PROCEEDINGS OF SCIENCE

Theory lessons from flavour data

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The strong hierarchies of the masses and CKM mixing elements of the Standard Model fields suggest new physics providing some dynamical explanation. In this talk we review different philosophies to attack this puzzle in relation to the Higgs hierarchy problem, using partial compositeness as a guiding example. Given the strong experimental bounds from flavour physics and the lack of clear signals of new physics at LHC, a multi-scale dynamical explanation of the flavour hierarchies emerges as the most natural candidate.

The Eleventh Annual Conference on Large Hadron Collider Physics (LHCP2023)
22-26 May 2023
Belgrade, Serbia

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https://pos.sissa.it/

PoS(LHCP2023)079

1. Flavour data: the flavour puzzle

The flavour sector of the Standard Model (SM) presents very peculiar structures. Fermions are organised in three families which are indistinguishable for the gauge interactions. The SM thus have a global $U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$ flavour symmetry (complex rotations among the three families) only broken by the Higgs Yukawa couplings $Y_{u,d,e}$, $\mathcal{L} \supset \bar{\psi}^i_L H^{(c)} (Y_\psi)_{ij} \psi^j_R$. Furthermore, these Yukawa couplings are very hierarchical, generating very hierarchical masses, and suppressed CKM mixing elements among the quark families when the electroweak (EW) symmetry is broken. These features point towards some underling dynamical explanation still unknown (flavour puzzle). In particular, third-family Yukawas are $O(0.01-1)$, breaking the $U(3)^5$ flavour symmetry to $U(2)^5$. We can write the SM Yukawa couplings in the quark sector with the $U(2)$ spurions, $\Delta_u \sim 2_q \times 2_u$, $\Delta_d \sim 2_q \times 2_d$ and $V_q \sim 2_q$,

$$Y_u = y_t \begin{pmatrix} \Delta_u & \epsilon_t V_q \\ 0 & 1 \end{pmatrix}, \quad Y_d = y_b \begin{pmatrix} \Delta_d & (\epsilon_t - 1) V_q \\ 0 & 1 \end{pmatrix}. \tag{1}$$

V_q is the leading breaking of $U(2)$, with $|V_q| \sim 0.04$. Its smallness contributes to explain the huge suppression in the SM of flavour changing neutral currents (FCNC) or the neutron electric dipole moment. Precisely, meson-mixing or electric dipole moments impose strong bounds above the PeV range on new physics (NP) with generic flavour structure, since they would strongly affect these observables [1]. However, we also expect NP at the TeV scale to stabilise the Higgs mass from radiative corrections (hierarchy problem). We first discuss two paradigms to address the flavour puzzle assuming there is NP at the TeV stabilising the EW scale:

(1) Flavour hierarchies are addressed at the TeV scale by the same physics that solves the hierarchy problem. Flavour observables can only be partially protected from large NP effects.

(2) Flavour hierarchies are addressed at a scale much higher than the TeV. Then, NP solving the hierarchy problem at the TeV scale typically couples universally to some sector of the SM.

As we illustrate below with the example of partial compositeness, the first possibility remains unsatisfactory as the most sensitive flavour observables can push the bound of NP to the $10-100$ TeV range. On the other hand, LHC searches are starting to challenge the second possibility, setting unavoidable bounds of around 10 TeV on universal NP.

2. An example: partial compositeness

Partial compositeness [2] can nicely illustrate both paradigms.[1] In composite Higgs models, one assumes the existence of a new composite sector with a confining scale around the TeV scale. The Higgs boson then appears as a composite state and is typically a pseudo-Nambu-Goldstone boson of the spontaneous breaking of a global group of the composite sector, triggered by the strong dynamics. In the partial compositeness paradigm, Yukawa couplings between SM fermions and the Higgs are induced via mixing couplings in a far UV scale $\Lambda_{\rm UV}$ of the form

$$\mathcal{L} \supset \Lambda_{\rm UV}^{\frac{5}{2}} \sum_i \left(\lambda^i_q \, \Lambda_{\rm UV}^{-\Delta^i_Q} \, \bar{q}^i_L \, O^i_Q + \lambda^i_u \, \Lambda_{\rm UV}^{-\Delta^i_U} \, \bar{u}^i_R \, O^i_U + \lambda^i_d \, \Lambda_{\rm UV}^{-\Delta^i_D} \, \bar{d}^i_R \, O^i_D \right), \tag{2}$$

[1] See [3] for a pedagogical review.

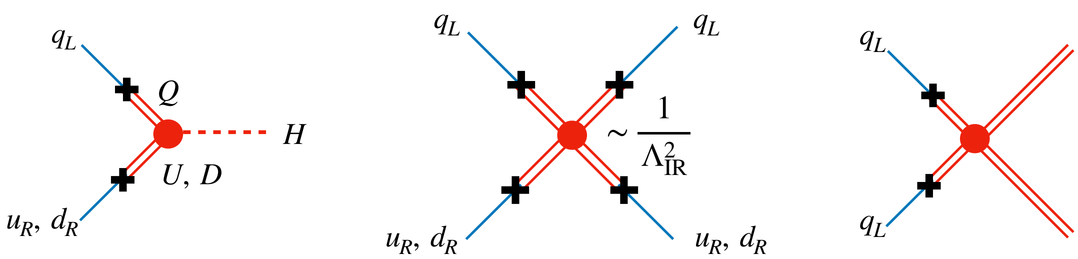

Figure 1: Diagrams of several contributions in partial compositeness. Left: generation of the SM Yukawas. Center: Contributions to $\Delta F = 2$ processes from the strong dynamics. Right: Production of resonances of the composite sector in LHC. Blue lines represent SM fields and red ones composite states.

where $O^i_{Q,U,D}$ are operators of the strong sector, with scaling dimensions $\Delta^i_{Q,U,D}$, interpolating some fermionic resonances Q^i, U^i, D^i with masses of the order the confinement scale $\Lambda_{\rm IR}$. Proto-Yukawas between Q, U, D and the Higgs boson emerge from the strong dynamics, that are propagated to the SM fermions through the mixing terms of Eq. (2), as illustrated in Fig. 1 (left).

In the anarchic scenario [4, 5], corresponding to the first paradigm, mixing terms in the UV do not have any hierarchical structure and are $O(1)$. However, the strong dynamics can generate large anomalous dimensions for the operators $O^i_{Q,U,D}$, making these mixing terms very hierarchical when are run down to the confinement scale, $\Lambda_{\rm IR}$, explaining the flavour hierarchies. The left-handed (LH) mixing terms in the IR should reproduce the CKM elements

$$(\Lambda_{\rm IR}/\Lambda_{\rm UV})^{\Delta^i_Q - \frac{5}{2}} \lambda^i_q \sim (V_{td}, V_{ts}, 1). \tag{3}$$

Then, to reproduce the diagonal SM Yukawas, the right-handed (RH) ones should be

$$(\Lambda_{\rm IR}/\Lambda_{\rm UV})^{\Delta^i_U - \frac{5}{2}} \lambda^i_u \sim (y_u/V_{td}, y_c/V_{ts}, y_t)\,, \quad (\Lambda_{\rm IR}/\Lambda_{\rm UV})^{\Delta^i_D - \frac{5}{2}} \lambda^i_d \sim (y_d/V_{td}, y_s/V_{ts}, y_b)\,. \tag{4}$$

This gives an approximate $U(2)$ flavour symmetry that can partially protect flavour observables. Still, it is not enough: in Fig. 1 (center) we show typical contributions from the strong dynamics that meson-mixing observables can receive in this paradigm. In particular, kaon mixing imposes a bound of several tens of TeV on the scale of NP: $\Lambda_{\rm IR} \gtrsim \sqrt{y_d y_s}\, 5\times 10^5$ TeV ~ 30 TeV, where 5×10^5 TeV is the experimental limit of the imaginary part of the Wilson coefficient of $(\bar d_L s_R)(\bar d_R s_L)$ [1]. The reason behind this strong bound relies in the way this paradigm breaks the $U(2)$ symmetry: the mixing terms $\lambda_{q,u,d}$ for the light families are in representations of $U(2)$, $\lambda_q \sim 2_q$, $\lambda_u \sim 2_u$ and $\lambda_d \sim 2_d$, which do not correspond to the SM spurions described above. Given the suppression of λ_q fixed by the CKM mixing elements, λ_d must be too large to reproduce $\Delta_d \sim \lambda_q \times \lambda_d$.

In the Minimal Flavour Violation (MFV) scenario [6, 7], corresponding to the second paradigm, the strong sector is assumed to have a $U(3)$ flavour symmetry. The fermionic resonances then appear in representations of $U(3)$. As an example, we can choose for all of them to be a 3_q.[2] The proto-Yukawas and anomalous dimensions of the strong sector respect this flavour symmetry, and all flavour hierarchies are inherited from hierarchical mixing terms of Eq. (2) in a far UV (postponing the flavour puzzle to the UV physics that generates these mixing terms). Note that λ_q can be chosen

[2] For a recent systematic study of different options, see [8].

to respect the flavour symmetry, and $\lambda_{u,d}$ to be a $\sim 3_q \times 3_{u,d}$ (same spurions as the SM Yukawa couplings). Bounds from flavour observables are, at most, the same of MFV [9] or weaker, being in the most constraining cases at the few TeV range. However, to explain the largeness of the top Yukawa, λ_q must be $O(1)$, generating universal large mixing terms for LH quarks. Valence quarks will sizeably couple to the resonances of the composite sector leaving LHC signals as illustrated in Fig. 1 (right) and imposing strong LHC limits and possibly other flavour-diagonal bounds. We can however extract a first interesting conclusion: **promoting NP fields to representations of flavour symmetries can be an effective way to improve flavour bounds.** This idea has actually been applied in multiple models (see e.g. [10]).

3. Theory lessons: multiscale flavour

None of the above paradigms manages to reconcile flavour and LHC physics to reduce the bounds of NP to the TeV, in their generic implementation. There is however a third paradigm:

(3) **Flavour hierarchies are addressed at several scales: third-family Yukawas can be generated at the TeV scale, but light-family flavour is explained at higher scales.**

This option can reduce the NP couplings to light generations, weakening LHC bounds. Also, the breaking of universality between third and light families can be as low as the TeV scale, as this paradigm allows to use the SM representations of spurions to break $U(2)$. Furthermore, minimal $U(2)$ breaking can improve the flavour bounds with respect to MFV scenarios, assuming some partial alignment between the mass and interaction basis in the down-quark sector [11].

A type of models realising this idea are those where the suppression of light-family Yukawas is due to the existence of hierarchical NP scales, implementing a kind of seesaw mechanism. Then, one expects light Yukawas to be naturally suppressed by Λ_3/Λ_i, where Λ_3 is the scale associated to the generation of third-family Yukawas (possibly linked to the stabilisation of the Higgs mass), and Λ_i is the scale generating the i−th family Yukawas. Non-universal gauge extensions of the SM [12], or composite sectors developing several confining scales [13] can realise this idea. One then expects interesting signals in observables testing the breaking of universality between third and light families, as $B \to D^{(*)}\tau\bar{\nu}$, $B \to K^{(*)}\nu\bar{\nu}$, $B \to K^{(*)}\ell^+\ell^-$, many of them showing currently experimental tensions with respect to the SM prediction. Also, this class of models can leave interesting signals in light-flavour transitions (e.g. $K \to \pi\nu\bar{\nu}$), which are potentially measured with a precision that can overcome the CKM-mixing suppression expected for this class of models. New data from B-physics (Belle-II, LHCb), or kaon physics (NA62) is expected in the coming years, testing these hypotheses. Ultimately, the Z-pole measurements of the Future Circular e^+e^- Collider will have the power to further test these scenarios [11].

Acknowledgments

We thank Stefan Pokorski for useful comments on the manuscript. This work has been supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program under grant agreement 833280 (FLAY) and by the grant CSIC-20223AT023. The author also acknowledges the support of the Spanish Agencia Estatal de Investigacion through the grant "IFT Centro de Excelencia Severo Ochoa CEX2020-001007-S".

References

[1] R.K. Ellis et al., *Physics Briefing Book: Input for the European Strategy for Particle Physics Update 2020*, 1910.11775.

[2] D.B. Kaplan, *Flavor at SSC energies: A New mechanism for dynamically generated fermion masses*, *Nucl. Phys. B* **365** (1991) 259.

[3] G. Panico and A. Wulzer, *The Composite Nambu-Goldstone Higgs*, vol. 913, Springer (2016), 10.1007/978-3-319-22617-0, [1506.01961].

[4] Y. Grossman and M. Neubert, *Neutrino masses and mixings in nonfactorizable geometry*, *Phys. Lett. B* **474** (2000) 361 [hep-ph/9912408].

[5] T. Gherghetta and A. Pomarol, *Bulk fields and supersymmetry in a slice of AdS*, *Nucl. Phys. B* **586** (2000) 141 [hep-ph/0003129].

[6] R. Rattazzi and A. Zaffaroni, *Comments on the holographic picture of the Randall-Sundrum model*, *JHEP* **04** (2001) 021 [hep-th/0012248].

[7] G. Cacciapaglia, C. Csaki, J. Galloway, G. Marandella, J. Terning and A. Weiler, *A GIM Mechanism from Extra Dimensions*, *JHEP* **04** (2008) 006 [0709.1714].

[8] A. Glioti, R. Rattazzi, L. Ricci and L. Vecchi, *Exploring the Flavor Symmetry Landscape*, 2402.09503.

[9] G. D'Ambrosio, G.F. Giudice, G. Isidori and A. Strumia, *Minimal flavor violation: An Effective field theory approach*, *Nucl. Phys. B* **645** (2002) 155 [hep-ph/0207036].

[10] J.M. Lizana, J. Matias and B.A. Stefanek, *Explaining the $B_{d,s} \to K^{(*)}\overline{K}^{(*)}$ non-leptonic puzzle and charged-current B-anomalies via scalar leptoquarks*, *JHEP* **09** (2023) 114 [2306.09178].

[11] L. Allwicher, C. Cornella, G. Isidori and B.A. Stefanek, *New physics in the third generation. A comprehensive SMEFT analysis and future prospects*, *JHEP* **03** (2024) 049 [2311.00020].

[12] M. Bordone, C. Cornella, J. Fuentes-Martin and G. Isidori, *A three-site gauge model for flavor hierarchies and flavor anomalies*, *Phys. Lett. B* **779** (2018) 317 [1712.01368].

[13] G. Panico and A. Pomarol, *Flavor hierarchies from dynamical scales*, *JHEP* **07** (2016) 097 [1603.06609].