Proposal for a GDR of the Intensity Frontiers

all names

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1 Introduction

The need for a GDR in physics at the intensity frontier has been established, in order to bring the community together, exchange ideas and knowledge. The role of this GDR would be to stimulate the emergence of common projects within the French community, facilitating the collaboration between different laboratories and between theorists and experimentalists. This would provide greater visibility of this large community on a national level. There is a need to come together in order to discuss how research plans for the future should be shaped; including the decision of which experiments to become involved in. The GDR would function through carefully planned workshops, both for the entire group where more general talks and discussions could be held and specialised subgroups allowing close collaborations to emerge. Topics dedicated to the interplay between different subgroups could also be beneficial on specific topics such as lepton and quark flavour or rare B decays and searches for hidden particles. We further hope to use these workshops as an opportunity to put the younger members of the community in the spotlight, by giving postdocs the responsibility of organising and chairing some meetings, and by creating an environment where PhD students feel confident to present their work and interact with physicists from other laboratories.

We envisage the GDR to be divided into several subgroups which would both function independently and together:

- Rare, radiative and semi-leptonic decays
- CP violation/charmless hadronic decays
- Heavy flavour production and spectroscopy
- Charm and Kaon physics
- Lepton Flavour (Neutrinos/Taonic/muonic decays/(g-2))
- Future experiments BelleII, FCC, (SHIP)

In the subsequent sections we will provide a brief introduction and motivation to these themes as well as summarise the past, current and the proposed near-future work of the French community.

More specifically, we plan to organize a general kick-off meeting, to bring the whole community together in order to define and consolidate collaborations and goals. This would be followed by a series of smaller meetings, more intimate and focused on specific themes. The format of these meetings would be free, and decided according to the specific needs and objectives, and it would be encouraged for younger members of the community to participate in the organisation and the discussion. The emphasis on having smaller meetings would be to allow detailed discussions and brainstorming within a specialised area. We believe that the GDR structure would be beneficial to those working on high energy physics who are focussed on the intensity frontier in both consolidating the existing activities and prompting the creation of new projects and collaborations.

2 Rare, radiative and semileptonic B decays

The LHCb collaboration has produced a large set of results related to the exclusive $b \to s\ell\ell$ decay modes and their results are currently dominating the field. In the special case of the $\mathcal{B}(B_s \to \mu\mu)$, the CMS collaboration is also significantly contributing and after combining the two results, it turned out that the long searched $\mathcal{B}(B_s \to \mu\mu)$ is only slightly lower than, but compatible with, the value predicted in the Standard Model (SM). The $\mathcal{B}(B_d \to \mu\mu)$ decay has also been seen, its branching ratio is also compatible with the value predicted by the SM.
Joint work between experimentalists ans theorists have allowed to identify an ensemble of observables which are at the same time sensitive to the couplings to different possible sources of New Physics (NP) and as immune as possibie to non factorizable QCD effects. In this framework, after comparing the experimental values of those observables, as well as of $\mathcal{B}(B \to K\mu\mu)$ and $\mathcal{B}(B_s \to \phi\mu\mu)$, with the theoretical estimates derived in the SM, one finds considerable discrepancies (of the order of 3 to 3.5 standard deviations). It appears, however, that the most significant discrepancies occur near the charm production threshold, a region notoriously difficult for theoretical description of these decays because it requires 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. For that reason, as of now, it is not clear whether the current discrepancies are due to the lack of theoretical control of the $c\bar{c}$ contributions, or they indicate the presence of NP couplings. If the second option is adopted, the angular observables of $B \to K^*\mu\mu$ and $B_s \to \phi\mu\mu$ decay modes provide very stringent constraints on the scenarios of physics BSM. It is important to note that these results were confirmed for the $B^0 \to K^*\mu\mu$ analysis by the BELLE collaboration. 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. The results found there are in agreement with SM but currently quite limited in statistics.
Another experimental result which has also provoked some interest in the flavor physics community is that $R_K = \mathcal{B}(B \to K\mu\mu)/\mathcal{B}(B \to Kee)_{\mathrm{low}-q^2}$ was found to be 2.6σ smaller than predicted in the SM, which suggests the violation of universality of the coupling to leptons (LFUV). Such a puzzling phenomenon should be scrutinized with higher statistics and tested in other similar situations, such as R_K at high-q^2's, $R_{K^*,\Lambda^{(*)}}$ at both low- and high-q^2's. This observation is adding to an already noted problem of $R_{D^{(*)}} = \mathcal{B}(B \to D^*\tau\nu_\tau)/\mathcal{B}(B \to D^*\mu\nu_\mu)$ for which the experimental result, first measured at the B-factories and then confirmed at LHCb, is $(2 \div 4)\sigma$ larger than predicted in the SM. There are very few phenomenologically viable theoretical scenarios of NP which can simultaneously explain that $R_K^{\mathrm{exp}} < R_K^{\mathrm{SM}}$ and that $R_{D^{(*)}}^{\mathrm{exp}} > R_{D^{(*)}}^{\mathrm{SM}}$. To further understand the origin of the LFUV one can envisage doing the angular analysis of all the mentioned decay modes, and from the ratios of angular observables check whether or not a similar size of the LFUV is indeed observed. Furthermore, to facilitate a comparison with theory it is more sound to compare $B_s \to D_s^{(*)}\ell\nu_\ell$ because the theoretical uncertainty related to the chiral extrapolation in the light valence quark on the lattice is completely avoided in this way. Moreover, the emission of soft photons can differently affect $B^- \to D^{0(*)}\ell^-\bar{\nu}_\ell$ and $B^0 \to D^{-(*)}\ell^+\nu_\ell$, the modes which are usually averaged. Such a problem is much less significant of one works with $B_s \to D_s^{(*)}\ell\nu_\ell$ decays.
Most of the models pretending to describe the LFUV effects allow for the lepton flavor violation (LFV) too. For that reason it is of great interest to measure the LFV modes such as $B_s \to \mu\tau$, $B \to K^{(*)}\mu\tau$, $B_s \to \phi\mu\tau$, which can now be probed thanks to the large statistics achievable at the LHC. Experimental bounds on $\mathcal{B}(B_s \to \mu e)$ and $\mathcal{B}(B_s \to K^{(*)}\mu e)$ can be greatly improved thanks to the unprecedented statistics of the LHC data. These results can be very useful for phenomenology of the LFV decays and for the bigger picture that could ultimately lead to a theory of flavor of quarks and leptons.
The work of this part of GDR will be carried out within two working groups (theory and experiment) and the outcome of their works and discussions will be presented at the annual workshops that will unite both the theorists and experimenters and which will be organized following the agenda described below.

a. Year One: Workshop on the LFUV in B and B_s decays

During this workshop the theorists will discuss a general scenario of NP, in an effective field theory approach, and isolate the observables which are most sensitive to the couplings to the vector (scalar) and/or axial (pseudoscalar) operators. Experimenters and theorists will elaborate on the feasibility of the distribution of $B_{(s)} \to D^*_{(s)}\ell\nu_\ell$ according to the polarization of the outgoing vector meson. Furthermore, a contact with other leptonic observables should be made in order to test several plausible scenarios of NP which result in LFUV.

b. Year Two: Workshop on the angular distribution of various decay modes
With the new and more accurate experimental data it becomes mandatory to assess the hadronic uncertainties on the theory side. 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. An other interesting subject could be the angular analysis of $B^0 \to K^*\tau\tau$ and the study of new observables taking into account the direct access to the *tau* polarization. The study of $b \to s\ell\ell$ transition in b-baryons is quite new and the identification of interesting observables for the $\Lambda_b \to \Lambda^*\mu\mu$ may be interesting. Possible phenomenological ideas on how to relate the hadronic quantities in several decay modes will be discussed as they might be helpful in cancelling a large part of hadronic uncertainties. Ideas on how to treat the non-resonant $c\bar{c}$-contributions would be very welcome. Participants will also address the question *"Which physics BSM?"*

c. Year Three: Workshop on the lepton flavor violation in b-decays
Revisiting the LFUV problem: discuss the new constraints on $R_{K^{(*)},D^{(*)},\Lambda^{(*)}}$ obtained in Belle II, and attempt drawing more accurate conclusions concerning the new physics scenarios. Focus then on the LFV modes and on interpretation of the results found by LHCb. The issues related to the identification of τ in the final state should be revisited. Work on the package of codes that would include all possible constraints relevant to the LFV at low and high energy and see what are the lessons one can learn about the Yukawa sector from the data.

d. Year Four: Workshop on the relation to Higgs
Assess the current situation concerning the extraction of the Yukawa couplings from experimental data. In what way those data can be related to the low-energy physics observables and b-decay observables in particular. In order to address the issue of "*Which theory of flavor?*" we will try and combine the searches made at Belle II with those made at NA62 and KOTO experiments. Address the issue of (in)compatibility of the conclusions found in the Yukawa sector through the low-energy experiments with the LHC findings at the TeV-scale.

3 CP Violation

The discovery of Physics Beyond the Standard Model (BSM) is the main target of current high energy experiments. One way to search for this "New Physics" is to measure precisely some parameters which are precisely predicted by the theory. In this respect, CP violation is particularly interesting because in the SM, it originates from a single parameter. All the CP violating observables in the K, B and D meson sectors are thus directly related and their combined study provides a highly powerful test of the whole SM dynamics. Indeed, most model of New Physics are far less restrictive and allow for a plethora of new CP-violating sources. None of the delicate interplays between observables expected in the SM should survive to 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 is a purely hadronic phenomenon in the SM, originating from the quark couplings. However, dedicated strategies have been designed and CP-violating observables are actually among our best windows. For example, in CP-violating asymmetries, most of the uncertainties cancel between the numerator and the denominator, so that we can construct measurable quantities with small uncertainties. Alternatively, some observables are predicted to be so small that they can be considered forbidden in the SM, and simply observing a non-zero value would unequivocally signal the presence of New Physics.

The French community has been deeply involved in CP-violation experiments for many years (CPLEAR, NA48, BaBar, LHCb, ...). Expertise has been developed in several key aspects of CP-violation: amplitude analyses, tagged-time-dependent angular analyses, flavour tagging, neutral objects, ... More specifically, the French community has been involved in the measurements of the Unitarity angles α, γ and ϕ_s. Among other decay channels, the following have been studied in detail: $B_{(s,d)} \to D^0 K^{*0}$, $B_{(s,d)} \to \bar{D}^0 hh$, $B_s^0 \to D_s K$, $B_s^0 \to J/\psi\phi$, $B_s^0 \to J/\psi \bar{K}^{*0}$. Other studies, of b hadrons to charmless final states will be commented in Sec. 4. One of the outcome of the work done is ϕ_s is illustrated on Figure 1.

Expertise has also been acquired on designing, building and maintaining key elements of the detectors: trigger and calorimeters.

In the coming years, most of the experimental effort will go in LHCb and its upgrade plans. One of the biggest challenge will be to store and analyse the enormous quantity of data from the LHC.

From the theory side, ... CKMfitter, QCD challenge, precision challenge, sub-leading diagram estimation, penguin pollution, ...

In the 4 following years (2017-2020), we will not only continue the measurements started many years ago, with the full run2 data-set of the LHC, but also explore new routes:

- several ways to measure γ and α;
- continue efforts on ϕ_s and control of sub-leading penguins contributions;
- explore CP violation in baryons;
- CP violation in charm is still to be discovered.
- CP violation in kaon: Are we planning to perform some lattice studies, for example of the ε' matrix elements? Also, theorists are certainly following closely the NA62 experiment which aims at $K^+ \to \pi^+ \nu\nu$.
- EDM: should we include the nEDM experiment? It is among the IN2P3 projects.

For all these items, the synergy between experimental and theoretical communities is essential, because a major discovery can not come if the uncertainties are not under control in both places.

We will also actively participate to the brainstorming on future upgrade of the LHCb experiment, i.e. plans for the 2025-2035 period.

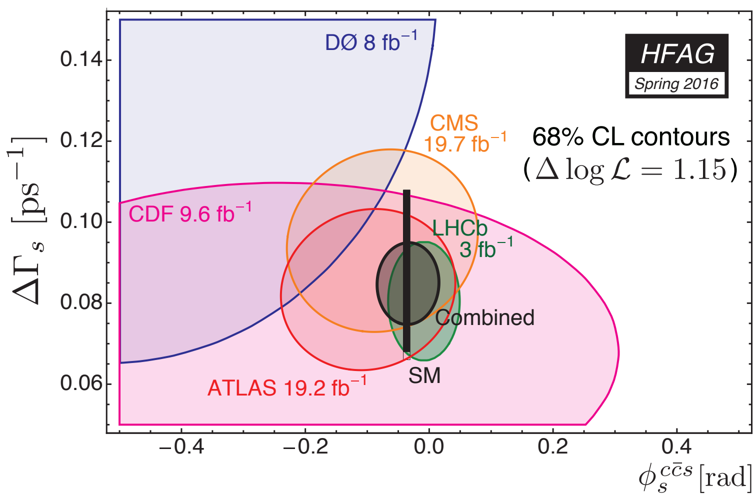

Figure 1: 68% CL regions in B_s^0 width difference $\Delta\Gamma_s$ and weak phase ϕ_s obtained from individual and combined CDF, D0, ATLAS, CMS and LHCb likelihoods of $B_s^0 \to J/\psi\phi$, $B_s^0 \to J/\psi KK$, $B_s^0 \to J\psi\pi\pi$ and $B_s^0 \to D_s^+ D_s^-$.The expectation within the Standard Model is shown as the black rectangle.

4 Charmless b Hadron Decays

The study of of b-hadron decays to hadronic final states with no charmed particles allow for a rich array of studies. A few examples are the measurements of branching fractions, CP asymmetries, weak and strong phases and the CKM angles; they probe the dynamics of weak and strong interactions. The typical branching fractions of these modes are below 10^{-5} and thus their analyses are feasible only with large data samples and the use of powerful tools to reject background. The LHCb experiment is an adequate experimental environment for these analyses, offering the possibility to study decays of light B mesons, B_s mesons and b baryons.

In particular, CP-violation related studies of charmless b-hadron decays have a number of theoretical applications and that provide a probe to new physics, along the lines described in Sec. 3. For instance, the decays $B^0 \to K_S^0 \pi^+\pi^-$ and $B^0 \to K_S^0 K^+K^-$ are dominated by $b \to q\bar{q}s$ $(q = u, d, s)$ loop transitions. Mixing-induced CP asymmetries in such decays 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 Cabibbo-Kobayashi-Maskawa mechanism **??**. However, the loop diagrams that dominate the charmless decays can have contributions from new particles in several extensions of the Standard Model, which could introduce additional weak phases **????**. A time-dependent analysis of the three-body Dalitz plot allows measurements of the mixing-induced CP-violating phase **????**. The current experimental measurements of $b \to q\bar{q}s$ decays **?** show fair agreement with the results from $b \to c\bar{c}s$ decays (measuring the weak phase β) for each of the scrutinised CP eigenstates. There is, however, a global trend towards lower values than the weak phase measured from $b \to c\bar{c}s$ decays. The interpretation of this deviation is made complicated by QCD corrections, which depend on the final state **?** and are difficult to handle. An analogous extraction of the mixing-induced CP-violating phase in the B_s^0 system (β_s) will, with a sufficiently large dataset, also be possible with the $B_s^0 \to K_S^0 K^\pm \pi^\mp$ decay, which can be compared with that from, *e.g.* $B_s^0 \to J/\psi\,\phi$.

An impressive harvest of results from charmless hadronic B mesons decays was obtained by the B factories. Several french groups participated in these studies within the BaBar experiment, and in particular, a part of the present LPNHE-LHCb group. The LHCb experiment is already playing an important role in this area of physics, with the participation of the LPC and LPNHE groups. Both have contributed to the LHCb analysis of the decay modes $B_s^0 \to K_S^0 h^+ h'^-$ $(h^{(\prime)} = \pi, K)$ with 1 fb^{-1} of data, which are being pursued with 3 fb^{-1}. In particular they are performing amplitude analyses (aka Dalitz-plot analyses) of

$B^0 \to K^0_S\pi^+\pi^-$ and $B^0 \to K^0_S K^+K^-$ decays. At LHCb, the first step of the charmless b hadron decays physics programme is to establish the signals of yet unobserved rare modes. The only yet-unobserved $B^0_s \to K^0_S h^+h'^-$ mode is $B^0_s \to K^0_S K^+K^-$. The LPC group also performs analyses of $B_s \to \rho^0\rho^0$, and $\Lambda^0_b(\Xi^0_b) \to phh'h''$ decays.
All the analyses mentioned above provide a long-term physics programs that can profit from the LHCb upgrade. These analyses proceed in increasingly complex steps, which become more and more sensitive to new physics observables with the growing dataset, and with more observed decay modes. One of the long-term goals is to perform full flavor- and time-dependent Dalitz-plot analyses of the $B^0_s \to K^0_S h^+h'^-$ modes to the measure the weak phases β and β_s. Recent theoretical and experimental activity has focused on the determination of the CKM angle γ from charmless B meson decays using and refining the methods proposed in Refs. **???**. The LPNHE group is checking the applicability of the method described in the last reference to the LHCb physics analysis. Moreover, with the upgrade of LHCb, more modes, eventually with more neutral hadrons, are being considered.

5 Heavy Flavor Production and Spectroscopy

Quantum Chromodynamics (and the quark model out of which it grew) is one of the fundamental building blocks of the Standard Model. It has been extensively validated over the decades, and is very well understood. However, due to the non-perturbative behaviour that follows from the large self-coupling of low-energy gluons, the practical implications of QCD are still very much an active subject of research. This was vividly illustrated in the realm of spectroscopy recently, when the first compelling observation of pentaquark ($qqqq\bar{q}$) states was made by LHCb [?] just over fifty years after their existence was predicted [?]. This discovery came as a surprise to experimentalists and theorists alike: the possible existence of such states was known, but the quark composition of quasi-stable pentaquark resonances (let alone their masses, widths, and production mechanisms) was not.

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 4σ level with Standard Model expectations **?**. 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. There are numerous instances in which QCD input is needed for the interpretation of measurements, notably for $B^0 \to K^{*0}\mu^+\mu^-$ in which local tensions of 3σ were seen by LHCb in two regions of phase space [?], corresponding to an overall tension of 3.4σ with the SM prediction of **?**. The significance of the tension depends strongly upon the SM theory prediction and its uncertainties. To take a third and final example, QCD processes are an inherent background to all physics at the LHC, and in some cases Monte Carlo predictions of their spectrum need to be included in the fit itself. Tuning of the Monte Carlo models requires not only work from the phenomenology community but also measurements of production cross-sections across a range of transverse momentum and pseudorapidity.

The HEP community in France is engaged in this field, both on the experimental and theory sides. For practical reasons most experimental measurements have come from LHCb in recent years. LHCb-France has been involved on multiple fronts: spectroscopy of exotica (LAL, LAPP, LPNHE), spectroscopy of non-exotic resonances (LAL, LPNHE), and measurements of production rates (CPPM, LAL, LAPP, LPNHE). This list is not exhaustive, and there are far too many results to discuss them individually; purely by way of illustration we point to recent contributions by French groups to studies of exotic 4- and 5-quark resonances [?, ?], discoveries of two Ξ_b resonances and precise measurements of their mass splittings [?, ?], and measurements of the J/ψ production cross-section with the new 13 TeV LHC data [?]. Numerous theory groups are also actively involved, and we do not dare attempt an exhaustive list[1]. As well as hadron production, there is substantial French expertise in spectroscopy theory. For example, the opening theory review talk at the 2014 Workshop on Heavy Quark Baryons at LHCb[2], a workshop organised by LHCb to which external experts were invited, was given by a member of IPNL. This is both recognition of this expertise and an illustration of the demand for productive theory-experiment crosstalk.

During the coming years, several analyses in this area are planned by LHCb-France. These include studies in beauty baryon spectroscopy following on from the observations of three Ξ_b resonances, searches for the doubly heavy Ξ_{cc} baryons, and measurements of production cross-sections at new centre-of-mass energies (including the 13 TeV Run-2 data and in heavy-ion collisions). Assuming that the Ξ_{cc} searches are successful, they in particular will lead to fruitful exchanges with theory: their masses and properties will have immediate implications for QCD models, and theory input will be very useful for the next step, namely observing and studying their excitations.

[1] In the author list of one review paper of heavy flavour production alone [?], we counted eight French laboratories: IPNO, IRFU, LAL, LAPTh, LLR, LPC, LPSC, and SUBATECH.

[2] `https://indico.cern.ch/event/317758/`

6 Charm and Kaon Physics

6.1 Charm at the intensity frontier [V. Gligorov]

Precise studies of the properties and decays of charmed hadrons are motivated as almost-null tests of the Standard Model (SM). In terms of CP violation, charm hadron decays involve only the first two generations of quarks, and CP violation in decay is therefore expected to occur at below the per mil level in the SM. Additionally, compared to beauty or strange hadrons, the mixing of neutral charm hadrons is slow, with both the $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/(2\Gamma)$ parameters at around the percent level. CP violation in charm decays has not been observed so far, and existing experimental limits are at the few per mil level. Theoretical predictions of charm CPV are difficult as long distance contributions dominate; CPV in decay close to the present experimental limits could be accommodate within the SM or could be signs of NP, and progress on the theory side will be required to disentangle the two. Similarly in the case of mixing, or CP violation in the interference of decay and mixing, more precise experimental results are needed to stimulate progress on the theoretical predictions.

In addition, charmed hadrons are also an interesting place to study rare and forbidden transitions, for example FCNS or lepton number violating decays. This is because charm hadrons are produced extremely copiously at the LHC (the $c\bar{c}$ cross-section is roughly 10% of the total inelastic cross-section!), while their short but measurable decay times make them relatively simple to reconstruct and separate from background. Indeed within France, the only recent studies of charmed hadron decays were performed by the LAL-Orsay LHCb group, which studied the rare decays $D^0 \to \pi\mu\mu$ (with same sign muons) and $D^0 \to K\pi\mu\mu$. The former is of interest because the copious production rate of charmed hadrons allows effective limits to be placed on Majorana neutrinos. The latter is the charmed counterpart of $B \to K^*\mu\mu$ and has now been observed for the first time by LHCb, albeit within a dimuon q^2 region dominated by the omega and rho resonances. It should in principle share much of the same phenomenology of $B \to K^*\mu\mu$ once large signal yields become available, with the complication of much higher backgrounds from decays to hadronic resonances (such as KPirho) which subsequently decay to dimuon pairs.

In the upcoming period, the most critical work will be to improve the limits on CPV, both in decay and the interference of mixing and decay, as well as to make ever more precise measurements of charm mixing parameters using both the $D \to hh$ and $D \to K_s hh$ decay modes with the full Run II LHCb dataset. In addition, LHCb should obtain large samples of FCNC decays such as $D^0 \to K\pi\mu\mu$, potentially allowing for an observation of the nonresonant (in the dimuon spectrum) decay and a measurement of angular observables similar to the ones which characterise $B \to K^*\mu\mu$. Finally, making more precise measurements of charm hadron lifetimes, in particular in the less well understood baryon sector, could aid the development of HQE tools and techniques required to eventually obtain precise SM predictions for mixing and CPV in the charm sector.

6.2 New Kaon observables [D. Guadagnoli]

Kaon mixing and decays belong traditionally to the most constraining processes for physics beyond the SM. In this section we provide motivations for searches of certain K decays, in particular lepton-flavor violating (LFV) ones of the kind $K \to (\pi)e\mu$. These motivations rest to a good extent upon discrepancies found in recent LHCb and B-factory data. The most striking effect is in the quantity known as R_K **?** that, at face value, signals beyond-SM lepton flavor non-universality (LFNU). Interestingly, the effect is consistent in magnitude and size with the other discrepancies. Without further assumptions, LFNU at a non-SM level implies LFV at a non-SM level. In fact, to account for R_K one needs to invoke new interactions distinguishing between leptons of different generations, for example lepton-lepton couplings with a new vector boson or quark-lepton couplings with a scalar leptoquark. The fermions involved in such interactions are generally not in the mass eigenbasis – this basis doesn't even exist at the scale of these interactions, usually above the EWSB scale. After EWSB, rotation of the quark and lepton fields to the mass eigenbasis generates LFV effects along with the LFNU ones.

One theoretically appealing way to generate new-physics shifts of the required size is to invoke an effective

interaction involving dominantly quarks and leptons of the third generation **?**. Then, the amount of LNU pointed to by R_K actually allows to quantify rather generally the expected amount of LFV to be in the ballpark of 10^{-8}, which happens to be within reach at LHCb's run 2. This argument, reported in Refs. **??**, motivates searches of LFV B decays as a promising direction at LHCb.
This very argument has implications in K physics as well, in decays of the kind $K \to (\pi)\ell\ell'$, such as $K_L \to e^\pm\mu^\mp$ and $K^+ \to \pi^+ e^\pm \mu^\mp$. Experimental limits on these modes are more than ten years old: $\mathcal{B}(K_L \to e^\pm\mu^\mp) < 4.7 \times 10^{-12}$ **?**, $\mathcal{B}(K^+ \to \pi^+ e^- \mu^+) < 1.3 \times 10^{-11}$ **?**, $\mathcal{B}(K^+ \to \pi^+ e^+ \mu^-) < 5.2 \times 10^{-10}$ **?**. Theoretical expectations for the above decays are straightforwardly calculable after suitably normalising the decay modes of interest in order to cancel phase-space factors. Defining $\beta^{(K)}$ as the ratio of the new-physics Wilson coefficient responsible for the decay in the numerator over the SM Wilson coefficient responsible for the normalising decay, we get

$$\frac{\Gamma(K_L \to e^\pm\mu^\mp)}{\Gamma(K^+ \to \mu^+\nu_\mu)} = |\beta^{(K)}|^2 \ , \tag{1}$$

$$\frac{\Gamma(K^+ \to \pi^+\mu^\pm e^\mp)}{\Gamma(K^+ \to \pi^0\mu^+\nu_\mu)} = 4|\beta^{(K)}|^2 \ . \tag{2}$$

To get a numerical idea of the effects to be expected, we need a model predicting $|\beta^{(K)}|^2$. For the sake of definiteness, here we use "model A" of Ref. **?** (any other motivated model, for example Ref. **?**, will do), thereby obtaining $|\beta^{(K)}|^2 = 2.15 \times 10^{-14}$. Use of eqs. (1) then implies

$$\mathcal{B}(K_L \to e^\pm\mu^\mp) \approx 6 \times 10^{-14} \ , \tag{3}$$

where we have used $\mathcal{B}(K^+ \to \mu^+\nu_\mu) \approx 64\%$ and $\Gamma(K^+)/\Gamma(K_L) \approx 4.2$ **?**. In addition

$$\mathcal{B}(K^+ \to \pi^+ e^\pm\mu^\mp) \approx 3 \times 10^{-15} \ . \tag{4}$$

after use of $\mathcal{B}(K^+ \to \pi^0\mu^+\nu_\mu) \approx 3\%$.
While the K^+ LFV mode is clearly too suppressed (within the considered model!), the K_L one, eq. (3), has a branching ratio close to 10^{-13}. Such a rate may actually well be reachable at the NA62 experiment. As concerns LHCb, it should be noted that, although K mesons are produced copiously, their lifetimes are typically too long for the detector size – with the exception of the K_S. A dedicated study is thus necessary to understand the actual LHCb capabilities for the above decays.

7 Lepton Flavor

8 Future Experiments

There are a large variety of future experiments at the intensity frontier planned in the coming years. Here we have divided them into two categories: those searching directly for physics beyond the Standard Model, and flavour physics experiments which can indirectly probe high energy scales through precision measurements.

8.1 WISPs

In this subsection we focus on searches for weakly interacting new light particles, commonly called WISPs, of which the two canonical candidates are 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 expected to solve 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 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 in a Lagrangian term $\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$. These 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 recently been several studies indicating possible discoveries of such particles in various astronomical observations: either as an explanation for excessive white dwarf cooling or anomalous transparency of the universe to gamma rays, and most excitingly as an explanation for the soft excess of X-rays from the coma cluster (at 200 eV) and/or the oscillatory modulation of X-rays from the Perseus cluster (and even, perhaps, an explanation for an observed 3.55 keV X-ray line). These hints all point to a very light ALP ($< 10^{-12}$ eV) with a coupling $g_{a\gamma\gamma} \sim \mathcal{O}(10^{-11} \div 10^{-12})\text{GeV}^{-1}$. However, while this is a very interesting region to probe, such a particle could have a wide range of masses and couplings.

Hidden photons are new (massive) gauge bosons which mix kinetically with the visible photon via a dimensionless kinetic-mixing parameter χ. While one motivation of these is as a possible explanation for the 3σ discrepancy between the measured and calculated value of the muon dipole moment – this would require a hidden photon in the $\mathcal{O}(100)$ MeV range with $\chi \sim \mathcal{O}(10^{-3})$ – they also appear generically in top-down constructions of beyond-the-Standard Model physics. They have been proposed as perhaps the most natural force carriers for light dark matter particles, or could even make up the dark matter themselves.

Intensity frontier experiments searching for these 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; 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.

Important upcoming experiments include:

- Axion haloscopes (magnetic resonant cavity experiments) ADMX-HF, YMCE and WISPDMX at the University of Washington, Yale and Hamburg respectively are all expected to report results soon, probing axion masses in the μeV range.
- The FUNK experiment in Karlsruhe uses a dish antenna to search for dark matter hidden photons.

- The helioscope SHIPS at Hamburg searches for hidden photons produced in the sun.
- 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.
- The IAXO helioscope at CERN uses a magnetic field to search for ALPs produced in the sun. It is expected to operate over the next decade and there are significant synergies with the French community.
- The SHIP beam dump experiment using the SPS proton beam at CERN has a substantial input from French theorists and experimentalists. It has the potential to search for particles in the GeV range, which included heavier ALPs, as well as other candidates such as right-handed neutrinos. Its development will encompass much of the lifetime of the proposed GDR.
- There will be electron beam-dump experiments HPS, DarkLight and MESA at SLAC, JLab and Mainz respectively, with the latter running in about 2020. These will provide high intensity competition to hidden-photon searches in the $10 - 1000$ MeV range.
- The BMV experiment at Toulouse received ANR funding in 2014 to build phase two and complement its 2007 results. It can perform photon regeneration searches; it also included an X-ray regeneration experiment.
- There is also a proposal to use the Tore Supra tokamak at Cadarache to search for ALPs. This would be particularly interesting to unite with the plasma physics community.

8.2 Future programs related to CP violation, rare decays of heavy flavours and lepton flavour violating processes

As far as CP violation and rare b-flavoured hadrons or τ decays are concerned, the two main players at the horizon of 2025 are the LHCb upgraded LHCb experiment at CERN and the Belle II experiment at KEK. Several large or medium scale projects related to Flavour Physics are envisaged to probe Beyond Standard Model Physics. Among them, there are prospective studies to educate the possibility to run the LHCb spectrometer in the High Luminosity phase of the LHC or to make use of high intensity beam lines (*e.g.* SPS and FCC injectors) with fixed target experiments.

A possible long-term strategy for high-energy physics at colliders, after the exploitation of the LHC and its High Luminosity upgrade, considers a tunnel of about 100 km circumference, which takes advantage of the present CERN accelerator complex. The Future Circular Collider (FCC) concept follows on the successful experience and outcomes of the LEP-LHC complex of experiments. A possible first step of the project is to fit in the tunnel a high-luminosity $e^+e^?$ 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 as the ultimate goal of the project.

Future Circular Collider study groups have been formed in a design study hosted by CERN, aiming at a Conceptual Design Report and a review cost in time for next European Strategy milestone (2018-2019). The unprecedented statistics at the Z pole ($\mathcal{O}(10^{12-13}Z$ decays) potentially delivered by the high-luminosity $e^+e^?$ collider can be studied in particular to explore further the Flavour Physics case at large. In that framework, several french teams, gathering small groups of experimentalists and phenomenologists, are contributing to the design study in Flavour studies.

There is a Physics potential of the measurements of rare decays of b-hadrons, which can complement the knowledge and anticipated results from the current and foreseen b-Physics programs (LHCb upgrade and SuperKEKB B-factory). In that respect, french contributions are mainly focused on rare electroweak penguins which 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 New Physics if seen. Heavy right-handed neutrals are natural candidates to explain LFV phenomena. They can be as well searched for directly at FCC-*ee*. A number of low energy experiment are addressing this very question through the search for LFV by muon capture on nuclei (*e.g.* COMET in Japan) or the radiative decay of large ensemble of muons (*e.g.* in Europe).

One objective of the GDR is to address the complementarity of these high intensity machines, at large scale apparatus or low-energy experiments.

9 Conclusion