UV COMPLETE CHIRAL FROGGATT-NIELSEN MODELS

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may 4, 2019, Granada

Planck 2019

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Outline

- Mass hierarchies and Froggatt-Nielsen models: simplest U(1) examples
- Global versus gauge symmetry
- Field theory models with chiral heavy fermions
- Flavorful axion
- Conclusions

Fermion mass hierarchies and Froggatt-Nielsen models

- Standard Model gives no hint on the hierarchies of fermion masses and mixings.

$$\frac{m_u}{m_t} \sim 10^{-5} \qquad\qquad \frac{m_\nu}{m_t} \sim 10^{-13}$$

$$V_{CKM} \sim \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

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An old profilic idea (Froggatt-Nielsen, 79) :
flavor U(1), spontaneously broken symmetry.

Fermions of different generations have different charges

Fields: $Q_i \ , \ U_i^c \ , \ D_i^c$
Charges $q_i \ , \ u_i^c \ , \ d_i^c$ $\longrightarrow$ horizontal/family symmetry

One needs charged « flavons » Φ breaking the symmetry.
Renormalizable level: only top Yukawa (and the bottom for two-Higgs doublet models/SUSY) exists.

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The other Yukawas are generated through non-renormalizable operators

$$\mathcal{L}_{Yuk} = y_{ij}^u \left(\frac{\Phi}{M}\right)^{-\frac{q_i+u_j+h_2}{X_\Phi}} Q_i U_i^c h_2 + y_{ij}^d \left(\frac{\Phi}{M}\right)^{-\frac{q_i+d_j+h_1}{X_\Phi}} Q_i D_i^c h_1 + \cdots$$

after symmetry breaking

$$m_{ij}^u = y_{ij}^u \ \epsilon^{-\frac{q_i+u_j+h_2}{X_\Phi}} v_2 \ , \ m_{ij}^d = y_{ij}^d \ \epsilon^{-\frac{q_i+d_j+h_1}{X_\Phi}} v_1$$

where $\epsilon = \dfrac{\langle\Phi\rangle}{M} \sim \lambda = 0.22$

Quarks masses and mixings are given by ($q_{13} = q_1 - q_3 \ X_\Phi = -1$

$$\frac{m_u}{m_t} \sim \epsilon^{q_{13}+u_{13}} \ , \ \frac{m_c}{m_t} \sim \epsilon^{q_{23}+u_{23}} \ , \ \frac{m_d}{m_b} \sim \epsilon^{q_{13}+d_{13}} \ , \ \frac{m_s}{m_b} \sim \epsilon^{q_{23}+d_{23}}$$

$$\sin\theta_{12} \sim \epsilon^{q_{12}} \ , \ \sin\theta_{13} \sim \epsilon^{q_{13}} \ , \ \sin\theta_{23} \sim \epsilon^{q_{23}} \ .$$

Good fit to to data ➡ larger charges for the lighter generations

$$q_1 > q_2 > q_3 \ , \ u_1 > u_2 > u_3 \ , \ d_1 > d_2 > d_3$$

$$m_t \sim 1 \qquad m_b \sim \epsilon^3 \qquad m_\tau \sim \epsilon^3$$

$$m_c \sim \epsilon^4 \qquad m_s \sim \epsilon^{5\div 6} \qquad m_\mu \sim \epsilon^5$$

$$m_u \sim \epsilon^8 \qquad m_d \sim \epsilon^{7\div 8} \qquad m_e \sim \epsilon^9$$

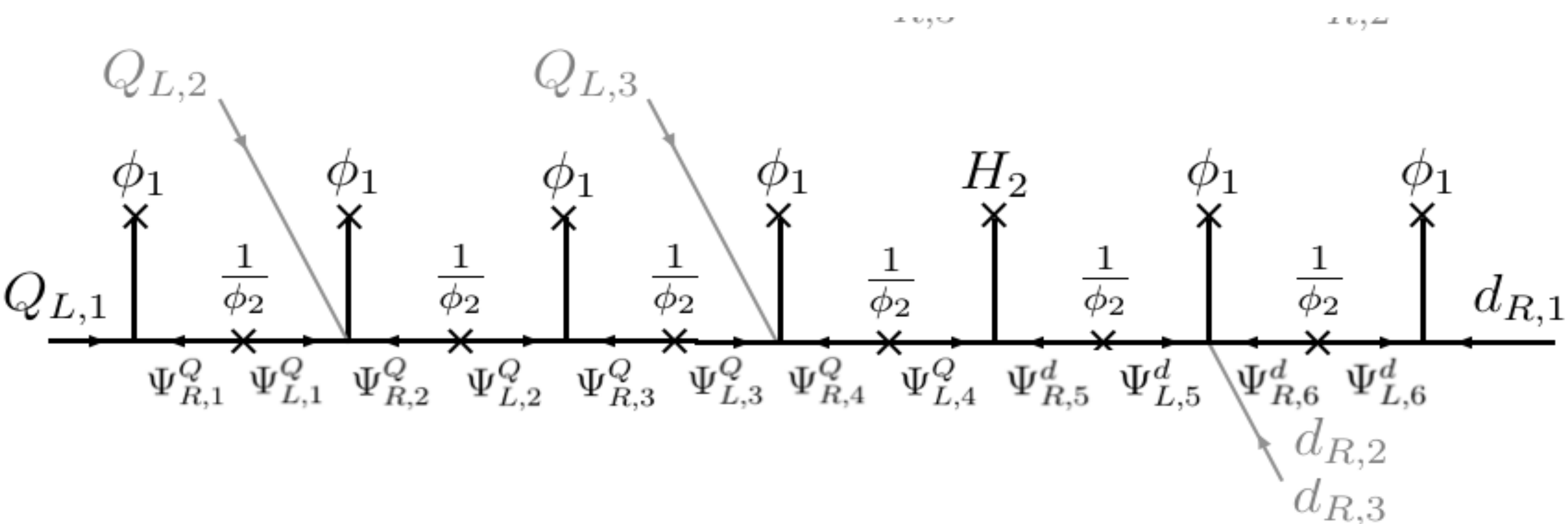
$$V_{us} \sim \epsilon \qquad V_{ub} \sim \epsilon^3 \qquad V_{cb} \sim \epsilon^2$$

- **Origin** of non-renormalizable operators ?

- String theory/supergravity

  In this case $M = M_P$

- Mixing of light fermions with heavy fermions of mass $M \sim \langle \Phi_2 \rangle$



All the papers we are aware of assume heavy fermions to be vector-like wrt $U(1)_X$ $\longrightarrow$ $X_{\Phi_2} \equiv X_2 = 0$

- $U(1)_X$ can be global or local

In both cases we can consider mixed anomalies

$$U(1)_X - G_a - G_b \longrightarrow A_a \sim \mathrm{Tr}(X T_a^2)$$

where $G_{a,b} = SU(3)_c, SU(2)_L, U(1)_Y$

If heavy fermions are vector-like, mixed anomalies are completely determined by the SM fermions.

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Minimal models: one spurion and holomorphic couplings: relations mass matrices-mixed anomalies (Ibanez-Ross; Binetruy-Ramond…)

$$\det\left(Y_U Y_D^{-2} Y_L^3\right) = \varepsilon^{3/2(A_2+A_1-2A_3)}$$

$$\det\left(Y_U Y_D\right) = \varepsilon^{A_3+3(h_1+h_2)} \ ,$$

which can also be combined into

$$\det\left(Y_D^{-2} Y_L^2\right) = \varepsilon^{A_2+A_1-\frac{8}{3}A_3-2(h_1+h_2)}$$

- Minimal number of heavy fermions equal to the exponent of the determinant of the mass matrix (Leurer-Nir,Seiberg)

$$2N_Q^H + N_U^H + N_D^H = A_3 + 3(h_1+h_2)$$ etc

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Global versus gauge symmetry

Fermion masses/mixings for one spurion and holomorphic couplings strongly imply non-vanishing mixed anomalies.

OK if $U(1)_X$ is global. In this case, the model has an axion with flavor-dependent couplings to fermions : flavorful axion (Wilczek;Calibbi,Goertz,Redigolo,Ziegler,Zupan; Ema, Hamaguchi,Moroi,Nakayama)

Stronger couplings to light quarks: $\frac{q_i}{V} \; \partial_m a \; \bar{q}_i \gamma^m \; q_i$

Couplings to gauge fields similar to DFKZ models $\frac{E}{N} = \frac{A_1+A_2}{A_3} \sim \frac{8}{3}$

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However, quantum Gravity/String Theory does not like global symmetries: typically explicitly broken by gravity and nonperturbative effects.

If $U(1)_X$ is gauged, models with one spurion and heavy vector-like fermions generally incompatible with anomaly cancelation →

- Stringy origin, Green-Schwarz mechanism

- Field theory, but heavy chiral fermions

Field theory models with chiral heavy fermions

$$-\mathcal{L}_{\rm mass} = y_i \Phi_2 \Psi_i \Psi_i^c$$

$X_2 \neq 0$ → Heavy fermions vector-like wrt SM gauge group, but chiral wrt $U(1)_X$

Anomaly cancels between heavy and light fermions

$$A_a^{SM} + A_a^{\rm heavy} = 0$$

Use one flavon Φ_1 and a second for fixing the heavy fermion masses $M = \langle \Phi_2 \rangle$

$$\mathcal{L}_{Yuk} = y_{ij}^u \left(\frac{\Phi_1}{\Phi_2}\right)^{\frac{q_i+u_j+h_2}{X_2-X_1}} Q_i U_i^c h_2 + \cdots$$

with $\frac{V_1}{V_2} \sim \sin\theta_c \sim 0.22$

It can be shown that the contribution of heavy fermions to the SM gauge couplings running is completely determined by the mixed anomaly of light SM fermions

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Contribution of heavy fermions

$$\frac{1}{g_a^2}(\mu) = \frac{1}{g_a^2}(\Lambda) - \frac{b_a^{SM}}{8\pi^2} \ln \frac{\Lambda}{\mu} + \frac{A_a^{SM}}{X_2} \ln \frac{\Lambda}{V_2}$$

In MSSM, the heavy fermions contribution preserves unification if

$$A_2^{SM} = A_3^{SM} = \frac{3}{5} A_1^{SM}$$

which is also the prefered relation from the mass matrices viewpoint.

- There is an analogy with the stringy Green-Schwarz case: below heavy fermion masses the field theory model is similar to the stringy one

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The simplest way to satisfy

$$A_2^{\rm heavy} = A_3^{\rm heavy} = \frac{3}{5} A_1^{\rm heavy}$$

with heavy fermions in « complete SU(5) representations »
(different $U(1)_X$ charges) .

We have explicit examples with anomaly-cancelation. Strong perturbativity limits on the heavy-fermion masses, similar to the vector-like FN models (Calibbi, Lalak,Pokorski,Ziegler)

$$M \geq 10^{14}\ GeV$$

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A flavorful axion

The model has a physical axion

$$\Phi_i = (V_i + r_i)\ e^{\frac{i a_i}{V_i}}$$

$$\theta_X \sim X_1 V_1 a_1 + X_2 V_2 a_2$$ Goldstone eaten by the gauge boson

$$a_{PQ} \sim X_2 V_2 a_1 - X_1 V_1 a_2$$ Peccei-Quinn axion

PQ symmetry is protected by the gauge symmetry, accidental.

Any difference in low-energy couplings compared to « standard » flavorful axion ?

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Yes, since below the scale of heavy fermions the effective action of the form

anomaly heavy fermions

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm Yuk} - A_a^{SM} \frac{a_{PQ}}{f_a} F_a \tilde{F}_A$$

The low-energy couplings to gauge fields are then determined both by heavy and light fermions . We find

Couplings to gauge fields

$$\frac{C_a}{C_{q_i}} = \frac{A_a^{SM}}{q_i} \frac{X_1^2 V_1^2 + X_2^2 V_2^2}{X_1 V_1^2 + X_2 V_2^2}$$

Couplings to quarks

contribution heavy fermions

Flavorful axion couplings correspond to $X_2 = 0$

Conclusions

- Field-theory gauged FN models with chiral heavy fermions more natural: dynamical mass,low-energy anomalies, axion
- Structure of mass matrices for minimal Yukawas naturally preserves gauge coupling unification in MSSM
- Low-energy axion couplings slightly modified compared to the flavorful axion.
- We have explicit examples, perturbativity in minimal setup favors large axion decay constants $f \geq 10^{14} \ GeV$

THANK YOU

Backup slides