Report on the Flavianet Network activities

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The main activities of the European network Flavianet are summarized. All of them revolve around the current and future flavour physics experimental programs, and aim both for a better understanding and control on the low-energy hadronic physics, and for identifying new promising directions in the quest for Physics beyond the Standard Model.

1. Introduction: What is Flavianet?

Flavianet is a research and training network within the EU framework program 6, which will last four years (2006-2010). It comprises 45 institutions ("nodes") spread throughout Europe (Fig.1), with over 200 participating scientists. In many ways, Flavianet is a descendent of the previous, phenomenology-oriented networks EuroDaphne I and II in the 90's, and Euridice in the early 00's[1]. These networks were built upon the experimental programs pursued at Frascati, i.e. physics up to the GeV scale[2]. In Flavianet, as will be detailed below, the scientific objectives have been broaden, but maintaining the tradition of close connection with experimental programs.

The main purposes of European RTN's are research, and training through research. In practice, this means that the EU is funding Ph.D. and postdoc positions. For the duration of the contract, the equivalent of 34 years of early stage research positions (Ph.D. or first-time postdocs), and 8 years of experienced research positions (postdocs) are available. In addition, young scientists have the opportunity of presenting their work at the yearly collaboration meetings, and to attend several advanced schools supported by the EU. Finally, funds can also be used to finance inter-node stays to promote internal collaboration.

Within European networks, Flavianet specificity is its focus on low-energy phenomenology, with emphasis on quark flavour physics. The long-title of the network is:

Figure 1. Flavianet participating institutes.

Entering the high-precision era of flavour physics through the alliance of lattice simulations, effective theories, and experiment.

In other words, participating scientists are engaged at addressing the broad issue of flavour physics in the Standard Model (SM) and beyond, and studies of the interplay with the collider experiments like those at the LHC[3]. Since most

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Table 1
Flavianet scientific goals and working groups.

	I	II	III	IV	V	VI
Hadronic uncertainties - QCD						
Meson-Meson int.	•			•		
Strong chiral LEC's	•			•	•	
m_q and α_S	•	•	•		•	
Spectroscopy		•	•	•	•	•
Lightcone distr. amp.		•		•	•	
γ vac. pol., $(g-2)_\mu$			•	•		•
Hadronic uncertainties - Electroweak						
V$_{us}$ from K and τ	•		•		•	•
Weak chiral LEC's	•		•	•	•	
K matrix elements	•			•	•	
D & B non-leptonic		•	•	•		•
D & B semileptonic		•	•	•	•	•
Monte-Carlo	•	•	•			•
Global CKM fits	•	•	•			
Search for New Physics in flavour experiment						
Rare K and B decays	•	•		•	•	
$b \to s$ transitions		•		•	•	•
τ and charm			•	•	•	•
SUSY GUT's		•			•	
SUSY alternatives	•	•		•	•	
Global CKM fits	•	•	•			

flavour physics observables are affected by non-perturbative QCD effects, for this program to be successful, a major effort has to be devoted to reducing hadronic uncertainties. Indeed, it is only with a sufficient control on these that the fundamental parameters can be extracted. Once obtained, and taken together with high-energy collider observables, a definite pattern of deviations with respect to the SM will hopefully emerge, opening the paths towards the next level of understanding. Within Flavianet, all available tools to deal with non-perturbative QCD effects are put to use, namely lattice QCD, effective theories, and experimental inputs.

The network activities are thus articulated along two axes: First, improving the theoretical control over hadronic effects, both for pure QCD observables, and for flavour-changing transitions, and second, searching for New Physics in low-energy flavour experiments, both in model-independent and dependent ways. In practice, the network scientists, comprising both theorists and experimentalists (from the KLOE, NA48/NA62, Belle, Babar, LHCb collaborations), are organized into six working groups:

- I Kaon physics
- II Beauty physics
- III Tau, Charm and Quarkonia
- IV Analytic approach to non-perturbative QCD (effective theories)
- V Lattice methods
- VI Radiative return & Monte-Carlo tools

These working groups are based on the individual expertises of nodes and participating scientists. To give to the network a strong unity of goal, and to drive internal collaborations, the detailed scientific objectives are set somehow orthogonally to the working groups, see Table 1.

2. Recent scientific activities

Given the large number of scientists involved, all the activities cannot be summarized here. Over 300 papers were published during the first year of Flavianet, and probably as much since then. For a full review of the activities, we refer to the reports sent back to Brussels, which can be downloaded from the Flavianet website[4]. Therefore, in the present talk, only a few selected topics will be presented, most drawn from the 2007 Flavianet report. In advance, all apologies for any missing work and/or reference. Further, mostly Flavianet papers are included – citation to related works can be found from them.

2.1. New Physics searches and models

Most models of New Physics involve either additional flavoured particles, or new interactions among known ones. These induce additional contributions to low-energy flavour transitions, in particular to the flavour-changing neutral currents (FCNC). Being suppressed in the SM, the FCNC are very powerful tools to test for the presence of New Physics. At the same time,

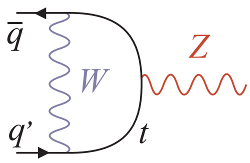

Figure 2. Example of FCNC: The Z penguin, proportional to $V_{tq}^{\dagger}V_{tq'}$.

extensive data on the FCNC have already been obtained, without any signal of New Physics. Therefore, generically, the experimentally measured strengths of FCNC transitions scale as predicted by the CKM paradigm of the SM, i.e. as (see Fig.2)

$$\begin{array}{ccc} b\to s\sim\lambda^2 & b\to d\sim\lambda^3 & s\to d\sim\lambda^5 \\ (=|V_{tb}^{\dagger}V_{ts}|) & (=|V_{tb}^{\dagger}V_{td}|) & (=|V_{ts}^{\dagger}V_{td}|) \end{array} \quad (1)$$

in terms of the Cabibbo angle $\lambda \approx 0.2$.

These transitions are significantly suppressed, especially in the $s \to d$ sector, and immediately imply that New Physics, if present, cannot be both light and generic. By this is meant that if deviations with respect to the SM are written in terms of new effective interactions, e.g. as

$$\mathcal{L}_{eff} = \left(\frac{c_{bs}}{\Lambda^2}(\bar{b}\Gamma s) + \frac{c_{bd}}{\Lambda^2}(\bar{b}\Gamma d) + \frac{c_{sd}}{\Lambda^2}(\bar{s}\Gamma d)\right)(\bar{\nu}\Gamma\nu)$$

with Γ some Dirac structures, then either the New Physics mass-scale Λ is very large, well above the TeV scale and beyond the reach of the LHC, or its flavour-changing couplings are suppressed, ensuring sufficiently small coefficients c_{ij}. In fact, since a too large mass-splitting between the electroweak and New Physics scales is theoretically unappealing, if not outright unstable, it is the c_{ij} which have to be small – this fine-tuning problem is the so-called New Physics flavour puzzle.

In view of this puzzle, the first task is to collect as much experimental information as possible on the $b \to s$, $b \to d$ and $s \to d$ transitions, and then, to check if all these observables are consistent with each other, within errors. Two groups currently perform global CKM fits, UTfit[5] and CKMfitter[6], using different statistical methodologies for the treatment of errors[7]. Their results are in good agreements (see Fig.3), and, even generically allowing for the presence of New Physics, do not show any significant deviation with respect to the SM (see however [8]).

2.1.1. Bottom-up approaches

In view of this state of fact, the least we can do to accommodate new particles below the TeV scale is to force the New Physics contributions to scale exactly as in Eq.(1), by imposing that

$$c_{qq'} \sim V_{tq}^{\dagger}V_{tq'} \quad (2)$$

Enforcing this apparently unnatural scalings of the $c_{qq'}$ corresponds to the Minimal flavour Violation hypothesis, a name which in fact includes several intrinsically different implementations. The two main classes are "Constrained" MFV, and "Symmetric" MFV. In the former, one enforces by hand the absence of new effective operators below the electroweak scale, as well as of new CP-violating phases[9]. In the latter, one requires that only the Yukawa couplings can break the large $SU(3)^5$ flavour symmetry present in the gauge sector of the Standard Model. All the flavour-breaking operators can then be systematically reconstructed in terms of the Yukawa couplings[10]. In both cases, specific testable correlations between low-energy observables are predicted, even if no New Physics model needs to be fully specified.

Within Flavianet, several groups are studying the implementations and consequences of MFV in various contexts. In particular, within the MSSM, 1- the phenomenological implications of MFV were investigated at large $\tan\beta$[11] and in the B sector[12], 2- the quasi-fixed point behaviour of MFV under the RGE was established[13], and 3- MFV was shown to be a viable alternative to R-parity[14]. In non-supersymmetric context, were studied e.g. the MFV connection with the LHC in the presence of extra quarks[15], the constraints one could draw from the electroweak precision observable $Z \to b\bar{b}$[16], and the MFV constraints in the lepton sector and leptogenesis[17].

2.1.2. Top-down approaches

The bottom-up approaches are powerful tools to evidence or constrain possible patterns of de-

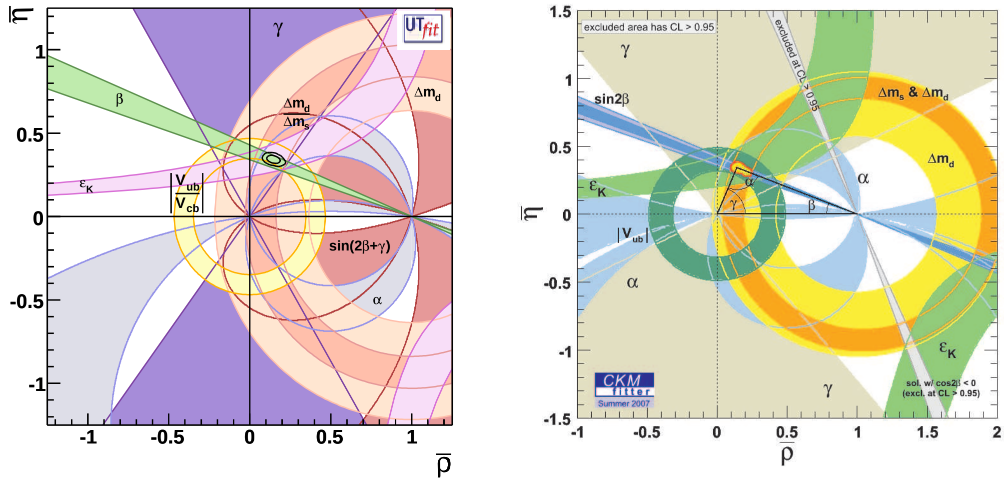

Figure 3. Global CKM fit performed by UTfit[5] and CKMfitter[6], respectively.

viations with respect to the SM, but ultimately, such patterns must emerge from a fully dynamical model. The alternative route towards finding New Physics is thus to start from specific models, and study their low-energy signatures.

Within Flavianet, special emphasis was laid first on the MSSM [11–17] and on supersymmetric GUT scenarios[18]. Second, alternatives to supersymmetry were also studied, with the purpose of distinguish them from supersymmetry, or for their own sake. In particular, and among others, the little Higgs theory[19], Higgless theories[20], extra-dimensions[21], and unparticles[22] have all received some attention.

2.2. Predicting hadronic observables

Let us move to the second axis of scientific activities, which has for goal the theoretical control over hadronic uncertainties.

2.2.1. K physics

Kaon physics was at the core of the Eurodaphne and Euridice network activities, and still represent a great deal of the concerted efforts of Flavianet. A detailed account is given in Ref.[23], while here, we will simply review the main highlights.

An essential task of Flavianet is to prepare for the upcoming experiments aiming at measuring the $K \to \pi\nu\bar{\nu}$ decay rates at CERN (NA62) and in Japan (J-Parc). This means studying these rare K decay modes for their exceptional cleanness and sensitivity to New Physics, but also, importantly, identifying new opportunities. For example, 1- other rare K decays like $K_L \to \pi^0\ell^+\ell^-$, though less clean, are sensitive to a larger class of New Physics effects, 2- leptonic and semi-leptonic modes allow us to extract[2] V_{us}, to test universality, or to learn about pion scattering, 3- radiative decays like $K \to (\pi)\gamma^{(*)}\gamma^{(*)}$ can help us to theoretically control rare K decays, ΔM_K and $K_L \to \mu^+\mu^-$, all very sensitive to New Physics, and 4- forbidden decays like $K \to (\pi)e\mu$ could offer clear signals of lepton flavour violation.

To deal with QCD effects at the scale relevant for Kaon physics, a powerful tool is at hand: Chiral Perturbation Theory[3] (ChPT). Therefore, many Flavianet activities aim at pushing ChPT to the next level of precision, i.e. at NNLO $\sim \mathcal{O}(p^6)$. For example, the matching between $SU(2)$ and $SU(3)$ ChPT was analyzed in Ref.[25], the $\eta \to 3\pi$ decay was treated in Ref.[26], and $\gamma\gamma \to \pi\pi$ was studied in Ref.[27]. Also, semi-

[2] Though part of the Flavianet objectives, τ physics will not be reviewed here (see e.g. [24]). Nevertheless, it should be said that hadronic τ decays also permits to extract V_{us}.
[3] Another tool is Lattice QCD, also used within Flavianet, but not reviewed here – see Ref.[4] for more information.

leptonic rare K and $K_{\ell 3}$ decay form-factors received a lot of attention, both theoretically and experimentally[28].

At the NNLO level, the number of free parameters or Low-Energy Constants (LEC) allowed by the Chiral symmetry, is becoming large, and experimental input alone can no longer be used to fix all of them. Reverting thus to theory, the $1/N_C$ approach, with N_C the number of colours, offers to determine these LEC, and was extensively studied[29].

2.2.2. B physics

The activities of Flavianet encompass all aspects of B physics, using the various effective theories at hand (QCDf, SCET, HQET), as well as Lattice QCD. In addition, inputs from experiment is now extensive, thanks to the B-factories at Belle and BaBar, and is expected to grow even further in the near future with the advent of LHCb, all being experiments with Flavianet participations. Finally, the physics case for constructing a SuperB factory was and is still under study[30].

1- *Semileptonic B decays*, exclusive like $B \to P\ell\nu_\ell$, $P = \pi, K, D, ...$ or inclusive, provide the CKM matrix elements V_{ub} and V_{cb} once the $B \to P$ matrix element form-factors are known. Theoretical works therefore focussed on reducing their hadronic uncertainties, using either lattice QCD[31], or QCD light-cone sum-rules[32]. Further, when P is sufficiently heavy, it is possible to probe the scalar part of the transition, where specific New Physics effect could be present, e.g. charged Higgs effects in the MSSM at large $\tan\beta$[33].

2- *Hadronic B decays* in two or three mesons give us access to various angles and sides of the Unitary Triangle (UT), but suffer from relatively large theoretical uncertainties. Still, the now precise data on the branching ratios, direct and time-dependent CP-asymmetries permits to test our current understanding and tools, and to extract useful constraints on the UT. Studies in general concentrate on some flavour $SU(2)$ or $SU(3)$ multiplets of final states, no matter whether the final mesons are pseudoscalar, vector, charmed or not,... For example, have been studied the $B \to KK$ modes[34], the penguin dominated $B \to \pi K$ modes and the presence or not of a puzzle in the CP-asymmetries[35], the tree-dominated $B \to \pi\pi$ modes[36], the modes with η, η' in the final state[37], the $B \to VV$ modes, with $V = \rho, K^*, ...$[38], as well as the modes with c-quarks in the final state[39], i.e. $B \to D\bar{D}, \psi K, ...$

3- *Radiative and rare B decays*, $B_{s,d} \to \ell^+\ell^-$, $b \to s\ell^+\ell^-$ and $b \to s\gamma$ (both inclusive and exclusive), are interesting for their relative cleanness, and sensitivity to New Physics effects. In particular, the theoretical prediction for $b \to s\gamma$ has reached the NNLO level[40], and its rather good agreement with experiment provides one of the toughest constraints on New Physics models. The other studies involving $b \to s\gamma$ as well as the other modes were done in more general settings, working out their combined constraints on New Physics models (see Section 2.1).

4- *$B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ mixing parameters* were re-analyzed both in the SM[41] and in various New Physics models[42], now that the latter has been measured at Fermilab. As for radiative decays, the $B_{d,s}$ mixing parameters are essential ingredients to global CKM fits[7,8], see Fig.3, as well as to studies of specific New Physics models (see Section 2.1).

2.2.3. The strong coupling constant

The QCD coupling constant α_S is among the least well-known fundamental parameters of the SM. However, it enters in the prediction of many flavor-physics observables, and thus needs to be measured as precisely as possible. Several techniques are available, and have been exploited by Flavianet groups to give the remarkably consistent values:

$$\begin{array}{ll} \Upsilon(1S) \text{ decays}: & \alpha_S(M_Z) = 0.119^{+0.006}_{-0.005} \text{ [43]} \\ e^+e^- \to had.: & \alpha_S(M_Z) = 0.119^{+0.009}_{-0.011} \text{ [44]} \\ \tau \text{ decays}: & \alpha_S(M_Z) = 0.119^{+0.008}_{-0.008} \text{ [45]} \end{array}$$

Another important application of a precisely known $\alpha_S(M_Z)$ is to test for unification of the three SM coupling constants. Such a test is a highly non-trivial check of the particle content and spectrum of New Physics models. For instance, it is well known that unification fails

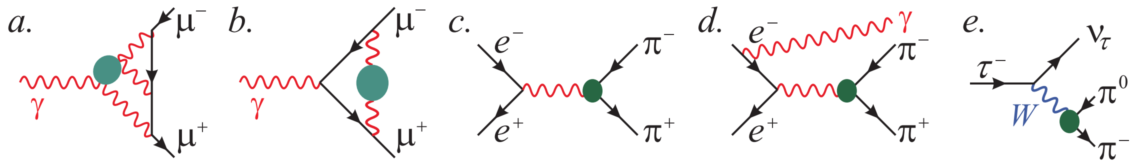

Figure 4. $a-b$: light-by-light and vacuum polarization hadronic contributions to a_μ. $c-e$: energy scans, radiative return, and τ decay data used to estimate $a_\mu^{\pi\pi}$.

within the SM, but not within its supersymmetrized version, the MSSM. In this latter case, the extra particles above the electroweak scale accelerate the running of the couplings just such as to drive them to unification. Several works have improved the treatment of the QCD and threshold effects in the long running of α_S up to the GUT scale[46].

Finally, some of the techniques allowing to extract α_S can be adapted to extract also the charm- and bottom quark masses[47]. These are important inputs in various low-energy hadronic quantities, e.g. $m_c(m_c)$ enters in the prediction of the rare K decay rates, but also for testing Yukawa coupling unification at the GUT scale.

2.2.4. The muon anomalous moment

The $a_\mu = (g-2)_\mu/2$, though being a flavour-conserving observable, is known theoretically and experimentally to such a high precision that it offers a unique constraint on New Physics. Further, there is at present a 3.4σ discrepancy[48]:

$$a_\mu^{\text{exp}} = 116\,592\,08.0\,(6.3) \times 10^{-10}$$
$$a_\mu^{\text{SM}} = 116\,591\,78.5\,(6.1) \times 10^{-10}$$
$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (29.5 \pm 8.8) \times 10^{-10}$$

However, this is generally not yet seen as an unambiguous signal of New Physics because, at this level of precision, hadronic quantities are involved. This is where the expertise of Flavianet in dealing with low-energy QCD effects enters. These hadronic contributions are of two kind: the so-called light-by-light, and hadronic vacuum polarization graphs (Fig.4), contributing for

$$a_\mu^{\text{lbl}} = (11 \pm 4) \times 10^{-10}$$
$$a_\mu^{\text{hvp}} = (692 \pm 6) \times 10^{-10}$$

to a_μ^{SM}, respectively. Obviously, even if extremely difficult to estimate[49], a_μ^{lbl} is three time smaller than Δa_μ, and therefore cannot explain it. On the other hand, Δa_μ is equal to about 4% of the $a_\mu^{\text{hvp.}}$. Thus, even though a_μ^{hvp} can be related to experimentally measured quantities, it is nevertheless needed to a very challenging percent-level accuracy.

Through dispersion relations, a_μ^{hvp} is expressed as a momentum integral over the $e^+e^- \to hadron$ cross-section, times a kernel function. This kernel strongly weights the low-momentum part of the integral, making the $\pi^+\pi^-$ contribution to a_μ^{hvp} dominant. Several techniques are then used and combined to estimate $a_\mu^{\pi\pi}$ from experiment (Fig.4): the $e^+e^- \to \pi^+\pi^-$ energy scans, the radiative return method[4], and τ decay data (for the latter, up to isospin breaking corrections). In all these cases, special care is needed to deal with QED radiative corrections, which involve precise computer tools developed or updated recently (Photos, Tauola[50], Phokhara[51]).

There is another, equally important application of the extracted hadronic contribution to the photon vacuum polarization: it permits to run the QED coupling up to the electroweak scale, where it can be used as input to global fits to the SM. Given the overall precision achieved for electroweak precision observables like M_Z, $\sin\theta_W$, m_W,..., such fits probe the SM at the quantum level, and severely constrain the allowed range for the Higgs mass, as well as the parameter space of any New Physics model with sub-TeV new particles.

[4] At present, mostly with data from KLOE, but similar analyses at B-factories should complement their data in the future.

3. Conclusion

This short and partial review of Flavianet activities (more information can be found on the web[4]) shows that they are fully inscribed within the global endeavour aiming at discovering New Physics. The Flavianet program focuses on the now precise low-energy quark flavour observables – dealing with their inherent hadronic uncertainties being one of its specialized tasks. To this end, all the resources of effective theories and lattice methods are called in, supplemented by available experimental data.

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