Family symmetries in particle physics

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The Standard Model (1 generation)

Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y$

$L = (L_1, L_2) = (\nu_L, e_L)$ is doublet of $SU(2)_L$
e_R just $U(1)_Y$
(νSM: add ν_R, complete singlet)

Scalar H also doublet of $SU(2)_L$
$\langle H \rangle$ breaks $SU(2)_L \times U(1)_Y \to U(1)_{em}$

Mass terms: $m_e L_2 e_R$ not invariant under $SU(2)_L$

But $y_e[H^\alpha L_\alpha]e_R$ is... $\langle H \rangle = (0, v)$
$y_e v L_2 e_R \to m_f L_2 e_R$ with $m_e = y_e v$

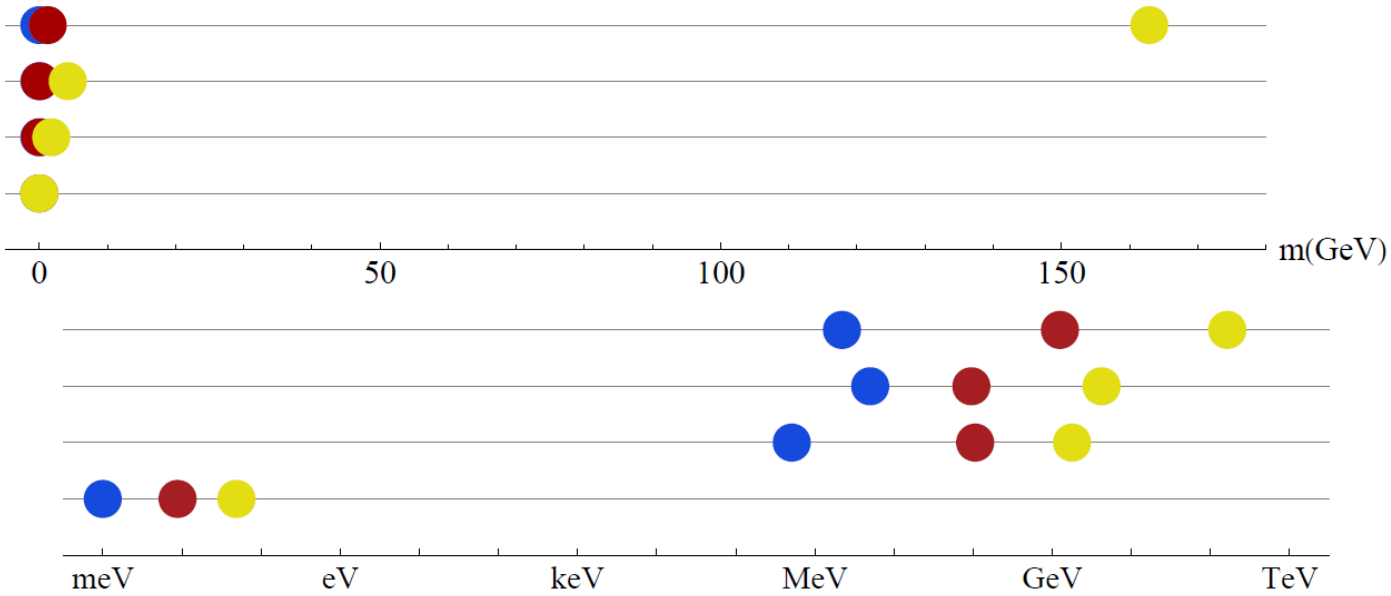
The Standard Model is very successful but...

- Neutrinos have masses (νSM)
- Dark matter (no viable explanation)
- Matter / antimatter asymmetry (no viable explanation)
- Hierarchy problem (fine-tuning between parameters)
- Strong CP problem (fine-tuning between parameters)
- Gauge couplings (additional free parameters) - GUT?
- Flavour problem (many additional free parameters) - FS?

BSM solutions involve additional fields and symmetries

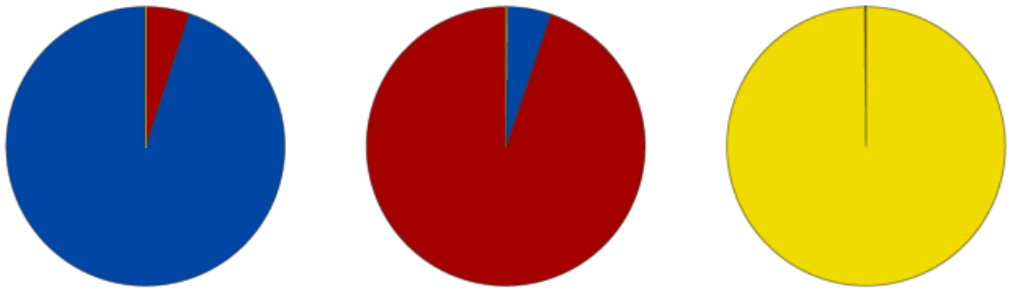
The Standard Model flavour problem: masses

3 fermion generations? Masses span orders of magnitude?



The Standard Model flavour problem: mixing

3 generations of quarks, small mixing



3 generations of leptons, large and peculiar mixing

(mixing between weak and mass eigenstates)

Beyond the Standard Model with family symmetries

Without $y_f[HF]f_R$, $\mathcal{L}_{\nu SM}$ has accidental symmetry $SU(3)^6$

FS: upgrade subgroup of $SU(3)^6$ to actual symmetry of $\mathcal{L}$

1. Generations charged differently under FS
2. Yukawa couplings no longer invariant
3. FS must be broken somehow...

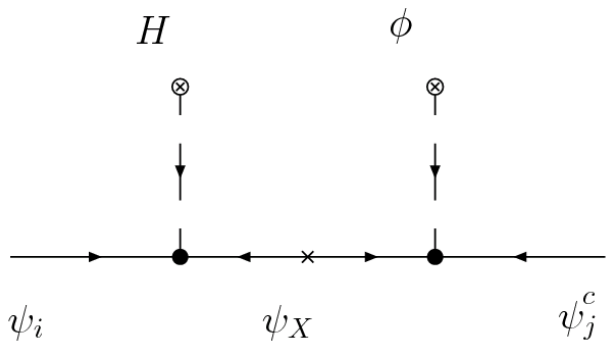
FS must be broken

Breaking expectations

- Familon(s) ϕ, charged under the FS
- $y_f H F_i f_{Rj}$ not invariant but $(y_f/M_X) H \phi^{ij} F_i f_{Rj}$ is

Masses from VEVs

$$m_f^{ij} \propto \frac{y_f \langle H \rangle \langle \phi^{ij} \rangle}{M_X}$$



Abelian example: $U(1)$ + single familon

$U(1)$ assignments

Field	$U(1)$
H	**0**
ϕ	**−1**
Q_3	**0**
d_{R3}	**0**
Q_2	**1**
d_{R2}	**1**
Q_1	**2**
d_{R1}	**2**

$$\mathcal{L}_d = H(y_{33} Q_3 d_{R3} + y_{23}(\phi/M_X) Q_2 d_{R3} + y_{32}(\phi/M_X) Q_3 d_{R2} + y_{22}(\phi/M_X)^2 Q_2 d_{R2} + \ldots)$$

Respective mass matrix

$$M_d \sim m_b \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}$$

$\frac{\langle\phi\rangle}{M_X} = \epsilon$

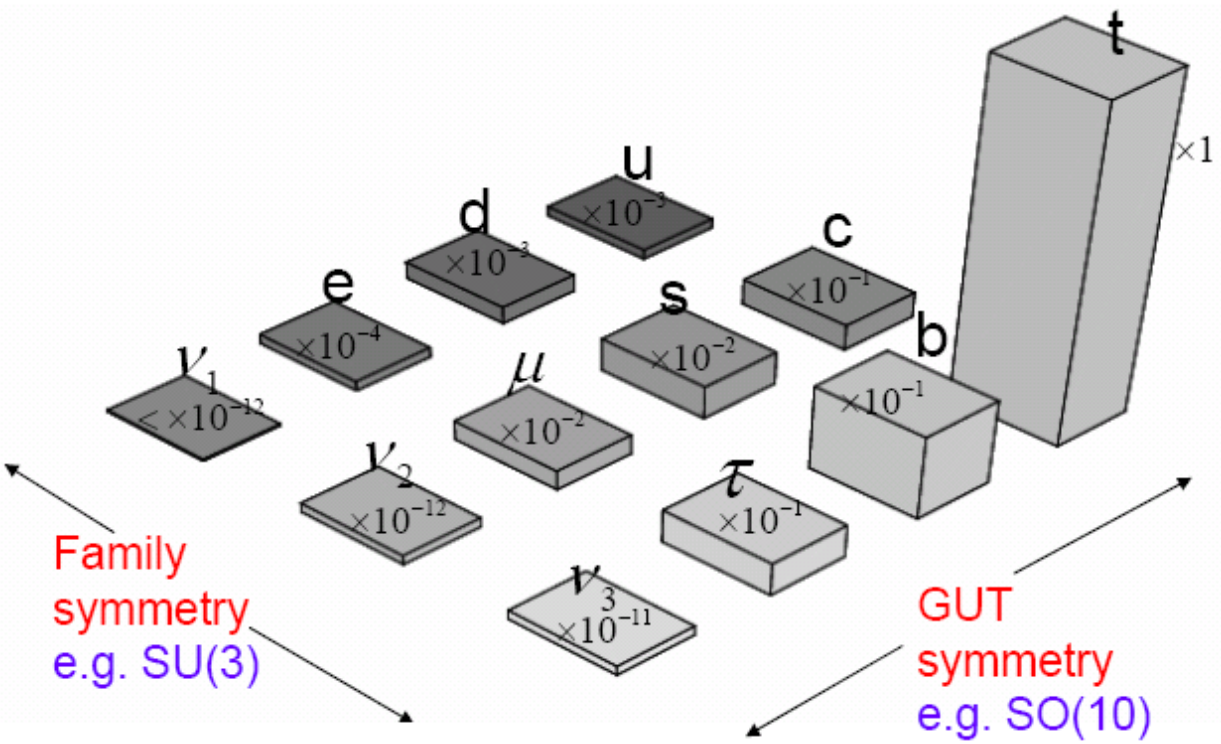
Each entry has a y_{ij} parameter!

Non-Abelian?

3 reasons

- 3 generations explained naturally
- νSM: FS $\subset SU(3)^6$; $SO(10)$ GUT: FS $\subset SU(3)$
- Lepton mixing strongly suggests non-Abelian FS

$SO(10) \times SU(3)$?



Family assignments $SU(3)$ + familons

Fermions and familons

- Fermions F_i, f_{Rj}: FS triplets
- Familons ϕ^i_A: FS anti-triplets
- Invariant mass terms: $(\phi^i_A F_i)(\phi^j_B f_{Rj})H$

Desired VEVs

$$\langle \phi_{23} \rangle \propto (0, 1, -1)\epsilon$$
$$\langle \phi_{123} \rangle \propto (1, 1, 1)\epsilon^2$$

Mass matrices example

Term 123 L / 23 R

$$+y_{\odot}(\phi^{i}_{123}F_{i})(\phi^{j}_{23}f_{Rj})H$$

Respective mass matrix

$$+y_{\odot}\begin{pmatrix} 0 & \epsilon^{3} & -\epsilon^{3} \\ 0 & \epsilon^{3} & -\epsilon^{3} \\ 0 & \epsilon^{3} & -\epsilon^{3} \end{pmatrix}$$

Mass matrices example

Term 23 L / 123 R

$$+y_{@}(\phi^{i}_{23}F_{i})(\phi^{j}_{123}f_{Rj})H$$

Respective mass matrix

$$+y_{@}\begin{pmatrix} 0 & 0 & 0 \\ \epsilon^{3} & \epsilon^{3} & \epsilon^{3} \\ -\epsilon^{3} & -\epsilon^{3} & -\epsilon^{3} \end{pmatrix}$$

Aspects of Family Symmetries

Effective Alignments
IdMV, Miguel Levy, Ye-Ling Zhou, arXiv:1903.10506

Dark Side of the Seesaw (Dark Matter and Neutrino Masses)
Subhaditya Bhattacharya, IdMV, Biswajit Karmakar, Stephen F. King, Arunansu Sil, arXiv:1806.00490

Leptogenesis (BAU)
Fred Bjorkeroth, IdMV, Maria Luisa Lopez-Ibanez, Aurora Melis, Oscar Vives, arXiv:1904.10545

Multi-Higgs controlled FCNCs (flavour problem)
IdMV, Jim Talbert, arXiv:1908.10979

Supersymmetry (flavour problem)
IdMV, Maria Luisa Lopez-Ibanez, Aurora Melis, Oscar Vives, arXiv:1807.00860