A Taste of the Flavour Problem: Is Symmetry the Missing Ingredient?

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June 26, 2020

Overview

Do We Need Flavour Symmetries?

Gauge Sector

Gauge Principle and Renormalization: Strong and EW interactions of all particles are determined by 3 parameters

Flavour Sector

~ 20 "Yukawa" parameters (masses, mixings, and CP-phases)
The flavour sector has no similar process to that of the gauge sector that allows full description through a minimal set of parameters

Flavour Symmetries

Reductionist Approach: Y_{ij} from 1st principles	Anthropic Principle / Anarchy

... But Do We Want Them?

Neutrino Oscillations

- Initial Data compatible with highly symmetric patterns, eg:

$$|U_{\mathsf{TBM}}|^2 = \begin{pmatrix} 2/3 & 1/3 & 0 \\ 1/6 & 1/3 & 1/2 \\ 1/6 & 1/3 & 1/2 \end{pmatrix} \tag{1}$$

TBM can be very successfully obtained from simple A_4 models. Other successes were found with other small discrete groups and other LO approximations to neutrino mixing

- Experimental Advances: Details/Intricacies and precision, leading to a departure from minimality

Depart from minimality $\rightarrow$ flavons to induce flavour SSB and add complexity to the models

Mixings: Not the only reason

The number of free parameters has a significant increase, even in simple BSM theories

Example: nHDMs and the Yukawa structure

$$-\mathcal{L}_{\mathsf{Y}} = \sum_{a=1}^{n} \left[\overline{Q_L} \Gamma_a \phi_a d_R + \overline{Q_L} \Delta_a \tilde{\phi}_a u_R \right] + \text{h.c.} \tag{2}$$

Flavour Symmetric Models can avoid the sharp increase of dofs by either the requirement of invariance, or by relating the dofs

Two-sided benefits!

- Predictive power
- Underlying reason for the specific patterns of nature

The modular Symmetry

What is the modular Symmetry?

The modular group acts on the complex modulus τ $(\Im(\tau) > 0)$ as

$$\gamma : \tau \to \gamma\tau = \frac{a\tau + b}{c\tau + d} \tag{3}$$

Two Generators: S_τ and T_τ

$$S_\tau : \tau \to -\frac{1}{\tau} \qquad T_\tau : \tau \to \tau + 1 \tag{4}$$

Relations: $\Gamma_N : (S_\tau)^2 = (S_\tau T_\tau)^3 = (T_\tau)^N = \mathbf{1}$

Isomorphisms: $\Gamma_2 \simeq S_3, \Gamma_3 \simeq A_4, \Gamma_4 \simeq S_4, \Gamma_5 \simeq A_5$

Why the modular Symmetry?

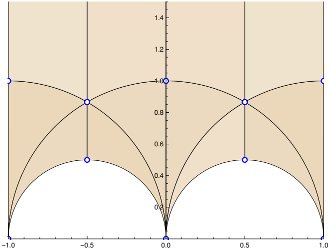
- Neutrino mass as modular forms
- Low-N Γ_N have found continued applications in Flavour models for neutrino oscillations
- Top-Down approach: Modular invariance plays a role in String Theory. May justify the choice of Flavour Symmetry
- Reduce (or eliminate) the need for flavons: increases predictive power and reduces the dependence on UV-completions

Stabilizers

Why Should I care about Stabilizers?

- Unbroken Symmetries lead to too simplistic results.
- (Quasi-)Realistic mixing patterns can be obtained by SSB of the Flavour Symmetry
- Leaving different sub-groups unbroken in both the relevant sectors ($\ell^{\pm}$, ν) may lead to interesting results (ex: A_4 and TBM)
- Adding flavour carrying gauge-singlets (of unknown UV origin) leads to effective Yukawa interactions and increasingly complex, yet still predictive mixing patterns.
- Stabilizers are special points where the action of some element leaves the point invariant. That is, vevs of the modular field that leave at least one (non-trivial) element of Γ_N unbroken!

Stabilizer List: A Helpful Tool for Model Building



	γ	τ_γ
$\mathcal{C}_2$	bc	$1+i, 0$
	b	$-\frac{1}{2}+\frac{i}{2}, \frac{1}{2}+\frac{i}{2}, i\infty$
	a	$i, 1, -1$
$\mathcal{C}_3$	ba	$-\frac{1}{2}+\frac{i\sqrt{3}}{2}, \frac{1}{2}+\frac{i\sqrt{3}}{2}, \frac{1}{2}+\frac{i\sqrt{3}}{2}, -\frac{1}{2}+\frac{i\sqrt{3}}{2}$
	c	$\frac{1}{2}+\frac{i\sqrt{3}}{2}, -\frac{1}{2}+\frac{i\sqrt{3}}{2}, -\frac{1}{2}+\frac{i\sqrt{3}}{2}, \frac{1}{2}+\frac{i\sqrt{3}}{2}$

2HDMs

General 2HDM

- One of the simplest BSM extensions
- The miracle of FCNC suppression of the SM is no longer a given
- Sharp increase in flavour parameters

2HDMs and flavour symmetries

- Texturize Yukawa matrices such that FCNC are absent at tree level (type-I and type-II)
- Reduces dofs $\rightarrow$ increases predictive power

2HDMs

BGL: another approach

- FCNC are still present at tree-level, but connected to the CKM parameters
- Compliance with flavour data leads to meaningful constraints on the models

x2HDMs

Generalities

- approximate symmetries for the Yukawa parameters (spoiled by hypercharge)

$$\begin{aligned} \Gamma_1 &= \pm\Delta_2 \equiv \Gamma \\ \Delta_1 &= \quad \Gamma_2 \equiv \Delta\text{'} \end{aligned} \qquad 16\pi^2 \frac{d}{d\ln\mu}(\Delta_1 - \Gamma_2) = g'^2 \Delta$$

- Tree-level FCNCs: connected to LH and RH CKM parameters
- Compliance with flavour data leads to meaningful constraints
- low-energy remnant of MLRM for x2HDM-1 (motivation)

x2HDMs - preliminary phenomonological analysis

Characteristic tell-tales due to simplistic shape of FCNC

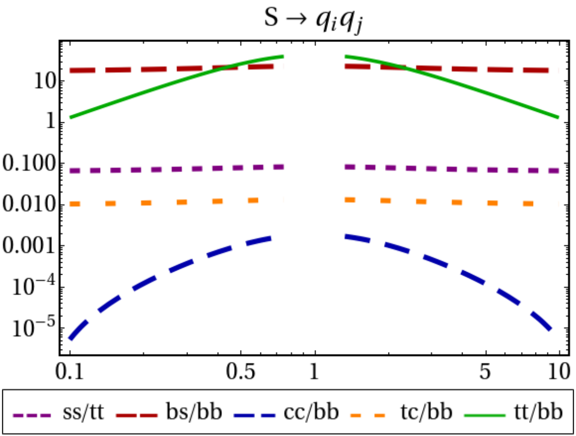
FCNCs

$$N_d^1 = \frac{1}{v}\left(\tan 2\beta D_d - \sec 2\beta V_L^\dagger D_u V_R\right), \quad N_d^2 = -\frac{1}{v} V_L^\dagger D_u V_R$$
$$N_u^1 = \frac{1}{v}\left(\tan 2\beta D_u - \sec 2\beta V_L D_d V_R^\dagger\right), \quad N_u^2 = \frac{1}{v} V_L D_d V_R^\dagger$$

Imposing $\Delta M_P^{\mathrm{NP}} \sim 0$ leads to

$$V_R \approx \begin{pmatrix} 1 & 6.65 \times 10^{-5} & 3.86 \times 10^{-4} \\ -3.92 \times 10^{-4} & 0.169 & 0.986 \\ 1.20 \times 10^{-7} & -0.986 & 0.169 \end{pmatrix}. \quad (5)$$

Flavour couplings also drive nonstandard Higgs decays



Assumptions: Alignment limit, $M_S = M_A = 1.5$TeV

Summary

Flavour Symmetries have copious applications to model building

Modular Symmetry

- Exclude the need for flavons
- Top down approach
- Goal: provide a good tool for model building

x2HDMs

- Approximate symmetries may be well-motivated
- Parameter reduction leading to interesting and restrictive flavour structures
- Predictive structure helps falsify the model