A clockwork model of flavor

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LIO International Conference on Flavour Physics

April 19th 2018

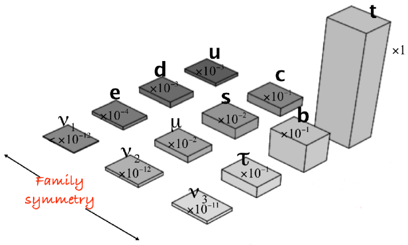
Outline

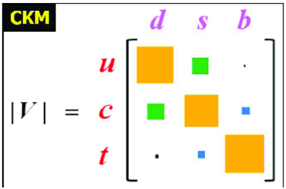
The flavor puzzle of the SM

- The matter content of the SM comes in **3 <u>almost</u> <u>identical</u> generations**
  - Symmetry broken by Yukawa couplings

$$-\mathcal{L}_Y = \bar{q}_L Y_d d_R H + \bar{q}_L Y_u u_R \tilde{H} + \bar{\ell}_L Y_e e_R H + h.c.$$

- **Masses** $M_u = L_u Y_u R_u^\dagger,\ M_d = L_d Y_d R_d^\dagger$ and **mixing**, $\mathbf{V_{CKM}} = L_u L_d^\dagger$ are **hierarchical!**





The flavor puzzle of the SM

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$$-\mathcal{L}_Y = \bar{q}_L Y_d d_R H + \bar{q}_L Y_u u_R \tilde{H} + \bar{\ell}_L Y_e e_R H + h.c.$$

- Rotations are "not physical" in the SM ,only **masses** and $\mathbf{V_{CKM}}$

Where does flavor come from?

- **Geometrical:** *à la* Warped x-dimensions $\Lambda_{\rm NP} \sim \Lambda_{\rm Natural}$ Randall&Sundrum'98
- **Dynamical:** Horizontal symmetries $\Lambda_{\rm NP} \gg \Lambda_{\rm Natural}$ Froggatt&Nielsen '78
- ...

The clockwork mechanism

- Generic mechanism to produce exponential hierarchies

Choi & Im '15, Kaplan & Rattazzi '15,Giudice & McCullough'16

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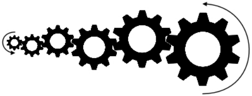


$$g_{\rm eff} = g \times q^{-N}$$

$$\frac{1}{q} \times \frac{1}{q} \times \ldots \times \frac{1}{q} \quad \text{N - times}$$

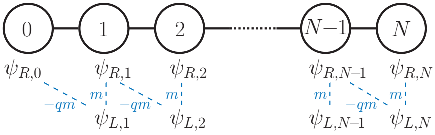
Kamenik's at PLANCK'17

- **Effective scale:** $\Lambda_{\rm eff} = \Lambda / g_{\rm eff}$

Solve the EW hierarchy problem by making $v_{\rm EW} = M_P \times q^{-N}$

Clockworking a single fermion

- **Chiral fermion** $\psi_R \Longrightarrow$ Chain of "mirror" N vector-like fermions Giudice & McCullough'16



$$\mathcal{L}_{\psi_R} = i\sum_{j=0}^{N} \bar{\psi}_{R,j} \not{D} \psi_{R,j} + i\sum_{j=1}^{N} \bar{\psi}_{L,j} \not{D} \psi_{L,j} - m\sum_{j=1}^{N} \left(\bar{\psi}_{L,j}\psi_{R,j} - q\bar{\psi}_{L,j}\psi_{R,j-1}\right) + \text{h.c.},$$

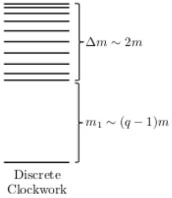
- **Asymmetric** "off-site" interaction

> **One** chiral fermion remains
>
> $N + (N+1)\ \chi$ symmetries $-\ 2\ N\ \chi$-breaking parameters

- The N-vector-like fermions $m_k \sim m$: **Gears**

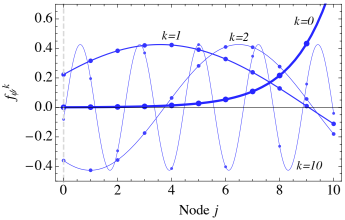
The clockwork physical basis

- **Spectrum**
  - **Mass gap:** $M_1 \simeq m(q-1)$
    - ★ **Limit** $q \to 1 \Longrightarrow$ A light gear
  - **Spectrum:** Within a band $\sim 2m$
    - ★ **Limit** $q \gg 1 \Longrightarrow m_k \sim qm$: **compressed**



McCullough&Giudice arXiv: 1610.07962

- **Mixings**



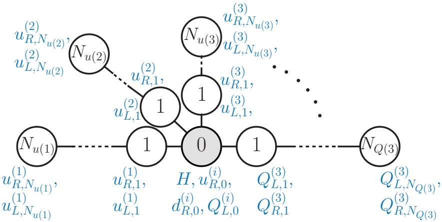
- **Overlaps** f_ψ^k**:** Mixings with the 0-th “node”

$$\psi'_{R,k} = \sum_{j=0}^{N} V^R_{jk}\psi_{R,j}, \quad f^k_\psi = V^R_{0k}$$

Clockwork mechanism

$f^0_\psi \sim 1/q^N$ for $q > 1$

A clockwork model of flavor



Simple recipe

1. Each SM field ψ in a family i has a clockwork chain $(q_{\psi_{(i)}},\ N^{\psi(i)})$
2. Identify the massless fermions with the SM fields
3. Make the SM-Higgs doublet interact to all chains at the "0-node"

$$\mathcal{L}_{c'k} = \sum\left(\mathcal{L}_{u_R^{(i)}} + \mathcal{L}_{d_R^{(i)}} + \mathcal{L}_{Q_L^{(i)}}\right) - \sum\left[\left(Y_D\right)_{ij}\bar{Q}^{(i)}_{L,0} H\, d^{(j)}_{R,0} + \left(Y_U\right)_{ij}\bar{Q}^{(i)}_{L,0}\tilde{H} u^{(j)}_{R,0} + \text{h.c.}\right],$$

4. Adjust $(q_{\psi_{(i)}},\ N^{\psi(i)})$ to reproduce the exponential flavor hierarchies

The flavor clockwork in action

- Start with **anarchic** Yukawa matrices Y_U, Y_D

$$\left(Y_U^{\rm SM}\right)_{ij} = f_{Q(i)}\ (Y_U)_{ij}\, f_{u(j)}, \qquad \left(Y_D^{\rm SM}\right)_{ij} = f_{Q(i)}\ (Y_D)_{ij}\, f_{d(j)}$$

  - **Zero-mode overlaps:** $f_{\psi(i)} \sim q_{\psi(i)}^{-N_{\psi(i)}}$

- This produces . . . Froggatt & Nielsen '78
  - CKM mixings

$$(V_{\rm CKM})_{ij} = \frac{f_{Q(i)}}{f_{Q(j)}}, \quad i < j$$

Fix doublet overlaps

  - Masses of SM quarks

$$m_{u(i)} \sim v\, f_{Q(i)}\, f_{u(i)}, \quad m_{d(i)} \sim v\, f_{Q(i)}\, f_{d(i)}$$

Fix singlet overlaps

The flavor clockwork in action

- **Phenomenological scalings**

$$f_{Q(1)} \sim \lambda^3, \quad f_{Q(2)} \sim \lambda^2, \quad f_{Q(3)} \sim 1,$$
$$f_{u(1)} \sim \lambda^5, \quad f_{u(2)} \sim \lambda^2, \quad f_{u(3)} \sim 1,$$
$$f_{d(1)} \sim \lambda^5, \quad f_{d(2)} \sim \lambda^3, \quad f_{d(3)} \sim \lambda^3.$$

- **Illustrative benchmark for proto-Yukawas**

$$Y_U = \begin{pmatrix} 2.68 - 1.14\,i & 1.15 + 0.34\,i & -1.28 + 0.63\,i \\ -0.35 - 1.00\,i & 0.53 + 0.28\,i & 0.28 + 1.14\,i \\ -1.13 + 0.85\,i & 0.19 + 0.31\,i & 0.76 - 0.12\,i \end{pmatrix},$$
$$Y_D = \begin{pmatrix} -1.76 + 0.57\,i & 0.57 - 0.09\,i & 0.30 + 0.10\,i \\ 0.23 + 0.52\,i & 0.04 - 0.91\,i & 0.73 - 0.67\,i \\ 0.23 + 0.43\,i & -0.63 - 0.16\,i & 0.04 - 0.97\,i \end{pmatrix},$$

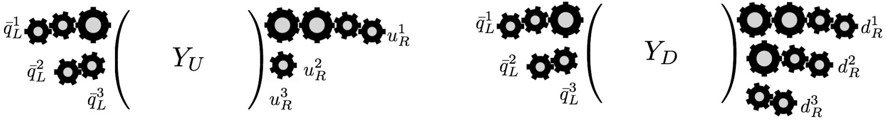
  - Lead to the right quark masses and CKM!

    Similar to solutions of flavor puzzle in Randall-Sundrum or Froggatt-Nielsen

Variations of the flavor-clockwork model

- "Randall-Sundrum" variation: **Same** $N_{\psi(i)} = N$ for all ψ and i, **different** $q_{\psi(i)}$
  - Large number of mirror fermions: $9 \times N$
  - Unsuppressed $Q(3)$ and $u(3) \Longrightarrow q \sim 1 \Longrightarrow$ **Light gears**

- "Froggatt-Nielsen" variation: **Same** $1/q = \lambda$ for all ψ and i, **different** $N_{\psi(i)}$
  - Number of mirror fermions can be minimized
  - $q \gg 1 \Longrightarrow$ **Compressed gear spectrum** $m_k \simeq qm$
  - **Artist's impression of the FN setup**



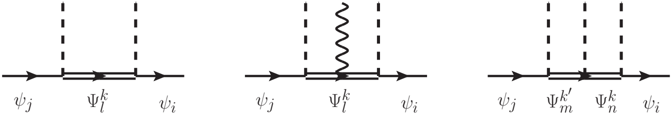
  - This setup require **5** doublet gears, **7** u-type gears and **11** d-type gears

Low-energy consequences: The clockwork GIM mechanism

- **Gears** (VLQs) can have disruptive effects in low-energy flavor observables!

  Bobeth *et al.* JHEP 1704 (2017) 079

  - Contributions to FCNCs can push the **flavor-mass scale to PeV!**
  - **Example:** Contributions to Higgs and weak boson couplings



Anomalous $d_{L(i)} d_{L(j)}$ Z couplings:

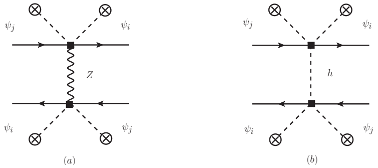
$$[\delta g_L]_{ij}^{Z_d} = \frac{v^2}{4} f_{Q(i)} f_{Q(j)} \left[Y_D M_d^{-2} Y_D^\dagger \right]_{ij}$$

Clockwork GIM mechanism

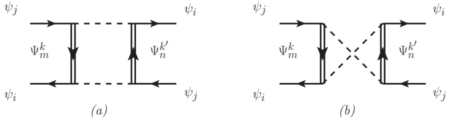
SM-gear mixing via Higgs $\Longrightarrow$ **Overlap** $\sim (f_{\psi(i)})^2$ suppression!

Low-energy consequences: Neutral-meson mixing

- **Tree-level** at $\mathcal{O}(v^4/m^4)$



- **Loop-level** at $\mathcal{O}(v^2/m^2)$



- **However** these contributions are very suppresed by overlaps
  - **For example**, K-$\bar{K}$ mixing the “leading” contribution is of the type

$$(f_{Q(1)}f_{Q(2)})^2\,(\bar{s}_L\gamma^\mu d_L)^2 \sim \lambda^{10}\,(\bar{s}_L\gamma^\mu d_L)^2$$

★ Same parametric suppression (and structure) as the top-box in the SM!

Low-energy systematically: SMEFT

- **Contributions of the gears in the SMEFT if $m \gg v_{\rm EW}$** Buchmuller & Wyler'88,...

$$\mathcal{L}^{(6)}_{\rm SMEFT} = \sum w_i\, \mathcal{O}_i$$

$\mathcal{O}^{(1)}_{HQ}$	$\left(H^\dagger i \overleftrightarrow{D}_\mu H\right) \bar{Q}_L \gamma^\mu Q_L$	$\mathcal{O}^{(1)}_{QQ}$	$(\bar{Q}_L\gamma^\mu Q_L)(\bar{Q}_L\gamma_\mu Q_L)$
$\mathcal{O}^{(3)}_{HQ}$	$\left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right) \bar{Q}_L \gamma^\mu \tau^I Q_L$	$\mathcal{O}^{(3)}_{QQ}$	$(\bar{Q}_L\gamma^\mu \tau^I Q_L)(\bar{Q}_L\gamma_\mu \tau^I Q_L)$
$\mathcal{O}_{Hu}$	$\left(H^\dagger i \overleftrightarrow{D}_\mu H\right) \bar{u}_R \gamma^\mu u_R$	$\mathcal{O}^{(1)}_{Qd}$	$(\bar{Q}_L\gamma^\mu Q_L)(\bar{d}_R\gamma_\mu d_R)$
$\mathcal{O}_{Hd}$	$\left(H^\dagger i \overleftrightarrow{D}_\mu H\right) \bar{d}_R \gamma^\mu d_R$	$\mathcal{O}^{(1)}_{Qu}$	$(\bar{Q}_L\gamma^\mu Q_L)(\bar{u}_R\gamma_\mu u_R)$
$\mathcal{O}_{Hud}$	$\left(\tilde{H}^\dagger i D_\mu H\right) \bar{u}_R \gamma^\mu d_R$	$\mathcal{O}_{dd}$	$(\bar{d}_R\gamma^\mu d_R)(\bar{d}_R\gamma_\mu d_R)$
$\mathcal{O}_{uH}$	$(H^\dagger H)\, \bar{Q}_L \tilde{H} u_R$	$\mathcal{O}_{uu}$	$(\bar{u}_R\gamma^\mu u_R)(\bar{u}_R\gamma_\mu u_R)$
$\mathcal{O}_{dH}$	$(H^\dagger H)\, \bar{Q}_L H d_R$		

- **Match neutral-meson mixing to one-loop accuracy at $\mathcal{O}(v^2/m^2)$**
  - $\psi^2 H^2 D \longrightarrow$ **tree-level** matching
  - ψ^4 operators $\longrightarrow$ **one loop** matching
  - EW RGE of $\psi^2 H^2 D$ at **one-loop**
  - **One-loop** matching between SMEFT and Low-Energy-EFT

Low-energy observables

- **EWPO:** Weak boson LH and RH couplings to the quarks Falkowski, Gonzalez-Alonso, Mimouni.'17

$$M_d \gtrsim 5 \text{ TeV}, \quad M_u \gtrsim 0.5 \text{ TeV}, \quad M_Q \gtrsim 0.1 \text{ TeV}$$

  - One of strongest bounds from $Z \to b_L b_L$: **It is not suppressed by overlaps!**

- **Rare decays:** $\Delta S = 1$, $\Delta B = 1$, $\Delta C = 1, \ldots$

$$M_d \gtrsim 5 \text{ TeV}, \quad M_u \gtrsim 0.1 \text{ TeV}$$

- **Neutral-meson mixing:** K-$\bar{K}$, B-$\bar{B}$, D-$\bar{D}$, ... M. Bona *et al.*'16, UTfit collaboration
  - The contributions of the gears is complicated ...

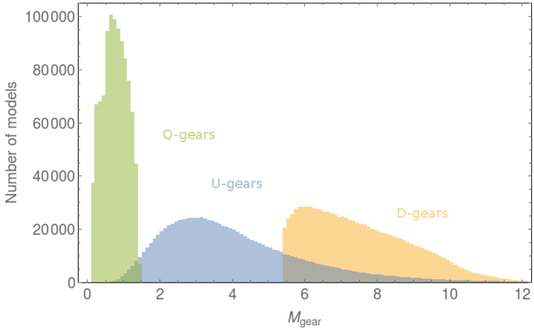
Process	U	D	Q	UD	UQ	DQ
B_s-$\bar{B}_s$	λ^4, ¤*	λ^4, $\times$ and ¤				
B_d-$\bar{B}_d$	λ^6, ¤*	λ^6, $\times$ and ¤				
K-$\bar{K}$	λ^{10}, ¤*	λ^{10}, $\times$ and ¤	λ^{13}, ¤*†		λ^{13}, ¤†	λ^{12}, $\times^\dagger$
D-$\bar{D}$	λ^{10}, $\times$ and ¤	λ^{10}, ¤			λ^{10}, $\times^\dagger$	

$\dagger$ = χ-enhancement; $*$ =logarithmic enhancement

Bounds scanning over models

- **Strategy:** Scan over anarchic proto-Yukawas leading to suitable $Y^{\rm SM}_{U,D}$
  - For each model, derive the stringest bounds on M_d, M_u, M_Q from all observables

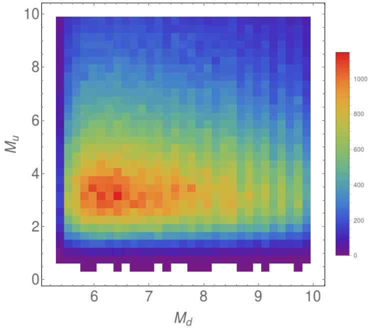
- **Scan 1:** Assume only 1 type of gear active (decouple the other two)



  - ***U*- and *D*-gears can be very light $M_{u,d} \lesssim 10$ TeV**
  - ***Q*-gears unconstrained!**

Bounds scanning over models

- **Strategy:** Scan over anarchic proto-Yukawas leading to suitable $Y^{\rm SM}_{U,D}$
  - For each model, derive the stringest bounds on M_d, M_u, M_Q from all observables
- **Scan 2:** Fix $M_Q = 2$ TeV and put bounds on M_u and M_d
  - **Rationale:** Dangerous contributions to meson mixing from QU and QD diagrams



Most of our clockwork models can live at the TeV scale!

Bounds scanning over models

- **Strategy:** Scan over anarchic proto-Yukawas leading to suitable $Y^{\rm SM}_{U,D}$
  - For each model, derive the stringest bounds on M_d, M_u, M_Q from all observables

- **Remember our benchmark model**...

$$Y_U = \begin{pmatrix} 2.68 - 1.14\,i & 1.15 + 0.34\,i & -1.28 + 0.63\,i \\ -0.35 - 1.00\,i & 0.53 + 0.28\,i & 0.28 + 1.14\,i \\ -1.13 + 0.85\,i & 0.19 + 0.31\,i & 0.76 - 0.12\,i \end{pmatrix},$$

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- We obtain ...

$$M_u \gtrsim 3.8\ \text{TeV}, \quad M_u \gtrsim 5.9\ \text{TeV}, \quad (M_Q = 2\ \text{TeV})$$

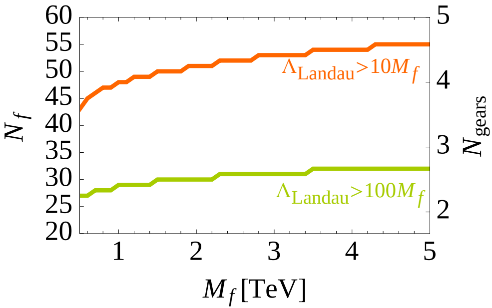
Bounds from Landau poles in α_s

- New colored states change the β-function of QCD

$$\frac{d\alpha_s}{d\ln\mu} = -2\beta_0\frac{\alpha_s^2}{4\pi}, \quad \beta_0 = \frac{11N_c - 2N_f}{3},$$

  - For $N_f \gtrsim 16$ QCD develops a UV Landau pole!

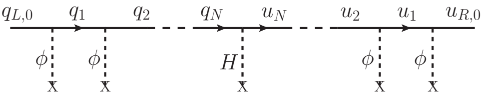
- Demanding $\Lambda_{QCD} > 100 \times M_{\rm gear}$ we set a bound on N_f



- **In our benchmark** $N_f = 34 \Longrightarrow \Lambda_{\rm QCD} \sim 100$ **TeV**

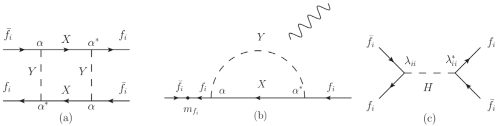
Comparison with Froggatt-Nielsen mechanism

- Clockwork model of flavor looks similar to **Froggatt-Nielsen**
  - **Horizontal symmetry** $\mathcal{H}$ ($U(1)$)
    - Different charges to fields in different generations
    - Add mirror VLQs and scalars (**flavon**) charged under $\mathcal{H}$



$$\mathcal{L}_Y = (Y_D)_{ij} \left(\frac{\langle \phi \rangle}{M} \right)^{H(\bar{Q}_i)+H(d_j)} \bar{Q}_i H d_j + (Y_U)_{ij} \left(\frac{\langle \phi \rangle}{M} \right)^{H(\bar{Q}_i)+H(u_j)} \bar{Q}_i \tilde{H} u_j$$

- Hierarchies in **small parameter** $\langle \phi \rangle / M$ given **dynamically** by the charges!
- **Richer phenomenology** $\Longrightarrow$ Flavons, gauged horizontal bosons, etc

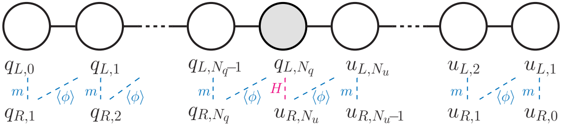


  - Bounds typically in the order of 50 TeV - 1 PeV Calibbi, Lalak, Pokorski, Ziegler arXiv: 1204.1275

Pointing to a UV completion of the clockwork flavor model

- Clockwork mechanism is nondynamical as is
  - **Where does the q spurion comes from?**
- It can be UV-completed with an $\mathcal{H}$ *à la* FN!

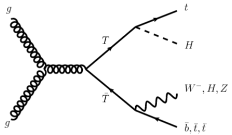
$$q\, M = \langle \phi \rangle \gg M$$



- **"Inverted" Froggatt-Nielsen mechanism**
- Does it help reducing flavon contributions?

Collider signatures from the clockwork gears

- **Pair-produce** lightest gears of Q-type at the **LHC** via gg fusion



  - Heaviest gears decay down the clockwork-chain
  - Eventually they decay into t_L, b_L and h, W and Z

- **LHC** searches of VLQs set bounds typically of $\mathcal{O}(1)$ TeV
- Need more sophisticated searches ...

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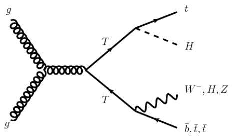

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- **LHC** searches of VLQs set bounds typically of $\mathcal{O}(1)$ TeV
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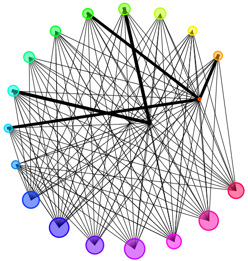
- Psychodelic collider pheno (in progress) . . .



  - **Decay patterns of gears**
    - **Central node:** SM fermion
    - **Colored bulbs:** Gears classified by mass (order) and width (size)
    - **Lines:** Decays with thickness representing BR
  - **Simulating this in MG for promising signals!**

Conclusions

- **Clockwork mechanism:** Solution to the EW hierarchy problem by reducing M_P
- **Can we solve the flavor puzzle within this paradigm with low mass scale?**

YES! ...

- ... If we forget about *"Where does the clockwork comes from?"*
- **If not,** we are in a Froggatt-Nielsen setup with $<\phi>\gg M$ ...