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Clockwork Flavor

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Can one solve SM flavor puzzle with clockwork?

Clockwork: generic mechanism to generate large hierarchies

• in couplings: suppressed by N-node 'gear ratio' factor

Choi, Kim & Yun, 1404.6209 Choi & Im, 1511.00132 Kaplan & Rattazzi, 1511.01827 Giudice & McCullough, 1610.07962

- in scales: $\Lambda_{\rm eff} = M/g_{\rm eff}$; M = actual UV d.o.f. mass
 - Example: EW Planck hierarchy $v_{\rm EW} \sim M_{\rm Pl} \times q^{-N}$

see talk by Matthew McCullough

Clockworking fermion



• Results in particular mass structure:

$$\mathcal{M}_{\psi} = m \begin{pmatrix} 1 - q \ 0 \ \dots \ 0 \\ 0 \ 1 \ -q \ \dots \ 0 \\ \vdots \ \ddots \ \ \ddots \ 0 \\ 0 \ \dots \ 0 \ 1 \ -q \end{pmatrix}$$

Clockworking fermion

Spectrum: massless zero-mode + N massive 'gears'

$$\psi'_{R,k} = \sum_{j=0}^{N} V_{jk}^{R} \psi_{R,j} \qquad \qquad m_{k}^{2} = m^{2} \left(1 + q^{2} - 2q \cos\left(\frac{k\pi}{N+1}\right) \right)$$



SM flavor puzzle



Most of SM Yukawa couplings are tiny: result of clockworking?

need to also reproduce alignment & hierarchy of CKM

Clockwork flavor

Flavor hierarchy from zero mode overlaps with Higgs

• Higgs couples to N-th node



• similar to RS with Higgs on IR brane, fermions in bulk

Clockwork flavor



Comparison with RS

- unlike RS, single clockwork cannot solve hierarchy problem and SM flavor puzzle at same time
 - clockwork gravity in continuum: hierarchy problem solved by large volume not due to warping
 see also Antoniadis et al., hep-th/0103033
- proposed clockwork flavor does not have continuum limit
 - all nodes gauged by SM group no gears for gauge bosons, gravity



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- proposed clockwork flavor does not have continuum limit
 - all nodes gauged by SM group no gears for gauge bosons, gravity
 - to address hierarchy problem, could couple whole clockwork flavor model to N-th gear of clockworked gravity

Comparison with Froggatt-Nielsen



Flavor constraints

Mixing of zero mode with gears



- dominant effect in modified Higgs Yukawas
 - flavor (& CP) violating
 - departures from SM values for 3rd gen. (t,b)
- modifications of Z,W couplings at $\mathcal{O}(v^4/m^4)$

 $\mathcal{L}_W^{\text{eff}} \sim -\frac{1}{m^4} f_{Q(i)}^0 (Y_U Y_U^{\dagger} Y_D Y_D^{\dagger})_{ij} f_{Q(j)}^0 (\bar{Q}_{L,0}^{(i)} H^c \gamma^{\mu} H Q_{L,0}^{(j)}) (H^{c\dagger} i D_{\mu} H).$

 $Q_{L,0}^{(j)}$ $d_{R,k''}$ $Q_{L,k'}$ $u_{R,k}$ $Q_{L,0}^{(i)}$

Flavor constraints

Corrections suppressed by zero mode overlaps

• similar to RS-GIM

see e.g. S. Davidson et al., 0711.3376

Relatively mild flavor constraints from meson mixing

$$D^{0} - \bar{D}^{0}: \qquad m \gtrsim 1.7 \text{ TeV},$$

$$B_{s} - \bar{B}_{s}: \qquad m \gtrsim 1.5 \text{ TeV},$$

$$B_{d} - \bar{B}_{d}: \qquad m \gtrsim 2.2 \text{ TeV},$$

$$K^{0} - \bar{K}^{0}: \qquad \begin{cases} m \gtrsim 8.6 \text{ TeV}, \\ m \gtrsim 2.3 \text{ TeV} \text{ (if no NP weak phase).} \end{cases}$$

- dominated by Higgs, Z exchange
- note: no gluon, Z gears!

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- Relatively mild flavor constraints from meson mixing
 - dominated by Higgs, Z exchange
 - note: no gluon, Z gears!
 - predictions for Higgs & EW precision observables

 $|\delta y_t| \lesssim 1\% \qquad |\delta g_L^{Z\bar{b}b}| \lesssim 10^{-4}$

possibly accessible at next-gen colliders

see e.g. Contino et al., 1606.09408 Bicer et al., 1308.6176

LHC searches

Clockwork flavor gears can be at O(TeV)

small inter-gear mass gaps O(m/N)

How to search for them at the LHC?

- Q gears QCD pair produced
- decay $Q \rightarrow Q' + h, Z, W; q + h, Z, W$
 - multiple thresholds at LHC?
 - long decay chains?
 - "modulating" x-section





Conclusions

Model of flavor based on clockwork mechanism

- shares particularities with RS & FN
 - obstacles to continuum version
 - no elegant simultaneous solution for EW hierarchy
- effects in flavor physics under control for O(1TeV) gears!
 - associated effects in Higgs & EW observables
 - gears can be searched for in high p⊤ processes
 - novel x-section 'modulation' signatures

