Anomalous Z'

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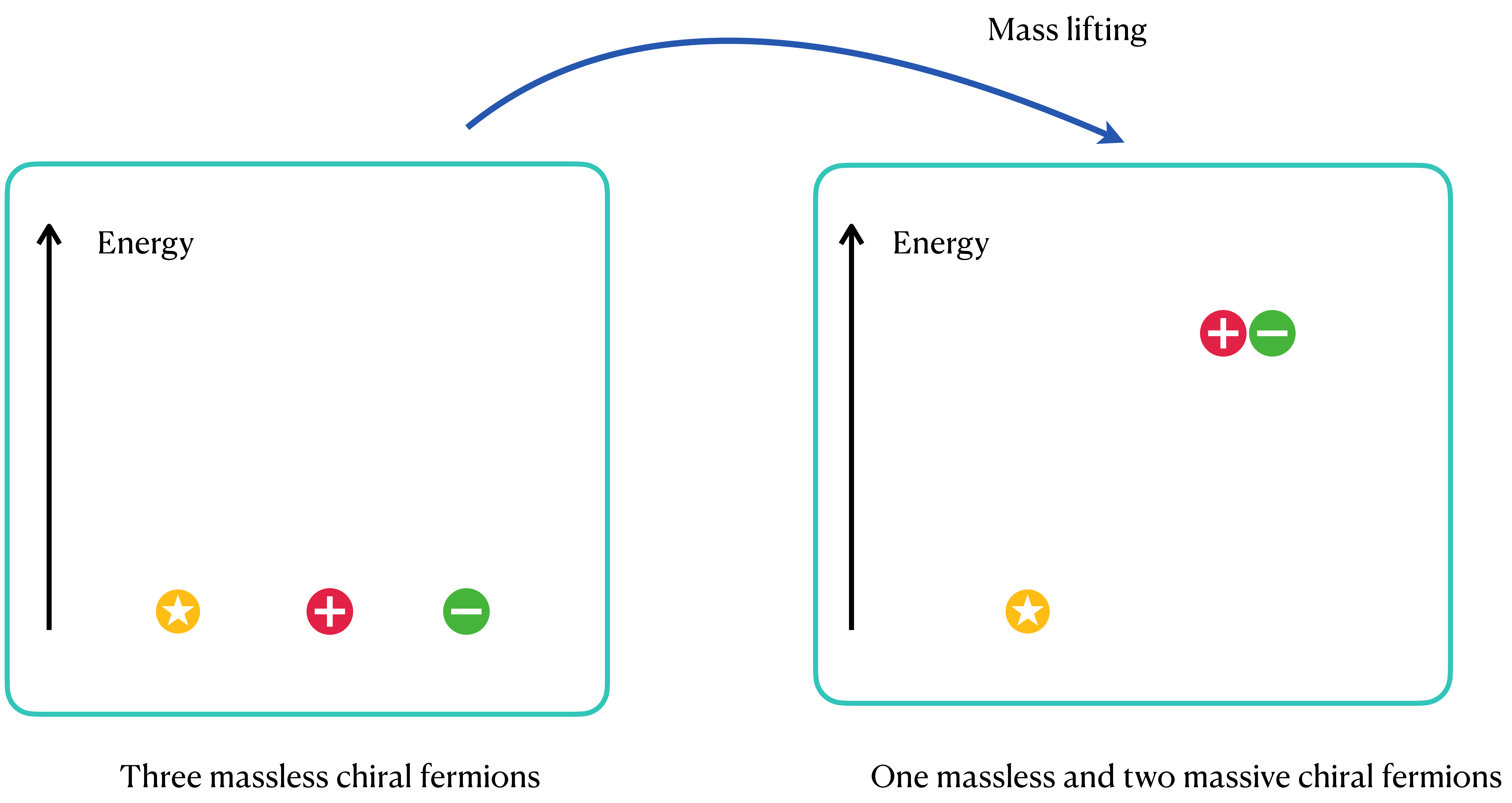
Based on

Pascal Anastasopoulos, Ignatios Antoniadis, K.B., François Rondeau *JHEP* 07 (2024) 232
+ Arno Goudeau (in progress …)

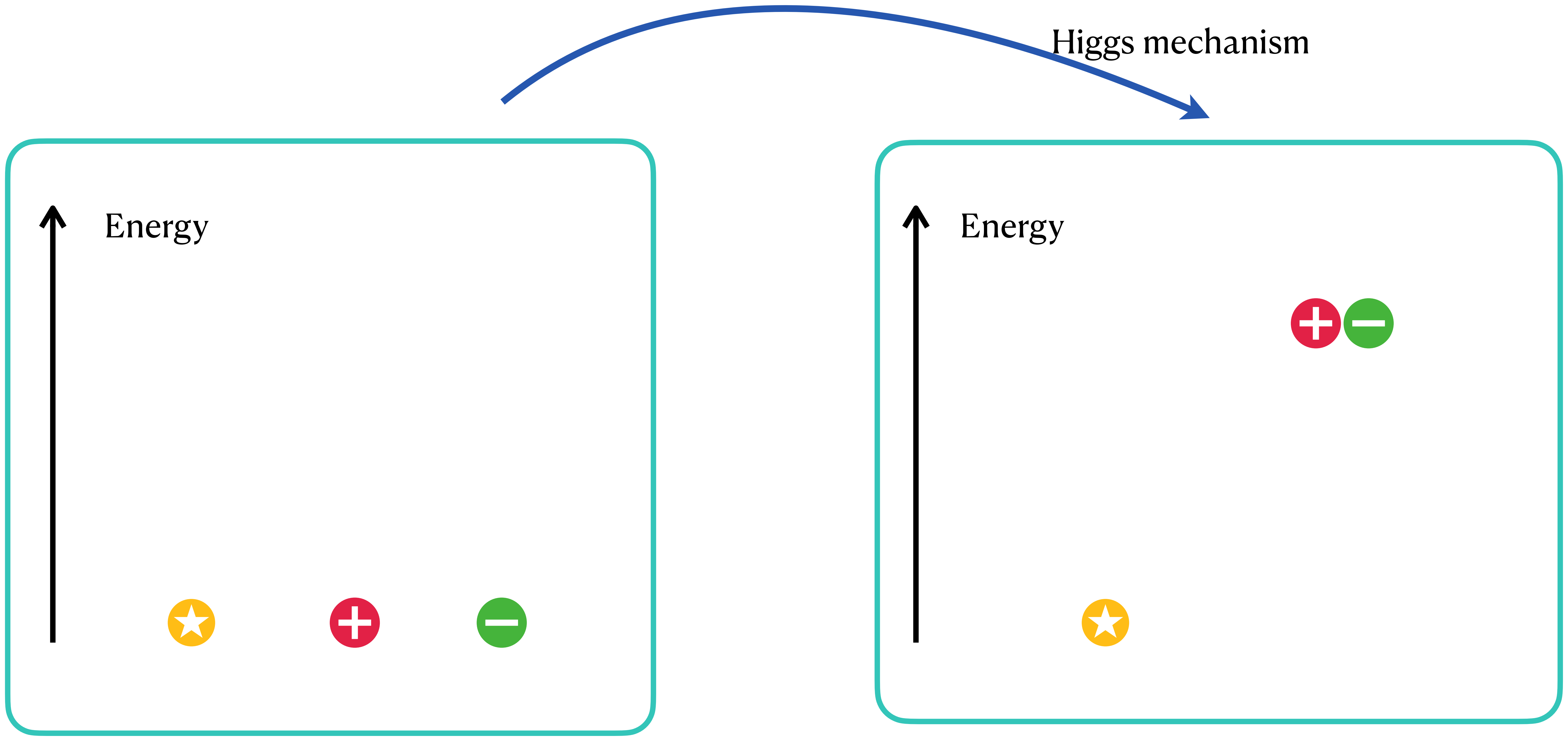
Workshop on the Standard Model and Beyond, Corfu 2024

The general idea

Separating the chiral fermions



The EFT will look anomalous

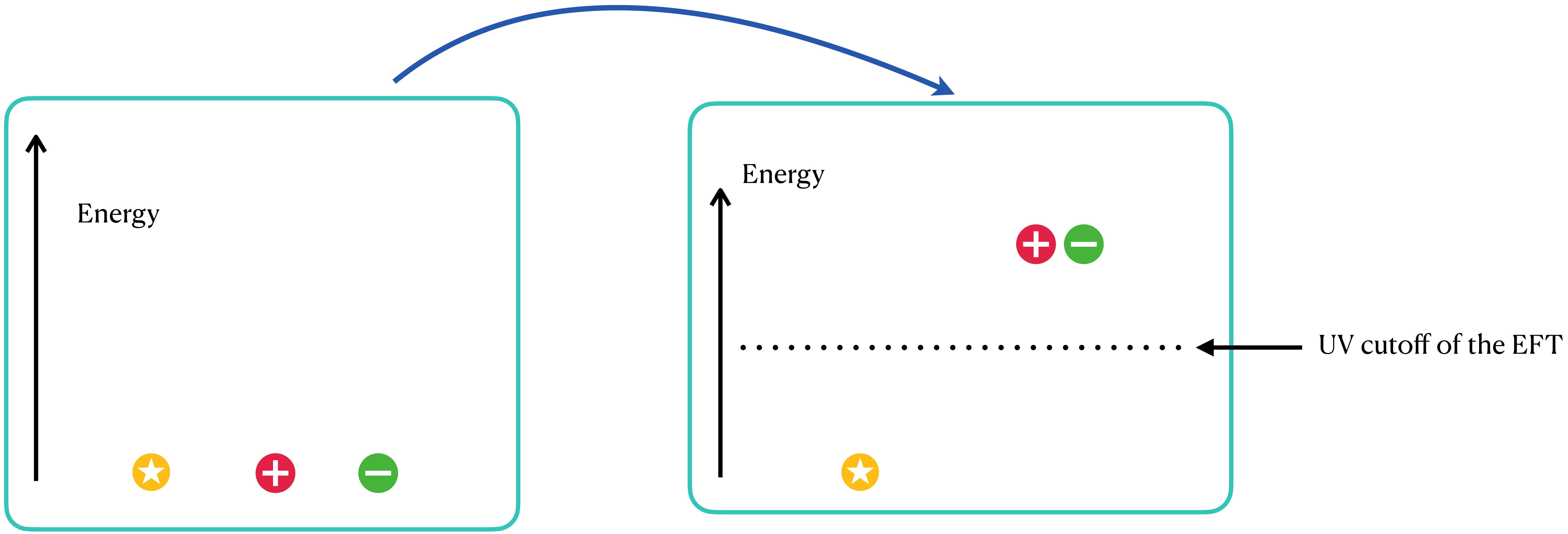


Three massless chiral fermions

One massless and other massive fermions

Anomaly cancellation among the three

The EFT will look anomalous



Three massless chiral fermions

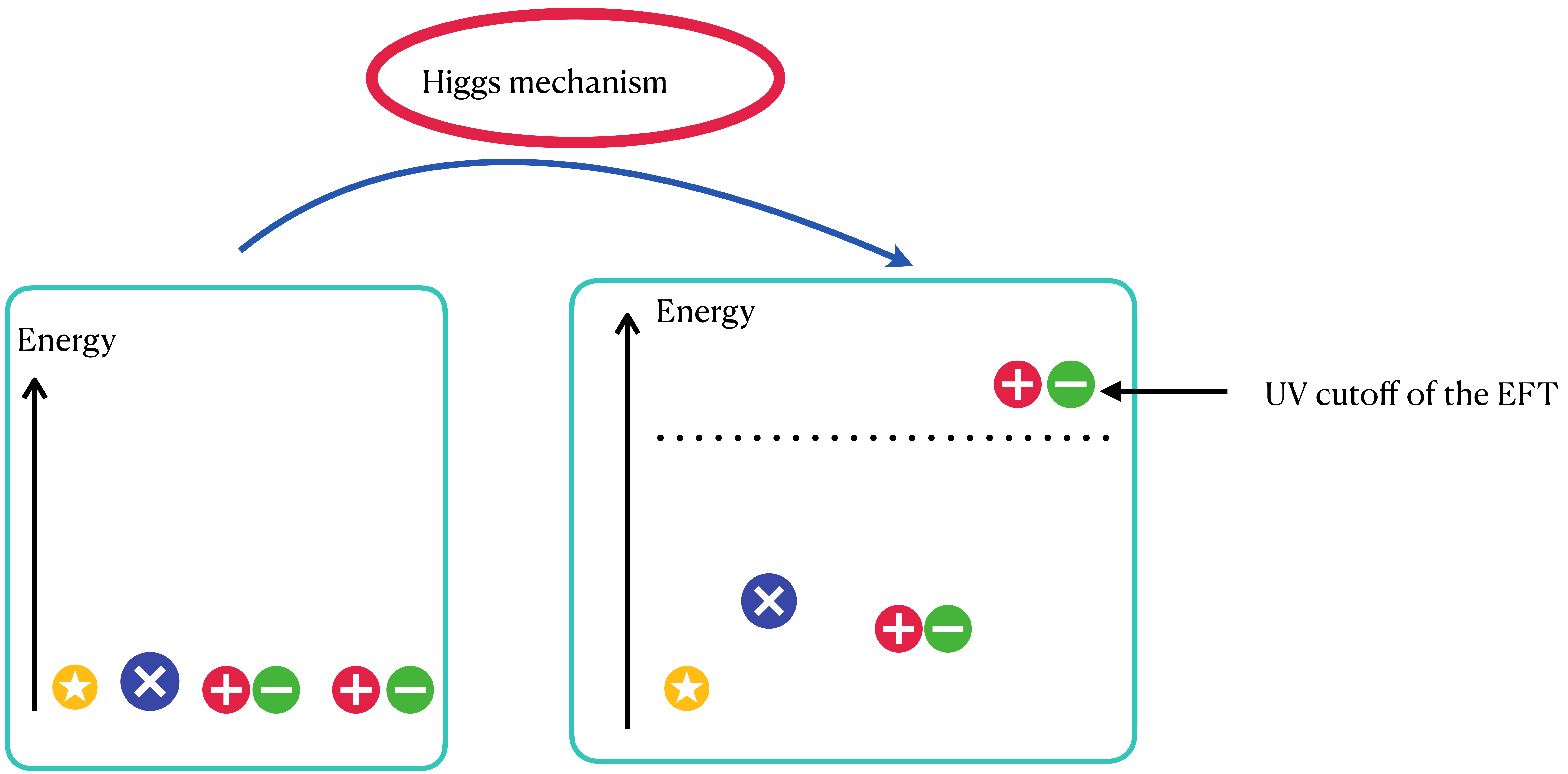
Anomaly cancellation among the three

One massless and two massive chiral fermions

Anomaly cancellation lost in the EFT

Old story but very few explicit realizations

A perturbative EFT field description



Many massless chiral fermions
+
Gauge bosons

Hierarchy of Yukawa couplings
Hierarchy gauge vs Yukawa couplings

Hierarchy might lead to non-perturbative coupling

Example: top quark in SM

Aiming for:

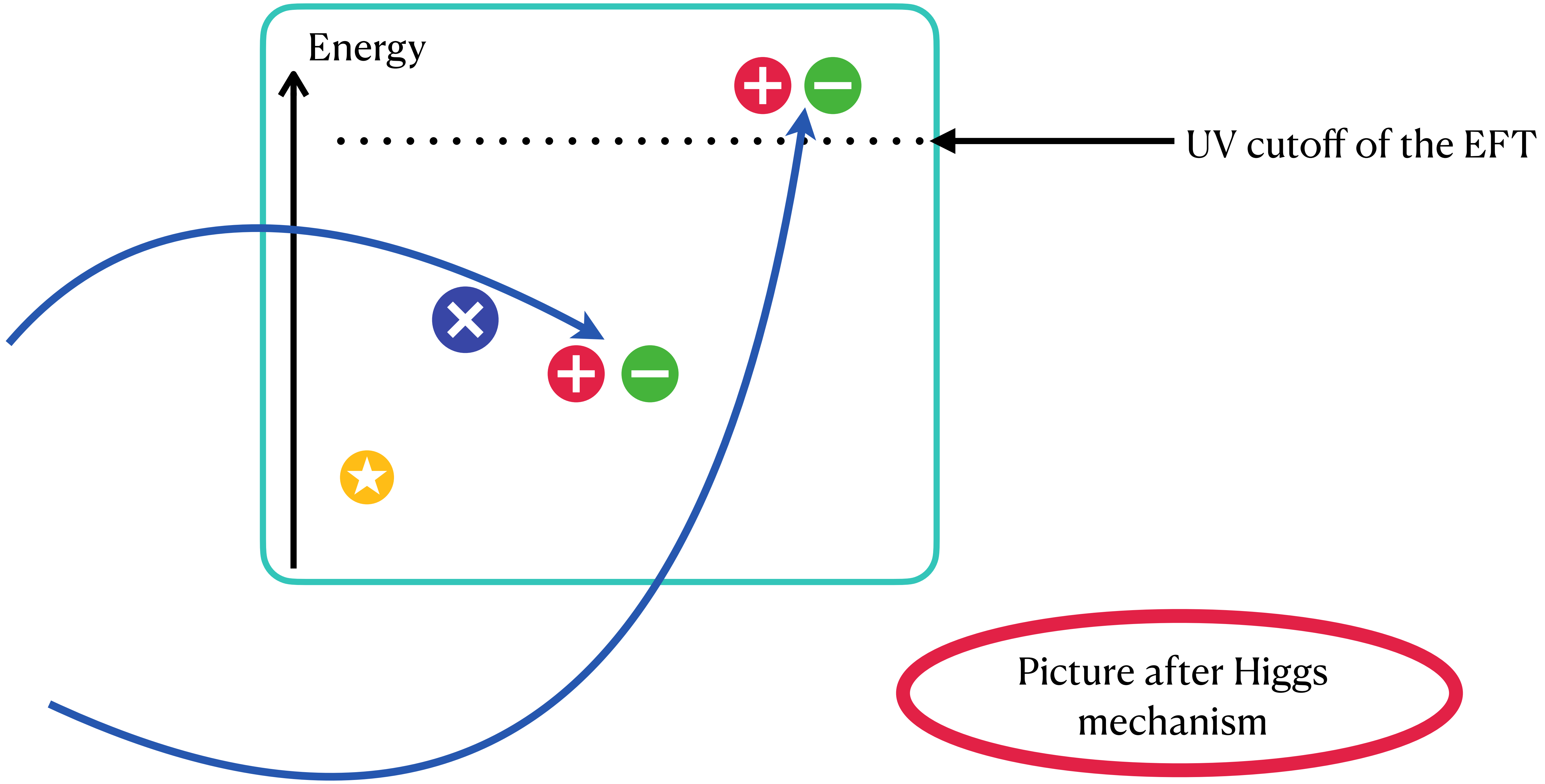
Our objective is:

To orchestrate a situation in which the contributions to the anomalies of the $U(1)_A$ gauge symmetry cancel out between:

- the light fields present in the effective field theory

and

- the (non-observable) heavier chiral fermions.



An explicit Model:

Our objective is:

To orchestrate a situation in which the contributions to the anomalies of the $U(1)_A$ gauge symmetry cancel out between:

- the light fields present in the effective field theory = Standard Model

and

- the (non-observable) heavier chiral fermions = New (secluded) sector

The Model Field Content

Our objective is:

To orchestrate a situation in which the contributions to the anomalies of the $U(1)_A$ gauge symmetry cancel out between:

- the light fields present in the effective field theory

and

- the (non-observable) heavier chiral fermions.

			$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_A$
SM sector	$\mathbf{Q}_L^f$	$f = 1, 2, 3$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$z_{\mathbf{Q}}^f$
	$u_R^{c,f}$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	z_u^f
	$d_R^{c,f}$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	z_d^f
	$\mathbf{L}_L^f$		$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$z_{\mathbf{L}}^f$
	$e_R^{c,f}$		$\mathbf{1}$	$\mathbf{1}$	1	z_e^f
	$\nu_R^{c,f}$		$\mathbf{1}$	$\mathbf{1}$	0	z_ν^f
Secluded sector	$\psi_L^{\mathbf{L}_i}$		$\mathbf{1}$	$\mathbf{2}$	$y_{\mathbf{L}}^i$	$q_{\mathbf{L}}^i$
	$(\psi_R^{\mathbf{L}_i})^c$	$i = 1, .., N_{\mathbf{L}}$	$\mathbf{1}$	$\mathbf{2}$	$-y_{\mathbf{L}}^i$	$\widetilde{q_{\mathbf{L}}}^i$
	$\psi_L^{e_j}$		$\mathbf{1}$	$\mathbf{1}$	y_e^j	q_e^j
	$(\psi_R^{e_j})^c$	$j = 1, .., N_e$	$\mathbf{1}$	$\mathbf{1}$	$-y_e^j$	$\widetilde{q_e}^j$
	$\psi_L^{d_k}$		$\mathbf{3}$	$\mathbf{1}$	y_d^k	q_d^k
	$(\psi_R^{d_k})^c$	$k = 1, .., N_d$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-y_d^k$	$\widetilde{q_d}^k$
	$\psi_L^{\mathbf{Q}_m}$		$\mathbf{3}$	$\mathbf{2}$	$y_{\mathbf{Q}}^m$	$q_{\mathbf{Q}}^m$
	$(\psi_R^{\mathbf{Q}_m})^c$	$m = 1, .., N_{\mathbf{Q}}$	$\bar{\mathbf{3}}$	$\mathbf{2}$	$-y_{\mathbf{Q}}^m$	$\widetilde{q_{\mathbf{Q}}}^m$

Table 1: The particle content of the model

Masses through Higgses

$$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle S \rangle = \frac{v_S}{\sqrt{2}},$$

$$v \ll v_S$$

		$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_A$
$\mathbf{Q}_L^f$	$f = 1, 2, 3$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$z_{\mathbf{Q}}^f$
$u_R^{c,f}$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	z_u^f
$d_R^{c,f}$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	z_d^f
$\mathbf{L}_L^f$		$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$z_{\mathbf{L}}^f$
$e_R^{c,f}$		$\mathbf{1}$	$\mathbf{1}$	1	z_e^f
$\nu_R^{c,f}$		$\mathbf{1}$	$\mathbf{1}$	0	z_ν^f
H		$\mathbf{1}$	$\mathbf{2}$	$1/2$	z_H
$\psi_L^{\mathbf{L}_i}$		$\mathbf{1}$	$\mathbf{2}$	$y_{\mathbf{L}}^i$	$q_{\mathbf{L}}^i$
$(\psi_R^{\mathbf{L}_i})^c$	$i = 1, .., N_{\mathbf{L}}$	$\mathbf{1}$	$\mathbf{2}$	$-y_{\mathbf{L}}^i$	$\widetilde{q_{\mathbf{L}}}^i$
$\psi_L^{e_j}$		$\mathbf{1}$	$\mathbf{1}$	y_e^j	q_e^j
$(\psi_R^{e_j})^c$	$j = 1, .., N_e$	$\mathbf{1}$	$\mathbf{1}$	$-y_e^j$	$\widetilde{q_e}^j$
$\psi_L^{d_k}$		$\mathbf{3}$	$\mathbf{1}$	y_d^k	q_d^k
$(\psi_R^{d_k})^c$	$k = 1, .., N_d$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-y_d^k$	$\widetilde{q_d}^k$
$\psi_L^{\mathbf{Q}_m}$		$\mathbf{3}$	$\mathbf{2}$	$y_{\mathbf{Q}}^m$	$q_{\mathbf{Q}}^m$
$(\psi_R^{\mathbf{Q}_m})^c$	$m = 1, .., N_{\mathbf{Q}}$	$\bar{\mathbf{3}}$	$\mathbf{2}$	$-y_{\mathbf{Q}}^m$	$\widetilde{q_{\mathbf{Q}}}^m$
S		$\mathbf{1}$	$\mathbf{1}$	0	q_S

Masses through Higgses

$$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle S \rangle = \frac{v_S}{\sqrt{2}},$$

$$v \ll v_S$$

$U(1)_A$ gauge boson mass

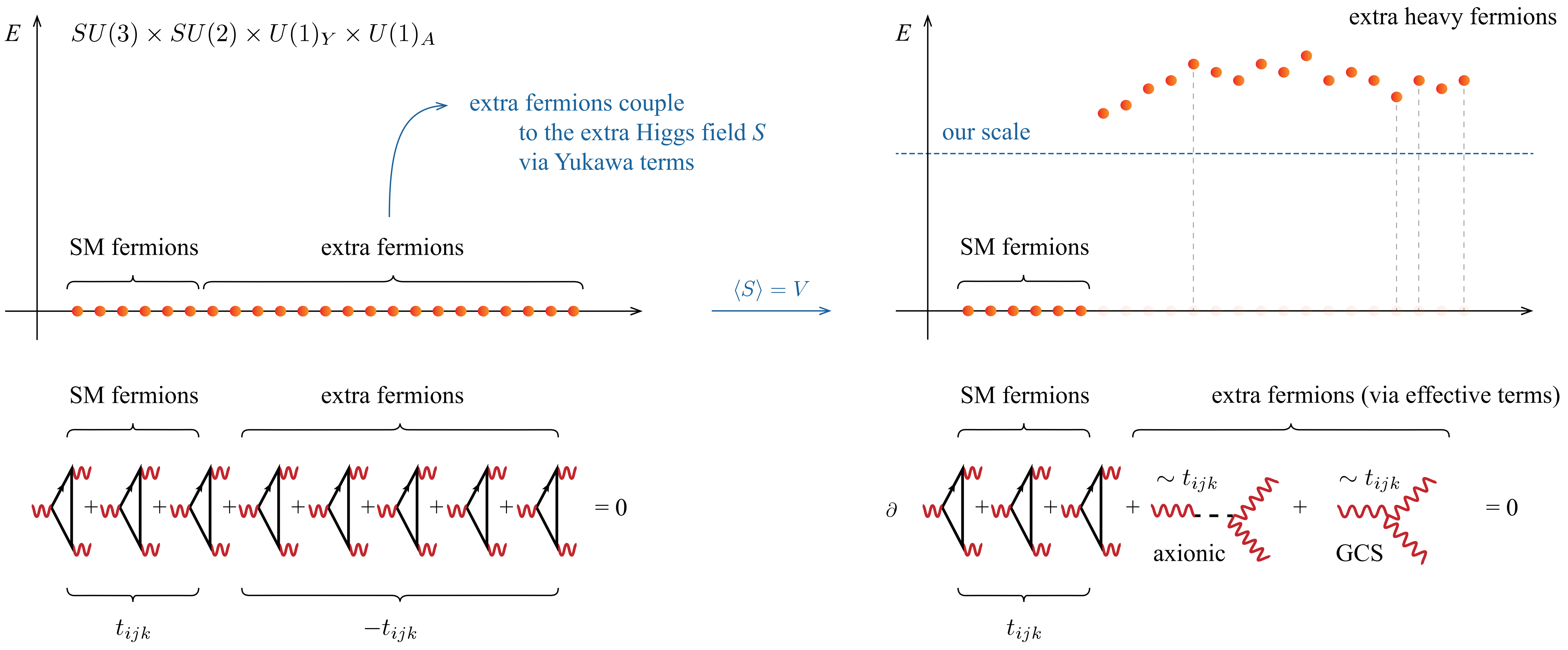
$$M_A \sim g_A |q_S| v_S .$$

Yukawa terms $Y_{ij} \bar{\psi}^i_L \psi^i_R \tilde{S}$, where by $\tilde{S}$ we denote S or S^*

$$M_{\psi,ij} = Y_{ij} v_S$$

$$Y_{ij} \propto \delta_{ij}$$

		$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_A$
$\mathbf{Q}^f_L$	$f = 1,2,3$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$z^f_{\mathbf{Q}}$
$u^{c,f}_R$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	z^f_u
$d^{c,f}_R$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	z^f_d
$\mathbf{L}^f_L$		$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$z^f_{\mathbf{L}}$
$e^{c,f}_R$		$\mathbf{1}$	$\mathbf{1}$	1	z^f_e
$\nu^{c,f}_R$		$\mathbf{1}$	$\mathbf{1}$	0	z^f_ν
H		$\mathbf{1}$	$\mathbf{2}$	$1/2$	z_H
$\psi^{\mathbf{L}_i}_L$		$\mathbf{1}$	$\mathbf{2}$	$y^i_{\mathbf{L}}$	$q^i_{\mathbf{L}}$
$(\psi^{\mathbf{L}_i}_R)^c$	$i = 1,..,N_{\mathbf{L}}$	$\mathbf{1}$	$\mathbf{2}$	$-y^i_{\mathbf{L}}$	$\widetilde{q_{\mathbf{L}}}^i$
$\psi^{e_j}_L$		$\mathbf{1}$	$\mathbf{1}$	y^j_e	q^j_e
$(\psi^{e_j}_R)^c$	$j = 1,..,N_e$	$\mathbf{1}$	$\mathbf{1}$	$-y^j_e$	$\widetilde{q_e}^j$
$\psi^{d_k}_L$		$\mathbf{3}$	$\mathbf{1}$	y^k_d	q^k_d
$(\psi^{d_k}_R)^c$	$k = 1,..,N_d$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-y^k_d$	$\widetilde{q_d}^k$
$\psi^{\mathbf{Q}_m}_L$		$\mathbf{3}$	$\mathbf{2}$	$y^m_{\mathbf{Q}}$	$q^m_{\mathbf{Q}}$
$(\psi^{\mathbf{Q}_m}_R)^c$	$m = 1,..,N_{\mathbf{Q}}$	$\bar{\mathbf{3}}$	$\mathbf{2}$	$-y^m_{\mathbf{Q}}$	$\widetilde{q_{\mathbf{Q}}}^m$
S		$\mathbf{1}$	$\mathbf{1}$	0	q_S



E
$SU(3) \times SU(2) \times U(1)_Y \times U(1)_A$
extra fermions couple
to the extra Higgs field S
via Yukawa terms
SM fermions
extra fermions
$\langle S \rangle = V$
E
extra heavy fermions
our scale
SM fermions
SM fermions
extra fermions
$= 0$
t_{ijk}
$-t_{ijk}$
SM fermions
extra fermions (via effective terms)
∂
$\sim t_{ijk}$
$\sim t_{ijk}$
axionic
GCS
$= 0$
t_{ijk}

Exploration of potential models

The Complete Model anomaly cancellation equations

Cancellation of the anomalies contributions

$$
\begin{aligned}
Tr[Y]_{SM} &= Tr[Y]_{secluded} &&= 0, \\
Tr[YYY]_{SM} &= Tr[YYY]_{secluded} &&= 0, \\
Tr[YT_2T_2]_{SM} &= Tr[YT_2T_2]_{secluded} &&= 0, \\
Tr[YT_3T_3]_{SM} &= Tr[YT_3T_3]_{secluded} &&= 0, \\
Tr[T_3T_3T_3]_{SM} &= Tr[T_3T_3T_3]_{secluded} &&= 0,
\end{aligned}
$$

$$
\begin{aligned}
Tr[q_A]_{SM} &= -Tr[q_A]_{secluded} &&\equiv t_A, \\
Tr[YYq_A]_{SM} &= -Tr[YYq_A]_{secluded} &&\equiv t_{YYA}, \\
Tr[Yq_Aq_A]_{SM} &= -Tr[Yq_Aq_A]_{secluded} &&\equiv t_{YAA}, \\
Tr[q_Aq_Aq_A]_{SM} &= -Tr[q_Aq_Aq_A]_{secluded} &&\equiv t_{AAA}, \\
Tr[q_AT_2T_2]_{SM} &= -Tr[q_AT_2T_2]_{secluded} &&\equiv t_2, \\
Tr[q_AT_3T_3]_{SM} &= -Tr[q_AT_3T_3]_{secluded} &&\equiv t_3.
\end{aligned}
$$

Anomalies contributions = Triangular Feynman diagrams

		$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_A$
$\mathbf{Q}_L^f$	$f=1,2,3$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$z_{\mathbf{Q}}^f$
$u_R^{c,f}$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	z_u^f
$d_R^{c,f}$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	z_d^f
$\mathbf{L}_L^f$		$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$z_{\mathbf{L}}^f$
$e_R^{c,f}$		$\mathbf{1}$	$\mathbf{1}$	1	z_e^f
$\nu_R^{c,f}$		$\mathbf{1}$	$\mathbf{1}$	0	z_ν^f
H		$\mathbf{1}$	$\mathbf{2}$	$1/2$	z_H
$\psi_L^{\mathbf{L}_i}$		$\mathbf{1}$	$\mathbf{2}$	$y_{\mathbf{L}}^i$	$q_{\mathbf{L}}^i$
$(\psi_R^{\mathbf{L}_i})^c$	$i=1,..,N_{\mathbf{L}}$	$\mathbf{1}$	$\mathbf{2}$	$-y_{\mathbf{L}}^i$	$\widetilde{q_{\mathbf{L}}}^i$
$\psi_L^{e_j}$		$\mathbf{1}$	$\mathbf{1}$	y_e^j	q_e^j
$(\psi_R^{e_j})^c$	$j=1,..,N_e$	$\mathbf{1}$	$\mathbf{1}$	$-y_e^j$	$\widetilde{q_e}^j$
$\psi_L^{d_k}$		$\mathbf{3}$	$\mathbf{1}$	y_d^k	q_d^k
$(\psi_R^{d_k})^c$	$k=1,..,N_d$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-y_d^k$	$\widetilde{q_d}^k$
$\psi_L^{\mathbf{Q}_m}$		$\mathbf{3}$	$\mathbf{2}$	$y_{\mathbf{Q}}^m$	$q_{\mathbf{Q}}^m$
$(\psi_R^{\mathbf{Q}_m})^c$	$m=1,..,N_{\mathbf{Q}}$	$\bar{\mathbf{3}}$	$\mathbf{2}$	$-y_{\mathbf{Q}}^m$	$\widetilde{q_{\mathbf{Q}}}^m$
S		$\mathbf{1}$	$\mathbf{1}$	0	q_S

Exploration of potential models

STEP 1: Reduce number of parameters

Constraints from SM fermions masses

SM Yukawa couplings

$$\begin{aligned} \bar{\mathbf{Q}}^i_L H d^j_R &\to -z^i_{\mathbf{Q}} - z^j_d + z_H &= 0,\\ \bar{\mathbf{Q}}^i_L \tilde{H} u^j_R &\to -z^i_{\mathbf{Q}} - z^j_{u_R} - z_H &= 0,\\ \bar{\mathbf{L}}^i H e^j_R, &\to -z^i_{\mathbf{L}} - z^j_{e_R} + z_H &= 0. \end{aligned}$$

Dirac neutrino mass

$$\bar{\mathbf{L}}^i \tilde{H} \nu^j_R \to -z^i_{\mathbf{L}} - z^j_{\nu_R} - z_H = 0,$$

Majorana neutrino mass

$$\bar{\nu}^{c,i}_R \nu^j_R \frac{\tilde{S}^n}{\Lambda^{n-1}} \to z^i_{\nu_R} + z^j_{\nu_R} - (\varepsilon^{ij}_\nu)^n n\, q_S = 0,$$

$\varepsilon^{ij}_\nu = \pm 1$ depending if we use S or S^*

		$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_A$
$\mathbf{Q}^f_L$	$f = 1,2,3$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$z^f_{\mathbf{Q}}$
$u^{c,f}_R$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	z^f_u
$d^{c,f}_R$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	z^f_d
$\mathbf{L}^f_L$		$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$z^f_{\mathbf{L}}$
$e^{c,f}_R$		$\mathbf{1}$	$\mathbf{1}$	1	z^f_e
$\nu^{c,f}_R$		$\mathbf{1}$	$\mathbf{1}$	0	z^f_ν
H		$\mathbf{1}$	$\mathbf{2}$	$1/2$	z_H
$\psi^{\mathbf{L}_i}_L$		$\mathbf{1}$	$\mathbf{2}$	$y^i_{\mathbf{L}}$	$q^i_{\mathbf{L}}$
$(\psi^{\mathbf{L}_i}_R)^c$	$i = 1,..,N_{\mathbf{L}}$	$\mathbf{1}$	$\mathbf{2}$	$-y^i_{\mathbf{L}}$	$\widetilde{q_{\mathbf{L}}}^i$
$\psi^{e_j}_L$		$\mathbf{1}$	$\mathbf{1}$	y^j_e	q^j_e
$(\psi^{e_j}_R)^c$	$j = 1,..,N_e$	$\mathbf{1}$	$\mathbf{1}$	$-y^j_e$	$\widetilde{q_e}^j$
$\psi^{d_k}_L$		$\mathbf{3}$	$\mathbf{1}$	y^k_d	q^k_d
$(\psi^{d_k}_R)^c$	$k = 1,..,N_d$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-y^k_d$	$\widetilde{q_d}^k$
$\psi^{\mathbf{Q}_m}_L$		$\mathbf{3}$	$\mathbf{2}$	$y^m_{\mathbf{Q}}$	$q^m_{\mathbf{Q}}$
$(\psi^{\mathbf{Q}_m}_R)^c$	$m = 1,..,N_{\mathbf{Q}}$	$\bar{\mathbf{3}}$	$\mathbf{2}$	$-y^m_{\mathbf{Q}}$	$\widetilde{q_{\mathbf{Q}}}^m$
S		$\mathbf{1}$	$\mathbf{1}$	0	q_S

Constraints from the extra fermions Yukawa's

Secluded sector Yukawa couplings

$$
\begin{aligned}
\bar\psi_L^{\mathbf{L}_i}\psi_R^{\mathbf{L}_i}\hat S \quad &\rightarrow \quad -q_{\mathbf{L}}^i - \widetilde{q_{\mathbf{L}}}^i + \varepsilon_{\mathbf{L}}^i q_S &= 0\\
\bar\psi_L^{e_j}\psi_R^{e_j}\hat S \quad &\rightarrow \quad -q_e^j - \widetilde{q_e}^j + \varepsilon_e^j q_S &= 0\\
\bar\psi_L^{d_k}\psi_R^{d_k}\hat S \quad &\rightarrow \quad -q_d^k - \widetilde{q_d}^k + \varepsilon_d^k q_S &= 0\\
\bar\psi_L^{\mathbf{Q}_m}\psi_R^{\mathbf{Q}_m}\hat S \quad &\rightarrow \quad -q_{\mathbf{Q}}^m - \widetilde{q_{\mathbf{Q}}}^m + \varepsilon_{\mathbf{Q}}^m q_S &= 0
\end{aligned}
$$

$\hat S$ denotes either S or S^*

$$\varepsilon_{\mathbf{L}}^i, \varepsilon_e^j, \varepsilon_d^k, \varepsilon_{\mathbf{Q}}^m = \pm 1$$

		$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_A$
$\mathbf{Q}_L^f$	$f = 1,2,3$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$z_{\mathbf{Q}}^f$
$u_R^{c,f}$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	z_u^f
$d_R^{c,f}$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	z_d^f
$\mathbf{L}_L^f$		$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$z_{\mathbf{L}}^f$
$e_R^{c,f}$		$\mathbf{1}$	$\mathbf{1}$	1	z_e^f
$\nu_R^{c,f}$		$\mathbf{1}$	$\mathbf{1}$	0	z_ν^f
H		$\mathbf{1}$	$\mathbf{2}$	$1/2$	z_H
$\psi_L^{\mathbf{L}_i}$		$\mathbf{1}$	$\mathbf{2}$	$y_{\mathbf{L}}^i$	$q_{\mathbf{L}}^i$
$(\psi_R^{\mathbf{L}_i})^c$	$i = 1,..,N_{\mathbf{L}}$	$\mathbf{1}$	$\mathbf{2}$	$-y_{\mathbf{L}}^i$	$\widetilde{q_{\mathbf{L}}}^i$
$\psi_L^{e_j}$		$\mathbf{1}$	$\mathbf{1}$	y_e^j	q_e^j
$(\psi_R^{e_j})^c$	$j = 1,..,N_e$	$\mathbf{1}$	$\mathbf{1}$	$-y_e^j$	$\widetilde{q_e}^j$
$\psi_L^{d_k}$		$\mathbf{3}$	$\mathbf{1}$	y_d^k	q_d^k
$(\psi_R^{d_k})^c$	$k = 1,..,N_d$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-y_d^k$	$\widetilde{q_d}^k$
$\psi_L^{\mathbf{Q}_m}$		$\mathbf{3}$	$\mathbf{2}$	$y_{\mathbf{Q}}^m$	$q_{\mathbf{Q}}^m$
$(\psi_R^{\mathbf{Q}_m})^c$	$m = 1,..,N_{\mathbf{Q}}$	$\bar{\mathbf{3}}$	$\mathbf{2}$	$-y_{\mathbf{Q}}^m$	$\widetilde{q_{\mathbf{Q}}}^m$
S		$\mathbf{1}$	$\mathbf{1}$	0	q_S

Anomaly equations from SM fermions

Cancellation of the anomalies contributions

$$
\begin{aligned}
Tr[q_A]_{SM} &= \textstyle\sum_f [6z^f_{\mathbf{Q}} + 3z^f_u + 3z^f_d + 2z^f_{\mathbf{L}} + z^f_e + z^f_\nu] &&= t_A,\\
Tr[YYq_A]_{SM} &= \textstyle\sum_f [6(y^f_{\mathbf{Q}})^2 z^f_{\mathbf{Q}} + 3(y^f_u)^2 z^f_u + 3(y^f_d)^2 z^f_d + 2(y^f_L)^2 z^f_{\mathbf{L}} + (y^f_e)^2 z^f_e] &&= t_{YYA},\\
Tr[Yq_Aq_A]_{SM} &= \textstyle\sum_f [6y^f_{\mathbf{Q}}(z^f_{\mathbf{Q}})^2 + 3y^f_u(z^f_u)^2 + 3y^f_d(z^f_d)^2 + 2y^f_L(z^f_{\mathbf{L}})^2 + y^f_e(z^f_e)^2] &&= t_{YAA},\\
Tr[q_Aq_Aq_A]_{SM} &= \textstyle\sum_f [6(z^f_{\mathbf{Q}})^3 + 3(z^f_u)^3 + 3(z^f_d)^3 + 2(z^f_{\mathbf{L}})^3 + (z^f_e)^3 + (z^f_\nu)^3] &&= t_{AAA},\\
Tr[q_AT_2T_2]_{SM} &= \textstyle\sum_f [3z^f_{\mathbf{Q}} + z^f_{\mathbf{L}}] &&= t_2,\\
Tr[q_AT_3T_3]_{SM} &= \textstyle\sum_f [2z^f_{\mathbf{Q}} + z^f_u + z^f_d] &&= t_3,
\end{aligned}
$$

Impose relations from Yukawa coupling constraints:

$$
\begin{aligned}
Tr[q_A]_{SM} &= \textstyle\sum_f [2z^f_{\mathbf{L}} + z^f_e + z^f_\nu] &&= t_A\\
Tr[YYq_A]_{SM} &= -\tfrac{1}{2}\textstyle\sum_f [3z^f_{\mathbf{Q}} + z^f_{\mathbf{L}}] &&= t_{YYA}\\
Tr[Yq_Aq_A]_{SM} &= -2\textstyle\sum_f [3z^f_{\mathbf{Q}} + z^f_{\mathbf{L}}] z_H &&= t_{YAA}\\
Tr[q_Aq_Aq_A]_{SM} &= \textstyle\sum_f [z_H^3 + 3z_H(z^f_{\mathbf{L}})^2 + (z^f_{\mathbf{L}})^3 - 3z_H^2 z^f_{\mathbf{L}} - 18z_H^2 z^f_{\mathbf{Q}} + (z^f_\nu)^3] &&= t_{AAA}\\
Tr[q_AT_2T_2]_{SM} &= \textstyle\sum_f [3z^f_{\mathbf{Q}} + z^f_{\mathbf{L}}] &&= t_2\\
Tr[q_AT_3T_3]_{SM} &= 0 &&= t_3
\end{aligned}
$$

$$t_{YYA} = -\frac{1}{2}t_2\ , \quad t_{YAA} = -2z_H t_2\ , \quad t_3 = 0. \qquad t_A = 0\ , \quad t_{AAA} = -6z_H^2 t_2$$

(neutrino Dirac mass constraints)

		$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_A$
$\mathbf{Q}^f_L$	$f = 1, 2, 3$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$z^f_{\mathbf{Q}}$
$u^{c,f}_R$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	z^f_u
$d^{c,f}_R$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	z^f_d
$\mathbf{L}^f_L$		$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$z^f_{\mathbf{L}}$
$e^{c,f}_R$		$\mathbf{1}$	$\mathbf{1}$	1	z^f_e
$\nu^{c,f}_R$		$\mathbf{1}$	$\mathbf{1}$	0	z^f_ν
H		$\mathbf{1}$	$\mathbf{2}$	$1/2$	z_H
$\psi^{\mathbf{L}_i}_L$		$\mathbf{1}$	$\mathbf{2}$	$y^i_{\mathbf{L}}$	$q^i_{\mathbf{L}}$
$(\psi^{\mathbf{L}_i}_R)^c$	$i = 1, .., N_{\mathbf{L}}$	$\mathbf{1}$	$\mathbf{2}$	$-y^i_{\mathbf{L}}$	$\widetilde{q_{\mathbf{L}}}^i$
$\psi^{e_j}_L$		$\mathbf{1}$	$\mathbf{1}$	y^j_e	q^j_e
$(\psi^{e_j}_R)^c$	$j = 1, .., N_e$	$\mathbf{1}$	$\mathbf{1}$	$-y^j_e$	$\widetilde{q_e}^j$
$\psi^{d_k}_L$		$\mathbf{3}$	$\mathbf{1}$	y^k_d	q^k_d
$(\psi^{d_k}_R)^c$	$k = 1, .., N_d$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-y^k_d$	$\widetilde{q_d}^k$
$\psi^{\mathbf{Q}_m}_L$		$\mathbf{3}$	$\mathbf{2}$	$y^m_{\mathbf{Q}}$	$q^m_{\mathbf{Q}}$
$(\psi^{\mathbf{Q}_m}_R)^c$	$m = 1, .., N_{\mathbf{Q}}$	$\bar{\mathbf{3}}$	$\mathbf{2}$	$-y^m_{\mathbf{Q}}$	$\widetilde{q_{\mathbf{Q}}}^m$
S		$\mathbf{1}$	$\mathbf{1}$	0	q_S

Universality hypothesis

Assume universality with respect to both U(1)'s

$\forall\ i = 1, ..., N_{\mathbf{L}}$	$\forall\ j = 1, ..., N_e$	$\forall\ k = 1, ..., N_d$	$\forall\ m = 1, ..., N_{\mathbf{Q}}$
$\varepsilon^i_{\mathbf{L}} = \varepsilon_{\mathbf{L}}$	$\varepsilon^j_e = \varepsilon_e$	$\varepsilon^k_d = \varepsilon_d$	$\varepsilon^m_{\mathbf{Q}} = \varepsilon_{\mathbf{Q}}$
$y^i_{\mathbf{L}} = y_{\mathbf{L}}$	$y^j_e = y_e$	$y^k_d = y_d$	$y^m_{\mathbf{Q}} = y_{\mathbf{Q}}$
$q^i_{\mathbf{L}} = q_{\mathbf{L}}$	$q^j_e = q_e$	$q^k_d = q_d$	$q^m_{\mathbf{Q}} = q_{\mathbf{Q}}$
$\widetilde{q_{\mathbf{L}}}^i = \widetilde{q_{\mathbf{L}}}$	$\widetilde{q_e}^j = \widetilde{q_e}$	$\widetilde{q_d}^k = \widetilde{q_d}$	$\widetilde{q_{\mathbf{Q}}}^m = \widetilde{q_{\mathbf{Q}}}$

		$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_A$
$\mathbf{Q}^f_L$	$f = 1, 2, 3$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$z^f_{\mathbf{Q}}$
$u^{c,f}_R$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	z^f_u
$d^{c,f}_R$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	z^f_d
$\mathbf{L}^f_L$		$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$z^f_{\mathbf{L}}$
$e^{c,f}_R$		$\mathbf{1}$	$\mathbf{1}$	1	z^f_e
$\nu^{c,f}_R$		$\mathbf{1}$	$\mathbf{1}$	0	z^f_ν
H		$\mathbf{1}$	$\mathbf{2}$	$1/2$	z_H
$\psi^{\mathbf{L}_i}_L$		$\mathbf{1}$	$\mathbf{2}$	$y^i_{\mathbf{L}}$	$q^i_{\mathbf{L}}$
$(\psi^{\mathbf{L}_i}_R)^c$	$i = 1, .., N_{\mathbf{L}}$	$\mathbf{1}$	$\mathbf{2}$	$-y^i_{\mathbf{L}}$	$\widetilde{q_{\mathbf{L}}}^i$
$\psi^{e_j}_L$		$\mathbf{1}$	$\mathbf{1}$	y^j_e	q^j_e
$(\psi^{e_j}_R)^c$	$j = 1, .., N_e$	$\mathbf{1}$	$\mathbf{1}$	$-y^j_e$	$\widetilde{q_e}^j$
$\psi^{d_k}_L$		$\mathbf{3}$	$\mathbf{1}$	y^k_d	q^k_d
$(\psi^{d_k}_R)^c$	$k = 1, .., N_d$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-y^k_d$	$\widetilde{q_d}^k$
$\psi^{\mathbf{Q}_m}_L$		$\mathbf{3}$	$\mathbf{2}$	$y^m_{\mathbf{Q}}$	$q^m_{\mathbf{Q}}$
$(\psi^{\mathbf{Q}_m}_R)^c$	$m = 1, .., N_{\mathbf{Q}}$	$\bar{\mathbf{3}}$	$\mathbf{2}$	$-y^m_{\mathbf{Q}}$	$\widetilde{q_{\mathbf{Q}}}^m$
S		$\mathbf{1}$	$\mathbf{1}$	0	q_S

Anomalies from the extra fermions

Cancellation of the anomalies contributions

$$
\begin{aligned}
Tr[q_A]_{secluded} &= \Big(2\varepsilon_{\mathbf{L}} N_{\mathbf{L}} + \varepsilon_e N_e + 3\varepsilon_d N_d + 6\varepsilon_{\mathbf{Q}} N_{\mathbf{Q}}\Big) q_S && = -t_A, \\
Tr[YYq_A]_{secluded} &= \Big(2\varepsilon_{\mathbf{L}} y_{\mathbf{L}}^2 N_{\mathbf{L}} + \varepsilon_e y_e^2 N_e \\
&\quad + 3\varepsilon_d y_d^2 N_d + 6\varepsilon_{\mathbf{Q}} y_{\mathbf{Q}}^2 N_{\mathbf{Q}}\Big) q_S && = -t_{YYA}, \\
Tr[Yq_Aq_A]_{secluded} &= -q_S^2\Big(2y_{\mathbf{L}} N_{\mathbf{L}} + y_e N_e + 3y_d N_d + 6y_{\mathbf{Q}} N_{\mathbf{Q}}\Big) \\
&\quad + 2q_S\Big(2\varepsilon_{\mathbf{L}} y_{\mathbf{L}} q_{\mathbf{L}} N_{\mathbf{L}} + \varepsilon_e y_e q_e N_e \\
&\quad + 3\varepsilon_d y_d q_d N_d + 6\varepsilon_{\mathbf{Q}} y_{\mathbf{Q}} q_{\mathbf{Q}} N_{\mathbf{Q}}\Big) && = -t_{YAA}, \\
Tr[q_Aq_Aq_A]_{secluded} &= q_S^3\Big(2\varepsilon_{\mathbf{L}} N_{\mathbf{L}} + \varepsilon_e N_e + 3\varepsilon_d N_d + 6\varepsilon_{\mathbf{Q}} N_{\mathbf{Q}}\Big) \\
&\quad - 3q_S^2\Big(2q_{\mathbf{L}} N_{\mathbf{L}} + q_e N_e + 3q_d N_d + 6q_{\mathbf{Q}} N_{\mathbf{Q}}\Big) \\
&\quad + 3q_S\Big(2\varepsilon_{\mathbf{L}} q_{\mathbf{L}}^2 N_{\mathbf{L}} + \varepsilon_e q_e^2 N_e \\
&\quad + 3\varepsilon_d q_d^2 N_d + 6\varepsilon_{\mathbf{Q}} q_{\mathbf{Q}}^2 N_{\mathbf{Q}}\Big) && = -t_{AAA}, \\
Tr[q_AT_2T_2]_{secluded} &= (\varepsilon_{\mathbf{L}} N_{\mathbf{L}} + 3\varepsilon_{\mathbf{Q}} N_{\mathbf{Q}}) q_S && = -t_2, \\
Tr[q_AT_3T_3]_{secluded} &= (\varepsilon_d N_d + 2\varepsilon_{\mathbf{Q}} N_{\mathbf{Q}}) q_S && = -t_3.
\end{aligned}
$$

		$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_A$
$\mathbf{Q}_L^f$	$f = 1,2,3$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$z_{\mathbf{Q}}^f$
$u_R^{c,f}$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	z_u^f
$d_R^{c,f}$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	z_d^f
$\mathbf{L}_L^f$		$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$z_{\mathbf{L}}^f$
$e_R^{c,f}$		$\mathbf{1}$	$\mathbf{1}$	1	z_e^f
$\nu_R^{c,f}$		$\mathbf{1}$	$\mathbf{1}$	0	z_ν^f
H		$\mathbf{1}$	$\mathbf{2}$	$1/2$	z_H
$\psi_L^{\mathbf{L}_i}$		$\mathbf{1}$	$\mathbf{2}$	$y_{\mathbf{L}}^i$	$q_{\mathbf{L}}^i$
$(\psi_R^{\mathbf{L}_i})^c$	$i = 1,..,N_{\mathbf{L}}$	$\mathbf{1}$	$\mathbf{2}$	$-y_{\mathbf{L}}^i$	$\widetilde{q_{\mathbf{L}}}^i$
$\psi_L^{e_j}$		$\mathbf{1}$	$\mathbf{1}$	y_e^j	q_e^j
$(\psi_R^{e_j})^c$	$j = 1,..,N_e$	$\mathbf{1}$	$\mathbf{1}$	$-y_e^j$	$\widetilde{q_e}^j$
$\psi_L^{d_k}$		$\mathbf{3}$	$\mathbf{1}$	y_d^k	q_d^k
$(\psi_R^{d_k})^c$	$k = 1,..,N_d$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-y_d^k$	$\widetilde{q_d}^k$
$\psi_L^{\mathbf{Q}_m}$		$\mathbf{3}$	$\mathbf{2}$	$y_{\mathbf{Q}}^m$	$q_{\mathbf{Q}}^m$
$(\psi_R^{\mathbf{Q}_m})^c$	$m = 1,..,N_{\mathbf{Q}}$	$\bar{\mathbf{3}}$	$\mathbf{2}$	$-y_{\mathbf{Q}}^m$	$\widetilde{q_{\mathbf{Q}}}^m$
S		$\mathbf{1}$	$\mathbf{1}$	0	q_S

Exploration of potential models

STEP 2: Solve the anomaly equations

Solving in the case where all N's are non zero

12 parameters: $y_{\mathbf{L}}$, y_e, $y_{\mathbf{Q}}$, y_d, $q_{\mathbf{L}}$, q_e, $q_{\mathbf{Q}}$, q_d, q_S, z_H, $N_{\mathbf{L}}$ and $N_{\mathbf{Q}}$

We demand:

- All charges are rational numbers.
- The lepton-like extra fermions $\psi^{\mathbf{L}}$ have electric charges 0 or ± 1, and ψ^e electric charge ± 1.
- The quark-like extra fermions $\psi^{\mathbf{Q}}$ and ψ^d have electric charges $\pm 1/3$ or $\pm 2/3$. Indeed, this condition ensures that when the color forces confine, the resulting bound states can all carry integer charges.
- We will consider $\varepsilon_{\mathbf{L}} = 1$, $\varepsilon_e = -1$, $\varepsilon_d = 1$ and $\varepsilon_{\mathbf{Q}} = -1$

We get:

$$y_{\mathbf{L}} = \pm\frac{1}{2}, \quad y_{\mathbf{Q}} = \pm\frac{1}{6}, \quad y_d = \pm\frac{2}{3}, \quad y_e = \pm 1, \qquad N_{\mathbf{L}} = N_{\mathbf{Q}}.$$

		$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_A$
$\mathbf{Q}_L^f$	$f = 1, 2, 3$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$z_{\mathbf{Q}}^f$
$u_R^{c,f}$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	z_u^f
$d_R^{c,f}$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	z_d^f
$\mathbf{L}_L^f$		$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$z_{\mathbf{L}}^f$
$e_R^{c,f}$		$\mathbf{1}$	$\mathbf{1}$	1	z_e^f
$\nu_R^{c,f}$		$\mathbf{1}$	$\mathbf{1}$	0	z_ν^f
H		$\mathbf{1}$	$\mathbf{2}$	$1/2$	z_H
$\psi_L^{\mathbf{L}_i}$		$\mathbf{1}$	$\mathbf{2}$	$y_{\mathbf{L}}^i$	$q_{\mathbf{L}}^i$
$(\psi_R^{\mathbf{L}_i})^c$	$i = 1, .., N_{\mathbf{L}}$	$\mathbf{1}$	$\mathbf{2}$	$-y_{\mathbf{L}}^i$	$\widetilde{q_{\mathbf{L}}}^i$
$\psi_L^{e_j}$		$\mathbf{1}$	$\mathbf{1}$	y_e^j	q_e^j
$(\psi_R^{e_j})^c$	$j = 1, .., N_e$	$\mathbf{1}$	$\mathbf{1}$	$-y_e^j$	$\widetilde{q_e}^j$
$\psi_L^{d_k}$		$\mathbf{3}$	$\mathbf{1}$	y_d^k	q_d^k
$(\psi_R^{d_k})^c$	$k = 1, .., N_d$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-y_d^k$	$\widetilde{q_d}^k$
$\psi_L^{\mathbf{Q}_m}$		$\mathbf{3}$	$\mathbf{2}$	$y_{\mathbf{Q}}^m$	$q_{\mathbf{Q}}^m$
$(\psi_R^{\mathbf{Q}_m})^c$	$m = 1, .., N_{\mathbf{Q}}$	$\bar{\mathbf{3}}$	$\mathbf{2}$	$-y_{\mathbf{Q}}^m$	$\widetilde{q_{\mathbf{Q}}}^m$
S		$\mathbf{1}$	$\mathbf{1}$	0	q_S

				Model a		Model b		Model c	
		$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_A$	$U(1)_Y$	$U(1)_A$	$U(1)_Y$	$U(1)_A$
$\mathbf{Q}_L^f$	$f=1,2,3$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$1/3$	$1/6$	$2/3$	$1/6$	$1/3$
$u_R^{c,f}$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$-10/3$	$-2/3$	$-8/3$	$-2/3$	$-4/3$
$d_R^{c,f}$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$8/3$	$1/3$	$4/3$	$1/3$	$2/3$
$\mathbf{L}_L^f$		$\mathbf{1}$	$\mathbf{2}$	$-1/2$	1	$-1/2$	2	$-1/2$	1
$e_R^{c,f}$		$\mathbf{1}$	$\mathbf{1}$	1	2	1	0	1	0
$\nu_R^{c,f}$		$\mathbf{1}$	$\mathbf{1}$	0	-4	0	-4	0	-2
H		$\mathbf{1}$	$\mathbf{2}$	$1/2$	3	$1/2$	2	$1/2$	1
$\psi_L^{\mathbf{L}_i}$		$\mathbf{1}$	$\mathbf{2}$	$-1/2$	-3	$-1/2$	-3	$-1/2$	-1
$(\psi_R^{\mathbf{L}_i})^c$	$i=1,\cdots,N_{\mathbf{L}}$	$\mathbf{1}$	$\mathbf{2}$	$+1/2$	6	$+1/2$	5	$+1/2$	2
$\psi_L^{e_j}$		$\mathbf{1}$	$\mathbf{1}$	-1	-3	$+1$	-3	-1	-1
$(\psi_R^{e_j})^c$	$j=1,\cdots,2N_{\mathbf{L}}$	$\mathbf{1}$	$\mathbf{1}$	$+1$	0	-1	1	$+1$	0
$\psi_L^{d_k}$		$\mathbf{3}$	$\mathbf{1}$	$-2/3$	0	$2/3$	$1/3$	$-2/3$	0
$(\psi_R^{d_k})^c$	$k=1,\cdots,2N_{\mathbf{L}}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$+2/3$	3	$-2/3$	$5/3$	$2/3$	1
$\psi_L^{\mathbf{Q}_m}$		$\mathbf{3}$	$\mathbf{2}$	$+1/6$	0	$+1/6$	$1/3$	$+1/6$	0
$(\psi_R^{\mathbf{Q}_m})^c$	$m=1,\cdots,N_{\mathbf{L}}$	$\bar{\mathbf{3}}$	$\mathbf{2}$	$-1/6$	-3	$-1/6$	$-7/3$	$-1/6$	-1
S		$\mathbf{1}$	$\mathbf{1}$	0	3	0	2	0	1
t_2				6		12		6	
t_{YYA}				-3		-6		-3	
t_{YAA}				-36		-48		-12	
t_{AAA}				-324		-288		-36	

Table 3. Examples of anomaly-free solutions, with all $N_i s \neq 0$. Model a: Anomaly-free solution with $q_{\mathbf{L}} = q_e, q_d = q_{\mathbf{Q}}$, and $N_{\mathbf{L}} = 1$, $z_L = 1$. Model b: Anomaly-free solution with $q_{\mathbf{L}} = q_e, q_d = q_{\mathbf{Q}}$, and $N_{\mathbf{L}} = 3$, $z_L = 2$. Model c: Anomaly-free solution with $q_{\mathbf{L}} = q_e, q_d = q_{\mathbf{Q}}$, and $N_{\mathbf{L}} = 3$, $z_L = 1$.

Energy domain of validity

I: The UV cut-off of the EFT

The EFT UV Cutoff: Preskill bound

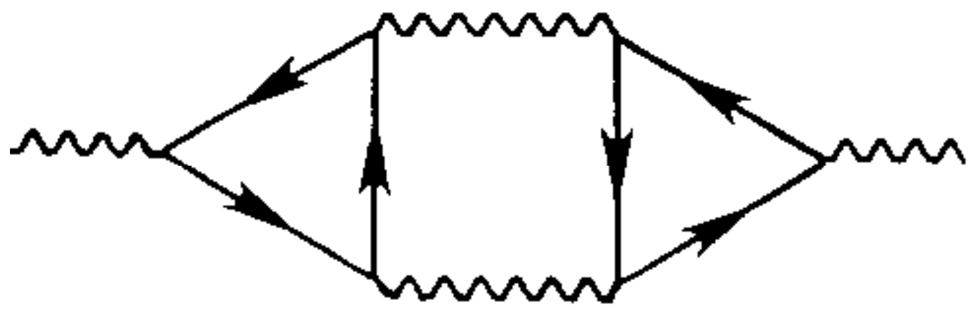
The vector boson Z' obtains its mass M_A as the sum of two distinct contributions:

$$M_A^{(0)} = g_A|q_S|v_S$$

Tree-level Higgs contribution

$$M_A^{(1)} \simeq \left| \frac{[g_A^3 t_{AAA}^{(light)} + 2g_A^2 g_Y t_{YAA}^{(light)} + g_A g_Y^2 t_{AYY}^{(light)} + g_A g_2^2 t_2^{(light)} + g_A g_3^2 t_3^{(light)}]\Lambda_{eff}}{64\pi^3} \right|$$

One-loop radiative contribution



We assume knowledge of the mass M_A and the coupling constant g_A of the $U(1)_A$ gauge boson, denoted as Z', either through theoretical calculations or experimental measurements.

We want to infer the value of the cut-off energy from this information

The EFT UV Cutoff: Preskill bound

Often quoted is the Preskill cutoff

$$\Lambda_{eff} \sim \left| \frac{64\pi^3 M_A}{[g_A^3 t_{AAA}^{(light)} + 2g_A^2 g_Y t_{YAA}^{(light)} + g_A g_Y^2 t_{AYY}^{(light)} + g_A g_2^2 t_2^{(light)} + g_A g_3^2 t_3^{(light)}]} \right|$$

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More precisely, the Preskill bound is

$$\Lambda_{eff} \lesssim \left| \frac{64\pi^3 M_A}{[g_A^3 t_{AAA}^{(light)} + 2g_A^2 g_Y t_{YAA}^{(light)} + g_A g_Y^2 t_{AYY}^{(light)} + g_A g_2^2 t_2^{(light)} + g_A g_3^2 t_3^{(light)}]} \right|$$

The EFT UV Cutoff

The effective theory cut-off scale Λ_{eff} will be approximately equal to the mass scale of the heavy fermions, i.e.,

$$\Lambda_{eff} \simeq M_f$$

the heavy secluded fermion mass originates from the Yukawa coupling

$$M_f \simeq Y_{ij} v_S \simeq v_S$$

The EFT UV Cutoff: Preskill's bound domain of validity

The ratio of the loop-induced mass with respect of the tree-level one is now of order:

$$\frac{{M_A}^{(1)}}{{M_A}^{(0)}} \simeq \frac{g_A^2 \left| t^{(h)}_{AAA} \right|}{64\pi^3 q_S} \xrightarrow[\text{all extra fermions heavy}]{} \frac{{M_A}^{(1)}}{{M_A}^{(0)}} \simeq \frac{3 g_A^2 z_H^2 N_{\mathbf{L}}}{16\pi^3}$$

Indeed, the dominance of the anomaly loop-induced mass for the Z'_A requires that $g_A {z_H}^2 N_{\mathbf{Q}} \sim 10^3$. To achieve a light Z'_A with a mass $M_A \ll M_f$, it necessitates a coupling $g_A \ll 1$. This, in turn, implies significantly large charges and/or a large number of fields $N_{\mathbf{Q}}$, especially if we assume $q_S = 1$.

The EFT UV Cutoff

One potential resolution to this issue is that only some of the fermions are heavy enough

fermions $\psi_L^{\mathbf{L}i}$ with large charges $q\mathbf{L} \gg q_S$ are heavy and inaccessible.

$$\frac{M_A{}^{(1)}}{M_A{}^{(0)}} \simeq \frac{g_A^2 \left|t^{(h)}_{AAA}\right|}{64\pi^3 q_S} \qquad \xrightarrow[N_{\mathbf{L}}\psi_L^{\mathbf{L}} \text{ heavy}]{} \qquad \frac{M_A{}^{(1)}}{M_A{}^{(0)}} \simeq \frac{3 g_A^2 q_{\mathbf{L}}^2 N_{\mathbf{L}}}{32\pi^3}$$

$g_A^2 q_{\mathbf{L}}^2 N_{\mathbf{L}}$ that needs to be of order $\sim 10^3$.

The EFT UV Cutoff

$$\Lambda_{eff} \simeq M_f \qquad M_f \simeq Y_{ij} v_S \simeq v_S \qquad M_A^{(0)} = g_A |q_S| v_S$$

$$\Longrightarrow \qquad \Lambda_{eff} \simeq \frac{M_A}{g_A q_S} \qquad (q_S > 0)$$

In the case where g_A is hierarchically the smallest coupling in the theory, the magnetic Swampland Conjecture can be used to put a bound as:

$$\Lambda_{eff} \lesssim \Lambda_{QG} \simeq g_A M_P \Rightarrow M_A \lesssim g_A^2 M_p$$

Energy domain of validity

II: Above the new fermions scale: the UV model

To make sense of our UV model description: a perturbative QFT, we request:

A model which can be valid many orders of energy scales above the new fermions scale

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Mass of Z' << Mass of new fermions

implies:

Coupling of Z' << Yukawa coupling of new fermions

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But:

The coupling of Z’ must not be too small so that we can detect the Z’

implies:

Yukawa couplings of new fermions are of O(1)

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To make sense of our UV model description: a perturbative QFT, we request:

A model which can be valid many orders of energy scales above the new fermions scale

and

Yukawa couplings of new fermions are of O(1)

imply:

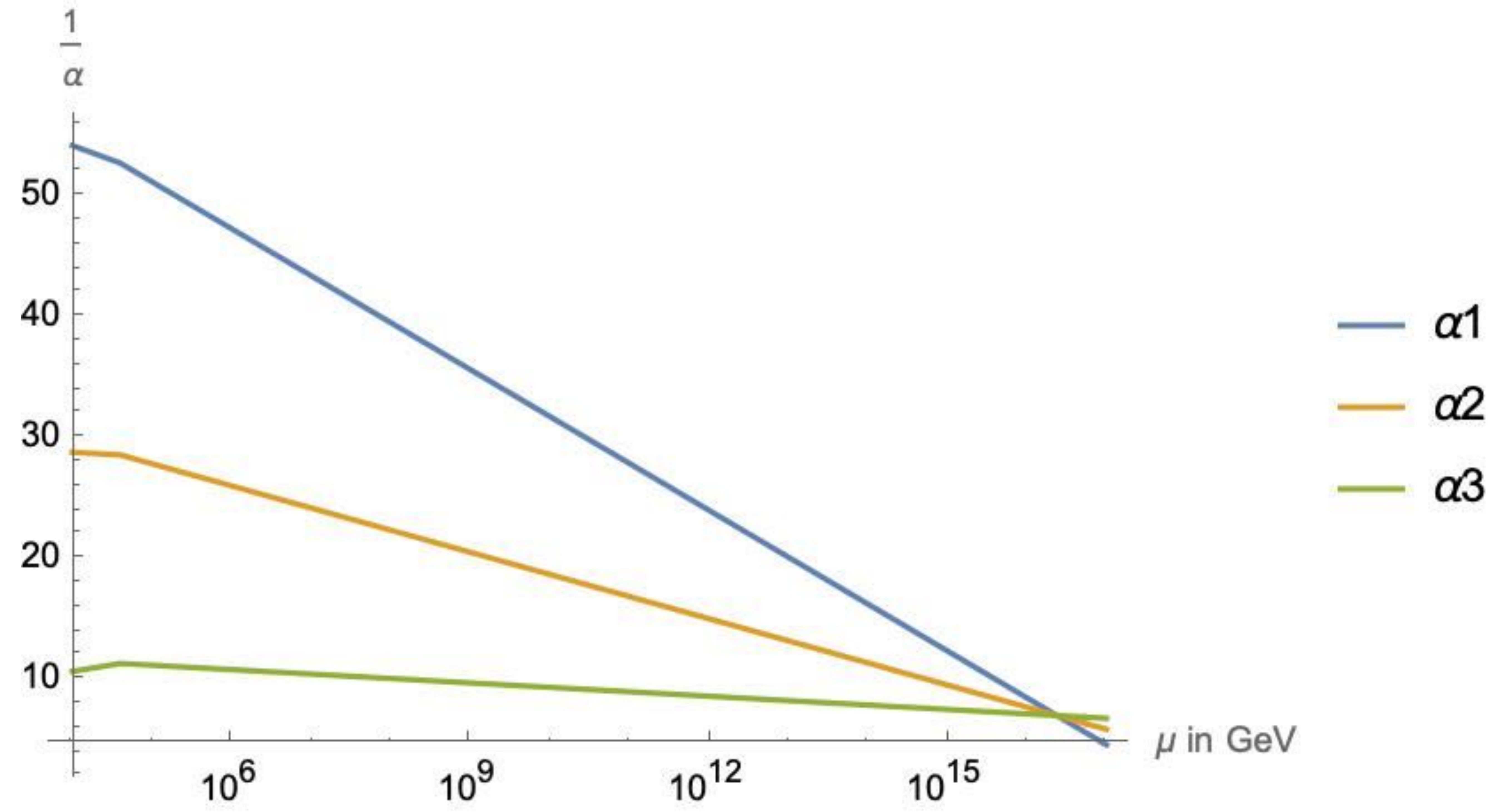
The RGE should make the Yukawa couplings not grow with increasing energy:

The contributions from gauge interactions to the RGE of the Yukawa couplings should dominate

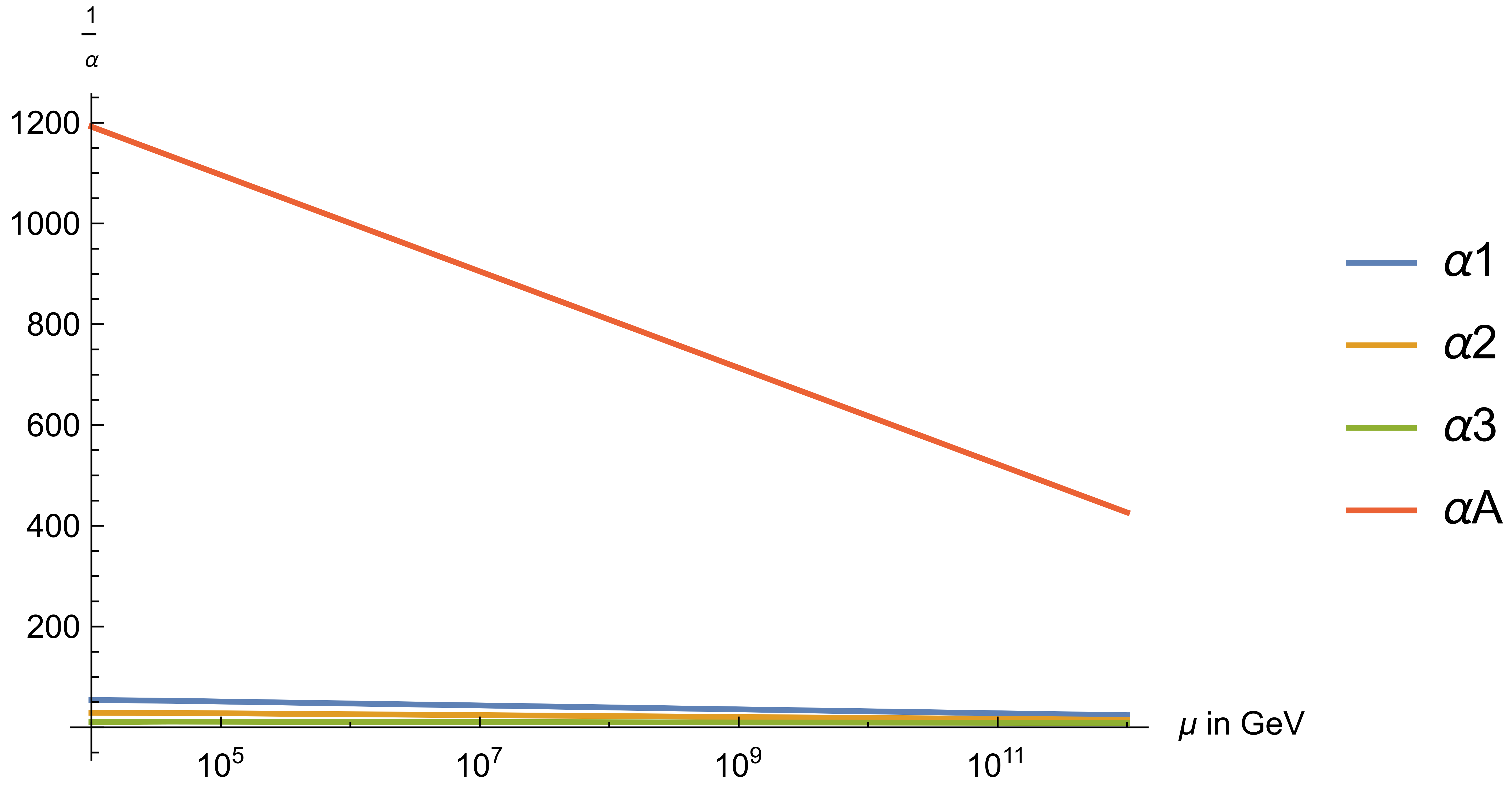
A SUSY example

		$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_A$
$\mathbf{Q}_L^f$	$f = 1, 2, 3$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$-1/48$
$u_R^{c,f}$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$97/48$
$d_R^{c,f}$		$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$-95/48$
$\mathbf{L}_L^f$		$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$-1/48$
$e_R^{c,f}$		$\mathbf{1}$	$\mathbf{1}$	1	$-95/48$
$\nu_R^{c,f}$		$\mathbf{1}$	$\mathbf{1}$	0	$97/48$
H_1		$\mathbf{1}$	$\mathbf{2}$	$1/2$	-2
H_2		$\mathbf{1}$	$\mathbf{2}$	$1/2$	2
$\psi_L^{\mathbf{L}_i}$		$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$35/8$
$(\psi_R^{\mathbf{L}_i})^c$	$i = 1, \cdots, N_{\mathbf{L}}$	$\mathbf{1}$	$\mathbf{2}$	$+1/2$	$9/2$
ψ_L^e		$\mathbf{1}$	$\mathbf{1}$	$+1$	0
$(\psi_R^e)^c$	$j = 1, \cdots, 2N_{\mathbf{L}}$	$\mathbf{1}$	$\mathbf{1}$	-1	0
ψ_L^d		$\mathbf{3}$	$\mathbf{1}$	$-2/3$	$5/4$
$(\psi_R^d)^c$	$k = 1, \cdots, 2N_{\mathbf{L}}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$+2/3$	$-9/8$
$\psi_L^{\mathbf{Q}_m}$		$\mathbf{3}$	$\mathbf{2}$	$+1/6$	2
$(\psi_R^{\mathbf{Q}_m})^c$	$m = 1, \cdots, N_{\mathbf{L}}$	$\bar{\mathbf{3}}$	$\mathbf{2}$	$-1/6$	$-15/8$
S		$\mathbf{1}$	$\mathbf{1}$	0	$1/8$
S'		$\mathbf{1}$	$\mathbf{1}$	0	$-1/8$
S_2		$\mathbf{1}$	$\mathbf{1}$	0	$-3/2$
S_2'		$\mathbf{1}$	$\mathbf{1}$	0	$11/8$

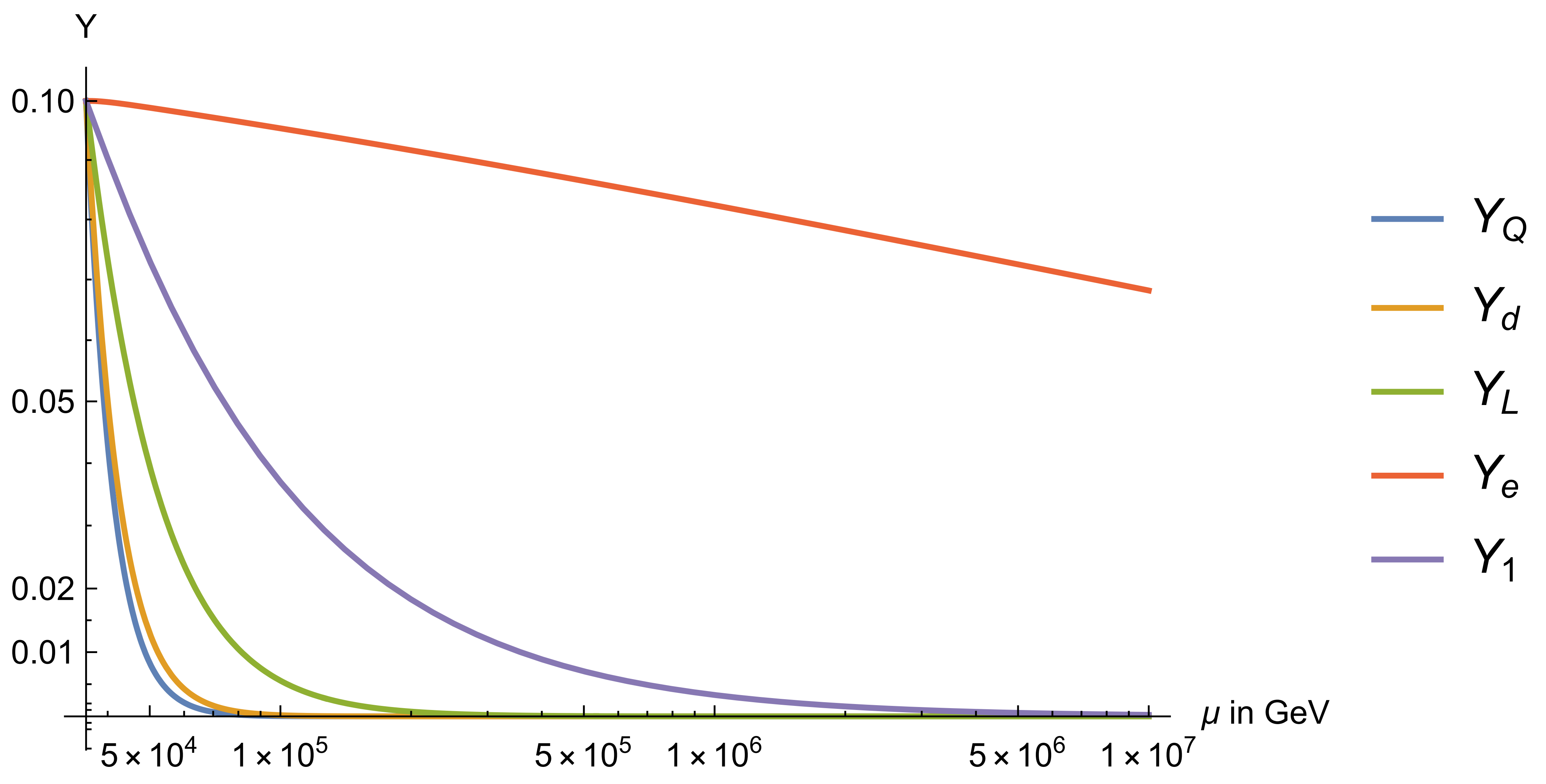
SUSY, as a bonus, allows easily to unify the couplings



1/α
50
40
30
20
10
10^6
10^9
10^12
10^15
μ in GeV
α1
α2
α3



1/α
1200
1000
800
600
400
200
μ in GeV
10^5
10^7
10^9
10^11
α1
α2
α3
αA

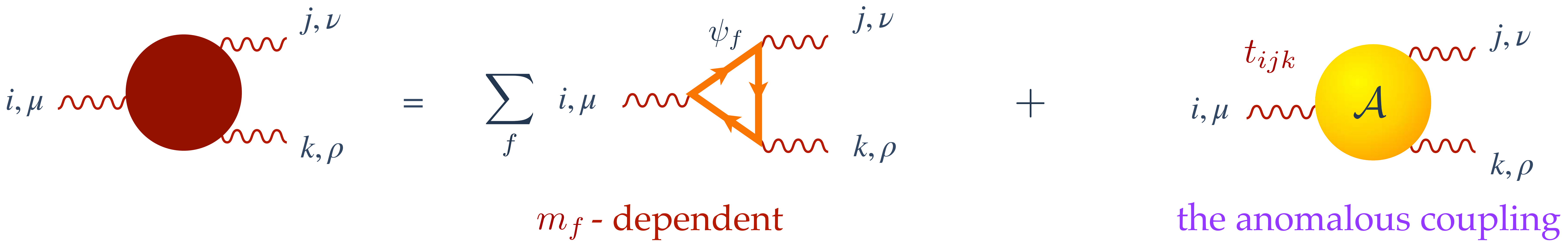

Y
0.10
0.05
0.02
0.01
5 × 10^4
1 × 10^5
5 × 10^5
1 × 10^6
5 × 10^6
1 × 10^7
μ in GeV
Y_Q
Y_d
Y_L
Y_e
Y_1

Conclusions

In summary, we have build models whith an anomalous Z’ in a range of energies and free of anomalies above a scale much below the Planck scale.

In a SUSY set-up, we can find models that allow to unify the couplings.

Work in progress …



i, μ
j, ν
k, ρ
=
∑ f
ψ_f
+
t_ijk
𝒜
m_f - dependent
the anomalous coupling