

# Anomaly free Froggatt-Nielsen model of flavor

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**CKM**

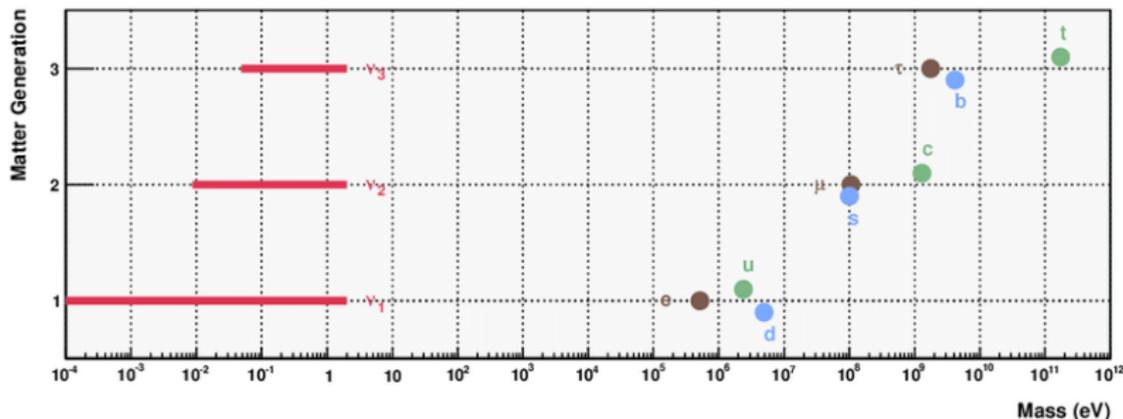
	<i>d</i>	<i>s</i>	<i>b</i>
<i>u</i>	Orange	Green	Black
<i>c</i>	Green	Orange	Blue
<i>t</i>	Black	Blue	Orange

$$|V| = \begin{bmatrix} u & d & s & b \\ c & & & \\ t & & & \end{bmatrix}$$

**PMNS**

	1	2	3
<i>e</i>	Orange	Green	Black
$\mu$	Green	Orange	Blue
$\tau$	Black	Blue	Orange

$$|U| = \begin{bmatrix} e & 1 & 2 & 3 \\ \mu & & & \\ \tau & & & \end{bmatrix}$$



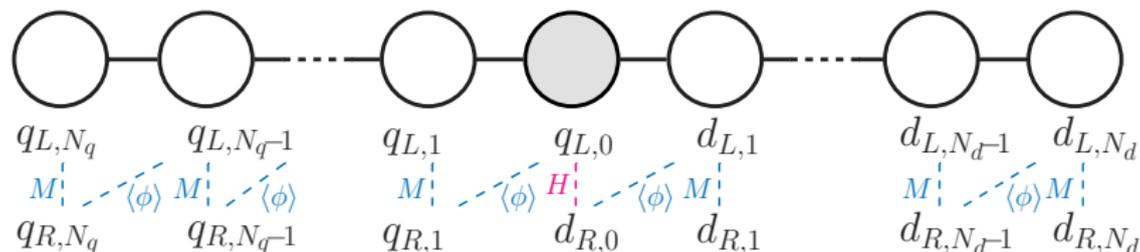
Dynamical solution with an extra anomaly-free abelian group

[R. Alonso et al. : 1807.09792]

[A. Smolkovic, MT, J. Zupan: 1905.xxxx]

## One generation example

$G_{FN} = U(1)$  with charges  $[\phi] = 1$ , fermions  $[d_{R/L,n}] = +n$ ,  $[q_{R/L,n}] = -n$ .



$$\mathcal{L}_1 = \mathcal{L}_{kin} + \mathcal{L}_q + \mathcal{L}_d + (Y_0^d \bar{q}_{L,0} d_{R,0} H + \text{h.c.}),$$

$$\mathcal{L}_{kin} = i \sum_{n=1}^{N_q} \bar{q}_{R,n} \not{D} q_{R,n} + i \sum_{n=0}^{N_q} \bar{q}_{L,n} \not{D} q_{L,n} + i \sum_{n=0}^{N_d} \bar{d}_{R,n} \not{D} d_{R,n} + i \sum_{n=1}^{N_d} \bar{d}_{L,n} \not{D} d_{L,n},$$

$$\mathcal{L}_q = - \sum_{n=1}^{N_q} (M_n^q \bar{q}_{L,n} q_{R,n} - Y_n^q \phi \bar{q}_{L,n-1} q_{R,n} + \text{h.c.}),$$

$$\mathcal{L}_d = - \sum_{n=1}^{N_d} (M_n^d \bar{d}_{L,n} d_{R,n} - Y_n^d \phi \bar{d}_{L,n} d_{R,n-1} + \text{h.c.}).$$

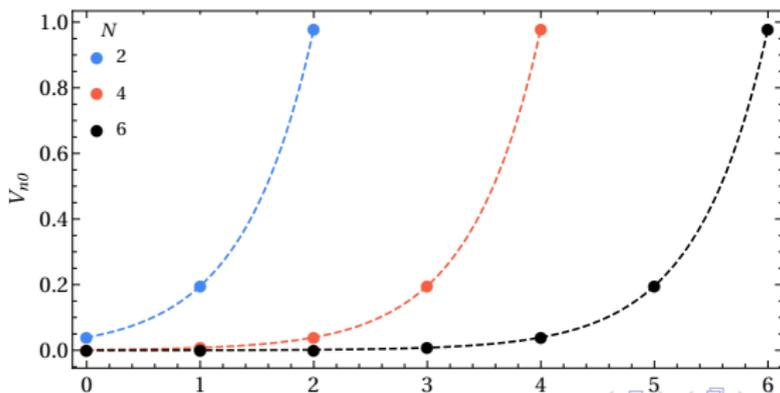
- Flavon vev  $\langle \phi \rangle$  spontaneously breaks  $G_{FN}$ ,
- $N_q \times (N_q - 1)$  mass matrix for  $q$  and  $(N_d - 1) \times N_d$  for  $d$ ,
- $N_q + N_d$  massive eigenstates and two massless eigenstates (zero modes)

$$q'_{L,0} = \sum_{n=0}^{N_q} V_{n0}^{qL} q_{L,n}, \quad d'_{R,0} = \sum_{n=0}^{N_d} V_{n0}^{dR} d_{R,n}.$$

Overlap of the zero modes with the  $n$ -th node ( $Y_n^d = Y_n^q = 1$ ,  $M_n^d = M_n^q = M$ )

$$V_{n0}^{qL} = \mathcal{N}_0^{qL} \left( \frac{M}{\langle \phi \rangle} \right)^{N_q - n}, \quad V_{n0}^{dR} = \mathcal{N}_0^{dR} \left( \frac{M}{\langle \phi \rangle} \right)^{N_d - n},$$

- for  $\langle \phi \rangle \gg M$  and large  $N_{q(d)}$ , the zero mode - zero node overlap is exponentially suppressed



The zero modes acquire mass once Higgs acquires a vev

$$m_d \simeq V_{00}^{qL} V_{00}^{dR} \frac{Y_0^d v}{\sqrt{2}} \simeq \frac{Y_0^d v}{\sqrt{2}} \left( \frac{M}{\langle \phi \rangle} \right)^{N_q + N_d}.$$

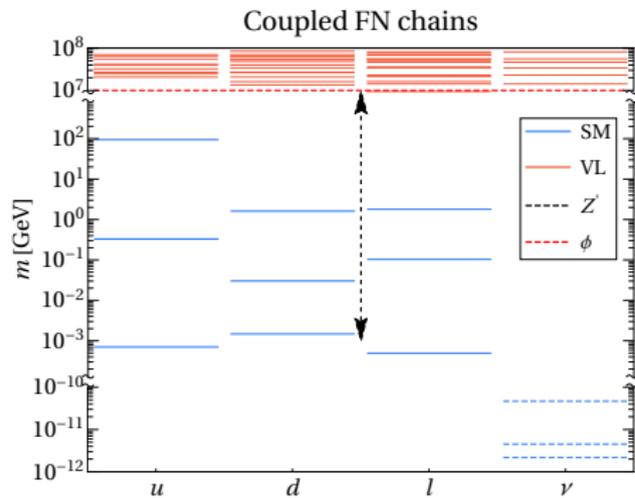
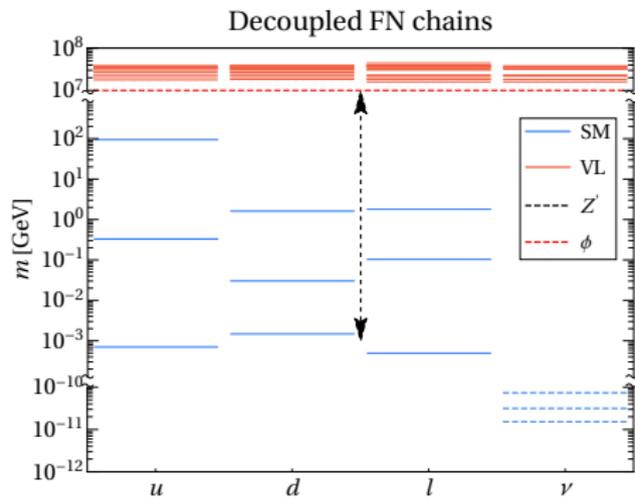
Extend this model to three quark generations with  $G_{FN} = U(1)^3$  (decoupled chains)

$$\frac{M_1}{\langle \phi_1 \rangle} = \frac{M_2}{\langle \phi_2 \rangle} = \frac{M_3}{\langle \phi_3 \rangle} \simeq \lambda = \sin \theta_C \sim 0.2,$$

$$(m_d)_{ij} \simeq \lambda^{N_{q(i)} + N_{d(j)}} \frac{v}{\sqrt{2}}, \quad (m_u)_{ij} \simeq \lambda^{N_{q(i)} + N_{u(j)}} \frac{v}{\sqrt{2}}.$$

Another minimal model can be obtained assuming  $G_{FN} = U(1)$  (coupled chains).

Both models are easily generalized to include leptons and PMNS matrix.



# Z' phenomenology

$G_{FN} = U(1)$ , extra gauge boson with gauge coupling  $g'$ .

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}Z'^{\mu\nu} + B_\mu J_Y^\mu + W_\mu^a J_{W^a}^\mu + Z'_\mu J_{FN}^\mu,$$

If  $\epsilon \rightarrow 0$  we neglect kinetic and mass mixing and have ( $f = u, d, \ell, \nu$ )

$$\mathcal{L} \supset Z'_\mu \sum_{f,i,j} \left[ g' c_{f_L}^{ij} (\bar{f}_L^{(i)} \gamma^\mu f_L^{(j)}) + g' c_{f_R}^{ij} (\bar{f}_R^{(i)} \gamma^\mu f_R^{(j)}) \right],$$

Couplings from rotation to mass basis

$$c_{u_L}^{ij} = (V_{u_L}^\dagger c'^{qL} V_{u_L})_{ij}$$

Both diagonal and off-diagonal entries!

$$c_{u_L} = \begin{pmatrix} -2.722 & -0.411 + 0.102i & 0.004 + 0.013i \\ -0.411 - 0.102i & -2.228 & 0.025 + 0.058i \\ 0.004 - 0.013i & 0.025 - 0.058i & -0.002 \end{pmatrix}$$

$$c_{u_R} = \begin{pmatrix} 2.932 & 0.058 + 0.155i & 0.004 + 0.005i \\ 0.058 - 0.155i & 0.992 & 0.078 - 0.049i \\ 0.004 - 0.005i & 0.078 + 0.049i & 0.009 \end{pmatrix}$$

Rich collection of processes to look at!

### Flavor diagonal

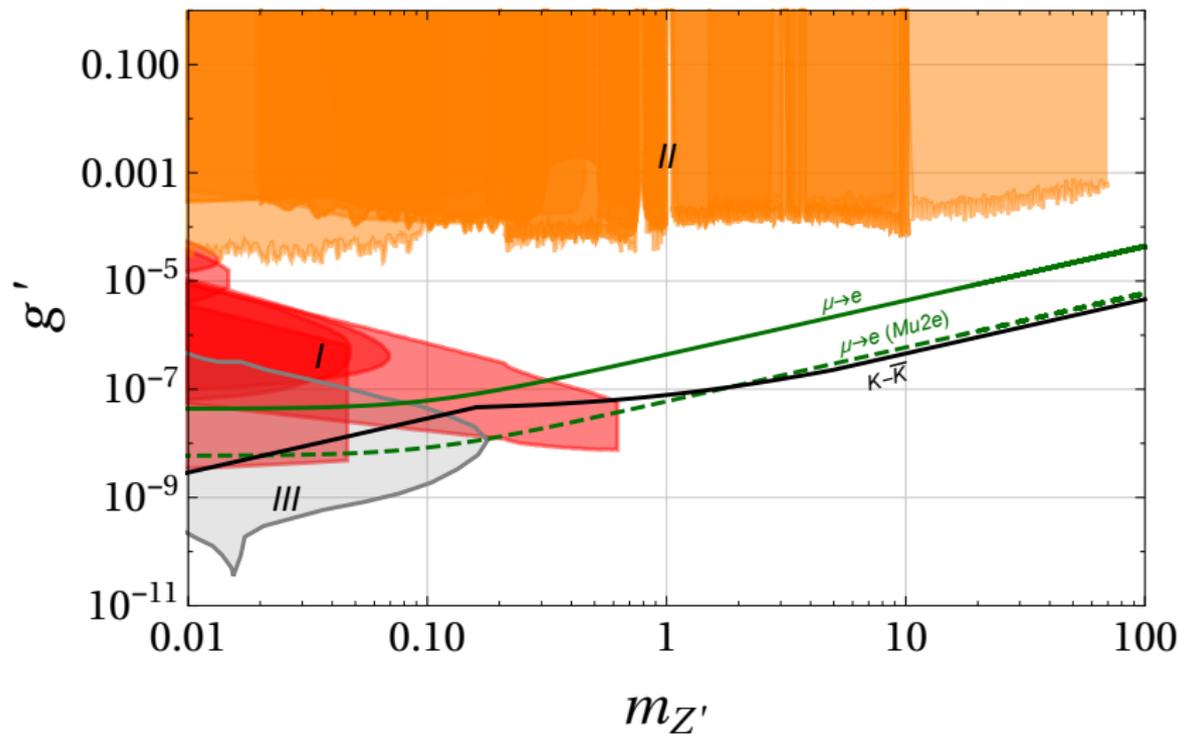
- Direct  $Z'$  production
- Atomic Parity Violation
- Neutrino trident
- Anomalous magnetic moment
- SN1987A
- White dwarf cooling

### Flavor off-diagonal

- Meson mixing  
( $K^0 - \bar{K}^0$ ,  $B_q - \bar{B}_q$ ,  $D^0 - \bar{D}^0$ )
- $\mu \rightarrow e$  conversion
- Decay to three leptons  
( $\tau \rightarrow 3\mu$ ,  $\tau \rightarrow 3e$ ,  $\mu \rightarrow 3e$ )
- Radiative decays  
( $\tau \rightarrow e\gamma$ ,  $\tau \rightarrow \mu\gamma$ ,  $\mu \rightarrow e\gamma$ )
- Rare meson decays ( $K^+ \rightarrow \pi^+ \mu^+ e^-$ )

Preliminary!

Strongest bounds on parameter space



## Summary and Conclusions

- we identified a simple anomaly free twist of FN models of flavor;
- expansion in  $M/\langle\phi\rangle \sim \lambda$  can reproduce fermion mass spectrum;
- can be gauged;
- rich phenomenology for  $Z'$ ;
- $Z'$  can be light.