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Opportunities From Precision Flavour Physics

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The possible role of precision flavour physics, and particularly of B physics, in the next decade is briefly discussed. A few 2–3σ deviations from the Standard Model found in present B data are reviewed as potential forerunners of new physics signals to be looked for in next-generation experiments. The prospects for theoretical calculations, in particular those based on lattice QCD, to match the expected progress in experimental precision are also presented.

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1. Introduction

The role and purpose of flavour physics, and particularly B physics, need to be reassessed after the end of the B factories and the advent of the LHC era. In the past ten years, B physics focused on the determination of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1] parameters within the Standard Model (SM), trying (successfully) to confirm experimentally the Kobayashi-Maskawa mechanism for CP violation. Nowadays this task is accomplished: the phase in the CKM matrix is the dominant source of CP violation in meson decays. In spite of this success, the SM still gives a phenomenological description of flavour and CP violation without providing any explanation of these phenomena. A more fundamental theory of flavour and CP violation beyond the SM and is missing at present.

In any case, the search for physics beyond the SM through virtual effects in flavour-changing neutral current (FCNC) and CP-violating processes always remained the goal-of-choice for flavour physics, taking advantage of the multiple suppression factors (GIM mechanism [2], weakly-coupled loops, small mixing angles, etc.) that characterize these processes in the SM. Indeed, already present data put strong bounds on flavour and CP violation beyond the SM. In particular, kaon data (and to a lesser extent D data [3]) require either a New Physics (NP) scale well beyond the TeV region or a mechanism to suppress the flavour- and CP-violating couplings [4]. In other words, sensitivity to the exchange of particles with masses in the multi-TeV range (and even beyond) and/or possibility to put non-trivial contraints on the NP Lagrangian characterize flavour physics in general.

As far as B physics is concerned, present data are less constraining, given the larger experimental errors and the larger SM contributions with their theoretical uncertainties. For example, the B_d mixing amplitude can still accomodate loop contributions from weakly-coupled particles lighter than 1 TeV [4]. Yet B physics has the clear advantage that many channels sensitive to NP contributions of different origin are available, allowing the exploration of a broad range of NP options. Furthermore, one can argue that NP should more likely affect the third generation. For instance, in many SUSY-GUT scenarios, large neutrino mixing angles imply large flavour-changing transitions between the third and the second generation [5].

In the next decade, B physics will fully enter the precision measurement era moving from the “10%” to the “1%” typical accuracy and improving experimental sensitivities by an order of magnitude. The accessible NP scale will be pushed in the multi-TeV region with NP possibly already having been discovered by direct searches at the LHC. In any case, B physics could provide a crucial contribution to the NP search and characterization.

Assuming that one order-of-magnitude improvement in experimental precision will allow us to detect NP contributions to B transtions, a first reasonable question is whether we should not be start seeing some deviations today. Indeed, a few 2–3σ deviations from the SM are found in present B data. They could be the forerunners of actual new physics signals. In Section 2 we present the most promising ones.

A second crucial question is whether the theoretical calculation of the Standard Model amplitudes is precise enough not to hinder NP contributions irrespective of the experimental achievements. In particular, hadronic uncertainties need to be controlled at the $\mathcal{O}(1\%)$ level. Although there are “theoretically clean” measurements which can provide unambiguous signals of NP with-

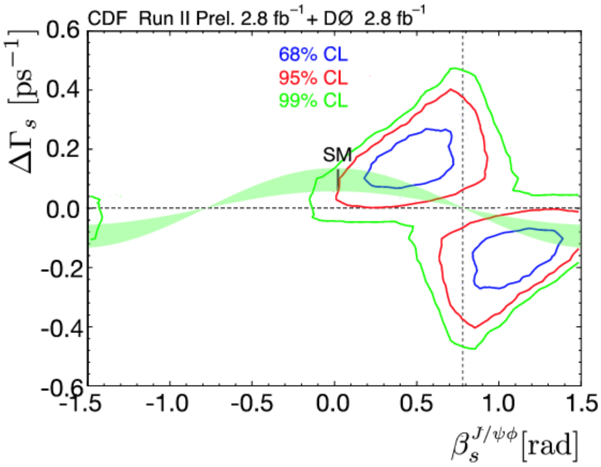

Figure 1: 68%, 95% and 99% confidence regions in the $\beta_s^{J/\psi\phi}$–$\Delta\Gamma_s$ plane ($\beta_s^{J/\psi\phi} = -\phi_s$) from the preliminary combination of the CDF and DØ results [8].

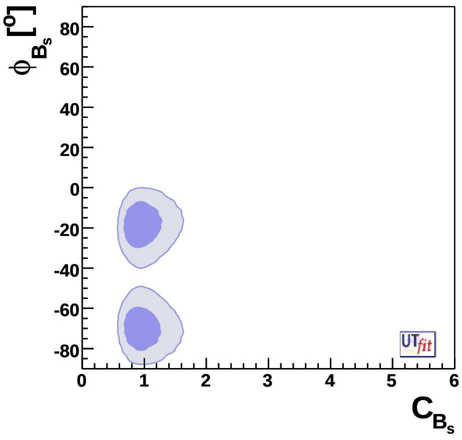

Figure 2: 68% (dark) and 95% (light) probability regions in the NP parameter space (C_{B_s}, ϕ_{B_s}).

out relying on theoretical inputs, a systematic study of the NP flavour structure needs a precise determination of several hadronic parameters. The precisions reachable in the next years by non-perturbative methods, particularly lattice QCD, are critically reviewed in Section 3 and compared with the requirements coming from the next-generation experiments in B physics.

2. Deviations From The Standard Model In *B* Physics

Overall, flavour data are in excellent agreement with the SM expectation at the present level of accuracy. Yet there are a few processes showing 2-3σ deviations which could be the harbringers of NP signals. Certainly, the importance of these effects should not be overemphasized, as low-significance deviations could result from statistical fluctuations, which are expected in the presence of several different measurements. However, these are processes potentially sensitive to NP contributions. In particular, the observed deviations are expected in several interesting NP scenarios. Therefore, while it is premature to get excited about NP, it is certainly worth keeping an eye on these processes.

The first herald of NP we consider is the phase $2\phi_s$ of the B_s mixing amplitude. In the SM (with the CKM phase convention), this phase is very small. It is given by $2\phi_s = -2\beta_s = -0.041 \pm 0.004$, where the angle $\beta_s = \arg\left(-(V_{tb}^* V_{ts})/(V_{cb}^* V_{cs})\right)$ is precisely determined by the Unitarity Triangle (UT) fit [6]. A NP amplitude carrying a new CP-violating phase contributing to the B_s mixing can drastically change this prediction.

Recently, a time-dependent angular analysis of $B_s \to J/\psi\phi$ was performed at the Tevatron [7, 8]. From this measurement, one can extract a combined determination of $\Delta\Gamma_s$ and $\beta_s^{J/\psi\phi}$. The angle $\beta_s^{J/\psi\phi}$ is $-\phi_s$ up to doubly-Cabibbo-suppressed terms. In the same approximation the B_s mixing phase vanishes, so that a large $\beta_s^{J/\psi\phi}$ is a clean NP signal. The combination of the CDF and DØ measurement is shown in fig. 1. The combined measurement is found to be compatible with the SM at 2.12σ.

The UTfit collaboration combined in a Bayesian fit the available results on $B_s \to J/\psi\phi$ from the Tevatron with other constraints coming from $\Delta\Gamma_s$, the B_s lifetime in flavour-specific final states, the dimuon charge asymmetry and the semileptonic asymmetry using theoretical correlations among the observables under the assumption that NP contributions to tree-level dominated processes are negligible.

Using also with the measurement of mass difference Δm_s, one can find a bound on the NP contribution to the B_s mixing amplitude. This contribution can be described by the parameters C_{B_s} and ϕ_{B_s} defined as

$$C_{B_s} e^{2i\phi_{B_s}} = \frac{\langle B_{d,s}|H_{eff}^{full}|\bar{B}_{d,s}\rangle}{\langle B_{d,s}|H_{eff}^{SM}|\bar{B}_{d,s}\rangle} = \frac{\Delta m_s}{\Delta m_s^{\rm SM}} e^{2i(\phi_s+\beta_s)} . \quad (2.1)$$

Perfoming a full fit [9], one gets the allowed regions in Figure 2. The deviation from the SM goes up to 2.9σ [10, 9]. Notice that confirmed evidence for a new CP-violating phase would rule out the class of models with minimal flavour violation [11], with intriguing implications for the NP flavour structure, in particular if new particles are found at the LHC.

For these reasons, the B_s mixing phase is bound to play a major role in the indirect searches for NP in upcoming years. Indeed the NP contribution to this phase could still be much larger than the SM one. If this is the case, its determination is a null test of the SM, almost free of theoretical uncertainty. A 5σ measurement of ϕ_s could even be possible at the Tevatron, if the present central value is confirmed. In any case, this is one of the flagship measurement of LHCb, which should be sensitive to a value of ϕ_s as small as to few degrees. For such values, however, theoretical uncertainties coming from subleading amplitudes cannot be neglected anymore and could limit the accuracy achievable on ϕ_s.

Another NP-sensitive decay showing a potentially interesting deviation from the SM prediction is $B \to \tau\nu$. The measured branching ratio is [12]

$$BR_{\rm exp}(B \to \tau\nu) = (1.73 \pm 0.34) \times 10^{-4} . \quad (2.2)$$

while the SM prediction is given by

$$BR(B \to \tau\nu) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B . \quad (2.3)$$

The Fermi constant G_F, the B (τ) mass m_B (m_τ) and the B lifetime τ_B are precisely measured. The main sources of theoretical uncertainties are the B meson decay constant f_B and the CKM matrix element $|V_{ub}|$. In the following, $\overline{BR}$ denotes the prediction obtained with eq. 2.3. It coincides with the SM prediction if $|V_{ub}|$ and f_B are determined with NP-insensitive methods. Otherwise, the deviation of $\overline{BR}$ from the measurement shows the presence of a non-standard contribution to the $B \to \tau\nu$ amplitude within the NP scenario used to determine $|V_{ub}|$ and f_B.

The status of the comparison between the measurement in Eq. (2.2) and the theoretical prediction $\overline{BR}$ is summarized in the following Table 1 from Ref. [6].

In the "no-fit" scenario, one uses the determination of f_B from lattice QCD and $|V_{ub}|$ from the average of inclusive and exclusive $b \to u$ semileptonic decays (involving theoretical input from operator product expansion techniques in the inclusive case and a combination of lattice QCD and QCD sum rules in the exclusive ones). This scenario uses a NP-independent determination

scenario	$\|V_{ub}\| \times 10^4$	f_B (MeV)	$\overline{BR} \times 10^4$	pull
no-fit	36.7 ± 2.1	200 ± 20	0.98 ± 0.24	1.8σ
UUT	35.0 ± 1.2	200 ± 20	0.87 ± 0.20	2.2σ
UT	35.2 ± 1.1	196 ± 11	0.84 ± 0.11	2.5σ

Table 1: Results for $|V_{ub}|$, f_B, $\overline{BR}$ and the pull between $\overline{BR}$ and $BR(B \to \tau\nu)_{\rm exp}$ in different scenarios (see text).

(neglecting presumably small NP contributions to tree-level semileptonic decays) of the theoretical inputs and is therefore appropriate to measure generic non-standard contributions to the $B \to \tau\nu$ decay amplitude. As shown in Table 1, the significance of the deviation from the SM, given by the presence of a non-standard $B \to \tau\nu$ amplitude, is rather small (1.8σ), partly due to the uncertainty of the SM prediction which is not negligible with respect to the experimental error.

However, if we are generically interested in a deviation from the SM, whatever the origin is, then we can do better exploiting the SM correlations among flavour observables. Using the SM UT fit, the determination of both $|V_{ub}|$ and f_B can be improved [13], resulting in a more precise SM prediction for $BR(B \to \tau\nu)$ and therefore an increased sensitivity to possible deviations. Indeed, the UT scenario in Table 1 shows that the errors of $|V_{ub}|$ and f_B are halved by using the SM UT. As a consequence, the significance of the discrepancy between the measurement and the prediction of $\overline{BR}$ increases to 2.5σ.

Of course, there is a price to pay for the larger significance. We can no longer disentangle a genuine NP effect in the decay amplitude from a deviation from the scenario adopted in the UT fit. This a good example of the dual role of flavour physics in NP studies. On the one hand, flavour physics can be used to look for significant deviations from the SM regardless of the details of the NP involved. Potentially, it is very effective in accomplishing this task as the only requirement is to compute the flavour observables as precisely as possible in the SM, fully exploiting the SM correlations to reduce the uncertainties. Indeed, should NP escape detection from direct searches at the LHC, flavour physics could still provide evidence that the NP scale is not too far away. On the other hand, if some information about NP is known, hopefully from high p_T physics, then the study of flavour physics can provide unique insights on the structure of the underlying NP model. Admittedly, this is a difficult and long-term program for which we need to rely on theory in order to control the uncertainties that could reduce the possibility for flavour physics to disentangle different NP scenarios.

The case marked as "UUT" in Table 1 corresponds to an intermediate scenario: NP is allowed to enter the UT fit provided it is of minimal flavour violation type. In this case, correlations are less stringent so that the UT fit decreases only the error of $|V_{ub}|$. Thus the prediction of $\overline{BR}$ is not as precise as in the previous case and the significance of its deviation from the measured value is reduced to 2.2σ.

This is the appropriate case to discuss, as a concrete example, the type-II 2 Higgs Doublet Model (2HDM-II) [14]. In this model, one simply obtains

$$BR(B \to \tau\nu) = BR(B \to \tau\nu)_{\rm SM} \left(1 - \tan^2\beta \frac{m_B^2}{m_{H^+}^2}\right)^2 , \tag{2.4}$$

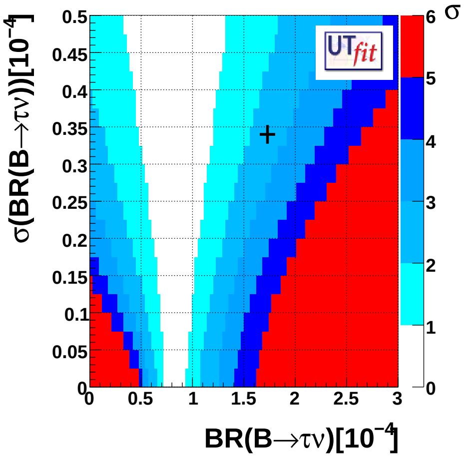

Figure 3: Compatibility plot for $BR(B \to \tau\nu)$. The cross marks the current world average. Colours give the agreement (in number of σ) with the data-driven SM prediction.

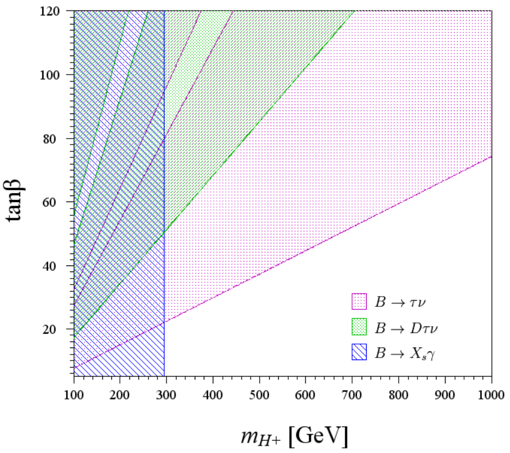

Figure 4: Regions in the $(m_{H^+}, \tan\beta)$ parameter space of the 2HDM-II excluded at 95% probability by $BR(B \to \tau\nu)$, $BR(B \to D\tau\nu)/BR(B \to D\ell\nu)$ and $BR(B \to X_s\gamma)$.

where m_{H^+} is the mass of the charged Higgs boson and $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets. From Eq. 2.4, one can see that the charged Higgs contribution typically suppresses the SM prediction of $BR(B \to \tau\nu)$. As the experimental average is larger than the SM prediction, a bound on the ratio $\tan\beta/m_{H^+}$ is obtained. Figure 4 shows the bounds in the $(m_{H^+}, \tan\beta)$ parameter space induced by the constraints coming from the measurements of $BR(B \to \tau\nu)$, $BR(B \to D\tau\nu)/BR(B \to D\ell\nu)$ and $BR(B \to X_s\gamma)$ are shown. Combining these three measurements, one gets the following bound with 95% probability [6]:

$$\tan\beta < 7.4 \frac{m_{H^+}}{100\,\mathrm{GeV}}\,, \tag{2.5}$$

together with $m_{H^+} > 295$ GeV. Following Ref. [6], one can make a prediction for $BR(B_s \to \mu^+\mu^-)$, another flagship measurement of LHCb, finding

$$\begin{aligned} BR(B_s \to \mu^+\mu^-) &= (4.3 \pm 0.9) \times 10^9 \\ &\quad ([2.5, 6.2] \times 10^9 \text{ @95\% probability}) \end{aligned} \tag{2.6}$$

The 95% upper bound in Eq. (2.6) is stronger than the present upper limit from direct searches at the Tevatron, $BR(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-8}$ at 95% C.L. [15]. Yet, the latter will be certainly improved by LHCb which is expected to probe this branching ratio down to the SM value, $BR(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.7 \pm 0.5) \times 10^{-9}$.

The last deviation from the SM we want to discuss is located in the UT fit. The present result of the SM UT fit is shown in Figure 5 together with the 95% probability regions selected by the various constraints [6]. Clearly some constraints, in particular those coming from the measurements of the CP-violating parameters $\sin 2\beta$ and ε_K, do not perfectly overlap. This can be seen as a deviation of the measured $\sin 2\beta$ from the value selected by the other constraints (alternatively, one can consider

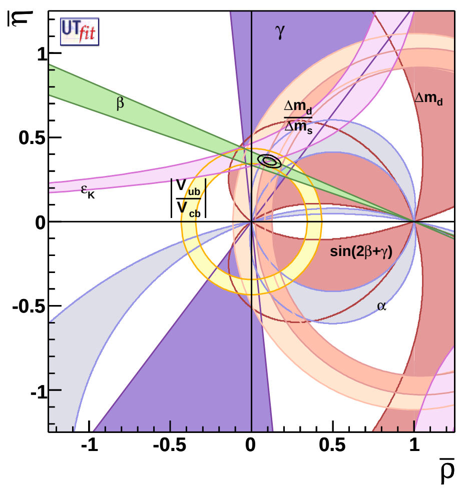

Figure 5: Result of the UT fit within the SM. The contours display the 68% and 95% probability regions selected by the fit in the $(\bar{\rho},\bar{\eta})$ plane. The 95% probability regions selected by the single constraints are also shown.

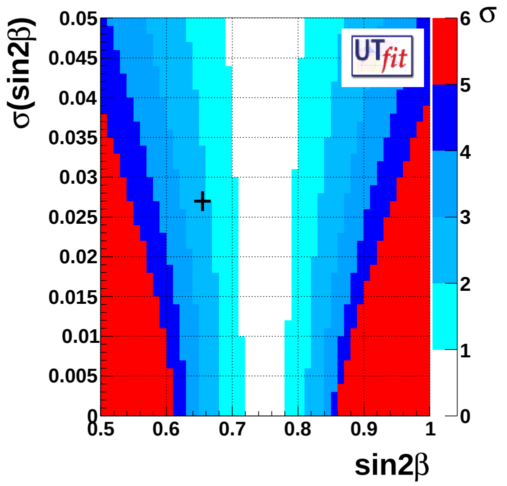

Figure 6: Compatibility plot for $\sin 2\beta$. The cross marks the current world average. Colours give the agreement (in number of σ) with the data-driven SM prediction.

the difference between the fit and the lattice determinations of the bag parameter B_K entering ε_K). The significance of this deviation is shown in Figure 6. The value $\sin 2\beta_{\mathrm{J}/\psi\mathrm{K}} = 0.655 \pm 0.027$, measured from time-dependent *CP* asymmetry in in the decays $B \to J/\psi K$, deviates from the UT fit determination (not including $\sin 2\beta_{\mathrm{J}/\psi\mathrm{K}}$) $\sin 2\beta_{\mathrm{fit}} = 0.751 \pm 0.035$ at about 2.2σ.

Actually, $\sin 2\beta_{\mathrm{J}/\psi\mathrm{K}}$ has always been somewhat smaller than $\sin 2\beta_{\mathrm{fit}}$ and this "tension" was already observed some years ago. However, this effect reduced with time and furthermore it could be almost entirely ascribed to theoretical uncertainties in the determination of $|V_{ub}|$ from inclusive decays [13]. Recently this issue was revived by the combined effect of the increasing precision of B_K computed on the lattice and a reanalysis of the theoretical expression of ε_K [16, 17]. In Ref. [17] it was pointed out that some approximations commonly used in the formula for ε_K are no longer justified. In particular, the theoretical expression of ε_K used a fixed value of $\pi/4$ for the phase δ_0 of the $K \to \pi\pi$ $\Delta I = 1/2$ amplitude A_0 and neglected a subleading (in the CKM convention) term proportional to $\mathrm{Im}A_0/\mathrm{Re}A_0$. Indeed, using the measured value of δ_0 and the value of $\mathrm{Im}A_0/\mathrm{Re}A_0$ estimated using $(\varepsilon'/\varepsilon)_K$, the theoretical prediction of ε_K is reduced by about 8% and the corresponding constraint in the $(\bar{\rho},\bar{\eta})$ plane is shifted upward.

This is a good example of how indirect NP searches should work. With the reduction of experimental and theoretical uncertainties, the sensitivity to NP contributions increases and discrepancies could appear in observables previously compatible with the SM. Clearly, in the case of ε_K, it is premature to draw any conclusion: not only is the statistical significance low, but also there are other neglected terms in the theoretical expression for ε_K, such as power-suppressed terms of $\mathcal{O}(m_K/m_c)^2$, which could be non-negligible as well.

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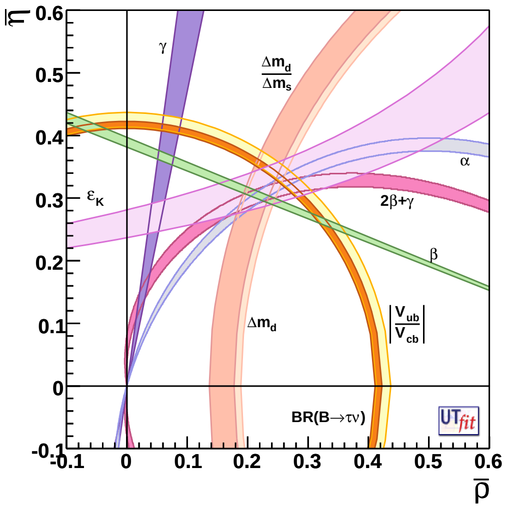

Figure 7: UT fit within the SM extrapolated using expected results from next-generation flavour experiments and future lattice QCD calculations (see text). Central values of the constraints are chosen from the present UT fit. The contours display the 68% and 95% probability regions selected by the fit in the $(\bar{\rho},\bar{\eta})$-plane. The 95% probability regions selected by the single constraints are also shown.

3. The Future Of Hadronic Uncertainties

There are flavour observables, such as ϕ_s in the previous section, wich are sensitive to NP irrespective of theory uncertainties (at least to some extent). In other cases, as for $BR(B \to \tau\nu)$, the theory error can be reduced with the help of additional measurements. Yet, in order to exploit the full power of flavour physics for NP search and, even more, characterization, improved theory predictions are essential. In particular, hadronic uncertainties need to be controlled with an unprecendented accuracy. We can consider for example the UT analysis. An extrapolation of the UT fit using the expected precision of next-generation flavour experiments is shown in Figure 7 [18, 19, 20].

This Figure is obtained using the extrapolation of lattice results in Table 2 taken from the Appendix of Ref. [20]. The study presented there showed that the lattice predictions for the hadronic parameters entering the UT fit could reach a $\mathcal{O}(1\%)$ precision as the available computer power will reach a few PFlops, namely within 5-10 years.

Comparing the fourth and fifth columns of Table 2, it is reassuring to see that the results obtained after three years followed the extrapolations of Ref. [20] quite well, with only one exception due to the lack of new studies for that parameter. Lattice QCD seems able to keep up with the upcoming progress expected from next-generation flavour physics experiments, allowing to fully exploit their potential in searching for and constraining NP.

However, lattice QCD is unable compute hadronic parameters relevant for several important observables. For example, inclusive modes in semileptonic B decays rely on the heavy quark expansion. For this class of decays, it seems unlikely that theory alone could be able to reach the required accuracy, due to the difficulties related to computing matrix elements of subleading operators. On the other hand, data can be used to control the unknown terms. The perspectives for

Measurement	Hadronic Parameter	Status End 2006	6 TFlops (Year 2009)	**Status End 2009**	60 TFlops (Year 2011)	1-10 PFlops (Year 2015)
$K \to \pi l \nu$	$f_+^{K\pi}(0)$	0.9 %	0.7 %	0.5 %	0.4 %	$<$ 0.1 %
ε_K	$\hat{B}_K$	11 %	5 %	5 %	3 %	1 %
$B \to l \nu$	f_B	14 %	3.5-4.5 %	5 %	2.5-4.0 %	1.0-1.5 %
Δm_d	$f_{Bs}\sqrt{B_{B_s}}$	13 %	4-5 %	5 %	3-4 %	1-1.5 %
$\Delta m_d/\Delta m_s$	ξ	5 %	3 %	2 %	1.5-2 %	0.5-0.8 %
$B \to D/D^* l \nu$	$\mathscr{F}_{B \to D/D^*}$	4 %	2 %	2 %	1.2 %	0.5 %
$B \to \pi/\rho\, l \nu$	$f_+^{B\pi}, \ldots$	11 %	5.5-6.5 %	11 %	4-5 %	2-3 %
$B \to K^*/\rho\, (\gamma, l^+ l^-)$	$T_1^{B \to K^*/\rho}$	13 %	——	13 %	——	3-4 %

Table 2: Prediction of the accuracy on the lattice QCD determinations of various hadronic parameters from the Appendix of Ref. [20]. The fifth column has been added following the update of Ref. [21].

reaching a target accuracy of a few percent are encouraging [22].

Finally, two-body non-leptonic B decays looks more problematic as far as hadronic uncertainties are concerned. When applicable, predictions are based on some formulation of factorization valid in the infinite mass limit [23]. Also in these cases, accuracy is limited by uncalculable power-suppressed terms. The strategy of using data typically requires the use of flavour symmetries, which however have a theoretical uncertainty themselves which cannot be precisely estimated. For these reasons, precision flavour physics with non-leptonic decays is particularly difficult. Each decay mode requires a careful assessment of the involved hadronic uncertainties which otherwise could mask or fake a NP signal.

4. Conclusions

In these proceedings, we have discussed a few processes which already show a 2-3σ deviation from the SM which could be the forerunners of new physics signals for the next-generation flavour experiments. Indeed, the era of precision flavour physics is already starting with LHCb at the LHC and will likely continue in the next decade with a super flavour factory [19]. Identification and characterization of new physics in the TeV and multi-TeV regions are the achievable goals, exploiting the rich phenomenology of B, D and K decays, together with lepton flavour violation, to probe many different NP scenarios. To fully pursue this program, a substantial reduction of theoretical uncertainties would be of great help. Theory will have hard (but stimulating) time trying to keep up with the expected experimental progress on a 10-year scale. Yet, as the case of lattice QCD seems to prove, the mission is not impossible. Flavour physics is ready to move to the precision era and play its part in challenging the SM harder and harder.

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