COLLOQUIA: LaThuile11

New physics searches in flavour physics

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Summary. — The origin of flavour and CP violation is among the most important open questions in particle physics. Imminent results from the LHC as well as planned dedicated flavour physics experiments might help to shed light on this puzzle. This talk concentrates on the NP sensitivity of the rare B decays $B_{s,d} \to \mu^+\mu^-$ and $B \to K^*\mu^-\mu^-$ and of the CP-violating phase in B_s mixing. A brief summary of a supersymmetric model with interesting signatures in the flavour sector is presented.

PACS `12.60.-i` – Models beyond the standard model.
PACS `13.20.He` – Decays of bottom mesons.

1. – Introduction

The tremendous progress in experimental flavour physics facilitated by the B factories, the Tevatron and other experiments shows that the CKM picture of flavour and CP violation describes the data well, both for tree and loop-induced processes. Since the Standard Model (SM) is only an effective theory valid up to some energy scale Λ, which is yet to be determined but is expected to lie in the TeV region from naturalness considerations, this success is a challenge for theories of new physics (NP). Assuming generic flavour and CP-violating couplings, the bounds on Λ from $\Delta F = 2$ processes exceed 10000 TeV [1]. On the other hand, given that a theoretical understanding of the hierarchical structure of quark masses and CKM mixings is still lacking, this paradox might simply indicate that the flavour structure of NP is related to the SM one. If in fact the Yukawa couplings, already present in the SM, are the *only* sources of breaking of the flavour symmetry, theories with this property of Minimal Flavour Violation (MFV, [2,3]) can have TeV-scale dynamics without being in conflict with observations [4].

Then again, MFV might well be too restrictive an assumption. Concrete models aiming to explain the origin of flavour often bring about a certain amount of non-minimal flavour violation (see, *e.g.*, [5-8]). Furthermore, the MFV principle does not preclude the presence of flavour-blind CP-violating phases [9,10]. Therefore, testing whether indeed the Yukawa couplings are the only source of flavour breaking and testing whether indeed the CKM phase is the only source of CP breaking are among the major goals of flavour physics in this decade.

TABLE I. – *SM predictions and 95% CL experimental upper bounds on the $B_q \to \mu^+\mu^-$ branching ratios* [11, 12].

Observable	SM prediction	Experimental bound
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	$(3.2 \pm 0.2) \times 10^{-9}$	$< 43 \times 10^{-9}$
$\mathrm{BR}(B_d \to \mu^+\mu^-)$	$(0.10 \pm 0.01) \times 10^{-9}$	$< 7.6 \times 10^{-9}$

The experimental prospects for progress in this direction are excellent, in view of planned dedicated flavour physics experiments like the Super B factories and searches for electric dipole moments (EDMs) or rare K decays; Moreover, in the near future, important results on $b \to s$ transitions are expected from the LHC. Sections. **2**-**4** will therefore discuss three particularly promising probes of NP at the LHC: the rare leptonic decays $B_{s,d} \to \mu^+\mu^-$, CP violation in B_s mixing, and angular observables in the $B \to K^*\mu^+\mu^-$ decay. Section **5** contains a brief summary of a model leading to interesting signatures in precision flavour experiments: supersymmetry with hierarchical squark masses, effective MFV and flavour-blind phases.

2. – $B_{s,d} \to \mu^+\mu^-$

The decays $B_{s,d} \to \mu^+\mu^-$ are strongly helicity suppressed in the SM and have not been experimentally observed yet; the current upper bounds still lie one/two orders of magnitude above the SM predictions (see table I) but will be improved in the near future by the Tevatron and LHC experiments.

Concerning NP effects in $B_s \to \mu^+\mu^-$, in models where only the SM Wilson coefficient C_{10} receives NP contributions, an order-of-magnitude enhancement of the branching ratio is disfavoured due to constraints from inclusive and exclusive $b \to s\ell^+\ell^-$ transitions on C_{10}. In that case, $\mathrm{BR}(B_s \to \mu^+\mu^-) \lesssim 10^{-8}$ [13].

Much larger enhancements are possible in principle in models with contributions to the scalar and/or pseudoscalar Wilson coefficients $C_{S,P}$. In two-Higgs-doublet models, a neutral Higgs penguin contributes to the branching fraction with an enhancement factor of $\tan\beta^4$, where $\tan\beta$ is the ratio of Higgs VEVs. In the MSSM, this dependence is even $\tan\beta^6$. Consequently, an upper bound $\mathrm{BR}(B_s \to \mu^+\mu^-) < 10^{-8}$ would already constrain numerous well-motivated NP scenarios, such as SUSY GUTs with a unification of Yukawa couplings [14]([1]).

An important test of MFV is represented by the measurement of the ratio of the two $B_q \to \mu^+\mu^-$ branching ratios. In MFV (as defined in [3]), it is simply given by

$$(1) \qquad \frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_d \to \mu^+\mu^-)} = \frac{\tau_{B_s} f_{B_s}^2 m_{B_s}}{\tau_{B_d} f_{B_d}^2 m_{B_d}} \left| \frac{V_{ts}}{V_{td}} \right|^2 .$$

While a simultaneous enhancement over the SM satisfying (1) would be a strong indication in favour of MFV, a non-SM effect incompatible with (1) would immediately rule out MFV. Figure 1 (for details see [16]) shows possible values of this ratio attained in

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([1]) On the other hand, even within the MFV MSSM very large $\tan\beta$ would remain a valid possibility if the trilinear couplings are small, such as in gauge mediation scenarios [15].
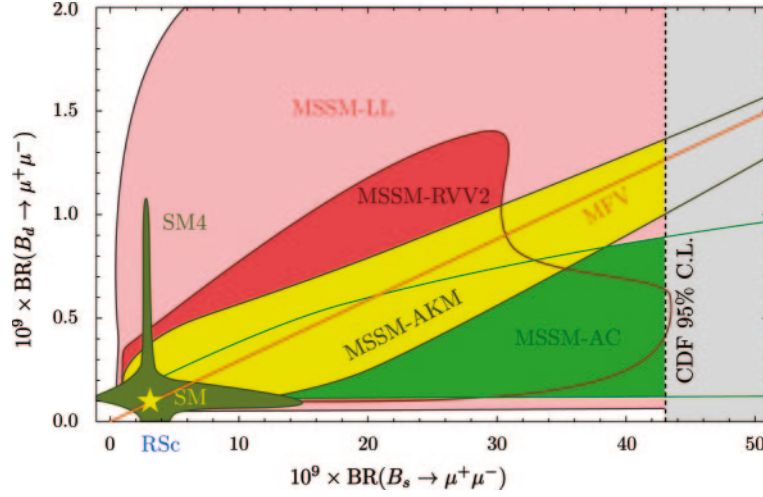
Fig. 1. – Correlation between the branching ratios of $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ in MFV, the SM4 and four SUSY flavour models. The gray area is ruled out experimentally. The SM point is marked by a star. Taken from [16].

several non-MFV models: four SUSY flavour models studied in [5] and the SM with 4 generations [12]. This highlights the power of the correlation between $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ to discriminate between different NP models.

3. – CP violation in B_s mixing

In the SM, CP violation in B_s mixing is a small effect since the relevant combination of CKM elements has an accidentally small phase,

$$(2) \qquad \phi_s \equiv \arg(M_{12}) = 2\beta_s \equiv 2 \ \arg\left(-\frac{V_{ts}^* V_{tb}}{V_{cs}^* V_{cb}}\right) \approx -0.04 \,.$$

Recently however, two experimental hints for a possibly large non-SM contribution to ϕ_s have emerged. One concerns the mixing-induced CP asymmetry $S_{\psi\phi}$ extracted from the time-dependent CP asymmetry in $B_s \to J/\psi\phi$ decays,

$$(3) \qquad A_{\mathrm{CP}}^s(\psi\phi, t) \equiv \frac{\Gamma(\bar{B}_s(t) \to \psi\phi) - \Gamma(B_s(t) \to \psi\phi)}{\Gamma(\bar{B}_s(t) \to \psi\phi) + \Gamma(B_s(t) \to \psi\phi)} \approx S_{\psi\phi} \sin(\Delta M_s t) \,,$$

where $S_{\psi\phi} = -\sin\phi_s$. The other concerns the charge asymmetry A_{SL} in dimuon events at D0, which can be related to the semileptonic CP asymmetries in flavour-specific B_d and B_s decays, $a_{\mathrm{SL}}^{d,s}$, as [17]

$$(4) \qquad A_{\mathrm{SL}} \approx \left(a_{\mathrm{SL}}^d + a_{\mathrm{SL}}^s\right)/2 \,,$$

with $O(10\%)$ uncertainties on the coefficients on the right-hand side of (4).

While 2009 results on $S_{\psi\phi}$ showed a discrepancy with the SM somewhere in the ballpark of 3 standard deviations [18], 2010 updates seem to be in agreement with the
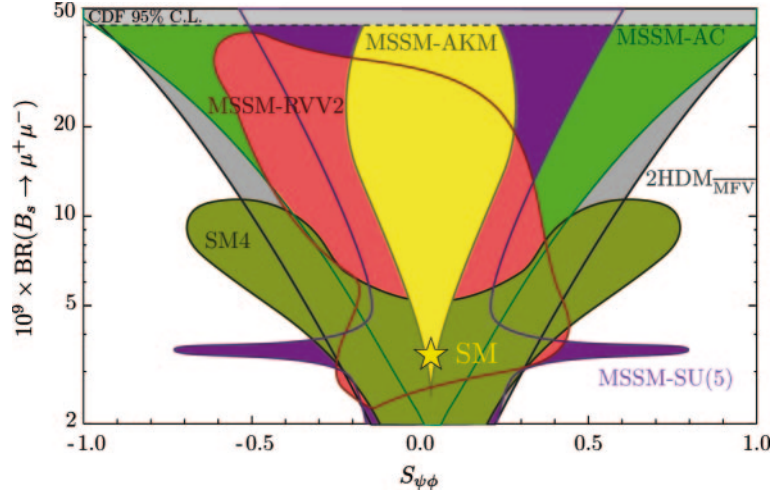
Fig. 2. – Correlation between the branching ratio of $B_s \to \mu^+\mu^-$ and the mixing-induced CP asymmetry $S_{\psi\phi}$ in the SM4, the two-Higgs doublet model with flavour blind phases and three SUSY flavour models. The SM point is marked by a star.

SM at the 1σ level [19, 20], although no combination has been performed yet. The D0 result on $A_{\rm SL}$ deviates by 3.2σ from the SM [21], interestingly pointing in the same direction as the possible effect in $S_{\psi\phi}$([2]).

If these hints turn out to be genuine signals of NP in B_s mixing, it would have far-fetching consequences, in particular for theories with MFV. If a theory satisfying MFV does not have any source of CP violation beyond the CKM phase, a sizable B_s mixing phase cannot be generated. Even if the MFV theory has flavour-blind phases, this is nontrivial. While a two-Higgs doublet model with MFV and flavour-blind phases can generate a sizable ϕ_s [23, 24], this possibility is precluded in the MSSM by the impact of constraints like $B \to X_s\gamma$ and $B_s \to \mu^+\mu^-$ [5]. A confirmation of ϕ_s deviating significantly from the value in (2) would thus immediately rule out many well-motivated theories, including the MFV MSSM.

Another interesting tool to discriminate between NP models is the correlation between $S_{\psi\phi}$ and the branching ratio of $B_s \to \mu^+\mu^-$. In many models, sizable deviations from the SM prediction for ϕ_s are tied to the presence of scalar currents, which can also affect $B_s \to \mu^+\mu^-$. This is the case e.g. for the two-Higgs doublet model with MFV and flavour-blind phases (2HDM$_{\overline{\rm MFV}}$) or for the SUSY flavour model of Agashe and Carone (AC, [25]). As shown in fig. 2, sizable $S_{\psi\phi}$ implies a sizable enhancement of BR($B_s \to \mu^+\mu^-$) in these models, while the converse is obviously not true. In the SM4, on the other hand, even the converse statement is true: If $B_s \to \mu^+\mu^-$ is found with a rate significantly enhanced with respect to the SM, this model unambiguously predicts a sizable deviation also in $S_{\psi\phi}$. In yet other models, like in the $SU(5)$ model of [26], both observables can be enhanced independently of each other, but a simultaneous enhancement is unlikely.

([2]) After this talk was given, preliminary data on $B_s \to J/\psi\phi$ from the LHCb experiment were presented [22] also showing a preference for an effect in the same direction, although still with a small significance.

4. – $B \to K^* \mu^+ \mu^-$

The exclusive decay $\bar{B} \to \bar{K}^{*0}(\to K^- \pi^+)\mu^+ \mu^-$ gives access to many observables potentially sensitive to NP [27-31, 13]; since it is a "self-tagging" decay, it also allows a straightforward measurement of CP asymmetries.

The decay poses several theoretical challenges. In addition to calculating the 7 $B \to K^*$ form factors, one has to estimate non-factorizable strong interaction effects. At intermediate values of the dilepton invariant mass squared q^2, resonant charmonium production leads to a breakdown of quark-hadron duality. The most studied region is the low q^2 region, where QCD factorization can be used to calculate non-factorizable corrections [32, 33] and light-cone sum rules to calculate the form factors [34, 30]. The high-q^2 region above the charmonium resonances has recently attracted increasing attention [13, 35]. While QCD factorization and LCSR methods are not applicable in this kinematical domain, a local operator product expansion in powers of $1/\sqrt{q^2}$ allows a systematic calculation of the observables [36, 35]. In [35], it has been argued that, in contrast to the low-q^2 region, non-perturbative corrections *not* accounted for by the form factors are small (see also [37]).

A complete set of observables accessible in the angular distribution of the decay and its CP-conjugate is given by the 9 CP-averaged angular coefficients S_i and the 9 CP asymmetries A_i, defined in terms of the angular coefficients $I_i, \bar{I}_i$ as [30]

$$(5) \qquad S_i = (I_i + \bar{I}_i)\bigg/\frac{\mathrm{d}(\Gamma + \bar{\Gamma})}{\mathrm{d}q^2}\,, \qquad A_i = (I_i - \bar{I}_i)\bigg/\frac{\mathrm{d}(\Gamma + \bar{\Gamma})}{\mathrm{d}q^2}\,.$$

Not all of the S_i and A_i are both theoretically interesting and experimentally promising. In addition, at B factories, at the Tevatron and at the early LHC, statistics is quite limited so a full angular analysis is not possible and it might be easier to consider one- or two-dimensional angular distributions depending on a limited set of observables.

In addition to the observables([3]) which have already been studied by BaBar [39], Belle [40] and CDF [41]—the differential branching ratio, the forward-backward asymmetry and the K^* longitudinal polarization fraction—two observables sensitive to NP that could be extracted from a one-dimensional angular distribution are the CP-averaged S_3 and the CP-asymmetry A_9. While they are both negligibly small in the SM, they could be nonzero in NP models with right-handed currents [27, 30].

Two additional observables could be extracted from a two-dimensional angular distribution and might be accessible even during the early LHC running: the CP-averaged observable S_5 and the CP-asymmetry A_7. In [31], it has been shown that even with an integrated luminosity of only $2\,\mathrm{fb}^{-1}$, LHCb can measure S_5 with a precision that already allows to probe certain NP scenarios. Since A_7 is accessible from the same angular distribution, the naive expectation is that the sensitivity should be comparable. Just as A_9, A_7 is a T-odd CP asymmetry, meaning that it is not suppressed by small strong phases [28]. Sizable effects in A_7 of up to 20% are expected in well-motivated NP scenarios like the one discussed in the next section.

([3]) See [38] for a dictionary between different notations for the $B \to K^* \mu^+ \mu^-$ observables.

5. – CP violation in supersymmetry with effective MFV

As mentioned in the introduction, the MFV principle provides a symmetry argument to explain the absence of any evidence for flavour violation beyond the SM, but does not address the absence of signals of CP violation beyond the CKM phase, *e.g.* in EDMs.

In supersymmetry, a different way to address the flavour problem is to assume a strong hierarchy between the squarks of the first two *versus* the ones of the third generation: the heaviness of the former helps evading the strong bounds from K physics, while the lightness of the latter preserves the SUSY solution to the gauge hierarchy problem. For a generic flavour structure of the soft SUSY breaking terms, this hypothesis is however by far insufficient to ensure the absence of excessive flavour violation and needs to be extended by some amount of flavour alignment (see [42] and references therein).

In ref. [43], the hierarchical sfermion idea was combined with a specific flavour symmetry-breaking pattern inspired by MFV. The starting point is a global flavour symmetry in the quark sector of the form

$$(6) \qquad G_F = U(1)_{\tilde{B}_1} \otimes U(1)_{\tilde{B}_2} \otimes U(1)_{\tilde{B}_3} \otimes U(3)_{d_R},$$

where $\tilde{B}_i$ acts like baryon number, but only for the right-handed up-type and the left-handed (s)quark fields. G_F is subsequently broken down to baryon number by a single spurion, the down-type Yukawa coupling Y_d. As a consequence, it was shown in [43] that the theory is essentially MFV-like at low energies (therefore the name "Effective MFV"), with the most significant constraint coming from CP violation in neutral kaon mixing.

Interestingly, hierarchical sfermions also ameliorate the SUSY CP problem compared to MFV since the one-loop contributions to the experimentally accessible EDMs involve the superpartners of first generation fermions. Therefore, in ref. [44] the Effective MFV (EMFV) framework was analyzed allowing all the CP violating phases not forbidden by the flavour symmetry. With hierarchical squark masses, the usual argument that flavour blind phases need to be tiny to meet the EDM bounds does not apply in EMFV.

The main results of [44] can be summarized as follows.

– The one-loop contributions to the EDMs are under control if the first generation up-squark and sneutrino masses fulfill the following bounds,

$$(7) \qquad m_{\tilde{u}} > 2.7 \,\text{TeV} \times (\sin \phi_\mu \tan \beta)^{\frac{1}{2}}, \qquad m_{\tilde{\nu}} > 4.0 \,\text{TeV} \times (\sin \phi_\mu \tan \beta)^{\frac{1}{2}}.$$

– Two-loop contributions from Barr-Zee–type diagrams not suppressed by first- or second-generation sfermion masses give contributions to the electron EDM that are in the ballpark of the experimental bound in the case of a sizable phase in the μ term, and are usually below it if the stop trilinear coupling (but not μ) is complex.

– Even if the EDMs are under control, potentially visible effects can arise in CP asymmetries in B physics, induced by one-loop contributions involving third generation sfermions to the magnetic and chromomagnetic $b \to s$ dipole operators.

As an example for the possible effects in B physics, fig. 3 shows the correlation between the mixing-induced CP asymmetry in $B \to \eta' K_S$ and the angular CP asymmetry A_7 (integrated in the low q^2 range) in $B \to K^* \mu^+ \mu^-$ discussed in sect. **4** for two scenarios: first, assuming an arbitrary phase of the μ term, second, assuming an arbitrary phase
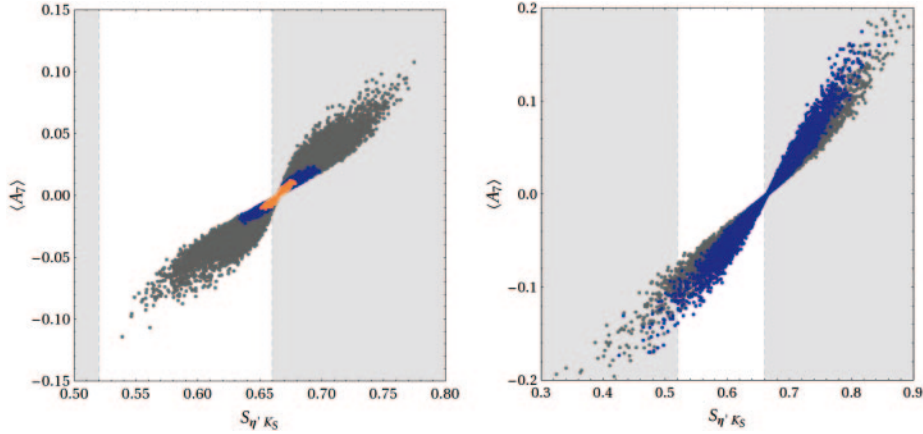
Fig. 3. – Correlation between the mixing-induced CP asymmetry in $B \to \eta' K_S$ and the angular CP asymmetry $\langle A_7 \rangle$ in $B \to K^* \mu^+ \mu^-$ in two scenarios with a complex μ term (left) or complex A_t term (right). The gray points are allowed by all constraints except d_e, while the blue points are compatible with all constraints. The orange points in the left-hand plot have $|\sin \phi_\mu| < 0.2$.

for the stop trilinear coupling. In particular in the second scenario, sizable effects in the CP asymmetries can be generated without violating the EDM bounds[4].

This study provides an example of a model with interesting signatures in flavour physics observables and also highlights the importance of dedicated flavour physics experiments, like EDM searches or Super B factories, as complements to the LHC. The results are applicable to all MSSM scenarios with hierarchical sfermions (see, *e.g.*, [8]), with possible additional effects in the presence of non-minimal flavour violation.

6. – Conclusions

The LHC era is in full swing, also in flavour physics. Imminent results on decays like $B_s \to \mu^+ \mu^-$ or $B \to K^* \mu^+ \mu^-$ and on CP violation in B_s mixing discussed in this talk will help shed light on the question whether there is new physics at the TeV scale, and subsequently whether the Yukawa couplings are the only source of breaking of the flavour and CP symmetries, as in the SM.

Supersymmetry with hierarchical squark masses, combined with Effective MFV [43, 44], can solve the SUSY flavour *and CP* problems and leads to potentially visible effects in CP asymmetries in B physics, without violating EDM bounds.

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[4] The signals in flavour physics arising in this second scenario are very similar to the effects in the MFV MSSM with a complex A_t term and a real μ term [45,5]. Of course, the two setups are easily distinguishable on the basis of their different spectrum.

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