A Cookbook of Flavorful Modifications to the Froggatt-Nielsen Mechanism

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The Big Picture

- When Froggatt-Nielsen (FN) explains the Standard Model (SM) flavor hierarchy, **new physics couplings are also determined** by the $U(1)_H$ symmetry. [Froggatt and Nielsen, Nucl.Phys.B (1979)]
- UV physics could **change this naive scaling** for the new physics couplings.
- A **description in terms of the new spurions** of the $SU(3)^5$ flavor symmetry, where we parameterize extra factors (referred to as *wrinkles*) using the **same power counting parameter** as in the original FN model, is an effective way to keep track of these changes. [Bordone et al, 1910.02641 and 2010.03297]
- We show the **example** of the S_1 **leptoquark**.

Froggatt-Nielsen Review

- The FN model is a mechanism to explain the **SM flavor yukawa hierarchies**. It includes a **heavy complex scalar f** called the **flavon** that couples to **multiple heavy fermion** species with mass $\sim M$.
- At high energies, SM **yukawa couplings are generated by "chains"** of multiple flavon insertions whose length is determined by the charge differences between fermions under a new $U(1)_H$ symmetry.

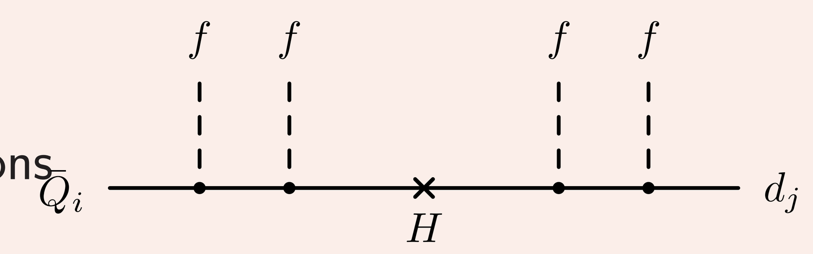


Figure 1: An example chain.

- For charges q_1 and q_2, the low energy yukawas are $Y_{ij} \sim \left(\frac{\langle f \rangle}{M}\right)^{|[q_1]+[q_2]|}$

The SM constraints are from CKM, PMNS, and fermion masses:

$$\frac{V_{ij}^{CKM}}{\lambda^{|[Q_i]-[Q_j]|}} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad \frac{U_{ij}^{PMNS}}{\lambda^{|[L_i]-[L_j]|}} \sim \begin{pmatrix} 1 & \lambda & \lambda \\ \lambda & 1 & 1 \\ \lambda & 1 & 1 \end{pmatrix}$$

$$\frac{y_i^u}{\lambda^{|[Q_i]+[\bar{u}_i]|}} \sim (\lambda^7, \lambda^3, 1) \qquad \frac{y_i^d}{\lambda^{|[Q_i]+[\bar{d}_i]|}} \sim (\lambda^6, \lambda^4, \lambda^2)$$

$$\frac{y_i^l}{\lambda^{|[L_i]+[\bar{e}_i]|}} \sim (\lambda^8, \lambda^4, \lambda^3)$$

Adding a Leptoquark

Add the **scalar leptoquark (LQ)** S_1 with SM charges $(\overline{3}, 1, 1/3)$ and Lagrangian

$$\mathcal{L}_{int} = -\Delta_{QL}^{ij} \overline{Q}_i^c \epsilon L_j S_1 - \Delta_{\bar{u}\bar{e}}^{ij} \bar{u}_i^c e_j S_1 + h.c.$$

Assuming $[S_1] = 0$ under $U(1)_H$, the **size of the spurions is fixed by the FN charges** of the SM fermions.

$$\Delta_{QL}^{ij} \sim g_L \lambda^{|[Q_i]+[L_j]|} \qquad \Delta_{\bar{u}\bar{e}}^{ij} \sim g_R \lambda^{|[\bar{u}_i]+[\bar{e}_j]|}$$

Adding Wrinkles: The Low Energy Description

But what if these charge assignments were not the whole story? Consider adding **wrinkles** to change the size of some spurions. We can **parameterize these with additional factors of** λ:

$$(Y_{\psi\overline{\chi}})^{ij} = (W_{\psi\overline{\chi}})^{ij} \lambda^{|[\psi_i]+[\overline{\chi}_j]|} \equiv \lambda^{\omega_{\psi\overline{\chi}}^{ij}} \lambda^{|[\psi_i]+[\overline{\chi}_j]|}$$

This description is indifferent to the UV source of wrinkles; we only need to analyze the number of factors of λ for a given spurion. While this number appears independent between different spurions in the low energy, UV mechanisms for generating wrinkles can cause correlations.

There are still some **constraints** from requiring that **radiatively generated yukawas** are smaller than the original ones. These follow from the charges of the spurions:

$$\left|\Delta_{QL}^{ij}\right| \geq \frac{1}{16\pi^2}\left|\left(Y_{Q\bar{u}} \cdot \Delta_{\bar{u}\bar{e}} \cdot Y_{L\bar{e}}^T\right)^{ij}\right| \qquad \left|\Delta_{\bar{u}\bar{e}}^{ij}\right| \geq \frac{1}{16\pi^2}\left|\left(Y_{Q\bar{u}}^\dagger \cdot \Delta_{QL} \cdot Y_{L\bar{e}}^*\right)^{ij}\right|$$

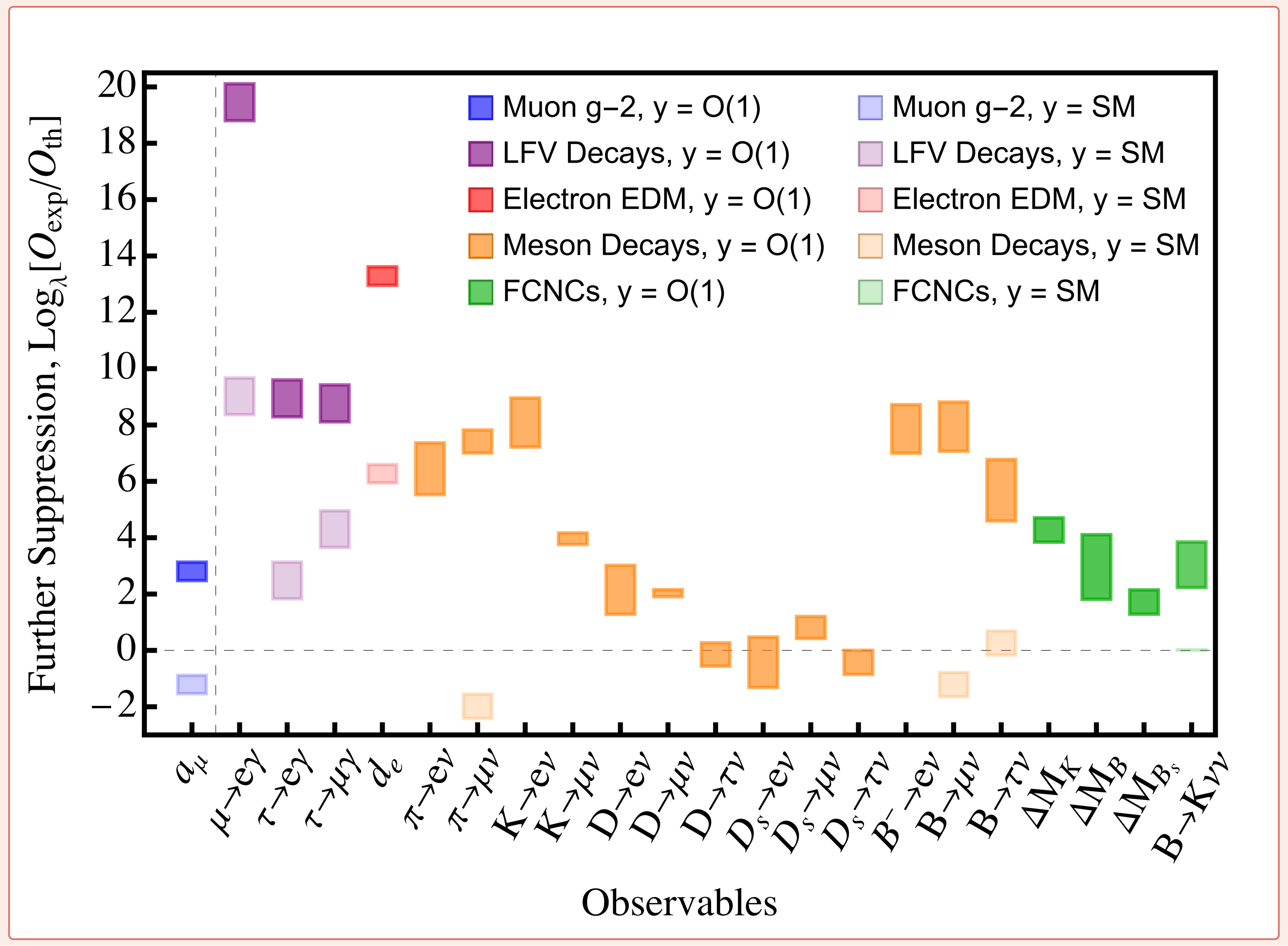
$$\left|Y_{Qu}^{ij}\right| \geq \frac{1}{16\pi^2}\left|\left(Y_{Qd} \cdot Y_{Qd}^\dagger \cdot Y_{Qu}\right)^{ij}\right| \qquad \left|Y_{Q\bar{u}}^{ij}\right| \geq \frac{1}{16\pi^2}\left|\left(\Delta_{QL} \cdot Y_{L\bar{e}}^* \cdot \Delta_{\bar{u}\bar{e}}^\dagger\right)^{ij}\right|$$

$$\left|Y_{L\bar{e}}^{ij}\right| \geq \frac{1}{16\pi^2}\left|\left(\Delta_{QL}^T \cdot Y_{Q\bar{u}}^* \cdot \Delta_{\bar{u}\bar{e}}^*\right)^{ij}\right|$$

Measurements and Constraints

The amount of **suppression required for theory to agree with experiment** for various observables is **shown below** for the S_1 LQ.

The darker boxes show the total amount of suppression that would be required for the leading BSM contribution if couplings were $\mathcal{O}(1)$. The lighter boxes show the required amount of suppression (or enhancement, in the muon g-2 case) required for a particular set of SM $U(1)_H$ charges to be consistent with experiment.



UV Complete Models

There are **multiple example UV mechanisms** that realize these *wrinkles* by making spurions larger or smaller than naively expected. These include:

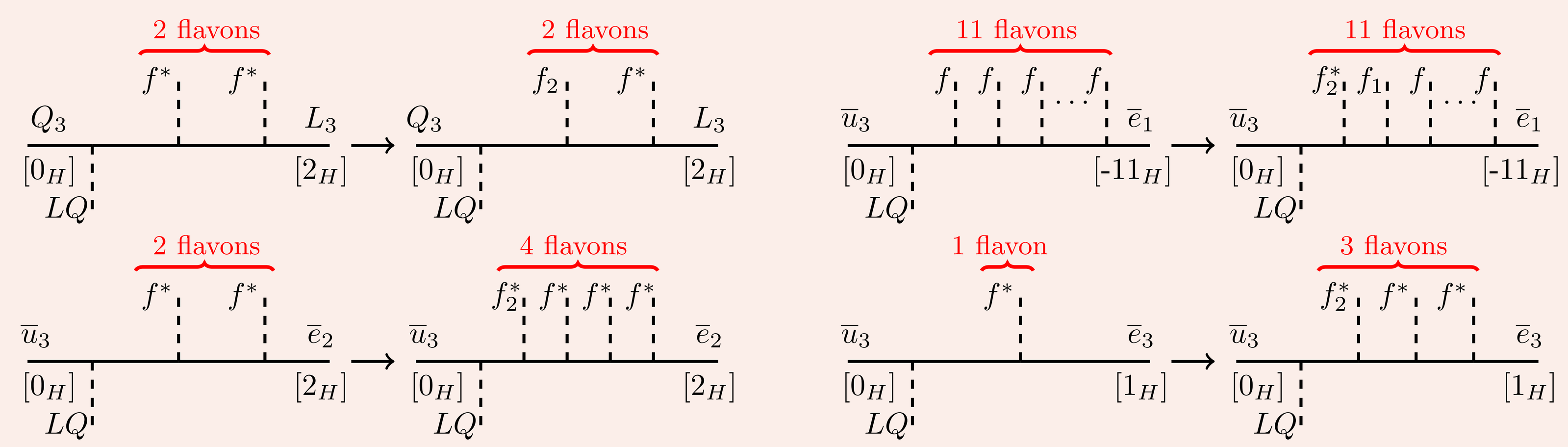
- **Adding extra flavons** charged under $U(1)_H$ and possibly additional symmetries. Charging the flavon under $U(1)_{B-L}$ or the LQ under $U(1)_H$ affects the LQ couplings without changing the SM couplings.
- **Removing fermions** of certain $U(1)_H$ charge **from the spectrum** of heavy fermions, and replacing them with multiple fermions with the same $U(1)_H$ charges but also other charges that require extra flavon insertions.

Example: Extra flavons

Consider a FN model that also respects $B - 3L_e$ symmetry.

Flavon	$U(1)_{B\text{-}3L_e}$	$U(1)_H$	
f	0	1	Ordinary flavon
f_1	3	1	Required to generate PMNS
f_2	-1/3	-1	Allows leptoquark couplings

Consider couplings of the top quark to the leptons. These extra flavons **make the right handed** μ, τ **lepton couplings smaller**, while the left handed lepton couplings and the right handed e coupling are unaffected.



Example: Missing heavy fermions

Consider introducing extra SU(3) symmetries that the SM fermions are neutral under, but some of the heavy fermions are charged under.

Particle	$SU(3)_1$	$SU(3)_2$	$U(1)_H$	
f	1	1	-1	Ordinary flavon
$f^{(1)}$	3	1	-1	Additional Flavons
$f^{(2)}$	1	$\overline{3}$	-1	Additional Flavons
$f^{(1,2)}$	$\overline{3}$	3	0	Additional Flavons
$\overline{\Psi}_M$, Ψ_M	1	1	$-M$, M	Fermions with every $U(1)_H$ charge except $M=1$
$\overline{\Psi}_0^{(k)}$, $\Psi_0^{(k)}$	$\overline{3}$	3	1	Fermions with SU(3)$_i$ charge

This "adds a wrinkle" by making every chain that would have contained Ψ_M longer by 1, and can be generalized to include more wrinkle factors.