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New Physics and flavour-violating processes

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Summary. — In the first part of this conference contribution, I will review the status of flavour physics in light of the recent anomalies reported in various observables and by different experiments. In the second part, I will briefly discuss possible interpretations of these anomalies in terms of New Physics.

1. – On the recent flavour anomalies

The first run of the LHC has left us with the discovery of a Standard Model (SM)-like Higgs boson and no clear evidence of New Physics (NP). The long-waited signals from new coloured particles predicted in natural theories such as supersymmetry and the composite Higgs framework have not found an experimental confirmation. Considering direct searches, so far the first set of data from the second run at 13 TeV has also shown great consistency with the SM([1]). However, several anomalies in flavour physics have been reported in various observables and by different experiments. The assessment of the true significance (or confidence level) of these anomalies is a difficult task, mostly because the SM predictions in various observables are not theoretically under control owing to the non-pertubative nature of the QCD strong interactions. A fair summary of the current anomalies is reported in fig. 1. This plot shows the nominal significance of the anomalies in terms of standard deviation versus the subjective "theoretical cleanliness" in arbitrary units. Inspired by this, I will briefly review the status of main flavour anomalies.

- $B \to K^* \mu^+ \mu^-$ angular observables

  In this decay process, the K^* meson further decays into a kaon and pion, giving rise effectively to a 4-body decay of the B-meson in the initial state. For this reason the kinematics of the whole decay is quite rich and various angular observables can

([1]) With the remarkable exception of the 750 diphoton anomaly, contribution from Riccardo Torre at this conference (unpublished).

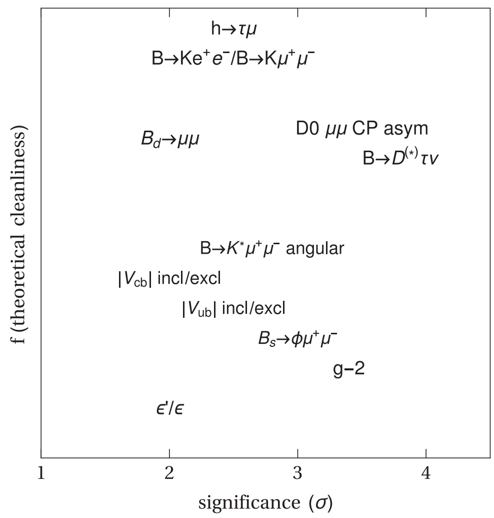

Fig. 1. – A comprehensive set of current flavour anomalies. On the vertical axis, a subjective and debatable variable, the "theoretical cleanliness", is reported while on the horizontal axis the significance quoted in the majority of papers is shown. From Z. Ligeti, talk at the "Rencontres de Moriond QCD and High Energy Interactions", March 2016.

be constructed and measured. In particular, LHCb [1] reported an anomaly in one of these called P_5'. The significance of this excess highly depends on the modelling of the hadronic uncertainties. The most optimistic analysis claims a discrepancy with the SM at more than 4σ [2] while the most pessimistic group claims that the data are compatible with the SM when taking into account the non-factorizable hadronic corrections in a conservative way [3].

- Branching ratios of $b \to s\mu^+\mu^-$ decays

  Various measurements of branching ratios are systematically low when compared with the SM predictions. Among the various decays, the most significative is the decay $B_s \to \phi\mu^+\mu^-$ [4], where some authors quote a discrepancy with the SM prediction at more than 3σ.

- R_K

  A general strategy to obtain theoretically clean observables is to consider ratios of physical quantities. This is the case of the observable R_K defined as $R_K \equiv \frac{Br\left(B\to K\mu^+\mu^-\right)}{Br(B\to Ke^+e^-)}$. The SM prediction is 1 with an error of less than 1% [5] ([2]), while the LHCb measurement [6] gives $R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$.

- $B_d \to \mu\mu$ and $B_s \to \mu\mu$

  These decay channels have been considered as golden probes in the search for NP. They are theoretically very clean and particularly sensitive to specific extensions of the SM where contributions to scalar currents are generated (*e.g.*, SUSY at large

([2]) See contribution from Marzia Bordone at this conference.

value of tan β). SM prediction for these observables are quite accurate with an error in the few percent range. Recent combined results from CMS and LHCb [7] and also from ATLAS [8] have shown a mild discrepancy of about 2σ.

- R_D and R_{D^*}

  These observables are defined as the ratio of decay rates $R_{D^{(*)}} \equiv \Gamma(B \to D^{(*)}\tau\overline{\nu})/\Gamma(B \to D^{(*)}\ell\overline{\nu})$ where $\ell = e, \mu$. It is quite impressive that (very) different experiments [9-13] obtained consistent results. A combination of these analyses [14] shows a discrepancy of about 4σ. The SM prediction is quite solid and most probably this is the most significant discrepancy in flavour physics.

- $h \to \tau\mu$

  In the SM the Higgs boson is flavour diagonal, so it is very interesting to look for possible flavour-violating decays of this particle. This would be a clear signal of NP without any theoretical uncertainty. Recently, CMS [15] has reported results for the search of lepton-flavour–violating decay $h \to \tau\mu$ showing an excess of events with a significance of more than 2σ. ATLAS also announced the result of a similar analysis [16] that is not inconsistent with the hint suggested by CMS. Data from the run at 13 TeV will be crucial to clarify the fate of this anomaly.

Concerning the remaining anomalies present in the plot, the discrepancies in the extraction of $|V_{ub}|$ and $|V_{cb}|$ from inclusive and exclusive measurements in the anomalous magnetic moment of the muon $(g-2)_\mu$ and in the kaon physics observables have stood since a long time. Unfortunately, to resolve these issues a series of theoretical and experimental improvements are required and hopefully some of them will be achievable in the future.

2. – New Physics?

Despite the long list of anomalies reported in flavour data, it is fair to say that the situation is inconclusive and we need more data (and more theoretical efforts) to understand the origin of these anomalies. However, in light of the present experimental scenario, it is in my opinion legitimate and interesting to start speculating on the possible structure of NP beyond these anomalies. In addition, specific models could give rise to predictions testable and the LHC and other experiments such as Belle II.

A general message that we could draw is that if one or more of these anomalies are confirmed, the NP will be non Minimally Flavour-Violating (MFV). According to the MFV assumption, the NP has a flavour-violating structure that is directly related to the Yukawa sector. Now this hypothesis is too restrictive, for example various anomalies have recently suggested a possible large breaking of the lepton flavour universality and the breaking induced by the Yukawa of the SM in the charged lepton sector is too small to accomodate the present data.

I will now briefly summarise the main theoretical ideas to address these anomalies in beyond-SM models.

- $h \to \tau\mu$

  Any model of NP that aims to explain this anomaly has to face the problem of obtaining a quite large decay rate (similar in size to the $\Gamma(h \to \tau\tau)$) while avoiding dangerous contribution to other lepton flavour decays like $\tau \to \mu\gamma$. Loop-induced decay and lepton mixing with vector-like state are in general not sufficient to explain this anomaly (see for example [17]). The option left is to extend the scalar sector of the SM model and in this way the anomalous data can be accommodated [17, 18].

- R_D and R_{D^*}

  The quark flavour transition relevant for this set of anomalies is $b \to c$. In the SM, this is mediated by charged currents, thus it is a tree level effect without a loop suppression. This means that the NP contribution has to be quite sizeable in order to correct the SM prediction. For this reason the NP required to explain this anomaly has to be particularly light or very strongly coupled. Indeed, any NP explanation has to pass a series of constraints ranging from electroweak precision tests, to other (correlated) flavour observables, up to stringent constraints from direct searches at the LHC of the new particle that mediated new contribution. However, viable models with spin-1 mediators (leptoquark or W') can be constructed (see for example [19]) and are preferred to models containing new scalars.

- The $b \to s\mu^+\mu^-$ saga

  It is very remarkable that a non-trivial list of anomalies can be explained in a very compact and simple way assuming that NP enters only some few effective operators involving a single Flavour-Changing Neutral Current (FCNC) transition $b \to s\mu^+\mu^-$. The anomalies that are in this list are: the $B \to K^*\mu^+\mu^-$ angular observables, R_K, the low value of some decay rate like $B \to \phi\mu^+\mu^-$ and the low value of $B_s \to \mu^+\mu^-$. Various groups (like [2, 20]) performed global fits of all the relevant data obtaining compatible results. The best fit values are obtained for NP that modifies the $\bar{b}_L\gamma^\alpha s_L\bar{\mu}\gamma_\alpha\mu$ or $\bar{b}_L\gamma^\alpha s_L\,\bar{\mu}_L\gamma_\alpha\mu_L$ effective operators. Starting from this model-independent analysis, it is easy to construct explicit models that induce the preferred operators at the tree level. This can be achieved with leptoquarks as well as with spin-1 resonances (see for example [21, 22]). Few works also considered induced effect at the 1-loop level as in [23]. Notice that, from a model building point of view, it is easy to accomodate these data because the overall effect has to be much smaller that the one required to explain the R_D and R_{D^*} anomalies.

3. – Conclusions

The field of flavour physics is living a quite vibrant and exciting time, more data will arrive very soon from a series of experiments (NA62,Belle II, mu2e, KOTO, COMET, etc.) but also (and in particular) from LHCb. This will hopefully clarify the present experimental situation revealing a possible NP or confirming the solidity of the SM.

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