# The New and gauge invariant Littlest Higgs model with T-parity

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- Non gauge invariance of the Littlest Higgs model with T-parity (LHT)
- Building the New Littlest Higgs model with T-parity (NLHT)
- Conclusions

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**LHT**

# Continuous symmetries: global symmetry

[Arkani-Hamed et al., 2002] [Cheng & Low, 2004]

**LHT** is an **EFT** that try to address the **fine tunning** problem of the **Higgs mass** in the SM assuming that the Higgs boson is a **composite state** of a **strong interacting sector** below the TeV scale. Hence it can be described by a $\boldsymbol{nl\sigma}$ **model**.

**Global group:**

$$\mathrm{G} = SU(5) \xrightarrow{\Sigma_0} SO(5)$$

where $\Sigma_0 = \begin{pmatrix} 0 & 0 & 1_{2\times2} \\ 0 & 1 & 0 \\ 1_{2\times2} & 0 & 0 \end{pmatrix}$ at the scale $f \approx 1-5$ TeV leading to 14 Goldstone bosons.

$\Pi = \pi^a X^a$, 14 GB **including the Higgs**.

$T^a\Sigma_0 + \Sigma_0 T^{aT} = 0;$ 10 broken generators

$X^a\Sigma_0 - \Sigma_0 X^{aT} = 0;$ 14 broken generators

Following **CCWZ** we introduce:

$$\xi = e^{i\frac{\Pi}{f}} \xrightarrow{G} V\xi U^\dagger = U\xi\Sigma_0 V^T\Sigma_0$$

$$\Sigma = \xi\Sigma_0\xi^T \xrightarrow{G} V\Sigma V^T$$

$V \in SU(5)$

$U = U(\Pi, V) \in SO(5)$

LHT

# Continuous symmetries: gauge symmetry

[Arkani-Hamed et al., 2002] [Cheng & Low, 2004]
[Illana & Pérez-Poyatos, 2021]

***Collective symmetry breaking*** idea: *the Higgs mass is proportional to two or more couplings that together break the global symmetry avoiding quadratic divergences.*

**Gauge group:** $G_g = ([SU(2)\times U(1)]_1 \times [SU(2)\times U(1)]_2 \subset SU(5)) \overset{\Sigma_0}{\to} (SU(2)_L \times U(1)_Y \subset SO(5))$

- Gauge generators: $(Q_1^a, Y_1)$, $(Q_2^a, Y_2)$. Gauge bosons: $(W_1^a, B_1)$, $(W_2^a, B_2)$, $(a = 1-3)$
- Broken gauge generators $\{X_g^\sigma\}$: $Q_1^a - Q_2^a,\ Y_1 - Y_2 \Longrightarrow \frac{W_1^a - W_2^a}{\sqrt{2}}, \frac{B_1 - B_2}{\sqrt{2}} = W_H^\pm,\ Z_H,\ A_H$ get masses order $f$.
- Unbroken gauge generators $\{T_g^\sigma\}$ : $Q_1^a + Q_2^a,\ Y_1 + Y_2 \Longrightarrow \frac{W_1^a + W_2^a}{\sqrt{2}}, \frac{B_1 + B_2}{\sqrt{2}} = W^\pm,\ Z,\ A$ remain massless at this stage.

Particularizing to an **infinitesimal transformation** in the direction of the **gauge generators**

$$\xi = e^{i\frac{\Pi}{f}} \overset{G}{\to} V\xi U^\dagger = U\xi\Sigma_0 V^T\Sigma_0$$

$$U = e^{i\sigma^b T^b} \approx 1 + i\sigma^b T^b$$

**Ansatz:** $$\sigma^b = \sum_{n=0}^{\infty} \frac{\sigma_n^b}{f^n}$$

$$V_g = V_g \approx 1 + i\alpha_g^\sigma X_g^\sigma + i\beta_g^\sigma T_g^\sigma$$

$$U_g = 1 + i\beta_g^\sigma T_g^\sigma - \frac{1}{2f}\alpha_g^\sigma [X_g^\sigma, \Pi] \sim T^\sigma$$ all $SO(5)$ generators

**LHT** **Goldstone bosons**

[Arkani-Hamed et al., 2002] [Cheng & Low, 2004]

Under the SM gauge group $SU(2)_L \times U(1)_Y$, the Goldstone matrix $\Pi$ decomposes as:

$$\Pi:\ 1_0(\eta) \oplus 2_{1/2}(H) \oplus 3_0(\omega) \oplus 3_1(\Phi),$$

$$H = \begin{pmatrix} -i\pi^+ \\ \frac{v+h+i\pi^0}{\sqrt{2}} \end{pmatrix},\quad \omega = \begin{pmatrix} -\frac{\omega^0}{2} & -\frac{\omega^+}{\sqrt{2}} \\ -\frac{\omega^-}{\sqrt{2}} & \frac{\omega^0}{2} \end{pmatrix},\quad \Phi = \begin{pmatrix} -i\phi^{++} & -i\frac{\phi^+}{\sqrt{2}} \\ -i\frac{\phi^+}{\sqrt{2}} & \frac{-i\phi^0+\phi^P}{2} \end{pmatrix}$$

The scalar fields $\eta, \omega^\pm, \omega^0$ are the WBGB *eaten* by $A_H, W_H^\pm, Z_H$.

When $H$ gets a *vev:* $SU(2)_L \times U(1)_Y \xrightarrow{\langle H\rangle = v} U(1)_Q$. $W^\pm,\ Z$ get a mass order $v$ after *eating* the WBGB $\pi^\pm,\ \pi^0$.

<u>**Physical scalars**</u>: $\boldsymbol{h}$ and the components of the complex triplet $\boldsymbol{\Phi}$. Total: $1\ +\ 6\ =$ **7 scalars.**

**LHT**

# Discrete symmetry: T-parity

[Arkani-Hamed et al., 2002] [Cheng & Low, 2004]

New heavy particles at the **TeV scale couple** to **SM particles** → **Conflicts with EWPD**.

**Solution: T-parity** discrete symmetry → **SM** particles **T-even** and most of the **new heavy particles T-odd (pair produced).**

Action of T-parity over the gauge group:

$(g_1, g_1')$ $(g_2, g_2')$

$$[SU(2) \times U(1)]_1 \overset{T}{\leftrightarrow} [SU(2) \times U(1)]_2$$

**Same couplings constants to each of the gauged subgroups** $g_1 = g_2 = \sqrt{2}g,\ g_1' = g_2' = \sqrt{2}g'$.

**Heavy gauge bosons** $W_H^{\pm}, Z_H, A_H \Longrightarrow$ **T-odd** and **SM gauge bosons** $W^{\pm},\ Z,\ A\ \Longrightarrow$ **T-even**.

On the Goldstone fields:

$$\Pi \overset{T}{\rightarrow} -\Omega\Pi\Omega \Longrightarrow \xi \overset{T}{\rightarrow} \Omega\xi^{\dagger}\,\Omega$$
$$\Omega = diag(-1,-1,1,-1,-1)$$

**Higgs doublet T-even and the rest T-odd.**

$$\Omega \in Z[[SU(2) \times U(1)]_1 \times [SU(2) \times U(1)_2]]$$

**LHT**

# Gauge and Goldstone bosons kinetic terms

[Arkani-Hamed et al., 2002]

[Cheng & Low, 2004]

**Gauge and T-parity invariant** kinetic term for the Goldstone bosons

$$\mathcal{L}_s = \frac{f^2}{8}\mathrm{Tr}[(D^\mu\Sigma)^\dagger D_\mu\Sigma]$$

where the covariant derivative is defined as

$$D_\mu\Sigma = \partial_\mu\Sigma - \sqrt{2}i\sum_{j=1}^{2}[g\,W_{j\mu}^a(Q_j^a\Sigma + \Sigma Q_j^{aT}) - g'B_{j\mu}(Y_j\Sigma + \Sigma Y_j^T)]$$

**Gauge interactions break** explicitly the **global symmetry.**

Gauge bosons kinetic term and self-interactions

$$\sum_{j=1}^{2}\left[-\frac{1}{2}\mathrm{Tr}\left(\widetilde{W}_{j\mu\nu}\widetilde{W}_j^{\mu\nu}\right) - \frac{1}{4}B_{j\mu\nu}B_j^{\mu\nu}\right]$$

**LHT**

# Fermions (leptons) and non gauge invariance

**Considered optional. Gauge generators $\{(Q_1^a - Q_2^a, Y_1 - Y_2)\}$ do not mix different subspaces.**

[Cheng & Low, 2004]
[del Aguila et al., 2019]

**Different T-parity assignations** found in the literature.

For fermions one introduces

$$\Psi_1 = \begin{pmatrix} -i\sigma^2 l_{1L} \\ 0 \\ 0_2 \end{pmatrix}, \quad \Psi_2 = \begin{pmatrix} 0_2 \\ 0 \\ -i\sigma^2 l_{2L} \end{pmatrix}, \quad \Psi_R = \begin{pmatrix} -i\sigma^2 (\tilde{l}_-^c)_R \\ i(\chi_\pm)_R \\ -i\sigma^2 l_{HR} \end{pmatrix}, \quad \Psi_L = \begin{pmatrix} -i\sigma^2 (\tilde{l}_-^c)_L \\ 0 \\ 0_2 \end{pmatrix}, \quad \Psi_L^\chi = \begin{pmatrix} 0_2 \\ i(\chi_\pm)_L \\ 0_2 \end{pmatrix}$$

Under the gauge group:

$$\Psi_1 \overset{G_g}{\rightarrow} V_g^* \Psi_1, \quad \Psi_2 \overset{G_g}{\rightarrow} V_g \Psi_2, \quad \Psi_R \overset{G_g}{\rightarrow} U_g \Psi_R, \quad \Psi_L \overset{G_g}{\rightarrow} U_g \Psi_L, \quad \Psi_L^\chi \overset{G_g}{\rightarrow} U_g \Psi_L^\chi$$

Under **T-parity**, **two different options** depending on the **T-parity assignation of $\chi_R$**:

| | | |
|---|---|---|
| 1. | $\Psi_1 \overset{T}{\leftrightarrow} \Omega\Sigma_0\Psi_2,\ \Psi_R \overset{T}{\leftrightarrow} \Omega\Psi_R,\ \Psi_L \overset{T}{\leftrightarrow} \Omega\Psi_L,\ \Psi_L^\chi \overset{T}{\leftrightarrow} \Omega\Psi_L^\chi$ | **T-even** $\chi_+$ |
| 2. | $\Psi_1 \overset{T}{\leftrightarrow} -\Sigma_0\Psi_2,\ \Psi_R \overset{T}{\leftrightarrow} -\Psi_R,\ \Psi_L \overset{T}{\leftrightarrow} -\Psi_L,\ \Psi_L^\chi \overset{T}{\leftrightarrow} -\Psi_L^\chi$ | **T-odd** $\chi_-$ |

- **T-even**: SM leptons $l_L = \frac{l_{1L} - l_{2L}}{\sqrt{2}}$
- **T-odd**: mirror leptons $l_{HL} = \frac{l_{1L} + l_{2L}}{\sqrt{2}}$, $l_{HR}$, mirror partner leptons $(\tilde{l}_-^c)_L, (\tilde{l}_-^c)_R$
- **Depending on the T-parity assignation**: T-even $(\chi_+)_L, (\chi_+)_R$ or T-odd $(\chi_-)_L, (\chi_-)_R$

LHT

# Fermions (leptons) and non gauge invariance

[Cheng & Low, 2004] [Illana & Pérez-Poyatos, 2021]

The mirror leptons $l_H$, receive mass from the T-invariant Yukawa Lagrangian

1. $\mathcal{L}_\kappa = -\kappa f\left(\bar{\Psi}_2\xi + \bar{\Psi}_1\Sigma_0\xi^\dagger\right)\Psi_R + h.c$ **T-even** $\chi_+$
2. $\mathcal{L}_\kappa = -\kappa f\left(\bar{\Psi}_2\xi + \bar{\Psi}_1\Sigma_0\Omega\xi^\dagger\Omega\right)\Psi_R + h.c$ **T-odd** $\chi_-$

while the T-even/odd $\chi_\pm$ and the mirror partner leptons receive a direct mass term

$$\mathcal{L}_{\tilde{M},M_\chi} = -\tilde{M}\overline{\left(\tilde{l}^c_-\right)}_L\left(\tilde{l}^c_-\right)_R - M_\chi\overline{(\chi_\pm)}_L(\chi_\pm)_R$$

Assumed to be a ***soft breaking*** of the **SO(5)** symmetry but **preserving gauge invariance.**

However, **none of the above Lagrangians is gauge invariant**. Remember that an infinitesimal $SU(2)_L \times U(1)_Y \subset SO(5)$ transformation has the form

$$U_g = 1 + i\beta_g^\sigma T_g^\sigma - \frac{1}{2f}\alpha_g^\sigma\left[X_g^\sigma, \Pi\right] \sim T^b$$

Take Yukawa Lagrangian #2

$$\mathcal{L}_\kappa \xrightarrow{G_g} -\kappa f\left(\bar{\Psi}_2 V_g^\dagger V_g \xi U_g^\dagger + \bar{\Psi}_1 V^T\Sigma_0\Omega\Sigma_0 V^*\Sigma_0\xi^\dagger U_g^\dagger\Omega\right)U_g\Psi_R + h.c$$

$\Omega$ commutes with the gauge generators but **not with all SO(5) generators**. The T-transformed of $\bar{\Psi}_2\xi\Psi_R$ is **not compatible with gauge invariance!**

NLHT

# Mass terms for the mirror partner fermions and $\chi$

[Illana & Pérez-Poyatos, 2021]

- The presence of **$\Omega$ spoils the gauge invariance** of the Yukawa Lagrangian **#2**. One must choose **option #1** $\Longrightarrow$ **gauge invariance fixes the T-parity of** $\chi_+$.
- The non linear transformation $U_g$ **also fixes the fermion content** of a SO(5) multiplet. They must be **completed** since SO(5) generators mix all its components. Mirror partner fermions and $\chi_+$ **not optional**!
- The **direct mass term** for the mirror partner fermions and $\chi_+$ also **spoils gauge invariance** since one **can not separate** components of a SO(5) multiplet to provide them different masses.

**Proposal:**

To provide masses to the mirror partner fermions and $\chi_+$ **preserving gauge invariance** $\Longrightarrow$ **complete the SU(5) multiplets**

$$\Psi_1 = \begin{pmatrix} -i\sigma^2 l_{1L} \\ i\chi_{1L} \\ -i\sigma^2 \tilde{l}^c_{1L} \end{pmatrix}, \quad \Psi_2 = \begin{pmatrix} -i\sigma^2 \tilde{l}^c_{2L} \\ i\chi_{2L} \\ -i\sigma^2 l_{2L} \end{pmatrix}, \quad \Psi_R = \begin{pmatrix} -i\sigma^2 (\tilde{l}^c_-)_R \\ i(\chi_+)_R \\ -i\sigma^2 l_{HR} \end{pmatrix},$$

so that the combination $(\chi_+)_L = \frac{\chi_{1L}+\chi_{2L}}{\sqrt{2}}$ pairs to $(\chi_+)_R$

and the combination $(\tilde{l}^c_-)_L = \frac{\tilde{l}^c_{1L}+\tilde{l}^c_{2L}}{\sqrt{2}}$ pairs to $(\tilde{l}^c_-)_R$.

NLHT

# Global symmetry group

[Illana & Pérez-Poyatos, 2021]

The mirror leptons $l_H$, the T-even $\chi_+$ and the T-odd mirror partner leptons receives their masses from the usual Yukawa Lagrangian

$$\mathcal{L}_\kappa = -\kappa f\left(\bar{\Psi}_2\xi + \bar{\Psi}_1\Sigma_0\xi^\dagger\right)\Psi_R + h.c$$

Full SU(5) invariant with complete multiplets.

But still the T-odd $(\chi_-)_L = \frac{\chi_{1L}-\chi_{2L}}{\sqrt{2}}$ and the T-even $\left(\tilde{l}_+^c\right)_L = \frac{\tilde{l}_{1L}^c-\tilde{l}_{2L}^c}{\sqrt{2}}$ need to be paired to a $(\chi_-)_R$ and $\left(\tilde{l}_+^c\right)_R$ to receive a **vector-like mass at least order $f$**. They **can not live in a new right-handed SO(5) multiplet** because it must be completed by gauge invariance.

**Proposal:**

To introduce the additional right-handed fermions, extend the global group by a factor

Generated by the **same set of matrices $(Q_1^a, Y_1)$, $(Q_2^a, Y_2)$**

$$\begin{array}{ccc} SU(5) & \times & \left([SU(2)\times U(1)]_1'' \times [SU(2)\times U(1)]_2''\right) \\ \downarrow \Sigma_0 & & \downarrow \hat{\Sigma}_0 \\ SO(5) & \times & [SU(2)\times U(1)]'' \end{array}$$

Breaking at the same scale $f$.

New symmetric tensor. We take $\hat{\Sigma}_0 = \Sigma_0$

NLHT

# New Goldstone fields and gauge group

[Illana & Pérez-Poyatos, 2021]

The spontaneous breaking of the extra piece of the global group induces **4 new Goldstone fields** parametrized by

$$\hat{\Pi} = \hat{\pi}^a \hat{X}^a, \qquad \hat{X}^a = \{Q_1^a - Q_2^a, Y_1 - Y_2\}$$
$$\hat{\xi} = e^{i\hat{\Pi}/f}, \qquad \hat{\xi} \xrightarrow{G} \hat{V}\hat{\xi}\hat{U}^\dagger = \hat{U}\hat{\xi}\Sigma_0\hat{V}^T\Sigma_0$$
$$\hat{\Sigma} = \hat{\xi}\hat{\Sigma}_0\hat{\xi}^T, \qquad \hat{\Sigma} \xrightarrow{G} \hat{V}\hat{\Sigma}\hat{V}^T$$

$$\hat{V} \in [SU(2)\times U(1)]_1'' \times [SU(2)\times U(1)]_2''$$
$$\hat{U} \in [SU(2)\times U(1)]''$$

**Gauge group:**

$$G_g = [SU(2)\times U(1)]_1 \times [SU(2)\times U(1)]_2 \subset \left([SU(2)\times U(1)]_1' \times [SU(2)\times U(1)]_2' \subset SU(5)\right) \times \left([SU(2)\times U(1)]_1'' \times [SU(2)\times U(1)]_2''\right)$$
$$\downarrow \Sigma_0, \hat{\Sigma}_0$$
$$SU(2)_L \times U(1)_Y \subset \left([SU(2)\times U(1)]' \subset SO(5)\right) \times \left([SU(2)\times U(1)]'' \subset [SU(2)\times U(1)]_1'' \times [SU(2)\times U(1)]_2''\right)$$

**Same gauge group and number of gauge bosons** as in the original LHT.

Particularizing for a gauge transformation, it is verified:

$$V_g = \hat{V}_g \approx 1 + i\alpha_g^\sigma X_g^\sigma + i\beta_g^\sigma T_g^\sigma$$
$$U_g = 1 + i\beta_g^\sigma T_g^\sigma - \frac{1}{2f}\alpha_g^\sigma [X_g^\sigma, \Pi] \sim T^\sigma \text{ all } SO(5) \text{ generators}$$
$$\hat{U}_g = 1 + i\beta_g^\sigma T_g^\sigma - \frac{1}{2f}\alpha_g^\sigma [X_g^\sigma, \hat{\Pi}] \sim T_g^\sigma \text{ only } [SU(2)\times U(1)]'' \text{ generators.}$$

**NLHT**

# New Goldstone fields and T-parity

[Illana & Pérez-Poyatos, 2021]

Under the SM gauge group, the new Goldstone matrix $\hat{\Pi}$ decomposes

$$\hat{\Pi}: 1_0(\hat{\eta}) \oplus 3_0(\hat{\omega})$$

$$\hat{\omega} = \begin{pmatrix} -\frac{\hat{\omega}^0}{2} & -\frac{\hat{\omega}^+}{\sqrt{2}} \\ -\frac{\hat{\omega}^-}{\sqrt{2}} & \frac{\hat{\omega}^0}{2} \end{pmatrix}$$

Under T-parity, all the **new Goldstone bosons are T-odd**

$$\hat{\Pi} \xrightarrow{T} -\hat{\Pi} \Longrightarrow \hat{\xi} \xrightarrow{T} \hat{\xi}^\dagger$$

They have the **same quantum numbers and T-parity** as the WBGB of the original LHT$\Longrightarrow$ **kinetic mixing**

$$\mathcal{L}_s = \frac{f^2}{8}\mathrm{Tr}[(D^\mu\Sigma)^\dagger D_\mu\Sigma] + \frac{f^2}{8}\mathrm{Tr}\left[\left(D^\mu\hat{\Sigma}\right)^\dagger D_\mu\hat{\Sigma}\right]$$

Contains mass terms for the gauge bosons. They are a $\sqrt{2}$ factor heavier than in the LHT.

A linear combination of $\eta$ & $\hat{\eta}$ , $\omega^\pm$ & $\hat{\omega}^\pm$, $\omega^0$ & $\hat{\omega}^0$ are the **new** WBGB *eaten* by $A_H, W_H^\pm, Z_H$.

The **remaining combination** is **physical**!$\Longrightarrow$ **4 new physical scalars** together with the Higgs boson and the 6 components of the T-odd complex triplet $\Phi$. **Total: 11 physical scalars**

**NLHT**

# New right-handed fermions

[Illana & Pérez-Poyatos, 2021]

For the remining fermions introduce **their right-handed components in a multiplet that transforms under the extra piece of the global group**

$$\hat{\Psi}_R = \begin{pmatrix} -i\sigma^2 (\tilde{l}^c_+)_R \\ i(\chi_-)_R \\ 0_{2\times 2} \end{pmatrix}, \qquad \hat{\Psi}_R \overset{G_g}{\to} \hat{U}_g \hat{\Psi}_R, \qquad \hat{\Psi}_R \overset{T}{\leftrightarrow} -\Omega\Psi_R$$

This kind of transformation does not mix subspaces.

Couple it through $\hat{\xi}$ to $\Psi_1$ and $\Psi_2$ in such a way that the mass terms of all fermions are contained in

$$\mathcal{L}_\kappa = -\kappa f\left(\overline{\Psi}_2 \xi + \overline{\Psi}_1 \Sigma_0 \xi^\dagger\right)\Psi_R + h.c$$

$$\mathcal{L}_{\hat{\kappa}} = \hat{\kappa} f\left(\overline{\Psi}_2 \hat{\xi} - \overline{\Psi}_1 \Sigma_0 \hat{\xi}^\dagger\right)\hat{\Psi}_R + h.c$$

Complete multiplets leads to a full $SU(5)$ invariant Lagrangian.

Lagrangian neither $SU(5)$ nor $[SU(2)\times U(1)]_1'' \times [SU(2)\times U(1)]_2''$ invariant but preserves the gauge symmetry.

No quadratic divergences to the Higgs mass!

**NLHT** **Top quark**

[Arkani-Hamed et al., 2002] [Cheng & Low, 2004] Work in progress

For the top quark, one implements the ***Collective symmetry breaking mechanism*** to avoid dangerous quadratic divergences to the Higgs mass proportional to the top Yukawa

Order 1 parameters.

$$\mathcal{L}_t = -\frac{i\lambda_1}{4} f \epsilon_{ijk}\epsilon_{xy}\left[\bar{Q}_{1i}\Sigma_{jx}\Sigma_{ky} + (\bar{Q}_2\Sigma_0\Omega)_i\tilde{\Sigma}_{jx}\tilde{\Sigma}_{ky}\right]t_R - \frac{\lambda_2}{\sqrt{2}} f\left[\bar{T}_{1L}\hat{X}T_{1R} + \bar{T}_{2L}\hat{X}^* T_{2R}\right] + h.c$$

where $\{i,j,k\} = 1,2,3,\ \{x,y\} = 4,5,$ $\tilde{\Sigma} = \Omega\Sigma_0\Sigma^\dagger\Sigma_0\Omega,$ $\hat{X} = \hat{\Sigma}_{33}^{-1/2}$ and the multiplets

**Top partners** required to **cancel the quadratically divergent contribution** of the top quark to the Higgs mass.

$$Q_1 = \begin{pmatrix} -i\sigma^2\mathcal{T}_{1L} \\ iT_{1L} \\ 0_2 \end{pmatrix}, \qquad Q_2 = \begin{pmatrix} 0_2 \\ iT_{2L} \\ -i\sigma^2\mathcal{T}_{2L} \end{pmatrix}$$

$$\mathcal{T}_{rL} = \begin{pmatrix} t_{rL} \\ b_{rL} \end{pmatrix}$$

$$Q_1 \xrightarrow{G_g} V_g^* Q_1$$
$$Q_2 \xrightarrow{G_g} V_g Q_2$$
$$Q_1 \xrightarrow{T} \Omega\Sigma_0 Q_2$$
$$T_{1R} \xrightarrow{T} T_{2R}$$
$$t_R \xrightarrow{\mathrm{T}} t_R$$

After diagonalization

$$M_t = \frac{v}{\sqrt{2}}\frac{\lambda_1\lambda_2}{\sqrt{\lambda_1^2+\lambda_2^2}}, \qquad M_{T_+} = \frac{f}{\sqrt{2}}\sqrt{\lambda_1^2+\lambda_2^2}, \qquad M_{T_-} = \frac{\lambda_2}{\sqrt{2}} f$$

NLHT

# Fermionic kinetic terms

[Illana & Pérez-Poyatos, 2021] + work in progress

Finally add kinetic term and gauge interactions for all fermions

$$\mathcal{L}_{F_L} = i\overline{\Psi}_1\gamma^\mu D_\mu^*\Psi_1 + i\overline{\Psi}_2\gamma^\mu D_\mu\Psi_2$$

$$\mathcal{L}_{F_R} = i\overline{\Psi}_R\gamma^\mu\left[\partial_\mu + \frac{1}{2}\xi^\dagger D_\mu\xi + \frac{1}{2}\xi\Sigma_0 D_\mu^*(\Sigma_0\xi^\dagger)\right]\Psi_R$$

$$\mathcal{L}_{\hat{F}_R} = i\overline{\widehat{\Psi}}_R\gamma^\mu\left[\partial_\mu + \frac{1}{2}\hat{\xi}^\dagger D_\mu\hat{\xi} + \frac{1}{2}\hat{\xi}\Sigma_0 D_\mu^*(\Sigma_0\hat{\xi}^\dagger)\right]\widehat{\Psi}_R$$

Same construction for quarks

where

$$D_\mu = \partial_\mu - \sqrt{2}ig\left(W_{1\mu}^a Q_1^a + W_{2\mu}^a Q_2^a\right) + \sqrt{2}ig'\left(B_{1\mu}Y_1 + B_{2\mu}Y_2\right)$$

For leptons

$$D_\mu = \partial_\mu - \sqrt{2}ig\left(W_{1\mu}^a Q_1^a + W_{2\mu}^a Q_2^a\right) + \sqrt{2}ig'\left(B_{1\mu}Y_1 + B_{2\mu}Y_2\right) + \frac{2}{3}ig'B_\mu 1_{5\times5}$$

For quarks

and

$$\mathcal{L}_{F_t} = i\bar{t}_R\gamma^\mu\left(\partial_\mu - i\frac{2}{3}g'B_\mu\right)t_R + i\overline{T}_{1R}\gamma^\mu\left(\partial_\mu - i\frac{2}{3}g'B_\mu\right)T_{1R} + 1 \leftrightarrow 2$$

**NLHT**

# Physical masses at leading order

[Illana & Pérez-Poyatos, 2021] + work in progress

The physical masses of the particles of the model are:

1. <u>Gauge bosons</u>

A factor $\sqrt{2}$ heavier than in the original LHT.

$$M_{Z_H} = M_{W_H} = \sqrt{2} g f, \qquad M_{A_H} = \sqrt{\frac{2}{5}} g' f$$

$$M_W = \frac{g v}{2} \approx 80.4 \text{ GeV}, \qquad M_Z = \frac{v}{2}\sqrt{g^2 + g'^2} \approx 91.2 \text{ GeV}$$

2. <u>Fermions</u>

- **Mirror leptons, T-even $\chi_+$, T-odd mirror partner leptons** $\quad m_{\ell_H} = \sqrt{2}\kappa_l f$
- **Mirror quarks, T-even $\chi_+^q$, T-odd mirror partner quarks** $\quad m_{d_H} = \sqrt{2}\kappa_q f$
- **T-odd $\chi_-$ , T-even mirror partner leptons** $\quad m_{\tilde{l}_+^c} = \sqrt{2}\hat{\kappa}_l f$
- **T-odd $\chi_-^q$, T-even mirror partner quarks** $\quad m_{\tilde{q}_+^c} = \sqrt{2}\hat{\kappa}_q f$
- **Top quark and T-even top partner** $\quad M_t = \frac{v}{\sqrt{2}} \frac{\lambda_1 \lambda_2}{\sqrt{\lambda_1^2 + \lambda_2^2}} = 173 \text{ GeV}, \quad M_{T_+} = \frac{f}{\sqrt{2}}\sqrt{\lambda_1^2 + \lambda_2^2}$
- **T-odd top partner** $\quad M_{T_-} = \frac{\lambda_2}{\sqrt{2}} f$

In the LHT, when included, T-odd mirror partner leptons and T-even $\chi_+$ received masses $\widetilde{M}$ and $M_\chi$.

T-even top partner is the heaviest particle in the NLHT.

# Physical masses

[Illana & Pérez-Poyatos, 2021]

3. Physical scalar masses

- Higgs $\Longrightarrow M_h$
- $\hat{\eta} \Longrightarrow M_{\hat{\eta}}^2 = \frac{72}{5} M_h^2 \frac{T_\kappa}{3\lambda_1^2\lambda_2^2 - 6g^4 - \frac{2}{5}g'^4 - 12T_\kappa}$
- $\hat{\omega} \Longrightarrow M_{\hat{\omega}}^2 = 8M_h^2 \frac{g^4 + T_\kappa}{3\lambda_1^2\lambda_2^2 - 6g^4 - \frac{2}{5}g'^4 - 12T_\kappa}$
- $\Phi \Longrightarrow M_\Phi^2 = 2\frac{f^2}{v^2} M_h^2$

$$T_\kappa = tr\left(\kappa_l \kappa_l^\dagger \hat{\kappa}_l \hat{\kappa}_l^\dagger\right) + 3tr\left(\kappa_q \kappa_q^\dagger \hat{\kappa}_q \hat{\kappa}_q^\dagger\right)$$

Coming from the logarithmically divergent part of the CW potential. Naturally light!

$3\lambda_1^2\lambda_2^2 - 6g^4 - \frac{2}{5}g'^4 - 12T_\kappa > 0$ to allow the **SM SSB**.

Coming from the quadratically divergent part of the CW potential. **Same relation as in the original LHT**.

4. Higgs quartic coupling

$$\lambda = \frac{1}{16\pi^2}\frac{\Lambda^2}{f^2}\left(g^2 + g'^2 + 3\lambda_1^2\right) = 0.13$$

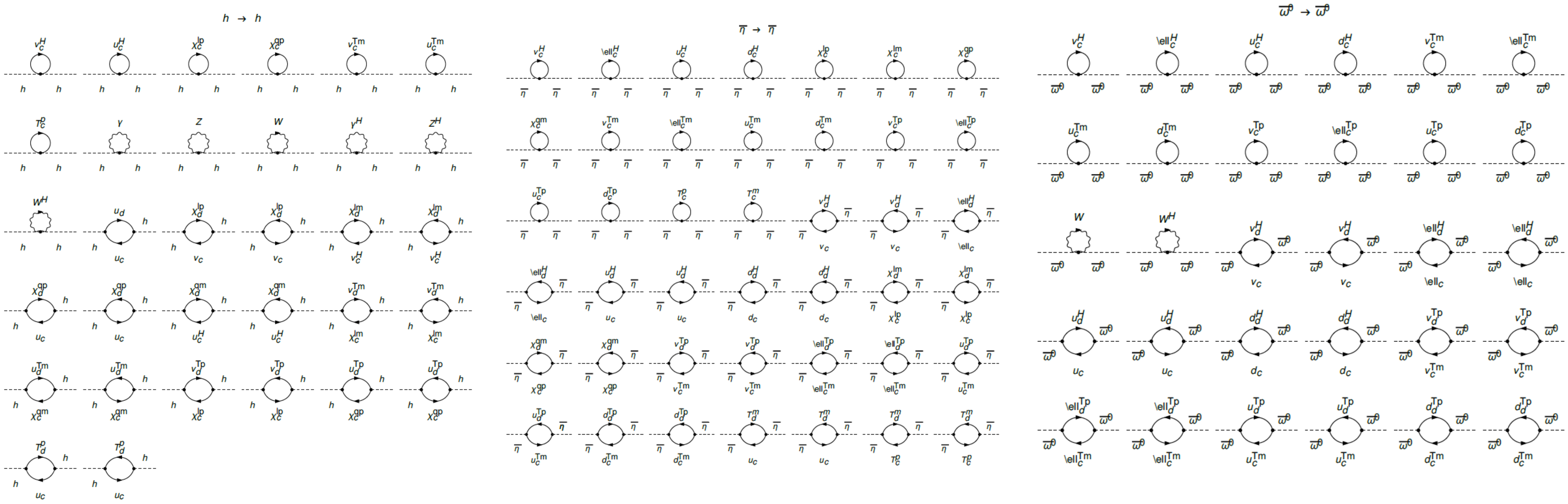
Explicit expression relating the cut-off scale $\Lambda$ and the top quark coupling $\lambda_1$.

**NLHT**

# Feynrules ⟹ FeynArts/FormCalc model file

[Work in progress]

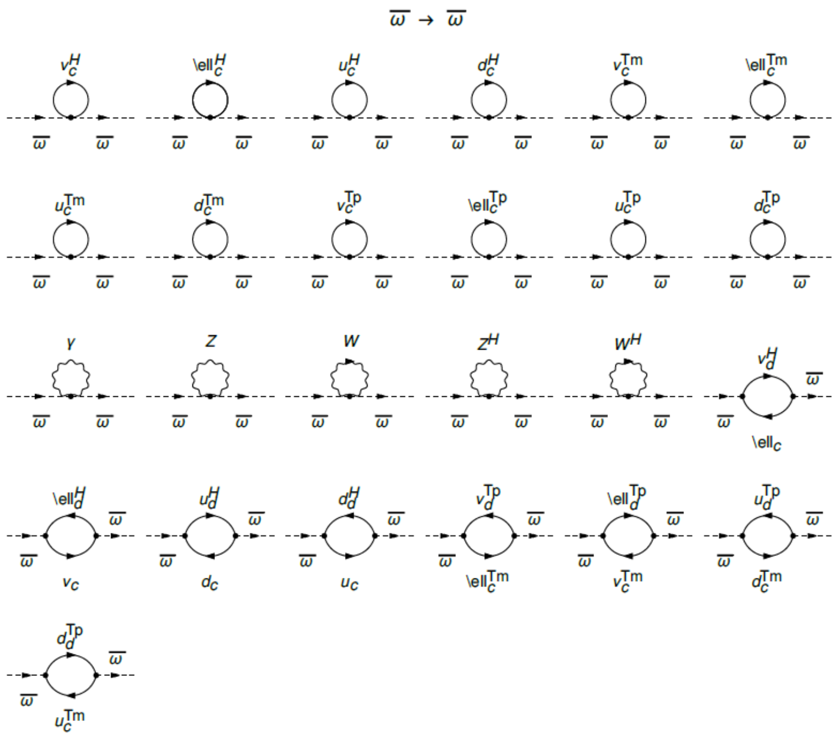
We have explicitly check the calculation of the new scalar fields masses using **the new FeynRules model file "NLHT"** done with **Thomas Hahn**



**NLHT**

# Feynrules ⟹ FeynArts/FormCalc model file

[Work in progress]




Ratio between $\hat{\omega}$ mass and higgs mass

**ratioomega = omegadiv / higgsdiv**

$$\frac{8\left(\text{Trace}[\kappa l.\kappa ldag.\kappa lhat.\kappa lhatdag]+3\,\text{Trace}[\kappa q.\kappa qdag.\kappa qhat.\kappa qhatdag]+g2^4\right)}{-12\,\text{Trace}[\kappa l.\kappa ldag.\kappa lhat.\kappa lhatdag]-36\,\text{Trace}[\kappa q.\kappa qdag.\kappa qhat.\kappa qhatdag]+3\,c1^2\,c2^2-\frac{2\,g1^4}{5}-6\,g2^4}$$

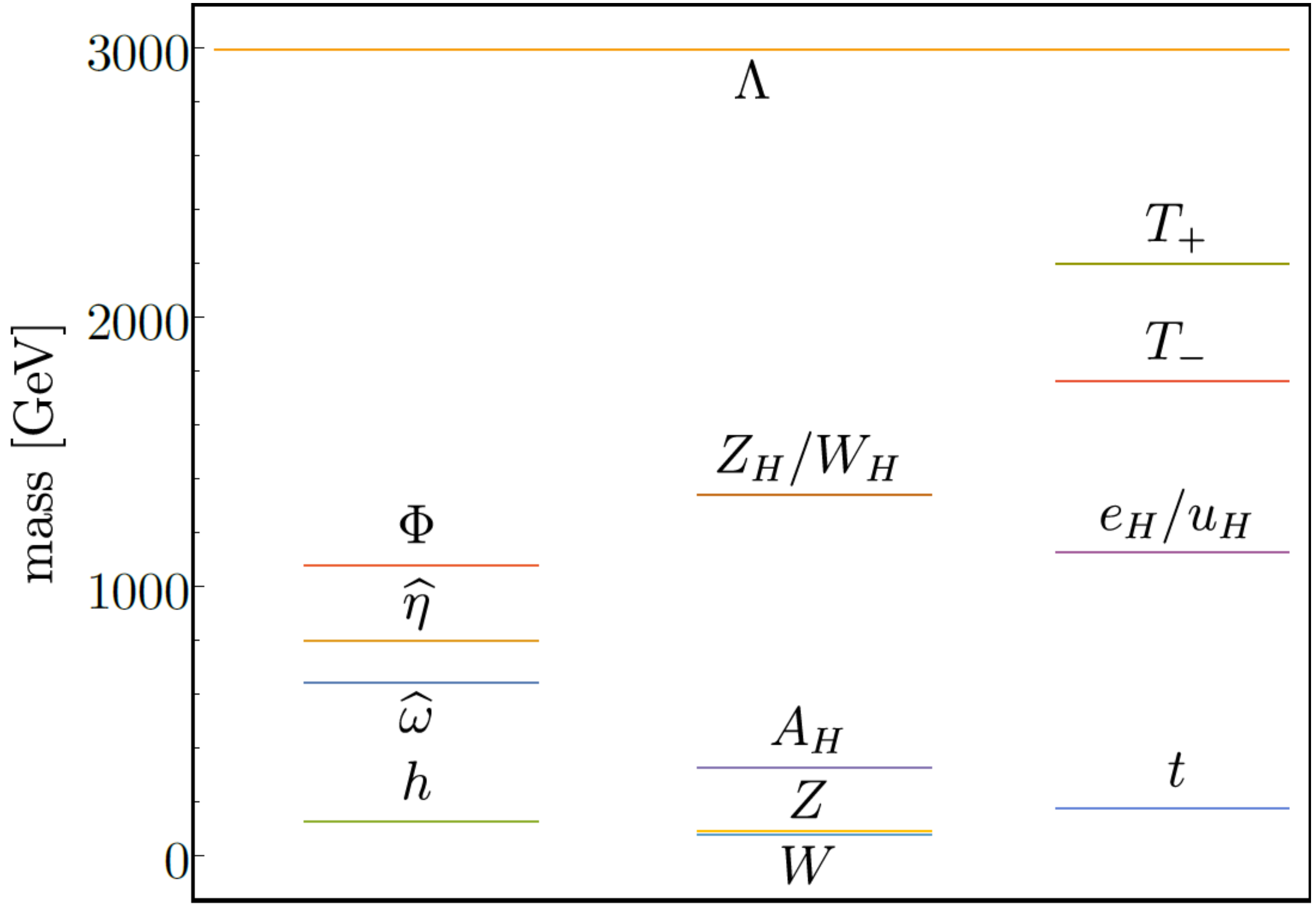
Ratio between $\hat{\eta}$ mass and higgs mass

**ratioeta = etadiv / higgsdiv**

$$\frac{72\left(\text{Trace}[\kappa l.\kappa ldag.\kappa lhat.\kappa lhatdag]+3\,\text{Trace}[\kappa q.\kappa qdag.\kappa qhat.\kappa qhatdag]\right)}{5\left(-12\,\text{Trace}[\kappa l.\kappa ldag.\kappa lhat.\kappa lhatdag]-36\,\text{Trace}[\kappa q.\kappa qdag.\kappa qhat.\kappa qhatdag]+3\,c1^2\,c2^2-\frac{2\,g1^4}{5}-6\,g2^4\right)}$$

**NLHT** **Spectrum**

[Work in progress]




For values of $f = 1.5$ TeV, $\kappa = 0.531$ and $\lambda = 1.241$

# Conclusions

- The **LHT** is **not gauge invariant** due to the **non trivial interplay** between the **non linear realization** of the **global symmetry** and **T-parity**.

- **Gauge invariance fixes** the content of the SO(5) **right-handed fermionic multiplet** $\Longrightarrow$ **mirror partner fermions** $\tilde{l}_-^c$ **and** $\chi_+$ **not optional** and the **T-parity of the latter is fixed**.

- To provide **mass terms for all fermions preserving gauge invariance**, we **completed the SU(5) left-handed multiplets** in such a way that **a combination with the right T-parity and quantum numbers pairs with the usual SO(5) quintuplet**.

- To provide mass terms to **the remaining combination, we extend the global group** by a factor $[SU(2)\times U(1)]_1'' \times [SU(2)\times U(1)]_2''$. This allows to introduce an **incomplete right-handed multiplet with the minimal content of fermion fields**. The **gauge subgroup** is still $[SU(2)\times U(1)]_1 \times [SU(2)\times U(1)]_2$ but **embeded in a larger global group**.

- The **spontaneous breaking of the extra piece** of the global group introduces **4 new light T-odd scalars**.

- **The Higgs and the new scalar masses do not receive quadratic divergences**.

- We have developed the **model file of the NLHT in FeynRules**.