Clockwork as a solution to the flavour puzzle

Rodrigo Alonso

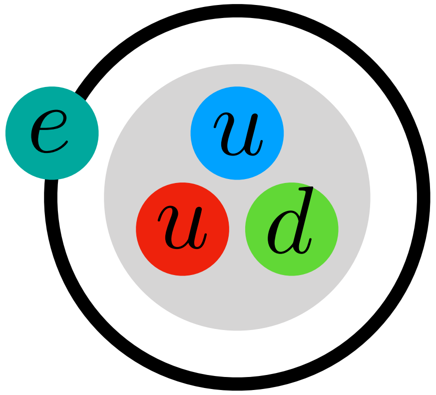
IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Beyond the BSM

02/10/2018

The Puzzle

...or who ordered ALL of that?



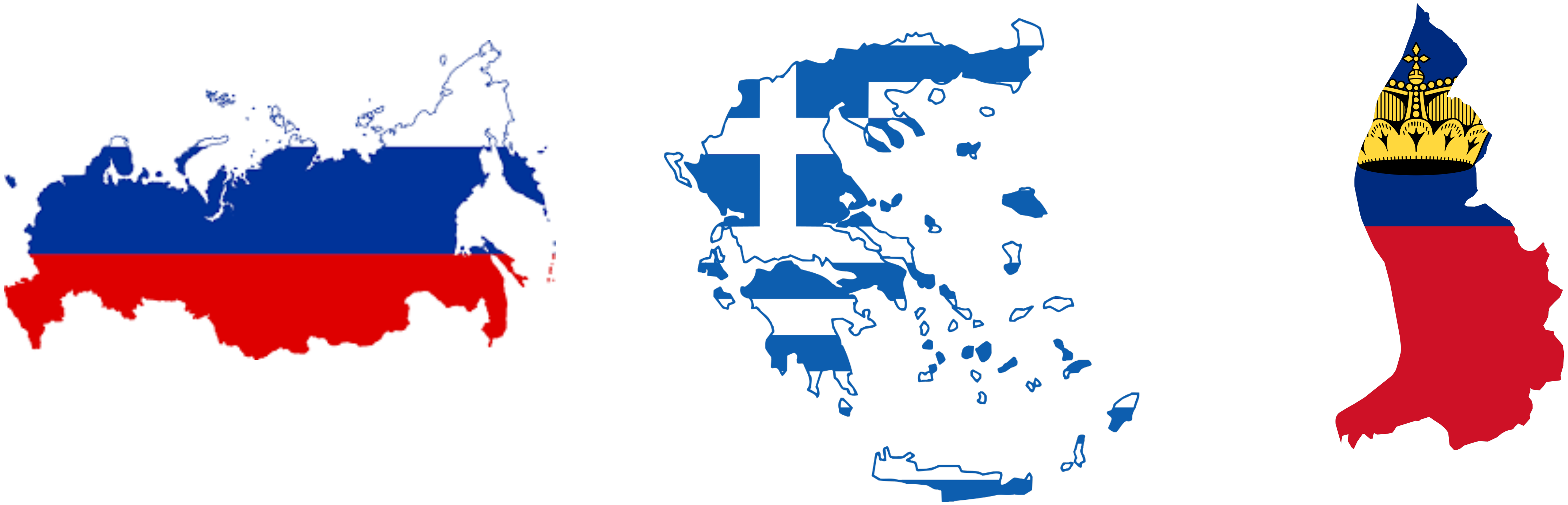
=US (you and I)

- ★ What are the other two generations for?
- ★ CP violation and the Baryon asymmetry of the universe?
- ★ SM cannot do BAU alone
and neutrinos can have CPV with 2 generations

The Puzzle

...or why are they all over the place?

$$\underset{\wr}{t} \qquad\qquad \underset{\wr}{c} \qquad\qquad \underset{\wr}{u}$$



Quarks

Leptons

$$V_{CKM} = \begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \qquad U_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & \sim 0.2 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

Our solutions thus far

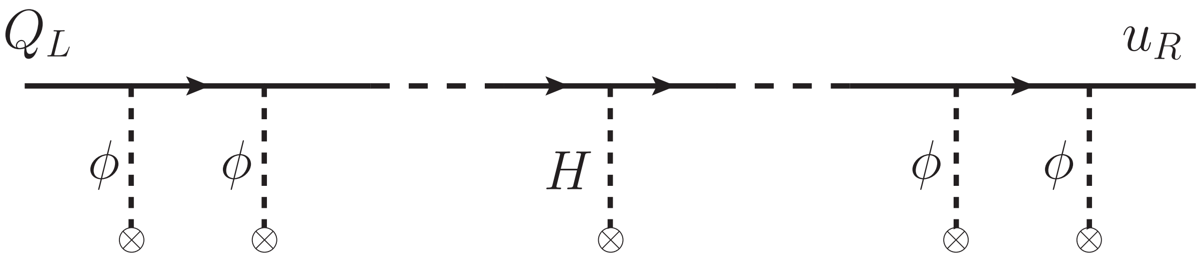
...or the narrow vision of a human

Symmetry

Froggatt-Nielsen

[Froggatt & Nielsen NPB147, '79]
[Anselm & Berezhiani NPB484, '96]
...

$$Y_{ij} \sim \left(\frac{\langle \phi \rangle}{\Lambda} \right)^{q_i + q_j}$$

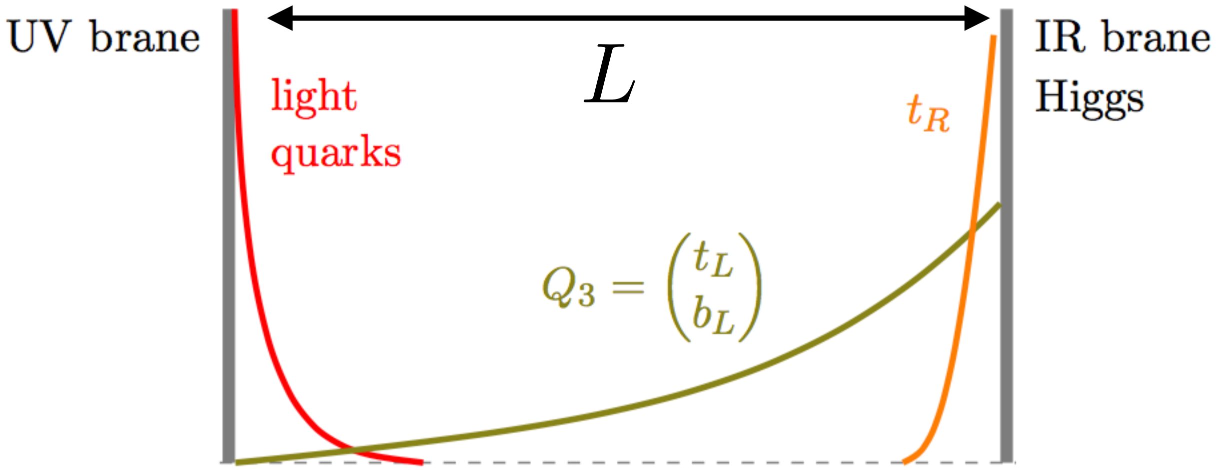


Localisation in Extra Dimension

Randall-Sundrum

[Randall & Sundrum PRL83, '99]
[Grossman & Neubert PLB474, '00]
...

$$Y_{ij} \sim e^{-(m_i + m_j)L}$$



https://raoulma.github.io/research/

The Clockwork mechanism

A nearest neighbor interaction that produces
a zero mode with exponentially small couplings

Scalars

[Choi & Im, JHEP1601, '16]
[Kaplan & Rattazzi PRD93, '16]

$$V = \lambda \left(\phi_N^* \phi_{N-1}^3 + \phi_{N-1}^* \phi_{N-2}^3 + \cdots + \phi_1^* \phi_0^3 \right)$$

	N	$N-1$	$N-2$	$\dots$	0
$U(1):$	1	$1/3$	$1/3^2$	$\dots$	$1/3^N$

$$\phi_j = (f + |\phi_j|) e^{i a_j / f}$$

The **last** link of the chain is coupled to an external sector

$$\frac{a_0}{f} G\tilde{G} \to \frac{a}{3^N f} G\tilde{G}$$

The Clockwork mechanism

Fermions

[Giudice & McCullough JHEP1702, '16]

$N + (N+1)$ **Weyl fermions, so one is massless**

$$-m \sum_{j=1}^{N} \left(\bar{\psi}_{L,j} \psi_{R,j} - q \bar{\psi}_{L,j} \psi_{R,j-1} \right)$$

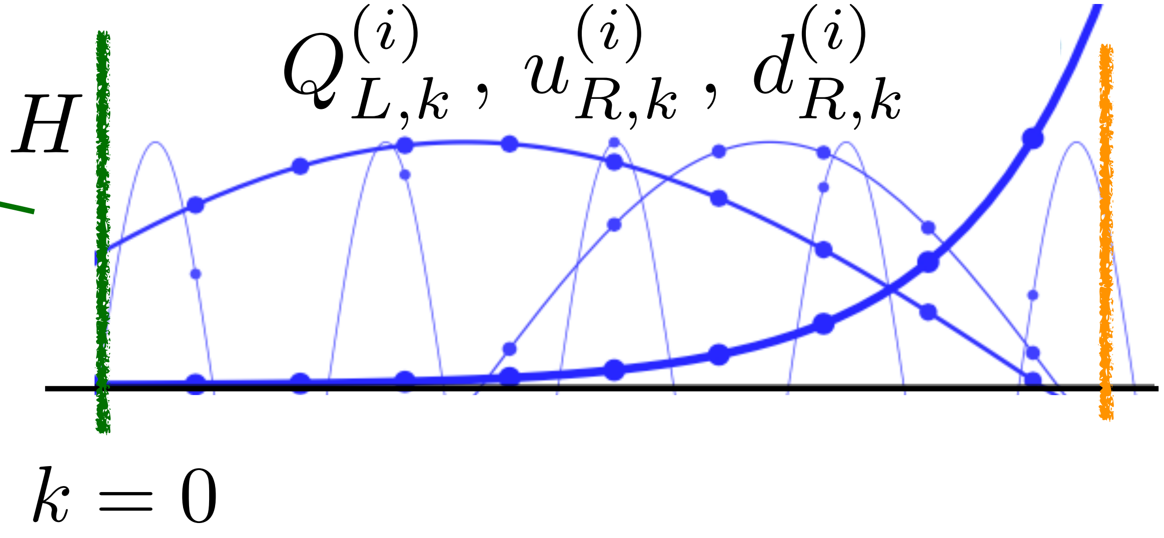
$$\begin{array}{cc} & \begin{array}{ccccc} \psi_{R,0} & & \cdots & & \psi_{R,N} \end{array} \\ \begin{array}{c} \bar{\psi}_{L,1} \\ \\ \vdots \\ \bar{\psi}_{L,N} \end{array} & m \begin{pmatrix} -q & 1 & 0 & \dots & 0 \\ 0 & -q & 1 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & -q & 1 \end{pmatrix} \end{array}$$

Zero mode

q>>1

$$\psi_R \simeq \sum_j \frac{1}{q^{N-j}} \psi_{R,j}$$

Clockworked flavour



$$(Y_D^0)_{ij}\,\bar{Q}^{(i)}_{L,0} H\, d^{(j)}_{R,0} + (Y_U^0)_{ij}\,\bar{Q}^{(i)}_{L,0}\tilde{H} u^{(j)}_{R,0}$$

We turn to the mass basis

$$Q^{(i)}_{L,0} = \frac{1}{q^{N_{Q(i)}}} Q^{(i)}_{L} + f^{k}_{Q(i)} (Q')^{(i)}_{L,k}$$

Same for u, d

$$Y_{ij} = q^{-N_{Q(i)}} Y^0_{ij} q^{-N_{u(j)}}$$

The zero modes have suppressed Yukawas!

[RA, Carmona, Camalich, Dillon, Kamenik, Zupan '18]

Clockworked flavour

Fermions

$$Y_{ij} = q^{-N_{Q(i)}} Y^0_{ij} q^{-N_{u(j)}}$$

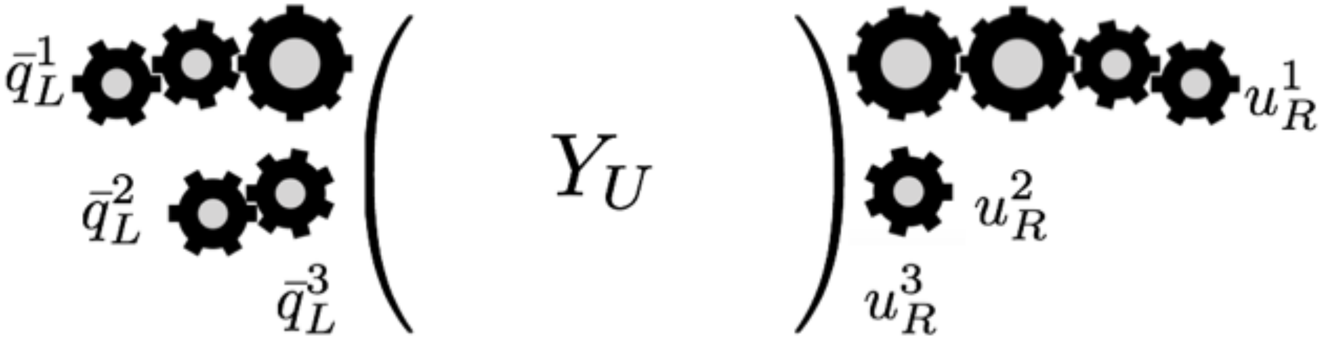
This hierarchical structure sets masses and mixings as familiar from RS

$$(V_{CKM})_{ij} \sim \frac{q^{N_{Q(j)}}}{q^{N_{Q(i)}}}\,, \quad i < j; \quad m_i \sim v\, q^{-N_{Q(i)}-N_{u(i)}}$$

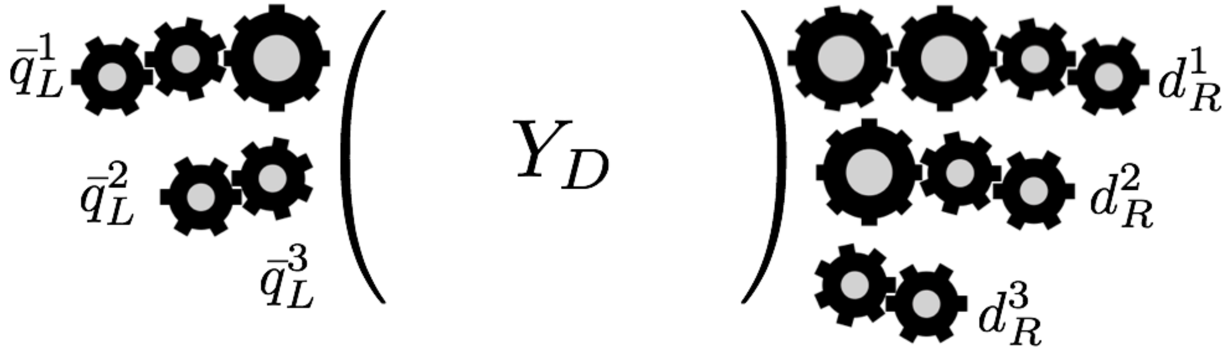
$$q \sim 1/\lambda \sim 5$$

So the natural choice of length for chains is:

Up type



Down type



Flavour phenomenology

The Flavour Gears

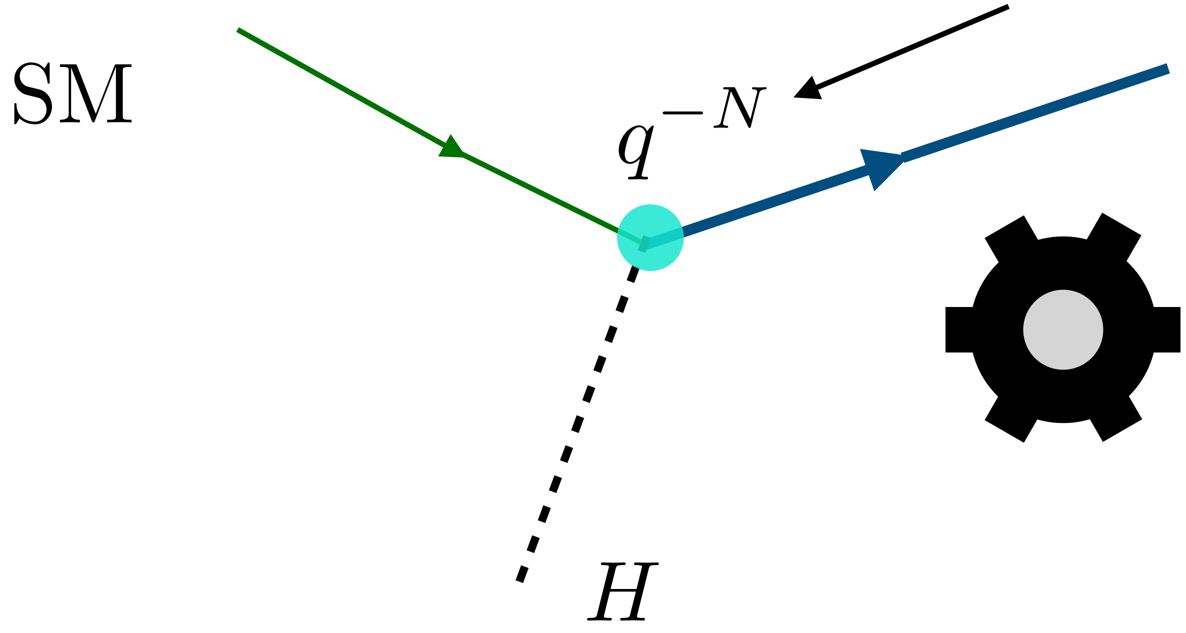
SM

$$+(Y_U^0)_{ij}\,\bar{Q}_L^{(i)}\,q^{-N_{Q(i)}}\,\tilde{H}\,f^k_{u(j)}\,u^{(j)}_{R,k}$$

$$+(Y_U^0)_{ij}\,\bar{Q}_{L,k}^{(i)}\,f^k_{Q(i)}\,\tilde{H}\,q^{-N_{u(j)}}\,u^{(j)}_R$$

SM

Flavour protection

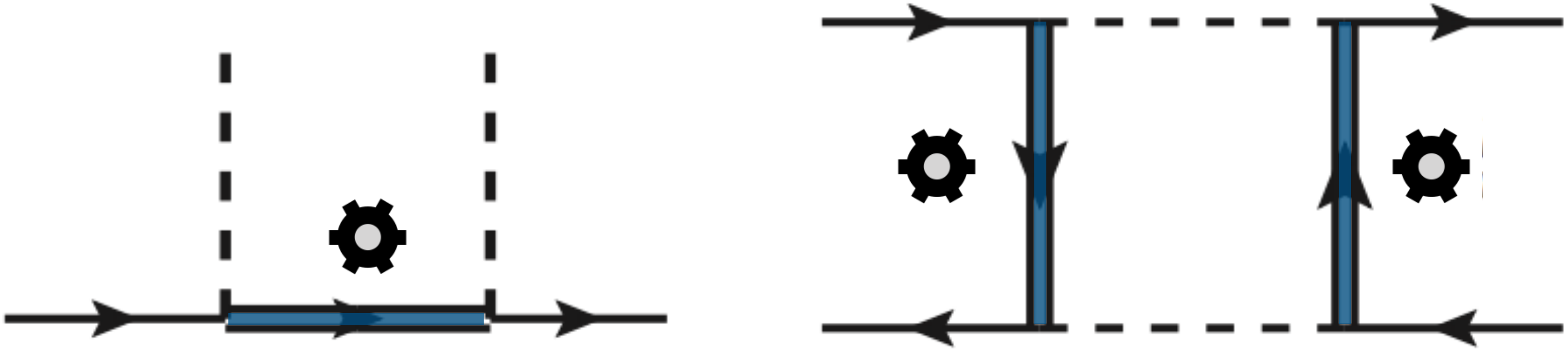


$$M_{\text{⚙}} \sim qm$$

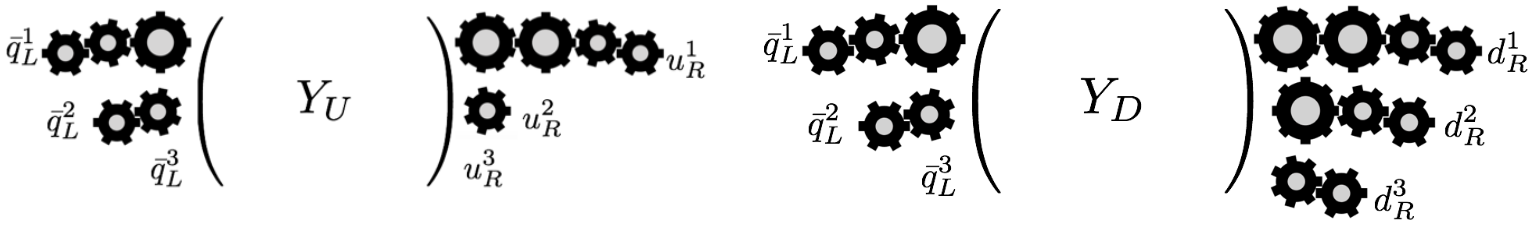
$$\Delta M_{\text{⚙}} \sim 2m$$

Flavour phenomenology

Low lying resonances.



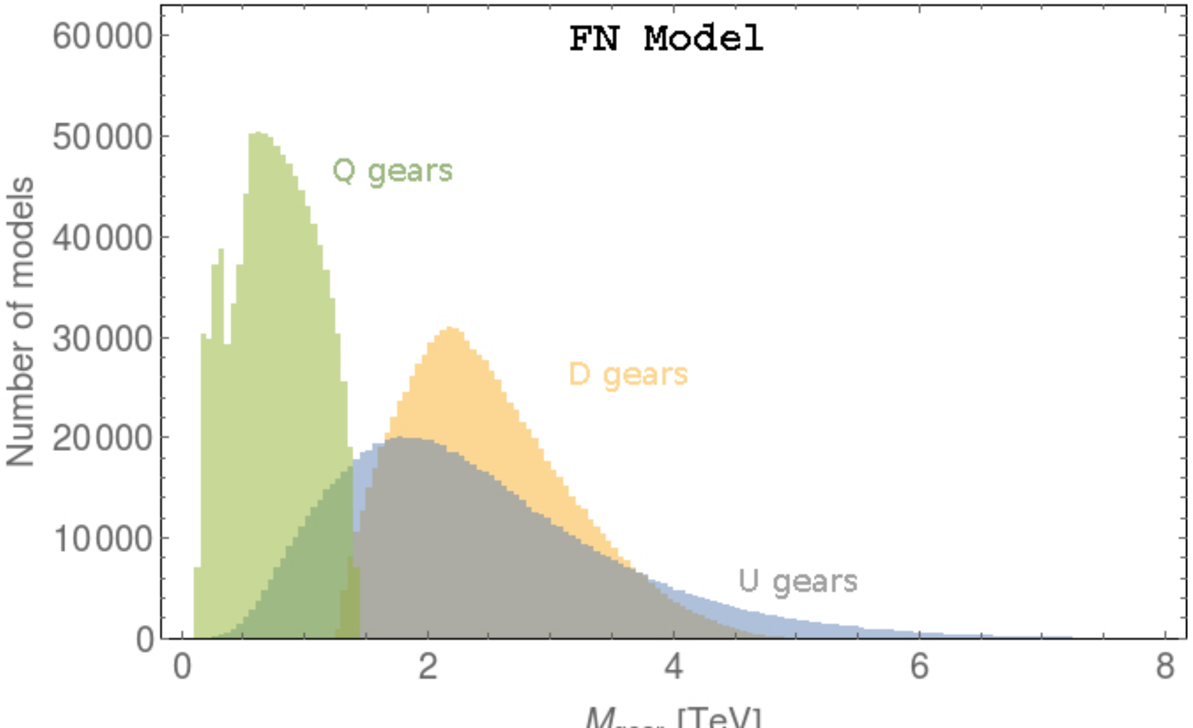
Qualitative understanding:



$d_{R,k}$ **Mediate d-type FCNC**
4TeV **suppressed by** q^{-N_Q}

$u_{R,k}$ **Mediate u-type FCNC**
0.5TeV **suppressed by** q^{-N_Q}

$Q_{L,k}$ **Mediate u,d-type FCNC**
0.5TeV **suppressed by** q^{-N_u}, q^{-N_d}



Gear production and decay

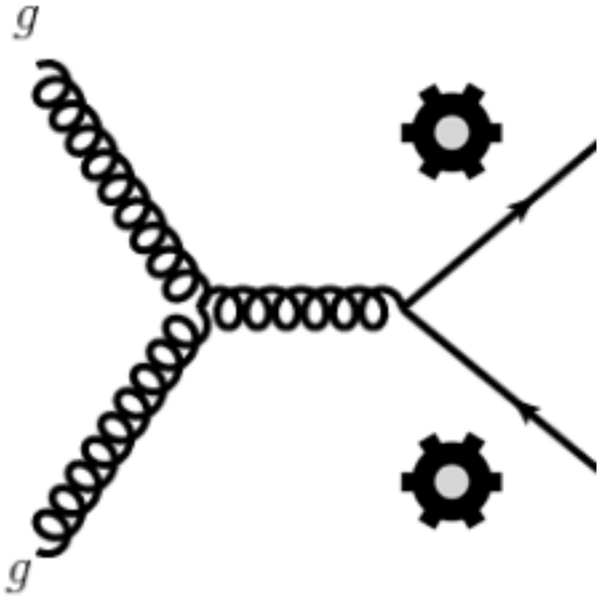
The Flavour Gears

SM

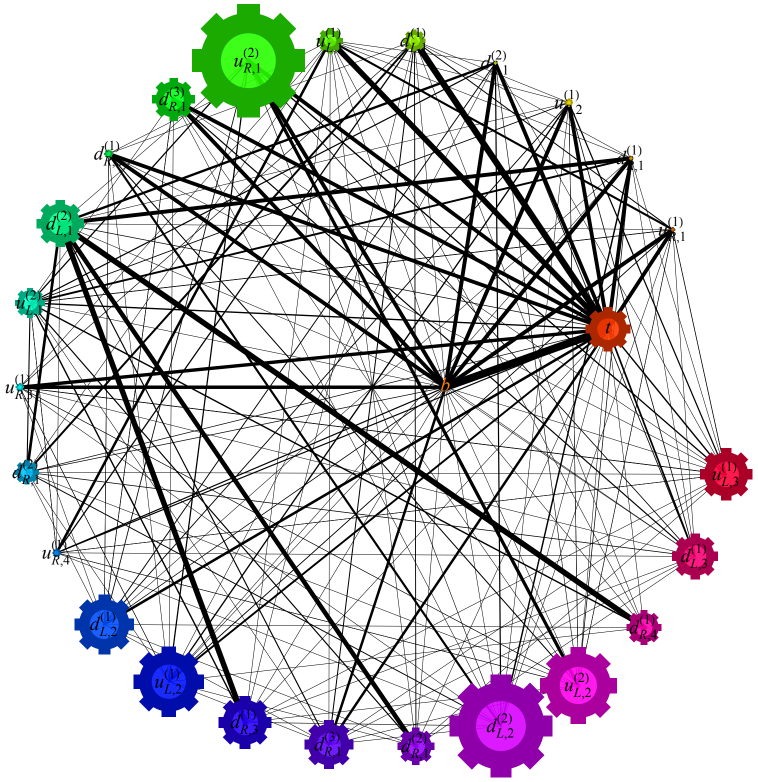
$$+(Y_U^0)_{ij}\,\bar{Q}_L^{(i)}\,q^{-N_{Q(i)}}\,\tilde{H}\,f^k_{u(j)}\,u^{(j)}_{R,k}$$

$$+(Y_U^0)_{ij}\,\bar{Q}^{(i)}_{L,k}\,f^k_{Q(i)}\,\tilde{H}\,q^{-N_{u(j)}}\,u_R^{(j)}$$

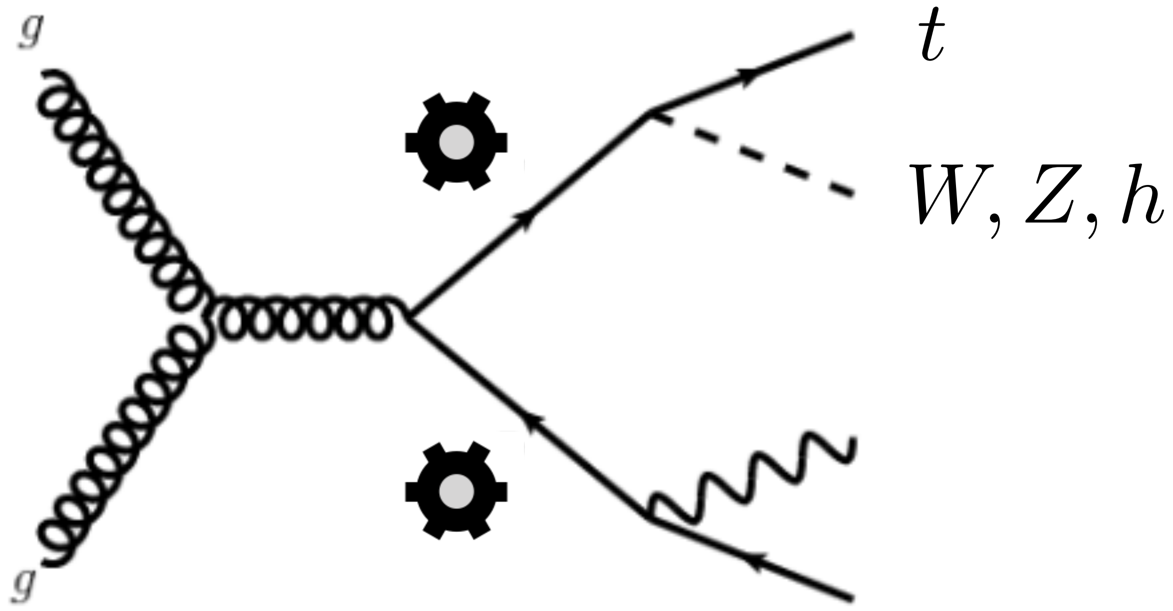
SM

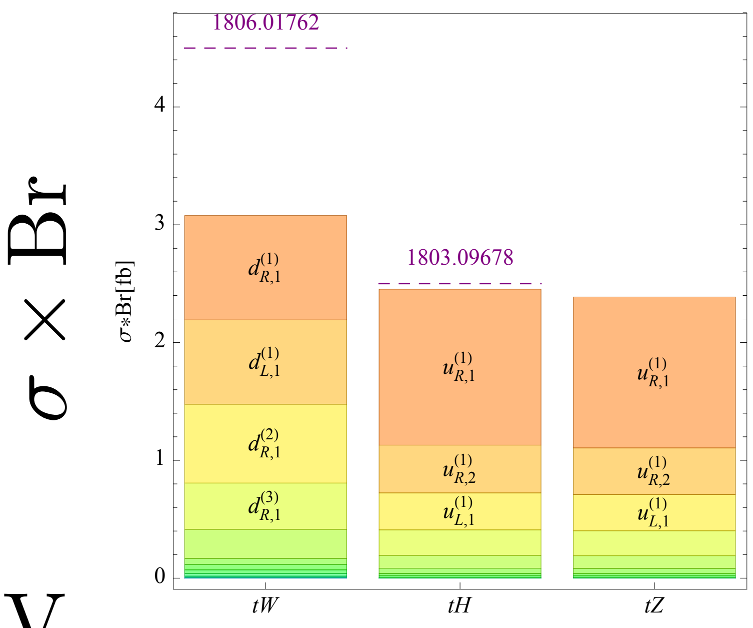


$$\partial_\mu + iG^a_\mu T_a$$

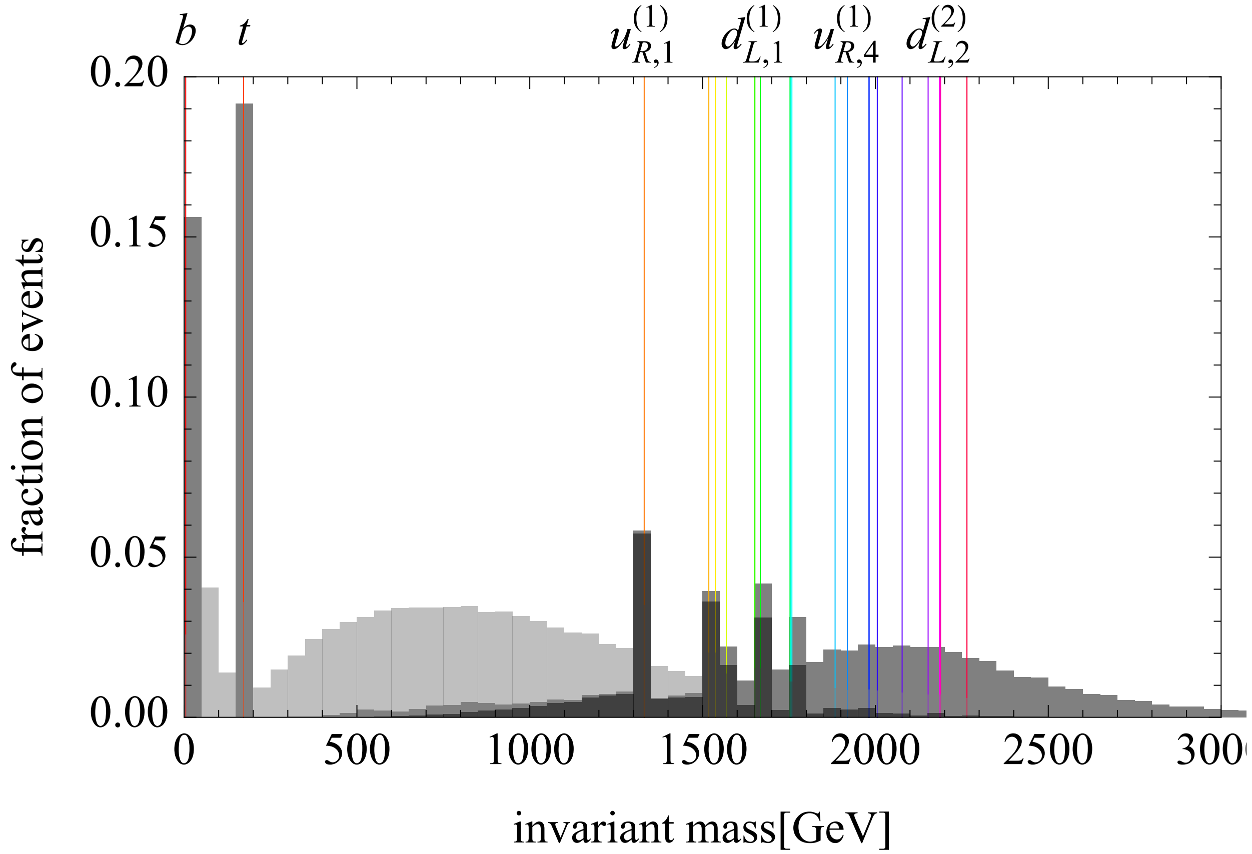


Collider phenomenology





$M_{⚙} > 1.3\text{TeV}$



Hemisphere Reconstruction

13TeV LHC

Symmetry origin and FN

Can we justify the fermion CW mass matrix with symmetry?

$$\begin{array}{ccc}
 & & \begin{array}{ccccc} \psi_{R,0} & \psi_{R,1} & & \cdots & \psi_{R,N} \end{array} \\
\begin{array}{c} \bar{\psi}_{L,1} \\ \\ \vdots \\ \\ \bar{\psi}_{L,N} \end{array} & m & \begin{pmatrix} -q & 1 & 0 & \dots & 0 \\ 0 & -q & 1 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & -q & 1 \end{pmatrix},
\end{array}$$

Symmetry origin and FN

Can we justify the fermion CW mass matrix with symmetry?

$$\begin{array}{cc} & \begin{array}{ccccc}\psi_{R,0} & \psi_{R,1} & \cdots & & \psi_{R,N}\end{array} \\ \begin{array}{c}\bar{\psi}_{L,1} \\ \\ \vdots \\ \bar{\psi}_{L,N}\end{array} & m\begin{pmatrix} -q & 1 & 0 & \dots & 0 \\ 0 & -q & 1 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & -q & 1 \end{pmatrix}, \end{array}$$

$(U(1)_V)^N$

$\times U(1)_{R,0}$

q bifundamental?

Need N q's

Symmetry origin and FN

Can we justify the fermion CW mass matrix with symmetry?

$$\begin{array}{ccc}
 & U(1)_H \quad \text{Charge} & \begin{array}{ccccc} 0 & 1 & 2 & \cdots & N \\ \psi_{R,0} & \psi_{R,1} & & \cdots & \psi_{R,N} \end{array} \\
\begin{array}{cc} \text{Charge} & \\ 1 & \bar{\psi}_{L,1} \\ \vdots & \vdots \\ N & \bar{\psi}_{L,N} \end{array} & m & \begin{pmatrix} -q & 1 & 0 & \dots & 0 \\ 0 & -q & 1 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & -q & 1 \end{pmatrix}, \nwarrow q^*
\end{array}$$

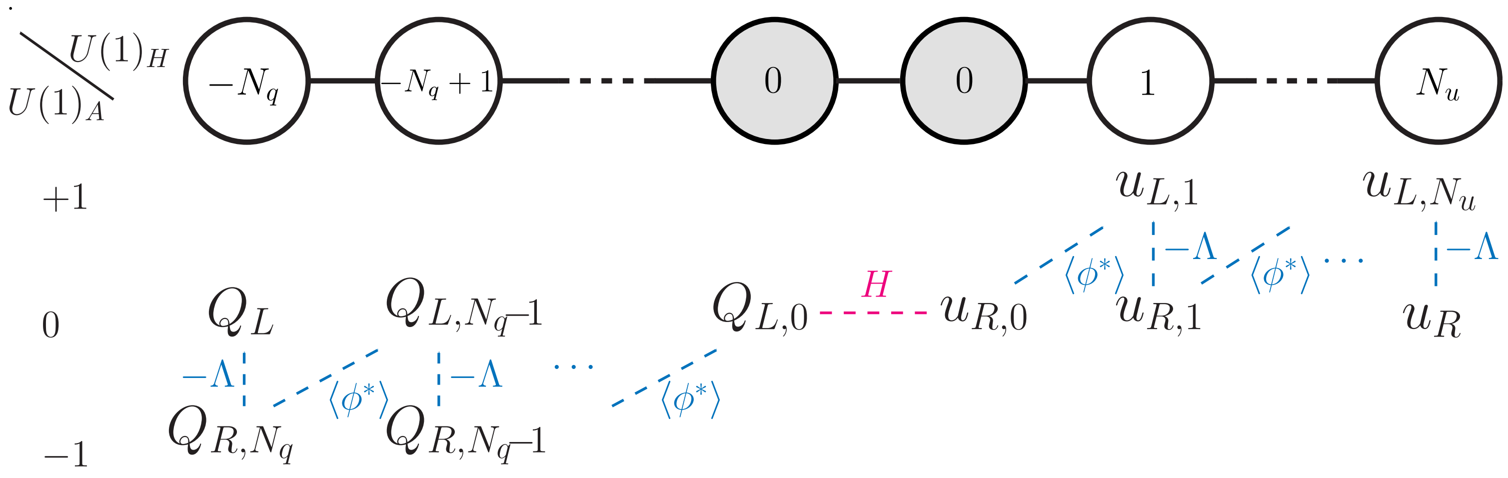
$$\boxed{\langle\phi\rangle = qm}$$

$$(Y_u^{\mathrm{SM}})_{ij} \sim \left(\frac{\Lambda}{\langle\phi^*\rangle}\right)^{N_{Q(i)}+N_{u(j)}}$$

Symmetry origin and FN

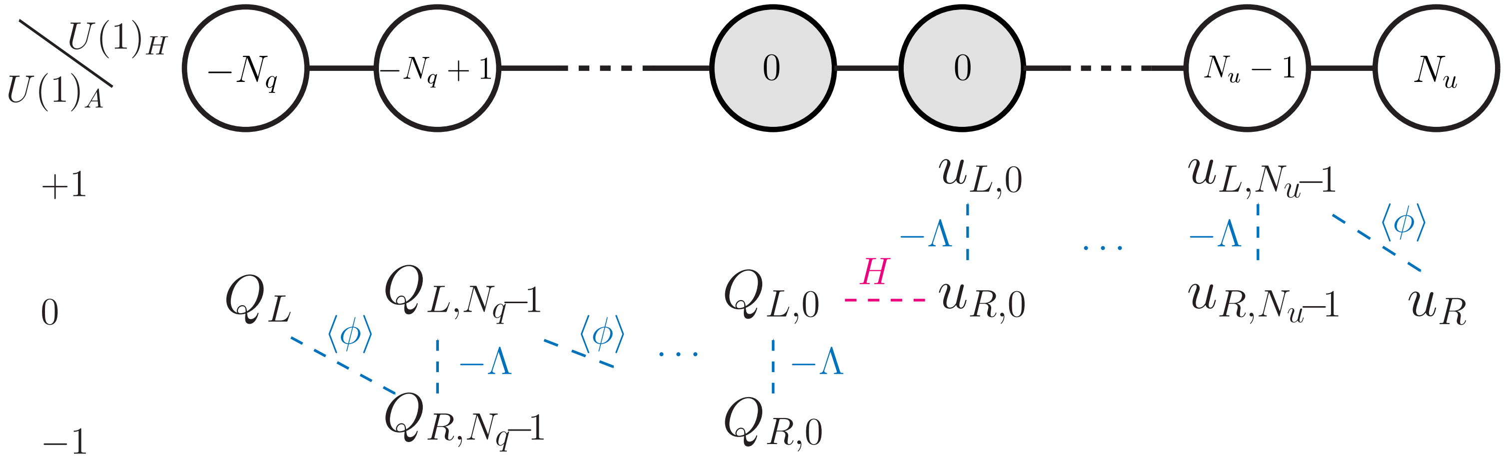
Is it different really?

CW



$$(Y_u^{\rm SM})_{ij} \sim \left(\frac{\Lambda}{\langle\phi^*\rangle}\right)^{N_{Q(i)}+N_{u(j)}}$$

FN



$$(Y_u^{\rm SM})_{ij} \sim \left(\frac{\langle\phi\rangle}{\Lambda}\right)^{N_{Q(i)}+N_{u(j)}}$$

Summary

- Flavour is an outstanding and longstanding puzzle
- Symmetry might once again illuminate our path
- FN = CW with a twist
- What is more, the models presented here aimed at addressing flavour do not suffer from the flavour problem

$$\overline{m}_u \sim \lambda^7,\, \overline{m}_c \sim \lambda^3,\, \overline{m}_t \sim 1, \qquad \overline{m}_d \sim \lambda^7,\, \overline{m}_s \sim \lambda^5,\, \overline{m}_b \sim \lambda^2,$$

Trying

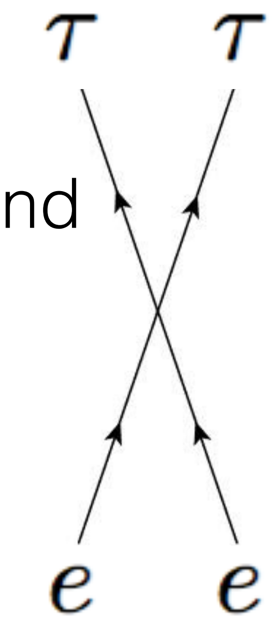
Spurion Analysis: MFV

bounds on 4 fermion Ops

MLFV

$$\bar{e}_R\gamma_\mu Y_e Y_e^\dagger e_R(\bar{e}_R\gamma_\mu e_R)$$

$$\|Y_e\|^2\frac{m_\alpha^2}{\sum m^2}\delta_{\alpha\beta}\delta_{\kappa\rho}\left(\bar{e}_R^\alpha\gamma_\mu e_R^\beta\right)\left(\bar{e}_R^\kappa\gamma^\mu e_R^\rho\right)$$

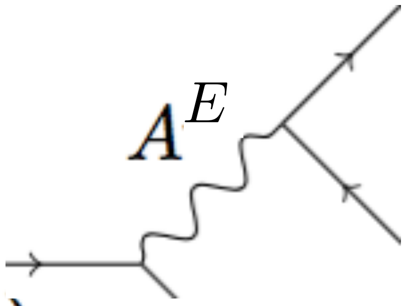


LEP Bound
~TeV

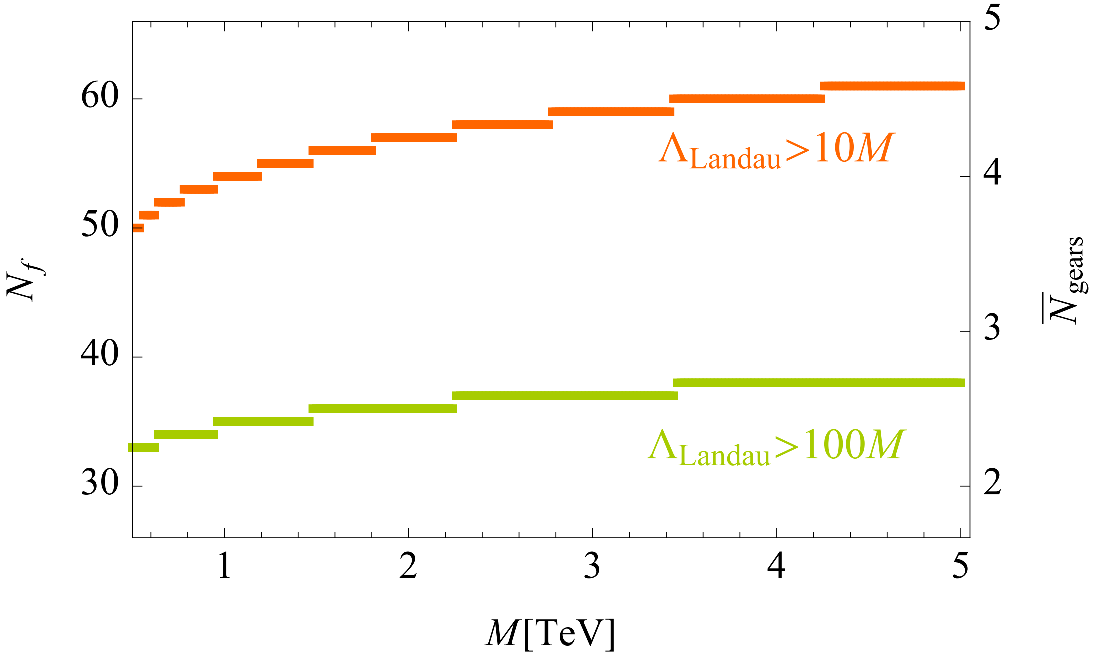
GLF

$$M_{A_\mu^E}^2\sim\mathcal{Y}_E^2\sim Y_e^{-2}$$

$$\frac{\delta_{\alpha\rho}\delta_{\beta\kappa}}{\sum m^2}\frac{m_\alpha^2 m_\kappa^2}{(m_\alpha^2+m_\kappa^2)}\|Y_e\|^2\left(\bar{e}_R^\alpha\gamma_\mu e_R^\beta\right)\left(\bar{e}_R^\kappa\gamma^\mu e_R^\rho\right)$$



Better Flavor Screening!



$$\beta_\lambda \supset 12\mathrm{Tr}\left(Y_U^\dagger Y_U + Y_D^\dagger Y_D\right)\lambda - 12\mathrm{Tr}\left(Y_U^\dagger Y_U Y_U^\dagger Y_U + Y_D^\dagger Y_D Y_D^\dagger Y_D\right)$$