Groupement de Recherche:
Intensity Frontier (GDR-InF)

Report and proposal for renewal

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1 Physics at the intensity frontier

Despite the remarkable success of the Standard Model (SM) of particle physics in describing the particles and the strong, electromagnetic and weak interactions between them, there is a general consensus in the physics community that physics beyond the SM (BSM) should exist. The latter is required to address established observational facts such as the neutrino masses and oscillations, the existence of dark matter, and the matter-antimatter asymmetry in the universe. Besides, such BSM physics could also address open conceptual questions like, for example, the hierarchy problems of the Fermi scale and of the cosmological constant, the hierarchy of the fermion masses, or the absence of CP violation in the strong force.

To probe BSM phenomena, physicists try to push beyond the existing frontiers of energy and intensity at controlled collision experiments. Experiments at the energy frontier are designed to produce and detect new particles whose mass is comparable to the energy frontier itself. At the intensity frontier, instead, one leverages on large experiments' luminosities, either to search for processes that in the SM are hugely suppressed or forbidden – e.g. lepton flavour violating decays, axions, EDM's – or to perform precise measurements of rare processes. This second group of tasks relies also on controlled theoretical uncertainties, and a larger sensitivity of the chosen rare process to BSM contributions. Examples in this class include tests of lepton flavour universality, the measurement of $(g-2)_\mu$, tests of the so-called Unitarity Triangle. Crucially, intensity-frontier experiments are sensitive to BSM physics at a much wider range of scales than experiments based on direct searches. This range of scales can go from sub-eV to thousands of TeV, i.e. well above the nominal energy of the experiment. Of course, this comes with the price of a larger model-dependence of the inferred conclusions. Historically, the two approaches of the energy and the intensity frontier have been very complementary, with hints of new physics first found at the intensity frontier, then established by direct searches. This interplay has insured some of the most spectacular discoveries in fundamental physics.

Regardless of the experimental strategy which will eventually lead to the discovery of BSM particles, measurements at the intensity frontier provide constraints and hints on the nature of the underlying dynamics, for example the couplings to fermions, i.e. the flavour structure. This is the clearest example of the above-mentioned complementarity, allowing the identification of the theory beyond the new phenomena through its quantum fingerprints. Given the present experimental standpoint, with no clear hints of new particles from direct searches, it is likely that the search for BSM phenomena will succeed only through diverse, complementary, innovative measurements, and the combination of all the available information. In this context, the intensity frontier will likely play a crucial role, given the plethora of measurements that are being done, those that are feasible and those that are conceivable in the short-medium term. In this context, the interplay between theory and experiment is pivotal, especially when it comes to interpreting and combining the results of the experiments, and to conceiving new measurements. Besides, there are challenges where the theory and experimental aspects are intertwined.

On the theory side, obtaining the best possible description in the SM of the process of interest is crucial. For example, non-perturbative effects need to be evaluated precisely using various advanced methods, i.e. calculations in Lattice QCD, QCD sum rules as well as the use of effective field theories to exploit symmetries and resum perturbation theory. The theorists in France working in this field are very active both in the interpretation of current data in terms of BSM models and in improving the precision on theoretical predictions for key observables.

From the experimental point of view, the challenge at the intensity frontier is to collect large and pure data samples, implying a detailed understanding of the detector performances and the use of sophisticated analysis techniques. Historically the French community has been largely active in the design, construction and exploitation of very successful experiments at the intensity frontier like, for example, CPLEAR, NA48 and BaBar. Today, it keeps playing a central role in running experiments like LHCb, Belle II, nEDM@PSI, but also contributes to planning experiments and facilities at the intensity frontier for the upcoming future, as is the case for COMET, SHiP, Codex-b, $(g-2)_\mu$@JPARC, τ-factory, ILC, FCC. There are other projects at the intensity frontier with no direct French experimental community involvement (e.g. NA62, KLEVER, KOTO, Mu2e, Mu3e, MEG, $(g-2)_\mu$@FNAL, facilities for axions searches). Providing complementary measurements, the evolution and results of these experiments are also followed with great interest by the community.

Thanks to forefront accuracy on both experimental and theoretical aspects, the intensity frontier is currently producing some of the most interesting results in fundamental physics, including some persistent, alluring discrepancies in lepton-universality tests in beauty decays, known as “B-anomalies”, and the $(g-2)_\mu$ anomaly. The French community is closely involved in numerous aspects of both sets of observations. If confirmed, these results could be milestones in the search for BSM physics. The GDR-InF has been and will hopefully remain the ideal arena in France to make further progress on both fronts, and on new ones, through systematic, structured exchanges, allowing to share knowledge and skills and thereby boost the success of these research directions.

2 The GDR intensity frontier (GDR-InF) in 2017-2021

As a natural way of sharing expertise and knowledge within a large French scientific community, favour exchanges between theory and experiment, and also as a follow up of a series of CNRS PEPS-PTI projects (Flagship measurements at LHCb, NouvPhysLHCb, Phenobas), in 2016 the Intensity-Frontier community in France proposed the establishment of a dedicated GDR. The proposal, signed by 61 permanent physicists belonging to 14 different laboratories of the IN2P3 and INP institutes, and one CEA institute, all with consolidated partnerships with Universities, was recommended by section 01 of the CoNRS in autumn 2016. After a decision made by the direction of the IN2P3 and INP institutes, the GDR-Intensity Frontier (GDR-InF) was officially created in 2017, the foreseen lifetime being 5 years. Today, taking postdocs and students into consideration, there are around 150 active members of the GDR-InF.

The organization of the GDR-InF includes: a "conseil de groupement", with a representative for each laboratory, convened at least once per year; two or three conveners for each working group, meeting regularly to propose and organise events; two co-directors, one theorist and one experimentalist, in charge of the coordination.

The GDR-InF was initially organized in six working groups: CP violation; rare, radiative and semi-leptonic B decays; charm and kaon physics; heavy flavour production and spectroscopy; interplay of quark and lepton flavour; future experiments. After the first two years, it was decided to merge "Rare, radiative and semi-leptonic B decays" and "Charm and kaon physics" working groups, as the current activity in France on the latter is on a smaller scale. It was further envisaged that this merging would foster relations between the two topics. In addition, despite it not having been initially foreseen, it seemed natural to open the "heavy-flavour production and spectroscopy" working group to discussions related to heavy-ion collisions results.

During the five years, many events of different nature have been organised by the GDR-InF (see the full list in appendix A). They were often the result of proposal by members of the GDR-InF, guided by the idea of organising events that could be genuinely interesting and adapted to the needs of the community, avoiding the duplication of pre-existing workshops. During these events an informal atmosphere was encouraged, leading to fruitful, enthusiastic and vibrant discussions. Since the community needs change over time, we adopted an evolving model making use of recurrent formats:

- *Intensity-Frontier lectures.* Dedicated to advanced topics in the domain, these provide insight into both theoretical and experimental aspects. These can also be held prior to a related workshop, to prepare the less experienced members of the attendees for the presentations. While the lectures generally target M2 and PhD students, postdocs and permanent researchers are also welcome. Whenever possible, the lectures are recorded and made available on the web.

- *Brainstorming meetings.* These small- or medium-size meetings, where discussions take priority over larger presentations, are the place to exchange ideas and possibly produce collaborative work among physicists either already working on a common project or planning to do so.

- *Topical GDR-InF workshops.* These workshops, open to international participants and speakers, have a more standard format and discuss hot topics in particle physics where members of the GDR-InF are involved.

- *Supported workshops.* These workshops, primarily proposed by other institutions, are co-organised by the GDR-InF if they are of interest to a significant part of the community, especially if a similar workshop has been proposed by members of the GDR-InF, in the spirit of avoiding duplication.

- *GDR-InF annual meetings.* Once a year the GDR-InF members gather to discuss the results of the community at large, and to give updates on ongoing research topics. This event is crucial for establishing connections and collaborations. All young researchers are invited to present their work, and some collaborative work is done.

The proposal highlighted a few objectives: to reinforce relations between theory and experiment; to facilitate collaborations between labs; to favour the emergence of common projects; to provide visibility for the French intensity-frontier community; to promote the young generation of physicists working in the field; to discuss the future experiments probing the intensity frontier.

Since 2017 the activities promoted by the GDR-InF have contributed to bringing the French intensity frontier community together. The different workshops provided an opportunity to discover in detail the research pursued in the different French laboratories, so that we are now more aware of the range of expertise existing in our community, both on the theoretical and experimental side. This helps in identifying possible synergies.

Many of the activities have been devoted to quark flavour physics, where there is the largest involvement of the GDR-InF community. While the range of experimental work in b physics and theoretical work on b, c and s physics is vast, a lot of relevance has been given to the so-called "b-anomalies", namely a coherent pattern of departures between measurements of semi-leptonic B-decay modes and the corresponding SM predictions. This pattern is being confirmed by the latest measurements as of this writing. There is a large involvement of the GDR-InF members in key analyses related to b-anomalies, both from the experimental side (with LHCb and Belle II) and on the theoretical side (with evaluation of form factors, global fits, model building). Some GDR-InF theorists work on the determination of the muon anomalous magnetic moment $(g-2)_\mu$, as well as on lepton flavour violating searches, where there is also experimental involvement (COMET, LHCb, Belle II). Given the connection with the b-anomalies, understanding a possible link between quarks and leptons is becoming of primary importance, and theorists are investigating this link. A smaller but very active community is focused on electric dipole moment (EDM) measurements. Unmeasured EDMs embody the so-called strong CP problem, in turn naturally connected with the vast topic of light, spinless particles, in particular axions. This research direction is followed with great interest by some of our theorists.

As a result of the interactions within the GDR-InF, some collaborative work has started. For example, during the latest annual meeting, group of people have gathered together to add features to the open source code `flavio` ; others have established a discussion group on EDM. The lectures on V_{cb} have lead to a publication by the lecturers. Theorists and experimentalists from LHCb and Belle II working on $b \to s\ell\ell$ transitions with τ in the final state have proposed an ANR project, BooST, that passed the preliminary selections and, although not financed, has allowed to put forward few lines of common work that can still be pursued.

The visibility of the French community at an international level has been promoted regularly inviting foreign speakers to our meetings and workshops, which are always open to international participants. In this way, we ensure that the activities ongoing in France are known about at an international level. In addition, the GDR-InF has participated in the organization of relevant international workshops.

Apart from knowing the broad panorama of activities conducted in France, newcomers and young researchers participating in the GDR-InF regularly have the opportunity of presenting their analyses, whether ongoing or finalized, and receive constructive feedback. We are proud that most of them work at the core of hot topics in particle physics today. Regular lectures have been set up to ensure a high level training of our students and postdocs on advanced topics in the field. Credits for attending the lectures are attributed by most doctoral schools. When possible, postdocs are appointed as conveners, and invited to participate in the organization of events.

In France there is also a large involvement in detector design, development of reconstruction algorithms and data-handling solutions, and detector-performance evaluation. The GDR-InF has taken care of promoting discussions on how to maintain and develop these skills, and on how they can be used for the benefit of the future experiments at the intensity frontier. Recurrent discussions lead to draw up a document, signed by all the members, which was submitted as input to the European Strategy for Particle Physics (ESPP). In addition, the GDR-InF has been and is still active in the ongoing French process of the "Prospectives nationales pour la physique de particules".

In order to keep the community bonded even in the difficult context of the on-going pandemic, some communication channels have been established, including a website collecting information (`http://gdrintensityfrontier.in2p3.fr/`); a mailing list used to advertise news of general interest; a Mattermost chat for informal discussions.

The GDR-InF strongly supports and encourages outreach activities, for example GDR-InF twitter and instagram accounts have been created and regular posts are made. In addition, in view of building a common outreach project, the GDR-InF has prepared a photo exhibition for the general public, which is going to be exposed in 2021-2022 in different locations in France (for more details see `http://gdrintensityfrontier.in2p3.fr/`).

3 Proposal for the renewal of the GDR-InF

In the previous section we discussed how over the last five years the French community at the intensity frontier has come together within the GDR-InF, improving connections among theory and experiment and among different research lines. We can definitely say that the French Intensity-Frontier community is stronger, more connected, and has been greatly enriched by the GDR-InF. Given these positive results, and given also the profusion of interesting measurements coming at the time of writing this document, we are still at the beginning of this journey.

The objectives of the previous proposal still stand, and deserve being pursued further. The GDR-InF will continue to play the role of bringing the French intensity frontier community together, reinforcing the interplay between the different lines of research, improving the visibility of our activities, promoting young researchers and helping planning the future of the field.

But as mentioned earlier, the place of the GDR-InF is particularly important given how vibrant the intensity frontier field is at present. The large amount of data that is being collected and that will be analysed and interpreted in the upcoming five years will have large repercussions for our understanding of the SM and what lies beyond. For example, it will finally clarify the nature of the current tensions in b-hadron physics with the SM predictions and possibly open a window on the BSM domain. We have enough tools and expertise to play a leading role in exploring this wealth of data and hopefully clarify the nature of the BSM physics. More than ever before, the GDR-InF plans to focus on stimulating the emergence of common projects, supporting their development and promoting the visibility of such projects at a national and international level. In addition, we will be proactive in stimulating exchanges with other particle-physics communities, including other GDRs and physicists from experiments on which the French community is not directly involved at present. The aim is to discuss our results in the context of the general picture of particle physics today. Outreach initiatives will also be organised, so that the general public can understand and appreciate the relevance of our research.

As in the past, the GDR-InF activities will be organised within several thematic working groups, which would both function independently and together. The structure of the working groups will be similar to the previous ones, with slight modifications reflecting the changing context in which the GDR-InF has evolved. While in the following sections of this document each working group will be described in detail, here we provide an overview of the various working groups:

- **CP violation.** With Belle II finally in full data taking period and LHCb resuming the operations, measurements of the parameters of the CKM matrix are expected to be further improved. The two experiments, in a complementary way, will push further one of the most precise tests of the SM. If BSM physics is found in (semi)-leptonic decays, it is legitimate to expect its imprinting also in CP observables from beauty, charm and strange hadrons decays. CP violation should also be understood in strong interactions, and the effort of EDM experiments and axion searches is particularly interesting in this respect.

- **Radiative, leptonic and semi-leptonic b-, c-, s-hadrons decays.** Radiative, leptonic and semi-leptonic b-, c-, s-hadron decays are powerful probes of BSM physics, provided that precise theoretical predictions can be made for experimentally clean observables. The b-anomalies are the most exciting, persistent signs of deviations from the SM in collider data at present. We have the chance of being involved in both LHCb and Belle II, experiments which in the next few years will definitely be in the position of confirming or disproving these results. More than that, we have an expert theoretical community that is scrutinizing these results and proposing possible BSM interpretations, as well as novel measurements.

- **Interplay of quark and lepton flavour.** At the moment some of the most interesting deviations from the SM are observed in lepton flavour universality tests in b-hadron decays, involving transitions of quarks into leptons. An approach mixing the quark and lepton sectors and combining measurements and theoretical advancements in both fields is of primary importance. The observed tension in the $(g-2)_\mu$ measurement should also be investigated in this context, and new measurements of purely leptonic decays, including τ decays and lepton flavour violating searches, should provide additional insights.

- **Heavy flavour production and spectroscopy.** Searches for BSM physics often rely on QCD predictions. Proton-proton and heavy-ions collisions at the LHC are ideal playgrounds to improve our knowledge on QCD. There is a wealth of new complex structures (i.e. tetraquarks, pentaquarks) observed for the first time and whose nature is not yet fully understood, but also production dynamics of well-known particles that are still to be studied.
- **Future at the intensity frontier.** Following the recommendations of the ESPP, the GDR-InF members, while profiting of the current facilities, promote a constant effort for planning the future of the field. It is important to guarantee a broad program of physics at the intensity frontier, complementary to the energy frontier, with both large scale experiments and smaller experiments dedicated to observables sensitive to BSM physics, and to decide together the involvement of the French community in order to optimize the available resources.

There are no changes foreseen in the organization of the GDR-InF, it will still be coordinated by a theorist and an experimentalist, a "conseil de groupement" and a team of working group conveners. Nonetheless, there are additional permanent physicists and laboratories joining the GDR-InF. The recurrent formats of events established so far and described in the previous section will be used as starting model for planning the activities, but we will keep the freedom of giving more emphasis to some format rather than others according to the needs.

We believe that this proposal of renewing the GDR-InF for another cycle of five years, consolidating the effort started in 2017, is of utmost interest for the physicists involved in the research at the intensity frontier, and in line with the scientific policy of our institutes. Acting to increase the productivity and the international recognition of those working in this field in France, the GDR-InF will allow the community to take full advantage of the exciting times we have ahead.

In the following subsections we describe in details the topics covered by each working group and their foreseen plans for the upcoming new cycle of the GDR-InF.

3.1 CP violation

Charge-parity (CP) violation has been an intriguing field since its first discovery in the kaon system. Apart from the interest in the phenomenon by itself and its relation to the matter-antimatter asymmetry, it is a very powerful probe for BSM physics. In fact, CP violation (or T violation, assuming CPT holds) in the SM originates from a single parameter: all the CP-violating observables in the K, D and B meson sectors are thus directly related, and their combined study provides a highly powerful test of the whole SM dynamics. Instead, most models of BSM physics are far less restrictive and allow for a plethora of new CP-violating sources: most of the delicate interplay between observables expected in the SM will no longer hold in the presence of new dynamics at the TeV scale.

When experimentally testing SM predictions, it is fundamental that the theoretical precision matches the experimental accuracy. A priori, this looks challenging because CP violation in the SM originates from the weak quark couplings, and manifests in hadronic systems in which non perturbative interactions must be understood. However, dedicated strategies have been designed to construct measurable quantities with controlled uncertainties, and CP-violating observables are actually among our best windows to look through when searching for BSM physics. For example, in CP-violating asymmetries, most of the uncertainties cancel between the numerator and the denominator. Alternatively, some CP observables are predicted to be so small that simply observing a non-zero value would unequivocally signal the presence of BSM physics.

The French community has been deeply involved in CP violation dedicated experiments for many years (CPLEAR, NA48, BaBar, LHCb, Belle II), building and maintaining key elements, like trigger systems, calorimeters and particle identification detectors. In addition, there is expertise in several powerful techniques needed to study CP violation: amplitude analyses, tagged-time-dependent angular analyses, flavour tagging, neutral objects reconstruction. On the phenomenological side, the CKMFitter collaboration [1], a French initiative, is precisely evaluating since years the coherence of CP violation measurements, through the well known Unitary Triangle (UT) test: the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix in the SM can be represented, in the absence of BSM physics, as a triangle whose sides and angles, determined from various observables, all have to agree for the triangle to close. The current status is shown in figure 1 on the left.

In the following we describe briefly some activities ongoing or planned in the near future for CP violation measurement in the B, D and K sector and in other observables.

3.1.1 CP violation in the B sector

In the context of BaBar and LHCb, the French community has been one of the main actors in the measurements of the unitarity angles, studying many channels like (quasi-)two-body charmless B decays for the determination of α, $B \to (c\bar{c})K$ for β, $B \to D^{(*)}K^{(*)}$ (with ADS/GLW and GGZS approaches) for γ and finally $B_s^0 \to J/\psi\phi$ for ϕ_s. This has always been accompanied by a proficuous theoretical work (see for example [2, 3]).

The measurement of ϕ_s is one of the most important goals of the LHCb experiment. The value of ϕ_s, precisely predicted in the SM, sets the scale for the difference between properties of matter and antimatter for B_s mesons. The predicted value is small and therefore the effects of BSM physics could change it significantly. The ϕ_s measurement obtained by LHCb, with the contribution of IN2P3 physicists, analyzing $B_s^0 \to J/\psi KK$, $B_s^0 \to J/\psi\pi\pi$, $B_s^0\ toD_s^+D_s^-$ and $B_s \to \psi(2S)\phi$ decays [4] is the most precise to date (-0.042 ± 0.025 rad), consistent with the SM expectation.

Data coming from the LHCb upgrade will lead to an error of the order of 0.01 rad, so that it will become fundamental to control the sub-leading contributions coming from the so-called penguin diagrams, not yet precisely estimated in QCD. The effort to control this contribution requires a strong collaboration with the theorists and eventually exploring new approaches.

Another domain in which the experimental French groups are active in LHCb, perpetuating the experience established in BaBar, are CP violation studies of charmless b-hadron decays. These decays have a number of theoretical applications and especially provide a probe to BSM physics. For instance, mixing-induced CP asymmetries in the charmless three-body decays $B^0 \to K_S^0\pi^+\pi^-$ and $B^0 \to K_S^0K^+K^-$ are predicted to be approximately equal to those in $b \to c\bar{c}s$ transitions, *e.g.* $B^0 \to J/\psi K_S^0$, by the CKM mechanism [5, 6]. However, the charmless three-body decays are dominated by $b \to q\bar{q}s$ $(q = u, d, s)$ loop transitions, which can have contributions from new particles, introducing additional weak phases [7–10]. A time-dependent analysis of the three-body Dalitz plot allows measurements of the mixing-induced CP-violating phase [11–14]. Although the current experimental measurements of $b \to q\bar{q}s$ decays [15] show fair agreement with the results from $b \to c\bar{c}s$ decays, a global trend towards values lower than the weak phase β measured from $b \to c\bar{c}s$ decays emerges. The interpretation of this deviation is complicated by QCD corrections, which depend on the final state [16] and are difficult to handle. These charmless three-body analyses provide a long-term physics program that can profit from the LHCb upgrade. In fact, these analyses proceed in increasingly complex steps, which become more and more sensitive to BSM observables with the growing dataset, and with more observed decay modes. With a larger dataset, an analogous extraction of the mixing-induced CP-violating phase in the B_s^0 system (ϕ_s) will be possible using the $B_s^0 \to K_S^0K^\pm\pi^\mp$ decay, which will be compared with that from, *e.g.* $B_s^0 \to J/\psi\phi$. Another long-term goals is the determination of the CKM angle γ from charmless B meson decays using and refining the methods proposed in Refs. [17–19].

3.1.2 CP violation in the D and K sectors

Kaon physics is the birthplace of CP violation, and has played a central role in establishing the CKM picture in the past five decades. Advances in lattice QCD may help to finally shed new light on the precisely measured direct CP-violation parameter ε'/ε.

CP violation in charm mesons is expected to be very small because the GIM mechanism is much more powerful for $c \to u$ transitions than for $s \to d$ or $b \to s, d$ transitions. However, BSM physics needs not respect this peculiar feature. For this reason, CP observables in charm mesons provide interesting windows where BSM physics could show up. The large cross section of charm in proton-proton collisions at LHC makes possible their measurement at LHCb with an unprecedented precision, that will be further reduced with the upgrade.

3.1.3 CP violation in other observables

In the SM, CP violation is a purely flavoured phenomenon, arising from the presence of three families of matter particles. This partly explains its strong suppression in physical observables, and thereby their high sensitivity to sources of BSM CP violation. At the same time, this feature is not fully understood and raises several questions.

First of all, CP violation by the strong interaction is mysteriously absent from the SM, in spite of the existence of the relevant CP-violating operator. This is the so called "strong CP problem". Besides, one solution to the strong CP problem involves a new particle, the axion. This could well be the dominant component of the elusive dark matter, whether in the form of axion cluster, cosmic strings, collective excitation, etc... Finally, strong CP

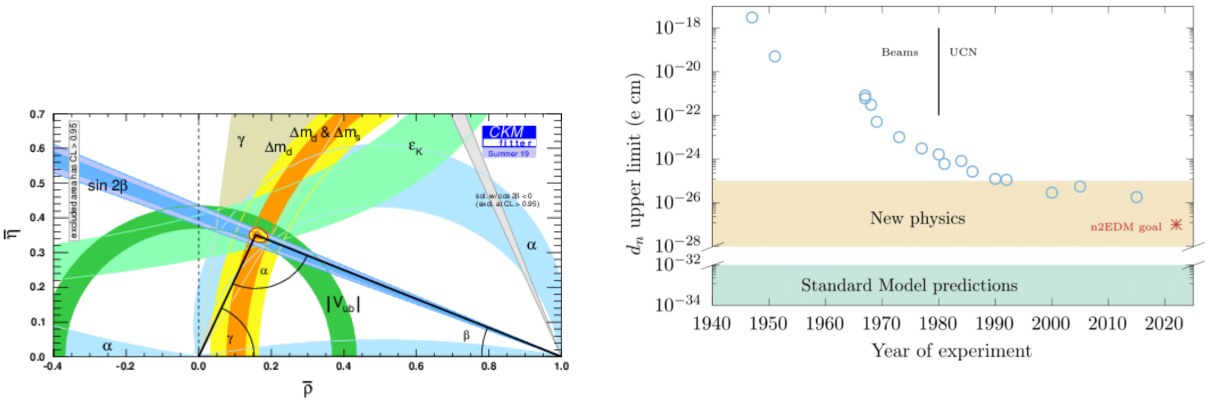

Figure 1: Left plot: the current status of the CKM unitarity triangle test from the CKMFitter collaboration [1]. Right plot: Evolution of the neutron electric dipole moment (nEDM) measurement as function of time.

violation could be related to the origin of the baryon asymmetry of the universe: starting from a symmetric, balanced situation, new sources of CP violation seem unavoidable. Therefore, it is clear that exploring CP violation in light mesons has implications well beyond the strict context of flavour physics, and may shed new light on some of the most fundamental puzzles.

If present, strong CP violation would deeply alter the picture, in particular for electric dipole moments (EDM). This observable is studied by the French community, who made a significant contribution to the recently published best upper limit on the neutron EDM [20] and is actively involved in the conception and construction of the next generation of neutron EDM experiments. The imprints of strong CP violation on low-energy observables could be present not only in the neutron EDM but also in CP violating interactions within the nuclei, and these effects could be within reach experimentally.

3.1.4 Plans for the GDR

- Measurements of CP observables are expected to largely improve in the next five years: additional measurements of γ and α should overconstrain the UT; CP violation in semi-leptonic b decays is expected to be assessed in a very clean way at Belle II; additional insights will be provided by LHCb in ϕ_s, that will reach an unprecedented precision, and with the study of CP violation in b baryons. Within the GDR-InF, we will discuss opportunities and complementarity offered by LHCb and Belle II to perform these measurements, assess with the theorists the impact of the results as they come out and search new ways to probe the SM with CP observables in the b sector.

- A major discovery can not be made unless both experimental and theoretical uncertainties are under control. Advances in controlling hadronic effects, for example using lattice simulations of QCD or analytic tools like sum rules can be expected. Discussion will take place to ensure that these results are accounted in the upcoming CP observables measurements of LHCb and Belle II.

- Improved limits on CP violation in charm, both in decay and the interference of mixing and decay, as well as precise measurements of charm mixing parameters are expected with the LHCb upgrade. Theorists and experimentalists should understand if a renewed effort on charm measurements could be of interest within the French community.

- The GDR-InF provides a unique forum for communities searching for CP violation at high and low energy. Experimental techniques and theoretical backgrounds are very different. Keep favoring the exchanges between these communities, will be one of the objectives of the GDR-InF, in order to explore the global complex question of CP violation from different and complementary perspectives.

- The concerted effort of low and high energy particle communities, cosmologists, experimentalists and theorists, in the study of the axions as a possible solution to the strong CP puzzle, favoured by the GDR-

InF in the past years, has been appreciated and so will have to be continued and intensified in the coming years.

3.2 Radiative, leptonic and semileptonic b-, c-, s-hadrons decays

Whether proceeding primarily through tree levels processes, as in the case of $b \to c\ell\nu$ transitions, or through loop processes, as in the case of $b \to s\gamma$ and $b \to s\ell\ell$ transitions, radiative, leptonic and semileptonic decays of beauty, charm and strange hadrons have sensitivity to vastly higher scales than those of the process being considered. In particular, $b \to s\gamma$ and $b \to s\ell\ell$ decays are flavour-changing neutral currents, and this suppression makes them natural candidates to study non-standard dynamics in the loops: BSM effects in these decays are expected at some level.

Theory can perform very precise predictions on these decays, and experiments accordingly precise measurements. The collaborative work of experimentalists and theorists has allowed to identify an ensemble of observables which are at the same time sensitive to the couplings to different possible BSM sources and minimally sensitive to so-called non-factorizable QCD effects, which are very hard to estimate. With the abundance of data produced by the LHC collisions, for the first time some of these decays can be observed, their properties measured and the prediction tested with better precision than ever. The French community is largely active both on the experimental and theoretical studies of these decays: it leads or is leading the effort on numerous LHCb, Belle and Belle II measurements, and on theoretical works on observables definition (see e.g. [21–28]), results interpretations (see e.g. [29–37]), assessing the effects of hadronic uncertainties (see e.g. [38–40]), future prospects (see e.g. [41, 42]), and model building (see e.g. [43]).

Over the last years, the LHCb collaboration has produced a wealth of data analyses related to exclusive $b \to s\ell\ell$ decay modes. These analyses show a coherent set of persistent deviations between measurements and SM predictions, and represent perhaps the most topical research subject in quark flavour physics at present. Of these results, lepton flavour universality tests have attracted most attention, because of the excellent control of both theory and experimental uncertainties [44]. These tests consist in the measurement of the observable $R_K = \mathcal{B}(B \to K\mu\mu)/\mathcal{B}(B \to Kee)_{(1-6)GeV^2}$ and the analogous quantity R_{K^*}, for a final-state with K^*. Originally found to be 2.6σ smaller than predicted in the SM [45], the latest measurement of R_K using the full LHCb dataset confirms the deviation with a higher statistical significance [46]. This result suggests evidence for the violation of the universality of the couplings to leptons (LFUV). The related R_{K^*} observable measured on Run 1 data shows a 2.1-2.5σ deviation and the update with the full LHCb dataset, on which French groups are involved, is eagerly awaited. The Belle experiment presented a new measurement of R_{K^*} compatible with the theory prediction, but less precise and statistically limited. The Belle II experiment, instead, should collect enough statistics to give new and independent insights on these measurements in the coming years. A first test of LFUV also appeared recently in the baryonic sector [47], and other complementary measurements from LHCb are expected.

The LFUV suggested by $R_{K^{(*)}}$ adds to a related problem in the ratios $R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\tau\nu_\tau)/\mathcal{B}(B \to D^{(*)}\mu\nu_\mu)$, concerning $b \to c\ell\nu$ transitions. Also in this case, the combination of the experimental results, obtained first at the B-factories and then at LHCb, are showing a $\sim3\sigma$ tension with respect to the SM prediction [15]. A simultaneous explanation of $R_{K^{(*)}}$ and $R_{D^{(*)}}$ tensions is complicated by the fact that the sizes of the discrepancies are comparable, but the former originates from $b \to s$ currents, which are loop in the SM, whereas the latter from $b \to c$ currents, which arise already at tree level. Nonetheless, and quite interestingly, theory frameworks allowing to describe both sets of discrepancies do exist, all the way from effective theories, to simplified models, to fully renormalizable models (see recent discussions in [48–52]). One possible underlying paradigm is that of leptoquarks.

Several further measurements, besides LFU tests, are envisaged to confirm or disprove the discrepancies seen in ratios. Models proposed for describing the LFUV effects hinted at by R_K generally allow for lepton flavour violation (LFV) too. Model-independent considerations in ref. [53] showed that from the measured size of R_K one could expect branching ratios of lepton flavour violating B meson decays around 10^{-8}, in the absence of further suppression mechanisms. This happens to be within reach at LHCb, and for this reason numerous LFV modes have been or are being searched for: $B_s \to \mu\tau$ [54]; $B \to K^{(*)}\mu\tau$ [55]; $B_s \to \phi\mu\tau$; $B_{(s)} \to \mu e$ [56]; $B \to K^{(*)}\mu e$ [57]. Given the matrix structure of flavour couplings, it is clear that LFUV and LFV measurements are highly complementary to constrain how the putative new physics couples to quarks and leptons, and to ultimately reconstruct the full set of couplings.

Crucially, the hints of non-standard LFUV dynamics seen in the $b \to s$ ratios R_K and R_{K^*} seem to be quantitatively confirmed by the host of branching-ratio measurements of semi-leptonic $b \to s$ modes (including notably $B_s \to \phi\mu\mu$, $B \to K^{(*)}\mu\mu$, as well as $\Lambda_b \to \Lambda\mu\mu$ decays [58–60]) and by the angular analysis of $B \to K^*\mu\mu$, where the SM theoretical estimates tend also to deviate from data, in particular in the angular observable known as P'_5 [61, 62]. It is worth to note that the discrepancy in the angular analysis of $B \to K^*\mu\mu$ appears mostly in a region, not very far from the charm production threshold, notoriously difficult for the theoretical description of these decays. In fact, in this region it is required an accurate estimate of the hadronic matrix element of a non-local operator corresponding to disconnected $c\bar{c}$-diagrams, which cannot be computed by means of numerical simulations of QCD on the lattice. Although recent calculations [63] strongly suggest that hadronic effects cannot possibly account for the observed P'_5 discrepancy, there is more caution on the angular observables than on the rest of the observed departures discussed above.

For certain decays, notably $B_s \to \mu\mu$, the CMS and ATLAS collaborations are also significantly contributing. The latest combination of its branching ratio measurements includes data taken from 2011 to 2016 and shows a 2.1σ tension with the theory prediction [64]. The last LHCb measurement includes also the first ever limit on the $B_s \to \mu\mu\gamma$ branching ratio in the region of high invariant di-lepton mass, following the method of Ref. [65].

On top of the very rich set of results involving muons, LHCb has also performed an angular analysis of the $B^0 \to K^*ee$ decay mode in the low dilepton invariant mass region q^2 [66]. This measurement, based on all the data collected by LHCb up to now, allows to put a strong constrain on the polarization of the photon in the $b \to s\gamma$ transition, nicely complementing the measurements of the decays involving real photons in the final state, like $B_s \to \phi\gamma$ and $B \to K^*\gamma$. In the SM the photon polarization in $b \to s\gamma$ transition is known to be left (right) for a b ($\bar{b}$) quark, modulo effect of the order of 4% due to the quark masses and the emission of soft gluons. Any deviation from this precise expectation would be a clear sign of BSM physics. In the next years, precise measurements of the photon polarization in $b \to s\gamma$ transitions are expected to come by both LHCb and Belle II, but some challenges need to be faced, like for example the study of the resonant K^* structure, requiring a close collaboration between theorists and experimentalists [67]. New limits were also obtained on the $B_{(s)} \to e^+e^-$ decays [68] at a level of few 10^{-9}.

The tau sector started to be probed by the B-factories, for example with the limit from BaBar on the $B^+ \to K^+\tau^+\tau^-$ decay [69]. More recently LHCb has set a first experimental limit on the $B_{(s)} \to \tau^+\tau^-$ decay [70], still a few orders of magnitude higher than the SM predictions but relevant in demonstrating the capabilities of hadronic machines for such searches. The flavour anomalies have reinforced the interest on the tau sector and, despite the experimental difficulties in reconstructing these modes, LHCb and Belle II are working to provide results in the coming years.

The possible BSM physics hinted in $b \to s\ell^+\ell^-$ transitions is expected to affect also $b \to s\nu\bar{\nu}$ transitions. The branching fractions of the still unobserved $B \to K^{(*)}\nu\bar{\nu}$ could deviate from their SM values and allow to discriminate between possible BSM solutions [71]. The theoretical predictions for these decays do not suffer from long distance uncertainties thanks to the fact that neutrinos do not couple to photons. Since neutrinos are not directly observed, but identified as missing invisible particles, $b \to s\nu\bar{\nu}$ searches can also constrain $b \to sX_{\text{dark}}$ where X_{dark} consists of invisible particles not present in the SM, for example dark matter constituents. The $B \to K^{(*)}\nu\bar{\nu}$ decays have not been yet observed, but the upper limits on their branching fractions set by Belle [72] are close to the SM expected values, so the large data sample collected by Belle II in the next years could allow a first observation.

Finally, despite no direct involvement of the French experimental community, the results from experiments looking at rare kaon decays, like NA62, aiming at $K^+ \to \pi^+\nu\bar{\nu}$, and KOTO, aiming at $K_L \to \pi^0\nu\bar{\nu}$, are relevant for understanding the theory of flavour: any hint of discrepancy with the SM there would have implications for the other meson sectors. Similarly, the large amount of charm mesons produced at LHCb allows one to study up-type FCNC: $c \to u\ell\ell$. In the coming years, results on these decays could become precise and could play a role in determining the global picture of flavour. For a recent phenomenological analysis by members of the GDR see Ref. [73].

3.2.1 Plans for the GDR

- Current and upcoming measurements of $b \to s\ell\ell$ transitions from LHCb will be soon facing analogous measurements performed at Belle II. The GDR-InF will be the forum where, profiting of our leading expertise in both the experimental measurements and the theoretical interpretation, we will discuss the

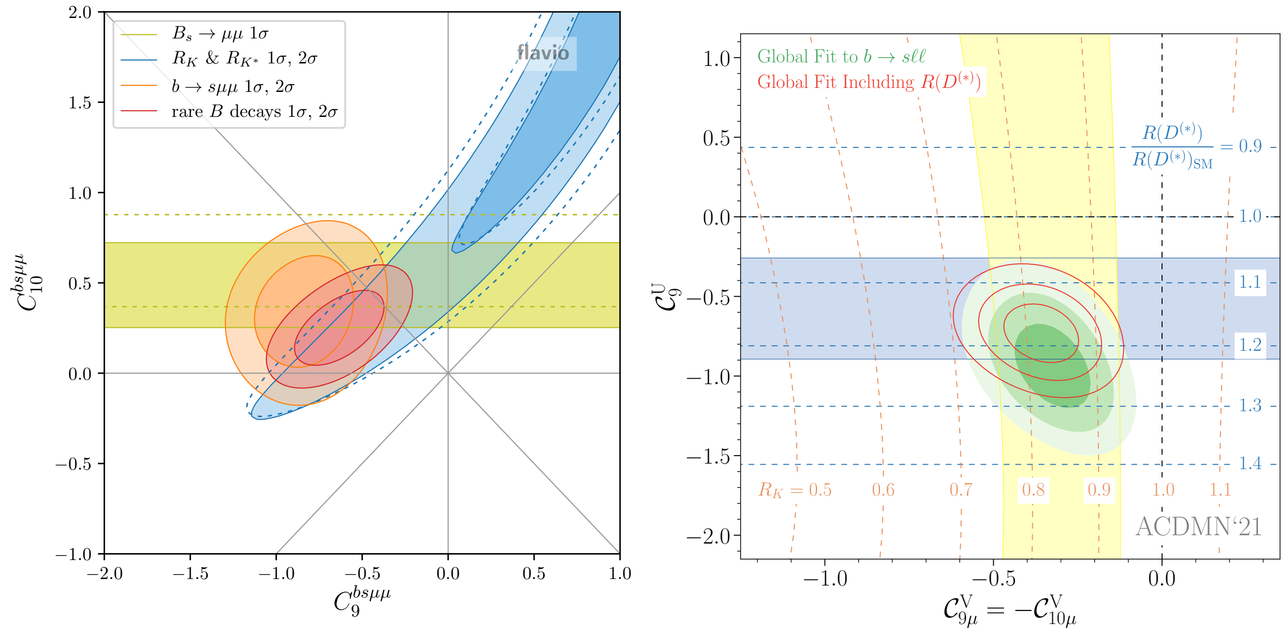

Figure 2: Phenomenological analysis of the rare decays constraints on BSM physics. The left plot shows a global fit results using $b \to s\mu\mu$ observables of the muon specific Wilson coefficient C_9 and C_{10} [50] . The right plot shows a global fit of the $b \to s\ell\ell$ observables adding or not the $R(D^*)$ measurements and separating the C_9 Wilson coefficient into LFU or LFUV couplings [74]. In both cases, the tension with the SM prediction corresponding to the origin of the plane, is significant.

coherence of the results, encourage a global interpretation and try to extract the leading message conveyed by data on the nature of physics beyond the SM.

- For the angular analyses of $b \to s\ell\ell$ transitions it is mandatory to assess the theoretical hadronic uncertainties. Lattice QCD and the QCD sum rule practitioners will try and evaluate the size of theoretical errors and discuss the appropriate methodology on how to account for various sources of systematic uncertainties. Possible phenomenological ideas on how to relate the hadronic quantities in several decay modes will be discussed, as they might be helpful in canceling a large part of hadronic uncertainties, as well as ideas on how to treat the non-resonant $c\bar{c}$-contributions.

- LHCb provides a unique opportunity to extend the measurement of $b \to s\ell\ell$ transition to the b-baryons sector, for example with the analysis of $\Lambda_b \to \Lambda^*\mu\mu$ decays. However this requires understanding the different contributions in the baryonic structures and the GDR-InF will continue supporting the exchanges started among theorists and experimentalists working on this topic.

- The analysis of final states with neutrinos requires improvements in the reconstruction techniques to estimate the amount of missing energy. This is the case, for example, of the search for the $B \to K^{(*)}\nu\overline{\nu}$ in Belle II, but also for final states with τ leptons, always accompanied by neutrinos, for both Belle II and LHCb. For the τ, in the context of the GDR-InF some discussion have already started among members of the two experiments and theorists, and some lines of collaborations that could be pursued in the future have emerged.

- Direct measurements of photon polarization in the radiative decays $B^0 \to f_{CP}\gamma$ and $B \to (hhh)\gamma$ modes (where h is a kaon or a pion) are expected to be pursued, with a detailed study of the resonant structure of the decay. It will be interesting to assess the complementarity and interplay of the $B \to K^*ee$ analysis at LHCb with the measurements at Belle II, and to explore the possibility of observing the suppressed $b \to d\gamma$ transitions and $B_{(s)} \to \gamma\gamma$ decays.

- Another topic which has recently been gaining both theoretical and experimental attention is the study of radiative semi-leptonic and rare decays e.g. $B \to \gamma\ell\nu$ or $B \to \ell\ell\ell'\nu$, $B_s \to \gamma\ell\ell$ or $B \to \ell\ell\ell'\ell'$ (and the analogous D and K decays) which are powerful probes of the structure of the decaying mesons and of possible BSM effects respectively. The GDR-InF will act as an important forum to bring together experimentalists at LHCb and Belle-II and theorists in France working on these decays.

- In order to understand the theory of flavour, the GDR-InF will ensure that not only b physics results, but also new results from kaon experiments (NA62, KOTO) and from charm measurements will be propagated and discussed within the community. In addition, the issue of the (in)compatibility of the conclusions found in the Yukawa sector through the low-energy experiments with the LHC findings at the TeV-scale will be discussed.

3.3 Interplay of quark and lepton flavour

As previously highlighted, several lingering tensions with respect to the SM theoretical expectations have been observed in a variety of low-energy observables based on semi-leptonic transitions. Particularly interesting examples of these are the ratios $R_K = \mathcal{B}(B \to K\mu^+\mu^-)/\mathcal{B}(B \to Ke^+e^-)$ [46] and the similarly defined R_{K^*} [75] and R_{pK} [47], determined in specific bins of di-lepton invariant-mass squared (q^2). All these observable follow the same trend, *i.e.* "a depletion of the rate of muons", exhibiting in the case of R_K a 3.1σ deviation from its SM prediction, as depicted in Fig. 3. Deviations from the SM predictions have also been observed in the ratios $R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\tau\bar{\nu})/\mathcal{B}(B \to D^{(*)}\mu\bar{\nu})$, see e.g. [76] for a recent review.

Most recently, the Muon $g-2$ experiment (FNAL) has confirmed [77] previous results from E821 (BNL) [78] on the anomalous magnetic moment of the muon, which are 4.1σ above the SM prediction obtained in Ref. [79]. This discrepancy can also be explained by BSM physics in semileptonic operators, which contribute to dipole transition at loop-level [80, 81], and that might be related to the "b-anomalies". However, it should be noted that there is not yet a consensus on the SM prediction: recent results from Lattice QCD [82] on the leading Hadronic Vacuum Polarization contribution disagree with Ref. [79] and seem to reduce this tension.

If these tensions in low-energy observables are confirmed, then one is indisputably in the presence of BSM physics, in particular models leading to modifications of the SM flavour paradigm. Since the above-mentioned tensions between SM predictions and experiment appear nested in an interface between the hadronic and the lepton sector, many of the proposed extensions of the SM typically include new states and interactions simultaneously acting upon both sector. Therefore, exploring the connection between the two sectors is of fundamental importance to test the scenarios proposed to explain these anomalies. This can be done in a model-independent way by using Effective Field Theories (EFT), or by using concrete BSM scenarios.

While the observed B-meson decay anomalies signal discrepancies with respect to the theoretical expectations, several other flavour processes are strictly forbidden in the SM by accidental symmetries. This is the case of charged lepton flavour violation (cLFV) transitions and decays. These processes are a priori possible once the SM lepton sector is minimally modified to accommodate neutrino oscillation data (SM extended via Dirac massive neutrinos), but the predicted rates would be highly suppressed by the smallness of neutrino masses. Therefore, any observation in the present or future generation of dedicated facilities would unambiguous signal the presence

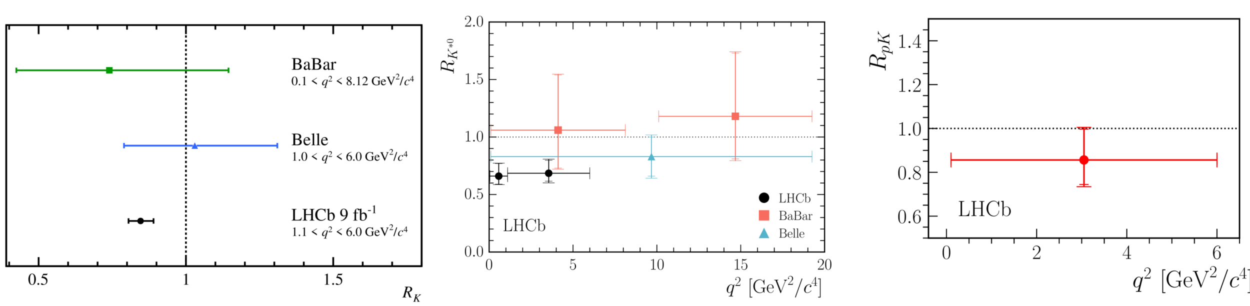

Figure 3: From left to right: measurements of the lepton universality observable R_K, R_{K^*} and R_{pK} from LHCb and the B-factories.

of BSM physics. Interestingly, many BSM solutions aiming at explaining the hints of lepton flavour universality violation also lead to cLFV decays in $\tau \to \mu$ transitions [48,53,83–85]. The most interesting modes are the purely leptonic $\tau \to \mu\gamma$, or the B-meson decays $B_s \to \mu\tau$ and $B \to K^{(*)}\mu\tau$. For this reason, the ongoing searches for these decays at Belle-II and LHCb can act as a further probe of these SM extensions.

Many facilities (world-wide) aim at searching for cLFV: MEG ($\mu \to e\gamma$), Mu3e ($\mu \to 3e$), Mu2e and COMET (both searching for $\mu - e$ conversion in Aluminium nuclei). Together with LHCb and Belle II, playing a leading role in τ and B-meson (semi)leptonic cLFV decays, such a comprehensive programme suggests that either a discovery of cLFV could take place in coming years, or that different bounds will become much stronger, significantly constraining possible New Physics scenarios.

In parallel, a flavour program could be pursued at FCCee running at the Z peak. In addition to cLFV decays, extensions of the SM can also predict sizable enhancements of the mode $B_c \to \tau\nu$ for example, which could be investigated at FCCee running at the Z peak (see: subsection 3.5.1).

From a theoretical point of view, numerous well motivated BSM constructions have been under intense scrutiny in flavour experiments in recent years. Some emerge as natural candidates to explain neutrino oscillation data and naturally open the door to extensive contributions to cLFV observables (purely leptonic and in semileptonic τ-lepton and meson decays). Others offer interesting solutions to the above-mentioned anomalies. Examples of such constructions include extended Higgs sectors (e.g., several realizations of 2HDM, type II seesaw, ...) [86,87], leptoquark models (vector and scalar) [88], SM extensions via heavy vector-like fermions, extended gauge sectors (e.g., additional Z' bosons) [89] or additional symmetries (flavour symmetries, or gauge ones, such as left-right symmetric models), and finally larger frameworks as general Supersymmetry, extra dimensional models and Grand Unified Theories.

Clearly, and in all cases, the path to identifying the BSM physics at work requires a strategy to disentangle among and disfavour some models. This will call upon a synergetic study of the different observables: these include purely leptonic processes, such as radiative $\ell_i \to \ell_j\gamma$, 3-body $\ell_i \to 3\ell_j$, etc., or processes involving hadron as is the case of semileptonic tau decays (such as $\tau \to \ell_i$+light hadrons), leptonic and semileptonic B-, D- and K-meson decays, and finally Higgs and Z flavour violating decays. The expected contributions arising in certain classes of models (or alternatively cast in terms of an EFT) must be confronted with the available data. This might then allow to readily exclude some of these well motivated scenarios, and possibly to discriminate among distinct realizations of flavour violating models.

The exploration of these observables, in particular the key interplay between flavour violation in the hadronic and leptonic sectors – as foreseen in this GDR, might offer additional insights into the lepton and quark flavour puzzle.

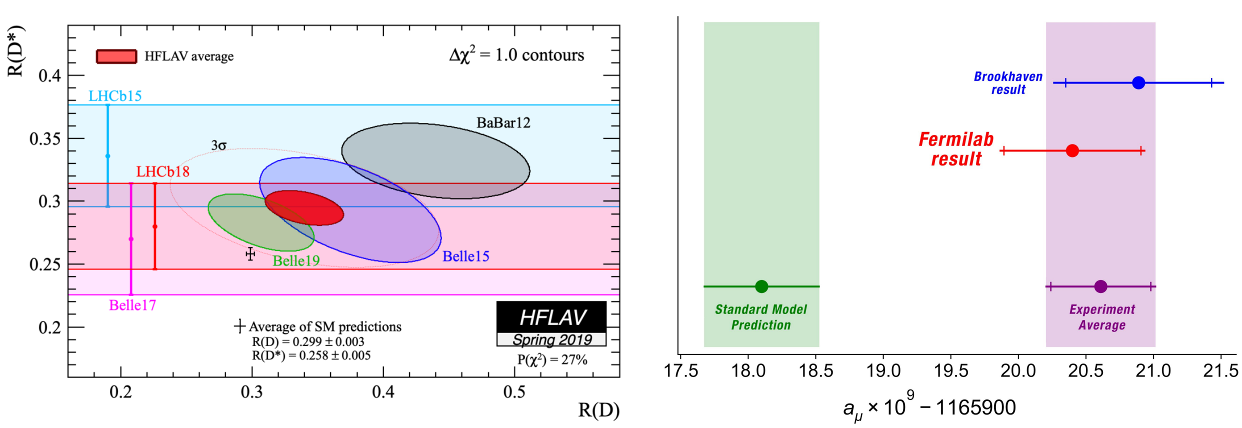

Figure 4: Left plot: measurements of the lepton universality observable R_D and R_{D^*} from LHCb and the B-factories [15]. Right plot: The anomalous magnetic moment of the muon [77].

3.3.1 Plans for the GDR

- The recent developments and results in flavour physics, particularly the b-anomalies, have made it crucial to carry out a dedicated analysis to fully understand the interplay of flavour in both quark and lepton sectors. The GDR-InF offers a unique opportunity to bring together theorists and experimentalists working in these fields, with the competences and interests to fully explore this interplay. It will promote dedicated workshops, joint studies and collaborations, hopefully contribute to the effort of understanding the underlying theory of flavour, and ultimately shed some light on the underlying BSM physics.

- Interpreting the recent results on $(g-2)_\mu$ will be a priority. The status of the SM predictions will be reviewed, as well as the possibilities to disentangle BSM contributions from hadronic uncertainties.

- The cLFV direct searches will soon provide new results, both in LHCb and Belle II, as well as in dedicated experiments (COMET, MEG, Mu2e, Mu3e). It will be crucial to work on a package that could include all the possible constraints relevant to cLFV at low and high energy and see what are the lessons one can learn about the Yukawa sector from the data.

3.4 Heavy flavour production and spectroscopy

Quantum Chromodynamics (QCD), together with the quark model out of which it grew, is one of the fundamental building blocks of the SM. Although already extensively studied over decades, the understanding of QCD production mechanisms and the properties of bound states are still very much active subjects of research. For instance, the properties of the pentaquark state ($qqqq\bar{q}$), observed by LHCb [90], are still largely unknown. Another example is provided by the exotic $\chi_c(3872)$: discussions are ongoing about its nature, as it could be a compact tetraquark or a molecule. The $\chi_c(3872)$ production in proton-proton collisions has been measured by LHCb as function of the charged particle multiplicity [91]. As shown in Fig. 5, predictions made with the co-movers approach [92] seems to favour a tetraquark bound-state over the molecule scenario, but other models and new studies are needed to confirm this statement.

More broadly, results from QCD and strong physics are frequently needed as inputs to other measurements or to their interpretation. For example, there is considerable interest in the decays $\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$: the ratio of branching fractions (in a restricted region of phase space) for $\ell = \mu$ and $\ell = \tau$ can be used to test lepton universality. The current world average, combining results from LHCb, BaBar and Belle, is in tension at the 3σ

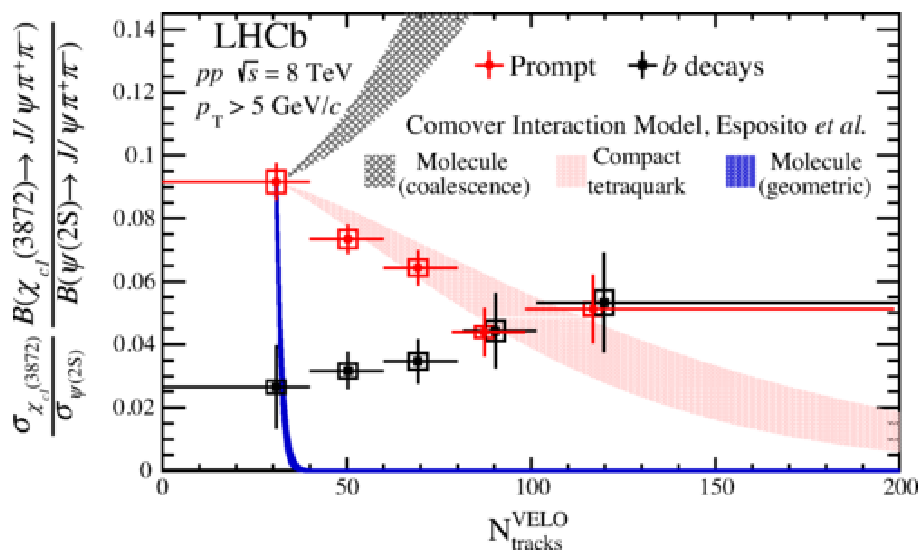

Figure 5: Ratios of the $\chi_c(3872)$ over $\psi(2S)$ in the $J/\psi + \pi^+ + \pi^-$ decay channel as a function of the number of tracks reconstructed in the VELO. The theory predictions based on the co-movers model favour the $\chi_c(3872)$ to be a tetraquark.

level with SM expectations [93]. One of the important systematic uncertainties in this measurement is associated with the spectrum and properties of excited charm resonances D^{**}, which could contaminate the final state with feed-down from $\overline{B} \to D^{**}\ell^-\overline{\nu}_\ell$: here, input from spectroscopy is needed for the measurement itself.

In addition to spectroscopic studies of new exotic states, the production of prompt heavy-flavour (HF) are also far from a complete understanding. For instance, HF's hadronisation mechanisms such as coalescence [94] and fragmentation [95] are still studied. Experimentally, fragmentation fractions have been measured by LHCb in proton-proton collisions with open-charm [96] and open-beauty [97, 98] mesons ratio with great precision. Baryon-to-meson ratios have been measured on the charm (Λ_c/D^0 ratio [99]) and beauty (Λ_B^0/B^0 ratio [100]) sector by LHCb in pPb collisions. The flat dependence of the Λ_c/D^0 ratio with transverse momentum measured by LHCb at forward rapidity is not confirmed by the same measurement made by the ALICE collaboration [101] where a strong p_T dependence of the ratio is observed. This tension between the two experiments raises questions on the rapidity dependence of hadronisation models, which at the moment is not considered.

Finally, a topic supported by the HEP community in France is the production dynamic of quarkonia. Quarkonia states such as the J/ψ have long been privileged probes to study nuclear medium properties, either for confined (i.e coherent energy loss [102], nuclear parton distribution functions (nPDFS) effects [103], co-moving medium [104]) or for the Quark-Gluon Plasma [105]. However, one needs a good grasp of the production mechanisms of such probe, usually studied in proton-proton collision, which is far from true. An example is the J/ψ state, for which the production of the $c\bar{c}$ as colour-singlet or as colour-octet is still under debate [106]. Investigations of other charmonium states such as η_c, χ_C^J would shed light on this long standing problem. The prompt production of the exotic $\chi_c(3872)$ has finally been observed, which may also bring a new insight into the production dynamics of the HF.

3.4.1 Plans for the GDR

- The GDR-InF will follow theoretical and experimental evolution on the heavy-flavour and exotic state production dynamic among the French community. In this subject there is considerable overlap with the GDR-QCD, and we will work in close collaboration with them.
- A particular accent will be put on the study of the polarisation of heavy-flavour states and on the opportunity that they provide.
- Production mechanisms of heavy mesons and baryons are studied both in proton-proton and ions collisions, providing complementary information. The GDR-InF will promote exchanges among the experimental and theoretical communities working in these different environments to favour the emergence of synergies.

3.5 Future of the intensity frontier

The 2020 European Strategy for particle Physics, to which the GDR-InF has contributed with a document provided as input, has stated again the importance of the intensity frontier for the upcoming years. In fact, it recommended a so-called Higgs factory as the highest priority to follow the LHC, while pursuing a technical and financial feasibility study for a next-generation hadron collider in parallel. It also put the accent on the exploitation of the current facilities, in particular the HL-LHC. In fact, the LHC is moving into its intensity phase within the lifetime of this GDR. This will increase the focus of the community on the intensity frontier, particularly since there is no immediate prospect for a new collider at the energy frontier. Moreover, there is a large variety of collider/beam dump experiments in preparation or construction, as well as experiments to search for weakly interacting new light particles, which can often be built on a tabletop. While there is substantial French involvement in all aspects of the theory relevant for these experiments, the experimental involvement is mainly concentrated on large collaboration efforts: we aim to support these groups and also to stimulate the involvement in new small experiments.

More recently, the intensity frontier was brought to public attention by the announcement of the measurement of the muon anomalous magnetic moment at Fermilab. The status of this measurement and whether it truly represents a discrepancy from the Standard Model is set to become one of the major topics of interest in the field for some time to come.

In the following we shall discuss the future of flavour physics experiments which can indirectly probe high energy scales through precision measurements; and experiments searching directly for new phenomena.

3.5.1 Future experimental programs at colliders

At the horizon of 2025, the two main players concerning CP violation, rare decays of heavy flavours and lepton flavour violating processes are the upgraded LHCb experiment at CERN and the Belle II experiment at KEK. Their synergy and complementarity have been assessed in the past and we should ensure to follow the results of both collaborations closely within the GDR-InF. The physics case for a second upgrade of LHCb, to run at the HL-LHC, was reviewed favorably by the LHCC in 2018 and a framework technical design report (FTDR) is being prepared this year with significant involvement from French institutes, including some additional laboratories with respect to the previous LHCb collaboration. For Belle II, where also the French involvement has increased with a new group created at CPPM, a possible upgrade is also under discussion, and we can profit from the connections of some members of the GDR-InF with the KEK colleagues in the framework of the TYL/FJPPL (Franco-Japan Particle Physics Laboratory).

A possible long-term collider strategy after the exploitation of the HL-HLC would be a tunnel of about 100 km circumference, which takes advantage of the present CERN accelerator complex. This Future Circular Collider (FCC) concept proposes, as a first step, an e^+e^- collider aimed at studying comprehensively the electroweak scale with centre-of-mass energies ranging from the Z pole up to beyond the $t\bar{t}$ production threshold. A 100 TeV proton-proton collider is considered to be the ultimate goal of the project. FCC study groups delivered a conceptual design report in 2018 with significant involvement of French groups. The unprecedented statistics at the Z pole, with $\mathcal{O}(10^{12-13})$ Z decays potentially delivered by the e^+e^- collider, can be studied in particular to explore further the flavour physics case at large. In that framework, several French teams consisting of both experimentalists and phenomenologists are contributing to the design study in flavour physics. The main focus is on rare electroweak penguins which, if dominated by SM contributions, are likely unique to the FCC: $B^0 \to K^*(892)\tau^+\tau^-$ and $B_s \to \tau^+\tau^-$. The large statistics at the Z pole can be used as well to scrutinize in particular Lepton Flavour Violating (LFV) Z decays, which would serve as an indisputable evidence for BSM physics, if seen. Heavy right-handed neutrals, natural candidates to explain LFV phenomena, can be as well searched for directly at FCC-ee.

3.5.2 Future experiments at accelerators

A number of low energy experiments are planned or already under construction at high intensity beam lines (*e.g.* at PSI, JPARC, Fermilab, SPS and FCC injectors), and there are proposals for a Gamma Factory at CERN with a wide physics potential in relation to the intensity frontier [107, 108]. These experiments are relatively cheap and several use existing accelerators with a new detector. Some of the most relevant for this proposal are listed here, the expected timeline is shown in Figure 6:

- g-2 at Fermilab measures the muon $g-2$ and has published first results in 2021, confirming the long-standing discrepancy. E34 at J-PARC will measure the muon $g-2$ using a different technique to that used by the Fermilab experiment. In combination these two should settle the experimental status of this intriguing anomaly.

- At the new MESA accelerator in Mainz 155 MeV electrons will be collided with unpolarized protons or ^{12}C nuclei. This enables high precision measurements of the weak mixing angle (P2) and the proton's form factor (MAGIX). In addition, dark matter is searched for in a beam dump experiment.

- Three experiments are conceived to detect long lived particles produced in LHC collisions: FASER, which is being installed 480m downstream from the ATLAS detector; CODEX-b, a proposal for a detector near the LHCb interaction point; MATHUSLA, an enormous surface detector ($200 \times 200 \times 20$ m) planned to be placed 100 metres above either ATLAS or CMS.

- The SHiP beam dump experiment at CERN planning to use the SPS proton beam and foreseeing a large detector significantly displaced from the interaction point, will be particularly sensitive to particles in the MeV-GeV range, such as heavy neutral leptons (neutrino portal), dark photons (vector portal), light scalars (scalar portal) and pseudoscalars (ALP), as well as possible supersymmetric partners (neutralinos, sgoldstinos, axinos, saxions). The SHiP beamline would be a perfect arena for experiments to detect the interactions of these particles with matter, i.e. for an accelerator based direct dark matter search. There is substantial input from French theorists and experimentalists.

- Mu2e at Fermilab and COMET at J-PARC are being constructed to search for $\mu \to e$ conversion in the vicinity of nuclei.
- At PSI, Mu3e is currently being constructed and will search for the LFV decay $\mu \to eee$, while MEG-II improves the reach for the LFV decay $\mu \to e\gamma$.
- Also at PSI, the n2EDM experiment is being installed at the ultracold neutron source [109]. It is designed to improve the sensitivity on the measurement of the neutron EDM by one order of magnitude compared to the present best measurement.

3.5.3 Weakly interacting new light particles searches

Weakly interacting new light particles, commonly called WISPs, have as two canonical candidates hidden photons and axion-like particles. Experiments to search for these are in many cases very cheap, and can often recycle older experiments.

The best motivated WISP is the QCD axion itself, which is the most widely-accepted solution to the strong CP problem but is associated with new physics above 10^9 GeV. Its mass may lie anywhere in the sub-eV range, and it is a very well-motivated and natural dark matter candidate. Axion-like particles (ALPs) are (pseudo)-scalars, perhaps cousins of the QCD axion but which do not obtain their masses from QCD. They are characterised by their coupling to photons ($g_{a\gamma}$), electrons (g_{ae}) and nuclei (g_{aN}).

ALPs are highly motivated from top-down constructions as generically arising when symmetries are broken at high scales, and also make attractive dark matter candidates. On the other hand, and perhaps most importantly, there have been several studies indicating possible discoveries of such particles in various astronomical observations. Recently, with very different parameters, ALPs were proposed to explain the excess of low-energy electron events at the XENON1T experiment. They have also been proposed as solutions to the anomalies in ^{8}Be decays [110]. In addition, the relationship between ALPs and flavour has just begun to be explored from a theoretical perspective, opening up the prospect of detection at K- and B-factory experiments. Similarly, due to their dijet or diphoton signature, they are interesting targets as prompt or long-lived particles at the LHC, which concerns very different parts of the parameter space. There is also a substantial overlap between axion searches and those for electric dipole moments (EDM), for which there is significant interest within the French community.

Hidden photons are new (possibly massive) gauge bosons X_μ which mix kinetically with the visible photon via a dimensionless kinetic-mixing term $\mathcal{L} \supset -\frac{\chi}{2} F_{\mu\nu} X^{\mu\nu}$. They are among the simplest and most natural extensions of the SM, usually as a portal to the dark sector; or may even constitute the dark matter themselves.

Intensity frontier experiments searching for WISPs either search for the particles as dark matter or attempt to directly produce them. In the dark matter case, the assumption that there is a large abundance of particles all around us greatly enhances the reach potential; on the other hand, for the very light ALPs this is unlikely to be the case. The dark matter searches consist of resonant cavities, helioscopes, and now many more exotic suggestions. Direct searches are broadly photon regeneration experiments (light shining through a wall), electron colliders or beam dumps. Flavour experiments like BaBar, Belle, KLOE, NA48 and NA64 have been searching for and putting limits on hidden photons, and the flavour experiments effort will continue in the future also within LHCb and Belle II. There is significant international interest in searches for WISPs, and an ever-growing list of proposals for new experiments. Upcoming dedicated experiments include:

- Axion haloscopes (magnetic resonant cavity experiments) ADMX, HAYSTAC, YMCE and WISPDMX will probe axion masses in the μeV range.
- GrAHal, a dedicated axion haloscope in development in Grenoble, taking advantage of the unrivaled intensity of the hybrid magnet under construction there. While some components are already built, it is still searching for funding to reach completion, but would produce the leading limits on axion dark matter and be a significant coup for physics in France.
- A new concept of dielectric axion haloscope, the MADMAX experiment, under preparation at DESY [111]. This will demonstrate the feasibility of the dielectric haloscope concept and produce competitive limits on ALPs in the 40-400 μeV region. MADMAX is part of the newly created International Research Lab (IRL) DMLab between the CNRS/IN2P3 and the Helmholtz association.

- CASPEr will probe the coupling of dark-matter axions to nucleons (g_{aN} and g_{ag}) by looking for variations in nucleon electric dipole moments; CASPEr-wind is an NMR experiment looking for the variation of electron spins caused by the coupling of g_{ae} between dark matter axions and electrons. First generation experiments have been performed, but many more phases are anticipated.
- The FUNK experiment in Karlsruhe uses a dish antenna to search for dark matter hidden photons, which are focussed much like visible light;
- The REAPR and ALPS-II photon regeneration experiments at Fermilab and DESY respectively will attempt to directly produce ALPs or hidden photons in the lab; they are "light shining through walls" experiments.
- The IAXO helioscope at CERN, using a magnetic field to search for ALPs produced in the sun, is expected to operate over the next decade and there are significant synergies with the French community. In addition, as a precursor BabyIAXO at DESY will detect or reject solar axions or ALPs with axion-photon couplings down to $g_{a\gamma} \sim 1.5 \times 10^{-11}\text{GeV}^{-1}$, and masses up to $m_a \sim 0.25$ eV.

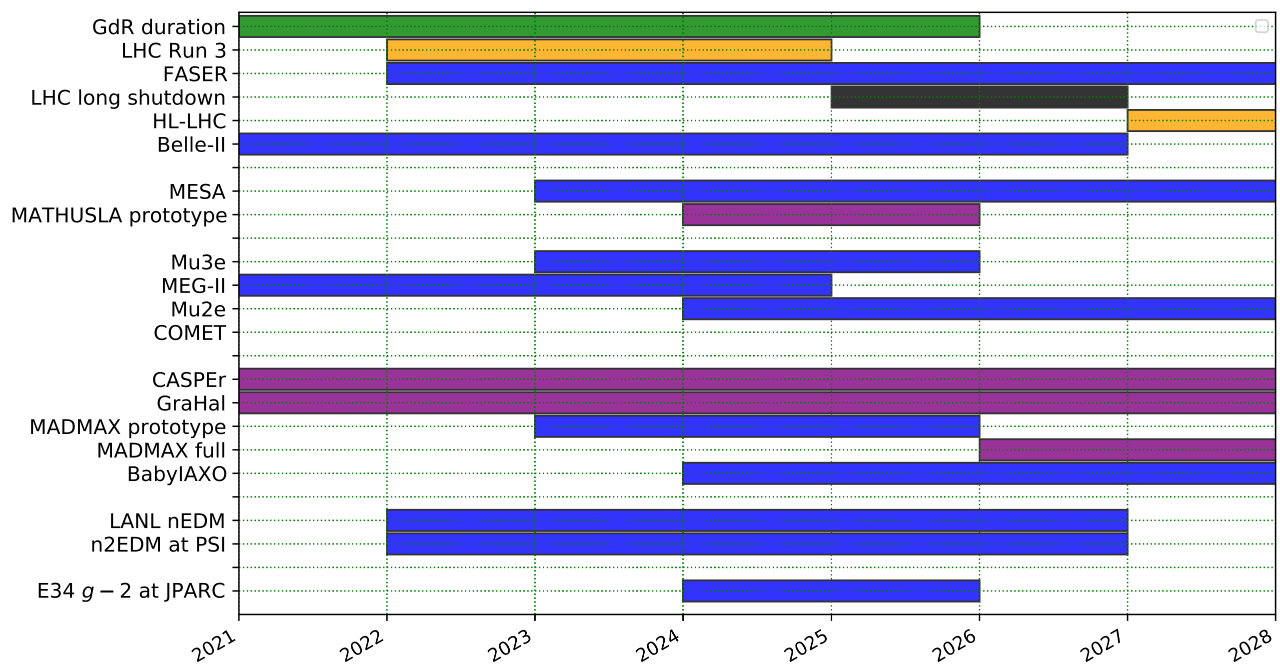

Figure 6: Timeline of the foreseen data taking periods for some of the experiments discussed in the proposal. The LHC running is shown in orange, confirmed or constructed experiments are shown in blue, planned experiments/those still seeking funding are shown in purple. Dates shown are according to current publicly available information; end dates may not be fixed. This timeline highlights the mixture of data taking and experiment preparation that will characterise the coming years, as well as the diversity of new types of experiment being planned or discussed, which is a major motivation of this GDR.

3.5.4 Plans for the GDR

- The GDR-InF will provide a forum for discussing among theorists and experimentalists the opportunities of the future flavour programs at colliders and the possible French involvement.
- The complementarity of the high intensity machines, at large scale apparatus or low-energy experiments, will be assessed. Although it will not be possible to participate actively in all the experiments discussed

above, their advancement and prospects will be followed, both from the theoretical and the experimental point of view. This will eventually allow to select those more interesting for their scientific potential and in which a larger involvement will be beneficial for the French community at the intensity frontier.

- There is significant international interest in searches for WISPs, and an ever-growing list of proposals for new experiments. One of the aims of the GdR-InF is to stimulate the French involvement in this burgeoning field, both from the experimental side and also from theory.
- Discussions will help to identify the emerging technologies and those already mastered at IN2P3 which could play an important role for future experiments, helping the French groups to propose key contributions.

4 Conclusion

Experiments at the intensity frontier are powerful tools to search for physics beyond the Standard Model. Historically, many new particles discovered in high-energy physics were first noticed via indirect evidence in high-intensity experiments, and only afterwards were confirmed by direct, targeted searches. Today, tantalizing hints of beyond-SM effects are emerging in experiments at the intensity frontier, and more data is soon to be available which will allow the experimental uncertainties to be further reduced. These results are subject to a detailed scrutiny by the theoretical community. It must be ensured that the uncertainties on theory predictions match the experimental accuracy of the planned experiments, that additional observables are proposed and that possible models alternative to the SM are investigated.

The French community at the intensity frontier has more than the critical size and the international reputation to be competitive in these searches and their interpretation. Since 2017, it has organized itself around a well-defined structure, the “GDR-Intensity Frontier", growing in cohesion and visibility, providing opportunities for fruitful exchanges among physicist at all stages of their carrier and at national and international level. The increase in the number of colleagues and laboratories joining this proposal demonstrate the growing interest of the French particle physics community in the GDR-Intensity Frontier activities.

We therefore consider it of utmost importance to sustain our collaborative efforts in searching for physics beyond the SM by renewing the GDR-Intensity Frontier for a second cycle of five years.

INTENSITY frontier GDR-InF

A Events organised by the GDR-InF 2017-2021

Annual Meetings

- GDR-InF Kickoff meeting: current trends in flavour physics, Paris, 29-31 March 2017
- GDR-InF Annual Workshop, Arles, 5-7 November 2018
- GDR-InF Annual Workshop, Sommières, 4-7 November 2019
- GDR-InF Annual Workshop, online, 28 September-16 October 2020
- GDR-InF Annual Workshop, TBD, Autumn 2021

GDR-InF Lectures: from theory to experiments and everything in between

- LF(U)V in B decays, by Martino Borsato and Diego Guadagnoli, Paris, 26-27 October 2017
- LF(U)V in B decays-II, by Lucia Grillo and Diego Guadagnoli, Paris, 13-14 February 2018
- V_{cb}, by Giulia Ricciardi and Marcello Rotondo, Paris, 2-3 July 2018
- γ and Dalitz plot analyses, by Anton Poluektov and Karim Trabelsi, Paris, 28-29 May 2019
- V_{ub}, by Aoife Bharucha and Patrick Owen, Paris, 30 September-1 October 2019
- Effective Field Theories Part I, 21 September-1 October 2020, online
- Effective Field Theories Part II, 31 May-11 June 2021, online

Topical Workshops

- Workshop on the Strong CP puzzle and Axions, LPSC (Grenoble), 14-16 May 2018
- Workshop on multibody charmless B-hadron decays, LPNHE (Paris), 6-7 June 2018
- Workshop on singly and doubly charmed baryons, LPNHE (Paris), 26-27 June 2018
- Workshop on obtaining the photon polarization via $B \to K\pi\pi\gamma$, IPHC Strasbourg, 10-11 April 2019
- Workshop on QED corrections to (semi-)leptonic B decays, Paris, 8-9 July 2019
- b-baryon fest, online, 5-6 November, 2020
- Polarisation measurements in ee ep, pp and heavy-ions collisions , IJCLab, 14-18 December 2020
- Virtual breakfast with g-2 , IJCLab, 19 May 2021

Brainstorming Workshops

- GDR-InF workshop: The future of the intensity frontier, CERN, 1-2 February 2017

Supported Workshops and Schools

- Rencontres de Physique des Particules, CPPM (Marseille), 24-26 April 2017
- Journée SHiP/Physique du secteur caché, LPNHE (Paris), 11 October 2017
- The 2nd LHCb open semitauonic workshop, LAL (Orsay), 13-15 November 2017
- École de Gif on Heavy Flavour physics, Clermont Ferrand, 10-14 September 2018
- 7th $b \to s\ell\ell$ workshop, Lyon, 4- 6 September 2019
- nEDM2021 Workshop , online, 14-19 February 2021

References

[1] CKMfitter Group collaboration, J. Charles, A. Hocker, H. Lacker, S. Laplace, F. R. Le Diberder, J. Malcles et al., *CP violation and the CKM matrix: Assessing the impact of the asymmetric B factories*, *Eur. Phys. J.* **C41** (2005) 1–131, [hep-ph/0406184].

[2] J. Charles, S. Descotes-Genon, Z. Ligeti, S. Monteil, M. Papucci, K. Trabelsi et al., *New physics in B meson mixing: future sensitivity and limitations*, *Phys. Rev. D* **102** (2020) 056023, [2006.04824].

[3] S. Descotes-Genon, A. Falkowski, M. Fedele, M. González-Alonso and J. Virto, *The CKM parameters in the SMEFT*, *JHEP* **05** (2019) 172, [1812.08163].

[4] LHCb collaboration, R. Aaij et al., *Updated measurement of time-dependent \it CP-violating observables in* $B^0_s \to J/\psi K^+K^-$ *decays*, *Eur. Phys. J. C* **79** (2019) 706, [1906.08356].

[5] N. Cabibbo, *Unitary Symmetry and Leptonic Decays*, *Phys. Rev. Lett.* **10** (1963) 531–533.

[6] M. Kobayashi and T. Maskawa, *CP Violation in the Renormalizable Theory of Weak Interaction*, *Prog. Theor. Phys.* **49** (1973) 652–657.

[7] G. Buchalla, G. Hiller, Y. Nir and G. Raz, *The Pattern of CP asymmetries in B —> s transitions*, *JHEP* **09** (2005) 074, [hep-ph/0503151].

[8] Y. Grossman and M. P. Worah, *CP asymmetries in B decays with new physics in decay amplitudes*, *Phys. Lett.* **B395** (1997) 241–249, [hep-ph/9612269].

[9] D. London and A. Soni, *Measuring the CP angle Beta in hadronic b —> s penguin decays*, *Phys. Lett.* **B407** (1997) 61–65, [hep-ph/9704277].

[10] M. Ciuchini, E. Franco, G. Martinelli, A. Masiero and L. Silvestrini, *CP violating B decays in the standard model and supersymmetry*, *Phys. Rev. Lett.* **79** (1997) 978–981, [hep-ph/9704274].

[11] Belle collaboration, J. Dalseno et al., *Time-dependent Dalitz Plot Measurement of CP Parameters in B0 —> K0(s) pi+ pi- Decays*, *Phys. Rev.* **D79** (2009) 072004, [0811.3665].

[12] BaBar collaboration, B. Aubert et al., *Time-dependent amplitude analysis of* $B^0 \to K^0_S\pi^+\pi^-$, *Phys. Rev.* **D80** (2009) 112001, [0905.3615].

[13] Belle collaboration, Y. Nakahama et al., *Measurement of CP violating asymmetries in* $B^0 - > K^+K^-K^0_S$ *decays with a time-dependent Dalitz approach*, *Phys. Rev.* **D82** (2010) 073011, [1007.3848].

[14] BaBar collaboration, J. P. Lees et al., *Study of CP violation in Dalitz-plot analyses of* $B^0 \to K^+K^-K^0_S$, $B^+ \to K^+K^-K^+$, *and* $B^+ \to K^0_S K^0_S K^+$, *Phys. Rev.* **D85** (2012) 112010, [1201.5897].

[15] HFLAV collaboration, Y. S. Amhis et al., *Averages of b-hadron, c-hadron, and τ-lepton properties as of 2018*, *Eur. Phys. J. C* **81** (2021) 226, [1909.12524].

[16] L. Silvestrini, *Searching for new physics in* $b \to s$ *hadronic penguin decays*, *Ann. Rev. Nucl. Part. Sci.* **57** (2007) 405–440, [0705.1624].

[17] M. Ciuchini, M. Pierini and L. Silvestrini, *New bounds on the CKM matrix from* $B \to K\pi\pi$ *Dalitz plot analyses*, *Phys. Rev.* **D74** (2006) 051301, [hep-ph/0601233].

[18] M. Gronau, D. Pirjol, A. Soni and J. Zupan, *Improved method for CKM constraints in charmless three-body B and B(s) decays*, *Phys. Rev.* **D75** (2007) 014002, [hep-ph/0608243].

[19] B. Bhattacharya, M. Imbeault and D. London, *Extraction of the CP-violating phase* γ *using* $B \to K\pi\pi$ *and* $B \to KK\bar{K}$ *decays*, *Phys. Lett.* **B728** (2014) 206–209, [1303.0846].

[20] C. Abel, S. Afach, N. J. Ayres, C. A. Baker, G. Ban, G. Bison et al., *Measurement of the permanent electric dipole moment of the neutron*, *Phys. Rev. Lett.* **124** (Feb, 2020) 081803.

[21] B. Capdevila, S. Descotes-Genon, J. Matias and J. Virto, *Assessing lepton-flavour non-universality from* $B \to K^*\ell\ell$ *angular analyses*, *JHEP* **10** (2016) 075, [1605.03156].

[22] S. Descotes-Genon, M. Novoa-Brunet and K. K. Vos, *The time-dependent angular analysis of* $B_d \to K_S\ell\ell$*, a new benchmark for new physics*, *JHEP* **02** (2021) 129, [2008.08000].

[23] Y. Amhis, S. Descotes-Genon, C. Marin Benito, M. Novoa-Brunet and M.-H. Schune, *Prospects for New Physics searches with* $\Lambda_b \to \Lambda(1520)\ell^+\ell^-$ *decays*, 2005.09602.

[24] M. Algueró, B. Capdevila, S. Descotes-Genon, P. Masjuan and J. Matias, *What* R_K *and* Q_5 *can tell us about New Physics in* $b \to s\ell\ell$ *transitions?*, *JHEP* **07** (2019) 096, [1902.04900].

[25] S. Descotes-Genon and M. Novoa-Brunet, *Angular analysis of the rare decay* $\Lambda_b \to \Lambda(1520)(\to NK)\ell^+\ell^-$, *JHEP* **06** (2019) 136, [1903.00448].

[26] S. Descotes-Genon, M. Novoa-Brunet, S. Fajfer and J. F. Kamenik, *Testing Lepton Flavour Universality in* $\Upsilon(4S)$ *Decays*, 2104.06842.

[27] M. Algueró, S. Descotes-Genon, J. Matias and M. Novoa-Brunet, *Symmetries in* $B \to D^*\ell\nu$ *angular observables*, *JHEP* **06** (2020) 156, [2003.02533].

[28] M. Algueró, A. Crivellin, S. Descotes-Genon, J. Matias and M. Novoa-Brunet, *A new B-flavour anomaly in* $B_{d,s} \to K^{*0}\bar{K}^{*0}$*: anatomy and interpretation*, *JHEP* **04** (2021) 066, [2011.07867].

[29] T. Hurth, F. Mahmoudi and S. Neshatpour, *Global fits to $b \to s\ell\ell$ data and signs for lepton non-universality*, *JHEP* **12** (2014) 053, [1410.4545].

[30] S. Descotes-Genon, L. Hofer, J. Matias and J. Virto, *Global analysis of $b \to s\ell\ell$ anomalies*, *JHEP* **06** (2016) 092, [1510.04239].

[31] T. Hurth, F. Mahmoudi and S. Neshatpour, *On the anomalies in the latest LHCb data*, *Nucl. Phys. B* **909** (2016) 737–777, [1603.00865].

[32] B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias and J. Virto, *Patterns of New Physics in $b \to s\ell^+\ell^-$ transitions in the light of recent data*, *JHEP* **01** (2018) 093, [1704.05340].

[33] T. Hurth, C. Langenbruch and F. Mahmoudi, *Direct determination of Wilson coefficients using $B^0 \to K^{*0}\mu^+\mu^-$ decays*, *JHEP* **11** (2017) 176, [1708.04474].

[34] M. Algueró, B. Capdevila, S. Descotes-Genon, P. Masjuan and J. Matias, *Are we overlooking lepton flavour universal new physics in $b \to s\ell\ell$?*, *Phys. Rev. D* **99** (2019) 075017, [1809.08447].

[35] A. Arbey, T. Hurth, F. Mahmoudi, D. M. Santos and S. Neshatpour, *Update on the $b{\to}s$ anomalies*, *Phys. Rev. D* **100** (2019) 015045, [1904.08399].

[36] M. Algueró, B. Capdevila, A. Crivellin, S. Descotes-Genon, P. Masjuan, J. Matias et al., *Emerging patterns of New Physics with and without Lepton Flavour Universal contributions*, *Eur. Phys. J. C* **79** (2019) 714, [1903.09578].

[37] T. Hurth, F. Mahmoudi and S. Neshatpour, *Model independent analysis of the angular observables in $B^0 \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^{*+}\mu^+\mu^-$*, 2012.12207.

[38] V. G. Chobanova, T. Hurth, F. Mahmoudi, D. Martinez Santos and S. Neshatpour, *Large hadronic power corrections or new physics in the rare decay $B \to K\mu^+\mu$?*, *JHEP* **07** (2017) 025, [1702.02234].

[39] A. Arbey, T. Hurth, F. Mahmoudi and S. Neshatpour, *Hadronic and New Physics Contributions to $b \to s$ Transitions*, *Phys. Rev. D* **98** (2018) 095027, [1806.02791].

[40] T. Hurth, F. Mahmoudi and S. Neshatpour, *Implications of the new LHCb angular analysis of $B \to K^*\mu^+\mu^-$: Hadronic effects or new physics?*, *Phys. Rev. D* **102** (2020) 055001, [2006.04213].

[41] T. Hurth, F. Mahmoudi, D. Martinez Santos and S. Neshatpour, *Lepton nonuniversality in exclusive $b{\to}s\ell\ell$ decays*, *Phys. Rev. D* **96** (2017) 095034, [1705.06274].

[42] T. Hurth, F. Mahmoudi, D. M. Santos and S. Neshatpour, *More Indications for Lepton Nonuniversality in $b \to s\ell^+\ell^-$*, 2104.10058.

[43] B. Capdevila, A. Crivellin, S. Descotes-Genon, L. Hofer and J. Matias, *Searching for New Physics with $b \to s\tau^+\tau^-$ processes*, *Phys. Rev. Lett.* **120** (2018) 181802, [1712.01919].

[44] S. Bifani, S. Descotes-Genon, A. Romero Vidal and M.-H. Schune, *Review of Lepton Universality tests in B decays*, *J. Phys. G* **46** (2019) 023001, [1809.06229].

[45] LHCb collaboration, R. Aaij et al., *Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays*, *Phys. Rev. Lett.* **113** (2014) 151601, [1406.6482].

[46] LHCb collaboration, R. Aaij et al., *Test of lepton universality in beauty-quark decays*, 2103.11769.

[47] LHCb collaboration, R. Aaij et al., *Test of lepton universality with $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decays*, *JHEP* **05** (2020) 040, [1912.08139].

[48] A. Angelescu, D. Bečirević, D. A. Faroughy and O. Sumensari, *Closing the window on single leptoquark solutions to the B-physics anomalies*, *JHEP* **10** (2018) 183, [1808.08179].

[49] J. Aebischer, W. Altmannshofer, D. Guadagnoli, M. Reboud, P. Stangl and D. M. Straub, *B-decay discrepancies after Moriond 2019*, *Eur. Phys. J. C* **80** (2020) 252, [1903.10434].

[50] W. Altmannshofer and P. Stangl, *New Physics in Rare B Decays after Moriond 2021*, 2103.13370.

[51] C. Cornella, D. A. Faroughy, J. Fuentes-Martín, G. Isidori and M. Neubert, *Reading the footprints of the B-meson flavor anomalies*, 2103.16558.

[52] A. Angelescu, D. Bečirević, D. A. Faroughy, F. Jaffredo and O. Sumensari, *On the single leptoquark solutions to the B-physics anomalies*, 2103.12504.

[53] S. L. Glashow, D. Guadagnoli and K. Lane, *Lepton Flavor Violation in B Decays?*, *Phys. Rev. Lett.* **114** (2015) 091801, [1411.0565].

[54] LHCb collaboration, R. Aaij et al., *Search for the lepton-flavour-violating decays $B_s^0 \to \tau^\pm\mu^\mp$ and $B^0 \to \tau^\pm\mu^\mp$*, *Phys. Rev. Lett.* **123** (2019) 211801, [1905.06614].

[55] LHCb collaboration, R. Aaij et al., *Search for the lepton flavour violating decay $B^+ \to K^+\mu^-\tau^+$ using B_{s2}^{*0} decays*, *JHEP* **06** (2020) 129, [2003.04352].

[56] LHCb collaboration, R. Aaij et al., *Search for the lepton-flavour violating decays $B^0_{(s)} \to e^\pm\mu^\mp$*, *JHEP* **03** (2018) 078, [1710.04111].

[57] LHCb collaboration, R. Aaij et al., *Search for Lepton-Flavor Violating Decays $B^+ \to K^+\mu^\pm e^\mp$*, *Phys. Rev. Lett.* **123** (2019) 241802, [1909.01010].

[58] LHCb collaboration, R. Aaij et al., *Angular analysis and differential branching fraction of the decay $B_s^0 \to \phi\mu^+\mu^-$*, *JHEP* **09** (2015) 179, [1506.08777].

[59] LHCb collaboration, R. Aaij et al., *Measurements of the S-wave fraction in $B^0 \to K^+\pi^-\mu^+\mu^-$ decays and the $B^0 \to K^*(892)^0\mu^+\mu^-$ differential branching fraction*, *JHEP* **11** (2016) 047, [1606.04731].

[60] LHCb collaboration, R. Aaij et al., *Measurement of the differential branching fraction of the decay $\Lambda_b^0 \to \Lambda\mu^+\mu^-$*, *Phys. Lett. B* **725** (2013) 25–35, [1306.2577].

[61] LHCb collaboration, R. Aaij et al., *Measurement of CP-Averaged Observables in the $B^0 \to K^{*0}\mu^+\mu^-$ Decay*, *Phys. Rev. Lett.* **125** (2020) 011802, [2003.04831].

[62] Belle collaboration, A. Abdesselam et al., *Angular analysis of $B^0 \to K^*(892)^0\ell^+\ell^-$*, 2016. 1604.04042.

[63] N. Gubernari, A. Kokulu and D. van Dyk, *$B \to P$ and $B \to V$ Form Factors from B-Meson Light-Cone Sum Rules beyond Leading Twist*, *JHEP* **01** (2019) 150, [1811.00983].

[64] LHCb collaboration, T. L. Collaboration, *Combination of the ATLAS, CMS and LHCb results on the $B^0_{(s)} \to \mu^+\mu^-$ decays*, .

[65] F. Dettori, D. Guadagnoli and M. Reboud, *$B_s^0 \to \mu^+\mu^-\gamma$ from $B_s^0 \to \mu^+\mu^-$*, *Phys. Lett.* **B768** (2017) 163–167, [1610.00629].

[66] LHCb collaboration, R. Aaij et al., *Strong constraints on the $b \to s\gamma$ photon polarisation from $B^0 \to K^{*0}e^+e^-$ decays*, *JHEP* **12** (2020) 081, [2010.06011].

[67] S. Akar, E. Ben-Haim, J. Hebinger, E. Kou and F.-S. Yu, *The time-dependent CP asymmetry in $B^0 \to K_{\rm res}\gamma \to \pi^+\pi^-K_S^0\gamma$ decays*, *JHEP* **09** (2019) 034, [1802.09433].

[68] LHCb collaboration, R. Aaij et al., *Search for the Rare Decays $B_s^0 \to e^+e^-$ and $B^0 \to e^+e^-$*, *Phys. Rev. Lett.* **124** (2020) 211802, [2003.03999].

[69] BaBar collaboration, J. P. Lees et al., *Search for $B^+ \to K^+\tau^+\tau^-$ at the BaBar experiment*, *Phys. Rev. Lett.* **118** (2017) 031802, [1605.09637].

[70] LHCb collaboration, R. Aaij et al., *Search for the decays $B_s^0 \to \tau^+\tau^-$ and $B^0 \to \tau^+\tau^-$*, *Phys. Rev. Lett.* **118** (2017) 251802, [1703.02508].

[71] S. Descotes-Genon, S. Fajfer, J. F. Kamenik and M. Novoa-Brunet, *Implications of $b \to s\mu\mu$ anomalies for future measurements of $B \to K^{(*)}\nu\bar{\nu}$ and $K \to \pi\nu\bar{\nu}$*, *Phys. Lett. B* **809** (2020) 135769, [2005.03734].

[72] Belle collaboration collaboration, J. Grygier et al., *Search for $B \to h\nu\bar{\nu}$ decays with semileptonic tagging at Belle*, *Phys. Rev.* **D96** (2017) 091101, [1702.03224].

[73] A. Bharucha, D. Boito and C. Méaux, *Disentangling QCD and new physics in $D^+ \to \pi^+\ell^+\ell^-$*, *JHEP* **04** (2021) 158, [2011.12856].

[74] M. Algueró, B. Capdevila, S. Descotes-Genon, J. Matias and M. Novoa-Brunet, ***$b \to s\ell\ell$** global fits after Moriond 2021 results*, in *55th Rencontres de Moriond on Electroweak Interactions and Unified Theories*, 4, 2021. 2104.08921.

[75] LHCb collaboration, R. Aaij et al., *Test of lepton universality with $B^0 \to K^{*0}\ell^+\ell^-$ decays*, *JHEP* **08** (2017) 055, [1705.05802].

[76] P. Gambino et al., *Challenges in semileptonic B decays*, *Eur. Phys. J. C* **80** (2020) 966, [2006.07287].

[77] Muon g-2 collaboration, B. Abi et al., *Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm*, *Phys. Rev. Lett.* **126** (2021) 141801, [2104.03281].

[78] Muon g-2 collaboration, G. W. Bennett et al., *Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL*, *Phys. Rev. D* **73** (2006) 072003, [hep-ex/0602035].

[79] T. Aoyama et al., *The anomalous magnetic moment of the muon in the Standard Model*, *Phys. Rept.* **887** (2020) 1–166, [2006.04822].

[80] F. Feruglio, P. Paradisi and O. Sumensari, *Implications of scalar and tensor explanations of $R_{D^{(*)}}$*, *JHEP* **11** (2018) 191, [1806.10155].

[81] J. Aebischer, W. Dekens, E. E. Jenkins, A. V. Manohar, D. Sengupta and P. Stoffer, *Effective field theory interpretation of lepton magnetic and electric dipole moments*, 2102.08954.

[82] S. Borsanyi et al., *Leading hadronic contribution to the muon 2 magnetic moment from lattice QCD*, 2002.12347.

[83] D. Bečirević, N. Košnik, O. Sumensari and R. Zukanovich Funchal, *Palatable Leptoquark Scenarios for Lepton Flavor Violation in Exclusive $b \to s\ell_1\ell_2$ modes*, *JHEP* **11** (2016) 035, [1608.07583].

[84] D. Bečirević, O. Sumensari and R. Zukanovich Funchal, *Lepton flavor violation in exclusive $b \to s$ decays*, *Eur. Phys. J. C* **76** (2016) 134, [1602.00881].

[85] C. Hati, G. Kumar, J. Orloff and A. M. Teixeira, *Reconciling B-meson decay anomalies with neutrino masses, dark matter and constraints from flavour violation*, *JHEP* **11** (2018) 011, [1806.10146].

[86] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher and J. P. Silva, *Theory and phenomenology of two-Higgs-doublet models*, *Phys. Rept.* **516** (2012) 1–102, [1106.0034].

[87] A. Crivellin, A. Kokulu and C. Greub, *Flavor-phenomenology of two-Higgs-doublet models with generic Yukawa structure*, *Phys. Rev. D* **87** (2013) 094031, [1303.5877].

[88] I. Doršner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Košnik, *Physics of leptoquarks in precision experiments and at particle colliders*, *Phys. Rept.* **641** (2016) 1–68, [1603.04993].

[89] P. Langacker, *The Physics of Heavy Z' Gauge Bosons*, *Rev. Mod. Phys.* **81** (2009) 1199–1228, [0801.1345].

[90] LHCb collaboration, R. Aaij et al., *Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays*, *Phys. Rev. Lett.* **115** (2015) 072001, [1507.03414].

[91] LHCb Collaboration collaboration, R. e. a. Aaij, *Observation of multiplicity dependent prompt $\chi_{c1}(3872)$ and $\psi(2s)$ production in pp collisions*, *Phys. Rev. Lett.* **126** (Mar, 2021) 092001.

[92] E. G. Ferreiro, *Charmonium dissociation and recombination at LHC: Revisiting comovers*, *Phys. Lett. B* **731** (2014) 57–63, [1210.3209].

[93] Heavy Flavor Averaging Group (HFAG) collaboration, Y. Amhis et al., *Averages of b-hadron, c-hadron, and τ-lepton properties as of summer 2014*, 1412.7515.

[94] S. e. a. Plumari, *Charmed Hadrons from Coalescence plus Fragmentation in relativistic nucleus-nucleus collisions at RHIC and LHC*, *Eur. Phys. J. C* **78** (2018) 348, [1712.00730].

[95] R. Gauld, J. Rojo, L. Rottoli and J. Talbert, *Charm production in the forward region: constraints on the small-x gluon and backgrounds for neutrino astronomy*, *JHEP* **11** (2015) 009, [1506.08025].

[96] LHCb collaboration, R. Aaij et al., *Measurements of prompt charm production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **03** (2016) 159, [1510.01707].

[97] LHCb Collaboration collaboration, R. e. a. Aaij, *Measurement of b hadron fractions in 13 tev pp collisions*, *Phys. Rev. D* **100** (Aug, 2019) 031102.

[98] LHCb Collaboration collaboration, R. e. a. Aaij, *Measurement of fs/fu variation with proton-proton collision energy and b -meson kinematics*, *Physical Review Letters* **124** (Mar, 2020) .

[99] LHCb collaboration, R. Aaij et al., *Prompt Λ_c^+ production in* pPb *collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *JHEP* **02** (2019) 102, [1809.01404].

[100] LHCb collaboration, R. Aaij et al., *Measurement of B^+, B^0 and Λ_b^0 production in* pPb *collisions at $\sqrt{s_{\rm NN}} = 8.16\,\rm TeV$*, *Phys. Rev. D* **99** (2019) 052011, [1902.05599].

[101] ALICE collaboration, S. Acharya et al., *Λ_c^+ production in pp collisions at $\sqrt{s} = 7$ TeV and in p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV*, *JHEP* **04** (2018) 108, [1712.09581].

[102] F. Arleo and S. Peigné, *Quarkonium suppression in heavy-ion collisions from coherent energy loss in cold nuclear matter*, *JHEP* **10** (2014) 073, [1407.5054].

[103] C. Gerschel and J. Hüfner, *A contribution to the suppression of the $\breve{j}/\psi$ meson produced in high-energy nucleus-nucleus collisions*, *Physics Letters B* **207** (1988) 253–256.

[104] E. G. Ferreiro, *Excited charmonium suppression in proton–nucleus collisions as a consequence of comovers*, *Phys. Lett. B* **749** (2015) 98–103, [1411.0549].

[105] A. Andronic et al., *Heavy-flavour and quarkonium production in the LHC era: from proton–proton to heavy-ion collisions*, *Eur. Phys. J. C* **76** (2016) 107, [1506.03981].

[106] J.-P. Lansberg, *New Observables in Inclusive Production of Quarkonia*, *Phys. Rept.* **889** (2020) 1–106, [1903.09185].

[107] M. W. Krasny, *The Gamma Factory proposal for CERN*, 1511.07794.

[108] D. Budker et al., *Atomic physics studies at the Gamma Factory at CERN*, 2003.03855.

[109] n2EDM collaboration, N. J. Ayres et al., *The design of the n2EDM experiment*, 2101.08730.

[110] A. J. Krasznahorkay et al., *Observation of Anomalous Internal Pair Creation in Be8 : A Possible Indication of a Light, Neutral Boson*, *Phys. Rev. Lett.* **116** (2016) 042501, [1504.01527].

[111] MADMAX collaboration, P. Brun et al., *A new experimental approach to probe QCD axion dark matter in the mass range above 40 μeV*, *Eur. Phys. J. C* **79** (2019) 186, [1901.07401].