicate that it is at least as significant as that of the misalignment mechanism (which is more standard). The difficulty in obtaining this contribution precisely stems from the fact that very large lattice simulations are required to describe the cosmological decay of the strings into axions. Much theoretical and numerical effort is being put into addressing this problem. Sheer computational power alone is at the moment insufficient, hence progress on this topic requires bold ideas and a multidisciplinary team of axion physics, lattice and cosmology experts (like the ones CSIC may reunite).

Axions and axion-like particles may also reveal themselves in low-energy flavour experiments. This can happen in two ways: by being produced in particle decays and by mediating rare or flavour violating processes. Many such flavor signatures are known and in fact an increasingly large fraction of the axion models currently under study have flavour predictions. This is another example of the remarkable interdisciplinarity of axion physics, which also plays a relevant role in flavour factories.

6. Machine-learning techniques

The application of state-of-the-art statistical methods and artificial intelligence (machine learning, ML) techniques is a promising way to improve the efficiency of analyses that involve complex sets of data. This applies in particular to LHC and DM searches.

One example of this is indirect detection, which is one of the leading techniques to explore the nature of (WIMP-like) dark matter. Similarly, ML techniques are currently being used on a regular basis by the ATLAS and CMS collaborations in order to discriminate signals from backgrounds. Due to their complexity, the analyses of data from these experiments are quite challenging from the statistical point of view.

A proposal in this sense is to work with data and simulations from the most sensitive (present and near-future) experiments of Indirect Detection and Collider searches (where several CSIC groups are involved), applying different ML paradigms as Supervised, Unsupervised and Semi-supervised Learning. Far from replacing the physics of interest (in our case, the physics of the DM), such tools would allow us to estimate in an agnostic way the effect of the “nuisance parameters” (i.e. the background). Similar techniques can be applied to direct detection of DM.

The successful accomplishment of this challenge would imply a radical qualitative improvement of the searches for DM, which so far do not exploit in general the capabilities of modern statistical modelling. Improvements are also welcome in LHC searches, which are already using these techniques but would become more sensitive to very rare events. It will also tighten the collaborations between different CSIC institutes and groups across the country.

A similar strategy can be used, in collaboration with (CSIC) experimental LHC groups in order to improve background estimates and discriminate BSM signals.

Last but not least, these collaborations will provide powerful tools to be used in many other branches of physics.

7. Determine the underlying mathematical structure behind the fundamental symmetries

It is a common belief that there is some fundamental reason for the presence of symmetries in nature. These symmetries include the examples of previous sections and other ones, such as gauge symmetries.

Indeed, the gauge theory of Yang-Mills and other gauge theories involving Higgs fields as well as spinors are central in the study of the basic properties of particles. From a mathematical point of view these theories lead to the study of moduli spaces, parametrizing gauge equivalence classes of solutions to the corresponding gauge equations, that are extremely rich, both from the physical and mathematical point of view. The study of the topology and geometry of the moduli spaces of instantons, monopoles, vortices, Higgs bundles and other soliton-type objects is indeed a very challenging problem of great interest in the mathematics and physics community. It is in fact an area of great interaction between these two communities.

2.4 CSIC leadership and multi-/inter-disciplinarity

All the previous questions are at the heart of many of the most active areas in particle and mathematical physics and involve four CSIC institutes: IFIC, IFT, IFCA and ICMAT. Generally speaking, the lines connected to the previous challenges, where these institutes have strong groups and can lead relevant projects are the following.

IFIC and IFT host several world-leading groups in particle physics phenomenology, with an outstanding international visibility in the theoretical study of symmetry violations, model building and flavour dynamics.

The experimental groups at IFIC and IFCA also have a well-known international reputation. The LHCb and Belle II experiments are the main actors in the exploration of the flavour sector and have an important presence at IFIC. We highlight the long experience of the LHCb group searching for new physics in rare hadron decays and the international leadership by the Belle II group in the development of instrumentation. The ATLAS and CMS groups at IFIC and IFCA have a complementary contribution in the study of flavour and CP violation, and a central role unraveling the underlying symmetries in the high-energy frontier. IFIC also participates in the search of lepton number violation via neutrinoless double beta decay, with several of its members involved in the NEXT experiment, and hosts several active members of the DUNE collaboration.

IFT participates in the Physics Preparatory Group that is taking care of the European Particle Physics Strategy Update 2018 – 2020 and has led the Invisibles and MultiDark projects, coordinating (national and foreign) research groups working in areas related to this challenge (flavour and neutrino physics, axion-like particles, WIMPs and other DM candidates, etc.). It is an active participant in experiments such as DUNE for neutrino science and proton decay studies and several DM collaborations, like Fermi-LAT, CTA and CDMS. Besides, it has a prominent group involved in QCD corrections to flavour- and DM-dynamics.

IFIC participates in the preparation of the "The Review of Particle Physics" by the Particle Data Group, contributing to the review on Tests of Conservation Laws, intimately related to the underlying symmetries in particle interactions, the main goal of this challenge.

Finally, there is also a very valuable experience in the study of the interplay between physics and differential and algebraic geometry at ICMAT, a world-class research centre in the field of mathematics.

More specifically, the potential involvement of the different institutes and groups in the key challenges of the previous section is the following.

1. Flavour experiments

On the experimental side, IFIC has a strong presence in the LHCb and Belle II experiments, which play the leading role in this front. Actually, the group at LHCb has a long-standing experience in the search of new physics in the decays of heavy hadrons, while the Belle II group plays a leading role in the data taking and detector operation, as well as in the development of instrumentation.

On the theoretical side, the IFT and IFIC institutes have active groups exploring possible theoretical scenarios behind the flavour issues and also performing and refining SM predictions for flavour processes. This includes highly especialized and competitive groups working in this aspect from the point of view of lattice QCD, which are already collaborating in a fruitful way.

2. Higgs, top and flavour

On the experimental side, IFIC and IFCA have strong experimental groups in the ATLAS and CMS collaborations, participating in working-groups related to Higgs physics. In particular, the ATLAS groups at IFIC have experience in the search of flavour violating top decays involving the Higgs, such as $t \to H\,c/u$, as well as in the search of Higgs decays violating lepton flavours, such as $h \to \tau\mu$. These have been used to set constraints on models with extended scalar sectors. On the theoretical side, IFT and IFIC have reputed groups producing ideas in this line. A fruitful collaboration between experiment and theory, as well as among researchers from different institutes, is therefore perfectly plausible and desirable.

3. Higgs, top and CP

The situation for this challenge is similar to the previous one. In the experimental part, IFCA is directly involved in the study of the Higgs production with final decay in WW. The IFCA group will be able, with the increase of data, to access the high mass regions of the differential cross section, and hence be sensitive to any deviation using effective field theory. In particular, possible CP observables could be studied upon the associate production $VH(WW)$. Furthermore, CP violation can also be searched for in the fermion sector. The interaction between the Higgs boson and top quark is explored by the ATLAS group at IFIC, which has coordinated the first direct search of CP violation in the Higgs-top coupling and is performing studies of the W-top-bottom vertex, including searches for CP violation.

On the theoretical side, IFT and IFIC have very active and prestigious researchers with long experience in this area.

4. Search for new symmetries

Concerning supersymmetry, IFT has well-known world leading experts. Some of them, in addition to IFIC researchers, are also leaders in international fit-performing groups and in the development of public codes to evaluate supersymmetric predictions. Actually the collaboration between IFT and IFIC is already a reality.

On the experimental side, the main experiment is LHC, where IFIC and IFCA have experimental groups participating in ATLAS and CMS, strongly involved e.g. in supersymmetry searches. CSIC also participates in the search for long-lived particles in ATLAS, CMS and LHCb, as well as in the dedicated experiment MoEDAL. Regarding future e^+e^- colliders, the IFIC and IFT institutes have experimental and theoretical (respectively) researchers, who are actively participating in the prospective studies.

Regarding the left-right symmetry there is a strong tradition about it at IFIC, where experienced and young reputed researchers have plenty of ideas in this line.

5. Axion physics

IFT and IFIC have very strong groups of theoretical research on axions and ALPs. Actually, some of the IFT and IFIC researchers are already collaborating. Some of the projects (as the one mentioned in the previous section) would benefit of the expertise of IFT and IFIC in lattice techniques, where these institutes have reputed groups, as well as the strong cosmology group at IFT.

6. Machine-learning techniques

This is a highly developing area which actually has connections to all the challenges. Both at IFT and IFIC there are reputed young researchers who are already experts in ML and are applying the latest techniques to LHC and DM searches. Likewise, at IFCA there is a dynamic ML group actively contributing to the CMS experiment. There is also an active program of formation of the new generations of scientists.

Hence, this is an area of research with great potential, which is likely to strengthen the collaborations between different CSIC institutes and groups.

7. Determine the underlying mathematical structure behind the fundamental symmetries

The leading role here is played by ICMAT, a very reputed math institute, with a very strong group working on the frontier between mathematics and physics. The potential collaboration with theoretical researchers is obvious, especially with those at IFT, where there are internationally reputed groups working in string theory and other physics areas which require sophisticated maths. In addition, both institutes share the same building, which will make the collaboration easier.

2.5 Strategic plan and resources

CSIC can (and should) play a leading role in the world-wide effort to understand the fundamental structure of matter. By joining forces with other prestigious research institutions, such as CERN or Fermilab, CSIC can substantially contribute to the resolution of the scientific problems discussed in this chapter. In order to achieve this goal, several requirements should be met:

- **Timeliness.** Flavour is about to live a golden age, with several experiments already (or very soon to be) actively exploring the flavour sector with unprecedented sensitivities. As usual in basic research, it is impossible to predict which revolutionary discovery will be made in this area and when, but the chances are good, as the indications of new physics related to flavour issues are overwhelming. Similarly, the high-energy frontier is currently being explored by the world's largest collider, the LHC, which will soon begin its high-luminosity phase. Given the high scientific relevance of these initiatives, CSIC must be strongly involved in them; otherwise, it will lag behind in this international enterprise.

- **Reinforcement of existing groups.** CSIC's current international leadership and visibility must be strengthened by reinforcing the existing activities. This can only be achieved by funding additional human resources and infrastructures to maintain and increase the excellence of the CSIC groups. This requires opportunities for young researchers, including not only predoctoral and postdoctoral positions but also, and very especially, stable positions for outstanding researchers who are at the peak of their productivity (combining youth and expertise) and often have to migrate to other countries with more opportunities.

- **Coordinated action.** It is highly desirable that the CSIC groups involved in this challenge strengthen ties in order to take advantage of the diverse and complementary expertise they possess in the different disciplines involved in this challenge (experimental particle physics, theoretical physics and mathematics). This will occur regardless of the desirable existing and forthcoming international collaborations.

We now proceed to discuss the strategic plan that implements these requirements and the resources that are foreseen to be necessary.

Strategic plan

The key challenges described in section 2.3 must be faced by taking the following concrete actions.

1. Flavour experiments

CSIC's presence in the LHCb and Belle II collaborations must be consolidated by strengthening the existing research teams as well as by promoting the emergence of new groups. The former necessarily implies the creation of new positions (permanent and non-permanent), while the latter can be achieved with specific calls for research grants. The participation in these experiments is fundamental, since they will certainly be the most prominent actors in the exploration of the flavour sector in the next decades.

The expected experimental data can only be exploited if a strong theoretical community is ready to take advantage of them. The calculation of flavour observables often involves the use of highly technical methods in order to reach the necessary accuracy. An improvement in several observables of interest is necessary, in particular due to the existing tensions in B-meson decays. New models must also be developed to interpret the data and derive conclusions. Therefore, it is also crucial to support the theory groups at CSIC with new human resources.

2. Higgs, top and flavour

CSIC is already involved in several flavour studies with the ATLAS and CMS detectors due to the participation of the experimental groups at IFIC and IFCA. This leading role must be maintained and supported with additional human resources.

Furthermore, CSIC must also be involved in the ongoing discussions about future collider experiments and visibly support the Spanish involvement in these international projects, which will certainly be central in the future particle physics.

A strong reinforcement of the existing theory groups is also crucial. This will be relevant in the case that a signal of new physics is discovered, since new models would become necessary, but also if the SM remains a good description, since precise calculations to increase the discriminating power of data would be more important than ever.

3. Higgs, top and CP

The actions to be taken for this challenge are analogous to the ones proposed for the previous one.

4. Search for new symmetries

Theoretical studies to identify novel setups and signatures must be performed. While some of the minimal scenarios beyond the SM are either ruled out or in strong tension with experimental data, next-to-minimal models may have exotic signals that easily evade the current bounds. This is the case in many non-minimal supersymmetric models or in scenarios with long-lived particles. The fundamental origin of the SM gauge interactions should also be one of the main motivations to search for new symmetries. Scenarios with extended symmetry groups are also linked to the other key challenges discussed in this chapter. For instance, new contributions to many flavour observables are expected in the presence of right-handed currents, and these are potentially within the reach of current and future flavour experiments. These lines of research should be pursued in the next years.

On the experimental side, the search for new symmetries necessarily implies the exploration of the high-energy frontier. Several groups at CSIC are already taking part of this key challenge, and they must be properly supported in their participation in ATLAS and CMS, as well as with additional human resources. Moreover, as already mentioned, CSIC should be involved in the planning of future colliders.

5. Axion physics

Given the growing relevance of this field, the theoretical research on axions and ALPs at IFT and IFIC must be reinforced in order to maintain the high visibility of the theory groups in these institutes. The mentioned relevance is demonstrated by the increasing number of experimental projects in this line, such as ADMX, CAST and IAXO, to mention a few.

This key challenge is particularly multidisciplinary, and this should lead to potential collaborations among diverse CSIC groups. A theoretical line to be pursued is the development of new axion models and the study of their phenomenology. In some cases the axion particle can serve as the dark matter of the Universe, hence leading to a potential interplay with the "Fate of the Universe" challenge **[ref. here]**. Lattice techniques are also necessary for many calculations in axion physics, and this links this key challenge to the "Solving Quantum Chromodynamics" challenge **[ref. here]**.

6. Machine-learning techniques

Machine-learning techniques represent a very active and promising tool to optimize data analyses and make the most of the above-mentioned complex experiments. There have already arisen groups of (experimental and theoretical) CSIC researchers developing techniques in this line.

CSIC must support the use of ML with concrete actions. First, a substantial upgrading of computational facilities is required. In addition, the collaboration among researchers of different fields must be strengthened with the organization of multidisciplinary scientific meetings and doctoral schools and courses. It is also crucial to establish knowledge-sharing platforms that allow for an easy and direct communication of the main ML resources among CSIC institutes and groups. The creation of interdisciplinary research grants is also to be considered.

7. Determine the underlying mathematical structure behind the fundamental symmetries

The mathematical study of Yang-Mills theories must be pursued due to its interest for particle physics. One should also keep in mind that these lines of research are interesting on their own, due to their impact in pure mathematics.

The leading role in this key challenge is played by ICMAT, the only CSIC institute devoted to mathematical research. It is therefore vital to reinforce its position with additional human resources. It is also desirable to achieve a fruitful collaboration between the already existing world-renowned physics and mathematics groups, as it happens in the most prestigious institutions of the world, like the IAS of Princeton or the Newton Institute of Cambridge. Therefore, collaboration with researchers at the IFT is to be encouraged, by organizing common activities of interest for both institutes: doctoral courses, conferences, and workshops and seminars.

As a final comment, the key challenges presented here are not the only interesting ones. Actually, basic science is a fast-moving area and it is quite likely that in the next years new lines of research connected to the previous ones (arising from experimental or theoretical advances) will appear. CSIC should be prepared to address them in an agile and flexible manner, so that it takes profit of the new opportunities. The best recipe for that is to maintain and improve the already excellent groups that CSIC possesses in this area of research.

Resources

This ambitious challenge can only be successfully finished by providing the required resources to the participating CSIC institutes and groups.

The participation of CSIC groups in experimental collaborations has a large economical impact on the institutes that harbour them. CSIC must maintain its current strategic position and support this participation with the required funding. This includes collaboration fees, as well as any other related expenses. For instance, the participation in ATLAS, CMS and LHCb will require regular visits to CERN, in Geneva, and these are expected to be particularly frequent in the next few years after the start of the HL-LHC, expected to be in 2026. Similarly, the participation in Belle II will necessarily require visits to Japan. Substantial hardware expenses are also expected.

As already emphasized, CSIC must be actively involved in the ongoing discussions about the future of particle physics. At the moment, this implies participation in scientific meetings discussing possible pp and/or e^+e^- collider experiments. In addition, the invitation of international experts for seminars at CSIC institutes is an important instrument to keep track of the discussions at the highest levels.

The theoretical and experimental groups involved in this challenge must be reinforced by funding new permanent positions. This is crucial due to the high complexity of the scientific questions described here, which can only be faced with the most talented young experts in the field. These permanents positions must come along with new postdoctoral and PhD positions, hence strengthening the capabilities of the research teams.

This challenge takes place in a rich international context. The interaction with researchers from other institutions is thus fundamental. This may take place in scientific meetings (conferences and workshops), which must be hosted by CSIC institutions in order to gain visibility. Visits to first-class research centres, such as CERN, DESY or Fermilab, are also mandatory. Finally, funding to host scientists from those centres, invited to give seminars or to enjoy long-term visits, should also be provided.

Annex: One slide summary for experts

Topic 9: Understanding the basic components of the Universe, its structure and evolution.

2 - Finding the underlying symmetries behind the fundamental components of matter

A central problem of particle physics: **Peculiar pattern of masses and mixing angles** of elementary particles (quarks and leptons), the well-known **“flavour puzzle”**. Solution must imply new and fundamental physics.

Main challenge: Find fundamental hidden symmetry or dynamical reason behind this mysterious structure.

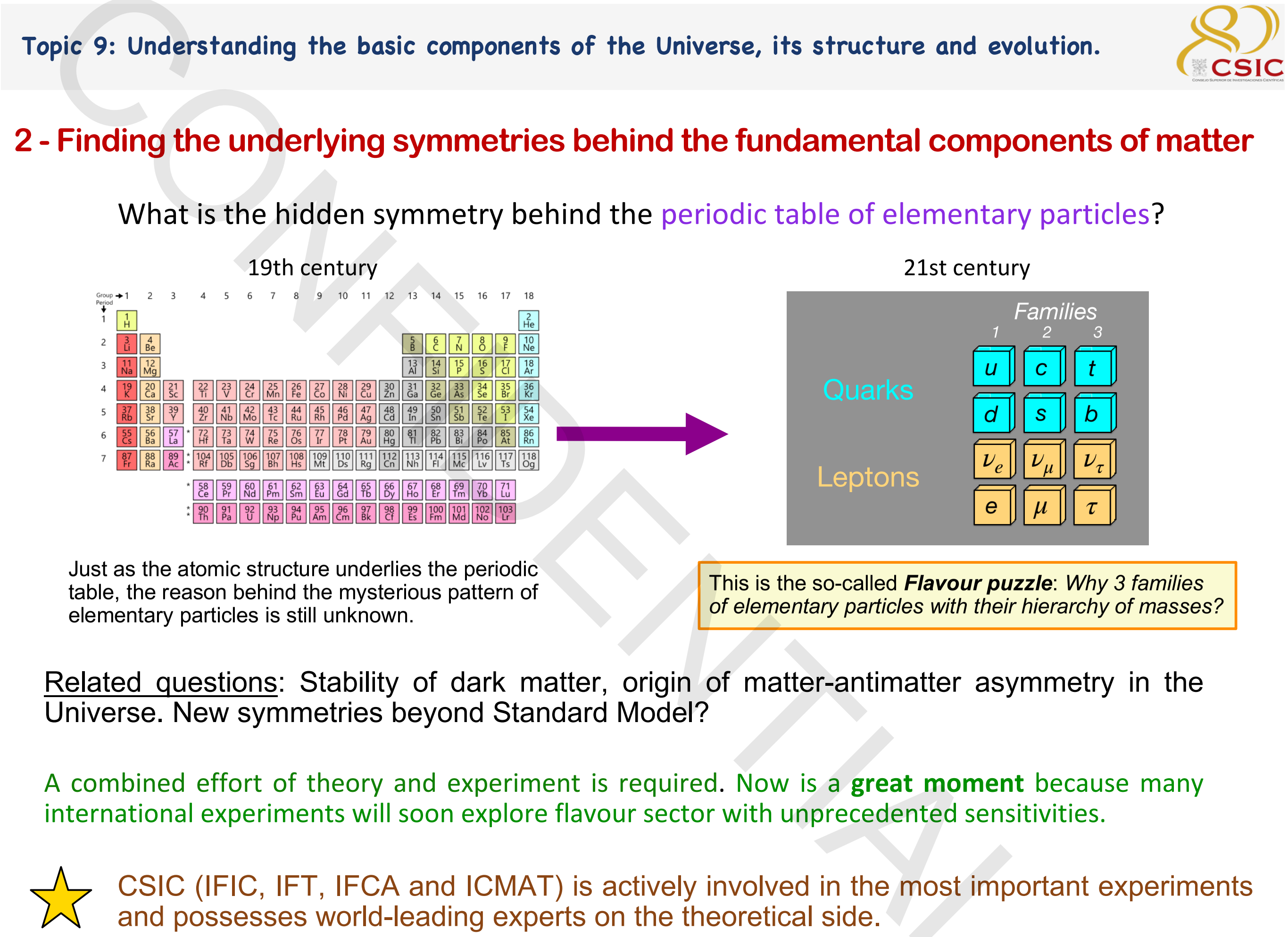
Other fundamental open questions, such as stability of dark matter or origin of matter-antimatter asymmetry in the Universe, are probably related to (same or different) existence of new symmetries beyond the Standard Model.

THEORY → **solution to these questions** ← **EXPERIMENT**

Challenge is **timely** because many international experiments will soon explore the flavour sector and related issues with unprecedented sensitivities.

- **IFIC**: Strong presence in LHCb and Belle II experiments, which play leading role in this challenge.
- **IFIC** and **IFCA**: Strong experimental groups in ATLAS and CMS collaborations, working on these and related topics, such as CP violation.
- **IFT** and **IFIC**: World-leading groups with very active and prestigious researchers producing high-impact ideas on flavour and connected issues. Active presence in leading neutrino and dark matter experiments.
- Complemented at the most fundamental level by the work of high-prestigious researchers of **ICMAT** and **IFT** on the mathematical foundations of these symmetries.

Annex: One slide summary for the general public



Topic 9: Understanding the basic components of the Universe, its structure and evolution.

2 - Finding the underlying symmetries behind the fundamental components of matter

What is the hidden symmetry behind the periodic table of elementary particles?

Just as the atomic structure underlies the periodic table, the reason behind the mysterious pattern of elementary particles is still unknown.

This is the so-called ***Flavour puzzle***: *Why 3 families of elementary particles with their hierarchy of masses?*

Related questions: Stability of dark matter, origin of matter-antimatter asymmetry in the Universe. New symmetries beyond Standard Model?

A combined effort of theory and experiment is required. Now is a **great moment** because many international experiments will soon explore flavour sector with unprecedented sensitivities.

CSIC (IFIC, IFT, IFCA and ICMAT) is actively involved in the most important experiments and possesses world-leading experts on the theoretical side.