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The Role of Flavor in ~~2016~~ 2026

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This talk explores the role of flavor physics to constrain beyond standard model phenomena and future prospects, from a theoretical point of view. Possible implications of some experimental results in tension with the standard model are discussed, such as the 4σ deviation in the $B \to D^{(*)}\tau\bar{\nu}$ decay rates. We use the examples of constraining new physics contributions to neutral meson mixing and the search for possible vector-like fermions to illustrate the expected progress over the next decade to increase the sensitivity to new physics at shorter distance scales. We also speculate about the ultimate limitations of (quark) flavor physics probes of new physics.

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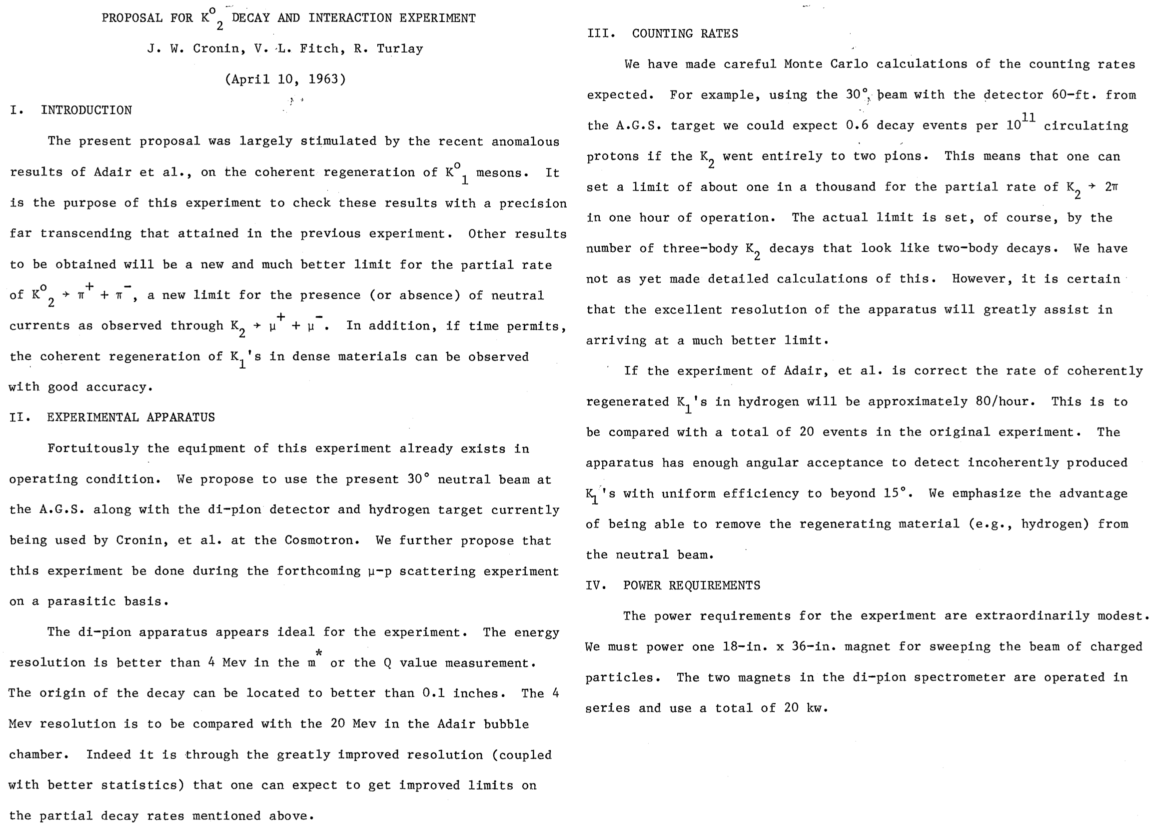
1. Introduction

I was asked to talk about the role of flavor physics to constraint new physics (NP). This is a subject on which there are many different views. Especially now, near the end of 2016, the prospects may seem both very bright and somewhat gloomy. One the one hand, $K^0-\overline{K}^0$ mixing, and in particular Δm_K and ε_K continue to provide some of the best constraints on NP, unchanged for about 50 years now. At the same time, the LHC had an amazing year collecting more than 10 times the data at 13 TeV than in 2015. This will yield a significant increase in the sensitivity to the NP mass scale (at the time of CKM 2016, or writing this proceedings, we know only the lack of rumors about discoveries using the 2016 data). After 2016, however, the next similarly significant increase in sensitivity will take many years. In flavor physics, NA62 took data in 2016 and by the end of this decade $K^+ \to \pi^+ \nu\bar{\nu}$ should be measured at the 10% level if it is near the SM expectation, Belle II is rapidly approaching, the LHCb late 2020s upgrade discussion toward 300/fb is gaining momentum, and there are also bright prospects for significantly improved sensitivities in electric dipole moment and charged lepton flavor violation experiments. So we can look forward to the guaranteed excitement of the upcoming flood of new data, with many opportunities for groundbreaking discoveries, definitely testing and understanding the SM much better, as well as face the uncertainties when NP may be discovered in laboratory experiments.

Going back to the basics, it is important to remember that the SM does not contain a dark matter candidate, nor can it explain the observed baryon asymmetry of the Universe. The solutions of these problems may be connected to the TeV scale, e.g., the weakly interacting massive particle paradigm and electroweak baryogenesis, but there are many other options, and there are no guarantees of accessible discoveries. We also discovered that neutrinos were massive; however, the implications of this crucially depend on unraveling whether neutrino mass terms do or do not violate lepton number (“Majorana vs. Dirac"). This leaves the hierarchy puzzle as the clearest connection between the incompleteness of the SM and our hope to be able to discover NP at the TeV scale. If the SM is valid to much higher energy scales than currently probed, we do not understand why the Higgs particle is so light. And if there is low energy supersymmetry, the 126 GeV Higgs mass seems a bit too high. So the situation is confusing and also exciting; or quoting Feynman, “I think it’s much more interesting to live not knowing than to have answers which might be wrong." Not to mention that given the evidence for a nonzero cosmological constant, one may wonder if even the right questions are being asked about fine tuning [1].

In any case, the key question is: What is the scale of NP? Theoretical prejudices of the 1990s, when it was often discussed how SUSY cascades would cause problems to understand LHC signals, now appear wishful thinking. At the same time, the evidence for the incompleteness of the SM is compelling, so in searching for NP, we should leave no stone unturned. The hierarchy puzzle might indeed tell us that the NP scale is connected to the electroweak scale, however, most physicists’ measures of fine tuning may be off, and NP could be $1-2$ orders of magnitude heavier than the electroweak scale. In this case, flavor physics may be an even more powerful probe of new physics, and its role in setting future directions even more crucial. If NP is within the reach of the LHC, its flavor structure probably has to be fairly similar to that of the SM, and minimal flavor violation (MFV) is probably a useful notion as a starting point. If NP is pushed to the $10-100$ TeV scale, then the suppressions of flavor-changing neutral currents (FCNCs) need to be less strong, and



PROPOSAL FOR K^o_2 DECAY AND INTERACTION EXPERIMENT

J. W. Cronin, V. L. Fitch, R. Turlay

(April 10, 1963)

I. INTRODUCTION

The present proposal was largely stimulated by the recent anomalous results of Adair et al., on the coherent regeneration of K^o_1 mesons. It is the purpose of this experiment to check these results with a precision far transcending that attained in the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K^o_2 \to \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \to \mu^+ + \mu^-$. In addition, if time permits, the coherent regeneration of K_1's in dense materials can be observed with good accuracy.

II. EXPERIMENTAL APPARATUS

Fortuitously the equipment of this experiment already exists in operating condition. We propose to use the present 30° neutral beam at the A.G.S. along with the di-pion detector and hydrogen target currently being used by Cronin, et al. at the Cosmotron. We further propose that this experiment be done during the forthcoming μ-p scattering experiment on a parasitic basis.

The di-pion apparatus appears ideal for the experiment. The energy resolution is better than 4 Mev in the m^* or the Q value measurement. The origin of the decay can be located to better than 0.1 inches. The 4 Mev resolution is to be compared with the 20 Mev in the Adair bubble chamber. Indeed it is through the greatly improved resolution (coupled with better statistics) that one can expect to get improved limits on the partial decay rates mentioned above.

III. COUNTING RATES

We have made careful Monte Carlo calculations of the counting rates expected. For example, using the 30° beam with the detector 60-ft. from the A.G.S. target we could expect 0.6 decay events per 10^{11} circulating protons if the K_2 went entirely to two pions. This means that one can set a limit of about one in a thousand for the partial rate of $K_2 \to 2\pi$ in one hour of operation. The actual limit is set, of course, by the number of three-body K_2 decays that look like two-body decays. We have not as yet made detailed calculations of this. However, it is certain that the excellent resolution of the apparatus will greatly assist in arriving at a much better limit.

If the experiment of Adair, et al. is correct the rate of coherently regenerated K_1's in hydrogen will be approximately 80/hour. This is to be compared with a total of 20 events in the original experiment. The apparatus has enough angular acceptance to detect incoherently produced K_1's with uniform efficiency to beyond 15°. We emphasize the advantage of being able to remove the regenerating material (e.g., hydrogen) from the neutral beam.

IV. POWER REQUIREMENTS

The power requirements for the experiment are extraordinarily modest. We must power one 18-in. x 36-in. magnet for sweeping the beam of charged particles. The two magnets in the di-pion spectrometer are operated in series and use a total of 20 kw.

Figure 1: The proposal for the experiment that discovered *CP* violation in 1964. (It's legible if you zoom in.)

MFV becomes less motivated. In either case, discovering deviations from the SM in the next generation of flavor physics experiments is possible, either from LHC-scale NP with SM-like flavor structure, or from heavier NP with more generic flavor properties. Any discovery inconsistent with the standard model would put a (rough) upper bound on the scale of new physics, which would in turn crucially impact future directions both in high energy theory and experiment.

Equally importantly, it is hard to anticipate the truly unexpected discoveries, and one should indeed test all exact and approximate conservation laws as precisely as possible, especially when the experimental sensitivity can substantially increase. After all, the discovery of *CP* violation itself was also a surprise, in an experiment whose primary goal was to check an anomalous kaon regeneration result (read Fig. 1, it is fascinating). Thus, searches for lepton flavor violation, possible dark sectors in many channels, are also important parts of future flavor experiments.

In fact, similar surprises did occur at BaBar and Belle — discovering a suite of new hadronic states. One of the most cited BaBar papers is the discovery of the excited $D_{sJ}^*(2317)$ meson with a mass much below prior expectations [2], and the most cited Belle paper is the discovery of the unexpectedly narrow charmonium-like state $X(3872)$ [3] (which will soon surpass in citations the ARGUS discovery of $B^0 - \overline{B}^0$ oscillation [4] — so much for using citations as a measure...).

Section 2 summarizes the current status of (quark) flavor physics and reviews some tensions with the SM predictions. These are some of the most often discussed topics recently, and they are also interesting because they may have the best chance to be established as clear deviations

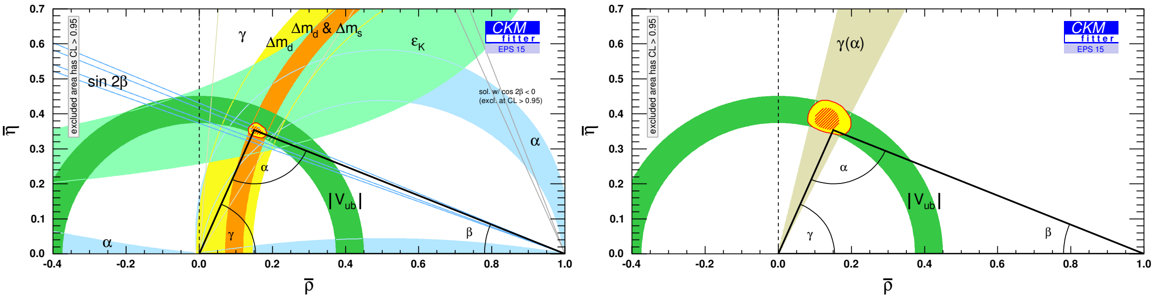


Figure 2: The standard model CKM fit and individual constraints (left); the CKM fit allowing for new physics in $B^0 - \bar{B}^0$ mixing (right) [5]. The colored regions show 95% CL.

from the SM, as more data is accumulated. Section 3 gives some examples of the expected future progress and improvements in sensitivity to NP, independent of the current data. Section 4 contains some comments on the ultimate sensitivity of flavor physics experiments to new physics.

2. Current status and near future

A detailed introduction to flavor physics is omitted here, as well as a review of the determinations of CKM elements; see, e.g., Refs. [6, 7]. The magnitudes of CKM elements are extracted mainly from semileptonic and leptonic K, D, and B decays, and $B_{d,s}$ mixing. These determine the sides of the unitarity triangle shown in Fig. 2 (left), which is a convenient way to compare many constraints on the SM and visualize the level of consistency. Any constraint which renders the area of the unitarity triangle nonzero, such as nonzero angles (mod π), has to measure *CP* violation. Some of the most important measurements are shown in Fig. 2 (left), together with the CKM fit in the SM. (The notation $\bar\rho$, $\bar\eta$ instead of ρ, η corresponds to a small modification of the Wolfenstein parametrization, to keep unitarity exact.) While there is good consistency, that does not address how large new physics contributions are allowed. As we see below, in the presence of new physics the fit becomes less constrained, as shown in Fig. 2 (right), and $\mathcal{O}(20\%)$ NP contributions to most FCNC processes, relative to the SM, are still allowed.

Several measurements show intriguing deviations from the SM predictions. Some of those that reach the $2-4\,\sigma$ level are depicted schematically in Fig. 3. The horizontal axis shows the nominal significance and the vertical axis relates to the theoretical cleanliness of the SM predictions. What I mean is some (monotonic) measure of the plausibility that a conservative estimate of the theory uncertainty may affect the overall significance by 1σ. All of these are frequently discussed, some have triggered hundreds of papers, and could each be the subjects of entire talks.

Currently, the $B \to D^{(*)}\tau\bar\nu$ rates, specifically the $R(D^{(*)}) = \Gamma(B \to D^{(*)}\tau\bar\nu)/\Gamma(B \to D^{(*)}l\bar\nu)$ ratios (where $l = e,\, \mu$) constitute the most significant discrepancy from the SM in collider experiments [8, 9, 10, 11, 12, 13] (aside from neutrino masses). The effect is at the 4σ level [14]. Figure 4 shows the current data, the SM expectations, as well as the expected Belle II sensitivity. These measurements show good consistency with one another. The theory is also on solid footing, since heavy quark symmetry suppresses model independently the hadronic physics needed for the SM prediction, most of which is constrained by the measured $B \to D^{(*)}l\bar\nu$ decay distributions.

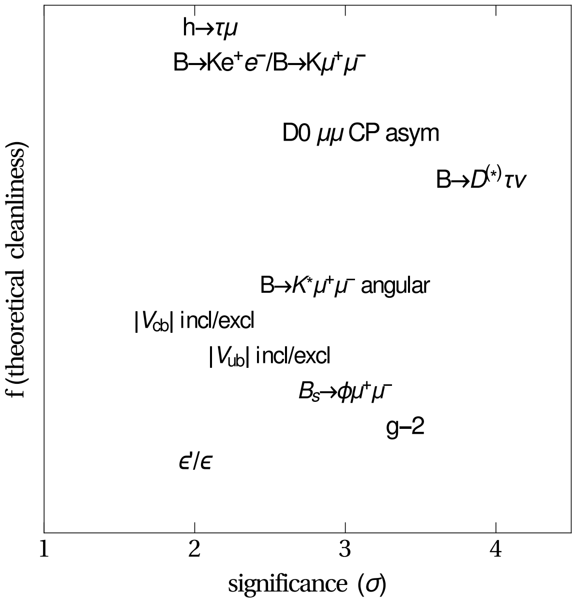


Figure 3: Some recent measurements in tension with the SM. The horizontal axis shows the nominal significance. The vertical axis shows (monotonically, in my opinion) an undefined function of an ill-defined variable: the theoretical cleanliness. That is, the level of plausibility that a really conservative estimate of the theory uncertainty of each observable may affect the significance of its deviation from the SM by 1σ.

	$R(D)$	$R(D^*)$
World average	0.403 ± 0.047	0.310 ± 0.017
SM expectation [15]	0.299 ± 0.005	0.257 ± 0.005
Belle II, 50/ab	± 0.010	± 0.005

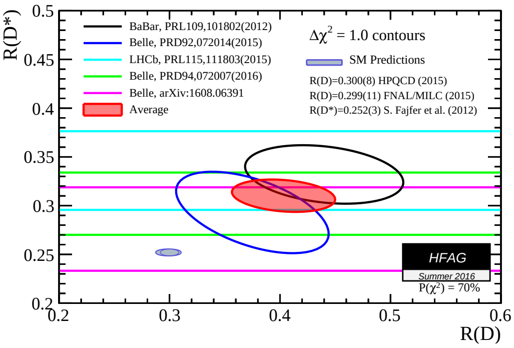


Figure 4: Left: measurements of $R(D^{(*)})$ [8, 10, 11, 12, 13], their averages [14], the SM predictions [15, 16, 17, 18], and future sensitivity [19]. Right: the measurements, world average (red), and SM prediction.

It is somewhat surprising to find so large deviations from the SM in processes which occur at tree level. The central values of the current world averages would imply that there has to be new physics at or below the TeV scale. Some scenarios are excluded by LHC Run 1 bounds already, and more will soon be constrained by the Run 2 data. To fit the current central values, mediators with leptoquark or W' quantum numbers are preferred, compared to scalars. Leptoquarks are favored if one requires the NP to be minimally flavor violating (MFV), which helps explain the absence of other flavor signals and suppress direct production of the new particles at the LHC from partons abundant in protons [20]. Currently the “simplest" models that fit the data modify the SM four-fermion operator (after Fierzing), and then the τ polarization is not affected, in agreement with its first measurement [13]. There are even viable scenarios in which $B \to D^{(*)}\tau\bar{\nu}$ are SM-like, but

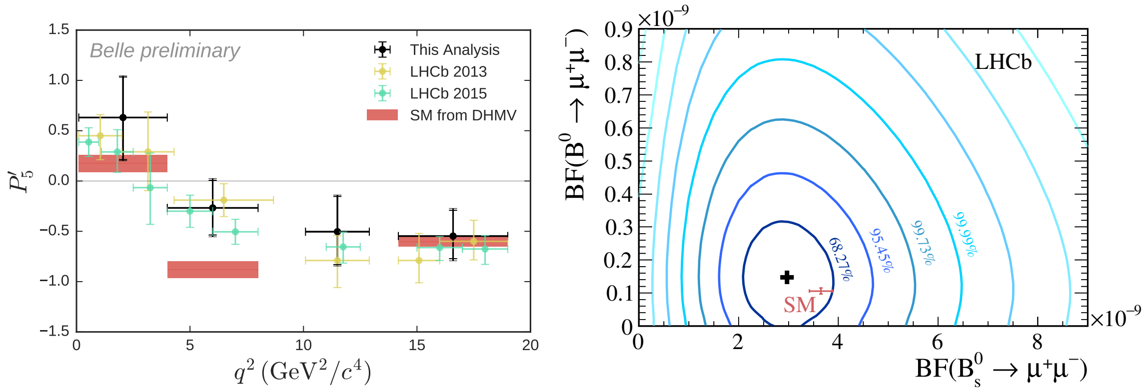


Figure 5: Left: The LHCb [33] and Belle [34] measurements of P_5' in $B \to K^* \mu^+\mu^-$. Right: The $B_{s,d} \to \mu^+\mu^-$ result from LHCb [42] (average with CMS and ATLAS measurements [43, 44] is not available).

$B \to D^{(*)} l\bar\nu$ are suppressed by interference between NP and the SM [21].

There are many further measurements that may help to clarify this anomaly. The $B \to D^{(*)}\tau\bar\nu$ rates seem to exceed [20] the LEP measurements of the inclusive $b \to X\tau\bar\nu$ rate [7], and the inclusive $B \to X_c\tau\nu$ rate [22] has not yet been measured. The $B \to D^{**}\tau\bar\nu$ rates will also give complementary information [23]. The equality of the e and μ rates are not well constrained, and the currently allowed differences [24, 25] open up (or keep open) many model building options [26]. In many scenarios, bounds on $b \to s\nu\bar\nu$ processes are very important [20, 27]. A lot will be learned, hopefully soon, from the comparison of LHCb and Belle II data with fully differential theory predictions [28]. If a deviation from the SM is established, it will strongly motivate to measure all possible semitauonic modes, both in $b \to c$ and $b \to u$ transitions [29, 30].

Another measurement which has drawn immense attention is the “P_5' anomaly" in a $B \to K^*\mu^+\mu^-$ angular distribution (see, e.g., Refs. [31, 32]), measured first at LHCb [33] and then at Belle [34]. The measurements are shown in the left plot in Fig. 5, together with a SM prediction [35]. These “optimized observables" are based on the SCET factorization theorem for semileptonic B decay form factors [36, 37], and constructing combinations from which the “nonfactorizable" (“soft") contributions cancel. (These are nonperturbative functions of q^2, which obey symmetry relations [38]; additional terms are either power suppressed or contain an explicit α_s factor.) The magnitudes of the correction terms, that is one’s ability to calculate the form factor ratios at small q^2 reliably, is debated [39] (and not well constrained by data yet). The tension between theory and the data is intriguing. Some of the simplest new physics explanations are Z'-like models, with nonuniversal flavor couplings. One may be concerned that the best fit is a new contribution to the operator $O_9 = e^2(\bar s\gamma_\mu P_L b)(\bar\ell\gamma^\mu\ell)$ in the effective Hamiltonian, the same term which would be modified if theoretical control over the $c\bar c$ loop contributions were worse than expected. (This was also emphasized recently in Ref. [40].) There are many possible connections to the $\sim 2.5\sigma$ anomaly in $\Gamma(B \to Ke^+e^-) \neq \Gamma(B \to K\mu^+\mu^-)$ as well [41].

For these observables, too, I trust that with improved measurements and theory, the source of the currently seen effects will be understood. With more data, one can test the q^2 (in)dependence of the extracted Wilson coefficients. In the large q^2 (small recoil) region one can make model independent predictions both for exclusive [45] inclusive [46] $b \to sl^+l^-$ mediated decays, which

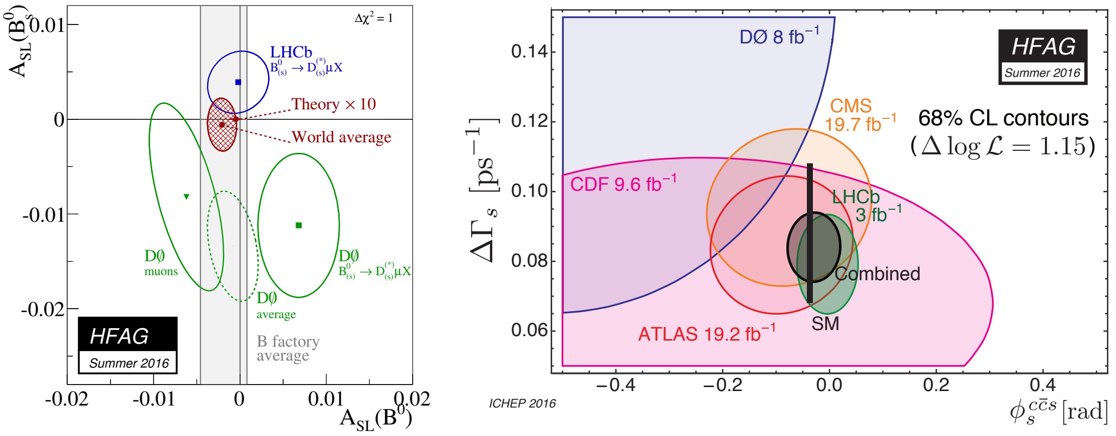


Figure 6: Left: bounds on *CP* violation in $B_{d,s}$ mixing, $a^{d,s}_{\rm SL}$. The vertical and horizontal bands show the averages of the separate B_d and B_s measurements, respectively, and the yellow ellipse is the DØ measurement. Right: measurements of $\phi_s \equiv -2\beta_s$ showing good consistency with the SM.

is complementary to the small q^2 region, and has different theory uncertainties.

If new physics is at play in these processes, it is likely to impact $B \to \mu^+\mu^-$, too. The very recent LHCb measurement [42] shown in the right plot in Fig. 5 is consistent with the SM, and no longer hints at an enhancement of $B_d \to \mu^+\mu^-$ [43]. Measuring a rate at the 3×10^{-9} level is impressive, and future refinements are high priority. The nonperturbative input in this case is just f_B, which is under good control in lattice QCD.

Another deviation from the SM expectations, which is theoretically very clean, and has been $3-4\,\sigma$, is the DØ measurement of the like-sign dimuon charge asymmetry in semileptonic decays of b hadrons, $(N_{\mu^+\mu^+} - N_{\mu^-\mu^-})/(N_{\mu^+\mu^+} + N_{\mu^-\mu^-})$ [47], shown in the left plot in Fig. 6. A nonzero signal could come from a linear combination of *CP* violation in B_s and B_d mixing, $a^{d,s}_{\rm SL}$ (see, e.g., Ref. [48]), and the SM prediction is well below the current sensitivity. Separate measurements of $a^d_{\rm SL}$ and $a^s_{\rm SL}$ from BaBar, Belle, and DØ are consistent in with the SM, and the recent LHCb update with 3/fb, $a^s_{\rm SL} = (0.39 \pm 0.33)\%$ [49], starts to be in tension with the DØ anomaly. If there is new physics in *CP* violation in B_s mixing, then one may also expect to see a deviation from the SM in the time-dependent *CP* asymmetry in $B_s \to J/\psi\phi$ and in related modes. Recent LHC measurements, however, are consistent with the SM, as shown in the right plot in Fig. 6. Most importantly, the theory uncertainties are well below the experimental sensitivity in the coming years, so a lot can be learned from more precise measurements.

It has long been known that kaon *CP* violation is sensitive to some of the highest energy scales. For the ε parameter, the SM is in good agreement with the data, and the NP contribution is constrained to be $\lesssim 30\,\%$ of that of the SM [50]. Calculating the SM prediction for direct *CP* violation, the ε' parameter, has been a multi-decade challenge, and progress is being made [51]. Results with several lattice spacings are needed to decide if NP is present. My views of the theoretical status of the measurements shown in Fig. 3, but not discussed here, are explained in Ref. [52].

These experimental hints of possible deviations from the SM are fantastic for several reasons. Unambiguous evidence for NP would obviously be the start of a new era, and would also provide a rough upper bound on the scale of NP, even if it is not seen directly at ATLAS & CMS. It is also

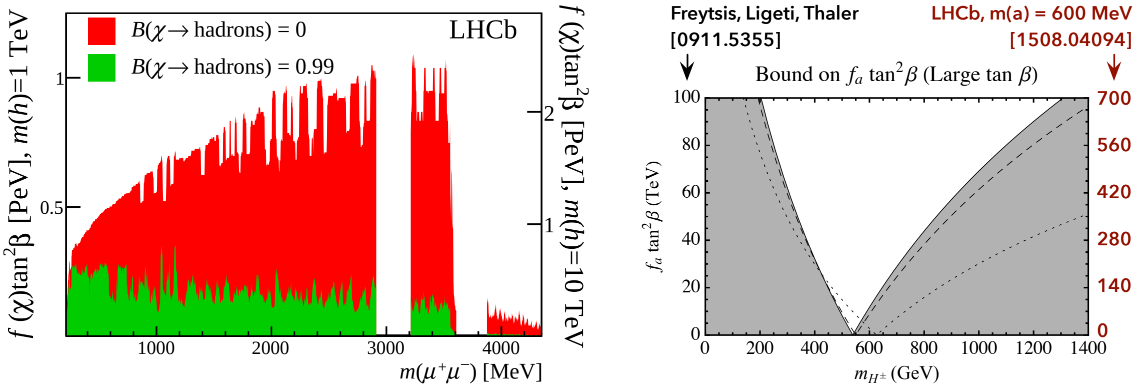


Figure 7: Left: LHCb bounds on $f_\chi^2 \tan^2\beta$ as a function of $m_{\mu^+\mu^-}$ [58] in the model [60]. Right: The bound as a function of $m_{H^\pm}$ in the same model; the right axis shows a nearly order of magnitude improvement.

useful to have experimental results challenge theory, since unexpected signals motivate both model building and revisiting the SM predictions. This was the case with the Tevatron anomaly in the $t\bar{t}$ forward-backward asymmetry, $A_{\rm FB}^{t\bar{t}}$, which disappeared due to refinements of the experimental results (the SM predictions also improved [53]). Concerning the recent $3\,\sigma$ hint for direct *CP* violation in the difference of *CP* asymmetries in $D \to K^+K^-$ and $D \to \pi^+\pi^-$, $\Delta A_{CP} = A_{K^+K^-} - A_{\pi^+\pi^-}$, I doubt the initial measurement near 1% could be attributed to the SM [54]. The central value of the world average has decreased since 2012, as has the significance of the hint for $\Delta A_{CP} \neq 0$. We probably still do not know how large ΔA_{CP} the SM could generate. However, exploring it taught us, for example, about how much (or how little) the quark and squark mixing matrices can differ and squark masses (don't) need to be degenerate [55, 56] in alignment models [57].

A measurement in which no anomaly is seen, but there is a nearly order of magnitude increase in mass-scale sensitivity due to a recent LHCb analysis [58], is the search for an axion-like particle, coupling to SM fermions as $(m_\psi/f_a)\, a\, \bar\psi \gamma_5 \psi$. Such models are also interesting, because they may have highly suppressed spin-independent direct detection cross sections [59]. The left plot in Fig. 7 shows the 95% CL lower bound on $f_\chi^2 \tan^2\beta$ in the model of Ref. [60], from the absence of a narrow $\mu^+\mu^-$ peak in $B \to K^*\chi\, (\chi \to \mu^+\mu^-)$ as a function of $m_{\mu^+\mu^-}$. The bound is shown for $m_{H^\pm} = 1\,$TeV and two values of the hadronic branching fraction of the axion-like particle. The right plot shows the bound on the same quantity as a function of $m_{H^\pm}$ (f_a in [60] is f_χ in [58]). The left vertical axis is the bound estimated in 2009 [60] from BaBar & Belle data with only a few bins, and the right vertical axis shows the LHCb bound [58]. The dashed (dotted) curve shows the bound for $\tan\beta = 3$ ($\tan\beta = 1$). In this model, for any value of $\tan\beta$, the NP contribution vanishes due to a cancellation for a certain value of $m_{H^\pm}$. There are promising proposals to utilize the upcoming huge LHCb data sets for related dark photon searches as well [61, 62]

3. Future increases in new physics scales probed

I would like to talk about three topics briefly in this part: (i) the future theory uncertainty of the measurement on $\sin 2\beta$ from $B \to J/\psi K_S$; (ii) the future sensitivity to NP in mixing of neutral mesons; (iii) sensitivity of flavor physics experiments to very heavy vector-like fermions.

3.1 What is the ultimate theory uncertainty of $\sin 2\beta$?

The theoretical uncertainty of the SM predictions for the time dependent *CP* asymmetries in the “gold-plated" modes $B \to J/\psi K_S$ and $B_s \to J/\psi\phi$ are of great importance. They arise from contributions to the decay amplitude proportional to $V_{ub}V_{us}^*$ instead of the dominant $V_{cb}V_{cs}^*$ terms. I refer to this as V_{ub} contamination, instead of the often used penguin pollution phrase (which is less correct and less clear). This effect did not matter in practice in the past, but it will be important for interpreting the full LHCb and Belle II data sets. During the BaBar/Belle era, the experimental precision was an order of magnitude above the nominal magnitude of the theoretical uncertainty, $\lambda^2(\alpha_s/\pi) \sim 0.004$. So even a factor of few enhancement of the latter did not matter.[1] A number of approaches have been developed, using a combination of diagrammatic and flavor symmetry arguments with various assumptions [65, 66]. (I hasten to add a triviality: there is no relation based only on $SU(3)$ flavor symmetry between final states which are entirely in different representations; e.g., ϕ is an $SU(3)$ singlet and ρ & K^* are members of an octet.) The experimental tests performed so far do not indicate big enhancements of the theory uncertainties.

The question that really matters in my opinion is not what it takes to set plausible upper bounds on the V_{ub} contamination, when the measurements agree with the SM, but what it would take to convince the community that NP is observed at LHCb and Belle II, especially if no NP is seen by ATLAS and CMS. Therefore, one cannot overemphasize the importance of starting from rigorous theoretical foundations, with well defined expansion parameter(s).

A relation based only on $SU(3)$ flavor symmetry, which cancels the V_{ub} contamination in $\sin 2\beta$ against other observables in the $SU(3)$ limit, reads [67]

$$\sin 2\beta = \frac{S_{K_S} - \lambda^2 S_{\pi^0} - 2(\Delta_K + \lambda^2\Delta_\pi)\tan\gamma\cos 2\beta}{1+\lambda^2}\,. \tag{3.1}$$

Here S_h ($h = K, \pi$) is the usual coefficient of the $\sin(\Delta m t)$ term in the time-dependent *CP* asymmetry [7] in $B \to J/\psi\, h^0$, $\lambda \simeq 0.225$ is the Wolfenstein parameter,

$$\Delta_h = \frac{\bar\Gamma(B_d \to J/\psi\, h^0) - \bar\Gamma(B^+ \to J/\psi\, h^+)}{\bar\Gamma(B_d \to J/\psi\, h^0) + \bar\Gamma(B^+ \to J/\psi\, h^+)}\,, \tag{3.2}$$

and $\bar\Gamma$ denotes the *CP* averaged rates. Using Eq. (3.1), it is possible to replace the V_{ub} contamination in the $\sin 2\beta \simeq S_{K_S}$ relation with isospin breaking, which could be smaller than the possibly enhanced V_{ub} contamination one wants to constrain. It also provides redundancy, replacing one theory uncertainty with a different one. For the $V_{cb}V_{cs}^*$ terms in the effective Hamiltonian, $\Delta_{K,\pi}$ violate isospin, but the $V_{ub}V_{us}^*$ terms generate nonzero Δ_h even in the isospin limit. The resulting constraint on the $\bar\rho - \bar\eta$ plane is shown in Fig. 8 [46].

Measuring all terms in Eq. (3.1) is not straightforward. Many of the current measurements of Δ_h and the production asymmetry of B^+B^- vs. $B^0\bar B^0$ in $\Upsilon(4S)$ decay, f_{+-}/f_{00}, are circular (the measurements of either assume that the other asymmetry vanishes) [68], so the slight tension in Fig. 8 should be interpreted with caution. To disentangle Δ_h from the production asymmetry,

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[1] Until about 1997 this was often estimated as $\lambda^2(\alpha_s/4\pi)$. Omitting the factor 4 anticipates some enhancement of the penguin matrix element, observed in charmless B decays [63] but not yet well constrained in decays to charmonia. Calculable $\mathcal{O}(10^{-3})$ effects arise from *CP* violation in K and B mixing, and the $\Gamma_{B_L} - \Gamma_{B_H}$ width difference [64].

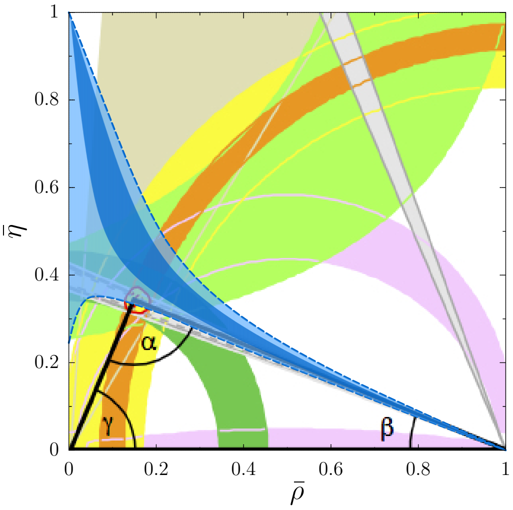

Figure 8: The dark (light) blue region shows the 1σ (2σ) constraint in the $\bar{\rho}-\bar{\eta}$ plane from Eq. (3.1) [67].

more precise measurements of the latter are needed. One option may be to utilize that isospin violation in inclusive semileptonic decay is suppressed by $\Lambda_{\rm QCD}^2/m_b^2$ [68]. (Similar suppression of $SU(3)$ symmetry breaking in inclusive B decays by $\Lambda_{\rm QCD}^2/m_b^2$ is the basis for a theoretically clean prediction for the ratio $\Gamma(B\to X_s\ell^+\ell^-)/\Gamma(B\to X_u\ell\bar{\nu})$ at large q^2 [46].)

It is an open question how well it will be possible to ultimately constrain (convincingly) the size of V_{ub} contamination in the measurements of $\sin 2\beta$ and $2\beta_s(\equiv -\phi_s)$. Given that $SU(3)$ flavor symmetry has been used to analyze B decays for decades, and previously unknown $SU(3)$ relations can be discovered in 2015, makes me optimistic that a lot more progress can be achieved.

3.2 New physics in SM loop processes

Although the SM CKM fit in Fig. 2 shows impressive and nontrivial consistency, the implications of the level of agreement are often overstated. Allowing new physics contributions, there are a larger number of parameters related to CP and flavor violation, and the fits become less constraining. This is shown in Fig. 9, which shows the determination of the unitarity triangle from tree-dominated decays only, which are unlikely to be affected by new physics. The plot on the left shows the current fit results, while the constraints in the plot on the right is expected to be achievable with $50\,\text{ab}^{-1}$ Belle II and $50\,\text{fb}^{-1}$ LHCb data [69]. The allowed region in the left plot is indeed significantly larger than in Fig. 2.

It has been known for decades that the mixing of neutral mesons is particularly sensitive to new physics, and probe some of the highest scales. In a large class of models, NP has a negligible impact on tree-level SM transitions (e.g., the measurements of γ, $|V_{ub}|$, and $|V_{cb}|$), and the 3×3 CKM matrix remains unitary. As a simple example, consider possible NP contributions to B and B_s meson mixing, which can be parametrized as

$$M_{12} = M_{12}^{\rm SM}\,(1+h_q\,e^{2i\sigma_q})\,, \qquad q=d,s\,. \tag{3.3}$$

The constraints on h_d and σ_d in the B_d mixing are shown in Fig. 10, and the constraint in the h_d-h_s plane is shown in Fig. 11. Both plots show the current constraints (left) and those expected to be

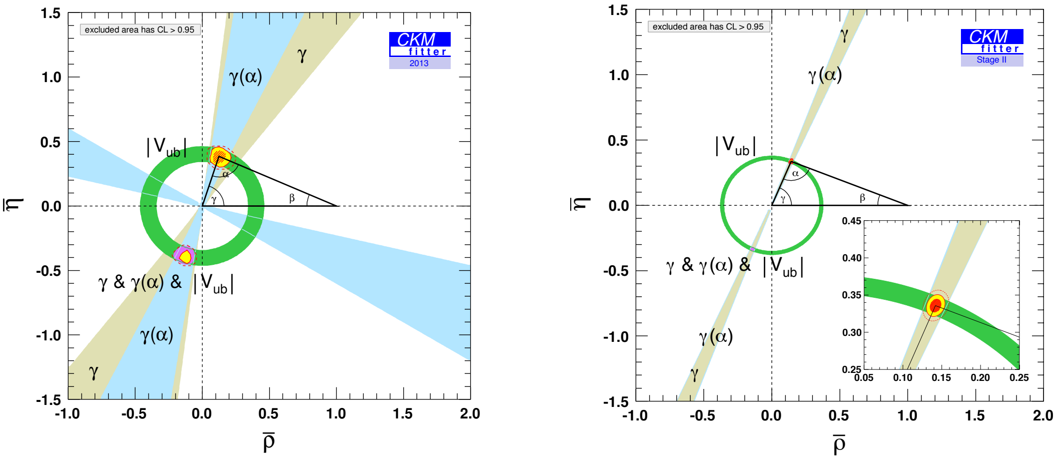

Figure 9: Constraints on $\bar{\rho}-\bar{\eta}$, allowing NP in the $B_{d,s}$ mixing amplitudes (left) and the expectation using $50\,\mathrm{ab}^{-1}$ Belle II and $50\,\mathrm{fb}^{-1}$ LHCb data (right) [69]. Colored regions show 95% CL, as in Fig. 2.

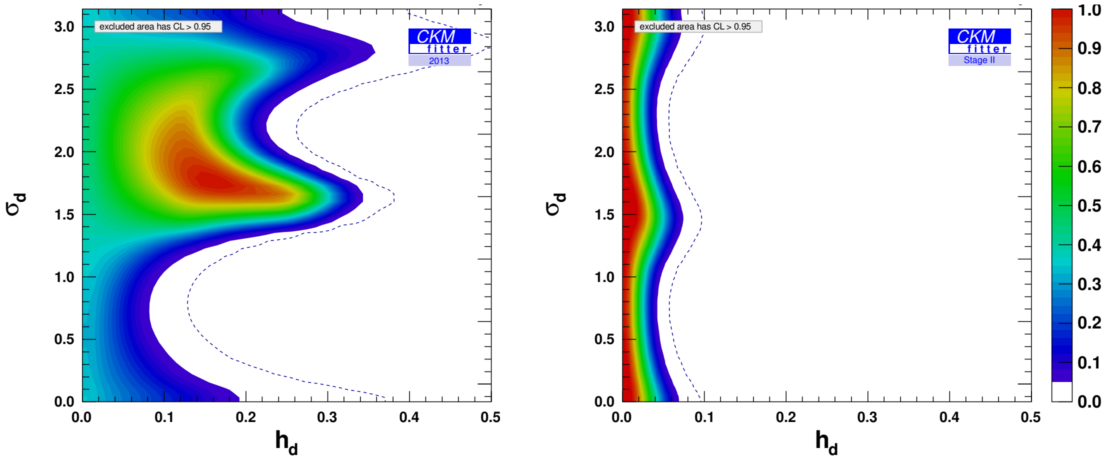

Figure 10: Constraints on the $h_d-\sigma_d$ parameters (left) and those estimated to be achievable using $50\,\mathrm{ab}^{-1}$ Belle II and $50\,\mathrm{fb}^{-1}$ LHCb data (right) [69]. Colored regions show 2σ limits with the colors indicating CL as shown, while the dashed curves show 3σ limits.

achievable with $50\,\mathrm{ab}^{-1}$ Belle II and $50\,\mathrm{fb}^{-1}$ LHCb data (right) [69]. Figure 10 shows that in the future the bounds on the "MFV-like regions", where NP flavor is aligned with the SM ($2\theta_d \simeq 0$ mod π), will be comparable to generic values of the NP phase, unlike in the past. Figure 11 shows that the bounds on NP in B_s mixing, which were significantly weaker than those in the B_d sector until recent LHCb measurements, are now comparable, and will comparably improve in the future.

As an example, if NP modifies the SM operator describing B_q mixing by adding to it a term

$$\frac{C_q^2}{\Lambda^2}\,(\bar{b}_L\gamma^\mu q_L)^2\,, \tag{3.4}$$

then one finds

$$h_q \simeq \frac{|C_q|^2}{|V_{tb}^* V_{tq}|^2}\left(\frac{4.5\,\mathrm{TeV}}{\Lambda}\right)^2. \tag{3.5}$$

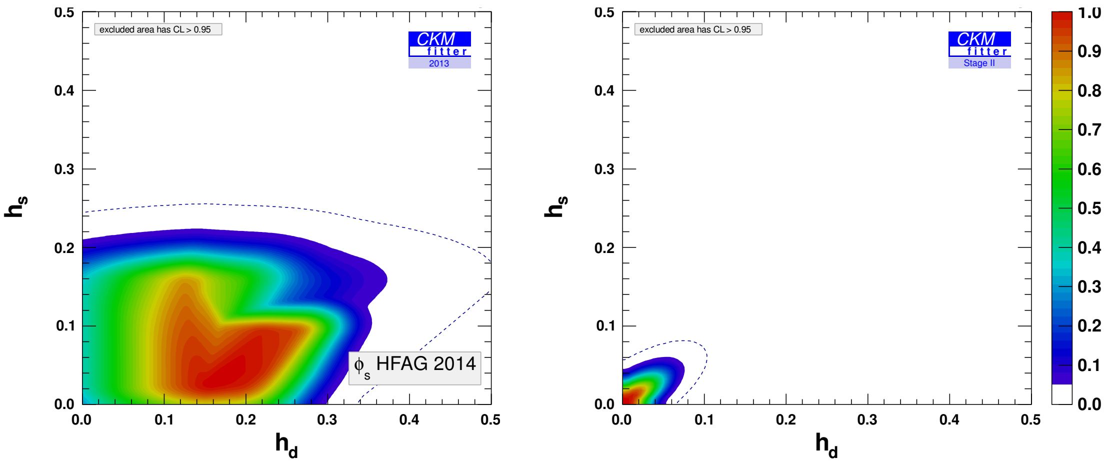

Figure 11: Constraints on the $h_d - h_s$ parameters now (left plot) and those estimated with 50 ab^{-1} Belle II and 50 fb^{-1} LHCb data (right plot) [69]. The notation is the same as in Fig. 10.

Couplings	NP loop order	Scales (TeV) probed by	
		B_d mixing	B_s mixing
$\lvert C_q\rvert = \lvert V_{tb}V_{tq}^*\rvert$	tree level	17	19
(CKM-like)	one loop	1.4	1.5
$\lvert C_q\rvert = 1$	tree level	2×10^3	5×10^2
(no hierarchy)	one loop	2×10^2	40

Table 1: The scale of the $B_{d,s}$ mixing operators in Eq. (3.4) probed, with 50 ab^{-1} Belle II and 50 fb^{-1} LHCb data [69]. The differences due to CKM-like hierarchy of couplings and/or loop suppression is shown.

We can then translate the plotted bounds to the scale of new physics probed. The summary of expected sensitivities are shown in Table 1. The sensitivities even with SM-like loop- and CKM-suppressed coefficients are comparable to the scales probed by the LHC in the next decade.

In $K^0-\overline{K}^0$ mixing the simplest analog of Eq. (3.3) is to parametrize NP via an additive term to the so-called tt contribution in the SM, $M_{12}^{K,tt} = M_{12}^{K,tt}\,(1+h_K\,e^{2i\sigma_K})$. The reason is the short distance nature of NP and the fact that in many NP models the largest contribution to M_{12}^K arise via effects involving the third generation. Substantial progress would require lattice QCD to constrain the long distance contribution to M_{12}^K at the percent level [69].

There are also strong constraints on NP from $D^0-\overline{D}^0$ mixing. Since the observed mixing parameters are probably dominated by long distance physics [70], it is hard to improve the bound from simply demanding the NP contribution to be below the measured values of the mixing parameters.

3.3 Sensitivity to vector-like fermions

Another illustration of the expected progress with well quantifiable increases in mass scale sensitivity, in both quark and lepton flavor experiments, is to consider extensions of the SM involving vector-like fermions, which can Yukawa couple to the SM [71]. These fermions can have masses M much greater than the weak scale, since they have a mass term even in the absence of

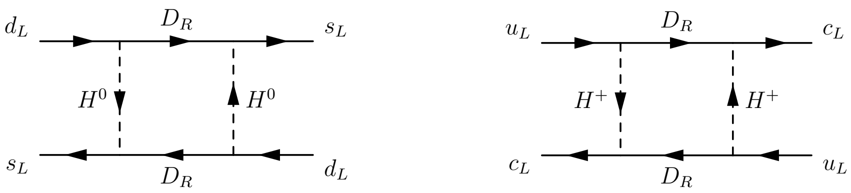

Figure 12: One-loop vector-like fermion contributions to K and D mixing in Model V [71].

electroweak symmetry breaking. These models are a class of simple extensions of the SM, which do not worsen the hierarchy puzzle. There are 11 renormalizable models [71] which add to the SM vector-like fermions in a single (complex) representation of the gauge group that can Yukawa couple to the SM fermions through the Higgs field (4 to leptons, 7 to quarks).

The precise definitions of the λ_i Yukawa couplings depend on the models, as do the forms of the Lagrangians. For example, what was labeled Model V in Ref. [71] contains vector-like fermions, D, with the same quantum numbers as the SM right-handed down-type quarks, which Yukawa couple to the SM left-handed quark doublets Q_L^i as

$$\mathscr{L}_{\rm NP}^{\rm (V)} = \bar{D}(i\not{D} - M)D - (\lambda_i \bar{D}_R H^\dagger Q_L^i + \text{h.c.})\,, \tag{3.6}$$

These new interactions generate Z couplings, e.g., in this Model V to the quarks,

$$\mathscr{L}_Z^{\rm (V)} = -\sum_{i,j} \left(\frac{\lambda_i^* \lambda_j m_Z^2}{g_Z M^2}\right) \bar{d}_L^i \gamma^\mu d_L^j Z_\mu\,, \tag{3.7}$$

which contribute to, and are constrained by, flavor-changing neutral currents.

These models also generate dimension-6 four-fermion operators, which contribute to neutral meson mixing. At tree level, the Z contribution in Eq. (3.7) yields coefficients of the form $(\lambda_i \lambda_j^*)^2 v^2/M^4$. At one loop, coefficients of order $(\lambda_i \lambda_j^*)^2/(4\pi M)^2$ are generated, which are neither CKM nor quark-mass suppressed, seemingly not considered in the literature. For large M, these one-loop contributions are more important than tree-level Z exchange. They are independent of the Higgs vacuum expectation value, v, and arise from short distances $\sim 1/M$. They can be calculated in the symmetric phase from the box diagrams in Fig. 12 with virtual scalars and the heavy vector-like fermions. The resulting effective Lagrangian in Model V is [71],

$$\mathscr{L}_{\rm mix}^{\rm (V)} = -\frac{(\lambda_i^* \lambda_j)^2}{128\pi^2 M^2} \left[\sum_{klmn} (\bar{u}_L^k V_{ki}\, \gamma_\mu V_{jl}^\dagger u_L^l)\, (\bar{u}_L^m V_{mi}\, \gamma_\mu V_{jn}^\dagger u_L^n) + (\bar{d}_L^i \gamma_\mu d_L^j)\, (\bar{d}_L^i \gamma^\mu d_L^j)\right] + \text{h.c.} \tag{3.8}$$

Table 2 shows the bounds on 5 of the 11 models for illustration (see also Ref. [72]). The upper rows for each model contain the current bounds, and the lower rows show the expected sensitivities in the next generation of experiments (in the next decade or so). For the vector-like fermions that couple to SM quarks, the bounds are shown separately from $\Delta F = 1$ and $\Delta F = 2$ processes. For the $\Delta F = 2$ bounds on the 1–2 generation couplings, the bounds are shown separately on the real and imaginary parts, since ε_K probes much higher scales than Δm_K in these models. (In the other cases the differences are of order unity.) We learn that the next generation of experiments will improve the mass scale sensitivities in the leptonic (hadronic) models by up to a factor of ~ 7 (~ 4).

Model	Quantum numbers	Bounds on M/TeV and $\lambda_i\lambda_j$ for each ij pair					
		$ij = 12$		$ij = 13$		$ij = 23$	
II	$(1,3,-1)$	220^a		4.9^b		5.2^c	
		1400^a		13^b		15^c	
III	$(1,2,-1/2)$	310^a		7.0^b		7.4^c	
		2000^a		19^b		21^c	
		$\Delta F = 1$	$\Delta F = 2$	$\Delta F = 1$	$\Delta F = 2$	$\Delta F = 1$	$\Delta F = 2$
V	$(3,1,-1/3)$	66^d $[100]^e$	$\{42,\ 670\}^f$	30^g	25^h	21^i	6.4^j
		280^d	$\{100,\ 1000\}^f$	60^l	61^h	39^k	14^j
VII	$(3,3,-1/3)$	47^d $[71]^e$	$\{47,\ 750\}^f$	21^g	28^h	15^i	7.2^j
		200^d	$\{110,\ 1100\}^f$	42^l	68^h	28^k	16^j
XI	$(3,2,-5/6)$	66^d $[100]^e$	$\{42,\ 670\}^f$	30^g	25^h	18^k	6.4^j
		280^d	$\{100,\ 1000\}^f$	60^l	61^h	39^k	14^j

Table 2: Bounds in some of the vector-like fermion models [71] on $M\,[\text{TeV}]/\sqrt{|\lambda_i\lambda_j|}$ in the leptonic models, and from the $\Delta F = 1$ constraints on the hadronic models. The $\Delta F = 2$ bounds show $M/\sqrt{|\lambda_i\lambda_j|^2}$, except for K meson mixing we show $\{M/\sqrt{|\text{Re}(\lambda_i\lambda_j^*)^2|},\ M/\sqrt{|\text{Im}(\lambda_i\lambda_j^*)^2|}\}$. The strongest bounds arise, or are expected to arise, from: *a*) μ to e conversion; *b*) $\tau \to e\pi$; *c*) $\tau \to \mu\rho$; *d*) $K \to \pi\nu\bar{\nu}$; *e*) $K_L \to \mu^+\mu^-$ (this involves $|\text{Re}(\lambda_1\lambda_2^*)|$ and is in square brackets because prospects for improvements are weak); *f*) K mixing; *g*) $B \to \pi\mu^+\mu^-$; *h*) B_d mixing; *i*) $B \to X_s\ell^+\ell^-$; *j*) B_s mixing; *k*) $B_s \to \mu^+\mu^-$, *l*) $B_d \to \mu^+\mu^-$.

3.4 Top, higgs, and new physics flavor

These are vast topics which I could not cover in detail in the talk, nor is it possible here.

Top quarks in the SM decay almost exclusively to bW, with the second largest branching fraction $\mathscr{B}(t \to sW) < 2 \times 10^{-3}$. Particularly clean probes of the SM are FCNC top decays, for which the SM predictions are below the 10^{-12} level. The current bounds are roughly at the level $\mathscr{B}(t \to qZ) \lesssim 10^{-3}$, $\mathscr{B}(t \to qg) \lesssim 10^{-4}$, and $\mathscr{B}(t \to qh) \lesssim 0.5\%$, with the precise limits depending on the ratio of $q = u, c$ produced by new physics. The ultimate LHC sensitivities are expected to be about a factor of 10^2 better, hence any observation would be a clear sign of NP. There is obvious complementarity between FCNC searches in the top sector, and low energy flavor physics bounds. Since t_L is in the same $SU(2)$ doublet as b_L, several operators have correlated effects in t and b decays. For some operators, mainly those involving left-handed quark fields, the low energy constraints exclude a detectable LHC signal, whereas other operators are still allowed to have large enough coefficients to yield detectable NP signals at the LHC (see, e.g., Ref. [73]).

The experimental richness of higgs physics, that several production mechanisms and many decay channels can be probed, are to a large extent due to the particular values of the Yukawa couplings. The quark and lepton couplings, and Y_t in particular, are important for higgs decays, as well as to determine the production cross sections from gg fusion, higgs-strahlung, $t\bar{t}$ and WZ fusion. The LHC has (almost) measured the $h\tau^+\tau^-$ coupling, and will also determine $h\mu^+\mu^-$ and $hb\bar{b}$, if they are near their SM values. Should the LHC or another future collider detect deviations from the SM branching ratios or observe flavor-non-diagonal higgs decays, that would of course be incredibly significant (for a recent discussion, see, e.g., Ref. [74]).

Any new particle that couples to the quarks and/or leptons, potentially introduces new flavor violating parameters. For example, in low energy supersymmetry, which is the favorite NP scenario of a large part of our community, squark and slepton couplings may yield measurable effects in FCNC processes and *CP* violation, give rise to detectable charged lepton flavor violation (CLFV), such as $\mu \to e\gamma$, etc. Observable *CP* violation is then also possible in neutral currents and electric dipole moments, for which the SM predictions are below the near future experimental sensitivities. The supersymmetric flavor problems, that TeV-scale SUSY models with generic parameters are excluded by FCNC and *CP* violation measurements, can be alleviated in several scenarios: (i) universal squark masses, when $\Delta\tilde{m}^2_{\tilde{Q},\tilde{D}} \ll \tilde{m}^2$ (e.g., gauge mediation); (ii) alignment, when $(K^d_{L,R})_{12} \ll 1$ (e.g., horizontal symmetry); (iii) heavy squarks, when $\tilde{m} \gg 1\,\text{TeV}$ (e.g., split SUSY). All viable models incorporate some of these ingredients. Conversely, if SUSY is discovered, mapping out its flavor structure may help answer questions about even higher scales, e.g., the mechanism of SUSY breaking, how it is communicated to the MSSM, etc.

An important implication of flavor constraints for SUSY searches is that the LHC bounds are sensitive to the level of (non-)degeneracy assumed. Most SUSY searches assume that the first two generation squarks, $\tilde{u}_{L,R}$, $\tilde{d}_{L,R}$, $\tilde{s}_{L,R}$, $\tilde{c}_{L,R}$, are all degenerate, which increases signal cross sections. Relaxing this assumption consistent with flavor bounds, results in substantially weaker squark mass limits from the LHC Run 1, around the 500 GeV scale [56]. Thus, there is a tight interplay between the flavor physics and LHC high-p_T searches for new physics. If there is new physics at the TeV scale, its flavor structure must be highly non-generic to satisfy current bounds, and measuring small deviations from the SM in the flavor sector would give a lot of information complementary to ATLAS & CMS. The higher the scale of new physics, the less severe the flavor constraints are. If NP is beyond the reach of the LHC, flavor physics experiments may still observe robust deviations from the SM, which would point to an upper bound on the next scale to probe.

4. Final comments and ultimate sensitivity

The main points I tried to convey through some examples were:

- *CP* violation and FCNCs are sensitive probes of short-distance physics in the SM and for NP;
- Flavor physics probes energy scales $\gg 1\,\text{TeV}$, the sensitivity limited by statistics, not theory;
- For most FCNC processes NP / SM $\gtrsim 20\%$ is still allowed, so there is plenty of room for NP;
- Of the several tensions between data and SM predictions, some may soon become definitive;
- Precision tests of SM will improve by $10^1 - 10^4$ in many channels (including CLFV);
- There are many interesting theory problems, relevant for improving experimental sensitivity;
- Future data will teach us more about physics at shorter distances, whether NP is seen or not, and could point to the next energy scale to explore.

With several new experiments starting (NA62, KOTO, Belle II, mu2e, COMET, etc.) and the upcoming upgrade of LHCb, the flood of new data will be fun and exciting (see Refs. [75, 19] for reviews of planned flavor experiments and their sensitivities). It will allow new type of measurements, and more elaborate theoretical methods to be used and tested. The upcoming experiments

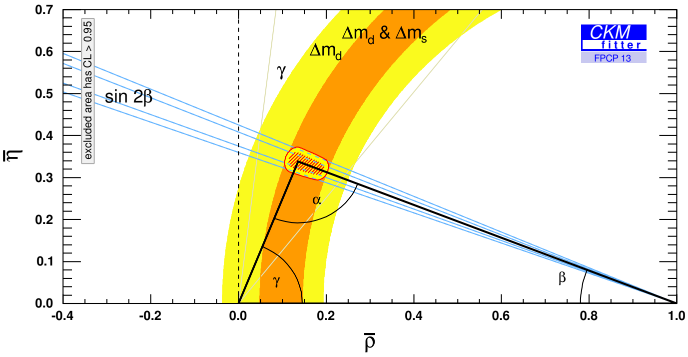

Figure 13: A test of the SM flavor sector that can improve by a factor of 10.

also challenge theory, to improve predictions and to allow more measurements to probe short distance physics with robust discovery potential. Except for the few cleanest cases, improvements on both sides are needed to fully exploit the future data sets. I am optimistic, as order of magnitude increases in data always triggered new theory developments, too.

It is also interesting to try to estimate the largest flavor physics data sets which would be useful to increase sensitivity to new physics, without being limited by theory uncertainties.[2] For charged lepton flavor violation, the SM predictions (from penguin and box diagrams with neutrinos) are (tens of) orders of magnitudes below any foreseeable experimental sensitivity, so if technology allows significant improvements, I think the justification is obvious (as it is for electric dipole moment searches). In quark flavor physics the situation is more complex. Amusingly, even in 2030, there will be theoretically clean B decay modes in which (experimental bound)$\big/$SM $\gtrsim 10^3$, e.g., $B \to \tau^+\tau^-$, $B \to e^+e^-$, and probably some more. However, based on what is known today, some observables will become limited by theory (hadronic) uncertainties. Identifying how far NP sensitivity can be extended is interesting, at least in principle, so below is a list for which 50/ab Belle II and 50/fb LHCb data will not even come within an order of magnitude of the ultimately achievable sensitivities. Of course, on the relevant time scale lots of progress will take place (see Ref. [76] for estimates of future lattice QCD uncertainties) and new breakthroughs are also possible.

- Probably the theoretically cleanest observable in the quark sector is the determination of the CKM phase γ from tree-level B decays. Irreducible theory uncertainty only arises from higher order weak interaction [77]. So the main challenges are on the experimental side.
- The theory uncertainty for the semileptonic CP asymmetries, $a_{\rm SL}^{d,s}$, discussed is Sec. 2 and in Fig 6, are also much below [78, 79] the expected 50/ab Belle II and 50/fb LHCb sensitivities.
- Another set of key observables are $B_{s,d} \to \mu\mu$ and $B \to \ell\nu$, where the nonperturbative theory inputs are only the decay constants, which will soon be known with $< 1\%$ uncertainties. In contrast, the expectation for the accuracy of $B_d \to \mu\mu$ with the full LHC data is $\mathcal{O}(20\%)$.
- It is often stated that the determination of $|V_{ub}|$ is theory limited. This entirely depends on the measurements available. In principle, the theoretically cleanest $|V_{ub}|$ determination I know,

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[2] In measurements without SM backgrounds, such as setting bounds on $\mu \to e$ conversion or $\tau \to 3\mu$ decay, the mass-scale sensitivity (to a dimension-6 NP operator) scales like $\Lambda \propto (\text{bound})^{-1/4}$. In measurements constraining SM–NP interference, $\Lambda \propto (\text{uncertainty})^{-1/2}$, and at some point precise knowledge of the SM contribution becomes critical.

which only uses isospin, would be from $\mathscr{B}(B_u \to \ell\bar{\nu})/\mathscr{B}(B_d \to \mu^+\mu^-)$ [80].

- I think that the SM prediction for *CP* violation in $D^0 - \overline{D}^0$ mixing is below the expected sensitivities on LHCb and Belle II. To establish this robustly, however, more theory work is needed (especially given the recent history of hints of *CP* violation in *D* decay).
- For $K^+ \to \pi^+\nu\bar{\nu}$ and especially for $K_L \to \pi^0\nu\bar{\nu}$, the current plans for NA62 and KOTO will stop short of reaching the ultimate sensitivity to NP achievable in these decays.

Thus, I guess(timate) that ~ 100 times the currently envisioned 50/ab Belle II and 50/fb LHCb data sets would definitely allow for the sensitivity to short distance physics to improve. Whether any of these ultimate sensitivities can be achieved at a tera-Z machine, an e^+e^- collider running on the $\Upsilon(4S)$, or utilizing more of the LHC's or/and a future hadron collider's full luminosity, is something I hope we shall soon have even more compelling reasons to seriously explore.

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