Radiative Origin of Fermion Masses in Latticized Theory Space

Based on: arXiv: 2601.10316

Presented by:

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Outline

- Introduction

- Fermion mass hierarchies from latticized theory space: Anderson chain

- The radiative mechanism with Anderson chain

Based on: arXiv: 2601.10316

- Radiative Anderson vs Chain mass model

- Summary

The Flavor problem

Recent reviews: Feruglio (2015), Altmannshofer et al.(2025)

- Large hierarchies in fermion mass spectrum

  - In the SM, the masses varies $10^{-6} \sim 1$ in EW scale
  - The quark mixings are hierarchical, but lepton mixings are anarchic

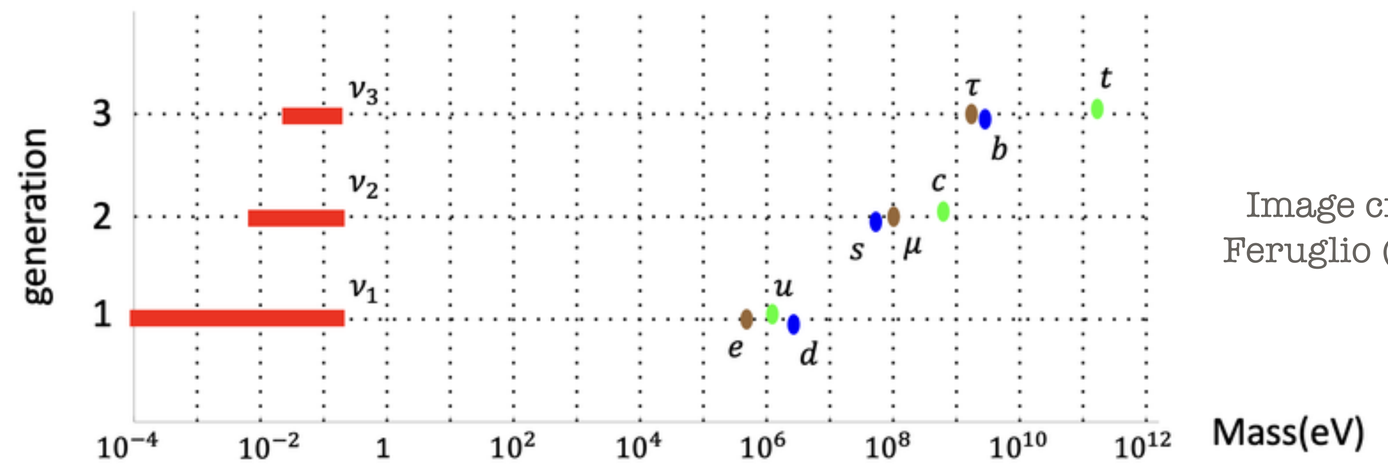


Image credit: Feruglio (2015)

- In the limit $Y = 0$, the action has enhanced global symmetry $[U(3)]^5$: masses are Technical natural parameters. Still, approximate flavor symmetries implies, existence of UV physics

- The incalculable parameters :

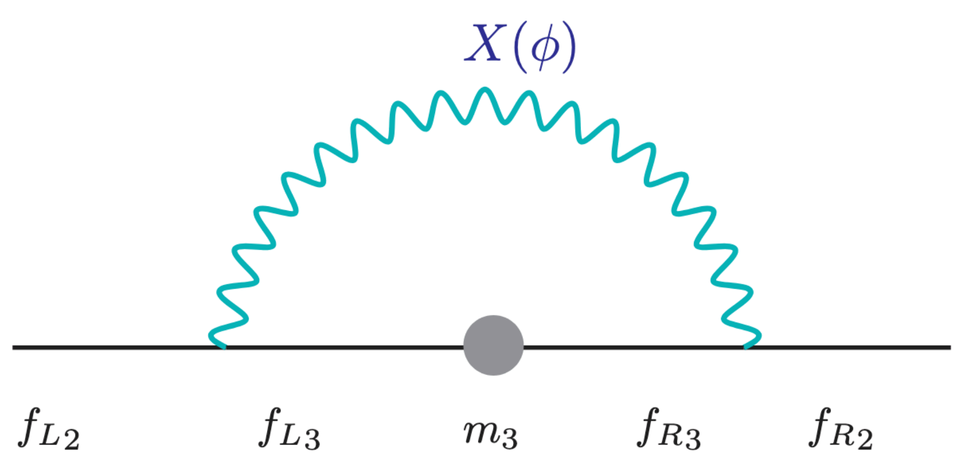
$$-\mathscr{L}_y = Y_i^u \bar{Q}_{Li} \tilde{H} u_{Ri} + Y_{ij}^d \bar{Q}_{Li} H d_{Rj} + Y_i^e \bar{L}_{Li} H e_{Ri} + h.c$$

  - 19 unknown real parameters in the unbroken phase

    In 2506.06423, some of the Yukawa are constrained through inequalities

Possible Explanation

- The well known theories of flavor: FN mechanism, Extra-dimensions, Clockwork mechanism etc, explains the flavor hierarchies, but not the computability
- The radiative mass generation mechanism: Mass generation through quantum corrections can explain both of these issues



- At the tree-level only third generation fermions are massive, fermion self-energy corrections induces mass for light fermions
- Loop suppression $\frac{1}{16\pi^2}$ explains the intergenerational hierarchy; Masses becomes partially computable parameters

Weinberg (1972), Georgi et al. (1973), Mohapatra (1974), Zee & Barr (1978)..
Balakrishna & Mohapatra (1988),....

- Flavor violating couplings with BSM particles X or ϕ are necessary

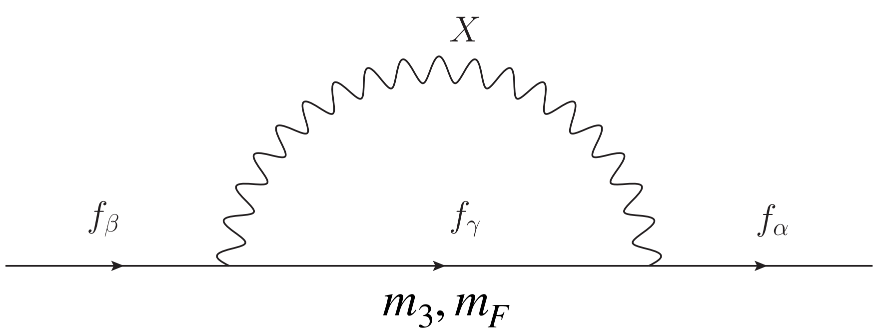
B. A Dobrescu & P.J. Fox (2008), Weinberg (2020), Jana et al. (2022,2024), Mohanta & Patel (2022,2023,2024,2025), Bonila et al.(2023)...

Radiative mechanism In gauge extensions

- Consider a toy framework with $f_{L\alpha}, f_{R\alpha}$ as chiral fermions and $F_{L,R}$ as VL fermions

$$(\mathscr{M})_{4\times 4} = \begin{pmatrix} 0 & \mu_L \\ \mu_R & M_F \end{pmatrix} \implies M^{(0)}_{ij} = -\frac{\mu_{Li}\mu_{Rj}}{M_F}; \qquad \text{Rank } = 1$$

- Flavor non-universal gauge interactions induces masses for the lighter fermions



$$(\delta M)_{ij} = \frac{{g_X}^2}{4\pi^2} q_{Li}\, M^{(0)}_{ij} q_{Rj} \left(B_0[M_X, m_3] - B_0[M_X, m_F]\right)$$

- For abelian extensions, at 1-loop level, only second generation fermions get mass
- Higher order corrections or Non-abelian gauge extensions can induce first generation mass

Mohanta & Patel (2022,2023,2024,2025)

- The phenomenologically allowed lowest new physics is $\gtrsim 10^{2-3}$ TeV
  - Experimental verification is beyond our reach
  - Higgs mass naturalness

Hierarchies from Theory space

PHYSICAL REVIEW LETTERS **120,** 221802 (2018)

Exponential Hierarchies from Anderson Localization in Theory Space

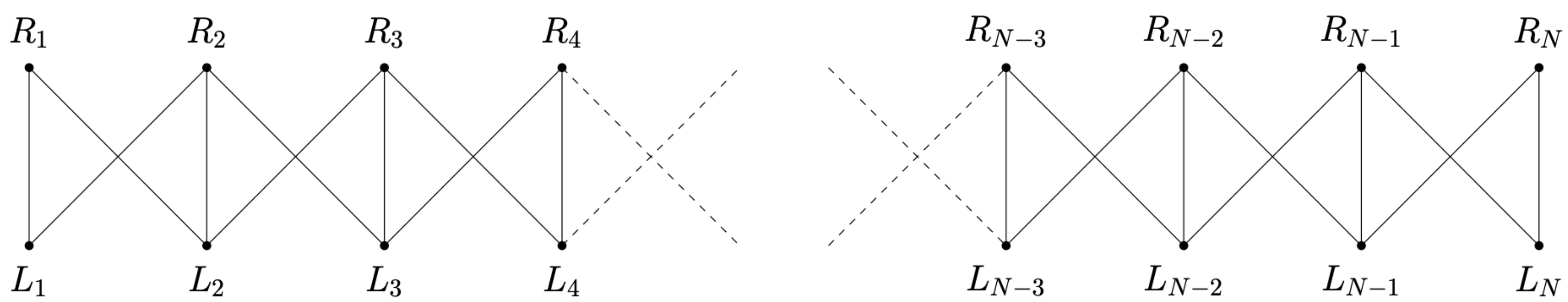
Nathaniel Craig[*] and Dave Sutherland[†]
Department of Physics, University of California, Santa Barbara, California 93106, USA

(Received 23 October 2017; published 30 May 2018)

- Anderson localization in theory space

$$M_{ij} = \epsilon_i \, \delta_{ij} + t \, (\delta_{i+1,j} + \delta_{i,j+1})$$

$\epsilon_i = [0, \text{W}]$, Disorder parameter, $G = \Pi_i^N U(1)_i$



- The form of M leads to exponential localization of the mass eigenstates
- There are no massless modes for the chain fields

N. Craig et al, (2018)

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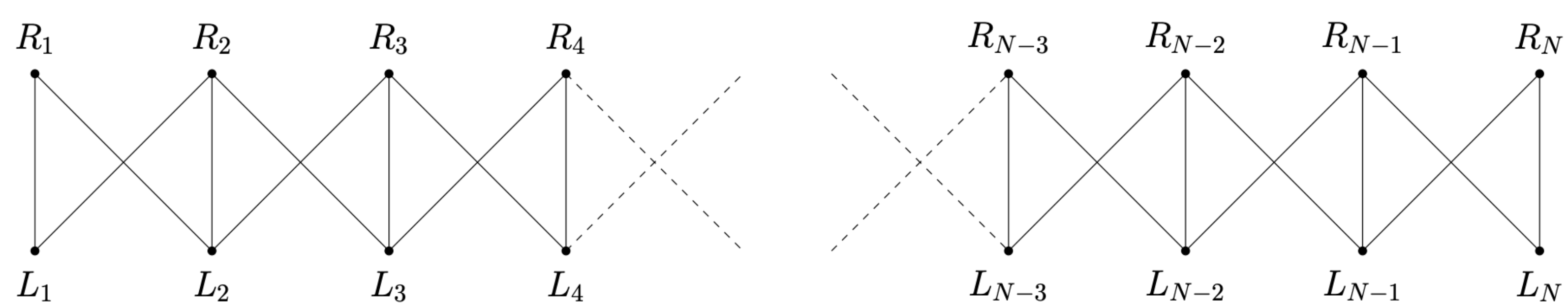

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- There are no massless modes for the chain fields

- Application: Anderson Partial compositeness

$$\mathcal{L} \supset -M_f(\eta_q^i \bar{q}^i Q^i + \eta_u^i \bar{u}^i U^i + \eta_d^i \bar{d}^i D^i + \bar{Q}^i Q^i + \bar{U}^i U^i + \bar{D}^i D^i) - Y_u^{ij} \bar{Q}^i \tilde{H} U^j - Y_d^{ij} \bar{Q}^i H D^j + \text{H.c.},$$

n_q^i, n_u^i, n_d^i are drawn from exponential profile of a localized scalar

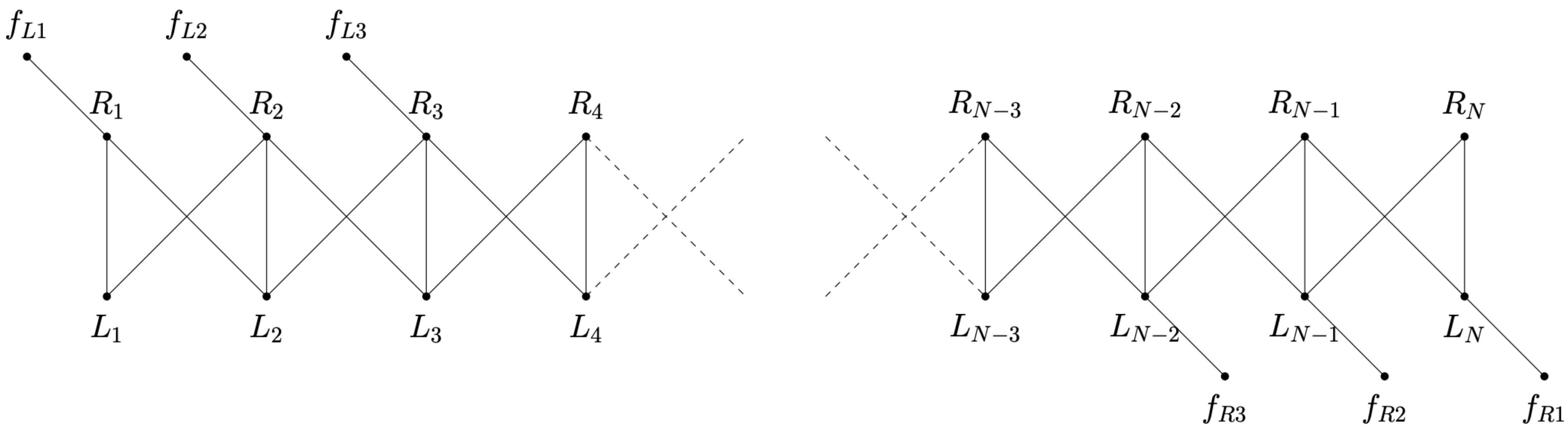
N. Craig et al, (2018)

RANK 1 FROM ANDERSON CHAIN

K. Patel, (2025)

- Consider a toy framework with $f_{L\alpha}$, $f_{R\alpha}$ as chiral fermions and L_i, R_i as lattice fermions (VL)

$$-\mathscr{L}_m = \sum_{\alpha=1}^{N_f} \left(\mu_\alpha \bar{f}_{L\alpha} R_\alpha + \mu'_\alpha \overline{L}_{(N+1-\alpha)} f_{R\alpha}\right) + \sum_{i,j=1}^{N} M^{(0)}_{ij} \overline{L}_i R_j + \text{h.c.}.$$



- The localization leads to massless modes

$$\mathscr{M}^{(0)} = \begin{pmatrix} (0)_{N_f\times N_f} & (\mu)_{N_f\times N} \\ (\mu')_{N\times N_f} & (M^{(0)})_{N\times N} \end{pmatrix}$$

$$\text{Rank}(\mathcal{M}) = \begin{cases} 2N_f & \text{for } N_f \le N < (2N_f - 1)\,, \\ N+1 & \text{for } N \ge (2N_f - 1)\,. \end{cases}$$

- The effective mass matrix $\quad m^{(0)}_{\text{eff}} \simeq -\,\mu\, M^{(0)^{-1}} \mu' \quad$ Rank $(m^{(0)}_{\text{eff}}) = 1$ for $N \ge 5$

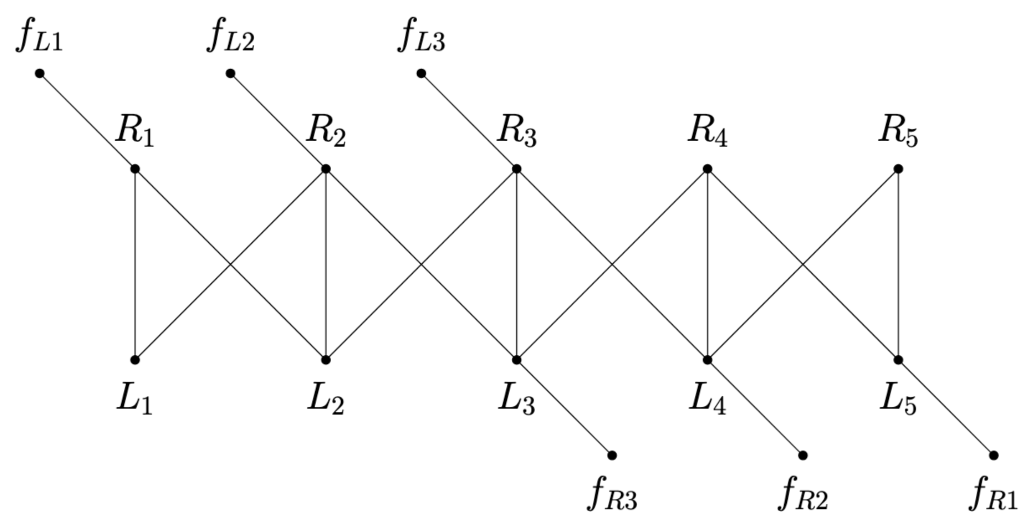
- The non-local effects can be introduced through additional interactions

K. Patel, (2025)

Loop induced Non-locality

- We choose $N_f = 3$ and $N = 5$

G. Mohanta & K. Patel, (2026)



$$\mu = \begin{pmatrix} \mu_1 & 0 & 0 & 0 & 0 \\ 0 & \mu_2 & 0 & 0 & 0 \\ 0 & 0 & \mu_3 & 0 & 0 \end{pmatrix}, \quad \mu' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \mu'_3 \\ 0 & \mu'_2 & 0 \\ \mu'_1 & 0 & 0 \end{pmatrix}, \quad \text{and} \quad M^{(0)} = W \begin{pmatrix} 1 & t & 0 & 0 & 0 \\ t & 1 & t & 0 & 0 \\ 0 & t & 1 & t & 0 \\ 0 & 0 & t & 1 & t \\ 0 & 0 & 0 & t & 1 \end{pmatrix}.$$

$$m_{\text{eff}}^{(0)} \simeq -\mu\, M^{(0)^{-1}} \mu'$$

$$m_1 = m_2 = 0, \quad m_3 \neq 0$$

- The non-locality can be induced if the chain have additional interactions with massive gauge bosons

$$-\mathscr{L}_X = g_X q \left(\overline{L}_i \gamma^\mu L_i + \overline{R}_i \gamma^\mu R_i \right) X_\mu$$

- The self-energy corrections to the lattice fermions

$$\delta M_{ij}^{(0)} = \frac{g_X^2 q^2}{12\pi^2} (-1)^{i+j} \sum_{k=1}^{5} \sin\left(\frac{ik\pi}{6}\right) \sin\left(\frac{jk\pi}{6}\right) m_k^{(0)}\, b_0[M_X^2, |m_k^{(0)}|^2]\,.$$

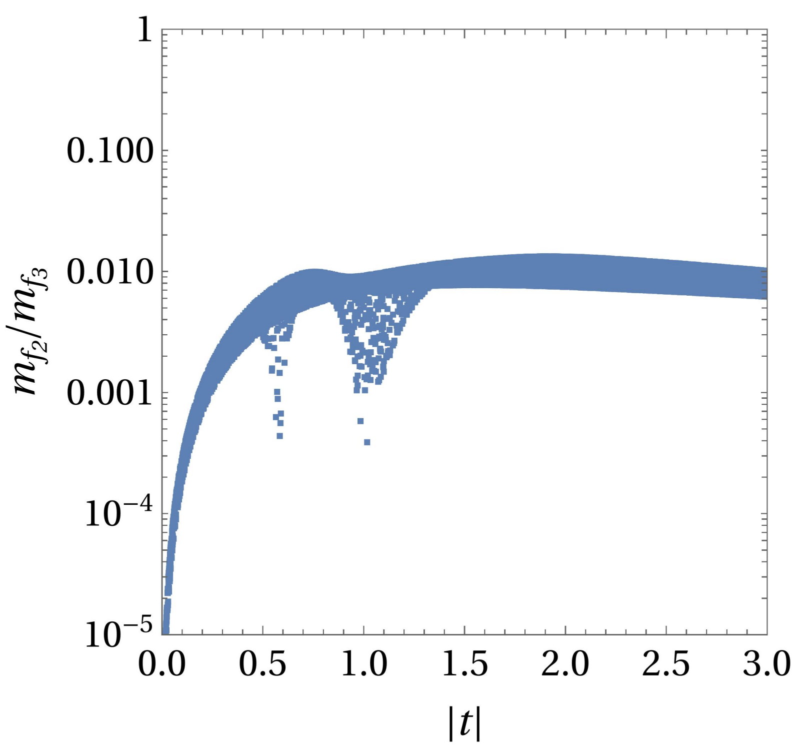
$$\mathscr{M} = \begin{pmatrix} (0)_{3\times 3} & (\mu)_{3\times 5} \\ (\mu')_{5\times 3} & (M^{(0)} + \delta M^{(0)})_{5\times 5} \end{pmatrix}, \qquad \mathscr{U}_{L,R} = \begin{pmatrix} \left(\mathbb{I}_3 - \frac{1}{2}\rho_{L,R}\rho_{L,R}^\dagger\right) u_{L,R} & -\rho_{L,R}\, U_{L,R} \\ \rho_{L,R}^\dagger\, u_{L,R} & (\mathbb{I}_5 - \frac{1}{2}\rho_{L,R}^\dagger \rho_{L,R})\, U_{L,R} \end{pmatrix}$$

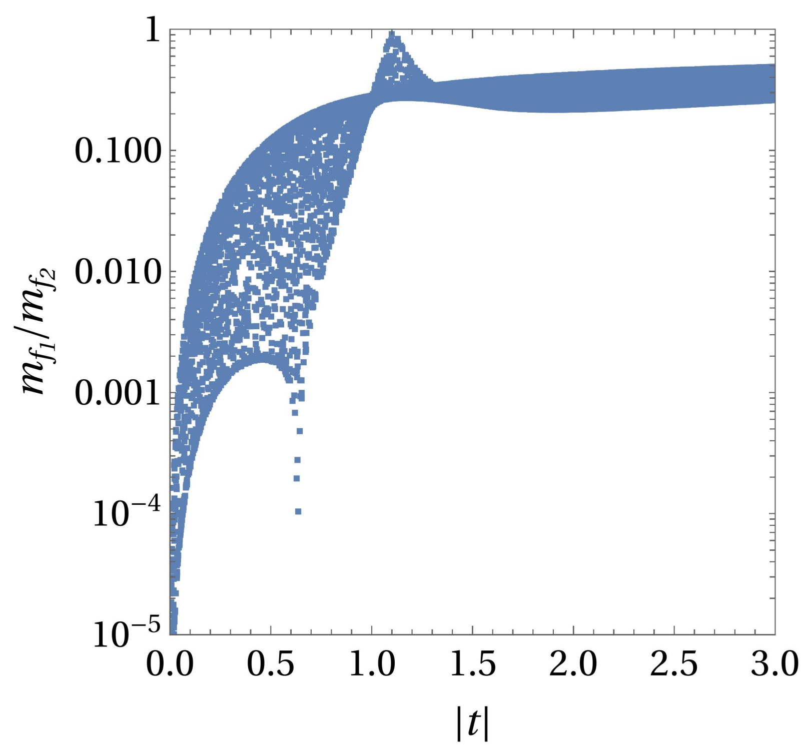
Loop induced Non-locality

G. Mohanta & K. Patel, (2026)

$$m_{\text{eff}} \approx -\mu M^{(0)^{-1}}\mu' + \mu M^{(0)^{-1}}\delta M^{(0)} M^{(0)^{-1}}\mu',$$

Quantum corrections in the UV theory generates masses for the SM particles





SM implementation: A radiative Anderson Model

Fields	Multiplicity	$G_{\rm SM}$	$U(1)_X$
$q_{L\alpha} = (u_{L\alpha}\ d_{L\alpha})^T$	3	$(3, 2, \frac{1}{6})$	0
$u_{R\alpha}$	3	$(3, 1, \frac{2}{3})$	0
$d_{R\alpha}$	3	$(3, 1, -\frac{1}{3})$	0
$l_{L\alpha} = (\nu_{L\alpha}\ e_{L\alpha})^T$	3	$(1, 2, -\frac{1}{2})$	0
$e_{R\alpha}$	3	$(1, 1, -1)$	0
H	1	$(1, 2, \frac{1}{2})$	1
$U_{Li,Ri}$	5	$(3, 1, \frac{2}{3})$	1
$D_{Li,Ri}$	5	$(3, 1, -\frac{1}{3})$	-1
$E_{Li,Ri}$	5	$(1, 1, -1)$	-1
S	1	$(1, 1, 0)$	-1

G. Mohanta & K. Patel, (2026)

- Three type of chain fermions
- Only one additional SM singlet scalar
- The new gauge interaction only for the chain fermions
- Straightforward generalization of the Toy model analysis generates hierarchical fermion masses

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- Asymptotic freedom and Landau poles: $g_i \equiv \sqrt{4\pi\alpha_i}$

$$\frac{d\alpha_i}{d\ln\mu} = \frac{\alpha_i^2}{2\pi} b_i \,.$$

$$b_3 = -7 + \frac{4}{3}N\,, \qquad b_2 = -\frac{19}{6}\,, \qquad b_1 = \frac{41}{10} + \frac{32}{15}N \qquad b_X = \frac{2}{3} + \frac{28}{3}N + \frac{1}{3}$$

  - N = 5 is the maximum value for which b_3 remains negative
  - The large contribution to $b_{1,X}$ by the new fermions indicates that the U(1) Landau poles are reached at much lower scales

$$\Lambda_{\text{Landau}} \simeq m_F \exp\left(\frac{2\pi}{b_{1,X}\,\alpha_{1,X}[m_F]}\right)$$

For N = 5, $m_F = 10$ TeV, and assuming $\alpha_X = \alpha_1$ at the scale m_F, we find that the Landau poles appear at

$\Lambda_{\text{Landau}} \sim 10^4$ TeV for $U(1)_X$ and at $\Lambda_{\text{Landau}} \sim 10^{11}$ TeV for $U(1)_Y$

Low-energy effects

- The FCNC couplings of X boson

$$\mathscr{L}_X \supset \sum_{f,\alpha,\beta} \left(\left(g^X_{f_L}\right)_{\alpha\beta} \bar{f}_{L\alpha}\gamma^\mu f_{L\beta} + \left(g^X_{f_R}\right)_{\alpha\beta} \bar{f}_{R\alpha}\gamma^\mu f_{R\beta} \right) X_\mu ,$$

$$\left(g^X_{f_L}\right)_{\alpha\beta} = g_X q_F \left(u^\dagger_{fL}\rho_{fL}\rho^\dagger_{fL}u_{fL}\right)_{\alpha\beta} ,$$

$$\left(g^X_{f_R}\right)_{\alpha\beta} = g_X q_F \left(u^\dagger_{fR}\rho_{fR}\rho^\dagger_{fR}u_{fR}\right)_{\alpha\beta}$$

- The modified Z couplings

$$\mathscr{L}_Z \supset \frac{g}{c_W} J^\mu_{Zf} Z_\mu + \sum_{f,\alpha,\beta} \left(\left(\delta g^Z_{f_L}\right)_{\alpha\beta} \bar{f}_{L\alpha}\gamma^\mu f_{L\beta} + \left(\delta g^Z_{f_R}\right)_{\alpha\beta} \bar{f}_{R\alpha}\gamma^\mu f_{R\beta} \right) Z_\mu ,$$

$$\left(\delta g^Z_{f_L}\right)_{\alpha\beta} = -\frac{g}{c_W} T^f_3 \left(u^\dagger_{fL}\rho_{fL}\rho^\dagger_{fL}u_{fL}\right)_{\alpha\beta} ,$$

$$\left(\delta g^Z_{f_R}\right)_{\alpha\beta} = 0 ,$$

- The modified Higgs couplings

$$-\mathscr{L}_Y \supset \sum_{\alpha,\beta} \left(g^h_f\right)_{\alpha\beta} \bar{f}_{L\alpha} f_{R\beta} \tilde{h} + \mathrm{h.c.},$$

$$\left(g^h_f\right)_{\alpha\beta} = \frac{m_{f\beta}}{v} \left(\delta_{\alpha\beta} - \frac{1}{2} \left(u^\dagger_{fL}\rho_{fL}\rho^\dagger_{fL}u_{fL}\right)_{\alpha\beta} \right) ,$$

Low-energy effects

- The FCNC couplings of X boson

$$\mathscr{L}_X \supset \sum_{f,\alpha,\beta}\left(\left(g^X_{f_L}\right)_{\alpha\beta}\bar{f}_{L\alpha}\gamma^\mu f_{L\beta} + \left(g^X_{f_R}\right)_{\alpha\beta}\bar{f}_{R\alpha}\gamma^\mu f_{R\beta}\right)X_\mu\,,$$

$$\left(g^X_{f_L}\right)_{\alpha\beta} = g_X q_F\left(u^\dagger_{fL}\rho_{fL}\rho^\dagger_{fL}u_{fL}\right)_{\alpha\beta}\,,$$

$$\left(g^X_{f_R}\right)_{\alpha\beta} = g_X q_F\left(u^\dagger_{fR}\rho_{fR}\rho^\dagger_{fR}u_{fR}\right)_{\alpha\beta}$$

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$$\mathscr{L}_Z \supset \frac{g}{c_W}J^\mu_{Zf}Z_\mu + \sum_{f,\alpha,\beta}\left(\left(\delta g^Z_{f_L}\right)_{\alpha\beta}\bar{f}_{L\alpha}\gamma^\mu f_{L\beta} + \left(\delta g^Z_{f_R}\right)_{\alpha\beta}\bar{f}_{R\alpha}\gamma^\mu f_{R\beta}\right)Z_\mu\,,$$

$$\left(\delta g^Z_{f_L}\right)_{\alpha\beta} = -\frac{g}{c_W}T^f_3\left(u^\dagger_{fL}\rho_{fL}\rho^\dagger_{fL}u_{fL}\right)_{\alpha\beta}\,,$$

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- The modified Higgs couplings

$$-\mathscr{L}_Y \supset \sum_{\alpha,\beta}\left(g^h_f\right)_{\alpha\beta}\bar{f}_{L\alpha}f_{R\beta}\tilde{h} + \text{h.c.}\,,$$

$$\left(g^h_f\right)_{\alpha\beta} = \frac{m_{f\beta}}{v}\left(\delta_{\alpha\beta} - \frac{1}{2}\left(u^\dagger_{fL}\rho_{fL}\rho^\dagger_{fL}u_{fL}\right)_{\alpha\beta}\right),$$

- The FCNC couplings has structure

$$(\Omega_{fL})_{\alpha\beta} \sim \mathcal{O}\left(\frac{|\mu_f|^2}{W_F^2}\right)\left[u^\dagger_{fL}\begin{pmatrix}\mathcal{O}(1) & \mathcal{O}(t_F) & \mathcal{O}(t_F^2)\\ \mathcal{O}(t_F) & \mathcal{O}(1) & \mathcal{O}(t_F)\\ \mathcal{O}(t_F^2) & \mathcal{O}(t_F) & \mathcal{O}(t_F^2)\end{pmatrix}u_{fL}\right]_{\alpha\beta} + \mathcal{O}\left(\frac{m_\alpha m_\beta}{|\mu'_f|^2}\right)$$

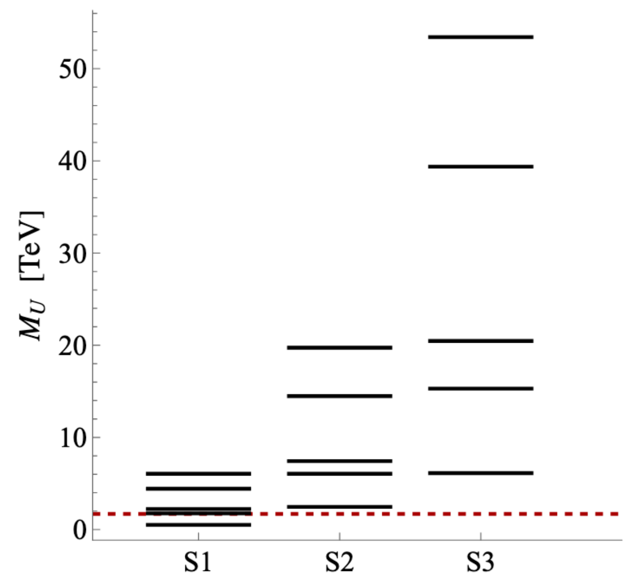
$$(\Omega_{fR})_{\alpha\beta} \sim \mathcal{O}\left(\frac{|\mu'_f|^2}{W_F^2}\right)\left[u^\dagger_{fR}\begin{pmatrix}\mathcal{O}(1) & \mathcal{O}(t_F) & \mathcal{O}(t_F^2)\\ \mathcal{O}(t_F) & \mathcal{O}(1) & \mathcal{O}(t_F)\\ \mathcal{O}(t_F^2) & \mathcal{O}(t_F) & \mathcal{O}(t_F^2)\end{pmatrix}u_{fR}\right]_{\alpha\beta} + \mathcal{O}\left(\frac{m_\alpha m_\beta}{|\mu_f|^2}\right)$$

Example solutions

Parameter	S1	S2	S3
M_X	1.0000×10^3	5.0000×10^3	1.0000×10^4
W_U	2.2275×10^3	7.4356×10^3	2.0468×10^4
W_D	1.3785×10^4	5.5603×10^4	3.7524×10^5
W_E	1.2654×10^4	4.5599×10^4	8.5562×10^4
t_U	$-0.97406 + 0.22612\,i$	$0.92063 - 0.32115\,i$	$0.90288 + 0.28292\,i$
t_D	$0.96155 - 0.25501\,i$	$-0.94969 + 0.31311\,i$	$0.92170 + 0.26315\,i$
t_E	$-0.98464 + 0.056430\,i$	$0.98916 + 0.049848\,i$	$0.97364 - 0.056887\,i$
μ_{u1}	160.91	-154.38	175.67
μ_{u2}	-200.42	214.71	266.54
μ_{u3}	-468.23	-366.25	-431.69
μ'_{u1}	-704.34	2.8361×10^3	-6.5243×10^3
μ'_{u2}	-705.15	-3.3540×10^3	5.9816×10^3
μ'_{u3}	1.9544	6.9431	-13.052
μ_{d1}	-45.449	-68.678	-57.186
μ_{d2}	-55.112	-93.576	-86.172
μ_{d3}	123.67	-167.36	139.02
μ'_{d1}	213.37	-401.06	-5.2015×10^3
μ'_{d2}	191.58	-687.41	2.6426×10^3
μ'_{d3}	439.24	-1.0884×10^3	5.4504×10^3
μ_{e1}	-22.151	13.327	-26.028
μ_{e2}	-22.016	-12.790	25.225
μ_{e3}	-169.67	-114.24	-169.25
μ'_{e1}	-94.749	-506.69	505.75
μ'_{e2}	-91.206	-436.48	-527.15
μ'_{e3}	706.20	-3.4530×10^3	3.6499×10^3

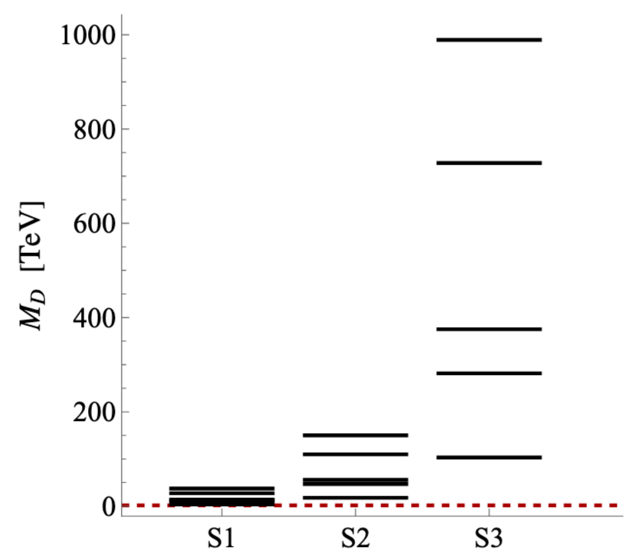
Phenomenology

- Direct search bounds



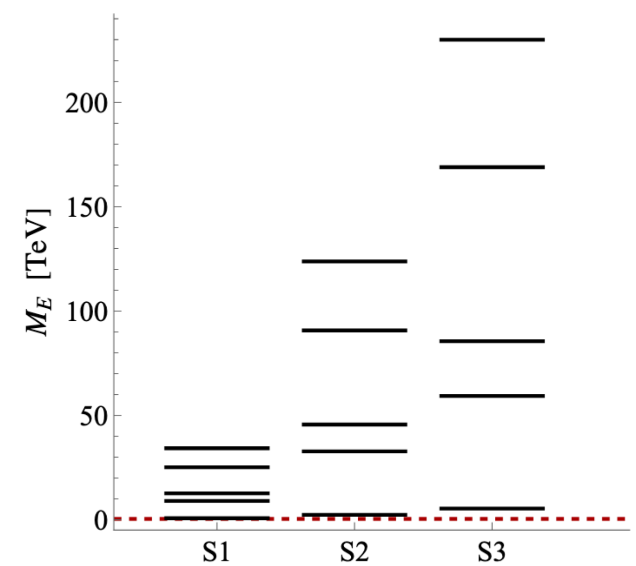
$M_U > 1.7$ TeV

ATLAS (2024)



$M_D > 1.56$ TeV

CMS (2023)



$M_E > 0.4$ TeV

ATLAS (2025)

Couplings	Constraint	S1	S2	S3
$(\delta g^Z_{uL})_{11}$	$(-0.8 \pm 3.1) \times 10^{-2}$	-7.4×10^{-4}	-7.4×10^{-5}	-1.6×10^{-5}
$(\delta g^Z_{uL})_{22}$	$(-0.15 \pm 0.36) \times 10^{-2}$	$\mathbf{-2.2 \times 10^{-2}}$	-1.3×10^{-3}	-2.9×10^{-4}
$(\delta g^Z_{uL})_{33}$	$(-0.3 \pm 3.8) \times 10^{-2}$	-2.3×10^{-2}	-1.3×10^{-3}	-3.2×10^{-4}
$(\delta g^Z_{dL})_{11}$	$(-0.9 \pm 4.4) \times 10^{-2}$	4.2×10^{-6}	6.3×10^{-7}	1.3×10^{-8}
$(\delta g^Z_{dL})_{22}$	$(0.9 \pm 2.8) \times 10^{-2}$	4.0×10^{-5}	5.1×10^{-6}	1.2×10^{-7}
$(\delta g^Z_{dL})_{33}$	$(0.33 \pm 0.17) \times 10^{-2}$	4.2×10^{-5}	5.3×10^{-6}	1.4×10^{-7}
$(\delta g^Z_{eL})_{11}$	$(-2.3 \pm 2.8) \times 10^{-4}$	1.3×10^{-6}	4.5×10^{-8}	4.5×10^{-8}
$(\delta g^Z_{eL})_{22}$	$(0.1 \pm 1.2) \times 10^{-3}$	1.2×10^{-4}	4.7×10^{-6}	3.3×10^{-6}
$(\delta g^Z_{eL})_{33}$	$(1.8 \pm 5.9) \times 10^{-4}$	1.5×10^{-4}	6.0×10^{-6}	4.8×10^{-6}

Falkowski et al. (2017)

- Neutral meson-antimeson transitions

Wilson coefficient	Constraint	S1	S2	S3
$\mathrm{Re}\,\boldsymbol{C}_K^1$	$[-9.6,\ 9.6] \times 10^{-13}$	4.25×10^{-15}	5.87×10^{-17}	-3.08×10^{-20}
$\mathrm{Re}\,\tilde{C}_K^1$	$[-9.6,\ 9.6] \times 10^{-13}$	5.68×10^{-14}	2.03×10^{-16}	-1.20×10^{-16}
$\mathrm{Re}\,C_K^4$	$[-3.6,\ 3.6] \times 10^{-15}$	$\mathbf{3.12 \times 10^{-14}}$	6.91×10^{-17}	-5.81×10^{-19}
$\mathrm{Re}\,C_K^5$	$[-1.0,\ 1.0] \times 10^{-14}$	$\mathbf{2.04 \times 10^{-14}}$	3.58×10^{-17}	-2.76×10^{-19}
$\mathrm{Im}\,\boldsymbol{C}_K^1$	$[-9.6,\ 9.6] \times 10^{-13}$	3.30×10^{-15}	6.32×10^{-17}	3.02×10^{-20}
$\mathrm{Im}\,\tilde{C}_K^1$	$[-9.6,\ 9.6] \times 10^{-13}$	-4.04×10^{-14}	-2.33×10^{-16}	-8.31×10^{-17}
$\mathrm{Im}\,C_K^4$	$[-1.8,\ 0.9] \times 10^{-17}$	$\mathbf{6.63 \times 10^{-16}}$	-1.15×10^{-18}	4.95×10^{-20}
$\mathrm{Im}\,C_K^5$	$[-1.0,\ 1.0] \times 10^{-14}$	4.34×10^{-16}	-5.98×10^{-19}	2.36×10^{-20}
$\lvert\boldsymbol{C}_{B_d}^1\rvert$	$< 2.3 \times 10^{-11}$	2.71×10^{-16}	5.90×10^{-18}	6.80×10^{-21}
$\lvert\tilde{C}_{B_d}^1\rvert$	$< 2.3 \times 10^{-11}$	1.02×10^{-14}	3.09×10^{-17}	1.35×10^{-16}
$\lvert C_{B_d}^4\rvert$	$< 2.1 \times 10^{-13}$	1.37×10^{-15}	3.03×10^{-18}	1.20×10^{-19}
$\lvert C_{B_d}^5\rvert$	$< 6.0 \times 10^{-13}$	1.68×10^{-15}	2.81×10^{-18}	1.00×10^{-19}
$\lvert\boldsymbol{C}_{B_s}^1\rvert$	$< 1.1 \times 10^{-9}$	3.46×10^{-15}	7.21×10^{-17}	1.05×10^{-19}
$\lvert\tilde{C}_{B_s}^1\rvert$	$< 1.1 \times 10^{-9}$	7.82×10^{-14}	5.29×10^{-16}	8.60×10^{-16}
$\lvert C_{B_s}^4\rvert$	$< 1.6 \times 10^{-11}$	1.35×10^{-14}	4.39×10^{-17}	1.19×10^{-18}
$\lvert C_{B_s}^5\rvert$	$< 4.5 \times 10^{-11}$	1.66×10^{-14}	4.07×10^{-17}	9.93×10^{-19}
$\lvert\boldsymbol{C}_D^1\rvert$	$< 7.2 \times 10^{-13}$	$\mathbf{5.15 \times 10^{-11}}$	1.18×10^{-13}	1.20×10^{-14}
$\lvert\tilde{C}_D^1\rvert$	$< 7.2 \times 10^{-13}$	9.43×10^{-14}	9.30×10^{-15}	1.15×10^{-15}
$\lvert C_D^4\rvert$	$< 4.8 \times 10^{-14}$	$\mathbf{2.64 \times 10^{-12}}$	1.06×10^{-14}	6.53×10^{-16}
$\lvert C_D^5\rvert$	$< 4.8 \times 10^{-13}$	$\mathbf{2.28 \times 10^{-12}}$	7.11×10^{-15}	4.00×10^{-16}

- Rare top decays

Observable	Current limit	HL-LHC sensitivity	S1	S2	S3
$\mathrm{Br}(t \to Zc)$	$< 2.4 \times 10^{-4}$	$\lesssim 2.3 \times 10^{-5}$	1.77×10^{-5}	5.40×10^{-8}	4.96×10^{-9}
$\mathrm{Br}(t \to Zu)$	$< 1.7 \times 10^{-4}$	$\lesssim 7.3 \times 10^{-6}$	1.96×10^{-7}	9.34×10^{-10}	6.05×10^{-11}
$\mathrm{Br}(t \to Hc)$	$< 7.3 \times 10^{-4}$	$\lesssim 8.5 \times 10^{-5}$	4.39×10^{-7}	1.30×10^{-9}	1.20×10^{-10}
$\mathrm{Br}(t \to Hu)$	$< 1.9 \times 10^{-4}$	$\lesssim 8.5 \times 10^{-5}$	4.86×10^{-9}	2.25×10^{-11}	1.46×10^{-12}
$\mathrm{Br}(t \to c\gamma)$	$< 4.0 \times 10^{-4}$	$\lesssim 5.2 \times 10^{-5}$	2.65×10^{-11}	8.87×10^{-14}	8.19×10^{-15}
$\mathrm{Br}(t \to u\gamma)$	$< 8.9 \times 10^{-5}$	$\lesssim 6.1 \times 10^{-6}$	3.95×10^{-13}	2.03×10^{-15}	1.32×10^{-16}

- Lepton flavor violation

Observable	**Upper bound**	**S1**	**S2**	**S3**
$\mathrm{Br}(\mu - e)$	7.0×10^{-13}	$\mathbf{8.1 \times 10^{-12}}$	1.3×10^{-14}	8.65×10^{-15}
$\mathrm{Br}(\mu \to 3e)$	1.0×10^{-12}	$\mathbf{1.4 \times 10^{-10}}$	2.1×10^{-13}	7.33×10^{-14}
$\mathrm{Br}(\tau \to 3\mu)$	2.1×10^{-8}	4.2×10^{-10}	5.4×10^{-13}	4.34×10^{-13}
$\mathrm{Br}(\tau \to 3e)$	2.7×10^{-8}	4.1×10^{-12}	4.1×10^{-15}	3.72×10^{-15}
$\mathrm{Br}(\mu \to e\gamma)$	4.2×10^{-13}	2.5×10^{-13}	3.8×10^{-16}	2.51×10^{-16}
$\mathrm{Br}(\tau \to \mu\gamma)$	4.4×10^{-8}	9.1×10^{-13}	1.3×10^{-15}	9.13×10^{-16}
$\mathrm{Br}(\tau \to e\gamma)$	3.3×10^{-8}	8.7×10^{-15}	1.1×10^{-17}	1.03×10^{-17}

Calibbi, Signorelli (2018)

Radiative Anderson vs Chain Model

Generating the fermion mass hierarchy at the TeV scale

Nima Arkani-Hamed[1,*] Carolina Figueiredo[2,†] Lawrence J. Hall[3,4,‡] and Claudio Andrea Manzari[1§]
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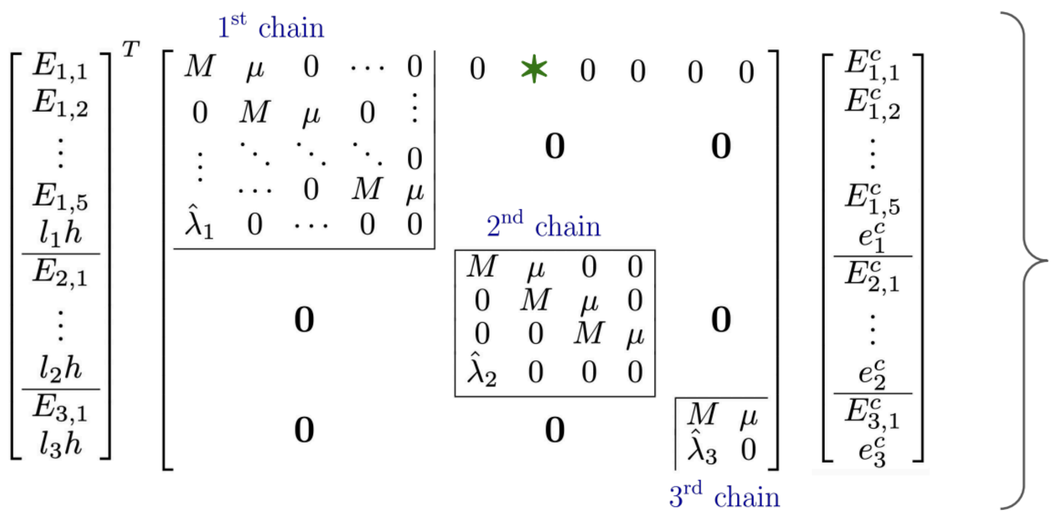

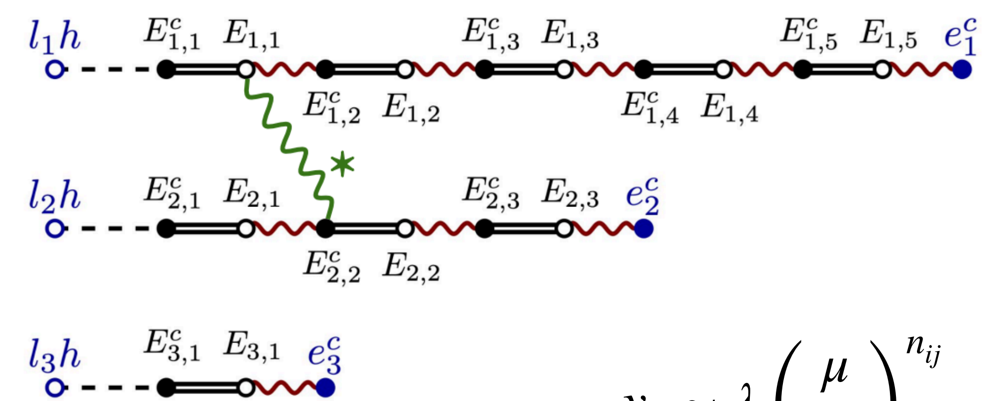

$$y_{ij} \sim \lambda \left(\frac{\mu}{M}\right)^{n_{ij}}$$

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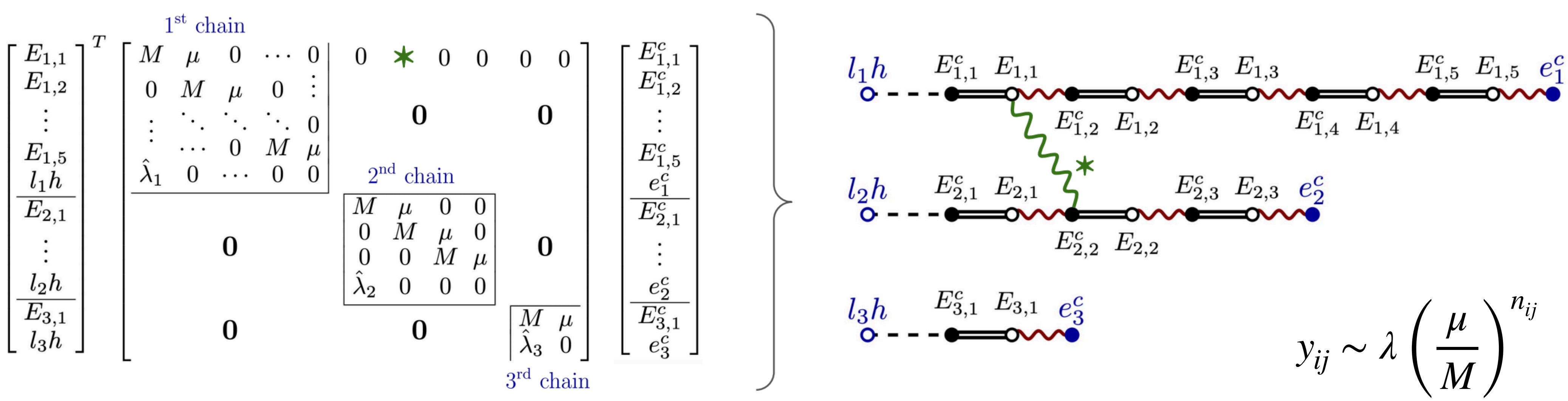
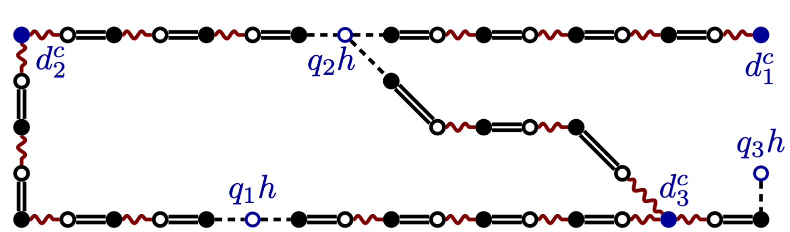


$$y_{ij} \sim \lambda \left(\frac{\mu}{M}\right)^{n_{ij}}$$



$$\Rightarrow \quad y^d_{ij}\, q_i d^c_j h \quad \text{with} \quad y^d \sim \begin{bmatrix} 0 & \epsilon^5 & \epsilon^5 \\ \epsilon^5 & \epsilon^4 e^{i\theta} & \epsilon^4 \\ 0 & 0 & \epsilon^2 \end{bmatrix}.$$

- Three generations fermions gets mass from three chains
- Chain model can explain the mixing hierarchy, but radiative Anderson can not. (?)
- No additional gauge or scalar interaction required for the chain model

Summary

- A radiative mass framework provides an effective mechanism for flavor puzzle
- The mechanism doesn't depend on absolute value of new physics scale, rather depends on separation with VL fermion masses.
- Anderson localization in theory space can lead to exponential hierarchical couplings. This feature can also give massless modes in the theory
- Additional gauge interactions (without disorder) can generate the loop-suppressed masses for the massless modes
- The lowest allowed new physics for the radiative mass framework in the SM with Anderson localization is 5 TeV.
- The model can explain the Higgs vacuum stability, since it has 5 VL fermion (in each sector also)

Gopalakrishna et al. (2019)

Thank you

Backup slides

SM implementation

- The scalar sector

$$V = -\frac{\mu_H^2}{2}H^\dagger H + \frac{\lambda_H}{4}(H^\dagger H)^2 - \frac{\mu_S^2}{2}|S|^2 \quad + \frac{\lambda_S}{4}|S|^4 + \frac{\lambda_{HS}}{2}H^\dagger H|S|^2$$

VEVs $$\langle H\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}, \quad \langle S\rangle = \frac{v_S}{\sqrt{2}}$$

The physical scalars $$\tilde{h} = \cos\phi\, h + \sin\phi\, s\,, \quad \tilde{s} = \cos\phi\, s - \sin\phi\, h$$

- The Gauge sector

$$D_\mu H = \left(\partial_\mu + ig\frac{\tau^i}{2}W_\mu^i + i\frac{g'}{2}B_\mu + ig_X X'_\mu\right) H\,, \qquad D_\mu S = \left(\partial_\mu - ig_X X'_\mu\right)S\,,$$

$$M_{G^0}^2 = \begin{pmatrix} \frac{1}{4}g'^2v^2 & -\frac{1}{4}gg'v^2 & \frac{1}{2}g'g_Xv^2 \\ -\frac{1}{4}gg'v^2 & \frac{1}{4}g^2v^2 & -\frac{1}{2}gg_Xv^2 \\ \frac{1}{2}g'g_Xv^2 & -\frac{1}{2}gg_Xv^2 & g_X^2\left(v^2+v_S^2\right) \end{pmatrix}, \qquad \begin{pmatrix} B \\ W^3 \\ X' \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W & 0 \\ \sin\theta_W & \cos\theta_W & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A \\ Z \\ X \end{pmatrix},$$

$$\tan\theta_W = \frac{g'}{g}\,, \qquad \tan 2\theta = \frac{2\,m_{YX}^2}{m_{YY}^2 - m_{XX}^2}\,,$$

$$m_{YY}^2 = \frac{g^2}{\cos^2\theta_W}\frac{v^2}{4}\,, \quad m_{XX}^2 = g_X^2\left(v_S^2 + v^2\right), \quad m_{YX}^2 = -\frac{gg_X}{\cos\theta_W}\frac{v^2}{2}$$

The Yukawa Lagrangian

- Straightforward generalization of the Toy model

$$
\begin{aligned}
-\mathcal{L}_Y = & \sum_{\alpha=1}^{3}((y_u)_\alpha\, \bar{q}_{L\alpha}\tilde{H}U_{R\alpha} + (y_u')_\alpha\, \overline{U}_{L(6-\alpha)}S^* u_{R\alpha}) + \sum_{i,j=1}^{5}\left(M_U^{(0)}\right)_{ij}\overline{U}_{Li}U_{Rj} \\
& + \sum_{\alpha=1}^{3}((y_d)_\alpha\, \bar{q}_{L\alpha}HD_{R\alpha} + (y_d')_\alpha\, \overline{D}_{L(6-\alpha)}Sd_{R\alpha}) + \sum_{i,j=1}^{5}\left(M_D^{(0)}\right)_{ij}\overline{D}_{Li}D_{Rj} \\
& + \sum_{\alpha=1}^{3}((y_e)_\alpha\, \bar{l}_{L\alpha}HE_{R\alpha} + (y_e')_\alpha\, \overline{E}_{L(6-\alpha)}Se_{R\alpha}) + \sum_{i,j=1}^{5}\left(M_E^{(0)}\right)_{ij}\overline{E}_{Li}E_{Rj} \\
& + \text{h.c.}\,,
\end{aligned}
$$

The VL fermion mass terms

$$
\left(M_F^{(0)}\right)_{ij} = W_F\left[\delta_{ij} + t_F\,(\delta_{i+1,j} + \delta_{i,j+1})\right],
$$

$$
\mu_{f\alpha} = (y_f)_\alpha \frac{v}{\sqrt{2}}\,, \quad \mu'_{f\alpha} = (y_f')_\alpha \frac{v_S}{\sqrt{2}}\,,
$$

generalization

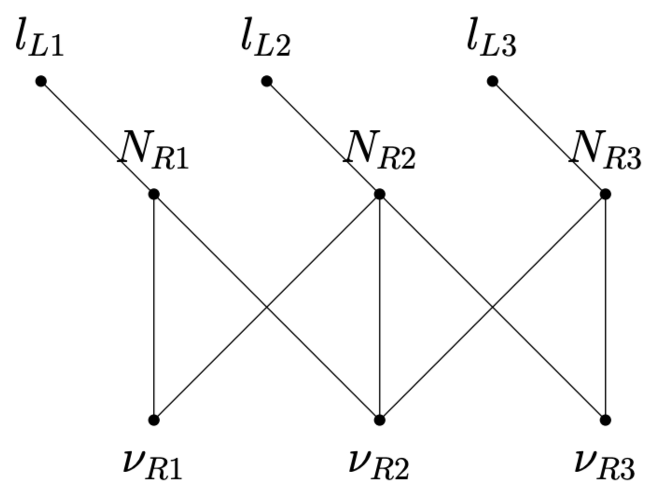
$$
\rho_L \to \rho_{fL} = -\,\mu_f M_F^{-1}, \;\; \rho_R^\dagger \to (\rho_{fR})^\dagger = -\,M_F^{-1}\mu_f', \;\; u_{L,R} \to u_{fL,fR},\; U_{L,R} \to U_{fL,fR}\,.
$$

- The charged SM fermion effective mass matrix

$$
m^f_{\text{eff}} \simeq -\,\mu_f\, M_F^{-1}\,\mu_f' \equiv M_f\,, \qquad u_{fL}^\dagger\, M_f\, u_{fR} = \text{Diag}(m_{f1}, m_{f2}, m_{f3})\,,
$$

Neutrino mass

$$-\mathcal{L}_\nu \supset (y_\nu)_\alpha \, \overline{l_{L\alpha}} \tilde{H} N_{R\alpha} + (y'_\nu)_{\alpha\beta} \, \overline{N_{R\alpha}} \, S^* \, \nu_{R\beta} + \frac{1}{2}\mu_\alpha \, \overline{\nu^c_{R\alpha}} \nu_{R\alpha} + \text{h.c.}\,.$$



$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_N \\ 0 & M_N^T & \mu \end{pmatrix} ,$$

$$(m_D)_{\alpha\beta} = \frac{v}{\sqrt{2}} (y_\nu)_\alpha \delta_{\alpha\beta} \,, \quad \mu_{\alpha\beta} = \mu_\alpha \, \delta_{\alpha\beta} \,,$$

$$(M_N)_{\alpha\beta} = \frac{v_S}{\sqrt{2}} (y'_\nu)_{\alpha\beta} \equiv W_N \left[\delta_{\alpha\beta} + t_N \left(\delta_{\alpha+1,\beta} + \delta_{\alpha,\beta+1} \right) \right] ,$$

The effective active neutrino mass matrix

$$M_\nu \simeq m_D \, (M_N^T)^{-1} \, \mu \, M_N^{-1} \, m_D^T \,.$$

Approximate eigenvalues

$$\frac{\mu v^2}{2W_N^2} \left\{ \frac{1}{(1-\sqrt{2}\,t_N)^2} , \frac{1}{(1+\sqrt{2}\,t_N)^2} , 1 \right\} .$$

Numerical Fitting

Solutions are obtained through χ^2 function minimisation technique

$$\chi^2 = \sum_i \left(\frac{O^i_{\rm th} - O^i_{\rm exp}}{\sigma_i} \right)^2$$

$i = 1,...,13$ (13 observables)

Observable	Value	Observable	Value
m_u	0.86 ± 0.15 MeV	m_e	0.499 ± 0.049 MeV
m_c	0.435 ± 0.013 GeV	m_μ	0.105 ± 0.0105 GeV
m_t	123.77 ± 0.85 GeV	m_τ	1.784 ± 0.1784 GeV
m_d	1.88 ± 0.13 MeV	$\lvert V_{us}\rvert$	0.22501 ± 0.00068
m_s	0.03747 ± 0.00326 GeV	$\lvert V_{cb}\rvert$	0.04183 ± 0.00079
m_b	1.908 ± 0.021 GeV	$\lvert V_{ub}\rvert$	0.003732 ± 0.00009
		$J_{\rm CP}$	$(3.12 \pm 0.13) \times 10^{-5}$

Huang & Zhou (2021), PDG (2024)

- The minimisation is done using MINUIT along with LAPACK & BLAS.
- We fit the observable at the renormalisation scale $\mu = 10^5$ GeV
- We choose

$$|y_i| : [0.1, \sqrt{4\pi}] , \quad \sum_i v_{ui}^2 + v_{di}^2 = (246)^2 GeV^2 , \quad m_3 \ll m_F \sim M_X$$

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Flavor violations

- Quark flavor violations: Meson-antimeson oscillations

$$\mathscr{H}_M^{\text{eff}} = \sum_{i=1}^{5} C_M^i Q_i^M + \sum_{i=1}^{3} \tilde{C}_M^i \tilde{Q}_i^M$$

$$\begin{aligned}
Q_1^{q_i q_j} &= \bar{q}_{jL}^{\alpha}\gamma_\mu q_{iL}^{\alpha}\bar{q}_{jL}^{\beta}\gamma^\mu q_{iL}^{\beta}\ ,\\
Q_2^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha}\bar{q}_{jR}^{\beta} q_{iL}^{\beta}\ ,\\
Q_3^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta}\bar{q}_{jR}^{\beta} q_{iL}^{\alpha}\ ,\\
Q_4^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha}\bar{q}_{jL}^{\beta} q_{iR}^{\beta}\ ,\\
Q_5^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta}\bar{q}_{jL}^{\beta} q_{iR}^{\alpha}\ .
\end{aligned}$$

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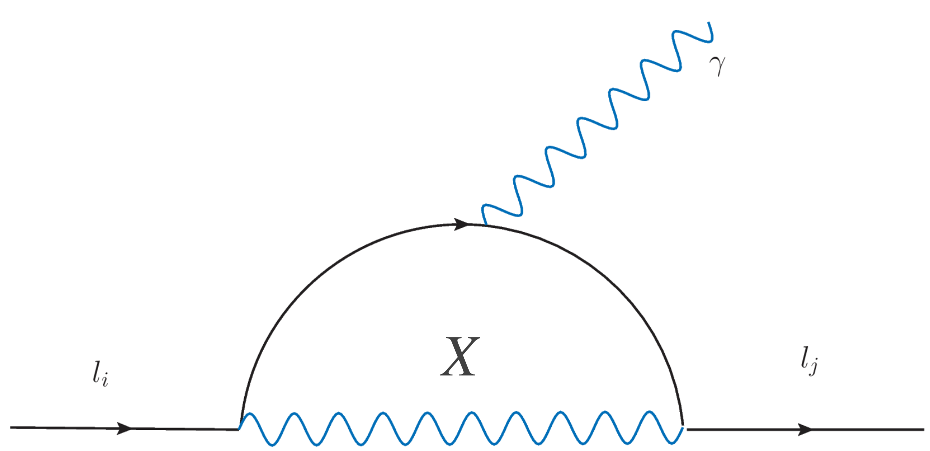
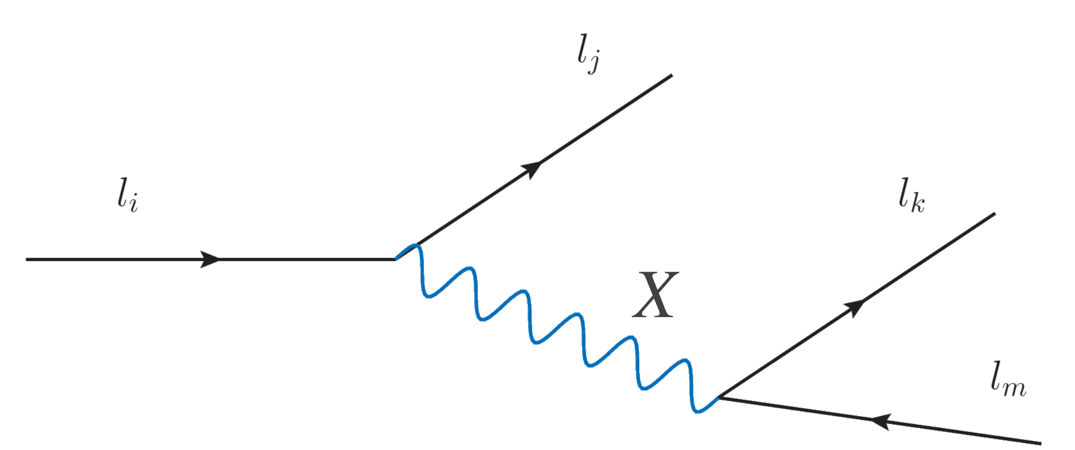
At TeV scale $K^0 - \bar{K}^0$ mixing couplings :

$$C_K^1 = \frac{g_X^2}{M_X^2}\left[\left(Q_L^d\right)_{12}\right]^2, \qquad \tilde{C}_K^1 = \frac{g_X^2}{M_X^2}\left[\left(Q_R^d\right)_{12}\right]^2, \qquad C_K^5 = -4\frac{g_X^2}{M_X^2}\left(Q_L^d\right)_{12}\left(Q_R^d\right)_{12}$$

and similar couplings for other $M - \bar{M}$ mixing are only non-vanishing

- The exchange of X boson also mediates following type of LFV process:





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