

BEACH 2014 Theory summary

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BEACH 2014 Theory Summary

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Abstract. I summarize key aspects of the quest for physics beyond the Standard Model in flavour physics as discussed at the BEACH 2014 conference in Birmingham.

1. Introduction

I thank the organisers for inviting me to BEACH 2014 in Birmingham and bestowing on me the honour of giving the theory summary. The many excellent theoretical talks, many of them review talks in their own right, make both for a rich source of topics and a challenge of selection; I apologise at the outset for omissions. The conference started with the low-energy QCD effects in spectroscopy and Kaon physics and ended with the early universe, reflecting appropriately the wide range of energy scales relevant to, and probed through, flavour physics (Figure 1). As indicated in the figure, flavour and heavy-quark physics has seen the birth and use of

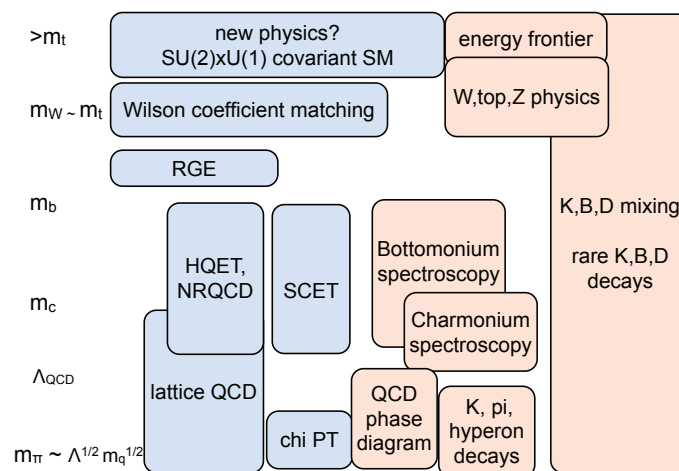


Figure 1. Energy scales, observables, and techniques relevant to flavour physics.

many fruitful theoretical concepts, including the weak Hamiltonian and its renormalisation-



group evolution, heavy-quark expansions/HQET/NRQCD and soft-collinear effective theory, and provides the impetus for many developments in lattice QCD.

2. Flavour physics and the BSM landscape

Flavour physics played a key role in constructing the Standard Model (SM), including the invention of Cabibbo mixing to address a 2σ tension in weak decay data [1], the resolution of a naturalness problem in the $K_L - K_S$ mass difference based on the then hypothetical charm quark [2], and the prediction of a third generation by Kobayashi and Maskawa [3] to accommodate CP violation in K_L decay (ϵ_K).

With the discovery of a scalar particle consistent, so far, with the SM Higgs boson, another naturalness problem looms larger than ever in the hierarchy between the electroweak scale and any fundamental scale at which new degrees of freedom appear, including M_{Planck} , M_{GUT} , M_{seesaw} . The known natural beyond-SM (BSM) scenarios all involve, so far hypothetical, particles at the TeV scale and were reviewed in the opening talk by Kamenik [4]. They all bring in new sources of flavour violation. Will flavour physics again be the lead in constructing the next Standard Model? Nobody knows, but it is entirely possible. Indeed, there are several interesting puzzles in the data, some new and some older but persistent, that have been discussed at this meeting. No BSM particles have been identified in the high- p_T experiments yet; this certainly raises the importance of virtual probes of the kind discussed at this conference. Even without a BSM discovery so far, the wealth of data has led to a great deal of bottom-up phenomenology in the last few years, largely phrased in terms of ad-hoc models or fits to effective field theory parameters, at the expense of top-down model building; indeed there was not much discussion of model-specifics at this meeting.

The discovery power of flavour physics arises as follows. A generic FCNC amplitude behaves as

$$\mathcal{A} = \mathcal{A}_{\text{SM}} + \mathcal{A}_{\text{BSM}}. \quad (1)$$

A typical observable, say a rare decay rate, provides a (schematic) constraint

$$|\mathcal{A}_{\text{BSM}}|^2 + 2 \text{Re} \mathcal{A}_{\text{BSM}}^* \mathcal{A}_{\text{SM}} = \Gamma_{\text{exp}}(1 \pm \Delta^{(\text{exp})}) - |\mathcal{A}_{\text{SM}}|^2(1 \pm \Delta^{(\text{SM})}). \quad (2)$$

Hence, although new physics decouples as M_Z^2/M_{NP}^2 , flavour observables can probe well beyond the energy frontier provided sufficient statistics and theoretical precision are available. It is perhaps worth comparing the situation in flavour physics with that in precision Higgs physics. Assuming a “little hierarchy” $M_Z \ll M_{\text{NP}}$, the leading BSM physics can be parameterized in terms of a large number of dimension-six, $SU(2)_W \times U(1)_Y$ invariant operators [5, 6]. B decays alone probe more than 100 operators even when assuming lepton flavour conservation, far more than in the Higgs case. (Disentangling them is a formidable but not impossible task, see below.)

Figure 2 [4] shows the energy scales probed by the four types of meson-antimeson mixing. The most stringent constraint comes from ϵ_K , pointing either to (approximately) CP-conserving new physics, to a substantial “little hierarchy” between the weak scale and the new physics, or to some kind of flavour suppression mechanism resulting in small mixing angles suppressing strangeness-changing neutral-current transitions. CP-conserving observables provide a less stringent constraint, especially for Kaons, but still apply in the absence of new sources of CP violation. It is worth noting that this situation can change qualitatively in the future, in particular with progress in lattice QCD that seems imminent (see below). Once a deviation is seen in one or more experiments, flavour physics may guide us toward an understanding of the origin of flavour, perhaps in the form of a dynamical theory, perhaps based on symmetry principles.

From the phenomenological point of view, matching the experimental precision comprises disentangling perturbative short-distance physics from long-distance nonperturbative QCD

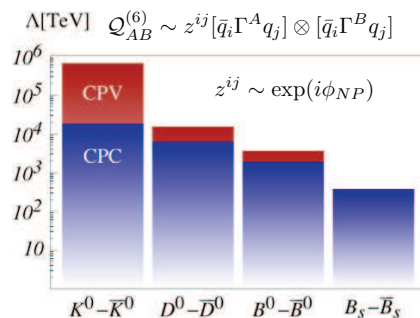


Figure 2. Generic bounds on the scale of CP violating and CP-conserving new physics from meson-antimeson mixing as shown by Kamenik [4].

effects, and calculating the latter or determining them from data was the subject of a number of presentations at this conference.

3. Kaons

CP violation in $K-\bar{K}$ mixing (ϵ_K) is the prototypical flavour precision observable and generically provides the most stringent constraints on physics beyond the SM [4]. It originates from $\Delta F = 2$ box diagrams with W and u, c, t quarks. The dominant contribution, involving internal top quarks, needs to be complemented by lattice calculations of the nonperturbative normalisation B_K , which is given in terms of the matrix element of a local operator,

$$B_K \propto \langle \bar{K}^0 | (\bar{s}_L \gamma^\mu d_L) (\bar{s}_L \gamma_\mu d_L) | K^0 \rangle.$$

Including perturbative calculations of short-distance charm and up contributions, one has [7]

$$|\epsilon_K| = (1.81 \pm 0.28) \times 10^{-3}, \quad \Delta M_K^{\text{SD}} = (3.1 \pm 1.2) \times 10^{-15} \text{ GeV}, \quad (3)$$

while experiment gives [8]

$$|\epsilon_K|^{\text{exp}} = (2.228 \pm 0.011) \times 10^{-3}, \quad \Delta M_K^{\text{exp}} = (3.484 \pm 0.006) \times 10^{-15} \text{ GeV}. \quad (4)$$

Comparing the measured value of ϵ_K to the theory prediction constrains the CKM unitarity triangle and allows to put constraints on BSM physics, which can involve additional local operators. The constraint from ΔM_K is less stringent due to the larger error and the unknown long-distance contribution, which could interfere destructively with a possible BSM contribution.

In fact, as discussed by Christ [9], already for ϵ_K accuracies have now reached the level where both refined lattice renormalisation schemes (or perhaps a direct calculation of the RG-invariant bag parameter \hat{B}_K) and precision determinations of the charm and up loop contributions become important. The latter two correspond to non-local matrix elements of the sort

$$\langle \bar{K}^0 | T \{ [(\bar{s}_L \gamma^\mu d_L) (\bar{c}_L \gamma_\mu c_L)](x) [(\bar{s}_L \gamma^\mu d_L) (\bar{c}_L \gamma_\mu c_L)](0) \} | K^0 \rangle.$$

These include a perturbative part from scales $\sim m_c$ (although $\alpha_s(m_c)$ is relatively close to the strong-coupling regime), which matches onto the same local operator, and further contributions from scales $\sim \Lambda_{\text{QCD}}$. Lattice QCD calculations with dynamical charm quarks are starting to

access the required correlation functions directly. These developments also raise the exciting prospect of extending the energy reach of ΔM_K as a probe of CP-*conserving* new physics by an order of magnitude in the near future.

Beyond mixing, the super-rare decays $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ and $BR(K_L \rightarrow \pi^0 \nu \bar{\nu})$ provide two further very clean probes of physics beyond the Standard Model, with SM theory errors at the 10% level. Though not discussed in any detail from a theory point of view at this conference, experiment is on the move: The goal at NA62 (K^+ , CERN, now running), where the Birmingham group is heavily involved, is a 10% measurement (assuming the SM branching ratio), while KOTO (J-PARC, restarting in 2015) expects to observe the K_L mode, which violates CP. Both will provide stringent constraints on, or measurements of, the sdZ vertices, very sensitive to $SU(2)$ -breaking BSM effects such as stop-scharm mixing originating from flavour-violating A -terms (eg [10, 11, 12]). Exciting lattice prospects were discussed [9] for a holy grail of Kaon theory, the two two-body $K \rightarrow \pi\pi$ decay amplitudes ($I = 0$ and $I = 2$). From a BSM point of view, the experimental value of the direct-CP violation observable $\epsilon'/\epsilon = (1.66 \pm 0.23) \times 10^{-3}$ [8] is complementary to mixing and rare K decay in that it conveys information about a variety of short-distance couplings, including the sdZ vertex and the chromo-dipole couplings $\bar{s}\sigma^{\mu\nu} P_{L,R} d G_{\mu\nu}$. From an SM/QCD point of view, there is also the question why the decay amplitude into the $I = 0$ final state is more than 20 times larger than that into the $I = 2$ state (the $\Delta I = 1/2$ rule), which predates the advent of the SM. Both questions require the computation of the complex amplitude ratio $A(I = 2)/A(I = 0)$. There is a long history of sophisticated and rather successful calculations based on chiral perturbation theory and the large- N_c limit, as reviewed by Pich [13]. The full-QCD, $N_c = 3$ results have been elusive so far. It is all the more remarkable that the RBC/UKQCD collaboration now appears on track for a fully realistic QCD calculation, with the prospect of a 20% calculation of ϵ'/ϵ . There are many more uses of Kaons, such as constraining the CKM matrix element V_{us} , for which I refer to [9, 13].

4. Heavy quarks

The three heavy quarks benefit, to varying degree, from a hierarchy $m \gg \Lambda$, which gives rise to heavy-quark spin symmetries and is the basis for various effective field theories. Brambilla reviewed the theory and applications of quarkonia spectra and furthermore discussed the nature of heavy-quark bound states close to or above threshold, where, unlike for states well below threshold, the heavy-quark expansion (formalised through NRQCD and pNRQCD) no longer leads to a calculable framework in terms of potentials (which could be determined perturbatively or via lattice QCD simulations) [14]. These include in particular states such as the $X(3872)$ that appear to behave as a molecular state made of two heavy-light systems. The nature of the $X(3872)$, which within experimental accuracies sits right on top of the $D^{0*} \bar{D}^0$ threshold, was discussed in more detail by Nieves [15]. If this picture is correct, it predicts a variety of other nearby states, and we may hope that more data will shed light on this very difficult multi-scale QCD problem. The fate of charmed hadrons in the quark gluon plasma, and other current topics in high-temperature QCD, were reviewed by Steinheimer [16]. Heavy and multiply-heavy baryons were the subject of talks by Azizi [17] and by Erkol [18].

5. Charm

Charm mixing and decay provide sensitivity to short-distance physics similarly to the Kaon case. Unfortunately, the benefits of having a (slightly) heavy quark are outweighed by the loss of chiral perturbation theory together with an adverse CKM/GIM structure, which leads, in the SM, to a complete long-distance dominance for mixing as well as decays, including rare ones. Petrov discussed $D - \bar{D}$ mixing and CP violation in hadronic charm decays [19]. If one assumes the absence of large cancellations between the SM and new-physics contributions, the measured

mass difference bounds the new physics scale, but less so than in the Kaon case (Figure 2). The non-observation of CP violation in mixing gives a (stronger) constraint (on CP-violating new physics); in this case the long-distance dominance in the SM leads to a suppression: the three-generation, CP-violating SM is approximately reduced to a two-generation, CP-conserving theory.

The situation is quite different for the difference of direct CP asymmetries, $\Delta a_{\text{CP}} = a_{\text{CP, KK}} - a_{\text{CP, } \pi\pi}$. Previously measured to be 3σ away from zero to much excitement, Δa_{CP} is no longer significant as of 2013. In order to turn this into a constraint on the new physics scale, one would require knowledge of (or make estimates about) the strong phases of the SM contributions.

Fajfer discussed a large number of rare semileptonic and radiative D decay rates and asymmetries [20]. All of them suffer from large and rather uncertain, long-distance-dominated SM contributions, but there are a few examples where the experimental bound still significantly exceeds the SM estimates and new physics could give a dominant contributions, such as $D^0 \rightarrow \mu^+ \mu^-$.

Overall, the power of charm to detect new physics still appears relatively bleak, with the exception of mixing. Eventually, lattice simulations with dynamical charm quarks may open up charm to precision phenomenology, at least for the $\Delta C = 2$ case (and perhaps beyond [19]).

6. Beauty and Truth

B physics comprises the lion's share of observables in flavour physics, many of them sensitive to SM parameters and/or new physics. The advent of the LHCb experiment has brought a wealth of measurements of new decay modes and unprecedented precision for old ones, though some of the most relevant constraints, notably $BR(B \rightarrow X_s \gamma)$, still come from the B -factories. Besides the mass splittings and CP violation in $B^0 - \bar{B}^0$ and $B_s - \bar{B}_s$ mixing, leptonic, rare semileptonic, and two-body hadronic decays were discussed at this conference. Important theoretical tools are lattice QCD and expansions in Λ/m_b . More specifically,

- Lattice QCD, reviewed by Jüttner [21], can provide B decay constants, comprising the nonperturbative input to $B \rightarrow \tau \nu$ and $B_q \rightarrow \mu^+ \mu^-$ decay, for dynamical, light quarks at their physical masses, with uncertainties of a few percent. Matrix elements of $\Delta B = 2$ operators needed for mixing can also be calculated with uncertainties of order 5%, and the same is true for form factors for a decay into a stable particle (with regard to QCD) such as a pion or a K , as long as the momentum transfer q^2 is close to maximal (the energy of the light particle is small). One needs to treat the b -quark in an effective theory (HQET or NRQCD), which can however be systematically implemented on a lattice. First calculations of $B \rightarrow K^*$ form factors have also appeared, but only for unphysical quark masses for which the K^* is stable. The realistic case of, for instance, $B \rightarrow K^* [\rightarrow K\pi] \mu^+ \mu^-$ would require a $B \rightarrow K\pi$ form factor calculation, which is at an early stage conceptually [22]. A complementary method, light-cone sum rules, was discussed by Khodjamirian; and can be used to obtain form factors at small q^2 (as well as other nonperturbative quantities). It also has the ability to describe a $B \rightarrow K\pi$ (or similar) form factor. Form factor calculations in a quark model were the topic of a talk by Hernandez [23].
- Observables related to mixing, the topic of a talk by Bobeth [24], comprise the mass difference, the lifetime difference, time-dependent CP violation in several modes, and CP violation in mixing (the flavour-specific or semileptonic CP asymmetries). Data show a good overall degree of consistency with the SM (Figure 3). In the case of B_d mixing, there is a mild tension. In the case of B_s mixing, the best fit is right on top of the SM expectation. One should note however that the consistency between the different inputs is not good, in particular, the D0 measurement of the dimuon charge asymmetry, which depends on

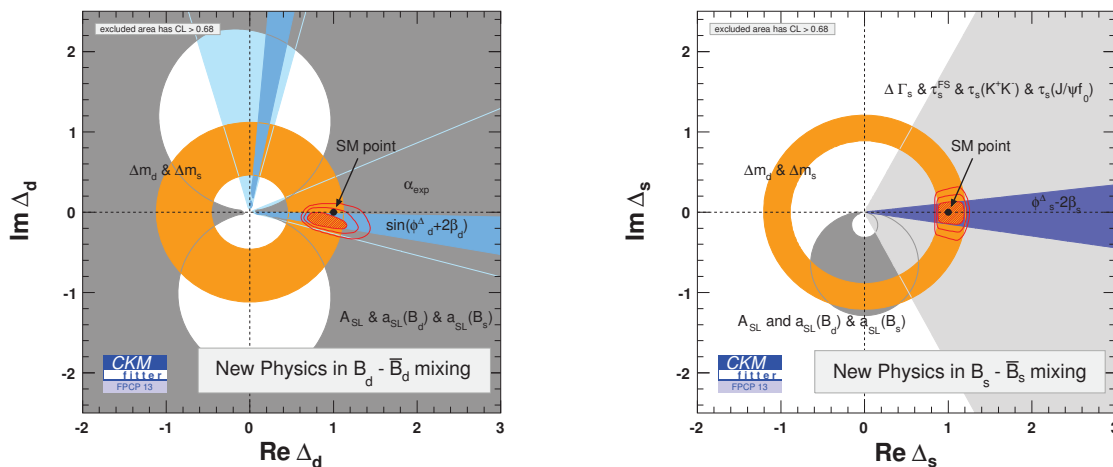


Figure 3. Combined constraints on $B_d - \bar{B}_d$ mixing (left) and $B_s - \bar{B}_s$ mixing (right) by the CKMfitter group (as of FCPC 2013) [25].

both the semileptonic CP asymmetry and on the lifetime differences, is about 3σ away from the SM prediction. Possible interpretations in terms of new decay modes of B_d were discussed by Bobeth [24]. In particular, it appears possible in a model-independent fashion to explain the discrepancy between the D0 result and other data with extra contributions to the lifetime difference $\Delta\Gamma_d$ (as opposed to the semileptonic CP asymmetry) from either four-quark operators or semileptonic operators with τ fields, without getting disagreement with exclusive B decay data.

Another issue that will become important with the increased accuracy with which LHCb measures time-dependent CP violation in B_d and B_s decays is the “penguin pollution” in the various decay modes, discussed by Fleischer at this conference [26] together with U -spin-symmetry-based methods for controlling these effects, which are not yet taken into account in official projected sensitivities.

Two-body charmless B decays exhibit QCD factorisation in the heavy quark limit, i.e., they factorise into perturbatively calculable kernels and nonperturbative objects such as form factors. Bell reported on the theory status including ongoing computations which will allow to compute direct CP asymmetries to next-to-leading order [27].

- The combined CMS-LHCb results on leptonic decay $B_s \rightarrow \mu^+\mu^-$ and $B_d \rightarrow \mu^+\mu^-$ read [28]

$$BR(B_s \rightarrow \mu^+\mu^-)^{\text{exp}} = 2.8_{-0.6}^{+0.8} \times 10^{-9}, \quad BR(B_d \rightarrow \mu^+\mu^-)^{\text{exp}} = 3.9_{-1.4}^{+1.6} \times 10^{-10},$$

and are consistent with SM expectations of

$$BR(B_s \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}, \quad BR(B_d \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10},$$

at the 1.2σ and 2.2σ levels, respectively, also showing a certain tension (which is 2.3σ in the ratio [28]). I find it extremely impressive that both rates are already measured to better than 40% accuracy, in spite of their extreme smallness, which shows the potential to find even small deviations from the SM, such as through a modified Zbs vertex. The theoretical expectations given above are the outcome of an NNLO-QCD and NLO-electroweak calculation, subject of a talk by Steinhauser [29], which also investigated issues

such as the fate of the helicity suppression underlying the smallness of the rate under soft photon emission. The theory errors, which now are below 10%, are dominated by parametric uncertainties from f_B and f_{B_s} , which will further reduce with progress on the lattice.

- The most intriguing picture presents itself when one goes to rare semileptonic $b \rightarrow sll$ decays, reviewed by [30], which entail several anomalies. The bulk of the information is provided by the angular analysis of $\bar{B} \rightarrow \bar{K}^* \mu^+ \mu^-$, which involves 12 separate angular observables, each of which a function of the dilepton invariant mass. A global fit to coefficients in the BSM effective Lagrangian indicates a discrepancy with the SM (Figure 4 (left); see also [31]). The effect can be attributed to a sizable negative BSM shift of the Wilson coefficient

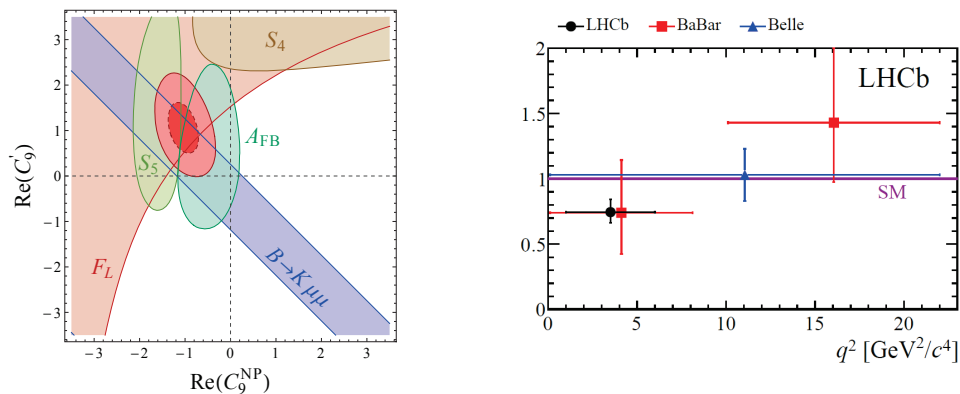


Figure 4. Left: Fit of $b \rightarrow sll$ data to two Wilson coefficients in the effective BSM hamiltonian [32]. Right: Lepton-number-(non)universality ratio $R_K = \Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-) / \Gamma(B^+ \rightarrow K^+ e^+ e^-)$ [33, 34].

C_9 , multiplying the operator $Q_9 \propto (\bar{s}_L \gamma^\mu b_L)(\bar{\mu} \gamma_\mu \mu)$. The devil may, however, be in the detail. The angular observables are quadratic functions in helicity amplitudes, the most complicated of which are the vector amplitudes, schematically

$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2) C_9 + \frac{2 m_b m_B}{q^2} \tilde{T}_\lambda(q^2) C_7 - \frac{16 \pi^2 m_B^2}{q^2} h_\lambda(q^2).$$

They involve interference of three different terms, including two nonperturbative local form factors and a further, nonlocal nonperturbative term. In order to claim an effect of the stated significance, the necessary precision on the form factors at small dilepton mass, more specifically on deviations from their relations in the heavy-quark limit, is on the order of 5% (Figure 5 left), and in my view it is doubtful that existing calculations (based mainly on light-cone sum rules) can be trusted to such a high level of precision. A conservative treatment of the power corrections [35] (see also [36]) results in a lower significance of the effect (Figure 5 right), of about 1σ only.

On the other hand, the picture of a negative correction to the SM Wilson coefficient C_9 is consistent with the relatively low branching ratio in the decay $B^+ \rightarrow K^+ \ell^+ \ell^-$. Also here the conclusion depends somewhat on nonperturbative form factor normalisations. The latter largely drop out of the ratio $R_K = \Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-) / \Gamma(B^+ \rightarrow K^+ e^+ e^-) = 0.745^{+0.090}_{-0.074}$ [34] (in the bin $1 \text{ GeV}^2 < q^2 < 6 \text{ GeV}^2$), which points at lepton universality violation. If this result stands, it could indeed be accommodated by a muon-specific negative shift to C_9 , consistent with what is inferred from the $B \rightarrow K^* \mu^+ \mu^-$ angular analysis, but in the

muonic operator only (as opposed to that containing the electronic vector current). Such scenarios are possible in UV-complete models, see e.g. [37]. In this context an interesting new development first shown at this conference is the systematic use of $SU(2) \times U(1)_Y$ -invariant effective theory, which appears justified by the likely hierarchy $M_{\text{NP}} \gg M_Z$. This rules out tensor operators as an explanation of any of the anomalies and allows to correlate the R_K measurement with $B_s \rightarrow \mu^+ \mu^-$ decay, and to rule out any role of scalar or pseudoscalar operators, leaving only the semileptonic current-current operators which includes the operator Q_9 mentioned above. Finally, the same decay $B^+ \rightarrow K^+ \mu^+ \mu^-$

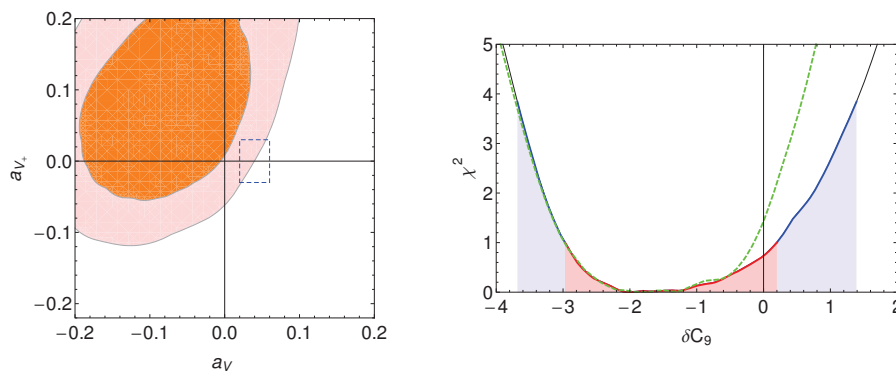


Figure 5. Left: profile χ^2 of the angular observable P'_5 in the $[1..6]$ GeV^2 bin, as a function of two power correction parameters. Right: profile χ^2 for the Wilson coefficient C_9^{NP} [30, 38].

also shows a rather pronounced resonant structure above the open charm threshold, the significance of which is unclear at present.

The intriguing situation on several fronts makes B -physics a definite place to watch for upcoming developments, such as updates of the angular analysis in $B \rightarrow K^* \mu^+ \mu^-$ with the full run I dataset, the first angular analysis in $B \rightarrow K^* e^+ e^-$, and high-statistics results based on the upcoming LHC run II and, before the decade is out, from the Belle 2 super flavour factory.

The top quark was also discussed at this meeting, in talks by Pecjak [39] and by Zhang [40]. Due to the unprecedented top samples at the LHC, it has started to become the subject of precision studies, among them searches for BSM effects in flavour-changing top decays. As with the lighter flavours, assuming a little hierarchy the BSM contributions to top production and decay can be described in terms of effective field theory and the data used to put model-independent constraints on its operator (Wilson) coefficients [40].

7. Leptons

In the lepton sector, flavour is known to be violated by neutrino oscillations. It is widely expected that lepton number is also violated, as happens in the seesaw models, which would give rise to the unique (and lepton-number-violating) dimension-5 operator beyond the Standard Model. All data is presently consistent with this picture, with exception of the well-known LSND anomaly. Status and prospects were reviewed by Pakvasa [41] and by Palazzo [42]. After the establishment of $\theta_{13} \approx 9^\circ \neq 0$, the main questions are: (i) do neutrino masses have a lepton-number-violating origin (search for neutrinoless double beta decay), (ii) is CP violated in the lepton/neutrino sector, (iii) is the neutrino mass hierarchy normal or inverted, (iv) are there sterile neutrinos (and if so at what scale)? There are indications in the global fit for a nonzero (“Dirac”, lepton-flavour-violating) CP-violating phase $\delta \in (\pi, 2\pi)$, although the significance depends on the mass

hierarchy and is never above 2σ . This and the other questions will, however, take a long time to resolve definitely. If lepton number is indeed violated, one can also have CP violation through the “Majorana” phases in the neutrino mass matrix.

The fact that lepton flavour violation is observed implies that charged lepton-flavour-violating processes must also occur, such as $\mu \rightarrow e\gamma$. They were the subject of a talk by Paradisi [43]. In the SM (supplemented by neutrino masses), the tiny masses of the neutrinos (when compared to the W mass) imply a near-perfect GIM cancellation, with no hope to see a signal. The situation can be very different beyond the SM. SUSY seesaw models, for example, communicate the flavour violation above the seesaw scale through to low-energy scales via renormalisable terms, such as off-diagonal elements of the slepton mass matrices. The resultant SUSY contributions can saturate the current bounds on many lepton-flavour-violating decay modes. An interesting aspect are relations within the general MSSM between the radiative lepton-flavour-violating decays and the flavour-conserving but BSM-sensitive anomalous magnetic moment $(g - 2)_\mu$ of the muon. The interest derives from the fact that the latter has shown a 3σ deviation from the SM prediction for a number of years now. The correlation and the theory of $(g - 2)_\mu$ was reviewed in more detail by Velasco-Sevilla [44].

8. Origin of matter

The most important aspect of CP violation may be that our existence may be thanks to it. More specifically, the observed excess of matter over antimatter in the universe can be explained by out-of-equilibrium CP-violating processes (together with violation of baryon number and charge conjugation symmetry) in the early universe. There are many models and mechanisms providing a successful baryogenesis, and it is impossible to conclude from the observation of the baryon asymmetry alone which one is correct. Some of the more compelling ones are, however, connected to CP-violating flavour physics at the TeV scale. Electroweak baryogenesis in a Two-Higgs-doublet model was discussed by Huber [45]. Here new degrees of freedom near the weak scale effect a strong first-order electroweak phase transition; the CP violating processes occurring in the course of this are found to be correlated with rare B decay and $B_s - \bar{B}_s$ mixing, as well as electric dipole moments of elementary particles. Schwaller discussed leptogenesis [46], whereby heavy SM singlets in a seesaw model decay to Higgs + lepton in a CP-asymmetric fashion; the necessary baryon number violation (which converts part of the lepton number into baryon number) takes place at much lower energies/temperatures via sphaleron processes. An important topic are thermal corrections to CP violation and a proper account of the tau Yukawa coupling.

9. Outlook

In conclusion, while it can be at times disappointing that the eagerly anticipated signatures of new physics below the TeV scale have not materialised, we are in the lucky circumstance of being showered with new results on a regular basis. While, for the time being, most of them imply ever tighter constraints on BSM physics, we should note that the arguments motivating physics at or near the TeV have not diminished. Any of the several tensions mentioned can, with more data and/or better theory, turn into significant falsifications of the Standard Model; and they may in fact already be pointing at a consistent picture. That the search for new physics would be a laborious affair was, by the way, predicted here in Birmingham, as the university motto attests (Figure 6 left). Thanks to our experimental colleagues, there is no shortage of work for flavour theorists these days. While, as in any ambitious project, success is not certain, I am confident that, in the end, Hilbert will be proven right (Figure 6 right).



Figure 6. Left: The University of Birmingham’s motto, “Through struggle to high energies.” Right: Hilbert’s tomb [Source: Wikimedia Commons].

Acknowledgment

I would like to thank the organisers warmly for such an exciting and perfectly organised conference. I am grateful to the many theory speakers for their clear presentations, which made my task easier than it could have been, and to Alexey Petrov for photographs used on my slides (not reproduced here). Support from the UK STFC under grants ST/J000477/1 and ST/L000504/1 is acknowledged.

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