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Flavour physics and indirect searches for new physics (Theory)

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ABSTRACT

The interplay of flavour and collider physics provides new opportunities for mapping possible routes beyond the Standard Model (SM). In recent years, a set of deviations between flavour physics measurements in semileptonic B decays and their respective SM predictions have been building up. These constitute at present the single, coherent array of deviations in collider observables. Another measurement that has been exhibiting a persistent deviation from the SM prediction is the anomalous magnetic moment of the muon. The understanding and interpretation of the implications of these measurements are therefore of utmost importance for their potential of discovery. This contribution aims at describing some of the most promising ways to progress on the theoretical and phenomenological sides.

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1 Introduction

While new physics (NP) searches are actively being pursued by the ATLAS and CMS experiments, aiming to discover new particles by direct detection, indirect searches, in particular in the flavour sector, can provide sensitivity to higher scales and point to specific directions. Therefore, indirect searches have been historically, and are, very complementary to direct ones. In flavour physics, the search for new physics is performed by analysing the virtual effects of new particles on flavour observables. An example among many are rare B decays, rare because they are examples of so-called flavour-changing neutral currents (FCNCs), namely processes suppressed by multiple mechanisms within the SM, and occurring only at loop level. The NP contributions can therefore be of a similar magnitude, making the FCNC rare B decays highly sensitive to potential physics beyond the SM.

The theoretical description of B decays involves disparate energy scales, and can thereby take advantage of powerful field theoretical tools to match experimental measurements with accurate predictions. These tools give collectively rise to the so-called operator product expansion (OPE), which allows to separate the different scales, leading to an effective weak Hamiltonian described in terms of effective operators and the associated couplings, referred to as Wilson coefficients. The short-distance effects are encoded in the Wilson coefficients, calculable within renormalization group improved perturbative QCD. The matrix elements of the effective operators are sensitive to long-distance QCD dynamics and encode non-perturbative dynamics, requiring alternative methods such as QCD light-cone sum rules (LCSR) and calculations using lattice QCD (LQCD). It is worth emphasizing that the latter methods are themselves well in the era of precision physics, due to the concurrence of algorithmic breakthroughs and of the dramatic increase in numerical capabilities.

Several deviations with the SM predictions have emerged in recent years in flavour physics, as we will discuss in the following. The most remarkable example of deviations concern b to c and b to s transitions, in both cases with two leptons in the final state ('semi-leptonic'). Especially striking is the fact that these deviations give rise to a coherent theoretical picture. Additional discrepancies, although more debated in the literature, have been reported in the kaon system [1, 2].

Our ignorance about BSM physics requires a diversified programme that, even within the flavour-physics domain, calls for a large set of complementary measurements. To properly identify the BSM model, if deviations are observed, studying its imprint on different observables is very important. There is full complementarity and many potential synergies in case some BSM signal emerges, among different b-hadron decays ($B_{u,d}$, B_s, Λ_b, etc.), CP violating and rare processes involving charm and kaons, as well as possible FCNC transitions with top-quark. French teams are involved in the calculations and studies of the implications of several NP sensitive observables. This document presents some (but not all) of the current activities and prospects.

2 Neutral currents

The LHCb collaboration announced in 2013 several deviations with the SM in the angular observables of $B \to K^* \mu^+\mu^-$ with the largest deviation of about 3σ for the observable P_5' [3]. These deviations were confirmed with more accumulated data and using different analysis methods. Moreover, the branching ratio of the decay $B_s \to \phi\mu^+\mu^-$ is found to be about 3σ below the SM predictions [4]. LHCb has in addition performed tests of lepton flavour universality (LFU) by measuring the ratios $R_K = \mathrm{BR}(B \to K^+\mu^+\mu^-)/\mathrm{BR}(B \to K^+e^+e^-)$ and $R_{K^*} = \mathrm{BR}(B \to K^{*0}\mu^+\mu^-)/\mathrm{BR}(B \to K^{*0}e^+e^-)$ yielding deviations with an experimental significance of 2.5σ [5–7]. As previously remarked, the different anomalies are all consistent with each other and follow a coherent pattern [8–11], all the way from the weak-effective theory, to the SM effective theory, to certain well-motivated simplified models [10], and possibly pointing to the existence of new vector currents. This coherence is an extremely non trivial fact. The extrapolation of the LHCb results has shown that the Run 2 LHCb dataset would be sufficient for a measurement of the deviations with more than 6σ significance [12]. We may therefore be on the verge of the discovery of NP. In particular, if the deviations in the ratios $R_{K^{(*)}}$ are confirmed, it would mean a violation of lepton flavour universality, and constitute the most exciting LHC discovery after the Higgs boson. We emphasize that new physics in the Yukawa sector will in general produce some degree of lepton non-universality.

2.1 Theoretical calculations in the Standard Model

To unambiguously distinguish between SM effects and NP phenomena, it is necessary to have precise predictions of the observables. For $b \to s$ exclusive semileptonic decays, naïvely the decay amplitude can be written in terms of form factors and Wilson coefficients, however this approximation can be improved by incorporating perturbative QCD factorization corrections. The main challenge lies in the computation of the hadronic effects in QCD. On one hand this requires the calculation of form factors parameterizing the desired meson transition matrix elements, possible via methods such as LCSR or LQCD. French researchers are involved in the calculation of these form factors in both domains of LCSR and LQCD. Work originated by the French group [13] shows that certain symmetries apply in the large energy limit and the number of independent form factors can be reduced up to symmetry breaking corrections [14]. On the other hand there are additional non-perturbative effects when factorization breaks down due to hadronic (charmonium) contributions to the quark loop mediating the decay. Further, French groups are involved in theoretical calculations of the form factors for the non-resonant channels which contribute to the background of $B \to K^*\ell\ell$ decays, for example $B \to K\pi\ell\ell$ [15].

2.2 Design and study of New Physics models

In order to interpret the experimental results in terms of specific NP scenarios, the first step is to follow effective theory approaches, by identifying the set of relevant operators and calculating the values of their Wilson coefficients preferred by data. A realistic NP scenario can incorporate new operators in addition to the SM ones. Hence, it is important to perform global fits to all the relevant Wilson coefficients [16]. Given the large number of parameters, this task necessitates the use of advanced statistical methods.

New flavour physics observables should be designed for LHCb and Belle II in order to provide cross checks and additional information on NP properties. Baryon decays, even if affected by larger hadronic uncertainties, can provide additional insights. Finally, lepton universality violation of O(10%) as measured is, in general, accompanied by potentially measurable lepton flavour violation with branching ratios of $\mathrm{O}(10^{-8})$ [17], which opens a whole set of additional searches. It will be necessary to calculate the new observables as accurately as possible, and to collaborate with experimentalists to design specific searches for the most promising decays and observables. Once clear patterns are established, the next step in the direction of identifying NP is to investigate simplified models. 'Simplified' denotes new models with just the new (renormalizable) interactions required to calculate the NP contributions to the concerned processes, while staying agnostic on the full mechanism that makes these models renormalizable, e.g. the specification of the spontaneous breaking of the possibly enlarged gauge symmetry. Reinterpreting the Wilson coefficients and operators in terms of new particles, corresponds to reverse-engineering the effective approach. This is a necessary step because simplified models also provide links to the high-p_T and dark matter searches. Thus, it will be necessary to recast the existing LHC direct searches to set constraints on the masses and couplings of the involved particles, and to study the reach of the experimental analyses and design specific analyses corresponding to new topologies. The final step will be to relate the most promising simplified models to truly UV-complete theories. We know that simplified models are unrealistic. Most importantly, if they involve new massive vectors, simplified models are incalculable beyond tree level, and have to be embedded in a UV-complete theory. At present, two different approaches are followed in the literature, either designing a UV-complete theory from the simplified model and performing predictions for collider and dark matter searches, or considering well-motivated UV complete theories and check which parameter regions can lead to flavour physics results matching the data.

3 Charged currents

While charged current decays are not loop-suppressed and therefore assumed to be less sensitive to new physics, there are two classes of anomalies in these decays which have received great attention and merit further scrutiny. The first is the long-standing discrepancy between the exclusive and inclusive measurements of the magnitudes of the elements of the CKM matrix V_{cb} and V_{ub}, and the second is discrepancy in the ratio of branching ratios for $B \to D^{(*)}\tau\nu$ and $B \to D^{(*)}\ell\nu$, known as $R_{D^{(*)}}$, hinting at lepton-flavour universality violation.

3.1 Exclusive and Inclusive determinations of the CKM matrix elements

The latest updates of the large discrepancy between inclusive and exclusive determinations are, for $|V_{ub}|$, at the 3.5σ level [18] and, for $|V_{cb}|$, at the 2σ level [19]. The inclusive method involves the measurement of the sum of branching ratios of all charged semileptonic B decays to final states containing a c or u quark, and the theoretical calculation of the same using the OPE. This is supposedly theoretically cleaner than the exclusive method, which compares the measurement of the branching ratio for a specific hadronic decay to the corresponding theoretical calculation which requires the relevant form factors. French researchers have been strongly involved in exclusive calculations, particularly the LCSR [20,21] and LQCD [22] form factor calculations and also in the calculation of theoretically motivated parameterizations for the form factors as a function of q^2, the square of the invariant mass of the leptons. There are several improvements needed in order to improve the accuracy of these calculations and work is in progress along these directions.

3.2 Lepton flavour universality ratios

Measurements from the B-factories and LHCb have detected an anomaly in the ratios R_D and R_{D*} [23], which has a combined significance of $\sim 3.1\sigma$. This has spurred substantial activity both on the side of improving SM predictions and building models able to explain such discrepancies and to concurrently withstand all existing constraints. The former task, of improving SM predictions, mostly boils down to improving predictions for the form factors, that constitute the main non-trivial part of the theoretical calculation [24]. On the model-building side, as for the case of the neutral current anomalies, the prime candidates are at present leptoquarks, for a number of good reasons. For example, leptoquarks have a built-in mechanism to allow for new effects in amplitudes such as those required by the semileptonic B decays concerned by the discrepancies, while at the same time suppressing new effects in other, strongly constraining processes such as meson mixings and lepton flavour violation in decays of leptons. Besides, leptoquarks naturally arise in grand unified frameworks. As a matter of fact, work is on-going to explore models of leptoquarks, in particular to construct explicit realizations of UV-complete models.

4 High precision tests of the CKM mechanism

Future experiments will test the CKM mechanism at the permille level in leading quark flavour transitions through a large set of observables. In order to reinterpret these measurements within the Standard Model and eventually detect deviations from it, theory predictions must be improved accordingly. French teams are strongly involved in Lattice QCD, analytical methods and phenomenological approaches to deepen our knowledge of the relevant hadronic matrix elements. Also statistical softwares like CKMfitter [25], a world leader in the field that is developed by French physicists, play a key rôle in high precision test of the CKM mechanism.

Table 1 shows a prospective example for the future Phase I and Phase II: in Phase 1, we assume that the collected data amount for LHCb to 23 fb^{-1} and for CMS/ATLAS to 300 fb^{-1}, whereas for Phase 2, we have considered for LHCb 300 fb^{-1} and for CMS/ATLAS 3000 fb^{-1}. The accuracies shown in this table corresponds to the hypothesis of an agreement among the various constraints within the SM.

A more detailed analysis of the observables involved and the projected theoretical and experimental accuracies is available in Sec. 2 of Ref. [26].

	Current	Phase I	Phase II
A	0.0120	0.0087	0.0072
λ	0.0007	0.0005	0.0004
$\bar{\rho}$	0.0085	0.0040	0.0019
$\bar{\eta}$	0.0087	0.0036	0.0016
$\lvert V_{ub}\rvert$	0.000096	0.000045	0.000031
$\lvert V_{cb}\rvert$	0.00070	0.00041	0.00033
$\lvert V_{td}\rvert$	0.00014	0.00009	0.00007
$\lvert V_{ts}\rvert$	0.00054	0.00040	0.00033
$\sin 2\beta$	0.015	0.006	0.003
α (°)	1.4	0.6	0.3
γ (°)	1.3	0.6	0.3
β_s (rad)	0.00042	0.00020	0.00010

Table 1: 68% CL uncertainties on the determination of CKM parameters from the CKMfitter global fit.

5 Anomalous magnetic moments of leptons

The anomalous magnetic moments of leptons, in particular that of the muon (a_μ), are also very promising avenues in the search for NP. These anomalous moments represent the deviation of the lepton's gyromagnetic ratio with respect to its value without quantum fluctuations. They can be calculated with impressive accuracy in the SM. Since the measurements made by the E821 experiment of the Brookhaven National Laboratory in the early 2000s, there remains a persistent $\sim 3.5\sigma$ disagreement between theory and experiment that has given rise to many NP scenarios to explain it. Today, experimental and theoretical uncertainties are close. However, a new experiment (E989) is currently taking data at Fermilab and a second one (E34) is planned at J-PARC in Japan. Both aim at reducing the experimental error by a factor of four, i.e. down to 0.15 ppm. A commensurate reduction of the theory uncertainties is therefore essential to fully exploit the new experimental results.

The precision of the SM prediction is currently limited by two hadronic contributions: that of the hadronic vacuum polarization (HVP) and the one induced by hadronic light-by-light scattering (HLbL). Note that the HVP also plays a capital role for our knowledge of the fine structure constant and of the Weinberg angle. The uncertainties on both these quantities will have to be improved to interpret measurements at future colliders.

French teams have significantly contributed to the calculation of both hadronic contributions and will continue to do so in the coming years. The most precise determinations of the HVP contribution come from dispersion relations applied to data for the cross section of $e^+e^- \to$ hadrons. These include fully model-independent analyses such as [27], as well as analyses that rely on a hadronic model for the spectral function [28]. These approaches will improve with more $e^+e^- \to$ hadrons data from existing experiments and future measurements from experiments such as Belle II.

The second approach that French teams have been using to compute the HVP contribution are massively parallel simulations in LQCD. A first complete computation was presented in [29], with uncertainties which are about six times larger than those from phenomenology. Since this publication, an ambitious program has begun to reduce uncertainties to a level more comparable to those of phenomenology. This requires advanced noise reduction techniques, the inclusion of electromagnetic and strong-isospin breaking effects, much larger statistics, simulations in larger volumes, and a general level of precision never achieved before in lattice calculations.

Both approaches will benefit from model-independent constraints of the kind investigated in [30] and for which future improvements are planned.

Another proposal for improving the precision of the HVP contribution is through the MUonE project [31]. This experiment proposes to determine the HVP contribution by directly measuring the effective electromagnetic coupling in the spacelike region via μe scattering data. Since this measurement does not cover the full range of spacelike momenta required, it will have to be supplemented either by $e^+e^- \to$ hadrons or LQCD results.

French scientists have also contributed significantly to determining the much more complex HLbL contribution, through models [32] and, more recently, using LQCD [33, 34], which is the only known way to determine this contribution from the SM alone. For the second approach, a coherent strategy is being put in place to obtain a determination of this contribution with a fully controlled, $O(10\%)$ uncertainty. It relies on combining two complementary studies. The first consists in computing contributions of individual hadronic states to the HLbL and, the second, in computing the HLbL quark diagrams directly.

6 Software development and statistical analysis

The computation of flavour observables including most general NP effects requires the calculation of Wilson coefficients in an enlarged effective theory basis, either at the weak scale or at a higher scale where the operator basis is formally invariant under the full SM gauge group (SMEFT). In either case, one has also to consistently include renormalization-group-running effects from the UV scale to the scale of the processes, typically m_b. Taking into account issues like operator mixing and large logs, the above tasks are not trivial, and are time-consuming. Likewise time-consuming is the task to reliably explore a parametric space of several Wilson coefficients. In order to explore as many different NP models as possible, it will be necessary to develop methods to automate the calculations. Work is on-going in this direction [35].

Tools to recast the constraints from the LHC high-p_T searches will also have to be used to obtain constraints on models under investigation. To reinterpret the available results, it is necessary to identify topologies similar to the ones used in the LHC analyses, simulate events with a Monte Carlo generator, estimate backgrounds, apply experimental cuts, simulate the detector response, and compare the results with the experimental data via likelihood maps. Similar tools can be used to study new channels, which can then be searched for at colliders.

Another constraint on NP scenarios concern dark-matter searches. Further constraints can also be considered, depending on the specific NP scenarios that explain the flavour data. In particular, if these scenarios involve CP violation, electric dipole moments can set strong constraints. These models may even involve novel avenues towards baryogenesis.

7 Link with direct searches

The existence of lepton flavour universality violation, if confirmed, should eventually leave imprints in direct searches as well. The most obvious one would be inclusive measurements yielding different multiplicities for different charged leptons. However, different leptons are characterized by different acceptance and reconstruction efficiencies, which, if not accounted properly, would produce instrumental non-universality even in the presence of flavour universal couplings. For instance for a 5 TeV resonance with 0.1 fb production cross-section at 14 TeV, an assumption of 15(5)% branching fraction to muons (electrons) roughly leads to the same individual signal sensitivity. This is due to the fact that the dilepton mass resolution is worse in the case of muon pairs than it is for electron pairs. Resonances reconstructed from electrons are accordingly narrower, implying that a much greater fraction of the signal points are accumulated around the mass of the resonance. Correspondingly the ratio of signal to background multiplicities around the resonance is better for the electron. The separation of 'physical' non-universality, induced by different couplings, from the detector-induced non-universality necessitates the definition of adequate statistical tests [36], and particular care has to be taken to avoid experimental ambiguities.

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