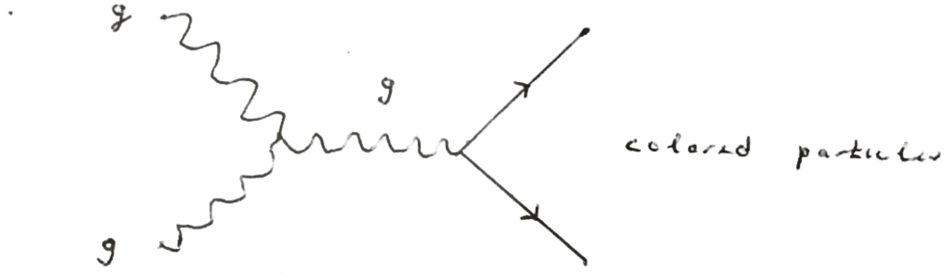
Neutral Naturalness

The biggest quantum correction to the Higgs mass in the SM is from the top loop. We would therefore expect the particles that cancel the top loop, the "top partners", to be light, with masses well below a TeV. In supersymmetric theories the top partners are the scalar partners of the top quarks, the "stops". In composite Higgs models the top partners are new fermions that are grouped together with the top quark in a representation of the global symmetry of which the Higgs is a pNGB. The non-discovery of the top partners at the LHC has led to these theories being severely fine tuned, at the per cent level or worse in simple models.

The reason that the LHC limits on these top partners are so strong is because they carry charge under SM color. Since the LHC is a hadron collider, it has tremendous reach for colored particles.



Since the top partners must be related to the top quark by a symmetry for the cancellation to work, and the top quark is colored, naively one would expect that the top partners would also be colored.

However, in general the top partners need not be colored. This is characteristic of scenarios in which the top and partners are related only by a discrete symmetry. In such a scenario, the bounds on the top partners are much weaker. Theories in which the top partners are uncolored are said to exhibit "neutral naturalness". The Mirror Twin Higgs (MTH) model is the best-known example.

In theories of neutral naturalness, although the top partners are not charged under the strong interactions, in some models they are charged under the weak and electromagnetic interactions. The top partners can be either scalars or fermions, depending on construction

Let us explore the conditions for neutral naturalness a little further. Consider a supersymmetric rotation,

$$q_\alpha \rightarrow \tilde{q}_\alpha$$

same color index

Supersymmetry commutes with the gauge interactions. If the top quark is colored, its scalar superpartner is also colored. Follows immediately from the form of the supersymmetric transformation.

Consider the top Yukawa coupling in the model of collective symmetry breaking that we studied,

$$\lambda_1 \hat{H}_1^\dagger \psi t_1^c + \lambda_2 \hat{H}_2^\dagger \psi t_2^c$$

The top partners are the extra fermion T in ψ and one linear combination of t_1^c and t_2^c, labelled T^c. Since the global $[SU(3)]^2$ symmetry commutes with color, the top partners are colored.

If we wish to construct a model of neutral naturalness, the symmetry that protects the Higgs mass should be one that does not commute with SM color.

Let us explore neutral naturalness in the form of the MTH model. Consider a scalar field H which transforms as a fundamental under a global $SU(4) \times U(1)$ symmetry. The potential for H takes the form,

$$V(H) = -m^2 |H|^2 + \lambda |H|^4$$

The global symmetry is broken to $SU(3) \times U(1)$, resulting in 7 Goldstone bosons. We parametrize the vev of H as f,

$$\langle H \rangle = \sqrt{\frac{m^2}{2\lambda}} = f$$

Now gauge an $SU(2)_A \times SU(2)_B$ subgroup of the global $SU(4) \times U(1)$ symmetry. Eventually we will identify $SU(2)_A$ with $SU(2)_L$ of the SM, while $SU(2)_B$ will correspond to a "twin" $SU(2)$. Under the gauge symmetry,

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

where H_A will eventually be identified with the SM Higgs, while H_B is its "twin partner".

Now the Higgs potential receives quadratically divergent contributions at one loop from the gauge interactions,

$$\Delta V = \frac{9\, g_A^2}{64\pi^2} H_A^\dagger H_A + \frac{9\, g_B^2}{64\pi^2} H_B^\dagger H_B$$

We impose a Z_2 "twin symmetry" under which $A \longleftrightarrow B$, so that $g_A = g_B = g$. Then the quadratically divergent contributions to the potential take the form,

$$\Delta V = \frac{9 g^2}{64\pi^2} \underbrace{\left(H_A^\dagger H_A + H_B^\dagger H_B \right)}_{\text{invariant under } SU(4) \times U(1)\,!}$$

We see that the one loop quadratically divergent contributions to the Higgs potential respect the full $SU(4) \times U(1)$ global symmetry. They do not contribute to the mass of the Goldstones.

As a consequence of the discrete twin symmetry, the quadratic terms in the Higgs potential respect the larger global symmetry. Even though the gauge interactions constitute a hard breaking of the global symmetry the Goldstones are prevented from acquiring a quadratically divergent mass.

This mechanism can also be employed to cancel the quadratically divergent contributions from the top Yukawa. Add to the theory twin top quarks and write the top Yukawa couplings as

$$y_t H_A Q_A t_A^c + y_t H_B Q_B t_B^c$$

Here (Q_A, t_A^c) and (Q_B, t_B^c) are only related by the discrete Z_2 symmetry. While Q_A and t_A^c carry charge under SM color, Q_B and t_B^c are assumed to carry charge under a twin color group $SU(3)_B$. Our color group $SU(3)_A$ is related to $SU(3)_B$ by the Z_2 twin symmetry.

The quadratically divergent contributions to the Higgs potential take the form,

$$\Delta V = \frac{3 y_t^2}{8\pi^2} \Lambda^2 \left(H_A^+ H_A + H_B^+ H_B \right)$$

Once again, this is invariant under the full $SU(4) \times U(1)$ global symmetry, and does not contribute to the mass of the Goldstones.

Let us explore how the cancellation of quadratic divergences from the top Yukawa coupling arises in the low energy theory of the Goldstone bosons. We parametrize the Goldstone bosons as $\Pi(x) = \sum_A \pi^A(x) T^A$, where A runs over the 7 broken generators. We can parametrize Π as

$$\Pi = \left(\begin{array}{ccc|c} 0 & 0 & 0 & h_1 \\ 0 & 0 & 0 & h_2 \\ 0 & 0 & 0 & h_3 \\ \hline h_1^+ & h_2^+ & h_3^+ & h_0 \end{array}\right)$$

where h_1, h_2 and h_3 are complex and h_0 is real. Then the object

$$\hat{H} = e^{i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix} + i \begin{pmatrix} h_1 \\ h_2 \\ h_3 \\ h_0 \end{pmatrix} + \cdots$$

transforms linearly under $SU(4) \times U(1)$, and can be used to write down the low energy Lagrangian for the Goldstone fields. In this basis the object

$$h = \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

is the Higgs doublet of the SM.

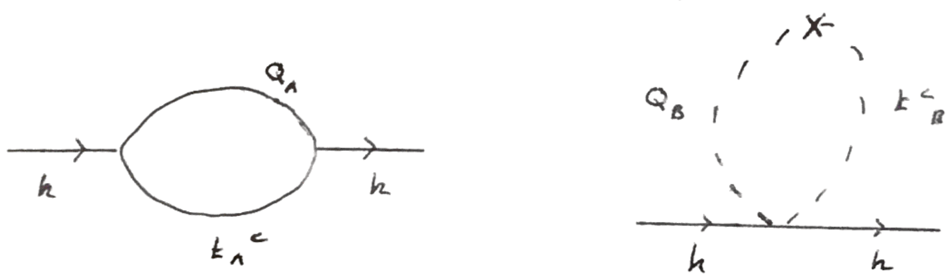
The top Yukawa coupling is given by,

$$y_t \hat{H}_A Q_A t_A^c + y_t \hat{H}_B Q_B t_B^c$$

We write out $\hat{H}_A$ and $\hat{H}_B$ in terms of the Goldstone fields. For simplicity, we keep track of just h. We obtain,

$$y_t h Q_A t_A^c + y_t \left(f - \frac{|h|^2}{2f} \right) Q_B t_B^c$$

There are two diagrams that contribute to the mass term for h at one loop.



Remarkably, the quadratic divergences of these two diagrams cancel exactly! The diagrams have exactly the same form as in the case of collective symmetry breaking that we studied earlier. However, now the top partners in Q_B and t^c_B are charged, not under SM color, but under a different twin color group.

Note that the twin symmetry that protects the Higgs mass does not commute with SM color, exactly as expected.