IL NUOVO CIMENTO Vol. 32 C, N. 3-4 Maggio-Agosto 2009
DOI 10.1393/ncc/i2009-10428-2

Colloquia: IFAE 2009

Rare B decays and minimal flavour violating New Physics

E. Baracchini

Department of Physics and Astronomy, University of California - 4129 Frederick Reines Hall Irvine, CA 92697, USA

(ricevuto il 19 Settembre 2009; pubblicato online il 14 Ottobre 2009)

Summary. — We discuss some interesting effective field theories beyond the Standard Model with explicit flavour symmetries, which can account for the available experimental results and, at the same time, provide interesting and falsifiable prediction on flavour-violating as well as flavour-conserving observables.

PACS 11.30.Hv – Flavor symmetries.
PACS 11.30.Pb – Supersymmetry.
PACS 13.20.-v – Leptonic, semileptonic, and radiative decays of mesons.
PACS 13.25.Hw – Decays of bottom mesons.

1. – Introduction

All the tests carried through in recent years on flavour-conserving electroweak precision observables as well as on the relevant Standard Model (SM) parameters controlling quark-flavour dynamics (also in several suppressed processes) have only reinforced the validity of the SM picture. Nonetheless, some experimental evidence, such as the presence of dark matter and neutrino oscillations, as well as the fermion mass hierarchy and the quantitative asymmetry between matter and antimatter in the universe, cannot be accounted for by the SM and imply that it is not a complete theory. If the SM is not a complete theory, some apparently conflicting theoretical requirements have to be taken into account: the experimental bounds to the NP scale coming from flavour observables have to be satisfied but, at the same time, new degrees of freedom would need to appear at the electroweak scale in order to stabilize the ultraviolet behaviour of the theory. This apparent contradiction is referred to as the *flavour problem*: if we insist that the new physics have to emerge in the TeV region, we have to conclude that the new theory possesses a highly non-generic flavour structure. From the analysis of $\Delta F = 2$ process, it can be shown [1] how flavour and $\mathcal{CP}$ violation remain the main tools to constrain (or detect) NP models, given the fact that any model with strongly interacting NP is beyond the reach of present direct search. As long as we are interested in low-energy processes, we can describe all NP effects without any loss of generality by means of an Effective Field Theory (EFT) approach, which takes into account only the degrees of freedom relevant at a certain energy scale. In this way, low-energy measurements can be used to constraint the NP parameter space and pattern correlation between different low-energy measurements can be used to establish particular characteristic of the underlying NP model, before the start of LHC. For these and all the reasons presented above, we are going to discuss in more details Minimal Flavour Violation (MFV) models, in particular at large value of tanβ (the ratio of the two Higgs vacuum expectation values, *i.e.* $\tan\beta = v_u/v_d$) and how we can use the experimental information available to constrain them.

2. – Minimal flavour violation models

The main idea of MFV is that flavour-violating interactions are linked to the known structure of Yukawa couplings also beyond the SM. As a result, non-standard contributions in FCNC transitions turn out to be suppressed to a level consistent with experiments even for $\Lambda \sim$ few TeV. One of the most interesting aspects of the MFV hypothesis is that it can easily be implemented within the general EFT approach to new physics [2,3]. This allows us to establish generally an unambiguous correlation among NP effects in various rare decays. These falsifiable predictions are a key ingredient to identify in a model-independent way the flavour structure of the new-physics model.

The MFV construction consists in identifying the flavour symmetry and symmetry-breaking structure of the SM and enforce it in the EFT. The pure gauge sector of the SM invariant under the largest symmetry group of flavour transformations is $\mathcal{G}_{\rm SM} = \mathcal{G}_q \otimes \mathcal{G}_l \otimes U(1)$, where $\mathcal{G}_q = SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R}$ and $\mathcal{G}_l = SU(3)_{L_L} \otimes SU(3)_{E_R}$ and three of the five $U(1)$ charges can be identified with the baryon number, the lepton number and hypercharge [4]. This large group is explicitly broken in the SM by the Yukawa interaction. The most restrictive hypothesis we can make to protect in a consistent way flavour mixing in the quark sector, is to assume that Y_D and Y_U are the only sources of $\mathcal{G}_q$ breaking also beyond the SM. The invariance of the SM Lagrangian under $\mathcal{G}_q$ can be then formally recovered elevating the Yukawa matrices $Y_{U,D}$ to non-dynamical fields (spurions) with appropriate transformation properties under $\mathcal{G}_q$. In terms of effective field theory formulation, we define an effective theory to have a Minimal Flavour Violation pattern in the quark sector if all higher-dimensional operators, constructed from the SM and Y_i fields, are invariant under $\mathcal{CP}$ and (formally) under the flavour group $\mathcal{G}_q$ [2]. According to this criterion, all the operators with arbitrary powers of the (dimensionless) Yukawa fields should be considered. However, a strong simplification arises by the observation that all the eigenvalues of the Yukawa matrices are small, except for the top one, and that off-diagonal elements of the CKM matrix (V_{ij}) are typically very suppressed. As a result, within this framework the coefficients of the higher-dimensional operators have the same CKM suppression of the corresponding SM amplitudes and thus their effects are expected to be small. As a consequence, the bounds on the new-physics scale are in the few TeV range. Moreover, the flavour structure of $Y_U Y_U^\dagger$ implies a well-defined link among possible deviations from the SM in FCNC transitions of the type $s \to d$, $b \to d$ and $b \to s$ (the only quark-level transitions where observable deviations from the SM are expected).

3. – Minimal flavour violation at large $\tan\beta$

In models with more than one Higgs doublet, the breaking mechanism of $\mathcal{G}_q$ and the $U(1)$ symmetries can be decoupled, allowing a different normalization of the $Y_{U,D}$ spurion fields with respect to the SM case with interesting phenomenological consequences in specific rare modes. In particular, in two-Higgs-doublet mode, with the two Higgses coupled separately to up-type and down-type quarks, the Lagrangian is invariant under a $U(1)$ symmetry, denoted $U(1)_{PQ}$, whose only charged fields are D_R and E_R (charge $+1$) and H_D (charge -1). The U_{PQ} symmetry prevents tree-level FCNCs and implies that $Y_{U,D}$ are the only sources of $\mathcal{G}_q$ breaking appearing in the Yukawa interaction (similar to the one-Higgs-doublet scenario). A more substantial modification of the one-Higgs-doublet model occurs if we allow sizable sources of $U(1)_{PQ}$ breaking. In fact, new dimension-four operator have to be considered, such as $\epsilon \bar{Q}_L Y_D D_R (H_U)^c$ or $\epsilon \bar{Q}_L Y_U Y_U^\dagger Y_D D_R (H_U)^c$ where ϵ denotes a generic $\mathcal{G}_q$-invariant $U(1)_{PQ}$ breaking source. Even if $\epsilon \ll 1$, the product $\epsilon \cdot \tan\beta$ can be $\mathcal{O}(1)$, inducing an $\mathcal{O}(1)$ non-decoupling correction to $\mathcal{L}_{Y_0}$. In this case, as discussed in some specific supersymmetric (SUSY) scenarios, $\mathcal{O}(1)$ corrections can be induced to the down-type Yukawa couplings [5], the CKM matrix element [6] and the charged-Higgs couplings [7, 8]. Since the b-quark Yukawa coupling becomes $\mathcal{O}(1)$, the large tanβ regime is particularly interesting for helicity-suppressed observables in B physics. One of the most clearest phenomenological consequences is a suppression (typically in the 10–50% range) of the $B \to l\nu$ decay rate with respect to its SM expectation [9]. Within the two-Higgs-doublet models, the charged-Higgs exchange amplitude introduces an additional tree-level contribution in semileptonic decays. Being proportional to Yukawa couplings of quark and leptons, this additional contribution is usually negligible. However, in $B^\pm \to l^\pm \nu$ decays, the $H^\pm$ exchange can compete with the $W^\pm$ one due to the helicity suppression of the latter. Anyway, the world average of the latest experimental results on $\mathcal{B}B^\pm \to \tau^\pm \nu$ [10] seems to point toward the opposite direction (being about two times the SM expectation), even if the errors are still large to assert a real discrepancy. The large b-quark Yukawa coupling arising in this particular scenario brings a pattern of enhancement and suppression in other B meson decays which, if verified or falsified, can point out the flavour structure of the NP [11]. Potentially measurable effects in the 10–30% range are expected also for $B \to X_s \gamma$ and ΔM_{B_s}, as well as $B_{s,d} \to l^+ l^-$. A very interesting feature of this particular realization is the connection with flavour-conserving observables, as the mass of the lightest Higgs m_{h^0} and the anomalous magnetic moment of the muon $a_\mu = (g-2)_\mu/2$. Without entering in the details (see [11]), we can state that, in the absence of fine-tuned solutions, the present experimental bounds on m_{h^0} [12] provide a strong support for a scenario with heavy squarks, $A_U \geq M_{\tilde{q}}$ and $\tan\beta$ well above the unity, which is a regime where the correlations among $\mathcal{B}(B^\pm \to \tau\nu)$, $\mathcal{B}(B_{s,d} \to l^+ l^-)$ and $\mathcal{B}(B \to X_s \gamma)$ are enhanced. On the other hand, a large $\tan\beta$ regime in the Minimal Supersymmetric SM (MSSM) could also provide a natural explanation of the measured 3σ discrepancy from the SM expectation in a_μ, $\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (2.9 \pm 0.9) \times 10^{-9}$ [13, 14].

An interesting feature of this kind of scenarios is the possible link with Dark Matter (DM). Reference [15] analyzes the correlations among different low-energy observables, under the additional assumption that the relic density of a Bino-like lightest SUSY particle (LSP) accommodates the observed DM distribution. The underlying hypotheses are a large value of $\tan\beta$, heavy soft-breaking terms in the squark sector and the GUT relations $M_1 \sim M_2/2 \sim M_3/6$ and $\mu > M_1$, which select the parameter region with the most interesting Higgs-mediated effects in flavour physics. These hypotheses imply that the lightest neutralino is Bino-like, with a possible large Higgsino fraction when $\mu = \mathcal{O}(M_1)$. In this scenario, the relic density constraint is fulfilled mainly via resonant processes, where neutralinos annihilate into down-type fermion pairs through a s-channel exchange close to resonance. The following low-energy observables are taken into account: $\mathcal{B}(B \to X_s \gamma)$, a_μ, $B_{s,d} \to \mu^+ \mu^-$, ΔM_{B_s} and $\mathcal{B}(B^\pm \to \tau\nu)$. The most significant impact of the dark-matter constraints is the non-trivial interplay between a_μ and the B-physics observables: the size of the suppression of $\mathcal{B}(B^\pm \to \tau\nu)$ depends on the slepton mass, which controls the size of the SUSY contribution to a_μ. In particular, it is found that $\Delta a_\mu > 2 \times 10^{-9}$ implies a relative suppression of $\mathcal{B}(B^\pm \to \tau\nu)$ larger than 10%.

The work in ref. [16] concentrates on $\Delta F = 1$ transition, or else rare decays amplitudes. The effective Hamiltonian for this class of decays includes the scalar-density operator with right-handed b quark $P_l^0 \propto (\bar{s}_L b_R)(\bar{l}_R l_L)$, which plays an important role in the large tanβ regime, but is usually neglected in the SM given the strong suppression of its Wilson coefficient. A global fit to several observables coming from $b \to sll$ and $b \to s\nu\bar{\nu}$ processes is performed and the deviation from the SM is accounted for by the quantity $\delta C_i = C_i^{\rm MFV} - C_i^{\rm SM}$, where C_i are the Wilson coefficients. The resulting ranges for δC_i are translated into bounds on the scale of new physics for each single operator. The results found allow for prediction of lepton flavour ratio and forward-backward asymmetry in $b \to sll$ transitions, where in some cases large space for deviation from the SM is left.

Another recent work [17] explores the possibility of using additional observables in $B \to K^*\mu\mu$ decays to test NP models. This is a golden channel for NP searches in FCNCs as $b \to s\gamma$ processes, but, as opposed to these, the four-body final state allows to study various angular observables. These are divided into CP-violating and CP-conserving terms and these terms are analyzed in different extensions of the SM, where clearly only the latter enters the MFV analysis. Various MSSM realizations with a MFV patter predict a strong correlation between the zeros of $B \to K^*ll$ forward-backward asymmetries and $\mathcal{B}(B \to X_s\gamma)$: ref. [17] shows that additional correlations can be found with the zeros of the CP-conserving functions, which are more than one. Studies are currently ongoing at LHCb to determine the experimental sensitivity to these observables [18].

In conclusion, we have presented a review of the MFV hypothesis together with some of the recent analyses on low-energy observables in this context. We showed how the present experimental results point to a NP with a highly non-generic flavour structure and how MFV models allow to protect flavour mixing without the need for fine tuning. The MFV hypothesis does not only prove to be motivated, but also predicts patterns among different decays and processes which can be falsified. Key role is in fact played by low-energies observables as rare B, K, τ and μ decays, underlying again the importance of a complementary study between low-energy and high-p_T physics.

REFERENCES

[1] Bona M. *et al.* (UTfit Collaboration), *JHEP*, **0803** (2008) 049.
[2] D'Ambrosio G., Giudice G. F., Isidori G. and Strumia A., *Nucl. Phys. B*, **645** (2002) 155.
[3] Cirigliano V., Grinstein B., Isidori G. and Wise M. B., *Nucl. Phys. B*, **728** (2005) 121.
[4] Chivukula R. S. and Georgi H., *Phys. Lett. B*, **188** (1987) 99.
[5] Hall L. J., Rattazzi R. and Sarid U., *Phys. Rev. D*, **50** (1994) 7048.
[6] Blazek T., Raby S. and Pokorski S., *Phys. Rev. D*, **52** (1995) 4151.
[7] Carena M. S., Garcia D., Nierste U. and Wagner C. E. M., *Nucl. Phys. B*, **577** (2000) 88.
[8] Degrassi G., Gambino P. and Giudice G. F., *JHEP*, **0012** (2000) 009.
[9] Hou W. S., *Phys. Rev. D*, **48** (1993) 2342.
[10] Heavy Flavour Averaging Group [HFAG], `http://www.slac.stanford.edu/xorg/hfag`.
[11] Isidori G. and Paradisi P., *Phys. Lett. B*, **639** (2006) 499.

[12] Barate R. *et al.*, *Phys. Lett. B*, **565** (2003) 61.
[13] Hertzog D. W. *et al.*, arXiv:0705.4617 [hep-ph].
[14] Jegerlehner F., *Acta Phys. Polon. B*, **38** (2007) 3021.
[15] Isidori G., Mescia F., Paradisi P. and Temes D., *Phys. Rev. D*, **75** (2007) 115019.
[16] Hurth T., Isidori G., Kamenik J. F. and Mescia F., *Nucl. Phys. B*, **808** (2009) 326.
[17] Altmannshofer W. *et al.*, *JHEP*, **0901** (2009) 019.
[18] Dickens J., Gibson V., Lazzeroni C. and Patel M., LHCb note CERN-LHCB-2007-039.