

# PACTS: 2018

– Particle Astroparticle Cosmology Tallinn Symposium –

## Clockwork Flavor

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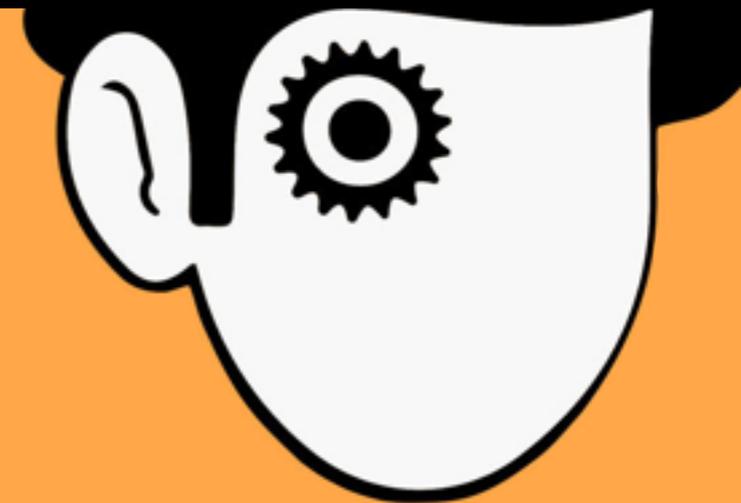
with R. Alonso, J. Martin Camalich,  
A. Carmona, B. Dillon, J. Zupan



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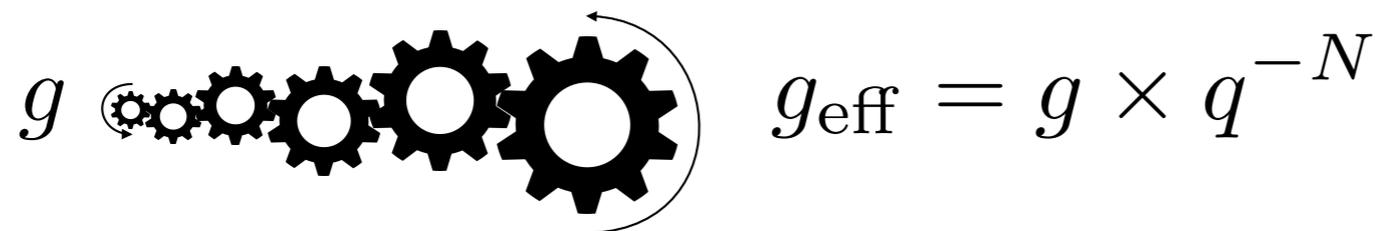
Talinn  
20/6/2018

# Can one solve SM flavor puzzle with clockwork?

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Clockwork: generic mechanism to generate large hierarchies

- in couplings: suppressed by N-node ‘gear ratio’ factor


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

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

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

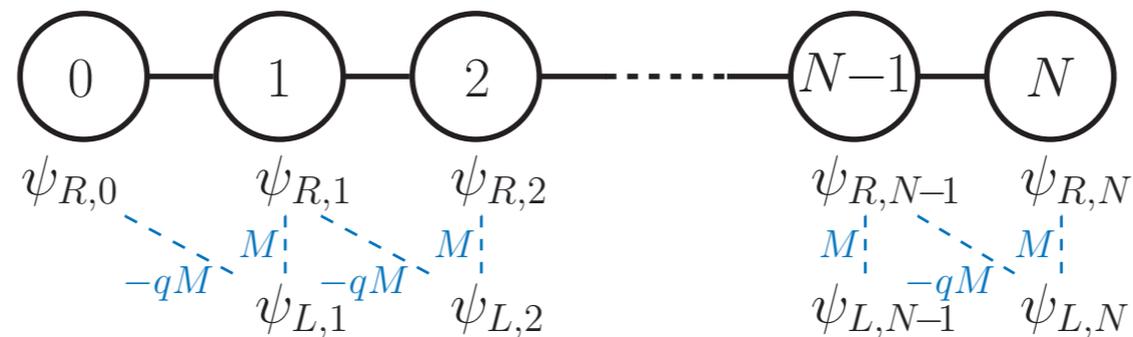
- in scales:  $\Lambda_{\text{eff}} = M/g_{\text{eff}}$  ;  $M =$  actual UV d.o.f. mass

- Example: EW - Planck hierarchy  $v_{\text{EW}} \sim M_{\text{Pl}} \times q^{-N}$

# Clockworking fermion

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Chain of vectorlike fermions + one chiral node:



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

- Results in particular mass structure:

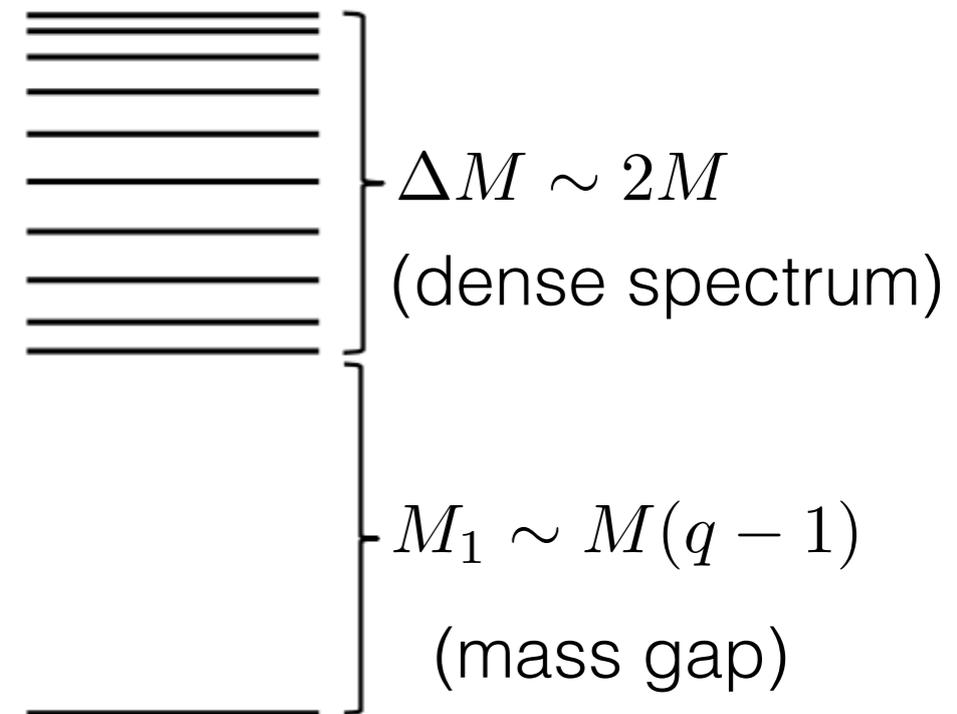
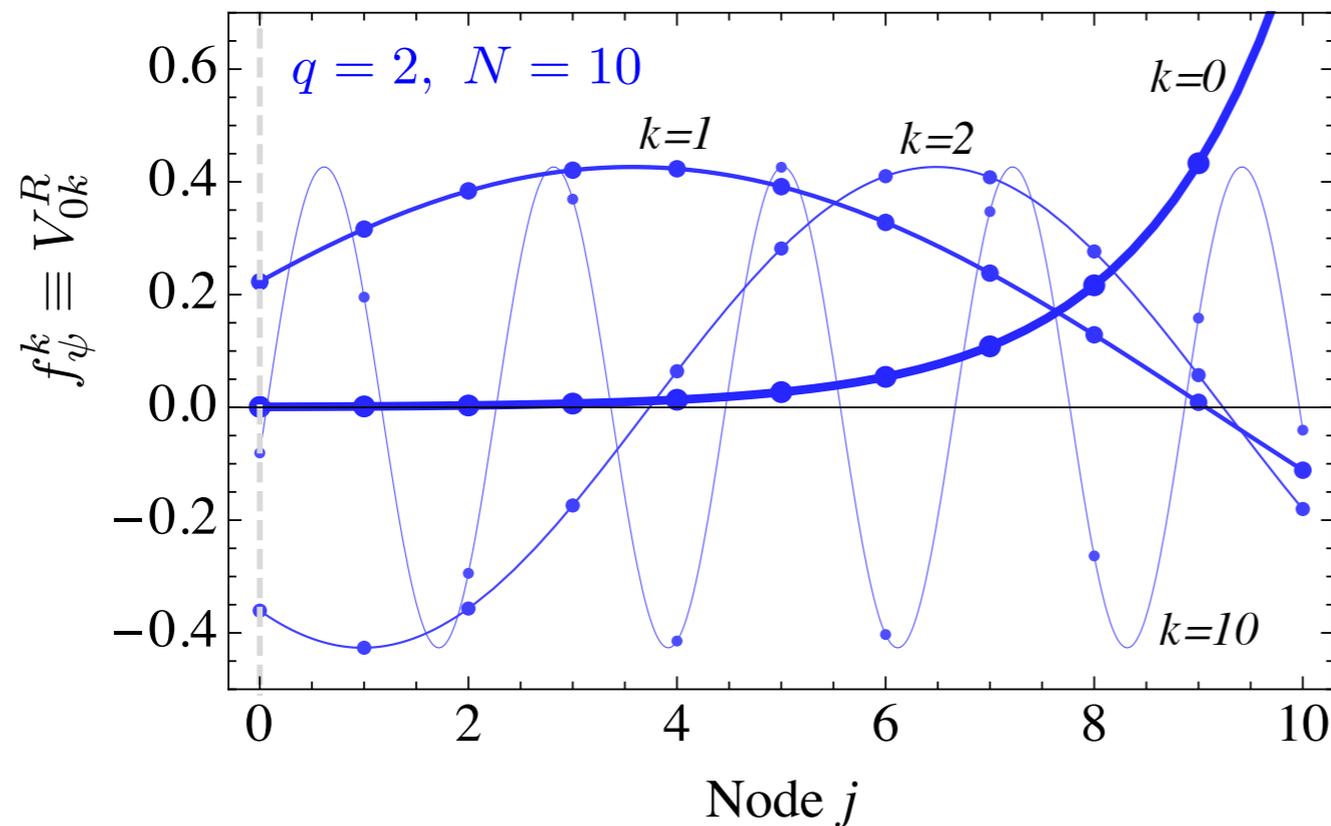
$$\mathcal{M}_{\psi} = M \begin{pmatrix} -q & 1 & 0 & \dots & 0 \\ 0 & -q & 1 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \dots & 0 & -q & 1 \end{pmatrix}$$

# Clockworking fermion

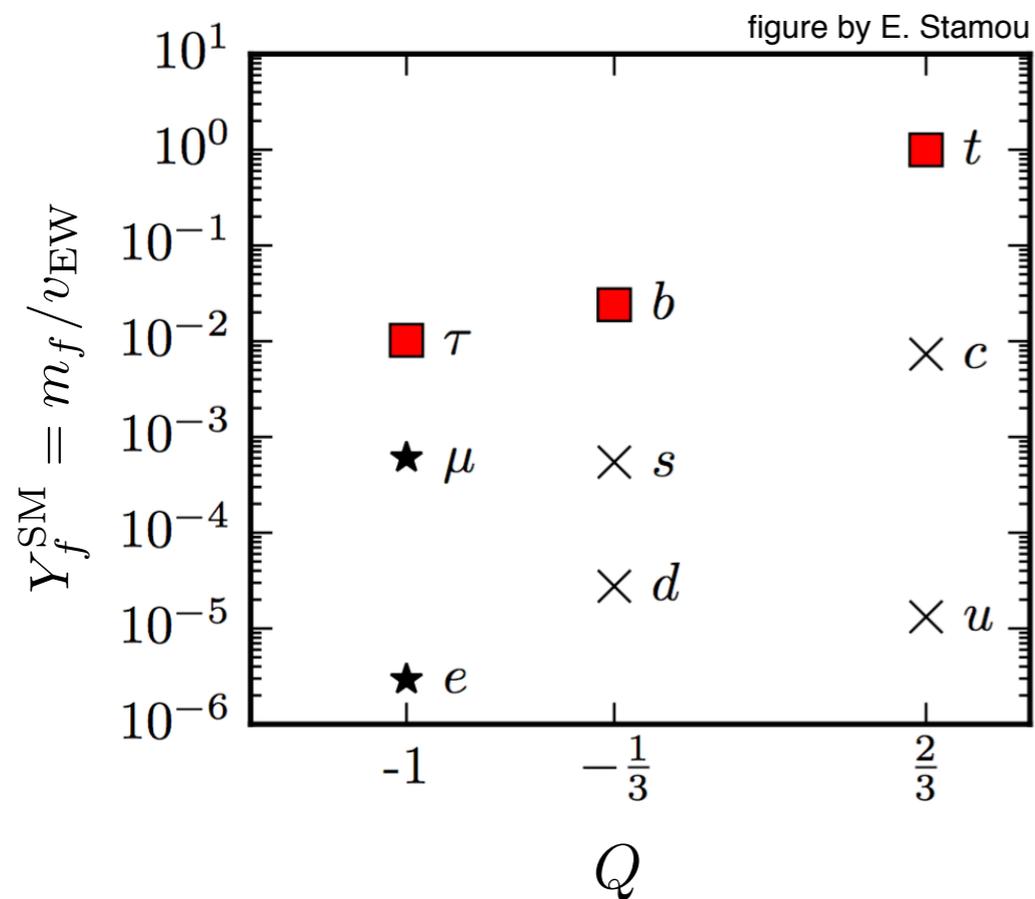
Spectrum: massless zero-mode + N massive ‘gears’

$$\psi'_{R,k} = \sum_{j=0}^N V_{jk}^R \psi_{R,j}$$

$$M_k^2 = M^2 \left( 1 + q^2 - 2q \cos \left( \frac{k\pi}{N+1} \right) \right)$$



# SM flavor puzzle



$$V_{\text{CKM}} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda \simeq \sin \theta_c \simeq 0.22$$

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

- need to also reproduce alignment & hierarchy of CKM



# Clockwork flavor

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## Flavor hierarchy from zero mode overlaps with Higgs

- $$f_\psi \equiv V_{00}^R = \begin{cases} \sim 1/q^N, & q \gg 1; \\ \frac{1}{\sqrt{1+N}}, & q \rightarrow 1. \end{cases} \quad \begin{aligned} (Y_u^{\text{SM}})_{ij} &= f_{Q(i)} (Y_U)_{ij} f_{u(j)} \sim q_{Q(i)}^{-N_{Q(i)}} (Y_U)_{ij} q_{u(j)}^{-N_{u(j)}} \\ (Y_d^{\text{SM}})_{ij} &= f_{Q(i)} (Y_D)_{ij} f_{d(j)} \sim q_{Q(i)}^{-N_{Q(i)}} (Y_D)_{ij} q_{d(j)}^{-N_{d(j)}} \end{aligned}$$

- For  $O(1)$   $Y_{U,D}$ , quark flavor structure determined by overlap hierarchies

$$\begin{aligned} q_{Q(1)}^{-N_{Q(1)}} &\ll q_{Q(2)}^{-N_{Q(2)}} \ll q_{Q(3)}^{-N_{Q(3)}} \\ q_{u(1)}^{-N_{u(1)}} &\ll q_{u(2)}^{-N_{u(2)}} \ll q_{u(3)}^{-N_{u(3)}} \\ q_{d(1)}^{-N_{d(1)}} &\ll q_{d(2)}^{-N_{d(2)}} \ll q_{d(3)}^{-N_{d(3)}} \end{aligned}$$



$$\begin{aligned} m_{u(i)} &\sim v f_{Q(i)} f_{u(i)} \\ m_{d(i)} &\sim v f_{Q(i)} f_{d(i)} \\ (V_{\text{CKM}})_{ij} &\sim f_{Q(i)} / f_{Q(j)} \end{aligned}$$

# Two limits of clockwork flavor

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1. Froggatt-Nielsen limit  $q_{u(i)} \sim q_{d(i)} \sim q_{Q(i)} \gg 1$  &  $N_{Q(1)} \gg N_{Q(2)} \gg N_{Q(3)}$

...

- somewhat reduced number of gears (VLQs) possible
- compressed spectrum  $q \sim 1/\lambda \Rightarrow M_k \sim qM$

2. Randall-Sundrum limit  $q_{Q(1)} \gg q_{Q(2)} \gg q_{Q(3)}$  &  $N_{Q(i)} = N_{u(i)} = N_{d(i)}$

...

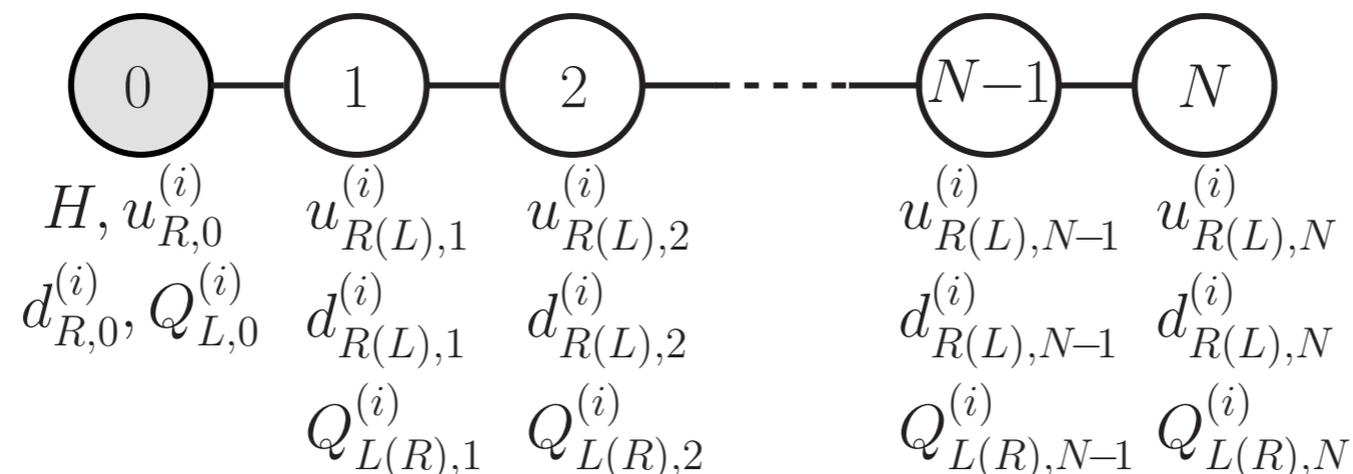
- large number of gears (VLQs):  $12 \times N$
- for 3rd gen:  $q \sim 1 \Rightarrow$  light gears

# Comments on RS limit

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- 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
- proposed clockwork flavor does not have continuum limit
- all nodes gauged by SM group - no gears for gauge bosons, gravity

see also Antoniadis et al.,  
hep-th/0103033

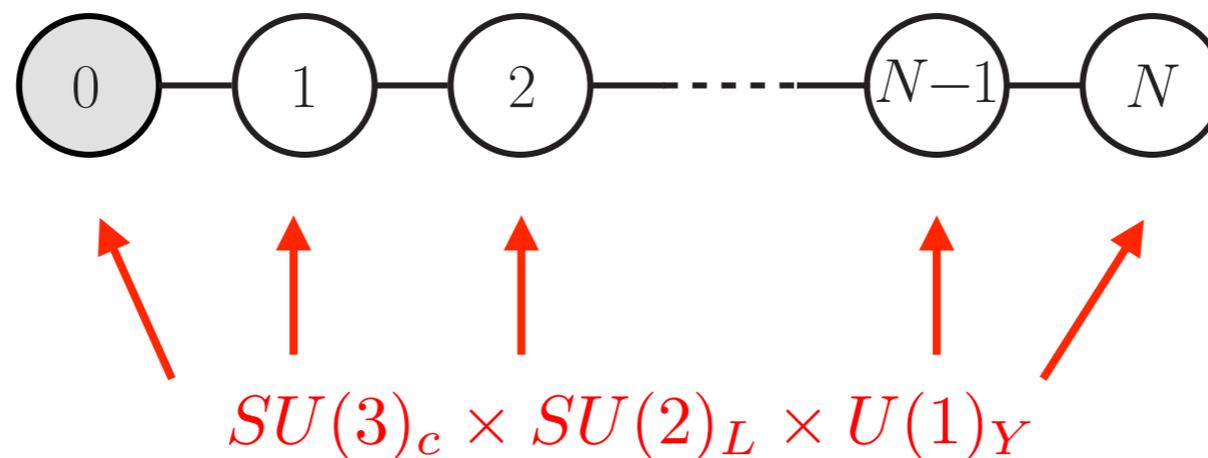


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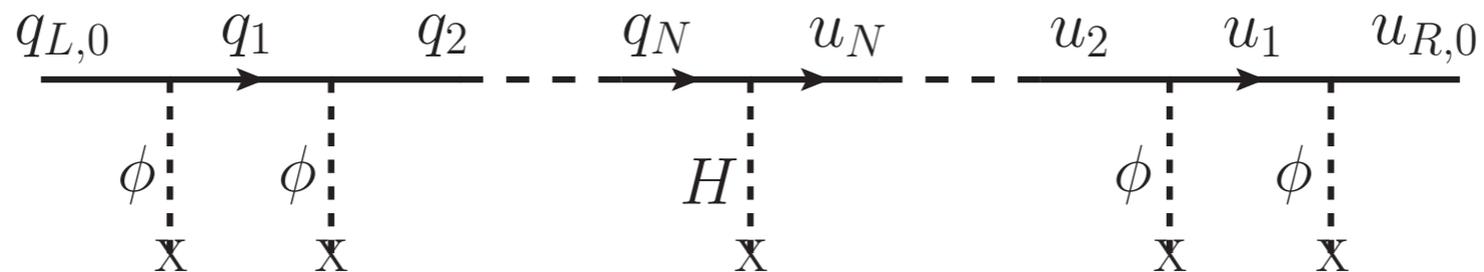
(to address hierarchy problem, could couple whole clockwork flavor model to N-th gear of clockworked gravity)

Giudice & McCullough, 1610.07962

# Comparison with Froggatt-Nielsen

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Clockwork resembles FN models



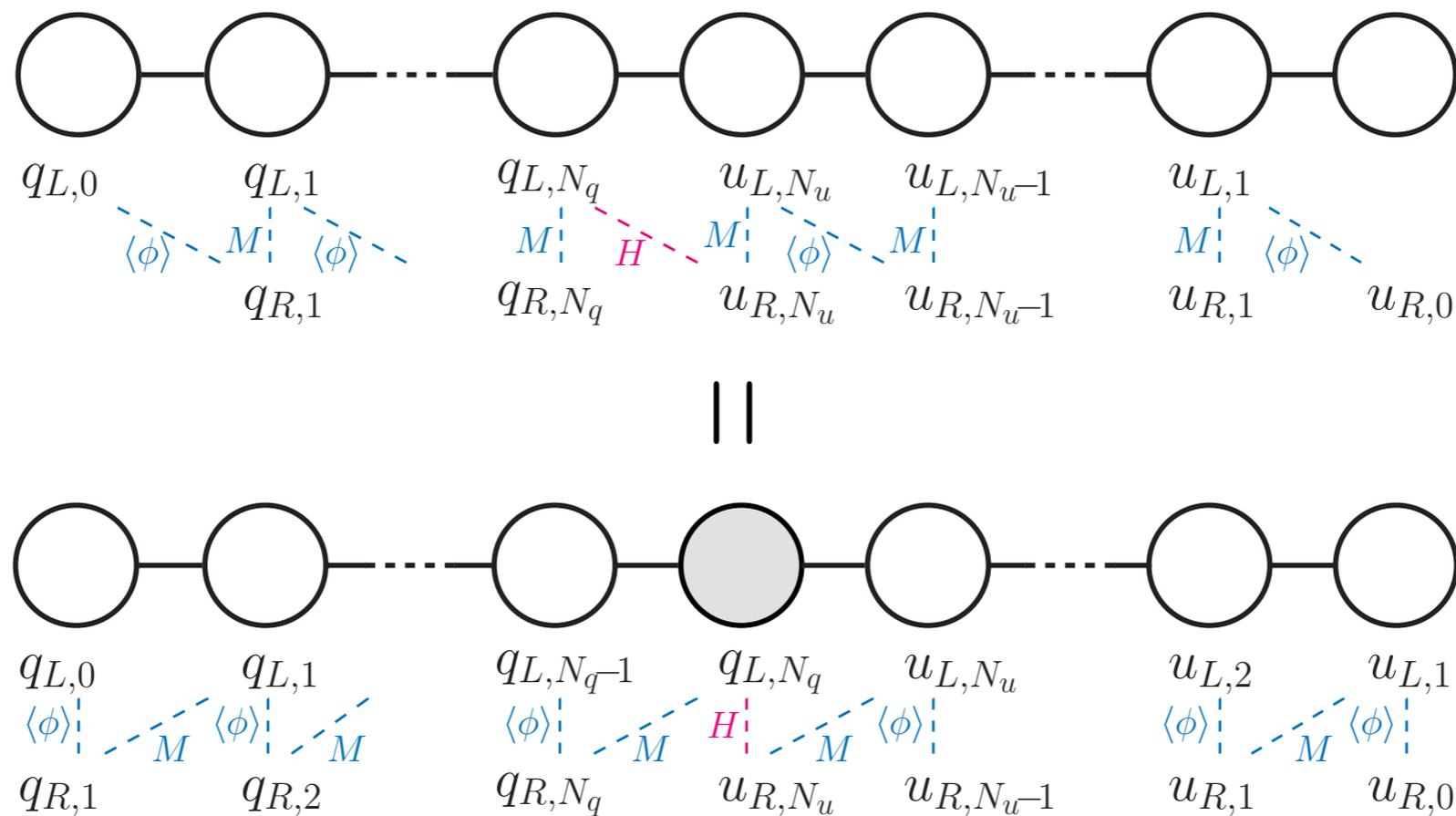
- usually expanded in limit  $\langle \phi \rangle \ll M$

$$\mathcal{L}_{\text{eff}} = (Y_U)_{\alpha\beta} \left( \frac{\langle \phi \rangle}{M} \right)^{N_{Q(\alpha)} + N_{u(\beta)}} \bar{Q}(\alpha)_L \tilde{H} u(\beta)_R + \text{h.c.}$$

- The FN limit of the clockwork corresponds to  $\langle \phi \rangle = -qM$

# Comparison with Froggatt-Nielsen

Clockwork resembles FN models (equivalence at low scale)



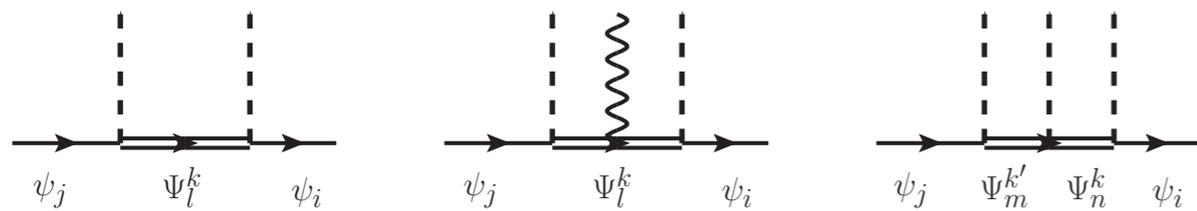
- The FN limit of the clockwork corresponds to  $\langle \phi \rangle = -qM$

However now  $qM \gg M$

# Low energy constraints

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## Mixing of zero mode with gears



$$(y_u^{\text{Higgs}})_{ij} \simeq (Y_u^{\text{SM}})_{ij} + f_{Q(i)}^0 f_{u(j)}^0 \frac{v^2}{m^2} Y_{U,D}^2,$$

$$(y_d^{\text{Higgs}})_{ij} \simeq (Y_d^{\text{SM}})_{ij} + f_{Q(i)}^0 f_{d(j)}^0 \frac{v^2}{m^2} Y_{U,D}^2,$$

- modified Higgs Yukawas
  - flavor (& CP) violating
- modifications of Z,W couplings
  - departures from SM values for 3rd gen. ( $f_{Q(3)} \simeq 1$ )

$$[\delta g_L]_{\alpha\beta}^{Z,d} = \frac{v^2}{4} f_{Q(\alpha)} f_{Q(\beta)} \left[ Y_D M_d^{-2} Y_D^\dagger \right]_{\alpha\beta} \Rightarrow \boxed{M_{d(\alpha)} \gtrsim 3.8 \text{ TeV}} \quad (\text{for } Y_D \sim 1)$$

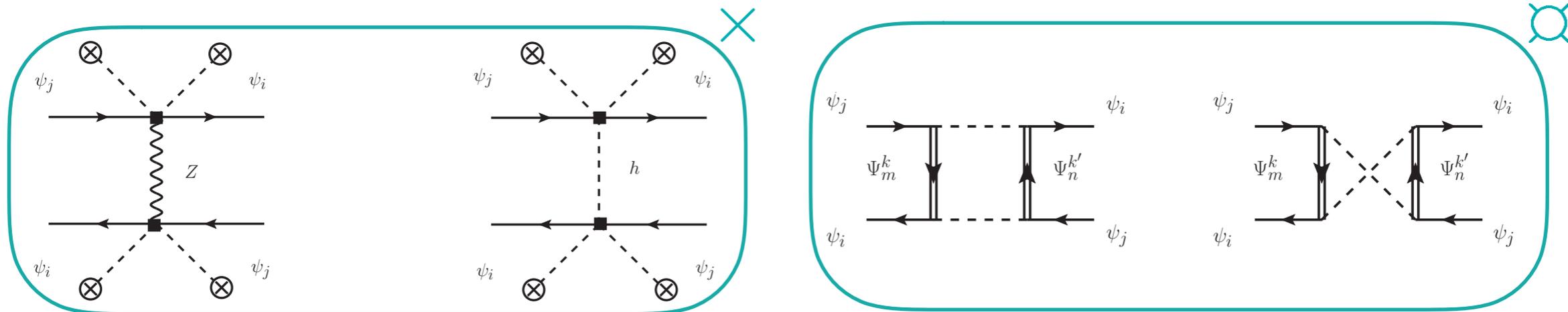
# Flavor constraints

Effects in flavor suppressed by zero mode overlaps

- similar to RS-GIM

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

- *Example:* neutral meson mixing  $[f_Q \sim (\lambda^3, \lambda^2, 1); f_u \sim (\lambda^4, \lambda, 1); f_d \sim (\lambda^4, \lambda^3, \lambda^2)]$



Process	$U$	$D$	$Q$	$UQ$	$DQ$
$B_s - \bar{B}_s$	$\lambda^4, \text{X}^*$	$\lambda^4, \text{X}$ and $\text{O}$	$\lambda^7, \text{X}^*$	$\lambda^7, \text{O}$	$\lambda^6, \text{X}$
$B - \bar{B}$	$\lambda^6, \text{X}^*$	$\lambda^6, \text{X}$ and $\text{O}$	$\lambda^9, \text{X}^*$	$\lambda^9, \text{O}$	$\lambda^8, \text{X}$
$K - \bar{K}$	$\lambda^{10}, \text{X}^*$	$\lambda^{10}, \text{X}$ and $\text{O}$	$\lambda^{12}, \text{X}^{*\dagger}$	$\lambda^{12}, \text{X}^\dagger$	$\lambda^{12}, \text{X}^\dagger$ and $\text{O}^\dagger$
$D - \bar{D}$	$\lambda^{10}, \text{X}$ and $\text{O}$	$\lambda^{10}, \text{O}$	$\lambda^{10}, \text{X}$ and $\text{O}$	$\lambda^8, \text{X}^\dagger$	$\lambda^{10}, \text{O}^\dagger$

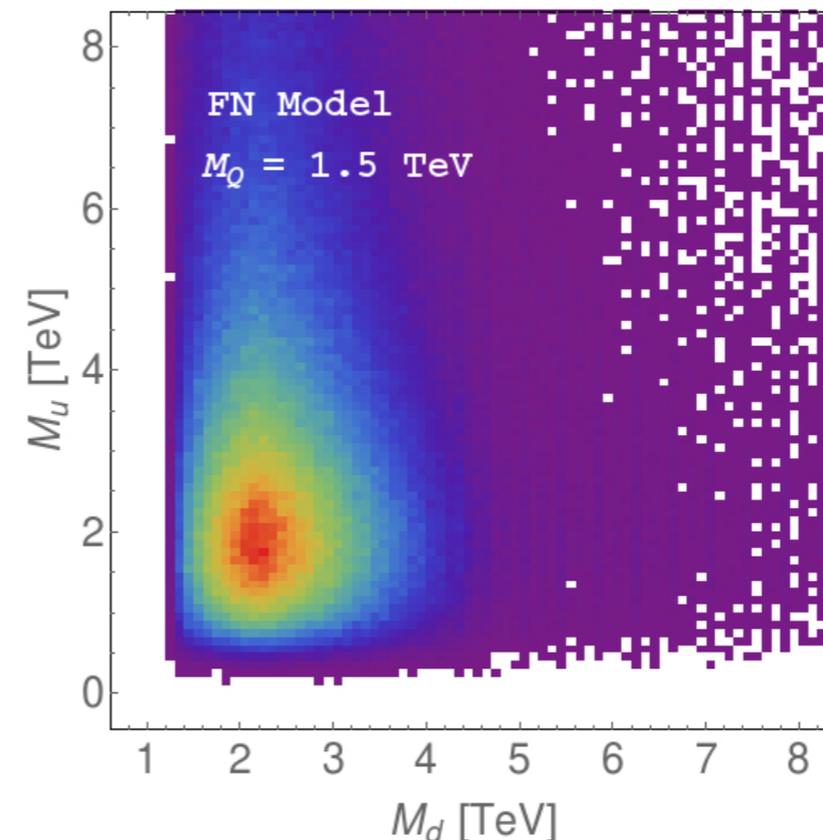
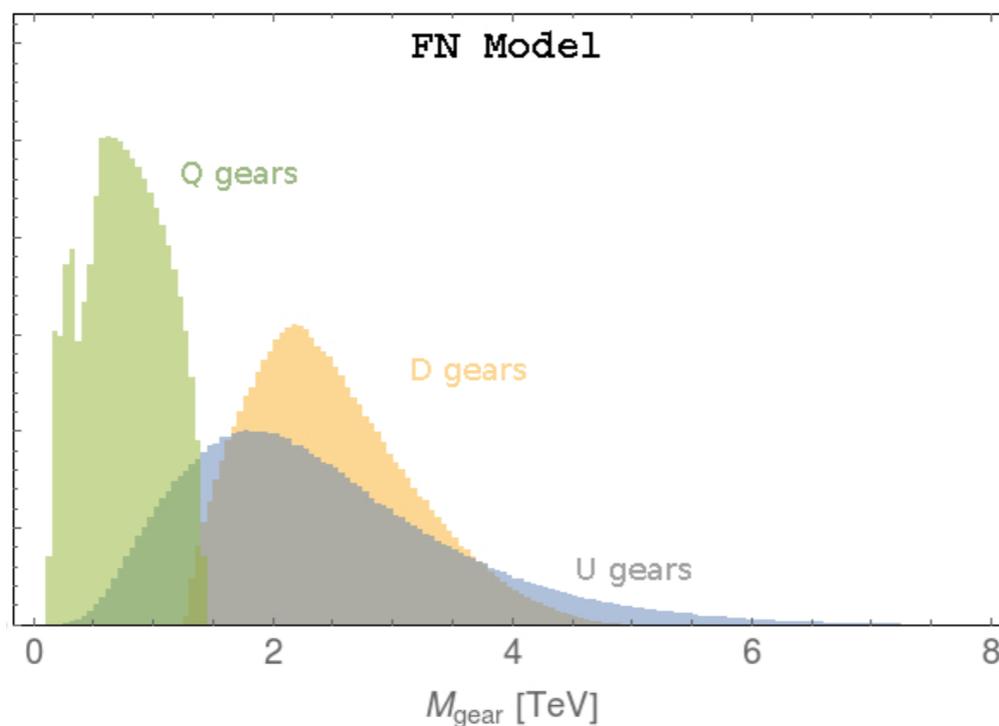
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see e.g. S. Davidson et al., 0711.3376

Mass & Yukawa parameter scan

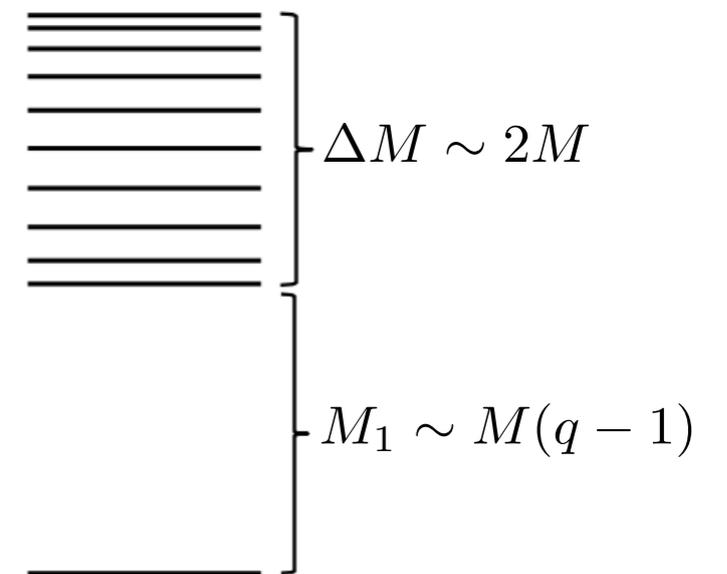




# LHC searches

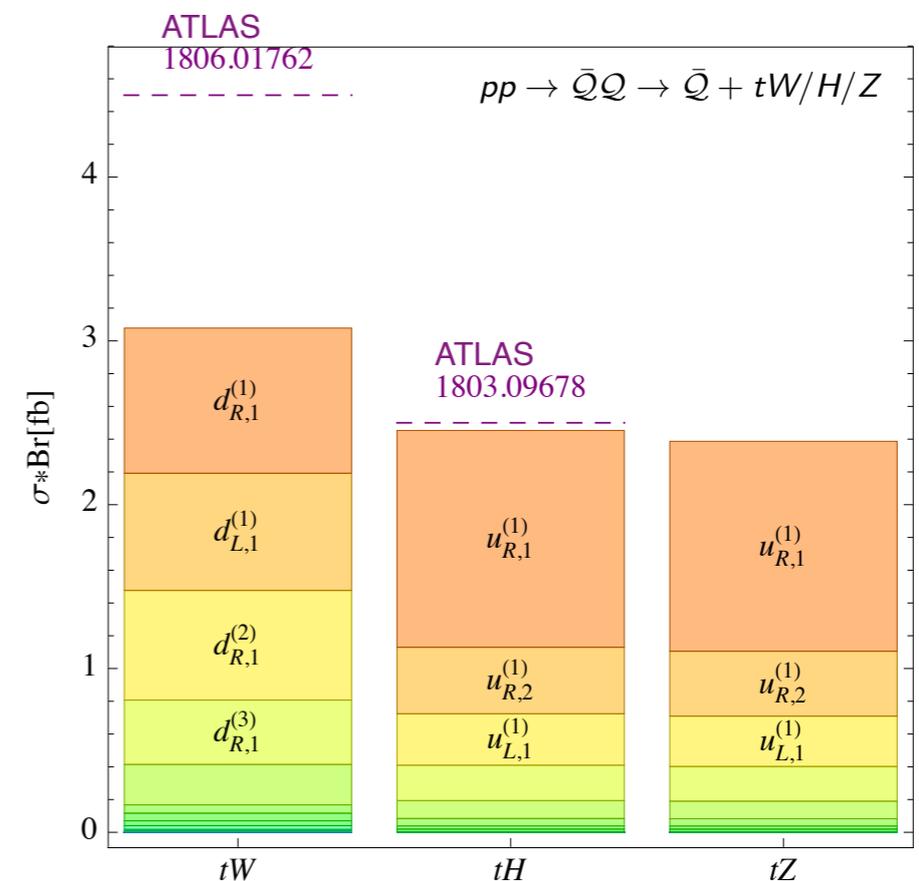
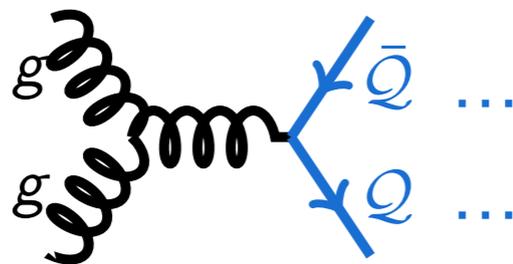
Clockwork flavor gears can be at  $O(\text{TeV})$

- small inter-gear mass gaps  $O(M/N)$
- decay  $Q \rightarrow Q' + h, Z, W; q + h, Z, W$



How to search for them at the LHC?

- Q gears QCD pair produced
  - multiple thresholds
- ➔ ‘effective’ VLQ x-section



# LHC searches

Clockwork flavor gears can be at  $O(\text{TeV})$

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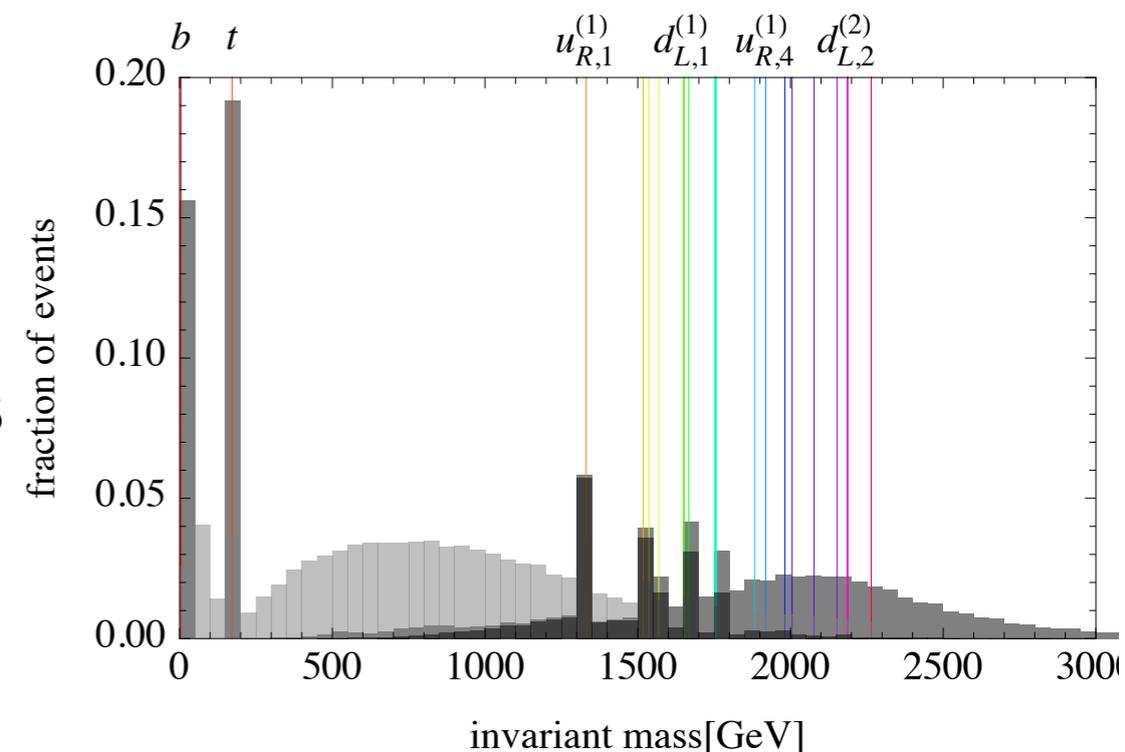
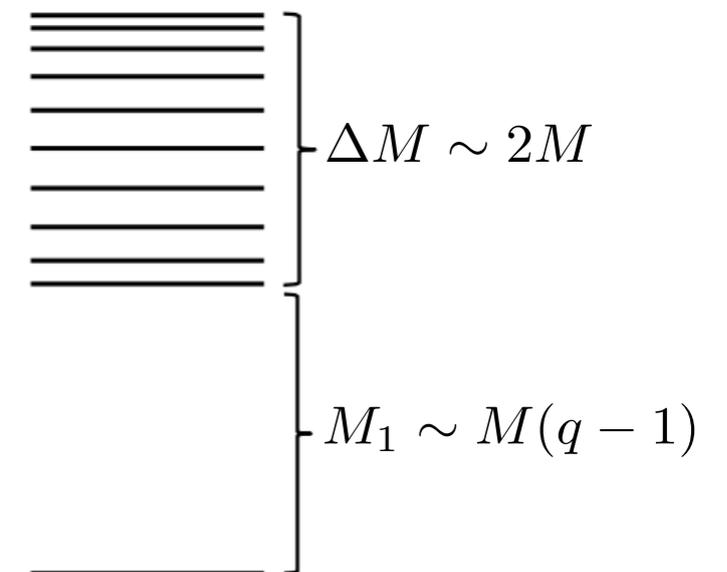
- Q gears QCD pair produced
- multiple thresholds
- ➔ disentangling long decay chains

modified 'hemisphere clustering'

see e.g. CMS-PAS-SUS-16-036

1502.04358

Sjostrand, Comput.Phys.Commun. 28 (1983) 229



# Conclusions

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## Model of flavor based on clockwork mechanism

- shares particularities with RS & FN
  - obstacles to continuum version
  - no elegant simultaneous solution for EW hierarchy
  - novel low energy limit of FN (/ flavon effects)
- effects in flavor physics under control for  $O(1\text{TeV})$  gears!
  - associated effects in Higgs & EW observables
  - gears can be searched for in high  $p_T$  processes
  - novel signatures of multiple VLQ decay chains

# Backup



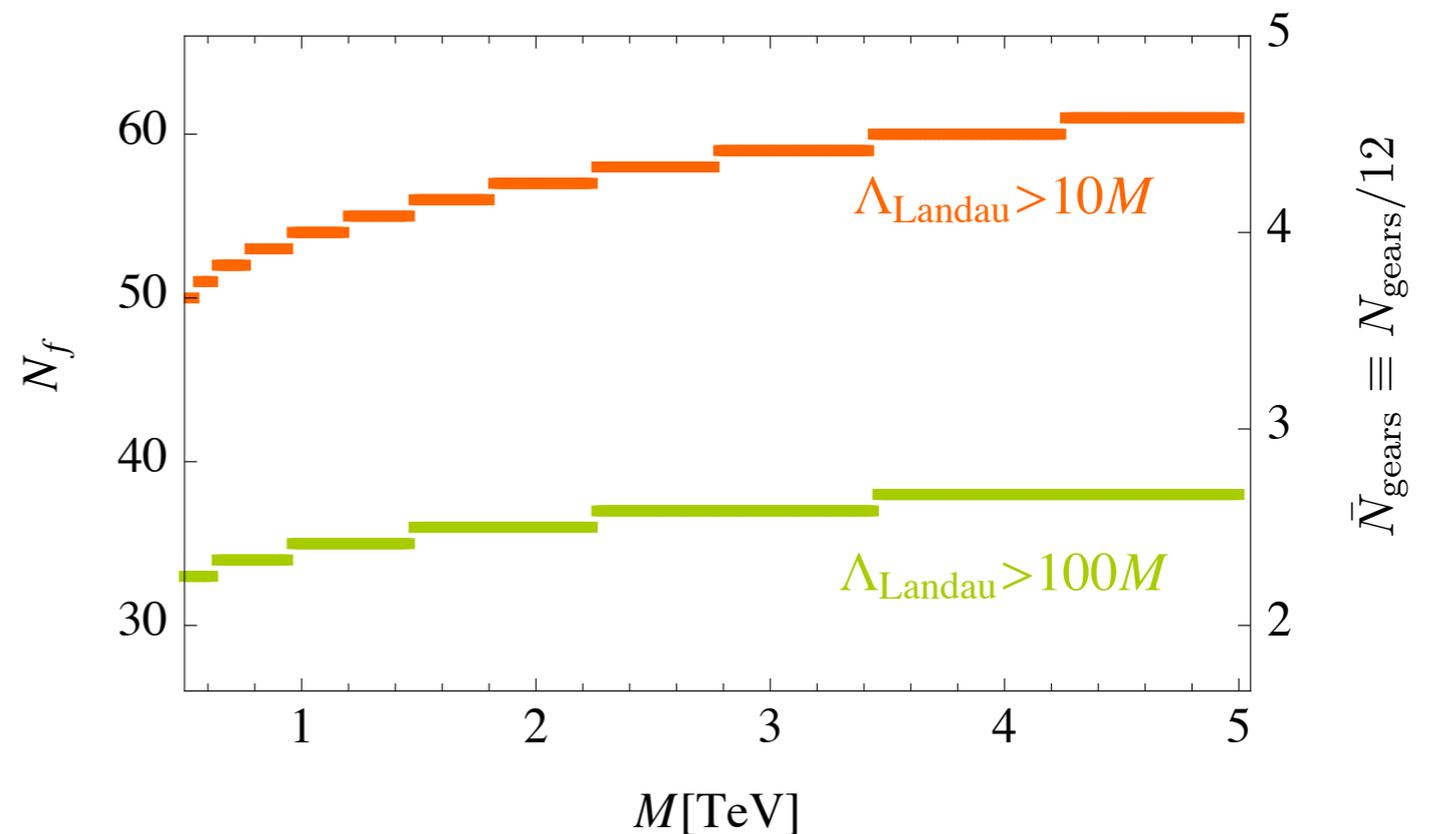
# Obstructions in the UV: QCD

Having a bunch of heavy quarks will affect the running of QCD coupling

- at 1-loop  $\frac{d\alpha_s}{d\ln\mu} = -2\beta_0 \frac{\alpha_s^2}{4\pi}, \quad \beta_0 = \frac{11N_c - 2N_f}{3},$
- for large number of gears, QCD develops Landau pole

$$\Lambda_{\text{Landau}} = M e^{\frac{-2\pi}{\alpha_s(M)\beta_0}}$$

$$N_f > 16 \quad (N_{\text{gears}} > 10)$$



# Obstructions in the UV: Higgs potential

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Gears have Yukawa couplings to the Higgs

- RG running of the quartic affected at 1-loop

$$\beta_\lambda \supset 12\text{Tr} \left( \tilde{Y}_U^\dagger \tilde{Y}_U + \tilde{Y}_D^\dagger \tilde{Y}_D \right) \lambda - 12\text{Tr} \left( \tilde{Y}_U^\dagger \tilde{Y}_U \tilde{Y}_U^\dagger \tilde{Y}_U + \tilde{Y}_D^\dagger \tilde{Y}_D \tilde{Y}_D^\dagger \tilde{Y}_D \right)$$

- possible destabilization of the potential for large  $Y_{U,D}$
- additional (scalar) d.o.f. contributions?  $\mathcal{L} \supset \lambda_S H^\dagger H \phi^2$

(On the other hand Higgs couplings to gluons, photons not affected)